Carrier dynamics in InAs quantum dots embedded in InGaAs/GaAs multi quantum well structures

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Abstract. Ground and multi excited state photoluminescence, as well as its temperature dependence, in InAs quantum dots embedded in symmetric In_{x}Ga_{1-x}As/GaAs (x=0.15) quantum wells (DWELL) have been investigated. The solution of the set of rate equations for exciton dynamics (relaxation into QWs or QDs and thermal escape) solved by us earlier is used for analysis the variety of thermal activation energies of photoluminescence thermal quenching for ground and multi excited states of InAs QDs. The obtained solutions were used at the discussion of the variety of activation energies of PL thermal quenching in InAs QDs. It is revealed three different regimes of thermally activated quenching of the QD PL intensity. These three regimes were attributed to thermal escape of excitons: i) from the high energy excited states of InAs QDs into the WL with follows exciton re-localization; ii) from the In_{x}Ga_{1-x}As QWs into the GaAs barrier and iii) from the WL into the GaAs barrier with their subsequent nonradiative recombination in GaAs barrier.

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1. Introduction
InAs quantum dots (QDs) embedded in strained InGaAs quantum well (DWELL) are of substantial interest due to their potential for fabrication of GaAs-based lasers emitted around wavelength region of 1.3 μm [1]. It has been shown that in comparison with the InAs/GaAs system, in DWELL structures the QD photoluminescence (PL) intensity can be improved and the QD PL maximum red shifted due to increasing both the dot density and sizes. Better crystalline quality of the material surrounding the dots and more effective carrier capture by the well also result in the increasing of the integrated PL intensity [2].

The influence of the growth conditions and capping InGaAs QW parameters on the InAs DWELL structure and resulting luminescence spectra have been studied by many authors [2-4]. However the peculiarities of carrier capture and relaxation in such a system have not been well established. The PL intensity variation versus temperature and mechanisms of carrier dynamic in InAs/InGaAs DWELL structures only start to be studied in last years [5-7] and still are under discussion.

In the present paper we investigate the exciton thermal escape in the InAs QDs embedded in the symmetric InGaAs/GaAs QW using temperature dependent measurements of the PL bands deals with ground (GS) and multi excited states (ES).
2. Experimental Results

The experimental set of samples was created using molecular beam epitaxy on (100) oriented 2''diameter semi-insulating GaAs substrates as was described earlier in [5, 7]. The photoluminescence (PL) spectra were measured in an 80-300 K temperature range under the excitation of the 514.5 nm line of a cw Ar+-laser at an excitation power density of 1000 W/cm². PL spectroscopy setup was presented earlier in [7].

In Fig.1 the PL spectra of the QD structure measured at 80-300 K are shown. In the 1.025-1.132 eV spectral range we observe the QD PL bands caused by the recombination of excitons localized at the QD ground state (the low energy peak) as well as at the four excited states (the high energy peaks) and the InGaAs quantum well (QW) PL band at the 1.305 eV (80K).

The temperature dependence of integrated over entire spectrum PL intensities and spectral positions for GS and ES states in a studied QD structure are shown in Fig.2a, b, respectively. As one can see (Fig. 2b) the energy separations between the QD states are non equidistant and equal to: 60 (1ES-GS), 53 (2ES-1ES), 44 (3ES-2ES) and 38 meV (4ES-3ES). PL peak positions shift to low energy with increasing temperatures by the same way for all PL bands (Fig.2b). It is shown earlier in [5] that these shifts are close to InAs band gap shrinkage with temperatures.

In all samples, the changes in the QD GS and ES integrated PL intensities with temperature can be divided into the three regions (Fig.2a). At low temperatures up to 110K (I) the integrated PL intensity does not change, but energy peak positions decrease. The process of PL intensity thermal quenching starts at 110K and it is characterized by two different rates: smaller in the temperature range T=110-180 (II) and higher at T=180-300 K (III).

3. Discussion

Thermal quenching of the QD PL intensity can be explained by thermal escape of excitons from the QDs into the GaAs barrier and wetting layer (WL) [6, 9] or in capping/buffer QWs with subsequent NR recombination [8], as well as by thermally activated capture of excitons by NR recombination centers [5] or by the loss of photo generated carriers in WL or QWs (before they are captured by QDs) due to their thermal escape into the GaAs barrier.

