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Interdiffusion and wavelength modification in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells by lamp annealing

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$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ single quantum well structures grown by molecular beam epitaxy were pulse annealed by a halogen lamp to determine the stability of their optical properties after such thermal treatment. The annealing time and temperature were 5 s and 650–850 °C, respectively. The shift in energy of the main peak in the low-temperature photoluminescence spectra was modeled by considering Al-Ga interdiffusion at the heterointerface and solving the appropriate Schrödinger equation for this region. The estimated interdiffusion constants D are $\sim 10^{-16}$–10^{-15} cm^2/s in this temperature range, which are almost three orders higher than the corresponding values reported for GaAs/$Al_xGa_{1-x}As$. For longer annealing times, up to 30 min, the linewidth (full width at half-maximum) of the excitonic transition in the 11 K photoluminescence spectrum continuously decreased from 12.5 to 7.7 meV, while the intensity maintained a high value.

The properties of a quantum well and the heterointerfaces forming it are intimately related to growth conditions and can also be affected by post-growth annealing during actual device processing. It has been shown by Camras and co-workers[1] that wavelength modification occurs in GaAs/$Al_xGa_{1-x}As$ quantum well lasers upon annealing at temperatures of 875–900 °C for periods of 3–10 h. A study of the wavelength modification is of importance and interest since it enables the determination of heterointerface interdiffusion effects and the estimation of the stability (spectral wavelength) of active devices. In this letter, we report for the first time the results of lamp and furnace annealing studies with InGaAs/InAlAs quantum wells grown by molecular beam epitaxy. The interdiffusion effects during rapid thermal annealing were explained by an error-function interdiffusion model and a solution of the Schrödinger equation for the modified quantum wells.

Undoped 120 Å $In_{0.53}Ga_{0.48}As/In_{0.52}Al_{0.48}As$ single quantum wells (SQW's) were grown by molecular beam epitaxy (MBE) on Fe-doped (001) InP:Fe substrates at 500 °C. The structures consist of a 1-μm undoped $In_{0.52}Al_{0.48}As$ barrier layer followed by a 120-Å $In_{0.53}Ga_{0.47}As$ well region and a 0.2-μm $In_{0.52}Al_{0.48}As$ barrier layer. The structures were grown with 3 min interruption at the heterointerfaces forming the SQW. Analysis of 10 K photoluminescence (PL) linewidths,[2] which are of the order of 10–12 meV with 3 min growth interruption at the interfaces, shows that the inverted (InGaAs on InAlAs) interface is two monolayers rough, assuming that the normal interface (InAlAs on InGaAs) grown under identical conditions is one monolayer rough.

The SQW structures were annealed in a halogen lamp station with a protective GaAs cap under flowing argon. The annealing time was kept fixed at 5 s while the temperature was varied in the range 650–850 °C. Low-temperature photoluminescence measurements were made with a 1-m scanning spectrometer, a liquid-nitrogen-cooled Ge detector, and lock-in amplification of the detected signal before recording. It is known that the dominant emission peak in the photoluminescence spectra of InGaAs/InAlAs quantum wells arises from bound-exciton recombinations at 11 K (Ref. 2) while the intrinsic first-electron-to-heavy-hole transition (E_{1h}) constitutes the main peak at 77 K.[3,4] The energy position of the main peak at both 11 and 77 K remained almost fixed up to an annealing temperature of 700 °C. Above that temperature, the peak moved rapidly to higher energies, as depicted in Fig. 1. This shift, which is

