

The Influence of Oxygen on Nanowire Surface Structure and Electronic Properties

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Bachelor Thesis,

Lund University,

Fall 2014

January 18, 2015



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Abstract

This thesis investigates the possibilities for setups measuring how the surface structure of nanowires (NWs) influences their electric properties. For this the abilities to clean surfaces and detect nanowires (NWs) are examined, and an attempt to build a setup is made.

Compared to the size of NWs and surface area measured in scanning tunneling microscopy (STM), an “infinite” surface of GaAs/AlGaAs was cleaned. The method of cleaning meant using hydrogen cleaning in order to remove oxide from the surface. By the use of STM it was found that hydrogen cleaning works for such an “infinite” surface.

In attempts to detect NWs the method Auger electron spectroscopy (AES) was used. The resulting spectra showed peaks from elements only found in the NWs which meant the AES works for detecting NWs.

The setup built should have the ability to perform electrical measurements of a sample in vacuum while heating the sample and giving the researchers the ability to control the oxidation of the sample. A prototype of such a setup was made and its operational ability was tested in air.

Acknowledgements

I would like to thank several persons for making this bachelor thesis possible. First and foremost I would like to thank my supervisor, Anders Mikkelsen, for giving me the chance to do my thesis in the division of synchrotron radiation. This meant I got a lot of great time in the laboratories, obtaining experience from all the equipment. I also would like to thank you for always finding time to help me.

I am grateful for the help given to me by Ph. D. student Andrea Troian, who acted as my 2nd supervisor. Thank you for spending all the time with me in the laboratories, explaining and performing experiments with me.

I would like to thank a couple of people for helping me in the laboratories: Rainer Timm, Estephania Lira, and Johan Knutsson. Thank you all for taking time to help me whenever I needed it.

A special thanks to Olof Persson for explaining and fixing the equipment used to obtain the I-V curves.

Last but not least I would like to thank everybody at the Division of Synchrotron Radiation for the nice and friendly atmosphere.

Abbreviations and Acronyms

AES	Auger Electron Spectroscopy
ALD	Atomic Layer Deposition
DOS	Density Of States
LED	Light Emitting Diode
NW	NanoWire
STM	Scanning Tunneling Microscopy, also for Microscope
UHV	Ultra-High Vacuum ($p < 10^{-9}$ mbar)

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Semiconductors	1
1.3	Transistors	3
1.4	Nanowires	3
1.5	Scanning Tunneling Microscopy	4
1.6	Auger Electron Spectroscopy	5
2	Method	6
2.1	Setup	6
2.2	Hydrogen Cleaning	7
2.3	Scanning Tunneling Microscopy	7
2.4	Auger Electron Spectroscopy	9
2.5	Heater	9
3	Results and Discussion	10
3.1	Scanning Tunneling Microscopy	10
3.1.1	Cross-sectional Sample	10
3.1.2	Oxidized surfaces	14
3.2	Auger Electron Spectroscopy	15
3.3	Heater	18
4	Summary and Outlook	21
	References	23

1 Introduction

1.1 Motivation

The science of studying and creating objects in the nanoscopic scale is a relatively new and growing field. The introduction of nanowires (NWs) and their possible use in electronics is an interesting branch of this field. One feature of NWs is their large surface to bulk ratio and as such the surface of NWs is important to study. The goal of this project is to learn how the surface structure of NWs influences their electric properties. In order to achieve this it is necessary to understand the surface structure and how the surface reacts to oxidation and hydrogen reduction. Another aim to achieve is to make measurement setups for studying the electrical conditions and surface structure together. For this an attempt is made to make two setups: one for measuring electric properties and surface structure at once, and one for electrical measurements while controlling the surface.

For surface studies it is easier to start with flat surfaces before studying NW surfaces. In order to study surfaces and electric properties different techniques are used. To study the structure of a surface Scanning Tunneling Microscopy (STM) is used. With STM it is possible to study how oxidation and hydrogen reduction affects the structure of a surface and the results of such studies can be seen in section 3.1. Auger Electron Spectroscopy (AES) is used to study the chemistry of a surface. This could e.g. be used to see if NWs have been successfully transferred to a substrate and if so which elements the NWs are composed of. The results of AES on substrates with NWs can be found in section 3.2. A heater is used for making the setup able to perform electrical measurements in vacuum while heating. The aim for the setup is to measure electric properties during oxidation. The progress of making this setup can be found in section 2.5 and the results from measurements with the setup can be seen in section 3.3. In order to perform good measurements with the above mentioned techniques it is important to learn the process of hydrogen cleaning: a process where native oxides are cleaned off a sample with the help of atomic hydrogen.

1.2 Semiconductors

As the name suggests semiconductors have properties between metals (generally good conductors) and insulators (poor conductors). However it is better to define the difference between the solids based on the density of states, as done by Hofmann[2]. Figure 1 illustrates the difference between metals and semiconductors/insulators.

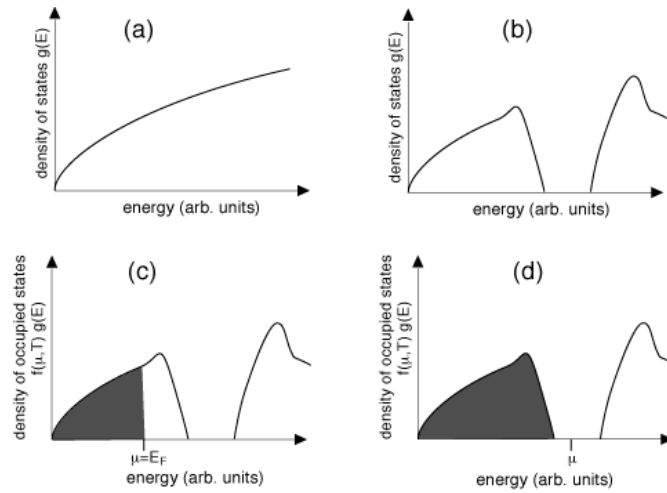


Figure 1: The difference in density of states (DOS) between metals and semiconductors/insulators. (a) DOS in the free electron model. (b) Qualitative DOS in the nearly free electron model with the appearance of gaps. (c) Occupied DOS (gray area) for a metal at $T=0K$: the chemical potential (or the Fermi energy) cuts through a finite density of states. (d) The same for a semiconductor/insulator: the chemical potential is in a region of vanishing density of states [2]. Figure from [3].

As seen in fig. 1 a semiconductor/insulator has a band filled with electrons up to a gap. The difference between semiconductors and insulators is then generally described by the size of the bandgap. For a semiconductor this bandgap should be small enough to allow thermally excited carriers to cross the bandgap. Generally a material with a bandgap below 3 eV is said to be a semiconductor and materials with larger gaps are said to be insulators[2].

Common semiconductors are the group IV elements Si and Ge. These materials have tetrahedral bonding, i.e., the four valence electrons are shared. This type of bonding can also be achieved when combining materials from groups III and V or groups II and VI. Such combinations are referred to as III-V and II-VI semiconductors[2]. The most commonly used semiconductor is Si, due to its abundance in nature (sand) among other things[4]. The reason for using combined semiconductors (e.g. III-V) is the ability of obtaining direct bandgaps and higher carrier mobility[1]. A direct bandgap means the semiconductor has the ability to absorb or emit photons, i.e. work well as a solar cell or LED. Examples of III-V semiconductors are gallium arsenide (GaAs), gallium phosphide (GaP), indium arsenide (InAs), and indium phosphide (InP).

The conductivity of a semiconductor can be affected by impurities. A controlled addition of impurities is called doping. As there are two types of charge carriers

(electrons and holes) there are two types of doping: n-doping, where the impurities increase the number of electrons, and p-doping, where the impurities increase the number of holes. As an example a group IV semiconductor can be n-doped by adding an impurity in the form of a group V atom which would share four of its five valence electrons with the surrounding atoms and the fifth electron would act as an extra electron in the semiconductor. In the same way, adding a group III atom to a group IV semiconductor would result in an extra hole in the semiconductor as only three valence electrons are available. Pure semiconductors, i.e. not doped, are called intrinsic.

