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Low Temperature Growth of GaAs on Si by Migration Enhanced Molecular Beam Epitaxy

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A single domain GaAs was epitaxially grown by a migration enhanced molecular beam epitaxy, which utilizes alternately chopped Ga and As_4 beams, on misoriented (100) Si substrates at 250 °C. The stress in the GaAs film was evaluated from x-ray diffraction measurements and from curvature radii measured by the reflection of a laser beam, and it was confirmed that the stress was decreased by low-temperature growth. Etch pit density was $\sim 5\times10^7$ cm^{-2} for the sample grown at 250 °C.

1. Introduction

For the direct growth of GaAs on Si substrates, large lattice misfit between GaAs and Si, large difference in thermal expansion coefficient and being polar on nonpolar system are preventing a growth of high quality film. The problem about a antiphase domain has been resolved by utilizing misoriented substrate,[1-3] and the mechanism of self-annihilation of antiphase boundary has become clear.[4] However, dislocation density is still rather high (10^6-10^8 cm^{-2}) even though two step growth,[1] strained-layer superlattice[5,6] and post or in-situ annealing[7,8] have been utilized for reducing the dislocation density. Among the above problems the influence of large difference in thermal expansion coefficient can be reduced by decreasing the growth temperature. However, the crystal quality is generally degraded by decreasing the growth temperature. Recently, Horikoshi et al.[9] developed so called migration-enhanced epitaxy (MEE), in which the Ga and As_4 beams are alternately impinging on the substrate surface, and represented a high quality of GaAs and AlGaAs films grown at 200-300°C on GaAs substrates. We applied this technique to the growth of GaAs on Si substrate for reducing the thermal stress in the films.

2. Experimental

The GaAs films were grown in a conventional molecular beam epitaxy (MBE) apparatus (ANELVA model 830). After thermal cleaning of misoriented Si (100) substrates tilted by 4° toward <011> at a substrate temperature above 850°C, the surface was exposed to As_4 flux at a substrate temperature of 250°C or 750°C. The domain direction of GaAs to Si substrate is known to be different by 90° depending on the temperature at which the sample surface is exposed to As_4 flux.[4,10] After exposure to As_4 flux, the first buffer GaAs layer (25 nm in thickness) was deposited by normal MBE at a growth rate of 100 nm/h at 250°C, followed by in-situ annealing under As_4 pressure at 580°C for 10 min to improve the crystal quality. Thereafter the 1.5 μm-thick GaAs films were grown by the MEE technique at substrate temperatures of 200-580°C. The beam flux intensities of Ga and As_4 during MEE were $J_{Ga}=6.4\times10^{14}/cm^2.s$ and $J_{As_4}=2.4\times10^{14}/cm^2.s$, respectively. The shutter opened durations for Ga and As cells were 1s and 3s, respectively, which gave approximately one monolyer growth per cycle. The stress in the film was evaluated from the warping of the substrate measured by a deflection of a laser beam reflecting from the sample surface. The stress was also evaluated from the lattice constant measured by the x-ray diffractometer, where (400) GaAs diffraction peak angle was carefully measured. The crystal quality was evaluated from the full width at half of maximum (FWHM) of the (400) GaAs diffraction peak. The etch pits were observed by scanning electron microscopy (SEM) after etching in electrolyte under illumination[11] and in the molten KOH.

3. Results and Discussion

Figure 1 shows the curvature radii of the samples grown by different procedures. The open circles are for the samples which are exposed to As_4 flux at a low temperature of 250°C after thermal cleaning ((A) series samples). The solid circles are for the samples which are exposed to As_4 flux at a high temperature of 750°C ((B) series samples). The theoretical curve is obtained by using the bi-metallic strip model.[12] The curvature radii for both series of samples increase with decreasing growth temperature except for the data at 200°C, which shows that the stress in the film is increased. The disagreement with the theoretical curve may be due to the too simplified model in which the strip is used, while the measured sample is a rectangular plate. Figure 2 shows the lattice constant perpendicular to the sample surface measured by the x-ray diffraction. The theoretical curve was derived as below. The stress parallel to the GaAs/Si interface T is given by:

