TITLE: Photoluminescence of InAs/GaAs Quantum Dots in the Presence of Subband 1.06 um Excitation

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Photoluminescence of InAs/GaAs quantum dots in the presence of subband 1.06 μm excitation

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Optical properties of InAs/GaAs self-assembled quantum dots (QDs) have been intensively studied during last several years which is mainly due to the promising applications of QD's structures as lasers with low threshold current [1]. Most of the experiments in this field are aimed on the studies of the electron-hole radiative recombination in QDs. However it is obvious that there exist non-radiative recombination channels which limit a quantum efficiency of QD's photoluminescence (PL) and thus increase a threshold for lasing. Apparently, these nonradiative processes are connected with the defects which are formed during the growth of QDs [1, 2]. In PL experiments these defects play a role of traps for photoexcited electrons and holes and thus decrease the number of carriers which recombine radiatively in QDs. A lifetime of the carrier trapped to the defect may be very long and, in principle, it becomes possible to release a trapped carrier by means of subband ($\hbar\omega_1 < E_g$, E_g — the band gap of InAs QD) optical excitation and thus to increase the PL quantum efficiency. The enhancement of quantum efficiency induced by the subband excitation was demonstrated earlier in epitaxially grown bulk GaAs [3]. In QDs such experiments were not carried out to our knowledge.

Here we present the first studies of the effect of additional subband excitation $\hbar\omega_1 =$ 1.17 eV ($\lambda = 1.06$ μm) on the PL of self-assembled InAs/GaAs QDs. We experimentally observe that PL intensity increases in the present of subband $\hbar\omega_1$ excitation and the relative increase up to 40% is obtained. We study the dependence of the relative increase of PL intensity on the density of $\hbar\omega_1$ excitation and observe the saturation of the relative increase of PL intensity at high power of subband light. The qualitative analysis of the experimental results is based on the model of photoionization of deep traps as a result of subband excitation.

Our studies had been made on sample with 10 layers of InAs QDs grown by Stranski–Krastanow method on (311) surface of semiinsulating GaAs substrate and coated by 100 Å GaAs layer. Experiments are carried out at $T = 77$ K. The cw-Ar ($\hbar\omega_0 = 2.41$ eV) or He-Ne ($\hbar\omega_0 = 1.96$ eV) lasers are used for the interband PL excitation. This optical source creates free carriers in GaAs barriers which are captured to InAs QDs and recombine radiatively. For subband excitation we use cw-YAG:Nd laser ($\hbar\omega_1 = 1.17$ eV). The beams from the both lasers are focused on the input of the 0.2 mm diameter optical fiber and thus transferred to the surface of the sample with InAs/GaAs QDs.

We present the results of stationary experiments when the PL intensity is constant in time and all transient processes after switching on/off the subband excitation are over. Figure 1 shows the measured PL spectra for the studied sample. Solid line is the spectrum measured without subband excitation. Typical inhomogeniously broadened PL spectral line is observed. The width of PL line FWHM = 52 meV indicates the relatively good quality of QD sample. The dashed line in Fig. 1 shows the PL spectrum when the sample

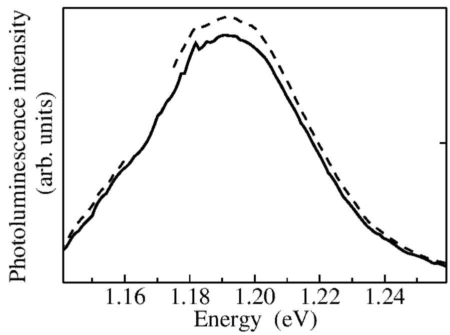

Fig. 1. Luminescence spectra of QD sample in the absence, $P_1 = 0$ (solid line), and in the presence, $P_1 = 250$ W/cm^2, (dashed line), of subband optical $\hbar\omega_1 = 1.17$ eV excitation. The density of interband $\hbar\omega_0 = 1.96$ eV excitation $P_0 = 0.17$ W/cm^2.

