Molecular beam epitaxial growth and luminescence of $In_xGa_{1-x}As$/$In_xAl_{1-x}As$ multiquantum wells on GaAs

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This letter reports the successful molecular beam epitaxial growth of high-quality $In_xGa_{1-x}As/In_xAl_{1-x}As$ directly on GaAs. *In situ* observation of dynamic high-energy electron diffraction oscillations during growth of $In_xGa_{1-x}As$ on GaAs indicates that the average cation migration rates are reduced due to the surface strain. By raising the growth temperature to enhance the migration rate and by using misoriented epitaxy to limit the propagation of threading and screw dislocations, we have grown device-quality $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.85}As$ multiquantum wells on GaAs with a 0.5–1.0 μm $In_{0.15}Ga_{0.85}As$ buffer layer. The luminescence efficiency of the bound exciton peak increases with misorientation and its linewidth varies from 11 to 15 meV.

The successful growth of GaAs on Si by molecular beam epitaxy[1-3] and the demonstration of high-performance electronic[4] and optoelectronic[5] devices are major achievements towards integrated technologies. However, GaAs-based optoelectronic devices operate at ~0.8 μm, and it is, therefore, important to examine the possibility of integrating 1.3–1.6 μm optoelectronic devices with Si devices and circuits. The difficulty primarily arises from the fact that $In_xGa_{1-x}As$ and $In_xAl_{1-x}As$ alloys with band gaps corresponding to this wavelength range have a 1–3% lattice mismatch with GaAs and a 5–8% mismatch with Si. In the case of the growth of these ternary alloys on Si an additional complexity would be antiphase disorder. We have investigated, as a first step, molecular beam epitaxial growth of mismatched InGaAs/InAlAs on GaAs, and show, for the first time, that quantum wells with superior surface morphology and excellent luminescent properties can be obtained. This is achieved, as will be described, with the help of a careful study of strained epitaxy by *in situ* electron diffraction experiments and a suitable variation of the growth parameters. Recently, the growth of InGaAs/InP on GaAs by metalorganic chemical vapor deposition has been reported.[6] However, there has been no report on the optical properties of such mismatched structures.

In the case of the growth of GaAs/Si, substrate misorientation appears to have some benefits in avoiding antiphase boundaries. However, even for the growth of InGaAs on GaAs, the theory of crystal growth suggests that misoriented growth may be of value since it can ensure a layer-by-layer growth under conditions where on-axis growth is three-dimensional.[7] This is possible because in misoriented growth, the surface has steps of length $l_s = d/\sin\theta$ where θ is the misoriented angle. If l_s is smaller than l_c, the growth of the average surface migration of impinging atoms occurs by the layer-by-layer mode. This growth mode is expected to produce a structure which is closer to the minimum energy configuration than the 3-d island growth. Since a structure with misfit dislocations is lower in energy than one with threading dislocations,[8] it is expected that misoriented growth will suppress threading dislocations. Also, since threading dislocations would in principle travel in the growth direction, their presence would affect the total luminescence of quantum wells grown on the strained system.

Strained InGaAs layers and $In_xGa_{1-x}As$/$In_xAl_{1-x}As$ multiquantum wells (MQW's) were grown by molecular beam epitaxy on (100) oriented and misoriented [2°–4° off (100)→(011)] undoped GaAs substrates. We have used *in situ* dynamic reflection high-energy electron diffraction (RHEED) studies to understand the surface kinetics and incorporation mechanisms during strained-layer epitaxy of $In_xGa_{1-x}As/In_xAl_{1-x}As$ on GaAs. The measurement system consists of a 10-keV electron gun focused on a phosphor-coated screen, both installed in the growth chamber, and an external photomultiplier followed by an amplifier.

Figure 1 shows RHEED oscillation data for growth of $In_{0.22}Ga_{0.78}As$ on GaAs. The data were recorded after the growth of a 0.25-μm GaAs buffer layer at 610 °C on (100) GaAs. The substrate temperature was then lowered to 520 °C and the growth of the ternary layer at a rate of 0.5 μm/h was initiated. It is apparent that in sharp contrast to high-quality lattice-matched layers, where the oscillations persist for several hundreds of monolayer growth, the oscillations in the case of strained epitaxy die quickly and the

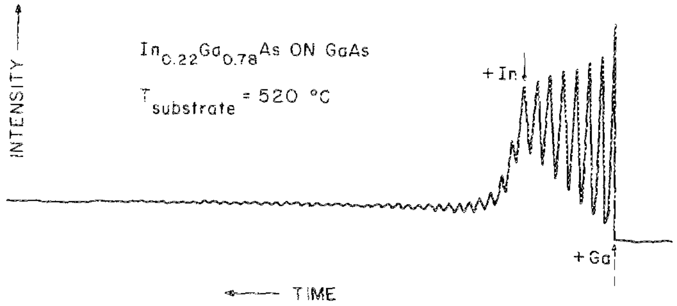

FIG. 1. Typical RHEED oscillations observed during growth of $In_{0.22}Ga_{0.78}As$ on (100) GaAs at 520 °C under As-stabilized conditions.

