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Interface structure and adhesion of wafer-bonded GaN/GaN and GaN/AlGaN semiconductors

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Material integrations of GaN/GaN and $Al_{0.25}Ga_{0.75}N$/GaN semiconductors through wafer bonding technology were reported in this work. The wafer surface and interface microstructures were characterized by scanning electron microscopy and energy dispersive x-ray spectroscopy. The interface adhesion (bonding strength) was estimated based upon the interface fracture energy γ_o measured by double-cantilever beam technique. The interface adhesion properties of several different wafer-bonded III-V semiconductors were also compared. By comparing the atomic chemical bond energy E_o with the measured interface fracture energy γ_o, the bondability of a few major III-V semiconductors was analyzed. © *2004 American Institute of Physics.*
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I. INTRODUCTION

Group III nitride semiconductors, such as GaN, AlN, and their ternary alloy $Al_xGa_{1-x}N$, have emerged as the leading materials for a variety of applications due to their high electron saturation velocity, high critical field, high thermal and mechanical stability, and good thermal conductivity.[1–4] Furthermore, the large band discontinuity creates an $Al_xGa_{1-x}N$/GaN heterointerface that can confine an unusually high density of electrons in a two-dimensional electron gas. A modulation-doped field-effect transistor based on the $Al_xGa_{1-x}N$/GaN heterostructures has shown encouraging high-frequency, high-power, and high-temperature performance.[5] One of the major challenges in group III nitride semiconductors is the heterogeneous integration of free standing GaN-based devices with dissimilar substrates.[3–6] Direct wafer bonding has been reported to be an ideal approach to integrate mismatched materials and has been used to fabricate a number of advanced microelectronic or photonic devices.[3,4,6,7]

Wafer bonding of GaN and other related semiconductors has been reported by a few research groups, such as GaN/GaAs,[3,4] GaN/InP,[6] and GaN/GaN.[7] However, to date, only a little effort has been focused on understanding the correlations among bonding process, wafer surface or interface microstructures, and interface adhesion. This work reports on the progress toward characterizing the surface microstructures and interface adhesion of wafer-bonded GaN and $Al_{0.25}Ga_{0.75}N$ semiconductors.

II. EXPERIMENT

GaN wafers were fabricated by growing a 0.5 and 2.0 μm GaN (0001) layer on sapphire substrates using metalor-

ganic chemical vapor deposition. The $Al_{0.25}Ga_{0.75}N$ (0001) wafers were prepared by depositing a 1250 Å $Al_{0.25}Ga_{0.75}N$ over the 2.0 μm GaN; both layers were grown by molecular-beam epitaxy on a SiC (111) substrate. The GaN and $Al_{0.25}Ga_{0.75}N$ wafers were cut into 1.0 cm×1.0 cm squares, and rinsed with acetone/methanol/isopropanol/deionized (DI) water. The wafers were then dipped into 50% HCl for surface oxide removal. After final DI water rinsing and blow drying with N_2, GaN/GaN and $Al_{0.25}Ga_{0.75}N$/GaN wafer pairs were mounted together in a steel fixture. The two types of wafer pairs were bonded at 1000 °C for 1 h under N_2 flow. To compare the interface structures of GaN(0001)/GaN(0001) and GaAs(111)/GaAs(111), a GaAs(111)/GaAs(111) wafer pair was also bonded at 600 °C for 1 h. The characterization of interface adhesion by double-cantilever beam test has been reported.[8,9] High-resolution scanning electron microscopy (SEM) was carried out on a Hitachi S4700 SEM. Cross-sectional transmission electron microscopy (TEM) was performed on a JEOL 2010F TEM system.

III. RESULTS AND DISCUSSION

Interface adhesions (interface fracture energy γ_o) of wafer-bonded nitrides (this work) and other III-V semiconductors are given in Table I. Note that also included in Table I are atomic chemical bond energy (eV/bond)[10] and atomic interface bond energy (J/m^2) for different crystalline surfaces. It is clear from Table I that the interface fracture energy γ_o has a proportional dependence on the interface chemical bond energy E_o. The interface fracture energy of GaN/GaN or $Al_{0.25}Ga_{0.75}N$/GaN wafers ($\sim$1.2 J/m^2) is significantly higher than that of InP/InP or GaAs/GaAs (0.5–0.6 J/m^2). Higher interface fracture energy of group III nitrides mainly results from two possible reasons. (1) The nature of their strong atomic chemical bonds since the adhe-

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TABLE I. Interface fracture energy γ_o, and comparisons of the atomic bond energy E_o with interface work of adhesion G_o of a few wafer-bonded semiconductors.

