Photoluminescence in delta-doped InGaAs/GaAs single quantum wells

L. V. Dao and M. Gal
School of Physics, University of New South Wales, Sydney, 2052 Australia

G. Li and C. Jagadish
Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, Institute of Advanced Studies, Australian National University, Canberra, 0200 Australia

(Received 6 October 1999; accepted for publication 18 December 1999)

We have studied the time integrated (cw) and time resolved photoluminescence (PL) spectra of Si δ-doped $In_{0.2}Ga_{0.8}As$/GaAs quantum wells (QWs), in which the δ doping layer was either at the center of the quantum well or outside the well, in the barrier region. We found that both the cw and the time resolved PL depended significantly on the position of the doping sheet. When the doping was at the center of the quantum well the luminescence spectrum displayed the characteristic features of the Fermi edge singularity, while in the case of barrier-doped QW, the PL spectra showed well-defined emission lines originating from transitions between subbands in the conduction and valence bands. From low-temperature time resolved PL experiments, we determined the effective hole capture times, the interband relaxation times (for holes), and the radiative decay times for both types of δ doping. We found that the interband relaxation time in the center-doped QWs is nearly two orders of magnitude shorter ($\tau = 3$ ps) than in samples doped in the barrier ($\tau = 200$ ps).
© *2000 American Institute of Physics.* [S0021-8979(00)01207-X]

I. INTRODUCTION

Delta doping (δ doping) is known to achieve effective and efficient doping of semiconductor quantum wells (QWs).[1–3] The majority of studies so far concentrated on the GaAs/AlGaAs QW system with the δ-doped layer placed at the center of the QW.[4–6] While this system can achieve high carrier densities in the well and is often used in device structures, it produces limited electron mobilities because the charge carriers and the impurities share the same region of space. A more efficient approach is to place the δ-doped layer outside the well, in the barrier region, so as to separate the mobile charge carriers from the ionized impurities and thus achieve higher mobilities. While the affect of the position of the δ-doped layer on the transport properties of QWs has been carefully studied and is well documented, its affect on the optical properties of the QW is less well known. We expect, for example, the line shape, energy, and intensity of radiative transitions to depend on the position of the doping layer since the internal electric field created by the doping is a strong function of the position of the doping layer. Similarly, in these systems at low temperatures, ionized impurity scattering is the dominant scattering mechanism, hence we anticipate the relaxation rates in the quantum wells to depend decisively on the position of the doping layer. Optical studies can also be used to help understand the nature of the electronic states involved, as well as provide a direct noncontact tool to study the carrier dynamics into and out of the quantum wells. For these reasons, we undertook to study the photoluminescence properties of center and barrier δ-doped InGaAs/GaAs QWs and measure its temporal evolution. The time resolved PL measurements were spectrally resolved so the various excited state emissions could separately be studied.

II. EXPERIMENT

The samples used in this study were grown by metalorganic chemical vapor phase epitaxy (MOVPE) and consisted of a single $In_{0.2}Ga_{0.8}As$ quantum well between GaAs barriers, grown on semi-insulating GaAs substrate. The mole fractions of the samples were determined from growth calibration data measured by x-ray diffraction and Rutherford backscattering. The position of the Si δ-doped layers was varied between samples: some samples were doped (at various positions) in the well, while others were doped outside of the well, on either side of the quantum well, at 10 nm from the side of the well. In this report, we shall concentrate on the center-doped and the (substrate-side) barrier-doped samples. Samples doped in the barrier at the surface side of the QW will not be discussed in this report for reasons to be clarified below. The samples discussed in this report had a sheet electron density which varied between 2×10^{12} and 4×10^{12} cm^{-2}. Other details of the Si δ doping can be found in our previous publications.[7]

