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Xu, Zhangcheng; Zhang, Yating; Hvam, Jørn Marcher; Xu, Jingjun; Chen, Xiaoshuang; Lu, Wei

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Carrier dynamics in submonolayer InGaAs/GaAs quantum dots

Zhangcheng Xu and Yating Zhang
Key Laboratory of Advanced Technique and Fabrication for Weak-Light Nonlinear Photonics Materials (Ministry of Education), TEDA College, Nankai University, Tianjin 300457, People’s Republic of China and National Laboratory for Infrared Physics, Chinese Academy of Sciences, Yutian Road No. 500, Shanghai 200083, People’s Republic of China

Jorn M. Hvam
Department of Communications, Optics and Materials, and Nano.DTU, Technical University of Denmark, DK-2800 Lyngby, Denmark

Jingjun Xu
Key Laboratory of Advanced Technique and Fabrication for Weak-Light Nonlinear Photonics Materials (Ministry of Education), Nankai University, Tianjin 300457, People’s Republic of China

Xiaooshuang Chen and Wei Lu
National Laboratory for Infrared Physics, Chinese Academy of Sciences, Yutian Road No. 500, Shanghai 200083, People’s Republic of China

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Carrier dynamics of submonolayer InGaAs/GaAs quantum dots (QDs) were studied by microphotoluminescence (MPL), selectively excited photoluminescence (SEPL), and time-resolved photoluminescence (TRPL). MPL and SEPL show the coexistence of localized and delocalized states, and different local phonon modes. TRPL reveals shorter recombination lifetimes and longer capture times for the QDs with higher emission energy. This suggests that the smallest SML QDs are formed by perfectly vertically correlated two-dimensional InAs islands, having the highest In content and the lowest emission energy, while a slight deviation from the perfectly vertical correlation produces larger QDs with lower In content and higher emission energy. © 2006 American Institute of Physics. [DOI: 10.1063/1.2219394]
QDs is about $5 \times 10^{11} \text{cm}^{-2}$ as reported in Ref. 6, about 15 000 SML QDs are probed at the same time. This explains the high density of sharp lines throughout the whole contour of the QD PL emission. At high excitation power density, a peak at 1.326 eV dominates the whole spectrum, and the peak energies for the three excitation points are identical, as shown in Fig. 1(b). This indicates that the peak at 1.326 eV originates from the delocalized states in the studied structure, corresponding to the QW states.7

In SEPL measurement with the excitation energy $E_{\text{ex}}$ tuned near to the edge of the density of states (DOS) in the QW ($E_{\text{ex}} = 1.336 \text{eV}$), a few sharp resonant lines and a resonant PL band appear within the broad PL band, near to one longitudinal optical [(LO) 31–36 meV] and 2LO (66 meV) phonon energies below the excitation energy, respectively, as shown in Fig. 2. To confirm that these sharp lines are not attributed to resonant Raman scattering, the polarization directions of the incident laser beam and the detected PL signal were set to be along the [110] and the [1, 1, 0] directions, respectively, in the backscattering geometry, as in Ref. 13. A Raman signal cannot be detected in this geometry, according to the selection rules.14 When the excitation energy is less than one GaAs LO-phonon energy above the lateral QW ground state in the SML-grown QDQW structure, the probability for the photon-excited carriers (excitons) to relax within the QW states by emission of only longitudinal acoustic (LA) phonons is less than the carrier (exciton) capture probability from QW to QDs by emission of LO phonons. Dots which can be accessed by emission of LO phonons are populated more efficiently, since their delta-function-like DOS can be accessed directly from the excited energy level in the QW by LO phonon emission.

The complex structure in the 1LO resonant peaks consists of several optical phonon modes whose energies are 36.7, 34.5, 32.9, and 31.3 meV, respectively, as shown in the inset of Fig. 2. We assign these lines to the LO phonon modes in the GaAs barrier, the GaAs/InAs interface, the InGaAs lateral QW, and the InGaAs QDs, respectively. The 2LO resonance occurs at the energy of 66 meV below the excitation energy, nearly two times the LO phonon energies of QW. The coexistence of several optical phonon modes indicates the complex structure of SML QDs.

The electron-hole (e-h) pairs (or excitons) generated in the GaAs barrier are either captured directly into the QW where they relax and are finally captured by the QDs, or they are directly captured by the QDs or recombine in the QW. Then the captured carriers will recombine inside the QDs.

Figure 3 shows the PL transient of QD states in SML InGaAs/GaAs QD structures, at an excitation density of 101 W/cm² (corresponding to $10^{17}$ electron-hole pairs/cm³ pulse). On the long timescale [Fig. 3(a)], the PL decay can be well fitted by a monoeponential function, and the decay time $\tau_d$ can be evaluated. On the short timescale [Fig. 3(b)], the PL transients can be fitted by the expression

$$I(t) \approx [\exp(-t/\tau_r) - \exp(-t/\tau_d)]/(\tau_r - \tau_d),$$

where $\tau_r$ is the rise time of PL transients, which can provide information on carrier capture into the QDs.

Fig. 4 shows the values of $\tau_d$ and $\tau_r$ plotted against the QD emission energy. With increasing QD transition energy, $\tau_d$ decreases from 840 to 500 ps, while $\tau_r$ increases from 35 to 60 ps.

For SK QDs, QDs with higher emission energy are believed to be smaller, and stronger electron-hole overlap occurs inside the QDs, resulting in longer lifetime.16 Recently, a reduction of the radiative lifetime for smaller SK QDs with higher emission energy has been observed, which was explained by the reduced electron-hole overlap integral due to the larger piezoelectric effect in larger QDs.17 However, in
In summary, we have explored the carrier dynamics of an InGaAs/GaAs QDQW structure formed by submonolayer deposition. The coexistence of the localized states of QDs and the delocalized states of QWs are revealed clearly in the MPL spectra. Different local phonon energies of the QDQW structure are obtained when the excitation energy is tuned close to the edge of DOS of QWs, indicating the complex structure of SML QDs. The recombination lifetime of SML QDs decreases with the increase of QD emission energy. This can be explained by assuming that SML QDs with higher emission energy have lower average In content and larger volume. The Auger carrier capture time for SML QDs increases with the increase of QD volume, which coincides with theoretical predictions.\(^{19}\)

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