Low resistance ohmic contacts to *n*-GaN and *n*-AlGaN using NiAl

D. B. Ingerly
Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706-1595

Y. Chen and R. S. William
Hewlett-Packard Laboratories, Hewlett-Packard Company, 3500 Deer Creek Road, Palo Alto, California 94304-1392

T. Takeuchi
Agilent Technologies, 3500 Deer Creek Road, Palo Alto, California 94304-1392

Y. A. Chang
Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706-1595

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The intermetallic compound NiAl (50:50 at. %) has been shown to be a low-resistance ohmic contact to *n*-GaN and *n*-AlGaN. NiAl contacts on *n*-GaN ($n=2.5\times10^{17}\,\mathrm{cm}^{-3}$) had a specific contact resistance of $9.4\times10^{-6}\,\Omega\,\mathrm{cm}^2$ upon annealing at 850 °C for 5 min. NiAl contacts annealed at 900 °C for 5 min in *n*-$Al_{0.12}Ga_{0.88}N$ ($n=2.4\times10^{18}\,\mathrm{cm}^{-3}$) and *n*-$Al_{0.18}Ga_{0.82}N$ ($n=2.7\times10^{18}\,\mathrm{cm}^{-3}$) had specific contact resistances of $2.1\times10^{-5}\,\Omega\,\mathrm{cm}^2$ and $4.7\times10^{-5}\,\Omega\,\mathrm{cm}^2$, respectively. Additionally, these contacts were subjected to long-term annealing at 600 °C for 100 h. On *n*-GaN, the contact specific contact resistance degraded from $9.4\times10^{-6}\,\Omega\,\mathrm{cm}^2$ to $5.3\times10^{-5}\,\Omega\,\mathrm{cm}^2$ after the long-term anneal. Contacts to *n*-$Al_{0.18}Ga_{0.82}N$ showed only slight degradation with a change in contact resistance, from $4.7\times10^{-5}\,\Omega\,\mathrm{cm}^2$ to $9.2\times10^{-5}\,\Omega\,\mathrm{cm}^2$. These results demonstrate the NiAl has great promise as a stable, low-resistance contact, particularly to *n*-AlGaN used in high-temperature applications. © *2000 American Institute of Physics.* [S0003-6951(00)02329-9]

In recent years GaN and its alloys have been used in a wide range of optical devices including light emitting diodes, laser diodes, and ultraviolet detectors.[1] In addition GaN and AlGaN semiconductors have tremendous promise for use in microwave power, high temperature, and high power applications. To recognize this potential and continue to improve existing devices, advances will have to be made to the ohmic contacts that these devices require.[1,2]

Much progress has been made in developing contacts to *n*-GaN in recent years. Subsequently, there have been a large number of metallizations evaluated for use as ohmic contacts to *n*-GaN, including Al,[3] Ti,[3,4] W,[5] Ti/Ag,[6] $PtIn_2$,[7] TiN,[4] Pd/Al,[8] Nd/Al,[9] Ti/Al,[10] and Ti/Al/Ni/Au.[11] While there are a large number of options, currently the most commonly used ohmic contacts to both *n*-GaN and *n*-AlGaN is Ti/Al. In all of these Ti/Al bilayer contact schemes, Ti is the bottom layer in contact with the substrate and Al is the capping layer. As with most ohmic contact metallizations, these contacts require thermal annealing to achieve low-contact resistances. The resulting reactions of Ti/Al on GaN are complex and are influenced by the choices such as the Al:Ti ratio of the metallization and the annealing conditions.[12]

Ruvimov *et al.*[13] evaluated the Ti/Al contact's microstructure after the annealing process. Amid a very complex reaction interface they detected that a layer of TiN had formed at the contact interface, and it was speculated that the formation of this TiN phase could result in an increase of nitrogen vacancies. However, when Luther *et al.*[14] evaluated annealed Ti/Al contacts TiN was not found, instead they determined that a thin layer (~2 nm) of AlN formed at the contact interface as a result of thermal annealing. They attributed the ohmic nature of the contact to the formation of the AlN layer; this follows their earlier results where the Ti/Al contacts became ohmic only once Al had diffused to the metal/semiconductor interface.[15] Both groups theorized that the formation of a nitride phase at the interface is essential for ohmic behavior as a result of a heavily *n*-type doped interface due to the presence of N vacancies.

