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Photoluminescence peculiarities in InGaAs/GaAs structures with different InAs quantum dot densities

T.V. Torchynska

ESFM–Instituto Politécnico Nacional, México D.F. 07738, México

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ABSTRACT

Emission peculiarities and X-ray diffraction (XRD) have been studied in GaAs/InGaAs/GaAs quantum wells (QWs) with different densities of embedded InAs quantum dots (QDs). The QD density decreased from 1.1×10^{11} to 1.3×10^{10} cm^{-2} when the QD growth temperature was increased from 470 up to 535 °C. The QD density changes are accompanied by the nonmonotonic variation of the photoluminescence (PL) intensity and peak positions: the highest PL intensity corresponds to lowest emission energy (1.3 μm) in InAs QDs obtained at the QD density equal to 3.4×10^{10} cm^{-2}.

PL temperature dependences have been studied in the range of 10–300 K with the aim to analysis the QD band gap shrinkage. It revealed the process of In/Ga intermixing that is characterized by nonmonotonic behavior versus QD growth temperatures and QD densities.

The XRD study has revealed high intensity peaks related to the diffraction of X-ray beam from (4 0 0) crystal planes in the cubic GaAs QW layers and GaAs substrates. It was shown that (4 0 0) diffraction peaks in GaAs QW layers shift to high angles, in comparison with the GaAs substrate, testifying the compression strain. The strain value in GaAs QW layers has been estimated and it is revealed that this value changes nonmonotonic with InAs QD density and its minimum corresponds to a QD density of 3.4×10^{10} cm^{-2}. It is shown that In/Ga intermixing is stimulated by the compression strains: higher level of strains provokes higher In/Ga intermixing.

Therefore, the shift of PL peak positions in InAs QDs versus QD density and size is the result of the influence of three factors: the quantum confined effect in QDs of different sizes, In/Ga intermixing, and the compression strain. The value of PL peak shift owing to the compression strains in QWs has been estimated as well. Physical reasons for the nonmonotonic variation of PL and strains in InGaAs/GaAs QWs versus InAs QD density have been discussed.

1. Introduction

InAs quantum dots (QDs) embedded in InAs/GaAs quantum wells (QWs) have attracted great attention for over two decades, owing to the wide applications of QD structures in: IR lasers for optical fiber communication [1–3], solar cells, and infrared photodetectors [4–6], as well as in electronic memory devices [7,8]. The problems related to strain relaxation and the consequent defect generation, as well as compositional intermixing, in strained InAs/GaAs QWs with InAs QDs have been studied in detail due to their great technological importance for optoelectronic devices. For the Stranski–Krastanov (SK) growth mode, it is generally known that the strain field induced by the lattice mismatch (7.1%) between the growing epitaxial InAs material and GaAs substrate, controls the local atom surface dynamics, including the adsorption, diffusion, desorption, and crystallization of atoms or radicals, as well as the creation of InAs QDs in the process of strain relaxation.

In lasers and photodiodes the surface density of QDs has to be high [9–12]. It was shown not long ago that the QD density can be enlarged by growing the QDs within $In_xGa_{1-x}As$/GaAs QWs [12–14]. Capping of InAs QDs by an $In_xGa_{1-x}As$ layer, as supposed, reduces the compressive strain in QD structures and suppresses In/Ga intermixing [12,15–17]. To create the high InAs QD density, the optimal composition of capping/buffer layers was estimated as $In_{0.15}Ga_{0.85}As$ [12,14]. But even for optimal QD growth parameters and the capping/buffer layer compositions, the InAs QD structures are characterized by emission none homogeneity [18–22]. Thus, the structural and electronic properties of InAs QDs coupled with InGaAs/GaAs QWs are still partially understood. In this paper, the physical reasons for the variation of photoluminescence (PL) intensities and PL peak positions of InAs QDs embedded in the GaAs/$In_{0.15}Ga_{0.85}As$/GaAs QWs versus QD density and size have been discussed.

1.1. Experimental conditions

A set of samples was prepared using molecular beam epitaxy on (1 0 0) oriented 2-inch diameter semi-insulating GaAs

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E-mail address: ttorch@esfm.ipn.mx

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substrates. Each structure first has a 200 nm GaAs buffer layer grown on the GaAs substrate. InAs QDs were grown on a second buffer layer with composition $In_{0.15}Ga_{0.85}As$ and a thickness 2 nm and were capped, first by a 10 nm $In_{0.15}Ga_{0.85}As$ layer and then by a 100 nm GaAs layer. InAs QDs were grown at five temperatures 470 (#1), 490 (#2), 510(#3) 525 (#4), and 535 (#5) °C during the deposition of InAs active regions (2.4 ML) and InGaAs layers as was described earlier [12,14]. The QD lateral size increases from 12 to 28 nm and the QD density decreases versus QD growth temperatures (Table 1). The dot size and density were determined by the AFM observation of parallel wafers that had not been overgrown by QWs [12,14].

Photoluminescence spectra were measured in the range of 10–300 K using excitation by the 536 nm line of a solid state laser model V-5 COHERENT Verdi at an excitation power density of 500 W/cm^2. PL spectra were dispersed by a SPEX 500M spectrometer with a thermoelectrically cooled Ge detector. The X-ray diffraction (XRD) experiments were made using the X-ray double crystal equipment, model of D-8 advanced (Bruker Co.), with the Kα1 line from a Cu source (λ=1.5406 A).

2. Experimental results

2.1. PL of QD structures

Typical PL spectra of the structure #4 measured at different temperatures are shown in Fig. 1. Two PL bands appear due to the recombination of excitons at a ground state (GS) and at the first excited state (1ES) in InAs QDs (Fig. 1). The strong PL intensity decay with temperature in this type of QD structures was studied early in [14].

