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Kinetics of strain relaxation in lattice-mismatched $In_xGa_{1-x}As/GaAs$ heteroepitaxy

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Abstract

In situ X-ray reciprocal space mapping (*in situ* RSM) during $In_{0.08}Ga_{0.92}As/GaAs(001)$ MBE growth and growth interruption is performed to investigate the extent to which the relaxation process is kinetically limited. It was found that significant additional relaxation is gained during interruption at rapid relaxation stage. This is clear indication that relaxation is kinetically limited, i.e., the available dislocation density and glide velocity are not sufficient to relieve the driving force. The observation that $In_xGa_{1-x}As/GaAs$ growth is kinetically limited suggests that altering growth conditions could allow the final threading dislocation density and configuration to be optimized.

1. Introduction

A metamorphic (lattice-mismatched) structure composed of III-V compound materials has been expected to be a candidate of super high efficiency solar cell as space and concentrator applications. Since the presence of threading dislocations in the III-V epitaxial layer can be detrimental to solar cell performance, the production of relaxed layers that have a minimal number of threading dislocations is desirable. Therefore, understanding dislocation mediated strain relaxation during heteroepitaxy is imperative to obtain high quality buffer layers. Recently, we successfully performed *in situ* X-ray reciprocal space mapping (*in situ* RSM) during InGaAs/GaAs(001) heteroepitaxial growth to investigate the strain relaxation mechanisms.[1] As a result, four thickness ranges (I~IV) with different relaxation mechanisms were classified, and the dominant dislocation behavior in each thickness range was identified. However, there is a lack of understanding of the degree to which the residual strain during hetroepitaxial growth is kinetically limited or whether that strain corresponds to a metastable equilibrium. If relaxation is kinetically limited, it may be possible to lower the final threading dislocation density by modifying the growth conditions. If the residual strain represents a metastable equilibrium, then measurements of the strain evolution can offer insight into limitations on the extent of relaxation. In this paper, we present *in situ* measurements of the film strain and crystal quality during the growth of InGaAs films on GaAs substrates, and discuss the effect of growth interruptions on the strain relaxation rate from *in situ* RSM.

2. Experimental

The experiments were performed at the synchrotron radiation beamline 11XU at SPring-8, Japan, using a MBE-XRD system.[2] After removal of the oxide layer of the GaAs(001) substrate, and the growth of a 0.1 μm-thick buffer layer, $In_{0.08}Ga_{0.92}As$ was deposited at a rate of 0.26 ML/s. The growth temperatures used was 466 °C. The X-rays were reflected by the (022) planes. The diffracted X-rays were detected by a two-dimensional CCD camera. While the CCD camera was being exposed, the sample and diffractometer was adjusted to obtain 022 RSM. Time resolution of this scan is 43 seconds. While the *in situ* RSM of 022 reflections was being measured, film growth of 7 scans (~300 sec) and interruption of 15 scans (~645 sec) were repeated.

3. Results and Discussions

Typical two dimensional ($[\bar{1}10]$-$[001]$ coordinates) RSM images with (a) 137, (b) 234 and (c) 590 nm in thicknesses are shown in Fig. 1. The peak position and the diffraction broadening of the InGaAs 022 diffraction change continuously with increasing film thickness.

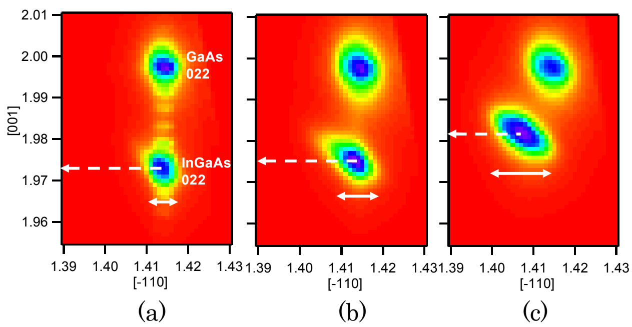

Fig. 1 *In situ* RSM for 022 diffractions with measuring time of (a) 5200, (b) 9600 and (c) 25000 sec. These correspond to the $In_{0.08}Ga_{0.92}As$ film thickness of 137, 234 and 590 nm, respectively. Dashed and lined arrows indicate the plane index along [001] and the diffraction broadening for InGaAs-022 peaks, respectively.

Figure 2 shows the evolution of plane index along [001] (L in Miller's index) and diffraction width during both growth and interruption. Index L is inversely proportional to the residual strain for the InGaAs film. The gray bands mark 300 sec periods of $In_{0.08}Ga_{0.92}As$ /GaAs(001) growth. Thickness ranges with different relaxation mechanisms (phase (I)~(IV)) are classified from correlation between the residual strain and the crystal quality.[3] It was found that significant additional relaxation is gained during interruption at rapid relaxation stage (phase III). This is clear indication that relaxation is kinetically limited, i.e., the available dislocation density and glide velocity are not sufficient to relieve the driving force. The observation that $In_xGa_{1-x}As$/GaAs growth is kinetically limited suggests that altering growth conditions could allow the final threading dislocation density and configuration to be optimized.

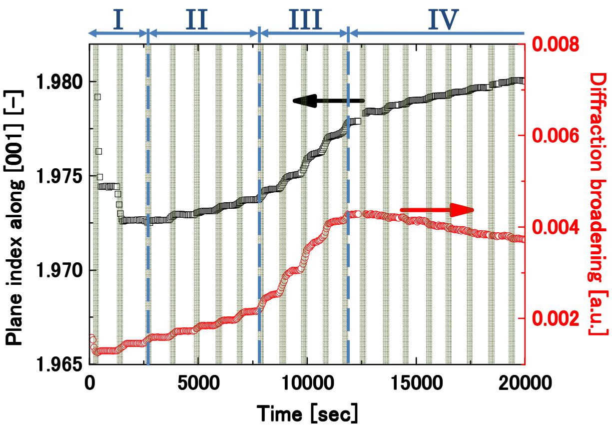

Fig. 2. Evolution of the plane index along [001] (proportional to strain relaxation) and diffraction broadening for the InGaAs 022 peaks during growth and growth interruptions. The gray bands mark 300 second periods of $In_{0.08}Ga_{0.92}As$/GaAs growth. Thickness ranges with different relaxation mechanisms (I)~(IV) are indicated.

On the other hand, it was found that strain relaxation during growth interruption gradually became small with increasing film thickness in Phase IV. This may be attributed to the fact that the thick film is almost at thermal equilibrium under the growth condition. This means that further glides of threading dislocations cannot be expected under the growth condition. Therefore, it is necessary to increase the dislocation velocity by additional thermal energy, i.e., increase in growth temperature or thermal annealing.

4. Summary

In situ real-time X-ray diffractions during lattice-mismatched InGaAs/GaAs(001) epitaxial growth and interruption are performed to observe the changes of residual strain and crystal quality. We found that at growth interruption, decrease in the residual strain and degradation of the crystal quality for the InGaAs film are significantly depend on the film thickness ranges. This means that optimization of not only growth/anneals conditions but also the film thickness ranges is important to obtain the InGaAs film with lower dislocation density.

References

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