GaAs film on Si substrate transplanted from GaAs/Ge structure by direct bonding

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(Received 13 January 2003; accepted 10 April 2003)

A process to transplant GaAs film from a Ge substrate to Si substrate using a direct bonding method is proposed. The scanning electron microscopy picture shows that the GaAs film is uniformly transplanted from Ge to Si. The high-resolution transmission electron microscopy image shows that GaAs is connected to Si by the covalent bonds. The stress of the bonded GaAs on Si is compared with GaAs/GaAs and heteroepitaxially grown GaAs/Ge(before bonding) by a 4.2 K photoluminescence method. The difference in the residual stress between the bonded GaAs/Si sample and GaAs/Si grown by two-step growth is explained by a thermal stress relaxation mechanism during the cooling process.
[DOI: 10.1063/1.1581976]

The heteroepitaxial technology of GaAs/Si is now of considerable interest to researchers to conquer problems such as large lattice mismatch (4.1%), difference in thermal expansion coefficients (2.5 times), etc., for optoelectronic devices.[1,2] Even if Si has excellent properties for electronic devices, its indirect band gap limits their optical properties. In contrast, GaAs, InP, and their alloy have excellent optical properties due to the direct band gaps. The integration of III–V and a Si substrate is a proper way to reduce the cost of the devices. The quality of the epitaxially grown GaAs on Si has scarcity for our expectations due to high-dislocation density.[3] So, researchers are looking for another alternative method for obtaining low-dislocation density GaAs layer on a Si substrate.

The direct wafer bonding technique[4] is one of the best alternatives to overcome the problems of the epitaxial growth. This technique has led to the result that material can be bonded to dissimilar material without degrading the crystalline quality.[5] The results had been suitable particularly for InP bonded to GaAs,[6] but III–V layers bonded to Si have also been reported.[7] The main problem is that it takes a long time to remove the substrate (usually GaAs) by etching the AlAs intermediate sacrificial layer, which prevents this technique from practical application. In order to overcome this problem, the SMART CUT process,[8] fast etching process,[9] etc., have been reported. This letter proposes a process to transplant the GaAs film to a Si substrate from GaAs grown on a Ge substrate. Because the defect density of GaAs film on a Ge substrate will be much lower than the heteroepitaxial GaAs on Si due to the small lattice mismatch, it is expected that the defect density of the GaAs film transplanted to Si from a Ge substrate is also smaller than heteroepitaxially grown GaAs/Si.

In our experiment, a 3 μm thick GaAs film was grown by metalorganic chemical vapor deposition (MOCVD) on a mirror-polished Ge substrate at 700 °C. The orientation of Ge substrate is (100) 5° tilted towards [111]. The Ge substrate was inserted into the MOCVD reactor as received from the company. It means the chemical etching was not performed prior to the growth. The GaAs/Ge and same size mirror-polished Si(100)substrate etched by HF to remove native oxides were placed together in a face-to-face configuration, as shown in Fig. 1(a), and transported in to the vacuum chamber where they were heated for 1 h at 700 °C with the pressure of 10^{-7} Torr as shown in Fig. 1(b). After this process, the sample was bonded together by direct bonding. After removing the sample from the vacuum chamber, the Ge substrate was mechanically pulled out, that means, removed from the GaAs/Si structure without damaging the GaAs film as shown in Fig. 1(c). The GaAs layer is transplanted to a Si substrate because the bonding of Si and Ga or As is stronger than that of Ge and Ga or As due to the large van der Waals radius of Ge compared with Si.[10] The remaining few 100 nm size Ge particles on the surfaces are removed using chemical etchants $2HF:0.5H_2O_2$ for 30 s. And the GaAs surface is cleaned by $30H_3PO_4:50H_2O:10H_2O$ for 3 s. The cross section of the bonded GaAs/Si sample has been studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The GaAs layer was also grown on GaAs substrate for comparison.