While the Ti/Al contacts work well on *n*-GaN, they become less effective ohmic contacts as the Al concentration increases in the semiconductor. This may be due to the increase in Schottky barrier height of the metal contacts with increasing Al mole fraction in the *n*-AlGaN.[16,17]

Qiao *et al.*[18] have reported a variation on the standard Ti/Al contacts; they used a thin Al cap and much thicker Ti layer. Upon annealing, Ti_3Al forms and the remaining Ti reacts with the AlGaN forming an $AlTi_2N$ layer. Termed an ''advancing'' contact by the authors, this structure results in a thick reaction layer. It is proposed that the remaining semiconductor region under the contact is nitrogen deficient and therefore highly *n* type. This advancing reaction resulted in a significant improvement over the conventional contacts, $5\times10^{-5}\,\Omega\,\mathrm{cm}^2$ compared to $2\times10^{-3}\,\Omega\,\mathrm{cm}^2$ using the standard Ti/Al on *n*-$Al_{0.22}Ga_{0.78}N$.

In this study the intermetallic compound NiAl (50:50 at. %) is investigated as an ohmic contact to *n*-GaN and *n*-AlGaN. NiAl is an excellent candidate for high temperature use, as it is stable to extremely high temperatures due to

its melting point of 1638 °C[19] and its oxidation resistance.[20] Binary and ternary phase diagram information indicates that the Ni–Al–Ga–N system meets the criteria formulated by Swenson *et al.*[21] for participating in an exchange reaction. During this exchange reaction, one element in the metal phase exchanges with another element in the semiconductor without the formation of new phases. In the case of NiAl on GaN and AlGaN, there should be an exchange of Al (from the metal) for Ga (from the semiconductor). The kinetic model of this reaction predicts that the Ga will diffuse throughout the metal film and an $Al_xGa_{1-x}N$ interface (where $x \approx 1$) should be formed. It is proposed that the formation of this interface will behave in the same manner as the interfaces (TiN, AlN, or $AlTi_2N$) produced by the annealed Ti/Al contacts, resulting in a highly *n*-type doped interface and a low resistance ohmic contact.

The exchange mechanism is a solid state reaction, which has been well studied and identified as a systematic approach for obtaining a desired metal/semiconductor interface.[22,23] This is in contrast to the complex reactions of the Ti/Al and other multilayer contacts. Using NiAl should then simplify the metal/semiconductor reactions and lead to more a defined and controlled reaction interface.

The GaN and AlGaN films were grown directly on the buffer layers deposited at low temperature on sapphire substrates using metalorganic vapor phase epitaxy. The *n*-GaN film was doped with Si to a carrier concentration of $2.5 \times 10^{17}\,cm^{-3}$, as measured by the Hall method. In this study *n*-AlGaN films of two different Al concentrations were used. One is a 1.5-μm-thick *n*-$Al_{0.12}Ga_{0.88}N$ film Si doped to a carrier concentration of $2.4\times10^{18}\,cm^{-3}$ and the other was 1.8 μm of $Al_{0.18}Ga_{0.82}N$ Si doped to a carrier concentration of $2.7\times10^{18}\,cm^{-3}$.

Prior to lithography, the substrates were ultrasonically degreased with warm acetone and methanol for 10 min each. These degreased substrates were then dipped into a H_2SO_4:H_3PO_4:H_2O (1:1:2) solution for 5 s and rinsed in H_2O. They were then etched in HCl:H_2O (1:2) for 4 min and again rinsed in flowing H_2O for 10 min. The etched substrates were then patterned using standard photolithography techniques. Once patterned, the substrates were placed in a HCl:H_2O (1:3) solution for 20 s, blown dry with N_2 gas, and immediately loaded into a vacuum chamber with the background pressure less than 2×10^{-7} Torr.

