Electrical, thermal, and microstructural characteristics of Ti/Al/Ti/Au multilayer Ohmic contacts to \( n \)-type GaN

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The electrical, thermal, and microstructural characteristics of Ti/Al/Ti/Au (30 nm/100 nm/30 nm/30 nm) multilayer Ohmic contacts to \( n \)-GaN (doping level \( 5 \times 10^{17} \) cm\(^{-3} \)) were studied. The lowest contact resistivity derived from the annealed contact was \( \rho_S = 3.0 \times 10^{-6} \) \( \Omega \) cm\(^2\). The contacts were robust and showed high-thermal stability. X-ray diffraction and Auger electron spectroscopy studies were made to investigate the microstructure of the annealed contacts. The key to the success of the contact was the Ti layers placed on both sides of the Al layer. Upon annealing, there occurred both in-diffusion and out-diffusion of the Ti layer in intimate contact with the GaN film. The in-diffusion of this led to the formation of TiN, while the out-diffusion of this led to the formation of Ti–Al alloys. The second Ti layer also in-diffused and out-diffused during annealing. However, due to the presence of Au, the out-diffusion was marginalized, and the in-diffusion was higher than the out-diffusion. The in-diffusion led to the formation of Ti–Al alloys with the remaining Al content. Consequently, both the Al and the Ti from the second Ti layer contents were almost fully consumed, and none of them were left to appear on the contact surface to form oxides. © 2003 American Institute of Physics. [DOI: 10.1063/1.1528294]

I. INTRODUCTION

GaN has been the topic of intense research and development activities during the past years. These activities have demonstrated that GaN has great potential for both micro-electronic and optoelectronic device applications for components of technologies such as power transmitters, receivers, full-color displays, and detectors.\(^1\) (Al, Ga, In)N forms a continuous and direct-band-gap alloy from 1.92 eV (InN) to 6.2 eV (AlN) with potential for emission and detection in the spectral range between visible and the ultraviolet wavelengths.\(^2\) GaN itself possesses a large band gap of 3.39 eV at room temperature, a very high breakdown field, and a high saturation velocity. However, the very success of all GaN technologies relies on the realization of robust and low-resistance Ohmic contacts, and many different techniques have so far been employed to obtain these contacts.\(^3\)–\(^7\)

Titanium- and aluminum-based metallization schemes have been used to form Ohmic contacts to GaN.\(^8\)–\(^17\) Titanium is of appreciable importance in forming stable contacts to GaN. It serves the purpose of a barrier film, and, if not oxidized, it provides good adhesion to the GaN surface. The presence of Ti [or Ti alloy(s)] at the interface also provides mechanical stability to the contacts. As it has a good sticking property to the GaN surface, the lift-off is reliable and reproducible.

In this article, we present electrical and microstructural characteristics of contacts to \( n \)-GaN made from Ti, Al, and Au. In the following, while Ti–Al denotes alloys of varying compositions, Ti/Al and Ti/Al/Ti/Au denote actual contacts, the Al being deposited on Ti to form Ti/Al, and Ti, Al, Ti, and Au being deposited successively to form the Ti/Al/Ti/Au contact. The latter is shown schematically in Fig. 1. Our objective is to thoroughly investigate the electrical behavior of the contact as a function of annealing temperature and annealing time, and to examine the fundamental physics underlying the microstructure thus obtained. We also assessed the thermal stability characteristics of the contacts.

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II. LITERATURE REVIEW

A. Features of Ti metallization

It is believed that upon annealing solid phase reactions between Ti and GaN forming TiN is possible since the heat of formation of TiN and GaN are $-265$ and $-110.9$ kJ/mol, respectively. N out-diffuses from the GaN lattice to form TiN and nitrogen vacancies without decomposing the crystal structure. N vacancies act as donors in GaN. The interfacial region thus becomes heavily doped, providing the configuration needed for tunneling contacts. Only 2 monolayers of TiN formed at the interface are sufficient to generate a $100\AA$-thick layer of GaN with a doping concentration of $10^{20} \text{cm}^{-3}$. The existence of a thin TiN layer at the interface between the metal contact and GaN has been observed by a transmission electron microscopy (TEM) micrograph in microstructures annealed in N$_2$ environment.

Distinct modification in electrical characteristics takes place as a result of the change in the Ti layer thickness, which is in intimate contact with the GaN. As Ti with a work function of $4.33 \text{eV}$ closely matches the electron affinity of GaN ($4.1 \text{eV}$), it produces a Schottky contact when deposited on $n$-GaN. Ti-based contacts are especially advantageous because they can reduce the native surface oxide upon alloying. GaN surfaces have a very high chemisorption affinity for oxygen. As a result, native oxides formed on the surface exhibit a thin insulating layer between the metal and the semiconductor. The most common form of the gallium oxide is about $50-100\AA$-thick Ga$_2$O$_3$.

