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Kinetics of strain relaxation in lattice-mismatched III-V heteroepitaxy

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1. Introduction

Lattice-mismatched structures composed of III-V compound materials have been expected to be candidates for super high efficiency solar cells for space and concentrator applications. Since the presence of threading dislocations in the III-V epitaxial layer can be detrimental to the solar cell performance, the production of relaxed layers that have 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* RSM (reciprocal space mapping) during InGaAs/GaAs(001) heteroepitaxial growth to investigate the strain relaxation mechanisms [1]. Moreover, in-plane anisotropies of strain relaxation was observed by *in situ* three dimensional (3D)-RSM, and interactions between α (dislocation lines along $[\bar{1}10]$) and β (dislocation lines along [110]) dislocations were discussed [2]. However, there has been a lack of understanding on the degree to which the residual strain during heteroepitaxial growth is kinetically limited or if the strain has saturated. 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 is saturated, then measurements of the strain evolution can offer insight into limitations on the extent of relaxation. In this paper, we present the result of *in situ* 3D-RSM during the growth of InGaAs films on GaAs substrates and growth interruptions, and discuss the strain relaxation along the two orthogonal in-plan directions.

2. Experimental

The experiments were performed at the synchrotron radiation beamline 11XU at SPring-8, Japan, using a molecular beam epitaxy (MBE) -X-ray diffraction (XRD) system [3]. After removal of the oxide layer of the GaAs(001) substrate, 0.1 μm-thick GaAs buffer layer was grown on the substrate. Then, a $In_{0.08}Ga_{0.92}As$ film 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 and the diffracted X-rays were detected by a two dimensional-charge coupled device (CCD) camera. While the CCD camera was being exposed, the sample and diffractometer was adjusted to obtain 3D-RSM. Measurement of a scan was 43 seconds. *In situ* RSM of 022 reflections were measured repeatedly during altering film growth of 7 scans and interruption of 15 scans, corresponding to 301 and 645 seconds, respectively.

3. Results and Discussions

To evaluate the in-plane anisotropies of strain relaxation during the crystal growth and the growth interruption, obtained 3D-RSM results were projected to two dimensions. Typical maps after measurements were made for 5225, 9643 and 24838 seconds are shown in Fig. 1, corresponding to the $In_{0.08}Ga_{0.92}As$ film thicknesses of 137, 234 and 588 nm, respectively. The vertical and horizontal axes represent plane indices along out-of-plane direction ([001]) and in-plane ([110] and $[\bar{1}10]$) directions. Upper and lower peaks originated from the GaAs 022 and the InGaAs 022 diffractions, respectively. As the film thickness is increased, the InGaAs 022 diffraction peaks shifted away from the GaAs peaks along the in-plane directions. This means that the strain of the InGaAs film relaxes with increasing film thickness. Furthermore, it can be seen that the distance between the GaAs and the InGaAs peaks along the [110] direction are larger than that of the $[\bar{1}10]$ direction. This is due to the in-plane anisotropies of the strain relaxation.

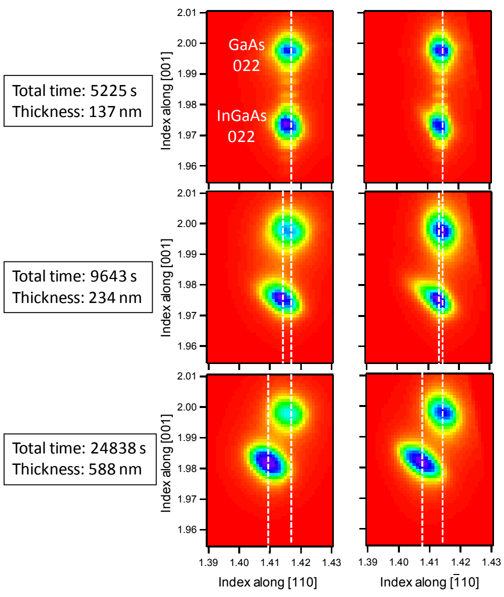

Fig. 1 Typical *in situ* RSM for 022 diffractions after measuring for 5225, 9643 and 24838 sec, corresponding to the $In_{0.08}Ga_{0.92}As$ film thicknesses of 137, 234 and 588 nm, respectively.

Time dependence of peak positions for the InGaAs 022 along the two in-plane directions is shown in Fig. 2. The white and blue bands indicate periods of crystal growth (300 sec) and the growth interruption (645 sec), respectively. The strain relaxation begins along the [110] direction after 5000 seconds, followed by relaxation along the $[\bar{1}10]$ direction after 8000 seconds. Following a rapid relaxation around 10000 seconds for both directions, the strain relaxation eventually saturates after exceeding 20000 seconds. These in-plane anisotropies of the strain relaxation have also been observed in our previous study without growth interruptions, and explained by the difference in dislocation velocity between α and β dislocations (i.e., α>β).

