

# Spatially Photoluminescence Spectroscopy of InAs/InGaAs Quantum Dot Nanostructures

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## 1. Abstract

Spatially resolved photoluminescence (PL) spectroscopy was performed in self-assembled InAs quantum dots (QD) embedded into Molecular Beam Epitaxy (MBE) grown  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$  multi-quantum-well heterostructures. This type of heterostructures currently is used for creation of new generation lasers for optical fiber communication. Strong inhomogeneity of the PL intensity is observed by mapping samples with different In/Ga composition of the layers covered

the quantum dots in the quantum well. Two different behaviors in the quantum dot PL maps are clearly observed and identified: 1) a reduction of the PL intensity is accompanied with a monotonous "blue" shift of the luminescence maximum at room temperature, and 2) the PL intensity degradation matches a stable peak position of the PL maximum.

**Key words:** photoluminescence spectroscopy, quantum dot (QD), inhomogeneity, multi excited state.

## 2. Resumen (Espectroscopia espacial de fotoluminiscencia de nanoestructuras de puntos cuánticos de InAs/InGaAs)

La espectroscopia de fotoluminiscencia (FL) de barrido fue realizada en puntos cuánticos (QD) autoensamblados embebidos dentro de heteroestructuras de multipozos cuánticos de  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$  crecidos por epitaxia de haces moleculares. Dos tipos de heteroestructuras son usadas para la creación de una nueva generación de láseres para comunicaciones por fibra óptica. Una fuerte inhomogeneidad de la intensidad de FL es observada por las muestras mapeadas con diferente composición de In/Ga de las capas que cubren los puntos cuánticos en el pozo cuántico. Dos diferentes comportamientos en los mapas de los puntos cuánticos son claramente observados e identificados: 1) una reducción en la intensidad de FL es acompañada con un desplazamiento monótono al "azul" del máximo de la FL a temperatura ambiente y 2) la degradación de la intensidad de FL igual a la estable posición del pico del máximo de FL.

**Palabras clave:** espectroscopia de fotoluminiscencia, punto cuántico (PQ), inhomogeneidad, estados multiexcitados.

## 3. Introduction

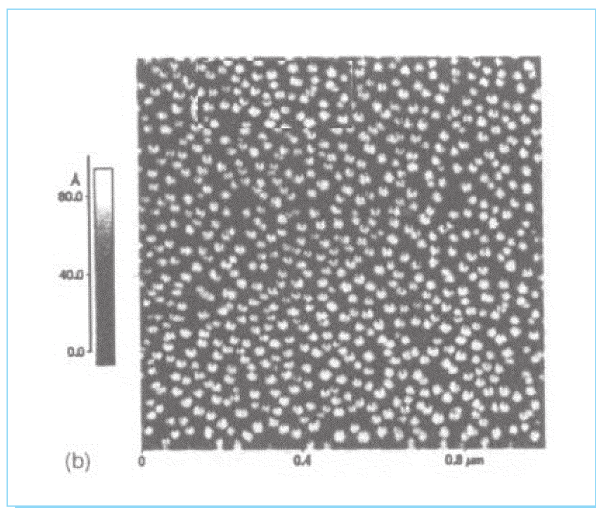
The formation of quantum dots (QD) as a result of Stranskiy-Krastanow growth of strained heterostructures is now widely used for the formation of semiconductor laser structures [1]. The semiconductor lasers, based on QD structures, exhibit many advantages such as low threshold current densities, high gain and high quantum efficiency [2]. The inhomogeneity of

individual QD parameters across the wafer (size, chemical components, stress) leads to broadening of the emission spectra resulting in loss of efficiency. This type of problems in QD structures were addressed using scanning PL study performed with sub-micron resolution [3] or by high-spatial resolution transmission electron microscopy techniques [4]. To develop mechanisms responsible for variation of the PL characteristics across the wafer, we report here a complementary scanning PL study performed at room temperature on QD grown with various technological routines.