While designing alloyed Ohmic contacts to GaN, individual metals, such as Ti, which can cause the native oxide on GaN surfaces, may ideally be in intimate contact with the GaN surface. Previous investigations suggest that Ti-only contacts become Ohmic contacts only after annealing at 900°C or above. Ti has the ability to reduce Ga$_2$O$_3$ upon annealing. While dissolving small amounts of oxygen, Ti can still maintain a stable $\alpha$-Ti phase with oxygen in solid solution. Therefore, when depositing and annealing Ti on GaN, it can be expected that the native oxide (e.g., Ga$_2$O$_3$) on the GaN surface will be reduced by Ti, and oxygen, dissolving in Ti film, will leave no insulating oxide at the metal–GaN inter-face. Al with a work function ($4.08 \text{eV}$) close to that of GaN is also known to reduce Ga$_2$O$_3$, and it is expected to do so in the case of GaN.

Chemical precleaning is often not very effective in removing this oxide layer. Use of chemical etchants including HF solutions, KOH solutions, and aqua regia have been used to remove the surface oxide. A plasma etching procedure has also been used prior to metal deposition. Although it has led to a successful reduction in surface oxygen level, it adds an extra step to the fabrication process.

B. Features of Al–Ti metallization

Ti/Al metallization yielded by far the lowest contact resistance to $n$-type GaN. However, the major problem for the Ti/Al bilayer is that both metals have a high propensity towards oxidation. It has been observed that, even with very low concentration of oxygen during alloying (parts per million), Ti–Al-based metal films suffer from significant oxygen contamination. Also, the Ti/Al bilayer has the potential of turning the film highly resistive upon alloying. The Al$_2$O$_3$ coating formed on Al during annealing is responsible for this increase in contact resistance. Ti also tends to oxidize and Al tends to ball up during alloying, resulting in a rough surface morphology of the Ti/Al contacts. In order to minimize the oxidation of the Ti–Al alloyed contacts, it is, therefore, customary to deposit a metal layer covering Al. In previous studies, metals such as Ni and Au, which are resistant to oxidation, were placed on the top of the Ti/Al contacts to prevent the oxidation of the contacts during alloying.

The present contact scheme of Ti/Al/Ti/Au uses a Ti/Au overlayer on the top of standard Ti/Al metallization. As a result, the Ti and Al layers are expected to undergo enhanced reactions to produce Ti$_x$Al$_{1-x}$ alloys. As it will be seen later, such an alloy produces low resistance at the interface. Also, it ties up excess Al, preventing it from balling up. Thus, the roughening of the metal films is reduced and the contacts to GaN become thermally stable.

III. EXPERIMENTAL METHOD

For the present study, $n$-GaN layers were grown by the plasma enhanced molecular beam epitaxy (MBE) method on (011) sapphire substrates ($\sim 400 \mu m$). The hydrogen plasma was used to clean the substrates prior to growth. The sapphire substrates were degreased with organic solvents. The substrates were then etched in a hot solution of H$_2$SO$_4$ and H$_3$PO$_4$ (H$_2$SO$_4$ : H$_3$PO$_4$ = 3 : 1) for about 20 min. They were next rinsed with deionized water and dried by blowing filtered nitrogen. They were subsequently transferred to the MBE chamber where indium was used to place them on Si templates that were mounted on molybdenum blocks with high-purity carbon screws. The sapphire was nitridated for about 15 min at 800°C. Prior to the GaN growth, a thin undoped AlN buffer layer, about 650 Å thick, was grown on it at a temperature of 800°C. This was followed by the growth of a 1-μm-thick GaN layer doped with Si.

Following GaN growth, the substrates were patterned by a photoresist to ensure that a mesa structure suitable for transmission line measurement (TLM) had been obtained.
These mesa structures were created by reactive ion etching (RIE) of the GaN epilayer. A Plasma-Therm 790 series chamber was employed for this purpose. RIE was accomplished by flowing Cl₂ gas at 15 sccm for 4 min. The base pressure was 10 mTorr and the operating power was 150 W. The etch depth was about 1 μm. The patterned samples were dipped into a HF:HCl:H₂O (1:1:10) solution for 30 sec to remove native oxides from the sample surface. The samples were loaded immediately for metal deposition. The composite metal layer Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) was next deposited. All the metals except Au were deposited by electron beam evaporation. Au was evaporated thermally. Following the metallization, metal lift-off was performed in acetone, which provided a linear configuration of pads with (300×300) μm² dimensions. The TLM structure thus created by the lift-off process had 11 rectangular contact pads of (300×300) μm² dimension. The spacings between them were 2, 5, 10, 15, 20, 30, 40, 50, 60, and 90 μm, respectively. A rapid thermal anneal of the samples was then performed in argon gas at various temperatures. Current–voltage (I–V) characteristics of various contact layers were measured before and after the thermal anneal. The TLM studies were made for those contacts that had linear I–V characteristics.

