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Anomalous Step Bunching of a Strained InGaAs Epitaxial Layer Grown on an Off-Angled GaAs Substrate

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The detailed dependence of strained InGaAs surface structure on substrate off-angles and off-directions is investigated using a newly developed technique to obtain a gradual change in off-angles on the same GaAs (001) substrate. It has been found that the strained InGaAs layers grown on 0.5° ~1.5° off-angled positions are corrugated into 3-D islands characterized by the plateau-type for the [1̄10] off-direction and the round terrace-type for the [110] off-direction. These anomalous surface evolutions may be explained using strain-assisted step bunching and exclusive growth on strain-alleviated areas.

1. Introduction

Recently, step bunching of GaAs epitaxially grown on off-angled substrates has been investigated using atomic force microscopy (AFM)[1,2]. Similar step bunching was reported for strained InGaAs grown on off-angled GaAs substrates and the effect of the step bunching on electrical properties in pseudomorphic HEMTs[3] and optical properties in strained quantum-well structures[4] have been discussed. However, the detailed behavior and mechanism of step bunching formation in the strained layers have not yet been sufficiently understood in comparison with those in the unstrained layers.

This paper reports on a detailed study of step bunching for strained InGaAs layers as a function of off-angles and off-directions. The difficulty of preparing GaAs substrates in a variety of off-angles and off-directions was solved using a novel technique to obtain a gradual change in off-angles in every direction on the same substrate. A fundamental difference is revealed in corrugation shapes, bunching periods, and surface roughness between the strained InGaAs layers and the unstrained GaAs layers.

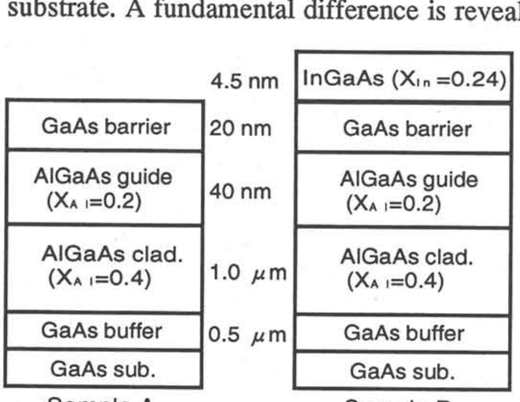

Fig. 1 Studied structures.

2. Experimental

Spherically patterned (001) GaAs substrates were prepared using a microlens fabrication process[5]. First, circular mesas were formed using wet etching involving SiO_2 mask patterns. After removal of the SiO_2 masks, spherical surfaces were obtained using a second etching. On the substrates two types of layer structures were grown for the surface structure evaluation as shown in Figure 1. The top layer of sample A, corresponding to the barrier layer for the laser diode structure[6], was 20-nm-thick GaAs grown on the AlGaAs guide

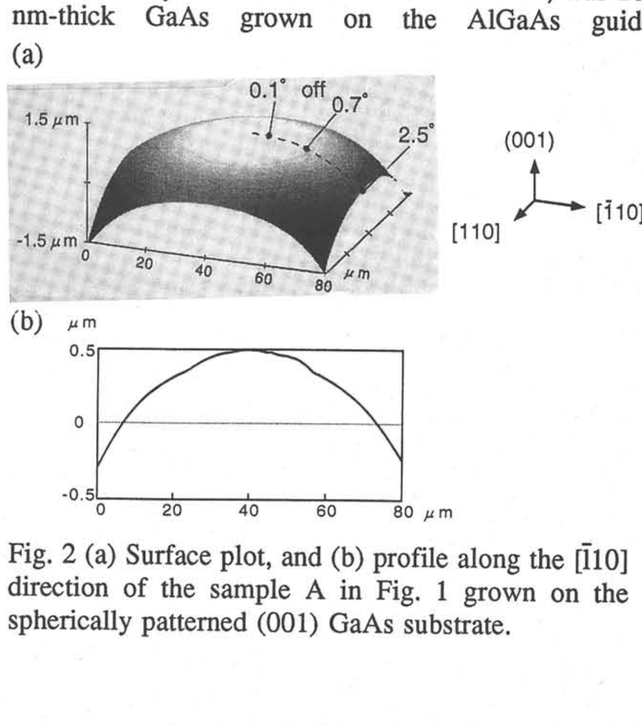

Fig. 2 (a) Surface plot, and (b) profile along the [1̄10] direction of the sample A in Fig. 1 grown on the spherically patterned (001) GaAs substrate.

