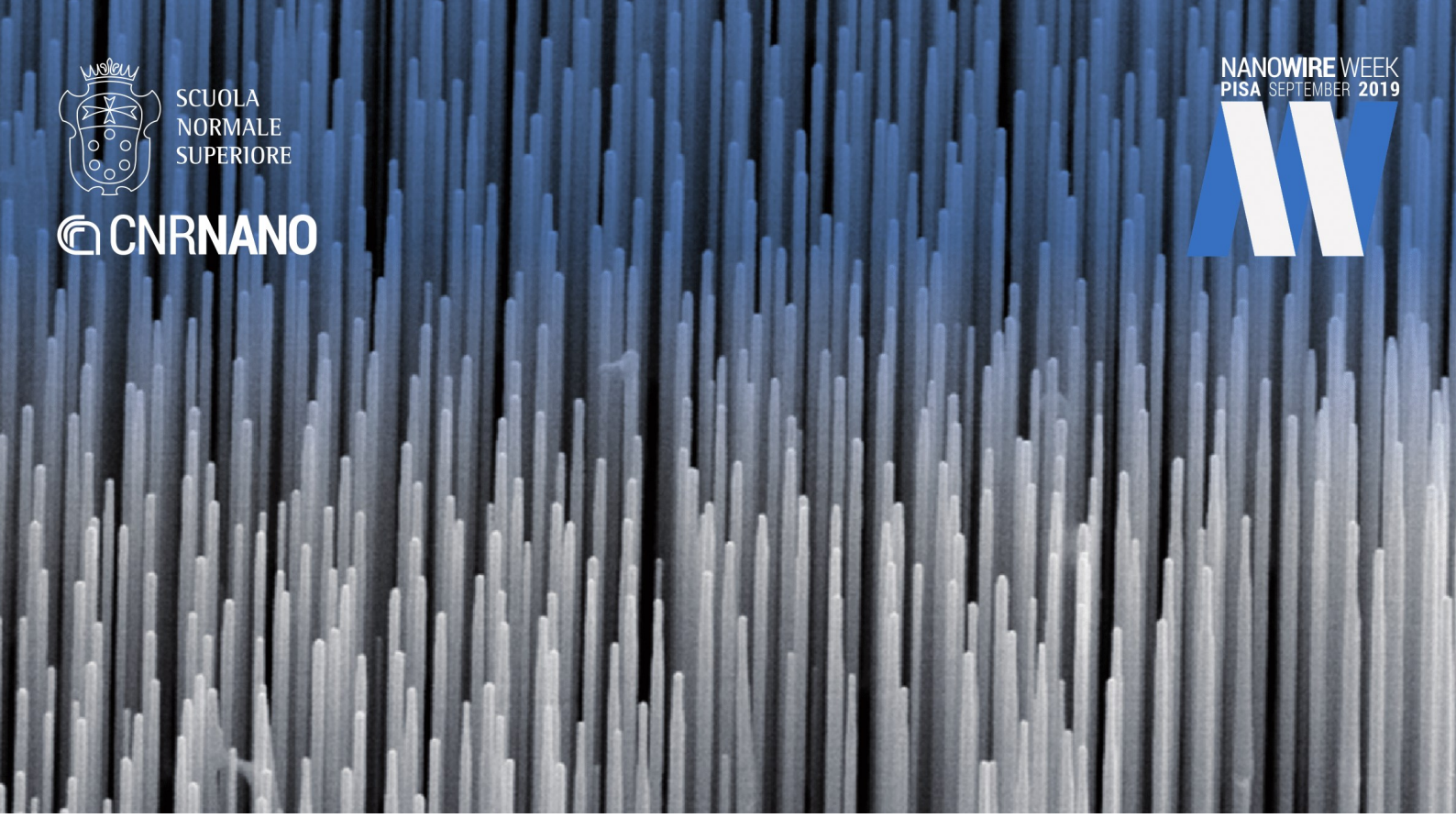

SCUOLA NORMALE SUPERIORE

CNRNANO

NANOWIRE WEEK PISA SEPTEMBER 2019

23 - 27 SEPTEMBER 2019 PISA, ITALY

NANOWIRE WEEK 2019
BOOK OF ABSTRACTS

SCUOLA NORMALE SUPERIORE

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ISTITUTO NANOSCIENZE CONSIGLIO NAZIONALE DELLE RICERCHE

NANOWIRE WEEK PISA SEPTEMBER 2019

NANOWIRE WEEK

PISA SEPTEMBER 2019

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ORGANIZERS & COMMITTEES

Conference chair	**Francesco Rossella**, Scuola Normale Superiore
Conference co-chair	**Lucia Sorba**, Istituto Nanoscienze-CNR
Organizing committee	**Francesco Rossella**, Scuola Normale Superiore **Lucia Sorba**, Istituto Nanoscienze-CNR **Silvia Rubini**, Istituto Officina dei Materiali-CNR **Stefan Heun**, Istituto Nanoscienze-CNR **Valentina Zannier**, Istituto Nanoscienze-CNR
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WELCOME ADDRESS

A warm welcome to *Nanowire Week 2019* (*NWW2019*) and to *Pisa*, *Italy* for the third edition of the Nanowire Week International Conference, the major event bringing together researchers and students committed to the experimental and theoretical investigation of nanowires.

Co-organized by Scuola Normale Superiore and Istituto Nanoscienze-CNR, with the scientific support of the International Steering Committee, *NWW2019* combines an inspiring scientific program and a lovely social program in the birth town of Leonardo da Vinci on the occasion of his 500th anniversary.

The Congress Palace of Pisa, Italy, will host the third *NWW* from September 23 to 27, 2019: a full week of lively discussions on all aspects of nanowire physics and technology, spanning from growth and design to device engineering and applications in different fields, from bio sensing to aerospace.

We are pleased to welcome about 250 participants from 24 countries, and we gratefully acknowledge all contributors for the impressive quality of the abstracts submitted. The scientific program consists of 15 invited talks, 58 contributed talks, 3 ”hot news” talks, 126 posters in 3 sessions, technical workshop by sponsors.

We are glad to offer six Poster Prizes awarded by leading publisher groups to the best poster presentations, and we invite you to contribute to the Focus Collection on Nanowires hosted by the journal *Nanotechnology* and associated to *NWW2019*.

It is a great honor and pleasure for us to chair and organize this event, and we look forward to meeting you at *NWW2019* in Pisa.

Francesco Rossella and Lucia Sorba
Nanowire Week 2019 Chairs

Pisa, palazzo dei Congressi, Plenary room

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PROGRAM OVERVIEW

NWW2019 welcomes 250 participants from 24 countries and includes 15 invited talks, 3 “hot news talks”, 126 posters in 3 sessions, technical workshops by sponsors.

Monday, Sept. 23	Tuesday, Sept. 24	Wednesday, Sept. 25	Thursday, Sept. 26	Friday, Sept. 27
09:00 - 09:20 **Opening remarks**	*Session:* *Synthesis/Properties* 09:00 - 09:30 (Invited) **E. SUTTER**	*Session:* *Microscopy* 09:00 - 09:30 (Invited) **T. YASUI**	*Session:* *Quantum* 09:00 - 09:30 (Invited) **H. ZHANG**	*Session:* *(Opto)Electronics* 09:00 - 09:30 (Invited) **U. PESCHEL**
Session: Synthesis 09:20 - 09:50 (Invited) **T. HAKKARAINEN**	09:30 - 09:50 **X. Li**	09:30 - 09:50 **E. Ngo**	09:30 - 09:50 **A. Ghirri**	09:30 - 09:50 **A. Jaffal**
09:50 - 10:10 **L. Guniat**	09:50 - 10:10 **P. McIntyre**	09:50 - 10:10 **C. Maliakkal**	09:50 - 10:10 **S. Khan**	09:50 - 10:10 **M.G. Bartmann**
10:10 - 10:30 **M. Zavarize**	10:10 - 10:30 **S. Collin**	10:10 - 10:30 **D. Arman**	10:10 - 10:30 **M. Nilsson**	10:10 - 10:30 **P. Laferriere**
10:30 - 10:50 **V. Zannier**	10:30 - 10:50 **M. Swinkels**	10:30 - 10:50 **T. Kanne**	10:30 - 10:50 **S. Dorsch**	10:30 - 10:50 **P. Poole**
10:50 - 11:30 Coffee Break	10:50 - 11:30 Coffee Break	10:50 - 11:30 Coffee Break	10:50 - 11:30 Coffee Break	10:50 - 11:30 Coffee Break
Session: Synthesis 11:30 - 12:00 (Invited) **S. MALDONADO**	*Session: Properties* 11:30 - 12:00 (Invited) **I. ZARDO**	*Session: Properties* 11:30 - 12:00 (Invited) **M. DEN HERTOG**	11:30 - 11:40 **R. Foddis/S. Paziani**	*Session: Quantum* 11:30 - 12:00 (Invited) **A. P. MICOLICH**
12:00 - 12:20 **L. Vincent**	12:00 - 12:20 **K. Bertness**	12:00 - 12:20 **H.A. Fonseka**	11:40 - 13:00 **Poster Session 3** **&** **Workshops by *Zurich Instruments*** **and by *Quantum Design***	12:00 - 12:20 **F. Jekat**
12:20 - 12:40 **R. Paul**	12:20 - 12:40 **M. Sistani**	12:20 - 12:40 **A. Dijkstra**		12:20 - 12:40 **D. Ferrand**
12:40 - 13:00 **Y. Liu**	12:40 - 13:00 **O. Moutanabbir**	12:40 - 13:00 **E. Dimakis**		12:40 - 13:00 **E. Strambini**
13:00 - 14:00 Lunch	13:10 - 14:00 Lunch	13:00 - 14:00 Lunch	13:00 - 14:00 Lunch	13:00 - 14:00 Lunch
14:00 - 15:40 **Poster Session 1**	14:00 - 14:10 **J. Lopez**	*Session: Modelling*	*Session: Energy*	*Session: (Opto)Electronics*
	14:10 - 15:40 **Poster Session 2** **&** **Workshop by *Oxford Instruments***	14:00 - 14:30 (Invited) **M. MAGNUSSON**	14:00 - 14:30 (Invited) **R. ANUFRIEV**	14:00 - 14:30 (Invited) **L. BOARINO**
		14:30 - 14:50 **F. Glas**	14:30 - 14:50 **P. Erdman**	14:30 - 14:50 **D. Verardo**
		14:50 - 15:10 **A. Bertoni**	14:50 - 15:10 **A. Campo**	14:50 - 15:10 **K. Peng**
		15:10 - 15:30 **M. Albani**	15:10 - 15:30 **K. Kawaguki**	15:10 - 15:30 **S. Peng**
15:40 - 16:00 **P. Kacman**	*Session: Properties*	15:30 - 15:50 **H. Hijazi**	15:30 - 15:50 **E. Dimaggio**	15:30 - 16:00 **Poster prizes**
16:00 - 16:20 **S. Gazibegovic**	15:40 - 16:10 (Invited) **N. MINGO**	*16:00 - 23:00* *Social excursion* *Conference dinner*	15:50 - 16:10 Coffee break	**Closing remarks**
16:20 - 16:40 **N. Morgan**	16:10 - 16:30 **S. Peli**		16:10 - 16:20 **P. Sutter**	
16:40 - 17:00 **M. Sobanska**	16:30 - 16:50 **A. Sivan**		16:20 - 16:40 **R. Wallenberg**	
17:00 - 17:20 Coffee break	16:50 - 17:10 Coffee break		16:40 - 17:00 **F. Braakman**	
Session: Synthesis 17:20 - 17:50 (Invited) **S. BARTH**	*Session: Properties* 17:10 - 17:40 (Invited) **S. MUKHERJEE**		17:00 - 17:10 **V. Mirabello**	
17:50 - 18:10 **T. Dursap**	17:40 - 18:00 **I. Geijselaers**		*Session: Hot News* 17:10 - 17:20 **T. Albrow**	
18:10 - 18:30 **M. Yukimune**	18:00 - 18:20 **M. De Luca**		17:20 - 17:30 **S. Cuesta**	
18:30 - 18:50 **M. Hocevar**	18:20 - 18:40 **M. Sonner**		17:30 - 17:40 **Y. Cheng**	
	18:40 - 19:00 **P. Uredat**			

INVITED SPEAKERS

ORAL SESSIONS

Monday, September 23

08:00 - 09:00 **Registration**

09:00 - 09:20 **Opening remarks**

09:20 - 13:00	Oral Session M1 *Synthesis*	Chair: L. Sorba
09:20 - 09:50	T. HAKKARAINEN Tampere University, Finland *Controlling nanowire growth with Ga droplets*	Invited I1
09:50 - 10:10	L. GÜNIAT Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland *Contact Angle Engineering for Vertical Nanowire Growth*	Contributed M1.1
10:10 - 10:30	M. ZAVARIZE State University of Campinas, São Paulo, Brazil *Pure and mixed metal phases as catalysts for InP nanowire growth*	Contributed M1.2
10:30 - 10:50	V. ZANNIER CNR and Scuola Normale Superiore, Pisa, Italy *Growth dynamics of InAs/InP nanowire heterostructures by Au-assisted chemical beam epitaxy*	Contributed M1.3

10:50 - 11:30 Coffee Break

11:30 - 13:00	Oral Session M2 *Synthesis*	Chair: N. Fukata
11:30 - 12:00	S. MALDONADO The University of Michigan, Ann Arbor, MI, USA *Electrochemical Liquid-Liquid-Solid Growth of Semiconductor Nanowires*	Invited I2
12:00 - 12:20	L. VINCENT CNRS-Université Paris Sud, France *Synthesis and characterisation of hexagonal-2H germanium in nanowires*	Contributed M2.1
12:20 - 12:40	R. PAUL Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland *Growth of Zn3P2 nanowire on graphene via van der Waals epitaxy for photovoltaic applications*	Contributed M2.2
12:40 - 13:00	Y. LIU University of Copenhagen, Denmark *InAs – EuS – Al hybrid nanowires*	Contributed M2.3

13:00 - 14:00 Lunch

14:00 - 15:40 Poster Session 1

15:40 - 17:00	Oral Session M3 *Synthesis* Chair:	R. LaPierre
15:40 - 16:00	P. KACMAN Institute of Physics Polish Academy of Science, Warsaw, Poland *Dual Role of Gold Droplets in the Growth of Inclined InAs Nanowires*	Contributed M3.1
16:00 - 16:20	S. GAZIBEGOVIC Eindhoven University of Technology, the Netherlands *Bottom-up grown 2D InSb nanostructures*	Contributed M3.2
16:20 - 16:40	N. MORGAN Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland *Toward Scalable III-V Nanowire Networks on Si*	Contributed M3.3
16:40 - 17:00	M. SOBANSKA Institute of Physics Polish Academy of Sciences, Warsaw, Poland *Application of amorphous AlxOy as a nucleation layer for selective area formation of GaN nanowires by PAMBE*	Contributed M3.4

17:00 - 17:20 Coffee Break

17:20 - 18:50	Oral Session M4 *Synthesis* Chair:	J.C Harmand
17:20 - 17:50	S. BARTH Goethe-Universität, Frankfurt am Main, Germany TU Wien, Vienna, Austria *Ge-based Nanowires with Metastable Composition: Hyper-Doping and Alloy Formation*	Invited I3
17:50 - 18:10	T. DURSAP Université de Lyon, France *Crystal phase engineering of self-catalyzed GaAs nanowires following the RHEED diagram during the MBE growth*	Contributed M4.1
18:10 - 18:30	M. YUKIMUNE Ehime University, Matsuyama, Japan *Polytypism transfer observed in GaAs/GaNAs core-shell nanowires*	Contributed M4.2
18:30 - 18:50	M. HOCEVAR Univ. Grenoble-Alpes, France *Critical radius and strain mapping in axial heterostructure nanowires*	Contributed M4.3

Tuesday, September 24, 2019

09:00 - 10:50	Oral Session Tu1 *Synthesis/Properties* Chair:	S.C. Barth
09:00 - 09:30	E. SUTTER University of Nebraska-Lincoln, Lincoln, NE, USA *Chiral twisted van der Waals nanowires*	Invited I4
09:30 - 09:50	X. LI University of Illinois at Urbana-Champaign, Urbana, IL, USA *Planarizing VLS Epitaxial <111> Nanowires by Elastocapillary Force*	Contributed Tu1.1
09:50 - 10:10	P. C. McINTYRE Stanford University, Stanford, CA, USA *Germanium-tin growth kinetics for high tin-content Ge-core/Ge1-xSnx shell nanowire light emitters*	Contributed Tu1.2

10:10	-	10:30	S. COLLIN Université Paris-Sud/Paris-Saclay, Palaiseau, France *Quantitative assessment of n-type and p-type doping in GaAs nanowires by cathodoluminescence*	Contributed Tu1.3
10:30	-	10:50	M.Y. SWINKELS University of Basel, Switzerland *Measuring optical absorption in single nanowires*	Contributed Tu1.4

10:50 - 11:30 Coffee Break

11:30	**-**	**13:00**	**Oral Session Tu2 *Properties***	**Chair:**	**R. Rurali**
11:30	-	12:00	I. ZARDO University of Basel, Switzerland *Phonons and phonon transport in semiconductor nanowires*		Invited I5
12:00	-	12:20	K. A. BERTNESS National Institute of Standards and Technology, Boulder, CO, USA *Surface phonon polariton modes in ordered arrays of GaN nanowires*		Contributed Tu2.1
12:20	-	12:40	M. SISTANI Technische Universität Wien, Vienna, Austria *Stimulated Raman scattering in Ge nanowires*		Contributed Tu2.2
12:40	-	13:00	O. MOUTANABBIR École Polytechnique de Montréal, Québec, Canada *Sn-containing group IV nanowires for Si-compatible mid-infrared photonics*		Contributed Tu2.3

13:00 - 14:00 Lunch

14:00 - 14:10 J. LOPEZ
Oxford Instruments – Asylum Research

14:10 - 15:40 Poster Session 2 & Workshop by Oxford Instruments – Asylum Research

15:40	**-**	**16:50**	**Oral Session Tu3 *Properties***	**Chair:**	**P. McIntyre**
15:40	-	16:10	N. MINGO *Thermal transport in nanowire interfaces*		Invited I6
16:10	-	16:30	S. PELI Sincrotrone Trieste S.C.p.A., Trieste, Italy *All-optical probing of nanomechanical properties of InAs nanowires*		Contributed Tu3.1
16:30	-	16:50	A. SIVAN Consiglio Nazionale delle Ricerche, Rome, Italy *Ultrafast transient optical absorption in InP nanowires*		Contributed Tu3.2

16:50 - 17:10 Coffee Break

17:10	**-**	**19:00**	**Oral Session Tu4 *Properties***	**Chair:**	**F. Martelli**
17:10	-	17:40	S. MUKHERJEE Ecole Polytechnique de Montreal, Montreal (Quebec), Canada *Isotopically programmed nanowires*		Invited I7

17:40	-	18:00	I. GEIJSELAERS Lund University, Lund, Sweden *Two dimensional electron gas formation in Wurtzite-Zinc-blende InP heterostructures*	Contributed Tu4.1
18:00	-	18:20	M. DE LUCA Sapienza Università di Roma, Italy *Unusual spin properties of wurtzite nanowires revealed by Zeeman splitting spectroscopy*	Contributed Tu4.2
18:20	-	18:40	M. M. SONNER Universität Augsburg, Augsburg, Germany Nanosystems Initiative Munich (NIM), München, Germany *Break-down of corner states and carrier localization by monolayer fluctuations in radial nanowire quantum wells*	Contributed Tu4.3
18:40	-	19:00	P. UREDAT Justus Liebig University Giessen, Giessen, Germany *Anomalous angle-dependent magnetoresistance in InAs nanowires*	Contributed Tu4.4

Wednesday, September 25, 2019

09:00	**-**	**10:50**	**Oral Session W1 *Microscopy*** **Chair:**	**E. Sutter**
09:00	-	09:30	*T. YASUI* Nagoya University, Japan *Nanowires meet microarray and AI for urine liquid biopsy*	Invited I8
09:30	-	09:50	E. NGO LPICM, CNRS, Ecole polytechnique, Palaiseau, France *In situ transmission electron microscopy study of surface effects on the growth of Ge nanowires*	Contributed W1.1
09:50	-	10:10	C. B. MALIAKKAL Lund University, Lund, Sweden *In situ studies on step-flow layer growth of GaAs nanowires*	Contributed W1.2
10:10	-	10:30	A. DAVTYAN University of Siegen,Siegen, Germany *Coherent X-ray diffraction from as grown single bent nanowires*	Contributed W1.3
10:30	-	10:50	T. KANNE University of Copenhagen, Denmark *Are III-V nanowires with epitaxial Al a unique material platform?*	Contributed W1.4

10:50 - 11:30 Coffee Break

11:30	**-**	**13:00**	**Oral Session W2 *Properties*** **Chair:**	**A Foncuberta**
11:30	-	12:00	M. DEN HERTOG Université Grenoble Alpes, Grenoble, France *Transmission electron microscopy experiments on electrically contacted semiconducting nanowires*	Invited I9

12:00	-	12:20	H. A. FONSEKA University of Warwick, Coventry, UK *Self-assembled quantum wires and dots in GaAsP-GaAsP core-shell nanowires*	Contributed W2.1
12:20	-	12:40	A. DIJKSTRA Eindhoven University of Technology, The Netherlands *Optical properties of direct bandgap hexagonal SiGe*	Contributed W2.2
12:40	-	13:00	E. DIMAKIS Institute of Ion Beam Physics and Materials Research, HZDR, Dresden, Germany *Complex quantum dots in III-As nanowires*	Contributed W2.3

13:00 - 14:00 Lunch

14:00	**-**	**15:50**	**Oral Session W3 *Modelling***	**Chair:**	**V. Dubrovskii**
14:00	-	14:30	M. H. MAGNUSSON Lund University, Lund, Sweden *Aerotaxy for mass production of nanowire materials – growth and modeling*		Invited I10
14:30	-	14:50	F. GLAS Université Paris-Sud, Univ. Paris-Saclay, Palaiseau, France *Nucleation statistics and length distributions for III-V nanowires in the very poor group V regime*		Contributed W3.1
14:50	-	15:10	A. BERTONI Istituto Nanoscienze – CNR, Modena, Italy *Tailoring Rashba spin-orbit coupling in polygonal semiconductor nanowires: a numerical study*		Contributed W3.2
15:10	-	15:30	M. ALBANI University of Milano-Bicocca, Milano, Italy *The interplay of morphology, composition and strain in metastable Ge/GeSn core/shell nanowires*		Contributed W3.3
15:30	-	15:50	H. HIJAZI Université Clermont Auvergne, Clermont-Ferrand, France *Si doping of vapor-liquid-solid GaAs nanowires: n-type or p-type?*		Contributed W3.4

16:00 - 19:30 Bus transfer, Excursion at vineyards and wine cellars of Cantine Leonardo

19:30 - 23:00 Aperitif and Conference Dinner at Villa Casale di Valli

Thursday, September 26, 2019

09:00 - 10:50	Oral Session Th1 *Quantum* Chair:	F. Rossella
09:00 - 09:30	H. ZHANG Tsinghua University, Beijing, China *Majorana nanowires and topological quantum computation*	Invited I11
09:30 - 09:50	A. GHIRRI Istituto Nanoscienze - CNR, Modena, Italy *Microwave assisted tunneling in hard-wall InAs/InP nanowire quantum dots*	Contributed Th1.1
09:50 - 10:10	S. A. KHAN University of Copenhagen, Denmark *Ballistic superconductor-semiconductor nanowire junctions*	Contributed Th1.2
10:10 - 10:30	M. NILSSON Lund University, Sweden; University of Basel, Switzerland *Forming parallel-coupled quantum dots & tuning the two-electron hybridization and spin states in InAs nanowires*	Contributed Th1.3
10:30 - 10:50	S. DORSCH Lund University, Sweden *Phonon and temperature gradient induced transport in InAs/InP nanowire double quantum dot devices*	Contributed Th1.4

10:50 - 11:30	Coffee Break	
11:30 - 11:40	R. Foddis/S. Paziani Zurich Instruments/Quantum Design	
11:40 - 13:00	Poster Session 3 & Workshops by Zurich Instruments and Quantum Design Italy	
13:00 - 14:00	Lunch	

14:00 - 17:00	Oral Session Th2 *Energy* Chair:	L. Geelhaar
14:00 - 14:30	R. ANUFRIEV The University of Tokyo, Japan *Ballistic thermal transport in silicon nanowires*	Invited I12
14:30 - 14:50	P. A. ERDMAN CNR and Scuola Normale Superiore, Pisa, Italy *Thermoelectric Conversion at 30 K in InAs/InP Nanowire generation*	Contributed Th2.1
14:50 - 15:10	A. CAMPO University of Basel, Switzerland *Thermal conductivity measurements of single semiconductor nanowires: a novel approach*	Contributed Th2.2
15:10 - 15:30	K. KAWAGUCHI Fujitsu Limited and Fujitsu Laboratories Ltd., Atsugi, Japan *Microwave energy harvesting using III-V nanowire backward diodes*	Contributed Th2.3
15:30 - 15:50	E. DIMAGGIO Universita' di Pisa, Italy *Quantum Dots Top-down fabricated silicon nanowires for thermoelectric*	Contributed Th2.4

15:50 - 16:00 Coffee Break

16:00 - 17:00	Oral Session Th3 *Microscopy*	Chair:	M. den Hertog
16:00 - 16:20	P. SUTTER University of Nebraska-Lincoln, Lincoln, NE, USA *Radial and axial nanowire heterostructures via solid-state reactions*		Contributed Th3.1
16:20 - 16:40	R. WALLENBERG Lund University, Sweden *Complex nanowire structures revealed by electron tomography*		Contributed Th3.2
16:40 - 17:00	F. BRAAKMAN University of Basel, Switzerland *Force sensing with nanowire cantilevers*		Contributed Th3.3

17:00 - 17:10 V. MIRABELLO
Nanotechnology (IOP Publishing)

17:10 - 17:40	Hot News Session	Chair:	H. Shtrikman
17:10 - 16:20	T. ALBROW University of Cambridge, UK *Single-nanowire spectrometers*		Hot News Th4.1
17:20 - 16:30	S. CUESTA Univ. Grenoble-Alpes, CNRS-Institut Néel, France *High-performance GaN axial p-n junction single-nanowire photodetectors*		Hot News Th4.2
17:30 - 17:40	Y. CHENG Lund University, Sweden *III-V nanowire-based solar cells for space applications*		Hot News Th4.3

Friday, September 27, 2019

09:00 - 10:50	Oral Session F1 *(Opto)Electronics*	Chair:	W. Prost
09:00 - 09:30	U. PESCHEL Friedrich-Schiller-University Jena, Germany *Modeling Semiconductor Nanowire Lasers*		Invited I13
09:30 - 09:50	A. JAFFAL Université de Lyon, France *Single photon emission with a Gaussian far-field at telecom wavelength from single InAs-InP quantum dot-nanowires monolithically grown on Si*		Contributed F1.1
09:50 - 10:10	M. G. BARTMANN Technische Universität Wien, Vienna *Germanium nanowire based bolometer for Mid-IR sensing*		Contributed F1.2
10:10 - 10:30	P. LAFERRIÈRE National Research Council of Canada and University of Ottawa, Canada *Multiplexed single photon source based on multiple quantum dots*		Contributed F1.3

			embedded within a single nanowire	
10:30	-	10:50	P. J. POOLE National Research Council Canada, Ottawa, Canada *On-chip integration of single photon sources via evanescent coupling of tapered nanowires to SiN waveguides*	Contributed F1.4

10:50 - 11:30 Coffee Break

11:30	**-**	**13:00**	**Oral Session F2 *Quantum***	**Chair:**	**H. Zhang**
11:30	-	12:00	A.P. MICOLICH University of New South Wales, Sydney, Australia p-GaAs nanowire transistors with near-thermal limit gating		Invited I14
12:00	-	12:20	F. JEKAT II. Institute of Physics B, Aachen, Germany *Electron pair charging in gate-defined quantum dots in indium antimonide nanowires*		Contributed F2.1
12:20	-	12:40	D. FERRAND Université Grenoble Alpes and CNRS Institut NEEL, Grenoble, France *Control and probe of the hole quantum state in a nanowire quantum dot*		Contributed F2.2
12:40	-	13:00	E. STRAMBINI CNR and Scuola Normale Superiore, Pisa, Italy *Magnetically-driven anomalous phase shift in InAs nanowire Josephson Junctions*		Contributed F2.3

13:00 - 14:00 Lunch

14:00	**-**	**15:30**	**Oral Session F3 (*Opto)Electronics***	**Chair:**	**A. Micolich**
14:00	-	14:30	L. BOARINO INRiM (Istituto Nazionale di Ricerca Metrologica), Torino, Italy *Memristive and neuromorphic functionalities in metal-oxide nanowires*		Invited I15
14:30	-	14:50	D. VERARDO Lund University, Sweden Drastic Enhancement of Fluorescence Detection by using Lightguiding Nanowires		Contributed F3.1
14:50	-	15:10	K. PENG University of Oxford, United Kingdom *Terahertz frequency devices using semiconducting nanowires*		Contributed F3.2
15:10	-	15:30	S. Peng Stanford University, Stanford, CA, USA *Mid-infrared emission from GeSn/Ge core-shell nanowires with nanophotonic light extraction*		Contributed F3.3

15:30 - 16:00 POSTER PRIZES by Nanotechnology (IOP) and the Nanoscale journal family (RSC)

CLOSING REMARKS

POSTER SESSIONS

Poster Session 1 Monday 23 September 2019

P1.01	N. Anttu, H. Mäntynen, T. Sadi, A. Matikainen, J. Turunen, and H. Lipsanen *Comparison of the FMM, FEM and FDTD methods for the modeling of absorption in nanowire arrays*
P1.02	Y. Berdnikov, N. Sibirev, A. Alaferdov, S. Moshkalev, V. Khayrudinov, H. Lipsanen and A. Bouravleuv *Growth of GaAs nanowires on graphite nanoplatelets*
P1.03	O. Cernohorsky, H. Faitova, N. Basinova, S. Kucerova, J. Grym *Modeling of supersaturation in chemical bath deposition of ZnO nanorods*
P1.04	E. D. Leshchenko, M. Ghasemi, V. G. Dubrovskii and J. Johansson *Composition and crystal structure of gold catalyzed ternary nanowires*
P1.05	M. Amato, S. Ossicini, E. Canadell, and R. Rurali *Doping of hexagonal Si and GaAs nanowires from first-principles*
P1.06	E. Scalise, F. Grassi, F. Montalenti, L. Miglio *Template effect of the nanowire core on the growth of hexagonal Si/Ge shell:a first principles modeling*
P1.07	N. V. Sibirev, Y. S. Berdnikov *Stabilization of metastable phase in GaP nanowires via elastic stress*
P1.08	A.Sitek, M. Urbaneja Torres, A.Manolescu *Localization-dependent properties of prismatic nanowires*
P1.09	A. Spirina, N. Shwartz *Monte Carlo simulation of planar GaAs nanowire growth*
P1.10	O. Arif, V. Zannier, D. Ercolani, Ang Li, F. Rossi, S. Salimian, S. Roddaro, F. Rossella, F. Beltram and L. Sorba *Strain Relaxation Mechanisms in InAs/InP/GaSb Core-Multishell Nanowires*
P1.11	M. Al Humaidi, P. Schroth, L. Feigl, J. Jakob, A. Al Hassan, A. Davtyan, H.Küpers, L. Geelhaar, T. Baumbach and U. Pietsch *Impact of flux shadowing on self-catalyzed GaAs/(In,Ga)As core/shell nanowires grown in patterned arrays*
P1.12	G. Badawy, S. Gazibegovic, S. Heedt, F. Borsoi, S. Koelling, P. Leubner, M. A. Verheijen, L. Kouwenhoven, E. P. A. M. Bakkers *Stemless InSb nanowires and nanostructures for quantum devices*
P1.13	D. Beznasyuk, R. Tanta, J-H. Kang, A. Wulff, M. Espineira Cachaza, D. Viazmitinov, T. Stankevic, S. Marti-Sanchez, M. Rajpalke, J. Arbiol and P. Krogstrup *Towards high mobility InAs/InGaAs/GaAs(Sb) scalable nanowire networks*
P1.14	Y. Chen, N. Anttu, S. Sivakumar, E. Gompou and M. H. Magnusson *Towards in-situ size control of aerotaxy nanowire growth*
P1.15	A. Danescu, M. Vetorri, X. Guan, Ph. Regreny, J. Penuelas and M. Gendry *Impact of the Ga flux incidence angle on the growth kinetics of self-assisted GaAs nanowires on Si(111)*
P1.16	M. Friedl, D. Dede, N. Morgan, L. Güniat, L. Ghisalberti, W. Kim, A. Balgarkashi, J. B. Leran, A. Fontcuberta i Morral *Selective-area growth of III-V nanowire networks on GaAs substrates*
P1.17	D. Pan, Ji-Yin Wang, W. Zhang, L. Zhu, X. Su, F. Fan, Y. Fu, S. Huang, D. Wei, L. Zhang, M. Sui, A. Yartsev, H. Q. Xu and J- Zhao *Dimension Engineering of High-Quality InAs Nanostructures on a Wafer Scale*
P1.18	A. Liudi Mulyo, M. Krishnappa Rajpalke, P. E. Vullum, H. Weman, K. Kishino and B.O. Fimland *The influence of AlN buffer layer on the growth of self-assembled GaN nanocolumns on graphene*
P1.19	X. Zhang, M. Ahmed Abdelhameed, W. Jevasuwan, Y. Sugimoto and N. Fukata *Fabrication of p-Si/i-Ge core-shell and p-Si/i-Ge/p-Si core-double shell nanowires by bottom-up and top-down methods*
P1.20	F. Bastiman, H. Küpers, C. Somaschin, V. G. Dubrovskii and L. Geelhaar *Analysis of incubation time preceding the Ga-assisted nucleation and growth of GaAs nanowires on Si(111)*
P1.21	L. Ghisalberti, S. Escobar Steinvall, W. Craig Carter, A. Fontcuberta *Vapor-Liquid-Solid growth: Wetting angle and nanowire geometry and their relation to nanowire growth morphologies*

P1.22	G. Gregoire, H. Hijazi, C. Bougerol, A. Trassoudaine, D. Castelluci, R. R. LaPierre, V. G. Dubrovskii, E. Gil, Y. André *Gold free InAs nanowires grown by HVPE*
P1.23	J. Jung, Roy L. M. Op het Veld, Di Xu, V. Schaller, M. A. Verheijen, M. Pendharkar, Joon Sue Lee, S. Koelling, L. Kouwenhoven, C. Palmstrom, H. Zhang, E. P. A. M. Bakkers *Selective area semiconductor-superconductor networks*
P1.24	M. Zeghouane, J. Jridi, G. Avit, Y. André, C. Bougerol, E. Gil, P. Ferret, Dominique Castelluci, Y. Robin, V- G. Dubrovskii, H. Amano, and A. Trassoudaine *Composition control of self-induced and selective growth (In,Ga)N nanowires by HVPE*
P1.25	M. Kolíbal, Y.Wang, T. Šikola *Collector droplet behavior during formation of nanowire interconnects*
P1.26	T. Mita, R. Fujiwara, M. Yukimune, R. Tsutsumi, F. Ishikawa *Molecular beam epitaxial growth of various diluted nitride nanowires*
P1.27	T. Musálek, S. Stanislav, L. Kachtík, T. Šikola, M. Kolíbal *Effect of n-doping on MBE-grown InAs nanowires*
P1.28	T. Nurmamytov, K. Ferfolja, M. Fanetti, S. Rubini *Growth of MnAs/GaAs heterostructures in self-catalyzed GaAs nanowires*
P1.29	T. Ohno, M. Yukimune, R. Fujiwara, K. Nagashima, T. Yanagida, F. Ishikawa Synthesis of GaAs/TiO2 composite nanowires
P1.30	P. Perla, T. Mörstedt, P. Zellekens, D. Grützmacher, M. I. Lepsa, Th. Schäpers *In-situ prepared superconducting Al and Nb contacts on InAs nanowires*
P1.31	M. R. Piton, T. Hakkarainen, E. Koivusalo, E. M. Fiordaliso, E. Leschenko, S. Kölling, H. V. A. Galeti, A. G. Rodrigues, D. Lupo, P. M. Koenraad, V. Dubrovskii, Y. G. Gobato and M. Guina *Incorporation and activation of Te dopant in self-catalyzed GaAs nanowires*
P1.32	M. Rossi, G. Badawy, S. Gazibegovic, R. Op het Veld and E. P. A. M. Bakkers *Versatile platform for in-situ fabrication of InSb nanowire Majorana devices*
P1.33	M. M. Eremenko, S. V. Balakirev, N. E. Chernenko, O. A. Ageev, M. S. Solodovnik *Effect of Si native oxide thickness on GaAs nanowire growth on Si(001) substrate*
P1.34	E. Stutz, M. Friedl, S. Escobar Steinvall, R. Paul, M. Zamani, N. Tappy, T. Burgess, H. Hoe Tan, P. Caroff, C. Jagadish and A. Fontcuberta i Morral, *Functional properties of earth-abundant nanowires and nanosails*
P1.35	E. Tamburri, S. Politi, M. Tomellini, M. L.Terranova, M.Cirillo, M. Lucci *Ni nanoparticles on ordered arrays of carbon nanotubes: innovative multifunctional nanowires*
P1.36	R. Tsutsumi, N. Tsuda, B. Zhang, W. M. Chen, I. A Buyanova, F. Ishikawa *Characteristics of GaAs/AlGaAs core-multishell structures having native oxide AlGaO outermost shell*
P1.37	I. Verma, V. Zannier, D. Ercolani, F. Beltram and L. Sorba *Morphology control by tuning growth parameters of InSb nanostructures: from 1D to 3D*
P1.38	M. Sobanska, N. Garro, K. Klosek, A.Cros and Z. R. Zytkiewicz *Influence of Si substrate preparation on polarity of GaN nanowires grown on Si(111) by PAMBE: Kelvin Probe Force Microscopy studies*
P1.39	M. Hoskam, A.G. Schellingerhout, P. Leubner, D. Varjas, E.P.A.M. Bakkers *One-dimensional helical states in SnTe topological crystalline insulator nanowires: Modelling and growth*
P1.40	E. Scalise, D. Migas, A. Sarikov, F. Montalenti, L. Miglio *Why Si/Ge nanowires can have the hexagonal diamond crystal structure?*

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P2.01	E. Appert, T. Cossuet, F. Donatini, A. M. Lord, J. L. Thomassin, J. Pernot and V. Consonni *Polarity-dependent high electrical conductivity of selective area grown ZnO nanowires by chemical bath deposition*

P2.02	P. Gaffuri, E. Appert, O. Chaix-Pluchery, L. Rapenne, E. Sarigiannidou, M. Salaün, and V. Consonni *Gallium doping of ZnO nanowires by chemical bath deposition*
P2.03	Z. Azimi, A. S. Ameruddin, H. H. Tan, C. Jagadish, J. Wong-Leung *Engineering InGaAs Nanowire Composition by Selective Area Metal Organic Vapour Phase Epitaxy*
P2.04	S. B. Alam, C. Røhl Andersen, F. Panciera, O. Hansen, F. M Ross, N. Akopian, K. D. Thelander, K. Mølhave *Electrical characterization of nanowires combined with in-situ TEM imaging*
P2.05	J. David, V. Zannier, S. Martí-Sánchez, O. Arif, D. Ercolani, L. Sorba, M. Gemmi, J. Arbiol *Analyses of III-V Semiconductor Nanowires Coupling Advanced Transmission Electron Microscopy Techniques*
P2.06	J. A. Gott, R. Beanland, H. Aruni Fonseka, J. J. P. Peters, Y. Zhang, H. Liu, A. M. Sanchez *In-Situ observation of Σ3 {112} twin boundary motion at atomic resolution in III-V nanowires*
P2.07	A. AlHassan, J. Lähnemann, O. Marquardt, S. J. Leake, H. Küpers, M. Niehle, D. Bahrami, F. Bertram, R. B. Lewis, A. Davtyan, A. Trampert, L. Geelhaar, U. Pietsch *Enhanced cathodoluminescence of nXRD- and TEM-measured mixed phase in single as-grown core-multi-shell nanowires*
P2.08	J. Jakob, P. Schroth, L. Feigl, M. Al Humaidi, A. Davtyan, A. Al Hassan, U. Pietsch and T. Baumbach *Quantification of in situ RHEED for height-resolved analysis of polytypism in nanowires*
P2.09	S. Kucerova, H. Faitova, J. Vesely, O. Cernohorsky, N. Basinova and J. Grym *TEM study of growth mechanisms of highly ordered ZnO nanorods*
P2.10	K. Kuwahara, R. Ishihara, K. Ishida, S. Yoshimura, K. Shimomura *Compositional analysis of InP/GaInAs heterostructure nanowires grown by self-catalytic VLS mode using MOVPE*
P2.11	S. Lehmann, N. Vainorius, M. E. Pistol and K. A. Dick *Advanced III-V heterostructures based on crystal phase controlled nanowire templates*
P2.12	A. Li, Y. Chen, W. Li, O. Arif, V. Zannier, D. Ercolani, F. Beltram, L. Sorba and X. Han *Atomic resolution STEM study on the interface of catalyst-free growth of InAs NWs on Si*
P2.13	Y. Liu, J. Knutsson, S. Lehmann, N. Wilson, E. Young, C. J. Palmstrøm, K. A. Dick, A. Mikkelsen, R. Timm *Crystal phase selective bismuth incorporation in GaAs nanowires*
P2.14	S. Martí-Sánchez, C. Koch, Y. Liu, P. Krogstrup, J. Arbiol *Epitaxy and interfaces in hybrid nanowires for Majorana-based topological quantum computing*
P2.15	T. Matsuda, K. Yano, S. Shimomura, Y. Shimizu, F. Ishikawa *Bi segregation in GaAs/GaAsBi/GaAs core-multishell nanowires*
P2.16	M. R. Zamfir, J. L. Maurice, L. I. Florea, P. Legagneux, É. Ngo, L. Vincent, C. Renard, C. S. Cojocaru, D. Pribat *The non-catalysed growth of NiSi nanowires observed in situ in the environmental transmission electron microscope*
P2.17	J. Penuelas, T. Dursap, L. Fouquat, P. Regreny, C. Botella, A. Danescu, M. Gendry, C. Chevallier, N. Chauvin, M. Bugnet *III-V core / oxide shell nanowires for water splitting*
P2.18	P. Prete, D. Wolf, F. Marzo, N. Lovergine *GaAs-AlGaAs quantum well tube nanowires: correlating luminescence with nanowire size and inner multi-shell 3D structure through nano-scale spectroscopic imaging and transmission electron microscopy tomography*
P2.19	D. Bahrami, A. Davtyan, R. Zhe, T. Anjum, A. Al Hassan, J. Herranz, E. Spurio, L. Geelhaar, D. V. Novikov, R. Timm and U. Pietsch *Impact of electrical current on the structural properties of single as-grown GaAs nanowires*
P2.20	C. Baratto, V. Demontis, R. Mati, M. Rocci, M. Donarelli, G. Faglia, D. Ercolani, F. Beltram, L. Sorba, S. Roddaro, F. Rossella *Individual InAs nanowires for conductometric sensing*
P2.21	F. Floris, L. Fornasari, V. Bellani, A. Marini, F. Banfi, S. Roddaro, D. Ercolani, M. Rocci, F.Beltram, M. Cecchini, L. Sorba and F. Rossella *Self-Assembled InAs Nanowires as Optical Reflectors*

P2.22	N. Ben Sedrine, J. Cardoso, J. P. Teixeira, D. Nd. Faye, R. Ribeiro-Andrade, A. Gustafsson, P. M. P. Salomé, J. C. Gonzàlez, B. Daudin, A. J. Neves, E. Alves, K. Lorenz, J. P. Leitão, M. R. Correia and T. Monteiro *Probing the optical properties of III-V nanowires for optoelectronic applications*
P2.23	S. Beretta, M. Bosi, L. Seravalli, F. Rossi, G. Trevisi, P. Frigeri, E. Gombia, C. Ferrari *Growth of germanium nanowires using isobutyl germane and their structural and electrical characterization*
P2.24	E. Cara, F. Ferrarese Lupi, L. Mandrile, A. M. Giovannozzi, N. De Leo, L. Boarino *Self-closing Au-coated silicon nanowires for surface-enhanced Raman spectroscopy*
P2.25	B. C. Da Silva, O. D. D. Couto Jr., C. A. Senna, B. S. Archanjo, M. A. Cotta and F. Iikawa *Probing Electronic Band Structure of Hexagonal Gallium Phosphide using Photoluminescence Excitation Spectroscopy*
P2.26	D. de Matteis, E. Fadaly, M. De Luca, M. López-Suárez, E. Bakkers, R. Rurali, I. Zardo *Raman characterization of GaAs-Ge and GaAs-SiGe core-shell NWs*
P2.27	S. Escobar Steinvall, N. Tappy, M. Friedl, W. Kim, T. LaGrange, M. Ghasemi, E. Stutz, J. B. Leran, R. Paul, M. Zamani, R. Zamani, A. Fontcuberta i Morral *Zinc phosphide nanowire growth by molecular beam epitaxy and their functional properties*
P2.28	J. Lähnemann, M. O. Hill, J. Herranz, O. Marquardt, G. Gao, A. Al Hassan, A. Davtyan, S. O. Hruszkewycz, M. V. Holt, C. Huang, I. Calvo-Almazán, U. Jahn, U. Pietsch, L. J. Lauhon and L. Geelhaar *Correlated nanoscale analysis of the emission from wurtzite versus zincblende (In,Ga)As/GaAs nanowire core-shell quantum wells*
P2.29	L. Hrachowina, X. Zou, A. Yartsev, M. Borgström *Passivation study of InP nanowires using TRPL and EBIC*
P2.30	R. Ishihara, K. Kuwahara, S. Yoshimura, K. Ishida, K. Shimomura *Comparison of continuous growth and regrowth InP / GaInAs core-shell nanowires using self-catalytic VLS mode*
P2.31	M. Jansson, L. Francaviglia, R. La, R. Balagula, J. E. Stehr, C. W. Tu, A. Fontcuberta i Morral, W. M. Chen, I. A. Buyanova *Effects of exciton localization on recombination in Ga(N)AsP nanowires investigated by cathodoluminescence spectroscopy*
P2.32	W. Kim, J. Vukajlovic-Plestina, A. Balgarkashi, L. Güniat, M. Friedl, N. Morgan, D. Dede, J. B. Leran and A. Fontcuberta i Morral *Si dopant incorporation studies in ordered GaAs nanowire arrays on silicon*
P2.33	J. Lähnemann, D. van Treeck, O. Brandt, S. Fernández-Garrido, L. Geelhaar *Circumferential and one-sided (In,Ga)N shells on GaN nanowires: From self-assembled to ordered arrays*
P2.34	J. Płachta, A. Kaleta, S. Kret, T. Kazimierczuk, P. Baranowski, P. Kossacki, G. Karczewski, J. Kossut, T. Wojtowicz and P. Wojnar *Valence band splitting in wurtzite and zinc blende (Cd,Mn)Te/(Cd,Mg)Te nanowires accessed by magnetooptical spectroscopy*
P2.35	A. Portone, L. Ganzer, F. Branchi, R. Ramos, M. J. Caldas, D. Pisignano, A. Camposeo, E. Molinari, G. Cerullo, L. Persano, D. Prezzi, T. Virgili *Tailoring optical properties in nanostructured organic semiconductor*
P2.36	A. Reszka, K. P. Korona, S. Tiagulskyi, S. Kret, R. Bozek, A. Pieniążek, M. Sobanska, K. Klosek, Z. R. Zytkiewicz, and B. J. Kowalsk *Growth polarity switching in (Al,Ga)N/GaN nanowire LEDs studied by scanning electron microscopy related techniques*
P2.37	F. Rispoli, F. Sansone, L. Baldini, S. Beretta, R. Verucchi, L. Aversa, N. Musayeva, C. Ferrari *Chemical functionalization and characterization of germanium nanowires*
P2.38	O. Saket, J. Wang, F. H. Julien, M. Morassi, N. Amador-Mendez, F. Bayle, J.-C. Harmand,N. Gogneau, M. Tchernycheva *Correlated electrical and optical assessment of doping in GaN nanowires*

P2.39	A. G. Schellingerhout, P. Leubner, D. Vakulov, E. P. A. M. Bakkers *MBE growth and characterization of PbTe nanowires*
P2.40	A. M. da Silva, C. Lenz Cesar, A. Cavalli, E. P. A. M. Bakkers, A. A. de Souza, M. A. Cotta *Optical detection of cell adhesion forces: application of InP nanowire arrays to probe the effect of N-acetylcysteine on adhered bacteria*
P2.41	A. K. Sivan, L. di Mario, A. Galan-Gonzalez, A. Gallant, D. A. Zeze, D. Atkinson, F. Martelli *Optical properties of Cu- and Co- doped ZnO nanowires*
P2.42	M. M. Sonner, L. Janker, D. Rudolph, D. Ruhstorfer, A. Sitek, M. Döblinger, A. Manolescu, G. Abstreiter, J. J. Finley, A. Wixforth, G. Koblmüller, H. J. Krenner *Electron cycloids in a radial quantum well of a GaAs/AlGaAs nanowire heterostructure driven by a surface acoustic wave*
P2.43	A. Sorokina, N. Anttu, T. Sadi, B. Asamoah, T. Hakala, V. Khayrudinov and H. Lipsanen *Characterization of the light emission from III-V nanowires by modeling and experimental approaches*
P2.44	R. Tanta, D. Beznasyuk, J. H. Kang, A. Wulff, M. Espineira Cachaza, D. Viazmitinov, T. Stankevic, M. Rajpalke and P. Krogstrup *Bismuth incorporation in selective area grown nanowires*
P2.45	N. Vainorius, S. Lehmann, K. A. Dick and M. E. Pistol *Raman Scattering of Wurtzite GaAs and InP Nanowires*
P2.46	V. G. Dubrovskii *Morphology evolution of catalyst-free III-V nanowires grown by selective area epitaxy*
P2.47	R.R. Reznik *Non-trivial phenomena during MBE growth of N-based nanostructures on silicon*
P2.48	Reza R. Zamani, S. Escobar Steinvall, L. Ghisalberti, M. Zamani, E. Stutz, R. Paul, J. B. Leran, T. LaGrange, A. Fontcuberta i Morral *Insights into structural and chemical properties of zinc phosphide superlattice-like nanowires*
P2.49	M. Karimi, X. Zeng, B. Witzigmann, L. Samuelson, M. T. Borgström and H. Pettersson *Room temperature high responsivity SWIR/NIR photodetectors based on InAsP/InP NW array heterostructures*

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P3.01	A, Ghukasyan, R. LaPierre *Making and modelling thermoelectric devices based on vertical III-V nanowire arrays on silicon*
P3.02	A.Bianchi, U. Anselmi Tamburini *Thermo-piezoelectric generators based on Al/N-codoped ZnO nanorods*
P3.03	E.A. Bochicchio, K. Korzun, I. Kolpakov, J. Quik, J.E.M. Haverkort, E.P.A.M. Bakkers *InP nanowire solar cells*
P3.04	J. Fast, E. Barrigon, M. Kumar, L. Samuelsson, M. Borgström,1 A. Burke, H. Linke *Characterization of InAs/InP heterostructure single nanowire devices for hot carrier photovoltaics with electron beam induced current*
P3.05	W. Jevasuwan, C. Junyi, T. Subramani, N. Fukata *Al-catalyzed Si Nanowires Formed by Chemical Vapor Deposition and Application in Photovoltaic Device*
P3.06	I. Kolpakov, K. Korzun, E. Bochicchio, E. Bakkers, J. Haverkort. *Top-down etched GaAs nanowires for the ultimate efficiency nanowire solar cell*
P3.07	T. Mathieu-Pennober, M. Foldyna, M. Al-Ghzaiwat, V. Piazza, A. Jollivet, F.H. Julien, M. Tchernycheva *Limiting factors in the current collection of Si nanowire solar cells under concentrated illumination*
P3.08	D. Prete, V. Zannier, D. Ercolani, L. Guazzelli, C. Chiappe, F. Beltram, L. Sorba, F. Rossella *Electrical and thermal transport in gate-all-around suspended-InAs nanowires FETs*

P3.09	J.K. Wang, L. Lu, T. Sodhi, P. Chretien, F. Houzé, F. H. Julien, N. Gogneau and M. Tchernycheva *Piezoelectric energy nanoharvester based on vertically-aligned GaN nanowires*
P3.10	D. P. Wilson, A.S. Sokolovskii, V. G. Dubrovskii, R. R. LaPierre *Photovoltaic Light Funnels Grown by GaAs Nanowire Droplet Dynamics*
P3.11	T. Akamatsu, M. Sasaki, H. Kameda, K. Tomioka, J. Motohisa *InP/InAsP/InP heterostructure nanowire LEDs for a single photon emitter*
P3.12	N. Amador, N. Guan, J. Wang, A. Kapoor, C. Bougerol, L. Mancini, M. Foldyna, S. Das, S. Som, F.H. Julien, J. Eymery, C. Durand and M. Tchernycheva *Colour optimization of white flexible nanowire LEDs*
P3.13	T. Arjmand,T. Nguyena, B. Salemb, M. Bawedinc, C. Ternona *Silicon nanonet, a promising material for flexible and large-scale electronics*
P3.14	A.Balgarkashi, W. Kim, S. Escobar Steinvall, L. Guniat, M. Friedl, N. Morgan, D, Dede, J.B Leran, A. Fontcuberta i Morral *Localized emitters in self-catalyzed InAs/GaAs nanowire heterostructure arrays on silicon*
P3.15	C. Blumberg, F. Wefers, J. Meier, N-Weimann, G. Bacher, W. Prost *Site- and polarity-controlled GaN nanowires on silicon for high-speed LEDs*
P3.16	S. R. Gosain, R. André, Y. Genuist, G. Nogues, K. Kheng, J. Cibert and E. Bellet-Amalric *Tapered ZnSe/ZnMgSe core/shell NWs for directed single photon emission*
P3.17	D. Hatakeyama, Y. Matsui, R. Togashi and K. Kishino *Fabrication of nanocolumn photonic crystal (NC-PC) structure with enhanced optical confinement by controlling NC diameter*
P3.18	D. Huffacker *Current-Injected III-V Nanowire Optical Interconnect*
P3.19	Y. Katsumi, H. Gamo, J. Motohisa, K. Tomioka *First demonstration of vertical surrounding-gate transistor using InP nanowires*
P3.20	S. Skalsky, Y. Zhang, J. A. Alanis, H. Liu, P. Parkinson *Direct Measurement of Cavity Reflectivity in High-Yield Room-Temperature Nanowire Lasers*
P3.21	S. Peng, M. Braun, A. Meng, Z. Shang, A. Salleo, P. C. McIntyre *GeSn mid-infrared nanophotonic resonant absorbers*
P3.22	M. Spies, A. Ajay, F. Donatini, M. I. den Hertog, E. Monroy, B. Gayral *Electrical tunability of single quantum dots embedded in GaN nanowires*
P3.23	V. N. Trukhin, I. A. Mustafin, V. Khayrudinov, H. Lipsanen *Transient reflectivity and ultrafast dynamic of electrons and holes in GaAs NWs*
P3.24	V. Zeller, F. Dirnberger, T. Koller, C. Schüller, T. Korn, D. Abujetas, J. Sánchez-Gil and D. Bougeard *Engineering the spontaneous emission in semiconductor nanowires*
P3.25	Y. Zhang, H. Aruni Fonseka, G. Davis, A. Velichko, A. M. Sanchez, D. J. Mowbray, M. Aagesen, H. Liu *Self-catalyzed high-quality core-shell gaasp nws on silicon and their application on optoelectronics*
P3.26	Q. D. Zhuang, Z. M. Jin, H. Alradhi, I. Sandall, X. R. Chen, J. Shao, Z. M. Wang *Mid-infrared infrared photodetectors based on InAs-nanowire/silicon hybrid Heterostructures*
P3.27	L. Viti, V. Zannier, F. Rossi, L. Sorba, M. S. Vitiello *InAs/InAsP quantum dots in semiconductor nanowires: transport properties and application in terahertz photonics*
P3.28	Z. S. Momtaz, S. Servino, V. Demontis, V. Zannier, D. Ercolani, F. Rossi, L. Sorba, F. Beltram, F. Rossella, S. Roddaro *Tuning tunneling rates in InAs/InP quantum dots*
P3.29	T. Albrow-Owen, Z. Yang, J. Alexander-Webber, H. Cui, S. Hofmann, H. Joyce, T. Hasan *Single nanowire devices enabled by SU8 embedding*
P3.30	C. Barone, H. Rotzinger, J. N. Voss, C. Mauro, A. V. Ustinov, S. Pagano *Nonlinear transport and electric noise reduction induced by percolation mechanisms in granular aluminum oxide nanowires*

P3.31	S. Dorsch, B. Delalkhan, S. Fahlvik and A. M. Burke *Applying transverse electric fields in double quantum dot devices using enhancement mode nanowires for spin-transport measurements*
P3.32	D. J. Carrad, M. Bjergfelt, T. Kanne, M. Aagesen, F. Krizek, E. M. Fiordaliso, E. Johnson, P. Krogstrup, J. Nygård, T. Sand Jespersen *Shadow mask platform for in-situ patterning of epitaxial superconductors on semiconductor nanowires*
P3.33	P. Uredat, P. Hille, J. Schörmann, M. Eickhoff, M. T. Elm, P. J. Klar *Bias-dependence of universal conductance fluctuations in single GaN:Ge nanowires*
P3.34	F. Thomas, L. Gubser, A. Baumgartner, C. Jünger, M. Nilsson, G. Fülop, V. Zannier, F. Rossi, L. Sorba, I. Zardo, C. Schönenberger *Electrical properties of integrated InAs/InP heterostructure quantum dots*
P3.35	M. Nilsson, A. Pally, C. Jünger, S. Lehmann, K. A. Dick, V. Maisi, C. Thelander, R. Delagrange, D. Chevallier, A. Baumgartner and C. Schönenberger *Tunnel spectroscopy of superconducting proximity effect in InAs nanowires using aligned crystal-phase quantum dots*
P3.36	R. L. M. Op het Veld, J. Jung, D. Xu, V. Schaller, M. A. Verheijen, M. Pendharkar, J. Sue Lee, S. M. E. Peters, S. Koelling, L. Kouwenhoven, C. Palmstrom, H. Zhang, E. P. A. M. Bakkers *In-plane InSb nanowire networks for quantum devices*
P3.37	L. Stampfer, T. Mutas, S. A. Khan, D. J. Carrad, P. Krogstrup, T. Sand Jespersen *Ballistic transport in VLS-grown InSb Nanocrosses*
P3.38	P. Ghamgosar, M. Gilzad Kohan, F. Rigoni, N. Almqvist, I. Concina, A. Vomiero *Metal oxide nanowire p-n junctions for solar energy detection/harvesting*

ABSTRACTS

I1 - Controlling nanowire growth with Ga droplets

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Keywords: self-catalyzed growth, size uniformity, growth direction

Ga droplets play an important role in enabling self-catalyzed growth of binary GaAs and GaP ternary GaAsSb, GaAsP nanowires (NW) without the need of foreign catalyst metal such as Au. Besides acting as the liquid phase in the vapor-liquid-solid (VLS) growth, Ga droplets can be used for pre-conditioning the substrate surface for NW nucleation[1-3] and manipulating the NW diameter[4] and growth direction[5].

Here, we present an overview of self-catalyzed NW grown on Si(111) surface pre-patterned using a lithography-free technique based on droplet epitaxy and spontaneous oxidation[1], providing extreme NW size uniformity down to the sub-Poissonian level[2]. We discuss the aspects related to NW nucleation yield and reproducibility and extend the methodology from binary GaAs to ternary GaAsSb NW materials.

The uniformity of the NW ensembles allows deterministic in situ control of the NW growth direction. The position of the Ga droplet and the shape of the liquid-solid interface is first manipulated using an annealing step subsequent to the vertical VLS growth. A change from vertical to horizontal growth is then achieved by resuming the VLS growth after the annealing step. Two different populations (Type 1 and 2) are observed depending on pinning of the Ga droplet at a single twin-plane, which forms on the otherwise defect free zinc blende structure in the beginning of the second VLS step. The probability for forming Type 1 or Type 2 structures depends on the growth parameters including NW density, annealing time, and As flux, which can be optimized to achieve 100% yield for Type 1 horizontal growth.

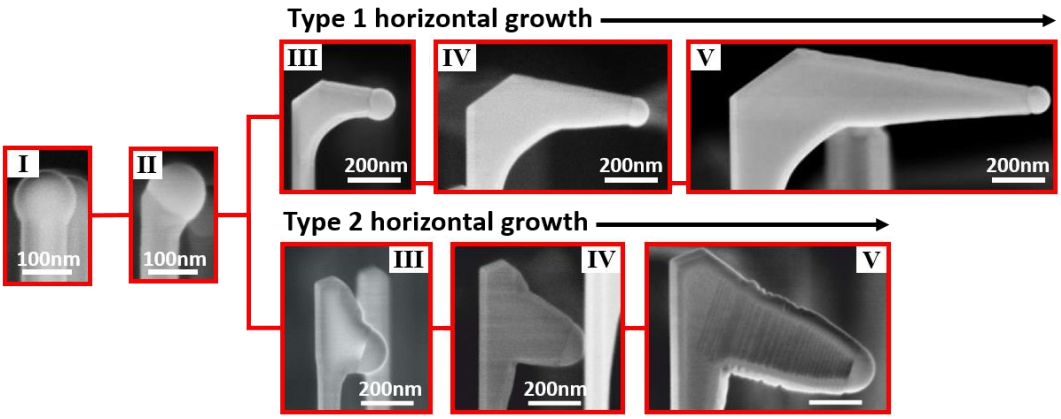

Figure 1. *The steps for changing the NW growth direction: (I) GaAs NW after 20 min vertical growth, (II) after in situ annealing for droplet modification, and after (III) 5 min, (IV) 10 min, and (IV) 20 min horizontal growth in Type 1 and Type 2 configurations.*

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M1.1 - Contact Angle Engineering for Vertical Nanowire Growth

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Large Si surfaces patterned with vertically-ordered III/V nanowires (NWs) is a key challenge for a variety of different fields such as photovoltaics,[1] sensing[2] and LEDs.[3] Arrays with a high yield of vertical NWs with great optoelectronic properties serve as a milestone for further device development. To obtain such systems, the self-catalyzed VLS growth mechanism appears to be a promising option, combining perfect crystalline quality with CMOS compatibility.[4]

Currently, the most conventional way to grow patterned arrays is to etch holes in an oxide mask on Si (111) and to precede the growth with a Ga pre-deposition. However, it has been shown that in this system, the hole aspect ratio and the As gradient in the catalyst droplet determines whether the NW growth will become vertical or not.[5] Therefore, a limited range of hole dimensions has been shown to result in a high vertical yield.

In this work, we present a novel way of growing vertical NW arrays on Si (111) by initiating the growth on diversely sized Si nanopillars. By a precise contact angle engineering of the catalyst droplet[6], this system permits to grow wires of very different diameters at a good yield, enabling a higher degree of freedom in the growth of nanowire arrays. Simulations have been conducted to characterize the droplet stability on nanopillars, and a thorough comparison between experimental yield and simulated contact angles gives insight to the underlying conditions for a high quality NW growth.

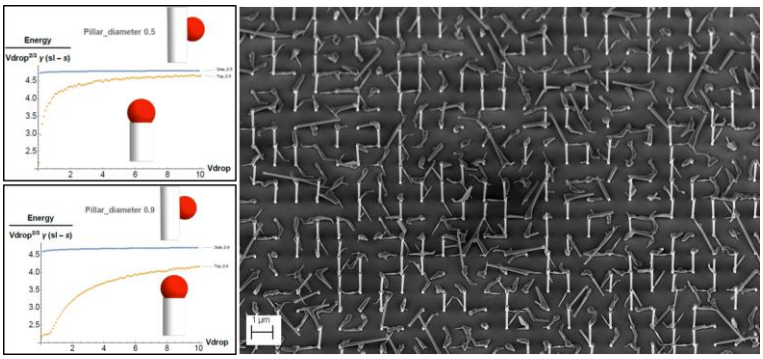

Figure 1. *Simulations showing the droplet surface energy with respect to the pillars size, along with an SEM image of GaAs NW arrays on Si (111) nanopillars*

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M1.2 - Pure and mixed metal phases as catalysts for InP nanowire growth

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Keywords: InP nanowire, VLS growth, AgAu nanoparticles

Semiconductor nanowires (NWs) are currently under intense investigation, both as basic science, to understand the nanostructure formation dynamics, and for technological applications in areas such as optoelectronics and energy harvesting, among many others. Au catalysts have been widely explored in semiconductor nanowire synthesis; however, some characteristics of this type of synthesis limit the nanowire potential applications. So in order to find an alternative to gold, many other metals, such as Cu, Sn, Pd, have been explored in nanowire synthesis over the last few years.

In this work we explore Ag, Au and AgAu nanoparticles as catalysts for planar and vertical InP nanowire growth. Both metals present many similar properties, such as crystal structure, melting point and ductility. In a previous work[1], we have shown that colloidal Ag nanoparticles can be used to catalyze VLS growth of InP NWs by Chemical Beam Epitaxy and studied associated surface mechanisms. In this work, we have explored nanoparticles obtained by the gas aggregation method, which allows size and composition control (in case of alloys). These nanoparticles show a pure metal phase, with no passivating cap layer from the colloidal chemistry. Substrates of InP and GaAs of different crystallographic orientations and polarity were used for same growth conditions. Scanning electron microscopy provides nanowire shape statistics while transmission electron microscopy was used to investigate chemical and structural properties.

By varying the substrates, the metal catalyst composition and keeping the same growth conditions, we observe that NWs tend to grow in planar or vertical mode depending on the polarity and orientation of the substrate. Au catalyzed InP NWs tend to grow in planar mode on GaAs(111)A and vertical on GaAs(111)B, with mixed populations on GaAs(100). Ag catalyzed NWs, however, show the opposite behavior, i.e. grow planar on GaAs(111)B and vertical on GaAs(111)A, with mixed populations on GaAs(100). For the NWs catalyzed by the AgAu nanoparticle alloy, planar and vertical populations are present on both GaAs(111)A and GaAs(111)B substrates, but with different concentrations in each case. Similar behavior is observed with InP substrates. More strikingly, InP NWs catalyzed by AgAu nanoparticles show different configurations, on both GaAs (111)A and GaAs (111)B substrates. One is a "hybrid" nanowire, that starts the growth vertically and then smoothly turns into a planar nanowire. Another configuration observed shows a tendril-like nanowire, growing around a vertical nanowire. The NWs catalyzed by nanoparticles obtained by gas aggregation method also present a "baloon" like shape in the nanowire apex, which is currently under investigation. These results indicate the importance of the metal nanoparticle and surface chemistry to determine nanowire growth mode.

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M1.3 - Growth dynamics of InAs/InP nanowire heterostructures by Au-assisted chemical beam epitaxy

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The InAs/InP system is particularly suitable for the realization of axial nanowire (NW) heterostructures like quantum dots (QDs) and superlattices by Au-assisted growth.[1,2] Indeed, the very low solubility of both As and P into Au allows to obtain atomically sharp interfaces in both growth directions.[3] However, the chemical composition of the nanoparticle (NP) changes when the growth is switched from one material to the other one,[3,4] and this affects the NP stability, the NW growth mode (straight or kinked) and the growth rate. In particular, InP grows with a higher amount of In into the NP than InAs at the same temperature.[3,4] As a consequence, when switching from one material to the other, transient effects dominate during the time period of the NP reconfiguration, and the precise control of the thickness of thin InP and InAs alternating segments, which is fundamental for the realization of QDs and superlattices, can be very challenging. In this contribution we present a study of the thickness/diameter dependence of two InP barriers and of the InAs QD in between, inserted along InAs NWs grown by means of Au-assisted chemical beam epitaxy. We found a broad variability of the InP segment thickness within the same as-grown sample, resulting in InAs NWs with asymmetric and non-homogeneous InP barriers (Figure 1). We explain the results by considering the NP reconfiguration dynamics which dominates at the early stages of the growth in both growth sequences. Moreover, we propose a strategy to control the growth rate and the dynamics of the barriers, by inducing the NP reconfiguration before starting the InP growth. This allows for the realization of InAs/InP NW heterostructures of different diameters, all having symmetric InP barriers with well controlled thickness.[5]

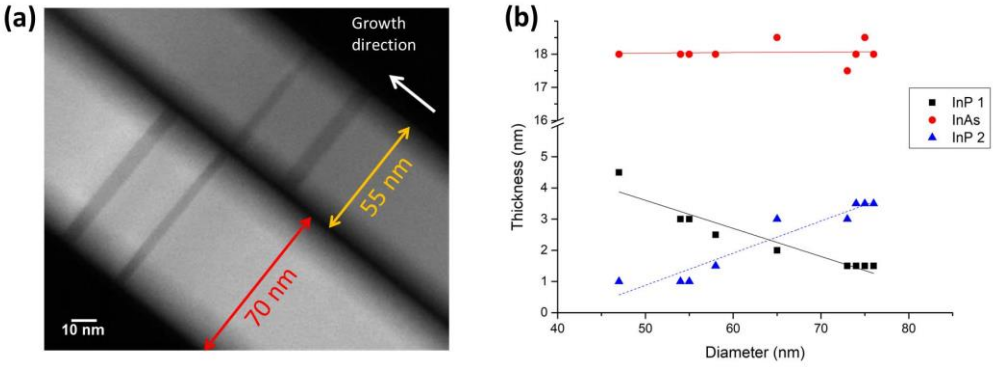

Figure 1. *Representative STEM image (a) and thickness/diameter plot (b) of several NWs of the same sample grown using NPs obtained from Au film dewetting, in which we have inserted two InP barriers (dark contrast) realizing an InAs QD in between. The barrier asymmetry and the opposite thickness/diameter dependence of the first and the second barrier are clearly seen, indicating a different growth dynamics.*

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I2 - Electrochemical Liquid-Liquid-Solid Growth of Semiconductor Nanowires

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This presentation describes and details an approach to use conventional electrochemical apparatus to grow high quality crystalline covalent semiconductor nanowires using liquid metal solvents. The approach, denoted as electrochemical liquid-liquid-solid (ec-LLS) crystal growth, has strong parallels to vapor-liquid-solid (VLS) nanowire growth. In both methods, a liquid metal serves as the medium for crystal nucleation and growth. The salient difference is that in ec-LLS an electrochemical potential gradient is used rather than a thermal or pressure gradient to drive precursor activation and subsequent product crystallization. In this way, the need for furnaces and pumps are avoided entirely. Instead, ec-LLS only requires control over an applied bias or a current, which can be performed with simple and readily available electronics with excellent temporal resolution. This presentation will show ec-LLS tactics developed by my group specifically for the growth of Si and Ge (micro) nanowires on a variety of substrates. Examples will be shown that highlight the attainability quality of these materials and possible applications for as-prepared nanowires. Additional results will be shown that detail how process parameters affect the resultant morphologies and crystallographic properties. Specific recent work on the use of in-situ TEM methods to inform on nanowire growth by ec-LLS will be emphasized.

M2.1 - Synthesis and characterisation of hexagonal-2H germanium in nanowires

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Our goal is to synthesize the hexagonal crystal phase Ge-2H which may offer a possible direct band-gap optical transition. We investigate two approaches.
1) Stress induced phase transformation. Ge nanowires with standard diamond structure (3C) undergo plastic deformation under external shear stress leading to a phase transformation toward the 2H-hexagonal phase and resulting in a quasi-periodic 3C/2H heterostructures along the <111>-oriented NW axis. The transformation is dependent upon various key parameters: the diameter of the nanowires and the crystallographic direction, the stress that can be viewed as the driving force for the phase transformation, and the temperature.
2) Growth of GaAs/Ge core/shell structures. GaAs nanowires are used as template to epitaxially transfer the wurtzite structure to the Ge shell. The GaAs-w and Ge-2H structures take advantage to present almost the same lattice constants. GaAs nanowires were grown directly in a E-TEM microscope (NANOMAX) at 400°C using TMGa and TBAs precursors. By changing the III/V flux ratio, we manage to monitor in-situ the wurtzite/zing-blende polytytpism of the GaAs nanowire. Lateral overgrowth is then performed with Ge_2H_6. We observe, in real time at the atomic scale, the epitaxial growth of Ge-2H. The dependence of the formation of intrinsic stacking faults on the growth conditions can be discussed.

Finally, those heterostructured allotrope nanowires were characterized by various complementary methods such as Raman, NIR absorption, thermal conductivity measurements to gain insight into the basic fundamental properties of this promising Ge-2H structure.

M2.2 - Growth of Zn_3P_2 nanowire on graphene via van der Waals epitaxy for photovoltaic applications

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Keywords: zinc phosphide, graphene, van der Waals epitaxy

Zinc phosphide (Zn3P2) is a promising earth abundant solar cell material. Zn_3P_2 has a direct band gap transition of 1.5 eV [1], which is close to the optimum solar energy conversion range. It has a large optical absorption coefficient of >104 cm^{-1} near its band edge [2], and a minority carrier diffusion length reported ~10 µm [1,3]. Additionally, as both zinc and phosphorous are earth abundant elements it could possibly make solar cells more economical for large-scale deployment.

Due to the large lattice parameter and high coefficient of thermal expansion of Zn_3P_2, the choice of substrate for epitaxial growth is limited and this largely affects the epitaxial growth quality. In order to obtain Zn_3P_2 thin film growth independent of substrate lattice parameter we use van der Waals epitaxy using commercial graphene as a substrate. Another effective way to reduce the dependence on the substrate is by growing nanowire. Nanowires are known for accommodating higher lattice mismatch than thin films, due to efficient elastic relaxation at the lateral free surface [4][6][7]. Additionally, these nanowires can be grown on graphene, where graphene could potentially function as a novel low-cost, transparent, and flexible electrode for nanowire based solar cells [5]. In this work, we first explain the growth mechanism of Zn_3P_2 on graphene, starting with a triangular flake morphology that can eventually turn into a thin film. We then move to the growth of Zn_3P_2 nanowires on graphene using indium and gold as catalysts. First, we establish the optimal growth conditions for the nanowires on graphene. Finally, we compare these results to that of the thin films on graphene. Raman spectroscopy and cathodoluminescence are used to confirm the crystalline quality of the nanowires and to detect the presence of impurities.

