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Carrier dynamics in strain-induced InGaAsP/InP quantum dots

H. Koskenvaara*, J. Riikonen, J. Sormunen, M. Sopanen, H. Lipsanen

Optoelectronics Laboratory, Micronova, Helsinki University of Technology, P.O. Box 3500, FIN-02015 HUT, Finland

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Abstract

Carrier dynamics of strain-induced InGaAsP/InP quantum dots (QDs) is investigated. In this structure, self-assembled InAs islands on the surface act as stressors and create a lateral confinement potential in the near surface InGaAsP/InP quantum well. Photoluminescence (PL) measurements reveal that decreasing the distance from the QD to the surface significantly diminishes the QD–PL intensity, presumably due to surface states of the InAs islands. Moreover, time-resolved measurements show a faster decay of the QD–PL with decreasing distance. To analyze the carrier dynamics, rate equation model is applied and surface state-related transitions are taken into account. The model is found to agree with measurements, and thus provides a possible explanation for the observed temporal behavior of the carriers.

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Keywords: Strain induced; Quantum dots; Photoluminescence; MOVPE

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1. Introduction

Coherent Stranski–Krastanow growth is known to be applicable in the fabrication of semiconductor quantum structures. One way to utilize self-assembled islands in the fabrication of quantum dots (QDs) is to use the islands as stressors [1]. The tensile strain underneath the islands locally reduces the band gap of a near-surface quantum well (QW). The resulting lateral confinement potential is nearly parabolic for both electrons and holes, and the vertical confinement is achieved by the interfaces of the QW. The important advantage of the strain-induced quantum dot (SIQD) approach is the possibility to optically measure and straightforwardly model the strain effects caused by the self-assembled islands. What is more, the SIQDs provide a viable means to study the carrier dynamics in nearly perfect zero-dimensional systems as well as the interaction of the QW and the islands on the surface. In the last decade, carrier dynamics of GaInAs/GaAs SIQDSs formed by InP stressors have been intensively studied. However, InP-based structures are needed for the operation at the 1.55 μm telecommunication wavelengths. Only a few works on dynamics of GaInAs/InP near surface QWs have been published [2,3].

In this paper, InGaAsP/InP SIQDs induced by InAs stressor islands are studied. The effects of varying the distance between the QDs and the surface were investigated by continuous wave photoluminescence (PL) and time-resolved photoluminescence (TRPL). The rate equation model was used to calculate the carrier dynamics in the SIQD structure.

2. Experimental

The samples were fabricated by metal organic vapor-phase epitaxy (MOVPE) in a horizontal quartz glass reactor under atmospheric pressure. Further details of the growth procedure are described elsewhere [4,5]. According to atomic force microscopy observations, the areal density of the QDs was approximately $10^9\,\mathrm{cm}^{-2}$.

The PL measurements were conducted at 10 K, utilizing a diode pumped frequency doubled Nd:YVO$_4$ laser ($\lambda = 532\,\mathrm{nm}$) for excitation. A liquid N$_2$ cooled germanium detector and standard lock-in techniques were used to record the PL spectra. For the time-resolved measurements,

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*Corresponding author. Tel.: +358 9 451 5313; fax: +358 9 451 3218.
E-mail address: hannu.koskenvaara@hut.fi (H. Koskenvaara).

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the samples were excited with 150 fs pulses from a mode locked Ti:sapphire laser ($\lambda = 800$ nm) and the luminescence was detected with a cooled microchannel plate photomultiplier and time correlated single photon-counting electronics. The approximate temporal resolution of the system was 30 ps.

3. Results and discussion

The structure of the SIQD samples and the lateral modulation of the QW band edge along with the discrete energy levels of the QD are shown schematically in Fig. 1(a) and (b). The 10-nm $In_{0.77}Ga_{0.23}As_{0.59}P_{0.41}$ QW is slightly compressively strained. Fig. 1(c) shows PL spectra from the SIQD sample with a 10 nm thick cap layer, measured with different excitation intensities. At low excitation intensity, peaks from the QW and the QD ground state (QD0) and a weak peak from first excited state (QD1) can be seen. When excitation intensity is increased, luminescence from the higher QD states is clearly observed.

To study the effects of the InAs islands and the wetting layer on the carrier dynamics, the thickness of the InP capping layer was varied between 4 and 13 nm. Fig. 2 shows that the PL intensity of the QD states decreases when the cap thickness is decreased. It is proposed that this is due to capture of carriers from the QD to the surface. The tensile strain induced by the stressor reduces also the vertical barrier between the QDs and the surface, as shown by Wang et al. for GaAs/AlGaAs SIQDs [6]. The effect is qualitatively similar for InGaAsP/InP SIQD as well which might contribute to the increase in surface-related recombination. The depleted carriers recombine non-radiatively via surface states of the InAs wetting layer or the InAs islands. Alternatively, carriers captured into the QD states of the InAs island can recombine radiatively at other wavelengths [4]. In the following, all these processes are acknowledged as surface processes. In Fig. 2, the intensity ratio of the QD peak to the QW peak decreases by nearly three orders of magnitude when the cap thickness is decreased from 13 to 4 nm.

