

# Integration of GaN with Si using a AuGe-mediated wafer bonding technique

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This letter describes integration of GaN with Si using a AuGe alloy as a bonding material. GaN is first grown on GaAs and then GaN/GaAs/AuGe/Si and GaAs/GaN/AuGe/Si structures are fabricated by wafer bonding. For the latter structure, the GaAs substrate is removed by mechanical and chemical etching. From the current–voltage measurements of both structures, it is found that the bonded interfaces do not obstruct the carrier transport. Furthermore, the optical reflection measurements reveal that AuGe works well as a mirror, which is a suitable characteristic for the integration of GaN light-emitting devices with Si. © 2000 American Institute of Physics. [S0003-6951(00)03750-5]

The monolithic integration of GaN-based optoelectronics with Si-based microelectronics makes it possible to fabricate “smarter” devices. The realization of the monolithic devices relies on the achievement of device-quality GaN on the Si substrates, which has motivated several studies on the heteroepitaxial growth of GaN on Si.<sup>1–3</sup> However, the heteroepitaxy presents significant challenges due to the large mismatch in lattice constants ( $\sim 20\%$ ) and thermal expansion coefficients ( $2.6 \times 10^{-6} \text{ K}^{-1}$  for Si and  $5.6 \times 10^{-6} \text{ K}^{-1}$  for GaN), and their properties are still poorer than those grown on sapphire, the much widely used substrate.<sup>4</sup>

An alternative approach to optoelectronic integration is wafer bonding. This technique has been applied to many material combinations such as InP on Si, InP on GaAs, GaAs on Si, and so on.<sup>5–8</sup> Regarding GaN on Si, direct bonding by atomic rearrangement is likely to be difficult chiefly due to the same reasons for the heteroepitaxial growth mentioned above. Also, for the Si(001) surface, on which Si devices are fabricated generally, the mismatch in crystalline structure with hexagonal GaN obstructs the direct bonding. A solution to avoid these issues is a metal-mediated low-temperature bonding technique. Recently, Wong *et al.* reported the integration of GaN/sapphire with Si using a Pd–In metallic bond and excimer laser liftoff.<sup>8</sup> On the other hand, this study describes the integration of GaN/GaAs with Si using a AuGe alloy as a bonding material.<sup>7</sup> There are two reasons for the use of GaAs substrates for GaN growth. The first reason is the close matching of the thermal expansion coefficient of GaN with that of GaAs ( $5.7 \times 10^{-6} \text{ K}^{-1}$ ) in comparison to that of sapphire ( $7.3 \times 10^{-6} \text{ K}^{-1}$ ). This characteristic prevents the bending of the wafer and enables bonding of a wide area. The other reason is that GaAs can be removed by mechanical polishing and chemical etching, by which GaN is easily transported onto Si. It will also be demonstrated that AuGe does not obstruct carrier transport across the bonded interfaces, and that AuGe potentially works as a mirror which may enhance the output efficiency of GaN light-emitting devices on Si.

The sample structures investigated here are schematically shown in Fig. 1. In sample A, the backside of GaAs is

bonded with Si, while in sample B the surface of GaN is bonded with Si and then GaAs is removed. For both cases, the GaN layers on GaAs were grown by atmospheric-pressure metalorganic vapor phase epitaxy (MOVPE) in the following manner. First, a 10-nm-thick AlAs layer was grown at 700 °C using trimethylaluminum and tertiarybutylarsine as source precursors on *n*-GaAs(001) substrates ( $1.4 \times 10^{18} \text{ cm}^{-3}$ ) which were mirror polished on both sides. Then, GaN approximately 0.26- $\mu\text{m}$ -thick was successively grown at 600–650 °C using triethylgallium and dimethylhydrazine. We have recently found that GaN grown on AlAs is in the hexagonal phase even on the GaAs(001) substrate.<sup>9,10</sup> The present samples, as well, were confirmed by x-ray diffraction to be *c*-oriented hexagonal GaN (*h*-GaN) with GaN[10 $\bar{1}0$ ] $\parallel$ GaAs[1 $\bar{1}0$ ] in the in-plane direction. The root mean square value of the GaN surface roughness was estimated by atomic force microscopy to be 10 nm. In the following discussions, the GaN-on-AlAs/GaAs(001) heterostructure is simply referred to as GaN/GaAs.

Following the epitaxy, the samples were cut into pieces of a size of (3×3) mm<sup>2</sup>, and also, *n*-Si(001) of a similar size was prepared. The resistivity of the *n*-Si substrate was

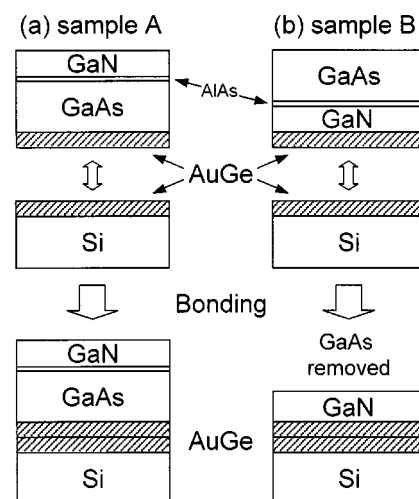


FIG. 1. Schematic views of the fabricated samples. In sample A (a), the backside of GaAs is bonded with Si, while in sample B (b), GaN is bonded with Si and GaAs is removed.