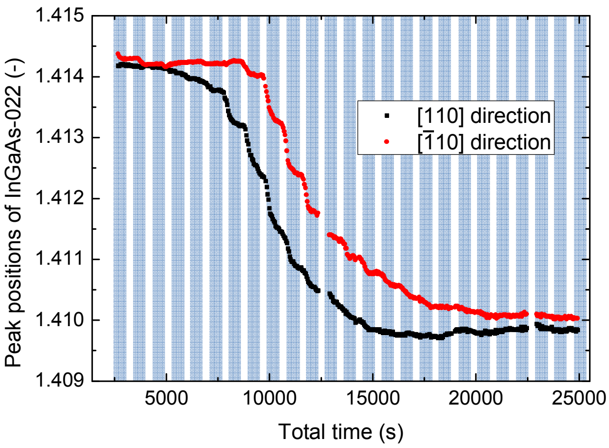

Fig. 2 Time evolution of peak positions for the InGaAs 022 peak along [110] and $[\bar{1}10]$ directions. The white and blue bands indicate periods of crystal growth and growth interruption, respectively.

In order to discuss the kinetics of strain relaxation, the degree of relaxation, normalized by the change in lattice constant, is plotted as a function of the film thickness (Fig. 3(a)) and also those during interruptions (Fig. 3(b)). It is found that the lattice relaxes significantly during interruption for film thickness between 200 and 350 nm. This is a clear indication that the relaxation is kinetically limited, i.e., the available dislocation density and glide velocity are not sufficient to relieve the strain. The observation that relaxation during continuous $In_xGa_{1-x}As/GaAs$ growth is kinetically limited suggests that altering growth conditions could allow the final threading dislocation density and configuration to be optimized.

Furthermore, from Fig. 3(b), we find that the relaxation during growth interruptions strongly depends on in-plane directions. The relaxation during interruptions initiates along the [110] direction rather than along $[\bar{1}10]$ direction. This is explained that the relaxation along the [110] direction can reach saturation more readily due to the high dislocation velocity of α dislocations. Additionally, it is observed that the peak height in the $[\bar{1}10]$ direction is smaller than that of the [110] direction. We believe that this is due to the limitation of β dislocation motions by blocking process with orthogonally aligned α dislocations.

Finally, in film thickness over 400 nm, it is found that strain relaxation during growth interruption become is reduced. This may be attributed to the fact that relaxation of the thick film is almost saturated. This means that further glides of threading dislocations cannot be expected in the growth condition. Therefore, it is necessary to increase the dislocation velocity by thermal energy, i.e., by increase in growth temperature or thermal annealing.

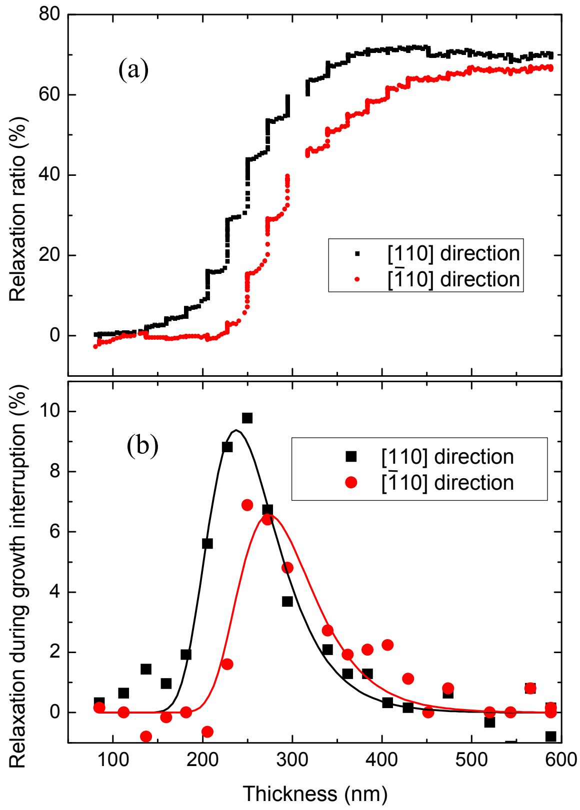

Fig. 3 Film thickness dependence on the degree of relaxation for $In_{0.08}Ga_{0.92}As$ film (a) and that during growth interruptions (b).

4. Summary

In situ RSM during the lattice-mismatched InGaAs/GaAs(001) epitaxial growth and the interruption have been performed to discuss the kinetics of strain relaxation. We found that the degree of the relaxation during the growth interruption depends on both the film thickness and in-plane directions. Furthermore, it was found that strain relaxation are kinetically limited under the growth condition employed in this study. By choosing optimal growth conditions or post growth processing, dislocation motions will be more enhanced toward the saturation, resulting in high quality crystals with lower dislocation density.

References

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