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M2.3 - InAs – EuS – Al hybrid nanowires

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Keywords: III-V nanowire, molecular beam epitaxy, ferromagnetic insulator

Material development holds promise as the basis of topological quantum computing with Majorana fermions. These quasiparticles have been predicted to be formed in semiconductor nanowires coupled to conventional superconductors.[1-2] This prediction was followed by a series of experiments providing strong evidence.[3-4] However, in the current system, an external magnetic field along the NW axis is always needed to realize Majorana states. Therefore, in order to integrate and scale up qubit devices, it is aimed to induce a self-sustaining parallel magnetic field on semiconductor–superconductor hybrid NWs. Composite materials using ferromagnetic insulators (FMIs) in close proximity to a semiconductor – superconductor structure have been proposed as a solution to reach a zero-field topological state[5], where the effective Zeeman splitting is induced by an magnetic exchange coupling by the FMI. In this work, we grow epitaxial semiconductor – ferromagnetic insulator – superconductor InAs-EuS-Al hybrid nanowires in-situ in the molecular beam epitaxy system. The results show the superconducting hard gap, the transport hysteresis and the shape-defined magnetic single domain structures based on well-controlled epitaxy, which suggests that this highly ordered material system is a promising platform for scalable topological quantum computing.

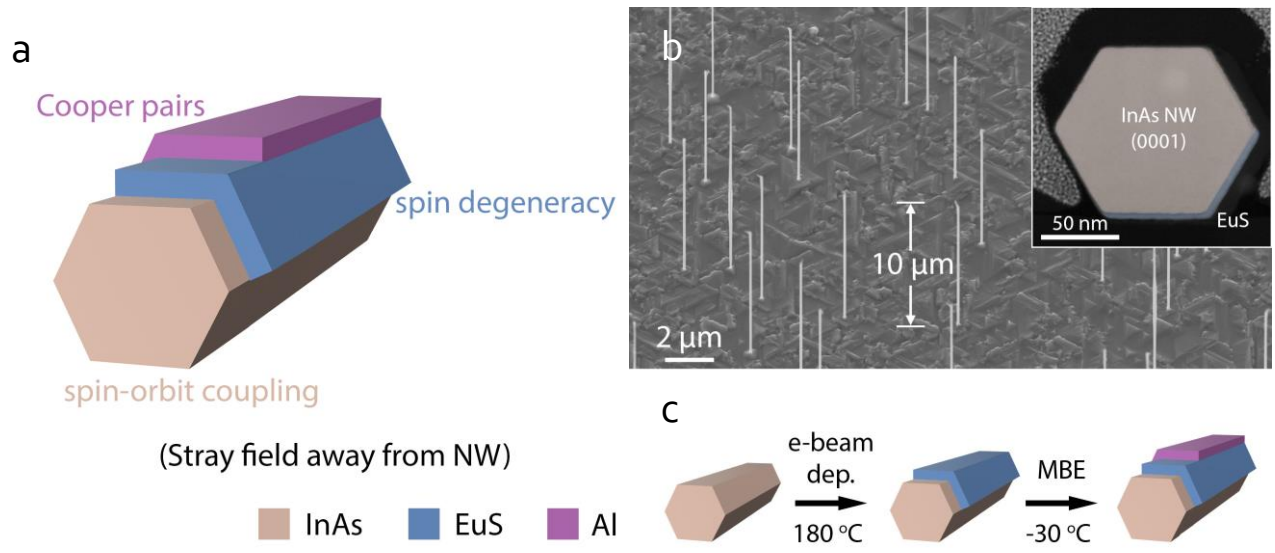

Figure 1. *(a) The concept of InAs-EuS-Al NWs. (b) The morphology of grown NWs. (c) The schematic of NW growth method.*

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M3.1 - Dual Role of Gold Droplets in the Growth of Inclined InAs Nanowires

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Keywords: inclined nanowires, (001) substrate, nano-craters

One of the most important applications of InAs and InSb nanowires is in producing hybrid semiconductor/superconductor devices used in the quest of Majorana fermions. The pursuit of fabricating devices for performing nonabelian-braiding operations requires formation of intersections of such nanowires and further networks. Recently, the growth of 'Y' and 'K'-shape InAs nanowires, consisting of two interconnected wurtzite nanowires was reported [1]. The latter containing an additional zinc-blende nanowire in between the two and occasionally embedding a purely wurtzite two-dimensional plate. Both 'Y' and 'K'-shaped structures are obtained by using {001}-oriented substrates, on which the nanowires grow with their growth axis along one of the <111> directions, thus inclined to the {001} surface.

For both, vertical (grown on a {111}B substrate) and inclined nanowires it is common that their nucleation is guided by Au catalyst. We show that on the {001}-type surfaces the Au droplets carry an additional crucial role that necessarily precedes the nanowire emergence, i.e., they assist formation of nano-craters with strongly faceted {111}B side walls. Only once these facets become sufficiently large and regular, the gold droplets start nucleating and guiding the growth of nanowires. Au-induced formation of the craters and the onset of nanowires on the {111} facets inside the craters are confirmed by the results of Monte Carlo simulations [2].

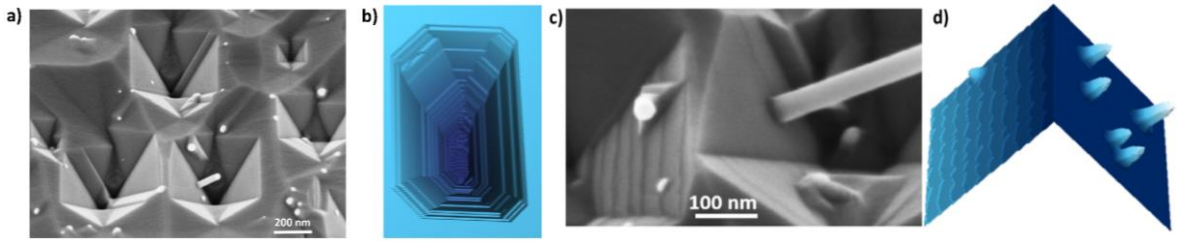

Figure 1. *a) SEM image of a (001)-oriented substrate with nano-craters and a nanowire emerging from the crater side facet. b) A crater in a (001) surface with {111}-oriented side facets, as obtained by Monte Carlo simulations. The growth of nanowires on stepped and smooth {111}-surfaces: c) observed by SEM; d) simulated theoretically.*

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[3] **Acknowledgement:** Financial support from the Polish National Science Center (Grant Nr 2016/23/B/ST3/03725) is acknowledged.

M3.2 - Bottom-up grown 2D InSb nanostructures

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Keywords: InSb, two-dimensional, free-standing

Low-dimensional high-quality InSb materials are promising candidates for next-generation quantum devices due to the high carrier mobility, low effective mass, and large g-factor of the heavy element compound InSb. Various quantum phenomena are demonstrated in InSb two-dimensional (2D) electron gases and nanowires. A combination of the best features of these two systems (pristine nanoscale and flexible design) is desirable to realize, *e.g.*, the multiterminal topological Josephson device. Here, controlled growth of 2D nanostructures, nanoflakes, on an InSb platform is demonstrated.[1] An assembly of nanoflakes with various dimensions and morphologies, thinner than the Bohr radius of InSb, are fabricated by metal-organic vapor phase epitaxy (MOVPE) technique. Importantly, the growth of either nanowires or nanoflakes can be enforced experimentally by setting growth and substrate design parameters properly. Hall bar measurements on the nanostructures yield mobilities up to ≈20 000 $cm^2\ V^{-1}s^{-1}$ and detect quantum Hall plateaus. Electronic assessment of the material marks this system as a viable nanoscale 2D platform for future quantum devices, thermal rectifiers, field emitters, IR detectors, *etc*.

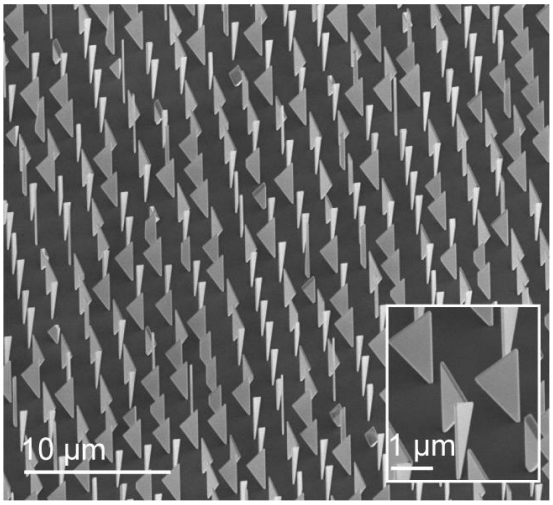

Figure 1. *Growth of InSb nanoflakes under high catalyst particle supersaturation. A 30°-tilted SEM image of InSb nanoflakes. Inset: magnified area shows the facetted morphology of the structures.*

Reference

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M3.3 - Toward Scalable III-V Nanowire Networks on Si

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Keywords: scalable, networks, silicon

InGaAs is an ideal material for near-infrared photodetection at telecommunications wavelengths, but its devices typically require the use of bulk III-V substrates which are incompatible with CMOS processing.[1] Vertical InGaAs nanowires grown on Si have been proposed as a promising route to integration with Si electronics, but creating devices typically requires transferring them to a second substrate in a horizontal configuration, which is not scalable to industrial production.[2] Recently, arrays and networks of high-quality horizontal InGaAs nanowires have been demonstrated by selective area epitaxy on III-V substrates by growing them on top of GaAs nanomembrane buffers.[3] Extension of this technique through monolithic integration of GaAs nanomembranes on Si (001) offers the opportunity to create scalable, high-performance infrared photodetectors at a fraction of the cost of current InGaAs-based devices. This, however, requires a reliable method to grow defect-free GaAs nanomembranes on Si. In this work, we investigate the growth of GaAs nanomembranes on Si by molecular beam epitaxy. Specifically, we combine a number of established defect reduction techniques, including v-groove trenches, aspect ratio trapping and migration enhanced epitaxy, and characterize the resulting nanostructures. We demonstrate highly-faceted nanomembrane structures several micrometers in length that exhibit large defect-free regions, which may be suitable as a template for future horizontal InGaAs nanowires. Furthermore, we explore the impact of diverse substrate topographies, including high aspect ratio trenches and raised v-groove structures, on GaAs growth and nucleation to better understand how the morphology of the grown structures can be controlled.

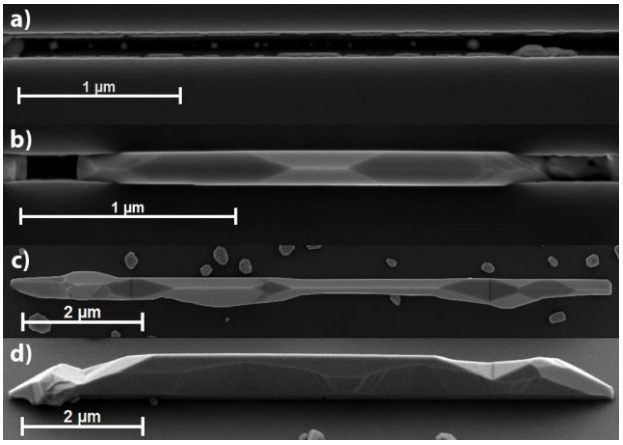

Figure 1. *Scanning electron micrographs of GaAs nanostructures on (001) Si showing a) nucleation at bottom and sides of v-groove trench, b) appearance of faceting and corresponding top ridge during growth, c) top view and d) tilted view of resulting nanomembranes, which will be shown to contain large defect-free regions.*

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[4] **Acknowledgements:** Funding from Swiss National Science Foundation, NCCR QSIT

M3.4 - Application of amorphous Al_xO_y as a nucleation layer for selective area formation of GaN nanowires by PAMBE

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Keywords: selective area growth, GaN nanowires, molecular beam epitaxy

It was recently found that self-induced formation of GaN nanowires (NWs) can be achieved by plasma-assisted MBE on crystalline Al_2O_3(0001) if the substrate is covered by an amorphous Al_xO_y (a-Al_xO_y) buffer.[1] Moreover, much faster formation of GaN NWs was found on a-Al_xO_y than on nitridated Si substrates (SiN_x/Si) under the same growth conditions.[2] These findings pave the way for selective area growth (SAG) of GaN NWs on a variety of materials by using a-Al_xO_y as a nucleation layer.

In this work GaN growth was performed on GaN/sapphire and SiN_x/Si substrates with stripes of 15 nm thick a-Al_xO_y. On GaN/sapphire substrate formation of well-organized GaN NWs was found on a-Al_xO_y stripes, while a rough compact GaN layer was obtained on bare, crystalline parts of the substrate. Since the compact layer forms under N-rich conditions while the growth of GaN NWs takes place under local excess of Ga,[3,4] the ratio of NW length *h* to the thickness of the compact layer *d* can be tailored by adjusting the growth conditions. The respective modelling was performed taking into account dependence of NW incubation time as a function of growth parameters (Fig.1a-b).[5] In agreement with calculations we found that the value of *h/d* ratio can be increased by increasing the Φ_N/Φ_{Ga} flux ratio. On the other hand pure SAG was observed on SiN_x/Si substrates (Fig.2). This was achieved by such adjusting the growth parameters that nucleation of GaN on Si_xN was prevented (incubation time longer than the growth duration), so GaN NW growth took place on a-Al_xO_y stripes only. Importantly, the same effect of pure SAG was found for PECVD-deposited SiN_x on GaN/sapphire templates. In that way, our results indicate that application of a-Al_xO_y nucleation layer is an efficient tool for controlling spatial distribution of GaN NWs. Finally, the importance of surface Ga diffusion for enhancement/retardation of NW formation at the edge of the a-Al_xO_y pattern on GaN/sapphire and SiN_x/Si substrates is discussed.[6]

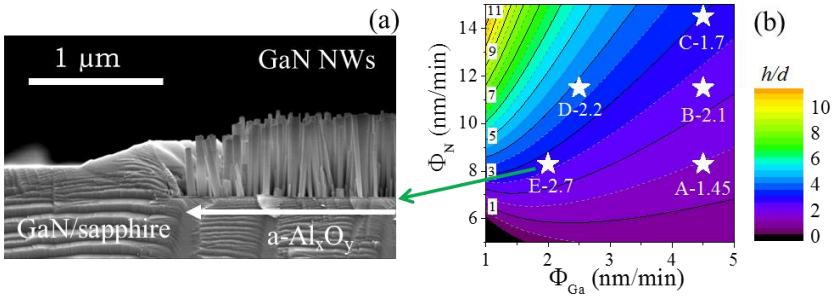

Fig. 1. *(a) Micrograph of GaN NWs and the compact layer on the GaN/sapphire substrate with a-Al_xO_y stripe; (b) calculated h/d ratio vs. Ga and N fluxes and experimental values of h/d for growths at 814ºC for 120 min.*

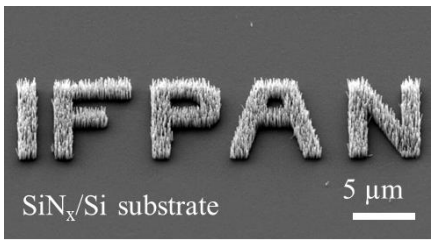

Fig. 2*. Bird's eye-view SEM micrograph of GaN NWs grown selectively on SiN_x/Si substrate with a-Al_xO_y nucleation pattern.*

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I3 - Ge-based Nanowires with Metastable Composition: Hyper-Doping and Alloy Formation

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Keywords: metastable composition, germanium

This talk will address the formation of nanowires and nanorods of materials with metastable compositions and demonstrate the significant changes in physical properties associated with their composition. All the growth studies are carried out either in solution or by gas phase techniques using the metal to be in corporate in the Ge host lattice as a growth seed. This approach allowed the formation of highly crystalline, metastable $Ge_{1-y}Ga_y$ (y~0.03%) as well as $Ge_{1-x}Sn_x$ (x=0.13-0.28) nanowires and nanorods at low temperatures.[1-3] The materials have been characterized by different analytical methods including TEM, EDX, Raman spectroscopy as well as XRD. Generally, a homogeneous incorporation of unusually high contents of Sn and Ga in the Ge lattice has been observed. The high incorporation efficiency also alters the physical properties significantly. While hyperdoped $Ge_{0.97}Ga_{0.03}$ shows quasi-metallic behavior in temperature dependent transfer characteristics,[1] $Ge_{0.81}Sn_{0.19}$ reveals still semiconducting behavior in equivalent experiments.[4] Moreover, the formation of $Ge_{1-x}Sn_x$ with x>0.09 causes the transformation to a direct bandgap material, while the the solid solubility limit according to the binary phase diagram (~ 1 at% Sn in Ge) has to be overcome. The efficient absorption and emission in the mid-IR range (<~0.55 eV) makes $Ge_{1-x}Sn_x$ very attractive materials for CMOS-compatible optoelectronic devices based purely on group IV elements. The high crystal quality of CVD-grown, epitaxial $Ge_{0.81}Sn_{0.19}$ nanowires can be illustrated by the analysis of their photoluminescence under different temperature and illumination conditions.[5] This research is funded national funding bodies.[6]

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M4.1 - Crystal phase engineering of self-catalyzed GaAs nanowires following the RHEED diagram during the MBE growth

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III-V semiconductors NWs obtained by the vapor-liquid-solid (VLS) mechanism, Au-catalyzed or self-catalyzed, exhibit a Zinc-Blende (ZB) or a Wurtzite (WZ) structure[1], depending on the growth conditions, and more particularly on the amount of III and V element fluxes[2-4]. Indeed, it has been established that the structure of these NWs is dictated by the contact angle of the catalyst, which depends on the V/III flux ratio. In this work, we studied the crystalline structure of self-catalyzed GaAs NWs during their growth on silicon substrate by molecular beam epitaxy (MBE), following the RHEED diagram (Fig.1.a). The intensity evolution of the ZB and WZ diffraction spots along the [1-10] azimuth was measured during the growth as a function of the growth conditions. By adapting the Ga and As fluxes during growth, it is then possible to control the structure of the GaAs NWs, ZB or WZ. Controlled ZB/WZ/ZB sequences have been achieved in self-catalyzed GaAs NWs using this procedure (Fig.1.b and c)[5].

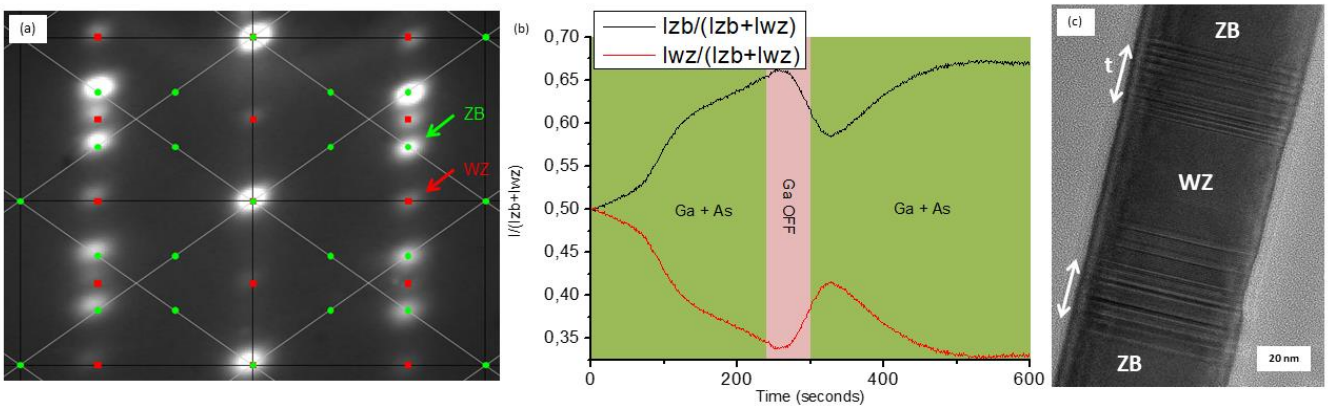

Figure 1. *(a) RHEED diagram along [1-10] azimuth of the self-catalyzed GaAs NWs wherein ZB and WZ phases are present. Green dots show ZB spots, red squares show WZ spots. Arrows indicate the analyzed spots. (b) $I_{zb}/(I_{zb}+I_{wz})$ and $I_{wz}/(I_{zb}+I_{wz})$ intensity ratios measured as a function of the growth time* ***and (c)*** *Bright-field TEM image, of a ZB-WZ-ZB sequence realized by this procedure. The scale bar on the image corresponds to 20 nm.*

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M4.2 - Polytypism transfer observed in GaAs/GaNAs core-shell nanowires

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Keywords: Molecular beam epitaxy, GaAs, Dilute nitrides

III-V semiconductor nanowires (NWs) are promising as building blocks in nanoelectronics and nanophotonics. Dilute nitride GaNAs materials of physics and technological interest due to the tunability of their lattice constant and band gap. The incorporation of a few percent of nitrogen into GaAs leads to an anomalous reduction of the band gap, which makes this material suitable for near infrared regime light emitters and solar cells [1]. And thus the GaNAs NWs would extend the functions of GaAs related NWs.[2,3] The GaAs NWs are known to include both zinc blende (ZB) and wurtzite (WZ) polytype. These crystal structures are known to affect the band gap structure, and their accurate understanding and control are required. We here report on the investigations of polytype in GaAs/GaNAs/GaAs core-multishell NWs.

We grew the GaAs/GaNAs/GaAs nanowires by plasma assisted molecular beam epitaxy using constituent Ga-induced vapor-liquid-solid growth on Si(111) substrates. Fig. 1(a) and (b) are grain size distributions of GaNAs nanowire containing 2% nitrogen obtained by electron backscatter diffraction in transmission electron microscopy. As seen in the figure, the grain size of WZ varies between 0.1-0.3 µm. However, the distributions of ZB showed Gaussian like distribution peaked at around 0.30-0.35 µm. That corresponds to the diameter of the NW. Fig. 1(c) is the result of x-ray diffraction for the series of GaNAs core-multishell nanowires nominally containing of 0, 2, and 3% nitrogen. We observe WZ-related GaAs(0002) peak at the lower angle side of ZB GaAs(111) peak. The intensity of the GaAs(0002) peak decreases with the increase of the constituent nitrogen. The polytypism of the NW was hence considered to be transferred from WZ to ZB by the introduction of GaNAs shell.

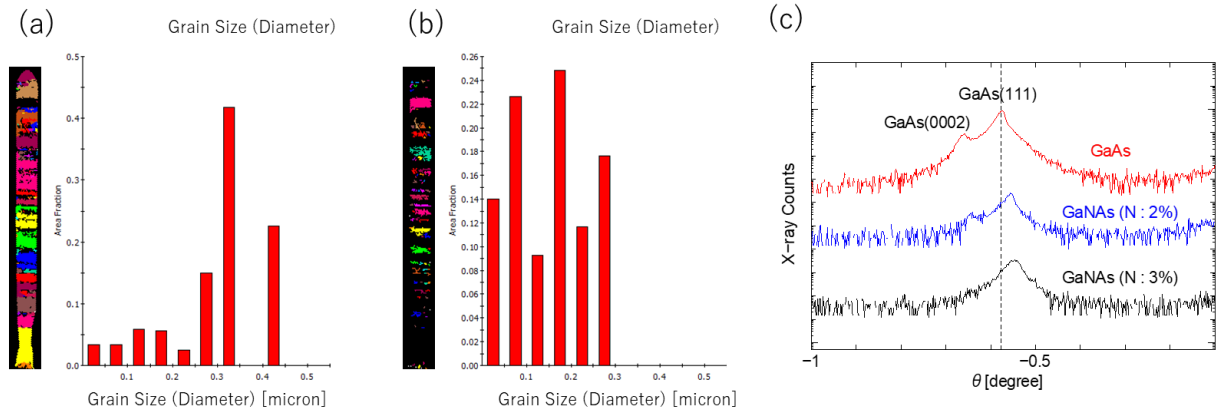

Figure 1. *Grain size of (a)ZB and (b)WZ. (c) x-ray diffraction measurement of GaNAs nanowires containing 0, 2, and 3% nitrogen, showing GaAs(0002) and GaAs(111) peak.*

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M4.3 - Critical radius and strain mapping in axial heterostructure nanowires

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Keywords: nanowires, heterostructures, strain

InAs/GaAs axial heterostructure nanowires constitute a perfect playground to study strain relaxation because of the large lattice mismatch between InAs and GaAs and the ability to create ternary alloys. For a given lattice mismatch, the release of the mechanical strain generated at the interface is set by alpha, the ratio between the interface length and the nanowire radius. This parameter controls the critical radius above which dislocations appear at the interface between two materials. Controlling alpha is therefore of fundamental importance for the realization of axial heterostructure nanowire devices.
Here, we present both theoretical and experimental data on heterostructures with various values of alpha and lattice mismatch. We first explore experimentally the conditions for the growth of coherent InAs/GaAs nanowire heterostructures and present a full characterization of the interface. We then present calculations of the critical radius as a function of alpha which we compare with our experiments.
The nanowires are grown using the Au-assisted vapour liquid solid mechanism by molecular beam epitaxy. We access a wide range of interface lengths and radii through different growth parameters.[1] The nanowires structural and chemical properties are studied by high resolution transmission electron microscopy coupled with energy dispersive X-ray spectroscopy. We use the geometrical phase analysis technique to image the strain fields at the InAs/GaAs interface.
For coherent interfaces, the strain is released elastically by bending planes along the axis of the nanowire and in the radial direction.[2] We show that those experimental data can be reproduced accurately using finite element calculations. Simulations show that strain is considerably reduced at the interface by introducing an interface length of few nanometers, contributing to loosen the constraints on the diameter.

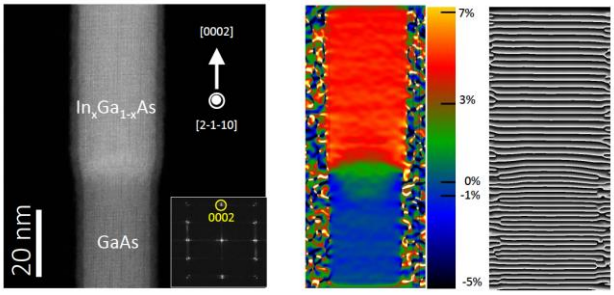

Figure 1. *HRSTEM image of an InAs/GaAs axial heterostructure. Mapping of the strain component ε_{zz}. HRSTEM image after Fourier filtering of the [0002] Bragg reflection.*

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I4 - Chiral twisted van der Waals nanowires

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Semiconductor nanowires have mostly been synthesized from conventional three dimensional (3D) crystalline materials. Layered crystals, in which covalently bonded sheets are held together by weaker van der Waals forces, have emerged as a class of materials with extraordinary properties not found in 3D crystals. Shaping layered materials into nanowires could open up new, tunable structural, optoelectronic, and electronic transport/device characteristics.

Here, we discuss the realization of this vision, namely the synthesis and emerging properties of van der Waals nanowires of layered crystals, formed by combining the concepts of vapor-liquid-solid (VLS) growth and van der Waals epitaxy. Germanium (II) sulfide (GeS), a 2D/layered chalcogenide semiconductor with anisotropic structure analogous to that of black phosphorus, was grown in nanowire form by a VLS process.[1] High-quality van der Waals nanowires crystallize with layering along the wire axis[1,2] and show bright, size dependent band-edge luminescence. A strong propensity for forming screw dislocations, often found for layered crystals,[3] introduces extraordinary properties. Eshelby twist, induced by a torque on the ends of a cylindrical solid due to the stress field of an axial dislocation, causes a chiral structure of the layered nanowires and leads to spontaneous, size-tunable twist moiré patterns between the van der Waals layers along the wires.[4] The interplay between the chiral structure and progressively changing optoelectronic properties in these helical twist moirés can be detected by combined nanobeam electron diffraction and nanometer-resolved STEM cathodoluminescence spectroscopy. While many other unique properties are yet to be discovered, van der Waals nanowires represent a versatile platform for exploring emerging phenomena associated with variable interlayer twist in layered materials.[5]

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[5] **Acknowledgements** This work was supported by the National Science Foundation, Division of Materials Research, Solid State and Materials Chemistry Program under Grant No. DMR-1607795 and by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award No. DE-SC0016343.

Tu1.1 - Planarizing VLS Epitaxial <111> Nanowires by Elastocapillary Force

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Keywords: VLS, nanowire, alignment

Achieving high density and yield of semiconductor nanowire arrays remains one of the biggest challenges for array based nanowire devices. We have previously reported Selective Lateral Epitaxy (SLE), an in situ self-aligned epitaxial method[1], which achieved perfect alignment with crystal orientation precision in plane. However, the yield of using SLE to achieve planar GaAs nanowire array reduces and the process window significantly shrinks for smaller nanowires (<~ 70 nm).[2] For post-growth alignments, the dielectrophoresis assembly method has achieved one of the highest yield of single nanowire arrays with yield of 98.5%.[3] However, this method is limited to low density applications with over 10 µm pitch between the nanowires, since the electric fields from adjacent electrodes influence each other. There have been reports on achieving higher densities of single nanowire arrays with pitches of a couple of microns, but the yield of a single nanowire per site was significantly lowered compared to dielectrophoresis assembly.

We hereby report an elastocapillary force alignment method that is extremely simple yet much more precise with high yield and better density. No complex setup is needed for the elastocapillary force alignment since it merely takes advantage of the nature of nanowires bending in water. We first grow <111> oriented III-V (including GaAs, InP, InAs) nanowires epitaxially on either (110) GaAs or InP substrates using the Vapor-Liquid-Solid (VLS) mechanism with Au nanoparticle locations defined by electron beam lithography. We then dip the sample in water for planarization. We show up to 98.8% yield of planar single/multiple GaAs nanowire arrays with (75 x 15) x 6 sites (6750 total) and submicron pitch between the nanowires. Also, the nanowire arrays have been achieved on the entire 1.6 cm x 1.2 cm size GaAs substrate demonstrating the applicability of the elastocapillary method over large areas.

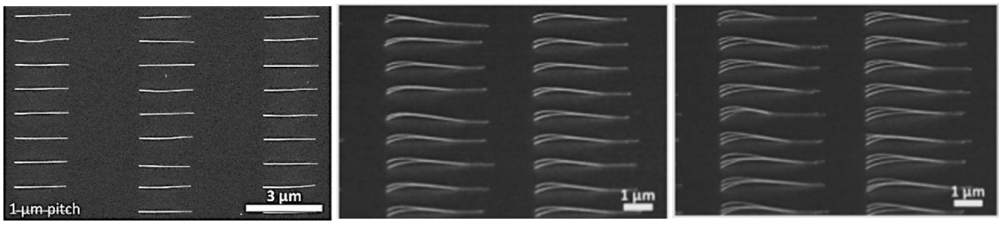

Figure 1. *SEM images (from left to right) of arrays of single, double and triple GaAs nanowires (25 nm diameter 2.5 µm long) on (110) GaAs substrates after elastocapillary force alignment.*

Our calculations show that by having the right design of nanowire length and diameter, even higher density of nanowire arrays can be achieved. Also, there is no physical limitation on the size of the substrate in which elastocapillary force alignment can be applied upon. This method is highly effective and facile, and can potentially be utilized to realize mass production of bottom-up grown planar nanowire based architectures.

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Tu1.2 - Germanium-tin growth kinetics for high tin-content Ge-core/$Ge_{1-x}Sn_x$ shell nanowire light emitters

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Germanium-tin is a promising alloy system for novel light sources and optical sensing in the mid-IR. For sufficiently high Sn compositions, the material has a direct band gap near 0.5 eV, thus permitting its application as an efficient mid-infrared light emitter and detector. The main challenge to growth of high-quality single crystal epitaxial layers of direct-gap $Ge_{1-x}Sn_x$ is the large lattice mismatch relative to available bulk substrates (e.g. ~14 at% misfit of diamond cubic Sn on Ge) and the low equilibrium solubility of Sn in Ge (~1 at%). Core-shell Ge/$Ge_{1-x}Sn_x$ nanowire structures take advantage of small-radius Ge nanowires as compliant substrates for high quality single crystal $Ge_{1-x}Sn_x$ shell growth.

We demonstrate that, for $Ge_{1-x}Sn_x$ shell growth by chemical vapor deposition (CVD) using GeH_4 and $SnCl_4$ precursors in H_2 carrier gas, introduction of $SnCl_4$ in the growth environment prompts a sudden switching from axial Au-seeded nanowire vapor-liquid-solid growth to radial shell growth, suggesting that Sn adsorption disrupts the hydrogen termination of the Ge <111> nanowire sidewalls. The time dependence of $Ge_{1-x}Sn_x$ shell deposition [Fig. 1(a)] on misfitting Ge cores is consistent with an initially slow growth regime resulting from the large elastic energy stored in the shells when their thickness is less than the core radius, followed by a steady-state regime in which growth is limited by precursor transport to the shell surface during CVD. Increasing the $SnCl_4$ partial pressure and reducing the growth temperature while avoiding nucleation of Sn surface particles results in incorporation of increasingly metastable Sn compositions in single-crystal core/shell wire arrays [Fig. 1(b)]. Up to 14 at% Sn shells are investigated, resulting in room temperature photoluminescence consistent with strong direct-gap emission from both the shell and the highly tensile-strained Ge core [Fig. 1(c)].

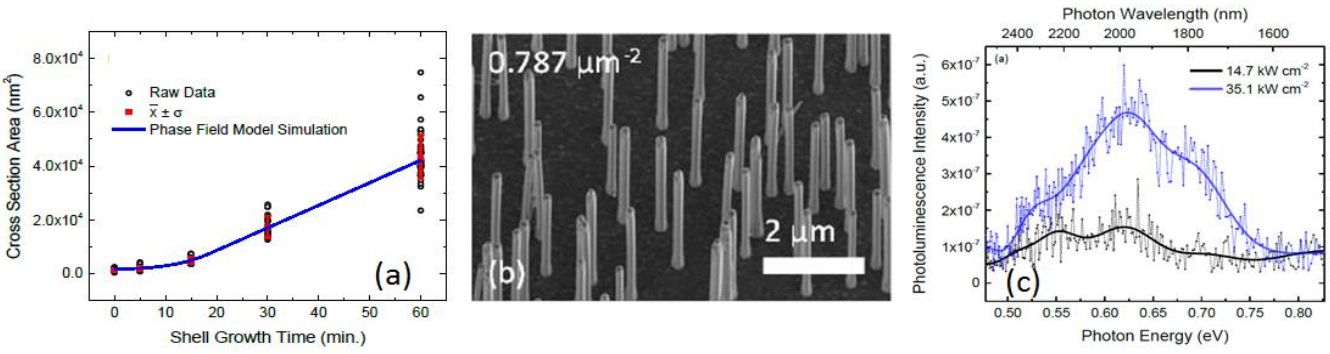

Figure 1. *(a) Nanowire cross-section area change versus GeSn shell growth time. (b) <111>-oriented single crystal Ge-core/$Ge_{0.88}Sn_{0.12}$-shell assembly grown on Ge(111) substrate. (c) Room-temperature single-nanowire photoluminescence spectrum for a nanowire transferred to a template-stripped Au substrate, consistent with GeSn shell and tensile-strained Ge core Γ-valley emission at ~0.55 eV and ~0.62 eV, respectively, and increasing L-valley Ge core emission (0.68 eV) at high excitation power densities.*

Tu1.3 - Quantitative assessment of n-type and p-type doping in GaAs nanowires by cathodoluminescence

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Keywords: Doping, GaAs, cathodoluminescence

Precise control of doping in single nanowires (NWs) is essential for the development of nanowire-based opto-electronic devices. In a previous work, we have demonstrated the quantitative analysis of electron concentration in Si-doped shells of GaAs NW using cathodoluminescence (CL) mapping[1] as a rapid, contactless measurement method of the carrier density in single nanowires. Here, we extend this work to a series of self-catalyzed Be-doped (core and shell) and Si-doped (shell) GaAs NWs grown under different conditions by Molecular Beam Epitaxy using the Vapour Solid Liquid method. High-resolution CL mapping is performed at low- and room-temperature. CL spectra can be analyzed selectively in different regions of the nanowires. Room-temperature luminescence is fitted with the generalized Planck's law and an absorption model, and the bandgap and band tail width can be extracted. For Be-doped GaAs NWs, the bandgap narrowing provides a quantitative determination of the p-type doping concentration ranging from about 1×10^{18} to 3×10^{19} cm^{-3}, in good agreement with the target doping levels. For Si-doped GaAs NWs, the electron Fermi level and low-temperature FMHM are used to assess the n-type doping concentration from approximately 4×10^{17} to 6×10^{17} cm^{-3}. These findings confirm the difficulty to reach highly-doped n-type GaAs nanowires, and may be due to doping compensation. Notably, signatures of heavily-doped ($5 - 10 \times 10^{18}$ cm^{-3}) GaAs:Si at the very top of NWs are unveiled.[2] The luminescence analysis method has been further validated on a wide series of p-type and n-type GaAs planar reference thin films.[3]

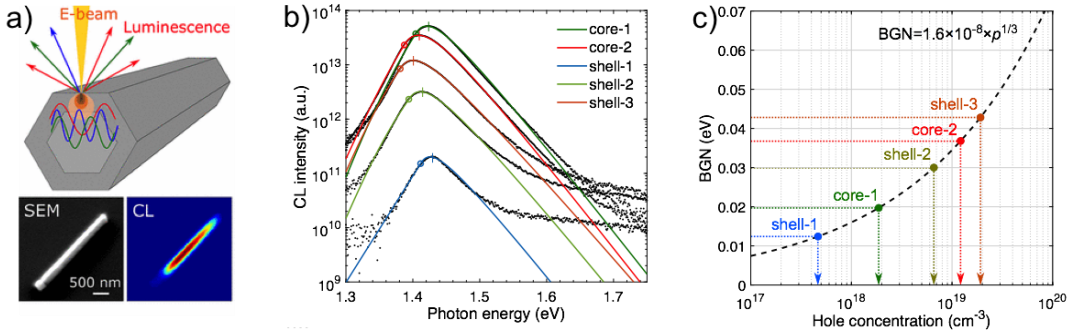

Fig. 1. *a) Schematic of the CL beam excitation, SEM and CL mapping; b) CL spectra of Be-doped GaAs NWs (black dots) and fits (colored lines). Vertical bars mark the CL peak positions, and open circles mark the bandgap deduced from the fit of the generalized Planck's law; c) Empirical relation used to access the hole concentration from the BGN values, from [1,3].*

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[4] **Acnowledgement:** This project has been supported by the French government - ANR-IEED-002-01 and by the ANR projects Nanocell (ANR-15-CE05-0026) and Hetonan (ANR-15- CE05-0009).

Tu1.4 - Measuring optical absorption in single nanowires

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Keywords: Optical Absorption, Single Nanowires

Nanowires are very promising building blocks for optoelectronic as well as photovoltaic applications, thanks to their enhanced absorption cross-section enabled by photon confinement. Understanding and characterizing light absorption at the nanoscale is crucial for progress in these fields. However, measuring the absorption cross-section of single nanowires has faced significant challenges. In this work we present a novel method for measuring the absorption cross-section of single nanowires. When comparing with other methods that have been developed recently,[1,2] this method offers a greater sensitivity as well as a larger temperature range in which it can be applied.

The measurements are performed using a suspended microplatform commonly used for thermal transport measurements.[3] A nanowire is suspended on a single microplatform and the device is operated under vacuum conditions. For the absorption measurement a laser is focused on the nanowire, causing an increase in the temperature of the nanowire and, in turn, of the microplatform. The temperature increase of the microplatform is directly proportional to the laser power absorbed in the nanowire and the thermal conductance from the platform to the heat sink.

The method is tested by measuring the absorption in some zincblende GaAs nanowires for several different excitation wavelengths and polarization and comparing these results to results obtained using FDTD simulations.

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I5 - Phonons and phonon transport in semiconductor nanowires

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Keywords: phonons, thermal transport, phonon engineering, crystal phase, twinning superlattice, Raman spectroscopy

The recently growing research field called *"Nanophononics"* deals with the investigation and control of vibrations in solids at the nanoscale. Phonon engineering leads to a controlled modification of phonon dispersion, phonon interactions, and transport.[1,2]

Nanowires (NWs) form an ideal template to study thermal transport behavior at the nanoscale thanks to the intrinsic 1D nature of transport in these materials, as well as the possibility to obtain different types of heterostructures, under different geometries, combining different materials and/or crystal structures that would not be possible in bulk materials. However, engineering and probing phonons and phonon transport at the nanoscale is a non-trivial problem.

In this talk, we discuss how phononic properties can be engineered in NWs and the challenges and progresses in the measurement of the thermal conductivity of nanostructures.

We demonstrate the versatility of Raman spectroscopy and show that it can be used to determine the main crystalline, phononic, and electronic properties of the most challenging type of heterostructure: a nanoscale system with constant material composition (Ge), but different crystal phases (cubic and hexagonal).[3] The general procedure that we establish can be applied to several types of heterostructures. The concept of phonon engineering in NWs is exploited in superlattice (SL) NWs. We experimentally show that a controlled design of the NW phononic properties can be decided à la carte by tuning the SL period.[4]

Finally, Raman thermometry is used to probe the temperature profile along the NWs upon application of a thermal gradient, enabling the differentiation between ballistic and diffusive flow regimes.

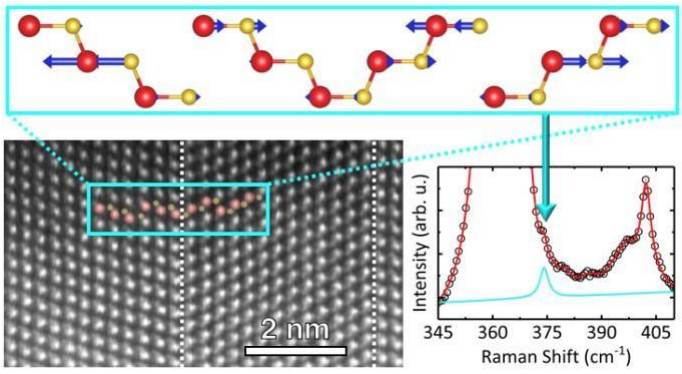

Figure 1. *Cartoon illustrating one of the twinning superlattice phonon modes.*

References

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Tu2.1 - Surface phonon polariton modes in ordered arrays of GaN nanowires

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We will discuss surface phonon polariton (SPhP) peaks in Raman spectroscopy data taken on GaN nanowire arrays. These arrays were fabricated with a high degree of pitch and diameter uniformity using selective area growth with patterned buffer layers by molecular beam epitaxy.[1,2] This high degree of uniformity allowed a broad range of diameters from 120 nm to 340 nm and pitch spacings from 300 nm to 1500 nm or more, resulting in a broad range of volume fill factors for the arrays. Raman spectra were acquired in the backscatter geometry using 532 nm laser light and a microscope objective lens with a numerical aperture of 0.6. The SPhP peaks appear at approximately 690 cm^{-1} and 710 cm^{-1}. For most samples, the peaks shift slightly upward with nanowire diameter. The most striking variation is that the intensity of the peaks varies strongly with pitch, being greatest around pitch of 400 nm to 500 nm and decreasing by factors of up to 6x as the pitch increases to 750 nm.

We conducted several experiments to determine the critical aspects of the geometry and phonon modes. Most significantly, we find that arrays that have been overcoated with a thin layer of AlGaN display a progressive disappearance of the SPhP peaks as the array pitch increases and the self-shadowing that occurs during MBE growth is slowly removed, allowing the AlGaN coating to move progressively farther down from the tip along the sidewalls. The AlGaN layer is typically about 4 nm thick on the sidewalls and therefore too thin to have a significant effect on the volume-averaged dielectric constant. However, this layer applies sufficient strain to cause dislocation formation at the shell-core interface. We therefore explain the peak disappearance as strain-induced broadening and dampening the optical phonon response. We have also found no difference between arrays with nanowires arranged apex-to-apex in rows instead of flat-to-flat. This result implies that details of the nanowire cross-section or neighboring nanowire surfaces are irrelevant to the SPhP mode energies. Finally, the peak areas increase slightly with temperature as would be expected from thermally driven increases in phonon mode occupancy.

Although there are slight shifts of approximately 1 to 3 cm^{-1} in the SPhP peak energies with diameter and pitch, the change in fill factor for our arrays varies from 0.1 to 0.9, and the large shifts of 100 cm^{-1} predicted by an effective medium model[3] at the extremes of this range do not appear. We tentatively explain the peaks as due to surface phonon modes shifted by the application of electromagnetic boundary conditions to the polarization fields generated by relative ionic motion to the bulk transverse optical phonons A_1(TO) and E_1(TO). The intensity behavior of the peaks arises from the array interference with the incoming plane laser plane wave such that electric fields are enhanced at the surface region for pitch spacings comparable to the wavelength of the laser light.

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Tu2.2 - Stimulated Raman scattering in Ge nanowires

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Keywords: Germanium, stimulated Raman scattering, metal-semiconductor heterostructure

Investigating group-IV based photonic components is a very active area of research, with particular interest in developing effective light sources. However, due to the indirect band-gap of these materials, conventional light emitting diodes and lasers cannot be realized. In this context, there is considerable interest in developing nanoscale group-IV based Raman lasers.[1] Nevertheless, the low quantum yield of stimulated Raman scattering (SRS) in Si and Ge requires large device footprints and high lasing thresholds. Consequently, the fabrication of integrated energy-efficient Raman lasers is challenging.[1,2] Here, we report, a systematic investigation of SRS in axial Al-Ge-Al nanowire heterostructures with ultra-small Ge segments contacted by self-aligned Al leads (see figure 1a). These quasi-1D heterostructures with abrupt metal-semiconductor interfaces reassemble a Ge segment monolithically integrated within monocrystalline Al mirrors that also serve as effective heat-sinks. The measured Stokes intensities of devices with different Ge lengths (L) and diameters (d) are shown in figure 1b. Mode resonances in these nanocavities result in a measured SRS threshold as low as 60 kW/cm^2. Our findings provide a platform for elucidating the high potential of future monolithically integrated nanoscale low-power group-IV based Raman lasers.

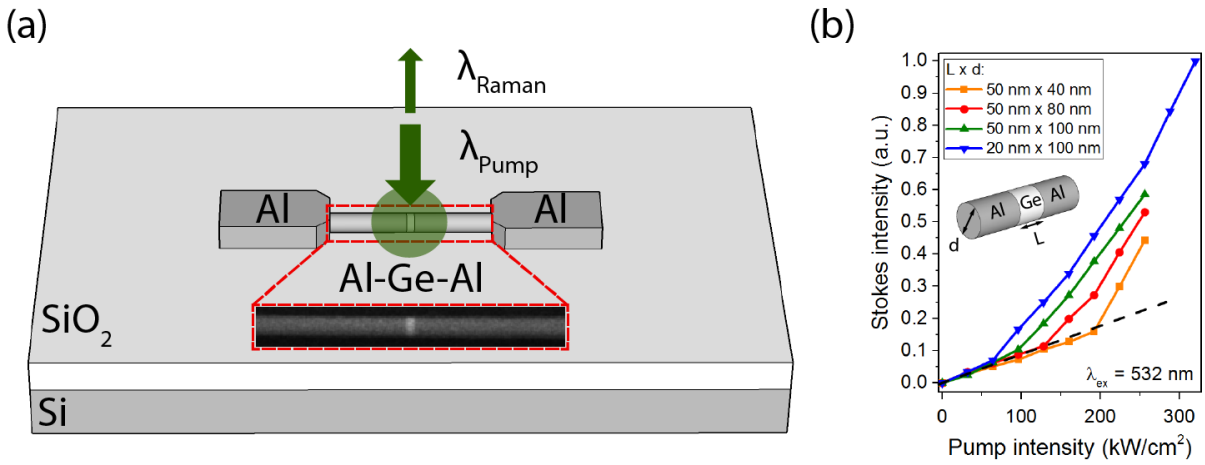

Figure 1. *(a) Schematic illustration of the Ge nanowire based SRS device. A SEM image of the actual device is shown in the inset. (b) Measured Stokes intensity as a function of the laser power for excitation with a λ = 532 nm laser for different Ge nanowire geometries (L x d).*

References

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Tu2.3 - Sn-containing group IV nanowires for Si-compatible mid-infrared photonics

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Keywords: Silicon-germanium-Tin, Silicon mid-infrared photonics, Strain engineering

III-V compound semiconductor nanowires have been successfully used for a precise and simultaneous control of lattice parameters and bandgap structures bringing to existence a variety of functional nanoscale heterostructures and low-dimensional systems. Extending this paradigm to group IV semiconductors will be a true breakthrough that will pave the way to creating an entirely new class of silicon-compatible clean energy conversion, optoelectronic, and photonic devices. With this perspective, germanium-tin (GeSn) and silicon-germanium-tin (SiGeSn) alloys have recently been the subject of extensive investigations as new material systems to independently engineer lattice parameter and bandgap energy and directness. The ability to incorporate Sn atoms into silicon and germanium at concentrations about one order of magnitude higher than the equilibrium solubility is at the core of these emerging potential technologies. In this presentation, we will address the epitaxial growth and stability of these metastable nanowires with focus on Ge/GeSn core/shell nanowires with a sub-30 nm core (Fig. 1). The reduced dimension of the Ge core was found to facilitate the growth of GeSn shell at a Sn content of ~10at.%, about 10-fold higher than the equilibrium solubility. We will discuss the optical and electronic properties and present strategies to integrate these nanowires in fabrication of short wavelength infrared (SWIR) and mid-infrared (MIR) optoelectronic devices. Finally, by using a microfabricated strain engineering platform, we will show that tensile strain allows tuning of the optical properties of Ge/GeSn core/shell nanowires in the SWIR and MIR range, thus laying the groundwork to implement innovative optoelectronic devices.

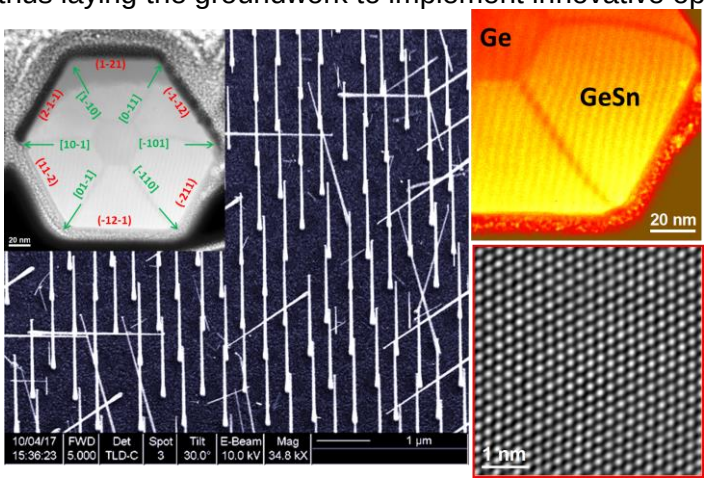

Figure 1. *SEM image of an array of as-grown sub-30 nm Ge nanowires; Inset: High-resolution cross-sectional TEM image of a Ge/GeSn core-shell nanowires. Right: Close-up image in temperature color scale (top) and high-resolution image of the GeSn shell (bottom).*

I6 - Thermal transport in nanowire interfaces

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I will cover two different topics related to nanowire thermal transport. First, I will briefly review some recent attempts to re-measure the quantum of thermal conductance at low temperature. I will present a simple model to show that the large-scale shape of the contacts, far away from the nanowire, can still affect transport through the wire, even if the part of the contact immediately touching the wire is in a catenoidal shape. This fact can hinder the measurement of the quantum of thermal conductance.[1]

As a second topic, I will present new calculations of thermal conductance across nanowire twin boundaries, and interfaces between different polytype phases of groups III-V and IV materials. In particular, I will show our use of *ab-initio*-trained neural network interatomic potentials, and explain the interest and advantages of this with respect to standard, parameterized interatomic potentials.[2]

References

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Tu3.1 - All-optical probing of nanomechanical properties of InAs nanowires

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Keywords: InAs nanowires, mechanical nanometrology, time-resolved photoacoustic

Ultrafast optical spectroscopies are emerging as the go-to techniques to access the mechanical properties of semiconductor NWs.[1] In order to make further progress a table-top, low intensity pump technique is required in conjunction with a full modeling of the systems optoacoustic dynamics allowing to retrieve the relevant acoustic parameters encoded in the time-resolved optical trace. We investigate the mechanical properties of wurtzite InAs NWs by means of time-resolved photoacoustic measurements, implementing the Asynchronous Optical Sampling (ASOPS) technique.[2] By measuring the extensional mode periods on sets of NWs of different heights we unambiguously characterize the excited acoustic modes. Finite element modeling (FEM) of the optoacoustic dynamics, and its comparison with the optical time-resolved traces, allows retrieving the NWs acoustic parameters. We identify the correct boundary conditions to be enforced in the classical acoustic pipe-model and yielding results in agreement with the experimental ones. Expanding the present technique to include a broad-band probe will open the path to the retrieval of the thermal properties of semiconducting NWs.[3,4]

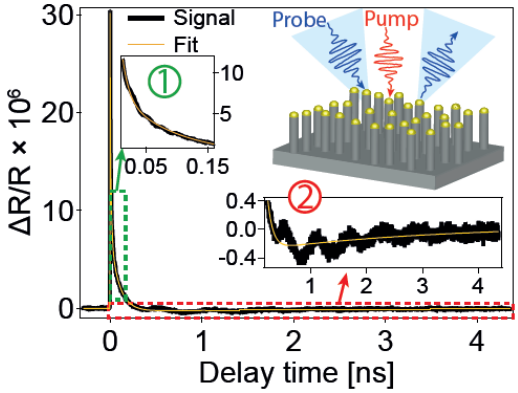

Figure 1. *Relative reflectance change in InAs NW sample from time-resolved photoacoustic measurement.*

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[4] Francesco Banfi acknowledges financial support from Université de Lyon in the frame of the IDEXLYON Project -Programme Investissements d' Avenir (ANR-16-IDEX-0005).

Tu3.2 - Ultrafast transient optical absorption in InP nanowires

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Keywords: InP, nanowires, wurtzite, ultrafast spectroscopy

In order to develop optimized optical devices based on nanowires (NWs) it is important to study how the charge carriers excited into the material behave after excitation. In this study we present Transient Absorption (TA) measurements on InP NWs at room temperature (RT) using the pump-probe technique with a time resolution of about 50 fs. For the measurements, the NWs have been mechanically transferred from the pristine sample onto quartz supports. The InP NWs, grown by MOVPE, contain both zincblende (ZB) and wurtzite (WZ) sections. At RT, ZB InP has a band gap of 1.35 eV and a spin-orbit (SO) separation in the valence band (VB) of 110 meV. In the WZ structure, the VB loses the degeneracy and three transitions between the valence bands and the conduction band have been reported[1] as (at low temperature): A=1.486–1.508 eV; B=1.53–1.539 eV, and C=1.665-1.690 eV. The values at RT are smaller by about 80 meV[2].

The TA spectra in fig. 1(a) show five peaks, corresponding to decreased absorption from the NWs upon the photoexcitation. The energies of those signals well agree with the energies expected for the five electronic transitions expected in these NWs with mixed lattice polytypes. In particular, we attribute the signals observed at 1.374 eV and 1.46 eV to absorption bleaching at the E_{gap}(ZB) and E_{gap}+SO(ZB) energies, respectively, and the signals at 1.402 eV, 1.428 eV and 1.6 eV to absorption bleaching at the A, B and C transition energies relative to the WZ. The energies depend on the pump intensity, due to band-gap renormalization. Moreover, the inspection of the TA dynamics (fig. 1(b)) reveals shorter decay timescales for higher probe frequencies, indicating an efficient relaxation of the higher energetic carriers photo-excited onto high-energy states of the conduction band.[3]

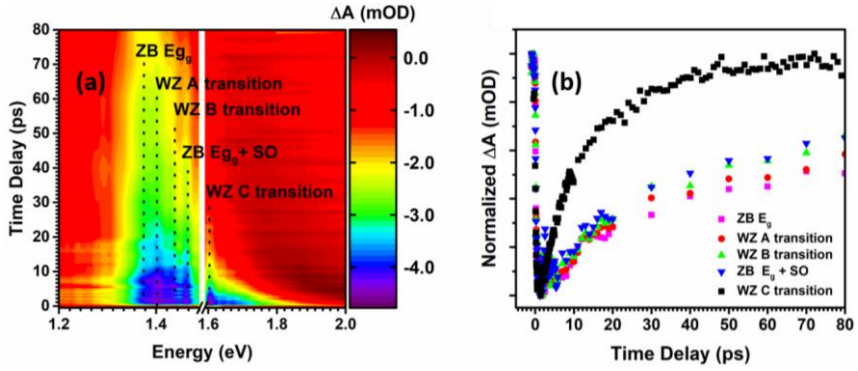

Figure 1. *(a) 2D colormap of TA of InP NWs with indicated the observed transitions; (b) Kinetics of the different energy peaks.*

References

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[3] **Acknowledgements:** This work has received funding from the Horizon 2020 program of the European Union for research and innovation, under grant agreement no. 722176 (INDEED).

I7 - Isotopically programmed nanowires

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Keywords: Silicon nanowires, Stable isotopes, Phonon engineering, Crystal polytypism

I will describe the development of isotopically programmed nanowires (NWs) as a versatile platform to engineer new phenomena related to nuclear spin, phonons, and electronic bandgap properties. Harnessing these processes in NWs with tailor-made isotopic compositions provides a wealth of opportunities to create an entirely new class of quantum structures and devices. For instance, the precise control of the distribution of nuclear spin-full ^{19}Si atoms in a nuclear spin-free ^{28}Si nanowire paves the way to realize new qubits and quantum memories. Moreover, the difference between isotopes in lattice dynamics can be exploited to control phonon transport in NWs. I will discuss the properties of phonon scattering in isotopically deliberately mixed $^{28}Si_x{}^{30}Si_{1-x}$ NWs having the highest mass disorder (x ~ 0.5).[1,2] To highlight the influence of isotope scattering, the phonon behavior in these $^{28}Si_x{}^{30}Si_{1-x}$ NWs are compared with isotopically pure ^{29}Si NWs with the same reduced mass. I will also demonstrate how the combined effects of mass disorder and the presence of polytypic crystal phase (Fig 1a) within the NWs affect the lattice thermal conductivity.[2] Additionally, from the temperature dependent (from 300K down to 4K) measurements, I will elucidate the influence of the crystal anharmonic effect, the isotopic effect on the phonon behavior of the NWs. Also, the knowledge of field evaporation in atom probe tomography (APT) from isotopically programmed nanoscale materials[3] helped in generating three-dimensional atomistic maps of the isotopes within a single $^{28}Si_x{}^{30}Si_{1-x}$ NW, revealing a bizarre isotopic distribution (Fig 1b). I shall highlight the possible reason which might have led to such an isotopic distribution within the $^{28}Si_x{}^{30}Si_{1-x}$ NWs. Finally, I would also point towards future directions related to isotope engineering at the nanoscale, involving nuclear spin manipulation and luminescence from isoelectronic defect centers within single NWs.

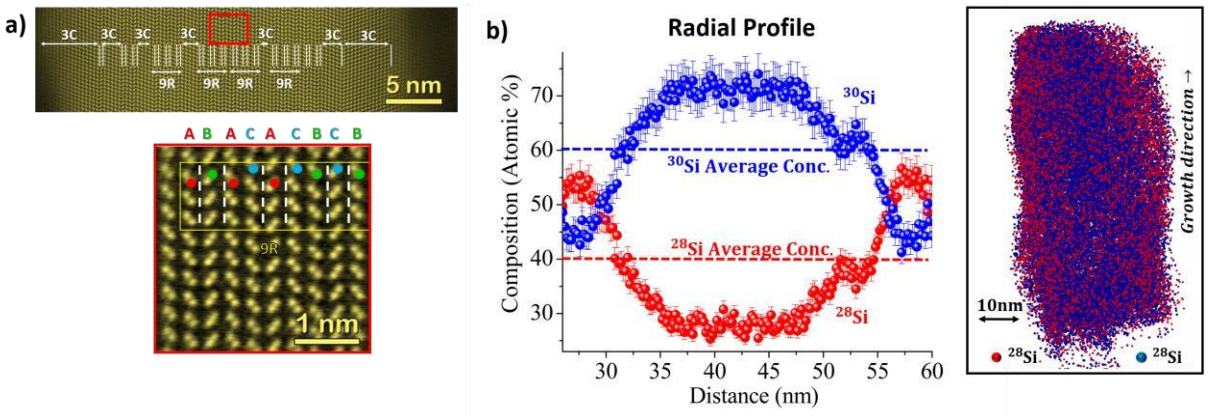

Figure 1. *(a) High-resolution HAADF-STEM image of a polytypic isotopically mixed $^{28}Si_x{}^{30}Si_{1-x}$ NW, showingthe central part of the NW to be polytypic (rhombohedral or 9R), bounded by the diamond cubic (3C) Si domains. (b) Radial concentration profile showing the distribution of ^{28}Si and ^{30}Si within a single $^{28}Si_x{}^{30}Si_{1-x}$ NW and (alongside) the 3D APT reconstruction of the NW.*

References

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Tu4.1 - Two dimensional electron gas formation in Wurtzite-Zinc-blende InP heterostructures

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Keywords: Wurtzite, InP, 2DEG

In many electronic components, like in the high electron mobility transistor (HEMT), two dimensional electron gases (2DEGs) are used as charge carriers[1]. The mobility of these 2DEGs is limited by two main processes: Coulomb scattering on ionized donors and scattering on interface roughness[2]. The first of these two problems was strongly reduced by Mimura et al. in 1980, by the introduction of modulation doping in HEMTs[3]. However, the interface roughness is inherent to the use of material heterostructures, due to material intermixing and strain.

It is possible to create a heterostructure[4] that is atomically sharp[5] and has minimal strain[6] by using different crystal phases of the same material. An example of such heterostructure is a Wurtzite-Zinc-blende (wz-zb) InP interface. This interface shows a type-II band alignment[7], which makes it a great candidate for a 2DEG with high mobility.

In this work we present a 2DEG formed at a wz-zb interface using modulation doping. For this we use single interface wz-zb InP nanowires of which the wz segment is doped with sulphur (n-type). Power-dependent photoluminescence (PL) at 5 K temperature shows emission reducing in energy with reducing excitation power density (EPD). This is typical behavior for photoluminescence from a type-II band alignment[8]. The type-II shift is less for the modulation doped nanowires compared to unintentionally doped nanowires of the same geometry. This indicates the formation of a 2DEG in the zb-InP at the type-II interface.

The type-II recombination energy at high EPD can be used to estimate the valence band offset between wz-zb InP. We find this band offset to be ΔE_V=50±20 meV, which is in agreement with previously calculated values[7,9].

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Tu4.2 - Unusual spin properties of wurtzite nanowires revealed by Zeeman splitting spectroscopy

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The knowledge of the value and anisotropy of the carrier gyromagnetic, *g,* factor in semiconducting nanowires (NWs) is crucial for their potential applications in several fields, such as spintronics and topological quantum computation, and can also provide insightful information about the symmetry characteristics of the underlying electronic structure. In the case of III-V NWs with a zincblende (ZB) crystal structure, the *g*-factors are readily available from the same material in the bulk form. However, this is not the case of NWs with the wurtzite (WZ) structure, as WZ has no bulk counterpart in many important III-V semiconductors, such as GaAs, InP and InAs.

Here, we present a complete experimental and theoretical investigation of the Zeeman splitting (ZS) of the fundamental exciton transition in WZ InP NWs[1]. The excitonic *g*-factors are derived by the ZS of the spin levels observed by photoluminescence measurements under magnetic fields *B* up to 29 T directed along different NW crystallographic directions. In addition to being about three times greater than in ZB InP, the *g*-factor in the WZ phase is strongly anisotropic (50%) upon variation of the direction of *B* from parallel to perpendicular to the WZ $\hat{c}$ axis. Interestingly, ZS exhibits a marked sublinear dependence on the field whenever *B* points along the NW axis, a feature common to other III-V WZ NWs (*e.g.*, InGaAs[2] and GaAs[3]). These findings are quantitatively reproduced by a theoretical approach considering: *i*) the spatial dependence of the vector potential in the $k\cdot p$ Hamiltonian, *ii*) the admixing between wavefunctions of the A (heavy-hole, HH, like) and B (light-hole, LH, like) valence bands (VBs) characteristic of the WZ lattice and *iii*) the excitonic effects *via* the Bethe-Salpeter equation. Both experiments and theory agree that the non-linearity is borne by just one of the two Zeeman split components due to the interplay between the symmetry of the VB wavefunctions and their spin. Our study solves the puzzle of the nonlinear ZS found in III-V WZ NWs comprising even InAs and GaN[4]. Therefore, the properties here discussed appear to be general features of WZ crystals and may play a relevant role in several WZ NW systems, which could become the building blocks of topological quantum computers.

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Tu4.3 - Break-down of corner states and carrier localization by monolayer fluctuations in radial nanowire quantum wells

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Nanowires (NWs) and NW-based heterostructures exhibit less favorable growth conditions on the side facets resulting in pronounced structural and compositional fluctuations within ternary semiconductor NWs and at the interfaces of such heterostructures. Despite this clear evidence, most theoretical work has focused on symmetric hexagonal shapes of quantum wells (QW) embedded in NW heterostructures.

Here, we demonstrate that commonly observed imperfections of realistic, asymmetric QW ring structures embedded in radial GaAs-$Al_{0.3}Ga_{0.7}As$ NW heterostructures have major impact on their optical and electrical characteristics[1]. In particular, we reveal the role of the variations of the quantum well thickness at different facets on the optical recombination dynamics and electrical transport properties. These typically occurring thickness fluctuations observed here by transmission electron microscopy (Fig. 1a) result in a pronounced localization of charge carriers along the NWs, which are clearly visible in the optical experiments. Our experimental data exhibit clear spectral shifts and a multi-peak structure of the emission along the NW due to spatially separated, yet interconnected quantum well systems. Moreover, charge carrier dynamics induced by a surface acoustic wave show an efficient charge transfer between interconnected quantum well systems on sub-nanosecond timescales. We corroborate our experimental findings by theoretical modelling, unambiguously showing that even minute deviations from the perfect hexagonal shape, on the order of only a few monolayers, lead to full localization of the charge carriers and perturb the commonly assumed six-fold symmetric ground state (Fig. 1b).

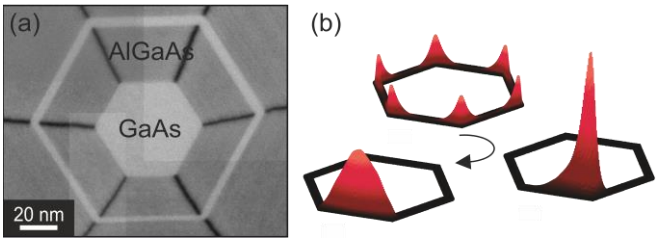

Figure 1. *(a) STEM cross-sectional images of a GaAs-$Al_{0.3}Ga_{0.7}As$ core-shell NW, showing clear deviations from the perfect hexagonal shape and pronounced variations of the QW thickness on different facets. (b) Ground state localization for increasing cross sectional asymmetry showing a transition from corner to side states.*

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Tu4.4 - Anomalous angle-dependent magnetoresistance in InAs nanowires

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Keywords: electronic transport, boundary scattering, magnetotransport

Here, we present magnetotransport properties of single InAs nanowires grown by selective-area metalorganic vapor-phase epitaxy[1]. In order to measure single nanowires, InAs nanowires have been detached from the substrate and transferred to an insulating SiO_2/Si substrate. Afterwards electronic contacts have been fabricated by electron beam lithography and electron beam evaporation. The InAs nanowires exhibit quantum interference effects at temperatures below 20 K and a large positive magnetoresistance effect at elevated temperatures up to 200 K. For a magnetic field applied perpendicular to the nanowire axis, a kink occurs in the positive magnetoresistance curve, which is not present for a parallel orientation of the magnetic field as shown in Fig. 1 (a). The kink originates from diffuse boundary scattering, which arises in narrow transport channels under the influence of a magnetic field. Angle-dependent magnetoresistance measurements have been conducted showing an anomalous angle-dependence, which can be related to the diffuse boundary scattering (see Fig. 1 (b)). We performed numerical simulations to study in detail the effect of diffuse boundary scattering under varying conditions, such as channel width, impurity concentration, etc. Based on the numerical simulations, we derived a model for parameterizing the magnetoresistance curves and their angle-dependent behavior in excellent agreement with the experimental data as shown in Fig. 1 (b). Our analysis and results further illuminate the electron transport in InAs nanowires and contribute to a better understanding.

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I8 - Nanowires meet microarray and AI for urine liquid biopsy

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Extracellular vesicles (EVs) of 40-5000 nm in diameter have shown promising features as biomarkers for early cancer and other disease diagnoses. EV-encapsulated microRNAs (miRNAs) and EV membrane proteins have been found in various body fluids of both healthy subjects and cancer patients. The difference in the EV-encapsulated miRNAs and EV membrane proteins between the two groups of people may represent a warning sign for various disease scenarios. To take advantage of their full potential as biomarkers, methodologies that investigate the correlation between various disease scenarios and profiled miRNAs or profiled EV membrane proteins are strongly required. Conventionally, three major methodologies have been used for EV collection: ultracentrifugation or differential centrifugation, immunoaffinity-based capture, and size exclusion chromatography. Some emerging methodologies have been reported as promising alternatives, including polymer precipitation, microfluidic-based platforms, and size-based filtration. However, none of the existing methodologies for collecting EV-encapsulated miRNAs have satisfied the requirements for non-invasive urine-based early cancer diagnoses due to the low concentration of EVs in urine.

Here we propose an oxide nanowire-based methodology via charge-based isolation for collecting urine EV-encapsulated miRNAs that unveils over 1000 species of urinary miRNAs of different sequences [1] and elucidates the correlation between the surface charge and membrane proteins of EVs. Since the surface charge is determined by molecular compositions of EV surface consisting of lipid bilayers, membrane proteins, and proteoglycans, and therefore, reflects donor cell information, the surface charge should have a stronger relationship to miRNAs inside EVs and expressed membrane proteins on EVs than conventional classification items of density, size and immunoaffinity. Nanowire-induced charge-based isolation of EVs and *in-situ* extraction of miRNAs or profiling of EV membrane proteins are the two key points. We utilize our methodology to identify urinary miRNAs that could potentially serve as biomarkers for cancer for not only urologic malignancies (bladder and prostate), but also non-urologic ones (lung, pancreas, and liver).

This methodology moves researchers towards the goal of miRNA-based non-invasive and early cancer diagnoses from urine and will be a powerful tool that offers a new strategy for researchers to achieve a comprehensive understanding of EV surface charge, as it relates to molecular compositions, and of its roles in the human body. The present device concept will provide a foundation for work towards the long-term goal of urine-based early diagnoses and medical checkups for cancer.

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W1.1 - *In situ* transmission electron microscopy study of surface effects on the growth of Ge nanowires

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Keywords: nanowires, transmission electron microscopy, surface passivation

Germanium nanowires (GeNWs) can be used to create devices with novel architectures. However, this requires a detailed understanding and control of the growth process. In this regard, *in situ* Transmission Electron Microscopy (TEM) is a powerful tool for gathering insights about these processes. In this study, we used a modified TEM to carry out the Vapor-Liquid-Solid (VLS) *in situ* growth of GeNWs with Au as a catalyst using two different types of source: a Ge_2H_6 Chemical Vapor Deposition source and a Ge Molecular Beam Epitaxy (MBE) source. Using a MBE source provides two advantages: it allows sending precursor atoms one by one, slowing down the growth kinetics and easing *in situ* observations; it also eliminates the influence of atomic hydrogen, produced by the dissociation of Ge_2H_6, which considerably influences the surface dynamics[1]. We show that, depending on the source used, the obtained GeNWs have different faceting. This can be explained by a hydrogen passivation layer on the NW sidewalls, which modifies their surface energies. Additionally, without this passivation layer, the Au catalyst droplet is leaking out, forming an Au wetting layer on the NW sidewall. This layer can enhance the diffusion of Ge atoms during the growth, and thus facilitate the transport of Ge from the Au/NW interface to the NW sidewall, possibly explaining the NW degrowth (Figure 1)[2].

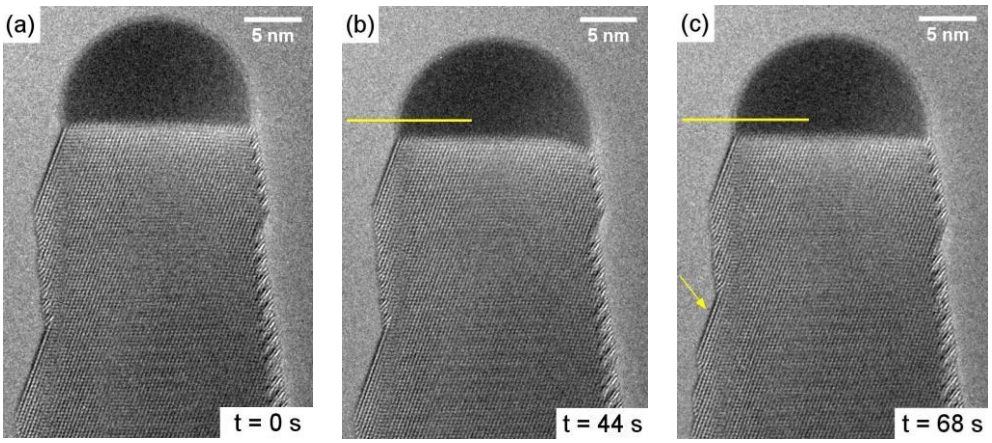

Figure 1. *Bright Field TEM micrograph of a degrowing GeNW obtained by the VLS method using a Ge MBE source. a) The initial stage of the GeNW. b) 44 s after a), the GeNW has degrown 3 (111) atomic layers. The yellow line indicates the initial height. c) 68 s after a), Ge atoms have appeared at the region marked by the yellow arrow. The same Ge atoms from the degrown (111) atomic planes would reappear on the sidewall.*

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W1.2 - *In situ* studies on step-flow layer growth of GaAs nanowires

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The current mechanistic understanding of the nanowire (NW) synthesis process is insufficient for the level of control on an atomic scale required for technological applications. NW growth occurs in two steps: formation of a critical nucleus followed by step-flow across the liquid-solid interface. Most theoretical models explaining NW growth assume the step-flow to be effectively instantaneous and the NW growth rate to be limited by the slow nucleation.[1] Earlier reports on *in situ* imaging of nanowire growth at relatively low precursor partial pressures demonstrated that step-flow can indeed be slow.[2] We study, using *in situ* TEM imaging the step-flow layer growth kinetics of GaAs NWs at precursor partial pressures comparable to that of a typical (*ex situ*) MOCVD growth.

We have grown GaAs nanowires in a Hitachi HF3300S aberration-corrected environmental TEM connected to a CVD system. We used trimethylgallium (TMGa) and arsine as the Ga and As precursors respectively. High resolution, high-frame-rate videos (~20 fps) enable us to determine the growth time for each bilayer (step-flow time) as well as the waiting time between successive layers (incubation time).

