

## Wafer Bonding of Silicon Carbide and Gallium Nitride

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### ABSTRACT

Wafer bonding of SiC and GaN may prove important in the formation of high power heterojunction devices. Results of bonding SiC (C or Si surface) onto GaN (Ga surface) are presented. The samples were n-type 6H SiC and epitaxial n-type 2H(wurzite) GaN grown on SiC. The results demonstrate bonding for both possibilities, but the bonding of the C surface SiC to Ga surface GaN is more readily accomplished. A lower resistance was found for the C-face SiC/Ga-face GaN. The results indicate that the polarity of the interface is important for bonding of these materials.

### INTRODUCTION

Silicon carbide is considered for high power and high temperature semiconductor device operation because the material exhibits a wide bandgap (3.0 eV) and high thermal conductivity (5W/cm°C). The operation of silicon carbide bipolar junction transistors with an even larger bandgap emitter would display increased current gain due to improved emitter efficiency. The larger bandgap of the emitter would restrict the diffusion of holes from the base to the emitter, resulting in high electron injection efficiency into the base. Additionally, the increased bandgap of the emitter allows the base to be heavily doped, thereby decreasing the base resistance. Also, since SiC is an indirect bandgap material, free carriers exhibit longer lifetimes, compared to a direct bandgap material such as GaN. The increased lifetime yields a long diffusion length, and a high base transport factor. Furthermore, these devices have a short base width, which further enhances the transport factor, thereby increasing the current gain. Gallium nitride is a natural choice for a larger bandgap emitter for SiC. Gallium nitride not only has a higher bandgap, 3.4 eV, than SiC, it also has a high thermal conductivity, 1.3W/cm°C. With a lattice constant of 3.18Å for GaN and 3.08Å for SiC epitaxy is possible, but the lattice mismatch (~3.4%) can significantly limit the quality of the epitaxial film [1,2].

The poor wetting of GaN on 6H-SiC(0001) substrates impedes direct nucleation and frequently results in GaN films of poor crystallinity. The use of an AlN buffer layer has been demonstrated to be effective in improving the crystallinity as well as in reducing the defect density in the GaN films, but simultaneously inhibits carrier injection across the AlN/SiC interface due to the insulating nature of AlN and its high band gap [3]. Reports of the growth of GaN directly onto 6H-SiC(0001) have noted the observation of an amorphous interlayer or zinc-blende inclusions at or near the GaN/SiC interface. Epitaxial growth by conventional techniques, e.g., molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), is affected by lattice mismatch strain. During MBE and MOCVD growth dislocations form to relax the strain energy as the layer thickness exceeds a critical value, known as the critical thickness. It is energetically preferred for dislocations to nucleate on the surface of the layer, subsequently

gliding down towards the interface, and drawing threading dislocations behind, most of which remain during further layer growth [4]. The critical thickness is on the order of 0.2 $\mu\text{m}$ . The dislocation density observed for GaN on SiC at a thickness of 0.5 $\mu\text{m}$  is typically about  $5 \times 10^9 \text{cm}^{-2}$  [3].

Direct wafer bonding is an alternative method of forming a heterointerface or heterojunction. It is an appropriate technique for materials of high lattice mismatch or with chemical instabilities. The method of direct bonding enables the formation of atomic bonds across atomically flat surfaces of different materials without introducing threading dislocations. Direct wafer bonding has proved its capability in enabling new classes of heterogeneous devices [4]. This study explores approaches for wafer bonding of SiC and GaN. Mechanisms of direct bonding are proposed based on the experimental observations. We also report initial I-V measurements of a SiC/GaN bonded interface.

