Enhanced nonradiative Auger recombination in *p*-type modulation doped InAs/GaAs quantum dots

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The photoluminescence efficiency and carrier recombination time of *p*-type modulation doped InAs/GaAs quantum dots (QDs) have been measured as a function of doping density. At 10 K the carrier lifetime decreases from 1200 to 350 ps over the doping range of 0 and 30 acceptors/QD. This behavior is attributed to an enhancement of the Auger-type recombination due to the presence of extrinsic holes in the QDs. The hole density dependence of the Auger process is found to be weaker than in bulk semiconductors and quantum wells (QWs). © *2008 American Institute of Physics*. [DOI: 10.1063/1.2975961]

There is considerable interest in the application of *p*-type modulation doping to semiconductor quantum dots (QDs), mainly with the aim of obtaining the predicted temperature independent operation of a QD laser.[1,2] Reports of carrier processes in these systems[3–6] include studies of carrier relaxation mechanisms[7–10] and carrier recombination dynamics.[7] In the latter a reduced photoluminescence (PL) decay time for a highly doped structure was attributed to increased nonradiative recombination at centers introduced by the doping.[7] However in this work only one doping level was studied at a level significantly above that typically used in laser devices.

In this letter, we report a study of the low temperature carrier lifetime in *p*-type modulation doped 1.3 μm emitting InAs/GaAs QDs, with doping densities varying from 0 to 30 acceptors/QD. Both the carrier lifetime and the PL intensity decrease with increasing doping. These trends are explained by increasing Auger recombination, although this increase is weaker than in higher dimensional systems.

Self-assembled InAs QDs were grown by molecular beam epitaxy on GaAs substrates. The QDs were grown within 8 nm $In_{0.15}Ga_{0.85}As$–GaAs quantum wells (QWs) to give a dot-in-a-well (DWELL) structure.[11,12] Five samples with undoped QDs (QDU) and 6 (QDH6), 12 (QDH12), 18 (QDH18), and 30 (QDH30) acceptors/QD were studied. QDU and QDH30 have six QD layers; the other samples have seven layers. The thicknesses of the GaAs spacer layer between the DWELLs were 45 nm for QDU and QDH30 and 50 nm for the other structures. Within the spacer layers 6-nm-thick Be doped regions were placed 9 nm below each DWELL.

The 10 K PL emission wavelengths are 1211, 1190, 1193, 1191, and 1209 nm for samples QDU, QDH6, QDH12, QDH18, and QDH30, respectively. These very similar wavelengths indicate that the physical structure of the QDs is not significantly affected by the doping. The room temperature emission of all samples is close to 1.3 μm, with a strong integrated PL intensity, decreasing by no more than 75% compared to the respective low temperature value, confirming a high structural quality.

Time-resolved PL (TR-PL) was performed at 10 K using a mode-locked Ti:sapphire laser with a repetition rate of 76 MHz and a pulse width of ~180 fs. The excitation wavelength was 740 nm, which excites carriers above the GaAs band edge. Transient PL signals were detected for a 10 nm band centered at the peak of the ground state emission by a streak camera. The system resolution was 76 ps.

Figure 1 shows the 10 K PL decay transients for all five samples. The excitation power density was 0.74 W/cm^2, low enough to excite only emission from the ground state transition. The extracted carrier lifetimes are 1240, 710, 460, 410, and 350 ps for QDU, QDH6, QDH12, QDH18, and QDH30, respectively. The decay time hence decreases monotonically with increasing doping level.

Figure 2 plots the doping dependence of the integrated PL intensity relative to that of QDU for different excitation wavelengths. Squares (515 nm), circles (633 nm), and triangles (740 nm) represent excitations above the GaAs band

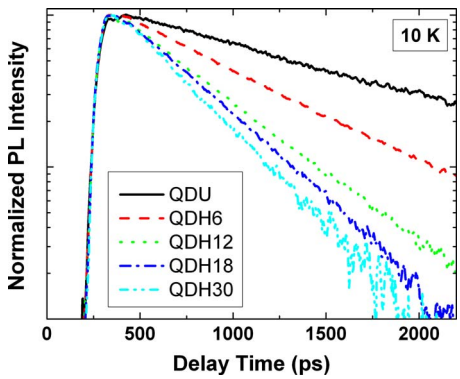

FIG. 1. (Color online) 10 K PL decay transients measured at the peak emission wavelength of each of the five samples.

