Thermal processing of strained InGaAs/GaAs quantum well heterostructures bonded to Si via an epitaxial lift-off technique

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We have investigated the effects of thermal cycling on the optical properties of $In_{0.2}Ga_{0.8}As/GaAs$ single quantum well films bonded to Si(001) via the epitaxial lift-off technique. The optical and structural quality of the bonded films were monitored using cathodoluminescence (CL) imaging and spectroscopy. The films were stable through the temperature range (500–700 °C) used in normal $In_xGa_{1-x}As$ device processing. However, annealing at temperatures greater than ~700 °C resulted in layer intermixing accompanied by a blue-shift in the CL peak energy. The shifts in the CL peak energy were modeled by considering In–Ga interdiffusion at the interface and solving the Schrödinger equation using appropriate band profiles for this region. © *1997 American Institute of Physics.* [S0003-6951(97)03612-7]

The hybridization of III-V/Si materials is important in the optimization of opto-electronic integrated circuits (OEICs) which finds many applications in broadband and coherent optical communication networks and in optical recording. Although impressive advances have occurred in achieving high quality GaAs via heteroepitaxial growth on Si, the quality of GaAs grown by this process has generally been insufficient for device applications.[1,2] The problems encountered with heteroepitaxial growth have stimulated different research groups to investigate alternate routes in achieving monolithic integration of dissimilar crystalline materials.

One technique that has shown considerable success in integrating GaAs with Si is the epitaxial lift-off technique (ELO).[3] This technique make use of the selective removal of a very thin AlAs sacrificial layer between the substrate and the active layer. After the lift-off, the layer structures can be grafted to quasi arbitrary substrates. It has been established by a number of research groups that this technique does not suffer from the problems encountered with heteroepitaxial growth.[4–7] However, development of devices via the epitaxial lift-off process has been restrained partly due to doubts about long-term stability and thermal cycling effects on these films.[8] In this letter, we have examined the effects of rapid thermal annealing (RTA) in the temperature range of 600–850 °C on the optical and structural properties of $In_{0.2}Ga_{0.8}As/GaAs$ quantum well (QW) films bonded to Si(001) substrates via an epitaxial lift-off technique. The sample studied was grown by metalorganic chemical vapor deposition (MOCVD) on a GaAs(001) substrate using a 640 °C growth temperature. Starting from the GaAs substrate, the sample consists of a 500 Å AlAs buffer layer, a 2100 Å GaAs buffer layer, a 65 Å $In_{0.20}Ga_{0.80}As$ QW, and a 100 Å GaAs capping layer. The basic steps of ELO are illustrated in Fig. 1 and are similar to those discussed by other authors.[3,8] The samples described above were coated with a thick layer of Apiezon type-W black wax, which provides mechanical support to the thin film during the time it is free. The stress induced by black wax slightly bows the wafer when etching the sacrificial layer, allowing reaction products to escape more easily. The epilayer is separated from the substrate by selectively etching the AlAs layer by using a 10% dilute solution of hydrofluoric acid. the epitaxial film which is now separated from the host GaAs substrate is rinsed in deionized water and placed on a surrogate Si substrate. Once the film is properly placed, excess water is gently squeezed out and blotted with filter paper. The sample is left to dry with a small weight on the film. As the water escapes, separation between the lift-off film and the new substrate decreases until the short range, van der Waals forces can hold the two together.[3] After the bonding is complete, wax is dissolved in a solution of trichloroethane. Rapid thermal annealing was performed in a reducing atmosphere of forming gas to minimize oxidation of the sample during the

