Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 122-124

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Formation of Strain-Free GaAs-On-Si Structures by Annealing under Ultrahigh Pressure

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Variation of residual strain in GaAs-on-Si structures formed by MOCVD is investigated by annealing them under ultrahigh pressures up to 2.1GPa. It has been found that the strain is linearly decreased with increase of pressure and it becomes zero at a pressure around 1.9 GPa. It has also been found that the strain weakly depends on annealing temperatures ranging from 300°C to 500°C. Concerning the crystalline quality of the annealed GaAs films, slight increase in the channeling minimum yield in Rutherford backscattering spectrometry has been observed.

1.Introduction

A GaAs-on-Si structure is important in fabrication of future electronic and photonic devices. In this structure, however, mismatch of the thermal expansion coefficient between the film and substrate is a serious problem for fabricating minority carrier devices such as semiconductor lasers and heterojunction bipolar transistors, since it produces residual defects and strain in the film.

In order to solve the thermal mismatch problem, we have proposed a novel method based on a general property of materials such that a soft material has a relatively large thermal expansion coefficient [1,2]. In this method, an amorphous film deposited on a single-crystal substrate is crystallized in solid phase by annealing under ultrahigh pressure (UHP), so that the thermal mismatch strain is compensated by the elastic strain, as schematically shown in Fig.1. It has been found in the Ge-on-Si structures that the residual strain in the films is reduced to about 1/10 by annealing at 2.1GPa (21kbar) and that the crystalline quality of the films is not degraded during the annealing process. However, it is generally difficult to grow GaAs films by solid phase epitaxy from amorphous phase.

In this paper, we attempt to reduce the residual strain in GaAs films which have already been grown on Si substrates by MBE (molecular beam epitaxy) or MOCVD (metalorganic chemical vapor deposition) methods, by means of subsequent annealing under UHP.

2.Experimental Procedure

GaAs films were grown on Si(100) substrates by low pressure MOCVD method using TMG (trimethyl gallium) and AsH_3, in which the substrate temperature was first kept at 500°C and then increased to 750°C. Thickness of GaAs films was about 3μm and the etch pit density of the films was on the order of $10^6 cm^{-2}$

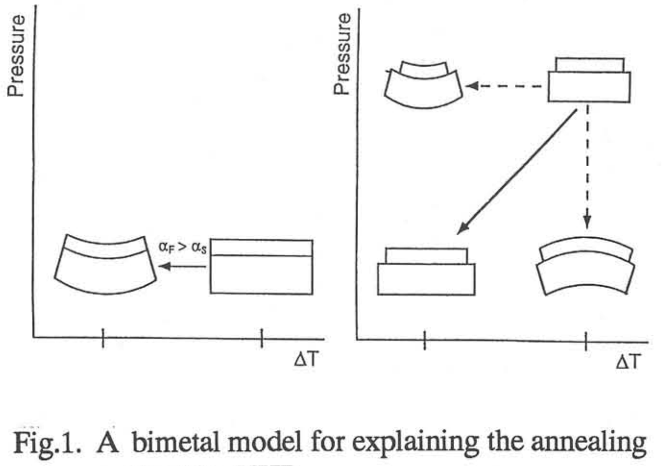

Fig.1. A bimetal model for explaining the annealing method in UHP.

UHP up to 2.1GPa was generated using a piston-cylinder-type pressure appratus. An electric furnace with a maximum temperature of 600°C was placed in the cylinder and the space in the cylinder was filled with Ar gas (pressure transmission medium). The initial gas pressure was 0.2 GPa and it was increased to a working pressure by movement of the piston. During annealing, temperature of the sample was controlled within ±1°C using a thyristor-controlled power supply. The samples were annealed at temperatures ranging from 300 to 500°C either at atmospheric pressure (AP) or at UHP up to 2.1 GPa. The annealing time was changed in the range from 20 min to 160 min.

The residual strain in the films was measured from the peak shift in X-ray diffraction analysis and their crystalline quality was characterized by Rutherford backscattering spectrometry (RBS) and through observation of the etch pit density on the surface of GaAs films. The etch pits were formed by dipping the samples in molten KOH kept at 350°C for 30 sec.

3.Results

Figure 2 shows the annealing time dependence of the residual strain in GaAs films, in which the annealing temperature and pressure were kept at 300°C and 1.22 GPa, respectively. We can see from this figure that the strain in the UHP-annealed samples is less than 1/3 of that in the as-grown sample and this value is independent of the annealing time longer than 20 min. This result suggests that the rearrangement of atomic bonding at the film / substrate interface has been completed within 20 min under these conditions. Thus, we decide to use the annealing time of 40 min in the following experiment.

Figure 3 shows variation of the residual strain plotted against the pressure during annealing. In this figure, the negative value in the vertical axis corresponds to the compressive strain in the films. We can see from this figure that the residual strain in the films is linearly decreased with increase of the pressure and that the strain-free film can be obtained around 1.9 GPa. The pressure dependence is similar to the case of Ge-on-Si structures [2]. Furthermore, real strain-free condition has been achieved for the first time in the case of GaAs-on-Si structures. We can also see that the strain weakly depends on the annealing temperature. These results agree fairly well with a simple theoretical calculation[2], in which the strain-free condition in the GaAs-on-Si structure is satisfied at 1.7 GPa for annealing at 400°C.

Figure 4 shows RBS channeling spectra for the samples annealed at 300°C for 40 min at AP and at 1.59 GPa. We can see from this figure that the channeling minimum yield in the UHP-annealed sample is a little higher than that of the AP-annealed one. Concerning the etch pit density, there was no large difference between the AP- and UHP-annealed samples and these value were on the same order as the values of an as-grown film ($7.4 \times 10^6 cm^{-2}$).