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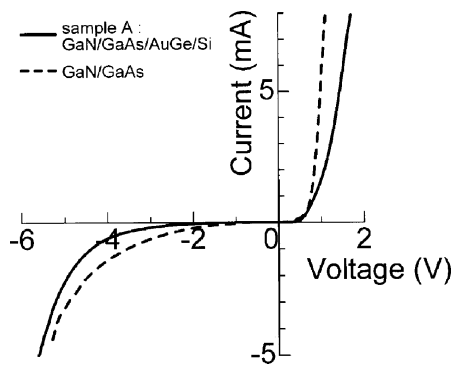


FIG. 2.  $I$ - $V$  characteristics of GaN/GaAs/AuGe/Si formed by bonding (sample A) and GaN/GaAs for comparison measured at RT. The GaN layer was biased positive.

0.007–0.02  $\Omega$  cm, which corresponds to the carrier concentration of  $1-7 \times 10^{18} \text{ cm}^{-3}$ .<sup>11</sup> The Si substrates were given a rinse in HF:H<sub>2</sub>O=1.5:100 solution and blown dry to remove surface oxide. Then, 50-nm-thick AuGe films were deposited onto the backside of GaAs (sample A) or the surface of GaN (sample B), and a clean Si substrate. The AuGe-coated samples were stacked face to face, i.e., GaN/GaAs/AuGe/Si (sample A) and GaAs/GaN/AuGe/Si (sample B), in intimate physical contact. The bonding process was carried out in a hydrogen ambient at 280–300 °C for 30 min. For sample B, GaAs was thinned by mechanical polishing to about 100  $\mu\text{m}$  and removed completely by chemical etching in H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O=5:1:1 solution, which was preliminarily confirmed to have an excellent selectivity for the GaN-(AlGa)As system. The surface of the GaN layer left on Si was slightly degraded compared with that of as-grown GaN, but still optically smooth.

For the investigation on the carrier transport properties, ohmic contacts were formed using Al for both  $n$ -Si and GaN after bonding (and removal of GaAs in the case of sample B). The diameter of the Al contact for GaN was 0.8 mm. The ohmic nature of these electrodes had been confirmed in preceding to the present study. The current-voltage ( $I$ - $V$ ) characteristics of the bonded heterostructures were measured at room temperature (RT). In this study, forward bias means that the GaN side is biased positive with respect to the Si side.

Figure 2 shows the  $I$ - $V$  characteristics of sample A and, for comparison, GaN/GaAs, that is, the sample before being bonded with Si. An ohmic contact to  $n$ -GaAs in the reference sample was formed by deposition and annealing of AuGe. As seen in Fig. 2, both curves are essentially the same, exhibiting the clear rectifying properties. The reason for the higher resistance in sample A, which is implied in the voltage ranges above 0.5 V and below -1 V, is unknown at present, but at least it is not related to the bonded interface, as is proved below. Those  $I$ - $V$  characteristics strongly suggest that the bonded interface does not affect the carrier transport properties, regardless of the presence of the conduction band offset at the  $n$ -GaAs/ $n$ -Si interface (0.579 eV).<sup>6</sup> This can be achieved only when both AuGe/ $n$ -GaAs and AuGe/ $n$ -Si contacts are ohmic. In principle, the former contact is ohmic, but the latter contact should be Schottky. A clue to explaining why AuGe/ $n$ -Si behaves as ohmic can be found in the study by Ma *et al.*<sup>7</sup> They have revealed that

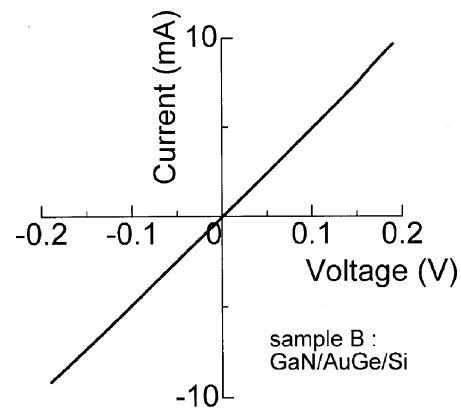


FIG. 3.  $I$ - $V$  characteristic of sample B (GaN/AuGe/Si) measured at RT. The GaN layer was biased positive as is the same as Fig. 2.

solid-phase epitaxial regrowth of GeSi alloys on the Si substrate occurred during the bonding process of GaAs and Si using the AuGe alloy. Based on their observation, we consider that the formation of a narrower band-gap material of GeSi on Si facilitates the carrier injection, making the AuGe/ $n$ -Si contact ohmic.

