Direct bonding of heterogeneous wafers using surface activated bonding method at room temperature

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ABSTRACT

We successfully bonded the GaAs (p-type) wafer and Si (n-type) wafer at room temperature using the surface activated bonding method (SAB). The SAB is the unique bonding method utilizing the strong adhesive force that the surface essentially has. It is enough in order to make a strong interface that the surfaces of two wafers are made atomically clean by argon fast atom beam (Ar-FAB) in ultra high vacuum (UHV) and brought into contact. The bonded interface was as strong as that made by the conventional annealing process and no void was found in the interface when no particle remains on the surface. It is a unique advantage of SAB that residual thermal stresses caused by thermal expansion mismatch are not generated since no heating process is required. No layer of high electrical resistance in the interface was expected since the electrical characteristic (I-V characteristic) showed sharp rectification. Also the 1.3μm InGaAsP strained-layer quantum-well laser diode (LD) fabricated on InP substrate was bonded on GaAs substrate by SAB method. It shows no degradation of photoluminescence (PL) intensity after it is bonded.

INTRODUCTION

Recently there has been much interest in the integration of dissimilar semiconductor materials as a key technology for optoelectronic integrated circuits (OEICs) and more functional optoelectronic devices and circuits. This is because it will make much progress to the processing speed of CPU if signal interconnection is carried out optically. It is necessary for optical signal interconnection that Si and GaAs as the electronic device and GaAs and InP as the optical device are integrated monolithically. Heteroepitaxial growth is one of the promising methods for its integration and a massive effort has been made. (1-2) The room temperature operation of the GaAs-based and InP-based laser diode (LD) on Si has been achieved. (3) The lattice constant of these materials differs considerably and it needs high temperature process, so that the threading dislocation caused by a lattice mismatch and thermal expansion mismatch have been the greatest constraints. Hence the thick buffer layer is required for good characteristic and reliability of LD since good crystallization is a key to the characteristic of LD. Another approach is the direct bonding of the dissimilar semiconductor wafers. It has an advantage of reducing the dislocation density in the interface caused by a high lattice mismatch. Besides this advantage, it allows the integration of materials with an orientation mismatch. InP-based long wavelength laser on GaAs or Si substrate was achieved by wafer direct bonding. (4-5) But the conventional wafer bonding method requires annealing process at high temperature and thermal expansion mismatch is inevitable. It was reported that annealing process above 550°C caused the degradation of the LD characteristic and electrical conduction of the bonded interface. (6) We developed the surface activated bonding (SAB) method that makes it possible that dissimilar semiconductor materials can be directly bonded at room temperature. And its bonding strength is as large as that achieved by the conventional annealing method.

The SAB method is the unique bonding method that utilizes the strong adhesive force that the surface essentially has. The concrete procedure is as follows. At first, the surfaces of two wafers to be bonded are cleaned by argon fast atom beam (Ar-FAB) bombardment in ultra high vacuum (UHV). Then the inactive layer such as the native oxide layer is removed and the active surface is exposed. The meaning of 'active' is that the surface has the strong adhesive force. After that procedure, the two wafers are brought into contact and the strong interface is formed. After cleaned by Ar-FAB bombardment, the surface gets gradually contaminated even in UHV environment and loses its adhesive force. Hence it is important that two surfaces are brought into contact as soon as possible.

DIRECT BONDING OF GaAs AND Si WAFER BY SAB METHOD

Experimental

Direct bonding of GaAs and Si was achieved by applying the SAB method. Fig1 is the schematic of the bonding apparatus we used. It consists of six chambers, that is, two

