Strain relaxation and defect reduction in InxGa1−xAs/GaAs by lateral oxidation of an underlying AlGaAs layer


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Heterogeneous growth of ternary semiconductors facilitates band gap engineering and expands both optical and electrical device applications as compared with their binary constituents. However, most ternary semiconductors have different lattice constants from that of the substrate, and lattice mismatch can lead to problems. Two different growth technologies that have been used to yield highly strain-relaxed epitaxial layers with few threading dislocations are compliant epitaxy and metamorphic epitaxy. For compliant epitaxy, a very thin deformable layer is used as the substrate. In contrast, metamorphic epitaxy, a very thin deformable layer is used as the substrate. However, this technique requires sophisticated processing to produce the compliant substrate. In contrast, metamorphic growth utilizes a thick graded buffer layer to relieve strain and to confine most defects. Krishnamoorthy et al. found that the distribution of threading dislocation in the substrate and in the epi-layer depends on the magnitude of the misfit strain and on the growth conditions. Recently, high-quality low-defect InGaAs grown on GaAs with misfit strain up to 3.5% has been demonstrated by the metamorphic technique.

Other than these two growth techniques, there are different mechanisms that can induce strain relaxation. One of them is oxidation. Native Al-bearing oxide formed by lateral oxidation of AlGaAs has been commonly used in many electro-optical devices, such as current confinement and distributed Bragg reflector mirrors for vertical cavity surface emitting lasers. However, it is also noted that oxidation of a buried AlAs layer has induced strain relief in the overlying strained InGaAs layer. As much as 50%–90% relief of residual strain has been reported.

In a previous work, we have grown In$_{0.25}$Ga$_{0.75}$As on GaAs substrate by molecular beam epitaxy (MBE) at relatively low growth temperatures (LT) and low growth rates. It is found that the threading dislocation density can be as low as 10$^7$ cm$^{-2}$ in a 5000 Å In$_{0.25}$Ga$_{0.75}$As film, as compared to 10$^{10}$ cm$^{-2}$ when grown at normal temperatures around 450°C. In this work, the relaxation of low-temperature grown In$_{0.25}$Ga$_{0.75}$As and In$_{0.4}$Ga$_{0.6}$As as a function of layer thickness is measured before and after laterally oxidizing an underlying Al$_{0.98}$Ga$_{0.02}$As layer. The relaxation as a function of layer thickness has been measured by cross-sectional transmission electron microscopy and x-ray analysis. It is found that oxidation of the Al$_{0.98}$Ga$_{0.02}$As layer improves the relaxation of the strained In$_x$Ga$_{1-x}$As layer. Moreover, the interfacial misfit dislocations have been removed, and the threading dislocation density has decreased approximately by one order of magnitude after oxidation. © 2000 American Institute of Physics.

The In$_{0.25}$Ga$_{0.75}$As samples were grown by solid-source MBE with a valved-arsenic cell at 300°C with 0.5 monolayers (ML)/s growth rate and 3 × 10$^{-7}$ Torr arsenic overpressure. The growth temperature and growth rate of In$_0$Ga$_x$As were as low as 250°C and 0.25 ML/s to minimize the generation of threading dislocations. Prior to the growth of the strained layer, a 1000 Å GaAs buffer layer and a 1000 Å digital Al$_{0.98}$Ga$_{0.02}$As were grown at the normal growth temperature (~580°C) followed by a thin 30 Å GaAs layer at the same temperature. The digital Al$_{0.98}$Ga$_{0.02}$As oxidation channel consisted of a series of 50 ML AlAs and 1 ML GaAs layers to prevent degradation of the surface morphology after the oxidation. The insertion of the 30 Å GaAs spacer layer is to avoid the direct contact of the softer InGaAs with AlAs to facilitate the generation of interfacial misfit dislocations and also to keep reactive aluminum isolated during the growth temperatures change. Several sets of In$_{0.25}$Ga$_{0.75}$As samples with different thickness were grown, i.e., 125, 250, 500, 1000, 2000, and 5000 Å. To study the effect of strain relaxation by lateral oxidation, we have grown two In$_{0.25}$Ga$_{0.75}$As samples of 500 and 2000 Å, respectively, on digitized Al$_{0.98}$Ga$_{0.02}$As oxidation channels. Also, In$_{0.4}$Ga$_{0.6}$As of 500 and 1000 Å in thickness were used for similar studies.

