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Carrier dynamics in p-type InGaAs/GaAs quantum dots

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Abstract In this study we investigate the carrier relaxation dynamics in p-type doped InGaAs/GaAs quantum dots using time-integrated and time-resolved photoluminescence. The experiment shows that while a strong phonon bottleneck is observed in the undoped samples, with a 680 ps rise time of the photoluminescence intensity, the intra-dot relaxation time (31 ps) of the p-type doped samples is reduced significantly due to scattering of photo-excited electrons with the doping-induced holes.

1 Introduction

InGaAs quantum dots (QDs) have been a focus of research due to their potential application in high-performance lasers and optoelectronics. Three-dimensional confinement of electrons and holes in QDs leads to atomic-like electronic spectra consisting of well-separated energy states. The discrete electronic states cause a significant reduction in the interaction efficiency between electrons and phonons, which may result in significantly slower intraband relaxation relative to higher dimension materials [1, 2]. The carrier relaxation and capture into quantum dots play a central role in determining the performance of QD lasers and have been extensively studied in recent years. Various relaxation mechanisms have been proposed, such as Auger processes [3], electron–hole interactions [4] and multi-phonon processes [5]. P-type doping of quantum dots can greatly improve the performance of QD lasers because of effective compensation of the closely spaced hole states [6]. Gundogdu et al. [4] found an extremely fast carrier relaxation from the barrier to the ground states in doped InAs QDs, especially in the p-type samples, which was attributed to efficient electron-hole scattering. Siegert et al. [7] studied carrier dynamics of modulation doped InAs QDs with different excitation conditions to determine the contribution of different mechanisms of carrier relaxation. However, the details of the relaxation mechanism depend sensitively on the features of the QDs, such as the composition, dot size, doping density, temperature, excitation density and wavelengths etc. and it is difficult to identify the precise relaxation mechanisms from experiments [5, 8–11].

2 Experimental

Three types of InGaAs QD samples, undoped, direct doped and modulation doped p-type samples, grown on a semi-insulating (100) GaAs substrate by low-pressure metalorganic chemical vapour deposition (MOCVD) have been used for this study. For the undoped sample, a 200 nm GaAs buffer layer was grown at 650 °C on a semi-insulating GaAs substrate, followed by the $In_{0.5}Ga_{0.5}As$ dots which were grown and capped with 11 nm GaAs at 550 °C. After a 1 min growth interruption, the sample was

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capped with 200 nm of GaAs as the temperature was ramped to 650 °C. The direct doped p-type sample was grown under the same conditions as the undoped sample except the QDs were grown in the presence of $\mathrm{CC1_4}$. For the modulation doped samples, after growth of the undoped $\mathrm{In_{0.5}Ga_{0.5}As}$ dots, a 11 nm thick GaAs capping layer and after a 1 min interruption, a 10 nm thick GaAs layer was grown as the temperature was ramped to 650 °C. A 20 nm thick doped GaAs layer was grown at 650 °C. Finally, a 170 nm undoped GaAs capping layer was grown at 650 °C.

Time-integrated photoluminescence (PL) was performed using 532 nm laser excitation and a cooled InGaAs photodetector at the output slit of a 0.5 m monochromator. The time-resolved photoluminescence (TRPL) experiment was performed with a PL up-conversion technique [12]. A laser pulse with pulse duration of 80 fs, pulse energy of 1–10 μJ and 1 kHz repetition rate is used for excitation. The luminescence from the sample was collected in a backward geometry and mixed in a nonlinear β-barium borate (BBO) crystal with a variable delayed gating pulse (800 nm, 80 fs, 20 μJ) to generate a sum-frequency signal. A time resolution of 150 fs and spectral resolution of 2 nm can be obtained using this setup. Wavelengths of 800 nm for excitation into the GaAs barrier (GaAs bandgap at 300 K is about 1.43 eV) and 925 nm for direct excitation of the QD layer (the second excited state of the QDs) have been used. The excitation intensity is about 15 μJ/cm^2 or 50 μJ/cm^2 for 800 nm and about 5 μJ/cm^2 or 15 μJ/cm^2 for 925 nm.