$$T=\varepsilon E_{GaAs}/\nu_{GaAs}, \quad (1)$$

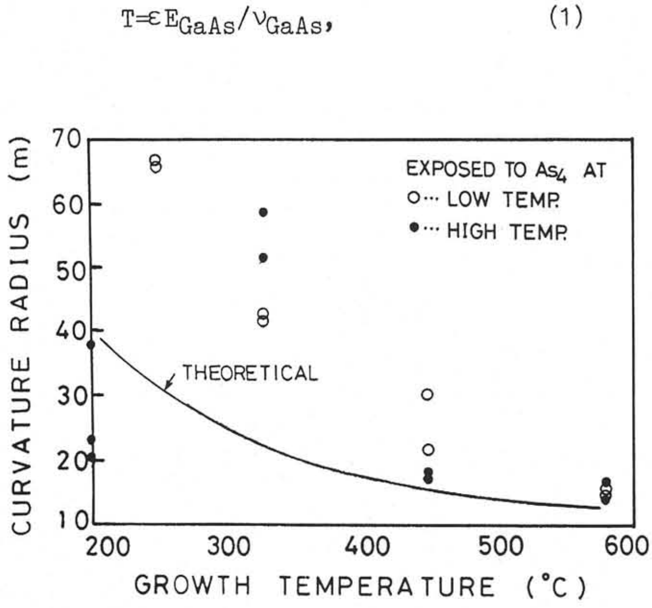

Fig. 1. Curvature radius measured by the reflection of a laser beam as a function of growth temperature.

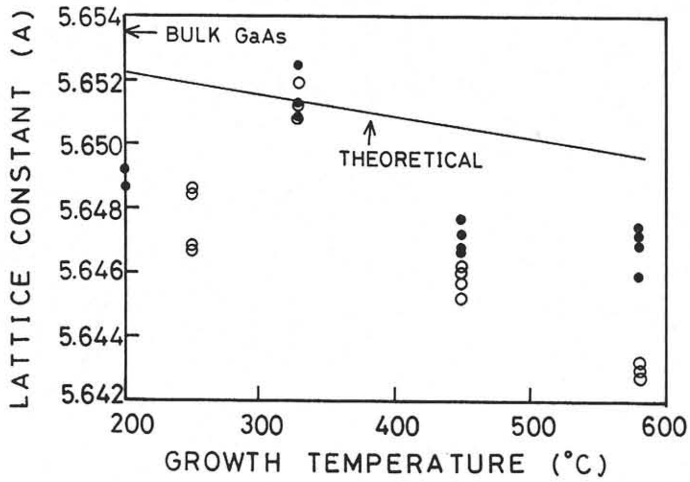

Fig.2. Lattice constant measured by x-ray diffraction as a function of growth temperature. The meanings of o and • are the same as in Fig. 1.

where ε is the strain in the direction perpendicular to the surface, E_{GaAs} is Young's modulus for GaAs, and ν_{GaAs} is Poisson's ratio for GaAs. ε is calculated using the following formula:

$$\varepsilon=(d-d_0)/d_0, \quad (2)$$

where d is the lattice spacing in GaAs on Si, and d_0 is the lattice spacing in bulk GaAs. From the bi-metal theory the stress parallel to the interface T can be derived.[12] Therefore, the lattice constant d can be calculated. We evaluated the stress in GaAs from the lattice constant and the curvature radius. The calculation from the lattice constant was carried out using the equations (1) and (2). In the calculation from the curvature, the following equation is used:[13]

$$T=E_{Si}d_{Si}^2/(6Rd_{GaAs})/(1-\nu_{Si}), \quad (3)$$

where E_{Si} is Young's modulus for Si, d_{Si} and d_{GaAs} is the thickness of Si wafer and GaAs film, respectively, and ν_{Si} is Poisson's ratio for Si. R is the curvature radius of the wafer. The results are shown in Figs. 3(a) and 3(b) for (A) and (B) series samples, respectively. Open and solid circles corresponds to the data obtained from the lattice constant and the curvature radius, respectively. Both series of samples have the same tendency, that is, the stress derived from the lattice constant is larger