1.3 Transistors

Transistors are very important parts in microelectronic devices as they can be used as amplifiers or as switches[2]. One typical transistor used in integrated circuits is the metal oxide field effect transistor (MOSFET), illustrated in fig. 2. The

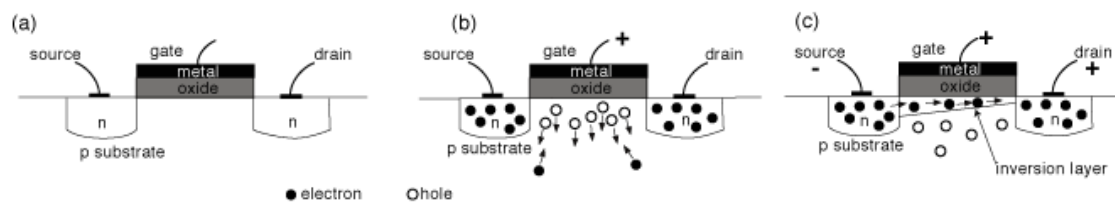


Figure 2: Design and working principle of a n-MOSFET transistor. (a) Without applied voltage (b) With a small positive gate voltage (c) with a gate voltage large enough to generate an inversion layer and an applied voltage between source and drain[2]. Figure from [3].

n-MOSFET consists of two n-doped regions in a p-doped substrate. Between the two regions is an oxide on the substrate. Metal electrodes are contacted on the oxide (gate), and the two n-doped regions (source and drain). With no applied voltage to the gate no current flows in the transistor. However, when a large enough voltage is applied to the gate, the holes in the substrate (p-doped) beneath the oxide are repulsed and electrons are attracted. These electrons create an inversion layer and a current of electrons can flow between the source and drain[2]. In this way, applying voltage to the gate, the MOSFET can work as an amplifier or switch.

1.4 Nanowires

The nanowires (NWs) studied in this thesis are mainly InP NWs, i.e. III-V semiconductor NWs. InP has a direct bandgap in the visible light region which

means it would be a great material for e.g. LEDs or solar cells, however, using an InP substrate for a solar cell would be very expensive. Using InP NWs as the active component on a cheaper substrate, e.g. Si, could be a solution. NWs are cylindrically shaped structures with diameters in the nanometer range and lengths in the micrometer range. This means NWs normally have a length to width ratio of 100 or more and they are therefore often referred to as one-dimensional structures - meaning they show interesting properties, not found in three-dimensional structures[1]. The small size of NWs also means they have a large surface to bulk ratio. This means that the surface structure of NWs is important to understand. For purposes such as using NWs for solar cells it is important to understand how the surface structure influences the electric properties.

The vapor-liquid-solid technique (VLS) is a common way of growing semiconductor NWs and the technique is illustrated in fig. 3. The VLS technique uses a

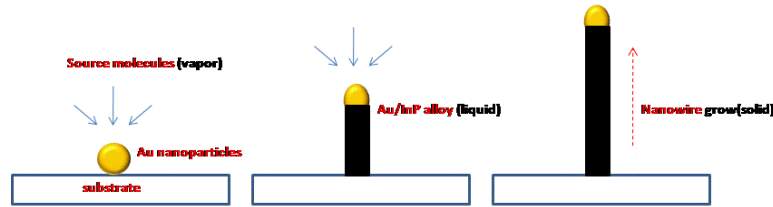


Figure 3: Vapor-liquid-solid technique, a way to grow NWs. Figure from [5].

catalyst to grow NWs and this catalyst is commonly liquid metal, mainly gold (Au). As a gold (Au) particle is deposited on the substrate the sample is annealed and the group V precursor is introduced as a vapor. The group III precursor is introduced as the temperature is lowered and the III-V materials precipitate directly under the Au-particle[1].

1.5 Scanning Tunneling Microscopy

The STM is used to study the structure of solid surfaces. It is based on quantum mechanical tunneling and the microscope is situated in ultra-high vacuum (UHV), i.e. pressure lower than 10^{-9} mbar. The schematic setup of an STM is illustrated in fig. 4. As an atomically thin, conducting, tip is brought near (around 10 \AA) a conducting surface, a bias is applied between the two. This results in a tunneling current (pA-nA) which is determined by the local DOS of the sample and the tip. As the tip is moved across the surface this current is kept constant by adjusting the tip height. The tip height is adjusted by a piezo crystal which changes in size if a bias is applied. An image is then obtained by showing the piezo crystals

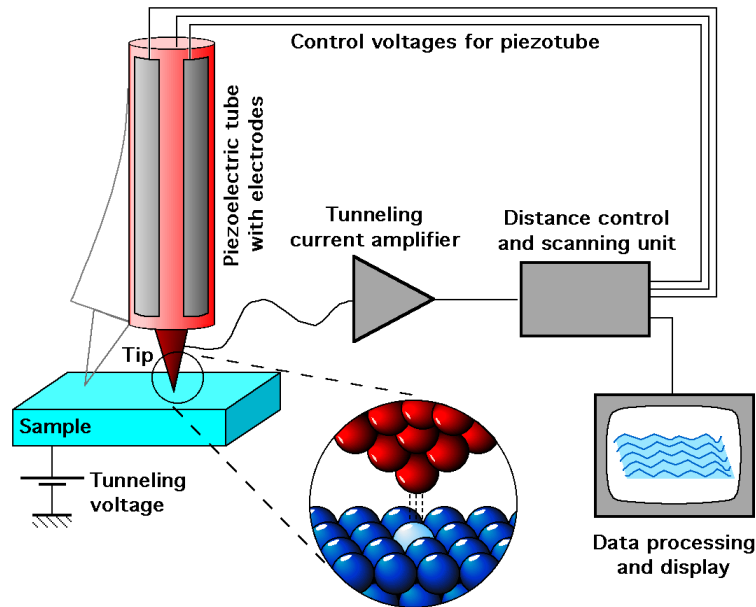


Figure 4: Schematic view of an STM. Figure from [6].

displacement in height at every point in a chosen color scale[1]. Images from the STM have a resolution making it possible to see individual atoms. The resulting image is largely affected by the shape and state of the tip. One occurring defect is something called a double-tip. When this happens the features of the sample are scanned twice and thus appear twice on the image. The resulting image is a convolution of the shape of the tip and of the actual sample.

1.6 Auger Electron Spectroscopy

With AES it is possible to study the chemistry of a surface. AES is a surface sensitive analyzing technique that makes use of the Auger effect. By the use of an electron gun the sample is bombarded with high energy electrons. As an incoming electron knocks out an inner shell electron this vacancy is filled by an outer shell electron. This transition will release energy which may be transferred to another outer electron which is then ejected from the atom. The kinetic energy of this ejected Auger electron will be equal to the energy released in the transition minus the binding energy of the ejected Auger electron. From the kinetic energy of the Auger electron it is possible to determine what element/elements the sample is made of.

2 Method

For this bachelor thesis much time, 26 days, was spent doing experimental work. These 26 days were approximately equally distributed between work with the vacuum chambers (STM and AES) and work on/with the Heater.