	InP	GaAs	GaAs (111)	GaP	GaN	$Ga_{0.75}NAl_{0.25}$
Interface fracture energy	0.46[8]	0.55[8]	0.61	0.61	1.21	1.15
Bond energy (eV/bond)[10]	1.74	1.63	1.63	1.78	2.24	2.41
Number of atoms ($\times 10^{18}/m^2$)	5.80	6.27	7.21	6.73	7.61	7.71
Atomic bond energy $E_o(J/m^2)$	3.23	3.27	3.76	3.83	5.45	5.95
Work of adhesion G_o (J/m^2)	0.92[8]	1.1[8], 1.8[9]	1.22	1.22, 2.34[9]	2.42	2.3
Ratio G_o/E_o (%)	28%	34%, 55%	33%	32%, 61%	44%	38%

[a]For InP, GaAs, and GaP: face (001); for GaN and GaAlN: face (0001), or specified in the table.

[b]The ratio will be 38% and 42% if the Young's moduli of 85.3 and 103.0 (see Ref. 12) GPa instead of 121.3 and 144.7 GPa (see Ref. 9) were used for GaAs and GaP systems, respectively.

sion of a well-fused interface is primarily determined by the strength of the newly formed interface chemical bonds during wafer bonding.[8,9] The chemical bond energy of nitrides are inherently higher than that of other cubic semiconductors; that is, 2.2 eV > 1.7 eV. (2) The bonding surface of wurtzite group III nitrides is a close-packed plane of (0001), whose number of atoms per unit area on this plane is higher than that of a (001) plane, which is the normal bonding surface of zinc blende semiconductors, such as InP and GaAs. This higher interface atomic density can also lead to the higher surface fracture energy per unit area needed to delaminate the bonded interface for wurtzite nitrides. To verify this interface atomic density effect, the interface fracture energy γ_o of (111)GaAs/(111)GaAs was compared with that of (001)GaAs/(001)GaAs and a deviation of about 10% was found; that is, 0.61 versus 0.55 J/m^2. This difference is reasonably consistent with the fact that the atomic density of (111)GaAs is 15% higher than that of (001)GaAs. The relatively lower interface adhesion of the $Al_xGa_{1-x}N$/GaN compared to GaN/GaN is presumably due to the higher surface roughness of an $Al_{0.25}Ga_{0.75}N$ wafer (surface roughness rms of 6.0 nm for $Al_{0.25}Ga_{0.75}N$ versus rms of 3.0 nm for GaN). The local topography on the wafer surface might cause the geometrically uneven distribution of bonding pressure, leading to locally high strain. It is also known that a rough surface leads to a weak direct wafer bonding, and hence is susceptible to pressure and stress, leading to interface fracture. In addition, the thermal mismatch between GaN and $Al_{0.25}Ga_{0.75}N$ could cause built-in thermal stress, also resulting in decreased interface quality.

Table I also shows the data of G_o/E_o, the ratio of interface work of adhesion ($G_o = 2\gamma_o$) to atomic chemical bond energy in unit area for a few wafer-bonded semiconductors, indicating the relative strength of the wafer-bonded interfaces to the bulk semiconductors. Note that the G_o/E_o ratios of the wafer-bonded semiconductors are in the seemingly high range of 28% to 61%. A closer examination of these numbers presented below suggests otherwise. Generally, the atomic bond energy is proportional to the cohesive energy of the crystal and thereby to the melting point. Therefore, it is worth noting that the atomic bond energy of InP (1.74 eV/bond) given by Ref. 10 is surprisingly high, while that of GaP (1.78 eV/bond) is somewhat low. It is commonly understood that the bond energy of GaAs should be higher than that of InP. The bond energy given in Ref. 10 was obtained