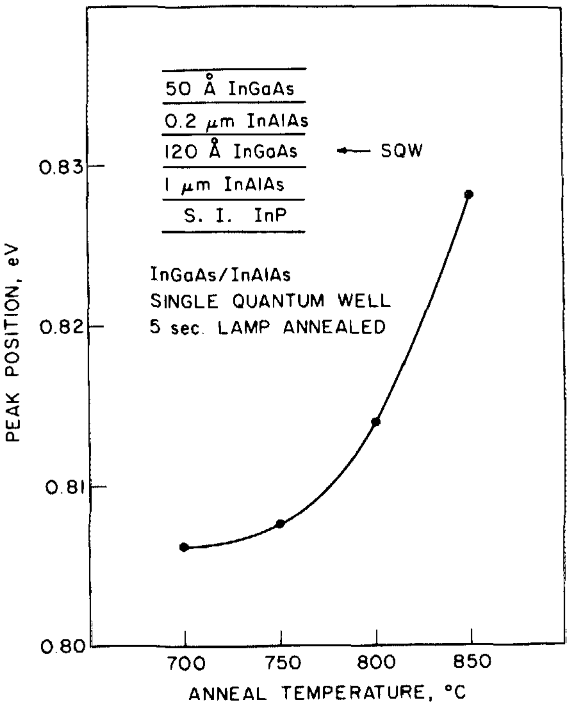

FIG. 1. Variation of peak energy position of main 77 K photoluminescence transition with lamp annealing temperature in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ single quantum wells. The schematic of the structure is shown in the inset.

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caused by the modification of the quantum well due to atomic interdiffusion at the heterointerfaces, is quite large. A peak energy shift of 22 meV was observed after 5 s lamp annealing at 850 °C. In comparison, Meehan *et al.*[5] observed an energy shift of 53 meV in a GaAs/AlGaAs 85 Å quantum well after 10 h of furnace annealing at 900 °C.

The variations of 11 K photoluminescence (main peak) linewidth and peak intensity with annealing temperature are depicted in Fig. 2. The increase in intensity is probably due to annealing of nonradiative centers in the well and heterointerface regions. This is counteracted at higher annealing temperatures by interdiffusion effects and diffusion of nonradiative defects from the barrier regions into the well. The initial reduction of linewidth is due to small interdiffusion which, in effect, drastically reduces the island size. At higher anneal temperatures an inhomogeneous alloyed region increases the linewidth.

The shift of the main PL peak at different annealing temperatures was modeled by solving the Schrödinger equation for the quantum well with graded interfaces caused by atomic interdiffusion. During annealing, Ga and Al interdiffuse at the InGaAs/InAlAs heterointerfaces. If we assume that both elements have a common interdiffusion coefficient D, which is independent of the Al composition x in the resulting graded quaternary $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.47}\mathrm{In}_{0.53}\mathrm{As}$ interface region, then the spatial profile of x is given by

$$x = 1 - \frac{1}{2}\left(\operatorname{erf}\frac{h-z}{2\sqrt{Dt}} + \operatorname{erf}\frac{h+z}{2\sqrt{Dt}}\right), \qquad (1)$$

where z is the distance measured from the center of the InGaAs well, h is the half-width $(L_z/2)$ of the well in an as-grown sample, and t is the annealing period. From several recent reports,[6-9] the dependence of E_g on x in $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.47}\mathrm{In}_{0.53}\mathrm{As}$ is estimated to be

$$\begin{aligned} E_g(\mathrm{eV}) &= 0.74 + 0.73x\ (300\ \mathrm{K}) \\ &= 0.79 + 0.73x\ (77\ \mathrm{K})\,. \qquad (2) \end{aligned}$$