2.1 Setup

A schematic sketch of the vacuum chamber setup can be seen in fig. 5. The only

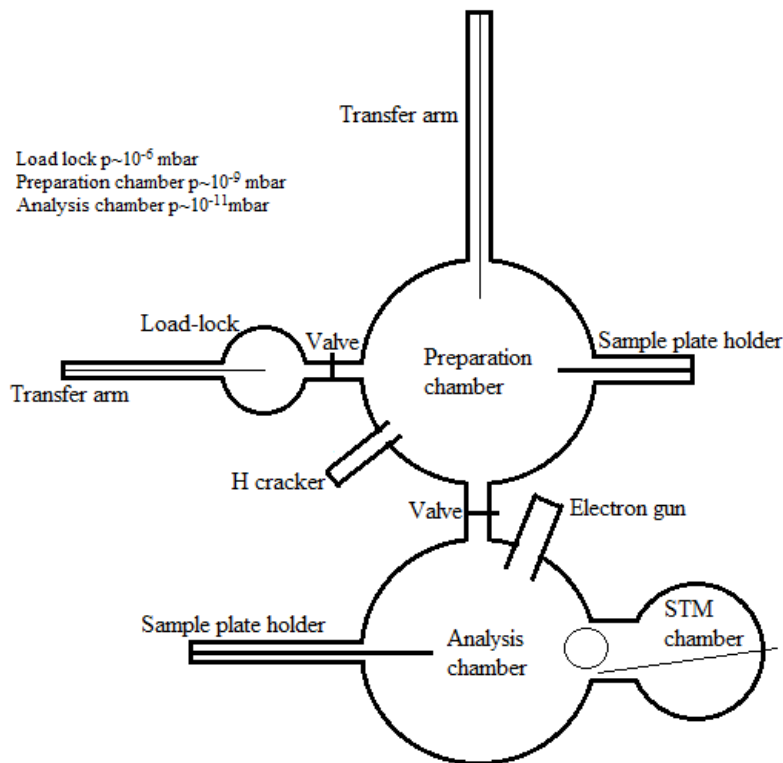


Figure 5: Schematic sketch of the setup for the vacuum chambers.

part allowed to be in contact with air is the load-lock. Samples are put on a sample plate and the sample plate is inserted into the load-lock after the load-lock has been vented to atmospheric pressure. When the load-lock has been pumped down in pressure ($\sim 10^{-6}$ mbar) the valve to the preparation chamber can be opened and the sample plate can be moved to the preparation chamber using the transfer arm. In the preparation chamber there is a sample plate holder, where the sample plate

is placed for e.g. hydrogen cleaning, and a transfer arm for moving the sample plate to the analysis chamber.

There is a valve between the preparation and analysis chambers in order to keep as high and constant vacuum as possible in the analysis chamber. During the experiment the pressure in the chambers was typically in the order of 10^{-8} mbar for the preparation chamber and 10^{-11} mbar for the analysis chamber. In the analysis chamber is a sample plate holder where the sample is placed for e.g. AES. For AES the electron gun, which is mounted on top of the analysis chamber, is used, see fig. 5. In order to perform STM the sample plate must be moved to the STM stage (in the STM chamber); this is done using the wobble stick, seen in fig. 5 as a line through the STM chamber. The circle seen between the analysis chamber and STM chamber in fig. 5 is the carousel which is used for storing sample plates.

2.2 Hydrogen Cleaning

When a III-V semiconductor is exposed to air it will oxidize, i.e. the surface will obtain a thin layer of native oxide. This is a problem for surface studies, especially for STM which requires a conducting sample. For cleaning native oxide of samples the introduction of hydrogen (H) has been important, due to the fact that the atomic hydrogen (H^*) reacts with the oxides and creates more volatile products which desorbs at low temperatures[1]. Therefore the temperature needed to desorb the oxides of the sample can be lowered. Without the hydrogen the temperature needed to desorb the oxides would be higher than that which would lead to semiconductor decomposition. Atomic hydrogen is obtained by thermally cracking H₂ gas into free radicals. This is done with the hydrogen cracker (H cracker) mounted on top of the preparation chamber, see fig. 5. The H cracker is a tungsten (W) filament which is heated to around 1700 C°. As H₂ gas is allowed to flow around the filament it is thermally cracked when it is introduced into the preparation chamber. In the preparation chamber the sample is annealed to a suitable temperature for reaction with H^* . As H^* is introduced into the chamber the pressure should rise to around 10^{-6} mbar. The sample should be kept at elevated temperatures for some minutes after turning off the H₂ gas in order to desorb possible absorbed hydrogen. The time and temperature for the cleaning varies for different samples[1].

2.3 Scanning Tunneling Microscopy

The STM was mainly used on a cross-sectional GaAs sample which is illustrated in fig. 6. This sample was $\sim 300 \mu\text{m}$ thick and had a 500 nm thick layer of AlGaAs

under 500 nm GaAs. STM was performed on two differently prepared cross-sectional samples; one which was cleaved in vacuum and one which was cleaved in air. As a test STM was also performed on two samples with a 1 nm thick oxide layer obtained through a process called Atomic Layer Deposition (ALD). The samples with oxidized surfaces were both InAs; the difference was the composition of the thickness controlled oxide layer. The compositions of the ALD oxides were HfO_2 and Al_2O_3 .

Figure 6 illustrates a sketch of the cross-sectional sample and as can be seen the edge with different layers would be interesting to study. The first cross-sectional sample was cleaved in the analysis chamber, i.e. in vacuum, so that STM could be performed on an uncontaminated cleaving. This sample was cleaved below the sample holder (which holds the sample on the sample plate) so the edge was not possible to reach. As such the sample was taken out of vacuum and moved up in the sample holder. In response to this the sample had to be cleaned (H cleaning) before being put in the STM again. The sample was cleaned for 25 minutes at a sample temperature of around 500 C° . After this STM was performed which showed that the sample was still not clean enough and thus the cleaning process was repeated one more time. During the STM, after the second cleaning, unsuccessful attempts were made to find the interface between the materials at the edge.

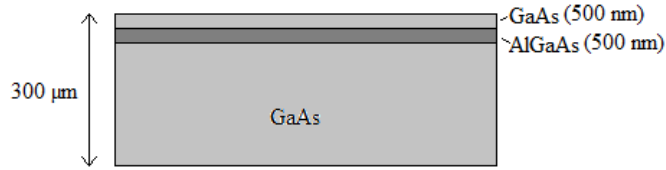


Figure 6: Sketch of the cross-sectional sample. Note that it is not drawn to scale.

As the edge on the first cross-sectional sample was not well defined, a new cross-sectional sample was prepared. This new sample was cleaved in air to make sure the edge would be accessible. The first cleaning of this sample was for 40 minutes at a sample temperature of around 450 C° . However this cleaning did not appear to have gone well and after some inspection of the equipment the sample was cleaned a second time. This time the cleaning was performed at a sample temperature of around 550 C° for 20 minutes. The interface at the edge was not possible to find for this sample either. Eventually, after a third cleaning for 10 minutes at 530 C° , and a few more scans with the STM, the study of the cross-sectional sample was ended.

For the oxidized surface samples no cleaning was done before the STM in order to not desorb the intentional oxide layer. Instead these samples were only annealed

to desorb any potential hydrogen. For both samples the annealing meant heating the sample to around 250 C° for 10 minutes. As these ALD oxides were insulating it was important to set the right values during the scans in order to not crash the tip into the sample. This was done by using high voltages and very low tunneling currents, as a low tunneling current corresponds to keeping the tip far away from the sample.

2.4 Auger Electron Spectroscopy

AES was performed on two NW samples. The first sample was InAs NWs on a Si substrate. This sample and a piece of InAs as reference was glued to the sample plate using In glue. Before AES the sample was mildly heated (around 150 C°) for 10 minutes to evaporate water. The reason for only heating mildly was to not melt the In glue. For the AES the sample was put in the analysis chamber and the electron gun was lowered into position. When the sample and the electron gun were roughly aligned the electron gun was turned on with an energy of 3 keV on the electrons. The position was then tuned by doing fast scans at the energy of the elastic peak (3 keV) from the electron gun. When in position fast scans were done at the energy of In peak in order to find either the NW sample or the reference sample.