Concerning the rectifying properties, that will originate from the GaN/GaAs heterointerface. The carrier concentration and the resistivity of the GaN layer were estimated by the Hall effect measurement to be  $1.5 \times 10^{11} \text{ cm}^{-3}$  with  $n$ -type conductivity and  $1.1 \times 10^4 \Omega \text{ cm}$ , respectively. Namely, GaN/GaAs is an  $n$ - $n$  isotype heterojunction with the different carrier concentrations. In order to estimate the built-in potential, which plays an important role in determining the carrier transport properties, the Fermi levels in GaAs and GaN were calculated from their carrier concentrations. Another physical parameter necessary for calculating the built-in potential is the band offset. There is no available data of the band offset at the  $h$ -GaN/GaAs(001) interface. However, if we use the conduction band offset experimentally determined for cubic GaN/GaAs(001) of -0.03 eV (type II band alignment)<sup>12</sup> and that theoretically predicted for cubic GaN/ $h$ -GaN of 0.154 eV,<sup>13</sup> the conduction band offset between  $h$ -GaN and GaAs(001) is presumed to be 0.154–0.03 eV=0.151 eV (type I band alignment). Using these quantities, the built-in potential was evaluated to be approximately 0.4 eV, which is close to the experimentally observed turn-on voltage of 0.6–0.7 V (see Fig. 2), and considered to be the origin of the rectifying properties.

Let us move on sample B. The  $I$ - $V$  characteristic of sample B was measured at RT and the result is shown in Fig. 3. An ohmic character is clearly observable. As was discussed with Fig. 2, the AuGe/Si contact is ohmic. Therefore, Fig. 3 provides another interesting finding that the AuGe/GaN contact is also ohmic at least for the present sample with a relatively high resistivity. From the slope the resistance was evaluated to be 20.4  $\Omega$ . Since the resistance of  $n$ -Si is less than 0.15  $\Omega$ , the resistance of 20.4  $\Omega$  directly reflects that of the GaN film. Using the resistivity measured by the Hall effect measurement and the dimension of the Al electrode, the expected resistance is calculated to be 53  $\Omega$ . The difference is probably caused by the expansion of the current pass due to the absence of a mesa structure.

The results on both samples A and B indicate that the

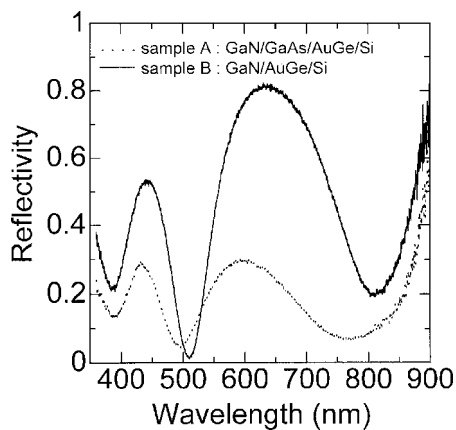


FIG. 4. Reflection spectra of samples A and B measured at RT.

electron injection from Si substrates to GaN or vice versa is possible through the interface bonded via the AuGe alloy. This is expected to be a strong merit for the integration of actual devices. Also, it should be emphasized that the bonding was conducted at less than 300 °C, which enables us to apply this technique to the integration of GaN with metalized Si devices. A remaining issue toward the achievement of integration of GaN devices with Si devices will be the diffusion of Au into Si because Au easily diffuses in Si and forms deep levels, as is well known. However, the formation of GeSi on Si during the bonding process and the low bonding temperature may suppress the interaction between Au and Si.

When GaN light-emitting devices are integrated on Si, it is important for the improvement of the output efficiency to prevent the photoabsorption in Si. For this purpose, GaN/AuGe/Si (sample B) seems to be a promising structure because AuGe may work as a mirror. In order to ascertain this, reflectivity was measured at RT. The light from a halogen lamp passed through a monochromator was irradiated to the samples from the surface normal, and the reflected light was detected by a photomultiplier. The results for the samples A and B are compared in Fig. 4. The spectrum of sample A is determined by the reflection of the irradiated light at the GaN surface and at the GaN/GaAs interface, while the spectrum of sample B mainly by that at the GaN surface and at the GaN/AuGe interface. Therefore, the observed oscillations are due to the interference of the light in the GaN films and, indeed, corresponded well to the designed film thickness of

0.26  $\mu\text{m}$ . Due to the higher reflectivity of AuGe than GaAs, the reflectivity of sample B is basically higher than that of sample A, suggesting higher potential of sample B for optoelectronic applications. In sample B, the reflectivity in a shorter wavelength region is smaller than that in a longer wavelength region. This is due to the decrease of the reflectivity of AuGe in a short wavelength region, and if we can find other bonding materials which have a higher reflectivity, the reflectivity will be improved further.

In summary, GaN was integrated with Si using AuGe as an adhesion material. The fabricated structures were GaN/GaAs/AuGe/Si and GaN/AuGe/Si. The  $I$ - $V$  measurements at RT revealed that the bonded interfaces do not obstruct the carrier transport, which can be an advantage for devices requiring the current injection through Si. Furthermore, the reflectivity measurements revealed that AuGe works as a mirror. This characteristic is suitable for the integration of GaN light-emitting devices with Si.

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