For explanation of our experimental results in the DWELL structures, we consider the two-stage process of the exciton capture (thermal escape), as proposed by us earlier in [8]. In our case, exciton capture and thermal emission from QDs occur not only through the WL states, as was proposed earlier in [6, 9], but also through the capping/buffer InGaAs QW states [8]. Following our model [8], the activation energies of the PL quenching have to correspond to $E_{\text{GaAs-OW}}$ (or $E_{\text{GaAs-WL}}$), $E_{\text{OW-QD}}$, and $E_{\text{GaAs-QD}}$ in different temperature ranges. The corresponding energy diagram for a studied QD structure is presented in figure 3. The energy band gaps for the WL and capping InGaAs QW layers (1.43 and 1.46 eV, respectively) were estimated on the base of the PL excitation spectrum of the same type of QD structures presented in [4].

In the low-temperature range I (< 110K) the processes of exciton thermal escape from QW into GaAs layer and from QDs into QW are negligible. As a result, the PL integrated intensity W(T) in the temperature range I is constant (Fig.2a). The thermal quenching process is essential in the temperature ranges II and III (Fig.2a). For a quantitative determination of the activation energies $E_a$ of the PL thermal quenching process, the $\{W_{\text{max}}/W(T) - 1\}$ dependences of the integrated QD PL intensity for GS and ES states was plotted versus temperature in the Arrhenius plot (Fig.4). $W_{\text{max}}$ is the integrated intensity obtained at 80 K. Two distinct linear regions with corresponding activation energies $E_a$ (II) and $E_a$ (III) are observed (Fig.4).

For all PL bands studied the value $E_a$ (II) = 52-55 meV satisfies nearly the energy difference between the GaAs and buffer InGaAs QW energy band gaps (Fig.3). Therefore, thermal quenching of the QD PL intensity in the range II, apparently, is due to the decrease of an exciton flow to the QDs caused by thermal escape of excitons from the buffer InGaAs QW layer into the GaAs barrier followed by a subsequent NR recombination in the GaAs layer.
The Ea (III) values corresponding to the range III for GS, 1ES, 2ES and 3ES PL bands are the same and equal to 200 meV. It is found that this value equal nearly to the energy difference between the GaAs and capping InGaAs QW energy band gaps (Fig. 3). It testifies PL thermal quenching in these QD PL bands is due to the decrease of an exciton flow to the QDs caused by thermal escape of excitons from the capping InGaAs QW layer into the GaAs barrier followed by a subsequent their NR recombination in the GaAs layer.

The Ea values in the range III for the 4ES state are smaller than one mentioned above for GS, 1-3ES states and equal to 181 meV (Fig. 4). This thermal quenching process is attributed to thermal escape of excitons from the high energy excited states (4ES or 3ES) of InAs QDs into the WL with follows exciton re-localization.

4. Conclusion

We study a thermal activation of localized excitons at GS and multi ES states using the temperature dependent PL spectroscopy in the ensembles of InAs QDs embedded in the symmetric In0.15Ga0.85As/GaAs quantum wells. Thermal quenching of QD PL intensity is analyzed within the model of two-stage thermally activated escape of the excitons from the QDs into the QW/WL and then from the QW/WL into the GaAs barrier. It is shown that thermal quenching of the QD PL intensity for GS and ES PL bands is determined by decreasing of the exciton flow to the QDs caused by thermal escape of excitons from the capping/buffer InGaAs QWs (or WL) into the GaAs layer.

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Figure Caption

Figure 1. Typical PL spectra measured at different temperatures: 80 (1), 100 (2), 150 (3), 200 (4), 250 (5) and 300K (6).

Figure 2. Temperature dependencies of GS and ES integrated PL intensities (a) and peak positions (b).
Figure 3. Energy band diagram for the investigated QD structures at 80K.

Figure 4. GS and ES integrated PL intensity dependences versus temperature presented in a semi log plot of \([W_{\text{max}}/W(T) - 1] - 1/T\).