The second sample was InP NWs on a Si substrate with a piece of InAs as reference. These pieces were held in place on the sample plate with welded Nb foil instead of In glue. This meant the sample could be H cleaned before AES and this was done for 25 minutes at a sample temperature of around 380 C°. After this the sample was positioned in the same way as the previous sample and again fast scans over the In peak energy were done in order to find the samples. When an In peak was found the fast scans were done at the P peak and As peak energies in order to distinguish between the InP NW sample and the InAs reference. When a P peak was found a full scan was performed. The InP NW sample was cleaned a second time for 45 minutes at a sample temperature of 390 C° and the AES procedure was repeated.

2.5 Heater

The heater was an attempt of building a vacuum compatible probe station able to perform electrical measurements while being able to heat and control the surface of the sample. This means it would be able to measure the temperature, current and voltage during the oxidation process, i.e. study how oxidation affects the

electric properties. Working on the heater meant spending a lot of time trying out different materials and configurations. Most work was spent on establishing contact between the wires going to air and the contacts on the sample plate. As a prototype eventually was built there was only time to test it on three samples in air: GaAs, InP, and the cross-sectional sample.

For the GaAs and InP Au foils were glued on top of the samples using In glue and the Au foils were then used as contacts for the measurement of the resistance. The same was done on the cross-sectional sample as well as the sample was glued onto a sapphire piece using In glue. This sapphire piece was then used to connect a third Au foil contact giving the possibility to measure the resistance through the cross-sectional sample.

3 Results and Discussion

In this section the results of the performed experiments are presented and analyzed. The images from the STM were obtained from the SPIP 6.3.3 program. The information from the AES and the heater was saved as text files and the graphs were then done using the program MATLAB.

3.1 Scanning Tunneling Microscopy

3.1.1 Cross-sectional Sample

For the materials in the cross-sectional sample, see fig. 6, the GaAs was highly doped (conducting) and the AlGaAs would serve as an insulating layer. By using this layout such a cross-sectional sample could serve as a tool for measuring the electronic properties of a NW, this will be discussed more in section 4. If NWs were to be mounted on a cross-sectional sample it would be done in air, therefore it was important to investigate how the cleaning affected the surface of the cross-sectional sample.

The cross-sectional sample cleaved in vacuum can be seen in fig. 7. The images are taken in the middle of the sample, i.e. on the GaAs surface. In both images it can be seen that the surface is very flat, the height difference over the entire pictures is less than 1 nm. The height differences which there are, comes from the terraces/steps, the diagonal lines that can be especially seen in fig. 7a. These steps differ one atomic layer in height and are presented in this pattern for surface energy minimization, i.e. this pattern is energetically favorable. In a magnification of

fig. 7b it is possible to distinguish rows of atoms running diagonally, orthogonal to the terrace direction. The bright spots that can be seen in both images are most likely spots with high concentration of dopants. This assumption is based on the fact that the GaAs is highly doped and spots with high concentration of dopants should have a high local DOS, resulting in this local increase in tunneling current.

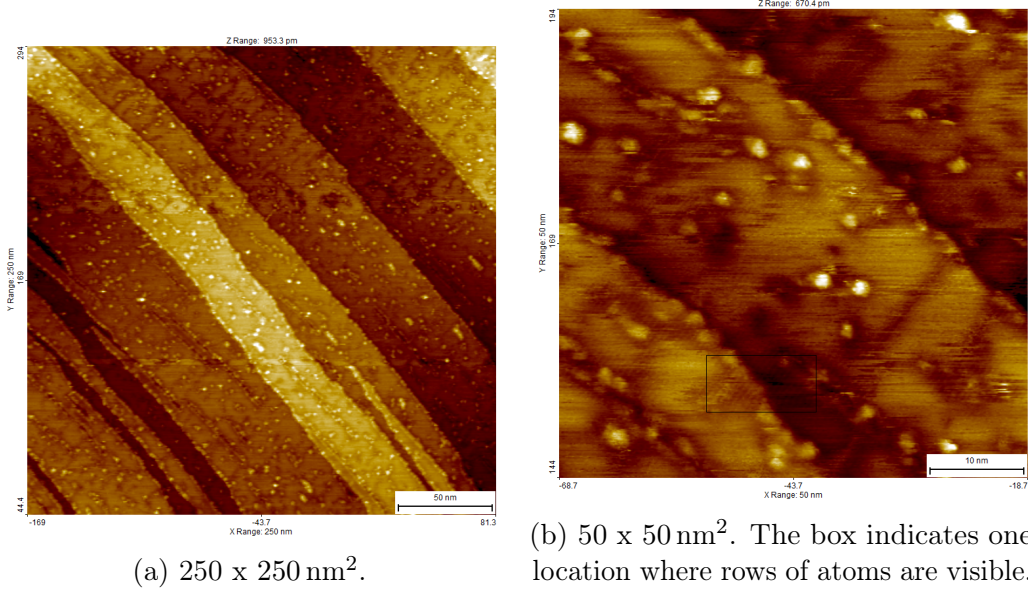
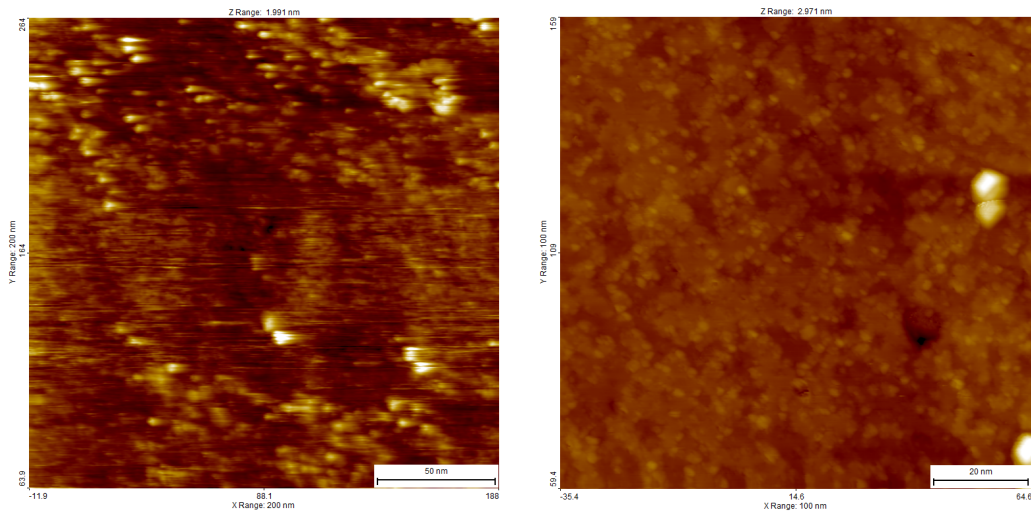


Figure 7: Cross-sectional sample cleaved in vacuum.

Figure 8 shows the first cross-sectional sample, from fig. 7, after it had been exposed to air. As mentioned in the method, section 2.3, the sample was not sufficiently clean after one cleaning which can be seen in fig. 8a. In this image (of a flat surface) the surface looks lumpy and rough, with a height difference of 2 nm over the picture. No terraces are visible so this height difference comes from the white dots, i.e. oxides not removed during cleaning. After the second cleaning, fig. 8b, the sample looked reasonably clean. The surface had lumps but overall small roughness, the height difference in the image comes from the oxides, the white lumps. There were no terraces as the ones in fig. 7. One probable explanation for this was that the sample had indeed been reasonably cleaned but that the cleaning had been “too effective”, meaning that the cleaning had modified the surface by destroying the terrace structure.



(a) $200 \times 200 \text{ nm}^2$, one time cleaned. (b) $100 \times 100 \text{ nm}^2$, two times cleaned.

