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Generation of the Surface Cross-Hatch Pattern in $In_xGa_{1-x}As/GaAs$ Epitaxial Layers Grown by MOCVD

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The generation of the surface cross-hatch pattern (CHP) in InGaAs/GaAs heterostructures grown by low-pressure metal-organic chemical vapor deposition method has been studied. The change in CHP under various growth conditions has been discussed. Cracks shown in the GaAs tensile layer capped on a 2.8 μm thick $In_{0.12}Ga_{0.88}As$ layer indicate that stress is concentrated at the valleys of the CHP. The CHP maintains its form throughout the growth process and the distance between the CHP valleys remains the same after a certain InGaAs layer thickness. The depth of the CHP valleys increases as the thickness of the InGaAs layer increases. We propose that the CHP is developed in the later stage of the growth by stress concentration which induces growth suppression at the CHP valleys.

1. INTRODUCTION

Epitaxial growth of lattice-mismatched III-V semiconductors is of great interest in the applications of optoelectronic and electronic devices.[1-3] InGaAs/GaAs is one of the most attractive materials due to its high electron mobility and large Γ-L valley separation. InGaAs/GaAs is often used in lasers,[1] heterojunction bipolar transistors,[2] and high electron mobility transistors.[3] However, the critical thickness (h_c) often limits the application of the large lattice-mismatched material system. The lattice mismatch between InAs and GaAs ($\Delta a/a$ = 7.16 %) commonly produces many surface defects which result in a cross-hatched surface morphology. The strain in the InGaAs layers on GaAs can be elastically accommodated only when the thickness of the $In_xGa_{1-x}As$ layer is less than the h_c for a particular InAs mole fraction. To improve the final device performance, it is crucial to decrease the number of defects. By studying the stain relief in the InGaAs/GaAs heterostructure associated with the cross-hatched surface morphology, we will be able to produce thicker epitaxial layers with high In contents.

Cross-hatch pattern (CHP) was first reported by Burmeister[4] in GaAsP/GaAs heterostructures and also investigated in other lattice-mismatched systems such as GaAs/Si[5] and InGaAs/InP.[6] Although many complicated factors appear to be involved in the generation of the CHP, surface step pile-ups resulting in the surface corrugation is the most agreeable explanation.[7,8] However, there seem to be other factors involved in the generation of the CHP, especially in the later stage of the epitaxial layer growth. In this work, the changes in the CHP in the InGaAs/GaAs material system under various growth conditions and the mechanism of the CHP during the later stage of the epitaxial growth have been examined.

2. EXPERIMENTS

Epitaxial layers of $In_xGa_{1-x}As$ have been grown on exact (100) and (100) tiled towards [110] direction GaAs substrates by low-pressure metal-organic chemical vapor deposition (MOCVD) method. The MOCVD equipment consists of a vertical growth chamber and the susceptor is rotated at 1400 rpm to insure thickness and composition uniformity. Trimethylindium and triethylgallium were used as group III sources and 100 % AsH_3 as group V source. High purity H_2 purified by a Pd-cell was used as a carrier gas. The growth temperature of the epitaxial layers varied from 495 °C to 615 °C, the V/III ratio from 78 to 108, and the indium content from 6.4 % to 30.0 %, respectively. The growth chamber pressure was 60 torr, the source line pressure was 130 torr, and the total shroud flow was 12 l/min. After a 10 minute pre-bakeout at 700 °C, a GaAs buffer layer of 0.3 μm was grown for each sample. The surface morphology and cross-section of the InGaAs/GaAs samples were studied by Nomarski optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

3. RESULTS AND DISCUSSION

Figure 1 shows commonly observed Nomarski optical micrographs of bulk InGaAs layers grown on GaAs substrates. Cross-hatch pattern (CHP) normally appears in the form of perpendicular lines on (100) surfaces aligned in the $[0\bar{1}\bar{1}]$ direction as shown in Fig. 1 (a). For the layers grown on misoriented GaAs substrates, CHP appears as a network of crossing lines in directions of $[0\bar{1}\bar{1}]$ and $[0\bar{1}1]$ as shown in Fig. 1 (b). Figure 2 shows the surface morphology

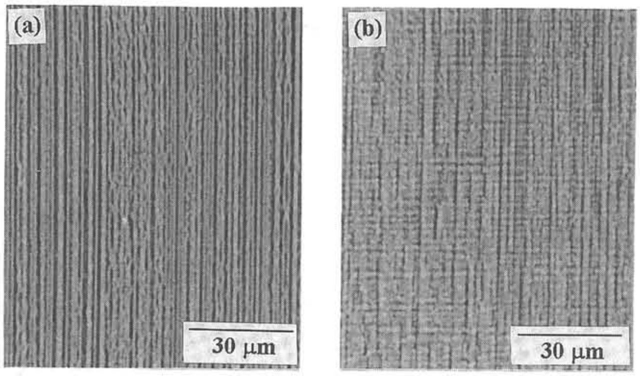

Fig. 1. Normarski optical micrographs of $In_{0.12}Ga_{0.88}As$ layers grown on (a) an exact (100) GaAs substrate and (b) a (100) 2° off toward [110] GaAs substrate at 555°C.

