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In Situ Surface Roughness Analysis of InGaAs Layers Grown on GaAs by MBE

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Abstract: An optical investigation of the surface roughness which arises when InGaAs is grown on GaAs is performed in situ. This analysis provides a measurement of the InGaAs critical layer thickness, establishing some correlation between the surface roughness and the misfit dislocations created to relieve the strain in the InGaAs layer.

1. INTRODUCTION

Surface roughness develops rapidly on lattice-mismatched epitaxial material. This roughness can be easily observed by optical microscopy or SEM when the mismatched layer is thick enough. For relatively low misfits ($f<0.02$), surface ridges aligned with crystallographic directions, so called cross hatch, are frequently observed as shown in Fig.1, but their origin is poorly understood. To clarify their origin, we performed a new in situ analysis of the surface roughness of $In_yGa_{1-y}As$ single layers grown on (001) oriented GaAs substrates. The InGaAs/GaAs system has already been extensively studied for its potential application in optoelectronics. Critical InGaAs layer thickness for misfit dislocation generation has given rise to some controversy[1]. The present work gives some more informations to understand the relaxation mechanism for this system.

2. METHOD OF IN-SITU ROUGHNESS MONITORING

A laser beam was used to detect the onset of the InGaAs layer surface roughness. We applied this analysis to the low misfit case ($0<y<0.20$), while a cross-hatched surface is developing. A schematic illustration of the in situ analysis is shown on Fig.2. A conventional MBE apparatus was set up with two viewports having assymetric positions relative to the substrate. A 10-mW-HeNe laser beam was directed at the sample surface through the first viewport. The light scattered by the sample roughness toward the second viewport was detected with a photomultiplier. Lock-in detection was not found to be necessary. The other sources of light in the MBE

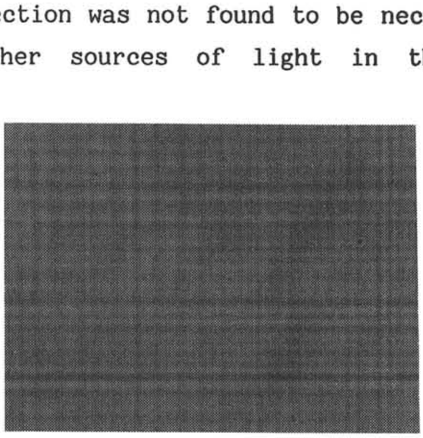

Fig.1 Typical cross-hatched morphology of an InGaAs layer grown on GaAs.

system were minimized during the measurements, and the background intensity detected by the photomultiplier mainly came from parasitic reflections of the laser light itself.

When a cross-hatch pattern is formed on the sample surface, it acts like a two-dimensional random grating for the incident light. In such a case, it is observed that the scattered light confined into two particular planes as shown in Fig.2. By rotating the sample, this diffracted pattern also rotates as changing its shape. Even if there is no grating-like pattern on the surface, the roughness aligned with some crystallographic direction will give preferential directions for light scattering. Therefore, by monitoring the scattered (or diffracted) light while rotating the sample, the roughness can be characterized as a function of its azimuthal orientation.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 3 shows the evolution of the azimuthal spectra of the scattered light intensity obtained during the growth of $In_{0.175}Ga_{0.825}As$ on GaAs. The experimental procedure was the following: InGaAs growth was initiated on a GaAs buffer layer at 500°C. The growth was periodically interrupted to record the scattered light intensity during one full rotation of the sample. By this way, the roughness was characterized as a function of its azimuthal orientation at several $In_yGa_{1-y}As$ layer thicknesses.

After exceeding a critical thickness, the onset of a cross-hatched roughness was clearly identified by peaks coming out of the background intensity. We were able to determine this critical layer thickness (CLT) with an accuracy of 25 Å as seen on Fig.3.

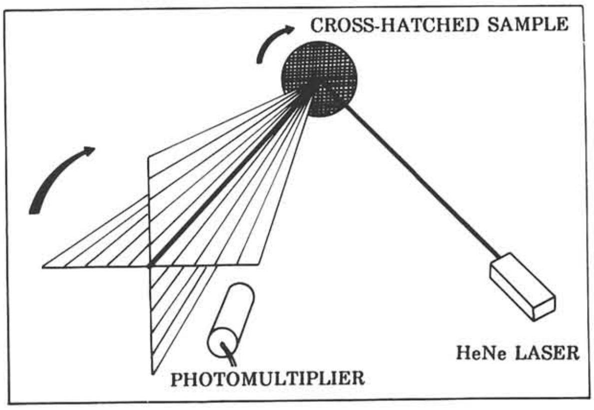

Fig.2 Schematic illustration of the in situ analysis.

