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Emission of InAs quantum dots embedded in InGaAs/InAlGaAs/GaAs quantum wells

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ABSTRACT

Photoluminescence (PL), its temperature dependences and X-ray diffraction (XRD) have been investigated in MBE grown GaAs/$Al_{0.3}Ga_{0.7}As/In_{0.15}Ga_{0.85}As$/InAlGaAs/GaAs quantum wells (QWs) with embedded InAs quantum dots (QDs). Studied QD structures are the important part of low-threshold, high-power lasers for optical fiber communication systems. Three types of QD structures with different capping layers (GaAs, $Al_{0.3}Ga_{0.7}As$ and $Al_{0.1}Ga_{0.75}In_{0.15}As$) were investigated. The comparison of the impact of capping layer compositions on PL parameters of InAs QDs and the process of Ga/Al/In intermixing has been obtained.

QD emission is analyzed in the temperature range of 10–500 K and the QD emission shift has been compared with the temperature shrinkage of band gaps in the bulk InAs and GaAs crystals. Different changes of QD compositions owing to Ga/Al/In intermixing have been revealed in studied structures. The XRD study is used to control a composition of QW layers and to confirm additionally that the efficiency of Ga/Al/In intermixing depends on capping layer types.

The thermal decay of integrated PL intensities has been investigated as well. The PL thermal decay 557-fold in the range 10–300 K is revealed in the structure with GaAs capping layer in comparison with the 6- and 20-fold PL decays in structures with $Al_{0.3}Ga_{0.7}As$ and $Al_{0.1}Ga_{0.75}In_{0.15}As$ capping layers, respectively. The reason of PL spectrum transformation and the mechanism of PL thermal decay in QD structures with different capping layer compositions have been analyzed and discussed.

1. Introduction

In the past 20 years, zero-dimensional quantum dot (QD) systems with three-dimensional quantum confinement have attracted considerable attention due to fundamental and application reasons [1–3]. The most studied subject is the self-assembled (SA) semiconductor QDs formed by the Stranski–Krastanov growth mode. In these QD systems the strong localization of electronic wave functions permits to realize a new generation of photonic and electronic devices. The InAs/GaAs and InAs/InP QDs have been used as an effective active medium in electronic devices: lasers and light emitting diodes, infrared photo-detectors, solar cells and non-volatile memories [4–8]. However, the SA InAs/GaAs and InAs/InP QD systems are characterized by non-homogeneity of their parameters: QD sizes, compositions and densities, resulting in the difficulties in manipulating the optical and electrical properties [1–8].

It was shown not long ago that the InAs QD density can be enlarged to $7 \times 10^{10}\ cm^{-2}$ at the growth of QDs within strained InGaAs/GaAs quantum wells (QWs) [3,9,10]. For InP-based InAs QDs the InAlGaAs or InGaAsP alloys are used as a matrix QW material. However, the intrinsic phase separation and As/P intermixing at the InGaAsP/InP interface limit the formation of InAs QDs with a symmetric shape [11]. Moreover a lower mismatch at the InAs/InAlGaAs interface does not permit to obtain InAs QDs of big sizes on the InP substrate [12].

A crucial aspect for the realization of efficient light-emitting devices operated at room temperature is the thermal decay of QD emission. The PL intensity decay in InAs/InGaAs QDs, as a rule, is attributed to the thermal escape of carriers from QDs into the wetting (WL) or QW layers, or in the GaAs barrier, followed by the carrier recombination via nonradiative centers [13–20]. It was confirmed experimentally [19–22] that the thermal escape of carriers (electron and hole) from QDs takes place as the escape of excitons or correlated electron–hole pairs. In this case introducing the additional AlAs [23], InAlAs [24–27], AlGaAs [28,29] or InAlGaAs layers into InGaAs/GaAs QWs leads to enlarging the potential barriers for the exciton thermal escape from QDs and, as

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it is expected, can permit the application of QD structures at higher temperatures [30,31]. Additionally, the AlGaAs or InAlGaAs layers in QWs can reduce the elastic strains and influent on the process of Ga/In/Al intermixing [32].

A further step in QD emission stimulation deals with understanding the process of carrier thermal escape and the identification of final electronic states for this escape. It was shown earlier [13,19–21] that the PL thermal decay in InAs/InGaAs/GaAs QW structures is characterized by a set of stages related to the exciton escape from QDs into WL, QW or GaAs barriers, which depends essentially on the localization of nonradiative recombination (NR) centers [19,20,33]. In high quality InAs/InGaAs QD structures at least three PL thermal decay stages with different activation energies were detected in the range of 10–500 K [19,21]. Note that the majority of published papers [23–28] report the thermal decay of InAs QD emission investigated at the temperatures of 10–300 K. The last fact, apparently, is the reason why the PL thermal decay with smallest activation energies, such as 83–98 meV [23] or 120–250 meV [27], has been detected mainly. Thus the deep understanding of exciton thermal transitions could be obtained from the emission study at 10–500 K in the QD structures with different compositions of InAlGaAs capping layers.

