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Observation of dark line defects in InGaAs/GaAs strained layer superlattices by photoluminescence topography

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The behavior of dark line defects (DLDs) in molecular beam epitaxy grown InGaAs/GaAs strained layer superlattices (SLSs) has been studied by photoluminescence (PL) topography. The density of DLDs parallel to the [011] was larger than that of those perpendicular to the [011] and increased with increasing number of SLS periods. These DLDs were considered to be originated from the locally deformed lattices by the misfit stress. The relaxation model of stress in MBE-grown InGaAs/GaAs SLSs was proposed from the obtained results.

1. Introduction

The strained InGaAs/GaAs system has been actively studied in recent years because of its potential applications to electronic and optoelectronic devices [1]. This system was revealed to have a large number of dislocations caused by large lattice mismatches (~ 7%) [2]. Fitzgerald et al. [3] have observed scanning cathodoluminescence (CL) and transmission electron microscopy (TEM) images of AlGaAs/InGaAs/GaAs heterostructures and discussed the relation between the direction of the dislocations and the residual elastic strains.

Photoluminescence (PL) topography, which gives us information on spatial variations of PL emission using an image detector instead of measuring PL spectra, also enables us to characterize the nonradiative centers such as dark spots (DSs) or dark line defects (DLDs) [4]. We have been evaluating the crystallinity of various GaAs wafers and molecular beam epitaxy grown (MBE-grown) InGaAs/AlGaAs/GaAs multilayer or superlattice structures by PL topography [5,6].

In this study, the misfit strains in MBE-grown InGaAs/GaAs strained-layer superlattices (SLSs) with various superlattice periods and growth temperatures were characterized by PL topography. Finally the relaxation mechanism of stress in this system was discussed.

2. Experimental

InGaAs/GaAs SLSs were grown by MBE using a Riber model MBE 2300 R&D system. Substrates were prepared from the indium-doped semi-insulating (100) GaAs wafers (EPD: 10^3 cm^{-2}). The growth temperature was varied from 500°C to 575°C. The SLS samples were composed of alternation of 70 Å thick $In_{0.1}Ga_{0.9}As$

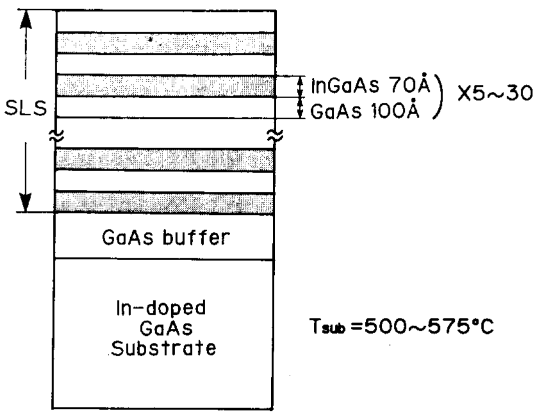

Fig. 1. A Schematic illustration of sample structure.

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and 100 Å thick GaAs layers, and the related period was varied from 5 to 30 as shown in fig. 1. The thickness of each layer was controlled by observing reflection high energy electron diffraction (RHEED) intensity oscillation.

PL topography was carried out at the temperature about 50 K using an infrared Vidicon TV camera (Hamamatsu C-1965) where a cw krypton ion laser light (6471 Å, 600 mW) was used as an excitation source and an IR-80 high-pass filter was adopted to suppress the laser light and to observe the PL emission only.

3. Results and discussion

Fig. 2 shows the PL topograph patterns of the samples with various SLS periods at the substrate temperature: 550 °C. The cross-stripe pattern of dark lines as seen in the figure was observed in all SLS samples. Similar patterns have also been observed by CL observations [1,2]. Such dark lines were not observed so far in a thicker layer (1 μm thick $In_{0.1}Ga_{0.9}As$); however, a cross-hatch pattern was revealed by Nomarski microscope observation on the surface. It was concluded that this pattern was caused by the misfit stress between GaAs and $In_{0.1}Ga_{0.9}As$ [6]. On the other hand, the cross-hatch pattern has never been observed on the surface of SLSs, although a similar pattern in the DLDs with a different density was observed by PL topography. This result suggests that the misfit stress in thick $In_{0.1}Ga_{0.9}As$ on GaAs will be relaxed by forming wrinkles on its surface, but that in SLSs by introducing some defects it is observed as dark lines.