Figure 8: The first cross-sectional sample after exposure to air. Image (a) after one cleaning and image (b) after a second cleaning.

Searching for the edge on the first sample was found to be very difficult and after only failed attempts the sample was examined in an optical microscope, fig. 9. The edge with the layers was the top edge in fig. 9. As ridges and waves could be seen under microscope it was clear why finding the edge in the STM, nanometer scale, was very difficult.

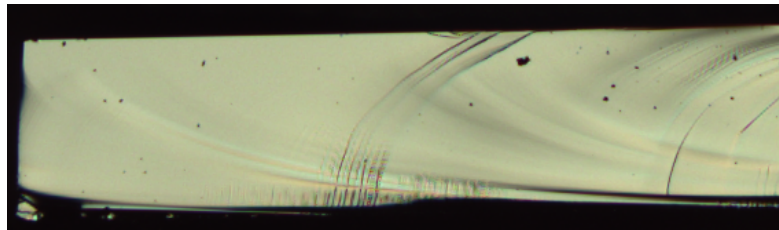
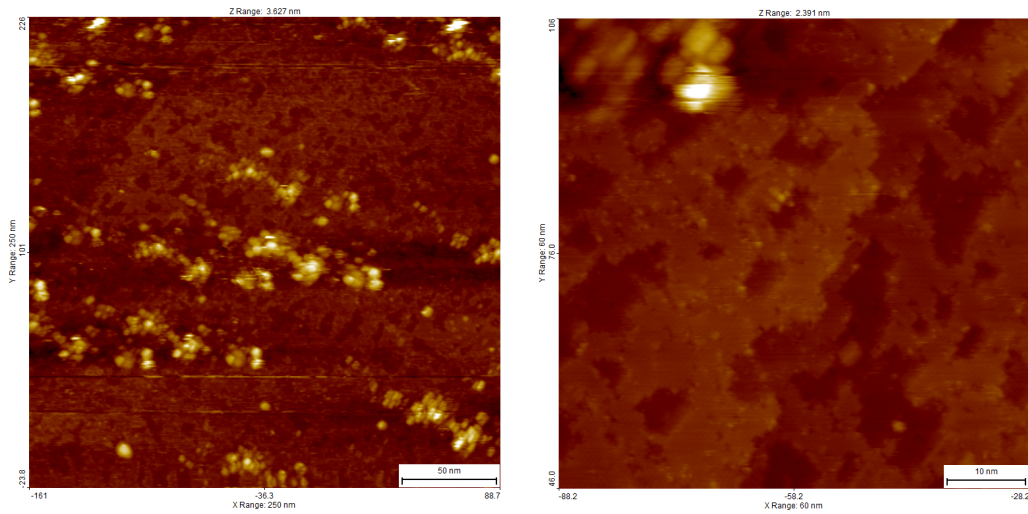


Figure 9: The first cross-sectional sample in optical microscope.

For the second cross-sectional sample, cleaved in air, it was seen that at least two cleanings would be necessary. As for the first sample two cleanings seemed to reasonably clean the sample but destroy any terrace structure, see fig. 10. However, a geometrical pattern of islands/immersions was visible and in similarity to the terraces this pattern is due to surface energy minimization. The height differences in fig. 10 are due to the not removed oxides, i.e. the white lumps, as was the case for the first sample after two cleanings.



(a) 250 x 250 nm², two times cleaned. (b) 60 x 60 nm², two times cleaned.

Figure 10: The second cross-sectional sample after cleaning two times.

The edge and the interface were not found on the second sample either. Figure 11 represents an example of the images obtained when scanning near the edge. The height difference in this image is big (14.5 nm) and nothing could be distinguished among these big ridges.

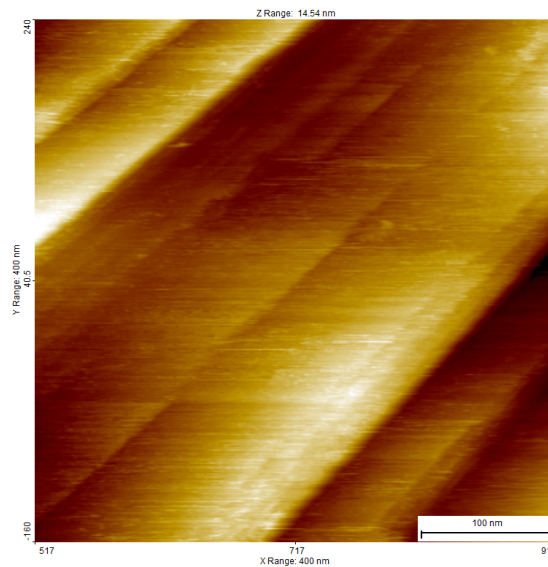


Figure 11: 400 x 400 nm², near the edge on the second cross-sectional sample after two cleanings.

One thing that was learned during the STM of the cross-sectional sample was the affect functioning equipment can have on a scientist. As can be seen in fig. 12 atomic resolution was obtained for around 25 nm when scanning a 150 x 150 nm² image. This resulted in two things: awe for the beauty of those 25 x 150 nm², and depression when realizing that a resolution like that was possible but unattained for the other scans. However, the important result obtained from scanning the cross-sectional sample was clear even without atomic resolution: the hydrogen cleaning proved to be effective for the flat GaAs surface.

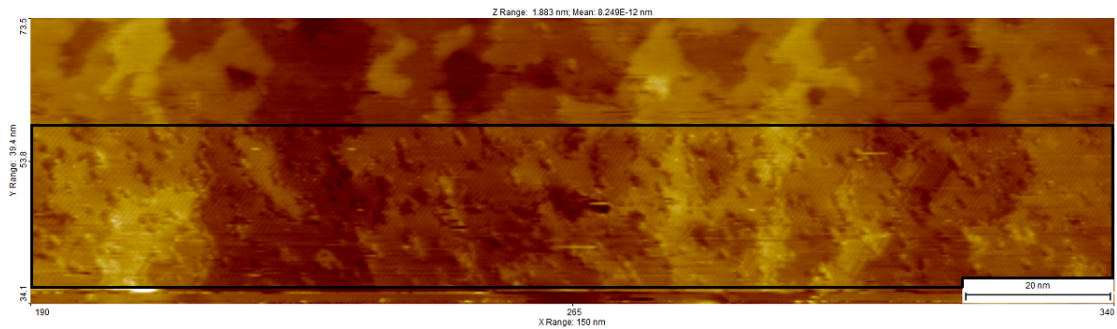


Figure 12: 25 x 150 nm² of atomic resolution marked on the image.

3.1.2 Oxidized surfaces

For the STM on the oxidized surfaces no good image was achieved. The hope before scanning on these samples was that the images were going to show the interface between the ALD oxides and the InAs. The reason for hoping this was that when the STM scans a surface the tunneling gap is around 1 nm. With the ALD oxide layers being 1 nm the thought was that the usual 1 nm vacuum gap could be exchanged for the 1 nm insulator (oxide layer) gap. However, as can be seen in fig. 13 and fig. 14, the resulting images did not give a clear idea of what was being scanned.