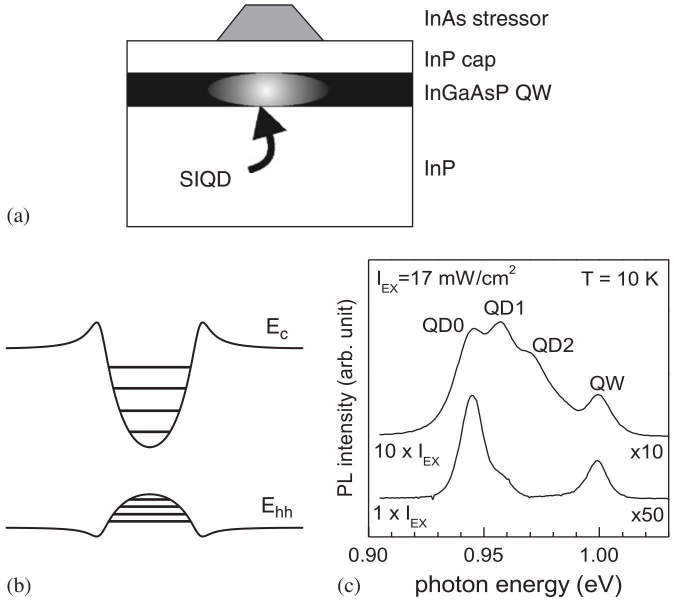

Fig. 1. (a) Structure of the SIQD sample. (b) The schematic deformation of the conduction band and the heavy hole band in the InGaAsP QW. Discrete energy levels of the induced QD are also shown. (c) PL spectra from SIQD sample measured with different excitation intensities. Positions of the QW and three quantum dot (QD0–QD2) peaks are marked in the picture.

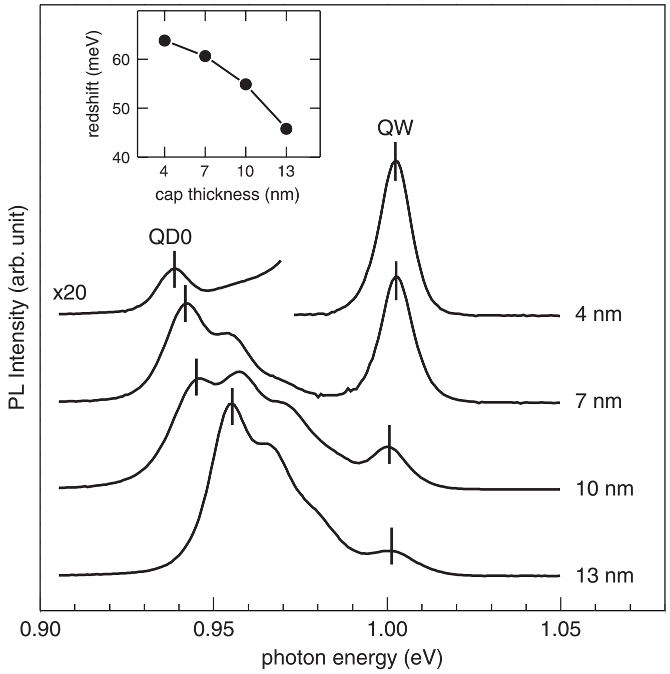

Fig. 2. PL spectra from the SIQD samples with cap thicknesses from 4 to 13 nm. Redshift of the QD0 peak from the QW peak as a function of cap thickness is shown in the inset.

Thus, the carrier capture from the QD states to the surface seems to be a much more intense effect than the capture from the QW.

The inset in Fig. 2 shows that the QD0 redshift, i.e., the energy difference between the QW and the QD0 peaks, increases from 46 to 64 meV when the cap thickness is decreased from 13 to 4 nm. This is due to the fact that the strain, which induces the SIQD potential, decreases with the distance from the surface.

It is well known that the carrier dynamics in QDs can be modeled with rate equations. Detailed representation of typical rate-equation model can be found in Ref. [7]. It has been reported that the results from the above model are in good agreement with the experimental data measured from the InP stressor induced QDs in InGaAs/GaAs structures [7]. However, we found that the model, as such, does not explain the carrier dynamics in our samples. To study the effect of the surface processes, a new equation to represent the population of electrons in the surface states was introduced. Transition rate terms from the QW and different QD states to the surface states were also added along with a surface recombination term (including the recombination in the InAs islands).

It was assumed that the capture rates from all the QD states (and the QW) to the surface states are proportional to the electron density of the QD states (and the QW) and to the density of empty surface states. The probability of the transition from the different QD states to the surface states was assumed to be equal. The surface recombination rate was set to be linearly proportional to the electron density in the surface states, as the first approximation.

Also new equations for transitions from the QW to each QD level were added to the model. The probability of electron capture from the QW to each QD level is assumed to be equal. All the above rates are also proportional to the electron density in the initial state and the density of available states in the final state. Actually, these assumptions are not valid at high QW electron density, immediately after the excitation pulse. However, the transitions from QW are the faster, the higher the carrier density is [8]. That produces the effect contrary to observed increase in TRPL decay rates.