by adding the heat of formation (the energy required to separate the compound into elements in the standard state) to the heat of atomization of the elements. The discrepancy might be caused during the calculations. Considering the adjustment of cohesive energy, one would expect G_o/E_o for InP to be higher and that for GaP to be smaller. Moreover, note that Young's moduli of GaAs and GaP used in this study is only about 70% of those used in Ref. 9. This difference should be considered when comparing the data from these two studies. If the Young's moduli of 85.3 GPa for GaAs and 103.0 GPa for GaP (see Ref. 11) were used instead of 121.3 and 144.7 GPa, respectively,[9] the G_o/E_o ratios for GaAs/GaAs and GaP/GaP would be about 38% and 42%, instead of 55% and 61%, respectively, as listed in Table I. Combined with all these considerations, the G_o/E_o ratio of these different semiconductors would be narrowed down to roughly 30%–40%, suggesting that, in comparison with the bulk semiconductors, the interface region only has the relative strength of about 30%–40%. There are two factors that may account for the comparably low interface energy. (1) The wafer-bonded interface is not composed of 100% well-fused crystalline bonds.[3,4,8,9] The interfacial imperfections introduce a large number of dangling bonds and a local amorphous region of about 20%–30%,[8] forming many local weakly bonded interface areas, which can certainly reduce the overall interface adhesion. It is worth noting that the prebonding semiconductor interfaces in Ref. 9 were cleaned *in situ* with hydrogen and bonded in a vacuum. Consequently, neither interface oxide nor amorphous interface layer/nanoinclusions was observed. One would expect a higher interface adhesion from these samples (listed in Table I). (2) Even for a well-fused interface, such as that in Ref. 9 and that shown in Fig. 1, compared with the bulk crystalline region, its interface fracture energy is still very low. This is presumably due to the imperfections, such as point defects and impurities, as well as to the screw dislocations and the lattice distortion induced by interface misalignment, capped along the interface region, which can result in a weaker crystalline boundary.[8] Between these two factors, the latter accounts predominately for the resultant low interface fracture energy.

Figures 1(a) and 1(b) show the high-resolution SEM and cross-sectional TEM images on the wafer-bonded interface of a GaAs(111)/GaAs(111) semiconductor prepared at 600 °C, while Fig. 2 presents the interface of a wafer-bonded GaN/GaN and $Al_{0.25}GaN_{0.75}$/GaN samples prepared at
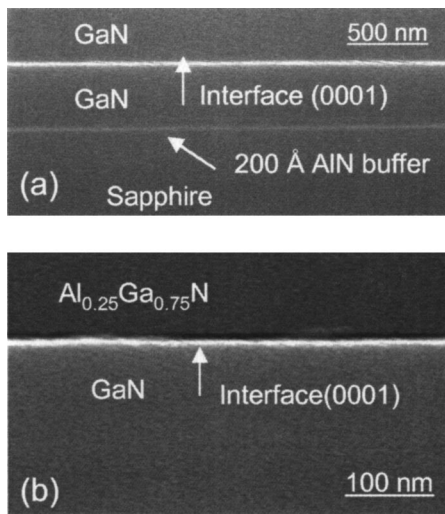
FIG. 1. (a) High-resolution SEM image of the interfaces of the wafer-bonded GaAs(111)/GaAs(111). (b) Cross-sectional TEM image of the interfaces of the wafer-bonded GaAs(111)/GaAs(111).

1000 °C for 1 h. Both SEM and TEM images of GaAs(111)/GaAs(111) and a SEM image of GaN/GaN indicate uniform and well-bonded interfaces. The amorphous nanoinclusions observed in GaAs(001)/GaAs(001), GaAs(001)/InP(001), and GaAs(001)/GaN bonded interfaces[3,8] were not seen in the GaAs(111)/GaAs(111) system. Even though the TEM interface image of GaN/GaN is not available in this study, it is reasonable to expect that the GaN/GaN interface would also show a similar uniform boundary. The different interface morphologies of wafer-bonded (001) and (111) surfaces might indicate that the atomic diffusion mechanism and driv-
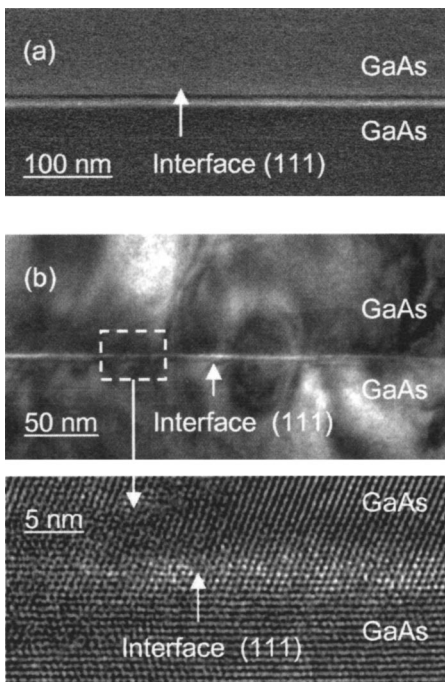