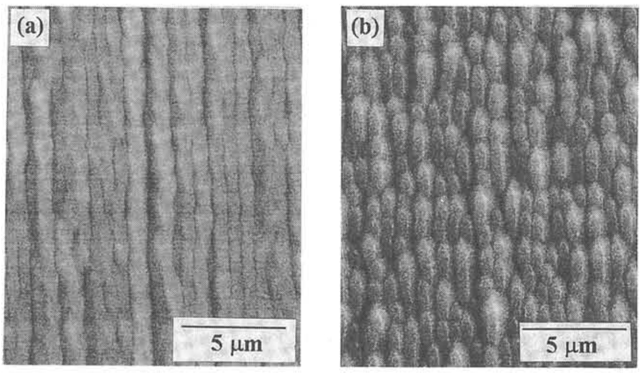

Fig. 2. SEM micrographs of $In_xGa_{1-x}As$ layers grown on GaAs at 555 °C where (a) x = 0.11 and (b) x = 0.30.

of $In_xGa_{1-x}As$ layers grown on GaAs at 555 °C with varying In content. At low In contents, straight CHP lines are aligned in the $[0\bar{1}\bar{1}]$ direction and at higher In contents, elongated island-like pattern is shown. Figure 3 shows the surface CHP of $In_{0.12}Ga_{0.88}As$/GaAs at different growth temperatures. As the growth temperature increases, the distance between the CHP lines increases. A clearer and distinct CHP is shown for the sample grown at a higher temperature. As shown in the above results, various forms of CHP appear in the growth of InGaAs/GaAs heterostructures depending on the growth condition.

Kavanagh *et al.*[8] suggested that surface corrugation which developed from the surface steps created by dislocation formation at the interface were observed in a 1 μm thick $In_{0.15}Ga_{0.85}As$/GaAs layer. The amplitude and distance between the CHP lines were approximately 120 nm and 375 nm, respectively. However, for the sample studied in this work, the depth of the CHP valleys was approximately 200 nm and the average distance between the CHP lines was 830 nm. Both amplitude and distance of the CHP valleys shown in our sample are greater than values of the CHP formed by surface step pile-ups. Therefore, we presume that there must be other factors besides the surface step formation involved in the development of the CHP which increases the depth and distance of the CHP valleys. It is well known that samples experiencing uniaxial or biaxial stress showing surface notches exhibit stress concentration at the notch tip.[9] Therefore, it is reasonable to believe that certain amount of stress is concentrated at the valleys of the CHP.

In order to verify the stress concentration at the CHP valleys, an $In_{0.12}Ga_{0.88}As$ layer with a thickness of 2.8 μm was grown on an exact (100) GaAs substrate. A GaAs layer with a thickness of 0.3 μm was grown on InGaAs as a cap layer. The cross-sectional TEM micrograph in Fig. 4 shows cracks at the valleys of the CHP in the tensile GaAs cap layer. From this result, we conclude that at the growth temperature, the sample exhibits a wavy surface with stress concentrated at the valleys and as the temperature is cooled down to room temperature, cracks occur at the CHP valleys in the tensile layer to relief strain. Bulk InGaAs layers grown on GaAs has been known to undergo 70 % in-plane relaxation with residual strain still remaining in the epitaxial layer.[10] Therefore, we conclude that the residual strain remaining in the InGaAs layer is not uniformly distributed throughout the layer but is concentrated at the valleys of the CHP.

In Fig. 4, there are also dark lines (marked by arrows) bellow each crack extended from the (GaAs cap)/(InGaAs) interface into the InGaAs layer. These lines were observed by high resolution TEM and no defect formation was found near or at the lines. Therefore, we predict that these lines indicate non-uniform alloy distribution, most likely Ga or In concentrated at the lines. We also note that these lines do not extend all the way to the (InGaAs)/(GaAs buffer layer) interface and stop at the InGaAs layer thickness of approximately 1 μm. These dark lines indicate that the valley of the CHP maintained its position from the early stage of growth. The skeleton of the CHP is formed after a

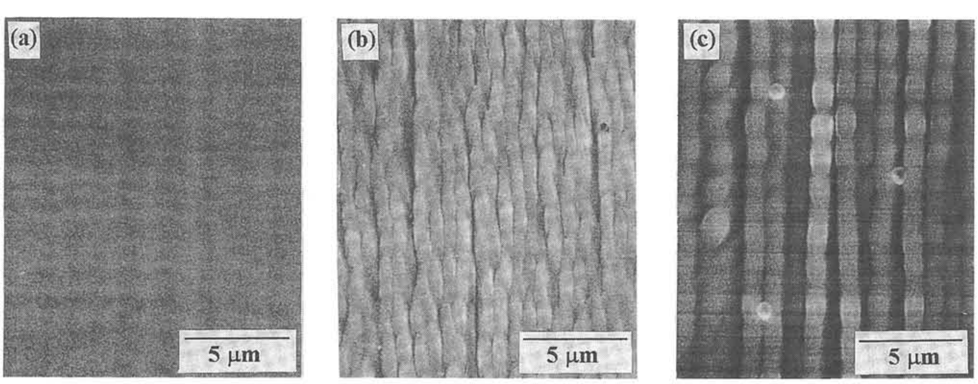

Fig. 3. SEM micrographs of $In_{0.12}Ga_{0.88}As$ layers grown on GaAs at (a) 495 °C, (b) 555 °C, and (c) 615 °C.