Nominally 120 nm NiAl (50:50 at. %) films were deposited by radio frequency sputter deposition from a single compound target. X-ray diffraction (XRD) confirmed these films are in the B2 crystal structure when deposited under the sputtering conditions used. After deposition, the photoresist was lifted off in acetone leaving the patterned metal on the wafers. Following liftoff, the contacts were annealed in an AG Associated MiniPulse rapid thermal annealing (RTA) system with flowing argon gas. For the long-term thermal annealing studies the metal contacts were sealed in quartz ampoules under a vacuum of less than 5×10^{-7} Torr with sacrificial *n*-GaN; and placed in conventional furnaces for heat treatment. The current–voltage *(I–V)* characteristics were measured across two circular contact pads each with an 80 μm radius and the contact's specific contact resistance (ρ_c) was measured with a circular transmission line model pattern.[24]

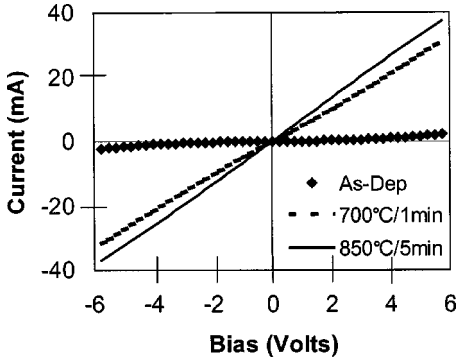

FIG. 1. *I–V* behavior of NiAl/*n*-GaN contacts for different annealing conditions.

The *I–V* characteristics of the NiAl/*n*-GaN contacts are shown in Fig. 1 for three different annealing conditions. It can be seen that the as-deposited contacts have rectifying characteristics, but after annealing they exhibit linear *I–V* behavior. The resistance of the contact continued to decrease as the annealing temperature and times increased. After annealing at 700 °C for 1 min, the specific contact resistance was still relatively high at $1\times10^{-3}\,\Omega\,cm^2$. However, after annealing at 850 °C for 5 min, the specific resistance contact dropped to $9.4\times10^{-6}\,\Omega\,cm^2$.

Figure 2 shows the *I–V* characteristics of the NiAl/*n*-$Al_{0.18}Ga_{0.82}N$ contacts. The results for these contacts are similar to that of the NiAl/*n*-GaN contacts in that the resistance of the contacts decreased with increased annealing temperatures. However, it is significant that even upon annealing at 800 °C for 1 min little improvement in the contact resistance was shown, but upon annealing at 850 °C for 5 min the *I–V* behavior becomes linear and the contact resistance decreases significantly. It should be noted that the trends in the *I–V* behavior of the NiAl-*n*-$Al_{0.12}Ga_{0.88}N$ are virtually the same as those found in Fig. 2. For NiAl contacts annealed at 900 °C for 5 min on *n*-$Al_{0.12}Ga_{0.88}N$ and *n*-$Al_{0.18}Ga_{0.82}N$, the specific contact resistance was found to be $2.1\times10^{-5}\,\Omega\,cm^2$ and $4.7\times10^{-5}\,\Omega\,cm^2$, respectively.

These contacts were tested for suitability in high temperature and high power applications by subjecting them to long term thermal annealing. NiAl/*n*-GaN contacts RTA

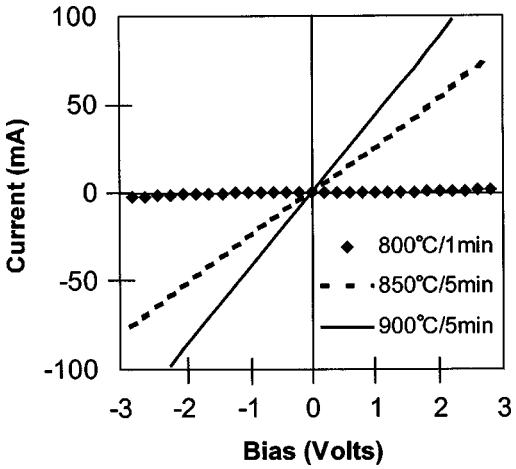

FIG. 2. *I–V* behavior of NiAl/*n*-$Al_{0.18}Ga_{0.82}N$ contacts for different annealing conditions.

TABLE I. Specific contact resistance of NiAl contacts.