The density of the DLDs was increased with increasing the number of the SLS period. The internal stress in the SLS structures is relaxed by the lattice relaxation of each layer whose thickness is thinner than the critical value [7]. The layer thickness of all $In_{0.1}Ga_{0.9}As$ layers was smaller than the critical value. Therefore we consider that we could take the standpoint that these DLDs were not caused by the misfit dislocation, but were caused by the misfit stress between the $In_{0.1}Ga_{0.9}$ As layers and the GaAs layers. However, PL topograph observations indicate the difference in PL aspects between misfit stress and dislocation qualitatively. In order to confirm this point, the cross section of the SLSs should be observed by transmission electron microscopy (TEM).

It is not known why we could observe the relaxation of the misfit stress by PL topography. We consider the direction of the DLDs. The DLDs were lines parallel or perpendicular to the [011] direction. The density of DLDs parallel to the [011] was about 400 lines/cm and it was larger than that of those perpendicular to the [011]. We think that this difference is caused by the growth mechanism of the layer on the surface. Asai [8] reported on anisotropic lateral growth in GaAs layers on (001) substrates and found that the fastest growth direction is the [110] and the slowest is the [$\bar{1}$10] direction. Therefore the progress of the [011] steps on the GaAs (100) surface in our case should be more preferential than that of the [01$\bar{1}$] steps. As a result, the surface stress in the [01$\bar{1}$] direction is relaxed in a shorter distance than in the [011] direction as the $In_{0.1}Ga_{0.9}As$ layers grow. This difference in the direction of the progress of steps corresponded well to the difference in the density of DLDs. We think that the $In_{0.1}Ga_{0.9}As$ lattice will be deformed locally by the compressive stress, as Grundmann et al. [9] reported from the results of double-crystal X-ray diffraction, and therefore the PL emission efficiency in the deformed region will be degraded to be observed as a DLD by PL topography.

If the generation of DLDs is dependent on the progress of steps, the behavior of DLDs should be changed by the growth temperature. Fig. 3 shows the change of the PL topograph pattern of the samples with 10 SLS periods when the growth temperature was varied from 500 to 575 °C. When the growth temperature was 575 °C, no stripe pattern was observed. This situation might be understood in such a way that the growth temperature was so high that the stuck indium atoms were eliminated from the surface, and, as a result, the superlattice structure was not completed. When the growth temperatures were lower than 550 °C, the densities of the DLDs in the [011] and [01$\bar{1}$] directions were increased with decreasing growth temperature. For example, the density in the [011] direction was about 400 lines/cm at 550 °C and it