The cw PL apparatus consisted of a 1 mW HeNe laser emitting in the green ($\lambda = 543$ nm), a 0.27 m grating spectrometer equipped with a Peltier cooled charge coupled device (CCD) camera. The sample was cooled to $T = 10$ K using a closed-cycle refrigerator. The time resolved experiments were based on the PL up-conversion technique,[8] and were performed using a femtosecond self-mode-locked Ti sapphire laser. The pulse width was 80 fs, the repetition rate 85 MHz, and the output power was 200 mW at $\lambda = 780$ nm. In order to achieve a consistent excitation density in all the samples, the emission wavelength of the laser was frequency doubled and $\lambda = 390$ nm was used as the excitation source. This way, only the front surface of the samples were excited and not the δ-doped layers. However, this is only valid for

 © 2000 American Institute of Physics

Reuse of AIP Publishing content is subject to the terms at: https://publishing.aip.org/authors/rights-and-permissions. Download to IP: 136.186.72.15 On: Thu, 29 Sep 2016 12:20:17

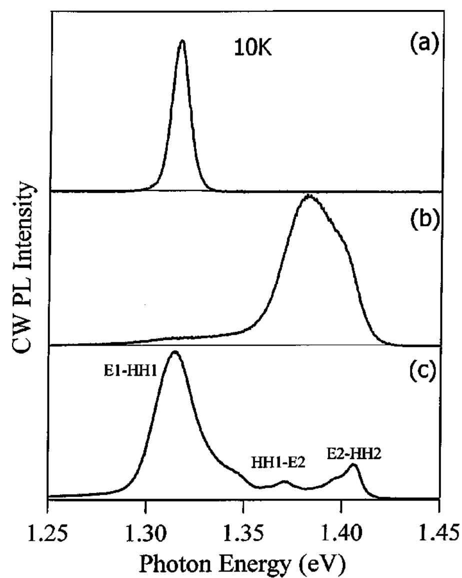

FIG. 1. CW photoluminescence of the δ-doped InGaAs/GaAs quantum wells. (a) is the spectrum of the undoped QW, (b) is the sample doped at the center of the well and (c) is doped in the barrier.

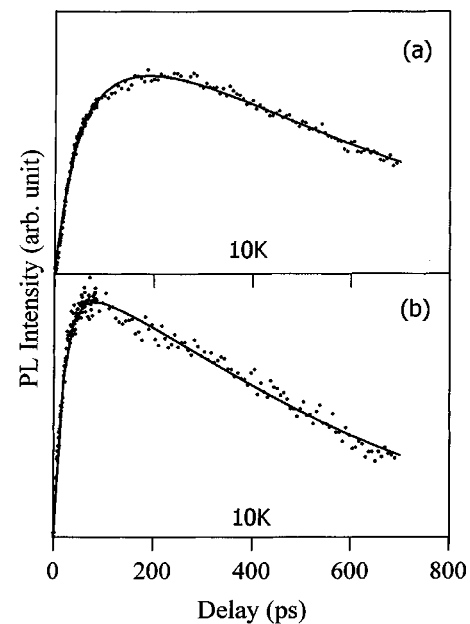

FIG. 2. Temporal evolution of the photoluminescence of the (a) undoped and the (b) center-doped sample, as measured by the PL up-conversion technique.

the center and the substrate-side-doped samples and *not* for the samples where the doping sheet was close to the surface.