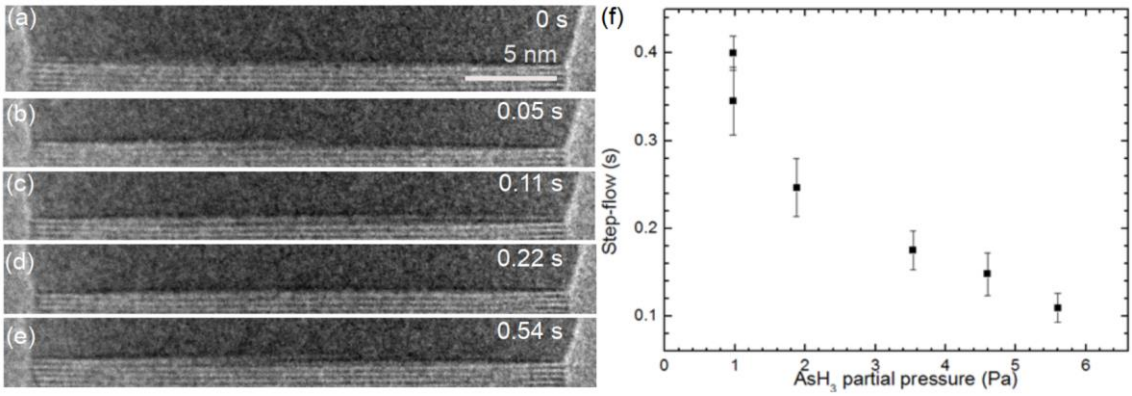

Figure 1. *(a-d) TEM images of a growing GaAs nanowire - catalyst interface showing the step-flow growth of a layer. Time past image (a) is denoted on the top right. After the ending of a layer in (d) the next starting of the next layer is shown in (e). (f) Step-flow time as a function of AsH_3 pressure at the sample.*

The step-flow time decreases with increasing AsH_3 flow, indicating that the step-flow time is mainly limited by the As availability. The concentration of As dissolved in the catalyst droplet during growth is small[3] supporting this observation. In a separate experiment we studied the incubation time and step-flow time as a function of TMGa flux. Except for very low TMGa fluxes, the step-flow time is independent of Ga flux. However, the incubation time between bilayers significantly decreases with increasing Ga precursor flux. This trend was also observed in stochastic simulations based on nucleation modelling. At typical MOCVD conditions step-flow time contributes significantly to the overall growth rate.

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W1.3 - Coherent X-ray diffraction from as grown single bent nanowires

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Keywords: Coherent X-ray diffraction, bent nanowire

The aim of the experiment was to investigate the strain state along the growth axis of bent nanowire (NW) by x-ay nano-diffraction. The sample of investigation was a GaAs/InAs/GaAs core – shell NW with asymmetric grown thicker AlGaAs/$In_{0.5}Al_{0.5}As$ as reported in [1] (see figure 1a). Fig 1 (b) shows the scanning electron microscopy (SEM) image of the NW measured at ID01 beamline of ESRF using available nano-focusing setup. Here measured the GaAs 111 reflection at different positions along the growth axis of the bent NW. Figure 1(c) represents the projections of the 3D reciprocal space map measured at the bottom part of the NW.

Reciprocal space maps were recorded from different segments of the NW and combined together in order to produce the RSM from entire NW shown in figure 1d. The width of the peak remains constant along the NW growth axis. The data analysis are on the way in order to extract the strain profile along the facets via FEM modeling.

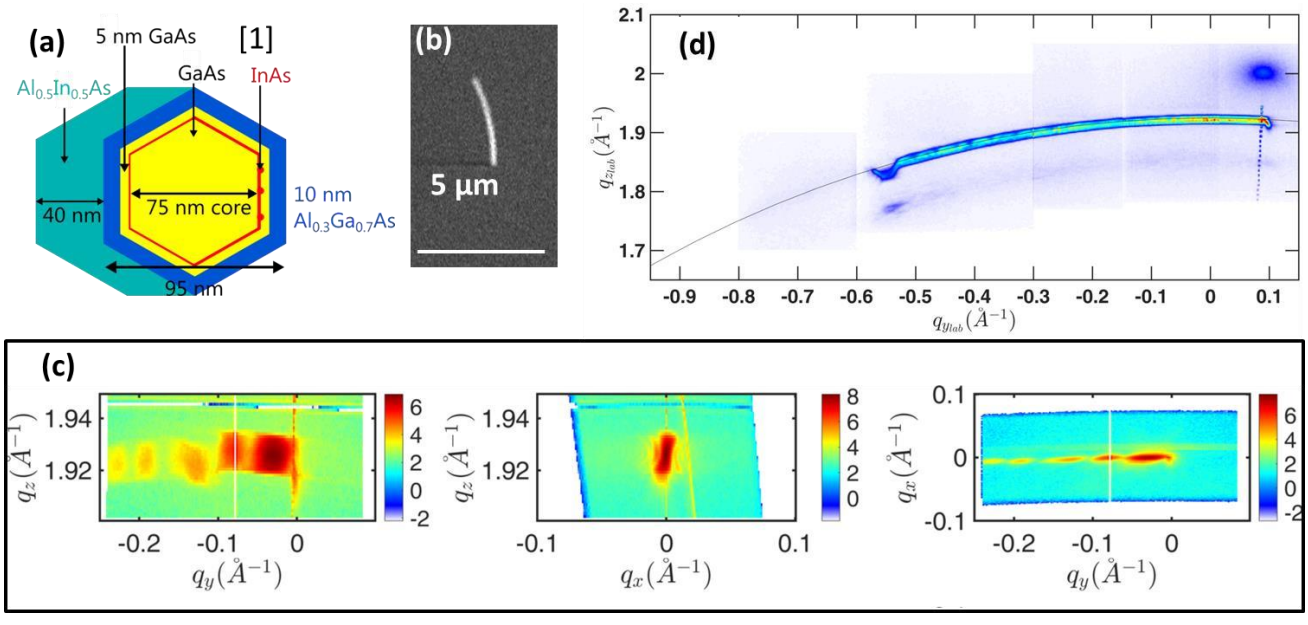

Figure 1. *Structure of bent NW (a,b) and reciprocal space maps collected from basis of the NW (c) and from entire NW (d).*

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W1.4 - Are III-V nanowires with epitaxial Al a unique material platform?

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Keywords: Molecular beam epitaxy, topological materials, semiconductor-superconductor, bi-crystal engineering

III-V semiconducting nanowires with atomically abrupt and epitaxially aligned Al have proven as a particularly promising materials platform for quantum transport experiments. At low temperatures the superconductivity of Al induces a clear gap in the density of states of the semiconductor. The clean bi-crystal interface is believed to play a paramount role in the particular “hardness” of the superconducting gap induced by Al. But is Al unique?

In this study we assess other material combinations that can possibly yield large grain hetero-epitaxial interfaces with comparable physical parameters. We focus on single element superconductors that can be grown in-situ on InAs nanowires with substrate temperatures ranging from -150°C to 200°C. We discuss and predict the driving forces that play the defining role in the minimization of the superconducting grain excess energy. The latter effectively determines the bi-crystal interfacial domains, grain sizes and morphology. We show examples of promising candidates that could answer the title’s question and we discuss electrical measurements indicating that these materials are promising for quantum transport experiments.

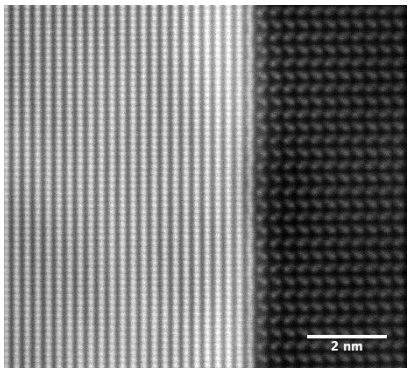

Figure 1. *High-resolution-high-angle-annular-dark-field-scanning-transmission-electron-microscope micrograph of an InAs nanowire with a new promising non-Al superconductor candidate.*

I9 - Transmission electron microscopy experiments on electrically contacted semiconducting nanowires

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Keywords: In-situ TEM, semiconducting nanowires

Semiconducting nanowires (NWs) are widely studied because the properties that stem from their three-dimensional, nanoscale nature open up new opportunities for device design. Due to small wire to wire variations in bottom up synthesized NWs, it can be challenging to understand the differences in response to electro-optical signals between different NWs from the same growth substrate. With the aim to better understand the structure properties relation at the single NW level, we perform electro-optical characterization on the same single NW that is characterized by TEM based techniques[1-4]. Another important aspect to allow successful device integration of NWs is the quality of the NW/metal contacts. We describe different kinds of semiconducting NW devices fabricated on electron transparent Si3N4 membranes, to perform correlated experiments or in-situ electrical transmission electron microscopy (TEM) to contribute to the understanding of NW contact formation. We demonstrate an original approach to create a very abrupt contact on Ge NWs using a thermally-induced propagation reaction of Al in the extremities of a Ge or SiGe NW[5]. To understand and control the metal diffusion into the NW that creates a metallic phase, detailed characterization at atomic length scales is necessary to understand how the metal atoms diffuse and incorporate into the formed phase at the reaction front and how these parameters relate to the electrical properties of the same interface. We combine both in-situ phase propagation of a metal-semiconductor phase of Al in Ge and SiGe NWs in the TEM with more detailed structural and chemical characterization after the reaction has finished to understand the diffusion phenomena in these nano objects[6].

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[7] **Acknowledgements:** Financial support from the ANR-COSMOS (ANR-12-JS10-0002) project, the AGIR 2016 Pole PEM funding from Grenoble Alpes University (UGA), the French National Research Agency via the GaNEX program (ANR-11-LABX-0014) and LANEF (ANR-10-LABX-51-01), the European Research Council (ERC, Grant Agreement 758385) and AMADEUS/CampusFrance program is acknowledged. We benefited from a collaboration with the LEMMA group, the access to the technological platform NanoCarac of CEA-Minatech and Nanofab from institute NEEL.

W2.1 - Self-assembled quantum wires and dots in GaAsP-GaAsP core-shell nanowires

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Keywords: nanowire quantum wires, nanowire quantum dots, GaAsP nanowires

Similar to structures formed on non-planar surfaces in thin films, self-assembled nano-features form on free standing nanowires due to their 3-dimensional, faceted shape. While some of these features could be unfavourable to the intended device application, others have been shown to exhibit superior properties compared to their intentionally grown counterparts[1].This work studies triangular shaped, relatively As rich quantum wires (QWRs) formed at the edges of hexagonal GaAsP-GaAsP core-shell nanowires (see Figure 1). In contrast to previously reported QWRs grown on nanowires[2], these QWRs form only on three of the six edges due to the three-fold polarity present on the {111} planes in cubic zincblende materials. The QWRs are found to form at the {112}B corners of the nanowires demarcated from the core by a P-rich band. Their wire-like form is verified by tracing the same nanowire along sequential microtome slices.

A uniqueness of these QWRs is their ability to convert to quantum dots (QDs), resulting from the twinning of the nanowire core. As the QWRs are present only on every alternating {112} edge, a rotational twin about the [111] growth axis truncates the QWRs and translates them to the alternative three edges. Sequential twining separates the QWRs in the axial direction forming QDs, with a dot height equivalent to the twining segment thickness, as show in Figure 1

Electronic simulations carried out using nextnano© software on structures with composition and dimension values consistent to those experimentally obtained show that these could indeed behave as optically active QWRs and QDs. Micro photoluminescence (PL) measurements carried out along the length of the twinned nanowires, including polarisation, power and temperature dependent studies, complement the structural findings, confirming the presence of two different types of quantum structures emitting in the wavelength ranges suggested by the simulations. These results demonstrate a form of self-assembled quantum structures that can switch between QWRs and QDs, simply by controlled twinning of the nanowire core.[3]

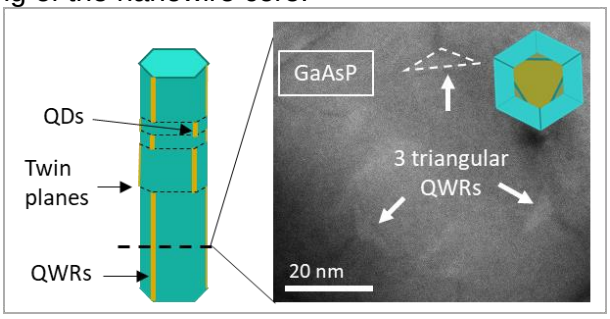

Figure 1. *Annular dark field STEM image of a cross section from a nanowire showing the three triangular QWRs formed in the region shown by the schematic. Inset within the STEM image shows a schematic of the cross-section*

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W2.2 - Optical properties of direct bandgap hexagonal SiGe

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Keywords: direct bandgap, hexagonal silicon germanium, photoluminescence

Silicon and germanium are incapable of efficiently emitting light because of their indirect bandgap. However, when the crystal structure is changed from their natural cubic phase to the hexagonal phase, pure germanium and SiGe alloys are predicted to exhibit a direct bandgap when the Ge content is above ~60% [4].

Hexagonal Si[1] and SiGe[2] shells have been realized by using epitaxial wurtzite-GaP nanowire templates, forcing the group-IV crystal into the hexagonal crystal structure. The optical properties of the group IV shells have been greatly improved by use of a GaAs core, which is lattice matched to germanium.

In this work we study the optical properties of hexagonal SiGe alloys in detail by utilizing both spectrally- and time-resolved photoluminescence as a function of temperature. We find strong experimental evidence for direct band gap emission of this novel material. Photoluminescence can be measured from single wires up to room temperature. Additionally, we demonstrate emission tunability in the range from 1.9 µm to 3.5 µm.

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W2.3 - Complex quantum dots in III-As nanowires

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Keywords: self-catalyzed, strain engineering, bandgap tuning

Single quantum dots in the core of freestanding semiconductor nanowires is a promising scheme for the realization of on-demand sources of single photons or entangled photon pairs in quantum technology systems. Here, we demonstrate that complex quantum-dots can be grown in self-catalyzed III-As nanowires and their emission can be tuned in a wide range of wavelengths.

The quantum dots are formed inside self-catalyzed GaAs nanowires (grown on Si substrates by molecular beam epitaxy) by first growing an axial $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ heterostructure in pulsed mode [1]. The $Al_xGa_{1-x}As$ segments are grown as digital alloys with a precise control of the composition, the thickness, and the crystal structure (absence of stacking faults) [3]. Then, the nanowires are overgrown all-around with an $In_xAl_{1-x}As$ layer in a core/shell fashion. Owing to the large lattice-mismatch with the shell, the thin core develops tensile hydrostatic strain [1] and the emission from the dot is strongly red-shifted. Furthermore, distinct exciton-biexciton features are identified in photoluminescence measurements.

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I10 - Aerotaxy for mass production of nanowire materials – growth and modeling

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Keywords: Nanowires, Aerotaxy, growth modeling

Aerotaxy[1] growth of III–V nanowires takes place in a cylindrical reactor with core–sheath flow, where an aerosol of size-selected Au seed particles is mixed with TMGa and AsH_3 at a growth temperature of approximately 550 °C. The nanowires grow at a rate of around 1 µm/s, and the production rate is roughly $3{\cdot}10^{10}$ wires per hour. The same number of wires would fit on a 4'' wafer with 0.5 µm spacing, but Aerotaxy requires no substrate and no lithography. Even more importantly, Aerotaxy is a continuous and scalable flow-through process, and it is thus a prime candidate for cost-efficient mass production of nanowire materials.

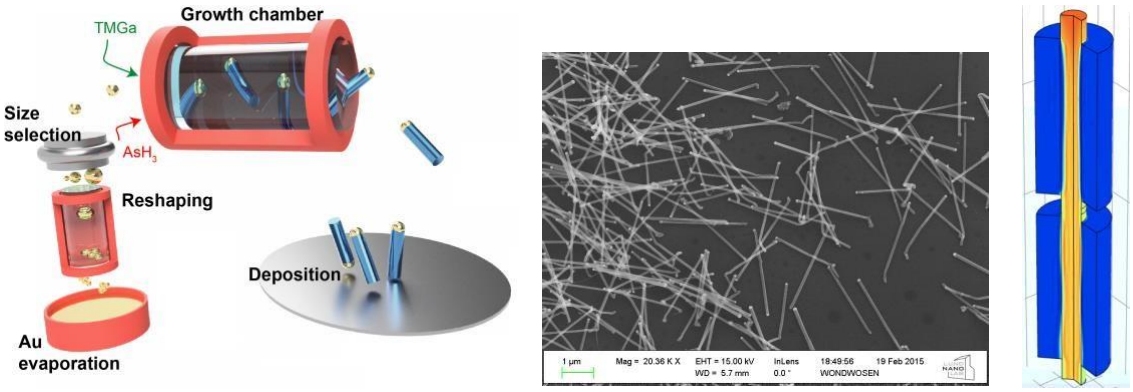

Figure 1. *(left) A schematic of the Aerotaxy process. (center) Typical growth results for GaAs nanowires. (right) a CFD model of the Aerotaxy reactor, showing the Au seed particles concentrated in the core of the gas flow.*

A comprehensive overview of the Aerotaxy process and growth results will be presented, including growth of ternary compounds,[2] doping, and growth of pn-junctions for solar cell devices.[3] A new model for nanowire growth will also be presented, valid for the high partial pressures (up to 1 mbar) of the precursors used in Aerotaxy.[4,5] The model is applied to the Aerotaxy process using computational flow dynamics with chemically reacting species, yielding good agreement with the observed growth.

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W3.1 - Nucleation statistics and length distributions for III-V nanowires in the very poor group V regime

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Keywords: Nucleation, statistics, length distributions

The growth of semiconductor nanowires (NWs) in the vapor-liquid-solid mode offers a unique opportunity to study individual nucleation events in a nanosized medium. Such studies can now be performed at high spatial resolution and in real time in dedicated electron microscopes. These *in situ* experiments indeed confirm that NWs grow monolayer (ML) by monolayer,[1,2,3] the formation of each ML being triggered by a single nucleation event occurring at the solid-liquid interface.[3]

For NWs of III-V compounds, the volatile group V elements are present at low concentration (on the order of a percent, at most) in the liquid nanodroplet. The formation of a single ML then significantly depletes the droplet in group V element, which makes a new nucleation less likely after a first one than before. The nucleation events become anti-correlated in time and their statistics sub-Poissonian.[4,5]

This picture holds when the time for ML completion (after nucleation) is short compared with the interval between successive nucleations. This requires enough group V atoms in the droplet to build rapidly the solid ML. However, another regime is possible, where the number of group V atoms in the liquid at nucleation is even lower, namely below the group V content of a ML. Such a regime is easily achieved and is observed in some of our *in situ* experiments: the ML then progresses slowly since the system has to wait for the external fluxes to refill the droplet (this holds for wurtzite MLs, during the formation of which the solid-liquid interface remains planar). In this case, the kinetics and statistics of nucleation are deeply modified.

We simulate growth sequences of GaAs NWs corresponding to such conditions and calculate numerically and analytically the nucleation statistics. We investigate the distributions of the *growth times* (between nucleation and completion of a ML) and *waiting times* (between ML completion and next nucleation) and compare them with experiments. We find two extreme regimes, depending on group V desorption from the liquid (and hence on temperature).

These calculations are carried out using two expressions for the nucleation probability. The parameters intervening in the first one were obtained previously by modeling the growth of zinc blende GaAs NWs.[6] We develop another expression for wurtzite MLs, the parameters of which, *a priori* unknown, are optimized using our experimental results. We discuss these results and investigate their consequences for the length distributions of ensemble of NWs in this previously unexplored regime.

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W3.2 - Tailoring Rashba spin-orbit coupling in polygonal semiconductor nanowires: a numerical study

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Keywords: spin-orbit interaction, nanowires, k.p

The correct determination of spin-orbit coupling (SOC) in nanowires (NWs) and its tailoring by means of external fields is crucial for several applications of NWs, e.g. for the realization of quantum gates in topologically-protected quantum computing platforms. Surprisingly, recent experiments reported Rashba SOCs varying in a wide range, from 50 *meVnm*[1] to 270 *meVnm*[2], for InSb NWs with almost identical diameter.

Here we report our theoretical estimate of Rashba SOC in large InSb and GaAs NWs[3], based on a 8-band k.p description, as a function of size, doping and gate configurations. Our calculations are 3D by construction and fully take into account the complex polygonal symmetry[4], material and doping modulations, and gateinduced electric field, which are all crucial in determining electron gas localization[5].

Interestingly, for high carrier density we find a nonlinear electric field susceptibility of SOC, which abruptly changes its value around zero gate voltage. We trace this remarkable phenomenon to the interplay between quantum confinement, gate electric field and electronelectron interaction.

Both low (linear SOC) and high (non-linear SOC) carrier density regimes are investigated. We show that in core(multi-)shell NWs, specific interface-induced symmetry breaking results in stronger SOC with respect to homogeneous structures[6]. We analyze recent experiments in light of our calculations and we expose wave function engineering strategies to enhance and control SOC.[7]

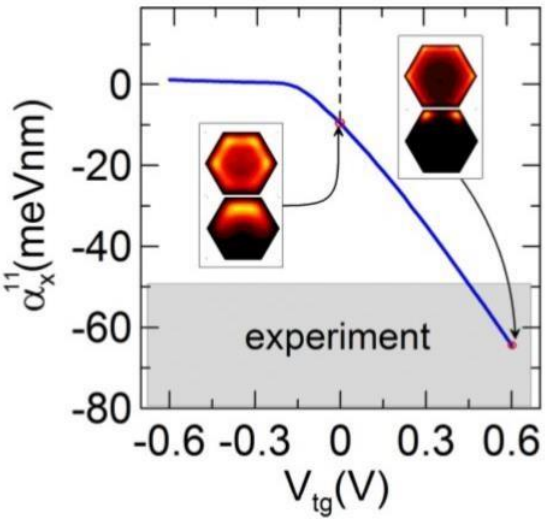

Figure 1. *SOC coefficient vs. top-gate voltage. The insets show the electron density and the ground state.*

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W3.3 - The interplay of morphology, composition and strain in metastable Ge/GeSn core/shell nanowires

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In the quest for direct band gap semiconductors, GeSn is a very promising option for opto-electronic devices operating at mid-infrared wavelengths. However, the low equilibrium solubility of Sn in Ge (~1 at.%) makes the alloy growth very challenging. Here we show that a Sn incorporation well above 10 at.% can be achieved in Ge/GeSn core/shell NWs by exploiting the enhanced strain relaxation provided by the NW geometry itself[1]. In particular, the partitioning of the strain between the core and the shell volumes permits a substantial release of the elastic energy, favouring the Sn incorporation. A systematic analysis by finite element modelling suggests the possibility of strain engineering by controlling the relative extent of the core and shell sizes[2].

Interestingly, for large core size, a continuous variation in the cross-section morphology is recognized from 6-fold to 12-fold, depending on the Sn flux. At the same time compositional segregation leads to an inhomogeneous distribution of Sn in the shell. A multi-scale analysis coupling ab-initio DFT calculations with a phase-field growth model[3] is here exploited to explain the deep connection between morphological changes and segregation effects during the shell growth. The role of incorporation-rate anisotropies in driving the actual faceting and Sn content of the shell is investigated. Results are shown in Fig. 1, well reproducing the experimental evidences.

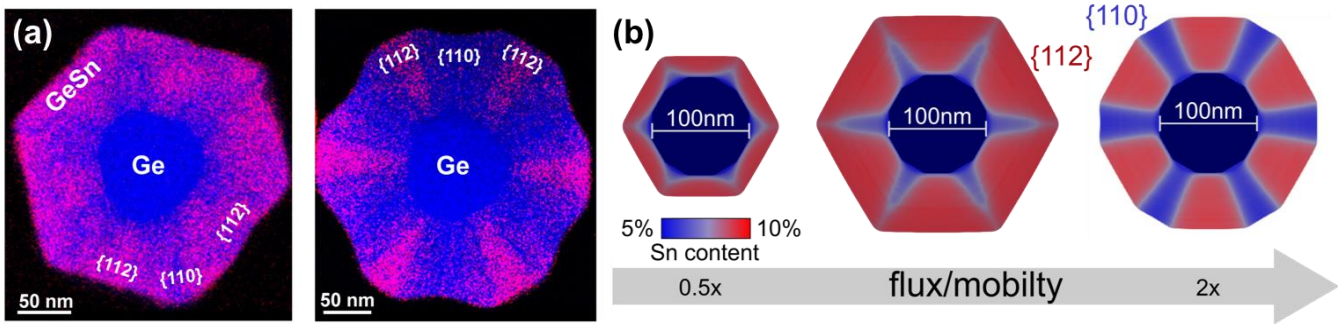

Figure 1. *Cross-sections from (a) experiments and (b) simulations of a core/shell NW for different growth parameters.*

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W3.4 - Si doping of vapor-liquid-solid GaAs nanowires: n-type or p-type?

H. Hijazi[1], G. Monier[1], C. Bougerol[2], C. Leroux[3], F. Leroy[4], D. Castellucci[1], A. Trassoudaine[1], P. E. Hoggan[1], N. Isik Goktas[5], R. R. LaPierre[5], V. G. Dubrovskii[6], E. Gil[1,6], C. Robert-Goumet[1], Y. André[1,6]

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In VLS process, doping of GaAs nanowires (NWs) with Si shows a large contrast depending on the growth technique: Hydride Vapor Phase Epitaxy (HVPE), where high mass input provides the highest growth rates (>100 µm/h)[1], produces always n-type NWs, whereas obtaining such a type in MBE is an exception rather than the rule. In this context, we developed a thermodynamic model that describes the influence of Si atoms present in the catalyst droplet (with concentration c_{Si}) on the nucleation of GaAs NWs.[2] The model predicts that adding Si to the droplet tends to inhibit the nucleation for high temperature and high c_{Ga} (HVPE conditions). This is in full agreement with our experimental observations where the growth is completely blocked in presence of 5% of Si, while with only 1%, very dense structures are obtained.

In order to better understand the behavior of Si atoms during growth, we consider in a second model its incorporation in the solid GaAs phase. This model is able to predict the impact of the growth parameters on the obtained NWs conductivity type.[3] Fig.1 shows the donors/acceptors ratio as function of c_{Ga}, for different c_{As} and temperatures T corresponding to HVPE and MBE conditions. For high As (>0.05) and Ga (>0.8) concentrations in the droplet (HVPE conditions), the model shows a n-type doping behavior, which is consistent with the optical characterizations of the NWs. However, p-type NWs should be obtained when the As concentration is lower, in agreement with experimental results for MBE.

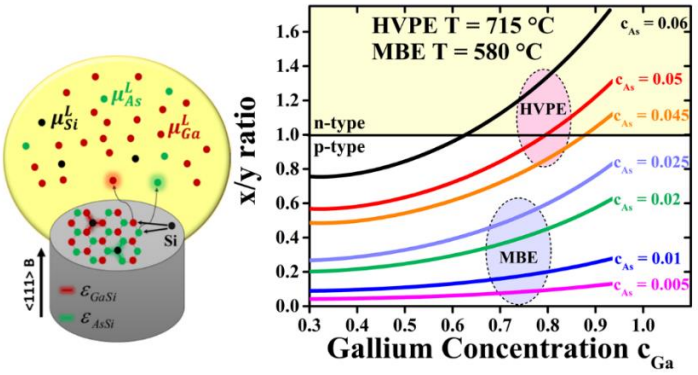

Figure 1. *Donors/acceptors (x/y) ratio of the Si in GaAs nanowires grown by VLS.*

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I11 - Majorana nanowires and topological quantum computation

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Keywords: Majorana, topological quantum computing

Majorana zero modes, a type of localized quasiparticles, obey non-Abelian exchange statistics. Topological quantum computation can be achieved by braiding these Majorana modes, which could in principle significantly reduce qubit decoherence and gate control errors in the device level. Therefore, searching for Majorana zero modes in various solid state systems is a major topic in condensed matter physics and quantum computer science. Since the first experimental signature observed in hybrid superconductor-semiconductor nanowire devices in 2012, this field has witnessed dramatic expansion in material science, transport experiments and theory. In this talk, I will review the progress and challenges in Majorana nanowires and discuss the roadmap towards the first topological qubit.

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Th1.1 - Microwave assisted tunneling in hard-wall InAs/InP nanowire quantum dots

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Charge transport in Quantum Dots (QDs) depends on the tunneling process that, in turns, is related to the electron wavefunctions and ultimately to the shape and size of the QD. Tightly confined QDs defined in heterostructured InAs/InP nanowires[1] exhibit different tunneling regimes associated to the population of charge states with different axial quantum number. The application of microwaves in non-resonant conditions may affect the charge transport characteristics. In the multi-photon regime, both virtual states in the electrodes and excited states within the QD can contribute to assist the tunneling process.[2]

Here we investigate single-electron tunneling in hard-wall InAs/InP nanowires in the presence of an off-resonant microwave drive. For source-drain bias up to few mV, Coulomb diamonds spread with increasing intensity as a function of microwave power and they also present multiple current polarity reversals. This behavior can be modeled in terms of multi-photon processes and evidences features that depend on the type of QD orbitals involved in the tunneling process. In particular, we focused on a Coulomb peak located at the threshold between manifolds having different longitudinal quantum numbers (Figure 1). Here we studied the effects of the microwave field on both ground state (radial wavefunction) and excited state (axial wavefunction). The experimental results are supported by simulations, which have been carried out by means of a simple model that clearly accounts for the experimental trends.[3] Overall these results give novel insights on understanding and manipulation of the electron wavefunctions in hard-wall InAs/InP nanowire quantum dots.

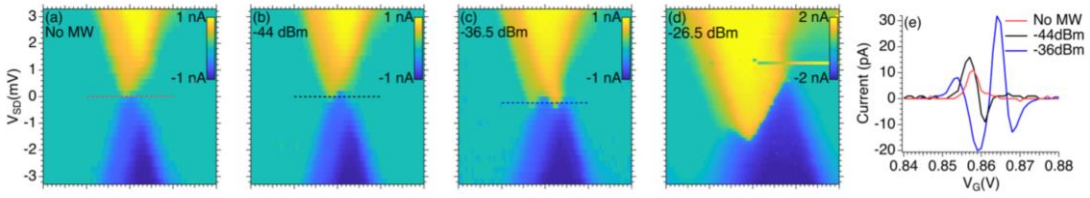

Figure 1. *(a,b,c,d) Measured current as a function of the source-drain bias (V_{SD}) and gate (V_G) voltage (T=2 K). The plot in (e) shows the line profiles taken along the dotted lines in panels (a), (b) and (c). The MW field of increasing power gives rise to a progressive splitting and broadening of the Coulomb diamonds with multiple current polarity reversals.*

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Th1.2 - Ballistic superconductor-semiconductor nanowire junctions

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Keywords: Nanowires, Ballistic Junctions, Majorana, Qubits

One-dimensional hybrid superconductor-semiconductor (SU-SE) nanowires are promising material platforms to host Majorana bound states which promises topologically protected qubits.[1,2] Considering the material requirements of tunability, strong spin-orbit coupling, large landé g-factor factor and superconductivity, in this research we grow single crystalline InAs, InSb and $InAs_{0.3}Sb_{0.7}$ nanowire networks (see **fig. 1, a-c**) with epitaxial Al shadowed junctions in single-step growth process using molecular beam epitaxy (MBE). We compare different material systems and discuss associated pros and cons. Furthermore, we characterize both in-situ and post-growth processed junctions and demonstrate in-situ SU-SE junctions exhibit defect-free surface morphology and enhanced electrical transport with sharp pinch-off and quantized conductance (see **fig. 1, d**).[3]

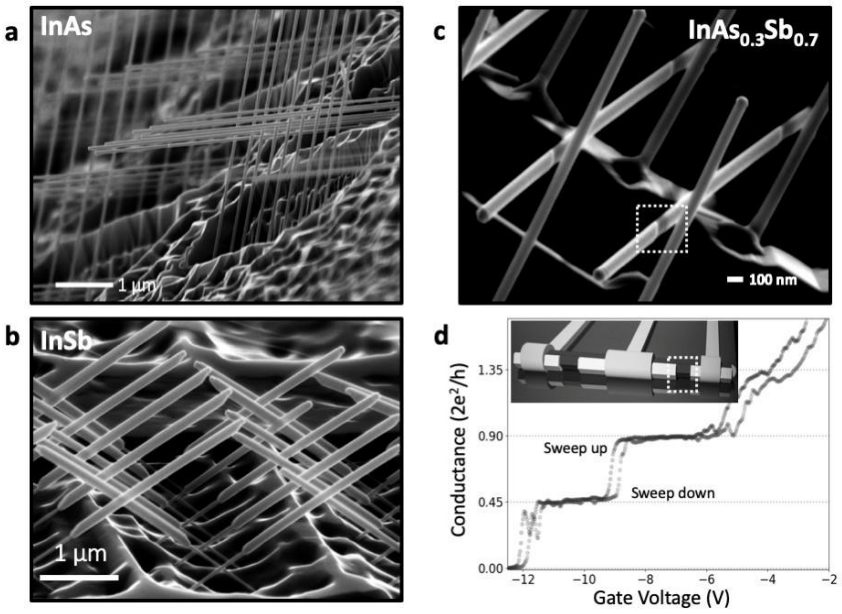

Figure 1. *(a) –(c) InAs, InSb and $InAs_{0.3}Sb_{0.7}$/Al nanowire networks with shadowed junctions (d) Transport measurement shows quantized conductance in $InAs_{0.3}Sb_{0.7}$/Al shadowed junction (white box in section c), inset device model.*

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Th1.3 - Forming parallel-coupled quantum dots & tuning the two-electron hybridization and spin states in InAs nanowires

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Keywords: Crystal-phase quantum dot, Parallel-coupled double quantum dots, Spin-orbit interaction

With the emergence of various spin- and Majorana-based concepts for qubits, there is a significant interest in spectroscopy on quantum dots (QDs) in materials with strong spin-orbit interaction, such as InAs and InSb. We use QDs formed by crystal-phase engineering during epitaxial growth of InAs nanowires [1] as a starting point to realize and electrically characterize the very first two electron-orbitals in parallel-coupled QDs [Fig.1(a,b)].

A set of three gates are used to reproducibly tune system from one QD into parallel double QDs, for which we can control the populations down to the last electrons [Fig.1(c)][2]. In this system, the intradot-tunnel coupling, and thus the two-electron single-triplet energy separation are highly tunable. This, together with high orbital-energy separations, interdot-charging energies, and effective g-factors, provide a large window for probing spin-transport. The experimental results display text-book examples on the magnetic-field evolution of the one-to-two electron transitions [Fig.1(d)][3], reproduce in detail with a double QD model including one orbital in each dot. In addition, the strong spin-orbit interaction in the system induces a hybridization of the singlet and triplet states, resulting in a magnetic-field dependent anticrossing of the states. We tune the magnitude of this anticrossing by tuning the intradot-tunnel coupling, and support the results with modeling.

The demonstrated strong tunability and control of both charge and spin states make this system highly interesting for fundamental studies of many-body correlated transport such as the spin-Kondo effect [4] and Cooper-pair splitting.

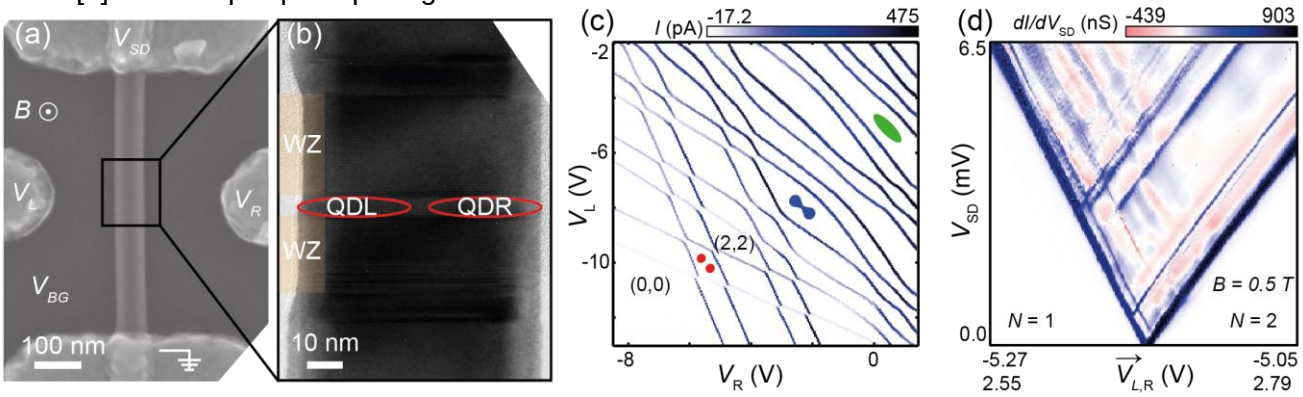

Figure 1. *(a) SEM of the NW device. (b) TEM of the crystal phase quantum dot, where the wurtzite (WZ) tunnel barriers are highlighted. (c) Current (I) as a function of the side gate voltages (V_L, V_R); the splitting of the single QD into two QDs is indicated. (d) Differential conductance (dI/dV_{SD}) as a function of bias (V_{SD}) and side gate voltage ($V_{L,R}$), recorded along the two first triplet points and with a magnetic field (B); all expected transitions from doublets to single/triplet states can be identified.*

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Th1.4 - Phonon and temperature gradient induced transport in InAs/InP nanowire double quantum dot devices

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Double quantum dot (DQD) devices offer possibilities to study fundamental spin transport physics and are promising candidates for the realization of spin and charge qubits.[1] Consequently, understanding fundamental carrier transport processes across such devices is highly relevant. Within devices based on two dimensional electron gases, it is known that charge sensing via quantum point contacts can lead to heating of the system by phonon emission, which enables additional transport mechanisms.[2,3] We present controlled studies of thermal interactions with epitaxially-defined DQDs to gain important insights into parasitic, temperature gradient induced currents in different interdot tunnel coupling regimes. Metal plunger gates and a side-heater are placed in close vicinity to the contacted nanowire (figure 1a). We combine finite bias spectroscopy (figure 1b) with measurements at no source-drain bias (figure 1c) to study the effect of thermal gradients and phonon assisted transport in DQD devices.

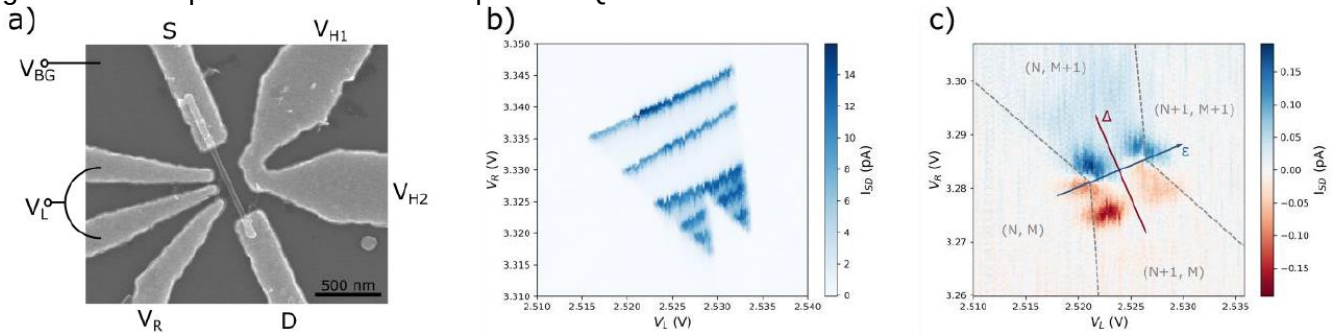

Fig 1. *a) SEM image of the device. An InAs nanowire with three InP barriers is contacted by source and drain (S, D). Two gates (V_L, V_R) act as plunger gates to the DQD. An additional side-heater (V_{H1}, V_{H2}) is used to lo create a temperature gradient across the device. The substrate acts as global backgate (V_{BG}). b) Finite bias spectroscopy with a source drain bias of V_{SD} = 3 mV and $|V_{H1}-V_{H2}|$ = 0 V. c) Temperature gradient and phonon induced current, measured with no applied V_{SD} and $|V_{H1}-V_{H2}|$ = 2 V. Guidelines highlight regions of constant charge (N, M) and relevant energy level detuning axes (ε, Δ).*

The clear presence of currents of opposite sign around the triple points in figure 1c indicate an interplay of two different effects. Along the dot level detuning axis Δ (figure 1c, red line), phonon absorption gives rise to phonon assisted transport across the DQD.[3] In addition, along the axis ε (figure 1c, blue line), a thermal gradient across the contacts induces a thermoelectric current.[2] We model our system using QmeQ[4] and find the results to be in good agreement with the experiment.

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I12 - Ballistic thermal transport in silicon nanowires

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Keywords: thermal conductivity, phonons, silicon, nanowires

Future of silicon-based microelectronics depends on solving the heat dissipation problem. A solution may lie in a nanoscale phenomenon known as ballistic heat conduction, which implies conduction of heat without heating the conductor. In semiconductor nanowires, ballistic heat conduction implies that the thermal conductivity of a nanowire depends on the nanowire length[1]. However, attempts to demonstrate this phenomenon experimentally are controversial and scarce, whereas its mechanism in confined nanostructures is yet to be fully understood.

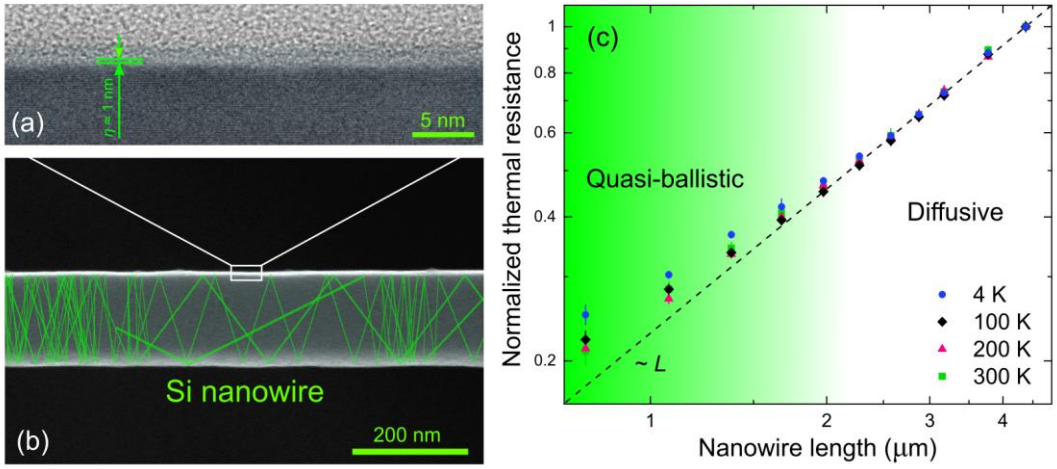

Figure 1. *(a) TEM image shows low surface roughness. (b) SEM image of silicon nanowire with simulated phonon paths. (c) Thermal resistance of short nanowires deviates from a linear diffusive trend indicating quasi-ballistic behavior.*

Here, we use time-domain thermoreflectance method[2] to demonstrate the quasi-ballistic heat conduction in silicon nanowires fabricated by top-down approach (Figure 1). Measuring nanowires of different shapes and sizes, we show that the ballisticity is the strongest in short nanowires at low temperatures (Figure 1) but weakens as the nanowire length or temperature is increased[3]. Yet, even at room temperature, quasi-ballistic heat conduction remains visible in short NWs. Our experiments and simulations show that the quasi-ballistic phonon motion in nanowires is essentially the Lévy walk like transport with short flights between the boundaries and long ballistic leaps along the nanowire axis.

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Th2.1 - Top-down fabricated silicon nanowires for thermoelectric generation

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The reduced thermal conductivity (kt) of silicon nanowires, largely demonstrated by several research groups [1,2], offers the opportunity of using silicon, which is a cheap, abundant, biocompatible, technologically feasible material, for thermoelectric applications.

We fabricated devices based on top down silicon nanowires and nanostructures (such as Si thin nanomembranes) following two main strategies.

A) High resolution electron beam lithography, together with advanced silicon processing, has been used for the top-down fabrication of devices based on suspended Si nanowires, completed with contacts and test structures for their thermoelectric characterization.

Devices based both on single nanowires and on large collections of Si nanostructures have been fabricated [2,3] and characterized.

B) A highly selective vertical etching, based on the metal-assisted catalysis, has been developed and improved, so that large arrays of silicon nanowires, placed in perpendicular to the silicon substrate, have been fabricated (silicon nanowire forests). This cheap technique allows the simultaneous fabrication of more than 10^7 nanowires/mm^2, with an average diameter smaller than 80 nm and more than 100 um long. A process for contacting the top ends of the nanowires, necessary for their electrical and thermal characterization, has been implemented and developed [4].

Test devices, based on Si nanowires and nanostructures (thin nanomembranes), have been fabricated both with strategy A) and B), and thermoelectric potentialities of Si at the nanoscale have been assessed. In particular, the thermal conductivity has been accurately measured on suspended Si structures, with a reliable technique based on the 3omega method. A clear relationship between thermal conductivity and surface roughness has been established [5,6].

The thermal conductivity, as also the electrical conductivity and the Seebeck coefficient, has been measured on devices based on silicon nanowire forests of several mm^2 [2,7]. Hence, these measurements are averaged on a large number of nanowires (more than 10^8). We achieved thermal conductivity values smaller than 5 W/(m K), confirming the strong reduction of the thermal conductivity already demonstrated on single (or very few) nanowires.

These macroscopic devices are very promising for future applications, because they can exploit at the macroscale the properties typical of Si nanostructures.

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Th2.2 - Thermal conductivity measurements of single semiconductor nanowires: a novel approach

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Keywords: single nanowires, thermal conductivity

Nanowires are ideal candidates for exploring the effect of low dimensionality on thermal transport due to the intrinsic 1D nature of transport in these structures. Furthermore, the reduced thermal conductivity in nanowires with diameters on the order of their phonon mean free paths or smaller is promising for applications in thermoelectric energy conversion.[1]

However, measuring the thermal conductivity of single nanowires is a non-trivial task. A wide range of measurement schemes is currently being used, all with their respective advantages and disadvantages.[2]

We present a new method based on Raman thermography and a resistive heater. The single nanowire is cantilevered on an electric heater and suspended in air. The heat flowing through the wire is controlled by the convective cooling of the wire, which is modelled as a heat fin. By measuring the temperature profile over the wire using Raman thermography the thermal conductivity of the wire can be

extracted. With this approach, interesting information about conductive and convective heat transfer at

the nanoscale can be derived.

This novel method has been tested on GaAs and InAs nanowires by comparing the results with those we obtained by other Raman, laser-heating based approaches[3] and with those available in literature, obtaining in both cases a good agreement.

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Th2.3 - Microwave energy harvesting using III-V nanowire backward diodes

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Microwave energy harvesting has drawn attention for reducing the dependency of the IoT sensors on batteries.[1] High-sensitivity diodes are expected to be developed as rectifiers. We are developing nanowire backward diodes (NW BWDs) that exhibit abrupt rectification at zero bias, regulated by the tunnel current. The NW BWDs have small capacitance suitable for ensuring high-frequency operations. In this study, we fabricate microwave energy harvesters using NW BWDs and demonstrate the RF-DC conversion from free-space propagating microwaves.

NWs were grown using the position-defined VLS growth method on the SiN-mask patterned substrates with Au catalysts.[2] A semi-insulating GaAs(111)B wafer with a 200-nm-thick n-GaAs film was used to perform the RF operations. Type-II p-GaAsSb/n-InAs NWs were grown using metal-organic vapor-phase epitaxy. The backward rectification property (i.e., current flow was only allowed for negative bias) was sensitive to the tunnel barriers formed at the p-GaAsSb/n-InAs hetero-interface, and it was successfully controlled with the Sb fraction of the p-GaAsSb NW segments.

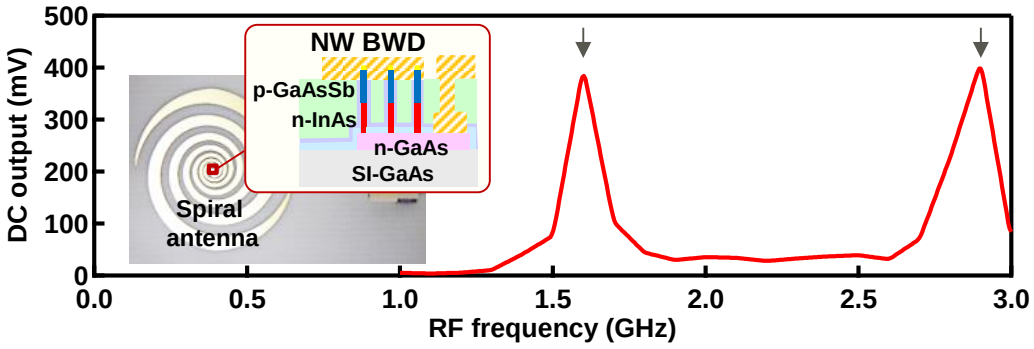

Figure 1. *RF-DC conversion from free-space propagating microwaves using harvester with nanowire backward diode.*

Microwave energy harvesters were fabricated using the NW BWDs (Fig. 1). A spiral antenna was used to collect the microwaves, and one NW BWD was mounted on the antenna center as a rectifier. The sensitivity of the NW BWDs was approximately 10^4 V/W, which was similar to that of the well-designed Schottky barrier diodes. The harvester received microwaves with frequencies of approximately 1.6 and 2.9 GHz and generated DC outputs of 0.4 V. A higher DC output voltage was obtained, when compared with that obtained while using μm-sized mesa BWDs processed from thin-film epi wafers.[3]

In summary, we successfully demonstrated microwave energy harvesting using harvesters with NW BWDs. These results are promising for the development of eco-friendly IoT sensor technology.[4]

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Th2.4 - Thermoelectric Conversion at 30 K in InAs/InP Nanowire Quantum Dots

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The progress in fabrication and control of nanostructured systems has opened new prospects for thermoelectric research[1,2] and has provided new ways to create improved thermoelectric devices[3]. Quantum dots (QDs) were soon identified as ideal systems to implementation efficient heat engines[4].

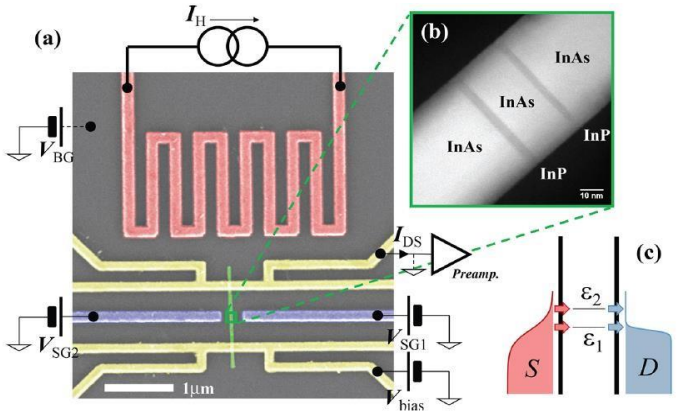

Figure 1. *(a) Scanning electron micrograph of the device. A local heater (red) is used to establish a temperature difference between the two ends of the NW (green) embedding an InAs/InP heterostructured QD. The QD electronic configuration can be controlled with a pair of side gates (purple) or using the conductive substrate. (b) Transmission electron micrograph of the heterostructured QDs. (c) Sketch of the energetics scheme: the QD implements a multilevel system that mediates heat and charge transport between a source (S) and drain (D) electrode, in the presence of thermal and electric biases.*

We briefly review the basic concepts necessary to describe thermoelectric transport, and we show how this effect can be exploited to construct a heat engine. We then focus on our experimental demonstration of high-temperature (30K) thermoelectric conversion in InAs/InP nanowire quantum dots[5] (see Fig. 1). The electrical conductance G and the thermopower S are obtained from charge transport measurements and accurately reproduced with a theoretical model accounting for the multilevel structure of the quantum dot. The electronic thermal transport is dominated by multilevel sequential heat transport. By taking into account two spin-degenerate energy levels, we are able to evaluate the electronic thermal conductance K and investigate the evolution of the electronic figure of merit ZT as a function of the quantum dot configuration and demonstrate ZT ≈ 35 at 30 K, corresponding to an electronic efficiency at maximum power close to the Curzon-Ahlborn limit.

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Th3.1 - Radial and axial nanowire heterostructures via solid-state reactions

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Hybrid nanostructures incorporating junctions between dissimilar materials are promising for applications in (opto-) electronics, energy conversion, *etc*. Nanowires (NWs) support two types of heterojunctions, radial and axial. Radial (core-shell) NW heterostructures have been produced by sequential growth of the core and shell. Axially segmented NWs have been fabricated *via* vapor-liquid-solid (VLS) growth, as well as alternative approaches such as post-growth oxidation, anodic alumina templated electrochemical deposition, or thermally activated diffusion.

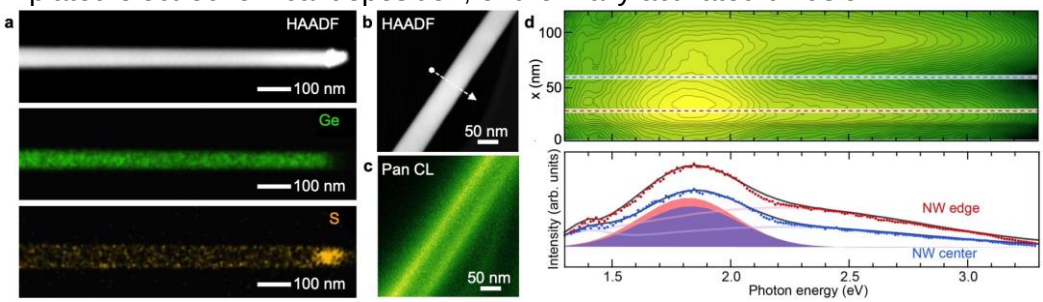

Figure 1. *Ge-GeS core-shell NWs.* ***a.*** *EDS analysis showing the Ge nanowire core and S-rich shell.* ***b.*** *HAADF-STEM image of a core-shell NW.* ***c.*** *Panchromatic STEM-CL map of the NW shown in b.* ***d.*** *Spectrum linescan across the NW (dashed line in b.) and representative CL spectra, showing the characteristic emission of the GeS shell.*

Here, we discuss avenues toward high-quality radial and axial NW heterostructures based on post-growth solid-state reactions. Radial heterostructures with semiconductor cores and chalcogenide shells are formed by reacting Ge and GaAs NWs with chalcogen (S, Se) vapor at moderate temperatures. Sulfurization of Ge NWs produces wide-bandgap Ge (II) sulfide shells, as shown by (S)TEM and EDS (Fig. 1a).[1] Sulfurization of III-V NWs gives rise to different heterostructures, including GaAs-Ga_2S_3 core-shell wires, hollow Ga_2S_3 tubes, and 1D/2D hybrids with layered GaS shells. Additional experiments provide an understanding of the reaction mechanisms.[2] The core-shell NWs show promising properties, including increased carrier mobility and bright luminescence detected on individual NWs using STEM cathodoluminescence (CL) spectroscopy (Fig. 1b-d). Forming axially segmented NWs by post-growth processing presents additional challenges. We demonstrate a novel approach toward realizing NWs with alternating semiconducting (Ge) and metallic (AuGe, AgGe) segments, which involves alloying, partial melting, and crystallization during slow cooling. Despite the absence of any rapid quenching, the metallic alloy segments crystallize in several metastable crystal phases, which are controllable *via* the NW diameter. These striking findings are explained by modifications of the binary phase diagrams at the nanoscale and their effects on the structural motifs in the melts during processing.

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Th3.2 - Complex nanowire structures revealed by electron tomography

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Keywords: Tomography, nanowire structure.

While most nanowire structures can be analyzed using transmission electron microscopy (TEM) projection images, some features, such as rotational symmetry/asymmetry, can get lost. Electron tomography (ET) is a useful method for retrieving the 3D structure, which can correlate both growth parameters to actual morphology, as well as explain measured properties. With increased complexity in the component design ET will be important for high-resolving 3D analysis.
Here we present electron tomographic studies of nanowire structures from two different material systems: Au-seeded and Sn-doped GaAs wires, and Au-seeded InAs-AlSb-InAs core-shell-shell wires. The GaAs-wires are grown using Aerotaxy while the core-shell-shell structure is grown using conventional metal organic vapor phase epitaxy (MOVPE). Both sets of wires were reconstructed using ET reconstruction algorithms: simultaneous iterative reconstruction technique (SIRT), discrete algebraic reconstruction technique (DART) and compressed sensing ET (CS-ET), from tilt-series (±75°) images (JEM-2200FS, HAADF detector). The reconstructions were calculated using the ASTRA toolbox for Matlab and Python.

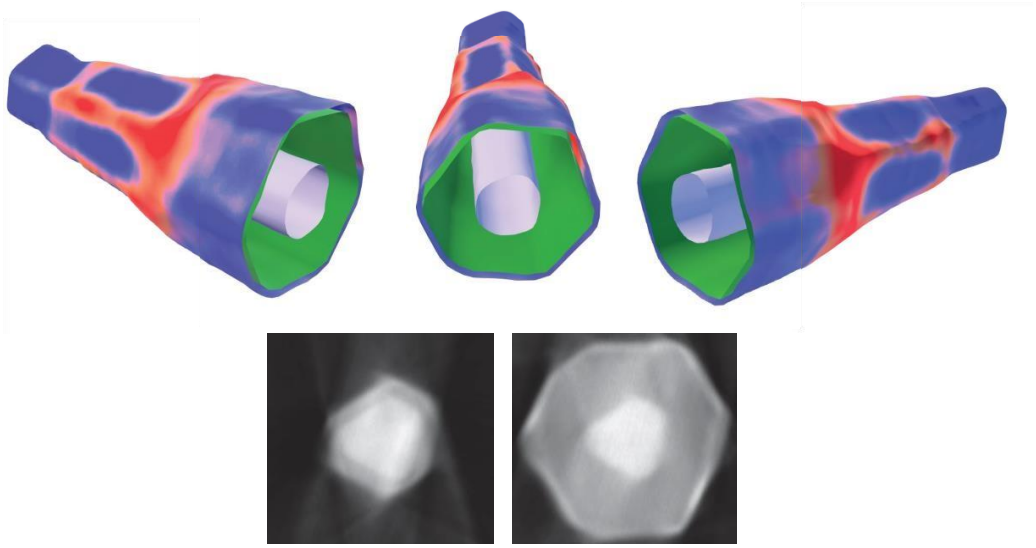

Figure 1. *The preferred facets are different for the core-material (InAs) and the first shell (AlSb) which is seen as a 30° rotation (the azimuthal angle) when going from the thin to the thick part. The outer shell InAs) thickness varies along the wire and can be imaged as a "heat-map". The outer shell grows thicker at corners and the facets of the thick part.*

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Th3.3 - Force sensing with nanowire cantilevers

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Nanometer-scale structures with high aspect ratios such as nanowires and nanotubes combine low mechanical dissipation with high resonance frequencies, making them ideal force transducers and scanning probes in applications requiring the highest sensitivity. Such structures promise record force sensitivities combined with ease of use in scanning probe microscopes. A wide variety of possible material compositions and functionalizations is available, allowing for the sensing of various kinds of forces. In addition, nanowires possess quasi-degenerate mechanical mode doublets, which allow for sensitive vectorial force and mass detection, as well as the opportunity to study classical coherent two-mode dynamics. These characteristics have enabled researchers to use nanowire cantilevers as vectorial probes of weak forces in various experiments[1], including imaging of sample surface topography[2,3], detection of optomechanical[4], electrical[2,3], and magnetic forces[5], and magnetic resonance force microscopy[6]. I will discuss the motivation behind using nanowires as force transducers, explain the methods of force sensing with nanowire cantilevers, and give an overview of the experimental progress so far and future prospects of the field.

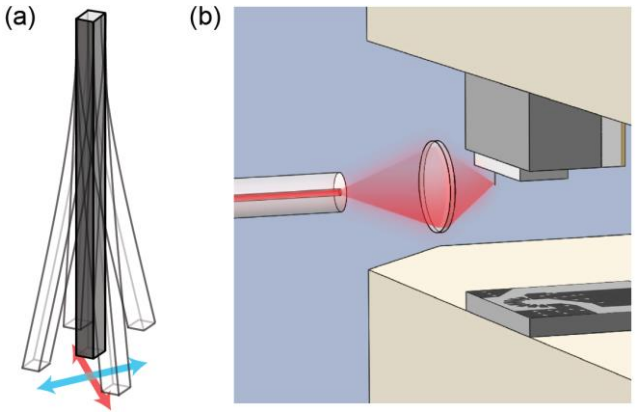

Figure 1. *(a) Schematic illustration of a nanowire cantilever exhibiting motion in two orthogonal flexural modes. (b) Schematic overview of scanning probe setup including nanowire cantilever and sample mounted on translation stages and optical readout*

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[7] **Acknowledgements:** We acknowledge the support of the Kanton Aargau, the ERC (Starting Grant NWScan), the SNF (Grant 200020-178863), the Swiss Nanoscience Institute, and the NCCR QSIT.

Th4.1 - Single-nanowire spectrometers

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Keywords: Optoelectronics, spectrometry, bandgap-engineering

Spectrometers with ever-smaller footprints are sought after for a wide range of applications where minimized size and weight are paramount, including emerging in-situ characterisation techniques[1]. Microspectrometers have typically been inspired by bench-top systems, based on interferometers or gratings, with miniaturised or integrated optics. When scaling toward the sub-millimetre-scale, these conventional designs are inherently limited by the adverse effects of shrinking their optical components or path lengths[2]. We report on an ultra-compact micro-spectrometer design based on a single compositionally-engineered[3] nanowire. This platform is independent of the complex optical components cavities or CCDs that constrain further miniaturization of current systems. We show that incident spectra can be computationally reconstructed from the different spectral response functions and measured photocurrents along the length of the nanowire. Our devices are capable of accurate, visible-range monochromatic and broadband light reconstruction, as well as spectral imaging from centimeter-scale focal planes down to lensless, single-cell-scale in-situ mapping.

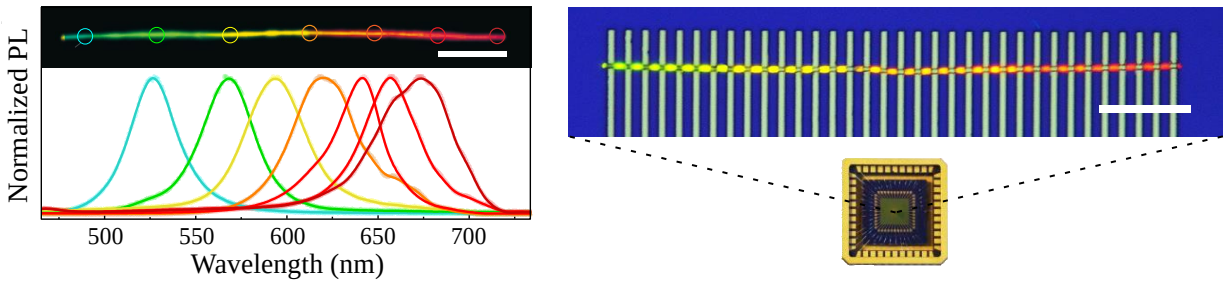

Fig. 1: *(left) Photoluminescent emission from different locations along a compositionally-engineered CdS_xSe_{1-x} nanowire. (right) A nanowire spectrometer within a packaged chip, featuring an electrode array fabricated on top of a CdS_xSe_{1-x} nanowire; magnified section shows a optical microscope image taken under UV illumination, with scale bar 10 μm.*

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Th4.2 - High-performance GaN axial p-n junction single-nanowire photodetectors

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Nanowire (NW) photodetectors constitute a promising approach to outperform planar devices in terms of responsivity-bandwidth product. Their low electrical cross-section leads to low electrical capacitance without any degradation of the total light absorption due to the antenna effect. Thinking of visible-blind UV photodetectors, GaN is a particularly adapted material. However, most demonstrations of GaN NW photodetectors are based on the metal-semiconductor-metal architecture. Such devices present high gain, but they are strongly sublinear and their time response is generally in the millisecond range. A responsivity enhancement is possible by inserting a heterostructure,[1] and linearity can be attained if the NWs are thin enough to be depleted,[2] but the time response remains a recurring problem.

In this work, we present an in-depth study of the performance of single GaN NW photodetectors containing an axial p-n junction. The device is designed with a p+/n+ tunnel junction as cap structure which enables to use the same metal scheme for contacting both ends of the NW. The individual specimens were selected and electrically contacted using electron beam lithography. Kelvin probe force microscopy (KPFM) was used to determine the location of the p-n junction. NWs with the junction properly located between the contacts display rectifying current-voltage characteristics.

The photovoltaic response to UV radiation scales sublinearly with the incident power when the device is not biased, behavior attributed to the presence of surface states. On the contrary, when the junction is under reverse bias, the role of the surface becomes negligible in comparison to the drift of photogenerated carriers in the depletion region. In these conditions, the contacted NWs are characterized by their linearity, high spectral selectivity (UV/visible contrast of several orders of magnitude) and high speed (in the microsecond range, limited by the RC time constant of the system). This result is the first demonstration of GaN NW photodetectors combining high spectral selectivity, linearity and fast response.

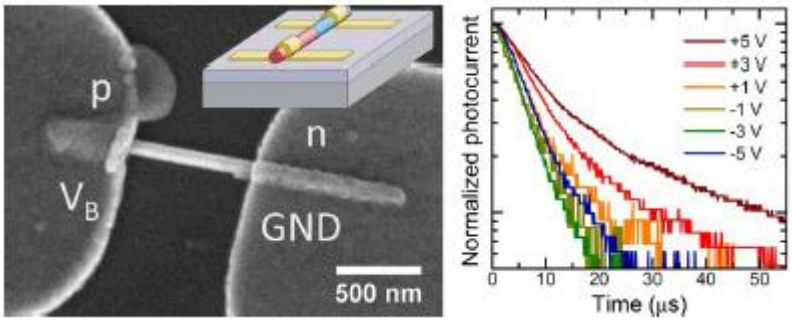

Figure 1. *Left: Scanning electron microscopy image of a contacted NW containing an axial p-n junction. Right: Time response measurements as a function of bias measured with a pulsed Nd-YAG laser (266 nm). The time response drops below 10 µs under reverse bias.*

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Th4.3 - III-V nanowire-based solar cells for space applications

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Space power systems require photovoltaics that are light-weight, efficient, reliable, and can withstand high-energy particle irradiation. Current space power systems use highly-efficient multi-junction, III-V based photovoltaic solar cells which nonetheless have modest specific power (power to weight ratio) because of the need for radiation shielding. Here we demonstrate that III-V nanowire (NW) solar cells have a radiation performance that is superior to their state-of-the-art planar counterparts. GaAs and InP NW solar cells with an efficiency η =12 % and 8 % (AMG 1.5G), respectively, have been irradiated with 100 keV and 350 keV ($1\cdot10^{11}$, $5\cdot10^{11}$ and $1\cdot10^{12}$ p^+/cm^2) protons and 1MeV ($5\cdot10^{14}$, $1\cdot10^{15}$ and $5\cdot10^{15}$ e^-/cm^2) electrons. Besides, we have performed Monte Carlo simulations to understand the origin of the observed high radiation-tolerance of the NW-based devices and designed guidelines to optimize the specific power of NW solar cells for space applications by jointly increasing their efficiency and radiation hardness.

		NW		planar
p^+/cm^2	Parameter	100 keV	350 keV	350 keV
10^{10}	J_{sc}/J_{sc0}	-	1.07±0.02	0.98±0.02
	V_{oc}/V_{oc0}	-	1.00±0.01	0.91±0.04
10^{11}	J_{sc}/J_{sc0}	0.95±0.02	1.01±0.02	0.83±0.02
	V_{oc}/V_{oc0}	0.90±0.01	0.97±0.01	0.68±0.02
$5\cdot10^{11}$	J_{sc}/J_{sc0}	0.88±0.03	-	-
	V_{oc}/V_{oc0}	0.81±0.01	-	-
10^{12}	J_{sc}/J_{sc0}	0.74±0.03	0.94±0.02	0.11±0.02
	V_{oc}/V_{oc0}	0.80±0.01	0.83±0.01	0.45±0.01

Table 1. *Degradation ratio summary of the different solar cell technologies in each experiment*

The high radiation tolerance of NW solar cells (see Table 1) reduces the need for shielding. Together their low packing fraction (9-14%), NW solar cells hold promise for high specific power, radiation-tolerant photovoltaics in space power systems.

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I13 - Modeling Semiconductor Nanowire Lasers

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Keywords: nanowires, lasers, modeling

Semiconductor nanowires can be forced to lase by optical pumping, a process, which is well documented by various experiments. In this contribution we explain how this process can be modeled while keeping a balance between accuracy and numerical costs.

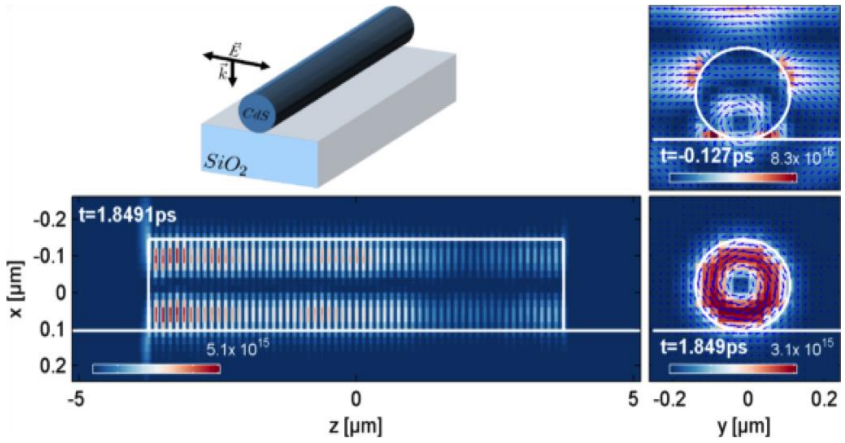

Figure 1. *Modeling lasing of a CdS nanowire placed on a silica substrate and pumped by an optical pulse incident from above. Lasing in a well-defined transverse mode sets in after around 1.7ps.*

A full description of the spectral properties of the lasing dynamics of resonantly excited semiconductor nanowires requires a treatment going far beyond conventional rate equations. To obtain that goal we coupled electromagnetic calculations based on the Finite Difference Time Domain (FDTD) scheme[1] with a quantum mechanical treatment of the resonant material based on the semiconductor Maxwell-Bloch equations.[2] As a result we could simulate a full lasing process (see Figure 1) and got quantitative agreement with respective experimental measurements.[3] As numerical costs areextremely high we also developed an alternative scheme for single mode nanowires, for which we assumed the field profile to be fixed. Such simplification resulted in a tremendous speed-up of the calculations and allowed to model whole pump-probe experiments.[5]

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[5] **Acknowledgements:** This research was funded by the German Research Foundation (DFG) in the framework of the research unit FOR1616 Dynamics and Interactions of Semiconductor Nanowires for Optoelectronics.

F1.1 - Single photon emission with a Gaussian far-field at telecom wavelength from single InAs-InP quantum dot-nanowires monolithically grown on Si

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Securing communications over long distances require single photon sources emitting in the telecom band. One major issue is funneling the emission of the photons into a directive Gaussian waveguide mode to efficiently couple the single photons to optical fibers.

Here we report our recent efforts to obtain a single photon emission and a Gaussian far-field radiation profile in the telecom O-band from single quantum dot-nanowires (QD-NWs) monolithically grown on Si. The InAs-InP QD-NWs were grown on Si(111) substrates by Vapor-Liquid-Solid (VLS) assisted solid-source Molecular Beam Epitaxy using In-Au droplets as a catalyst in-situ deposited at 500°C.[1] Low densities < 0.1/μm^2 of vertical QD-NWs were achieved with In-Au droplets formed with a low In/Au flux ratio. The growth conditions (axial versus radial growth) were tuned (Fig. 1.a) to optimize the source brightness and reduce the far-field divergence[2,3]: 1) The NW diameter is adapted to couple efficiently the QD emission with the fundamental waveguide mode and 2) the QD-NW has a needlelike tip with a small tapering angle (< 7°).

The control of the NW geometry allows us to demonstrate a Gaussian far-field radiation profile in the telecom O-band with an emission angle θ≈27° at room temperature (Fig. 1.b) from a single InAs-InP QD-NW. Moreover, the measurement of a single photon emission with $g^2(0) = 0.05$ (Fig. 1.c) at cryogenic temperature paves-the-way for the monolithic integration on Si of efficient QD-NW single photon sources in the telecom band.

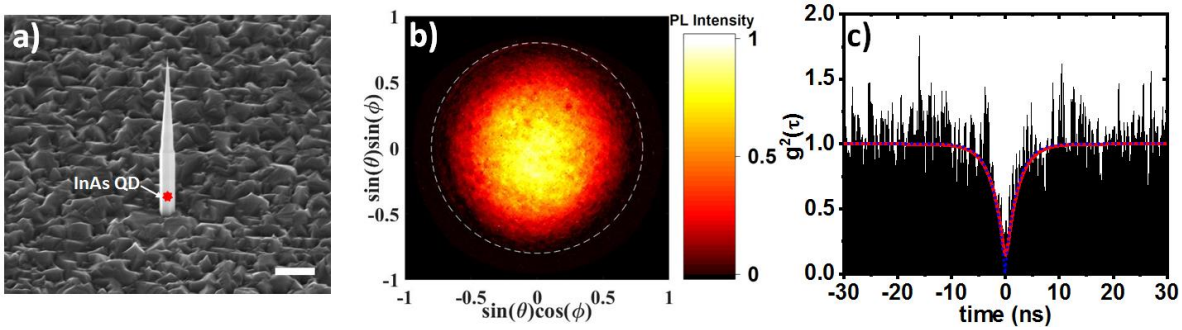

Figure 1. *a) SEM image of a single InAs-InP QD-NW with a needlelike geometry and a tapering angle < 7° (scale bar 1 μm). b) Far-field radiation profile of a single QD-NW at room temperature. c) Second-order correlation measurement of a single QD-NW emitting at 1328 nm at cryogenic temperature.*

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F1.2 - Germanium nanowire based bolometer for Mid-IR sensing

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Keywords: Germanium, nanowires, bolometer

With the ever growing number of applications demanding photodetectors in the mid-infrared, bolometers gained significant research interest over the last years. Per definition, a bolometer consists of an absorptive element linked to a thermal reservoir and a thermometer. Any radiation, which is incident on the absorptive element, will raise its temperature above that of the reservoir proportional to the radiation intensity.[1] Germanium (Ge) nanowires (NWs) embedded between two electrical contacts are perfect buildings blocks for bolometers. They have small thermal mass, and in addition, the same highly temperature dependent electrical resistance as bulk Ge-bolometers, which are already used since decades.[2] Here we present a Ge NW based infrared sensing device. As schematically shown in Figure 1. the NW is contacted via aluminum (Al) pads on a 40 nm thick Si_3N_4 membrane. An electrically contacted multi-layer graphene (MLG) flake is placed on the opposite side, acting as an absorber and electrostatic gate.[3] The suspended architecture of the device results in a highly selective heat transfer from the MLG to the NW. By using a thermally induced exchange reaction between the polycrystalline Al contact pads and the single crystalline Ge NW, the length and thus the thermal mass of the NW can be tuned (Inset Fig.1).[4] In addition, the resulting self-aligned single crystalline Al leads provide a highly effective heat link to the surrounding Al metallization which acts as the thermal reservoir.