3 Results and discussion

Figure 1 shows the time integrated PL of the undoped (a), direct doped (b) and modulation doped (c) p-type samples with a low excitation intensity of 2 mW at 77 K. A blue shift of 9 meV for the direct doped sample (b) and 29 meV for the modulation doped sample (c) relative to the spectrum of the undoped sample is observed, which suggests substantial carrier accumulation inside the QDs [11] in the doped samples. The blue shift of the modulation doped samples is larger than that of the direct doped sample, suggesting an effective hole collection with modulation doping.

In order to classify the carrier transport in the barriers and the carrier capture into the QDs the photo-excited carriers are created in the GaAs barrier using a laser wavelength at 800 nm, and the time evolution of the PL intensity from the QD ground state is monitored as shown in Fig. 2. Similar rise times (30–25 ps) are observed for undoped and doped samples, indicating that the doping does not substantialy modify the carrier transport and capture from the barriers. Electron transport in the barriers is very fast (<2 ps for a 200 nm capping layer thickness) and has minimal influence on the overall process of carrier transfer into the QDs in the C-doped p-type samples. The

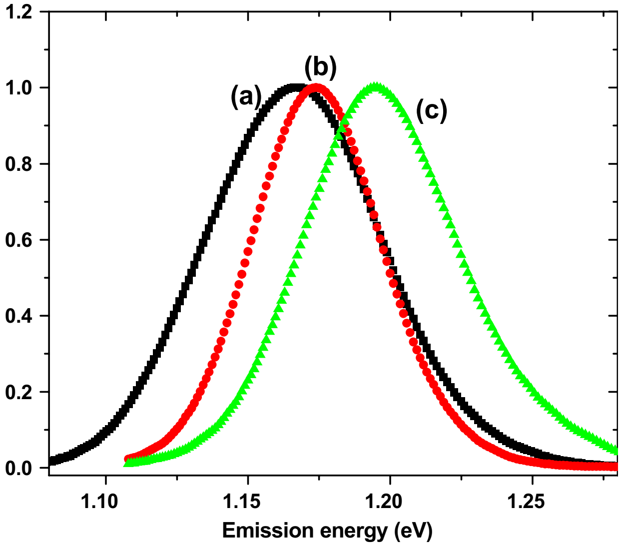

Fig. 1 Time integrated photoluminescence of an undoped (**a**), a direct p-type doped (**b**) and a modulation p-type doped (**c**) InGaAs/GaAs QDs sample at 77 K

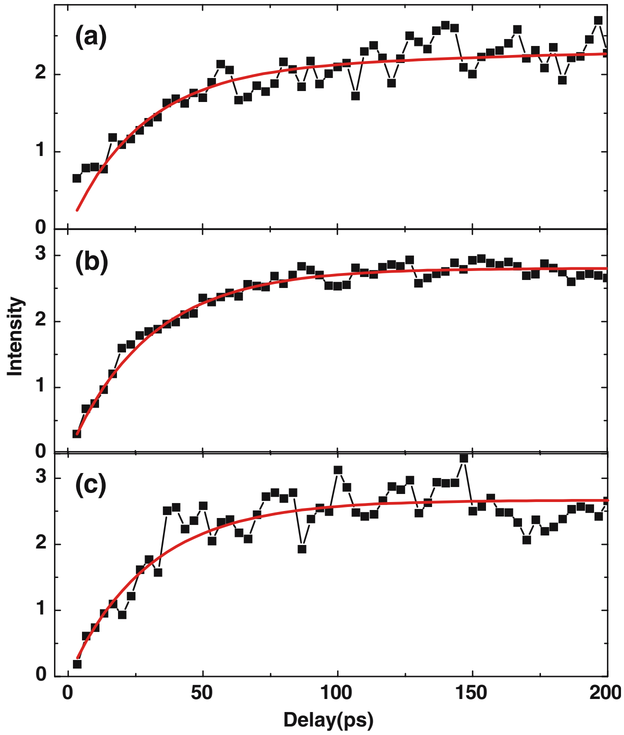

Fig. 2 Time evolution of photoluminescence intensity of an undoped (**a**), a direct p-type doped (**b**) and a modulation p-type doped (**c**) InGaAs/GaAs QDs samples is measured using a laser pulse at 800 nm for excitation. The photo-excited carriers are created in the GaAs barrier