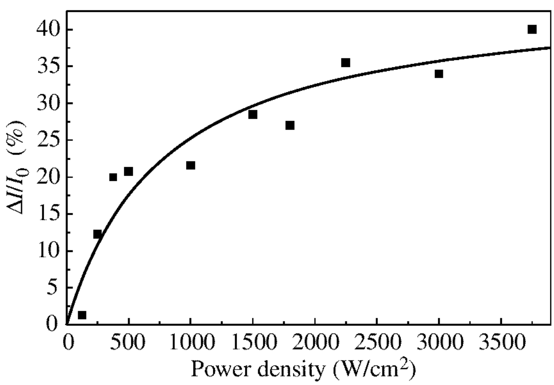

Fig. 2. The dependence of the relative increase of PL intensity $\Delta I/I_0$ on the density of subband $\hbar\omega_1 = 1.17$ eV excitation for $P_0 = 0.2$ W/cm^2, $\hbar\omega_0 = 1.96$ eV. Solid line shows calculated dependence.

is excited additionally by subband light (density on the sample $P_1 = 250$ W/cm^2). The relative increase $\Delta I/I_0 \sim 10\%$, of PL intensity ($\Delta I = I - I_0$) is observed. The subband excitation does not change the shape of PL line and thus the relative increase $\Delta I/I_0$ does not depend on the detected wavelength, $\hbar\omega_d$, of PL. We observe the relative increase of PL present for both interband excitations $\hbar\omega_0 = 2.41$ eV (Ar-laser) and $\hbar\omega_0 = 1.96$ eV (He-Ne laser). No PL is detected for $P_0 = 0$ at any value of P_1.

The dependence of relative increase $\Delta I/I_0$ on the subband excitation density P_1 for low interband excitation density, $P_1 = 0.2$ W/cm^2 is shown in Fig. 2. It is seen that this dependence is sublinear and $\Delta I/I_0$ increases rapidly only for low $P_1 < 500$ W/cm^2. For higher $P_1 > 500$ W/cm^2 $\Delta I/I_0$ shows a tendency to a saturation at the value of $\Delta I^{max}/I_0 \approx 40\%$. It has been noted that a big relative increase $\Delta I/I_0$ is observed only for low densities of interband excitation. Really we observed that $\Delta I/I_0$ decreases from 40% up to 4% when P_0 increases from 0.045 W/cm^2 to 1 W/cm^2.

The main idea of the explanation of the observed PL enhancement effect is similar to the case of bulk GaAs [3] and is based on the photoionisation effect of deep traps which capture the photoexcited carriers. The details of capture and recombination processes on these deep traps are not understood. Thus we limit our discussion by a simple model where only one type of carriers (electrons) are captured to one type of the deep traps. We assume that the capture of an electron to a deep trap takes place from a QD and a subband excitation releases a trapped carrier to the GaAs conduction band. Then the released carrier may be again captured to a QD and thus take part in the radiative recombination. Hence the PL intensity increases. The carriers are excited in the GaAs barriers with the generation rate $g \propto P_0$. Electrons and holes may be captured to QDs or to other defects and surface states. We consider QD structures with high PL quantum efficiency and thus assume that carriers from GaAs barriers are mostly captured to the wetting layer and then, from the wetting layer, they are effectively captured to QDs. In our model an electron may tunnel from a QD to a trap and the rate of this process is the main parameter which limits the quantum efficiency.

The proposed simple model gives results which are in a good qualitative agreement with the experimental observation which is demonstrated in Fig. 2. The solid curve shows the calculated dependence $\Delta I/I_0$ on P_1 using this model. Qualitatively the saturation at high P_1 means that all trapped electrons are released and thus recombine radiatively in QD before the nonradiative recombination on a trap takes place. In this case the quantum efficiency of the PL becomes unity. Obviously, this will not happen if the capture processes to other defects or surface states are present. The analysis show that qualitatively the enhancement of PL quantum efficiency and the saturation at high P_1 still takes place but the value of $\Delta I/I_0$ becomes smaller with the increase role of surface and defects non-radiative recombination.

We, however, do not exclude other models which qualitatively may give the PL quantum efficiency enhancement. Photoionisation of QDs in the presence of subband excitation may play a certain role in high quality QD structures and low P_0. In this case the subband induced release of an electron from a QD will increase the chance of meeting a hole in another QD. The subband excitation, in principle, may also change the surface and local electric fields which may result in the changes of the defects and surface capture rates.

In summary we experimentally observe the increase of the PL intensity in InAs/GaAs self-assembled QDs induced by subband 1.06 μm optical excitation. For low interband excitation density the relative increase reaches the value of 40%. The relative increase of PL intensity saturates at high density of subband excitation. We would like to point that the present observation may be useful in the attempts to decrease the threshold current density in QD lasers.

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References

[1] N. N. Ledentsov, V. M. Ustinov, V. A. Shchukin., P. S. Kop'ev, Zh. I. Alferov and D. Bimberg, *Semiconductors* **32**, 343 (1998).

[2] M. M. Sobolev, A. R. Kovsh, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, M. V. Maksimov and N. N. Ledentsov, *Semiconductors* **31**, 1074 (1997).

[3] A. V. Akimov and V. G. Shofman, *J. Luminescence* **53**, 335 (1992).