### IV. ELECTRICAL CHARACTERISTICS

#### A. Current–voltage characteristics

In order to obtain the lowest possible specific contact resistance (hereafter, referred to as contact resistivity ρₛ), electrical characterization of the Ti/Al/Ti/Au multilayer contacts to n-GaN was performed, optimizing various metal thicknesses, annealing times, and annealing temperatures. This contact is quite different from that of Fan et al., which was a Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/500 Å) multilayer contact. Nickel, which is believed to be an inert diffusion barrier between the top Au and Al layer was replaced with titanium in the present scheme. The rationale underlying this replacement was that, according to the phase diagram, Ti would react with Al during high-temperature annealing forming intermetallic (Ti, Al) alloy(s). This would then tie up with the excess Al in the contacts giving them the thermal stability that they need for robustness. That is, indeed, true will be apparent from the unchanged performances of these contacts even after long-term thermal stressing.

First, the Ti/Al/Ti/Au multilayer (300 Å/1000 Å/300 Å/300 Å) was deposited onto GaN (see Fig. 1) and then patterned using lift-off in acetone. As-deposited contacts showed nonlinear I–V characteristics, as evident from Fig. 2(a). The ratio of atomic concentration of Al to Ti in the as-deposited layer was 1.77. This Ti-to-Al ratio in the microstructure was, indeed, necessary to ensure sufficient availability of Al and Ti for reactions to produce (Ti, Al) alloy(s) that can be instrumental for lowering the contact resistivity during annealing. The thickness of the first titanium layer (that is, the one in intimate contact with n-GaN) was believed to have a major implication on the electrical characteristics of the contacts. In general, a thicker Ti interface layer (for example, 850 Å) resulted in a poor contact...
performance after annealing at 750 °C as compared to a thinner Ti interface layer. This was evident from the $I$–$V$ characteristics of Fig. 2(b) for the Ti/Al/Ti/Au (850 Å/1000 Å/300 Å/300 Å) contacts annealed at 750 °C for 30 s. Even after annealing at high temperature, these contacts had nonlinear characteristics implying that the reaction(s) responsible for the low-resistance behavior of the contacts had not probably been complete. One possible explanation for this might be that a thicker Ti layer (e.g., 850 Å) at the interface was not fully consumed in forming the (Al, Ti) phase(s) as a result of a reaction between Al and Ti. So, the excess Ti out-diffused Al layer forming a thin coating of Ti oxide on the metal surface. Another possibility would be that the thin Ti layer facilitated the in-diffusion of Al during annealing, and hence, the presence of Al at the interface improved the contact resistivity. In sharp contrast, the Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) contacts with a thinner Ti layer (300 Å) at the interface, exhibited near-linear $I$–$V$ characteristics (not shown) when annealed at 650 °C for 30 s. These produced a linear $I$–$V$ characteristic when annealed at 750 and 850 °C for 30 s. The results are depicted in Figs. 2(c) and 2(d), respectively. Thus, annealing at 650 °C was not sufficient enough to create those reaction products that could produce reasonably low contact resistivity.

B. Contact resistance

Contact resistances were derived by the TLM method. Mesas were defined to eliminate current flow at the contact edge. The resistance, $R_T$, between the two contacts was measured at 300 K using a four-point-probe arrangement. Contact resistivity $\rho_3$ was derived from a plot of $R_T$ versus the gap length. The least-squares method was used to fit a straight line to the experimental data, which were obtained from all available test patterns.

The thickness of the interfacial titanium layer, the annealing temperature for the contacts, and the annealing time were optimized to obtain the best possible contact resistivity. Consistent improvement in contact resistivity $\rho_3$ of the Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) contacts was observed until the annealing temperature was as high as 800 °C. The contacts were annealed at several temperatures between 600 and 850 °C for 30 s, and the $I$–$V$ plot tended to be more linear as the annealing temperature was increased from 650 to 800 °C.

The variation of the contact resistivity as a function of the annealing temperature is shown in Fig. 3. From Fig. 3 it is seen that the contact resistivity decreases with increasing annealing temperature until it reaches about 800 °C. Any further increase in annealing temperature had a marginal effect on the contact resistivity. This suggests that the solid intermetallic reaction(s) responsible for lowering the contact resistivity was complete at ~800 °C. As it will be seen later, low-resistance Ti$_x$Al$_{1-x}$ alloys were formed at that temperature.