## EXPERIMENTAL DETAILS

The SiC wafers were obtained from Cree Research, and 50 mm 6H (0001)<sub>Si</sub> n-SiC and 50 mm 6H (000 $\bar{1}$ )<sub>C</sub> n-SiC wafers used. A 1.5 $\mu\text{m}$  thick 2H(wurzite) (0001)<sub>Ga</sub> n-GaN film was grown by MOCVD onto (0001)<sub>Si</sub> SiC with a (conducting) AlN buffer layer. The (0001)<sub>Si</sub> SiC wafer and the (0001)<sub>Ga</sub> GaN film were on-axis, but the (000 $\bar{1}$ )<sub>C</sub> SiC wafer was cut 3° off-axis. Doping levels (n-type) were  $2 \sim 4 \times 10^{18} \text{cm}^{-3}$  in the SiC wafers and  $1 \times 10^{16} \sim 10^{17} \text{cm}^{-3}$  in the GaN film. The SiC wafer showed a resistance of less than 0.1 ohm-cm. The wafers were diced into 10 $\times$ 10 mm<sup>2</sup> pieces and subjected to a sequential bonding process consisting of *ex situ* wet cleaning, *in situ* dry cleaning, *ex situ* bonding and *in situ* annealing. *Ex situ* wet cleaning includes a standard RCA SC1 clean (NH<sub>4</sub>OH: H<sub>2</sub>O<sub>2</sub>: H<sub>2</sub>O=0.25:1:5, 80°C, 10min), DI water rinse (3min), N<sub>2</sub> blow dry and a standard RCA SC2 clean (HCl: H<sub>2</sub>O<sub>2</sub>: H<sub>2</sub>O=1:2:8, 80°C, 10min), DI water rinse (3min), N<sub>2</sub> blow dry. A final HCl dip was employed for the GaN and a final HF dip was used for SiC substrates (each 1min). *In situ* dry cleaning includes  $\sim 800^\circ\text{C}$  10min UHV annealing of SiC and  $\sim 550^\circ\text{C}$  10min UHV annealing of GaN.

After dry cleaning samples were removed from the UHV chamber into air and (0001)<sub>Si</sub> SiC/(0001)<sub>Ga</sub> GaN and (000 $\bar{1}$ )<sub>C</sub> SiC/(0001)<sub>Ga</sub> GaN pairs were positioned in a chuck and loaded back into UHV. Bonding was initiated through pressure applied to the surfaces while at room temperature. After the initial bonding, *in situ* annealing was employed to form a high density of bonds at the heterointerface. The *in situ* UHV annealing process included up to 5 annealing cycles at 890°C for times up to 30min. Longer anneal times were employed for the (0001)<sub>Si</sub> SiC/(0001)<sub>Ga</sub> GaN couples while a 10min anneal was sufficient for bonding of (000 $\bar{1}$ )<sub>C</sub> SiC/(0001)<sub>Ga</sub> GaN couples. The surfaces were characterized prior to bonding with AFM and AES. After the bonding sequence, IR light images of the bonded pairs were recorded to characterize the degree of bonding. I-V measurements of the bonded pair were completed after deposition of 2000Å of Ti on both sides of the bonded pair.

## RESULTS

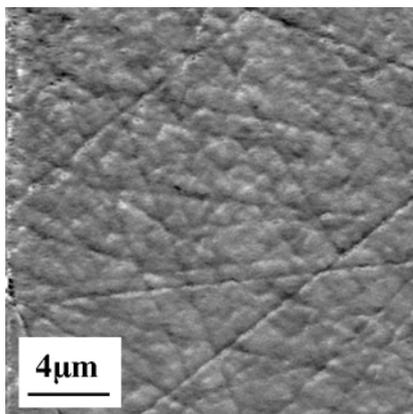
As is typical for as-received SiC wafers, the surfaces showed polishing scratch grooves, and 20 $\times$ 20  $\mu\text{m}^2$  AFM scans displayed an RMS roughness of  $20 \pm 5 \text{Å}$ . The GaN surfaces displayed similar grooves, which are also apparently related to the polishing scratches of the initial SiC substrates. An AFM image of a SiC surface is shown in Figure 1. The chemical properties of the

surfaces were examined by AES. To obtain measurements representative of the surfaces prior to bonding, the samples were removed from vacuum and held in ambient air for a period of time typical for bonding. The samples were then reloaded into the UHV system for AES measurements. The AES indicated monolayer oxidation of the SiC surface and the presence of monolayer levels of oxide and carbon contamination on the GaN surfaces (Figure 2).