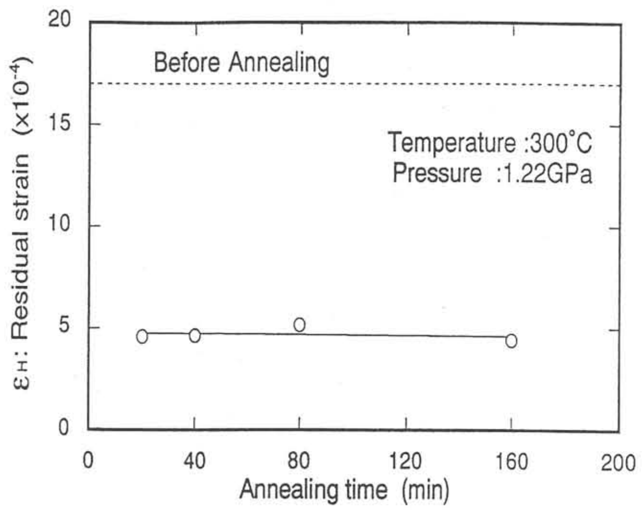

Fig.2. Variation of residual strain in GaAs films with annealing time.

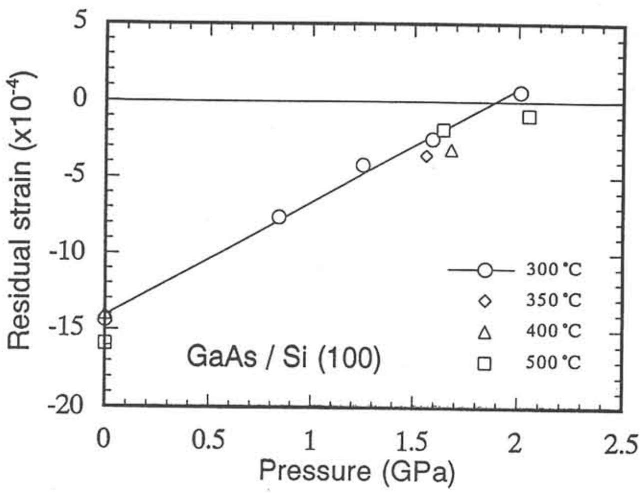

Fig.3. Variation of residual strain in GaAs films with pressure.

Typical results observed by a Nomarski optical microscope are shown in Fig.5, in which the UHP annealing was conducted at 2.05 GPa.

The both results of RBS and the etch pit observation show that the crystalline quality of GaAs films becomes a little worse by UHP annealing. We speculate that degradation of the film quality is mainly due to the insufficient rearrangement of the atomic bonding at the GaAs/Si interface. In order to make the rearrangement more perfect , it seems to be effective to etch GaAs films in line-and-space patterns.

4.Summary

It was found that the residual strain in GaAs films on Si substrates was linearly decreased with increase of pressure during annealing and that strain-free GaAs films were obtained at a pressure around 1.9 GPa. However, their crystalline quality was found to be a little worse than that of as-grown films. Improvement of the film quality in the UHP-annealed samples is now being investigated and they are being characterized using photoluminescence spectroscopy.

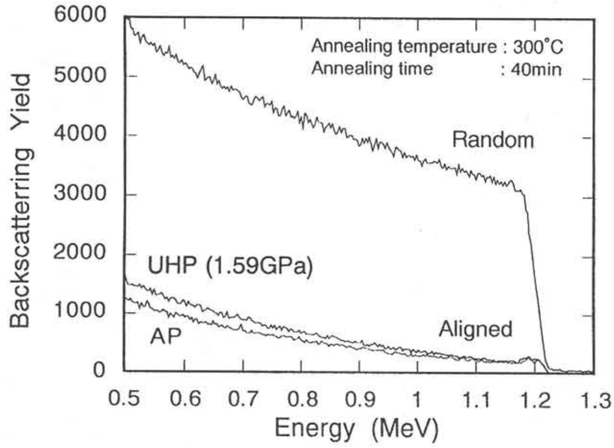

Fig.4. RBS spectra for AP- and UHP-annealed samples.

This works was partially supported by 1993 Grant-in-Aid for Scientific Research on Priority Areas "Crystal Growth Mechanism in Atomic Scale" (No.05211211) from the Ministry of Education, Science, and Culture of Japan.

[References]

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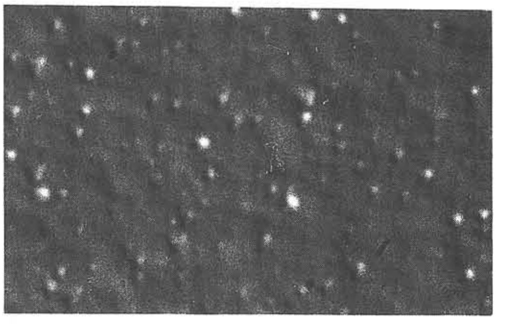
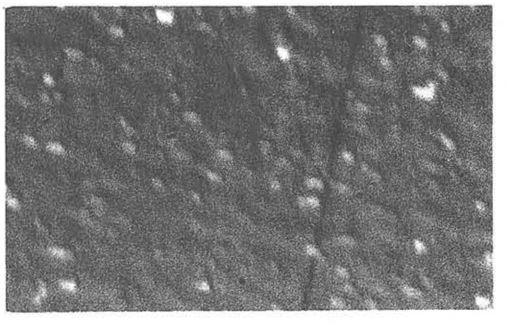


AP : 500°C



2.05GPa : 500°C

Fig.5. Nomarski optical micrographs of etched GaAs surfaces; (a) AP-annealed and (b) UHP-annealed samples.