To laterally oxidize AlGaAs layers, the InGaAs layer was processed by standard etching techniques to form 50 μm wide stripes separated by 5 μm trenches. The lateral oxidation was performed in a open tube furnace at 425°C with water vapor supplied by bubbling N$_2$ through water held at 85°C. The oxidation time was ~1 hour for the underlying Al$_{0.98}$Ga$_{0.02}$As layer to completely oxidize through. Cross-section and plan-view transmission electron microscope (TEM) analysis were used to study the quality of strained InGaAs film and to determine the density of misfit and threading dislocations in the epi-layers. X-ray measurements

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The strain relaxation in In$_{0.25}$Ga$_{0.75}$As and In$_{0.4}$Ga$_{0.6}$As grown on GaAs substrates at low temperature has been studied before and after laterally oxidizing an underlying Al$_{0.98}$Ga$_{0.02}$As layer. The relaxation as a function of layer thickness has been measured by cross-sectional transmission electron microscopy and x-ray analysis. It is found that oxidation of the Al$_{0.98}$Ga$_{0.02}$As layer improves the relaxation of the strained In$_x$Ga$_{1-x}$As layer. Moreover, the interfacial misfit dislocations have been removed, and the threading dislocation density has decreased approximately by one order of magnitude after oxidation. © 2000 American Institute of Physics.
were also performed to determine the indium content in strain layers and to measure the lateral and vertical strain by using [224] off-axis diffraction. From the x-ray data, the relaxation of sample was calculated.

In general, there are two kinds of interfacial misfit dislocations in strained layer epitaxy, 60° and 90° types. Their formation depends on the growth mode. The 60° misfit dislocations form mainly due to the Stranski–Krastanov growth mode and the 90° (pure edge-type) dislocations result from two-dimensional (2D) growth mode with low arsenic overpressure. Since streaky (1 × 1) reflection high-energy electron diffraction (RHEED) pattern appeared during the low-temperature growth of InGaAs, which is indicative of a 2D growth, it is likely that 90° misfit dislocations dominate in our samples. By assuming that all misfit dislocations in a completely relaxed In0.25Ga0.75As film are the 90° type, the linear dislocation density can be estimated. The mean distance between misfit dislocations along either [110] or [1 1 0] direction should be around 228 Å. From the cross-sectional TEM (XTEM) micrograph (Fig. 1), we have obtained the actual mean distance between misfit dislocations, which varies with the film thickness. The extent of strain relaxation in the as-grown In0.25Ga0.75As film is then estimated and shown in Fig. 1. Note that the estimated relaxation is on the high side since we assume all misfit dislocations are of 90° type, which relieve misfit strain twice as effectively as compared to the 60° type. This assumption needs to be further verified.

It is found that with the decreasing thickness of the LT In0.25Ga0.75As layer, the average distance between misfit dislocations becomes larger. Hence the film is more elastically strained and less relaxed. For the 250 Å thick film, there is only 17% relaxation. Moreover, no misfit dislocation is even observed in the 125 Å thick film, indicating that most strain is elastically retained. The extent of relaxation escalates first then gradually saturates as the film thickness increases. A 98% relaxation is achieved at 5000 Å in thickness. It is believed that at this thickness the misfit strain is almost completely relieved by the generation of misfit dislocations.