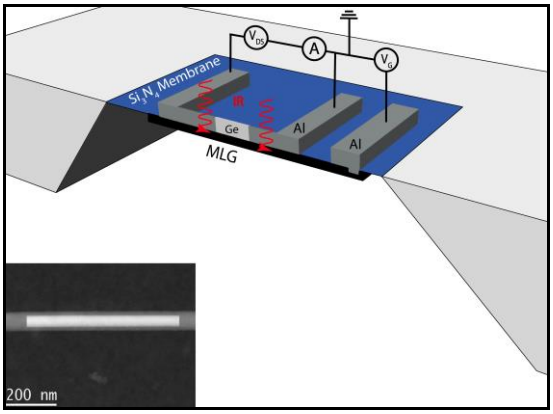

Figure 1. *Schematic cut through the bolometric sensing device. A Ge NW is contacted by Al on a Si_3N_4 membrane. On the backside of the membrane MLG acts as an electrostatic gate for the NW and IR absorber. The inset shows a TEM image of Ge NW segment contacted by two Al leads.*

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F1.3 - Multiplexed single photon source based on multiple quantum dots embedded within a single nanowire

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Keywords: Multiplexing, Nanowire, Quantum Dots

Optical-based information technologies require efficient sources of single photons and entangled photon pairs at high emission rates. Quantum dots (QDs) embedded within nanowire waveguides have demonstrated high purity single photon and high fidelity entangled photon pair generation.[1] Ultimate repetition rates, however, are limited by transition lifetimes of ~1ns. The selective-area vapor-liquid-solid epitaxial growth process[2] allows for the integration of multiple QDs within the same nanowire waveguide coupled to the same optical mode.[3] In this study we demonstrate such a multi-dot system. In particular, we show bright single photon emission from four QDs embedded within a single nanowire.

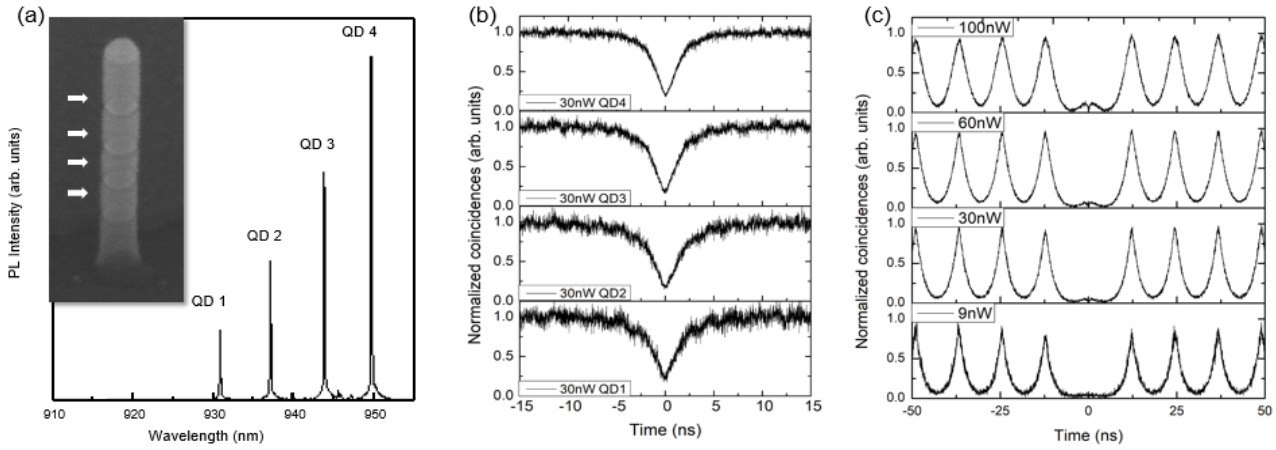

Figure 1. *(a) Photoluminescence spectrum of four QDs in one nanowire. Inset: Scanning electron microscope image of an InP nanowire containing four InAsP QDs. (b) Second-order correlation measurements of the four QDs under continuous wave excitation. (c) Second-order correlation measurements of QD3 under pulsed excitation as a function of power.*

Figure 1 shows a photoluminescence spectrum of a four QD nanowire where emission wavelengths have been tuned to achieve a ground state separation of ~7nm. Second-order correlation measurements demonstrate the single photon nature of the emitted photons from all four QDs. Our findings show that multiple QDs embedded within a single nanowire could potentially be used as a multiplexed single photon source with an emission rate determined by the number of incorporated emitters.[4]

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[4] **Acknowledgements:** The authors would like to acknowledge support from the Canadian Space Agency and the Natural Sciences and Engineering Research Council.

F1.4 - On-chip integration of single photon sources via evanescent coupling of tapered nanowires to SiN waveguides

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Keywords: Nanowire, single photon source, photonic integration

The integrated photonics platform has been identified as a practical way to realise quantum technologies, with integrated light sources being attractive for experiments requiring complex photonic circuits such as linear optics quantum computing and quantum simulations. Efforts to develop on-chip integrated sources include quantum dots (QDs) coupled to ridge, nanobeam and photonic crystal waveguides. In this work, we demonstrate a hybrid integration method based on the evanescent coupling of a nanowire waveguide mode, excited by a single QD, to an underlying ridge waveguide.

We use InAsP/InP nanowire QD sources grown using a combined selective-area and vapor–liquid–solid (SA-VLS) epitaxy approach[1] which have demonstrated single photon purities greater than 99%[2] and near-transform-limited linewidths of less than 4 μeV. Importantly, the nanowires can be grown with well-defined tapers[3] that can be tailored for optimal evanescent coupling. Using nanomanipulators individual nanowires are placed on SiN waveguides fabricated from ultra-low-loss silicon nitride films on SiO_2 coated Si wafers. Fig. 1a shows a SEM image of a nanowire on top of a SiN ridge before the final SiO_2 cladding layer is deposited. Modelling of this system, fig. 1b, predicts that for suitable nanowire taper lengths close to 100% optical coupling of the nanowire QD emission to the underlying SiN waveguide is possible. A measured value of 74% is obtained. The single photon purity of the nanowire source is measured at the output of the SiN waveguide where a $g^{(2)}(0)$ as low as 0.03 is observed.

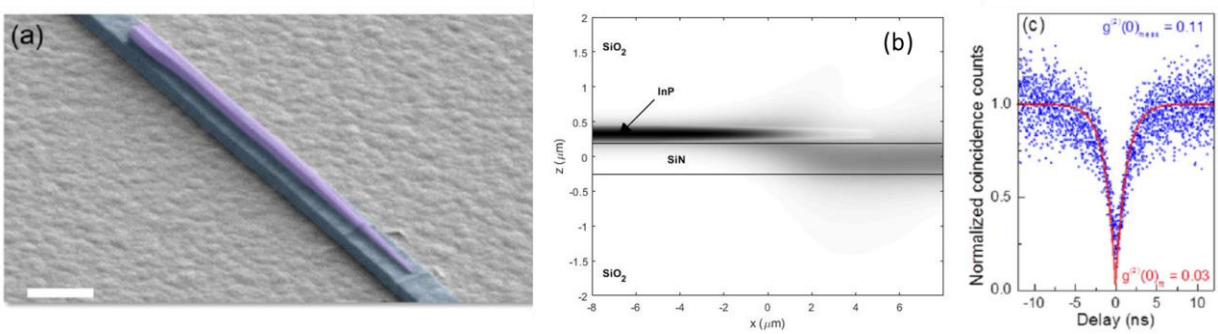

Figure 1. *a.) SEM image of a tapered nanowire on top of the SiN waveguide (scale bar is 1 μm), b.) A cross section through the waveguide showing the electric field E_y of the fundamental waveguide mode in the coupled device, c.) raw second-ordercorrelation function using cw excitation*

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[4] **Acknowledgements:** The authors would like to acknowledge support from the Canadian Space Agency and the Natural Sciences and Engineering Research Council.

I14 - *p*-GaAs nanowire transistors with near-thermal limit gating

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Keywords: p-GaAs, nanowire transistors, near-thermal limit gating

Modern integrated circuits are reliant on complementary architectures to minimize power draw. Continued miniaturization spurred the development of nanowire CMOS, recently focusing on III-V nanowire field-effect transistors (NWFETs) integrated on Si to obtain high performance at low cost. Progress has been better for *n*-type than for *p*-type; challenges with growth, doping and fabrication of high-quality gates and ohmic contacts have impeded progress for *p*-type NWFETs.

Candidates for *p*-type III-V NWFETs include GaSb, GaAs, In(Ga)As, InP and InSb. In-based materials are natively *n*-type, making GaSb is the prevailing *p*-type material. GaSb is challenging to grow, it is also natively *p*-type meaning it cannot be used for *n*-type devices. GaAs is intrinsic and can be used for both *n*- and *p*-type devices, but contacts have been a roadblock for *p*-GaAs NWFETs.[1]

We developed *p*-GaAs NWFETs with near-thermal limit gating, low contact resistance and competitive frequency response with strong potential for nanowire CMOS applications. The key to low resistance ohmic contact was adding a heavily Be-doped GaAs shell to the nanowire.[1] We obtain contact resistances as low as 30 k□ for a shell acceptor density N_A = 1.5×10^{19} cm^{-3}. This shell doping is so high that conventional metal-oxide gates fail,[2] however we found two clever ways to solve this.

The first involves ionic-gating, which not only still enables switching but gives a sub-threshold swing of 75 mV/dec, within 25% of the thermal limit and comparable with *n*-GaAs nanowire MOSFETs.[2] This highlights the strong gate effect obtained from an electrolyte-gate, but these gates also suffer poor time response. The second involves carefully etching the shell at the gate location to make a *p*-GaAs nanowire MESFET.[3] The advantage is that the gate is self-insulating due to the GaAs Schottky barrier. Our device beats comparable *p*-GaSb nanowire MOSFET structures,[4] giving a typical sub-threshold swing of 62 mV/dec, within 4% of the thermal limit, on-off ratio ~10^5, contact resistance ~30 k□, peak transconductance ~1 □S/□m and high-fidelity ac operation up to 10 kHz, opening the path to all-GaAs nanowire complementary circuits with simplified fabrication and improved performance.

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F2.1 - Electron pair charging in gate-defined quantum dots in indium antimonide nanowires

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Keywords: indium antimonide, quantum dot, electron pairing

We investigate InSb nanowires placed on bottom gates with mechanically exfoliated hexagonal boron nitride (h-BN) as a dielectric. The sample consists of five 50 nm wide finger gates with a spacing of 30 nm. The h-BN is placed on top of the finger gates. The nanowires are then placed mechanically onto h-BN.[1]

We present transport measurements on gate-defined quantum dots at temperatures down to 300 mK. Due to the dielectric, the time stability of our device improved to around 5 µeV/h. The charge stability diagram shows Coulomb diamonds with a charging energy of 2.3 meV and an orbital energy of 0.3 meV. From the magnetic field dependence of the excited states we extract a g-factor of about 75.

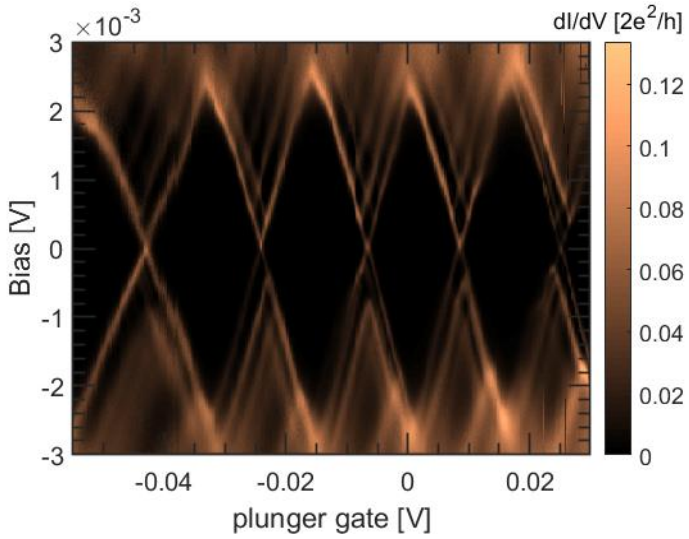

Figure 1. *Charge stability diagram of the gate defined quantum dot*

In a perpendicular magnetic field, the zero bias state splits at around 380 mT with a doubling of the gate-periodicity below and above the transition field. This splitting resembles the one reported by Shen *et al.* on nanowires partially covered by superconductors.[2] But since in our sample there is no superconductor involved, the doubling is of unknown origin. However, the change in periodicity implies a change of the pairing mechanism, possibly triggered by electron-electron interaction.

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F2.2 - Control and probe of the hole quantum state in a nanowire quantum dot

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Keywords: nanowire quantum dot, light hole state, magneto-optical spectroscopy.

Light hole states which are characterized by versatile optical selection rules are highly suitable for single spin optical manipulation. By contrast to self-assembled quantum dots, dots embedded in nanowires allow us to control the symmetry of the hole ground state by engineering the dot aspect ratio and the elastic strain (a switching towards a light hole ground state hole is expected for *L/D* >1)[1].

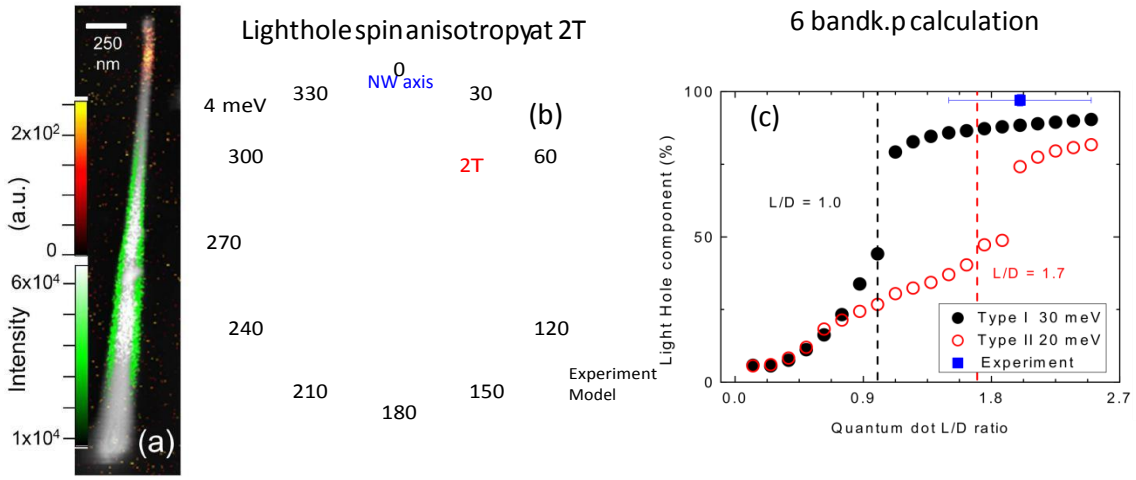

Figure 1. *(a) Scanning electron microscope and catholo-luminescence map of an isolated nanowire containing an elongated magnetic quantum dot[1]. (b) Zeeman shift anisotropy of the exciton line revealing a light hole ground state in the dot. (c) Light hole fraction of the hole ground state confined in the dot as function as the L/D length over diameter of the dot[1].*

ZnTe Nanowires containing elongated $Cd_{0.96}Mn_{0.04}Te$ magnetic quantum dots (*L/D*~2, see[1]) have been grown by molecular beam epitaxy, using the so-called vapour-solid-solid growth mode with a gold nanoparticle[2]. Low temperature photoluminescence spectroscopy has been performed on isolated vertical nanowires in a 3D vector magnet. Thanks to the presence of magnetic atoms in the dot, we managed to measure the anisotropy of the Zeeman shift of the dot exciton line at moderate magnetic field (2T). It revealed the presence of a light hole ground state for *L/D* aspect ratio larger than 2 in agreement with a 6 band k.p numerical calculation[1] (see fig 1.c). The light hole Landé factors are also in well agreement with the bulk values renormalized by the strain induced coupling with the split-off valence band.

References

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F2.3 - Magnetically-driven anomalous phase shift in InAs nanowire Josephson Junctions

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Keywords: Anomalous phase shift, Josephson phase battery, topological superconductivity

InAs nanowire combined with Al superconducting leads and external magnetic fields have been already demonstrated an optimal platform to engineer exotic states and study unconventional topologies. In these hybrid systems the interplay between spin-orbit coupling, superconductivity and Zeeman energy, results in a very rich physics where charge current, superconducting phase and spin are all interdependent. This interplay is at the base of novel quantum technologies[1] and Superconducting spintronics[2]. Within this context, a clear hallmark of the coupling between magnetism and superconducting current is represented by the anomalous phase shift (φ_0) predicted for a topological Josephson junction (JJ).

In this talk, I will reveal this anomalous phase shift in a Al/InAs(NW)/Al JJ in the presence of an external magnetic field. Differing from conventional JJs, in which time-reversal and parity symmetries impose an asymmetric current-phase relation (like *e.g.* $I_j=I_c \sin(\varphi)$, where I_c is the critical current and φ is the superconductor phase difference), in our JJ the presence of a Zeeman field and spin-orbit interactions brakes the two symmetries and induces a φ_0 shift in the Josephson current ($I_j=I_c \sin(\varphi+\varphi_0)$)[3,4]. This anomalous phase has been detected by embedding two InAs JJs in an Al SQUID interferometer (shown in figure), the basic device to probe the phase of the supercurrent. A clear and continuous φ_0 shift have been observed and controlled by an external in-plane magnetic field. The amplitude of the shift is consistent with the theoretical predictions and also the odd parity respect to the magnetic field, an essential hallmark of the anomalous phase, have been revealed for the first time.

The continuous magnetic-control of the anomalous phase makes our InAs JJs an promising platform for the implementation of Superconducting spintronic technologies like phase shifter and Josephson phase batteries[5].

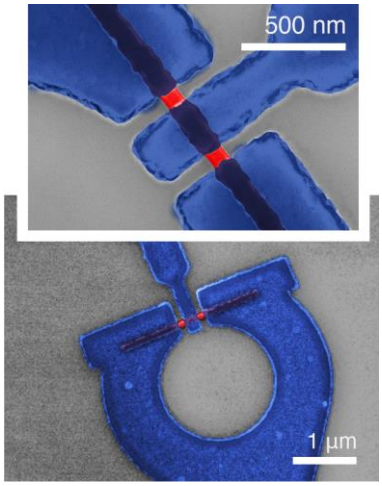

Figure 1. *A single InAs nanowire (in red) is embedded in an aluminum ring (in blue) thus defining a hybrid SQUID.*

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I15 - Memristive and neuromorphic functionalities in metal-oxide nanowires

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Memristive devices based on resistive switching mechanism have attracted great attention for the realization of next-generation memories and for hardware implementation of neuromorphic computing. Indeed, these two-terminal devices have been shown to be able to emulate synaptic plasticity functionalities that are considered milestones for memory and learning processes in human brain. In this scenario, memristive devices based on self-assembled nanowires (NWs) are considered particularly promising not only for the ultimate device scaling but also for the modulation of resistive switching properties through surface and/or quantum effects and for the realization of bio-inspired hardware nano-architectonics based on NW networks [1,2].

In this work, we have investigated the physical mechanism of resistive switching underlaying memristive behavior in a single crystalline ZnO NW model system. By properly adjusting the operating conditions, it was shown that these NW-based devices can exhibit all-in-one the typical memristive functionalities such as non-volatile bipolar resistive switching, multilevel switching, volatile switching and synaptic plasticity through the emulation of Ca^{2+} dynamics of biological synapses [3]. Moreover, single NW devices were reported to be optimal platforms for the investigation of the physical mechanism of switching that involves redox reactions and ionic transport at the nanoscale. New insights on the physical mechanism were achieved by means of a combined approach based on cyclovoltammetry, field-effect measurements and Transmission Electron Microscopy (TEM) analyses. Last, we report how the memristive behavior in such nanostructures can be affected by ionic contribution from ambient moisture that is responsible for the modulation of both electronic and ionic transport properties.

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F3.1 - Drastic Enhancement of Fluorescence Detection by using Lightguiding Nanowires

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Keywords: waveguiding, photonics, biosensors, single-molecule detection

Significant sensitivity enhancement and/or simplification in the detection of fluorescently marked biomolecules is of great interest in research and diagnostics. Semiconductor nanowires (NWs) can act as nanoscale optical fibers, collecting and guiding light emitted by surface-bound fluorophores,[1] and can thus be used as fluorescence signal integrators, enabling higher signal-to-noise ratio and directed emission of more efficient light collection.

We present a detailed study of the lightguiding efficiency in GaP NWs as a function of NW diameter and fluorophore wavelength. Employing a combination of modeling and experiment we identify the role of multiple waveguide modes and we show how to predict the lightguiding ability of the NWs in function of diameter and fluorescence wavelength by calculating the normalized frequency parameter.[2]

As a proof-of-concept in the context of bioanalytical sensing, we use this system to characterize the diffusion of cholera toxin-decorated GM1 gangliosides on a supported lipid bilayer (Fig. 1).[3] Diffusion of GM1 on a NW was detected via epifluorescence microscopy down to single-molecule level, and the simultaneous observation of hundreds of NWs provided significant statistics in short measurements times (~ 10 s). This highly parallel approach works optimally at low GM1 concentrations (< 1 μm^{-2}) and, if necessary, can be corrected for bleaching.[3]

We will also present initial results on the detection of antibodies, which serve as cancer biomarkers, directly in blood serum, allowing a direct comparison of contrast enhancement compared to state-of-the-art diagnostic techniques.[4]

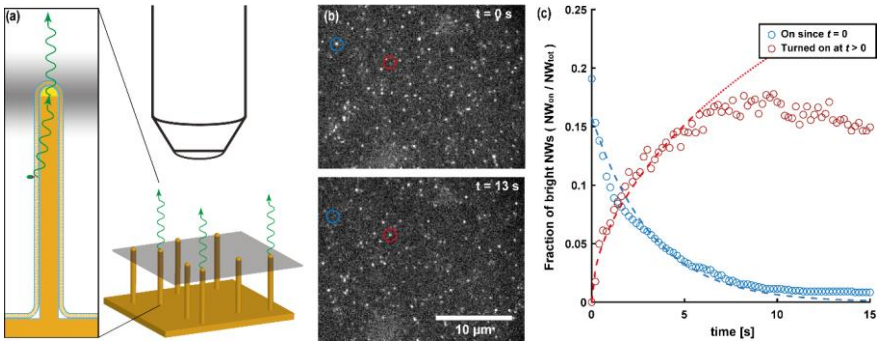

Figure 1. *(a) When a fluorescently labelled molecules diffuses on a NW, its emission is coupled into it, resulting in the NW 'turning on'. (b) Epifluorescence snapshot of the same area of a NW sample at different times during the acquisition: some NWs that are bright at t = 0 s are dark by t = 13 s (blue ring), and vice versa (red ring). (c) The fraction of bright NWs over time can be fitted with an analytical model, allowing to determine GM1 concentration and diffusivity in the lipid bilayer.*

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F3.2 - Terahertz frequency devices using semiconducting nanowires

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Keywords: Nanowire, Terahertz spectroscopy, photodetector

We have recently developed a range of high-frequency electronic devices based on nanowires. In this work we present a novel polarization resolving detector of terahertz radiation based on single InP nanowires and implement the detectors in a terahertz time domain spectroscopy system (THz-TDS). For materials characterization, THz-TDS has been proven to be a safe and powerful tool,[1] benefiting from the unique transmission properties, the non-ionizing nature of the THz radiation as well as the capability of measuring both amplitude and phase information.[2] An extended function for a THz-TDS system, e.g. ultrabroad spectral bandwidth, sub-wavelength spatial resolution and polarization-resolved sensitivity, will allow to investigate complex material systems with better accuracy. This is particularly desired in studying anisotropic materials, since the polarization information helps to remove artificial absorption features caused by the anisotropy of the material. Here, we demonstrate a type of photoconductive THz antenna with InP nanowires as the active material, which achieved broadband, low-noise and highly-sensitive THz detection in the THz-TDS system.[3,4] Additionally, they are capable of simultaneously measuring both orthogonal components of the THz electric field to realize polarizationresolved sensing,[5] paving the way for near-field THz imaging with nanoscale spatial resolution. To demonstrate the capabilities of our nanowire detectors, we successfully measured the birefringence value of an x-cut quartz and showed that all abovementioned advantages can be attributed to the nanosize volume and quasi-one-dimensional structure of single nanowires.[6]

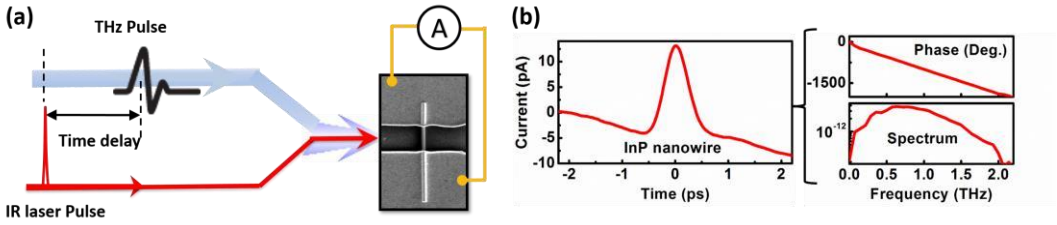

Figure 1. *(a) Schematic diagram of THz-TDS measurement with InP nanowire detectors and (b) representative signal.*

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[6] **Acknowledgements:** We thank the Engineering and Physical Sciences Research Council and Australian Research Council for financial support and Australian National Fabrication Facility for access to facilities.

F3.3 - Mid-infrared emission from GeSn/Ge core-shell nanowires with nanophotonic light extraction

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Keywords: germanium-tin, mid-infrared, electroluminescence

Mid-infrared light sources are key components for future chemical sensing, on-chip optical interconnect and LIDAR technologies. GeSn alloys can be synthesized under silicon CMOS compatible conditions. Therefore, direct band gap GeSn is a promising material for on chip integration of light emitters. Previous research on GeSn films has shown mid-infrared lasing at temperatures less than 90K[1]. It has also been shown that GeSn nanowires with high-Sn content exhibit strong direct-gap photoluminescence at room temperature[2]. Compared to GeSn thin films, GeSn nanowires are less constrained to lattice match with misfitting (e.g. Ge, Si) substrates and therefore may achieve higher Sn contents without strain and defects that promote non-radiative recombination. Additionally, unlike in a planar GeSn film where the emission angle is limited to < 13^0 by its high refractive index (n>4), GeSn nanowires provides a platform to design the optical density of states for highly efficient light extraction directly from the light emitting material.

We have designed, synthesized and characterized mid-infrared emission of GeSn/Ge coreshell nanowires with 9-12% Sn. Full wave FDTD simulations reveal that the geometry of GeSn/Ge nanowires can be tuned to be resonantly scattering at the direct band gap energy. To further enhance light extraction, we use FDTD simulations to optimize GeSn/Ge nanowires in photonic crystal arrays (Figure 1a) to maximize the density of photonic states above the light line within the emission spectrum. The light emitting device consists of vertical GeSn/Ge core-shell nanowires in-filled with PMMA, an ITO top contact and an aluminum bottom contact. Room temperature photoluminescence characterization reveals both direct- and indirect-gap emissions in the mid-infrared (Figure 1b), while electroluminescence characterization at 200 mA/cm^2 reveals direct bandgap emission at both 2000 nm and 2300 nm (Figure 1c). Optimization of nanophotonic light extraction efficiency will be discussed.

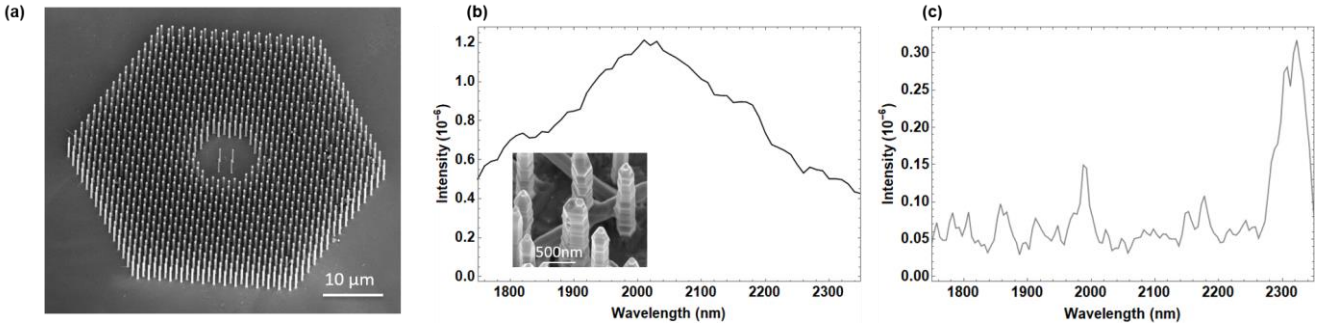

Figure 1. *(a) SEM image of GeSn nanowire photonic crystals (b) Photoluminescence spectrum of 9% GeSn/Ge core-shell nanowires; inset: SEM image (c) Electroluminescence spectrum of 9% GeSn/Ge core-shell nanowires.*

References

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P1.01 - Comparison of the FMM, FEM and FDTD methods for the modeling of absorption in nanowire arrays

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Keywords: optics modeling, absorption, nanowire array

Semiconductor nanowire arrays have received substantial interest for solar cells and photodetectors. Successful design of such devices relies typically on numerical modeling and optimization of the absorption of light. Here, we benchmark the performance, benefits, and drawbacks of three of the of the most popular optics modeling methods: the Fourier modal method (FMM),[1] the finite element method (FEM), and the finite-difference time-domain (FDTD) method.[3] We validate that each of the methods solves the problem successfully, both with regard to spectral response as well as to electric field distributions (Fig. 1). After that, we continue to test how much computational time and random-access memory — the two limiting factors in numerical modeling — the methods need.

As a summary, two very similar looking nanowire arrays can show very different behavior in the modeling – for example depending on the materials, geometry, the width of the wavelength range of interest, or even the type of output such as total absorption or spatially resolved absorption. A single method is not an optimum choice in general. Instead, for a successful design process, we propose to use a combination of all three methods. We give a guideline for how to choose the appropriate modeling method, which can speed up the calculation by up to a factor of 1000.

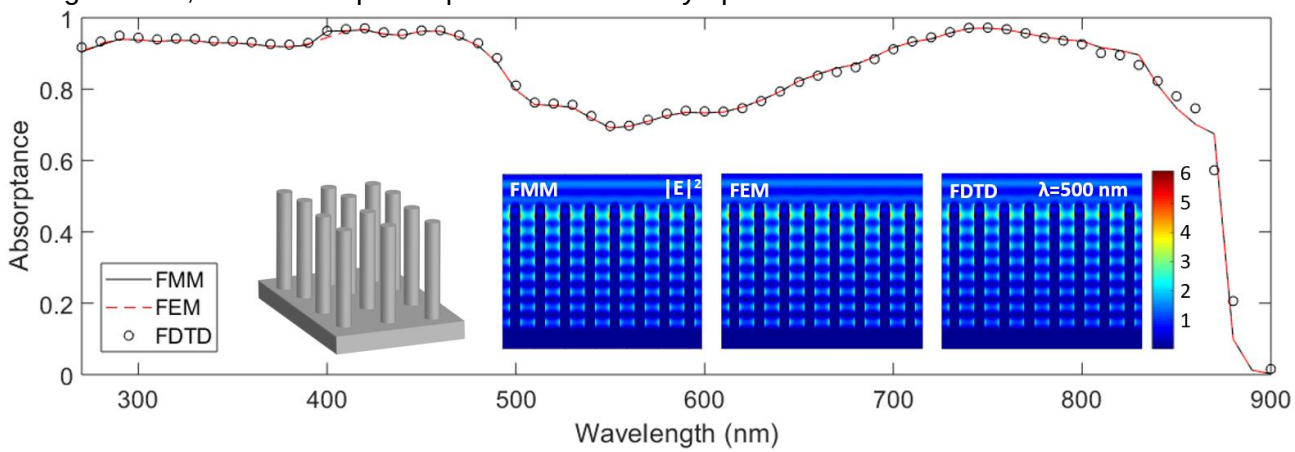

Figure 1. *(a) Absorptance of GaAs nanowires of 160 nm in diameter and 2000 nm in length, placed in a square array of 400 nm in pitch. The slight discrepancy in the FDTD results around the bandgap originates from the fitting of the refractive index to the tabulated wavelength-dependent refractive index, which is used directly in FMM and FEM. We will discuss the impact of this fitting issue in FDTD in detail. In the inset, a schematic of the array is shown together with* $|\mathbf{E}|^2$ at a wavelength of 500 nm.

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P1.02 - Growth of GaAs nanowires on graphite nanoplatelets

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Keywords: GaAs, graphite nanoplatelets

Recent years, new graphene/graphite-semiconductor hybrid structures are considered as promising materials for various optoelectronic applications[1]. In this work, the MOVPE growth of Au- and Ga-catalyzed GaAs nanowires (NWs) on top of SiO_2/Si(111) substrate covered by graphite nanoplatelets (GNPs) is investigated. GNPs are low defect graphitic surfaces with lateral sizes of few microns and thickness of tens of monolayers which can be deposited on nearly any substrate without complex processing with coverage up to centimeter range or more[2]. Despite the advantages of these substrates, the NW growth on GNPs remains almost uninvestigated. We demonstrate that either horizontal (planar) or inclined (non-planar) NWs can form depending on the relative positions of graphite nanoplatelets, as well as on the placement of catalyst nanoparticles.

We have developed the model, which is capable of the description of the experimentally observed scenarios of planar and non-planar NW growth: NWs with a gold-rich catalyst growth horizontally on flat central regions of GNPs; at the GNP edge horizontal NWs turn to inclined; horizontal NW growth with a gallium-rich catalyst is unstable and turns to inclined growth.

The model describes four modes of horizontal growth for the NWs contacting barrier on top of GNP. Figure 1 illustrates these growth modes. The analysis of the corresponding surface energies shows that the realization of each mode depends on the barrier material and catalyst composition.

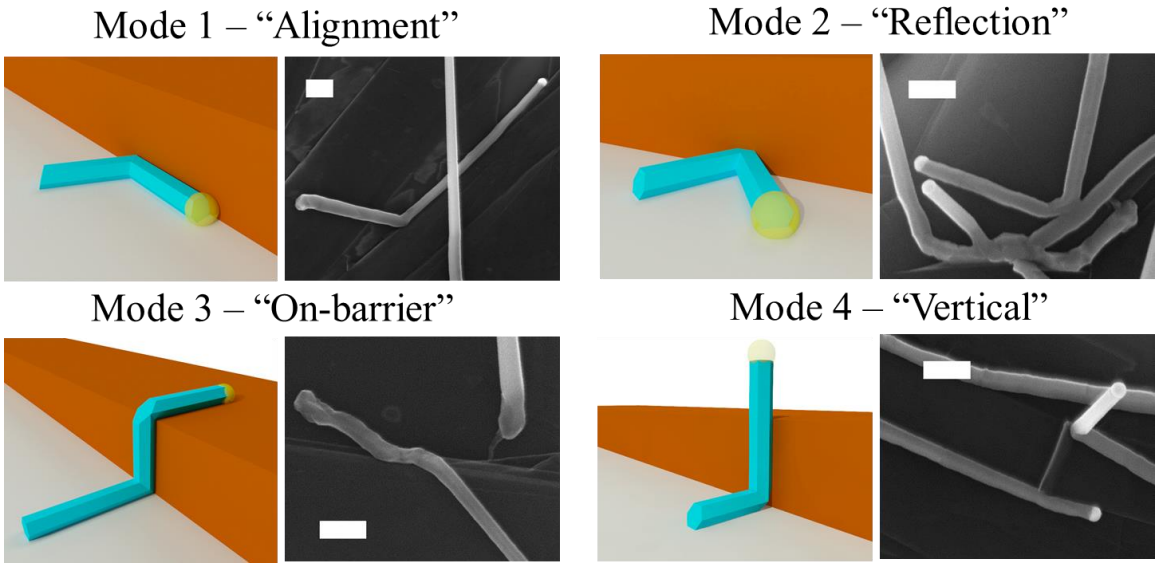

Figure 1. *Schematics of horizontal GaAs NW growth modes and corresponding SEM images. The scale bars correspond to 200 nm.*

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P1.03 - Modeling of supersaturation in chemical bath deposition of ZnO nanorods

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Keywords: ZnO nanorods, chemical reactor modelling, crystal growth

ZnO is a promising semiconductor material with potential applications in photonics and electronics. A variety of physical and chemical deposition techniques are available for the synthesis of ZnO nanorods[1]. Chemical bath deposition is easily accessible and non-expensive method, which has many adjustable parameters to produce desired nanorods in a large scale. During the synthesis of ZnO nanorods the growth units are gradually consumed from the region above the crystal surface, which results in space- and time-varying supersaturation. Detailed information about the interface supersaturation above the crystal surface is necessary for the understanding of the growth mechanisms and different growth velocities in specific crystallographic directions.

We grew hexagonal periodic arrays of ZnO nanorods on GaN substrates using FIB lithography with different inter-nanorod distances. The measured growth velocities of ZnO nanorods were used as input data to a COMSOL model, which calculates the time- and space-dependent concentration of the reactants within the reactor. We observed a change of the growth regime from diffusion limited to reaction limited when the inter-nanorod distance was varied. In the diffusion limited regime, the growth units are consumed by ZnO nanorods faster than they can be supplied by diffusion from the bulk solution. This leads to a strong competition for the growth units that are close to the nanorods and consequently to a distribution of nanorod heights within a single finite hexagonal pattern (Fig. 1). In the reaction limited regime, on the other hand, the nanorods grow independently on the others with the highest possible velocity, and their height is independent on the position within a pattern[2,3].

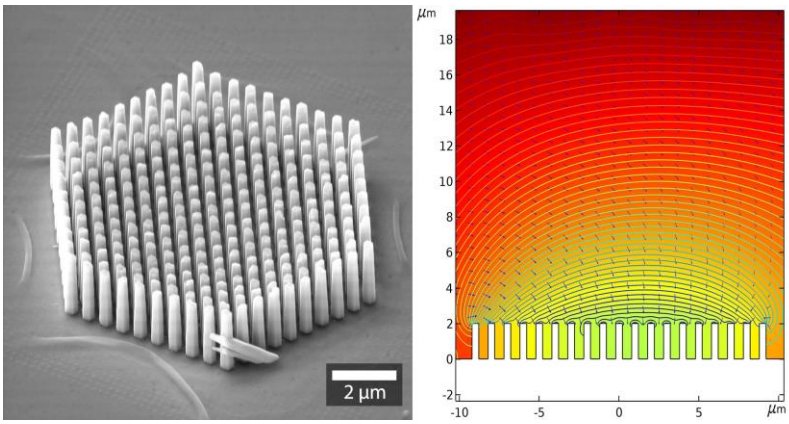

Figure 1. *A representative array of ZnO nanorods grown by chemical bath deposition on a GaN substrate using a PMMA mask patterned by FIB lithography (left). A corresponding concentration profile of Zn2+ ions calculated in COMSOL (right).*

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P1.04 - Composition and crystal structure of gold catalyzed ternary nanowires

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A high degree of crystal quality and full control over the morphology of semiconductor nanowires have enabled new classes of optoelectronic, biotechnology and energy harvesting applications. In this regard, ternary nanowires having a chemical composition, which is primarily determined by gas composition and growth temperature[1-3] offer the most potential. In such circumstances the need to precisely control the composition and extend the operating wavelength range becomes an urgent problem.

Here, we present a model for composition tuning of ternary solid material nucleating from a quaternary liquid melt and apply this theory to the nucleation-limited regime of vapor-liquid-solid Au-catalyzed and self-catalyzed growth[4]. The study covers appearance of the miscibility gap region where the formation of the homogeneous solid solution is thermodynamically forbidden. We use the equations which connect kinetics and thermodynamics to get the link between vapor and solid phases and compare the theoretical results with experimental data. Finally, we apply the developed thermodynamic model to predict the crystal structure of ternary nanowires.

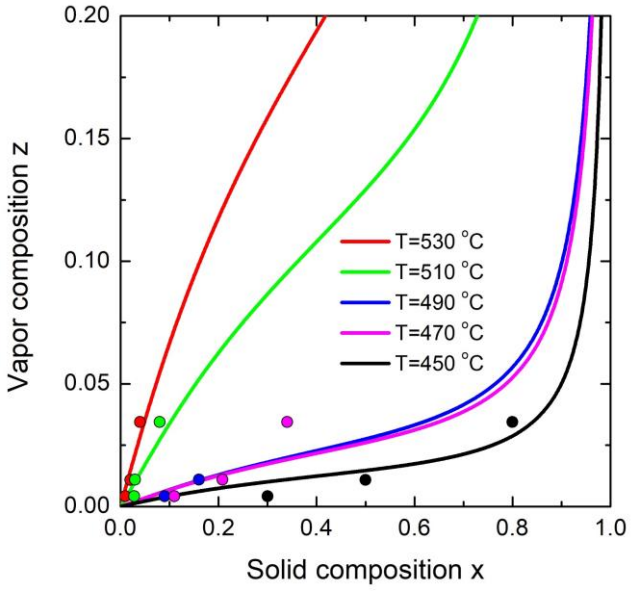

Figure 1. *Experimental[5] and theoretical liquid-solid composition dependence of $In_xGa_{1-x}Sb$ nanowires.*

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P1.05 - Doping of hexagonal Si and GaAs nanowires from first-principles

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Keywords: doping, crystal phase, hexagonal polytypes, density-functional theory

Recent advances in the growth of nanowires (NWs) have given access to crystal phases of many semiconductors that either are precluded in their bulk counterpart or require extreme temperature and pressure conditions to become stable. Of particular interest is the hexagonal phase of non-nitride III−V materials, Si and Ge, which can feature important differences in the electronic structure with the more common cubic structure, as well as in the vibrational properties. These observations lead to propose the use of these hexagonal polytypes for photovoltaic or thermoelectric applications, either as stand-alone materials or in combination with their cubic counterparts. The design of electronic devices, however, entirely relies on doping and thus all the envisaged applications will require a deep understanding of the atomic scale mechanisms that lead to the incorporation of dopants.

In this work we study the physics of common *p*- and *n*-type dopants in hexagonal Si by means of first-principles electronic structure calculations and compare our results with those for the well-known case of cubic NWs [Nano Lett. **19**, 866 (2019)]. We show that (i) as observed in recent experiments, at larger diameters *p*-type dopants prefer the hexagonal phase with respect to the cubic one as a consequence of the stronger degree of three-fold coordination of the former, while *n*-type dopants are indifferent to the polytype of the host lattice; (ii) the difference in formation energies leads, particularly in thicker nanowires, to larger concentration differences in different polytypes, which can be relevant for cubic-hexagonal interfaces that are the building blocks of crystal-phase superlattices; (iii) ultra-small diameters exhibit, regardless of the crystal phase, a pronounced surface segregation tendency for *p*type dopants. We also present and discuss some preliminary and unpublished results on GaAs.

Overall these findings shed light on the role of crystal phase in the doping mechanism at the nanoscale and could have a great potential in view of the recent experimental works on hexagonal NW polytypes.

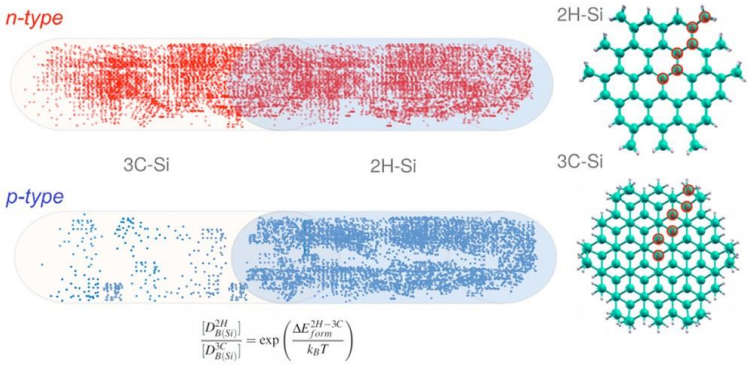

Figure 1. *Cartoon illustrating the concentration profiles of n- and p-type impurities across a cubic-hexagonal junction in Si.*

P1.06 - Template effect of the nanowire core on the growth of hexagonal Si/Ge shell: a first principles modeling

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Keywords: Hexagonal Si/Ge, core/shell nanowires, ab-initio modelling

Silicon is still by far the most widely used semiconductor in electronics, but its Achilles heel, i.e. the indirect bandgap, limits the development of silicon-based optoelectronic devices. Recent advances in the growth of nano-structures have given access to new meta-stable phase of Si, not present in nature. In fact, Si is known to be stable in its diamond cubic crystal structure, but under extreme pressure conditions, transition to the hexagonal phase can be observed. Recently, Bakkers *et al*., succeeded in the growth of hexagonal Si and Ge, by exploiting GaP/Si and GaAs/Ge core/shell nanowires (NWs)[1]. Besides, recent theoretical studies have predicted a direct band-gap nature for hexagonal Ge, which is preserved by alloying Ge with to up 30% Si. This new hexagonal crystal semiconductor, made of Silicon and Germanium, can potentially be a breakthrough for Si-based photonics and optoelectronics.

By first-principles simulations, the structural properties of GaAs/Ge interface have been studied, with the goal of understanding the mechanism responsible for the growth of the hexagonal Ge crystal. Firstly, we identify the <1100> orientation as the most stable for the NW side faces, then by modeling the core/shell interface in this direction, we show that it is not possible to create a defects-free interface between the hexagonal substrate and a cubic Ge layer. The structural evolution of the cubic Ge layer from 0 K to 1000 K, with a subsequent cooling down and equilibration at 300 K is illustrate in Fig.1, as obtained by performing *ab-initio* molecular dynamic (AIMD) simulations.

Despite the higher stability of the cubic phase, we predict that even below 300K the cubic crystal structure of the Ge layer is lost, then the Ge layer tends to re-crystallize in the hexagonal phase, possibly due to a transfer of the hexagonal crystal structure from the GaAs core, along the [1100] direction. Thus, our simulations evidence a crucial role of the NWs core as template for the growth of the hexagonal crystals. Finally, the role of hydrogen in the growth surface process is elucidated.

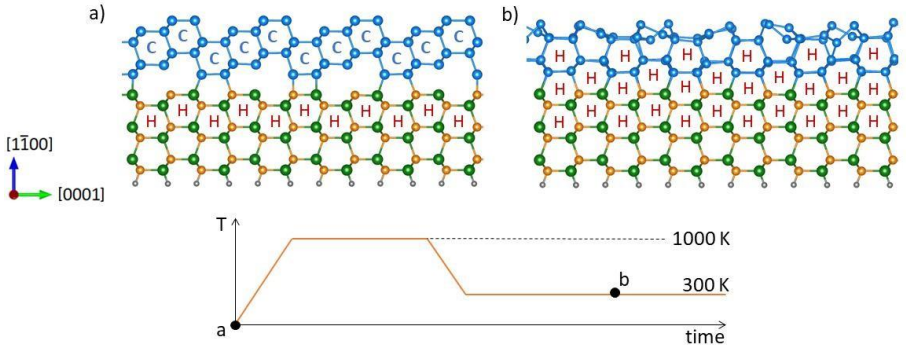

Figure 1. *AIMD simulation of the GaAs/Ge hexagonal/cubic structure: the initial (a) and final structure after temperature ramp and final equilibration at 300K (b). H and C labels indicate the hexagonal and Cubic arrangement, respectively.*

Reference

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P1.07 - Stabilization of metastable phase in GaP nanowires via elastic stress

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Crystal structure is one of the basic characteristics of a material which strongly influences its physical properties, such as symmetry, modulus of elasticity, density, band gap, Fermi level, surface energies etc. Most of III-V compounds except nitrides in the bulk phase form a face-centered cubic lattice, so called zinc blende crystal structure. In contradiction to it, metal catalyst III-V nanowires frequently demonstrates metastable hexagonal crystal structure, named wurtzite.

Usually such nanowire growth in metastable phase explains by crystallization at the triple-phase line[1]. The explanation requires, that nanowire growth proceeds in monocentric layer-by-layer growth, sidewalls surface energy is less for metastable wurtzite phase and nucleation at the triple line is more favorable than in the center. This conditions look diameter independent. The diameter dependence is recovered by considering a purely geometrical effect[2]. Nanowire growth rate in monocentric regime is product of nucleation rate and available nucleation area. It is clear that nucleation in the center is possible on the whole facet, while triple line nucleation is possible only in the perimeter of nanowire[2]. Also increasing nanowire radius leads to transition from monocentric growth regime to polycentric one[3]. So there is a certain critical value of nanowire radius above which nanowire always should grow in zinc blende crystal phase. Yet there are a lot of papers where experimentally observed thick GaP nanowires with wurtzite crystal phase[4].

Here another explanation for stabilizing the metastable phase in nanowires is demonstrated using the accumulation of elastic energy. It is well known that during the deposition of III-V materials on different substrates, large elastic stresses lead to the formation of quantum dots and, further, to a three-dimensional growth of bulk material in stable crystal phase. NW growth proceeds in a different way the islands are formed two dimensionally and the lateral growth of each layer starts only when the formation of a previous layer is fully completed[1]. Even more, most NW grows in the so-called mononuclear mode, when each layer formed only from one nucleus. In this case NW nucleus could be strongly affected by elastic stress of previous layer[5]. Despite in NW axial heterostructures elastic stresses could be effectively relaxed on the sidewalls[6]. Lattice mismatch between face-centered cubic (sphalerite) and hexagonal (wurtzite) phase could reach several percent, and for GaP elastic stress of the formation of stable phase on metastable layer reaches value of 12 meV per pair. This is greater than the difference in the energy of the formation of the cubic and hexagonal phase. So GaP nanowires could grow in wurtzite phase for any radius.

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P1.08 - Localization-dependent properties of prismatic nanowires

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Keywords: core-shell nanowires, corner and side states, localization

We show how the polygonal cross section influences the physical properties of quantum rings and shells obtained from core-shell nanowires. We study the advantages provided by such a geometry, which include the possibility to obtain a well-separated subspace of corner states. We also specify to what extent the geometry-induced properties are present in the unavoidably asymmetric realistic structures and consequently, how the shape of the cross section affects the experimental outcomes.

The prismatic shape induces a nonuniform particle distribution within the cross section. In particular, low-energy electrons are localized in the vicinity of the vertices, while the probability distributions associated with the higher states form maxima in the middle of the sides. In the case of the most common hexagonal structures this effect is relatively weak, i.e., there are only small deviations in the corner and side areas from the uniform distribution, and thus such structures resemble circular ones. The localization becomes considerable with decreasing the side thickness or the angles at the corners. Pronounce differences in the localization are present only for ultra thin hexagonal structures, but they can be obtained for a wide range of triangular structures. Here the low-energy electrons are accumulated in small corner areas, i.e., depleted from the sides. The corresponding states form a subspace of quasidegenerate corner states which are separated from the higher (side-localized) states by a gap which may exceed the room-temperature energy.[1] In this case, the Coulomb interaction leads to the formation of in-gap states which are either pairs of closeby electrons, or the excitonic states associated with symmetrically distributed particles. The former states enable contactless control of absorption[2] while the latter ones are the only optically active states in the excitonic spectrum.[3] The asymmetry present in realistic structures strongly affects the particle localization and may even prevent the formation of corner states. This happens when one of the sides is sufficiently wider than the others, inducing the ground state to be localized on that side, which becomes the only optically active region of the wire.[4] Moreover, the localization is very sensitive to the external electric and magnetic fields, providing a possibility to control geometry-induced effects, and thus the experimental outcomes.[5]

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P1.09 - Monte Carlo simulation of planar GaAs nanowire growth

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Keywords: planar nanowire, GaAs, Monte Carlo

Traditionally planar III-V nanowire (NW) growth occurs according to the vapor-liquid-solid (VLS) mechanism with Au as a catalyst [1]. The goal of present research is identification of VLS self-catalyzed growth conditions for planar III-V nanowires. A detailed study of the initial growth stages of planar GaAs NWs on GaAs substrates with (111)A, (111)B and (001) orientations was carried by Monte Carlo simulation. The number of NW growth directions is determined by the number of {111}B facets created on the droplet-crystal interface. Fig.1a shows the 3D model crystal formed under the Ga droplet on the (111)A substrate (before droplet displacement). There are three possible directions of wire growth. For unidirectional growth, it is necessary to ensure arsenic supply to only one of these three facets. This can be achieved by the gallium droplet relative arrangement on the surface, the substrate surface properties and the growth conditions (temperature, As/Ga flux ratio). Dependence of NW morphology on growth temperature is analyzed. Images of nanowires grown on (111)A surface at different temperatures are shown in Fig.1(b-d). At 800 K the Ga droplet splits to three parts initiating the growth of three planar GaAs nanowire because arsenic desorption at this temperature is rather low and it is enough arsenic to form three facets (Fig.1b). The optimal temperature for the stable NW growth at chosen flux ratio (As/Ga = 5) is T = 890 K (Fig.1c). In this case, enough arsenic is present on the surface to form one {111}B facet at the droplet-crystal interface connected to the substrate, and not too high to consume a droplet. At 950 K arsenic desorption from the substrate is high, so already at the initial stage the nanowire grows at the angle 70° to the (111)A surface (Fig.1d). This occurs because arsenic flows into the droplet mainly from the external flux, which leads to the formation of a {111}B facet not connected to the substrate. The non-planar wire growth stops due to the Ga droplet consumption. Later, at the non-planar wire base, a new Ga droplet is formed, which initiates the planar growth.

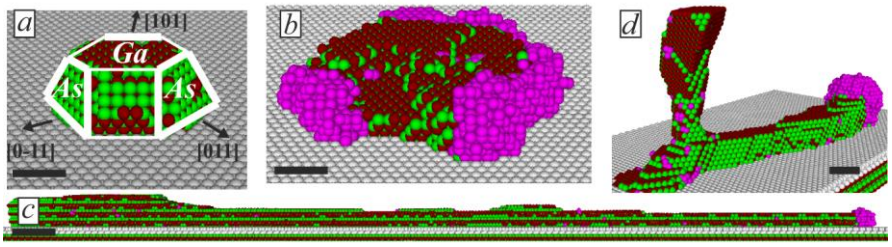

Figure 1. *Images of a) the 3D model GaAs nanocrystal formed under the Ga droplet after 0.05 s of growth at 800 K (the liquid droplet is made transparent to improve image visualization); the planar nanowires grown on the GaAs(111)A substrates: b) T = 800 K, t = 0.08 s, c) T = 950 K, t = 0.2 s, d) T = 890 K, t = 0.6 s. F(Ga) = 3 ML/s, F(As_2) = 15 ML/s. Scale bar 5 nm. The model substrate size is 120×20 nm.*

References

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P1.10 - Strain Relaxation Mechanisms in InAs/InP/GaSb Core-Multishell Nanowires

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InAs/GaSb core-shell nanowires (NWs) have attracted great attention because of very low lattice mismatch (0.6%), broken-gap band alignment (type-II) and small effective masses of electrons and holes in InAs and GaSb regions, respectively. Electronic devices fabricated with these heterostructures combine closely-spaced n-type and p-type conductors, and can display negative differential resistance due to transport across the broken gap junction.[1] Further interesting electronic configurations can be achieved if carriers in the InAs core and GaSb shell are decoupled.[2] To this end, in the present work we have inserted a thin InP barrier of different thicknesses in between InAs core and GaSb shell. Since InP is lattice mismatched with InAs and GaSb, understanding the strain relaxation in this system is crucial in view of its applications in NW-based electronic devices. Catalyst-free InAs/InP/GaSb core-multishell NWs are grown by chemical beam epitaxy on Si (111) substrates. Detailed morphological, structural and compositional studies of the NWs as a function of growth parameters are carried out by scanning and transmission electron microscopy and energy-dispersive x-ray spectroscopy.

Furthermore, by combining the application STEM-Moiré technique with geometric phase analysis (GPA), we have derived the residual strain in this system. The results reveal that in InAs/InP/GaSb core-multishell NWs with 1 nm thick InP barrier few defects were established at all {112} side facets, and no defects are found in {110} side facets. When the InP layer thickness is increased to 8 nm, defects were distributed along {110} side facets while the {112} side facets are defect-free. Finally using core-multishell nanowires with InP thickness exceeding 9 nm, our fabricated nanowire-based electronic devices in shell-shell configuration indicates NDR suppression. Current−voltage characteristics does not display NDR feature neither as a function of back gate nor temperature (from 4.2 K to RT).

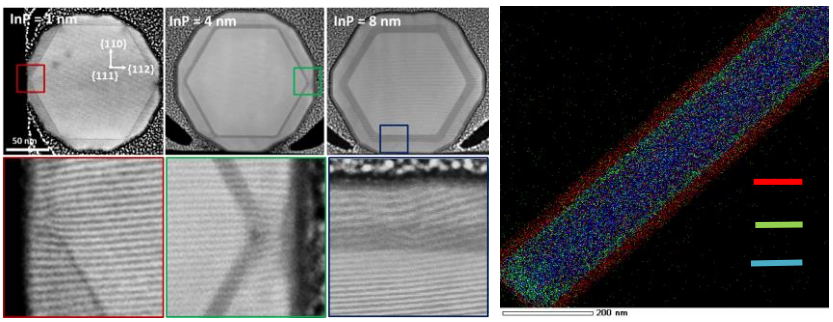

Figure 1. *Top row: STEM cross-sectional micrographs of samples with different InP barrier thickness (indicated in the figure). Bottom row: STEM-Moiré patterns of details of the top-row images marked with the colored boxes. Right panel: EDX map of InAs/InP/GaSb C-MS NWs.*

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P1.11 - Impact of flux shadowing on self-catalyzed GaAs/(In,Ga)As core/shell nanowires grown in patterned arrays

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Keywords: in-situ X-ray diffraction, Polytypism, Strain

In this work we investigate the influence of pitches in well-ordered arrays of nucleation centers on the crystal structure and the strain of growing core-shell nanowires (NWs). The NWs grow in arrays on silicon (111) substrates, which have been patterned by e-beam lithography with pitches ranging between 0.1 and 10.0 micron resulting in a different number density of NWs. For this investigation, we used a portable molecular beam epitaxy chamber (PMBE)[1] and performed in-situ time-resolved micro X-ray diffraction (XRD) during the growth of GaAs core NWs and the overgrowth of a (In,Ga)As shell.

We demonstrate that shadowing of the Ga flux by neighboring NWs influences the mean phase composition of the grown GaAs NWs exhibiting a varying ratio between zinc-blende (ZB) and wurtzite (WZ) polytypes. Whereas for the small pitches, i.e. dense NW arrays, the WZ phase is prominent, the cubic ZB phase dominates at lower NWs densities.[2]

During growth of the (In,Ga)As shell, we monitored the evolution of a non-uniform strain resulting in NW bending which is explained by asymmetric shell growth [2] appearing with different amount on arrays of different NWs densities. For NWs with small pitch the shell material was deposited mainly at the upper parts of the NWs. This results in an inhomogeneous strain distribution along the NWs growth axis and a higher bending at its upper parts. For arrays with lower number density, the strain is rather uniformly distributed along the NW length axis which results in a rather homogenous curvature of the bent NWs.

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P1.12 - Stemless InSb nanowires and nanostructures for quantum devices

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Keywords: InSb nanowires, growth kinetics, quantum devices

Indium-antimonide (InSb) nanowires (NWs) have been playing a key role in the quest for realizing topological quantum computing based on Majorana fermions[1]. The properties of InSb NWs, such as their strong spin-orbit coupling and high mobility, render them suitable for hosting topological phases when combined with a superconductor. Nonetheless, synthesis of these wires has proven to be rather challenging, since their nucleation requires a foreign-material stem at the expense of two drawbacks. In particular, the stem introduces material impurities in the InSb NW segment, and confines its length to a maximum of about 4 μm[2].

Here, we report the growth of defect-free zinc blende InSb NWs tens of microns long[3]. The use of a selective-area mask circumvents the need for a foreign stem, thereby enabling direct nucleation of InSb NWs on the substrate. Moreover, introduction of this mask gives rise to high growth rates as well as enhanced growth selectivity for Sb-rich conditions. Furthermore, we show that the omission of the foreign stem results in chemically pure InSb NWs as confirmed by atom probe tomography and as reflected in the significantly higher electron mobility in comparison to InSb NWs on stems.

To profit from the pristine quality of these stemless wires, we propose a shadow deposition technique that enables predefined contacts *in-situ*. We rely on two-dimensional InSb nanostructures, grown close to the NWs, as shadowing objects. Specifically, by fine-tuning chip design parameters, we can within statistical probability predetermine whether a stemless NW or nanostructure are locally formed.

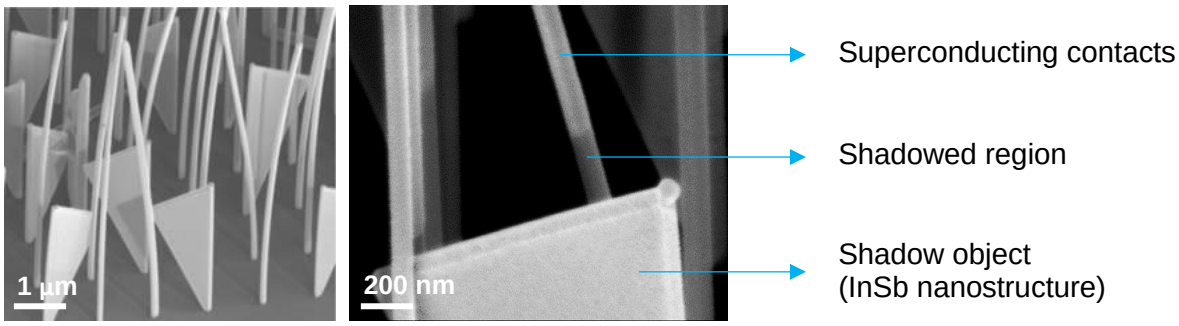

Figure 1. *(left) 30-degree tilt SEM of a field with InSb NWs and nanostructures. (right) A nanostructure shadowing a NW during Al deposition.*

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P1.13 - Towards high mobility InAs/InGaAs/GaAs(Sb) scalable nanowire networks.

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Keywords: selective-area growth, molecular beam epitaxy, III-V nanowires

One-dimensional channels made of semiconductor-superconductor materials with high effective spin-orbit coupling are promising systems to realize Majorana bound states (MBS). Qubits which employ these states are predicted to be topologically protected from decoherence and are therefore attractive as building blocks for quantum computing [1].

Forming nanowire networks by selective area growth (SAG) is a promising way for the realization of scalable MBS qubits. Thanks to ultra-high vacuum conditions, molecular beam epitaxy (MBE) of SAG nanowires allows high quality in-situ semiconductor-superconductor growth with high purity nanowire channels. Despite these advantages and a vast number of recently published results [2-5], the growth of SAG nanowires is not straightforward, and it still requires a deep understanding before being fully implemented for topological quantum computing.

In this work, we present MBE growth of SAG InAs nanowires on GaAs(100) substrates covered with a thin layer of SiO_x. In order to minimize the high lattice mismatch between InAs nanowires and the GaAs substrate, we use two buffer layers: (1) Sb-dilute GaAs and (2) $In_xGa_{1-x}As$. By using scanning electron microscope (SEM), atomic force microscope (AFM) and X-ray diffraction (XRD) analysis we study how the $In_xGa_{1-x}As$ growth temperature affects the selectivity of the growth and the final In composition in the structure. Finally, we perform preliminary transport measurements on the grown samples and discuss how the temperature affects the electron mobility in InAs nanowires.

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P1.14 - Towards in-situ size control of aerotaxy nanowire growth

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Keywords: light scattering, nanowires, aerotaxy

Nanowires are promising candidates for next-generation optoelectronic devices due to their strong light trapping with lower material consumption. A substrate-free way of nanowire growth has been achieved by the aerotaxy technique which leads to a potential way for commercial solar cells due to its low cost and high growth rate.[1,2] To control the size of the aerotaxy nanowires, we propose here a possible in-situ method to monitor the size of nanowires through a non-destructive optical process. In this method, a beam of light is illuminated in-situ, and the transmitted spectrum is collected. Our theoretical analysis shows that the nanowire diameter and length can be estimated by the peak position and peak-to-shoulder difference in the extinction spectrum. Those theoretical calculations agree with the extinction measurements as long as possible additional optical losses are carefully considered.

The theoretical calculations are performed with three methods: discrete dipole approximation[3], finite element method and Mie theory. With a perpendicular incidence to the nanowire axis, we find that the absorption cross section of a single nanowire shows TE/TM mode resonances when varying the diameter. Furthermore, a Fabry—Perot resonance is present in the extinction cross section as a function of nanowire length.

In the experiments, nanowires are accumulating on the quartz window of the measurement setup, which leads to increasing uncertainty when comparing with simulations. This uncertainty can be eliminated by considering both a sparse and a dense collection of nanowires on the quartz window in the optical simulations. Possible tapering of nanowires can lead to an increasing extinction in the long wavelength region of 700 to 800 nm. At last, we end up with a database of extinction spectra for a GaAs nanowire of varying diameter and length, which can be used to estimate the nanowire dimensions in-situ.

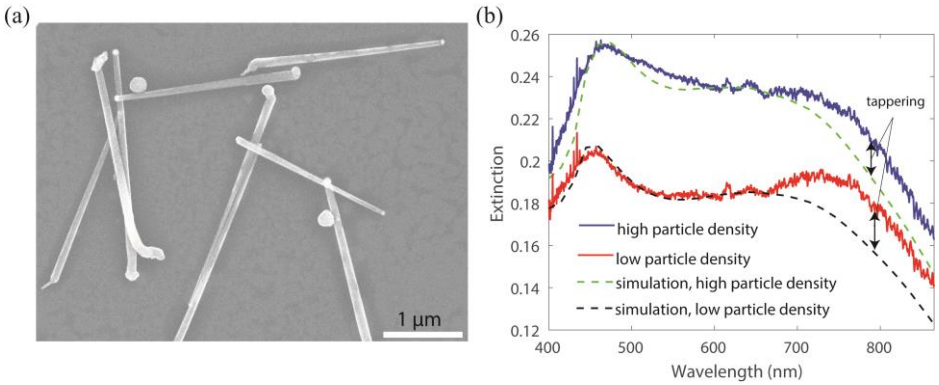

Figure 1. *(a) SEM image of aerotaxy nanowires. (b) Measured and modeled extinction spectra of nanowires shown in (a).*

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P1.15 - Impact of the Ga flux incidence angle on the growth kinetics of self-assisted GaAs nanowires on Si(111)

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Molecular Beam Epitaxy (MBE) allows obtaining nanowires (NWs) of III-V semiconductors via vapour-liquidsolid (VLS) mechanism: although the role of the incidence angle of group-III element flux has been theorized by many models [1-4], to the best of our knowledge it has not been experimentally verified yet. Herein we propose an experimental study on the role of the incidence angle (α) of the Ga flux, with respect to the Si(111) substrate normal, on the self-assisted growth kinetics of GaAs NWs, carried out by using two different Ga cells located at α = 9.3° and α = 27.9°. By using equivalent Ga^{α} fluxes corresponding to a GaAs planar growth rate of 0.5 ML/sec, and growth times in the 20 sec -80 min range, we observe significant differences both in the axial and radial growth rates of NWs.

Assuming (i) diffusion of Ga adatoms on both the SiO_2-terminated Si-substrate and the NW facets, (ii) direct impingement of Ga and As atoms across the Ga droplet surface and (iii) Ga droplets with a wetting angle $\beta(t) \in (\beta_{min},\beta_{max})$, we developed a semi-empirical model to describe the droplet evolution with growth time and the NW growth kinetics. By adopting material parameters in good agreement with existing data it is possible to simulate the kinetics of the NW growth and to reproduce accurately the axial growth rate for both Ga sources. Finally, the impact of the incidence angle of the Ga flux on the NW growth kinetics was experimentally demonstrated, as well as the influence of the surface of capture of As (i.e. of the Ga droplet volume) on the NW axial growth rate.

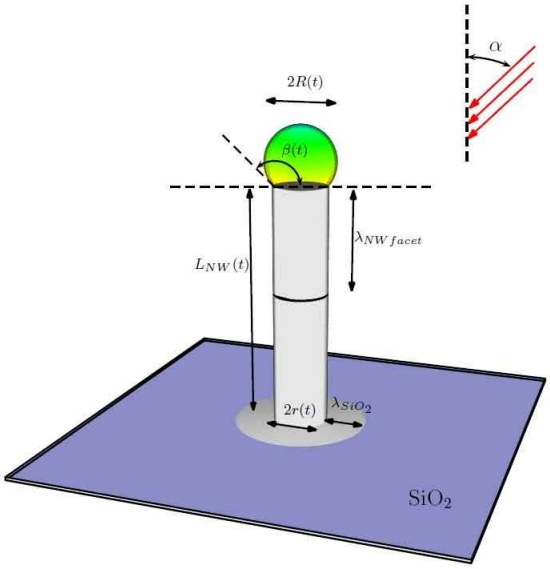

Figure 1. *Schematic for the NW geometry, the Ga flux incident angle α and the diffusion lengths.*

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P1.16 - Selective-area growth of III-V nanowire networks on GaAs substrates

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Keywords: MBE, InAs, Selective-Area

In this work, we present the growth of III-V semiconductor nanowires (NWs) by selective-area molecular beam epitaxy (MBE). In particular, we elucidate the effect of the substrate orientation, namely (111)B and (100) GaAs, on the nanowire and network morphology. The growth is performed by first growing defect-free GaAs nanoscale membranes (nanofins) that act as templates.[1] We then follow this by the growth of InAs, which creates InAs nanowires on top of these templates. Despite the large lattice mismatch, in-plane InAs and InGaAs NW networks have been grown on these substrates with NW lengths of up to a millimeter.

On GaAs (111)B, defect-free growth is possible along <11-2> crystalline directions, yielding the creation of Y-branched structures. The lack of readily available low-index facets along <11-2> leads to the formation of fast-growing {113} facets at the vertex of the GaAs templates.[2] These high-energy facets facilitate intermixing with InAs, yielding to the formation of InGaAs nanowires on top.[3]

Growth of NWs on GaAs (100) seems to be much more flexible largely due to the availability of low-energy (110) facets. The result is a significantly sharper interface between the GaAs templates and NWs, which now grow as pure InAs, as shown in Figure 1. The growth of these NWs has been observed to occur favorably along three crystal directions, also yielding the possibility to pattern NWs into higher-order branched networks. We illustrate the quality of these wires by measuring their electrical properties, including their conductivity and mobility. Their chemical purity has then also been probed by scanning transmission electron microscopy studies as well as Raman spectroscopy.

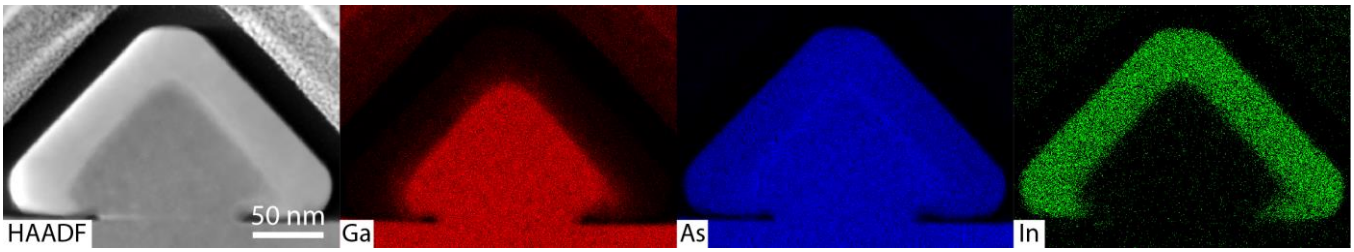

***Figure 1**: Scanning TEM energy-dispersive spectroscopy elemental mapping of InAs NW cross-section.*

The results of this work highlight the promising aspects of in-plane selective-area-grown III-V semiconductor NWs. This scalable growth approach to growing high-quality NWs and NW networks without limits on NW length offer tantalizing new opportunities III-V NW device integration.

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P1.17 Dimension Engineering of High-Quality InAs Nanostructures on a Wafer Scale

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Keywords: Dimensional control; InAs; molecular-beam epitaxy

Low-dimensional narrow-band-gap III-V semiconductors are key building blocks for the next generation of high-performance nanoelectronics, nanophotonics, and quantum devices.[1-3] Realizing these various applications requires an efficient methodology that enables the material dimensional control during the synthesis process and the mass production of these materials with perfect crystallinity, reproducibility, low cost, and outstanding electronic and optoelectronic properties. To date, much excellent work has been done to obtain one- and two-dimensional narrow-band-gap III-V semiconductors with different methods.[4-8] However, the progress toward methods that can satisfy above requirements (especially dimension modulation) remains limited. Here, we demonstrate an approach that provides a precise control of the dimension of InAs from one-dimensional nanowires to wafer scale free-standing two-dimensional nanosheets, which have a high degree of crystallinity and outstanding electrical and optical properties, using molecular-beam epitaxy by controlling catalyst alloy segregation. In our approach, two-dimensional InAs nanosheets can be obtained directly from one-dimensional InAs nanowires by silver-indium alloy segregation. Detailed transmission electron microscopy investigations provide solid evidence that the catalyst alloy segregation is the origination of the InAs dimensional transformation from one-dimensional nanowires to two-dimensional nanosheets and even to three-dimensional complex crosses. Using this method, we find that the wafer-scale free-standing InAs nanosheets can be grown on various substrates including Si, MgO, sapphire, GaAs, *etc*. The InAs nanosheets grown at high temperature are pure phase single crystals and have a high electron mobility and a long time-resolved terahertz kinetics lifetime. Our work will open up a conceptually new and general technology route toward the effective controlling of the dimension of the low-dimensional III-V semiconductors. It may also enable the low-cost fabrication of free-standing nanosheet-based devices on an industrial scale.[9]

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P1.18 - The influence of AlN buffer layer on the growth of self-assembled GaN nanocolumns on graphene

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Graphene has recently been utilized as a growth substrate for the III-N semiconductor nanocolumn (nanowire or nanorod) materials, particularly GaN,[1] because of its unique properties such as transparency and high in-plane electrical conductivity. This hybrid system is envisioned to improve the performance and functionalities of optoelectronic devices, such as light-emitting diodes[2] and laser diodes, especially in the ultraviolet range. Nevertheless, the absence of dangling bonds in graphene often results in nanocolumns either grown in non-vertical directions or/and with low density. Previous works of Liudi Mulyo *et al.*[1] and Hayashi *et al.*[3] have successfully demonstrated high-density, verticallyaligned GaN nanocolumn growth on single-layer and multi-layer graphene, respectively, by employing a thin AlN buffer layer. That being said, the influence of the AlN buffer layer on GaN nanocolumn growth and its impact on graphene properties are still not well understood.