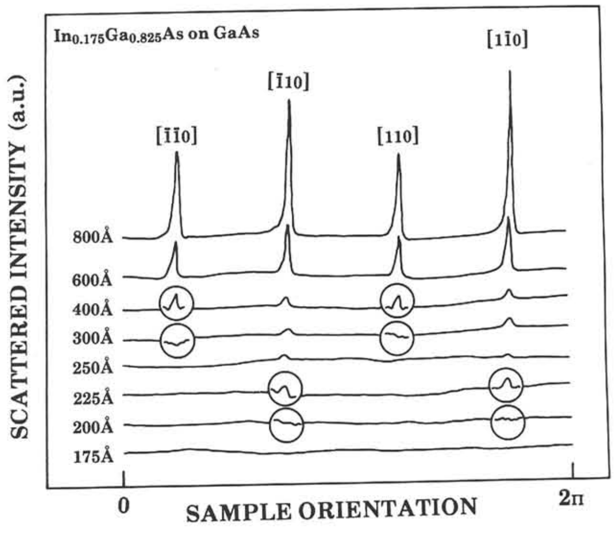

Fig.3 Azimuthal spectra of the scaterred light intensity obtained during the growth of $In_{0.175}Ga_{0.825}As$ on GaAs. The total InGaAs layer thickness is indicated for each spectrum. The intensity is magnified by a factor of 5 in the encircled insets.

We compared this CLT, measured for several compositions y, with the CLT for the generation of misfit dislocations. This latter CLT has been determined by other authors using photoluminescence[2] or photoluminescence microscopy[1]. These measurements are highly sensitive to the presence of misfit dislocations. The results are plotted in Fig.4. It is obvious that these approaches yield equivalent CLT. Therefore, it indicates that roughness lines (RL) are developing at the earliest stage of the relaxation process, as soon as the first dislocations are generated.

This in situ roughness monitoring turns out to be a simple, rapid, and reliable tool to measure the CLT of mismatched epilayers (f<0.02). We estimated its sensitivity by post growth roughness measurements. We grew a 60-nm-thick $In_{0.15}Ga_{0.75}As$ layer on GaAs. The CLT of this sample was determined to be 32.5 nm by our method. Then, the surface roughness of the 60-nm-thick layer was evaluated by talystep measurement. Figure 5 shows a surface profile of this sample along the [110] direction. The roughness lines which are most clearly detected are roughly 1nm in height, with an average spacing around 50 µm. This height is equivalent to 3 monolayers. It means that the in situ analysis is sensitive to an initial roughness which is less than 3 monolayers. Probably 1- or 2-monolayer roughness can scatter enough light to be identified by our method. This surprizing result comes from the directional characteristic of the roughness which confines the scattered energy in preferential directions and makes it easily detectable.

Figure 3 suggests other important facts: [1$\bar{1}$0] RL are first formed. As the mismatched thickness increases, the amplitude of the scattered light increased rapidly, [1$\bar{1}$0] RL having a higher diffraction efficiency than [110] RL. This is likely due to assymetric dislocation densities or assymetric adatom diffusion length along these directions. Similar results were reported in Ref.3 where the assymteric dislocation density was observed and explained by the different nature of dislocation along these directions.

It is also interesting to note that the cross hatch is not formed for y>0.25. The roughness becomes more uniform and it loses its directional characteristic. Then the sensitivity of our analysis is drastically affected, and it makes our experiment inadequate to measure the CLT of dislocations in this material system. Several authors reported that when 0<y<0.2, most of dislocations are 60° mixed dislocations running near the InGaAs/GaAs interface[3]. But for higher indium compositions, edge dislocations are also observed and many dislocations thread toward the surface[4].

Therefore, we think the cross hatch is correlated to an orthogonal array of 60° mixed dislocations confined at the mismatched interface The directions of the

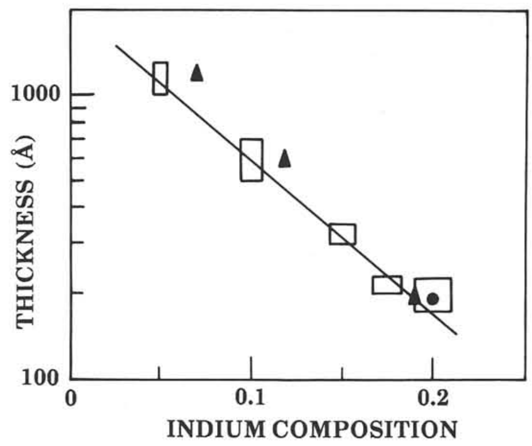

Fig.4 Critical layer thickness for the onset of roughness vs the indium composition. The results are plotted as error areas. The critical layer thickness for the generation of dislocations determined by Gourley et al[1](●) and Morris et al[2] (▲) is also shown.

