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Improved carrier collection in intermixed InGaAs/GaAs quantum wells

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We have used photoluminescence up conversion to study the carrier capture times into intermixed InGaAs/GaAs quantum wells. We have found that the capture into the intermixed wells is markedly faster than capture into the reference (unintermixed) quantum wells. The reasons for the significant reduction in the capture time is related to the shape of the intermixed quantum well. Such a reduction in the capture time is beneficial both in terms of the quantum efficiency and the frequency response of intermixed optoelectronic devices. © *1998 American Institute of Physics.* [S0003-6951(98)01849-X]

Quantum well intermixing (QWI) is a method of considerable recent interest due to its wide applicability in optoelectronics.[1] QWI is based on the modification of the shape of the quantum well, and allows the post growth adjustment of several key parameters, such as the effective band gap, the optical absorption coefficient, and the refractive index. This flexibility enables the monolithic integration of optoelectronic devices, such as lasers, modulators, waveguides, amplifiers, etc. onto a single chip.[2] QWI has also been used to fabricate blueshifted[3] and multiple-wavelength laser diodes, low threshold lasers, and lasers with saturable absorbers, in addition to improving the performance of high power lasers.[1] In this letter, we shall show that in addition to modifying the quantum well parameters mentioned above, QWI can also have a significant impact on the carrier capture into (intermixed) quantum wells. We shall show that in intermixed InGaAs/GaAs quantum wells, the carrier capture is faster than in similar but nonintermixed quantum wells. This efficient carrier capture can explain the relatively high quantum efficiency of intermixed light emitting devices, and may also result in improved frequency response of optoelectronic devices in general. The carrier capture times were determined from time resolved photoluminescence measurements using the photoluminescence up-conversion technique.

The photoluminescence (PL) up-conversion experiments[4] were performed using a femtosecond self-mode locked Ti:sapphire laser, using a $\mathrm{LiIO_3}$ nonlinear crystal. The laser was tunable between 750 and 900 nm, the pulse width was 80 fs, the repetition rate 85 MHZ, and the output power was 200 mW at $\lambda = 780$ nm. The time resolution of our system was approximately 200 fs. The optically excited carrier concentration was approximately 4×10^{10} carriers/cm^2. The samples were mounted in a variable temperature, closed cycle, He cryostat, the temperature of which could be varied between 8 and 300 K. In this study we shall discuss results obtained on a number of $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs quantum well (QW) samples grown by metalorganic chemical vapor deposition. Each sample contained two QWs: a 5-nm-wide $\mathrm{In_{0.15}Ga_{0.85}As}$ well and a 5-nm-wide $\mathrm{In_{0.3}Ga_{0.7}As}$ well embedded between 50-nm-thick GaAs barriers. To achieve intermixing, we used room temperature proton implantation in combination with rapid thermal annealing (RTA). Details of the implantation conditions can be found elsewhere.[5] We have previously shown that proton implantation can achieve very large energy shifts (up to 200 meV in GaAs/AlGaAs QWs) with good recovery in the optical properties after standard annealing procedures.[6] In this study, the InGaAs/GaAs QW samples were implanted with protons to a maximum dose of 5×10^{15} cm^{-2} and annealed at 900 °C for 30 s. The PL intensities have not degraded significantly after intermixing: For example, after implantation at a dose of 1×10^{15} cm^{-2} and annealing at 900 °C for 30 s, the PL intensity of the intermixed sample is still approximately 66% of the unimplanted sample. At the same time, the intermixing did produce significant peak shifts in the PL spectra, a can be seen in Fig. 1 where we display the normalized time integrated PL spectra of the reference (unimplanted) and intermixed samples. As can be seen, the peak energies of the PL emissions have blueshifted by various amounts depending on the composition of the QWs: The shift of the $\mathrm{In_{0.15}Ga_{0.85}As}$ well is approximately 10 meV, while the shift of the deeper $\mathrm{In_{0.3}Ga_{0.7}As}$ well is approximately 50 meV at an ion dose of 5×10^{15} cm^{-2}. We may therefore conclude that proton implantation followed by RTA did produce intermixed QWs, as confirmed by the PL peak shifts, and that the PL intensities were not reduced significantly by this procedure.