III. RESULTS AND DISCUSSION

A. CW PL results

The low-temperature PL spectra of the various samples are shown in Fig. 1. The PL spectrum of the undoped sample, shown in Fig. 1(a), exhibits a relatively narrow, symmetric emission line corresponding to the lowest energy exciton transition in the QW. The PL spectra of the δ-doped samples are quite different. The spectrum of the center-doped samples displayed in Fig. 1(b), is highly asymmetric with an almost steplike emission line shape combined with a distinct resonance at the Fermi energy. Resonance at the Fermi energy is well documented in III–V QWs and is the result of electron correlation enhancement at the Fermi edge, the so-called Fermi-edge singularity (FES).[9] The steplike line shape and the FES are attributes of recombination processes which occur without apparent momentum conservation as a result of the photogenerated holes (in n-doped samples) being highly localized. In spite of being doped at a similar level, the barrier-doped samples did not show the FES but instead exhibited several relatively narrow spectral features whose energy correspond to various transitions within the QW, as shown in Fig. 1(c). Since the carrier density in the two type of samples was comparable, the absence of the FES in the barrier-doped samples is an indication that the density of localized (photogenerated) holes is insignificant in these samples. The existence of localized holes in the center-doped samples and their absence in the barrier-doped samples can be understood if we consider the location of the trapping centers in this material. Hole localization in high quality InGaAs/GaAs QWs can either be caused by fluctuation in the In concentration, or be the result of interface defects at the quantum well-barrier (InGaAs/GaAs) interface. Our PL data imply that in our samples localization is caused by interface defects and not mole fraction fluctuations since the In variation is the same in all the samples of similar mole fraction. Since FES was only observed in the center-doped samples, we interpret this result as an indication that the holes are preferentially localized at the interface and that in the center-doped samples holes are more likely to be near the interface. This is consistent with the fact that in the center-doped samples the holes are repelled by the n-type doping towards the quantum well-barrier interface and thus are more likely to be near the interfaces and hence become localized. FES is therefore only observed in the center-doped InGaAs/GaAs QWs and not in the barrier-doped samples. In the barrier-doped samples, only momentum conserving optical transitions are allowed which were clearly observed in the PL spectra. It is interesting to note that in addition to the $\Delta n = 0$ transitions (e1$\rightarrow$hh1,e2$\rightarrow$hh2 and the complementary light hole transitions), we have also observed the e2$\rightarrow$hh1 transition, which is forbidden in a symmetric QW. In the barrier-doped samples, however, the quantum well potential is highly asymmetric due to the electric field induced by the doping layer and hence otherwise forbidden transitions are also observed.[10] These results are quite general and should also be observed in other systems. In fact, similar results were found by Kim *et al.* in the GaAs/AlGaAs system.[11] FES was only observed in the center-doped GaAs/AlGaAs material, while transitions between quantum well states were observed in the edge doped GaAs/AlGaAs samples.

B. Time resolved PL measurements

In Fig. 2, we display the time evolution of the luminescence signal in the first 700 ps after excitation, measured at $T = 10$ K. The time evolution of the undoped sample, shown in Fig. 2(a), is characterized by a relatively long PL rise time

Reuse of AIP Publishing content is subject to the terms at: https://publishing.aip.org/authors/rights-and-permissions. Download to IP: 136.186.72.15 On: Thu, 29 Sep 2016 12:20:17

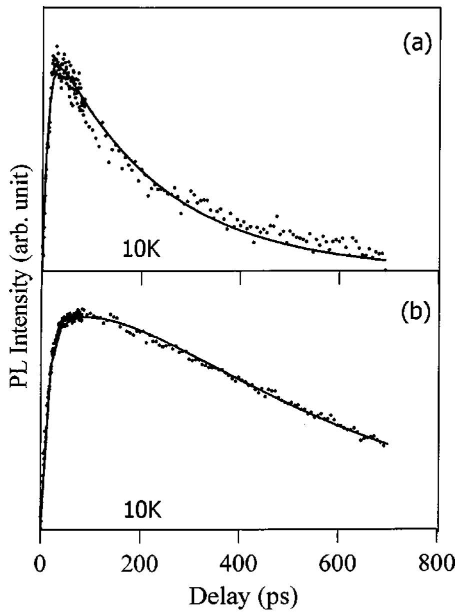

FIG. 3. Temporal evolution of the photoluminescence of the barrier-doped sample. (a) show the time resolved PL measured at the photon energy corresponding to the e2→hh2 and (b) corresponds to the e1→hh1 transition.