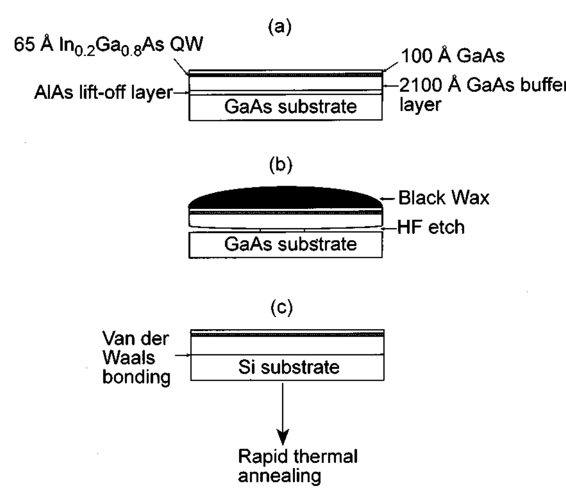

FIG. 1. Schematic diagram showing the epitaxial lift-off (ELO) process in steps (a)–(c).

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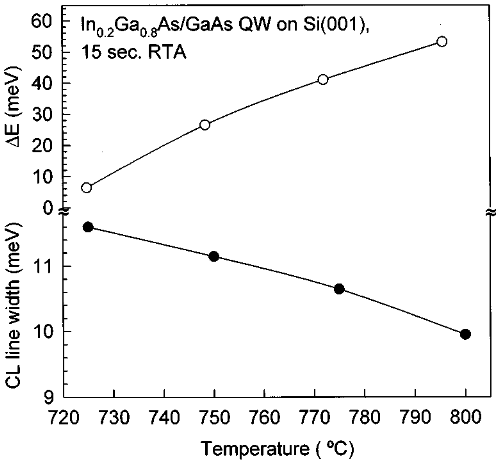

FIG. 2. Variation of the CL peak energy and linewidth in the $In_{0.2}Ga_{0.8}As$/GaAs QW films on Si as a function of the annealing temperature.

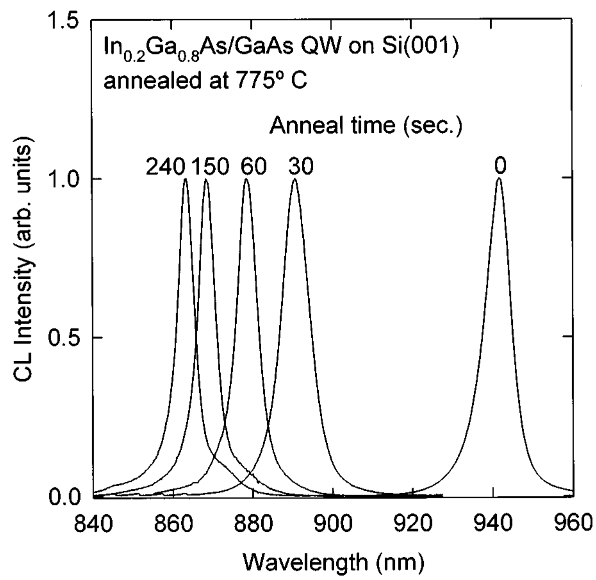

FIG. 3. CL spectra of the $In_{0.2}Ga_{0.8}As$/GaAs QW for various anneal times at 775 °C.

high temperature operation. The anneals for consecutive time intervals at each temperature were performed on the same sample to avoid uncertainties due to material variations. Anneals at different temperature were carried out on different samples.

The samples were examined after each anneal with cathodoluminescence (CL) imaging and spectroscopy. CL measurements were performed with a modified JEOL 840-A scanning electron microscope.[1] The light collected was dispersed by a 0.275 m spectrograph and detected with a liquid-nitrogen cooled Si array charge-coupled device (CCD) detector. An electron beam energy of 8 kV and a beam current of 2 nA were used to probe the samples. The temperature of the sample was maintained at 85 K during the CL measurements. From monochromatic CL imaging, we observe no evidence of dark line defect or misfit dislocation formation before and after the annealing.