The x-ray double diffraction scans about both [224] and [2 2 4] axes are performed on In0.25Ga0.75As films of 500, 2000, and 5000 Å to confirm the estimated relaxation obtained from the TEM analysis. From the x-ray data, both lateral and vertical mismatch strain of the InGaAs thin film can be determined, and the composition can be calculated with accuracy. This method and the growth calibration using RHEED intensity oscillation agree to ±2% for the indium composition. In addition, the x-ray analysis suggests that there is more relaxation in thicker In0.25Ga0.75As films and the relaxation approaches saturation after the film exceeds 2000 Å. This trend is consistent with the results obtained from TEM analysis, shown in Fig. 1. However, there is a small difference in the measured relaxation. The percentage of relaxation estimated from TEM is slightly larger than that from x-ray measurements. The difference results from our assumption of exclusive existence of 90° misfit dislocations in TEM analysis. In fact, both types of dislocations exist. Nevertheless, the small difference confirmed that most misfit dislocations are pure edge-type dislocations.

After the underlying digital Al0.98Ga0.02As layer was oxidized, the x-ray diffraction measurement of the In0.25Ga0.75As thin films was repeated. It is found that for the 500 Å thick sample, the strain relaxation increases from 24% in the as-grown sample to 44% upon lateral oxidation as shown in Fig. 1. However, for the 2000 Å thick In0.25Ga0.75As film, there is no obvious improvement in relaxation. This is due to the nearly complete relaxation (86%) already in the as-grown sample. Consequently, lateral oxidation is more effective to relieve strain when most strain in the epi-layer is still elastically retained.

Wet oxidation of the underlying AlGaAs layer not only induces strain relaxation but also leads to changes in microstructure in the overlying InGaAs layers. The changes can be seen in Fig. 2. Figure 2(a) is a XTEM micrograph of an as-grown 2000 Å In0.25Ga0.75As sample. There exist misfit dislocations at the interface between GaAs and InGaAs as well as threading dislocations in both the InGaAs and AlGaAs layers. The observed distribution of threading dislocations propagating into the substrate is consistent with the work by Krishnamoorthy et al. The average spacing among misfit dislocations is 268 Å and the density of threading dislocations is about 2 × 10^7 cm^-2. After the AlGaAs layer was oxidized, the misfit dislocations were eliminated as shown in Fig. 2(b), as most arsenic atoms in AlGaAs disappeared due to oxidation. In general, it is experimentally known that oxidation of AlGaAs leads to a volume reduction of about 10% due to material loss. It is not clear yet as to how much strain relaxation in the overlying InGaAs is induced by the volume reduction in the underlying oxide.

In addition to the elimination of misfit dislocations, it is worthy to note that the density of threading dislocations also decreases after lateral oxidation as shown in Fig. 2(b). It is found that the reduction is about an order of magnitude, independent of the initial density as shown in Fig. 3. It is believed that as the oxidation front proceeds laterally, material loss and hence volume reduction in the AlGaAs layer induce and exert a stress in the InGaAs layer to move the threading dislocations. As a result of dislocation interaction,
they annihilate each other, and the density of threading dislocations decreases. For the 500 Å In$_{0.25}$Ga$_{0.75}$As film, the density was estimated to be below $10^5$ cm$^{-2}$ in the thin layer after oxidation. The low defect density is rather attractive for the realization of minority carrier devices. However, for the 500 Å In$_{0.4}$Ga$_{0.6}$As layer, the reduced threading dislocation density after oxidation is still too high for any device application simply because of the overwhelming initial defect density.

In conclusion, the strain relaxation in low temperature grown In$_x$Ga$_{1-x}$As on GaAs is found to depend gradually on the layer thickness. For In$_{0.25}$Ga$_{0.75}$As, almost complete relaxation can be achieved when it exceeds 5000 Å. In thinner films, more strain is elastically retained and lateral oxidation of a buried AlGaAs layer help relax the strain significantly. Moreover, the lateral oxidation reduces the threading dislocations in the In$_x$Ga$_{1-x}$As film by an order of magnitude. This is a promising lattice-engineering technique to create a low-defect template for further epitaxy.

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