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Borgström, Magnus

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Optical investigation of InAs/InP quantum dots at different temperatures and under electric field

L. Landin*, M. Borgström, M. Kleverman, M.-E. Pistol, L. Samuelson, W. Seifert, X.H. Zhang

Solid State Physics, P.O. Box 118, Lund University, S-221 00 Lund, Sweden

Abstract

The electronic structure of InAs quantum dots in InP is fairly well known from theory as well as from experimental work using photocapacitance, DLTS and photoluminescence spectroscopy. Both electrons and holes are confined by more than 150 meV, allowing room-temperature luminescence from the quantum dots with emission around 1.5 μm . In this study we have investigated the temperature dependence of the emission from the dots and find an activation energy in this case was found to be about 110 meV. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: InAs; InP; Photoluminescence; Quantum dot; Temperature-dependance

1. Introduction

One of the driving forces for the research of quantum dots is the predicted drastic improvement in laser characteristics. The 3D-carrier confinement increases the quantum efficiency as well as the thermal stability and one can expect a reduction of the threshold current. Quantum dots of InAs in-between barriers of InP are interesting for applications in optical communication, since the emission is close to 1.55 μm . In addition, the photoluminescence is strong at room temperature.

It is well known that the P atoms on the InP surface are easily exchanged by As atoms, and in the case of InAs/InP quantum dots, local variations in the strain field around the dots may make the As/P exchange reaction even more complicated [1]. The As/P exchange reaction produces an excess of InAs. Nevertheless, AFM studies of the dots show high size homogeneity for dots grown at the same growth conditions [1,2]. The homogeneity is supposed to depend on a self-limiting process, caused by the local strain energy density around the dot during the growth. The energy density has a minimum on the surface of the dot and a maximum at the edge of the dot. The high energy density at the edge of the dots destabilizes the wetting layer in these areas and as a result there is a net flow of material away from these areas [3]. A result of the process is that the wetting layer is thinner around the dots than elsewhere. This will

give rise to a potential barrier for charge carriers in the wetting layer far away from the dots, and the diffusion of charge carriers into the dots will be suppressed unless the temperature is high enough.

2. Experiment

The sample used was grown by metalorganic chemical vapor deposition on $n^+\text{InP}$ substrates. The details of the growth are discussed elsewhere [2].

For one set of samples we grew a buffer layer of InP, about 210 nm thick. We deposited different amounts of InAs on the buffer layer; 1.5, 2.4 and 3.0 monolayers and completed the structures by a 100-nm thick cap layer of InP. Uncapped samples grown in the same way have been studied by AFM [2] as shown in Fig. 1. As we can observe in Fig. 1, there is an inverse behavior between the densities (ρ) and sizes of the coherent dots, most probably a consequence of the mass-distribution [4].

We will refer to these three samples according to their dot density. The sample with 1.5 monolayer we call LD (low density), the sample with 2.4 monolayers we call MD (medium density) and the one with 3.0 monolayers we call HD (high density). The samples were mounted in a liquid helium-cooled cryostat and for excitation we used a Ar-ion laser emitting at 488 nm. The photoluminescence from this set of samples was characterized by Fourier transform spectroscopy at different temperatures and for an excitation power of 50 mW. For detection we used an InSb detector.

* Corresponding author. Tel.: + 46-46-222-0337; fax: + 46-46-222-3637.

E-mail address: lars.landin@ftf.lth.se (L. Landin)

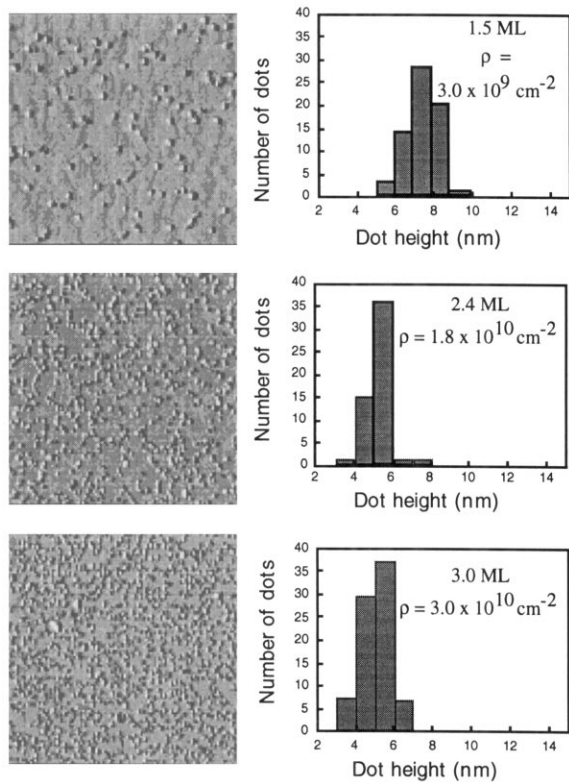


Fig. 1. Deposition-dependent height distributions of coherent InAs dots on InP, shown together with $2 \times 2 \mu\text{m}^2$, shaded AFM images acquired by contact mode imaging [2].