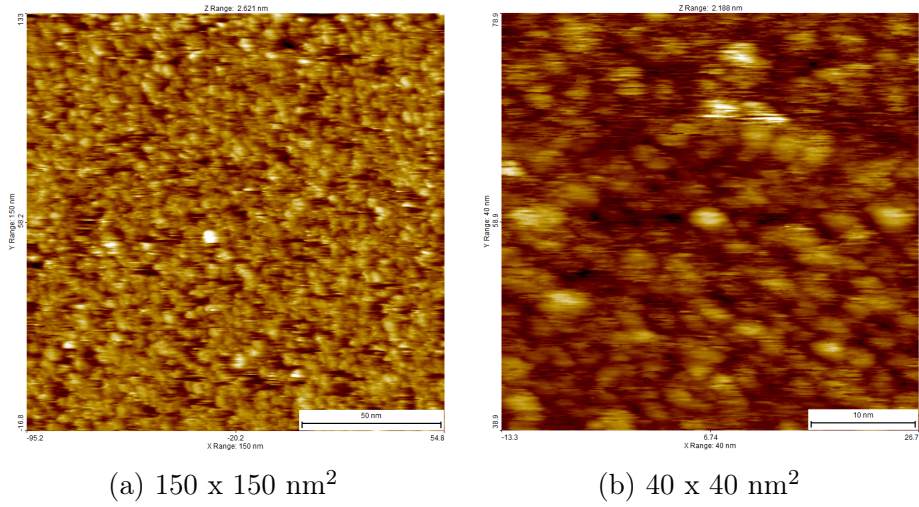


Figure 13: Oxidized surface sample with HfO₂.

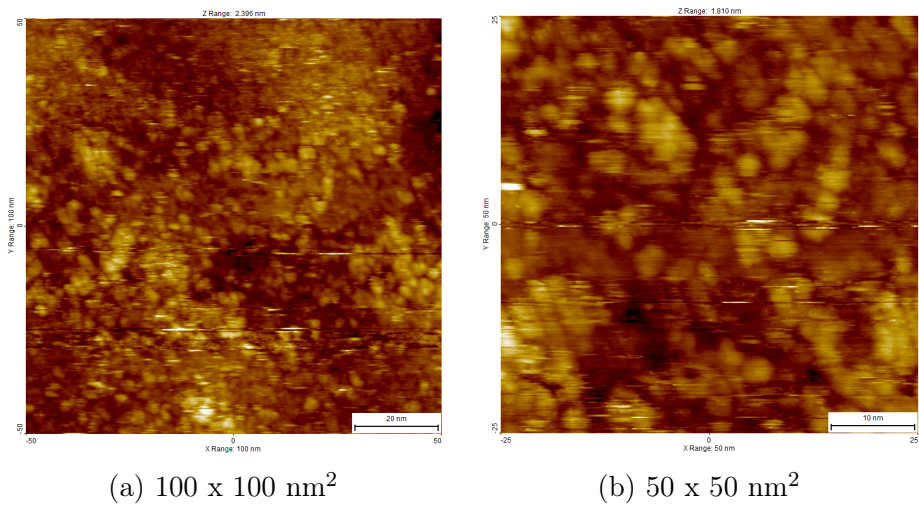


Figure 14: Oxidized surface sample with Al₂O₃.

3.2 Auger Electron Spectroscopy

The AES on the InAs NWs was not successful. The reason became clear as the In peak was the easiest to find; the In glue contaminated the sample, making it impossible to distinguish the signal from any of the samples from the glue. As such, no results were obtained from the AES on the InAs NWs. As the setup was changed to using welded Nb foils to keep the sample in place another advantage

was found. This advantage was the ability to perform H cleaning on the sample without the risk of melting any glue. For the new setup InP NWs were used and as a result of changing setup the InP NWs were detected with AES, see figs. 15 to 19. The literature values of the peaks for the elements involved can be seen in table 1.

Table 1: The literature values of involved peaks.

Element	E_{kin} [eV]
O	503
Si	92 and 1619
SiO ₂	76 and 1606
P	120
As	1228
In	404 and 410

Figures 15 and 16 show the full scan of the InP NW sample, fig. 15 after one cleaning and fig. 16 after two cleanings. Figures 17 to 19 show the individual peaks after one cleaning in graph (a) and after two cleanings in graph (b). The spectra show the kinetic energy of the detected electrons in eV on the x-axis and the intensity in arbitrary unit on the y-axis. All spectra were normalized with the program MATLAB. The idea was to compare the peaks and see how the cleaning affected the signal, i.e. if the signal to noise ratio had changed. No conclusions can be drawn from the full spectra. For the individual peaks the signals appear to be stronger compared to the noise after the second cleaning. However, more thorough measurements of the individual peaks need to be done in order to draw full conclusions. For the individual peaks it can be noted that they are all shifted a few eV towards lower energies. As this behavior is repeated in all spectra the shift comes from some slight misalignment between the electron gun and the sample.

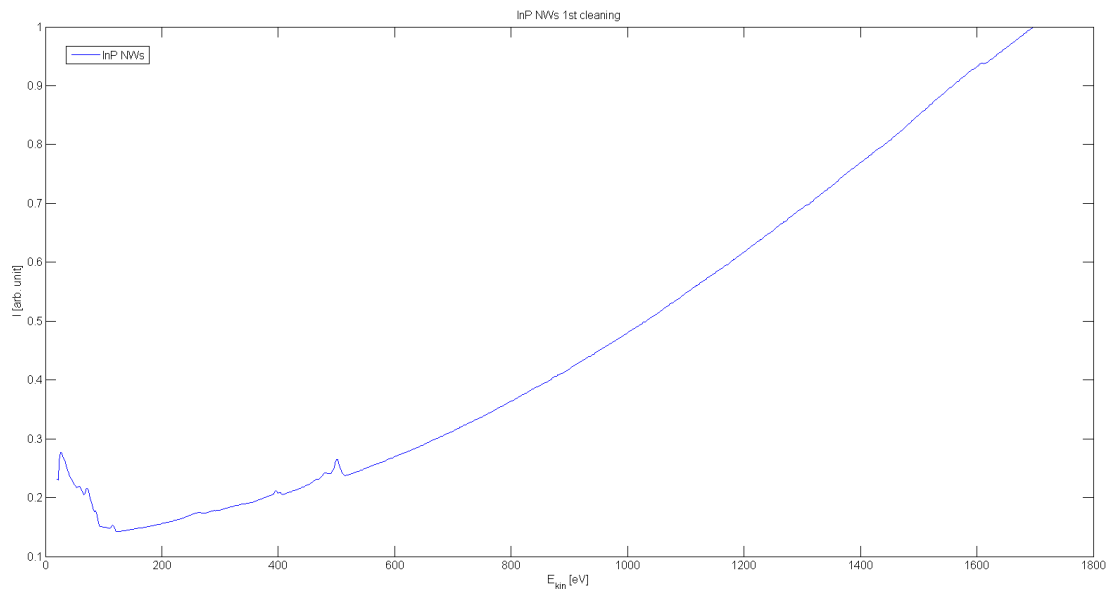


Figure 15: InP NWs. Full spectrum after one cleaning.

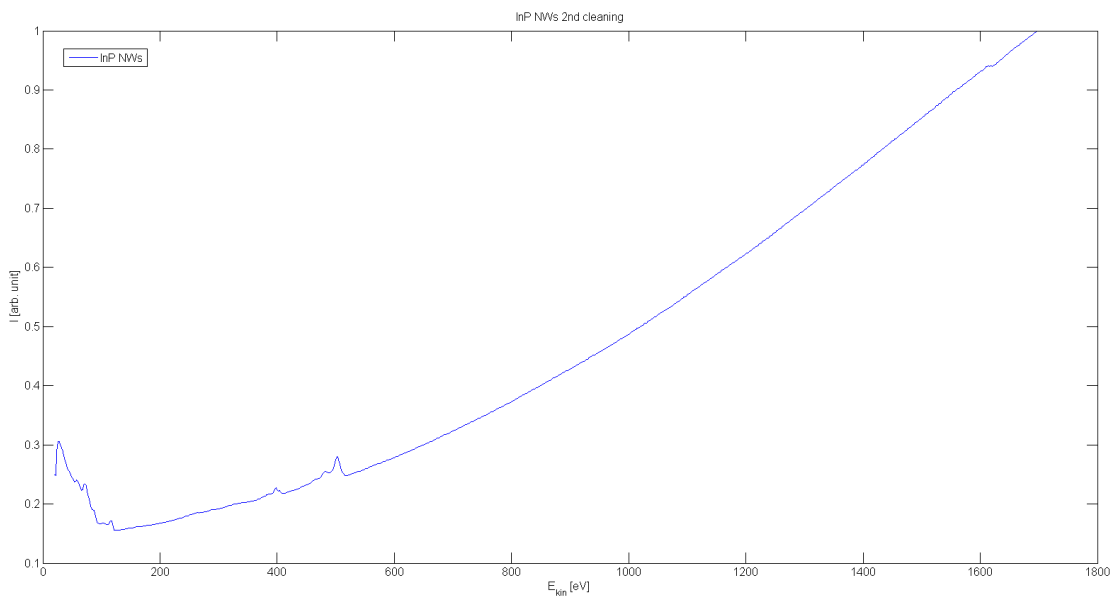


Figure 16: InP NWs. Full spectrum after two cleanings.