2. Experimental details

The solid-source molecular beam epitaxy (MBE) in V80H reactor was used to grow the waveguide structure consisting of the InAs self-organized QDs inserted into the 9 nm $In_{0.15}Ga_{0.85}As$ QW layer. The second buffer $In_{0.15}Ga_{0.85}As$ layer of 2 nm (buffer 2) was grown on the 300 nm $Al_{0.30}Ga_{0.70}As$ first buffer layer (buffer 1) and 2 in. (100) GaAs SI substrate (Fig. 1). The equivalent coverage of 2.4 InAs monolayers (QDs) was confined by the first capping (7 nm) $In_{0.15}Ga_{0.85}As$ layer (capping 1), then by 100 nm InAlGaAs second capping layer (capping 2) and by 10 nm AlAs, and 2 nm GaAs layers (Fig. 1). Three groups of QD samples with different second capping layers were investigated. In the first group the second capping layer is GaAs (#1), in the second group it is $Al_{0.30}Ga_{0.70}As$ (#2) and in the third group the composition of the second capping layer is $In_{0.15}Al_{0.1}Ga_{0.75}As$ (#3). Investigated QD structures were grown under As-stabilized conditions. QDs originating from the 2.4 InAs monolayers were grown at 510 °C with a growth rate of 0.05 ml/s, then capped by the 7 nm $In_{0.15}Ga_{0.85}As$ layer at 470 °C and capped by the rest of layers at 610 °C.

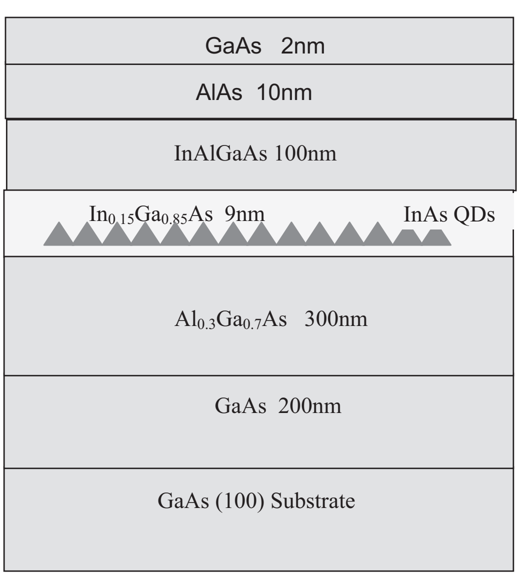

Fig. 1. The design of studied QD structures.

The in-plane density of QDs estimated at AFM study was 5×10^{10} cm^{-2}. QD samples were mounted in a closed-cycle He cryostat where the temperature is varied in the range of 10–500 K. The excitation light wavelength of 488 nm from a cw Ar+-laser with the power density of 500 W/cm^2 is used at PL measurements. The PL setup was presented earlier in [19,34]. X-ray diffraction (XRD) experiments were done using the XRD equipment of Model XPERT MRD with the Pixel detector, three axis goniometry and parallel collimator with the resolution of 0.0001 degree. XRD beam was from the Cu source, $K_{\alpha1}$ line $\lambda=1.5406$ Å.

3. Experimental results and discussion

3.1. PL spectra of QD structures

PL spectra of QD structures #1, #2 and #3 are complex consisting of four overlapping PL bands, which belong to the recombination of localized excitons at a ground state (GS) and the first (1 ES), second (2 ES) and third (3 ES) excited states in QDs (Figs. 2–4). The GS emission peaks at 10 K are 1.139 eV (#1), 1.118 eV (#2) and 1.066 eV (#3). Note that the GS emission peak at 1.29–1.30 μm is detected in #3 at 300 K that is interesting for the QD application in IR lasers. The deconvolution procedure has been applied to PL spectra, which permit to estimate the full width at half maximum (FWHM) of GS PL bands as 60 (#1), 50 (#2) and

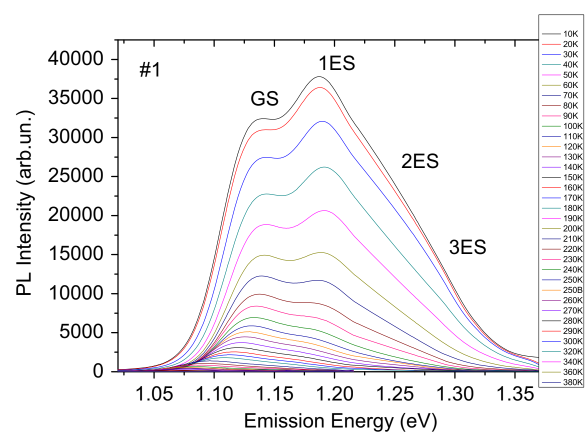

Fig. 2. PL spectra of the structure #1 measured at different temperatures.

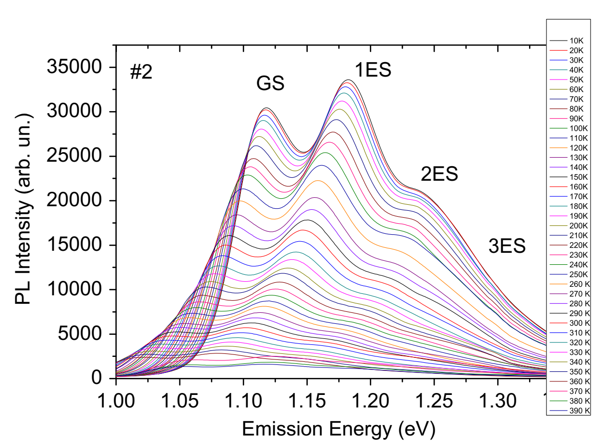

Fig. 3. PL spectra of the structure #2 measured at different temperatures.