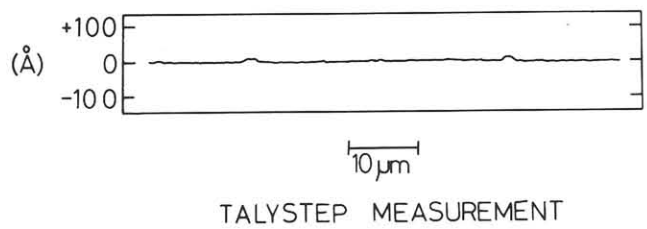

Fig.5 Talystep profile of a 60nm-thick-$In_{0.15}Ga_{0.85}As$ layer grown on GaAs.

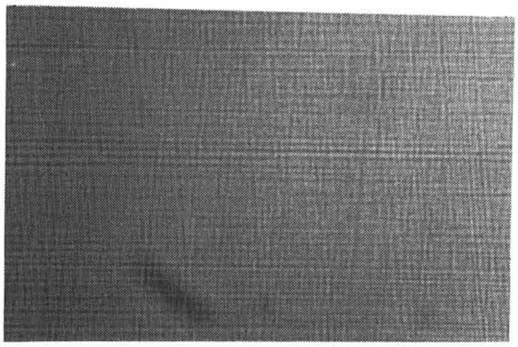

Fig.6 Cross-hatched morphology of InGaAs grown on a misoriented (001) GaAs substrate. The misorientation angle is 6° toward (111).

RL correspond to the trace of the gliding planes of 60° type dislocations, it means the {111} planes. This correspondence is more evident if we consider the cross hatch morphology of an InGaAs layer grown on a slightly misoriented GaAs substrate. Figure 6 shows the cross hatch developped on a (001) off surface with a misorientation angle $\varepsilon=6°$ toward (111). (111) planes and $(\bar{1}\bar{1}1)$ planes intersects the surface in the $[1\bar{1}0]$ direction, but $(\bar{1}11)$ planes and $(1\bar{1}1)$ planes have two different traces forming an angle α. Simple geometrical considerations lead to the following relation: $\tan(\alpha/2)=(\sin\varepsilon)/\sqrt{2}$. The roughness lines lie in the same directions: $[1\bar{1}0]$ and two other directions forming the angle α as seen in Fig.6.

We propose the following model to explain the origin of the cross-hatched morphology. At the initial stage, the relaxation mechanism is not uniform due to pairing or grouping of 60° misfit dislocations. Recently, Grundmann et al.[5] observed the coexistence of strained and fully relaxed domains in a 38-nm-thick $In_{0.23}Ga_{0.77}As$ quantum well grown on GaAs. Grouping of dislocations was observed in other mismatched systems[6]. Consequently, the sample surface exhibits isolated relaxed domains. These domains are probably band-shaped and their directions follow the directions of the dislocation lines. The probability of incorporating In and Ga atoms with the composition y on these domains becomes higher than on the remaining strained surface. It results in higher local growth rates and ridges are formed.

4. CONCLUSIONS

We have performed an optical in-situ analysis of surface roughness during the lattice-mismatched growth of InGaAs on GaAs substrate. This analysis was found to be sensitive to the roughness less than 3 monolayers and applicable to the determination of the critical layer thickness. The roughness formation was observed to be assymetrical between the two [110] directions, suggesting the different nature of dislocation or different adatom diffusion length along these directions.

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REFERENCES

1) P.L.Gourley, I.J. Fritz, and L.R. Dawson, Appl. Phys. Lett. **52** (1988) 377

2) D. Morris, A.P. Roth, R.A. Masut, C. Lacelle, J.L. Brebner, J Appl.Phys.**64** (1988) 4135

3) K.L. Kavanagh, M.A. Capano, L.W. Hobbs, J.C. Barbour, P.M.J. Maree, W. Schaff, J.W. Mayer, D. Pettit, J.M. Woodall, J.A. Stroscio and R.M. Feenstra, J. Appl. Phys. 64 (1988) 4843

4) K.H. Chang, P.K. Bhattacharya and R. Gibala, J. Appl. Phys. **66** (1989) 2993

5) M. Grundmann, U. Lienert, D. Bimberg, A. Fischer-Colbrie and J.N. Miller, Appl. Phys. Lett. **55** (1989) 1765

6) H. Strunk, W. Hagen and E. Bauser, Appl. Phys. **18** (1979) 67