($\tau_{\text{rise}}=200$ ps) when compared to the doped samples. This is a manifestation of the excitonic origin of this transition and has been reviewed by Shah *et al.* in detail.[12] In the (n-)doped materials, recombination is not excitonic and the time evolution of the recombination process is determined by the nature of the transition and the dynamics of the hole population.

The time evolution of the center-doped material, shown in Fig. 2(b), is determined by the transition between electrons at the Fermi energy and holes localized at the hetero-interface. This system was analyzed and reported in a previous publication[13] in which we showed that the effective hole capture time for the center-doped sample is $\tau_c=15$ ps, the interband relaxation time $\tau_i=3$ ps and the hole lifetime $\tau_r>1$ ns.

The time evolution of PL from a barrier-doped sample is shown in Figs. 3(a) and 3(b), which correspond to emissions between the e2→hh2 and the e1→hh1 transitions, respectively. In this case, the PL emission originates from momentum conserving transitions between electrons and holes in various subbands of the QW. In order to determine the various relaxation times from the time resolved PL measurements, the experimental results were simulated by a set of coupled rate equations in which the electron distribution was assumed to be unperturbed by the photoexcitation and only the hole dynamics was considered. Our model was based on a four-level system, where p_0 is the density of holes in the barrier, and $p_{1(2)}$ is the density of holes in the second (first) excited state, as shown below:

$$\frac{dp_0}{dt}=-\frac{p_0}{t_{c1}}-\frac{p_0}{t_{c2}},$$

$$\frac{dp_2}{dt}=\frac{p_0}{t_{c2}}-\frac{p_2}{t_{21}}-\frac{p_2}{t_{20}}+\frac{p_1}{t_{12}},$$

TABLE I. Various relaxation times measured by time resolved PL in InGaAs/GaAs quantum wells.

InGaAs/GaAs QW	t_c (capture) into QW)	t_{12}(interband relaxation)	t_{i0} (effective lifetime)
Undoped	200 ps		>800 ps
Center-doped	15 ps	3 ps	700 ps
Barrier- (e2→hh2)	12 ps	220 ps	470 ps
doped (e1→hh1)	12 ps	220 ps	590 ps

$$\frac{dp_1}{dt}=\frac{p_0}{t_{c1}}+\frac{p_2}{t_{21}}-\frac{p_1}{t_{10}}-\frac{p_1}{t_{12}},$$

where $t_{c1(2)}$'s are the effective capture times from the barrier into levels 1 or 2, t_{21} is the interband relaxation time between levels 1 and 2, and t_{10} and t_{20} are the respective effective lifetimes.

The solution to these equations are displayed in Figs. 3(a) and 3(b) as the solid curves. In Table I we summarized the various time constants that were derived from the fitting process for all three type of samples. In the case of the undoped sample, the PL rise time is determined predominantly by excitonic effects, namely, the scattering of excitons from the $K\neq 0$ to the $K=0$ optically active state. This time constant was found to vary between samples but is of the order of 100–200 ps and is similar to values found in GaAs/AlGaAs QWs.[12] In the case of the δ-doped samples, two particular outcomes need to be discussed: the similarity in the values of t_c (the capture times into the QW) for the center- and barrier-doped samples, and the large difference in the t_{12} values (interband relaxation time) between the two type of samples. The capture time into the well ($t_c\approx 12-15$ ps) is primary determined by diffusion, and to a lesser degree by drift, of carriers from the sample surface (where they are generated) to the edge of the well. Since the samples are of identical dimensions, it is therefore not surprising that the capture times are similar.[14] The large difference between the interband relaxation times ($t_{12}=3$ ps in the center-doped sample and $t_{12}=220$ ps in the barrier doped), is directly related to the position of the doping sheet. The energy difference between the $n=1$ and $n=2$ heavy hole states in these samples ($\Delta E_{12}=22$ meV) is less than an optical phonon energy and hence we would not expect high interband relaxation rates. The fact that the interband relaxation time in the center-doped QW is so short (≈ 3 ps) indicates that there is another very efficient scattering mechanism present in these samples. This is most likely a combination of ionized impurity scattering and interface scattering[15] which occurs predominantly in the center-doped samples in agreement with the results of the time-dependent PL measurements.