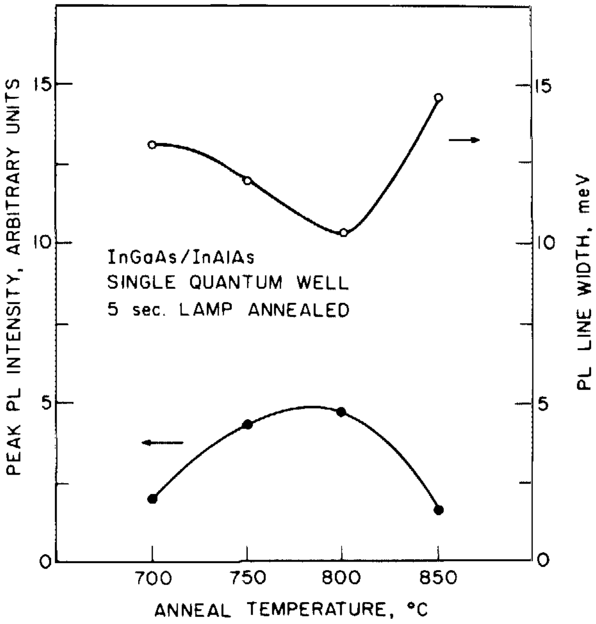

FIG. 2. Variation of intensity and linewidth of 11 K photoluminescence transition in InGaAs/InAlAs SQW with annealing temperature.

We have also assumed that the conduction-band discontinuity at the heterointerface, ΔE_c, is 60% of the total band-gap difference.[10] The electron effective mass is linearly approximated by $(0.0427 + 0.0353x)m_0$ and the heavy-hole effective mass is assumed to be $0.5m_0$, independent of x.[11]

The calculated peak energy shifts ΔE_{1h} as a function of $2\sqrt{Dt}$ are depicted in Fig. 3(a). The interdiffusion coefficients D at various temperatures are obtained by fitting experimental data with the theoretically calculated ones, as indicated in Fig. 3(a). The estimated values of D are plotted against inverse temperature in Fig. 3(b), from which an acti-

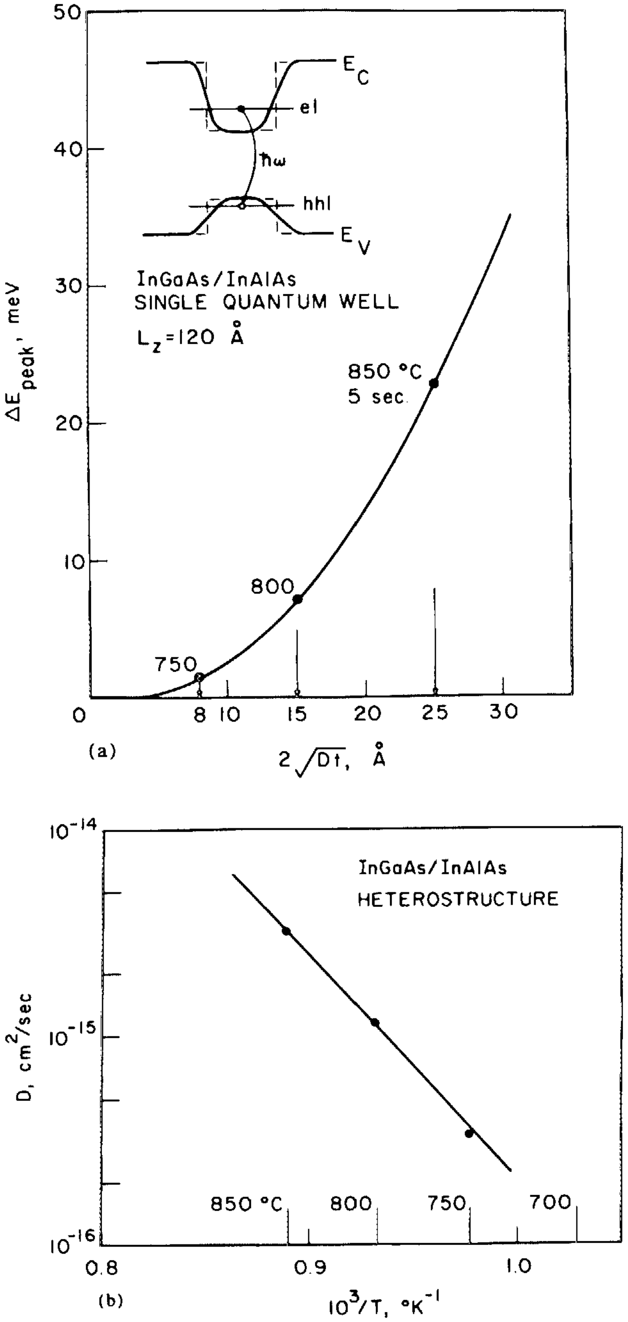

FIG. 3. (a) Calculated variation of the shift in energy position of the main photoluminescence transition (77 K) with interdiffusion distance $2\sqrt{Dt}$. The measured shifts at various temperatures are shown on the calculated curve. The inset depicts the energy-band diagram used for modeling. (b) Estimated variation of D with inverse temperature.