In this study, GaN nanocolumns were grown on commercially available chemical vapor deposition graphene (transferred to silica glass substrates) via AlN buffer layer by radio-frequency plasma-assisted molecular beam epitaxy. By varying the number of AlN migration enhanced epitaxy (MEE) cycles, and thus the morphology of AlN buffer layer, an insight towards the correlation between the structural and optical properties of the GaN nanocolumns grown on graphene can be obtained. It can be suggested that the GaN nanocolumn morphology and orientation are restrained by the formation of AlN on graphene. Due to the high surface tension of graphene, instead of AlN thin-film we observe two distinguished AlN formations: (i) AlN islands and (ii) AlN nanostructures grown along the grain boundaries and/or wrinkles of graphene. Using the same GaN growth conditions to that of the nanocolumns obtained on silica glass,[4] structure (i) leads to the formation of vertical GaN nanocolumns regardless of the AlN MEE cycles, whereas (ii) may result in random orientation of the nanocolumns depending on the AlN morphology. Additionally, there is limited growth of direct GaN nucleation on graphene. Although a higher number of AlN MEE cycles produce wider (more film-like) AlN coverage on graphene, the resulting GaN nanocolumns as well as the graphene properties turn out to be not ideal for further device processing. Surprisingly, we find that the graphene with the lower number of AlN MEE cycles (thus less AlN coverage) has the lowest level of nitrogen plasma damage. The GaN nanocolumn samples are characterized by means of high resolution X-ray diffraction, room temperature microphotoluminescence and micro-Raman measurements.

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P1.19 - Fabrication of p-Si/i-Ge core-shell and p-Si/i-Ge/p-Si core-double shell nanowires by bottom-up and top-down methods

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Keywords: Si/Ge, catalyst-free, core-shell

Core-shell nanowires (NWs) using silicon (Si) and germanium (Ge) have been expected as high mobility channels in next generation field effect transistors. Here, we report the synthesis of p-Si/i-Ge core-shell NWs and p-Si/i-Ge/p-Si core-double shell NWs by bottom-up (VLS) and top-down (NIL) methods. In Figure 1, SiNWs were formed by chemical-vapor-deposition (CVD) growth with vapor-liquid-solid (VLS) mechanism using Au catalysts and nanoimprinted lithography (NIL) process, respectively. p-Si/i-Ge core-shell and p-Si/i-Ge/p-Si core-double shell NWs were formed by using these two methods. Boron (B) doping was performed to realize p-type Si. The comparison between VLS and NIL approaches for both NWs was performed by investigating the morphology, crystallinity, doping properties in core-shell and core-double shell NWs. The NIL process was able to control the size and alignment of NWs, while the VLS process gave random structures. NIL process also has an advantage of suppressing metal contamination, which will give an advantage for a promising FET channel in NW transistors. Both NWs formed by VLS and NIL exhibited sharp interface between Si and Ge. The i-Ge showed a single crystal structure when the thickness was less than 15 nm. Raman spectroscopy measurements were also performed. The downshift and asymmetric broadening of i-Ge optical phonon peaks were detected for core-shell and core-double shell NWs, which are due to the Fano effect, indicating the hole gas accumulation in the i-Ge layer, as shown in Figure 2. This result indicates the formation of high electron mobility transistor (HEMT) structures in one-dimensional NWs.

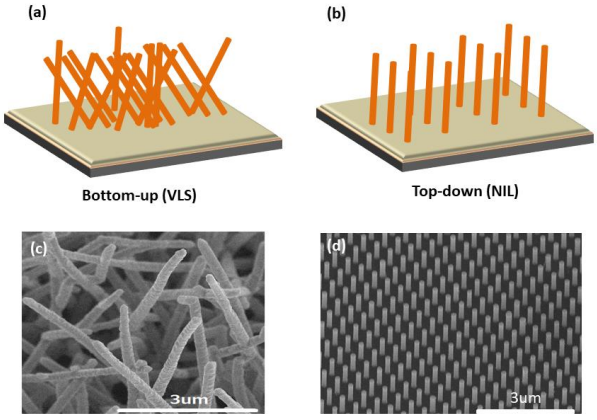

Figure 1. *The schematics of NWs (a) bottom-up method and (b) NIL method; The SEM of NWs (c) bottom-up method and (d) NIL method.*

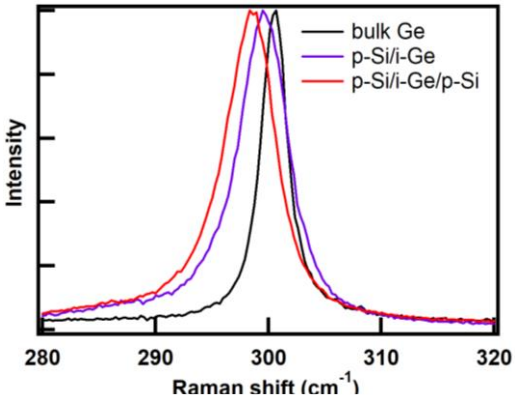

Figure 2. *The Ge optical phonons peaks observed for bulk Ge, p-Si/i-Ge core-shell NWs and p-Si/i-Ge/p-Si core-double shell NWs.*

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P1.20 - Analysis of incubation time preceding the Ga-assisted nucleation and growth of GaAs nanowires on Si(111)

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Keywords: Molecular beam epitaxy (MBE), reflection high-energy electron diffraction (RHEED), modelling

A particularly crucial aspect of understanding and controlling the formation of nanowires is nucleation because this stage typically determines their position and diameter. For Ga-assisted GaAs nanowires, nucleation is a fairly complex process that involves the formation of Ga droplets, the infusion and saturation of these droplets by incident As, the nucleation of an initial GaAs seed crystal under the droplet, and the evolution of the seed into a nanowire with the droplet seated on the top facet. Furthermore, other phenomena like the interaction between Ga and the substrate (typically Si covered by oxide) may be relevant. Naturally, any of these steps may be affected by the growth conditions, but the elucidation of the detailed interdependencies presents a formidable challenge. A parameter that can be probed *in situ* fairly easily is the incubation time that precedes nucleation. The central experimental idea of this study is to measure this parameter for Ga-assisted GaAs nanowires grown by molecular beam epitaxy on Si(111) substrates by reflection-high energy electron diffraction as a function of substrate temperature and As flux.

For a given temperature and Ga flux, the incubation time always increases with decreasing As flux and becomes infinite at a certain minimum flux, which is larger for higher temperature. For a given As and Ga flux, the incubation time always increases with increasing temperature and becomes infinite above 640 °C under typical conditions. The temperature dependence of the incubation time is extremely steep. It can be approximated by the Arrhenius-type function for temperatures lower than 620 °C, while for higher temperatures it increases much more rapidly. This peculiar behavior is reflected in the temperature dependence of the total density of all objects nucleated from Ga droplets after the end of growth.

We deduce that the incubation time for GaAs nanowires equals the sum of two constituent times, where the first is required to nucleate Ga droplets and the second to start the nanowires themselves by the precipitation of GaAs. From nucleation theory, we develop a model that takes both of these phenomena into account and quantitatively describes the incubation times versus the As flux and temperature over the entire range of the obtained data.

We believe that these results can be translated to other self-assisted III-V nanowires and possibly even a broader range of surface nanostructures. In particular, the existence of a maximum temperature and minimum flux for obtaining regular ensembles of surface nanostructures must be a general phenomenon, and imposes important limitations on the choice of relevant growth conditions for a given material-substrate combination.

P1.21 - Vapor-Liquid-Solid growth: Wetting angle and nanowire geometry and their relation to nanowire growth morphologies

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Keywords: Vapor-Liquid-Solid growth, Wetting Phenomena

The Vapor-Liquid-Solid growth of nanowires (NWs) is one of the most established methods. During growth, the physical processes occurring at the liquid-solid interface, in particular at the triple phase line (TPL), determine morphology and growth stability. The contact angle at the TPL is often used to characterize experimental results and relate them to nanowires' crystalline structure, growth orientation and growth yield.

In this work, we present simulations on the droplet stability at the NW tips for a variety of geometrical constraints and NW geometries. We compute the energies, shapes and stability of droplets at the tip of a nanowire with the Surface Evolver software [1][2][3]. In addition, we analyze the surface energy and the apparent wetting angle of droplets in two configurations. First, we investigate droplets constrained within cavities, to simulate initial stages of growth through an oxide mask. Then we analyze droplets wetting the tip of NWs with morphing cross sections. Fig.1a shows the energy of a droplet on top of a NW with a twinning superlattice in which the cross-section transitions from a hexagonal to a triangular shape, whilst Fig. 1b shows how apparent wetting angle changes with the position along the TPL's perimeter on a rectangular cross-section NW. We will explain how the variation in equilibrium contact angle and stability of the droplet affect NW growth and how this can be used to engineer growth directions and morphology.

These findings help clarify relationships between equilibrium and apparent contact angles, droplet volume, the NW shape and cross-sectional size, and the consequences of these physical and geometrical parameters on NW growth morphology.

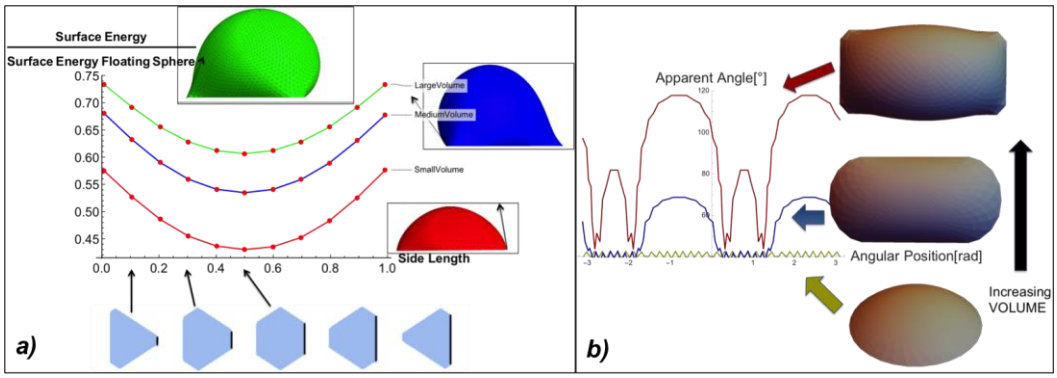

***Figure 1**. a) Computation of droplets surface energy as a function of the geometry of the constraining wetting plane**, b)** Computation of the wetting angle along the TPL for droplets wetting a rectangular plane*

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P1.22 - Gold free InAs nanowires grown by HVPE

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Keywords: nanowire synthesis, InAs, HVPE

InAs nanowires are of great interest for nanoscale electronics due to their high electron mobility and small electron effective mass. The growth of InAs nanowires has been widely documented by MBE and MOVPE but to our knowledge, only one group has succeeded to produce defect-free gold-catalysed InAs nanowires on GaAs substrate[1].

The capability of the hydride vapour phase epitaxy (HVPE) to produce ultra-long defect free GaAs nanowires has already been demonstrated[2]. In HVPE, high growth rate is due to the large material input ($\sim 10^{-3}$ atm for $GaCl$ and As_4) and high dechlorination rate of GaCl.

In this work, we show the first results of InAs nanowires grown by HVPE on Si (111) and GaAs (100) substrates at temperature ranging from 640°C to 680°C. Under these experimental conditions, thermodynamics states that vapor-solid (VS) growth using InCl and As_4 precursors is not favoured. Under indium rich condition, namely $6x10^{-3}$ atm for InCl gaseous precursors, indium liquid droplets nucleate and vapor-liquid-solid growth takes place as a function of As_4 input pressure ($7x10^{-4}$ atm for Fig 1), determining the In/As stoechiometry in the droplet. With respect to other growth methods, a high axial growth rate is obtained, up to 55 µm/h on Si and 70 µm/h on GaAs. Those results are consistent with the large material input and high dechlorination frequencies of precursors used in HVPE.

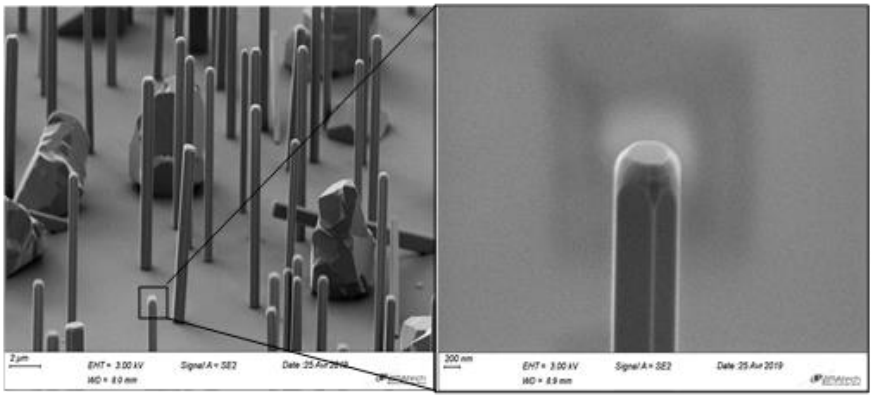

Figure 1. *SEM images of InAs nanowires grown on Si(111) at 640°C*

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P1.23 - Selective area semiconductor-superconductor networks

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Keywords: topological quantum computing, in-plane SAG

Proximitized hybrid semiconductor-superconductor nanowires are a promising candidate for future applications in quantum information processing.[1] A major contribution to their importance is the theoretically predicted existence of non-abelian states in the form of Majorana bound states. These states are topologically protected against local perturbations, which provides a basis for naturally fault tolerant quantum computing. This project entails the development of in-plane selective area grown semiconductor nanowires with an epitaxially grown superconductor. Transport measurements on the resulting wires showed a hard gap induced by the proximity effect as well as the characteristic transition from Cooper pair to a single-electron tunneling process. These properties show the potential of the hybrid system as a basis for topological networks.

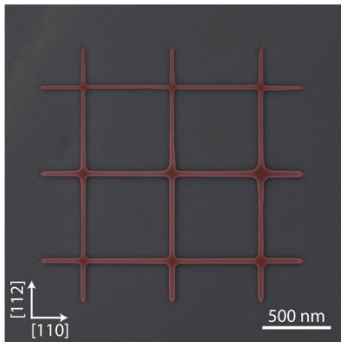

Figure 1. *InSb nanowire network grown on an InP substrate.*

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P1.24 - Composition control of self-induced and selective growth (In,Ga)N nanowires by HVPE

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Keywords: Nanowire Synthesis, Nitrides, HVPE, Thermodynamics, Selective Growth.

Ternary (In,Ga)N alloys with high InN contents are paramount for optoelectronic applications, particularly RGB LEDs and solid state lighting. Unfortunately, increasing the indium composition in solid InGaN remains a challenging task in planar epitaxy due to the miscibility gap at typical growth temperatures, lattice mismatch issues and indium segregation. Nanowires exhibit great properties such as efficient strain relieving capability and large specific area. That is why (In,Ga)N nanowires grown by different techniques have recently gained much attention. However, even in nanowires one should compromise between the increased indium composition, spatial homogeneity of (In,Ga)N and crystal purity. Today, the most reliable option to control the growth of well-ordered nanowires with a high degree of reproducibility is to proceed by Selective Area Growth (SAG). In this context, Hydride Vapor Phase Epitaxy (HVPE) is a growth process implemented in a hot wall reactor using chloride precursors, which makes use of near equilibrium partial pressures, shows unique features regarding the selective growth of nitride nanowires. This presentation will focus on a comprehensive study of HVPE grown (In, Ga)N nanowires, combining the growth technology, complementary chemical and structural analyses and theoretical modeling. The end result shows that InN content can be varied from 0 to 100% with a high degree of indium homogeneity along the nanowire length with a good crystal quality by this cost-effective technique using $InCl_3$ and GaCl as group III precursors. This is achieved by understanding the kinetics of interconnected chemical reactions in the vapor phase, and coupling them with the kinetically controlled composition of solid nanowires. The selective growth of well-ordered and vertically aligned (In,Ga)N nanorods with high aspect ratio is perfectly achieved. To the best of our knowledge, this is the first demonstration of the growth of regular SAG InN nanorods arrays which might have a high potential in applications benefiting from a large surface-to-volume ratio. These findings provide a convenient method to grow homogenous (In,Ga)N nanowires and could stretch further the performances of optoelectronic devices.

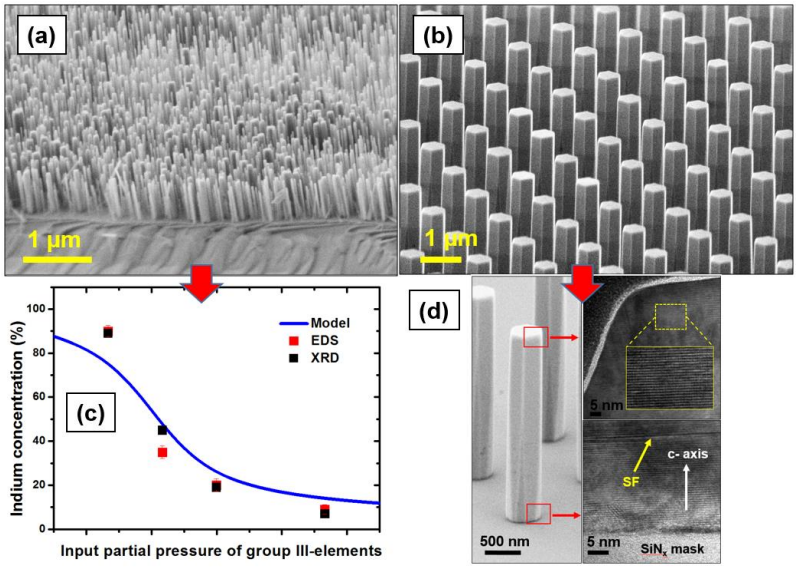

Figure1. *Homogenous growth of (a) self-induced InGaN nanowires and (b) selective growth of InN nanorods. (c) The input group-III elements partial pressure dependence on indium concentration in InGaN nanowires obtained from EDS and XRD measurements, fitted by theoretical model based on thermodynamic calculations. The full range of indium concentration in InGaN nanowires is obtained. (d) HR-TEM images taken from the top part of nanorod, showing a defect-free structural arrangement; from the bottom part of nanorod, where a few stacking faults can be observed as highlighted by the arrow.*

P1.25 - Collector droplet behavior during formation of nanowire interconnects

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Keywords: nanowire interconnects, catalytic droplet

Formation of nanowire networks is an appealing strategy for demonstration of novel phenomena at nanoscale, e.g. detection of Majorana fermions,[1,2] as well as an inherent step towards realization of complex nanowire-based architectures.[3] However, despite only a few attempts to do so,[4] a detailed description of mechanisms taking place during growth of such complex structures is lacking.

In this contribution, we will show the results of our real-time in-situ experiments of gold-catalyzed germanium nanowire growth inside a scanning electron microscope. When the two nanowires collide head-on during the growth, we observe in general two subsequent scenarios: (i) the two catalytic droplets merge into one and the growth continues as a single nanowire, or (ii) the droplets merge and subsequently split again, giving rise to the growth of two daughter nanowires (see Figure 1). The two cases occur under different experimental growth conditions, which is further verified and explained by the phase field simulations of the growth. Both the experiments and modeling indicate critical importance of the liquid-solid growth interface anisotropy for the formation of interconnects and shed more light onto the very complex mechanism behind.

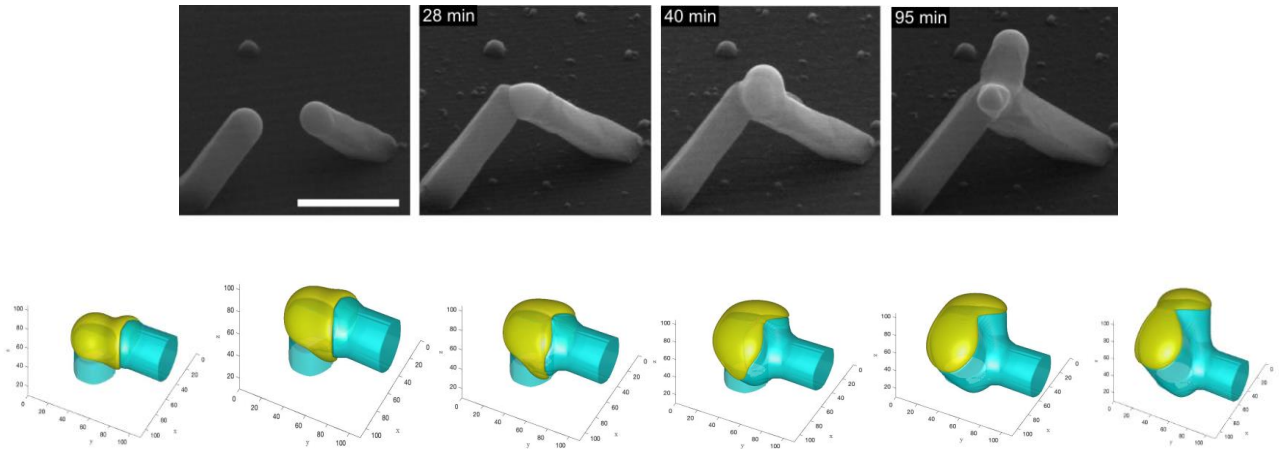

Figure 1. *Top: image sequence taken during the real-time observation of germanium nanowire growth in an SEM (tilted image). After merging, the collector droplet splits and the "X" shape is formed. Scale bar is 1 □m. Bottom: Snapshots taken during the phase field simulation of a nanowire system identical to the experimental one (Au-catalyzed Ge nanowires grown in <110> direction).*

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P1.26 - Molecular beam epitaxial growth of various diluted nitride nanowires

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Keywords: nanowire, X-ray diffraction, GaNAs

III-V Semiconductor nanowires are promising as a constituent material for realizing next-generation electronics and photonics devices. Among them, GaAs shows superior characteristics in devices such as laser and solar cell because of its high mobility and optical properties. Introducing a small amount of N into GaAs can bring about large variability in the lattice constant and the band gap. In contrast to the studies for thin films, studies on these diluted nitrides semiconductor nanowires are very limited and their characteristics are still unknown.[1] In this study, we report the growth and their structural characteristics of GaAs based various diluted nitride core multi-shell nanowires.

For the growth of the NWs, nucleation and core growth are performed using molecular beam epitaxy and constituent Ga catalyzed vapor liquid-solid (VLS) growth on Si (111) substrate. We grew five series of samples having their length about 3-5 μm and their diameter about 400 nm, containing core-multishell structures consisting of 1. GaAs, 2. GaAs/GaNAs/GaAs, 3. GaAs/GaInNAs/GaAs, 4. GaAs/GaNAsBi/GaAs, and 5. GaAs/GaNAs/GaAs/AlGaAs/GaAs. The dilute nitride shells were expected to be formed with its width about 20 nm surrounding the GaAs core having about 100 nm width. Fig. 1 shows the results of the x-ray θ-2θ scans around Si and GaAs(111) diffraction. The GaAs (111) peak was shifted to the high angle side by the N introduction. The introduction of In showed slight peakshift of the GaAs(111) peak, agreeing the expected increase of the lattice constant. Notably, the WZ-related GaAs(0002) peak was observed for most of the curves except the curves of GaNAs shell. The may suggests that the volume ratio of the WZ polytype is smaller for the samples of GaNAs shell compared to the other NWs.

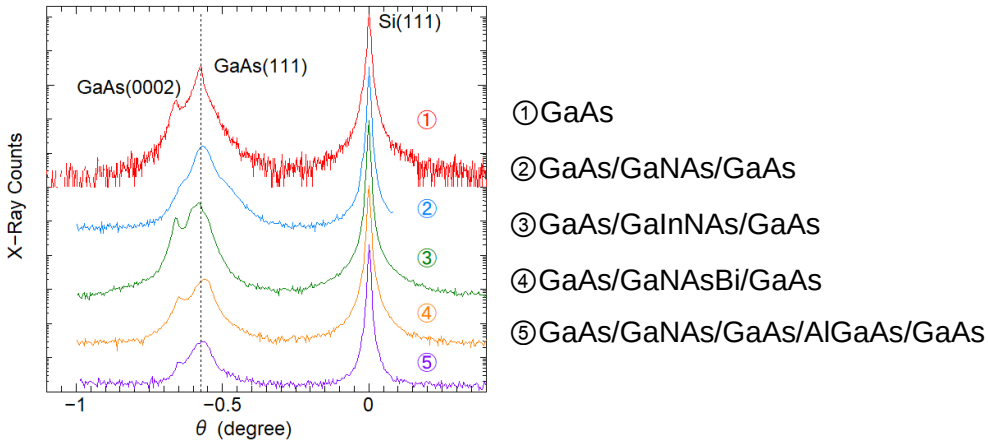

Figure 1. *X-ray diffraction curves for the nanowires investigated*

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[2] **Acknowledgements** We acknowledge the funding support from KAKENHI (No. 19H00855, 16H05970) from Japan Society of Promotion of Science.

P1.27 - Effect of n-doping on MBE-grown InAs nanowires

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Keywords: InAs, doping, optical properties

Successul future implementation of nanowire functional devices goes hand in hand with the achievement of reliable and precisely defined doping. In addition, plasmon resonance of III-V materials can be tuned towards the near-infrared part of the electromagnetic spectrum when high concentration of dopants is reached. However, controlled doping remains an important challenge since dopants tends to segregate close to the surface which results in heavily doped shell and slightly doped core. Moreover, it is natural to expect mechanism of dopant incorporation into the growing nanowire being dependent on the nanowire growth conditions and even on mechanism of the growth itself.

We report on in situ substitutional Si doping of InAs nanowires grown by MBE and its effects on optical properties and crystallographic nature of nanowires. While InAs/Si system was studied previously[1,2], here we show a direct comparison of nanowires prepared by two approaches: selective area epitaxy and gold-catalysed vapor-liquid-solid growth. The incorporation of dopants was evaluated by Raman spectroscopy and crystal structure of synthetized nanowires was examined using XRD and TEM. Furthermore, the effects of other n-dopants incorporation (C, Sn) on InAs nanowire morphology, crystal structure and optical properties were also investigated.

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P1.28 - Growth of MnAs/GaAs heterostructures in self-catalyzed GaAs nanowires

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Keywords: nanodots, MnAs, MBE

The introduction of substitutional transition metal ions in III-V compounds can add magnetic properties to the semiconducting materials, opening the way to applications in spintronic devices. Substitutional to group III cations, Mn has already been found to be promising dopant in III-V diluted magnetic semiconductor (DMS).[1] MnAs is a magnetic compound with Curie temperature above room temperature, compatible with III-V semiconductor growth and with demonstrated magnetoplasmonic activity.[2] The combination of magnetic Mn-based materials and quasi-1 dimensional III-V semiconductor nanowires allows the design of innovative spintronic and nano-photonic devices. Moreover, the small contact area between nanowires and substrate allows the growth on lattice-mismatched substrates and, hence, integration of GaAs based nanowires in existing Si-CMOS technology.

In this contribution we report on growth of MnAs nanodots in GaAs nanowires (NWs) by molecular beam epitaxy in self-catalyzed vapor-liquid-solid mode. GaAs NWs were fabricated on Si(111) substrates covered with native oxide using surface preparation technique to assure reproducibility of NW dimensions[3] as well as on Si/SiO_2 lithographically patterned substrates.

It is known that at usual NW growth temperatures Ga-Mn alloy exposed to As flux undergoes phase separation in GaAs and MnAs.[4] MnAs segments were fabricated by crystallization of Ga droplet alloyed with Mn under As beam.[4] We address here the saturation of Ga nanoparticle with Mn by means of Mn flux, as a function of Mn deposition time and temperature in GaAs NWs. Mn deposition in NWs of various dimensions will be reported. It was found that, as thin NWs (20-30 nm) are considered, an accurate control of Mn deposition parameters becomes crucial. Oversaturation of Ga droplet with Mn can lead to sidewall growth of parasitic nanoparticles. By controlling Mn deposition in GaAs NW, it is possible to alter the size of MnAs nanodot on top of NW. Our results will focus on Mn deposition in absence of other fluxes but data obtained by co-deposition of Mn with Ga and As will be discussed as well.

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[5] This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 722176.

P1.29 - Synthesis of GaAs/TiO_2 composite nanowires

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Keywords: Nanowire, GaAs, TiO_2

TiO_2 is known to be applicable for the electrodes of semiconductor-based photocatalysis providing photoinduced decomposition of water.[1] There are reports employing semiconductor nanowires for their use in photocatalyst and water splitting, showing efficiencies competitive to the other materials.[2] In a thin film, there is a report stabilizing photoanode functions for water splitting by TiO_2 coating on GaAs.[3] We here report the synthesis of TiO_2 coated GaAs nanowire for its future applications in photocatalysis.

GaAs nanowires were grown by molecular beam epitaxy using constituent Ga-induced vapor-liquid-solid growth on phosphorous-doped n-type Si(111) substrates. To obtain electronic conductivity, the nanowires were grown with doping Si to obtain n-type conductivity throughout the structure. We then sputter TiO_2 on the GaAs nanowire to form the TiO_2 coated layer on the surface of the GaAs nanowires. The sample was analyzed by scanning electron microscope equipped with energy dispersive X-ray spectroscopy (EDX). Figure.1 shows the structural configuration of a synthesized nanowire and its EDX elemental mappings for Ga, As, Ti, and O. From the analysis of the EDX intensity and the structure defined as the schematic illustration, we can deduce the diameter D of 215 nm and the outershell TiO_2 thickness t of 24nm. As a result, we could obtain GaAs/TiO_2 nanowire combining the GaAs nanowire molecular beam epitaxial growth and subsequent TiO_2 sputtering.

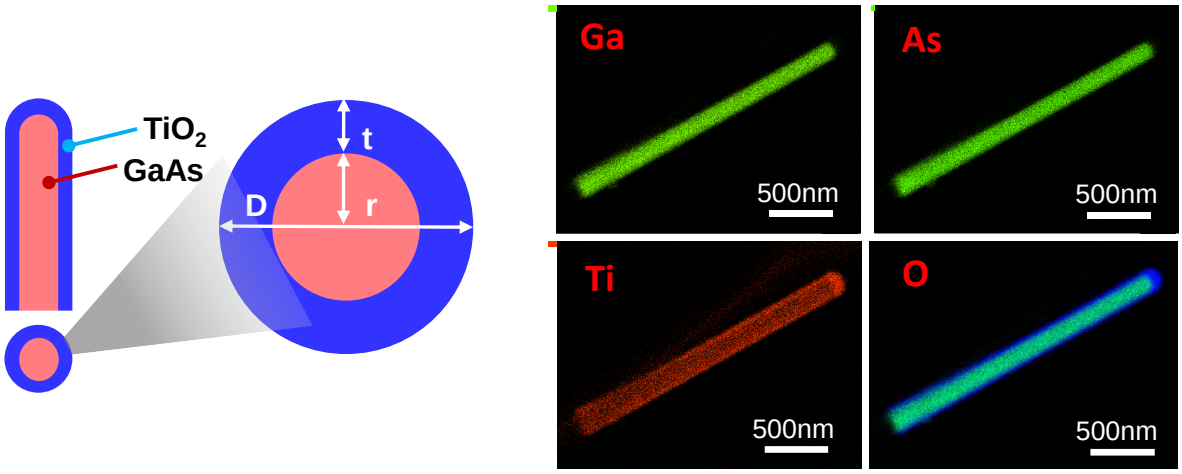

Figure 2. *Structural configuration of the wire sample and its EDX elemental mappings for Ga, As, Ti, and O.*

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[4] **Acknowledgements** We acknowledge the funding support from KAKENHI (No. 19H00855, 16H05970) from Japan Society of Promotion of Science.

P1.30 - In-situ prepared superconducting Al and Nb contacts on InAs nanowires

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Keywords: MBE, Superconducting contacts, InAs nanowires, In-Situ

Josephson junctions based on semiconductor nanowires are very attractive candidates for realizing hybrid superconducting quantum bits. The reason is that by using a semiconductor as a weak link gatecontrol of the Josephon supercurrent is possible. This allows to dispense with magnetic control via a SQUID. Heterostructures with semiconducting wires such as InAs or InSb nanowires have proven to have a great potential when combined with superconductors, i.e. Al, Nb, or Nb-compounds. For a better performance of these devices, the semiconductor-superconductor interface needs to be as transparent as possible. Here, we present a shadow mask based method to create in-situ prepared nanowire-based junctions without the necessity of ex-situ etching to form two closely spaced superconductor electrodes.

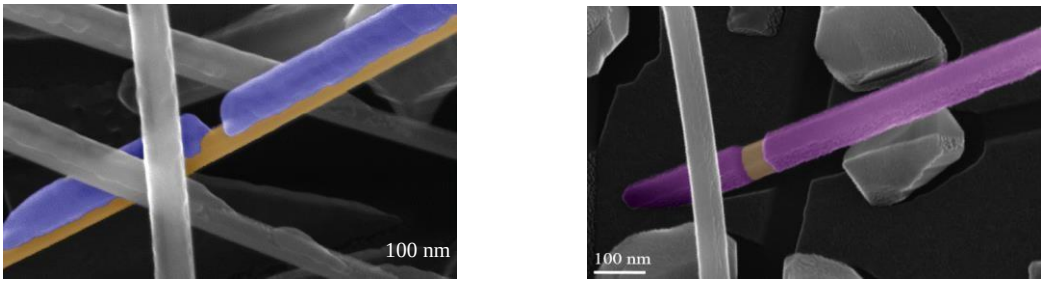

Figure 1. *Left image showing an in-situ prepared junction based on a InAs nanowire with Al half-shells. In the right image a corresponding junction with Nb electrodes is shown*

The nanowires are grown on pre-patterned Si (100) substrates, which are etched with a TMAH solution to reveal the (111) B facets. InAs nanowires are grown on these facets by molecular beam epitaxy while subsequently Al or Nb superconductors are deposited in-situ. Before deposition of the Al superconductor the sample is heated for arsenic desorption to avoid the formation of a large bandgap AlAs interface barrier.[1] Nanowires in this process are geometrically placed to cause a shadow on a wire grown on the neighboring facet during the metal deposition. The desired side-facets are aligned to face the metal source to obtain clean and smooth in-situ Josephson junctions.[2] The contacts deposited in this case are very smooth and uniformly covered along the length of the nanowire and do not cause any physical strain to the nanowire, as analyzed by scanning and transmission electron microscopy.[3]

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P1.31 - Incorporation and activation of Te dopant in self-catalyzed GaAs nanowires

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[2] *Physics Department, Federal University of São Carlos, São Carlos-SP, Brazil*
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Keywords: Te dopant incorporation, self-catalyzed growth, GaAs

A reliable doping procedure is key point for future device applications. The strongly amphoteric nature of Si in the vapor-liquid-solid process can be overcome by using Te as n-type dopant in GaAs NWs. Being a group VI element, Te provides n-type doping regardless of incorporation in As or Ga sites and therefore it has gained the attention of the NW growers[1-3]. Here, we present a detailed investigation of Te-doped self-catalyzed GaAs NWs grown in Si(111) wafers using a lithography-free oxide patterning technique[4] with a remarkable size uniformity[5] that is preserved in the presence of Te dopants. By combining atom probe tomography, off-axis electron holography, micro-Raman spectroscopy and single-nanowire transport characterization, we provide a spatial assessment of the Te concentration, free electron concentration and the built-in potential in Te-doped GaAs NWs. A theoretical model based on the experimental results shows that Te atoms are mainly incorporated by the VLS process through the Ga droplet, which leads to both axial and radial dopant gradients due to Te diffusion inside the NWs. In particular, we show that the activation of Te donor atoms is 100% at a doping level of 4×10^{18} cm^{-3}, which is a significant result in terms of future device applications.

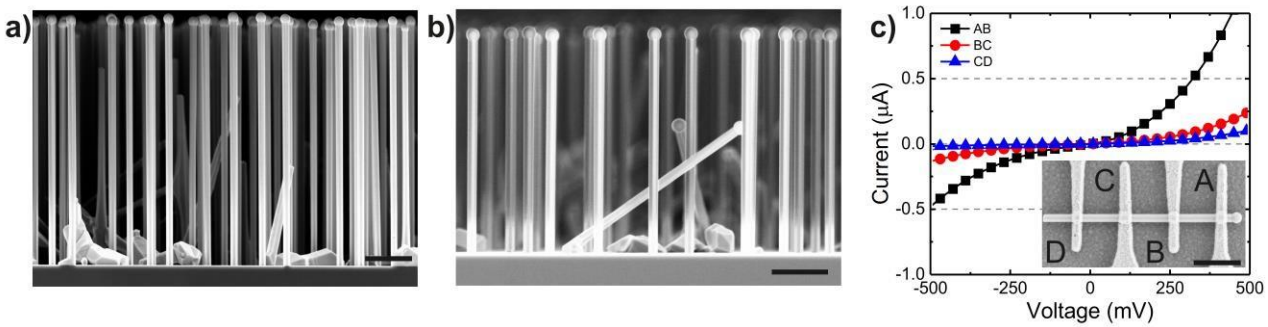

Figure 1: *Side view SEM image of (a) undoped and (b) Te-doped GaAs NWs. (c) Current-voltage characteristics of different regions along the NW axis as marked by the contacts pairs shown in the SEM image of the inset. All the scale bars are 1 μm.*

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P1.32 - Versatile platform for *in-situ* fabrication of InSb nanowire Majorana devices

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Keywords: nanowires, VLS, MOVPE, quantum devices, shadow deposition

InSb nanowires combined with a superconductor have recently gained a lot of attention because the first signatures of Majorana fermions have been detected in 2012 on a superconductor-semiconductor nanowire platform[1]. These first experiments suffered from device fabrication limitations, which compromised the quality of the nanowire, making the measurements somewhat noisy. On that account, the aim of our research is to tackle these fabrication issues to obtain high quality devices.

In order to ensure a clean and smooth superconductor-semiconductor interface, that is crucial to detect Majoranas, we developed a unique substrate fabrication process. With this technique we are able to grow InSb nanowires and InSb nanoflakes on the substrate and place them in predetermined positions. In particular, every InSb nanoflake is positioned in such a way that it shadows a large area of a rear InSb nanowire during a directional MBE deposition of superconducting material, thus selectively depositing the superconductor on only one part of the nanowire. Through this technique the Majorana device is fabricated *in-situ* with just a single MBE deposition, therefore it is possible to avoid using etchants to remove the superconductor from the other part of the wire (where it is not needed), which tends to be a rather harsh fabrication step, possibly damaging the nanowire surface.

The unique platform fabrication alongside with the new shadowing technique represents a new possibility to fabricate different and more complex InSb-based devices with high crystallinity and clean and smooth interfaces. The technique can be adapted to many different situations, for example a 4terminal Josephson junction can be fabricated with the shadowing of the nanoflakes on a rear crossed nanowire structure. This device could lead to further understanding of the behaviour of topological matter and Majorana fermions.

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P1.33 - Effect of Si native oxide thickness on GaAs nanowire growth on Si(001) substrate

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In our work we present results of experimental study of effect of silicon native oxide thickness on the GaAs nanowire growth on the Si(001) substrate by molecular beam epitaxy.

To study this effect, the Si(001) substrate was annealed at high temperature (900°C) in the silicon flux without substrate rotation, to create a flux gradient over the sample surface as a result of the misalignment of the axes of the substrate and the Si molecular source. Then the source of silicon was closed and the substrate temperature decreased to 600°C in the As4 flux. Upon reaching and stabilization the specified substrate temperature, GaAs of 500 nm thick was deposited with an equivalent deposition rate of 1 ML/s. The effective ratio of V/III fluxes during growth was 1.

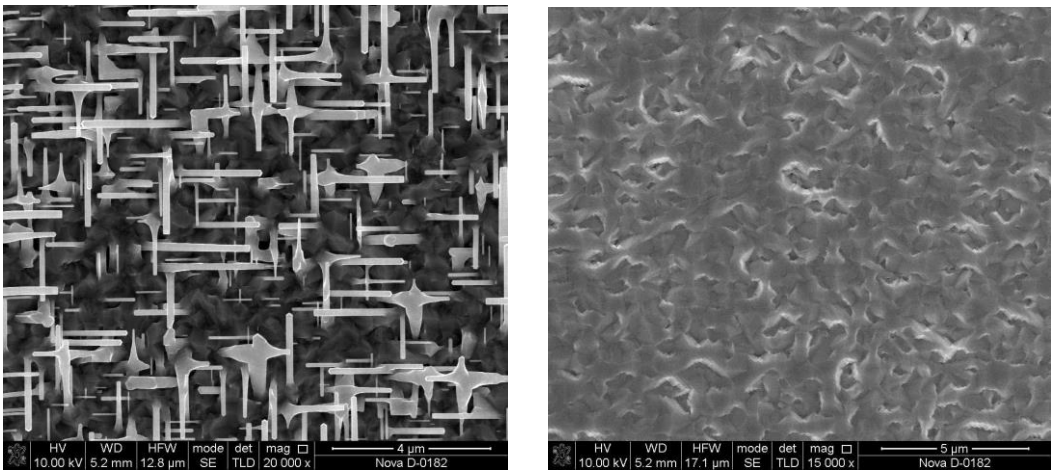

Figure 1. *SEM images of Si(001) sample surface in areas with complete and incomplete removing of SiOx film after deposition of 500 nm GaAs*

As can be seen from Figure 1, due to the presence of a silicon flux gradient at the annealing stage, areas with different thickness of the native oxide residual film were formed on the Si substrate surface. In this case, a polycrystalline film was formed in the areas without oxide. In areas with incomplete removal of native oxide, GaAs nanowires were formed. An intermediate region is observed between them with a gradual transition from a GaAs polycrystal to nanowires as the native oxide thickness increases.

Reference

[1] ***Acknowledgements:*** This work was supported by the Russian Science Foundation Grant No. 15-19-10006 and by the Grant of the President of the Russian Federation No. MK-477.2019.8. The results were obtained using the equipment of the Research and Education Center and Center for Collective Use "Nanotechnologies" of Southern Federal University

P1.34 - Functional properties of earth-abundant nanowires and nanosails

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Keywords: zinc phosphide, earth-abundant, passivation

The rapid development of the photovoltaic and optoelectronic industries and a rising demand for cheap and efficient products are straining the supply of rare elements often required for the fabrication of the most cost-effective devices. High-efficiency thin film solar cells made up of elements widely available in the Earth's crust are necessary for the widespread deployment of sustainable solar technology.

Zinc phosphide (Zn_3P_2) and zinc arsenide (Zn_3As_2) are earth-abundant compound semiconductors with promising properties. The 1.5 eV direct bandgap of Zn_3P_2, close to the optimum of the Shockley-Queisser limit, makes it a strong contender for photovoltaics applications, while the tunable [1] 1.0 eV direct bandgap of Zn_3As_2 is ideal for optoelectronics. The micrometer-range minority carrier diffusion lengths [2] and the strong visible light absorption in the phosphide material, together with the potentially very high hole mobilities in the arsenide [3] further justify investigation of these materials. Growing these materials in the form of nanostructures, such as nanowires and nanosails, is a solution to the lack of lattice- and thermal expansion-matched substrates for epitaxial growth, which has hindered the use of these materials in the past [4]. In addition to an efficient mismatch strain relaxation thanks to their small footprint, the geometries mentioned above have also been shown to be platforms for defect-free growth [5]. Furthermore, the fabrication of efficient devices requires careful charge control through the reduction of surface and bulk recombination while at the same time using band-matched contact materials for efficient photogenerated charge extraction. The scalable fabrication of high-quality planar and nanostructured devices out of these earth-abundant zinc pnictides could provide the renewable energy sources for powering a sustainable future society.

In the first part of this work, we have studied defect-free Zn_3As_2 nanosails grown by Metal-Organic Vapor Phase Epitaxy (MOVPE). We discuss their temperature-dependent carrier properties, showing that they are unintentionally degenerately p-doped. We also examine their metastable crystalline structure by Raman spectroscopy [4]. In the second part of this work, we study the passivation of Zn_3P_2 nanowires grown by Molecular Beam Epitaxy (MBE). A variety of surface treatments and coatings are compared and their effects on the optical properties of the nanowires are determined. We contrast the results on nanowires with similar surface treatments of thin films of the same material. Photoluminescence and cathodoluminescence techniques are used to assess the optical properties of the investigated structures.

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P1.35 - Ni nanoparticles on ordered arrays of carbon nanotubes: innovative multifunctional nanowires

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Keywords: Carbon Nanotubes, Ni nanoparticles, multifunctional devices

The feasibility to use aligned arrays of carbon nanotubes (CNT) as scaffold for the controlled deposition of Ni in form of nanoparticles or thin films opens interesting technological perpectives. The approaches developed in our labs enable to control the architecture of the CNT/Ni systems, satisfying the geometries required for the integration of such hybrid nanomaterials in a series of devices.

The Ni nanoparticles are generated by electrochemical routes on vertically oriented CNT bundles deposited by CVD synthesis or on CNT mats positioned on a multifinger device using a dielectrophoresis process.

The adjustment of the electrodeposition parameters enables the covering of the ordered CNT arrays by isolated Ni nanoparticles, by chains of contacting nanostructures, or by continue metallic thin layers.

The electrical characterizations of the samples evidenced that the transport mechanism and therefore the functional capabilities of the CNT/Ni systems are strongly influenced by the different organization of the Ni phase supported on CNT.

As regards the charge transport properties of the hybrid material, we found that CNT/Ni interconnects can reach resistance values up three order of magnitude lower with respect to bare CNT. Moreover, organized Ni-decorated CNT systems have proven to behave as highly efficient electrodes, due to their enhanced surface electrochemical reactivity.

The CNT/Ni nanowires are also interesting materials for gas sensing. Carefully arranged Ni particles can indeed strongly enhance the process of electron transfer from electro-donor systems to CNT, improving the overall sensing performances.

By the settled nanofabrication procedures, the feasibility to control the orientation/alignment of CNT bundles and some specific characteristics of the Ni coating, *in primis* separation and/or interaction between particles, makes such hybrid CNT/Ni nanowires reliable candidates for a wide range of applications, from integrated circuits and interconnections to electrodes and sensors. The methodologies here illustrated are attractive also for the fabrication of CNT/Ni nanowires for magnetic and spintronic applications.

P1.36 - Characteristics of GaAs/AlGaAs core-multishell structures having native oxide AlGaO outermost shell

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Keywords: nanowire, GaAs, AlGaAs, native oxide, EDS

The combination of semiconductors and oxides would have a strong potential for future applications as seen in metal-oxide-semiconductor devices where the high electronic properties of the semiconductors and various dielectric and insulating features of the oxides functionally work together. We have fabricated oxide heterostructure nanowires (NWs) by selective wet oxidation of the Al-rich AlGaAs outermost shell in the GaAs/AlGaAs core-shell type NWs grown on Si substrate.[1] However, the oxidation induced damages and diminished the optical properties of original NWs inside the oxide. The native oxidation of Al-rich AlGaAs at atmospheric conditions is well known phenomenon and and can be used for waveguiding in optical devices.[3] It, therefore, will be beneficial for GaAs NWs providing electrical and optical confinement of carriers and light, respectively. We thus report the synthesis and properties of GaAs-related core-multishell NW structure with the outermost AlGaO layer formed by the atmospheric native oxidation.

The investigated NWs have the GaAs/AlGaAsGaAs/Al-rich AlGaAs core-multishell structure and were fabricated by molecular beam epitaxy on Si (111) substrates. After the growth, the NWs were exposed to the atmosphere and naturally oxidized to convert the outermost Al-rich AlGaAs layer to an oxide layer. Figure 1 shows the scanning electron microscopy (SEM) image and cross-sectional elemental mapping of the NWs. We can see the formation of NWs having the intended GaAs/AlGaAs/GaAs/AlGaO core-multishell structure. From the photoluminescence studies, the oxide shell acts as a reasonably-efficient passivation layer. Moreover, the emission wavelength of the GaAs core can be tuned by changing the thickness of the shell layer, due to effects of shell-induced strain

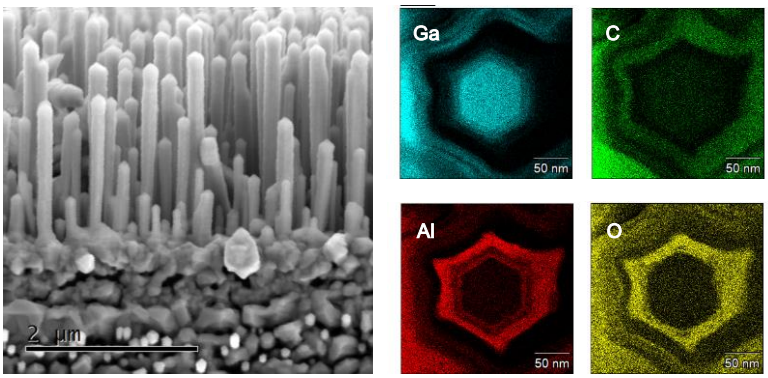

Figure 1. *Cross sectional SEM observation of a NWs and axially cross-sectional STEM-EDS elemental mappings.*

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P1.37 - Morphology control by tuning growth parameters of InSb nanostructures: from 1D to 3D

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Keywords: InSb morphology, Nanoflag, Nanocube, Nanowire

Indium antimonide (InSb), a narrow band gap III–V semiconductor exhibits strong spin orbit coupling and large Lande g factor making it a promising material in the field of optoelectronics and quantum computing. However effective development of InSb-based devices has been hindered by its very large lattice mismatch with the most widespread semiconductor systems. This makes it difficult to grow heteroepitaxial two-dimensional layers of InSb. Growth of nanostructures and in particular nanowires (NWs) allows to accommodate the interfacial strain even for materials with very large mismatch, generally without the formation of any defects[1]. Furthermore, the possibility to control and change the morphology of such nanostructures by tuning the growth parameters gives new exciting perspectives. In this contribution, we investigate the growth mechanisms of InSb nanostructures with different morphologies on InAs NW stems. InSb nanostructures such as nanowires (1D), nanoflags (2D) and nanocubes (3D) have been realized by means of Au-assisted Chemical Beam Epitaxy (CBE) by tailoring the growth parameters like growth temperature, precursor fluxes, sample rotation, and substrate orientation. The morphology of these nanostructures has been determined by means of scanning electron microscopy (see Fig.1).

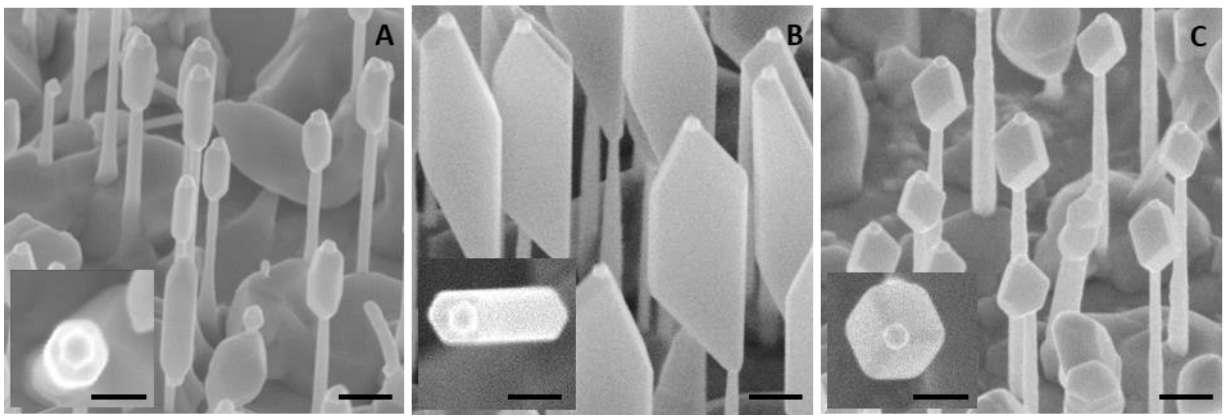

Figure 1. *SEM images of nanowires in (A), nanoflags in (B) and nanocubes in (C). The images are taken at 45° angle (scale bar: 200 nm). Top view of all the nanostructures are shown in the insets (scale bar: 100 nm).*

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P1.38 - Influence of Si substrate preparation on polarity of GaN nanowires grown on Si(111) by PAMBE: Kelvin Probe Force Microscopy studies

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Keywords: GaN nanowires, polarity, Kelvin Force Microscopy, molecular beam epitaxy

Growth of GaN nanowires (NWs) having polar, wurtzite structure on nonpolar Si substrates raises the issue of the GaN NW polarity. Depending on the interface chemistry and the details of the growth procedure the coexistence of NWs with different polarities inside the NW ensemble has been observed.[1,2] Since the specific polarity affects optical and electronic properties of NWs, reliable methods for its control and characterization are needed.

In this work we use Kelvin probe force microscopy (KPFM) to asses polarity of GaN NWs grown by plasma-assisted MBE on Si(111) substrates. Complementary images of KPFM, namely topography and contact potential difference (CPD) were analyzed.[3] They allow measuring the polarity of individual NWs over an area of tens of μm^2 and provide statistics on the polarity of the ensemble with an accuracy hardly reachable by other methods. Our studies show that uniformity of polarity of GaN NWs on Si(111) strongly depends on the procedure used for substrate processing prior to the NW growth. As high as 20% of NWs with reversed polarity (i.e. Ga-polar) were found if the Si substrate was etched in diluted HF and then annealed in the growth chamber to remove hydrogen passivation prior to the substrate nitridation. Despite the fact that such procedure leads to clean 7x7 substrate surface reconstruction some islands of residual oxide are apparently left that may induce growth of Ga-polar GaN NWs.[1] Additional substrate treatments (RCA etching, Ga cleaning, etc.) were tested. However, the best results, i.e. purely N-polar ensemble of NWs, were obtained on epi-ready Si wafers thermally deoxidized in the growth chamber at ~1000°C just prior to their nitridation. Interestingly, no mixed polarity with a certainty above 99.8% (~400 NWs analyzed) was found for GaN NWs grown under similar conditions on Si(111) substrates covered by a thin amorphous Al_xO_y buffer layer.[4] This shows the crucial role the chemistry at the GaN/Si(111) interface plays for polarity of GaN NWs.[5]

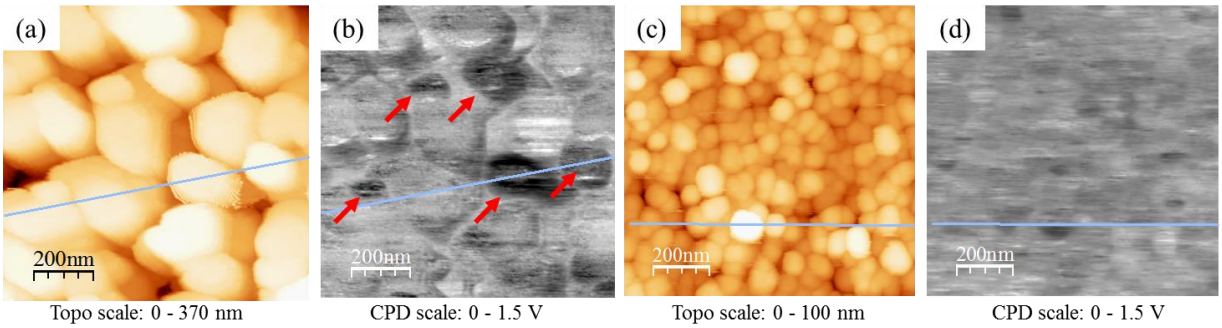

Fig. 1. *Topography and CPD maps of GaN NWs grown on Si(111) substrates prepared by HF-dip (a-b) and by thermal oxide desorption in the MBE chamber (c-d). Red arrows mark the NWs with reversed (i.e. Ga-) polarity.*

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P1.39 - One-dimensional helical states in SnTe topological crystalline insulator nanowires: Modelling and growth

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Keywords: SnTe, topological crystalline insulator, nanowires

Tin telluride (SnTe) is a topological crystalline insulator (TCI) with gapless surface states protected by mirror symmetry [1]. We have grown SnTe nanowires for the first time in Molecular Beam Epitaxy (MBE) with and without (see Figure 1.) metal catalyst particles. We can grow nanowires with either {100} or {111} facets. A layer of Al_2O_3 is deposited in ALD to protect the nanowires against oxidation, so that the SnTe surface facets remain pristine. The promise of MBE growth of SnTe nanowires is to solve the p-type doping problem [2], by growing under out-of-equilibrium conditions. Therefore, charge carrier densities are measured in transport measurements.
By modelling superconducting SnTe thin films we showed the realization of 2 and 4 Majorana fermions at each end of a superconducting p-junction for the {111} and {100} surface facets respectively. Besides that for nanowire energy dispersions indications of Dirac physics appear, but, so far, Dirac cones seem to be buried in the bulk bands for practical nanowire diameters. Furthermore, we investigate symmetry breaking by strain, substrates and electric fields for the purpose of SnTe higher order topological crystalline insulators (HOTCIs).

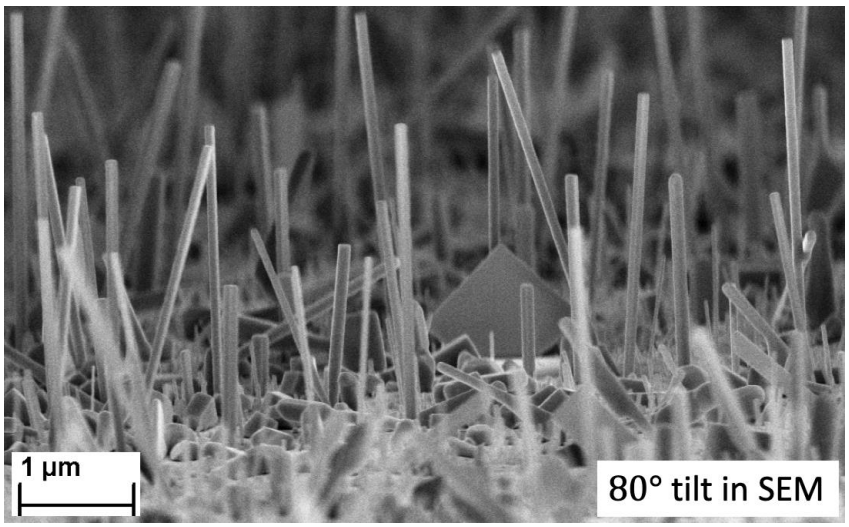

Figure 1. *SnTe {100} nanowires and nanoflakes grown in MBE without catalyst particles.*

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P1.40 - Why Si/Ge nanowires can have the hexagonal diamond crystal structure?

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Keywords: Hexagonal Si/Ge, core/shell nanowires, ab-initio modelling

Si and Ge nanowires (NWs) with hexagonal diamond (hd) structure have been recently realized1. These hd crystals can potentially be a breakthrough for Si-based photonics and optoelectronics, because of the direct band-gap nature of hd Ge, which is preserved by alloying Ge with up to 30% Si.

However, not much is known about thermodynamics and stability of the metastable hd crystals, and the fundamental aspects leading to the growth of the hd Si and Ge in core/shell NWs are not well understood. In our previous study[2], we identified the <1100> crystal orientation as the most stable one for the NW side faces, and we pointed out the fundamental role of the {1100} facets of the GaAs/GaP core as template for the crystal growth of the hd Si and Ge shell.

Our recent study on the surface energies of hd and cubic diamond (cd) Si and Ge evidences also how the high surface-to-volume ratio of the NWs is decisive to obtain the hd crystals. Because of the {1100} surface energy is much lower than the corresponding one for the cubic {112} surface, the surface energy of hexagonal NWs elongated in the <0001> direction over-compensates the lower cohesive energy of the cd phase, promoting the stability of the metastable hd crystals.

Our estimations of the total energies of Si and Ge NWs show a higher stability of the hd NWs as compared to the cd ones, up to a critical radius, and elucidate the role of the NWs in stabilizing the hd crystals.

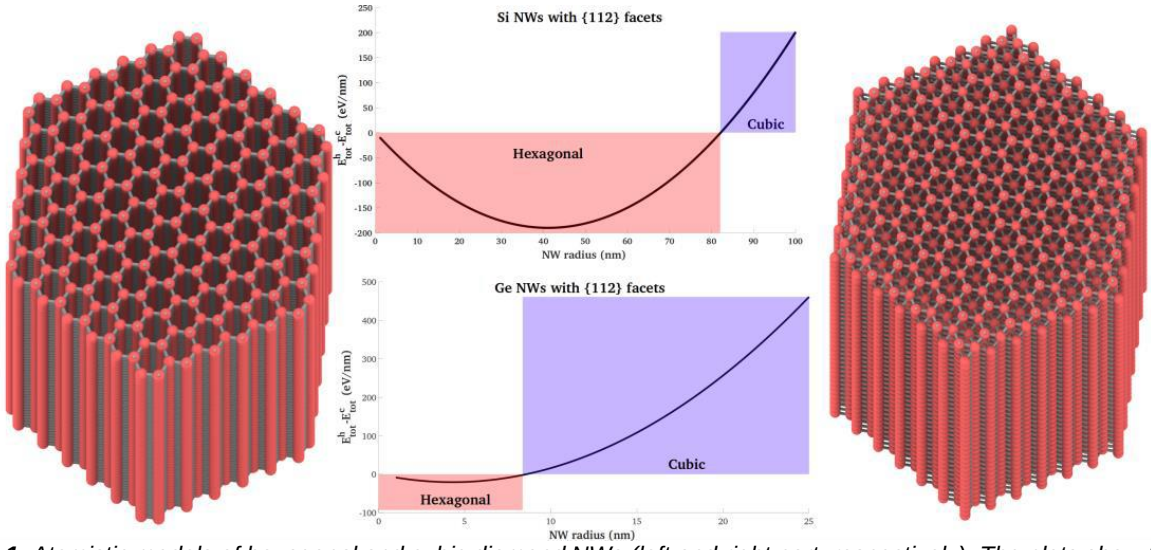

***Figure 1**. Atomistic models of hexagonal and cubic diamond NWs (left and right part, respectively). The plots show the estimated total energy difference between hd and cd NWs, both for Si and Ge vs. the radius of the NWs.*

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P2.01 - Polarity-dependent high electrical conductivity of selective area grown ZnO nanowires by chemical bath deposition

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Keywords: ZnO Nanowires, CBD, Polarity

Controlling the growth and properties of ZnO nanowires (NWs) is critical for their efficient integration into nanoscale engineering devices.[1] ZnO Wurtzite structure exhibits a spontaneous polarization field along the *c*-axis. The resulting polarity is known to affect the growth and properties of ZnO single crystals and epitaxial films,[2] but the polarity-induced effects are mostly unknown in NWs. While ZnO NWs spontaneously grown by vapor phase techniques are systematically Zn-polar, ZnO NWs grown by chemical bath deposition (CBD) can be of either O- or Zn-polarity,[3] which opens the way for more deeply investigating these effects. In this context, we thoroughly address the issue of the polaritydependent growth and properties of ZnO NWs by CBD following the selective area growth approach.[4] To leave polarity as the only varying parameter, ZnO NWs are grown under identical conditions, during the same run of experiment on O- and Zn-polar ZnO single crystals patterned by electron beam lithography with the same pattern consisting of fifteen different domains combining a wide range of hole diameters and periods. Well-ordered O- and Zn-polar ZnO NW arrays with high structural uniformity are grown on all the domains. The comparison of their typical dimensions unambiguously reveals that Znpolar ZnO NWs have significantly higher growth rates than O-polar ZnO NWs for all the fifteen domains.[4] The origin of the difference is discussed in the light of surface configurations and interactions in aqueous solution at the top polar *c*-faces of the ZnO NWs. Four-point probe resistivity measurements are additionally performed on single O- and Zn-polar ZnO NWs in patterned metal contact and multiprobe scanning tunnelling microscopy configurations, showing the high electrical conductivity of these NWs and its relationship with their polarity.[5] This is directly attributed to the massive incorporation of hydrogen into ZnO NWs by Raman scattering and cathodoluminescence measurements. These findings show the relevance of considering polarity as an important quantity to control the growth and physical properties of ZnO NWs by CBD.[6]

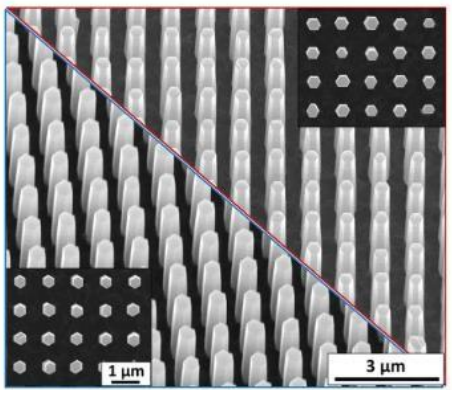

Figure 1. *Tilted-view FESEM images of selective area grown O- and Zn-polar ZnO NWs on O- and Zn-polar ZnO single crystals prepatterned using EBL. The top (i.e., red border) and bottom (i.e., blue border) triangular areas correspond to the growth on O-and Zn-polar ZnO single crystals, respectively. The insets are the corresponding top-view FESEM images*

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[6] **Acknowledgements:** This work was partly supported by the French RENATECH network through the CIME-Nanotech and PTA technological platforms in a cleanroom environment. Funding by the Carnot Institute Energies du Futur through the projects CLAPE and ECOLED is also acknowledged.

P2.02 - Gallium doping of ZnO nanowires by chemical bath deposition

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Keywords: ZnO nanowires, CBD, Doping

Over the last decade, ZnO nanowires (NWs) have been used for a wide variety of optoelectronic devices, including UV photodetectors and solar cells. For all these applications, their electrical properties, such as their conductivity and mobility, should be controlled as much as possible. ZnO is intrinsically ntype owing to the high density of hydrogen[1,2] and can intentionally be n-doped, for example, by Gallium. The doping of ZnO NWs has however been mainly performed by vapor deposition techniques. In the present work, ZnO NWs are doped with Gallium by using the low-cost, low-temperature, and easily implemented chemical bath deposition (CBD) technique. Gallium nitrate and ammonia are added in various concentrations to the standard precursors (i.e. zinc nitrate and HMTA[3]) in deionized water. It is shown by scanning and transmission electron microscopy (TEM) that this addition completely modifies the structural morphology of ZnO NWs. The formation mechanisms are thoroughly investigated and supported by thermodynamic simulations yielding speciation diagrams and solubility plots. The incorporation of Gallium dopants is further investigated by x-ray diffraction, energy dispersive x-ray spectrometry using scanning TEM, and temperature-dependent Raman spectroscopy. In particular, the occurrence of different additional modes in Raman spectra before and after annealing under oxygen atmosphere show the presence of the Gallium related defects and their incorporation mechanisms into ZnO NWs[4].

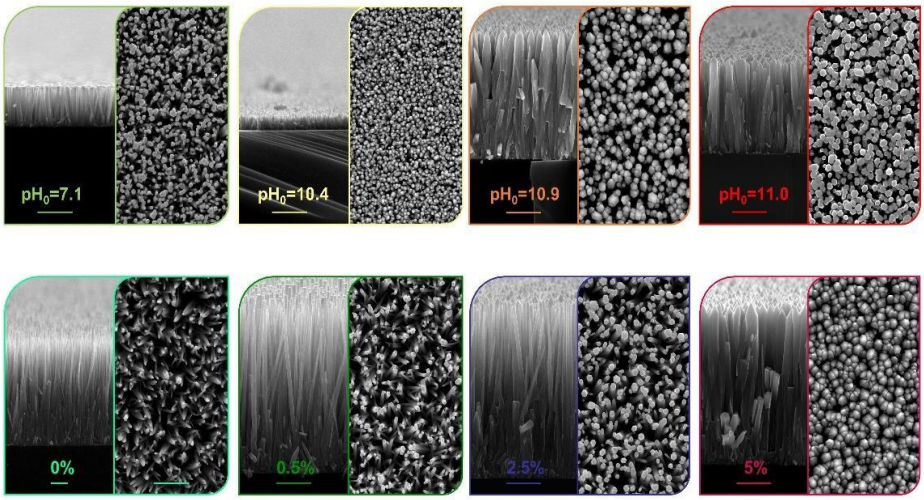

Figure 1. *(a) Cross-sectional view and top-view FESEM images of ZnO NWs grown by CBD with pH values in the range of 7.1-11 and for a given $[Ga(NO_3)_3]$ / $[Zn(NO_3)_2]$ ratio of 5 %. (b) Cross-sectional view and top-view FESEM images of ZnO NWs grown by CBD with $[Ga(NO_3)_3]$ / $[Zn(NO_3)_2]$ ratio values in the range of 0-5 % and for a given pH of 10.9. The scale bar is 1µm.*

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P2.03 - Engineering InGaAs Nanowire Composition by Selective Area Metal Organic Vapour Phase Epitaxy

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Keywords: $In_xGa_{1-x}As$; MOCVD; nanowires

Ternary and quaternary alloys of III-Arsenide semiconductor nanowires (NWs) are attracting significant interest as building blocks of future optoelectronic devices [1]. Amongst other advantages they feature tunable bandgap energies by varying the alloy composition. Recently, InGaAs nanowires were synthesized by vapor-liquid-solid (VLS) growth using Au nanoparticle catalysts [2]. However, pure wurtzite (WZ) and zinc blende (ZB) crystal structures could only be achieved for few $In_xGa_{1-x}As$ compositions and an inhomogeneous content of In was observed along the nanowires [2].

Here, we report the growth of vertically uniform $In_xGa_{1-x}As$ compositions for a wide compositional range ($0<x<1$) by optimizing growth conditions using selected area epitaxy (SAE) and metal organic chemical vapour deposition (MOCVD) on GaAs substrates. Our transmission electron microscopy (TEM) results show that GaAs has a predominantly ZB structure whereas InAs nanowires have a WZ crystal structure. For the GaAs nanowires, we observe a change in the stacking fault density along the length of the nanowires. In particular, the bases of the GaAs nanowires are heavily defective with increasingly thicker ZB twin segments (~ 150 nm thick) towards the top of the NW as can be seen in Figure 1.

We also observe that for a given nominal V/III ratio, the In/Ga composition within the nanowires is dependent on two factors: the growth temperature and the pitch size. We observe a higher Ga content in InGaAs nanowires with higher growth temperature and smaller pitch size. TEM analysis shows a trend from predominantly WZ phase for higher In content to predominantly ZB for higher Ga content.

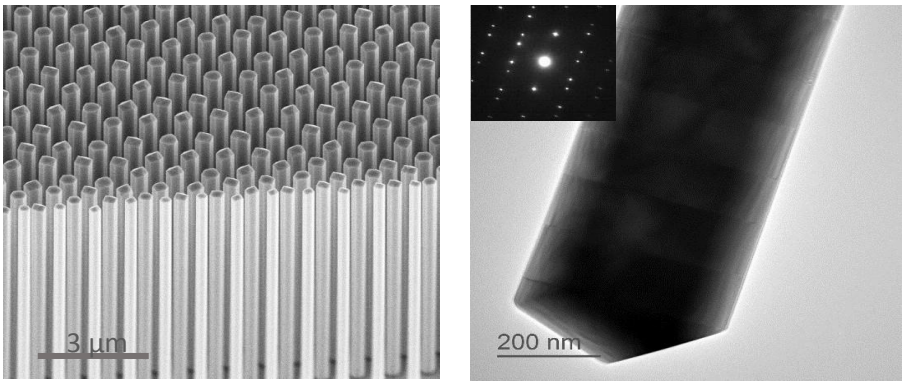

Figure 1. *(a) Scanning electron microscopy image of GaAs NW, (b) TEM image at the top of the GaAs NW.*

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P2.04 - Electrical characterization of nanowires combined with in-situ TEM imaging

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Keywords: Si, III-V nanowires, MEMS, in-situ TEM, electrical properties

We have developed unique microfabricated nanowire growth systems that enable epitaxial vapor phase (VPE) nanowire growth on monocrystalline Si cantilever substrates as shown in Fig 1 A). The chip systems enable both direct in-situ TEM observation of growth processes and electrical characterization of nanowires once they have formed bridges between cantilevers[1,2].

Here we electrically characterize silicon nanowires grown and electrically connected at their two ends in-situ in the TEM at room temperature and elevated temperatures. We observe that the nanowires, which are oxide-free directly after growth, have non-linear current-voltage characteristics, Fig 1 B). We further study the effects of surface modification on the electrical properties of the nanowire by oxidizing the nanowire surface in several stages, recording images at each stage. These observations show how the repeated oxidation decreases the conductivity. Finally, we present new chip designs for characterizing electrical and optical properties of III-V nanowires at the III-V ETEM at Lund University.

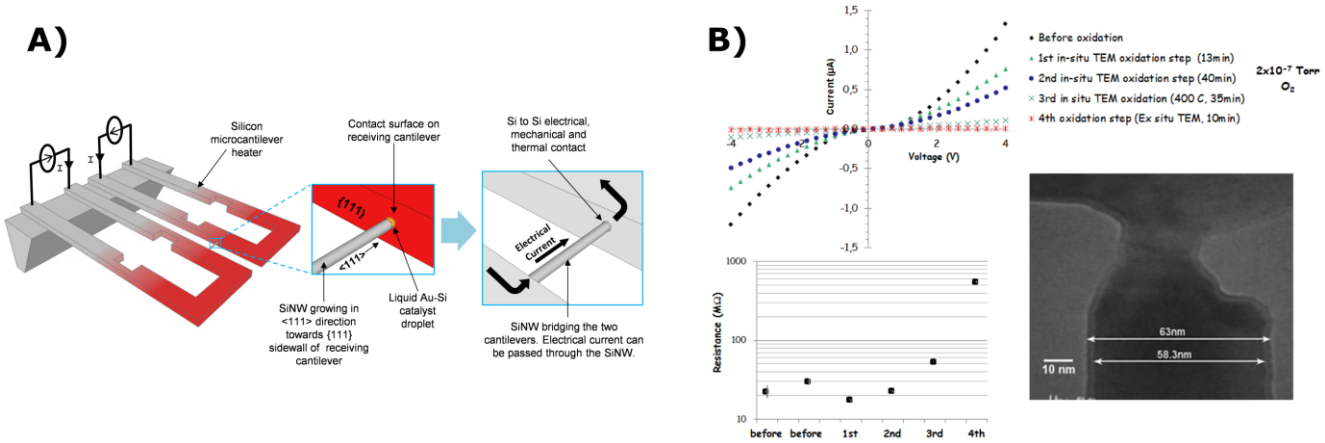

Figure 1. *(A) Schematics of experimental setup used for in-situ growth and electrical characterization of nanowires. (B) IV data and resistance of nanowire shown in TEM image at different surface oxidization steps.*

References

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[3] **Acknowledgements:**The measurements were performed at IBM T. J. Watson Research Center.

P2.05 - Analysis of III-V Semiconductor Nanowires Coupling Advanced Transmission Electron Microscopy Techniques

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Keywords: III-V Semiconductors, Transmission Electron Microscopy, Electron Diffraction Tomography

III-V Semiconductor nanowire systems (InAs, InP and InAsSb) have been studied by Electron Diffraction Tomography (EDT),[1] a technique widely used for crystallography but that also allows to identify very weak features when reconstructing the reciprocal space (RS) of the studied material in 3 dimensions.