In another set of samples the InAs dots were situated in-between two 2-mm thick epitaxial InP layers with a residual doping concentration of about 10^{15} cm^{-3} . The dots were randomly distributed with a density of about $2 \times 10^{10} \text{ cm}^{-2}$. Those samples were primarily used for deep level transient spectroscopy and photocapacitance spectroscopy in order to obtain the electronic structure of the dots. The binding energy for the electrons was determined to be 170 meV and the binding energy for the holes was 415 meV, as reported elsewhere [5]. The strong binding of the charge carriers in this system makes it suitable for room temperature applications. Schottky junctions were formed by defining semi-transparent Au contacts on the top InP layer and alloyed Au–Ge ohmic contacts on the InP substrate, in order to study how the dot luminescence depends on an electric field. Due to a requirement for high spatial resolution these measurements were not performed in the FTIR-system but in an μ -PL setup equipped with a dispersive monochromator. A tunable ti:sapphire laser was used for excitation. The emitted light was collected by a microscope, dispersed by a high-resolution monochromator, and detected by a Ge-detector.

3. Results and discussion

Low temperature PL-spectra for the three different

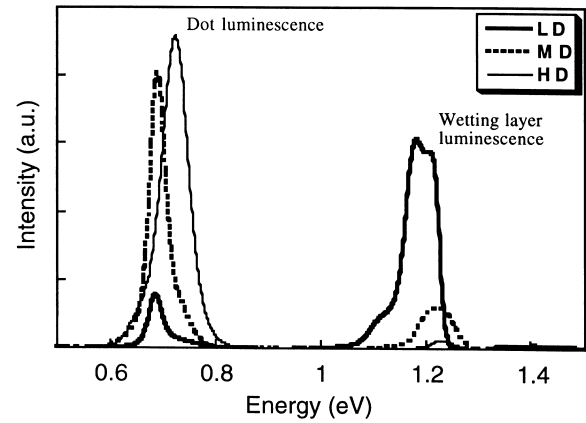


Fig. 2. Luminescence at 4 K for different dot densities.

depositions of InAs are shown in Fig. 2. It is clearly seen that the larger dot size in the LD sample gives rise to lower dot emission energy than in the MD sample and in the HD sample. We can also observe that the emission from the wetting layer is much stronger for the LD sample.

The temperature dependence of the dot luminescence is shown in Figs. 3 and 4. When the temperature is increased non-radiative recombination is activated [6]. Plotting the total luminescence from the quantum dots obtained at different temperatures in an Arrhenius plot, we found that the intensity of the dot luminescence from the HD sample decreases according to an activation energy of about 30 meV.

The dot luminescence from the LD sample behaves quite differently. The dot luminescence first increases strongly with temperature. Apparently, electrons and holes trapped in the wetting layer are thermally activated and are then free to move to the dots and contribute to the dot luminescence. Furthermore, it is known that the mechanisms for QD formation tends to surround the QDs by a thinner wetting layer, thus forming an activation energy for carrier capture into the dots. The activation energy, found by plotting the

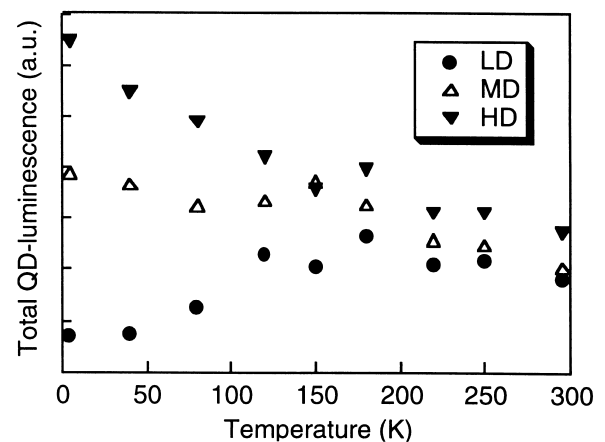


Fig. 3. Temperature dependence of the total dot luminescence for the three different samples.

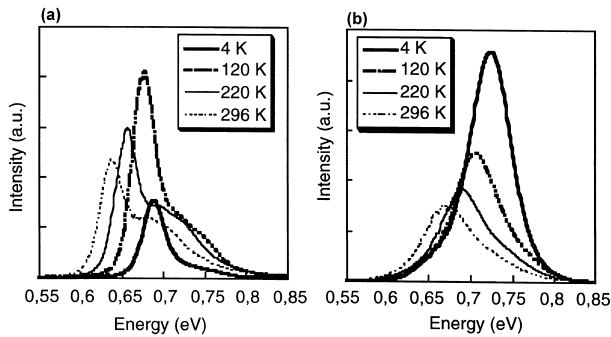


Fig. 4. Dot luminescence as a function of temperature for the LD sample (A) and for the HD sample (B). Dot densities $3.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^{10} \text{ cm}^{-2}$.

luminescence from the wetting layer obtained at different temperatures in an Arrhenius plot was in this case about 110 meV, which corresponds to the energy difference between 2 and 1 ML wetting layer [2,7].