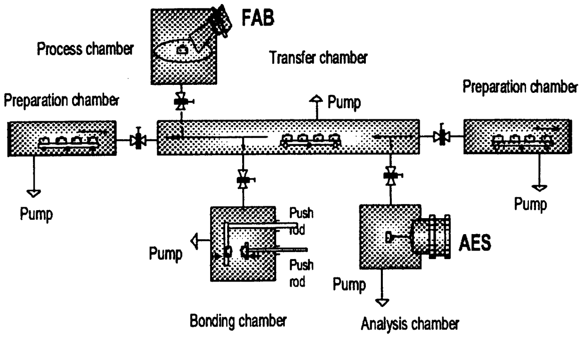

Fig1. The schematic of the bonding appratus

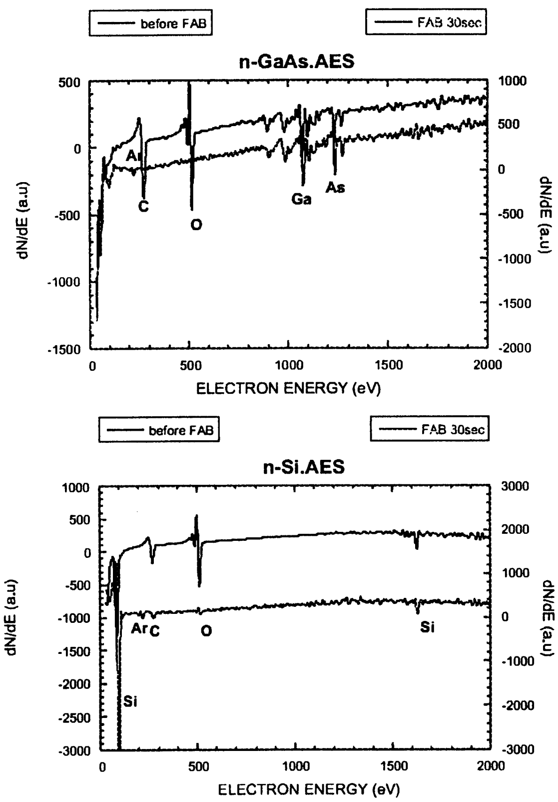

Fig2.AES spectra of Si and GaAs before and after FAB treatment

preparation chambers, a process chamber, a bonding chamber, an analysis chamber and a transfer chamber. Specimens are fixed on the holders and introduced into one of the preparation chambers. Then they are transferred into the processing chamber and cleaned by Ar-FAB bombardment. After that, specimens are transferred into the bonding chamber and brought into contact. The contact load can be controlled up to 100kgf. And the state of the surface can be investigated by X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES) in the analysis chamber. Chambers are evacuated to the vacuum of approximately 10^{-7}

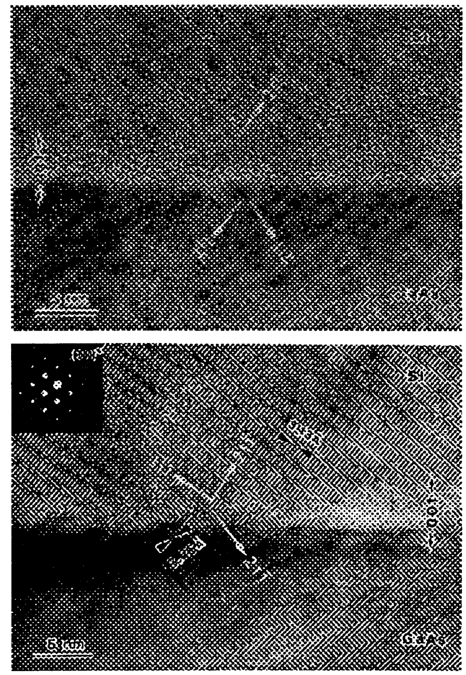

Fig3. High-resolution cross-sectional TEM views of the interface between Si and GaAs formed by SAB method. (Upper: with amorphous layer Lower; without amorphous layer)

Pa. Bonding and analysis are usually performed separately

The wafers used in this work were mirror-polished (100) p-GaAS and n-Si. The size of GaAs and Si wafer was 10 x 10mm and 15 x 15mm, respectively. The wafers to be bonded were cleaned before they are introduced into the bonding apparatus. Si wafer was cleaned with H_2SO_4 and H_2O_2 (4:1) and GaAs wafer was cleaned with acetone and ethanol. Then they were introduced into the bonding apparatus and treated by Ar-FAB bombardment in the process chamber. The accelerating voltage of Ar-FAB was 1.5kV and the quantity of dose is 2.38 x 10^{14}/cm^{2}sec. The treatment time of FAB was both 45 seconds. Fig2 is the Auger electron spectroscopy (AES) spectra of the wafers. The peaks of C, O almost disappeared after Ar-FAB bombardment. It can be known from this that the native oxide layer and the absorbate were sputtered away and the clean and active surface was exposed. So Ar-FAB bombardment for 45 seconds is expected to be adequate to make the surface clean. And the load for which the wafers were pressed face-to face was 10Mpa and pressing time was 60 seconds, which is enough time to the formation of the interface.