#### 4. Samples and results

The samples were created using molecular beam epitaxy technique; the samples were composed of three InAs self organized QD layers embedded into  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$  multi-layer heterostructure [5]. The variable parameter in the set was In-composition in the  $\text{In}_x\text{Ga}_{1-x}\text{As}$  layers covered the InAs QD. Two different compositions were studied with  $x = 0.1$  (structure ID #1361) and  $x = 0.15$  (#1360). Using atomic force microscopy on a sister samples with opened QD layers, we found that the individual dots were of 15 nm in base diameter and approximately 7 nm in height. The in-plane dot density was 7 to  $10 \times 10^{11} \text{ cm}^{-2}$ .

Figure 1 shows the image of Atomic Force Microscopy (AFM) of the sample 1360, showing the density and dot size, it was performed at Center of High Technology of Materials in New Mexico University, Albuquerque New Mexico, USA.



**Fig. 1.** AFM image of sample 1360, dot density is  $7 \times 10^{10} \text{ cm}^{-2}$ .

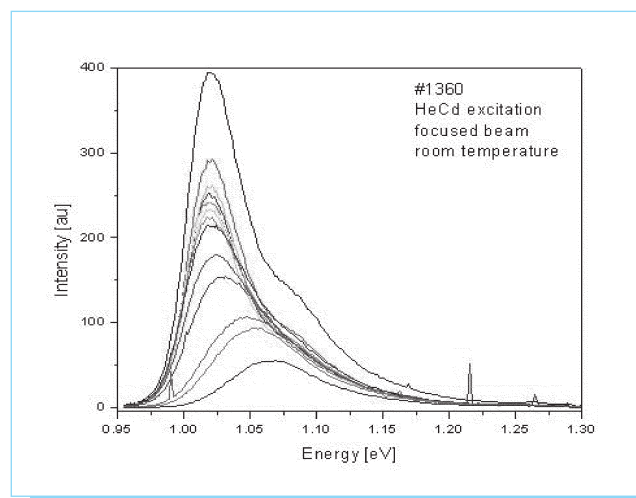
The scanning PL spectroscopy was performed at room temperature, using the CW HeCd laser (325 nm, 55 mW) as the excitation source. The laser spot of 1.4 mm diameter could be focused down to 12 microns for high-resolution mapping using UV beam expander and aberration free lenses. Samples were mounted on PC controlled X-Y moving stage.

Typical mapping area was 5 mm x 15 mm rectangle with the step of 0.5 mm. The PL spectrum was dispersed by SPEX 500M spectrometer and recorded by liquid-nitrogen cooled Ge-detector coupled with a lock-in amplifier. PL maps were obtained by the consecutive measurements of the PL spectrum at individual sample spots.

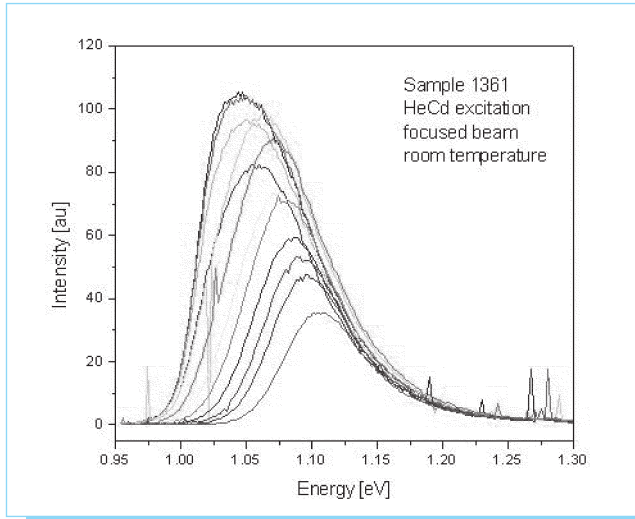
In figures 2 and 3 we present room temperature PL spectra measured along the PL intensity decreasing line-scans in both samples, which show quite different features. Specifically, in 1360 sample, a principal PL maximum maintains the spectral position at 1.020 eV within the band of 10 meV, while reducing the PL intensity by more than a factor of two.