Table 1
QD density and PL peak fitting parameters.

Structure number	E_0 (eV)	k ($\times 10^{-2}$ eV)	θ_{E0} (K)	N_{QD} (cm^{-2})
#1	1.090	4.88	135	1.1×10^{11}
#2	1.053	2.60	96	7.0×10^{10}
#3	1.037	2.64	100	3.4×10^{10}
#4	1.070	4.55	125	1.8×10^{10}
#5	1.074	4.51	130	1.3×10^{10}
Bulk InAs	0.415	2.25	83	

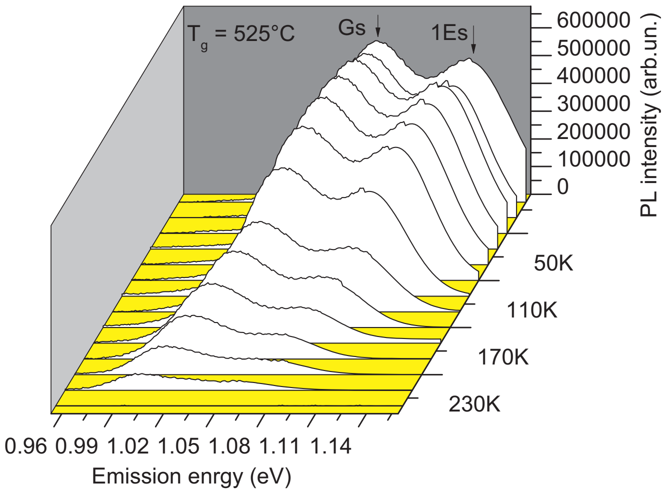

Fig. 1. Typical PL spectra measured at different temperatures at the excitation density of 500 W/cm^2 for structure #4.

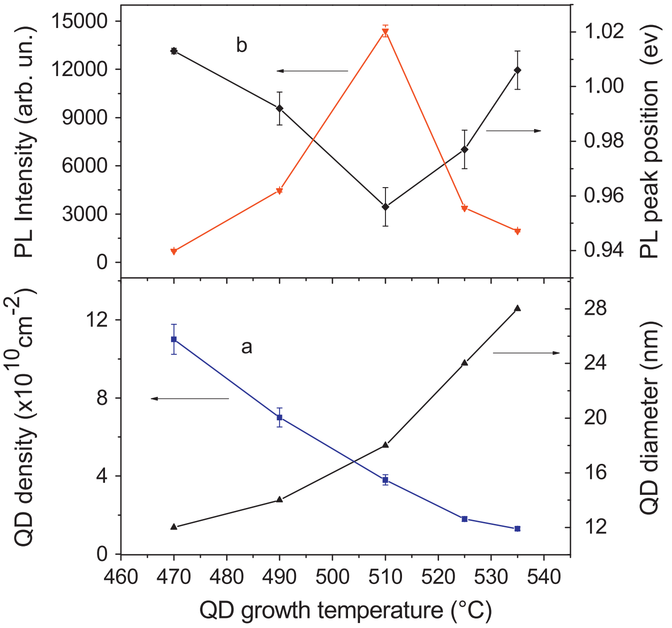

Fig. 2. Variation of QD density and lateral size (a), as well as the PL integrated intensity and GS PL peak positions (b) versus QD growth temperature.

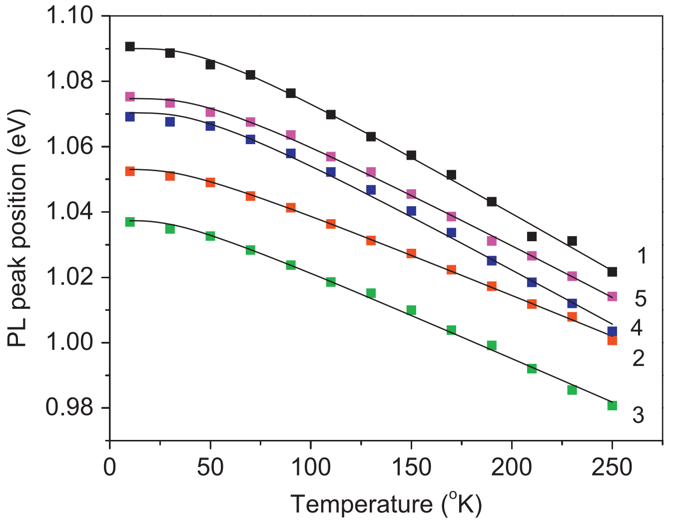

Fig. 3. Variation of PL peak positions versus temperature for structures: 1—#1, 2—#2, 3—#3, 4—#4, and 5—#5. The lines present the fitting results.

The QD density decreases from 1.1×10^{11} to 1.3×10^{10} cm^{-2} and the QD lateral size increases monotonically from 12 up to 28–30 nm (Fig. 2a) with increasing QD growth temperatures from 470 up to 535 °C. Thus, it is possible to expect monotonic PL intensity decrease and, simultaneously, the shift of PL peak positions to low energy owing to the quantum confined effect in QDs. Fig. 2b presents the integrated GS PL intensities and PL peak positions measured in all studied structures #1–#5. The nonmonotonic behavior of PL parameters has been detected, apparently, owing two possible reasons additional to the quantum confined effect: (i) the Ga/In atom intermixing between the InAs QDs and InGaAs QW layers, and/or (ii) the different levels of elastic strains in studied QD structures.

To analyze the process of Ga/In intermixing the PL spectra of InAs QDs have been studied at different temperatures (Fig. 1). The GS PL peaks shift to low energy with increasing temperature (Fig. 3) due to the shrinkage of QD optical gap, E_g. The lines in