Results

It is quite important to measure the mechanical bonding strength. The tensile strength of the joint was 10Mpa in average and this value is almost the same as that of the conventional annealing method. It is considered to endure any device fabrication process.

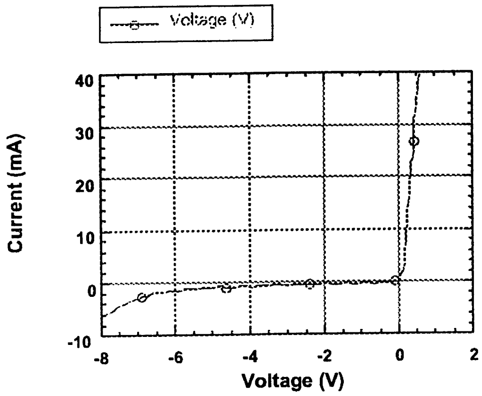

Fig4 I-V characteristic of the directly bonded GaAs and Si by SAB method at room temperature

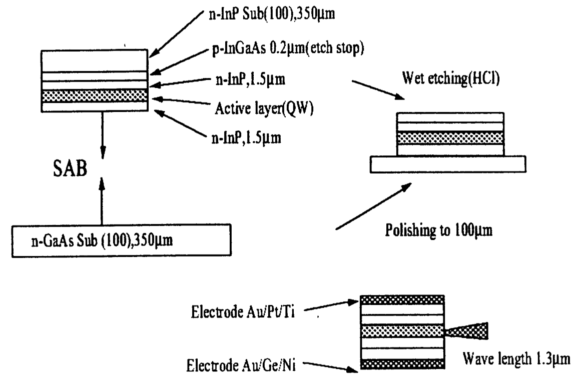

Fig5 The schematic of 1.3μm InGaAs LD fabricated on the GaAs substrate by SAB method

The interface of Si/GaAs bonded interface was investigated by transmission electron microscope (TEM) to confirm the bonding at the atomic level. Neither void nor porosity was found in the low magnification view and the threading dislocation was not formed. Fig3 is the high-resolution view of the bonded interface at high magnification. An amorphous intermediate layer of about 3nm thickness was found in most part of the interface boundary. But the direct bonding without an amorphous layer was partially formed. The EDX analysis showed the amorphous layer was composed of Si, C, and O. From this result, the amorphous layer is considered to be formed because of the defects introduced by Ar-FAB bombardment and the component of C, O are produced as the result of the surface contamination after FAB bombardment. The diffusion from Si to GaAs is also expected.

It is important to investigate the electrical characteristic of the bonded wafers when we actually design the device. Fig4 is the I-V characteristic of the directly bonded GaAs and Si. The sharp rectification means electrical conduct is good and layer of high electrical resistance does not exist.

LASER DIODE (LD) FABRICATED ON GaAs SUBSTRATE BY SAB METHOD

The long-wavelength InP-based laser emitting at 1.3-1.6μm is attractive for optical interconnection since Si is transparent at this wavelength. 1.3μm InGaAsP strained-layer quantum-well laser (InP-based) was fabricated on GaAs substrate by applying the SAB method.