Low-temperature (4.2 K) photoluminescence measurements were made with the samples mounted in a strain free manner on a cold finger. Excitation was provided by an Ar+ (514.5 nm) laser. The luminescence from the sample was analyzed by a scanning spectrometer and detected by a pho-

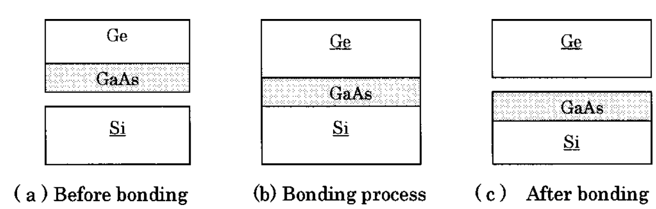

FIG. 1. Transplantation process of GaAs film from Ge substrate to Si substrate.

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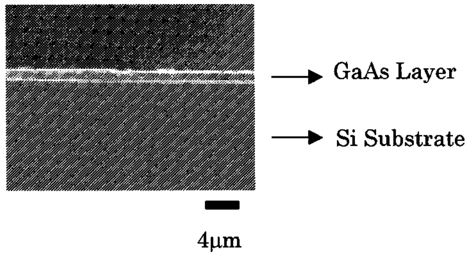

FIG. 2. The cross-sectional SEM image of a transplanted GaAs layer on Si substrate.

tomultiplier. The spectra were recorded after lock-in amplification.

The cross-sectional scanning electron microscope of the transplanted GaAs/Si is shown in Fig. 2. From Fig. 2, the GaAs film on Si looks uniformly transplanted to Si. Figure 3 shows the cross-sectional high-resolution TEM image of the transplanted GaAs layer on Si substrate. The GaAs/Si interface is relatively flat with the roughness of nearly 2 nm and the thick amorphous layer which is sometimes observed at the GaAs/Si interface,[11] is not observed in our sample. GaAs atoms are bonded to Si atoms by the covalent bonds, but some interfaces are irregularities due to misfit dislocations, which are marked by arrows in Fig. 3. The edge dislocations are clearly observed at the interface, periodically.

The observed 4.2 K photoluminescence spectra for GaAs/GaAs, GaAs/Ge, and GaAs/Si (transplanted from Ge) are shown in Fig. 4. In the homoepitaxially grown GaAs, the emission peaks at 1.514 and 1.493 eV due to free exciton and carbon acceptor impurity related level, respectively, are observed. But in the GaAs/Ge the free exciton peak is at 1.512 eV(833.6 nm). The shift is as small as 2.0 meV because the lattice constant and the thermal expansion coefficient of GaAs are almost the same as those of Ge. In the case of GaAs/Si (transplanted from Ge), the broad peak at the peak energy of 1.454 eV (852.0 nm) is observed, which is about 60 meV lower than the peak of homoepitaxial GaAs. This peak shift is due to the difference in the thermal expansion coefficients between GaAs and Si.

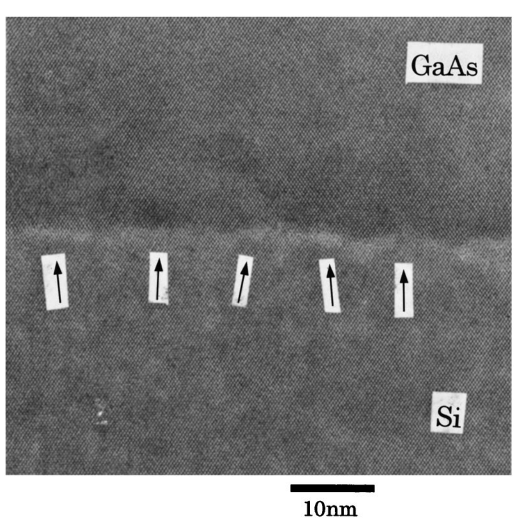

FIG. 3. The high-resolution cross-sectional TEM image of transplanted GaAs layer on Si substrate. The dislocations are indicated by arrows.