layer/AlGaAs cladding layer/GaAs buffer layer. The top layer of sample B, corresponding to the active layer for the laser diode structure, was 4.5-nm-thick strained InGaAs grown on the same layer structure as sample A. All of the layers were grown using atmospheric-pressure metalorganic vapor-phase epitaxy. Trimethylgallium (TMG), trimethylindium (TMI), trimethylaluminum (TMA), and AsH_3 were used as the source materials. The growth temperature was 610°C and the vapor pressure ratio of group V/group III raw materials was 20, during the growth of the GaAs barrier layer and the InGaAs layer. After growth, the samples were cooled down in 3 minutes to under 400°C in an AsH_3 atmosphere. The top surfaces of the samples were investigated on an AFM system in air.

Figure 2(a) shows an AFM surface plot of the sample A grown on the spherically patterned substrate. Figure 2(b) shows an AFM profile of the same sample along the $[\bar{1}10]$ direction including the (001) just position (top of the sphere). In the region where a distance from the (001) just position is from 15 μm to 40 μm, off-angles change from 0.7° to 2.5° without complication depending on the positions. Off-angle change within a distance of 15 μm from the (001) just position incurred some complications, however, off-angles in this area could be estimated using the inclination of (001) terraces in AFM profiles.

3. Results and Discussion

3.1 Step bunching observed using AFM surface plots

The surfaces of the GaAs and InGaAs layers with various off-angled positions were measured using a scanning area of 500 nm × 500 nm.

Monolayer steps were observed on both the GaAs and InGaAs layers for off-angles smaller than 0.2°, irrespective of the off-directions, which confirmed that InGaAs growth as well as GaAs growth proceeded layer by layer.

Figure 3(a) through 3(f) show the AFM surface plots of GaAs and strained InGaAs grown on various off-angled positions. Off-directions are represented by "A" and "B" for [110] and $[\bar{1}10]$, respectively, following the surface material compositions and off-angle values. At a 0.6°-off-angled position for GaAs, a relatively flat surface was maintained containing several 2-monolayer-height multisteps (Fig. 3(a)). When the off-angle increased to 2.5° , a typical periodic step bunching appeared with a roughness of 3~4 monolayer-heights (Fig. 3(b)). For InGaAs grown on the surface off-angled in the $[\bar{1}10]$ direction, periodically spaced 3-D islands extending along the [110] direction were observed at a 0.7°-off-angled position (Fig. 3(c)). These 3-D islands had descending multistep-sidewalls on both sides of the (001) plateaus. This anomalous step bunching was not found on the unstrained GaAs surfaces. As the off-angle increased, total area occupied by the plateau-type 3-D islands was reduced, and the steep step bunching, which formed multisteps descending only in the off-direction, was observed (Fig. 3(d)). For InGaAs grown on the surface off-angled in the [110] direction, (001) terraces with periodically wavy edges along the $[\bar{1}10]$ direction were observed at a 0.8°-off-angled position (Fig. 3(e)). The delaying part of the wavy terrace edges had steps closely bunched and the other part of the terrace edges had steps flowing on the preceding terraces, which formed round terrace-type 3-D islands. As the off-angle increased, the terrace edges became straighter along the $[\bar{1}10]$ direction (Fig. 3(f)).