IV. SUMMARY

In summary, we have measured the photoluminescence properties of δ-doped InGaAs/GaAs QWs. We found that the PL emission line shape, energy, and relaxation times are functions of the position of the doping sheet. We found that doping in the center of the QW, results in the holes being localized at the QW-barrier interface, and subsequently, a PL

Reuse of AIP Publishing content is subject to the terms at: https://publishing.aip.org/authors/rights-and-permissions. Download to IP: 136.186.72.15 On: Thu, 29 Sep 2016 12:20:17

line shape which corresponds to the FES. When the doping sheet is in the barrier, the density of localized holes in the QW is reduced and the PL emission comprises of the momentum conserving transitions between the conduction and valence band states. Using time resolved PL we measured the various relaxation times into and out of the well and found strong correlation between the position of the doping sheet and the values of the relaxation times.

[1] J. M. Fernandez, M. E. Lazzouni, L. J. Sham, and H. H. Wieder, J. Appl. Phys. **74**, 1161 (1993).
[2] G. Q. Hai, N. Studart, and F. M. Peeters, Phys. Rev. B **52**, 8363 (1995).
[3] M. L. Ke, D. Westwood, R. H. Williams, and M. J. Godfrey, Phys. Rev. B **51**, 5038 (1995), and reference therein.
[4] G. Q. Hai and N. Studart, Phys. Rev. B **55**, 6708 (1997).
[5] G. Q. Hai, N. Studart, F. M. Peeters, P. M. Koenraad, and J. H. Wolter, J. Appl. Phys. **80**, 5809 (1996).
[6] M. J. V. Bell, D. D. de Sousa, V. Anjos, and L. A. O. Nunes, Phys. Rev. B **58**, 7205 (1998).
[7] G. Li and C. Jagadish, J. Cryst. Growth **167**, 421 (1996).
[8] L. V. Dao, M. Gal, H. H. Tan, and C. Jagadish, in *Ultrafast Phenomena XI*, edited by T. Elsaesser, J. G. Fujimoto, D. A. Wiersma, and W. Zinth (Springer, Berlin, Heidelberg, 1998), p. 298.
[9] G. Coli, L. Calcagnile, P. V. Guigno, R. Cingolani, R. Rinaldi, L. Vanzetti, L. Sorba, and A. Franciosi, Phys. Rev. B **55**, R7391 (1997).
[10] R. A. Hopfel, R. Rogrigues, Y. Iimura, T. Yasui, Y. Segawa, Y. Aoyagi, and S. M. Goodnick, Phys. Rev. B **47**, 10 943 (1993), and reference therein.
[11] Y. Kim, M. S. Kim, and S. K. Min, Appl. Phys. Lett. **62**, 741 (1993).
[12] T. C. Damen, J. Shah, D. Y. Oberli, D. S. Chemla, J. E. Cunningham, and J. M. Kuo, Phys. Rev. B **42**, 7434 (1990).
[13] L. V. Dao, M. Gal, G. Li, and C. Jagadish, Appl. Phys. Lett. **71**, 1849 (1997).
[14] It is interesting to note that in samples where the doping sheet was between the sample surface and the QW (not discussed in this report), t_c was significantly longer than for samples which are the topic of this article ($t_c \approx 36$ ps). This increase in the diffusion time in these samples is related to the effect of scattering by the delta doped potential.
[15] M. Dur and S. M. Goodnick, Semicond. Sci. Technol. **13**, A143 (1988); M. Dur, S. M. Goodnick, and P. Lugli, Phys. Rev. B **54**, 17794 (1996).

Reuse of AIP Publishing content is subject to the terms at: https://publishing.aip.org/authors/rights-and-permissions. Download to IP: 136.186.72.15 On: Thu, 29 Sep 2016 12:20:17