All the reconstructions exhibit some star-shaped diffraction spots, whose branches are normal to the edges of the cross-sections (6 branches for InAs and InAsSb, 4 branches for InP, see Figure 1).

EDT alone is not sufficient to fully understand and explain the nature of these stars, so advanced Transmission Electron Microscopy techniques have been used on cross-sections prepared by Focus Ion Beam (FIB), and especially Electron Energy Loss Spectroscopy (EELS), High Angle Annular Dark Field (HAADF) imaging and Geometric Phase Analysis (GPA).[2]

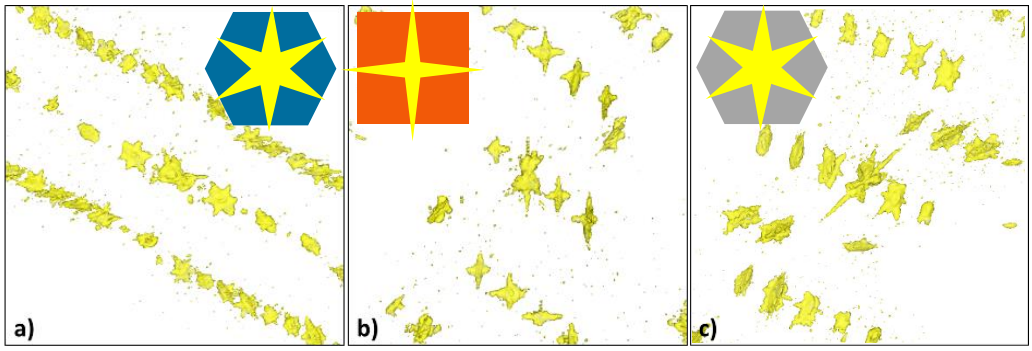

Figure 1. *3D reconstruction of the reciprocal space of a) InAs, b) InP and c) InAsSb nanowires*

These techniques are now showing unprecedented resolution and performance that allow us to observe nanomaterials with a different perspective, revealing novel features that could not be observed before. All these advances open a new way to a better understanding of the nanoworld.[3]

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P2.06 - In-Situ observation of Σ3 {112} twin boundary motion at atomic resolution in III-V nanowires

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Keywords: In-situ, Defects, STEM

Semiconductor nanowires (NW) are often described as being defect free due to their ability to expel mobile defects with long-range strain fields. Most defects can be detrimental to electronic properties and so the device performance.[1] Less than perfect tip regions are formed during the droplet consumption phase of self-catalyzed vapor-liquid-solid grown NWs.[2] The type and occurrence of defects in the tip region of NWs have been identified using aberration corrected scanning transmission electron microscopy (STEM), with the Σ=3 {112} twin boundary type defect, multiples of 3 monolayers (ML) in height, the most common. The stability of these defects has been probed by exposing the NWs to high temperatures in-situ whilst examining them at atomic scale with STEM. It is found that the type and specific configuration of defect dictate if and how the defect moves, with a range of velocities observed for different configurations and temperatures. The defect motion is found to be dependent on size, position, and surrounding environment of the defect, with the forces behind the motion being relatively large. The geometry of the NW is seen to be an important factor in how defects move. Examples of defect behavior are given and range from defects seen to be completely removed from the system, to some getting trapped from interacting with other defects, to some which do not move at all. An example of observed motion is shown in figure 1. An upper limit to activation energy for the motion of the Σ=3 {112} twin boundary type defects is found to be around 2eV in GaAsP NWs.[3]

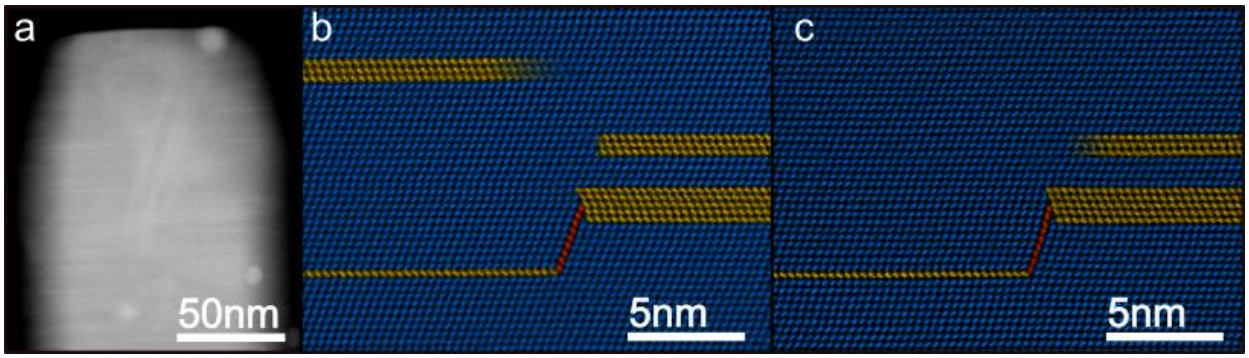

Figure 1. *a) ADF image of a defective GaAsP NW tip after catalyst droplet consumption. b) ADF-STEM image with added color showing a defect before being heated. c) ADF-STEM image of the same area shown in b) after being exposed to high temperature. The defect at the top left of the image is seen to move.*

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P2.07 - Enhanced cathodoluminescence of nXRD- and TEM-measured mixed phase in single as-grown core-multi-shell nanowires

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Keywords: structural properties, optical properties, core-shell nanowire heterostructures

We report on the direct correlation between the structural and optical properties of several single core-multi-shell GaAs/$In_{0.15}Ga_{0.85}As$/GaAs/AlAs/GaAs nanowires (NWs) grown by molecular beam epitaxy. Using selective area epitaxy on a Si (111) substrate pre-patterned by electron beam lithography, we grew well isolated NWs along a single line, which can be probed individually in the as-grown geometry. The polytype distribution along the NW growth axis was revealed by synchrotron-beam-assisted nano-X-ray diffraction techniques monitoring the axial 111 Bragg reflection. The optical properties of the same NWs were extracted by in-house cathodoluminescence spectroscopy. Comparing the optical and structural measurements, we reveal a correlation between the emission intensity and a particular structural phase within the NWs (see Figure 1). In particular, we found an enhanced quantum well emission from a mixed (M) phase segment, where the intensity is about 80 times higher than for the wurtzite (WZ) and zincblende (ZB) polytypes. The presence of this mixed phase was later confirmed by crosssectional transmission electron microscopy of a core-shell NW grown on a different substrate but with the same growth parameters. In conclusion, we demonstrated the feasibility of correlated nanoscale measurements on as-grown NWs and use this to link the emission properties of core-shell quantum wells to the crystal structure of the NWs.

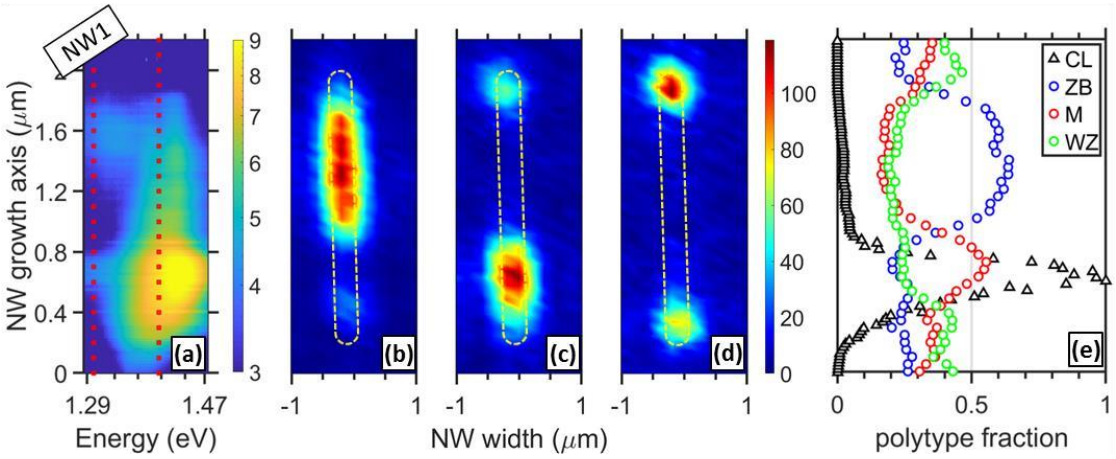

Figure 1. *(a) Hyperspectral cathodoluminescence map along the NW growth axis. (b-d) Maps of different Bragg reflections showing the ZB, M phase and WZ distributions, respectively. (e) Normalized CL intensity (black) and polytype fractions along the length of the NW (see legend).*

P2.08 - Quantification of *in situ* RHEED for height-resolved analysis of polytypism in nanowires

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Keywords: in situ, RHEED, polytypism

In situ characterization techniques can provide insight into fundamental aspects of nanowire (NW) growth, growth dynamics and the evolution of different crystal phases of polytypism inside the wires. Prominent methods are *in situ* transmission electron microscopy (TEM)[1] and *in situ* X-ray diffraction (XRD)[2] during NW growth, which are both limited to special equipment. *In situ* reflecting high-energy electron diffraction (RHEED) – in this context – has yet played a minor role. Although it is broadly available in most molecular-beam epitaxy systems, it was limited to rather qualitative observations.

We present an approach to gain more quantitative information on the evolution of crystal structure by *in situ* RHEED during NW growth. In particular, we demonstrate its potential by studying growth evolution of self-catalyzed GaAs NWs on Si(111) substrates, which exhibit the zincblende/wurtzite polytypism. The approach takes benefit from the absorption of electrons in the NWs influencing the local illumination conditions and leading to shadowing of their lower part with progressing growth. During growth, RHEED becomes increasingly sensitive to the region directly below the catalyst particle which we use for probing local changes in the crystal structure of NWs directly at the growth front. For this purpose, we estimate the impact of instrumental conditions, such as the incidence angle of the electrons, as well as structural properties, such as NW density, shape and orientation to the electron beam on the intensity evolution of RHEED during growth. Finally, our simulation model allows quantitative analysis of the time-resolved intensity evolution of phase-selective diffraction spots in the RHEED pattern and hence very precise extraction of the height-resolved distribution of the zincblende/wurtzite polytypes.

We confirm the results by simultaneously measuring the time-resolved *in situ* XRD and *in situ* RHEED signals during growth. Moreover, this combination of methods offers useful complementary information since XRD probes the whole NW volume, also the shadowed parts of RHEED.[3]

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P2.09 - TEM study of growth mechanisms of highly ordered ZnO nanorods

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Keywords: ZnO, TEM, nanorods

Zinc oxide (ZnO) is a well-known semiconductor material with a wide direct band gap (E_g~3.3 eV at 300 K) and a variety of nanostructures with a broad application potential. Particularly ZnO nanorods (NRs) have received considerable interest as building blocks of gas sensors, piezoelectric nanogenerators, photovoltaic devices, or pressure sensors.[1] Most of the applications require position-controlled ordered arrays of physically identical ZnO NRs. Position-controlled nanorod arrays can be obtained by selectivearea epitaxy on a suitable seed layer or substrate. The arrangement of the NRs in hexagonal arrays with equal distances between the nearest neighbors is fundamental for the growth of the NRs with identical physical properties.

The ZnO arrays were prepared by chemical bath deposition (CBD) through a poly(methyl methacrylate) (PMMA) mask on a sol-gel deposited ZnO seed layer or on a GaN substrate. Low growth temperature, reproducibility, and low cost are the most significant benefits of CBD. The PMMA on the seed layer was patterned by electron beam lithography (EBL). Patterning of the PMMA on the GaN substrate was performed by focused ion beam lithography (FIBL).

We present a detailed TEM study of the interface between the ZnO nanorods and the ZnO seed layer and of the body of ZnO NRs. We answer the question how the parameters of the growth process, such as the growth temperature, the concentration of precursors, and the growth time, affect the density and type of defects in ZnO NRs.[2]

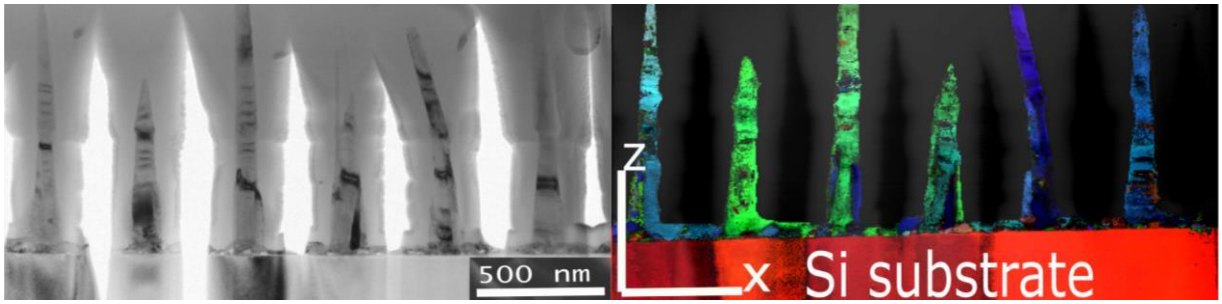

Figure 1. *TEM image of the ZnO NR (left) and nanodiffraction image showing the orientation of the NRs and of the crystallites forming the seed layer in the x-direction (right).*

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[2] University project GA UK No. 1501318 and The Czech Science Foundation project 17-00355S

P2.10 - Compositional analysis of InP/GaInAs heterostructure nanowires grown by self-catalytic VLS mode using MOVPE

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Keywords: self-catalytic VLS, hetero structure, InP

Self-catalytic VLS mode is one of the growth procedure for the III-V nanowires where the group III metal of nanowire use as catalysts. We have grown the InP nanowires and InP/GaInAs heterostructure nanowires by MOVPE using indium droplets as catalysts on InP substrate. In this paper, we have shown the compositional analysis of InP/GaInAs heterostructure nanowire by EDX.

InP/GaInAs heterostructure nanowires were grown on (111)B InP substrate. First, InP substrate was heated at 470 ^{o}C to obtain the In rich surface. Then the temperature was decreased to 400 ^{o}C, TMI was supplied to make In droplets. InP and GaInAs heterostructure nanowires were grown by supplying TMI, tBP and TEG, TMI, tBA, respectively. Nanowires were consisted of InP core and 6 GaInAs layers separated by InP layers. In the growth of GaInAs layers, the supply rate of TEG, tBA and growth time were changed in each layers. Figure 1 shows the HADDF STEM image of InP/GaInAs heterostructure nanowire. We found that the thickness of GaInAs layers were proportional to the growth time.

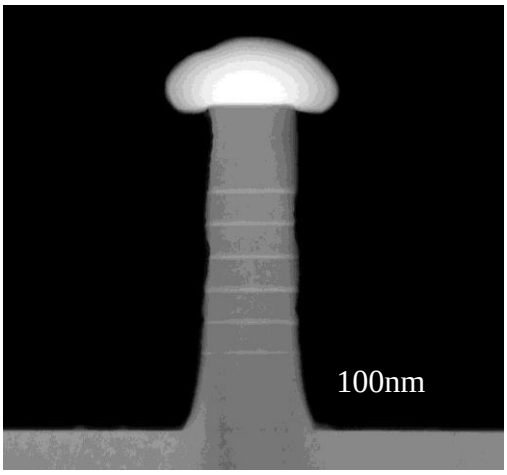

Figure 1. *TEM image of InP/GaInAs heterostructure nanowire grown by self-catalytic VLS mode using MOVPE*

The composition of this nanowire was measured by EDX analysis. From these results, the atomic percentage of In was between 50 % and 60 % in all the position. In the GaInAs layer, P was decreased below 20 % and As was increased over 30 % although the Ga percentage was around 3%. We have measured the photoluminescence from these nanowires and compared the relation between composition and PL wavelength.

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P2.11 – Advanced III-V heterostructures based on crystal phase controlled nanowire templates

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Keywords: III-V nanowire, wurtzite, zinc blende, heterostructure, MOVPE

III-V nanowires offer an ideal platform for the engineering of advanced 3-dimensional heterostructures. The unique possibility of controlled axial stacking of different crystal phases (wurtzite and zinc blende)[1] together with the core shell design allows for the combination of structural and compositional heterostructures[2–4]. This enables a variety of fundamental investigations for such structures[2,3]. Although the radial growth of compositional heterostructures can be mastered, the combination with crystal phase-controlled core nanowires is still challenging.

We present one example of aiming at full control over 3-dimensional III-V nanowire based architectures, the formation of rings of zinc blende GaAs. First, a thin zinc blende segment is axially sandwiched between wurtzite. Secondly, radial growth follows with a sequence of AlAs/GaAs/AlAs/ $Al_{1-x}Ga_xAs$ deposition. The axial GaAs wurtzite to zinc blende interfaces have a type II band alignment[5]. In combination with the radial packaging in AlAs we expect electron confinement to occur in the zinc blende GaAs rings with corresponding signatures to occur in luminescence experiments. We will present low temperature micro-photoluminescence data on such nanowire-based architectures to investigate their optical behaviour.

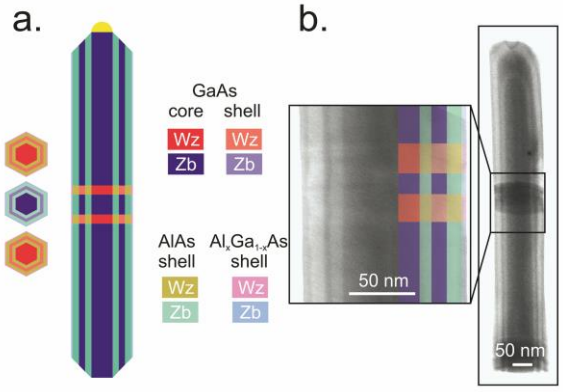

Figure 1. *(a.) Schematic view of an axial wurtzite/zinc blende heterostructure combined with a radial compositional heterostructure (GaAs-AlAs-GaAs-AlAs-$Al_{1-x}Ga_xAs$). (b.) Transmission mode scanning electron microscopic image of such a structure with axial and radial contrast differences indicating the structural and compositional heterostructure.*

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P2.12 - Atomic resolution STEM study on the interface of catalyst-free growth of InAs NWs on Si

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Keywords: Cs-corrected STEM, catalyst-free growth, heteroepitaxy

Catalyst-free heteroepitaxy growth of the III-V nanowires (NWs) on group IV materials offers an ideal platform for the integration of III-V compound semiconductors with silicon-based microelectronics. However, large lattice mismatch between most of the III-V materials with group IV materials has always been an obstacle for the heteroepitaxy growth. Taken the combination of InAs and Si as an example, lattice mismatch as large as 11.6% has to be overcame in order to integrate this high electron mobility material with silicon.

To understand the nucleation mechanism of the catalyst-free growth of large lattice mismatched NW system, taken the growth of InAs NWs on silicon for instance, we have performed chemical beam epitaxy growth of InAs NWs without assistance of any catalyst nanoparticles on silicon with different substrate etching and growth parameters. The microscopic morphology of the as grown sample taken by scanning electron microscopy reveals that both InAs islands and nanowires are grown on the HF treated Si wafer. In order to inspect the InAs/Si interface, the samples were then cut along the NWs growth direction by focus ion beam and then studied by Cs-corrected scanning transmission electron microscopy.

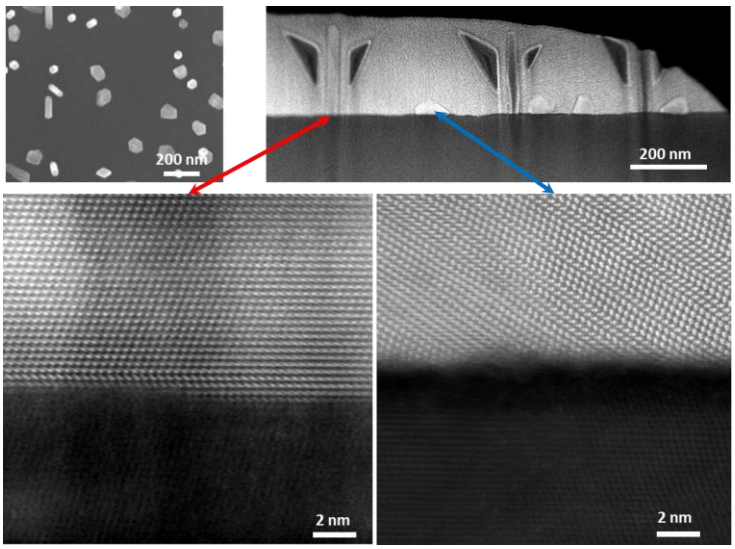

Figure 1. *Top row: SEM of tilted as grown InAs NWs on silicon (left) and the FIB cross-section lamella of the as grown sample (right). Bottom row: atomic resolution STEM-HAADF image of the NW/silicon (left) and island/silicon interfaces.*

With the help of the atomic resolution STEM-HAADF image and strain analysis, we have revealed the defect formation in at the InAs/Si interface and the growth mode dependence. The As-terminated first monolayer is suggested to be the initiation of the NW growth and the multinucleated In terminated initial layers are suggested to be the starting point of the growth of the InAs islands.

P2.13 - Crystal phase selective bismuth incorporation in GaAs nanowires

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Keywords: Bi incorporation, STM, GaAs nanowire

Bismuth (Bi) incorporation and alloying in III-V semiconductors such as InAsBi and GaAsBi have become a popular topic during recent years, due to a number of promising properties including band gap engineering, a large spin-orbit splitting, and predicted band inversion and topological behavior in the case of high Bi concentrations.[1] However, the realization of alloys with high Bi content by epitaxial growth has remained challenging. We follow a different approach and deposit Bi onto GaAs nanowires (NWs) containing both zinc blende (Zb) and wurtzite (Wz) facets, allowing us to study the incorporation of Bi atoms in different surface facets by scanning tunneling microscopy and spectroscopy (STM/S). In a similar way, our previous STM/S studies on GaAs:Sb NW surfaces showed a preferential incorporation of Sb atoms into GaAs{110} surfaces of Zb segments compared to GaAs{11-20} surfaces of Wz segments.[2] Here, we present STM/S studies obtained at 5K on the effect of Bi deposition on the morphology and electronic properties of GaAs NWs. We observe that Bi atoms tend to replace As atoms in the GaAs NW surfaces and form GaBi bonds, which have been considered to be unstable,[3] resulting in a band gap reduction. What's more, we also find a crystal structure dependent surface alloying process, where ordered Bi layers and atomic chains are formed on Wz {11-20} facets (Fig. 1A), while randomly distributed single Bi sites are found on Zb {110} facets (Fig. 1C). Lastly, signs of a length-dependent energy confinement effect in Bi-chains on Wz {11-20} facets are observed via STS.

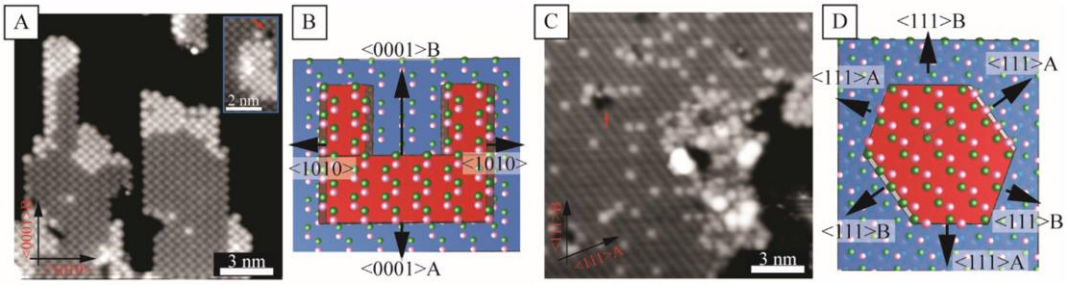

Figure 1. *STM images of the Bi incorporation within the topmost GaAs surface layer on the Wz {11-20} (A) and Zb {110} (C) facets of the NW, (B) and (D) show the model of the Wz{11-20} and ZB{110} surfaces.*

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P2.14 - Epitaxy and interfaces in hybrid nanowires for Majorana-based topological quantum computing

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Keywords: SAG, epitaxy, hybrid systems

One of the current endeavors in quantum technology consists in the development of topological quantum computers, which stand out as promising candidates because, contrary to the quantum states of ordinary individually trapped particles such as electrons, the topological properties of the quantum system ensure a higher stability when subjected to small perturbations [1]. Among the different classes of topological states, the so-called Majorana bound states are of great interest, as signatures of their appearance have been observed recently in hybrid III-V semiconductor-superconductor nanowires.[2-3] A way to induce the topological properties, without the need of external magnetic fields that could modify the band structure of the nanowire, is given by the coupling to ferromagnetic insulators. Composite tri-crystals of semiconductor-ferromagnetic insulator-superconductor materials, such as InAs-EuS-Al, have been proposed to overcome the challenge of building adequate topological systems[4], where the absence of crystal defects and impurities, particularly at the interfaces between materials, is of extreme importance[5,6].

Over the past years, nanowires have been mainly grown from a Vapor-Liquid-Solid (VLS) approach. However, integration of these unidimensional systems into functional devices remains challenging. For that reason, the development of high quality Selected Area Grown (SAG)[7,8,9] nanowire networks for is of special interest for the creation of a basis of topological quantum systems.

Our work is centered in the study of crystal quality at the heterointerfaces of our hybrid nanowires grown by VLS and SAG routes. Aberration corrected HAADF-STEM together with EELS and simulations have allowed us to evaluate, with atomic column precision, the quality of interfaces between the different constituents in varying geometrical layouts and growth conditions to observe favored crystal orientations depending on the promoted nanowire facets.

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P2.15 - Bi segregation in GaAs/GaAsBi/GaAs core-multishell nanowires

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Keywords: GaAs, Molecular beam epitaxy, segregation, Bismuth

GaAs-related compound semiconductor nanowires (NWs) can be applicable to nanoscale near-infrared optoelectronic devices. We have studied the growth and characteristics of Bi diluted GaAsBi containing nanowires focusing on its structural and optical characteristics.[1-3] We grew GaAs/GaAsBi/GaAs core-multi shell nanowires having Bi concentration of 2% at the GaAsBi shell by molecular beam epitaxy. The GaAs core was initially nucleated by the vapor-liquid-solid growth with constituent Ga catalyst. And afterwards we grew the shell layers under vapor-solid growth.[2] As seen in Fig. 1, we observed formation of core multi-shell structure from the cross-sectional scanning transmission microscopy (STEM). The cross section showed hexagonal structure with sharp facets with smooth sidewall even though the wire surface showed very rough surface from the SEM observation. The longitudinal and lateral cross section showed characteristic intensity modulation of the Bi element at the energy dispersive x-ray spectrometry (EDX) investigations. As seen in the figure, the Bi showed accumulation at the localized area, forming Bi rich clusters at the vertex of the hexagonal GaAsBi vertexes. The Bi rich area probably have smaller band gap, larger lattice constant, and three dimensionally specific strain status. Hence, these Bi segregation and the resulting Bi-accumulated nanostructures would be able to be applicable as quantum confined structures.

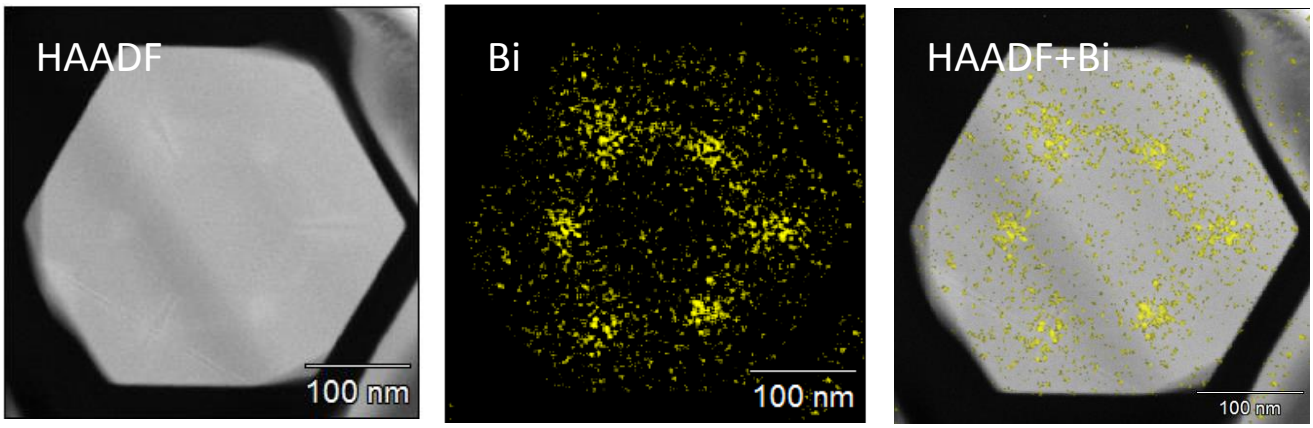

Figure 1. *Observed Bi accumulation in cross sectional STEM and EDX measurement of the GaAs/GaAsBi/GaAs core-multishell nanowires. The Bi was segregated and accumulated at the vertex direction within the shell.*

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P2.16 - The non-catalysed growth of NiSi nanowires observed *in situ* in the environmental transmission electron microscope

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Keywords: NiSi nanowires, in situ TEM, non-catalysed nanowire growth

Metallic nanowires (NWs) maybe of interest in many nano-electronics or plasmonics applications. Nanowires based on silicon are of particular interest as they are naturally compatible with Si technology. Among the latter, NiSi NWs are very conductive and could replace copper connections or transparent conductive oxides.[1] Regarding fundamental materials science, their growth occurs **in absence of a catalyst** and, so far, has not received a sound explanation. The aim of the present work is to understand this mechanism, by observing it *in situ* in the environmental transmission electron microscope (ETEM), in real time, and at the atomic scale.

Figure 1(left) shows a low-magnification image of the NWs grown *in situ* between 400°C and 450°C, using a mixture of SiH_4:H_2 1:250 at 4 Pa. Diffraction patterns of these wires generally correspond to the Ni_3Si_2 bulk structure but, quite interestingly, energy-dispersive X-ray spectroscopy gives a composition close to Ni:Si 50:50. Moreover, that phase is not the one which exists during growth: we see the passing of a phase boundary which stops the growth when it reaches the NW tip. Let us note here that this information would have remained hidden without *in situ* observation. The phase during NW growth is still under investigation. Figure 1(right) shows the passing of the phase boundary at the growth temperature.[2]

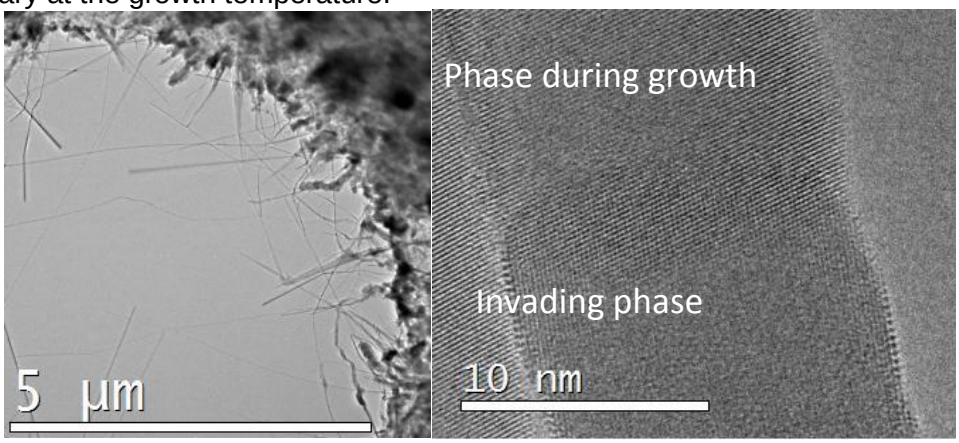

Figure 1. *left: general view after growth. Right: high resolution image of a nanowire showing the passing of the phase boundary.*

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P2.17 - III-V core / oxide shell nanowires for water splitting

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Keywords: IIIV Nanowires, core – shell, water splitting

Solar fuel cells are one of the most promising approaches of alternative energy production in the global effort to diminish fossil fuels[1]. In this context, III-V nanowires (NW) based photoelectrodes[2-6] are particularly attractive thanks to their high surface / volume ratio and their efficient charge separation and collection. Moreover these NWs can be integrated on low cost substrate and light absorption can be significantly improved in NW arrays. However III-V NWs suffer from corrosion in aqueous electrolyte that prevents their utilization for long period. In order to avoid the surface degradation of the III-V NW during photoelectrochemical cycle a particular attention has to be given to their surfaces. We proposed to grow an oxide shell transparent to visible light and compatible with the carrier transfer from the III-V to the electrolyte to increase the viability of these photoelectrodes.

GaAs NWs were grown by Molecular Beam Epitaxy (MBE) using the Vapor Liquid Solid method on silicon substrate. We used a capping / decapping process to protect III-V NWs facets before the growth of the oxide shell in another reactor. The capping was achieved with As at low temperature. Our *in situ* transmission electron microscopy (TEM) studies of the As decapping shows a two steps process. The first step consists in a crystallization process of the amorphous As phase around 300 ° C. In the second step, from 330 °C, the As shell desorbs and clean GaAs facets are obtained. Finally this method enables to obtain high surface quality before the oxide shell growth. TiO_2 and other oxide shell were deposited by atomic layer deposition or MBE. Their morphology, surface chemistry and structure were studied by transmission electron microscopy and x-ray photoelectron spectro(micro)scopy.

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P2.18 - GaAs-AlGaAs quantum well tube nanowires: correlating luminescence with nanowire size and inner multi-shell 3D structure through nano-scale spectroscopic imaging and transmission electron microscopy tomography

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Keywords: GaAs-AlGaAs core-multishell nanowires, cathodoluminescence, scanning transmission electron microscopy tomography

Quantum-confined III-V nanowires (NWs), such as quantum well tube (QWT) structures,[1] impact the design of NW-based photonic devices. Robust nano-scale correlation between the NW inner structure and related luminescence is required to fully understand the origin of radiative emissions and the nature of QWT confined carrier states. In this work MOVPE-grown GaAs-AlGaAs QWT NWs were studied by cathodoluminescence (CL) spectroscopic imaging in combination with scanning transmission electron microscopy (STEM) tomography, allowing for the first time nano-scale correlation between CL properties of as-grown NWs, their actual size and inner three-dimensional (3D) structure. Besides the core luminescence and defects-related contributions, each NW showed one or more QWT peaks, associated with regions of different diameters. Values of GaAs-shell thickness corresponding to each QWT peak were then determined from the NW diameters by employing a multi-shell growth model,[2] upon validation against experimental data obtained from analysis of the 3D-reconstructed STEM tomogram of QWT NWs.[3] We found that QWT peak energies as function of as-estimated (3-7 nm) GaAs-shell thickness are 40-120 meV below theoretical values of exciton recombination for uniform QWTs symmetrically wrapped around the core.[1] Analysis of the 3D tomograms further evidenced azimuthal asymmetries, and (azimuthal and axial) random fluctuations of the GaAs shell thickness, suggesting that the observed QWT emission redshift is prominently due to carrier localization. Indeed, CL mapping of QWT emission intensities along the NW axis allowed to image nano-scale localization of the emission (Fig. 1).

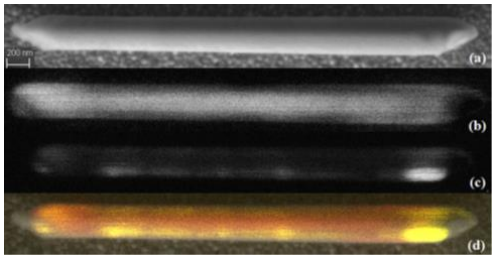

Figure 1. *(a) FE-SEM micrograph of a single core-multishell NW. Monochromatic CL images of the NW emission recorded at (b) 1.507 eV (core emission) and (c) 1.540 eV (QWT emission). (d) color-coded (red: core; yellow: QWT) superposition of the two images in (b) and (c) allows to better visualize spatial localization of the QWT emission.*

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P2.19 - Impact of electrical current on the structural properties of single as-grown GaAs nanowires

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Keywords: electrical conductivity, structural characterization, nanowires

In order to improve the performance of nanowire (NW)-based devices, it is crucial to understand the correlation between electrical and structural properties[1] at the individual nanostructure level. Here, we go one step further and systematically investigate the impact of electrical current passing through single GaAs NWs on their structural properties. Be-doped GaAs NWs grown by molecular beam epitaxy onto a pre-patterned Si 111 substrate were studied in three phases. In the 1st phase, we recorded reciprocal space maps (RSM)s of the symmetric 111 Bragg reflection from single NWs by means of nano-X-ray diffraction (nano-XRD) performed at beamline P23 of PETRA III. The respective Bragg reflection provides information about the axial lattice variation within the NW, shape/dimension, and its tilting with respect to the substrate normal (Figure 1a). In the 2nd phase, electrical current was applied to the same NWs in their as-grown geometry using the nano-probe of a FIB/SEM system at the University of Siegen (Figure 1b). Note that current-voltage curves were obtained systematically from those individual NWs that had been characterized before by nano-XRD. The 3rd phase was similar to the first, i.e. RSMs of the 111 Bragg reflection were acquired from the same NWs (Figure 1c).

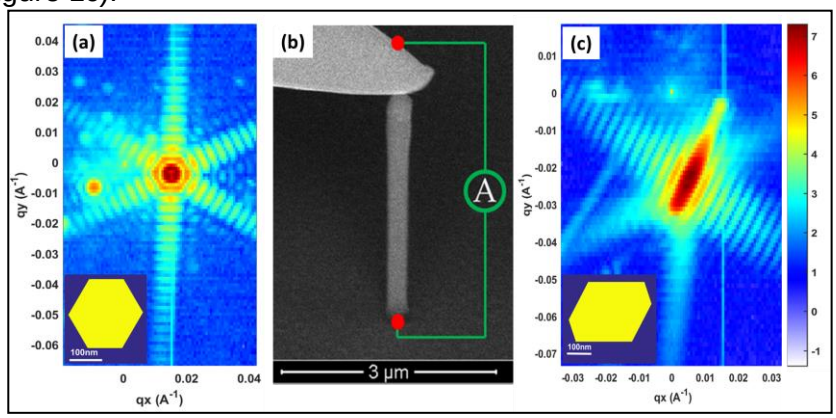

Figure 1. *Qx-Qy projection of 3D RSM of a single NWs before (a) and after (c) electrical Conductivity Measurement (b).*

Our results suggest significant changes in the NW morphology as a function of the electrical current running through the NW. These changes include deformation of crystallinity in the hexagonal symmetry of the NW cross-section, tilting and even bending, and finally possible introduction of defects within the crystalline lattice.

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P2.20 - Individual InAs nanowires for conductometric sensing

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Keywords: InAs nanowires; gas sensing; electrical transport; single nanowire device.

In this work, we used individual InAs nanowires to realize gas sensing devices for environmental monitoring application. Nanostructured materials have the advantage of large surface-to-volume ratio while single crystalline nanowires add stability and well defined crystalline facets exposed to gas. Nanowire arrays are exploited in sensing devices [1,2], yet they may suffer from considerable size dispersion and display unease of implementing electrical contacts in a vertical ensemble geometry. Individual nanowires overcome these limitations and provide unique opportunities for probing the surrounding environment at the nanoscale. Wurtzite InAs nanowires, prepared by gold-catalyzed chemical beam epitaxy [1] were provided with electrical contacts at both ends, exploiting the single nanostructure as building blocks to realize two different architectures of conductometric sensors: (a) the nanowire is in contact with SiO_2/Si substrate, and (b) the nanowire is suspended at approximately 250 nm from the substrate. We tested the source-drain current in presence of different chemical species diluted in synthetic air: humidity, ethanol and NO_2. We have to remark that a room temperature operation is demonstrated for both configurations. The comparison of the two different device architectures was made towards humidity: the results show that the availability of larger area of the nanowire surface for gas interaction in suspended nanowires is not reflected into a higher sensor response. The performance of the better performing substrate-bound device was then tested with NO_2 and ethanol, showing high response to NO_2 (in the ppm range), and Ethanol diluted in dry air. The current results provide new insights in the gas sensing device made of InAs nanowires in real operating conditions.

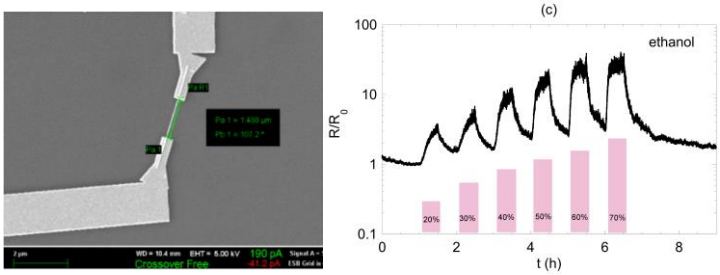

Figure 1. *(Left) SEM image of the individual nanowire device. (Right) Dynamic current variation as a function of the ethanol concentration (from 20% to 70%) at room temperature.*

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P2.21 - Self-Assembled InAs Nanowires as Optical Reflectors

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Keywords: Reflectivity, nanofluidics, core-shell

Subwavelength nanostructured surfaces are realized with self-assembled vertically-aligned InAs nanowires, and their functionalities as optical reflectors are investigated.[1] In our system, polarization-resolved specular reflectance displays strong modulations as a function of incident photon energy and angle. An effective-medium model allows one to rationalize the experimental findings in the long wavelength regime, whereas numerical simulations fully reproduce the experimental outcomes in the entire frequency range. The impact of the refractive index of the medium surrounding the nanostructure assembly on the reflectance was estimated. In view of the present results, sensing schemes compatible with microfluidic technologies and routes to innovative nanowire-based optical elements are discussed.

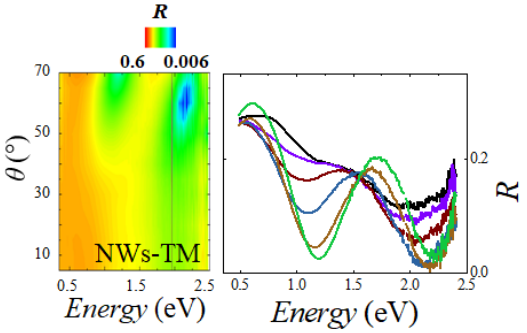

Figure 1. *Angle- and energy-resolved reflectance modulations in InAs nanowire assembly.*

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P2.22 - Probing the optical properties of III-V nanowires for optoelectronic applications

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Keywords: GaAs, AlGaN, doping

The most widely used semiconductors for optoelectronic applications are the compounds based on group III and group V elements. GaAs and related alloys are mostly used for near infra-red optical communications, near infra-red and visible light emitting diodes (LEDs) as well as solar cells. While, GaN and AlGaN are interesting in the short wavelength range for LEDs, solid-state lasers and color displays. Optoelectronic devices based on novel semiconductor nanowires (NWs) are foreseen to revolutionize nowadays technology in terms of superior performance and efficiency, besides the reduction of costs and material consumption.

The use of semiconductor NWs integrated in devices is governed by the realization and control of p-n junctions, obtained by the p and n-type doping of the base materials. Furthermore, for solid state emitters, the semiconductor NWs' emission can be tuned by incorporating rare earth ions via implantation and post-growth annealing. Doping can be performed by intentionally adding dopants during the growth (in-situ) or after the growth (ex-situ) by ion implantation. However, several issues and controversies still need to be investigated in order to access/control semiconductor properties at the nanoscale level.

In this work, we present our recent results on semiconductor NWs grown by molecular beam epitaxy: i) $Al_xGa_{1-x}N$ ($0 \leq x \leq 1$) NWs on Si (111) substrate implanted with europium (Eu) ions for efficient red nano-emitters[1], and ii) silicon-doped GaAs NWs on GaAs (111)B substrate with different silicon doping levels[2]. The optical and vibrational properties of these nanostructures, of utmost importance for optoelectronic applications, will be assessed using photoluminescence, cathodoluminescence and micro-Raman spectroscopy[3].

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P2.23 - Growth of germanium nanowires using isobutyl germane and their structural and electrical characterization

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Keywords: Germanium nanowires, growth, characterization

We report on the growth, structural and electrical characterization of germanium nanowires (NWs), proposed as a building block for the realization of novel sensors tailored to explosive detection.

Germanium NWs were grown by Vapor Phase Epitaxy using isobuthyl germanium, a novel Ge source as an alternative to the more commonly used germane.

The NW are grown using the standard Vapor Liquid Solid method on (001) and (111) silicon and germanium substrates, using gold nanoparticles of different size (20-80 nm) as catalyst.

Details of the growth process and the growth conditions will be discussed, with particular emphasis on the control of the length of the NWs and their tapering. Different NW density and orientations are obtained, depending on the precursor flow and on the substrate orientation. The NW crystalline structure was observed by Transmission Electron Microscopy (TEM), evidencing their high structural quality.

The optimization of the growth procedure resulted in Ge NWs up to 30 □m in length, vertically oriented on Ge (111) and Si (111) substrates.

The NWs were detached from the substrates with ultrasonication and dispersed on a carrier substrate with Au interdigitated electrodes. Single NWs were observed with Scanning Electron Microscopy (SEM) and contacted to Au electrodes with Pt deposited by Focused Ion Beam (FIB). Pt contacts were deposited with 50 pA and 30 kV ion beam current and acceleration voltage, respectively, at each ends of the NW. Linear I-V characteristics showed the ohmic nature of Pt-NW contacts. From RT resistance measurements, using two-terminal configuration, we obtained NW electrical resistivity values in the 0.05 - 0.5 ohm cm range.

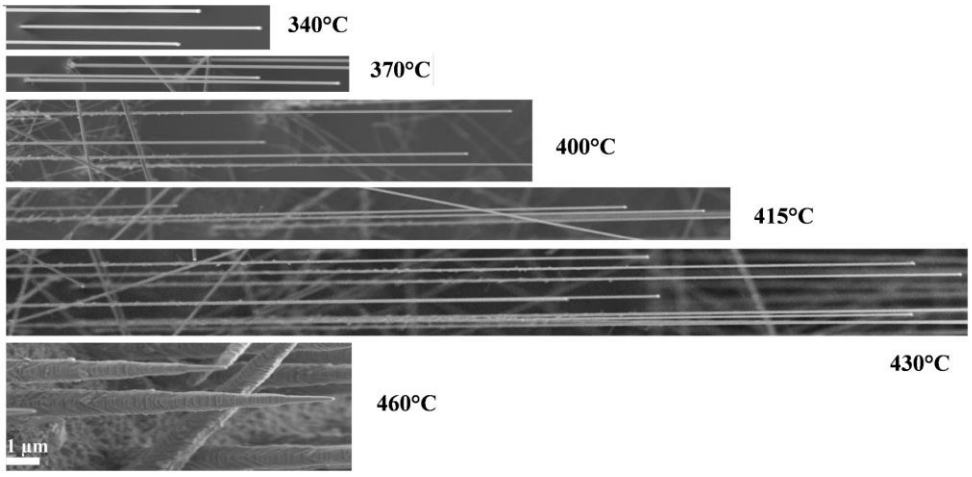

Figure 1. *Germanium nanowires growth at different temperatures*

P2.24 - Self-closing Au-coated silicon nanowires for surface-enhanced Raman spectroscopy

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Keywords: self-closing nanowires, metal-assisted chemical etching, surface-enhanced Raman spectroscopy

Controlling the location and distribution of hot spots, localized regions of extremely large enhancement, is a fundamental aspect of the fabrication of detection substrates for surface-enhanced Raman spectroscopy (SERS). This powerful vibrational spectroscopic technique requires substrates to provide significant enhancement and acceptable homogeneity for chemical and biological sensing. In recent years, the employment of self-closing 3D structures has served the purposes of hot spots engineering.

A versatile fabrication protocol has been developed for the realization of gold-coated silicon nanowires exploiting the combination of nanospheres lithography (NSL) and metal-assisted chemical etching (MACE). MACE allows a fine tuning of the length of the nanowires reaching high aspect ratios, prohibitive for standard reactive ion etching techniques, so to achieve highly flexible structures. The flexibility of the nanowires has been highlighted as the essential parameters to allow the formation of self-closing bundles of nanowires. The hot spots are located in the nanometric gaps at the tip-to-tip sites where the probe molecule is trapped [1]. On the other hand, the optimization of the lithographic parameters in NSL guarantees hot spots distributions across the substrate with long-range order, quantitatively evaluated by means of the correlation length parameter. Moreover, the density of the hot spots is maximized through the hexagonally close-packed symmetry of the nanostructures leading to large enhancement [2].

The performances of the substrate in analytical chemistry have been tested with model SERS-active molecules reaching high sensitivity with detection in the picomolar range of concentration.

Figure 1. *Cross-section scanning electron microscope (SEM) micrograph of the self-closing gold-coated silicon nanowires.*

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P2.25 - Probing Electronic Band Structure of Hexagonal Gallium Phosphide using Photoluminescence Excitation Spectroscopy

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Keywords: Wurtzite Gallium Phosphide, Valence Band Splitting, Photoluminescence Excitation

Hexagonal Gallium Phosphide is a large gap III-V compound appropriated for optoelectronic applications due to the pseudo-direct band gap[1]. However, basic parameters as the exact value of the fundamental gap and band splitting are still under debate, moreover, previous works have reported distinct optical results.[1-3]

Here we present a comprehensive study about wurtzite (WZ) GaP optical properties, grown with diameters in the micrometer range by Chemical Beam Epitaxy using a nanoparticle assisted method in which Vapor-Solid growth is enhanced, in order to provide a large volume of WZ GaP.[3]

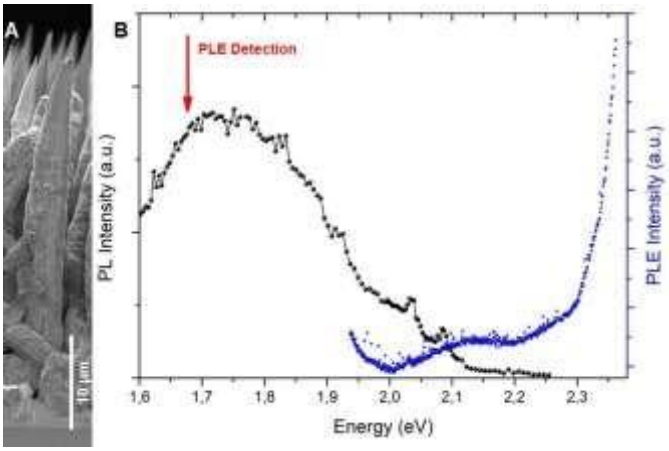

Figure 1. *(A) Side-view* SEM Image of GaP structures grown for 6 hours. *(B) Macro-PL and PLE spectra of the GaP structures performed at 10K, red arrow indicate the detection at 1.68 eV used in PLE measurements. A Xe lamp was used as excitation source for PLE experiments.*

Low temperature (10 K) micro and macro-photoluminescence (PL) and macro-photoluminescence excitation (PLE) techniques were used in this work. The both micro and macro-PL spectra show sharp emissions attributed to the bound exciton recombination around 2.0-2.1 eV and FWHM of approximately 1 meV and an additional broad band usually attributed to the deep level states. The absorptions around the fundamental band gap transitions have been measured by PLE. The feature shown between 2.0-2.1 eV can be related to the impurity transition and the absorption edge at ~ 2.2 eV is due to the fundamental band gap at 10 K, in agreement with the previous report. Additionally, the high energy absorption edges are due to the valence band splitting.

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P2.26 - Raman characterization of GaAs-Ge and GaAs-SiGe core-shell NWs

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Keywords: Raman; Hexagonal SixGe1-x; Core-shell nanowires

Semiconducting nanowires (NWs) are well established as very interesting systems for their optical and thermoelectrical properties, when compared to the corresponding bulk material. Their great potential lies in the possibility of tuning their characteristics through the synthesis process. Much work has been done to assess and to gain control of optical and electronical properties of NWs, and in this regard the use of group IV semiconductors (notably Si and Ge) in optoelectronics is limited by the indirect nature of their band-gap, that precludes easy integration with the widespread Si-based technologies. This stands when considering the cubic structure materials, but recent advances in NW synthesis made available crystal phases before only attainable in bulk under extreme conditions.[1]

For this work, the crystal structure transfer technique has been employed to produce hexagonal phase GaAs-Ge and GaAs-SiGe core-shell NWs.[2]

Different growth times and temperatures have been used for the GaAs-Ge NWs, to test the influence of these parameters on defect density and shell thickness.

The GaAs-SiGe NWs have been prepared in a variety of compositions, in order to investigate the effects of Si substitution in Ge over a wide range of cases. SEM, mass spectroscopy, atom probe tomography and XTEM analysis have demonstrated good control of the synthesis process.

We performed spatially resolved Raman spectroscopy measurements on these samples examining the spectra of single NWs. We mapped the response of WZ Ge with respect to the exciting and scattered light's polarizations and with respect to the excitation wavelength.[3]

We explored the behaviour of WZ Si_xGe_{1-x} phonon modes with respect to the Si fraction (x = 0.1, 0.2, 0.3, 0.4 and 0.5) in polarization dependent experiments. Together with theoretical calculations based on DFT and phonon optimized potentials, these analyses confirmed the formation of hexagonal phase materials and gave us broad insight into their phononic and optical properties.[4,5]

The results of this work constitute thus a first step towards a better understanding of direct band-gap group IV semiconductor NWs, promising materials for optoelectronic applications, and can be the basis of phonon engineering in alloy NWs.[6]

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P2.27 - Zinc phosphide nanowire growth by molecular beam epitaxy and their functional properties

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Keywords: zinc phosphide, growth, arrays

With an increasing demand for renewable energy, material solutions relying on readily available, earth-abundant materials become imperative. One material with potential as a photovoltaic absorber is Zn_3P_2, however, there are challenges in achieving high crystal quality and controllable doping in this material. The inability to find appropriate substrates with a matched lattice structure for epitaxial growth and the high thermal expansion coefficient of Zn_3P_2 make it difficult to produce high-quality crystalline material. To improve on these aspects, we explore growing Zn_3P_2 nanowires using molecular beam epitaxy (MBE), where the nanowire morphology allows for radial stress relaxation and improved crystal quality. Furthermore, Zn_3P_2 growth by MBE utilises growth temperatures significantly lower than other techniques, reducing the thermal expansion influence, whilst also allowing for precise control of the growth fluxes and introduction of dopants.[1,2]

Here we report Zn_3P_2 nanowires grown on InP (1 0 0) using In-catalysed vapour-liquid-solid growth in four different morphologies: vertical, zigzag, straight-tilted, and horizontal. The catalyst droplet nucleates preferentially at surface defects, allowing for tuning of the nanowire density by brief ion beam etching to induce defects. Furthermore, by adjusting the Zn to P ratio we can grow vertical Zn_3P_2 nanowires of different composition, varying from Zn-rich to P-rich. This has been shown to affect the intrinsic carrier type, opening the formation of homo-junctions in a single nanowire.[2] The optical properties of Zn_3P_2 nanowires were investigated by cathodoluminescence spectroscopy at 10 K. Compositional dependent emission from the vertical nanowires was observed in the range 1.32-1.35 eV, which is lower than the reported band gap and may originate from structural defects or InP quantum dots that form on the surface of the nanowires. To optimise these nanowires for devices, we further investigated their growth in arrays generated with an oxide mask patterned by electron beam lithography.

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P2.28 - Correlated nanoscale analysis of the emission from wurtzite versus zincblende (In, Ga)As/GaAs nanowire core-shell quantum wells

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Keywords: Polytypism, core-shell heterostructures, spatially-resolved measurements

Polytypism in semiconductor nanowires (NWs) has been extensively studied in the last years, although mostly in binary NWs, while its role in ternary alloys remains largely unexplored. Most eminently, the properties of wurtzite GaAs have been the subject of numerous publications, but little is known about the influence of the crystal polytype on ternary (In,Ga)As quantum well (QW) structures. In this work, we employ a combination of correlated, spatially-resolved measurement techniques to investigate core-shell NWs that contain extended segments of both the zincblende (ZB) and wurtzite (WZ) polytypes. Extended polytype segments are evidenced by electron backscatter diffraction (EBSD) and the growth of WZ is attributed to the droplet consumption during the final stage of the GaAs core growth. Cathodoluminescence (CL) spectral imaging reveals a blueshift of the QW emission energy by about 75 meV in the WZ segment. Nanoprobe x-ray diffraction (nXRD) and atom probe tomography (APT) enable k · p calculations for the specific sample geometry to unravel two comparable contributions to this shift. First, there is a 30% drop in In mole fraction going from the ZB to the WZ segment. Second, the QW is under compressive strain, which has a much stronger impact on the hole ground state in the WZ than in the ZB segment. These results highlight the role of the crystal structure in tuning the emission of (In,Ga)As QWs and pave the way to exploit the possibilities of three-dimensional bandgap engineering in core-shell NW heterostructures. Moreover, the set of correlated characterization techniques demonstrated in this work constitutes an advanced analytical toolkit for the investigation of semiconductor nanostructures.[1]

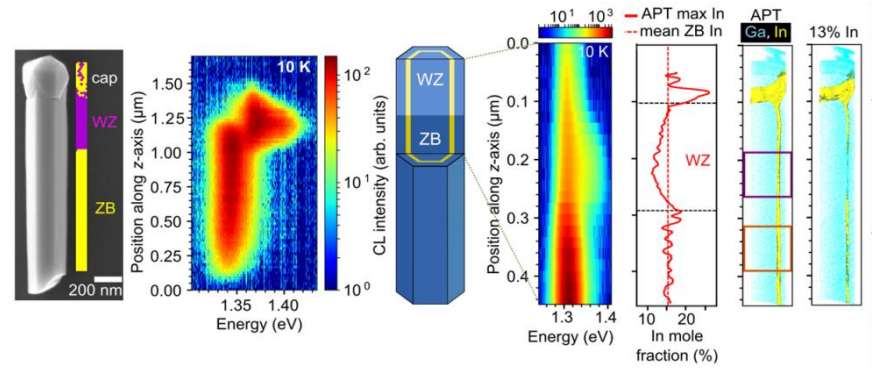

Figure 1. *Correlated EBSD and CL data (left) and CL and APT (right) for single (In,Ga)As QW NWs.*

Reference

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P2.29 - Passivation study of InP nanowires using TRPL and EBIC

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Keywords: InP, TRPL, EBIC

Photovoltaics is a promising technology for sustainable energy production. Nanowire solar cells are interesting because they only use a fraction of the active material while reaching similar efficiencies of photon absorption like thin films. In order to characterise as-grown photovoltaic nanowires and optimise growth parameters, electron-beam-induced current (EBIC) has been used[1]. However, due to the high surface-to-volume ratio in nanowires, surface passivation can play a crucial role to charge carrier dynamics[2], even though the surface recombination velocity of InP is quite low[3].

In this study, two approaches to investigate surface passivation of InP nanowires are presented. Firstly, by measuring TRPL the charge carrier lifetimes of InP nanowires with and without passivation layer are compared for nominally intrinsic (*i*), *p*-doped and *n*-doped (exemplarily shown in figure 1a) nanowires. Secondly, InP nanowires with *p-(i)-n* junctions with varied doping in the middle segment were investigated by EBIC. This demonstrated a field-effect of the passivation layers that changes the position and width of the depletion region, as shown by the data in figure 1b.

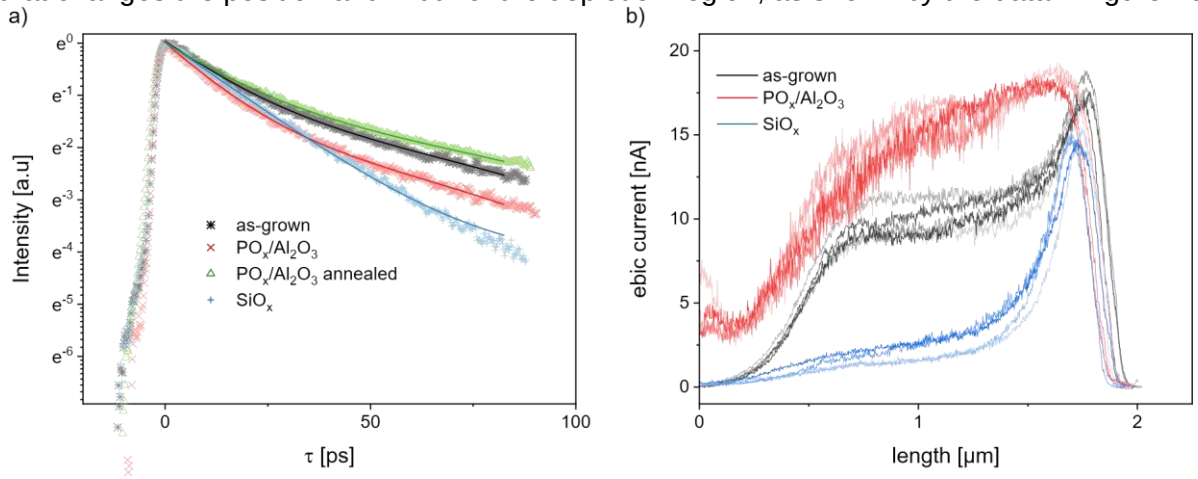

Figure 1. *a) TRPL of n-doped InP nanowires that are as-grown (black), or covered with PO_x/Al_2O_3 (red line before annealing and green line after annealing), or covered with SiO_x (blue). b) electron beam induced current of InP nanowires with a p-(i)-n junction. The same oxides as in a) are deposited and influence the junction by a field-effect.*

The comparison of the results of both series of experiments will advance the understanding of InP nanowire surface passivation, which is essential to produce InP nanowire solar cells with high efficiency and the foundation for tandem junction devices.[4]

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P2.30 - Comparison of continuous growth and regrowth InP / GaInAs core-shell nanowires using self-catalytic VLS mode

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Keywords: self-catalytic VLS, core-shell, InP

InP / GaInAs core-shell nanowires were fabricated by continuous growth and regrowth methods using self-catalytic VLS mode in MOVPE. In the core-shell nanowires, InP core was grown by using Indium as a catalyst.[1] Under the continuous growth of core-shell nanowires, the catalyst of In was remained at the tip of nanowires. In the regrowth core-shell nanowires, In was removed by wet chemical etching outside MOVPE reactor after the growth of InP core, and shell layers were regrown. In this paper, we show the comparison of these two growth methods about the structure and photoluminescence spectrum dependent on the number of shell layers.

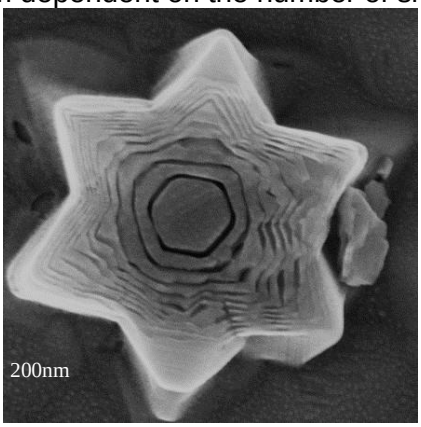

Figure1. SEM images of the cross-sections of 10 periods single-step core-multi shell nanowires

Figure 1 shows the cross-sectional image of 10 periods continuous growth core-shell nanowires observed by SEM. The cross-sectional shape of core-shell nanowires was hexagonal when the number of shell layers was low, and star-like shapes were obtained when the shell layers exceeded a specific periods.[2] These shapes were also confirmed in the regrowth nanowires. Furthermore, we have measured the photoluminescence (PL) from these nanowires and compared the spectrum between continuous growth and regrowth core-shell nanowires. The difference of PL spectrum was attributed to the existence of catalysts after the growth of nanowires.

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P2.31 - Effects of exciton localization on recombination in Ga(N)AsP nanowires investigated by cathodoluminescence spectroscopy

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III-V semiconductor nanowires (NW) represent a promising material system for future nanooptoelectronics and nano-electronics. Recent advances in growth techniques have enabled us to extend the NW growth to novel material systems, such as dilute nitride Ga(N,As,P) alloys. Alloying with nitrogen affects electronic properties of dilute nitrides and leads to the giant bowing in the bandgap energy. This enables high tunability of the bandgap energy in NWs by small alterations of the nitrogen content, advantageous for a variety of applications.[1]

The giant bandgap bowing also leads to the rather strong exciton localization within the band tail states due to local alloy fluctuations. In this work, we investigate effects of the nitrogen-induced exciton localization on carrier recombination in GaNAsP NWs grown by gas source molecular beam epitaxy on (111) Si substrates. In spite of a very low N content, [N], in these structures (up to 0.12 %), their bandgap energy can be tuned by more than 100 meV.[2] According to the performed transmission electron microscopy measurements, the NWs have predominantly zinc blende structure with a rather high density of structural defects, such as rotational twins. In the NWs with the low N content of 0.08%, these structural defects are found to promote non-radiative recombination, which causes a spatial variation of the luminescence peak position and its intensity, as revealed by cathodoluminescence (CL) measurements. We show that the exciton localization increases in the NWs with a higher [N] of 0.12%, which has several hitherto unexplored effects on the light emission in these structures. First of all, it suppresses the detrimental effects of the crystalline defects, allowing a higher and homogeneous luminescence yield along the nanowire axis. This is attributed to more efficient trapping of excited carriers/excitons to the localized states promoted by the N-induced localization and also presence of other NR channels. The increased localization also suppresses a blueshift of the emission with increasing excitation power caused by filling of the localized states. This further enhances the emission uniformity of the material. Secondly, we show that the exciton localization can be very strong, leading to three-dimensional quantum dot (QD)-like confining potentials, giving rise to very sharp emission lines in photoluminescence (PL) spectra. The formed QD are found to be randomly distributed across the NW, based on the performed CL mapping.

Our work demonstrates new avenues for bandgap and thus photonic engineering with NWs utilizing dilute nitride alloys.

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P2.32 - Si dopant incorporation studies in ordered GaAs nanowire arrays on silicon

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Keywords: III−V semiconductors on silicon, ordered array, doping

Since several decades, semiconducting nanowires (NWs) have been extensively studied for their potential in a large number of electrical and optical applications. For this potential to become a reality, mastering the doping of NWs is essential. In MBE-grown nanowires, the doping mechanism has been widely studied in the self-assembled growth regime.[1] However, self-assembly may mask additional underlying mechanisms/processes possibly leading to inhomogeneity in dopant profile along the nanowire. Here, we study the doping of GaAs nanowires obtained in an organized manner on silicon as a function of the array geometry. We first explain the mechanisms that allow us to achieve a reproducible high yield of vertical, ordered, self-catalyzed GaAs NW arrays grown on silicon by molecular beam epitaxy.[2,3] We then illustrate the homogeneity of the NW electrical properties by conductive AFM analysis on these arrays. The measurements are compared with four-point current-voltage characteristics of individual wires. In addition, effective silicon dopant incorporation as a function of the inter-wire spacing is shown, and the relevant Si dopant incorporation pathways will be discussed.

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[4] This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 722176.

P2.33 - Circumferential and one-sided (In,Ga)N shells on GaN nanowires: From self-assembled to ordered arrays

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Keywords: molecular beam epitaxy, core-shell heterostructures, cathodoluminescence

Core-shell nanowire (NW) heterostructures offer a route to increase the active region per substrate area, as the surface area scales with the NW length. For shell growth by molecular beam epitaxy (MBE), the constituents of binary and ternary materials usually impinge on different side facets due to the directionality of the molecular beams. This phenomenon has been given little attention and may detrimentally affect growth, in particular if lateral diffusion between the facets is limited, but also offers unexplored conceptual advantages. In this study, we investigate in detail the role of the flux directionality for the growth of (In,Ga)N shells around self-assembled, MBE-grown GaN NW arrays on TiN substrates.[1] This substrate choice enables a reduced NW density compared to conventional substrates such as Si, where shadowing prevents the growth of core-shell heterostructures.

For continuous substrate rotation, we demonstrate a homogeneous (In,Ga)N shell with a peak cathodoluminescence (CL) emission around 500 nm probed by hyperspectral line-scan imaging along the axis of the NWs. However, these NWs develop significantly enlarged top segments with increased In incorporation, which is unfavorable for device processing. The origin of these top segments lies in a pronounced metal diffusion towards the top of the NWs, as derived from a systematic analysis of the radial growth of GaN and (In,Ga)N shells on NWs complemented by simulations of the precursor diffusion. This diffusion is enhanced by the deposition geometry, as the anion and cation beams impinge on different side facets, while the NW top is exposed to both.

These insights lead us to an innovative approach for the shell growth: we rotate the substrate relative to the deposition sources step-by-step and pulse the shutters accordingly. This sequential procedure enables a directional deposition of (In,Ga)N even only on one side of the GaN NWs, which, for sufficiently high In content, is evidenced by a strain-induced bending of the NWs. We find that submonolayer deposition of the metals as well as the deposition sequence of In, Ga, and N, are crucial for In incorporation on the side facets. The morphology of these NWs reveals a significantly reduced growth on the top facet. By systematically varying the substrate temperature and the In/Ga flux ratio, we obtain homogeneous one-sided (In,Ga)N shells with an emission wavelength tunable between 380 and 500 nm.

We extend this approach to arrays of ordered NWs obtained by in-situ selective area sublimation of GaN templates,[2] which offer thicker (200–500 nm diameter) and more homogeneous NW cores for the subsequent (In,Ga)N growth. Again, the formation of enlarged top segments is suppressed. The shell emission is homogeneous along a single NW, but also the variation of the emission energy between NWs from the same sample is significantly reduced compared with the self-assembled NWs on TiN.

In conclusion, directional deposition opens up new perspectives for device design. Active regions with different functionalities may be combined on different side facets of one and the same NW, which, for example, could lead to RGB LEDs based on a single NW for ultra-high resolution displays.[3]

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P2.34 - Valence band splitting in wurtzite and zinc blende (Cd,Mn)Te/(Cd,Mg)Te nanowires accessed by magnetooptical spectroscopy

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Nanowires made of cadmium telluride (CdTe) crystallize both in zinc blende (ZB) and wurtzite (WZ) structures. Thanks to that, a unique opportunity to compare their valence bands arises. As shown in [1], the ZB (Cd,Mn)Te/(Cd,Mg)Te nanowires exhibit a valence band splitting with light-hole based ground state, caused by strain coming from core/shell mismatch. On the other hand, WZ nanowires have a valence band intrinsically split by crystal field with heavy-hole like ground state (A band).

Here, we present (Cd,Mn)Te/(Cd,Mg)Te nanowires grown in WZ and ZB phase by molecular beam epitaxy in vapour-liquid-solid mode. Cathodoluminescence combined with SEM and TEM is used to confirm the crystalline phase.

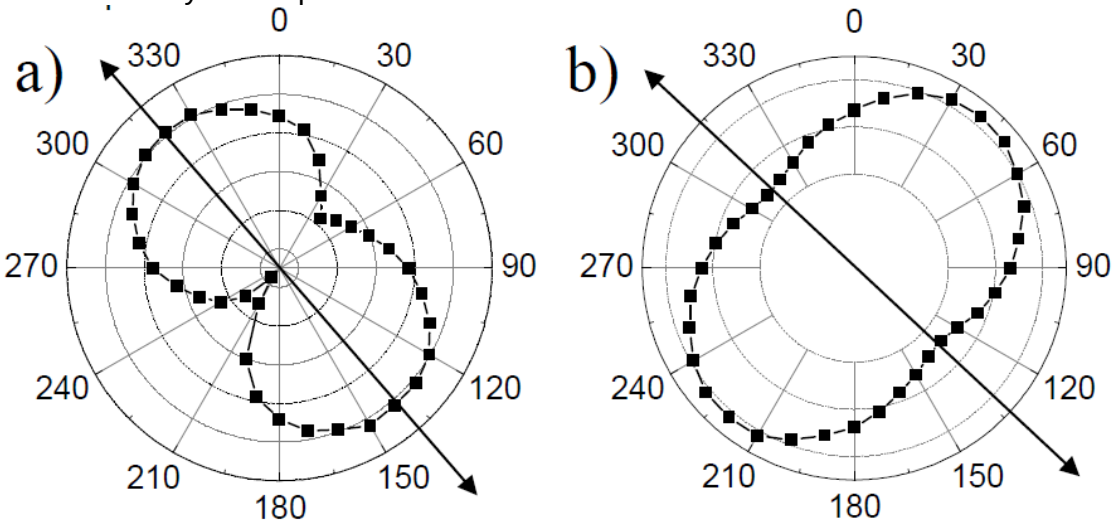

Figure 1. *Zeeman splitting in a) WZ b) ZB nanowire as a function of magnetic field direction, characteristic for a) heavy and b) light holes. Arrow marks the nanowire axis. B=2T, T≈5K, λ_{ex}=515nm*

A comprehensive comparison of the optical properties based on single ZB and WZ nanowires is presented. Significant differences are highlighted, making it easy to distinguish between those two cases. Magnetic field spectroscopy is performed, showing a different nature of the ground state – lighthole and heavy-hole like in ZB and WZ respectively.

Finally, all available data is utilized in combination with k·p calculations based on [2] in an attempt to derive valence band splitting parameters for both cases.

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P2.35 - Tailoring optical properties in nanostructured organic semiconductor

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Keywords: polymer nanowires, additive manufacturing, P3HT

Polythiophenes are the most widely employed semiconducting polymers in organic electronics. Their use in optics and photonics is instead limited by their high photo-induced absorption due to the interchain polaron pairs, which prevents the establishment of a window of net optical gain. Here we report on the photophysical properties of poly 3-hexylthiophene (P3HT) templated nanowires (NWs) with high degrees of supramolecular ordering and precise spatial organization, conferred by a soft nanolithographic fabrication approach.[1] We compared the optical properties of P3HT NWs with disordered films produced by spin coating and we found peculiar features, including a partially-polarized stimulated emission band, in contrast with the photo-induced absorption band observed in films. In combination with theoretical modelling, our experimental results reveal the origin of the primary photoexcitations dominating the dynamics for different supramolecular ordering, with singlet excitons in the nanostructured samples superseding the presence of polaron pairs, which are generally present in disordered films. The observation of optical gain opens the possibility to the use of polythiophene nanostructures as building blocks of active photonic devices and organic optical amplifiers. Moreover, we demonstrated that the manipulation of the supramolecular packing of the polymer chains is a viable strategy to direct optical properties through structural control.[2] In this framework, we are currently developing new fabrication approaches based on additive manufacturing technologies and especially on direct ink writing,[3] for the realization of organic elongated structures with controlled supramolecular order and peculiar photonic properties[4].

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P2.36 - Growth polarity switching in (Al,Ga)N/GaN nanowire LEDs studied by scanning electron microscopy related techniques

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Keywords: nanowire LEDs, cathodoluminescence, EBIC

III-N family nanowires (NWs) are promising building blocks for novel optoelectronic nano-devices including highly efficient emitters e.g. light-emitting diodes (LEDs) and lasers. The growth of high-quality nitride structures on silicon substrates enables integration with existing advanced Si microelectronics. To make possible a development and application of GaN-based nanowire structures, it is crucial to understand their fundamental optical and electrical properties. In this work we provide the nano-scale correlation of morphological, electrical and optical properties of GaN/(Al,Ga)N nanowire LEDs as observed by a combination of spatially and spectrally resolved cathodoluminescence (CL) spectroscopy and imaging, electron beam induced current (EBIC) technique and scanning electron microscopy (SEM). Local variations and inhomogeneities of optical and electrical properties and their correlation with the growth polarity of individual nanowires (which may unintentionally switch during the growth process) can be visualized by CL and EBIC contrast mapping. To complement the results, also photo- and electro- luminescence were studied. For the polarity assessment of the individual NWs Kelvin probe force microscopy and selective KOH etching procedure, were applied [1,2].

