Investigation of the mechanism for Ohmic contact formation in Al and Ti/Al contacts to n-type GaN

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We report on a study of Al and Ti/Al contacts to n-type GaN. Al contacts on n-GaN (7 \times 10^{17} \text{ cm}^{-3}) annealed in forming gas at 600 °C reached a minimum contact resistivity of 8 \times 10^{-6} \text{ Ω cm}^2 and had much better thermal stability than reported by previous researchers. Ti/Al (35/115 nm) contacts on n-GaN (5 \times 10^{17} \text{ cm}^{-3}) had resistivities of 7 \times 10^{-6} and 5 \times 10^{-6} \text{ Ω cm}^2 after annealing in Ar at 400 °C for 5 min and 600 °C for 15 s, respectively. Depth profiles of Ti/Al contacts annealed at 400 °C showed that low contact resistance was only achieved after Al diffused to the GaN interface. We propose that the mechanism for Ohmic contact formation in Ti/Al contacts annealed in the 400–600 °C range includes Ti reducing the GaN native oxide and an Al–Ti intermetallic coming into intimate contact with the GaN. © 1997 American Institute of Physics.

GaN has received great interest in the past few years for applications in blue/ultraviolet lasers, light emitting diodes, photodetectors, and high temperature/high power electronic devices. High quality Ohmic contacts are critical to these applications. Although many researchers have made Ohmic contacts to n-GaN with low contact resistivities, the mechanism for Ohmic contact formation has not been explained fully. The purpose of this investigation was to determine the mechanism for Al-based Ohmic contacts on n-GaN formed by annealing in the temperature range of 400–600 °C.

Contacts containing Ti/Al layers have displayed the lowest contact resistivity to n-type GaN. \cite{1,2} TiN has been observed \cite{3} at the interface of Ti/Al and Ti/Al/Ni/Au contacts annealed at 900 °C. Researchers have speculated \cite{1-3} that due to the formation of TiN when Ti reacts with GaN, a high concentration of nitrogen vacancies is created near the interface, causing the GaN to be heavily doped n-type. A thin layer of TiN has also been observed at the interface of unannealed samples that were etched by RIE prior to metal deposition. Without RIE prior to metal deposition, good Ohmic contacts have been fabricated by annealing Ti/Al films on n-GaN between 550 and 750 °C for 20 s; \cite{4} however, there are no reported investigations of Ti/Al contacts annealed in this temperature range that would reveal the mechanism for Ohmic contact formation.

n-type GaN layers on Al2O3 substrates were supplied by APA optics for electrical measurements. Samples were etched in dilute HCl and blown dry with nitrogen before they were loaded into the vacuum system. Al (150 nm) was deposited on n-GaN (7 \times 10^{17} \text{ cm}^{-3}, 138 \text{ Ω∕□}) and Ti/Al (35/115 nm) layers were deposited on n-GaN (5 \times 10^{17} \text{ cm}^{-3}, 163 \text{ Ω∕□}) by dc magnetron sputtering. Al layers were patterned by etching and Ti/Al layers by liftoff to define circular structures for measuring specific contact resistance by the transfer length method. The inner circular contact had a radius of 100 μm and gaps between inner and outer contacts ranged from 2 to 50 μm. Specific contact resistance was calculated from the circular contacts taking into account the circular geometry. \cite{5} Four probes were used to eliminate the effects of resistance between the probes and metal contacts. Al contacts were annealed in a quartz lamp furnace in an Ar/4% H2 atmosphere. Ti/Al contacts were annealed in an AG 610 rapid thermal annealing furnace in Ar that first flowed through a titanium getter furnace to remove oxygen and water vapor. X-ray photoelectron spectroscopy (XPS) depth profiles were performed using a Kratos analytical XSAM 800 pci system.

As deposited Al-only contacts ranged from Ohmic (as low as 1 \times 10^{-4} \text{ Ω cm}^2) to rectifying contacts. After being annealed at 600 °C in Ar/4% H2, all Al contacts were Ohmic with a best contact resistivity of 8 \times 10^{-6} \text{ Ω cm}^2. Two samples prepared on different occasions were annealed together at 600 °C in Ar/4% H2 and their contact resistivities were measured and plotted in Fig. 1 as a function of annealing time. Both had nonlinear I–V curves as deposited but became low resistance Ohmic contacts after annealing. Sample A reached its minimum resistivity after 1 min, while sample B was annealed for 8 min before it reached its minimum.

The different annealing times needed for formation of...
Al-only Ohmic contacts may be the result of different initial thicknesses of GaN native oxide, as exposure to humidity after HCl etching varied between samples prepared on different days. Al is known to reduce Ga$_2$O$_3$ on GaAs$^6$ and would be expected to do the same on GaN. Thus, we expect that upon annealing the Al reduces the native oxide on GaN and improves the electrical properties of the contact. To test this hypothesis, we deposited Al on GaN that had not been dipped in dilute HCl to remove the native oxide prior to Al deposition. As expected, these contacts were rectifying as deposited but became Ohmic after annealing, although the lowest specific contact resistance achieved was higher.