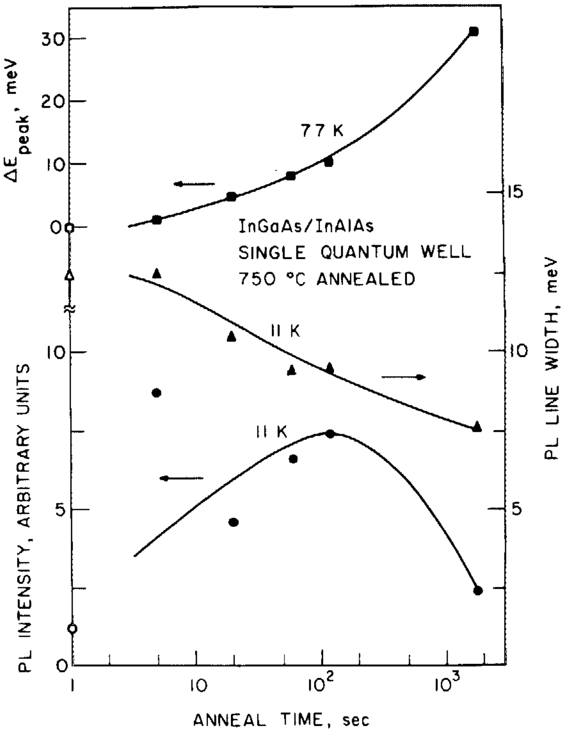

FIG. 4. Variation of low-temperature photoluminescence intensity, linewidth, and peak energy shift with annealing time in InGaAs/InAlAs single quantum well structures upon annealing at 750 °C. Open symbols on ordinate denote data for unannealed samples.

vation energy of 2.3 eV is obtained. The estimated interdiffusion coefficients are reduced by 25% when the rise and fall sections of the anneal cycle are taken into account.[12] The values of D obtained in this study are three orders higher than those reported for GaAs/AlGaAs structures.[1,5,13] There can be two possible reasons for this. First, the presence of In itself might enhance interdiffusion of Al-Ga in the InGaAs/InAlAs heterostructure. Second, a higher level of defects in the layers or the heterointerface might accelerate interdiffusion.

To study the effect of annealing time on the structural properties of the SQW, lamp or furnace annealing was done for 5 s – 30 min at 750 °C. Lamp annealing technique was used up to a duration of 2 min and conventional furnace annealing was employed for a duration of 30 min. Figure 4 shows the dependence of 77 K peak PL energy shift, 11 K PL intensity, and 11 K PL linewidth on annealing time. As the annealing time increases from 5 s to 30 min, the estimated interdiffusion coefficient decreases from 3.2×10^{-16} to 1.3×10^{-17} cm^2/s. Annealing of defects might be a possible reason for this decrease, since it would reduce defect-assisted diffusion. Other possible causes are the dependence of interdiffusion coefficient D on the Al composition x in the $(Al_xGa_{1-x})_{0.47}In_{0.53}As$ graded interface regions and a more complex well shape than the assumed linear grading. The PL linewidth was observed to decrease drastically as the annealing time increased. It should be noted that the measured linewidth of 7.7 meV after 30 min annealing is much smaller than that reported for as-grown InGaAs/InAlAs SQW structures.[2,3] Smoothening of the interfaces and annealing of defects are regarded as the reason for this decrease. The narrow linewidth, together with a high PL intensity obtained after annealing, can be extremely important for the fabrication of high-performance optical sources.

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