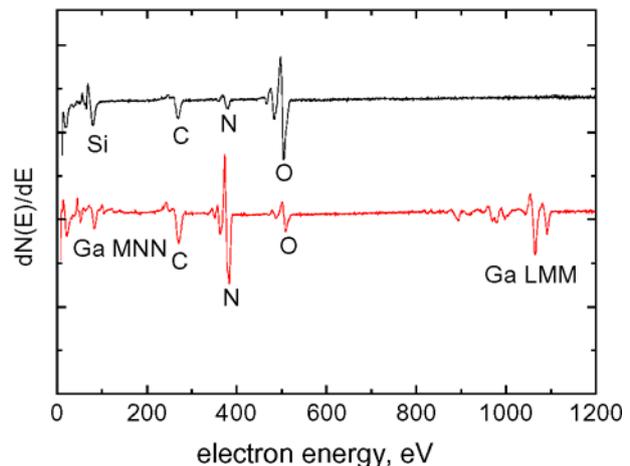
After *in situ* cleaning the surfaces were installed in a special sample holder to initiate the bonding process. The bonding process involved two steps, initial contact bonding with the samples placed in the holder in ambient air, and annealing of the contact bonded couple to initiate covalent bonding. Identical experiments were carried out for  $(0001)_{\text{Si}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  and  $(000\bar{1})_{\text{C}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$ . Many attempts to form a bonded interface using annealing temperatures less than  $800^{\circ}\text{C}$  were unsuccessful. For annealing at  $\sim 900^{\circ}\text{C}$  bonding was obtained for both SiC surfaces. For the  $(0001)_{\text{Si}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  partial bonding was obtained in only one experiment out of five attempts. However, for  $(000\bar{1})_{\text{C}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  effective bonding occurred in each of two attempts. For the latter case a single ten minute anneal proved effective while anneals for as long as 30 min. were attempted for the Si surface of SiC.

After the bonding process, the couple was removed from UHV and the bonding was characterized optically using infrared light. The presence of interference fringes indicates incomplete bonding. In addition, pressure applied to the surface will cause shifting of the fringes of an incomplete bonded surface. Optical images showed that the  $(0001)_{\text{Si}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  pair displayed partial bonding while the  $(000\bar{1})_{\text{C}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  pair displayed bonding over the whole area of the couple (Figure 3). Shown in Figure 3 are three couples after the bonding process. One  $(0001)_{\text{Si}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  was annealed to  $\sim 900^{\circ}\text{C}$  but bonding was not observed. In another case, where five  $900^{\circ}\text{C}$ , 30 min. annealing cycles were employed, partial bonding was observed. For the  $(000\bar{1})_{\text{C}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  pair, a uniform bonded interface was observed on each of two attempts.

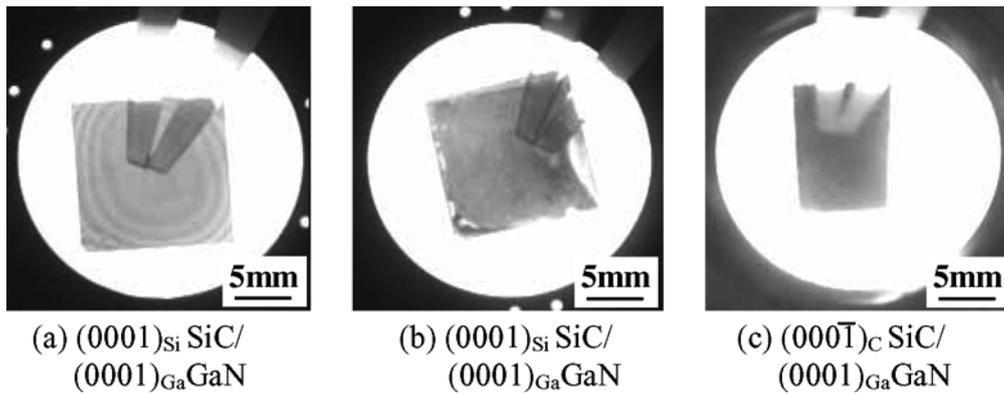
The electrical properties of the bonded couples were examined after metallization of the back side of the SiC wafers. Noting that both samples were n-type, we may expect near ohmic behavior. I-V measurements showed that the  $(000\bar{1})_{\text{C}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  pair has a smaller resistance than  $(0001)_{\text{Si}} \text{SiC}/(0001)_{\text{Ga}} \text{GaN}$  pair (Figure 4). The lower resistance indicates a more effective interface bond.



**Figure 1.** AFM image of as-received SiC show RMS roughness  $20 \pm 5 \text{ \AA}$  in  $20 \times 20 \mu\text{m}^2$  area



**Figure 2.** AES analysis of SiC and GaN after reloading from the air

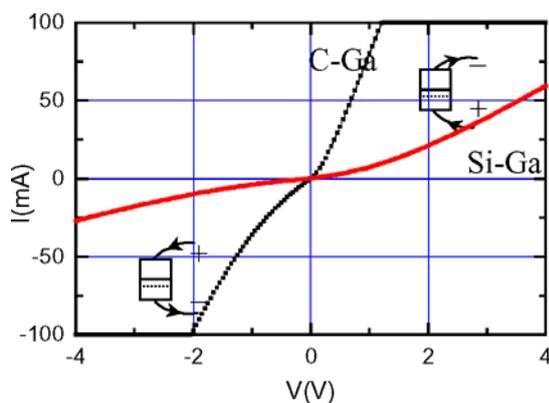


**Figure 3.** IR image of pairs after (a)UHV annealing of 890°C 30min, (b) 5 cycles of UHV annealing between RT and 890°C 30min, (c) UHV annealing of 890°C 10min

