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Evolution of the surface cross-hatch pattern in $In_xGa_{1-x}As/GaAs$ layers grown by metal-organic chemical vapor deposition

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The evolution of the cross-hatch pattern (CHP) in $In_xGa_{1-x}As/GaAs$ heterostructures has been studied. It is found that stress is concentrated at the valleys of the CHP from the results of crack formation at the CHP valleys in the thick GaAs cap layer grown on an InGaAs layer. Residual strain in the InGaAs/GaAs epitaxial layer showing a CHP is confined along the valleys of the CHP with a nonuniform distribution throughout the epitaxial layer. The skeleton of the CHP is formed at the beginning of the rapid strain relaxation period and the depth of the CHP valleys increases after most of the strain has been released. We propose that the development of the CHP in the later stage of the growth takes place by the growth suppression at the CHP valleys due to the high level of stress concentration. © *1996 American Institute of Physics.* [S0003-6951(96)02401-3]

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. The InGaAs/GaAs system is often used in lasers[1] and photodetectors[2] in the near-infrared, and in high electron mobility transistors.[3] However, the large lattice mismatch between InAs and GaAs ($\Delta a/a=7.16\%$) commonly results in a nonuniform surface morphology and creates defects at the InGaAs/GaAs interface. The strain in InGaAs layers on GaAs can be elastically accommodated only when the thickness of the $In_xGa_{1-x}As$ layer is less than the critical thickness (h_c) for a particular InAs mole fraction. The trend in the InGaAs/GaAs application is to increase the In content and epilayer thickness in excess of h_c. Thus, a precise control of the growth parameters to produce high quality crystal structures with a minimum number of misfit dislocations is crucial. The study on strain relief in the InGaAs/GaAs heterostructure associated with the cross-hatched surface morphology is essential for improving the final device performance.

Cross-hatch pattern (CHP) was first reported by Burmeister,[4] in the GaAsP/GaAs heterostructure and also investigated in other lattice-mismatched systems such as GaAs/Si (Ref. 5) and InGaAs/InP.[6] The generation of the CHP has also been extensively discussed. It was suggested that the CHP in the lattice-mismatched system was initiated from the nonuniform lateral growth induced by the impurity concentration near the dislocation sites,[7] the dislocation motion induced by the thermodynamic instability,[5] and the accelerated crystal growth and growth perturbations.[8] Recently, Chang *et al.*[9] suggested that the CHP in the InGaAs/GaAs system was directly related to the generation of misfit dislocations and the surface step pileup during growth. Many complicated factors seem to be involved in the generation of the CHP and it appears to be difficult to trace the evolution process in detail. Therefore, in this work, we have attempted to study the evolution of the CHP in several bulk and multilayer InGaAs/GaAs structures. We will examine the mechanism of the CHP in the InGaAs/GaAs material system during the later stage of the epitaxial growth.

Heteroepitaxial layers of $In_xGa_{1-x}As/GaAs$ were grown by the low-pressure metalorganic chemical vapor deposition (MOCVD) method. The MOCVD equipment consists of a vertical growth chamber and a susceptor which is rotated at ~1400 rpm during growth to ensure the thickness and composition uniformity. For the alkyl source (group III), trimethylindium and triethylgallium were used and for the hydride source (group V), 100% AsH_3 was used. High purity H_2 was used as a carrier gas. The V/III ratio was ~100, the growth chamber pressure was 60 Torr, the source line pressure was 130 Torr, and the total carrier gas flow was 12//min. Two types of GaAs substrates, at exact (100) orientation and misoriented (100) tilted by 2° toward [110], were used. Precleaned epiready GaAs substrates were used to reduce any complications in studying the surface morphology. After a 10 min prebake out at 700 °C, a GaAs buffer layer of 3000 Å was grown for each sample. The growth temperature of the buffer layer and InGaAs layer was 555 °C. The surface morphology and cross section of the InGaAs/GaAs samples were studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

Figure 1 shows a commonly observed surface morphology of a thick $In_{0.12}Ga_{0.88}As$ (~2.5 μm) layer ($\Delta a/a=0.86\%$) grown on an exact (100) GaAs substrate. CHP normally appears as a network of crossing lines in directions of $\langle 011\rangle$.[9] Kavanagh *et al.*[10] suggested that surface corrugations 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 where the amplitude and distance between the CHP lines were ~120 and 375 nm, respectively. However, in the sample shown in Fig. 1, the