The effect of the surface processes in the rate equation model is shown in Fig. 3. The dashed curves are calculated electron populations (proportional to PL intensity) using the parameters of a typical SIQD sample without the surface capture. The continuous curves are calculated with the same SIQD parameters, but taking into account the described surface processes. The surface processes are saturated after the excitation pulse. At lower QW carrier densities the transitions from the QD states to the surface become more prominent. This leads to a decreasing negative slope of the transient curve with time.

The adjusted rate equation model was applied to analyze the temporal behavior of the PL intensity of the two lowest QD levels and the QW peak. TRPL transients of the SIQD samples with a cap layer thickness of 7, 10 and 13 nm are shown in Fig. 4 (a), (c) and (e), respectively. The corresponding rate equation populations are shown in Fig 4 (b), (d) and (f). TRPL of the sample with a 4 nm thick cap layer could not be resolved due to low intensity. It can be observed that the thinner the cap layer is, the faster the PL intensity from QD states and the QW decays. This trend can be explained by the increase of electron recombination via surface processes with the decrease of the cap thickness.

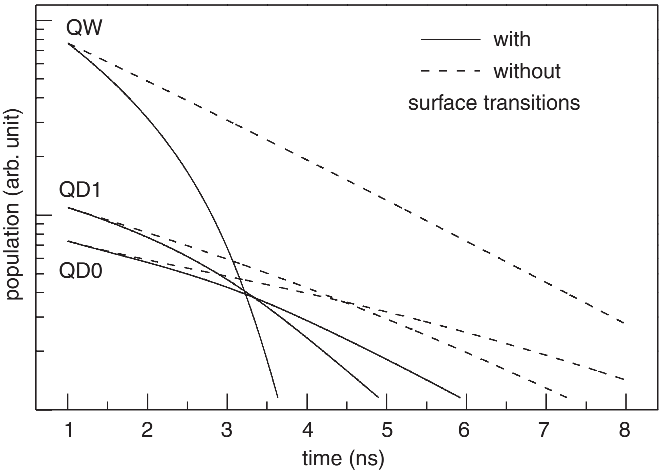

Fig. 3. QD state and QW populations of a typical sample as a function of time calculated by the rate equation model with and without surface transitions.

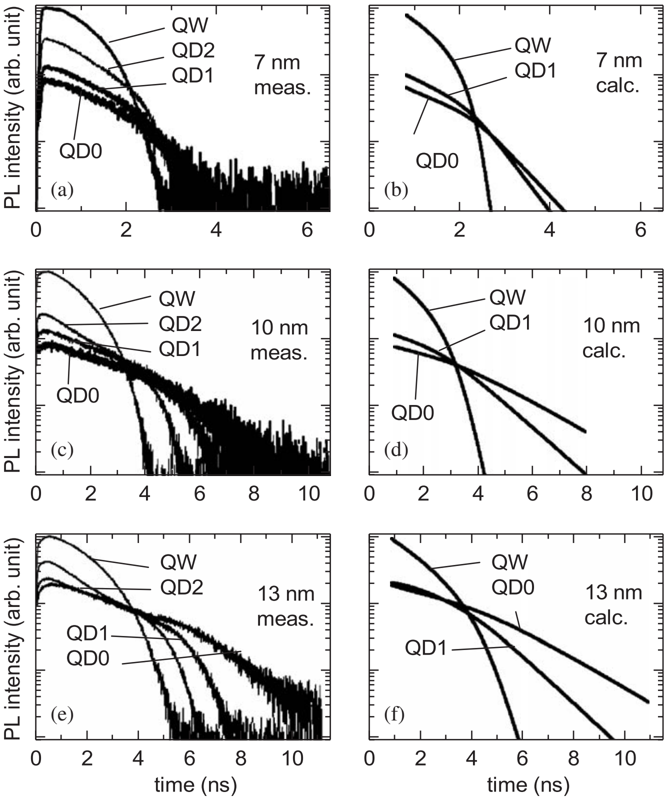

Fig. 4. TRPL results from the samples with a cap layer thickness of (a) 7 nm, (c) 10 nm, and (e) 13 nm. PL intensity curves from the QW, QD0, QD1, and QD2 states are shown. The corresponding rate equation calculations to TRPL results are shown in (b), (d), and (f).

It can be concluded from Fig. 4 that the applied rate equation model is in good agreement with the measurements. The probability of the capture from the QD states to the surface states increases by a factor of 14 when the cap layer thickness decreases from 13 to 7 nm. In addition, the probability of the capture from the QW to the surface states increases by a factor of about five. These results suggest that the capture from the QD levels is more pronounced than that from the QW. The position of the QDs under the InAs islands suggest that the InAs island itself and the surface states associated with it capture electrons more effectively than the InAs wetting layer.

4. Summary

In summary, carrier dynamics in strain-induced InGaAsP/InP QDs were studied. Decreasing the cap layer thickness, i.e., the distance from the QD to the InAs stressor on the surface resulted in the decrease of the PL intensity and the enhancement of the decay of the QD–PL intensity. A rate equation model including the capture of electrons to the surface was applied. The model was shown to agree qualitatively with the time resolved PL measurements.

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