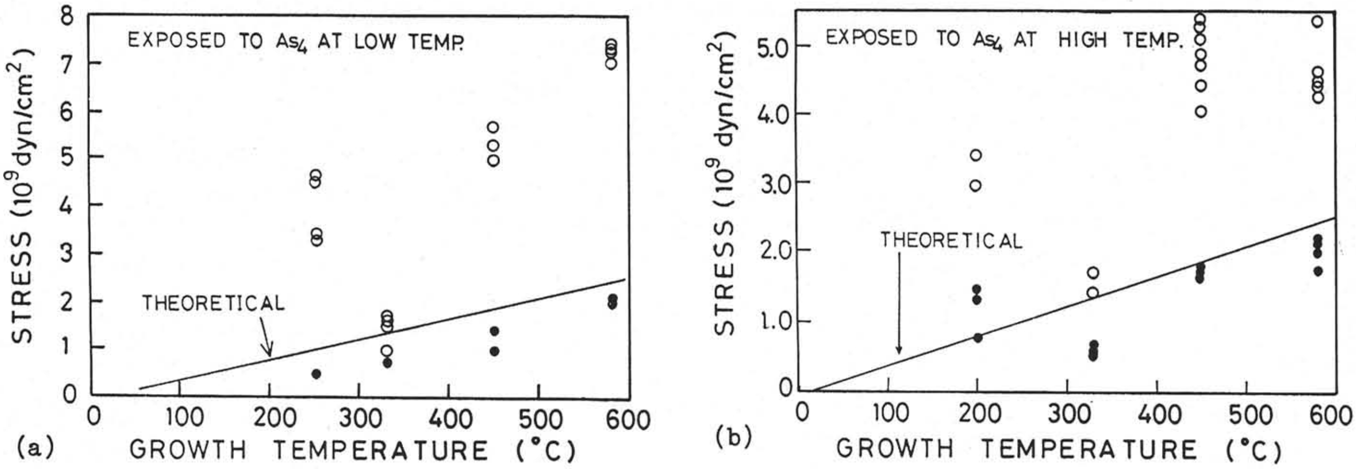

Fig. 3. Stress in the GaAs film for the samples exposed to As_4 flux (a) at low and (b) at high temperature. Open and solid circles are for the results obtained from lattice constant and curvature radius, respectively.

than the theoretical curve and the stress derived from the curvature is smaller than the theoretical curve. Ishida et al. also reported on the same system (GaAs on Si) that the stress obtained from the lattice constant is larger than that obtained from the curvature by a factor of 2.[14] To clarify the reason for these discrepancy, the further study will be necessary including the examination of the accuracy of the measurements, the validity of the model used in the theoretical calculation and the analysis method for the data. From the above results, it is roughly concluded that the stress is decreased with decreasing the growth temperature. Figure 4 shows the etch pit pattern of the sample in (A) series grown at 250°C. The large pits are aligned to the same direction, suggesting that the film is single domain structure. The large etch pit density is $6.6x10^3$ cm^{-2}. Figures 5(a)-(d) illustrate the surface morphology after electrochemical etching under illumination for (A) series samples. The small pits can be observed. However, the large pits as shown in Fig. 4 can not be observed in the samples grown at 330-580°C. The etch pit densities counted from Figs. 5(a)-(d) are shown in Fig. 6 together with the FWHM of the x-ray

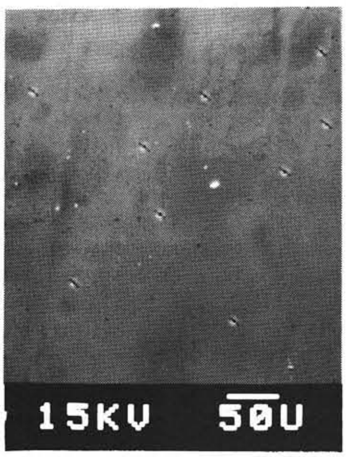

Fig. 4. An SEM photograph of the sample grown by MEE at 250°C after electrochemical etching under illumination.