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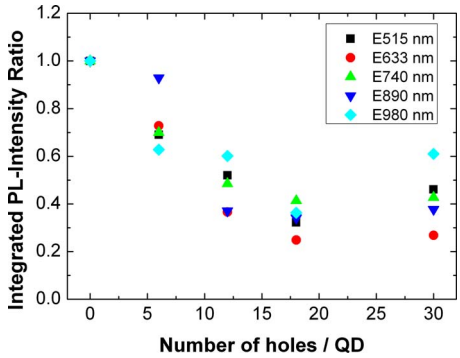

FIG. 2. (Color online) Ratio of the integrated PL intensity of the doped:undoped samples as a function of the number of holes per QD and for various excitation wavelengths at 10 K.

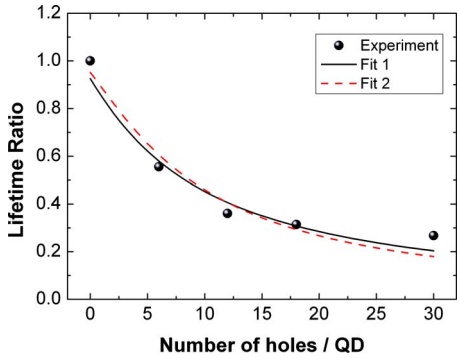

FIG. 3. (Color online) Ratio of the PL lifetimes plotted as a function of doping level. The solid and dashed lines are fits to the experimental data.

gap. Data are also shown for excitation into the wetting layer (inverted triangles) and directly into the QDs (diamonds). Although there is some scatter in the data, most likely due to errors associated with determining absolute PL intensities, a decreasing intensity with increasing doping level is clearly seen. In addition, this decrease is independent of the excitation wavelength, indicating that any nonradiative processes must involve carriers within the QDs and does not occur as carriers migrate to, or are captured into, the dots. Figure 2 suggests a saturation of the intensity falloff for doping levels above ~18 acceptors/QD. This is discussed further below.

We attribute both the reduction in the PL intensity and the decrease in the decay time with increasing doping to enhanced Auger nonradiative recombination resulting from the extrinsic holes. The PL intensity (I_{PL}) is given by

$$I_{\mathrm{PL}} = \frac{N_{\mathrm{eh}}}{\tau_r} = \left(\frac{\tau_{\mathrm{Aug}}}{\tau_r + \tau_{\mathrm{Aug}}}\right) G, \tag{1}$$

where τ_r and τ_{Aug} represent the radiative and Auger recombination times, respectively, G is the optical carrier generation rate, and N_{eh} is the density of electron-hole pairs. For systems with continuous energy states, e.g., bulk and QWs, the Auger recombination rate (R_{Aug}) can be written as

$$R_{\mathrm{Aug}} = \frac{N}{\tau_{\mathrm{Aug}}} = C_n N^2 P + C_p N P^2, \tag{2}$$

allowing an effective Auger rate in a p-doped system to be approximated as $1/\tau_{\mathrm{Aug}} \simeq C_p P^2$, where C_P and P (N) are the Auger coefficient and hole (electron) density, respectively. Because of their discrete energy levels, the dependence of the Auger recombination rate on hole density in QDs is expected to be weaker than for bulk and QWs. Although all holes confined within the QD can be excited to higher states during the Auger process, selection rules allow only holes in the ground state (a maximum of two) to recombine strongly with the photoexcited electron in the conduction band ground state. For very strong $\Delta n = 0$ selection rules only the ground state holes can recombine with the electron and $1/\tau_{\mathrm{Aug}} \simeq C_p P$. Calculations for realistic dot shapes indicate that while some $\Delta n \neq 0$ transitions are allowed, these are much weaker that the $\Delta n = 0$ ones.[13] Hence the dependence of the Auger recombination rate on doping density is expected to be slightly stronger than linear. In the following analysis the Auger recombination rate is set to $1/\tau_{\mathrm{Aug}} \simeq C_p P^n$, with the exponent ($n$) determined from a fitting to the experimental data.