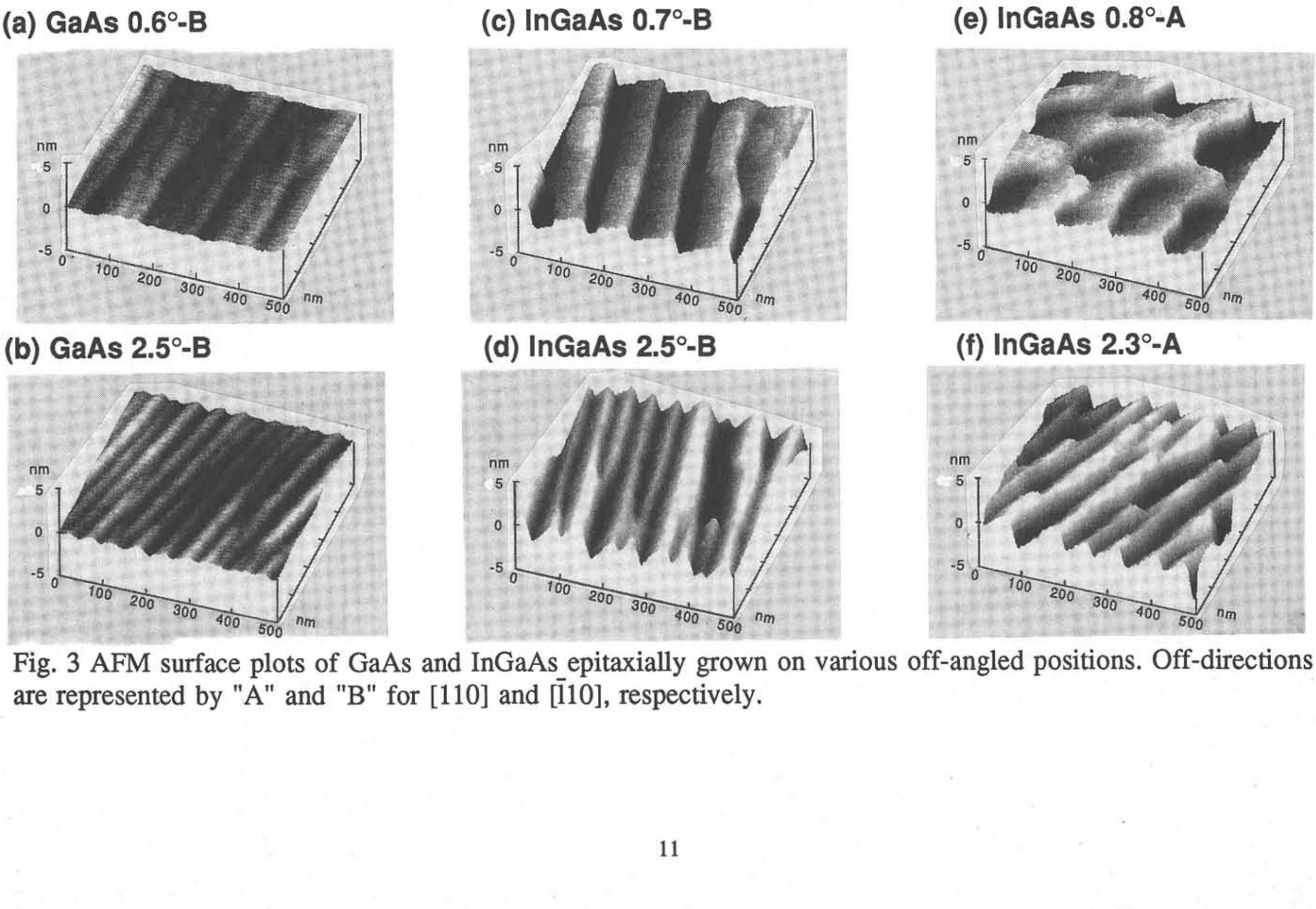

Fig. 3 AFM surface plots of GaAs and InGaAs epitaxially grown on various off-angled positions. Off-directions are represented by "A" and "B" for [110] and $[\bar{1}10]$, respectively.

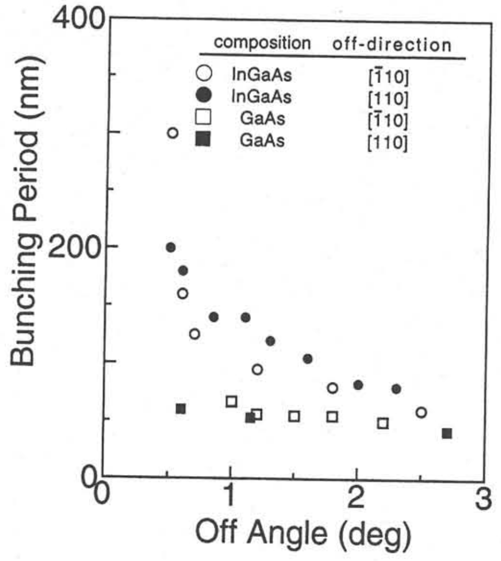

Fig. 4
The dependence of the bunching period on the off-angles.