The variation in the CL peak energy shift, ΔE, and the full width at half maximum (FWHM) as a function of annealing temperature is shown in Fig. 2 for samples annealed for 15 s. The energy position of the CL spectra remains the same (i.e., $\Delta E \approx 0$) for annealing temperatures up to 700 °C. Above that temperature, the peak moves rapidly to higher energies. The blue-shift in the CL peak position, as seen in Fig. 2, implies a significant change in the QW confinement potentials. As Ga and In interdiffusion smooths the initially abrupt $In_{0.2}Ga_{0.8}As$/GaAs quantum well interface, the bandgap increases, shifting the confined states to a higher energy. Similar results have been observed for pseudomorphic InGaAs/GaAs high electron mobility structures[9] and high hole mobility transistors after thermal annealing.[10] From Fig. 2, we also observe that the CL linewidth decreases as we increase the annealing temperature. The interface quality and the defects present in the unannealed sample could result in an initially large increase in CL linewidth. We suggest that on annealing, the interface roughness decreases and the defect density reduces, resulting in the observed reduction in linewidth. The reduction in the FWHM is also evidence for an increased well width and interface gradation, as the contribution of the interface roughness to the inhomogeneous broadening of the CL spectra reduces with annealing. The broadening is dominated by the alloy-disorder when a substantial intermixing of In and Ga has occurred.

In Fig. 3 we have plotted, as an example, the CL emission from the sample annealed at 775 °C for various anneal times. The CL peak moves progressively to higher energies with increasing anneal time. The CL linewidth decreases gradually as the anneal time increases for each annealing temperature as shown in Fig. 4. Also in Fig. 4 we have plotted the CL emission energies as a function of time for five different annealing temperatures. At temperatures between 600 and 700 °C we observe no change in CL peak energy, luminescence intensity, or linewidth after annealing for more than 7 min. This indicates that intermixing has not yet occurred and there is no catastrophic failure in these ELO films. We also observe no evidence that the films have lifted off from the surrogate Si substrate for $T \leqslant 800$ °C.

In order to have a better understanding of the nature of interdiffusion at the interfaces between the InGaAs QW and the GaAs barriers, a model is developed that relates the observed changes in the excitonic luminescence peak energy to interdiffusion through changes in the electron and hole confinement potential induced by a spatial variation in the In composition. In order to incorporate the interdiffusion-induced change in the composition profile of the barriers and QW layers, the confinement potential is made dependent on the In compositional profile. The assumption of one-dimensional diffusion from an initially abrupt interface into a semi-infinite solid is used here.[11] Based on this model, the spatial profile of In composition in this interdiffusion process for the entire QW region can be modeled as

$$c(x) = \frac{c_0}{2}\left[\operatorname{erf}\left(\frac{h+x}{2\sqrt{D_{\mathrm{In}}t}}\right) + \operatorname{erf}\left(\frac{h-x}{2\sqrt{D_{\mathrm{In}}t}}\right)\right], \tag{1}$$

where c_0 represents the initial concentration of In in the well at time $t=0$, h is the half width of the quantum well, D_{In} is

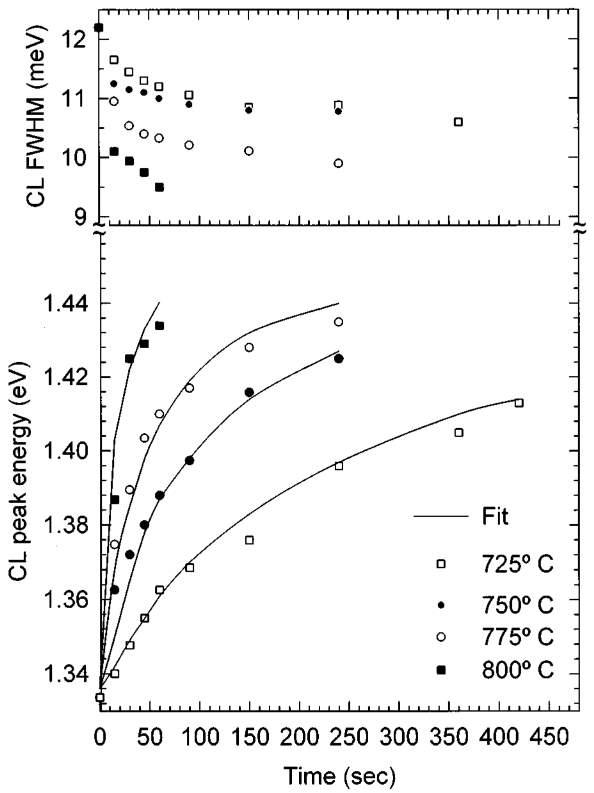

FIG. 4. Plot of the temporal evolution of the CL peak energy and linewidth at temperatures of 725, 750, 775, and 800 °C, respectively. The solid lines represent the fits to the theoretical model.