Al has a work function of 4.08 eV,$^7$ which is near the electron affinity of GaN ~4.1 eV $^8$ and may result in a low energy barrier between Al and $n$-GaN when they are in intimate contact. Other researchers have reported Ohmic as deposited Al contacts on $n$-GaN but have seen these contacts degrade rapidly upon annealing.$^2,4,10$ By annealing in form-

FIG. 1. Specific contact resistance as a function of annealing time in Ar/4% H$_2$ of two $n$-GaN samples with 150 nm Al contacts.

FIG. 2. Specific contact resistance as a function of annealing time in Ar of Ti/Al (35/115 nm) contacts on $n$-GaN annealed at 400 and 600 °C.

FIG. 3. XPS depth profiles of Ti/Al (35/115 nm) contacts on GaN as deposited (a) and annealed at 400 °C for 15 s (b), 45 s (c), and 3 min (d). Atomic percents of Al, Ti, O, Ga, and N are shown as a function of sputter time.
ing gas, we minimized the oxidation of Al, which may be the cause of increased resistance in earlier reports. The increase in contact resistivity in Fig. 1 after annealing for 60 min may be due to increased Al resistance from annealing. Although the samples were annealed below the Al melting point of 660 °C, some degradation of the Al surface morphology was noticeable after 1 h at 600 °C.

Ti/Al (35/115 nm) contacts were annealed in Ar at 400 and 600 °C, and their contact resistivities are plotted as a function of annealing time in Fig. 2. The sample annealed at 600 °C was Ohmic with contact resistivity $5 \times 10^{-6}$ Ω cm² after 15 s. Further annealing caused the resistivity to increase slightly. The sample annealed at 400 °C had high resistance after being annealed for 45 s but became Ohmic after 3 min and had a contact resistivity of $7 \times 10^{-6}$ Ω cm² after 5 min. We know of no reports in the literature of contacts to n-type GaN with such a low contact resistance following an anneal at a temperature this low, except when there was intentional RIE damage to the GaN surface.¹

XPS depth profiles of Ti/Al layers (35/115 nm) on GaN as deposited and annealed at 400 °C for 15 s, 45 s, and 3 min are shown in Fig. 3. The separate layers of Al and Ti on GaN can be seen in the as deposited profile. Profiles of samples annealed for 15 and 45 s show intermixing of Ti and Al layers, with no Al at the Ti/GaN interface. The depth profile of the sample annealed for 3 min clearly shows that Al has diffused through the Ti and reached the GaN surface. Thus, we observe that Ti/Al becomes a low resistance Ohmic contact to n-GaN at this low annealing temperature only after Al comes into contact with the GaN surface. The metal/GaN interface does not appear any less abrupt in the sample annealed for 3 min than in the as deposited sample, indicating that no reaction occurred between the metal contact and GaN layer.

Reports of Ti-only contacts to GaN¹⁰,¹¹ further suggest that the mechanism for Ohmic contact formation in the low-temperature Ti/Al contacts is not a reaction between Ti and GaN. Ti-only contacts become good Ohmic contacts only after being annealed at 900 °C and above.¹⁰ On the other hand, Ti is important in the Ti/Al contacts since the Ti/Al contacts had slightly lower contact resistivity and became Ohmic after shorter annealing times than did Al-only contacts. Gallium oxide will be reduced by Ti,⁶ and for small amounts of oxygen in Ti, the most stable phase is $\alpha$-Ti with oxygen in solid solution. Therefore, we would expect the native oxide on GaN to be reduced by the Ti with the oxygen dissolved into the Ti film, leaving no insulating oxide at the metal/GaN interface.

Based on our experimental observations, we propose the following mechanism for Ohmic contact formation in Ti/Al contacts to n-GaN: upon annealing the contact, Ti reduces the native gallium oxide on the GaN surface and Al diffuses through the Ti to make contact with the surface of the GaN in the form of an Al–Ti intermetallic phase that has a low work function, similar to that of Al. The intimate contact between the low work function intermetallic and n-GaN results in a low barrier height, allowing current to flow in either direction by thermionic or thermionic-field emission. Further studies using high resolution transmission electron microscopy will be conducted to verify this proposed mechanism.

In conclusion, Al (150 nm) and Ti/Al (35/115 nm) contacts to n-GaN were investigated to determine the mechanism for Ohmic contact formation in contacts annealed between 400 and 600 °C. Al contacts improved after being annealed at 600 °C in Ar/4% H₂, presumably by reducing the native oxide on GaN. Ti/Al contacts became Ohmic after annealing for 3 min at 400 °C, and the following mechanism was proposed: Ti reduces the native oxide on GaN and Al diffuses through the Ti layer, resulting in an Ohmic contact when a low work function Al–Ti intermetallic phase comes into contact with the GaN surface.

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