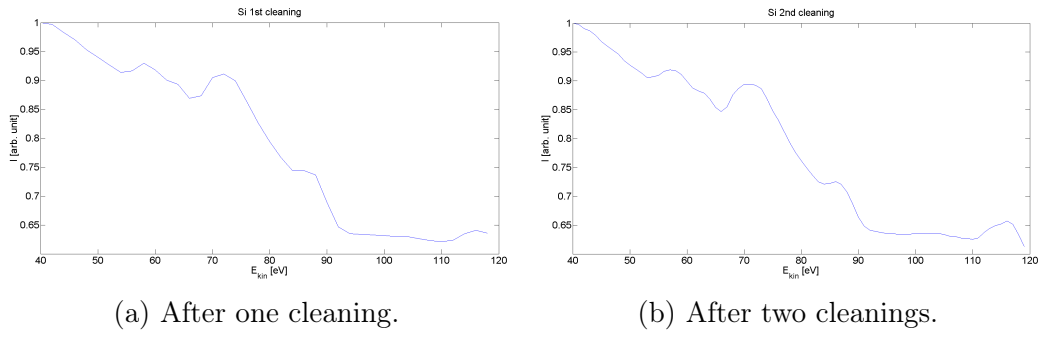


Figure 17: The Si and SiO₂ peaks from the substrate.

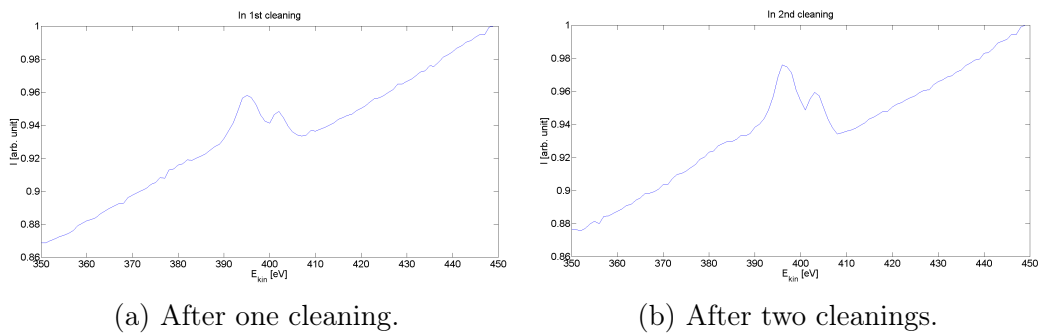


Figure 18: The In peak from the NWs.

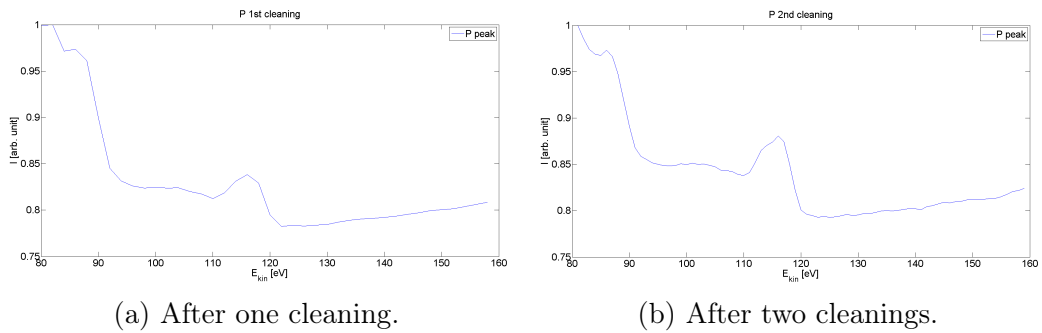


Figure 19: The P peak from the NWs.

3.3 Heater

For the vacuum compatible heater the extension of measuring change in resistance due to temperature would be to see the change in resistance due to oxygen adsorption. However, no measurements were ever done either in vacuum or by heating.

For this part of the thesis the only results were measurements of the resistance on the three samples. For the GaAs and InP the surface resistance of the samples was measured. For the cross-sectional sample the resistance through the sample was measured as well. The results can be seen in figs. 20 to 23.

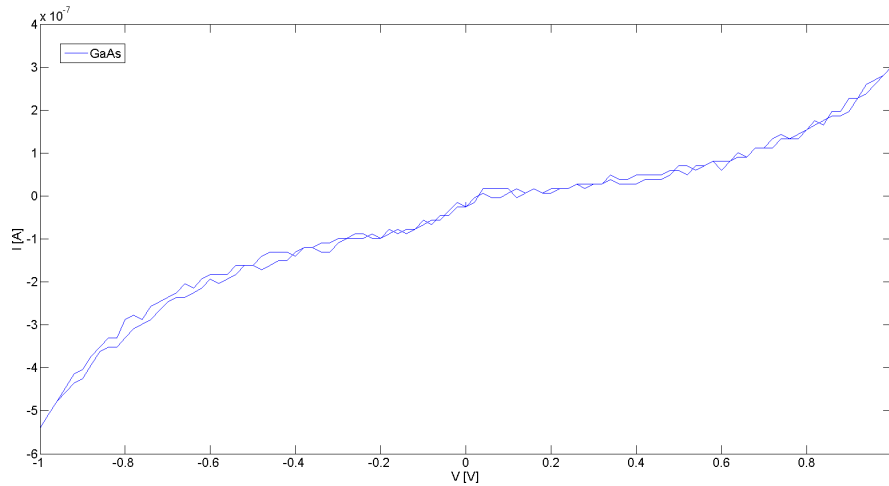


Figure 20: I-V characteristics for the GaAs sample.

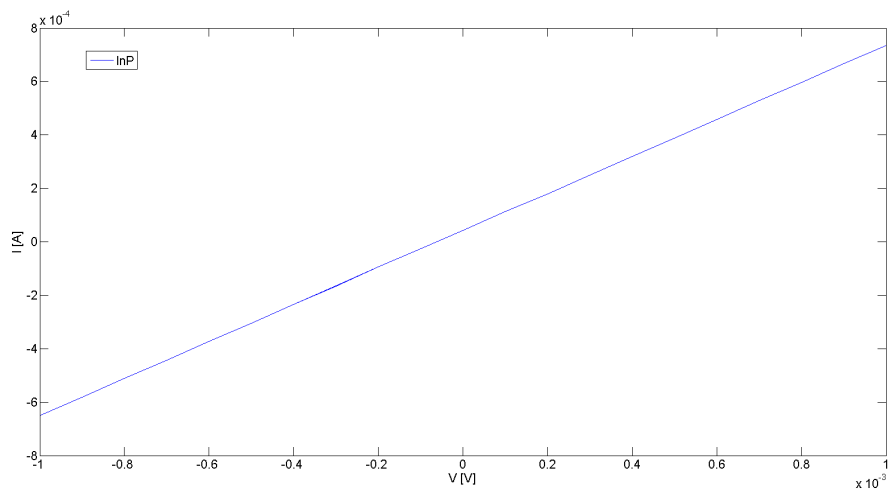


Figure 21: I-V characteristics for the InP sample.