FIG. 2. High-resolution SEM image of the interface of the wafer-bonded (a) GaN/GaN and (b) $Al_{0.25}GaN_{0.75}$/GaN. Both were bonded at 1000 °C for 1 h.
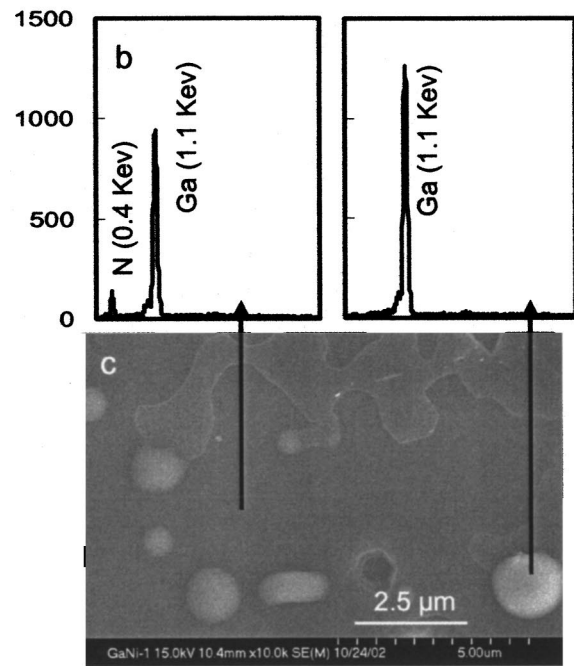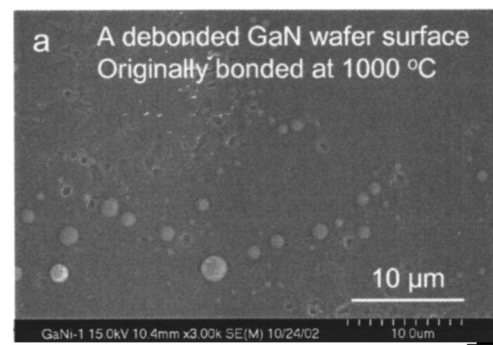

FIG. 3. (a) SEM image of a debonded GaN wafer surface showing Ga droplets due to GaN dissociation and Ga extraction. (b) The EDX spectra, showing the different chemical compositions at different locations. (c) SEM image in (a) with a larger magnification.

ing force requirement on the different crystalline planes during wafer bonding process are kinetically different, resulting in the different interface structures.

Figure 3 shows the SEM images of a debonded GaN wafer surface and the chemical compositions at different surface locations presented by the spectra of energy dispersive x-ray (EDX). Due to the GaN dissociation at bonding temperature and the poor wettability of Ga on the GaN surface, the Ga droplets with micron sizes were randomly localized on the wafer surface after nitrogen desorbed from the wafer interface region. This indicates that wafer bonding of nitrides at high temperature (~1000 °C) might cause serious interface deteriorations such as Ga segregation. Developing a low-temperature bonding approach is therefore essential for future integration of nitride semiconductors through wafer-bonding technology.

IV. SUMMARY

In summary, strong direct wafer bonding of the group III nitrides was typically created at 1000 °C. However, the Ga droplets due to GaN dissociation and Ga segregation were

observed on the debonded GaN wafer surface. Interface fracture energies γ_o of bonded group III nitrides are higher than those of other bonded III-V semiconductor wafers due to the nature of their stronger chemical bonds. It was also observed that wafer-bonded interface strength is typically about 30%–40% of the bulk semiconductor area, which mainly resulted from the large density of imperfections at the interface boundary. Wafer-bonded (001) and (111) surfaces show different interface structures, suggesting that the atomic diffusion mechanism and driving force requirement on the different crystalline planes during wafer bonding process may be kinetically different.

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