In order to determine the efficiency of carrier capture into the QWs, we have measured the time evolution of the PL intensity using the up-conversion technique. Typical results are shown in Fig. 2 where the points denote the experimental data, and the full lines represent the fitting with the following function:

$$I_{\mathrm{pl}}(t) = a\left(e^{-t/\tau_{\mathrm{cap}}} - e^{-t/\tau_{\mathrm{decay}}}\right).$$

That is, we used a single exponential to fit the capture of carriers into the well with a characteristic time τ_{cap}, and similarly, a single exponential provided an excellent fit for

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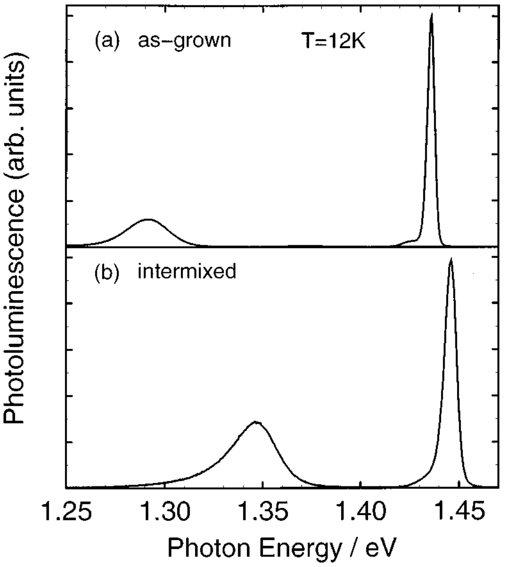

FIG. 1. (a) PL spectrum of a sample containing two 5-nm-wide $In_xGa_{1-x}As/GaAs$ QWs of different In mole fractions, measured at $T = 12$ K. The higher energy peak is due to excitonic transition in the $In_{0.15}Ga_{0.85}As/GaAs$ QW, while the low energy peak represents the $In_{0.3}Ga_{0.7}As/GaAs$ QW. (b) Same sample as shown in (a), after intermixing by proton implantation (ion dose 5×10^{15} cm^{-2}) and thermal annealing.

the decay of carriers from the well with an effective lifetime τ_{decay}. The effective capture time, τ_{cap}, is a measure of the probability that an optically excited carrier is captured into the well. The shorter this time, the larger the capture probability and hence the more efficient the capture process is. We have found that the capture times in the intermixed QWs were significantly reduced compared to the as-grown QWs. The results are summarized in Table I. Although not shown in the table, the capture times were found to be independent of the temperature between 10 and 100 K. The table also shows the effective decay times (τ_{decay}), which were also found to be reduced by intermixing. This effect, however, is not related to intermixing, but to the ion implantation induced increase in the nonradiative traps in the material, and has been observed by a number of researchers previously.[7]

It is well established that QWI is based on the modification of the shape of the QW by intermixing,[8] and these modifications are responsible for the observed PL peak shift, the changes to the optical absorption, and refractive index.[9] It appears from this study that the carrier capture is also affected by the QW profile. Intermixed QWs are known to be wider and contain concentration gradients along the growth direction.[1] Since diffusion and drift correctly describe the motion and capture of carriers in QWs with thick barriers,[10] the internal electric fields (i.e., concentration gradients) play a crucial role in the dynamics of carriers. The carriers in the intermixed QW are accelerated toward the well by the quasielectric fields produced by the composition gradients[10,11] and this additional ''pull'' is responsible of the reduction of the overall capture times.