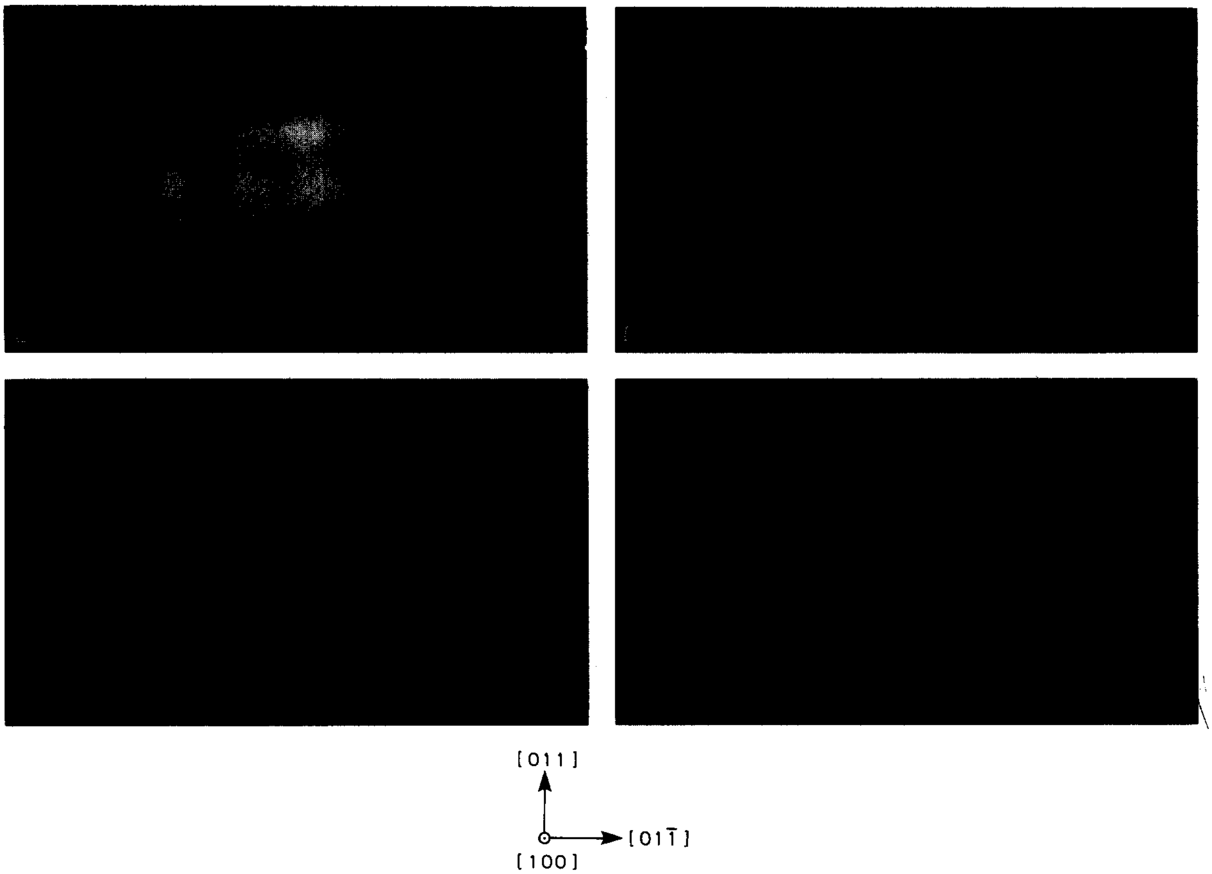

Fig. 2. PL topograph patterns from four MBE-grown $In_{0.1}Ga_{0.9}As/GaAs$ SLSs which have various superlattice periods: (a) 5 periods; (b) 10 periods; (c) 20 periods; (d) 30 periods. The substrate temperature was 550 °C. Marker represents 100 μm.

was about 700 lines/cm at 500 °C. We consider that this was caused by the change in the surface migration of the atoms. That is to say, the diffusion length is decreased with decreasing growth temperature, and the density of the DLDs, caused by the local relaxation of the misfit stress, was increased.

Here we propose a model for relaxation anisotropy of the stress in InGaAs/GaAs SLSs, as shown in fig. 4. The compressive stress is acting to the growing surface of the $In_{0.1}Ga_{0.9}As$ layer. This stress is accumulated with increasing layer thickness, and relaxed by deforming local lattices. But misfit dislocation will not be introduced because the thickness of the $In_{0.1}Ga_{0.9}As$ layers is thought to be thinner than the critical layer thickness. The lattice deformation in the [011] direction is more preferential than that in the [01$\bar{1}$] direction, since the lateral growth rate has an anisotropy. In other words, the compressive stress is relaxed within a shorter distance in the [011] direction than that in the [01$\bar{1}$] direction, since the growth of steps in the [01$\bar{1}$] direction is slower than in the [011] direction. These locally deformed $In_{0.1}Ga_{0.9}As$ lattices are observed as anisotropic DLD patterns by PL topography.

4. Conclusion

InGaAs/GaAs SLSs with various periods and growth temperatures were grown by MBE and characterized by PL topography. Cross-stripe patterns were observed in all samples except in the