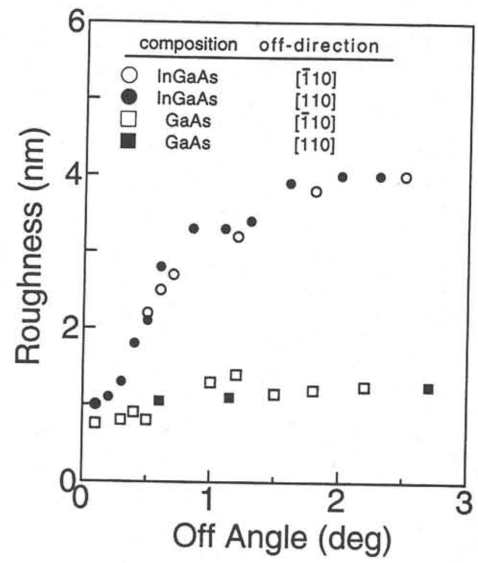

Fig. 5
The dependence of the surface roughness on the off-angles.

3.2 Dependence of Bunching Periods and Surface Roughness on Off-Angles

Figure 4 shows the dependence of the bunching period on off-angles for GaAs and InGaAs surfaces and Figure 5 shows the dependence of surface roughness on off-angles. The surface roughness means the average difference in height between the highest five peaks and the lowest five valleys in the area of 500 nm × 500 nm. For GaAs surfaces, bunching periods and surface roughness were kept around a value of 50 nm and 1~1.4 nm, respectively, for off-angles larger than 0.5°, irrespective of the off-directions. For InGaAs surfaces, the bunching period decreased from 200 nm to 80 nm as the off-angle increased from 0.5° to 1.5°, and surface roughness varied from 2 nm to 4 nm as the off-angle increased from 0.5° to 1.5°, and saturated at 4 nm for off-angles larger than 1.5°. The roughness of the InGaAs surfaces was two or three times larger than that of the unstrained GaAs surfaces. Furthermore, the bunching period and surface roughness were sensitive to off-angles ranging from 0.5° to 1.5°, where the plateau-type 3-D islands or the round terrace-type 3-D islands appeared on the surfaces.

3.3 Discussion

A new hypothesis is proposed to explain the surface evolution mechanism of the strained InGaAs. The structural difference between GaAs and InGaAs will come from a microscopic strain alleviation for the case of InGaAs. Once the step density begins to fluctuate, the thickness fluctuation occurs at the same time. The compressed lattice for InGaAs is expanded at thicker stacked portions and is compressed additionally at thinner stacked portions, which will enhance Ga, In, As sticking exclusively to the expanded portions, resulting in strain-assisted step bunching. As the strain-assisted step bunching proceeds, the material species consumption by the step-flow-mode growth will be reduced at thinner portions, which will promote an additional growth mode where step-flow growth occurs within strain-alleviated areas, producing the plateau-type 3-D islands for the [1̄10] off-direction, or the round terrace-type 3-D islands for the [110] off-direction.

4. Conclusion

The first detailed investigation of the surface structure of strained InGaAs in comparison with GaAs confirmed that anomalous step bunching occurs producing off-direction dependent corrugated 3-D surface structures for strained InGaAs layers grown on off-angled substrates. The results were explained in terms of strain-assisted step bunching and growth-mode transition to the limited area step-flow mode within strain-alleviated areas.

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References

1) J. Ishizaki, S. Goto, M. Kishida, T. Fukui and H. Hasegawa, Extended Abstracts of Int. Conf. on Solid State Dev. and Mat. (1993) 294.
2) M. Kasu and T. Fukui, Jpn. J. Appl. Phys., 31 (1992) L864.
3) T. Kikkawa, H. Ochimizu, K. Kasai and J. Komeno, 12th Symposium Record on Alloy Semiconductor Physics and Electronics (1993) 359.
4) K. Hiramoto, T. Tsuchiya, M. Sagawa and K. Uomi, Conf. Dig. of Int. Conf. on Metalorganic Vapor Phase Epitaxy (1994) 66.
5) H. Ishihara, T.Takeuchi, S. Yamazaki, T. Torikai and K. Taguchi, in Proc. 17th Europ. Conf. on Optic. Commun. (ECOC), vol.1, TuPS1-26, pp.377-380.
6) S. Ishikawa, K. Fukagai, H. Chida, T. Miyazaki, H. Fujii and K. Endo, IEEE J. Quantum Electron., vol.29,(1993)1936.