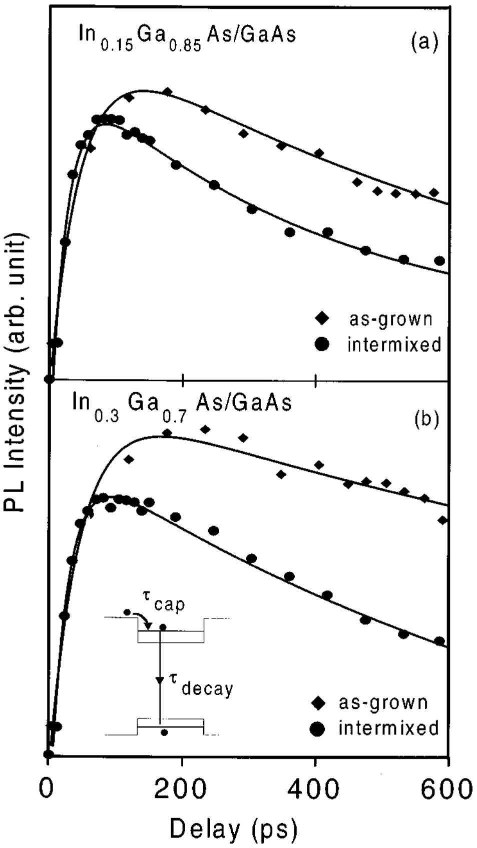

FIG. 2. (a) Time evolution of the PL, measured at $T = 12$ K, of the reference (as-grown) and intermixed $In_{0.15}Ga_{0.85}As/GaAs$ QWs. The points represent the experimental data, and the full line is the best fit using a single exponential function for the capture and another exponential for the decay. (b) Time evolution [as (a)] of the $In_{0.3}Ga_{0.7}As/GaAs$ QW. The insert illustrates the capture and decay time.

Reduction in the overall capture time in QWs was also observed by Morin *et al.*,[11] who studied the capture of photoexcited carriers into GaAs/AlGaAs QWs embedded in various types of graded confinement layers (used in typical laser structures). They found that carrier capture was appreciably shorter for QWs confined in the graded structures then those in the uniform (ungraded) structures. For example, the capture time was found to be 22 ps (at $T = 80$ K) for a

TABLE I. Effective capture times (τ_{cap}) and decay times (τ_{decay}) for intermixed $In_xGa_{1-x}As/GaAs$ quantum wells at $T = 12$ K.

	Reference (as-grown)		Intermixed (1×10^{15} ions/cm^{-2})		Intermixed (5×10^{15} ions/cm^{-2})	
Sample:	τ_{cap} (ps)	τ_{decay} (ps)	τ_{cap} (ps)	τ_{decay} (ps)	τ_{cap} (ps)	τ_{decay} (ps)
$In_{0.15}Ga_{0.85}As/GaAs$ ($L_z = 5$ nm)	45	820	25	400	20	250
$In_{0.3}Ga_{0.7}As/GaAs$ ($L_z = 5$ nm)	45	1500	25	1000	20	80

''simple'' QW but only 2 ps for a QW confined by graded-index layers. In these ''tailor'' made structures the magnitude of the graded layers is orders of magnitude larger than in the intermixed QWs, and hence the larger reduction in the capture time is to be expected.

The reduction in capture time may have favorable influence on intermixed optoelectronic devices: The relatively high quantum efficiency observed in intermixed QWs, a surprising fact considering the increased density of nonradiative traps, may be the result of the gain in carrier capture efficiency. In addition, intermixed QWs may also have improved frequency response since the upper limit of the modulation frequency is determined by the dynamics of the excited carriers, which in turn, is determined by carrier capture into the QWs (and carrier thermalization).

In summary, we have used PL up-conversion experiments to measure the carrier capture time into several InGaAs/GaAs QWs. We found that carrier capture into intermixed QWs is markedly shorter then capture into as-grown (unintermixed) wells due to the modification of the shape of the well by intermixing. Such a reduction in the capture times is beneficial in terms of the quantum efficiency and the frequency response of intermixed optoelectronic devices.

[1] See for example, *Quantum Well Intermixing for Photonics*, Milestone Series, edited by E. H. Li (SPIE, Bellingham, WA, 1997).

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