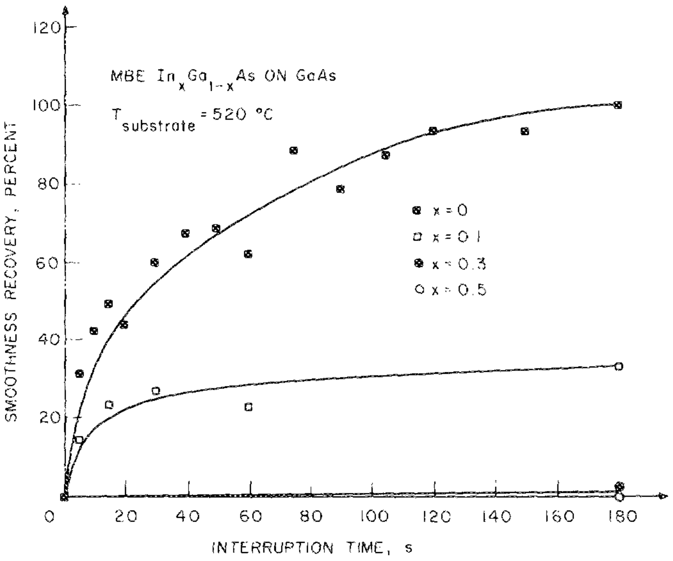

FIG. 2. Smoothness recovery vs interruption time during growth of $In_xGa_{1-x}As$ on (100) GaAs at 520 °C for $x = 0$, 0.1, 0.3, and 0.5.

pattern turns spotty. The latter indicates the onset of 3-d growth and roughness of the growth front. The observed decrease of the average RHEED intensity is a result of this roughness. Figure 2 shows the smoothness recovery time after growth interruption under As_4 flux for various alloy compositions with increasing In, up to 50%. The data support our observations in that increased strain inhibits cation migration. It is clear that strain plays a very important role in the surface kinetics and hence in the growth mode, and, therefore, may have considerable influence over the ideal growth conditions.

From the data of Fig. 1 it is apparent that increase of the substrate temperature and/or decrease of growth rate may assist the cations on the surface to migrate favorably and be incorporated at step edges. At the same time on a misoriented substrate ideal layer-by-layer growth can occur when the step size is nearly equal to the average cation migration length. We have grown $In_xGa_{1-x}As$ and $In_xGa_{1-x}As/In_xAl_{1-x}As$ MQW structures on (100) oriented and misoriented [2° and 4° off toward (011)] GaAs. In this particular study a 0.2-μm GaAs buffer layer was first grown at 610 °C at 1 μm/h followed by 250 Å of $In_{0.15}Ga_{0.85}As$ at 530 °C at a rate of 0.1 μm/h. Growth was then interrupted and the growth temperature and rate were changed to 570 °C and 1 μm/h, respectively. 1 μm of $In_{0.15}Ga_{0.85}As$ followed by ten periods of $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.85}As$ MQW ($L_Z = L_B = 100$ Å) was grown continuously under these conditions. The morphology of the (100) oriented and misoriented layers shows a slight cross-hatched pattern.

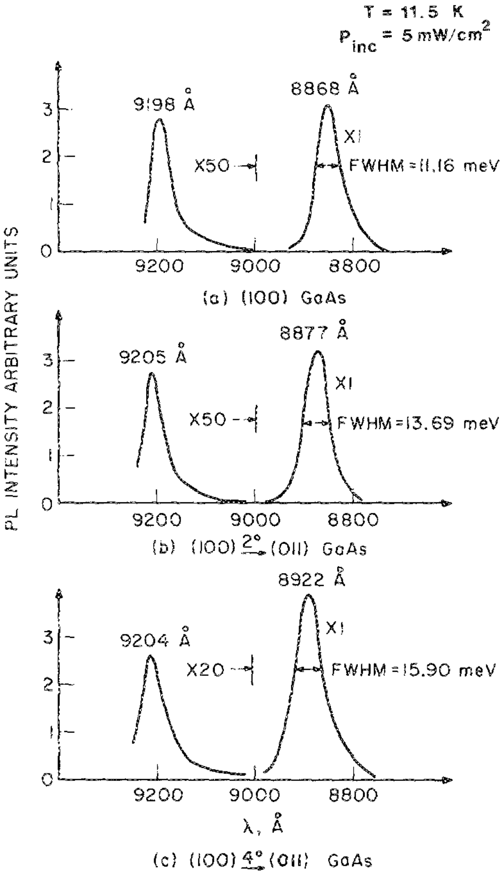

FIG. 3. Low-temperature photoluminescence spectra of $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.85}As$ multiquantum wells grown directly on GaAs for (a) (100) orientation, (b) 2° off (100) towards (011), (c) 4° off (100) toward (011).

Low-temperature photoluminescence (PL) measurements were made to ascertain the optical quality of the quantum wells. The samples were mounted in a strain-free manner in a He cryostat and the luminescence was analyzed by a 1-m Jarell–Ash scanning spectrometer. The spectra were detected by a Si photomultiplier and recorded. Typical spectra recorded for samples grown on oriented and misoriented MQW samples are shown in Fig. 3. The highest energy peak in the spectrum originates from quantum well bound exciton emissions. The peak at lower energies originates from the bulk $In_{0.15}Ga_{0.85}As$ layer. A steady increase in the intensity of the MQW emission is observed with increase of misorientation. The integrated PL intensity increases by almost a factor of 2 in going from (100) to 4° off toward (011), as depicted in Fig. 3. These results confirm the physical picture of the role of misorientation. The linewidths (FWHM) of the excitonic peaks are larger than the theoretically calculated ones, considering alloy broadening, but we believe that under optimum conditions, smaller spectral widths can be achieved. Therefore, at this stage it is not appropriate to use the linewidth data to obtain information on growth modes. We are now in the process of varying the growth parameters to grow material comparable in quality to lattice-matched crystals.

The results presented here indicate that the optimum growth conditions for strained InGaAs (InAlAs) on GaAs can be very different from those of corresponding lattice-matched alloys. These results open up the possibility of growing InGaAs (InAlAs)/GaAs/Si heterostructures. It should also be noted that the $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.85}As$ heterostructure has a large conduction-band offset, ΔE_c, and is, therefore, potentially very attractive for modulation-doped field-effect transistors, as well as optical modulators.

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