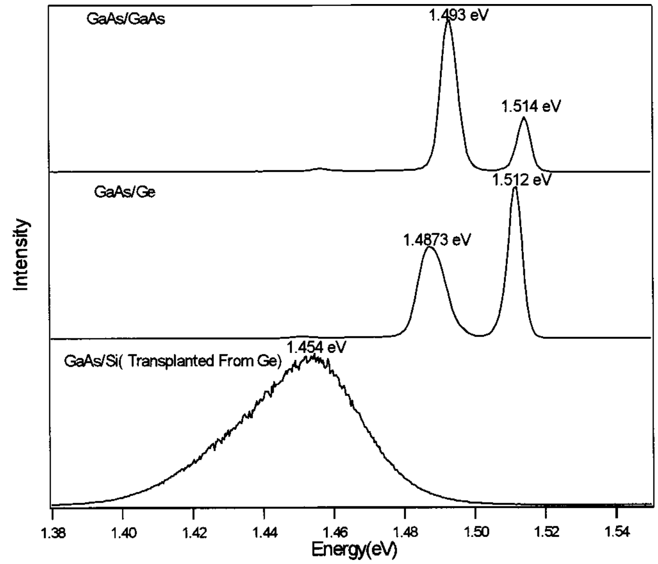

FIG. 4. 4.2 K photoluminescence spectra of a GaAs/GaAs, GaAs/Ge, and GaAs/Si (transplanted from Ge) samples.

When GaAs is bonded to a Si substrate at 700 °C, the strain caused by the lattice mismatch is relaxed by the generation of misfit dislocations as shown in the high-resolution transmission electron microscope (Fig. 3). When the Ge/GaAs/Si structure is cooled to the room temperature, the tensile stress is generated to the GaAs layer due to the thermal expansion mismatch by the bimetal model. It is interesting to note that the peak shift of our sample (60 meV) is larger than that of GaAs on Si grown by heteroepitaxial technique. The peak shift is about 30 meV in the case of GaAs on Si by two-step growth.[12] In the case of two-step growth, it is well known that the dislocation density at the growth temperature is low, whereas most of the dislocations are generated during the cooling process from the growth temperature.[13] It means that the dislocations are generated in order to relax the thermal stress during the cooling process. This results in the smaller stress than that calculated by the two thermal expansion coefficients using a bimetal model.[14]

The stress of GaAs on Si (transplanted from Ge) is about 6.0 kbar,[15] which is about twice larger than that of the GaAs grown on Si by a two-step growth method from the photoluminescence peak shift. It will mean that the relaxation of the thermal stress during the cooling process by generating threading dislocations will be negligible in our sample. When Si is bonded to GaAs/Ge structures at 700 °C, the misfit dislocations are already formed enough to relax the lattice mismatch. Therefore, the stress is increased during the cooling process based on the bimetal model, resulting in the larger stress compared with heteroepitaxially grown GaAs on Si.

Ignoring the temperature dependence of the thermal expansion coefficients, it is estimated that the stress as high as about 4.2 kbar is applied to the GaAs layer at room temperature (300 K). Therefore, it is necessary to check how the high stress affects the device performance in the future. The reduction of bonding temperature (700 °C) is also necessary to reduce the stress values. Hopefully, the transplanted GaAs/Si structure will be suitable for devices such as large area solar cells.

In summary, the GaAs film was transplanted to a Si substrate from GaAs/Ge structure. The SEM and TEM pictures clearly indicate the delineation between the GaAs film and Si substrate. The 4.2 K photoluminescence spectra show that the stress of the GaAs/Si (transplanted from Ge) sample is larger than that of heteroepitaxially grown GaAs/Si due to the difference in the stress relaxation mechanism during the cooling process.

This work was carried out as a part of ''Ground Research Announcement for Space Utilization'' promoted by the Japan Space Forum. The authors would like to thank Dr. Takamoto for supplying GaAs/Ge samples and Dr. Yu for the bonding experiment. One of the authors (N.C.) would like to thank the Japanese Government for the award of a ''Japanese Government scholarship.''

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