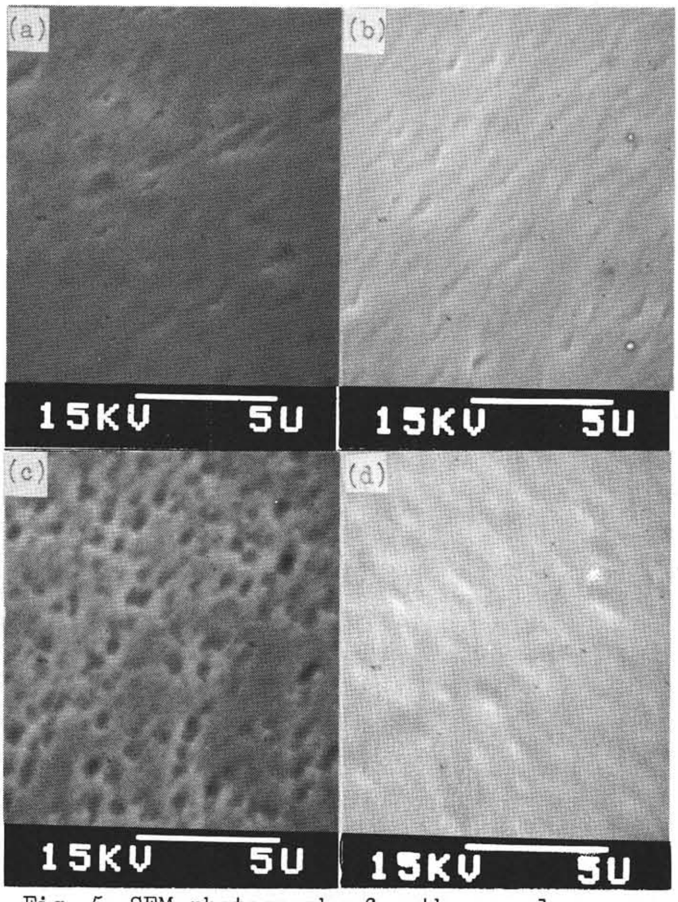

Fig. 5. SEM photographs for the samples grown at (a) 580°C, (b) 450°C, (c) 330°C, and (d) 250°C after electrochemical etching under illumination.

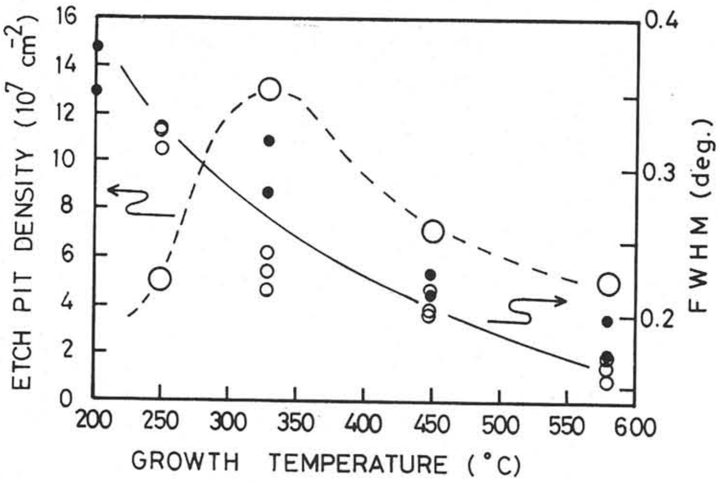

Fig. 6. Etch pit density for samples in Fig. 5 and FWHM of x-ray diffraction peak. o and • are for (A) and (B) series samples, respectively.

diffraction peaks as a function of growth temperature. Although the pit density is increased with decreasing the growth temperature, it is again decreased at 250°C. The small pit density of the sample grown at 250°C is 5×10^7 cm^{-2}. The FWHM is monotonously increased with decreasing the growth temperature, showing that the crystal quality is degraded at low temperatures. The lowering of the growth temperature has two affects. One is an insufficient surface migration of constituent atoms, which causes lattice defects and dislocations. Another is the reduction of the thermal stress which suppresses the generation of the dislocations. These two opposite actions compete in the actual system. At high temperatures above 450°C, the sufrace migration is enough large and the first effect may not be the main reason for the dislocations. At a low temperature of 250°C, the thermal stress reduction is one possible reason for the decreased etch pit density. At the middle temperatures, the stress reduction is not substantial and also the crystal quality is degraded, resulting in the high etch pit density. The similar mechanism may work for the sample grown at 330°C, which has the largest etch pit density.

In conclusion the single domain GaAs film has been grown on Si substrate at low temperatures of 250°C by MEE. The stress in the film is confirmed to be decreased by decreasing the growth temperature. The etch pit density ($\sim5\times10^7$ cm^{-2}) is relatively small even at such a low growth temperature.

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