On the contrary, the sample #1361 exhibits a gradual "blue" energy shift of the maximum starting at the wafer's center at 1.044 eV and approaching 1.11 eV at the periphery, which matches a three-fold degradation of the PL intensity.

These observations are statistically approved by mapping the PL maximum across the whole samples for a set of 115 data points measured in the scanning mode; in figure 4 we present these observations.

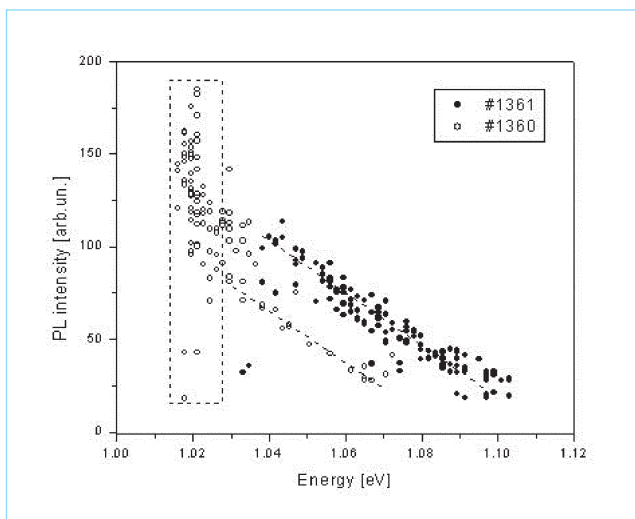


**Fig. 2.** Spatially resolved PL spectra at 300K on the sample #1360.



**Fig. 3.** Spatially resolved PL spectra at 300K on the sample #1361.

We have also noticed that the luminescence in the #1360 has at room temperature the highest intensity averaged across the wafer compared to #1361 3.2 times. Sample #1360 shows also a narrowest half width of the PL maximum in the set of three samples. It exhibits an additional peak at 1.08 eV, which was previously observed on high-quality QD samples and attributed to the luminescence through the excited states of



**Fig. 4.** PL intensity versus PL peak maximum position extracted from the 115 data points on both samples.

the holes in the QD [5]. These facts indicate that electronic quality of the QD structure is superior in the sample #1360 with  $x = 0.15$  composition of the covered layer. It is worth noticing, that the #1360 sample also shows partially features of the #1361 at the low PL intensity region. We can interpret the spectroscopic PL mapping results on the InAs/InGaAs QDs grown with different composition of covered InGaAs layer, as two different physical mechanisms taking place in various samples.

In #1361, a size of the dots is decreased gradually from the center of the wafer toward the sample periphery. This is exhibited as the "blue" shift of the PL maximum at room temperature.

This effect leads at the wafer periphery to shallower QD localized states (*i.e.* smallest electron and hole binding energy), poorer carrier localization and, as consequence, a higher probability of the carrier thermal ionization, which reduce room-temperature PL intensity. Regarding #1360 sample, the maximum position of the 1.02 eV PL band is maintained, and drop of the PL intensity can be related to inhomogeneous distribution of non-radiative centers, competing with QD luminescent transitions. We notice again that first mechanism is also contributed in this sample in areas with low PL intensity. Interesting is that maximum versus intensity slopes are very close in both samples.

The importance of changing the PL response in the investigated samples is that it indicates the level of quality they have, since the sample #1360 to be higher PL intensity at room temperature makes it more feasible for use in laser devices working systems for fiber optic communications.

## 5. Conclusions

We observed in this study that InAs/InGaAs QD structures have inhomogeneity of QD parameters in laser structures for optical fiber communication. Scanning PL spectroscopy suggests two distinctive mechanisms for such inhomogeneity. The first is variation of the QD size across the wafer and the second uneven spatial distribution of non-radiative defects. Both cases can be tailored by careful selection of the QD structure parameters and growth regimes.

In optical fiber communication systems, the light source operates at room temperature, besides their light output should be in the second or third window (1.3  $\mu\text{m}$ , 1.55  $\mu\text{m}$ ), which is why the results of these samples lead us to believe they are very good candidates for new laser materials systems for fiber optic communications.

### Acknowledgements

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