The InP-based laser wafer was grown using conventional MOCVD (metalorganic chemical vapor deposition), which consists of p-InGaAs etch stop layer, p-InP clad layer, InGaAs active layer, n-InP clad layer. The GaAs host substrate and the laser wafer were cleaned with acetone and ethanol before being introduced into the bonding apparatus. Ar-FAB bombardment was done for 30 seconds for both wafers and brought into contact with a pressure of 20Mpa. After bonding, the InP substrate was selectively etched by dilute HCl. Fig5 is the schematic of the fabricated laser diode

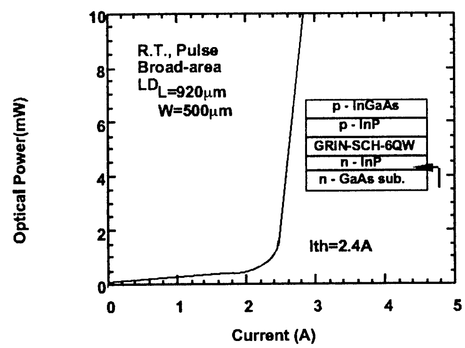

Fig6 I-L characteristic of the LD fabricated on the GaAs by SAB method

(LD). The ridge waveguide laser with 920μm of length and 500μm of width was made by cleavage. Fig6 is the measured result of the light output power versus the injection current. The threshold current was as low as 2.4A and the threshold current density was $500A/cm^2$. It is almost the same value as that of as-grown laser diode and this means the characteristic of laser diode was not degraded after it was bonded on GaAs substrate by SAB method. Fig7 shows the measured photoluminescence (PL) intensity of as-grown laser diode and that directly bonded on the GaAs host substrate. It can be known from comparison of PL intensity and FWHM (full width at half maximum) that the characteristic of the LD was not degraded after the LD was directly bonded by SAB method.

CONCLUSION

We have demonstrated that the strong bonding between Si wafer and GaAs wafer can be made by SAB method. The I-V characteristic, which is very important for actual device design, was measured and no layer of high electrical resistance was expected to exist. And 1.3μm InGaAsP laser diode was fabricated on GaAs substrate by SAB method and

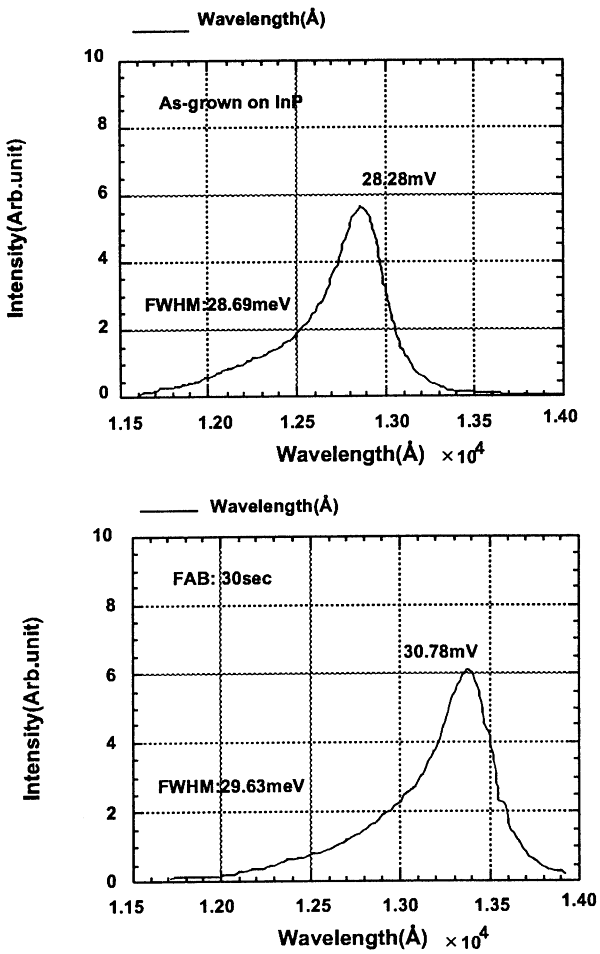

Fig7 Comparison of the PL intensity between as-grown LD and fabricated on GaAs substrate by SAB method.

it was confirmed from its PL intensity that its characteristic was not degraded after it was bonded on GaAs substrate. It can be said that direct semiconductor wafer bonding using the SAB method is promising as the elemental technology of OEICs.

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