GaN/(Al,GaN) LED nanowire structures with 3 GaN quantum wells and (Al,Ga)N barriers in the p-n junction region were grown on silicon (111) substrates without any catalyst by plasma-assisted molecular-beam epitaxy. Two kinds of the NWs morphology, appearing in the same growth process were observed by SEM. Inhomogeneities of the EBIC signal as well as differences in CL spectral features, can be correlated with differences in NWs morphology related to N and Ga growth polarities. As the nanowires grow along the hexagonal axis of the wurtzite structure, they can exhibit N- or Ga-polarity on its top surface. This property strongly depends on the growth conditions, doping of the particular part of the nanowire etc. Changing of such parameters during the growth process may lead to switching of the polarity in the nanowire. The growth polarity of the NW containing the heterostructure influences strength of inbuilt piezoelectric fields, it can also determine whether the structure works as an LED or not.

The acquired results enabled us to correlate the presence of active p-n junction and efficient QW luminescence with the polarity of the top parts of the nanowires. The working nanoLED structure occurred in the nanowires with Ga-terminated top parts. The switching off the diode structure can be caused by change in the piezoelectric fields occurring in nitride heterostructures or by inhibited p-type doping of the N-polar part of NW [3].

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P2.37 - Chemical functionalization and characterization of germanium nanowires

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Organic functionalization via covalent bonds of semiconductor nanomaterials has recently become a research area with a strong interest in the development of electronical devices and chemical sensors. This work concerns the functionalization of Ge nanowires (NWs) with organic molecules, to develop chemical sensors for explosives (*e.g.* TNT and similar). To obtain a high selectivity and sensitivity sensor, the nanostructures are decorated with chemical moieties able to interact with the explosive molecules.

Three different synthetic strategies are proposed for the functionalization of Ge NWs (**Fig.1**):

- Hydrogermylation of alkenes and alkynes on hydride-terminated Ge NWs[2]
- Alkylation by thiolation of Ge nanowires on hydride-terminated Ge NWs[3]
- Alkylation by Grignard reagent on halogenated-terminated Ge NWs[3]

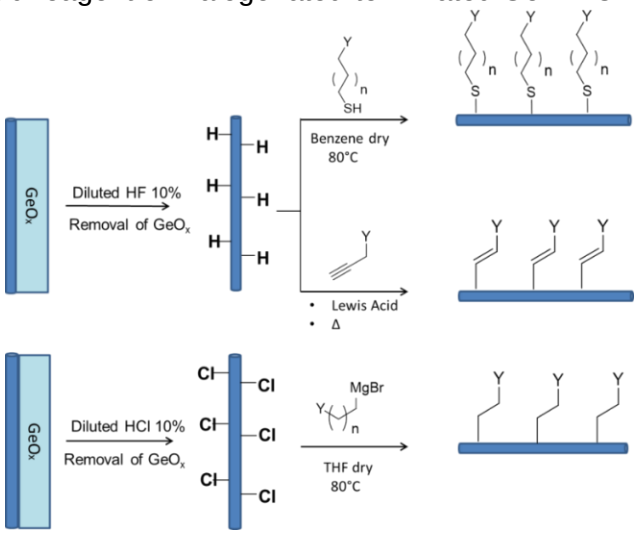

Fig 1: *Schematic illustrating the various routes to Ge nanowire functionalization*

The resulting organic functionalizations are characterized by transition electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), infrared spectroscopy (ATR-FTIR) and contact angle measurements.

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P2.38 - Correlated electrical and optical assessment of doping in GaN nanowires

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Keywords: GaN, optoelectronics, NWs, characterization, EBIC, PL, doping, PAMBE

Nitride materials find many strategic applications in optoelectronics, e.g. in solid state lighting. Nitride thin films suffer from structural defects arising from the lattice mismatch with the growth substrates. Nanowires (NWs) present advantages with respect to thin films, namely an improvement of the material quality leading to excellent optical efficiency. For device applications, it is important to measure and control the doping concentration, which is a non-trivial task in nanomaterials.

In this study, we optimize the p and n doping in GaN NWs and we demonstrate active p-n junctions with an abrupt doping profile. The NWs were grown on Si(111) substrate by plasma assisted molecular beam epitaxy under N-rich condition and by using Mg and Si for p-type and ntype doping, respectively. First, doping concentration was assessed on homogenously doped NWs using photoluminescence spectroscopy. In particular, p-doping level up to $10^{18}cm^{-3}$ was demonstrated, while preserving a good NW morphology showing only limited coalescence for very high-doped NWs. Next, p-n and n-p junctions were grown and analyzed by electron beam induced current (EBIC) microscopy (figure1). For p-n NWs, the EBIC mapping revealed an important radial deposition during the growth of the top Mg-doped segment, then surrounding the n-doped part and leading to a non-abrupt junction (Fig. 1 a)). On the contrary, for n-p NWs, the junction was found to be abrupt (Fig. 1b)), demonstrating the pure axial growth of the top n-doped portion of the NWs. By analyzing EBIC profiles (Fig. 1c)), the p-doping concentration in excess of $10^{18}cm^{-3}$ was extracted in agreement with optical analyses. Moreover, the minority carrier diffusion lengths for electrons and holes were determined.

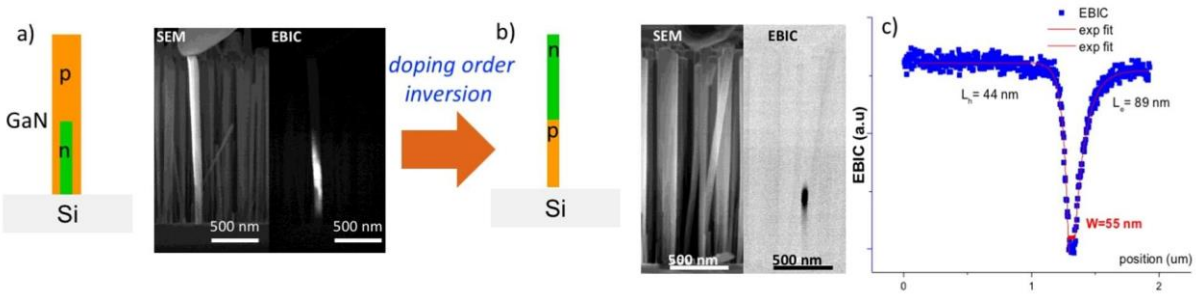

Figure 1: a) Schematic of a p-n NW, SEM image and EBIC map; b) schematic of a n-p NW, SEM image and EBIC map; c) analyses of the EBIC profile.

P2.39 - MBE growth and characterization of PbTe nanowires

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PbTe is a highly interesting material for quantum transport devices due to its strong spin-orbit coupling, high carrier mobility and small effective mass.[1] In the nanowire geometry one dimensional transport can be realized, and the material can be easily combined with lead as a superconductor, which gives rise to exciting possibilities for Majorana devices. It has been demonstrated that the background carrier concentration and carrier type can be controlled using the IV/VI ratio during nanowire growth.[2] In this work we demonstrate the MBE growth of defect-free PbTe nanowires on a silicon substrate. The nanowires feature a rock salt crystal structure, with {100} side facets and a <100> growth direction. The nanowires are several microns long with a diameter of 60 to 100nm. The carrier mobility, carrier density and gate response are measured on single nanowire devices, which show promising results for future experiments.

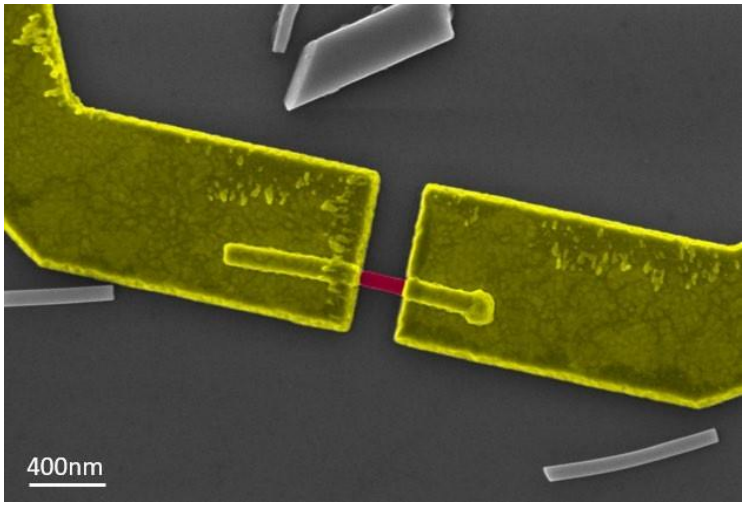

Figure 1. *False colored SEM image of a PbTe nanowire (red) device contacted with Cr/Au (yellow).*

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P2.40 - Optical detection of cell adhesion forces: application of InP nanowire arrays to probe the effect of *N-acetylcysteine* on adhered bacteria

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Keywords: nanowires, cell force sensor, bacteria

Probing cell adhesion forces is one of the approaches used to evaluate bacterial motility and surfaces interactions, which are crucial to the understanding of microorganism behavior. This work presents the application of Indium Phosphide (InP) nanowire arrays as force sensors to investigate the inhibitory effect of N-acetylcysteine (NAC) on adhered cells of the phytopathogenic bacteria *Xylella fastidiosa*.[1,2]
These bacteria produce extracellular polymeric substances (EPS), which allow them to adhere on a surface and to form biofilms.[2] NAC is a cysteine analog assumed to disrupt disulfides bonds and therefore remove EPS, among other antibacterial effects, but the NAC action mechanism is not yet clear[3]. In this work we analyzed in real time the effect of NAC on cells attached to the top of nanowires (Figure 1). Adhesion forces are measured by optical detection of nanowire deflections due to the forces from adhered cells, using Confocal Laser Scanning Microscopy (CLSM). The nanowire positions are localized after a 2D Gaussian fit of the laser reflection profile. Thus, the forces can be calculated using the linear theory of elasticity.[2]

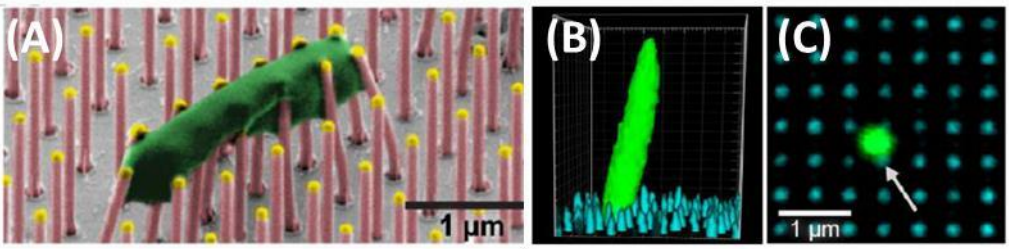

Figure 1. *(a) SEM image illustrating a bacterial cell horizontally adhered to the nanowires, (b) CLSM image showing a 3D renderization of a vertically adhered bacterial cell, (c) CLSM image at the plane of the top of nanowires, showing the laser reflection signal (blue) and the fluorescence signal from bacteria (green)[2].*

Changing the bacterial growth time and NAC concentrations (from 2mg/mL up to 20 mg/mL), we investigated the NAC action on single cells and biofilms. The dependence of adhesion forces on NAC concentrations and bacterial growth time shows that in some cases, the forces decreased after increasing NAC concentration. We also observed in real time the release of cells and biofilms upon NAC addition to the culture, followed by a decrease in force on the nanowires once the cells are free. Furthermore, the results suggest different behaviors for elongated cells; higher adhesion forces keep them attached after NAC addition, even after biofilm release.

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P2.41 - Optical properties of Cu- and Co- doped ZnO nanowires

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Keywords: ZnO, doping, optical properties, ultrafast spectroscopy

ZnO is a wide bandgap semiconductor with a large exciton binding energy (60 meV) at room temperature and is a useful material for near UV optoelectronic devices, transparent conducting devices, light emitting and piezoelectric devices[1,2]. Because of their ease of synthesis, ZnO nanowires (NWs) can be easily incorporated into nanoelectronics. The functionality of those devices can be modified by controlling doping type and levels. Cu replaces Zn, acting as an acceptor, and modifies the luminescence by introducing impurity levels. On the other hand, Co-doped ZnO exhibits magnetic properties exploitable in spintronics. In this work, we investigate the changes in the optical properties of ZnO NWs when doped with Cu or Co. The optical properties are probed by PL and ultrafast transient absorption spectroscopy (FTAS) with temporal resolution of 50 fs in pump-probe mode. The ZnO NWs are chemically grown by chemical bath deposition[3]. The NWs are about 3 µm long with and 100 nm wide. The samples consist of undoped, 1%, 5%, 10%, and, 20% Co- and Cu-doped ZnO NWs. We report a redshift in the near UV emission and an increase in the defect-related emission in case of doped NWs. We also observe a redshift in the bandgap bleaching signal in the FTAS. The dynamics of the bandgap bleaching becomes faster with increasing Co-doping. Further analysis of the bandgap bleaching and defect-related emission, and their dependence on doping levels will also be presented.[4]

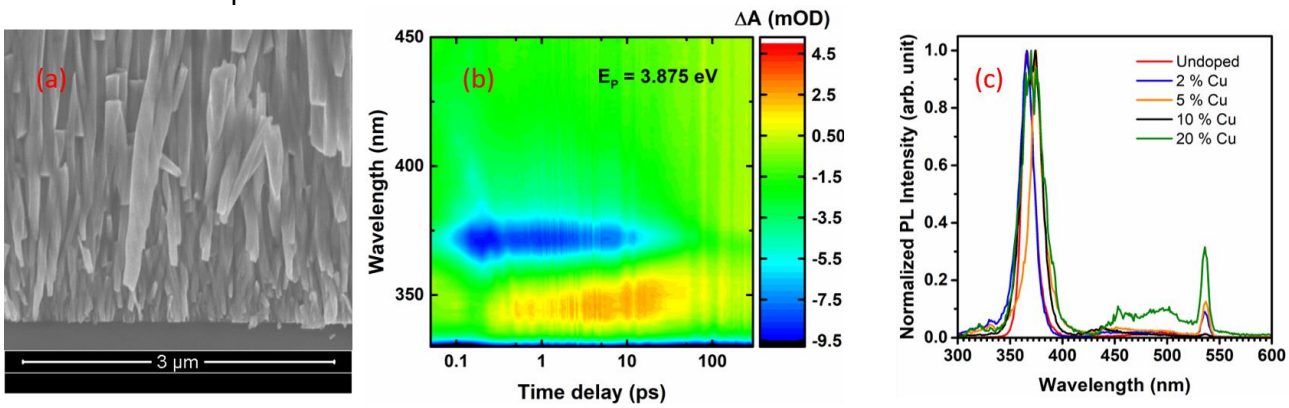

Figure 1. *(a) SEM image of cross-section of 10% Co doped ZnO; (b) False 2D colormap of FTAS of 1% Co doped ZnO NWs; (c) Normalized PL intensities for various doping concentrations of Cu.*

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[5] **Acknowledgements:** This work has received funding from the Horizon 2020 program of the European Union for research and innovation, under grant agreement no. 722176 (INDEED).

P2.42 - Electron cycloids in a radial quantum well of a GaAs/AlGaAs nanowire heterostructure driven by a surface acoustic wave

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Keywords: heterostructures, surface acoustic waves, acousto-electric effect, electrical transport

Surface acoustic waves (SAWs) are a versatile tool to probe and manipulate semiconductor nanostructures, such as nanowires (NWs)[1], at radio frequencies. When excited on piezoelectric materials, the large piezoelectric field of the SAW couples to charge carriers of NW structures. This leads to an ionization of excitons and induces spatio-temporal carrier dynamics of the such dissociated electrons and holes allowing to dynamically control the overlap of electrons and holes and thus the radiative emission of nanowires. Here, we deliberately use the native inhomogeneities[2] occurring in a hexagonal radial quantum well (QW) embedded in a GaAs-$Al_{0.3}Ga_{0.7}As$ NW heterostructure to directly observe electron cycloids driven by the gyrating electric field of a SAW. To this end, we employ using acousto-optoelectric spectroscopy, a contact-less stroboscopic photoluminescence spectroscopy technique. This transport is found to be highly efficient and occurs on a sub-nanosecond timescale.

The investigated NW exhibits significant inhomogeneities of QW thickness on different facets of the same NW inducing strong charge carrier localization on the side facets of radially embedded GaAs QW[2]. This results in two interconnected QW segments on neighboring facets for the investigated structure. Both QW segments are spatially offset along the NW with a small spatial overlap area, resulting in the localization of charge carriers mainly to two neighboring QW side facet along the NW. As a result, the structure exhibits a double peak structure in photoluminescence spectrum of the GaAs-QW near the overlap area. Moreover, a charge carrier transfer is distinguished between the two interconnected QW segments which can be triggered dynamically by a SAW. By employing a surface acoustic wave, time-resolved measurements reveal firstly periodic intensity modulation of both QW segments due to periodical separation of electrons and holes and an acoustically-driven carrier transport along the NW axis due to the gyrating electric field parallel to the NW. Secondly, an anticorrelated behavior between both segments is observed arising from a dynamically trigger carrier transfer between the two QW segments due to the oscillating electric field perpendicular to the NW axis. This in turn results in carrier transport in the QW along the axis of the nanowire and around the circumference of the radial QW.

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[2] M. M. Sonner, A. Sitek, *et al*, *Nano Lett.* **19** (2019) 3336-3343.
[3] **Acknowledgements:** Supported by Deutsche Forschungsgemeinschaft (DFG) via KR3790/6-1, KO4005/6-1, the Cluster of Excellence Nanosystems Initiative Munich (NIM), Icelandic Research Fund (project 163438-051).

P2.43 - Characterization of the light emission from III-V nanowires by modeling and experimental approaches

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The optical properties of III-V compound nanowires are different from the bulk materials. This difference leads to novel opportunities for manufacturing new types of light-emitting devices. However, due to the unique geometry of the nanowires, their interaction with light is rather complicated and their optical response demands careful analysis.

In this work, we consider the light emission from nanowires with two different modeling methods: 1) a method with an actual emitting dipole inside the nanowire, and 2) a method based on the Lorentz reciprocity where the response to an incident plane wave yields the far-field emission from a dipole in the nanowire. We compare these theoretical results with the directional emission measured with Fourier microscopy. The modeling was realized in the COMSOL Multiphysics environment[1] where the Maxwell's equations were solved using the finite element method. Fig. 1a represents a comparison of the modeling results from the two methods. To characterize the emission directivity with

Fourier microscopy, we have grown two types of III-V nanowires: 1) InP nanowires and 2) AlGaAs nanowires with a GaAs shell.[2] In Fig. 1b, a SEM image of the InP nanowires is shown.

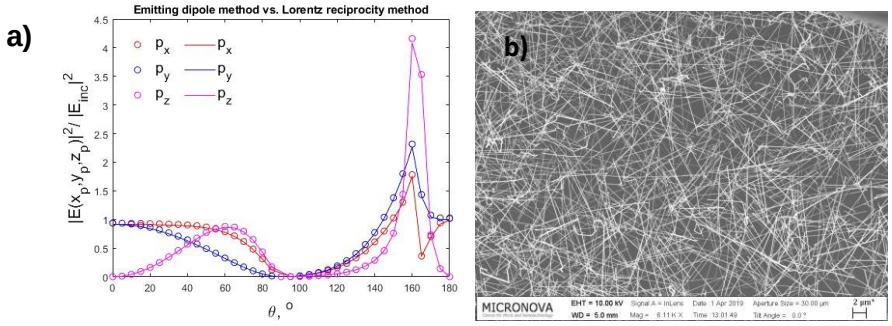

Figure 1. *a) Comparison of two models for the InP nanowire that is placed on the InP substrate (p_x, p_y, p_z correspond to the different dipole orientations, the circles correspond to the method based on an actual emitting dipole and the lines correspond to the Lorenz reciprocity method); b) SEM image of InP nanowires on Si substrate.*

We analyze how the modeling and measurement results agree with each other and propose guidelines to increase the accuracy of the theoretical predictions. Comparison of the theoretical and experimental results will provide a full picture of the efficiency and suitability of the different approaches for the characterization of light emission from semiconductor nanowires. The proposed guidelines will be useful for the design and analysis of nanowire-based light-emitting sources.

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P2.44 - Bismuth incorporation in selective area grown nanowires

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Towards the realization of quantum computing, hybrid semiconductor-superconductor nanowires (NWs) network has potential as platform for topologically protected qubits. III-V nanowire network has been demonstrated by Molecular Beam Epitaxy[1,2] and this research is a growing field in crystal growth[3,4,5]. The degree of topological protection will depend crucially on the strength of the spin orbit coupling, which means that not only the shape and crystal structure need to be engineered appropriately, but also the composition. Being the heaviest element in group V, Bismuth is a highly promising candidate, which could lead to several novel and relevant topological properties[6]. However, incorporation of Bismuth in III-V semiconductors induces modifications in morphology and bandstructure[7], which needs to be explored.
In this work, we present a study of the mechanisms of Bismuth incorporation in SAG InAs NWs grown in MBE, by variety of characterization methods such as cross-sectional TEM, X-ray diffraction, and µ-Raman spectroscopy.

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P2.45 - Raman Scattering of Wurtzite GaAs and InP Nanowires

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Unique properties of III-V semiconductor nanowires, such as high aspect ratio, efficient strain relaxation and polytypism, make them an attractive platform for novel applications and fundamental studies. Due to rapid development of growth methods it is now possible growing nanowires of high crystal quality in either a wurtzite or a zinc blende crystal phase, or even switching between them with high accuracy.[1,2] Only zinc blende is stable in bulk among III-V non-nitride semiconductors and wurtzite can only be accessed in nanowire geometry. Despite general interest in the wurtzite crystal phase and effort put to understand their properties, the full picture and many material parameters are to be determined. One such is the low frequency phonon modes, where almost no experimental studies have been reported.

In this work we studied phonon modes in InP and GaAs nanowires having high quality wurtzite crystal phase. We employed low temperature Raman scattering spectroscopy in a back scattering configuration where an undesirable luminescence background was avoided by tuning a Ti:Sapphire laser bellow the bandgap energy of the corresponding material system. Thanks to the improved signal to noise ratio we observed low frequency E_2^L phonon mode in both InP and GaAs at 54 cm^{-1} and 64 cm^{-1}, respectively. These values are in good agreement with the theoretical predictions.[3] Another wurtzite crystal phase specific high frequency E_2^H mode was visible at 261 cm^{-1} for GaAs and 308 cm^{-1} for InP in good agreement with previous observations.[4,5] Polarization dependent Raman scattering revealed similar selection rules for these two phonon modes where the intensity peaked when excitation and detection polarization was perpendicular to the $[000\bar{1}]$ direction. Furthermore, both InP and GaAs nanowires have shown a hint of LO mode at 295 cm^{-1} and 346 cm^{-1}, respectively, despite being forbidden in the backscattering configuration. We further find that the splitting between E_1(TO) and A_1(TO) modes is around 2 cm^{-1} in wurtzite GaAs.

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P2.46 - Morphology evolution of catalyst-free III-V nanowires grown by selective area epitaxy

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We present a new model for the length and diameter evolution of catalyst-free III-V nanowires (NWs) grown by selective area epitaxy (SAE). We consider simultaneous axial and radial growth of NWs, which is more typical for this technique than for the vapor-liquid-solid growth with a droplet on top. Analytic expressions for the time evolution of the NW length and diameter are derived[1], showing the following properties. As long as the NW length is shorter than the collection length of group III atoms on the sidewalls, the length evolves super-linearly and the diameter linearly with time. For longer NWs, both length and diameter increase sub-linearly with time. The scaling growth laws are controlled by a single parameter which depends on group V flux. The model fits well the data on the SAE InAs NWs grown by MBE[2] and GaAs NWs grown by MOCVD[3].

For example, Figures 1 (a) and (b) show the time evolution of the length and diameter of SAE InAs NWs, respectively, for pitches varying from 250 nm to 3000 nm. These NWs were grown by MBE in patterned arrays on SiO_2/Si(111) at 480 ^oC, with a fixed pore radius of 40 nm and variable pitches of the array[3]. In it seen that the model equations fit very well the data. Overall, our results can be used for controlling the catalyst-free growth of III-V NWs and their morphology, including ternary III-V NWs such as InAsSb[4].

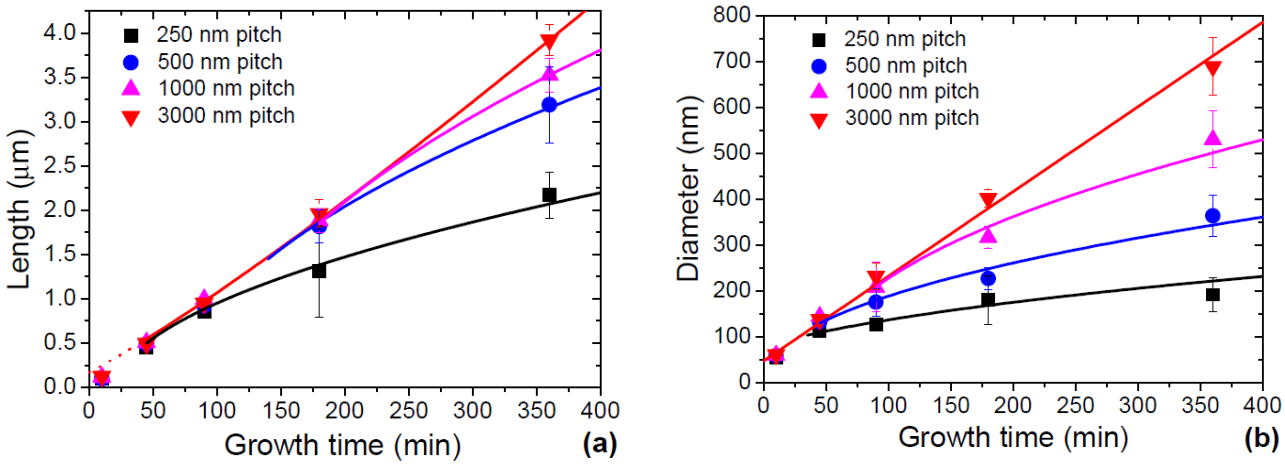

Figure 1. *Time evolution of (a) length and (b) diameter of InAs NWs grown by selective area MBE in patterned arrays on* SiO_2/Si(111) *with different pitches (symbols)[3], fitted by the model (lines)[1].*

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P2.47 - Non-trivial phenomena during MBE growth of N-based nanostructures on silicon

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The wide-gap nanoheterostructures based on GaN are of great interest for creating electronic and optoelectronic devices. Works in growing GaN on silicon have been very promising recently. However, the lattice misfit of such materials is 17%, which leads to the formation of defects of different nature.

In this work, in order to reduce the number of misfit dislocations a nanometer (about 50 nm) buffer layer of SiC was used for MBE GaN nanowires (NWs) growth. Since the difference in the lattice parameters is only 3%, so growth on such surface can radically reduce the density of structural defects in GaN.

Growth experiments are carried out using Riber Compact12 MBE setup. After the growth, the samples are studied by applying the scanning electron microscopy (SEM) and low- temperature photoluminescence (PL) techniques.

Comparison of photoluminescence spectra of grown GaN on hybrid and the most successful GaN NWs structures on silicon shows that the intensity of radiation from grown on SiC buffer layer GaN NWs is more than two times higher than the intensity from the best GaN structures on silicon. This fact leads to the conclusion that grown structures have fewer defects compared with GaN NWs on silicon substrate. This is caused by a smaller lattice constant mismatch between GaN and SiC compared with GaN and Si.

Besides we have discovered a novel mechanism that allows Si to be incorporated into GaN NWs beyond the solubility limit. It is based on the use of vicinal SiC/Si hybrid substrates. The NWs grown on step bunches of vicinal become heavily Si doped. This is verified by the observation of high carrier concentrations in PL and high Si-concentrations by SIMS. Moreover, Raman spectroscopy in concert with quantum chemical modelling indicates the formation of Ga(Si)N solid solution. The microscopic mechanism responsible for heavy doping and even alloying beyond the solubility is diffusion driven by the mechano-chemical effect, which allows extremely efficient injection of Si atoms at the step bunces of vicinal SiC/Si substrates.

Moreover, a possibility of GaAs, AlGaAs and InAs nanowires growth on a silicon substrate with a nanoscale buffer layer of silicon carbide has been demonstrated for the first time. The diameter of these NWs is smaller than diameter of similar NWs that were grown on a silicon substrate, because of significant lattice mismatch. In particular, InAs NWs diameter was less than 10 nm. In addition, based on photoluminescence measurements, it was found that, in case of AlGaAs NWs growth on such substrates, complex structure forms.

Finally, in this work we present the results of a set of experimental studies on the synthesis by molecular beam epitaxy and the study of the morphological and optical properties of InGaN nanostructures of branched morphology (resembling nano-flowers, NF) directly on the surface of the silicon substrate.

P2.48 - Insights into structural and chemical properties of zinc phosphide superlattice-like nanowires

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The structural and chemical aspects of one-dimensional semiconductors even at the atomic scale impact directly their physical properties. Aberration-corrected scanning transmission electron microscopy (AC-STEM) offers an ample range of techniques with which the material can be thoroughly studied with atomic resolution.[1] Here we study the structure of In-seeded Zn_3P_2 nanowires grown by molecular beam epitaxy (MBE). Zn_3P_2, unlike III-V compounds, does not have a polar structure, since it comprises of symmetrically-charged Zn-P-Zn trimers instead of cation-anion dumbbells (Fig. 1a). It also contains systematic vacant sites which can only be observed from the [100] orientation. These vacant sites provide a low energy pathway to form self-interstitials, leading to off-stoichiometry compositions, as can be seen in the elemental analyses and confirmed by simulated and experimental HAADF/ABF-STEM images.[2]

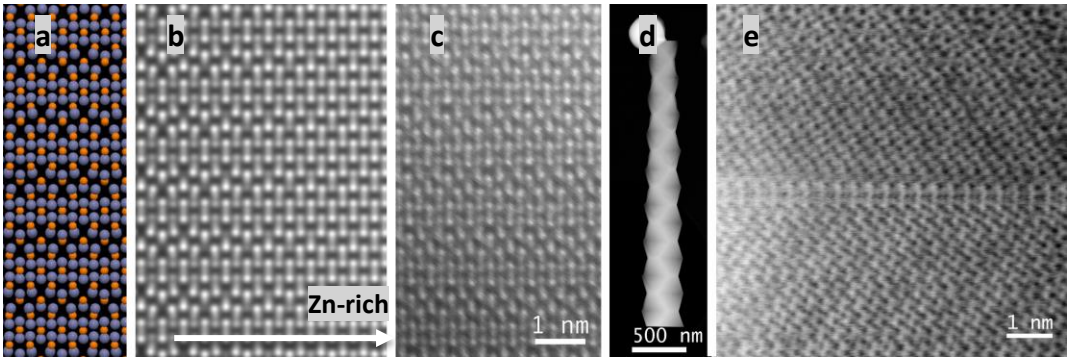

Figure 1. *Zn_3P_2 structure, (a) atomic model, (b) simulated HAADF-STEM image from (left) Zn_3P_2 stoichiometry to (right) Zn-rich compound, (c) HAADF-STEM, (d) overview, (e) ABF-STEM image of the stacking fault*

Moreover, the nanowires grown in the [101] direction can contain stacking faults resembling twin boundaries in twin-plane superlatticed III-Vs,[3] or inversion domain boundaries (IDBs) of doped II-VI (in particular ZnO)[4] nanowires. However, these stacking faults have fundamental differences with both twin boundaries and IDBs. Discrete AC-STEM tomography results reveal that although they reverse the lateral faceting and mirror the structure seen from the [100] zone axis, the mirroring does not occur fully in the [011] zone axis. On the other hand, analogous to IDBs in doped ZnO, the stacking faults contain higher content of In which originates from the seed particle, however, they cannot cause any polarity inversion. Understanding the structural properties of Zn_3P_2 nanowires is essential to understand their physical properties and open new routes in energy harvesting applications.

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P2.49 - Room temperature high responsivity SWIR/NIR photodetectors based on InAsP/InP NW array heterostructures

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Despite significant progress in development of disruptive infrared photodetectors, suitable for monolithic integration with silicon electronics, there are still major issues related to growth quality, poor responsivity, high dark current and limited spectral bandwidth. One interesting route towards merging high-performance III-V optoelectronics with silicon is self-assembled nanowires (NWs). Incorporating axial quantum heterostructure discs (QDiscs) in NWs combine the advantages of the small footprint and spectral tuning with quantum confinement in the embedded heterostructures for realizing broadband photodetectors. Here we report on IR photodetectors based on arrays of n+-i-n+ InP NWs with embedded InAsP quantum discs (QDiscs) in the intrinsic region. The device shows excellent room-temperature operation with a responsivity of 1200 A/W @ 980 nm and 1900 A/W @ 532 nm, both at 3.5 V bias, which is orders of magnitude higher than any responsivity value reported for NW array photodetectors in SWIR/NIR range.

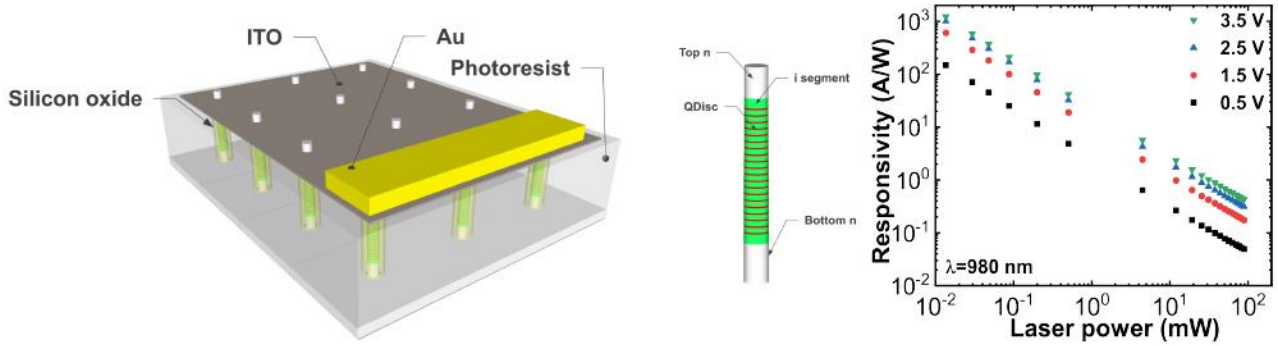

Figure 1. *Left) Schematic of fabricated NW array photodetector with embedded QDiscs. Right) Measured responsivity of the photodetector under 980 nm laser illumination demonstrating high sensitivity at room temperature*

Optoelectronics characterization reveals a clear spectral signature of InP ZB and WZ crystal structures in the spectrally resolved photocurrent (PC) data at 300 K. The observed onset of photocurrent (PC) at about 0.7 eV is attributed to collection of charge carriers generated in interband transitions in the InAsP QDiscs. The extracted responsivity from spectrally resolved PC measurements reveals an excellent sensitivity from 0.7 eV to visible wavelengths. Self-consistent theoretical model predicts the existence of a novel photogating feedback mechanism that reduces the electron barrier under illumination between the n_+-contact and the i-segment comprising the QDiscs. The barrier reduction enhances electron current injection and corresponding gain, orders of magnitude above the classical limit for photoconductive detectors, in perfect agreement with the experiments.

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P3.01 - Making and modelling thermoelectric devices based on vertical III-V nanowire arrays on silicon

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Keywords: thermoelectric, energy, III-V semiconductor

Nanostructured materials hold significant promise for improving the modest efficiencies of conventional thermoelectric devices.[1,2] These improvements result primarily from the spatial confinement of charge carriers and phonons, which serve to increase the power factor[2] ($S^{2}\sigma$) and to decrease the lattice thermal conductivity[3] (κ_{ph}), respectively. Such benefits may be realized in onedimensional nanowires due to modifications in the electronic density of states and the phonon dispersion relation. The combined effect is an increase in the dimensionless material figure of merit, $zT = S^{2}\sigma T/\kappa$, and a corresponding increase in the device efficiency. Our work endeavors to demonstrate the feasibility and improved efficiency of thermoelectric devices constructed from dense arrays of vertical III-V nanowires grown on silicon via the self-assisted vapor-liquid-solid method.[4] Predictive numerical models based on band theory[2] and Boltzmann transport[5,6] are used to guide the required material optimization, which inevitably involves a compromise between enhancing charge transport and hindering thermal conduction. Nanowire dimensions, composition, and surface roughness are used in conjunction with readily available bulk parameters as input variables in the numerical model.

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P3.02 - Thermo-piezoelectric generators based on Al/*N*-codoped ZnO nanorods

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ZnO is a functional oxide presenting a unique combination of electrical and optical properties and a wide spectrum of technological applications. The thermoelectric and piezoelectric characteristics of ZnO, combined with its high-temperature stability, low toxicity and low cost, are particularly attractive for energy harvesting applications. However, as a thermoelectric material ZnO presents two major limitations, represented by a very low electrical conductivity and a high thermal conductivity. The use of nanostructures represents a viable approach for obtaining a significant reduction in the thermal conductivity. The electrical conductivity of ZnO, on the other hand, is traditionally increased through doping with *Al* or *Ga* ions, resulting in an *n*-type conductivity. The doping with these elements, however, is notoriously difficult to achieve through solution chemistry. *p*-type doping is also of technological interest, although there are still questions concerning its stability and reproducibility. Among potential *p*-type dopants, besides Sb, As and P, nitrogen appears to be particularly interesting.

In this work, the thermoelectric and piezoelectric properties of films of nanorods of *Al*-doped, *N*-doped and *Al*/*N*-codoped ZnO nanorods will be presented. An innovative architecture, involving a conduction path parallel to the substrate has been developed. This geometry makes the realization of the devices much simpler than in the case of conduction perpendicular to the substrate and allows to realize devices presenting an extended area. Both glass and polymeric substrates have been investigated together with the possibility of patterning of the film by soft lithography. The synthesis of the ZnO nanorods have been realized using a hydrothermal growth process (chemical bath deposition) on a seed layer obtained by degradation of metal-loaded hydrogel or by deposition of ZnO nanoparticles by spin coating. The *p*-type doping of the produced films is then carried out at 480 °C using ammonia gas as nitrogen source. Thermoelectric and piezoelectric performance of the obtained nanorods will be presented.

P3.03 - InP nanowire solar cells

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Keywords: Nanowires, Ultimate limit, solar cells

In the last few years the need to diversify energy sources has become increasingly strong so as to reduce the dependence on fossil fuels, and photovoltaics has obtained a strong interest in renewable energies.

We report top-down etched InP nanowires (Fig.1) intended to both optimize the amount of light outcoupling as well as the directionality of the emitted light[1]. The light outcoupling can be increased by optimizing the tapering angle of our nanowires while the directionality can be optimized by using an external lens as shown in Fig. 2.

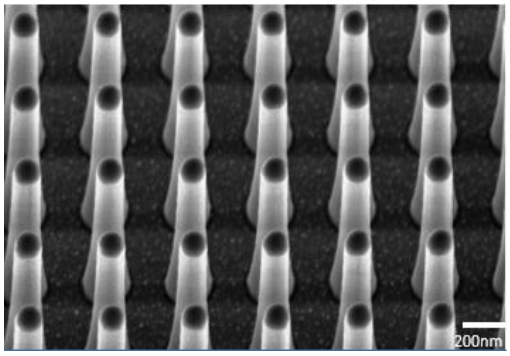

Figure 1. *InP nanowires*

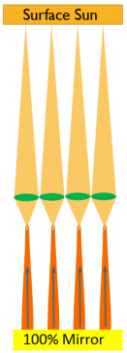

Figure 2. *Outcoupling of the light to reach the ultimate limit*

For our present 17.8 % efficiency InP nanowire solar cell, the loss in the open circuit voltage with respect to the radiative limit still amounts 272 mV. To avoid this loss and reach the radiative limit for the V_{oc}, we have to increase the external radiative efficiency (Eq. 1) towards unity.

$$\eta_{ext}^{PL} = \eta_{int}^{PL} P_{esc} \quad (1)$$

$$V_{OC} = V_{OC}^{Ultimate} - \left|\frac{k_B T}{q} ln \frac{\varepsilon_{in}}{\varepsilon_{out}}\right| - \left|\frac{k_B T}{q} ln(\eta_{ext}^{PL})\right| \quad (2)$$

Reaching a high η_{int}^{PL} is possible by passivating the wires to decrease surface recombination and by decreasing non-radiative recombination in the bulk of the nanowires. To increase the P_{esc}, we need to engineer the nanowire tapering for obtaining a high photon escape probability. Another loss is due to the second term in Eq. 2 ($\frac{\varepsilon_{in}}{\varepsilon_{out}}$). To completely avoid this photon entropy loss, we need to redirect all the emitted photoluminescence from the cell back to the sun (Fig.2) aiming at $\varepsilon_{out} \approx \varepsilon_{in}$ where we would reach the 46.7% ultimate limit. Nanowires allow to tailor the necessary light emission at open circuit conditions into the HE_{11} guided mode, which can, in principle, focused bask towards the sun, as shown in Fig.2.

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P3.04 - Characterization of InAs/InP heterostructure single nanowire devices for hot carrier photovoltaics with electron beam induced current

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Keywords: InAs/InP nanowire, Hot carrier solar cell, Electron beam induced current

III-V nanowires offer several advantages for hot carrier photovoltaics (HCPV) such as; extended hot carrier relaxation time,[1] the ability to grow lattice mismatched heterostructures,[2] and different ways to focus light absorption including the design of photonic or plasmonic elements.

In previous work, devices based on single InAs nanowires with small InP segments have been electrically characterized under global illumination and interpreted to work as a HCPV device based on the principle shown in fig. 1a.[3] The InP segment serves as a potential barrier for electrons (holes) in the conduction (valence) band (CB (VB)). Light focused on one side of the barrier excites electrons into the CB resulting in a non-equilibrium distribution. Hot electrons may then diffuse over the CB barrier while holes are unlikely to make it over the respective barrier in the VB due to their relatively high effective mass, resulting in charge-separation. In ref. [3] local carrier excitation was achieved by globally illuminating the wire and relying on absorption “hot-spots” that occur naturally in a nanowire where there is a wave mode maxima.[4] In this work carriers are locally excited using an electron beam induced current (EBIC) setup, in this way the excitation is spatially controllable, the result is shown in fig. 1b and c. The bright/dark contrast of the EBIC current implies that electron transport abruptly switches direction depending on which side of the barrier that is illuminated, which is expected as a consequence of charge separation. The generated current is also seen to decrease further away from the barrier as carriers have time to relax. This confirms that the InP barrier serves as a filter for high energy electrons.

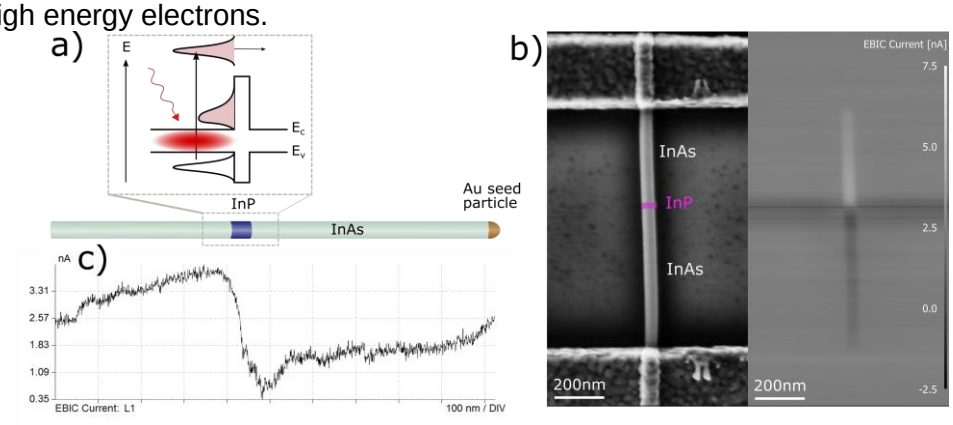

Figure 1. *a) An InAs/InP heterostructure nanowire serving as a HCPV device. b) SEM (left) and EBIC (right) image. c) Linecut of the EBIC image along the axial direction of the nanowire, y-axis shows EBIC current in nA and x-axis length in nm.*

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[5] **Acknowledgements**: We acknowledge financial support from the Swedish Research Council, the Swedish Energy Agency, and the Knut and Alice Wallenberg Foundation

P3.05 - Al-catalyzed Si Nanowires Formed by Chemical Vapor Deposition and Application in Photovoltaic Device

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Keywords: Silicon, Nanowire, Aluminum, Photovoltaic

Core-shell nanowire (NW)-based solar cells and gate-all-around NW field-effect transistors are hot research topics for advanced technology at this moment. Several NW formations and characterizations in our previous researches have been reported.[1-2] However, high performance devices are remaining in progress to accomplish owing to catalyst contamination or NW surface damage. In this study, we would like to present Al which has been proposed as a new alternative catalyst to form SiNWs.[3-4] The binary Al-Si phase diagram suggests SiNWs can be possibly grown by vapor-liquid-solid (VLS) mechanism at low eutectic temperature of 577 °C with Si composition of 12.6%. Moreover, the ease of Al removal and the capability of Al existence as a p-type dopant in Si are advantageous to overcome the catalyst contamination problems. In this experiment, the effects of substrate temperature on Al-catalyzed SiNW formation obtained by thermal chemical vapor deposition (CVD) were optimized. Al content and Al catalyst removal were observed. Structural and optical properties of SiNWs were discussed for photovoltaic application. The SiNW-based solar cell with p+-p-n-n+ structure was demonstrated. Figure 1(a) shows a TEM image of Al-catalyzed SiNW grown at 650 °C and the constant low Al content of 0.5% was estimated by energy-dispersive X-ray spectroscopy (EDS). EDS linescan showed decreasing of Si intensity toward the NW tip indicating the tapered shape of NW. SEM images in Fig. 1(b) showed good vertical NW structures which are suitable for SiNW-based solar cell fabrication. The light reflectance range measured by UV-Vis-NIR was detected below 10%. The better light absorption enhanced power conversion efficiency (PCE) of solar cells to 9.3 % as shown in Fig. 1(c).[5]

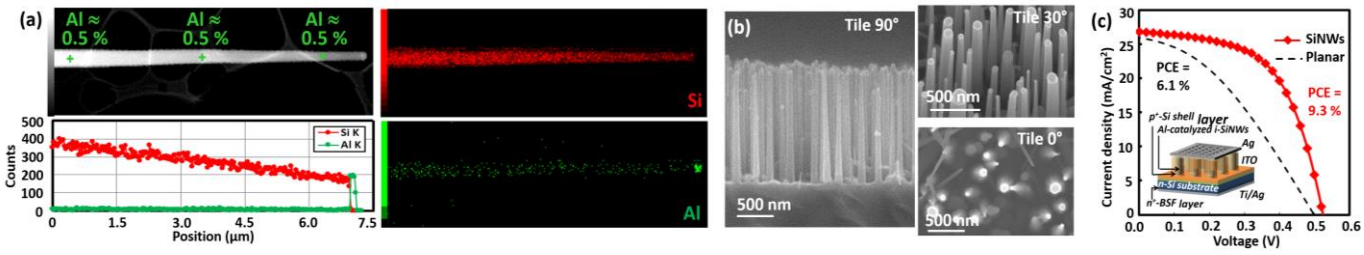

Figure 1. *(a) TEM image of Al-catalyzed SiNW grown at 650 °C and the average Al content estimated by EDS at different positions, (b) SEM images, and (c) current density and voltage (J-V) characteristics of Al-catalyzed SiNW-based solar cell compared to planar cell.*

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[5] **Acknowledgements** This work was supported in part by the JSPS KAKENHI Grant numbers 18K14096 and WPI-MANA, NIMS, Japan.

P3.06 - Top-down etched GaAs nanowires for the ultimate efficiency nanowire solar cell

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Nanowire technology opens a new promising route towards the next generation solar cells. Currently, the terrestrial solar market is based on single junction solar cells, where the power conversion efficiency (PCE) is limited by the Shockley-Queisser (SQ) limit of about 33%. [1] Over the recent years an increased effort was devoted to nanophotonic engineering as a promising route to overcome the SQ limit.

The short circuit current (I_{sc}) of a nanowire array solar cell can be controlled by changing the nanowires shape and array pitch [ref]. In this project we focus on the optimization of the open-circuit voltage (Voc) of a nanowire solar cell. The ultimate limit for the V_{oc} can be achieved if the external radiative efficiency ($\eta_{\mathrm{ext}}^{\mathrm{PL}}$) and the ratio between solid angles of incident $\varepsilon_{\mathrm{in}}$ and emitted light $\varepsilon_{\mathrm{out}}$ are unity.

$$V_{\mathrm{OC}} = V_{\mathrm{oc}}^{\mathrm{Ultimate}} - \frac{k_{\mathrm{B}}T}{q}\left|ln\frac{\varepsilon_{\mathrm{in}}}{\varepsilon_{\mathrm{out}}}\right| - \frac{k_{\mathrm{B}}T}{q}\left|ln\,\eta_{\mathrm{ext}}^{\mathrm{PL}}\right|$$

The external radiative efficiency $\eta_{\mathrm{ext}}^{\mathrm{PL}}$ can be estimated as the product of the internal radiative efficiency η_{int}^{PL} and the photon escape probability (P_{esc}). Nanowires feature a fundamentally larger P_{esc} than a planar layer since the light is emitted in a guided mode which adiabatically expands into air[2]. To increase η_{int}^{PL}, both the surface recombination velocity and the number of non-radiative recombination centers should be decreased.

Hereby, we present top-down fabricated GaAs nanowire arrays. We demonstrate that inductively coupled plasma reactive ion etching (ICP-RIE) can be used to obtain GaAs nanowires of optimal geometry. We further demonstrate that repetitive surface oxidation followed by oxide removal (digital etching) can greatly enhance the optical properties of the array. To decrease the surface recombination velocity, the passivation scheme is developed, where the surface of GaAs nanowires is passivated with lattice-matched InGaP. The latter passivation scheme greatly enhances the measured external quantum efficiency. Our study opens a new route towards the fabrication of an ultimate efficiency nanowire solar cell.

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P3.07 - Limiting factors in the current collection of Si nanowire solar cells under concentrated illumination

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Nanowires (NWs) with radial junction geometry allow to decouple the light absorption and the carrier collection. This is particularly advantageous for lower-quality materials having short minority carrier diffusion lengths such as hydrogenated amorphous Si (a-Si:H). Solar cells made of Si/a-Si:H radial junction NWs can be highly cost-efficient since they can be grown on large areas at rather low temperatures (around 400 °C) with plasma enhanced chemical vapor deposition techniques, leading to energy conversion efficiency over 9%.[1]

In this contribution, we analyze the parameters limiting the current collection in radial junction Si NW solar cells by using concentrated illumination (CI). The front contact is demonstrated to be the main limiting factor for illumination exceeding 0.2 W/cm². A novel contact architecture based on an ITO/silver NW sandwich is shown to lead to ten-fold increase of the current density under the CI.

The NW morphology and schematic are shown in Fig 1(a). It is clear from the figure that because of the NW morphology, it is difficult to obtain a conformal conductive ITO layer by magnetron sputtering, which results in a sheet resistance for the top contact of several kΩ/□. A laser source (wavelength of 532 nm) was used to illuminate a 1.6 mm² spot with a power density between 0.01 and 20 W/cm². Fabricated Si NW solar cells with a- Si:H absorber showed no irreversible damage even after CI 200 times stronger than the Sun. The short-circuit current density followed a linear dependence with illumination power up to 0.2 W/cm², then it exhibited a saturation due to the high in-plane resistance of the top contact [Fig. 1(b)]. This limitation was overcome using an Ag NW network on top of the ITO. By optimizing the Ag NW density, we have reached a saturation current 16 times higher than for the bare ITO.

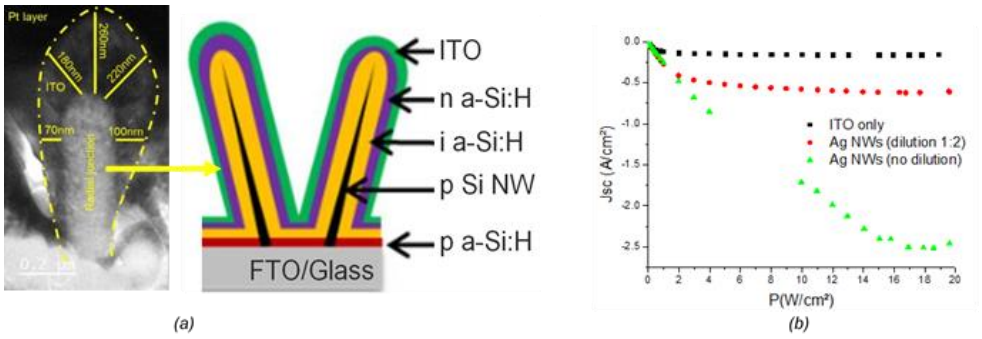

Figure 1. *(a) Schematic and TEM images[2] of the Si/a-Si:H NW. The varying thickness of the top-contact ITO is shown, (b) Short-circuit current obtained at different illuminating powers for Si/a-Si:H NW solar cells with different top contacts.*

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P3.08 - Electrical and thermal transport in gate-all-around suspended-InAs nanowires FETs

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Keywords: electrolyte-gated transistors, suspended nanowire devices, thermoelectricity,

Electrical properties of gate-tunable semiconductor materials are ubiquitous both in fundamental and applied nanophysics. A paradigm change envisions the use of soft-matter as the gate medium for applying impressively high static electric fields to semiconductors. This is the way of *iontronics* to electrostatic gating: using the movement and arrangement of ions to build up an electric double layer that is the ultimate responsible for the gating action. By exploiting the main concepts of *iontronics*, recently we proposed the use of ionic liquids in order to gate InAs NW-based devices, demonstrating unprecedented gating efficiency and gate-induced change of the temperature behavior in the device. Moreover, we studied ionic liquid dynamics with atomistic simulations, correlating hysteretic features to the microscopic parameters of the liquid [1]. Here we further overcome the limitations of conventional gating techniques by demonstrating the effectiveness of the ionic-liquid gate on suspended nanowire devices. The n-type nanostructure under study is an InAs nanowire suspended ~200 nm above the substrate: a configuration that makes conventional back-gate modulation of electrical properties ineffective at room temperature. We report the operation of ionic liquid gate on nanowire-based devices, showing a reproducible field effect control as well as mechanical stability upon thermal cycles between 300 K and 180 K, and device operation in set-and-freeze regime. On the same platform, we investigated thermal transport by exploiting the electrical steady-state 3ω-method [2]. Preliminary results suggest the field effect modulation of the thermal response of the system: we speculate that this could reflect the different morphologies of the two ionic species composing the ionic liquid, likely resulting in different thermal responses of ion layers tightly packed around the nanostructure. Our results could open the way to full benchmark and gate control of the thermoelectric figure of merit in nanowire-based devices by all-electrical method.

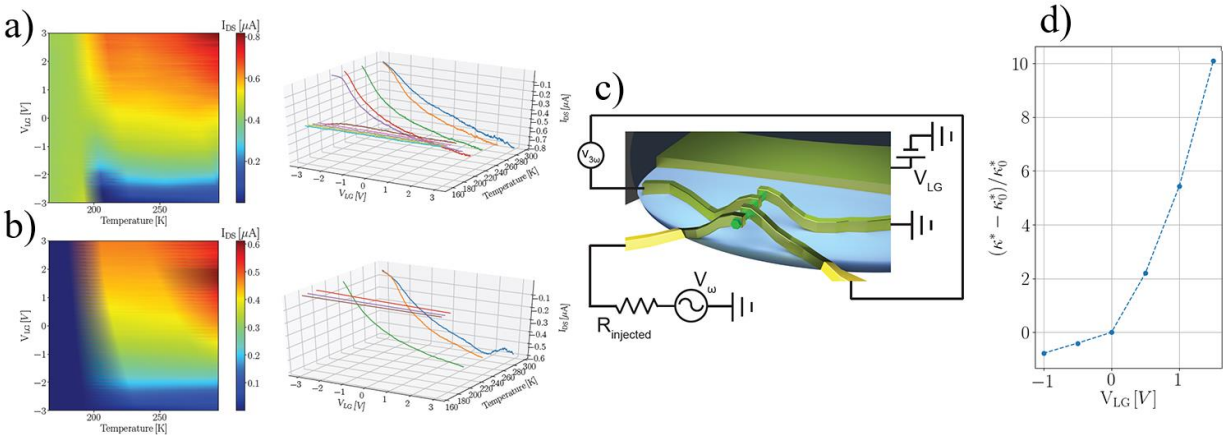

Figure 3. *(a)-(b) Set-and-Freeze operation of the liquid gate. (c) Conceptual device scheme with 3ω-method measurement circuit scheme in overlay. (d) Field effect modulation of the extracted thermal conductivity of the system, normalized with respect to the 0 applied gate value.*

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P3.09 - Piezoelectric energy nanoharvester based on vertically-aligned GaN nanowires

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Keywords: Nanowires, Piezogenerator, GaN, Deformation rate, Impdedance matching

With respect to bulk piezoelectric semiconductor materials, one-dimensional nanowires (NWs) present a higher sensitivity to mechanical forces, and thus offer a more efficient mechanical-electrical energy conversion. This broadens the range of potential applications of NW piezogenerators (e.g. they are well-suited for harvesting weak ambient deformations). Since the first experimental demonstration using ZnO in 2006,[1] NW-based piezoelectric nanogenerators have attracted a strong research interest and other NW materials like nitrides have shown their promise.[2]

In this work, we report on the fabrication and characterization of piezoelectric nanogenerators based on GaN NWs. We show that the electrical-mechanical conversion of the generators strongly depends on the deformation rate as well as on the load circuit.

The self-assembled -c polar GaN NWs were grown vertically on Si(111) substrate by plasma-assisted molecular beam epitaxy. To fabricate the generators, the as-grown GaN NWs were embedded into a polydimethylsiloxane (PDMS) matrix for mechanical stability and metallic contacts were deposited via a shadow mask (device schematic is shown in Fig. 1 (a)). Upon cyclic deformation (i.e. pressing and releasing), the device performance has been examined by recording the peak output voltage. In particular, the impact of the applied force, the deformation time, and the deformation frequency on the output voltage has been investigated (Fig. 1 (b)). The results show that a faster deformation favors a higher output voltage. The signal decay after releasing has been analyzed. To improve the harvesting efficiency, the load impedance matching to the nanogenerator under working conditions has also been explored.

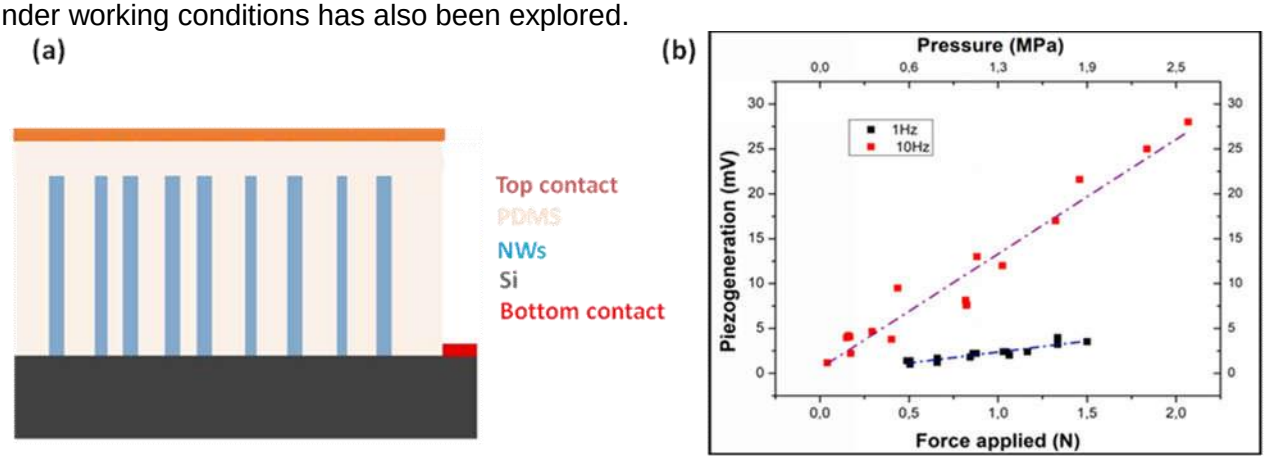

Figure 1 *(a) Schematic of the device structure. (b) Variation of peak output voltage with constant deformation time as a function of the applied force at different cycling frequency.*

P3.10 - Photovoltaic Light Funnels Grown by GaAs Nanowire Droplet Dynamics

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Keywords: self-catalyzed, modelling, V/III ratio

Self-catalyzed nanowires have been implemented in a wide range of technologies including photovoltaics, thermoelectrics, and betavoltaics [1]. Their advantages include strain-reduction at heterostructure boundaries and tunable optical properties depending on wire diameter [1, 2]. Using a liquid Ga droplet to self-catalyze GaAs nanowires eliminates the possibility of deep-level Au defects and provides more control over the diameter of the nanowire during growth. Wide diameter GaAs nanowires (~170 nm) are particularly good at absorbing the AM1.5D solar spectrum [3]. We present a method of controllably increasing the nanowire diameter during growth by altering the V/III flux ratio, and explain the changes in growth rate with the support of an analytical model [4].

GaAs nanowires are grown by selective area epitaxy on Si substrates in a gas source molecular beam epitaxy system. The nanowires are initially grown with a V/III ratio of 2 and a Ga impingement rate of 0.125 µm/h at 600 °C. The V/III ratio is reduced to 1 early in the growth, resulting in the droplet swelling and nanowire diameter increasing while maintaining a high array yield. The rapid increase in droplet volume is shown to result from an imbalance in the group V and III fluxes.

Additional simulations are performed to calculate the absorption within these wide, inverse tapered nanowires. The structures perform favorably when compared to straight nanowire arrays optimized for the solar spectrum. They exhibit multispectral effects along their lengths with more high energy, short wavelength light being absorbed deeper into the wire. The promising simulation results indicate that these structures are viable for photovoltaic applications while the multispectral effects present possibilities for more advanced tuning of the optical absorption.

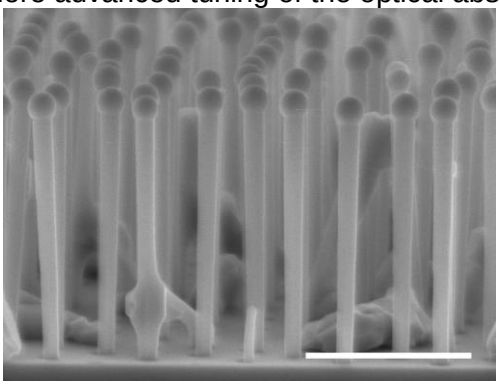

Figure 4. *Cross-sectional SEM image of inverse tapered nanowires. Scale bar is 1 µm.*

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P3.11 - InP/InAsP/InP heterostructure nanowire LEDs for a single photon emitter

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Keywords: III-V compound semiconductor, MOVPE, light emitting diodes

Quantum dots (QDs) by self-assembled growth have been reported as one of an efficient single photon emitter. While site-control of a single QD is still a challenge, selective-area growth of III-V nanowires (NWs) with axial heterostructures can embed quantum wells or QDs in site-controlled NWs.[1] Recently, we have confirmed photoluminescence (PL) emission from InAsP QDs in telecommunication bands.[2] In this study, we demonstrated vertical nanowire array LEDs using the InP/InAsP/InP heterostructure NWs, where InAsP was embedded for active layer in *p-i-n* structure grown by selective-area growth. The LEDs showed rectifying characteristics and electroluminescence (EL) from InAsP in the near infrared region.

p-InP(111)A substrates partially masked with 20nm-thick SiO_2 were used for NW growth. The periodical hole patterns on SiO_2 were made by electron-beam lithography and wet chemical etching. InP/InAsP/InP NWs with axial *p-i-n* junction and InAsP layer in *i*-InP were grown by MOVPE. The growth temperature was 660°C for *p*-InP, *i*-InP, and *n*-InP growth, and 580°C for InAsP and *i*-InP capping layer growth. The SEM image of grown NWs is shown in Fig.1(a). For the demonstration of NW-LEDs, the NW array was buried with benzocycrobutene (BCB) then the top parts of the NWs were exposed by reactive ion etching for electrode contacts. Indium tin oxide (ITO) and Au/Zn were used for surface and backside electrode, respectively. The NW-LEDs structure is illustrated in Fig.1(b).

EL spectra of the NW-LEDs at room temperature exhibited broad emission from 1.0 eV to 1.5 eV [Fig.1(c)]. The main peak at around 1.19 eV was originated from InAsP, which was characterized by PL.[1] The peaks at 1.36 eV and 1.44 eV were resulted from zincblende (ZB)- and wurtzite (WZ)-phase InP, as similar to InP NW-LEDs.[3] EL emission from InAsP at low temperature will be discussed.

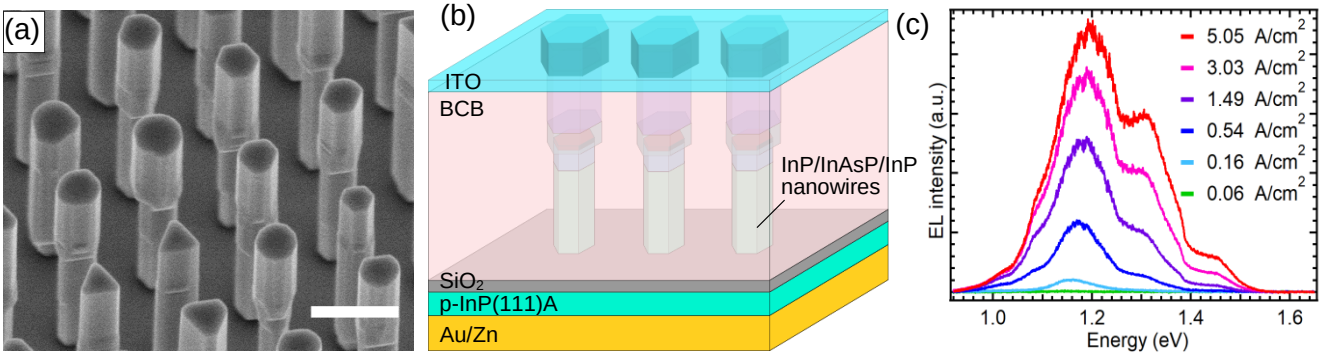

Figure 1. *(a) SEM image of InP/InAsP/InP NWs on InP(111)A substrates. (b) Illustration of the NW-LEDs structure. (c) EL spectra at room temperature under forward bias from 1.0 V to 1.6 V.*

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P3.12 - Colour optimization of white flexible nanowire LEDs

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Keywords: Nanowire, LED, Flexible, White, Electroluminescence, GaN

Flexible white light sources are the key building block for many emerging technologies. Today, these devices are made from organic semiconductors, which suffer from low brightness and short lifetime. One route to make long-lasting efficient flexible devices consists in the use of nanostructured inorganic emitters. Semiconductor nanowires (NWs) offer excellent optoelectronic properties combined with mechanical flexibility, making them well-suited candidates for flexible light emitting diodes (LEDs).

Here we report the fabrication and characterization of flexible white NW LEDs with a focus on the light colour quality. The devices rely on the blue electroluminescence from the InGaN/GaN NWs, which is downconverted by micro-sized phosphors with the emission wavelength and concentration adjusted to yield high correlated color temperature (CCT) and color rendering index (CRI) values. The NWs are grown by MOVPE on c-sapphire substrates. Their structure consists of seven core/shell InGaN/GaN quantum wells radially overgrown on n-GaN core and covered by a p-GaN shell. For the fabrication, the NWs are encapsulated in PDMS, peeled off from the substrate and contacted using a silver NW mesh to form a flexible transparent contact. A PDMS layer doped with micro-phosphors is added on the top. Five different phosphors with tens of microns grain size emitting from green to orange are investigated using both violet-blue and a blue-green NW-based LED pumps. Compared to the previous realizations [1], these new devices improve the CRI from 54 to 86 and show a colour tunable from a bluish cool white colour to a natural white and finally to a warm white [2].

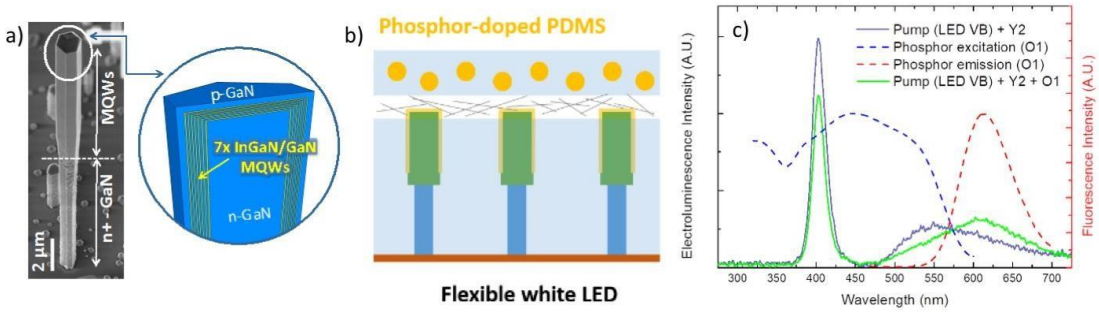

Figure 1. *a) Tilted SEM image of a core/shell InGaN/GaN NW and its schematic. b) Schematic of the device structure. c) EL spectra of a cool-white LED with the $Y_{2.94}Ce_{0.06}Al_5O_{12}$ phosphor and of a warm white LED with the additional $Sr_{1.95}Eu_{0.04}Tb_{0.01}Si_5N_8$ phosphor on top traced with the excitation and emission spectra of the second phosphor.*

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P3.13 - Silicon nanonet, a promising material for flexible and large-scale electronics

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Due to their flexibility, workability, lightness, fineness and reproducibility, randomly oriented nanostructured networks, also called nanonets (NNs), are an attractive material for flexible and large area electronics as a potential alternative to amorphous silicon or organic materials. Moreover, NN-based device integration process is based on simple technologies [1] and done at low temperature ($< 400^{\circ}C$) compatible with some flexible substrates. The device geometry can vary from a micro-to-millimeter scale. As a consequence, such a material provides an interesting path to low cost devices [2]. To this end, by combining bendable NNs based on Si nanowires (SiNWs) with rigid (Si/Si3N4) and flexible (Kapton) substrates, we report on the successful fabrication and electrical characterization of rigid and flexible resistors and transistors using bottom-up fabrication and standard microelectronic technology. Both type of resistors, flexible or not, exhibit high electrical performances with linear characteristics, even if current has to flow through a succession of tens to hundreds of SiNWs, depending on device geometry, and as many SiNW-SiNW junctions. Electrical performance of flexible transistors are still under study, but rigid transistors with long channel ($1000\mu m$) exhibit outstanding performances with high drain current up to 10^{-7} A, I_{On}/I_{Off} ratio as large as 10^5 and a better mobility as compared to a-Si and organic materials [3].

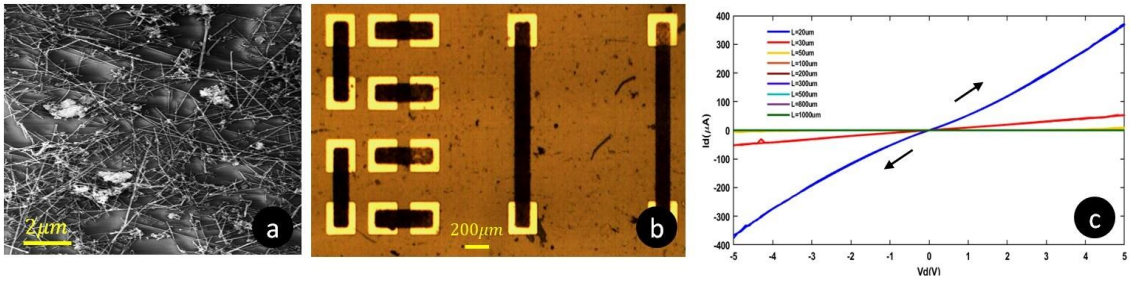

***Figure 1**: SEM image of as-fabricatedSiNN; (b) SEM image of SiNN-based devices; (c) Electrical characteristic of flexible NN-based resistor with channel length (L) from 20µm to 1000µm which clearly show the great conduction of NN through numerous NW/NW junctions (NW length = 7 µm).*

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P3.14 - Localized emitters in self-catalyzed InAs/GaAs nanowire heterostructure arrays on silicon

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Keywords: heterostructure, emitters, arrays

Switching NW growth from GaAs to InAs in a self-catalyzed manner is challenging as the group III droplet has to be completely exchanged from Ga to In. An abrupt change in the material composition at the interface therefore becomes difficult. On the other hand, incorporating In into the Ga catalyst droplet leads to a grading in the InAs-GaAs interface.[1] InAs/GaAs NW heterostructures reported so far have been achieved either with a top-down approach[2] or by using gold as the catalyst droplet.[3,4] Here, we report on the growth of InAs segments on top of GaAs NW arrays on Si by the self-catalyzed method. In order to obtain a sharp interface, we start by consuming the Ga droplet on top of the GaAs NW and continue by replacing it with an indium droplet. The results indicate that indium accumulates preferentially at the nanowire tips. The figure below depicts the growth strategy as well as chemical analysis of a GaAs nanowire with an In droplet, demonstrating that it is purely In. Crystallization of the In droplets into InAs and capping them with a GaAs shell leads to localized InAs segments within GaAs nanowires that could act as localized emitters. The optical properties of such segments are investigated using photo- and cathodoluminescence.