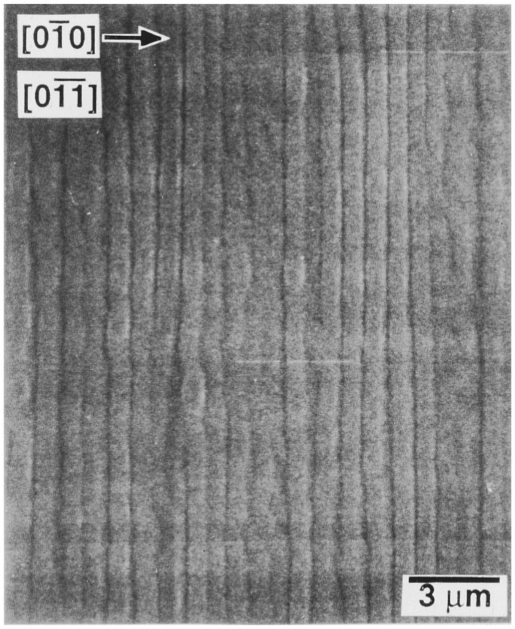

FIG. 1. SEM micrograph of an $In_{0.12}Ga_{0.88}As$ layer with a thickness of 2.5 μm grown on an exact (100) GaAs substrate at 555 °C.

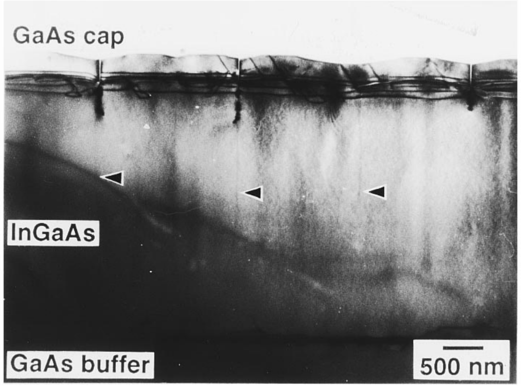

FIG. 2. Cross-sectional TEM micrograph of a 3000 Å thick GaAs cap layer and a 2.8 μm thick $In_{0.12}Ga_{0.88}As$ layer grown on an exact (100) GaAs substrate.

depth of the CHP valley is ~200 nm and the average distance between the CHP lines is 830 nm. Both amplitude and distance between the CHP valleys shown in Fig. 1 are larger than those presumably formed by surface step pileups. The grooves in the CHP shown in Fig. 1 are believed to have become deeper during the later stage of the epitaxial growth where most of the strain has already been released by the generation of surface steps. It is well known that material under uniaxial or biaxial stress showing a surface notch exhibits stress concentration at the notch tip.[11] Therefore, we propose that this deepening of grooves is a result of the stress concentration at the CHP valleys in the later stage of the growth.

In order to verify the stress concentration at the valleys of the CHP on the InGaAs layer, a sample was grown with a GaAs cap layer of 3000 Å and a 2.8 μm $In_{0.12}Ga_{0.88}As$ layer on an exact (100) GaAs substrate. A thick GaAs cap layer was grown on purpose to study the strain relief mechanism in the tensile layer. The cross-sectional TEM micrograph in Fig. 2 shows cracks at the valleys of the GaAs cap layer. We believe that at the growth temperature, the GaAs cap layer is under tensile stress and the stress is concentrated at the CHP valleys. As the temperature decreases to room temperature, cracks occur at the stress concentrated dark region. The bulk InGaAs/GaAs has been known to undergo 70% relaxation with residual strain still remaining in the epitaxial layer.[12] From the results in Fig. 2, 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. 2, we can also see that straight dark lines (marked by arrows) extend from the (GaAs cap)/(InGaAs) interface into the InGaAs layer just below each crack. These lines can be traces of impurity or strain field at the CHP valleys. However, high resolution TEM of this sample shows no trace of defect formation near or at the lines and therefore, we presume that these dark lines indicate nonuniform distribution of alloy composition with excess In or Ga at the lines. These lines do not extend all the way to the InGaAs/GaAs buffer layer interface but only to the InGaAs layer with a thickness of ~1 μm. These dark, straight lines clearly show that the valley of the CHP has maintained its position throughout the growth process. From the results in this and previous works, we suggest that the skeleton of the CHP network is formed after the InGaAs layer reaches its critical thickness and when a great number of dislocations are generated from the surface,[9,10] and after an InGaAs layer thickness of 1 μm, the CHP maintains its form throughout the growth process.