Substrate	Annealing conditions	Contact resistance (Ω cm^2)
n-GaN	850 °C/5 min	9.4×10^{-6}
n-GaN	8500 °C/5 min+600 °C/100 h	5.3×10^{-5}
n-$Al_{0.12}Ga_{0.88}N$	900 °C/5 min	2.1×10^{-5}
n-$Al_{0.18}Ga_{0.82}N$	900 °C/5 min	4.7×10^{-5}
n-$Al_{0.18}Ga_{0.82}N$	900 °C/5 min+600 °C/100 h	9.2×10^{-5}

treated at 850 °C for 5 min and NiAl/*n*-$Al_{0.18}Ga_{0.82}N$ RTA treated at 900 °C for 5 min were then annealed at 600 °C for 100 h. As Table I shows, the NiAl/*n*-GaN contacts exhibit some degradation as the resistance increases from $9.4\times10^{-6}\,\Omega\,\text{cm}^2$ to $5.3\times10^{-5}\,\Omega\,\text{cm}^2$. The NiAl/*n*-$Al_{0.18}Ga_{0.82}N$ contacts were less affected by the long-term anneal but the contact resistance degraded from $4.7\times10^{-5}\,\Omega\,\text{cm}^2$ to $9.2\times10^{-5}\,\Omega\,\text{cm}^2$ after 100 h at 600 °C. Despite the slight degradation in these contacts, these results suggest that NiAl is an excellent choice for high temperature applications.

The electrical results show that NiAl can be used successfully as an ohmic contact to *n*-GaN and *n*-AlGaN. This success gives further evidence to support the speculation that the formation of an AlN layer will lead to ohmic behavior. From a practical perspective, the contact resistance on *n*-GaN is higher than that often achieved using Ti/Al contacts. However, for *n*-AlGaN, the NiAl compares very favorably to Ti/Al. Ti/Al contacts fabricated on the same *n*-AlGaN used in this study had measured specific contact resistances of $2\times10^{-5}\,\Omega\,\text{cm}^2$ and $2.2\times10^{-4}\,\Omega\,\text{cm}^2$ when annealed at 650 °C for 5 min for *n*-$Al_{0.12}Ga_{0.88}N$ and *n*-$Al_{0.18}Ga_{0.82}N$, respectively.

One concern with using Ti rich contacts is that they lack oxidation resistance;[18] this is not a problem for NiAl contacts. Auger depth profiling of NiAl/*n*-GaN contacts annealed at 850 °C for 5 min in argon showed a thin layer of aluminum oxide forms on the surface of the metal contact and that there is no significant increase of oxygen in the NiAl film or at the contact interface. In addition to the oxidation resistance of these samples, scanning electron microscope images of NiAl/*n*-GaN contacts showed that the NiAl film remains continuous after being annealed at 850 °C for 5 min.

NiAl/*n*-GaN contacts annealed at 850 °C for 5 min were studied using XRD and no new phases were detected. This result is consistent with the proposed reaction, as it would be unlikely to see diffraction peaks from a thin AlN layer formed as a result of the Ga for Al exchange. Auger depth profiles were also consistent with the exchange reaction, but it was still not possible to resolve an AlN layer.

The proposed mechanism for ohmic contact formation of the NiAl contacts is similar to that proposed for Ti/Al.[12–14] Therefore, it is not clearly why the NiAl contacts to *n*-GaN have a higher resistance than the Ti/Al. It is possible that the NiAl has a larger work function resulting in a higher Schottky barrier height. It is also not clear why the NiAl contacts appear to be less affected than the standard Ti/Al by increasing Al concentration in the AlGaN semiconductor. Additional study of the contact interface will be required to answer some of these questions and elucidate if an AlN layer is the mechanism for forming low resistance contacts.

NiAl has been shown to be a low resistance ohmic contact to *n*-GaN and *n*-AlGaN. While the specific contact resistance on *n*-GaN is not as low as reported by other researchers using Ti/Al contacts, the results on *n*-AlGaN were very promising. The NiAl contacts seem to be less affected than the more commonly used Ti/Al contacts by increasing the atomic percent of Al in the *n*-AlGaN. Additionally, long-term thermal annealing at 600 °C for 100 h showed that while there was some degradation in contact resistance, from $4.7\times10^{-5}\,\Omega\,\text{cm}^2$ to $9.2\times10^{-5}\,\Omega\,\text{cm}^2$ for the *n*-$Al_{0.18}Ga_{0.82}N$, the NiAl contacts show good thermal stability. Results of Auger depth profiling and XRD used to characterize the contacts were consistent with the exchange mechanism and the formation of a thin AlN layer, however, they did not offer any conclusive proof. For use on *n*-AlGaN, particularly at high temperatures NiAl shows great promise as a stable low resistance ohmic contact.

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