The hole density per QD is divided into contributions from the optically generated carriers, Δp, and the doping, Δp_e, with $P^n = (\Delta p + \Delta p_e)^n$. Here it is assumed that Δp equals 1, a result of the low excitation power used for the lifetime measurements, and Δp_e varies from 0 to 30. The quantum efficiency of the undoped QDs is assumed to be 100%; hence the PL intensity of these dots equals G. When the Auger lifetime is inserted into Eq. (1), this equation can be rewritten as

$$I_{\mathrm{PL}} \simeq \frac{I_{\mathrm{PL}}^{\mathrm{undoped}}}{1 + \tau_r C_p (1 + \Delta p_e)^n}. \tag{3}$$

Equation (3) predicts a decreasing PL intensity (I_{PL}) with increasing doping level. In addition, the PL decay time (τ) will also decrease with increasing Δp_e since this is given by $1/\tau = 1/\tau_r + 1/\tau_{\mathrm{Aug}}$.

Figure 3 shows a fit to the lifetime data using Eq. (3). These data are chosen for analysis rather than the intensity data as they are less susceptible to experimental errors. Solid circles represent the doped:undoped lifetime ratios, with lifetimes determined from the decay transients being accurate to a few picoseconds. The solid line (fit 1) is the fit to all the data points. However, both the lifetime data and the intensity data suggest a saturation for doping levels above ~18 acceptors/QD and this may reflect a limit to the number of holes that can be accommodated by a QD. The above analysis has assumed that the number of holes in each QD to be equal to that provided by the doping. This is a reasonable assumption for low doping levels but will break down at high levels when the electrostatic energy of the QD shifts the confined hole states above the GaAs valence band edge. To account for this possible saturation, a fit has also been performed to just the 0–18 acceptors/QD data. This is shown in Fig. 3 by the dashed line (fit 2). Both fits give similar parameters, indicating that despite uncertainties in the number of holes/QD, relatively reliable parameters can be extracted. Values obtained for the exponent (n) and Auger coefficient (C_p) are 1.1 ± 0.2 and $(6 \pm 4) \times 10^{-5}$ ps^{-1} for fit 1 and 1.3 ± 0.3 and $(4 \pm 3) \times 10^{-5}$ ps^{-1} for fit 2.[14] As expected n is close to 1, consistent with strong selection rules between the discrete QD states. The Auger coefficient can be converted to effective two dimensional or three-dimensional (3D) values by using appropriate QD dimensions, with values of $C_p^{2\mathrm{D}} = (3.8 \pm 2.5) \times 10^{-14}$ cm^4/s and $C_p^{3\mathrm{D}} = (3.4 \pm 2.3) \times 10^{-27}$ cm^6/s obtained for fit 1. Reported values for the Auger coefficient in $In_{0.4}Ga_{0.6}As/GaAs$ QDs are on the order of 10^{-29} cm^6/s.[15] (In this work it appears that the Auger

coefficient was obtained using the total QD laser active region, therefore resulting in a relatively small value.) A value of 10^{-26} cm^6/s has been reported for bulk InAs.[16] The effective 3D QD Auger coefficient depends critically on the QD volume used for the conversion and also the QD density. In addition, the Auger coefficient and radiative recombination rate are expected to depend strongly on the dot parameters.[13]

Defect-related nonradiative recombination could also decrease both the PL life time and efficiency, although from the observation of the wavelength independent relative intensities (Fig. 2) these defects would have to be either in, or very close to, the QDs.[17] Significant defect-related recombination should result in a superlinearity of the PL intensity with excitation power density.[18] However a linear dependence, with an exponent very close to 1, is found for all samples over the excitation power density range of 0.1–100 W/cm^2. Over this range the photogenerated electron-hole density remains below 1 per QD and hence the Auger rate is expected to remain constant. This observed linear dependence therefore indicates that defect-related nonradiative carrier recombination from the ground state of the QDs does not contribute significantly to the reduction in the PL intensity and decay time.

In conclusion, the doping dependence of the low temperature carrier recombination time in *p*-type modulation doped QDs has been investigated. The carrier decay time decreases with increasing doping level. This behavior is attributed to an enhancement of the Auger-type recombination rate by the extrinsic holes. A weaker dependence on hole density is found in comparison to bulk and QWs, a result of strong selection rules for transitions between the discrete QD states.

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