To study the development of the CHP valleys, we inserted four AlAs mark layers with a thickness of 30 Å during the growth of a 2.5 μm thick $In_{0.12}Ga_{0.88}As$ layer with an interval of ~5000 Å as shown in the cross-sectional TEM micrograph in Fig. 3. As seen in Fig. 3, the valleys of the CHP maintain their position (indicated by arrows) fairly well during growth. It is also shown that the depth of the valleys increases as the epitaxial layer becomes thicker. It is well

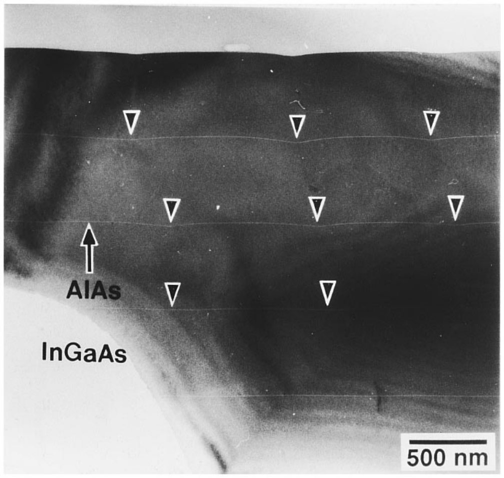

FIG. 3. Cross-sectional TEM micrograph of an $In_{0.12}Ga_{0.88}As$ layer with four AlAs mark layers with thicknesses of 30 Å grown at an interval of 5000 Å on a misoriented GaAs substrate.

known that most of the strain in the InGaAs/GaAs material system is received when the InGaAs layer thickness exceeded ~5000 Å for most of the InAs mole fraction.[12] Thus, in the sample shown in Fig. 3, we propose that the valleys of the cross-hatch lines are developed significantly in the later stage of the strain relaxation in which the generation of the surface steps is reduced and most of the strain has already been released. Furthermore, in this later stage, the misfit strain is mainly relaxed by the dislocation multiplication at the interface and not by the nucleation at the surface. We note that the increment of the valley depth becomes significant from the second mark layer (1.0 μm thickness of InGaAs layer) and the dark lines shown in Fig. 2 also start from an InGaAs layer thickness ~1 μm. Therefore, we presume that both of these results stem from of the stress concentration at the CHP valleys.

Previous works reported only the surface step pileups resulting in the CHP and surface corrugations. However, from the results shown in this work, we conclude that once the skeleton of the CHP is formed, most likely due to the surface step pileups, the CHP is developed by the growth suppression at the valleys of the CHP due to high stress concentration. A study on the continuous accumulation of stress at the CHP valleys is yet to be conducted. We assume that the stress concentration at the CHP valleys either promotes or is produced from the three-dimensional growth of the InGaAs layer. Further study is required to related the CHP evolution to the growth mode in the InGaAs/GaAs material system.

In conclusion, the evolution of the cross-hatch pattern has been studied by observing bulk InGaAs layer with a thick tensile cap layer and thin AlAs mark layers. The cracks at the valleys of the CHP in the tensile GaAs cap layer clearly indicate that stress is concentrated at the valleys. Thus, residual strain remaining in the bulk InGaAs/GaAs sample is expected to be confined at the CHP valleys. The CHP valley maintains its position during the growth of a thick InGaAs layer and the depth of the valleys increases in the later stage of the growth. The results suggest that the skeleton of the CHP is formed at the beginning of the growth where rapid lattice relaxation occurs by the nucleation of misfit dislocations from the film surface. After most of the strain is released, the CHP is developed further by the growth suppression at the valleys due to stress concentration in the later stage of the growth.

[1] M. Grundmann, U. Lienert, J. Christen, D. Bimberg, A. Fischer-Colbrie, and J. N. Miller, J. Vac. Sci. Technol. **8**, 751 (1990).
[2] A. F.-D. Chin and P. Bhattacharya, IEEE Trans. Electron Devices **36**, 2183 (1989).
[3] J. M. Ballingall, P. Ho, G. J. Tessmer, P. A. Martin, N. Lewis, and E. L. Hall, Appl. Phys. Lett. **54**, 2121 (1989).
[4] R. A. Burmeister, G. P. Pighini, and P. E. Greene, Trans. TMS-AIME **245**, 587 (1969).
[5] T. Nishioka, Y. Itoh, A. Yamamoto, and M. Yamaguchi, Appl. Phys. Lett. **51**, 1928 (1987).
[6] A. Salokatve and M. Hovinen, J. Appl. Phys. **67**, 3378 (1990).
[7] S. Kishino, M. Ogirima, and K. Kurata, J. Electrochem. Soc. **119**, 618 (1972).
[8] G. H. Olsen, J. Cryst. Growth **31**, 223 (1975).
[9] K. H. Chang, R. Gibala, D. J. Srolovitz, P. K. Bhattacharya, and J. F. Mansfield, J. Appl. Phys. **67**, 4093 (1990).
[10] K. L. Kavanagh, M. A. Capano, and L. W. Hobbs, J. Appl. Phys. **64**, 4843 (1988).
[11] F. A. McClintock and A. S. Argon, *Mechanical Behavior of Materials* (Addison Wesley, Reading, MA, 1966), p. 393.
[12] V. Krishnamoorthy, Y. W. Liu, L. Calhoun, H. L. Liu, and R. M. Park, Appl. Phys. Lett. **61**, 2680 (1992).