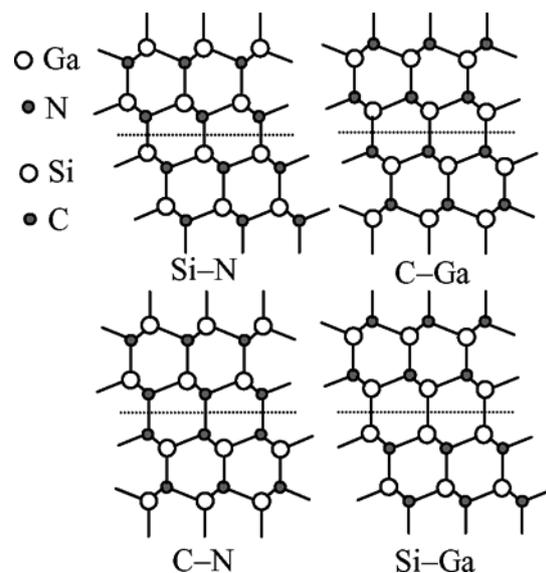
## DISCUSSION

The results presented here indicate a significant difference in the effectiveness of bonding the C or Si surface of SiC to GaN. In both cases, annealing to  $\sim 900^\circ\text{C}$  was necessary. It is likely that the annealing assists the bonding through contaminant removal and through atomic displacements to optimize the formation of chemical bonding.

It has been reported that in the case of epitaxial growth of GaN on SiC the strength of covalent bonds is diminished by the polarization induced by the surrounding atoms and the ionic component of the bonding is significant [5]. Therefore, the lowest energy interface occurs when “positive” ions bind to “negative” ions. This polarity determination can be applied to wafer bonding. With knowledge of electronegativity values, we can assume the bonding process of the elements (Figure 5). Table 1 gives the electronegativity values of the respective elements of GaN and SiC. Table 2 shows the difference in electronegativity and the amount of partial ionic character in the possible bonds [6].



**Figure 4.** I-V of directly bonded Si face SiC/Ga face GaN pair and C face SiC/Ga face GaN pair



**Figure 5.** Schematic  $[11\bar{2}0]$  projection of the GaN/SiC interface

**Table 1.** Electronegativity values

Element	Electronegativity
N	3.0
C	2.5
Si	1.8
Ga	1.6

**Table 2.** Bond and ionic character

Bond	Difference in Electronegativity	Ionic Character
N-Ga	1.4	39%
N-Si	1.2	30%
C-Ga	0.9	19%
C-Si	0.7	12%
N-C	0.5	7%
Si-Ga	0.2	1%

Of the four possible interface bonds, the Si-N bond has the highest electronegativity difference and the largest ionic character. So Si-N bonds at the interface will form a strong bond, which is partly covalent and partly ionic. The C-Ga bond has a slightly lower electronegativity difference and still has a 19% ionic character. So the C-Ga bonds will also provide a strong covalent and ionic bond. In contrast, N-C and Si-Ga have small ionic components, which will result in weaker bonding.

With this viewpoint of electronegativity difference, our results of effective bonding for  $(000\bar{1})_C$  SiC/ $(0001)_{Ga}$  GaN and only partial bonding of  $(0001)_{Si}$  SiC/ $(0001)_{Ga}$  GaN are explained.

## CONCLUSIONS

The results presented here demonstrate the potential of forming a bonded interface between GaN and SiC surfaces. Polarity is an important factor in wafer bonding of these materials. Ga-terminated GaN readily bonds to C-terminated SiC, but it was difficult to bond Si-terminated SiC to GaN. The  $(000\bar{1})_C$  SiC/ $(0001)_{Ga}$  GaN pair has the lower interface resistance. We are proposing that heterojunction devices [1,2] may be prepared from directly bonding  $(000\bar{1})_N$  n-type GaN and  $(0001)_{Si}$  p-type SiC. We are now exploring approaches to obtain smooth surfaces and to minimize surface contamination.

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