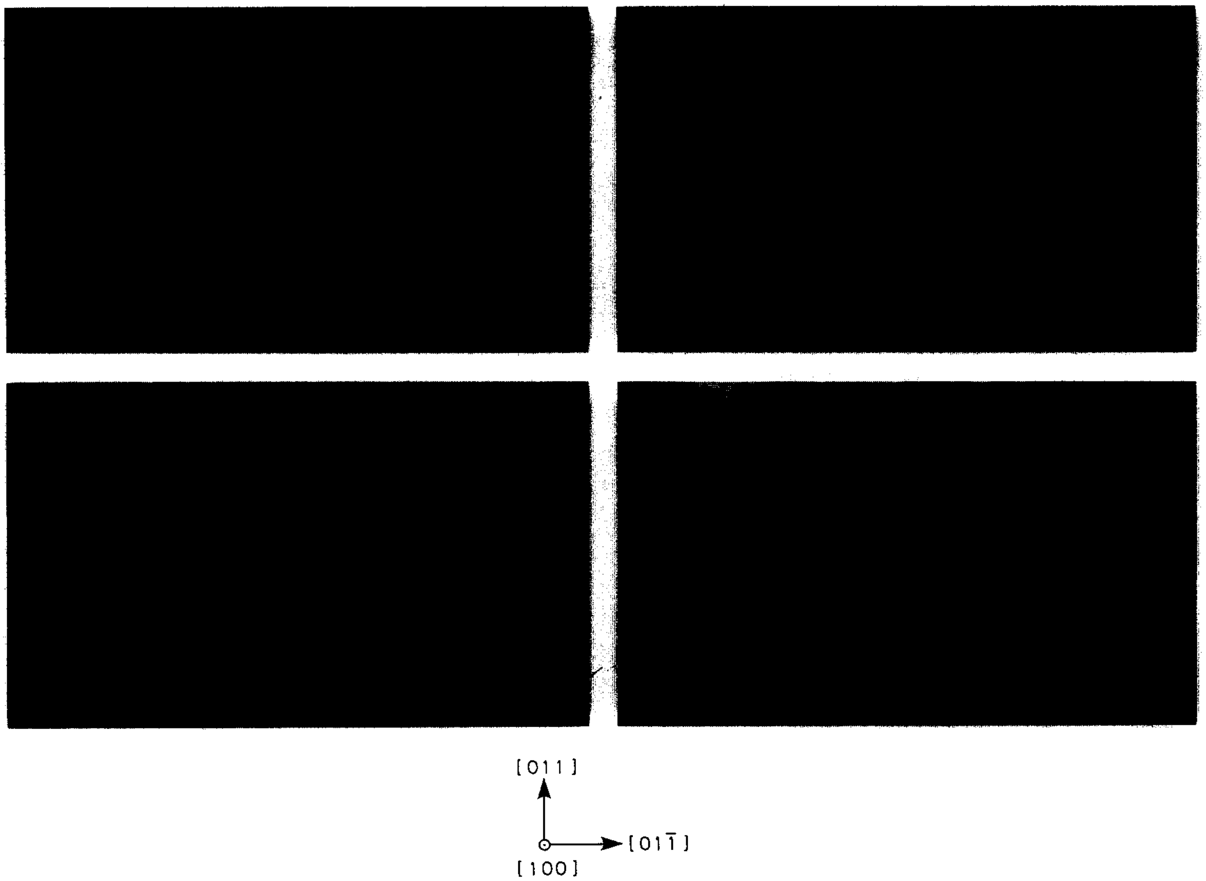

Fig. 3. Temperature dependence of the PL topograph patterns from MBE-grown $In_{0.1}Ga_{0.9}As/GaAs$ SLSs whose SLS period was ten. The growth temperature was: (a) 500 ° C; (b) 525 ° C; (c) 550 ° C; (d) 575 ° C. Marker represents 100 μm.

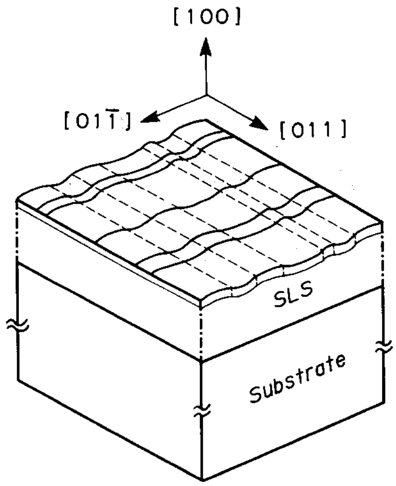

Fig. 4. A proposed model for the relaxation anisotropy of the stress in InGaAs/GaAs SLS.

one grown at 575 ° C. The density of the DLDs was increased with increasing SLS period and with decreasing growth temperature. The density of the DLDs parallel to the [011] was about 400 lines/cm and it was larger than that of those perpendicular to the [011]. This difference was thought to be caused by the anisotropy in the growth rates of steps in $In_{0.1}Ga_{0.9}As$ layers. That is to say, relaxation of the misfit stress in the [011] direction is more preferential than that in the [01$\bar{1}$]. This relaxation is accompanied with the deformation of the local lattices in the $In_{0.9}Ga_{0.9}As$ layers without introducing the misfit dislocations, because the thickness of the $In_{0.1}Ga_{0.9}As$ layer is thinner than the critical value. This lattice deformation results in the degradation of the efficiency of PL emission. As a result, this lattice deformation is observed as DLD by PL topography. Finally, we proposed a relaxation model of the stress which explains sufficiently the relaxation of the stress in InGaAs/GaAs SLSs.

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