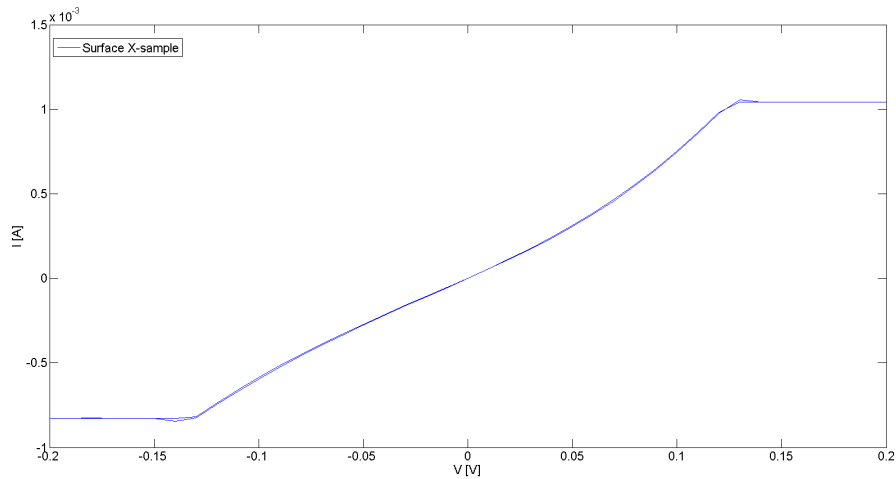


Figure 22: I-V characteristics for the surface of the cross-sectional sample.

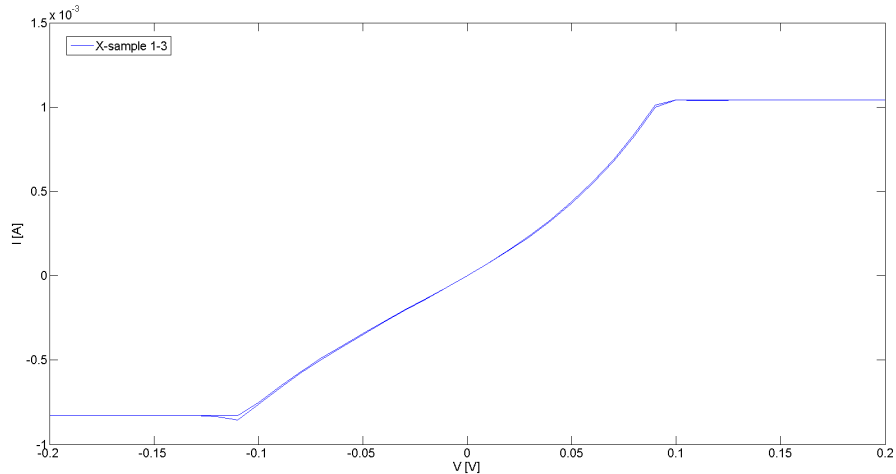


Figure 23: I-V characteristics through the cross-sectional sample.

Note the scales in figs. 20 to 23. The surface resistance of the GaAs sample is in the magnitude of $1\text{ M}\Omega$. The surface resistance of the InP sample is in the magnitude of $1\ \Omega$. The surface resistance as well as the resistance through the cross-sectional sample is in the magnitude of $100\ \Omega$. For the cross-sectional sample the magnitude of the resistance is questionably low considering the magnitude of the resistance for the GaAs sample, which was also doped. Even if the cross-sectional sample had higher doping concentration the difference should not be that big, especially not through the cross-sectional sample since the AlGaAs layer is insulating. The most probable explanation would be some contamination by

the In glue, which has low resistance. However, figs. 22 and 23 show a behavior for the cross-sectional sample which is not completely linear, despite the possible contamination. A completely contaminated sample would show a linear, ohmic, behavior such as the InP sample, fig. 21.

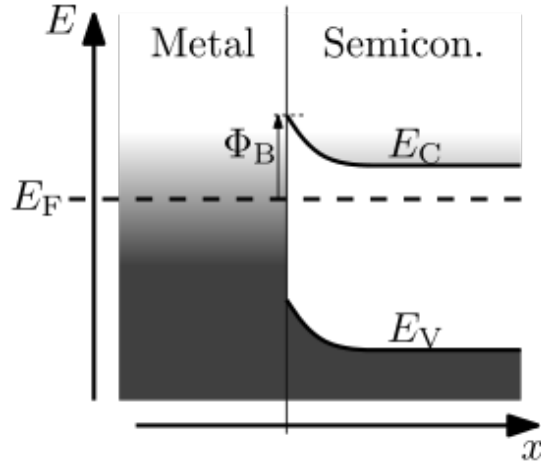


Figure 24: Schematic band diagram sketch of a Schottky barrier. Figure from [7].

The nonlinear behavior for the GaAs and the cross-sectional GaAs samples is most likely due to a Schottky barrier, illustrated in fig. 24. A Schottky barrier is a barrier which arises in a metal-semiconductor interface, making it more difficult for charge carriers to move between the materials. In the illustration, fig. 24, the Schottky barrier height at the metal-semiconductor interface is represented as the difference between the conduction band edge of the semiconductor and the Fermi level of the metal. The height of this potential barrier depends on the semiconductor composition, and GaAs has a high Schottky barrier, whereas InP has a low barrier.

4 Summary and Outlook

For the STM experiments the important result was that hydrogen cleaning was effective on the studied cross-sectional GaAs sample. The use of a cross-sectional sample can be an improvement in future experiments. By using the highly doped GaAs as electrodes with the AlGaAs as an insulating layer such a sample could be used to measure electronic properties of a NW. Figure 25 illustrates a schematic sketch of how the setup could look. The prospect of using this setup to measure electronic properties is the possibility to perform STM simultaneously. This would be a great advantage when studying the influence of contaminants as the influence

would be observed in both ways at once. This would be of help for explaining the surface structure's connection to the electronic properties. The cleaning worked for the cross-sectional sample. As the edge was never found the cleaning at the interface was not studied.

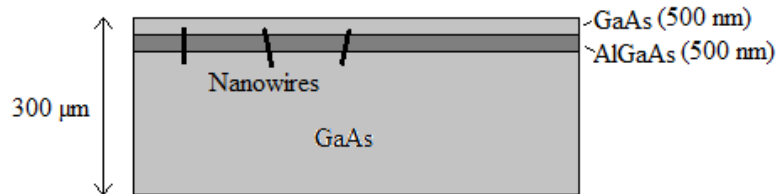


Figure 25: Schematic sketch of future use for a cross-sectional sample. Note that it is not drawn to scale.

For the AES a great result was that it is possible to detect NWs using this method. The extension of this could be to use AES to check if e.g. ALD on NWs has been successful. This means that AES can be of good use as a simple alternative to X-ray photoelectron spectroscopy (XPS).

The heater was supposed to have the ability to perform electrical measurements of NWs in vacuum while heating the NWs and giving the researchers the ability to control the oxidation of the NWs. This setup could serve as a quick and simple alternative/supplement for the setup with the cross-sectional sample presented above. However, as only a prototype of the heater was completed, this ability was never fully tested. For the prototype only the functionality was tested, in air, and the results were good.

The things I have learned from this bachelor thesis are plenty. After having performed hundreds of scans with the STM on different samples I have learned how to handle the vacuum chambers and transfer samples, clean samples with hydrogen cleaning, and of course how to perform scans with the STM. I learned how to interpret the images obtained during scans, understanding what is seen. For the AES I learned how to perform the experiment and how to interpret the spectra. From working on the heater I learned about building a setup with vacuum compatible components and from the measurements I learned about Schottky barriers.

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