From the temperature dependence of the luminescence from the HD sample, we conclude that the wetting layer between the dots is relatively smooth and 1 ML thick. There exist only very few traps (i.e. a two monolayer thick wetting layer) for the charge carriers, and the luminescence from the wetting layer is very weak even at 4 K. The LD sample on the other hand has a complex wetting layer with a lot of traps and consequently there is a strong wetting layer luminescence at 4 K. The traps do not locate the charge carriers when the temperature is increased giving rise to an increased dot luminescence. As a result of the increased charge carrier density in the dots in the LD sample, we can observe state filling effects when the temperature is raised. Fig. 4 shows the luminescence from the dots for different temperatures. We observe a band gap related red shift due to the increased temperature but for the LD sample we can, for higher temperatures, also identify excited states as shoulders 40 and 70 meV above the ground state, in good agreement with calculations [unpublished data]. The excited states can be seen more clearly in Fig. 5.

We have also studied the influence of an electric field on the luminescence. The electric field quenches the luminescence of the dots when the reversed bias is increased, with quenching occurring first on the high energy side, as can be seen in Fig. 6. The quenching is accompanied by a strong increase of the current through the sample. We consider three possible mechanisms for quenching: (i) tunneling of carriers through the field induced thin barriers, (ii) field induced carrier separation reducing overlap of the wave-functions and (iii) impact ionization by accelerated free carriers. The dots in the experiments pumped with a laser below the barrier energy. Calculation of the electric field in the dot layer gives a value of about $2 \times 10^4 \text{ V/cm}$. Since both the electrons and the holes are strongly confined the barrier width is not narrow enough for tunneling. For the electrons the barrier width can be estimated to 85 nm and for the holes its is even more, which is too much for tunneling.

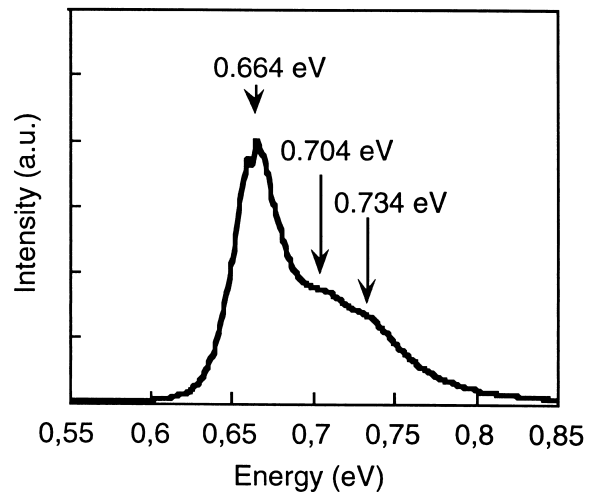


Fig. 5. Dot luminescence at 180 K for the LD sample. Excited states can be identified 40 and 70 meV above the ground state. The small dip in the ground state peak is due to water absorption.

The wave-functions for the ground state and the excited state have, according to calculation, approximately the same extent [8]. In a simple picture, quenching due to carrier wave-function separation should first occur for the ground state, which is opposite to the experimental observations. We, therefore, conclude that the quenching is due to impact ionization of the carriers in the dot free carriers accelerated to high energy by the field. It is easy to realize that such ionization will occur first for excited states, in agreement with experiments.

4. Summary

Due to the strong binding energies for electrons and holes in InAs quantum dots in InP, this system is suitable for room temperature applications. We have studied the temperature dependence of the photoluminescence from 4 K to room temperature. For low density samples the luminescence increase with temperature. We argue that the reason for

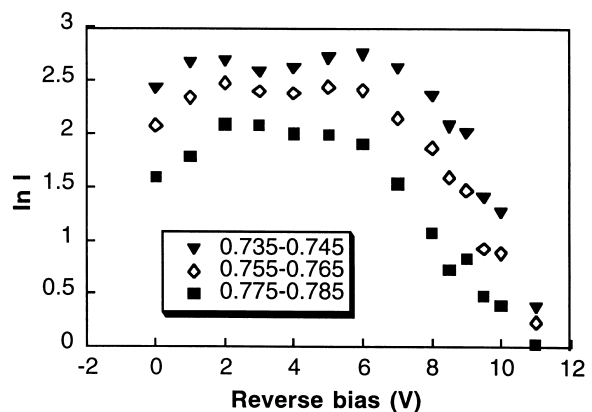


Fig. 6. Dot luminescence as a function of reversed bias voltage for different energy intervals.

this is that charge carriers are thermally activated from traps in the wetting layer and can then contribute to the dot luminescence. The activation energy for this process is found to be 110 meV, which corresponds to the energy difference between 2 and 1 monolayer. For high density samples the luminescence decreases with temperature. The activation energy is in this case 30 meV. We have also studied how the luminescence is quenched when an electric field is applied, suggesting an impact ionization mechanism.

Acknowledgements

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