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Luminescence from InP/GaInP Quantum Dots Excited by Micro-Photoluminescence or by Local Injection with Scanning-Tunneling Microscope

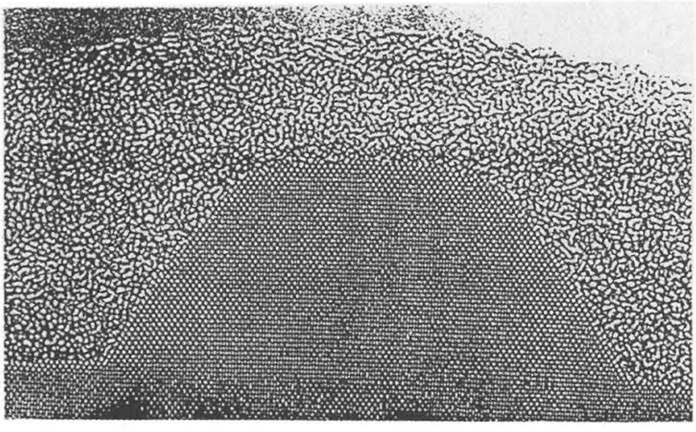
Lars SAMUELSON, Pedro CASTRILLO, Dan HESSMAN, Joakim LINDAHL, Lars MONTELIUS and Mats-Erik PISTOL

Lund University, Department of Solid State Physics, Box 118, S-221 00 LUND, Sweden

We describe the application of techniques for nano-optical studies of quantum dots fabricated via the Stranski-Krastanow growth mode by MOVPE. The first method is μ-PL in which excitation and detection is spatially restricted to 0.1 - 1 μm by masking of the sample. In the second technique we inject locally low-energy carriers from an STM tip into the semiconductor. These two techniques share the ability to perform spectroscopic investigations of single quantum dots, including excitation spectroscopies with energy selection either by the energy of the exciting light or by the potential applied between the STM tip and the sample.

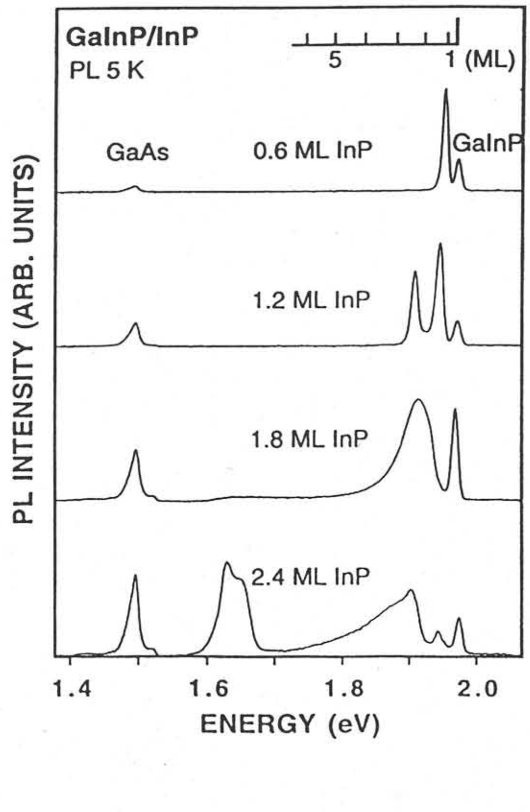
1. INTRODUCTION

When a compressively strained layer of e.g. InP is grown on the crystalline structure of GaAs or on a layer of GaInP lattice matched to GaAs, one observes a spontaneous transformation of a roughly two mono-layer (ML) thick film into nanometer scale islands of InP separated from the underlaying material by a 1 or 2 ML thick InP wetting-layer (WL). The details of this, so called Stranski-Krastanow (SK), growth mode are still debated. For InP islands it has been shown by TEM[1)] that the islands are strongly facetted with details in the facetting originating in the differences in the surface energies on the different surfaces. The TEM image below reveals the shape of an uncapped InP dot as seen in a side view of the island.