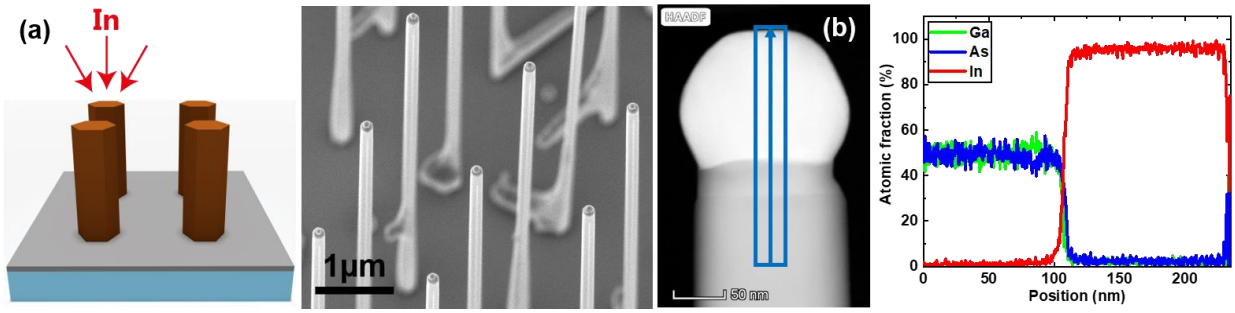

Figure 1. *(a) Growth schematic and SEM image of In droplets on top of a GaAs NW array. (b) HAADF-STEM image and corresponding EDX linescan showing the concentration profile along the droplet-nanowire interface.*

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P3.15 - Site- and polarity-controlled GaN nanowires on silicon for high-speed LEDs

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Keywords: SAE, LED, polarity

We will outline an approach for a site-controlled MOVPE growth of Ga-polar gallium nitride (GaN) nanowires (NW) onto a non-polar Si(111) substrate. The realized NWs serve as a template for subsequent shell growth of high-speed core-shell light emitting diodes (LED). The facets on these shells are on the *m*-plane of the wurtzite lattice, which is perpendicular to the $\vec{c}$-direction. Therefore, they are free of polarization fields and hence suitable for high-speed switching III/N LEDs[1,2], which are promising as application for visible light communication via free space or polymer optical fibers. The homogeneous growth of each NW is a prerequisite for the electrical operation of an array device consisting of several 1000 NW-LEDs. The homogeneity is commonly realized by selective area epitaxy (SAE) based on masks (SiO_x, Ti, SiN_x). Here we present a mask-free approach, which combines the advantages of SAE and self-catalytic growth. Polarity- and site-controlled growth of GaN islands (Fig. 1a) serves as the starting point for the subsequent NW growth[3]. Entirely Ga-polarity, enhanced vertical growth and a 100% fill factor are achieved by adjusting the following crucial epitaxy parameters. Entirely Ga-polar growth is promoted by using nitrogen carrier gas, only. While a high Si/Ga-ratio (4.2 ‰) enhances the vertical growth, it also leads to a degradation of the crystal facets and a reduced fill factor. Both effects do not occur if the V/III-ratio is adjusted depending on the NW height (1b, c and d). While the crystal forms a hexagonal cross section with 6 *m*-facets at the bottom, a six-point-star symmetry with twelve *m*-facets can be observed above ≈ 1 µm NW height (compare 1d and e). We assume, that the morphology change is caused by a reduced GaN volume growth rate for longer NWs and a constant *in-situ* SiN_x passivation, independent of the NW height. The results are supported by a qualitative model. Finally, NW-LEDs are realized by growing hexagonal m-planar shells around the NWs.[2]

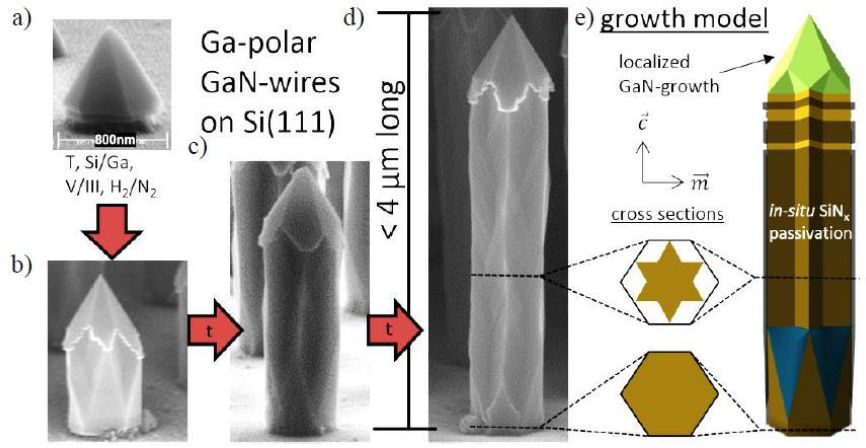

Figure 1. *a) Ga-polar GaN islands; b) NW shape attained under optimal epitaxy parameters; c,d) long NWs by extended growth duration; e) qualitative growth mode of NW, with height-dependent cross section change*

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P3.16 - Tapered ZnSe/ZnMgSe core/shell NWs for directed single photon emission

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Keywords: Nanowire, single photon source, molecular beam epitaxy

A QD-nanowire (NW) configuration provides not only the required quantum confinement for single photon emission but also the flexibility in realizing photonic devices. We have previously shown the possibility of single photon emission (SPS) upto room temperature with CdSe QD in ZnSe NW [1], but the quantum yield and collection efficiency were very low. We expect a significant improvement in the quantum yield- with an epitaxial ZnMgSe shell and in collection efficiency along the NW- with a thick shell, by maximizing the amount of light emitted from the quantum dot into the HE_{11} mode. In addition, a tapered geometry will provide directionality to photon emission from the nanowire in the far field due to adiabatic expansion of the fundamental mode during propagation [2].
Here, we report our work on the growth of vertically oriented and tapered ZnSe/ZnMgSe core-shell NWs by molecular beam epitaxy and 3D-simulations to optimize the QD-NW geometry for maximum collection efficiency along the NW. COMSOL simulation of a CdSe-QD emitting along the axis of a tapered ZnSe NW (*n*=2.66) points to a minimum diameter of 160 nm as required to minimize the dielectric screening effects and to couple the QD emission to the HE_{11} mode. The ZnSe NWs are grown on a ZnSe(111)B buffer layer with 10nm Au-nanoparticles at 350-400°C. Tapering of the NWs was realized by lowering the growth temperatures to the point where radial growth is enhanced without suppressing the axial growth. We also studied the effect of NWs inclination angle with respect to incident fluxes on growth of (Zn,Mg)Se shell. With a 10° NW tilt during shell growth, the tip of the core can be kept well above the 2D layer. Additionally, we obtained a smoother growth of shell on a NW of smaller tapering angle. With 120 min of shell growth at 300°C on tapered core with a 10° inclination angle, shells with 160 nm base diameter and 7 nm tip were achieved with the tip of the NWs more than 150nm above the 2D layer. With this thick but tapered shell having an optical index of *n*=2.63 close to that of the core, we hope to increase the collection efficiency many folds.

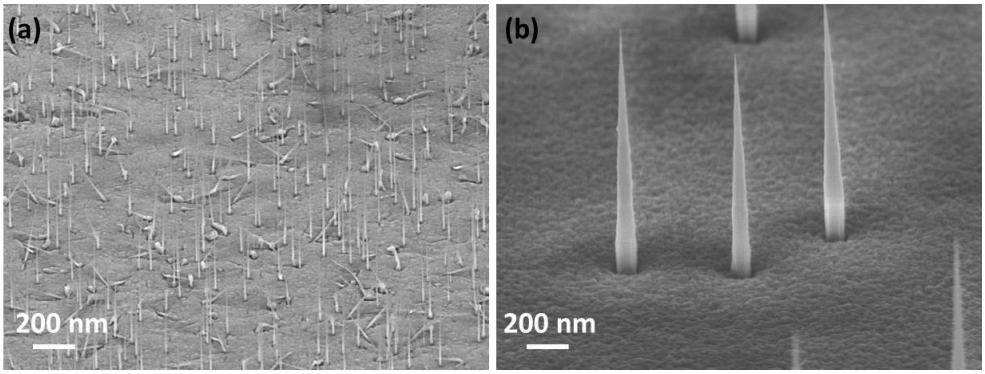

Figure 1. *SEM images after (a) ZnSe core growth at 350° C for 20 min and (b) additional ZnMgSe shell growth at 300° C for 120 min. The total core/shell diameter is more than 160 nm at the base and 7 nm at the tip- size of the Au nanoparticle.*

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P3.17 - Fabrication of nanocolumn photonic crystal (NC-PC) structure with enhanced optical confinement by controlling NC diameter

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Keywords: nanocolumn, photonic crystal, InGaN light emitting diodes

Nitride nanocolumns (NCs) exhibit the nanocrystal effects, such as the dislocation-free nature, strain relaxation in active layer, and high light extraction efficiency, which contribute to the improve emission efficiency of InGaN. Using regularly arranged InGaN/GaN NCs prepared by Ti-mask selective area growth[1], we fabricated NC photonic crystal (PC) LEDs with the directional radiation beams[2]. The PCs are utilized for the NC-PC surface emitting laser (SEL). For realizing the NC-PCSELs, it is necessary to confine the optical field in the InGaN active region. However, the NC diameter increases during the growth of Mg-doped p-type GaN, increasing the effective (averaged) refractive index at the p-GaN cladding, which lowers the optical confinement of the active region. In this study, we fabricated the optical confinement structure by increasing NC diameters in the underlying n-type GaN cladding region, which pushed the optical field downward increasing the optical confinement of the InGaN active region.

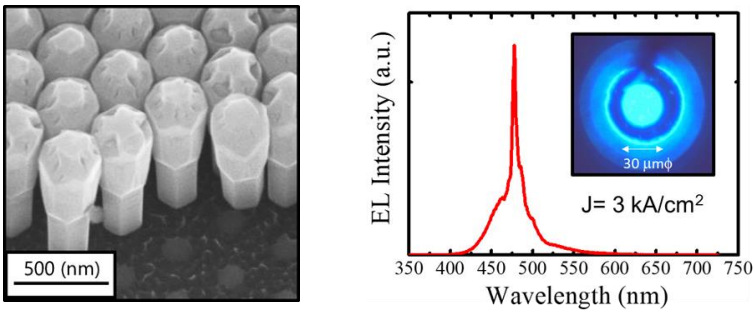

Figure 1. *(a) Bird's eye view SEM image of p-i-n based NCs with the period of 270 nm and (b) EL spectra of p-i-n NC LEDs observation by 5x objective lens (N.A.=0.13).*

We prepared Ti mask nanohole patterns with triangular lattices of 270 nm on GaN templates, using an electron beam evaporation, electron beam lithography, and inductively coupled plasma etching. Si-doped n-type GaN NCs was grown on the patterned templates under the N-rich condition by rf-plasma-assisted molecular beam epitaxy (rf-MBE). During the growth of n-GaN, the growth mode was switched to the Ga-rich condition, by which the NC diameter increased, increasing the filling factor from 45% to 80%. Subsequently, we grew InGaN/AlGaN MQW and Mg-doped p-type AlGaN/GaN superlattice cladding region (Fig 2(a)). The novel NC-PC structure exhibited a sharp 480 nm electroluminescence spectrum at 3 kA/cm^2 under the LED mode, having the full-width-at-half-maximum of 8.1 nm (Fig. 1(b))[3].

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P3.18 - Current-Injected III-V Nanowire Optical Interconnect

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Silicon photonics has gained increasing attention as a platform for optical communications. With all components, such as lasers, detectors and waveguides, built on silicon-on-insulator (SOI), the optical interconnect is an enabling technology for CMOS-compatible photonic integrated circuits. Many academic and industrial R&D groups, including Intel and IBM, have been pursuing the goal of inter- and intra-chip interconnects to fulfill the increasing demand for big data transport in telecommunications.

The goal of the proposed research is realizing III-V nanophotonic transceivers on an SOI platform. Our focus has been using “bottom-up” synthesis method to integrate vertical nanowire (NW) array with axial or core/shell heterostructures. Although the hetero-integration of NWs is free from threading dislocations, the defect states created by strain-induced misfits and surface defects can still serve as preferred sites for non- radiative recombination processes, which deteriorates the device performance. Other factors, such as materials/dopants inter-diffusion and heating effect, also make it difficult for current-injected NW lasers.

In this study, a pathway is proposed to address the abovementioned issues and to realize III-V NW photonic crystal lasers on SOI substrates. NW heterostructure with p-GaAs/i-InGaAs is designed to integrate on patterned SOI to optimize both electrical and optical confinement. Novel fabrication process for vertical NW array has been developed to build devices with high reliability. The preliminary results with arrayed p- type GaAs NW diodes on n-type SOI have been studied in detail as a stepping stone to improve the electrical design. In addition, the proof-of-concept studies, including optically pumped nanobeam lasers and electroluminescence from the NW photonic crystal cavity, show the possibility of nanowire lasers. It is worth noting that tunable wavelength can be achieved by tuning the material compositions and photonic crystal cavity designs, which shows great potentials in applications such as wavelength- division multiplexing (WDM). With better optical and electrical design, it is expected that current-injected NW photonic crystal lasers can be achieved, which will be a key component in on-chip optical interconnects and silicon photonic integrated circuits.

P3.19 - First demonstration of vertical surrounding-gate transistor using InP nanowires

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Keyword: MOVPE, III-V compound semiconductor, field-effect transistor

Miniaturization of field effect transistors (FETs) has serious problem in huge power consumption and performance due to the size and the thermionic physical limitation. Then, high mobility channel materials such as III-V compound semiconductors and multi-gate structures are being expected to solve the problem. Here, we report on first demonstration of vertical surround gate transistor (VSGT) using InP nanowires (NWs) grown by selective-area epitaxy. Among III-V NWs, InP NWs have a wurtzite singlecrystal structure with atomically flat facets[1], which is beneficial for good oxide-semiconductor interfaces[1].

Openings were formed on 18 nm-thick SiO_2 covered InP (111)A by electron beam lithography and etching. Then, InP NWs were grown by MOVPE [Fig 1(a)]. Growth temperature was 660°C, and a Zn pulse doped layer was grown for 2 minutes and 30 seconds to form an intrinsic segment to serve as channel region, then a Si doped layer was grown for 1 minutes, and an Sn pulse doped layer was grown for 3 minutes to form contact (drain) region. The pulse doping technique was to suppress lateral growth of the NWs[2]. The V/III ratio was 24.

Next, 10nm-thick $Hf_{0.8}Al_{0.2}O$ film was deposited as gate oxide film by atomic layer deposition, and tungsten (W) was wrapped as gate metal by RF sputtering. Moreover, the NWs were buried with benzocyclobutene (BCB). Furthermore, the gate metal and oxide on top of the NWs were etched by reactive ion etching to fabricate surrounding-gate structure. Finally, gate-drain isolation layer was formed by BCB and Ni/Ge/Au/Ni/Au were deposited for the drain and source metals. The devices were annealed at 350°C for 5 min.

The InP NW-VSGT are illustrated in Fig 1(b). The InP NWs were 102 nm in diameter. The heights of the Zn doped, Si doped, and Sn doped segments were 420 nm, 168 nm, and 504 nm, respectively. Fig 1(c) shows transfer characteristics of the InP NW-VSGTs. The switching properties was n-type enhancement mode with a threshold voltage (V_T) of 0.12 V. The drain current was modulated by gate voltage (V_G) with subthreshold slope (SS = $dV_G/d[\log(I_D)]$) of 79~109 mV/dec. The SS was decreased with increasing drain-source voltage. On-off ratio for drain current was 7 decades. Off-leakage current was 0.1 ~ 5.0 fA/μm. The drain-induced barrier lowering (DIBL) was estimated to be 137 mV/V. Peak transconductance (G_m) was 456 nS/μm. Further device optimization to decrease series resistance is required for high G_m.

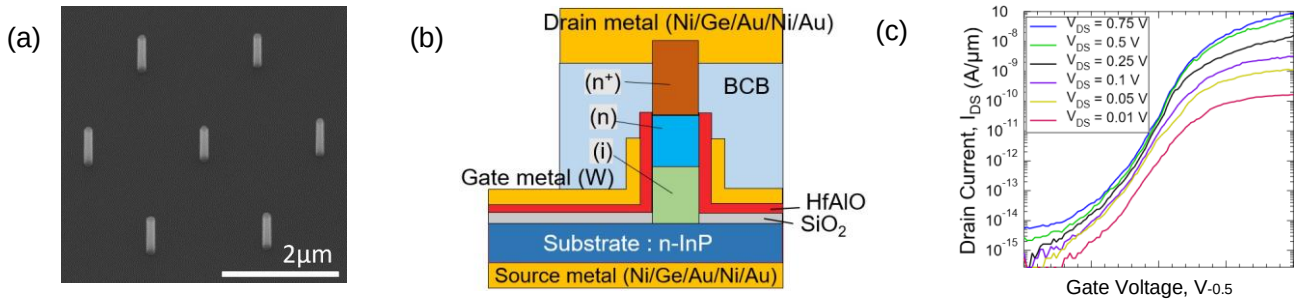

Figure 1(a). SEM image of the pulse-doped InP NWs. (b). Cross-sectional structure of a NW-VSGT. (c). Transfer characteristics of InP NW-VSGT.

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P3.20 - Direct Measurement of Cavity Reflectivity in High-Yield Room-Temperature Nanowire Lasers

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Keywords: Nanowire Laser, Cavity Measurements, Coherence Length

Lasers based on semiconductor nanowires have long been recognized as a promising architecture for room-temperature, low-threshold and high-yield nanoscale light sources with the possibility for direct heteroepitaxial growth. One of the primary advantages is the dual role of the nanowire as gain material and Fabry-Perot cavity. Over the past decade, significant research effort have led to components based on quantum-well gain regions and selective-area and self-catalysed growth. While optimization for gain can build on decades of research in planar laser structures, the optimization pathway for the cavity is more often based on simulation following by trial growths.

Recently, we have used a high-throughput methodology to study the role of inhomogeneity on nanolasers performance[1]. This has two advantages – firstly, we identify the yield and best-in-class for a given growth strategy, but more interestingly, by exploring correlations between geometrical or electronic behavior and lasing threshold, we are able to experimentally identify the critical limitation for yield or threshold. One outstanding issue has been the lack of a facile experimental method to determine end-facet reflectivity in the nanowire platform.

By coupling an optically-pumped nanowire laser to a time-resolved interferometer, we show that we are able to directly measure the coherence length and hence an end-facet reflectivity of 70% for a recently reported nanolasers structure based on GaAsP core and barrier layers with GaAs wells as gain material[2]. While reflectivity remains a significant limitation, we demonstrate nanosecond lasing and a route towards continuously emission in these high-quality structures.

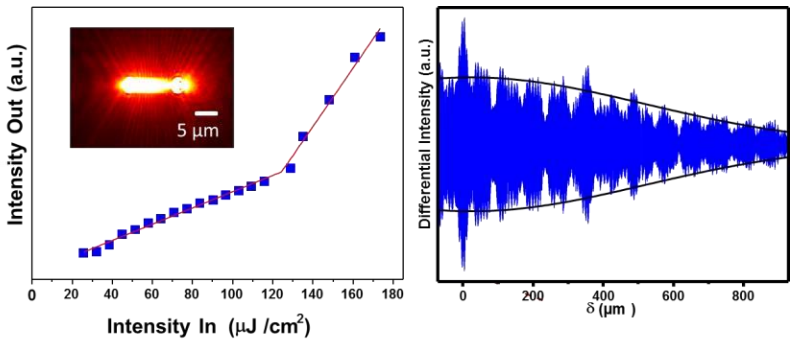

Figure 1. *(Left) Light-in vs Light-out curve for typical nanolaser and (inset) an above threshold image. (Right) Interferogram from end facet emission with a fit line indicating the ~800µm coherence length.*

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P3.21 - GeSn mid-infrared nanophotonic resonant absorbers

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Mid-infrared wavelengths are technologically crucial for chemical sensing, thermal imaging and LIDAR applications. Having been shown to exhibit a direct bandgap, GeSn alloys hold great promise as an efficient mid-infrared light absorbing material system, with the potential to be monolithically compatible with existing silicon technologies. Therefore, GeSn can open pathways for miniaturization of mid-infrared devices such as on-chip molecular sensors, optical interconnects and thermal cloaking devices. Compared to GeSn epitaxial thin films on typical (e.g. Si, Ge) bulk substrates, GeSn nanowires have advantages such as less misfit strain, providing the potential for lower defect denisities. Therefore, GeSn nanowires may constitute a superior medium for absorption and generation of photocarriers.

We demonstrate room temperature mid-infrared photodetection using resonantly absorbing GeSn/Ge core/shell nanowire photonic crystals. We have synthesized GeSn/Ge core/shell single crystal nanowires with 4% Sn that exhibit strong direct-bandgap photoluminescence at room temperature[1,2]. The vertical nanowire photodetection device consists of arrays of nanowires in-filled with PMMA insulating layer, an ITO top contact and an aluminum bottom contact. Using full wave FDTD simulations, we optimize Mie resonances of individual nanowires (300 nm in diameter) at the desired bandgap wavelength. We further engineer the absorption with nanowires arranged in photonic crystal arrays. To synthesize the nanowire device, gold catalysts were patterned on Ge [111] substrate and then two step VLS growth was performed to synthesize Ge core and GeSn shell, shown in Figure 1(a). We performed photocurrent characterization with an FTIR spectrometer at room temperature, shown in Figure 2b. The photocurrent spectrum of Ge nanowire photonic crystals indicates a four-fold enhancement due to resonant absorption, with the photocurrent spectrum tunable by varying the photonic crystal geometry.

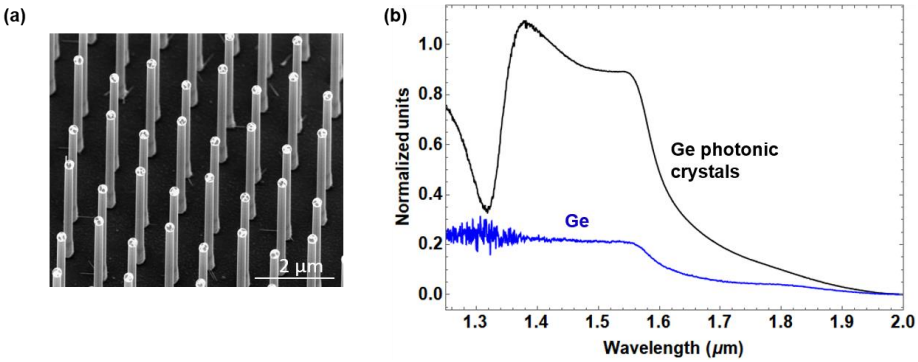

Figure 1. *(a) SEM image of GeSn nanowire photonic crystals (b) Photocurrent spectrum of randomly distributed Ge nanowire (40nm diameter, blue) and Ge nanowire photonic crystals (black).*

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P3.22 - Electrical tunability of single quantum dots embedded in GaN nanowires

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Keywords: GaN, quantum-confined Stark effect, micro-photoluminescence

Single GaN quantum dots have demonstrated their capability as single photon emitters at room temperature, thanks to the large band offsets between GaN and AlN[1,2]. These nano-objects could set the basis for the introduction of III-nitrides in the domain of quantum technologies. In this work we study the spectral tunability of the emission of a single GaN/AlN quantum dot in a GaN nanowire by applying external bias. The nanowires are dispersed and contacted on electron beam transparent Si_3N_4 membranes, so that transmission electron microscopy observations and micro-photoluminescence measurements under bias can be performed on the same nanowire[2,3,4]. This allows the direct correlation of the optical and electrical properties with the structural characteristics of the quantum dot. The samples under study consist of GaN nanowires grown by plasma-assisted MBE containing a single AlN/GaN/AlN insertion where the AlN barriers are 10 nm thick and the GaN insertion is 0.8 nm thick (nominal parameters). Three-dimensional calculations of the electronic structure taking the STEMmeasured morphology into account predict an internal electric field in the quantum dot around 3 MV/cm. In-situ micro-photoluminescence characterization of thin single nanowires display a single emission peak, which shifts with bias at impressive rates between 11.9 and 25.1 meV/V. Transitions to other charge states can be observed (arrow in the figure). The emission blue shifts when the external electric field compensates the internal electric field generated by the spontaneous and piezoelectric polarizations. It also vanishes with increasing generated photocurrent. The emission intensity scales superlinearly with the impinging optical power, suggesting a saturation of traps, probably point defects in the vicinity of the dot.

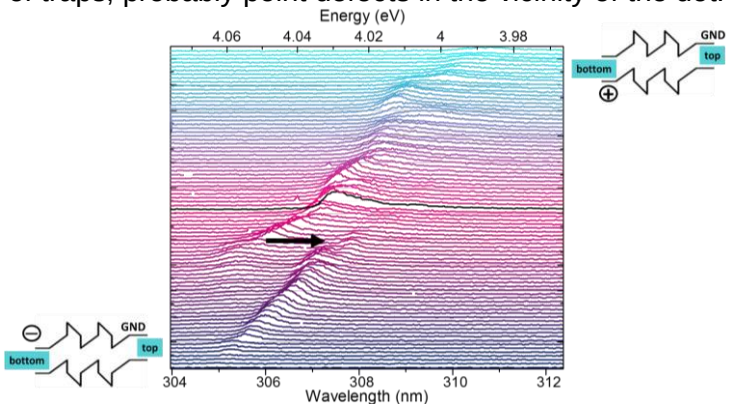

Figure 1. *Microphotoluminescence spectra applying from -4 to +4 V bias. The zero-bias measurement is indicated in black. The spectra are vertically shifted for visibility. The two schematics indicate the bias polarity: bottom = the bias compensates internal field, top = bias enhances internal field.*

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P3.23 - Transient reflectivity and ultrafast dynamic of electrons and holes in GaAs NWs

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Keywords: nanowires, reflectivity, terahertz emission, electron-hole plasma

Characterization of the charge-carriers dynamics in such nanostructures as the semiconductor nanowires has decisive importance for application of these materials in nanophotonics, nano- and bio-electronics.

In this work we present experimental results of the femtosecond reflectivity measurements of carrier dynamics and studies of screening processes of a local electric field by a nonequilibrium electron-hole plasma in ordered arrays of NWs based on GaAs. Using the reflectivity technique, we show that on the femtosecond time scale, momentum relaxation scattering processes occur, leading to a well-defined high temperature of electrons and holes, then lowering this temperature to the lattice temperature due to energy relaxation. On longer time scales bulk and surface recombination processes and diffusion define the change of reflectivity. The specific type of time and spectral dependence of the reflection coefficient from an array of nanowires differed from the corresponding dependences for bulk gallium arsenide [1], which, as was shown, is associated both with the manifestation of the optical properties of the metamaterial and with the properties of the nanocrystal itself. The second part of the study of carrier dynamics was based on the coherent spectroscopy method – optical pump-THz generation probe, which allow study the time evolution of the terahertz generation efficiency in nanocrystal, after ultrafast excitation by a femtosecond optical pulse of a nonequilibrium electron-hole plasma. The excitation of the nonequilibrium electron-hole plasma in a local electric field of semiconductor NWs leads to the charge carrier separation and, accordingly, to the changes in the generated terahertz radiation [2]. Time parameters of these changes will be due to the relaxation and recombination processes of charge carriers and their transport. Performed research allowed reconstructing the superfast screening of a local field in a nanocrystal, determined by a transport of charge carriers and their recombination. The dependence of initial fall time of THz emission, which is mainly determined by the local electric field, on the initial concentration of the photoexcited electron-hole plasma can be accounted for by a theory based on majority-carrier flow. The characteristic time obtained were used to determine the pulse relaxation time of the electrons [3].

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P3.24 - Engineering the spontaneous emission in semiconductor nanowires

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Keywords: semiconductor nanowires, nanophotonics, waveguides

Harnessing the technological potential of novel nanophotonic schemes based on Mie resonances and other near-field effects will require nanoscale material concepts which provide an efficient integration of the two key aspects of these schemes: the emission and the waveguiding functionalities. By intrinsically melding optical activity with tunable dielectric subwavelength waveguiding, direct bandgap semiconductor nanowires seem particularly attractive in this regard.

In this contribution, we demonstrate that the spontaneous emission in molecular-beam-epitaxially grown semiconductor nanowires can be controlled through their electro-magnetic environment. We first show that the emission lifetime of photo-excited electron-hole pairs in GaAs/AlGaAs core/shell nanowires[1,2] can be engineered over two orders of magnitude, allowing to approach 100 nanoseconds, an unusually long lifetime for a direct bandgap semiconductor. Interestingly, we find the diameter (d =550 to 65nm)[3] of the nanowire itself to be the major tuning parameter.

Moreover, in the single-mode regime of the waveguide, at the smallest nanowire diameters, we demonstrate that this emission lifetime can be manipulated by engineering the electro-magnetic environment of the nanowires through advanced nanofabrication techniques. Exploiting this unique handle on the spontaneous emission of the mobile emitters, we realize a spatial control of the mobile emitters along the 1D nanowire waveguide.

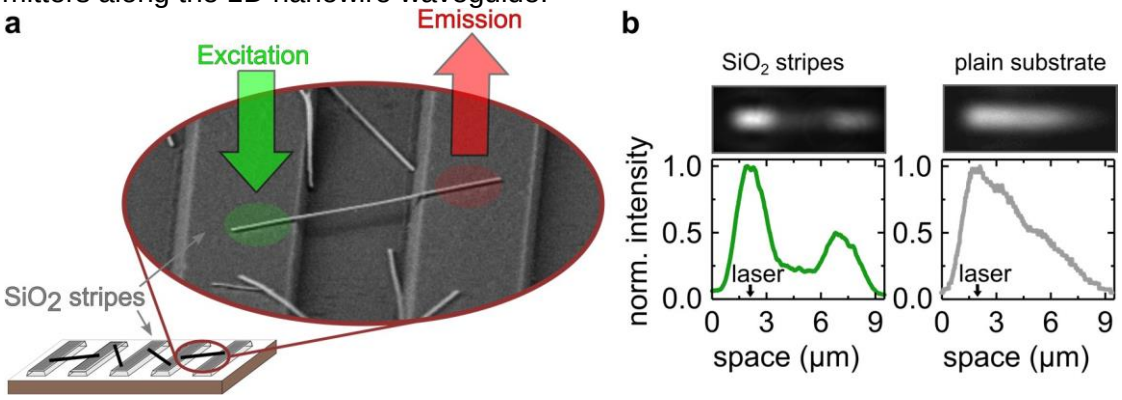

Figure 1. *Engineering the electro-magnetic environment: (a) Scanning electron micrograph of a 8μm long nanowire supported on both ends by a dielectric SiO_2 stripe. The approximately 3μm long region in between the stripes is surrounded by vacuum. (b) Microscope image of the PL intensity and the corresponding intensity profile (green) along the nanowire axis in comparison with the intensity of a nanowire lying on a plain SiO_2 substrate (grey).*

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P3.25 - Self-catalyzed high-quality core-shell gaasp nws on silicon and their application on optoelectronics

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Keywords: Nanowire, photovoltaics, photo emitters

The growth of self-catalyzed high-quality core-shell GaAsP nanowires (NWs) have been achieved on both patterned and un-patterned Si substrates by solid-source molecular bean epitaxy.[1,2,3,4] The NWs are highly uniform in morphology with almost stacking fault free zinc blend crystal structure.[5,6] The fabrication of high-quality single NW solar cells has been realized with a world record fill factor of 80.5%.[7] Their potential application on photovoltaic has been demonstrated by single NW detectors with a record-high photoresponsivity of 1.45×10^5 A/W and excellent specific detectivity up to 1.48×10^{14} Jones,[8] single NW solar cells with a record-high efficiency exceeding 10%[9] and water splitting devices with a wafer-scale solar-to-hydrogen conversion efficiency of 0.5%.[10] Their application on photo emitters has been demonstrated by building quantum well lasers with an ultra-low internal threshold of 0.9 μJ/cm^2/pulse and a narrow linewidth of 0.15nm.[11]

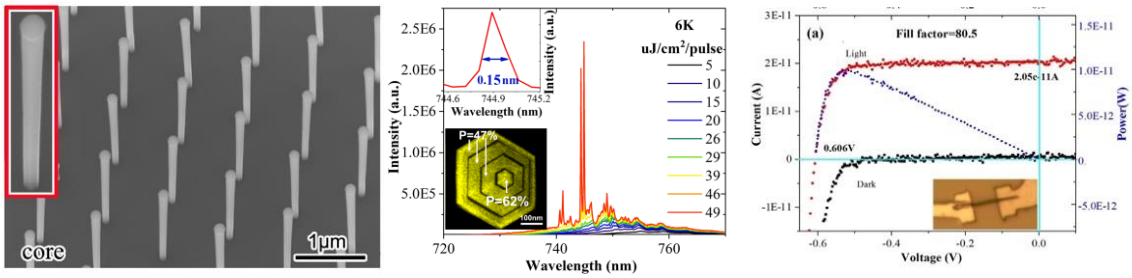

Figure 1. *Left. GaAsP NWs grown on patterned Si. Middle: single GaAs NW solar cell with a record-high fill factor of 80.5%. Right: GaAsP/GaAs quantum well single NW laser with an ultra-low internal threshold of 0.9 μJ/cm^2/pulse*

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P3.26 - Mid-infrared infrared photodetectors based on InAs-nanowire/silicon hybrid heterostructures

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Keywords: mid-infrared, photodetector, nanowire

As a one-dimensional material, InAsSb nanowire has been proposed to be the most promising candidate for realizing advanced infrared photodetectors operating at room temperature with high sensitivity. This is attributed to its unique features including direct bandgap, high mobility, enhanced light absorption and efficient separation and collection of photon-generated carriers. We herein report the realization of infrared photodetectors based on InAsSb nanowires on p-type silicon. This work shows the promising future of nanowires for device application in low-cost and high performance infrared photodetectors.

The InAsSb nanowires were grown on silicon wafers by droplet-assisted molecular beam epitaxy (MBE)[1]. The resulting nanowires have an average diameter of 80 nm and an average length of 3 um. Standard photolithography was used to proceed nanowire ensemble mesa photodetectors. Asymmetric I-V profile was observed for the devices with nanowire length longer than 3 um, which also demonstrate room temperature photoresponse peaked at 3.0 um as shown in the figure 1. The devices with shorter nanowire don't give photoresponse. This behavior was attributed to the carrier distribution of the hybrid heterostructure formed by InAsSb and silicon, which was confirmed in photoluminescence studies[2]. This demonstration reveals the promising application of utilizing nanowire for low-cost and high performance infrared photodetectors.

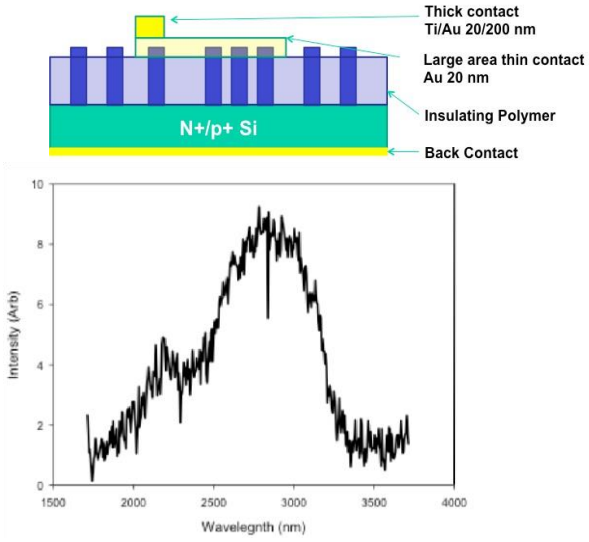

Figure 1. *Schematic of nanowire ensemble mesa device (top), and the room temperature photoresponse of the photodetctors with nanwire length of 5.0 um (bottom)*

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P3.27 - InAs/InAsP quantum dots in semiconductor nanowires: transport properties and application in terahertz photonics

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Keywords: quantum dot, nanowire, terahertz

Semiconductor nanowires (NWs) represent potential building blocks for the development of electronic and photonic components covering a wide range of applications, like energy harvesting,[1] chemical sensors[2] or light sources.[3] The growth of axially heterostructured NWs has pushed their domain of implementation even further. One of the most appealing perspectives is represented by the possibility to address or reveal the state of a single particle with semiconductor quantum dots; this refers not only to single electrons, but also to single photons.[4]

In particular, at infrared wavelengths, quantum well and quantum dot infrared photodetectors (QWIPs and QDIPs) offer the capability of ultrafast detection (> 1 GHz) with high responsivities (> 1 V/W).[5] QDIPs are expected to operate up to 150 K, thanks to the significantly reduced thermal generation of carriers as a result of the 3D energy quantization.[6] In this context, quantum dots realized along the axis of a NW can play a relevant role, owing to the impressive wealth of material combinations that can be implemented.

Here we report on the growth and transport properties of InAs/InAsP quantum dots. The electrical characterization of the devices shows that the energy levels within the dots are separated by only few meV (from 5 to 20, depending on the NW diameter), making them suitable for the realization of far-infrared detectors.

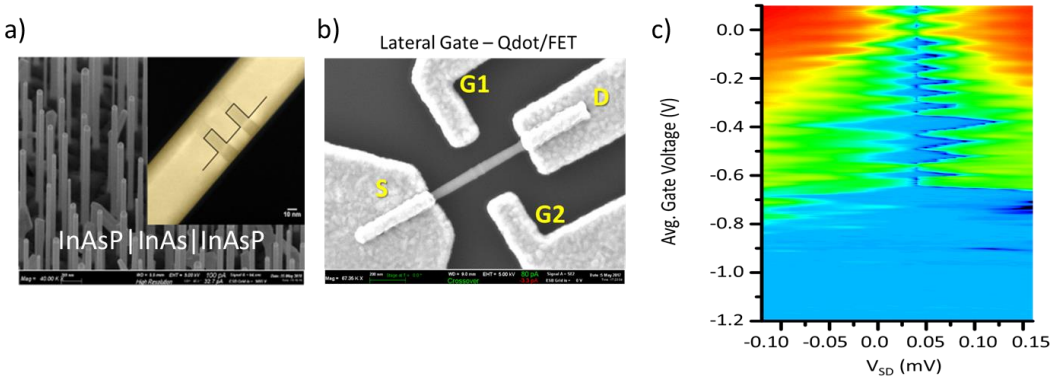

Figure 1. *a) SEM and HRTEM of the grown InAs/InAsP heterostructured NWs. b) SEM picture of the fabricated lateral-gate-FET. c) Conductance chart through the quantum dot as a function of source-drain bias (V_{SD}) and lateral gate bias (V_G).*

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P3.28 - Tuning tunneling rates in InAs/InP quantum dots

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Keywords: Quantum dots, Coulomb blockade, Electron tunneling rate

Single-electron transistors based on heterostructured nanowires represent a promising and robust building block for a range of applications[1-5]. However, many require a fine control of the tunnel coupling, which is typically fixed in devices with heterostuctured barriers. In this work, we demonstrate that electron tunneling rates can indeed be modulated by taking advantage of axially excited orbitals and field-effect control of the quantum dot spectrum.

We investigate 50 nm-diameter nanowires embedding a 19 nm InAs island defined by 5-6 nm-thick InP barriers. Figure (1) reports a typical charge stability diagram covering a filling range going from the limit of an empty dot up to a large number *N* of electrons (~ 30-40). We show that sharply enhanced tunneling can be obtained beyond a given gate voltage threshold which is consistent with the filling of axially-excited orbitals, based on simulations[6]. Such states have a significantly larger kinetic energy in the direction perpendicular to the barrier and thus a larger transmission probability is expected. Exploiting field effect we modulate the dot spectrum, induce crossings between the orbitals and demonstrate that the barrier transparency can be modulated over the range of tunneling rated going from 0.5 to 50 GHz. The possibility of obtaining a continuous modulation via a hybridization of weakly and strongly coupled orbitals is discussed.

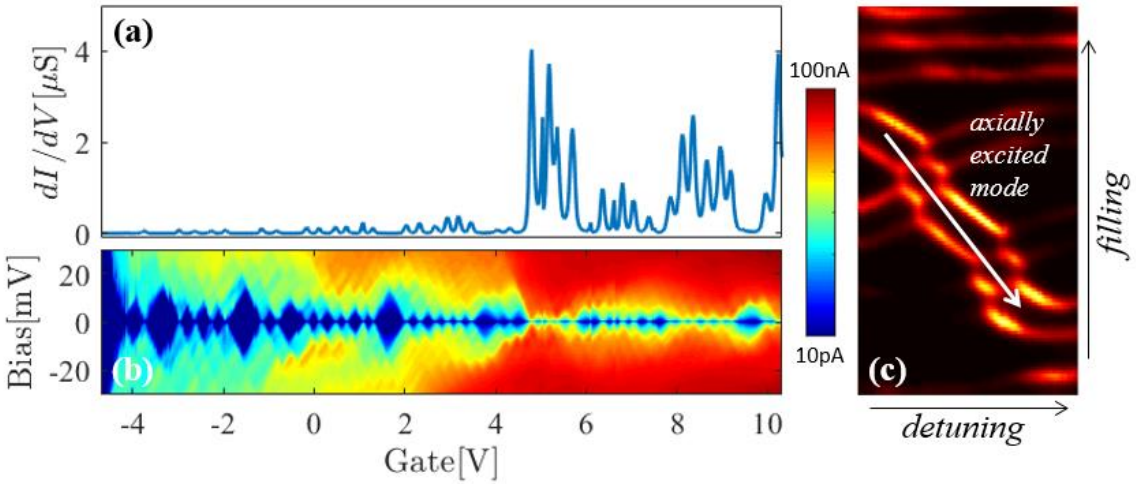

Figure 1. *Coulomb peaks (a) and diamonds (b) from the pinch-off up to N=36. (c) Linear regime current map at gate-induced crossings between strongly and weakly-coupled orbitals.*

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P3.29 - Single nanowire devices enabled by SU8 embedding

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Keywords: Embedded nanowires, nanowire optoelectronics, Hall effect

Despite the emergence of many optical techniques, direct electronic contact to individual, horizontally-alligned nanowires remains one of the foremost routes for studying physical phenomena. For nanowire diameters rising above 100 nm, the fabrication of electrodes at high resolution becomes increasingly challenging through typical lithographic and deposition processes, due to the thick metal layers – and thus resists – required. To address this, polymer layers can be used to create embedded nanowire structures, providing a planarized surface and allowing production of smaller, more complex device features.[1] Here, we present two such device studies made possible through a SU8 embedding process; a single nanowire spectrometer, based around a CdS_xSe_{1-x} nanowire; and the high magnetic field characterization of an InAs nanowire Hall bar (Fig. 1).

CdS_xSe_{1-x} nanowires are alloyed such that the composition, and thus the bandgap, varies continuously along their structure.[2] Embedding allows fabrication of a dense, parallel array of electrodes, forming a series of photodetectors with different spectral responses along the wire. We show that by electronically probing the photocurrent and cross-referencing with a pre-calibrated response function for each detector, it is possible to computationally reconstruct incident light signals. Such a platform represents arguably the simplest, most compact microspectrometer possible, independent of the complex optical components, cavities or CCDs that constrain further miniaturization of current systems. Despite their simplicity, these devices are capable of accurate monochromatic and broadband visible light reconstruction, as well as spectral imaging from centimetre-scale image planes down to lensless, single-cell-scale in-situ mapping.

InAs nanowires are promising candidates for quantum devices due to their high carrier mobility and strong confinement effects.[3] Single nanowire Hall bars allow direct characterisation of quantum transport phenomena, though require sub-diameter feature resolution (tens of nanometers). *Via* embedded structures, we measure the magnetic field dependent longitudinal and Hall voltages in an individual InAs nanowire at low temperatures, and explore the gate tunable spin-orbit coupling.

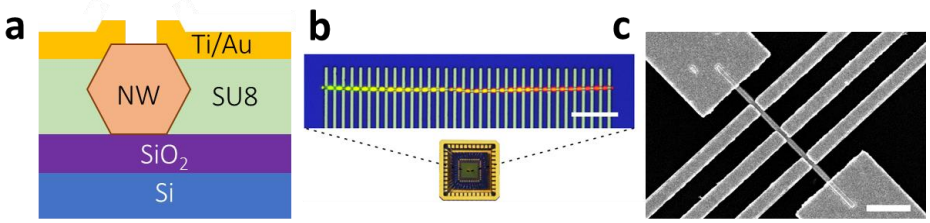

Figure 1. a*; Schematic of a polymer embedded nanowire device.* ***b****; Optical micrograph of a single* CdS_xSe_{1-x} *nanowire spectrometer device (scale bar is 10μm).* ***c****; Scanning electron micrograph of an InAs nanowire Hall bar (scale bar is 1μm).*

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P3.30 - Nonlinear transport and electric noise reduction induced by percolation mechanisms in granular aluminum oxide nanowires

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Keywords: superconducting nanowires, quantum electronics, electric noise spectroscopy

Nowadays, a challenging physics and engineering endeavor concerns the realization of large-scale quantum information processing machines using superconducting circuits. A promising alternative qubit architecture is based on superinductors, characterized by high kinetic inductance, such as granular aluminum.[1] This material, containing a significant amount of amorphous aluminum oxide, has a disordered nature and, therefore, requires a good knowledge of the transport and fluctuation mechanisms,[2] especially when patterned at the nanoscale level.

In view of all these considerations, detailed DC electric and magneto-transport measurements, as well as voltage-noise investigations, have been performed on granular aluminum oxide nanowires. A non-reversible resistance reduction has been observed by increasing the bias current and may be ascribed to permanent modifications of the nanowires structure. Moreover, a reversible resistive effect, evident in the temperature range 9 – 300 K, seems to be connected with a pronounced noise reduction (see Figure 1, for details).

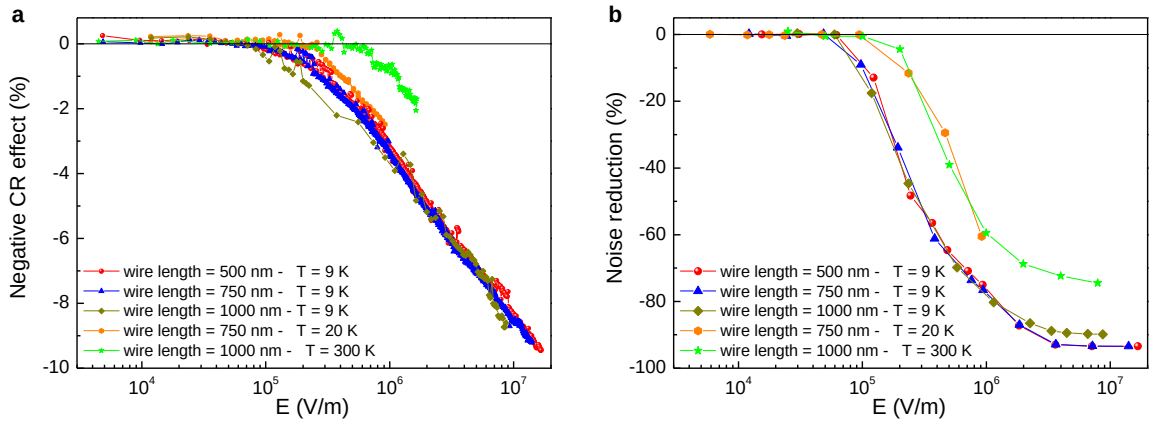

Figure 1. *The effect of increasing bias is the reduction of the nanowire resistivity (negative CR effect) and of the overall noise level*

This behavior has been already reported for other different materials, such as manganites[3] and metal-insulator composites.[4] However, differently from the case of magnetic multilayered structures, in granular aluminum oxide nanowires it does not have a magnetic origin but seems to be induced by percolation mechanisms. This is evidenced by the fact that all the experimental results can be explained in terms of a dynamic random resistor network model. Although being in the normal state, the identification of the charge carriers fluctuations is very important in the direction of reducing possible sources of decoherence in the superconducting state.[5]

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P3.31 - Applying transverse electric fields in double quantum dot devices using enhancement mode nanowires for spin-transport measurements

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Keywords: quantum dot, Pauli spin blockade, spin-orbit interaction

Double quantum dot (DQD) devices are attractive candidates for charge and spin qubits.[1] III-V nanowires (NW) offer platforms for DQD devices enabling fast spin rotation, electrical readout and large Landau g-factors. Due to spin-orbit (SO) interactions, electrons in the device experience an effective magnetic field, B_{SO}. The orientation of B_{SO} plays an important role in the presence of an applied external magnetic field, B_{ext}, as misalignment (alignment) of the two fields results in mixing (suppression of mixing) between singlet and triplet states in Pauli spin blockaded charge transitions.[2]

We use enhancement mode InAs NWs and side-gating to simultaneously define a DQD system and apply a transverse electric field in the sample plane.[3] We study the singlet-triplet splitting as a function of B_{ext} applied perpendicular to the sample plane and interpret the absence of a SO energy gap as evidence that B_{SO} is aligned with B_{ext}. This is the first demonstration of orienting B_{SO} out of the sample plane in a NW DQD device using an engineered electric field. We propose that enhancement mode NWs in conjunction with advanced gating architectures could enable full axial control over the orientation of B_{SO} in NW spin qubits – a prospect that may ultimately enable multiple NW spin-qubits to operate on-chip in the presence of a fixed-angle external magnetic field.[4]

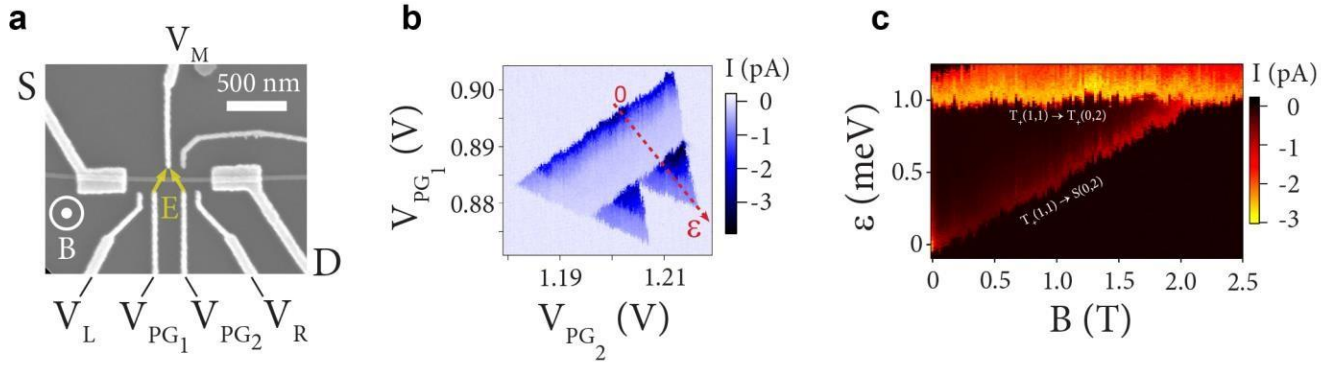

Figure 1. *a) Scanning electron microscope image of the device. Source (S) and drain (D) electrodes contact the nanowire, the double dot is formed with negative bias on the left, middle and right ($V_{L,M,R}$) barrier electrodes and positive bias enhances the dot occupancies using plunger gates $V_{PG1,2}$. The yellow arrows denote the gate-to-gate component of the transverse electric field applied, and the orientation of the applied external magnetic field is noted. b) Pauli spin blockaded finite bias triangle in gate space. The red arrow denotes the detuning axis used in (c). c) Evolution of the singlet and triplet levels in detuning energy as a function of the magnetic field applied perpendicular to the device substrate. The absence of a spin orbit energy gap suggests that the spin orbit field, B_{SO}, is aligned with the external field and oriented out of the substrate plane.*

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[4] **Acknowledgements**: We acknowledge support by the Swedish Research Council, Marie Sklodowska Curie Actions, Knut and Alice Wallenberg Foundation, and by NanoLund. Devices were fabricated in the Lund Nano Lab.

P3.32 - Shadow mask platform for *in-situ* patterning of epitaxial superconductors on semiconductor nanowires

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The importance of pristine interfaces and surfaces in nano-devices motivates the manufacture of ready-made devices under ultra-high vacuum. Here, we present a versatile platform for the growth of nanowires with patterned overlayers, while ensuring a pristine interface between the materials. The platform consists of silicon oxide bridges suspended above the growth substrate. The nanowires are grown in proximity to the bridges, and the overlayer subsequently deposited without breaking vacuum. Depositing at an angle slightly inclined from the substrate surface allows the bridges to act as a shadow mask for the overlayer material (Fig 1). The overlayers may be metallic, superconducting, insulating, or semiconducting. We focus on semiconductor/superconductor hybrids, since obtaining 'hard'-gap induced superconductivity requires a negligible interface impurity density and is crucial for applications in topological superconducivity.[1] Previous devices utilized the epitaxial interface between Al and InAs or InSb,[2,3] with sections of the Al removed by wet-etching. The significant advances enabled by our platform stem from eliminating etching entirely; doing so prevents damaging the semiconductor while also expanding the range of available materials choice without the restriction of needing a specific etchant. We have produced InAs nanowire hybrid devices using tantalum, niobium, indium and vanadium. Another advantage is that our shadow mask platform enables high-throughput parallel fabrication and is highly versatile. On each growth, we obtain many different technologically relevant device geometries, and can independently adjust the length of each segment on each nanowire by adjusting the bridge dimensions. We have investigated electrical transport in devices with the geometries in Figure 1(a-c). The devices we obtain using this platform exhibit high reproducibility and stability, and meet the requirement of a hard superconducting gap (Figure 1(d)). We expect this and similar platforms to find application across a wide range of nanotechnologies.

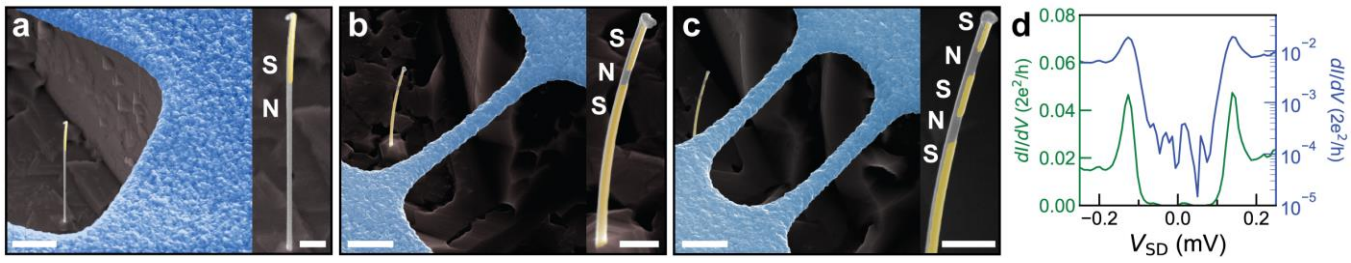

Figure 1. *(a-c) As-grown nanowire (N - grey) superconductor (S – yellow) hybrids on a substrate featuring a silicon oxide shadow mask (blue). The shadow mask enables, among others, (a) NS devices for tunnel probe experiments, (b) SNS devices for Josephson junctions or transistors with epitaxial contacts and (c) superconducting islands. Scale bars are 2 μm (main figures) and 500 nm (insets). (d) Linear (green) and logarithmic (blue) differential conductance vs. source-drain bias from an InAs/Ta NS device. The 100-fold conductance reduction in the superconducting gap is indicative of a pristine interface.*[1]

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P3.33 - Bias-dependence of universal conductance fluctuations in single GaN:Ge nanowires

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We present investigations of the magnetotransport properties of single Ge-doped GaN nanowires grown by plasma-assisted molecular-beam epitaxy. The doped GaN nanowires exhibit quantuminterference effects at low temperatures, such as the weak localization (WL) effect and universal conductance fluctuations (UCF). By analyzing the emerging quantum-interference effects the phasecoherence length l_φ can be determined in three different, independent ways, i.e., based on the magnitude of the conductance fluctuations rms(ΔG), the correlation field B_C, and the weak localization effect. As the phase-coherence is solely defined by inelastic scattering events the phase-coherence length is independent of the current applied. Nevertheless, we show that the magnitude of the conductance fluctuations rms(ΔG) is strongly affected by the applied bias. As a consequence evaluation of rms(ΔG) results in an alleged reduction of the obtained phase-coherence length, as can be seen in Fig. 1 (a) and (b). The bias-induced reduction of the UCF magnitude is caused by an increased number of uncorrelated energy intervals contributing to the electron transport at high current densities. To account for this effect, we introduced a bias-dependent length scale l_J in analogy to the thermal length l_T by Lee *et al.*[1] to modify the theoretical analysis of rms(ΔG) such that the extracted phase-coherence lengths are in good agreement with those extracted by the other two methods. Having achieved this consistent description, this also offers a novel way of determine the carrier concentration and carrier mobility of single Ge-doped GaN nanowires.

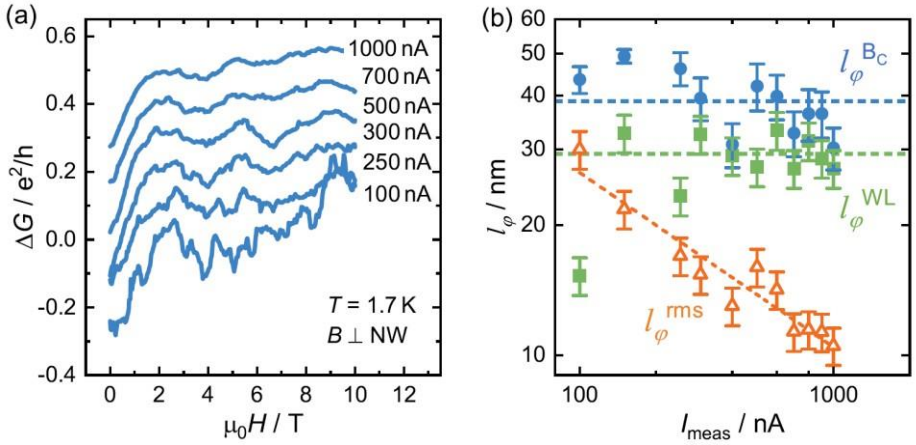

Figure 1: *(a) Magnetoconductance for measurement currents between 100 nA to 1000 nA. (b) Phase-coherence lengths determined by the three approaches.*

Reference

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P3.34 - Electrical properties of integrated InAs/InP heterostructure quantum dots

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Presently, there is an increasing interest in the investigation of superconducting subgap states forming in semiconductors with large spin-orbit coupling in close proximity to standard superconductors. For example, it has been proposed to use a quantum dot (QD) as a spectrometer to investigate exotic quantum states called Majoranas.[1] However, gate defined tunnel barriers typically employed in such devices suffer from a limited control over the position and quality of the barriers. Recently, InAs nanowires (NWs) with crystal phase engineered tunnel barriers contacted by superconducting contacts were introduced to systematically study such proximity systems.[2]

Here, we focus on the electrical properties of semiconducting InAs NWs with ~500meV high InP tunnel barriers forming atomically precise in situ grown quantum dots with hard-wall quantum confinement. We present a comprehensive characterization of such an InAs/InP heterostructure QD,[3,4] demonstrating very regular Coulomb blockade resonances over a large gate voltage range (Figure 1). Analyzing the resonance line shapes, we map the evolution of the tunnel couplings from the few to the many electron regime, with very symmetric, electrically tunable tunneling rates from <1μeV to >600μeV, and a transition from the temperature to the lifetime broadened regime, all of which can be understood in great detail based on the deterministic crystal structure. The investigation of adjacent lead states using these QDs suggest that integrated InAs/InP QDs provide a promising platform for electron tunneling spectroscopy in InAs nanowires, which can readily be contacted by a variety of superconducting materials.

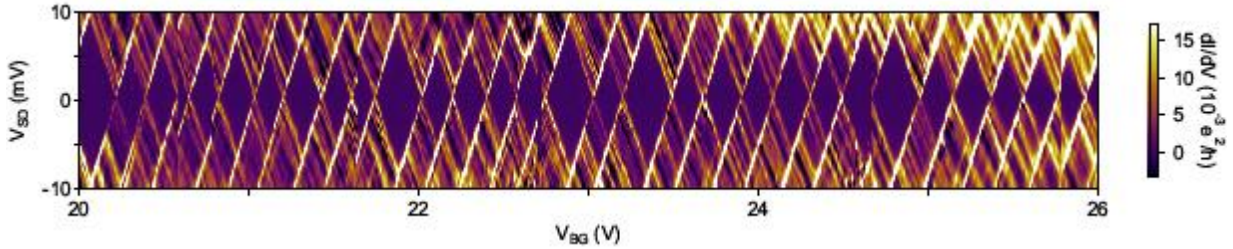

Figure 1. *Differential conductance as a function of the back gate V_{BG} and bias voltage V_{SD} for an InAs/InP QD device.*

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P3.35 - Tunnel spectroscopy of superconducting proximity effect in InAs nanowires using aligned crystal-phase quantum dots

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Superconductor-semiconductor hybrid InAs nanowire (NW) devices are strong candidates for study low-dimensional quantum transport phenomena such as Andreev bound states and Majorana bound states [1]. Quantum dots (QDs) formed in the NWs are utilized as spectroscopic tools to characterize such subgap states. Previously, the QDs have typically been obtained by relying on electrostatic gating and/or spontaneous formation.

In a recent study, we have probed the proximity-induced gap and the subgap states in the NW lead between the QD and the superconducting contact using a crystal-phase defined QD which provide more robust and controllable transport characteristics [2]. Here, the QDs are defined during NW growth by inserting two segments of wurtzite crystal phase in otherwise zinc blende InAs NW [3]. The hard-wall potential barriers provided by the conduction-band edge offset between the two crystal phases allow for probing the evolution of the proximity-induced gap and subgap states in a wide gate range. As a result of the gate-induced carrier-density modulation, the system transforms form being in the short junction limit where a soft proximity-induced gap is detected, to the long junction limit where the gap closes.

As a next step, we use epitaxial markers in the form of a selectively grown GaSb shell [4] to controllably align the superconducting contact with the crystal-phase QD. Thus, allowing for distance dependent studies of the induced gap and probing the proximitized region directly underneath the superconductor, which is important to evaluate the inherent characteristic of the induced gap and the subgap states. In addition, local side-gates will be employed to independently tune the subgap states.

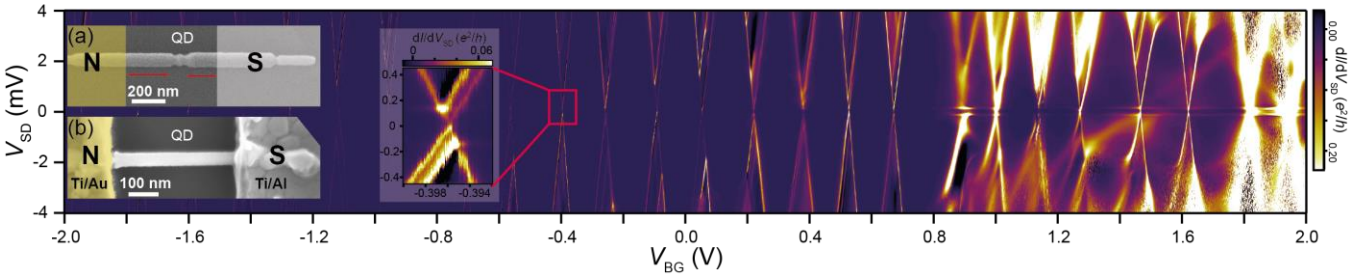

Figure 1. *Differential conductance (dI/dV_{SD}) as a function of bias (V_{SD}) and gate voltage (V_{BG}) for a crystal-phase QD in an InAs NW with one normal (N) and one superconducting (S) contact. Inset (a) the GaSb shell is used for aligning the contacts. (b) device after shell etch and contact fabrication.*

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P3.36 - In-plane InSb nanowire networks for quantum devices

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Keywords: InSb, Indium Antimonide, selective area growth

Growth of In-plane Selective Area Networks (InSANe) of InSb nanowires with a high crystal quality. Although InSb has a large lattice mismatch with Indium Phosphide (InP) (high bandgap substrate material), we manage to synthesize catalyst-free large single crystal nanowire networks. We investigate the nucleation and growth kinetics in different crystal orientations and show that the surface diffusion length of precursors is key to grow single crystalline networks. Transmission electron microscopy (TEM) analysis shows a zincblende InSb nanowire with a single twin defect a few nanometers above the interface with the underlying substrate. Low temperature transport measurements (e.g. Aharonov-Bohm interference) demonstrate a large electron coherence length of up to 10 µm confirming the high quality of the InSb nanowire networks. Our system is excellent for scalable, complex nanowire networks and holds great promise for Majorana topological quantum computing.

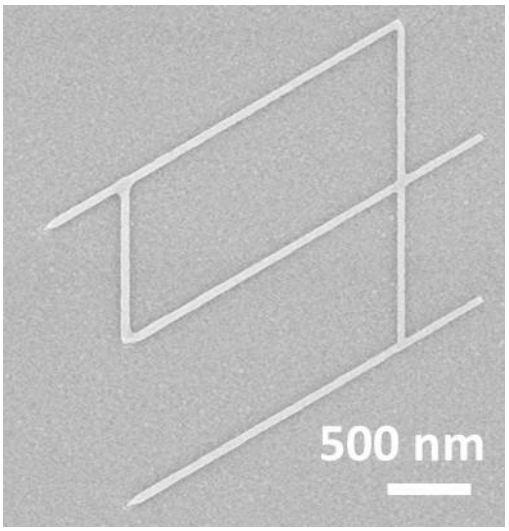

Figure 1. *Scanning electron micrograph of an in-plane InSb nanowire network designed for measuring one Majorana qubit [1]. The structure is selectively grown on an InP substrate.*

Reference

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P3.37 - Ballistic transport in VLS-grown InSb Nanocrosses

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Keywords: InSb, Nanocross, Ballistic Transport

We study the low temperature electron multi-terminal transport characteristics of InSb semiconducting nanocrosses with individual gate-control of each arm. The InSb nanocrosses were formed by growing nanowires from two opposing [111]B facets, created by wet etching a trench geometry on [100]-oriented InAs growth substrates.[2] Figure 1 shows a typical device. Terminals T1-T4 were contacted using Al, and each had an independent Ti/Au topgate. We performed a thorough characterization of terminals T1-T3 and find that each show at least one stable plateau of quantized conductance with magnetic field B = 6 T. Those individual quantum point contacts were characterized as a function of applied magnetic field and all gate-voltages thus providing insight on the Zeeman splitting as well as on the spatial distribution of the conduction channels inside the nanostructure. Finally, the conductance through two terminals, while both being in the single channel regime at the same time was investigated, demonstrating the conventional quantization of serial QPCs. This ballistic behavior, together with the ability to obtain hard-gap induced superconductivity[2] points to the suitability of this material for experimental realization of non-trivial topological states in multi-terminal Josephson Junctions as suggested by recent theory [1].

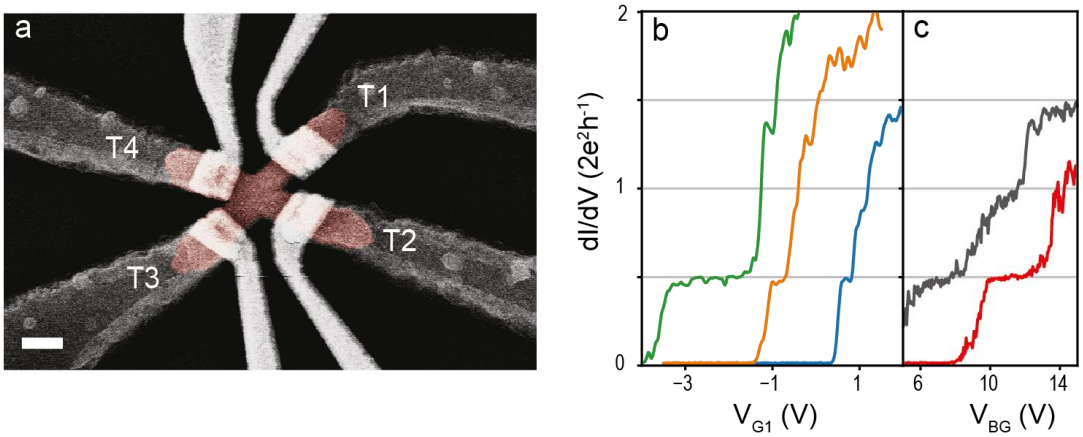

Figure 1. *a) Scanning Electron Micrograph of the device, featuring InSb nanocross (red), Al-contacts (dark grey) and Ti/Au topgates (white), insulated using HfO_2. Scalebar is 500 nm. b) Differential conductance between T1 and T2, dI/dV, vs topgate voltage V_{G1} with fixed backgate voltage V_{BG} = 12.7 V (green) 10 V (orange) and 7 V (blue). c) dI/dV vs V_{bg} for fixed V_{G1} = 0 V (black) and -0.7 V (red). Data taken with magnetic field B = 6 T.*

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P3.39 - Metal oxide nanowire p-n junctions for solar energy detection/harvesting

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Keywords: metal oxide nanowires, self-powered photodetectors, solar cells

Metal oxide (MOx) semiconductors can be shaped in form of nanowires (NWs), which can be profitably applied for energy harvesting in various configurations, including single junction solar cells, photodetectors and (photo)-electrochemical systems. Here we will illustrate two examples of MOx nanowires and their application as photodetectors and solar cells. A core-shell n-p junction is studied for photoconversion of Sun light. A wide band gap ZnO[1,2] or TiO_2 n-type single crystalline NW core is conformal covered by a Co_3O_4 or a Cu_2O p-type low band gap thin shell (Figure 1 a-b). The ZnO-based p-n heterojunction resulted in the fastest response oxide-based photodetector under visible light irradiation (Figure 1c). Such photodetector can be operated in a self-powered configuration, with no need of any external power source. Light response can be optimized by the intercalation of a thin (<10 nm) isolating buffer layer between the core and the shell. As a solar cell, instead, the ZnO-based device exhibits very low open circuit photovoltage, which impairs its functionality. The drawback can be removed by using a single crystal rutile TiO_2 NW core, which results in an open circuit photovoltage as high as 350 mV. We demonstrated that NW configuration induces strong light scattering, resulting in almost complete light absorption by applying a thin absorbing p-type layer, circumventing the issue related to low charge mobility in most of p-type optically active oxides. Future research direction deals with the investigation of the different photovoltaic behavior between ZnO and TiO_2 NWs, trying to clarify the origin of the different functionality, despite the similar position of conduction and valence band edges for the two oxides.

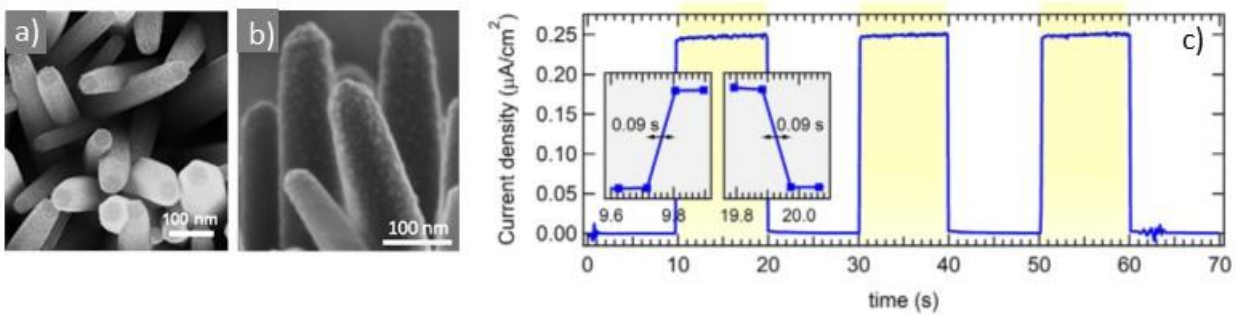

Figure 1. *Scanning electron microscopy of ZnO-Co_3O_4 core-shell NWs in top view (a) and cross section (b). (c) Light response at 0 V bias of a ZnO-Cu_2O junction under simulated Sunlight.*

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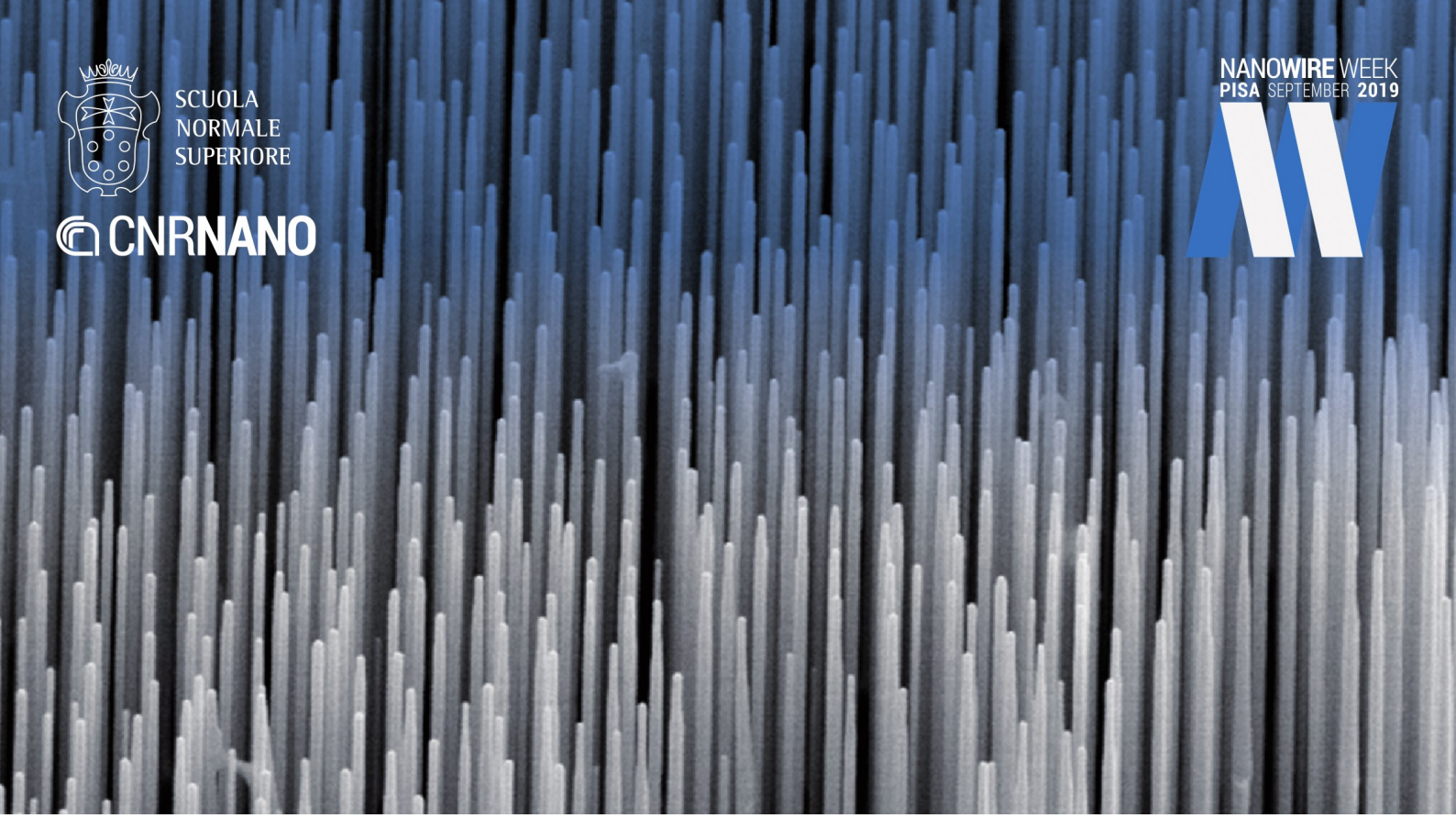

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