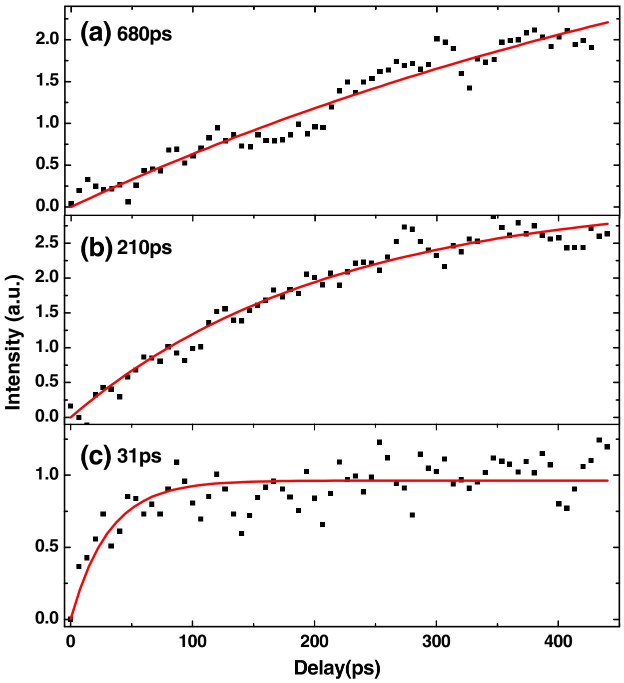

Fig. 3 Time evolution of photoluminescence intensity of an undoped (**a**), a direct p-type doped (**b**) and a modulation p-type doped (**c**) InGaAs/GaAs QDs samples is measured using a laser pulse at 925 nm for excitation

rise time in the evolution of the PL intensity therefore reflects the carrier capture into the QDs. Several mechanisms contribute to carrier capture into QDs such as emission of a resonant optical phonon (LO), multiple LO phonon emission, carrier–carrier scattering or phonon-assisted capture. The PL rise time for the QD ground state shows a weak dependence on excitation intensity and doping density. Such behaviour is characteristic of a phonon-assisted capture rather than a carrier–carrier scattering contribution.

The time evolution of the PL intensity of the ground state of the QDs is shown in Fig. 3 for the undoped (a), direct p-doped sample (b) and modulation p-doped (c) samples following excitation at 925 nm. The signal intensity can be fitted with a single exponential function $A[1 - \exp(-t/\tau_{rise})]$ where A is a fitting constant and τ_{rise} is the rise time. The fit yields rise times of 680 ps for the undoped (a), 210 ps for the direct p-doped (b), and 31 ps for the modulation p-doped samples. For direct excitation, the laser excites electrons into the excited state of the QDs; thus the relaxation from the excited states into the ground state of the QD is the main contribution. The long rise time observed in the undoped sample suggests that there is a strong phonon-bottleneck slowing the intra-dot relaxation. The fast relaxation time in the doped samples, which is almost independent of excitation intensity, suggests that the carriers built in by doping play an important role in the dominant relaxation mechanism. The carrier–carrier and carrier-LO phonon scattering can be attributed to fast relaxation in the doped samples. Ultrafast hole relaxation has been observed in undoped samples because of the proximity of the hole levels and the availability of various energy-broadened phonons [5]. In the case of ultrafast phonon-assisted relaxation the hole will be filled after the capture process in the undoped sample and the sample would resemble the p-doped sample. The experiment shows a remarkable difference in the rise time of the PL intensity for the doped and undoped samples which indicates a slow relaxation of the holes in the undoped sample. The scattering of holes can be less efficient than the scattering of electrons because of the larger change of the hole wave vector required for energy conservation. Electron and hole scattering can be contribute to fast relaxation of the electrons in the p-doped sample where the slow ''recapture'' of the holes can not contribute to the rise time of the PL because of the high built-in hole density. We conclude that in the p-doped sample the intra-dot carrier relaxation proceeds by scattering with the doping induced holes.

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