2. MACRO-PL STUDIES OF InP DOTS

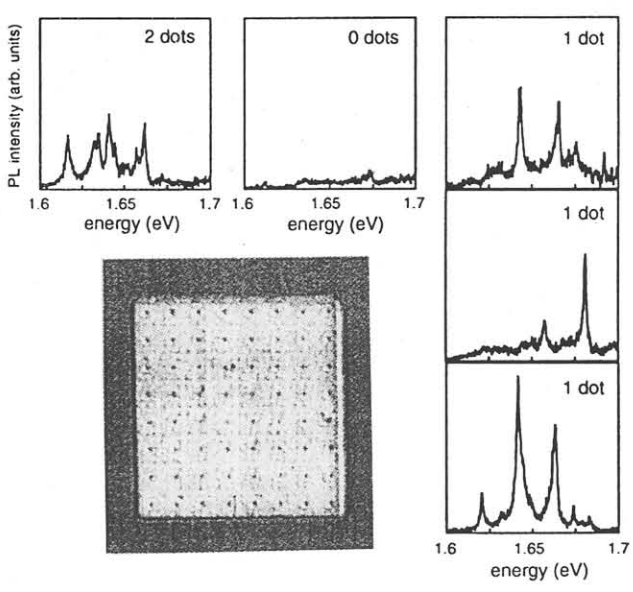
The density of dots can be controlled by the amount of InP deposited and by other growth parameters like the temperature and growth interupt times. A direct correlation is found between the formation of InP dots as seen by atomic force microscopy (AFM) and the appearance of a characteristic double luminescence peak positioned around 1.65 eV[2)]. This energy can be compared with that of the luminescence from the GaInP barrier material around 1.97 eV and that of the WL, with peaks around 1.94 eV and 1.91 eV for 1 ML and 2 ML thick InP wetting layer. The overview of the development of the PL shown, below tells that after deposition of about 2 ML of InP the transformation occurs.

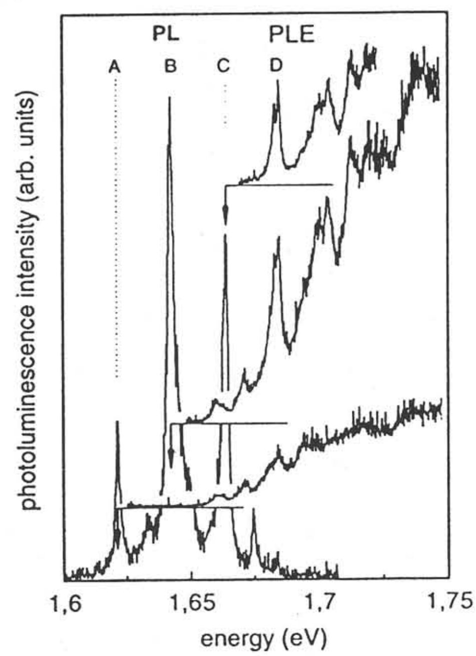


3. MICRO-PL STUDIES OF InP DOTS

One convenient way to access single or few quantum dots is to restrict the area from which PL is collected. The figure below shows how we have solved this problem by electron-beam lithography, metallization and lift-off. The large frame is an opaque gold film with 8 x 8 square windows with side 0.7 µm. With PL spectroscopy performed through an optical microscope and with the sample cooled to 5K we obtain PL spectra from the individual windows as shown in the small spectra around the image of the film[3]. From single window spectra like these it is easy to identify the pattern that a single window shows either (i) no detectable luminescence in the spectral region 1.6 - 1.7 eV, (ii) a set of typically 3-5 peaks dominated by two peaks which are in most cases stronger, or (iii) a rather large number of peaks which seem to correspond to two or three dots positioned just below the window investigated. From the behaviour seen in this figure it is easy to select single windows for detailed studies.

In the figure below is shown a typical detailed PL spectrum from a single InP quantum dot. In the figure is also shown the photoluminescence excitation (PLE) spectra obtained when detecting on different emission peaks. It can be seen that the emission seen in PL consists of several lines. These lines can be due to holes localised in different spatial positions in the quantum dot or they could be due to electrons which do not relax to the ground state due to e. g. a phonon bottleneck. From the PLE spectra it can be seen that there is no contribution from e. g. line B when detecting on line A, which also shows the lack of relaxation between the states which are responsible for the emission lines. At higher energies it can be seen in PLE that the lines A, B, and C do share excited states and thus originate from the same dot. The linewidth of the emission and of the peaks seen in PLE is rather large, about 1-2 meV. Time resolved measurements show that the emission has a lifetime of about 0.6 ns[3]. The peaks seen in PLE are seen to ride on a continuous background.





4. STM INDUCED LUMINESCENCE FROM InP DOTS

In the figure below is shown the tunnel induced luminescence from quantum dots. These spectra are obtained by the use of a scanning tunneling microscope and the measurement temperature was 77 K. At low biases (below 5 V, tip positive) there is emission[4] from individual luminescent states (partially formed quantum dots which are also present in the sample, in addition to the fully formed dots), which show an observable Stark shift. At a potential bias of 5 V we start to see emission from the quantum dots (at an energy of about 1.65 eV). This threshold corresponds to the onset of impact ionisation of excitons. These excitons, being neutral, diffuse about 1 μm before recombining[2]. It is the case that for this particular tip position there are no fully formed quantum dots immediately below the tip, and only partially formed dots are seen at low bias. It is necessary to use a high bias which create excitons which can diffuse to a nearby fully formed dot in order to get emission spectra from these dots. It is clear that tunnel induced luminescence is capable of exciting single quantum dots, with a high spatial resolution, particularily at low applied bias. It should be noted that for other tip positions we see emission from fully formed quantum dots also at low

References

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