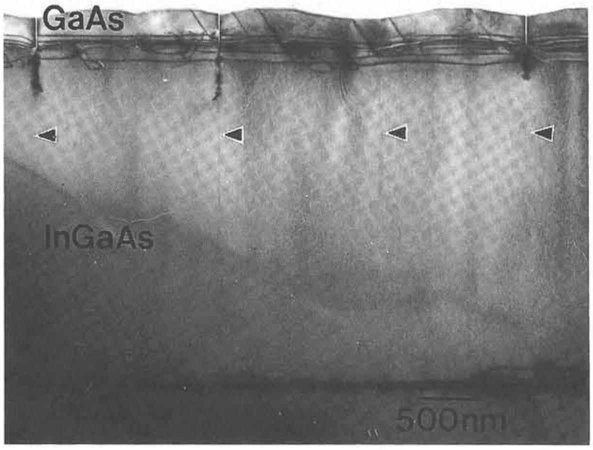

Fig. 4. Cross-sectional TEM micrograph of a 0.3 μm thick GaAs cap layer and a 2.8 μm thick $In_{0.12}Ga_{0.88}As$ layer grown on an exact (100) GaAs substrate.

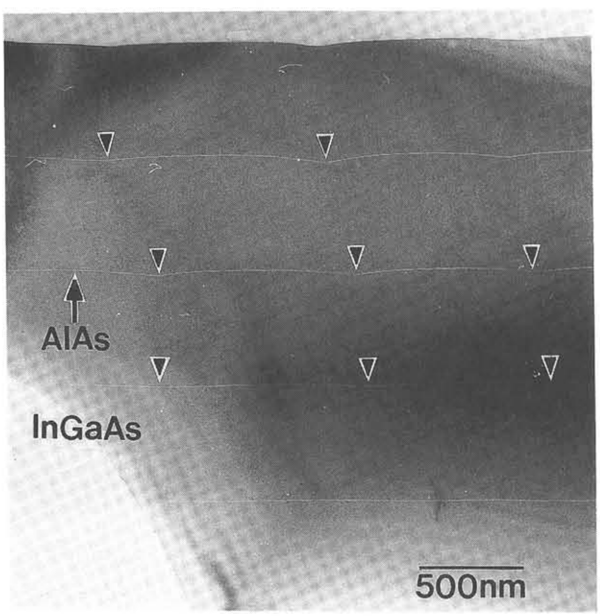

Fig. 5. Cross-sectional TEM micrograph of an $In_{0.12}Ga_{0.88}As$ layer with four AlAs mark layers with thicknesses of 300 nm grown at an interval of 0.5 μm on a misoriented GaAs substrate.

certain InGaAs layer thickness and then maintained its form throughout the growth process.

To study the development of the CHP valleys, we inserted four AlAs mark layers with a thickness of 300 nm in the growth of an $In_{0.12}Ga_{0.88}As$ layer with a total thickness of 2.5 μm. The AlAs mark layers were grown at an interval of 0.5 μm thick InGaAs layer. The TEM micrograph in Fig.5, shows that the CHP valleys maintained its position fairly well throughout the growth process. It is also shown that the depth of the CHP valleys increases as the epitaxial layer becomes thicker. The increment of the valley depth is significant at the second mark layer, at an InGaAs layer thickness of 1 μm. Coincidentally, the results of both Figs. 4 and 5 show that noticeable CHP valleys appear after an InGaAs layer thickness of 1 μm. We conclude that the CHP is initially generated by surface step pile-ups during the initial stage of the epitaxial growth of InGaAs layers where rapid strain relaxation occurs. After a certain InGaAs layer thickness (1 μm in this work), significant increase in the development of the CHP occurs by growth suppression at the CHP valleys where surface nucleation of defects is limited.

4. CONCLUSION

The change in the CHP for $In_xGa_{1-x}As/GaAs$ grown by MOCVD under various growth conditions has been studied. The surface of a sample with higher In content (InAs = 30.0 %) show elongated island-like pattern with CHP valleys aligned in both directions of $[0\bar{1}\bar{1}]$ and $[0\bar{1}1]$. At lower In content (InAs = 11.0 %), straight CHP lines are aligned in the $[0\bar{1}\bar{1}]$ direction. As the growth temperature increases, the CHP becomes more distinct and the distance between the CHP lines increases.

Cracks generated in the tensile cap layer grown on a bulk InGaAs layer clearly indicate stress concentration at the CHP valleys. The depth of the CHP valleys increases due to stress concentration. We believe that the CHP is initially generated by the surface step pile-ups where rapid strain relaxation occurs. However, after most of the strain has been released, stress concentration which induces growth suppression is the dominant factor in the later development of the CHP.

5. REFERENCES

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