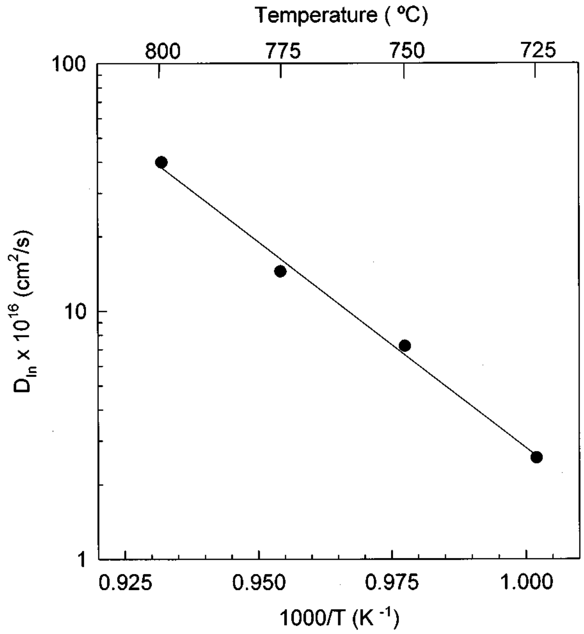

FIG. 5. Plot of the interdiffusion constant D_{In} as a function of annealing temperature.

the interdiffusion constant, t is the annealing time, and x is the distance from the center of the QW. The confined electron and hole energies were calculated by solving the Schrödinger equation for a quantum well with these graded interfaces using a transfer matrix method.[12] The effects of strain and composition on the effective masses, band gap, band offsets, and heavy hole-to-light hole band splitting were taken into account in these calculations.[12] The theoretical curves of the CL emission energy (solid lines in Fig. 4) were obtained by using the interdiffusion constant D_{In} as the only fitting parameter in these calculations, and D_{In} is therefore determined unambiguously. Interdiffusion constants of 2.563×10^{-16}, 7.2×10^{-16}, 1.45×10^{-15}, and 4.1×10^{-15} cm^2/s were obtained for 725, 750, 775, and 800 °C, respectively. The theoretically calculated values of D_{In} are plotted as a function of T^{-1} in the semi-logarithmic plot of Fig. 5, from which an activation energy of 3.303 eV is obtained. The Arrenhius-type behavior observed in Fig. 5 strongly supports this interdiffusion model. This activation energy and the measured values for D_{In} are similar to values obtained using photoluminescence experiments on as-grown $In_xGa_{1-x}As$/GaAs QWs ($x\approx0.20$).[13] Additionally, we observe no significant differences in the annealing-induced energy shifts between ELO and as-grown films. These results confirm the stability of ELO films during and after lift-off.

In summary, we have investigated the effect of rapid thermal annealing in the temperature range of 600–800 °C on the optical properties of strained $In_{0.2}Ga_{0.8}As$/GaAs QW films bonded to Si(001) substrates via ELO. We have observed that ELO films are stable for the thermal cycling employed in this study with no apparent peeling of the films from the Si substrate. We have also demonstrated that these structures are stable under normal device processing conditions (~600 °C). At higher annealing temperatures, we observe the intermixing of In and Ga atoms, resulting in a blue shift in the CL peak energy. We have determined the Ga/In interdiffusion constant, D_{In}, for various annealing temperatures, thereby enabling the determination of the activation energy for interdiffusion at the $In_{0.2}Ga_{0.8}As$/GaAs interface.

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