The contact resistivities of the contacts with several different Ti metal thicknesses, alloying temperature, and alloying time are listed in Table I. One can see from Table I that the Ohmic nature of the contacts depended on all parameters, and that the optimized value of the contact resistivity was reasonably low. This took place when GaN was so heavily doped in the vicinity of the metal–semiconductor interface that it led to an appreciable band bending of the conduction band. The semiconductor region at the interface thus became very thin, allowing the flow of electrons via tunneling. Notably, the $n$-GaN film employed for the present contact had relatively low doping (e.g., $5 \times 10^{17}$ cm$^{-3}$), and hence, it is speculated that the heavy doping was created by the formation of a thin TiN layer between Ti and GaN. Only a few monolayers of TiN were sufficient to create a thin GaN in the vicinity of the metal–semiconductor interface with a doping density as high as $10^{20}$ cm$^{-3}$, resulting from generation of nitrogen vacancies.

V. MICROSTRUCTURE

A. X-ray diffraction analysis

To gain insight into the solid-state reactions and interfacial products formed during annealing, x-ray diffraction of

![FIG. 3. Variation of contact resistivity as a function of annealing temperature for the Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) Ohmic contact to $n$-GaN.](image)

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**TABLE I.** Contact characteristics of Ti/Al/Ti/Au microstructures annealed at various temperatures.

<table>
<thead>
<tr>
<th>Ti/Al/Ti/Au contact thickness</th>
<th>Annealing temp. (°C)</th>
<th>Annealing time (s)</th>
<th>$I$–$V$ characteristics</th>
<th>Resistivity ($\Omega$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti/Al/Ti/Au 300 Å/1000 Å/300 Å/300 Å</td>
<td>As-deposited</td>
<td></td>
<td>Nonlinear</td>
<td>...</td>
</tr>
<tr>
<td>Ti/Al/Ti/Au 300 Å/1000 Å/300 Å/300 Å</td>
<td>650</td>
<td>30</td>
<td>Linear</td>
<td>$9.80 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ti/Al/Ti/Au 300 Å/1000 Å/300 Å/300 Å</td>
<td>750</td>
<td>30</td>
<td>Linear</td>
<td>$3.40 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ti/Al/Ti/Au 850 Å/1000 Å/300 Å/300 Å</td>
<td>800</td>
<td>30</td>
<td>Linear</td>
<td>$3.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ti/Al/Ti/Au 850 Å/1000 Å/300 Å/300 Å</td>
<td>850</td>
<td>30</td>
<td>Linear</td>
<td>$3.42 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

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Ti-Al alloys. The reflections corresponding to the Ti$_2$Al and Ti$_3$Al were distinct, and could not though the intensity of the peaks was low, both peaks corre-

The peak that appears around the 71.45° 2$	heta$ and the matched closely with the reflections from both Ti$_2$Al and Ti$_3$Al phases. This peak corresponded to the plane of Ti$_2$Al had very close spacings. Al-

There were two major differences in the x-ray patterns of the samples annealed at 650 °C and 750 °C. That no major additional reactions took place during annealing at 800 °C was evident from the fact that there was only a small change in resistivity (from $\rho_S=3.4\times10^{-6}\Omega\text{cm}$ to $\rho_S=3.0\times10^{-6}\Omega\text{cm}$) for samples annealed at that temperature.

B. Auger electron spectroscopic analysis

The Auger electron spectroscopic (AES) depth profile of the annealed contact is shown in Fig. 5. From this depth profile, it can be seen that an annealing at high temperature led to interdiffusion of Ti and Al into each other and even onto GaN. Both the Ti and the Al signals followed each other near the GaN interface, and this was presumably due to the presence of the Ti, Al phases in the sample. In fact, the AES depth profile shows an extensive reaction between Ti and Al, which was quite consistent with the XRD data according to which reactions between Ti and Al resulted in the formation of the TiN phases. An important issue related to the long-term reliability of the contact metallization could also be resolved from the AES depth profile. As apparent from this depth profile, Au steadily diffused through all the metal layers. However, the diffusion of Au appeared to be a

FIG. 4. X-ray diffraction spectra of Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) microstructure annealed for 30 s at (a) 650 °C and (b) 750 °C.

FIG. 5. Auger electron spectroscope depth profiles of Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) contacts annealed for 30 s at 750 °C.
common feature observed in Au-based contacts. Although Au diffusion poses a long-term reliability threat for some semiconductors and metal–semiconductor systems, the diffusion of Au appeared to be far less detrimental for the present metallization scheme, and hence, the reliability of the contacts after thermal stressing showed no apparent signs of degradation.

It was also seen from the AES depth profile that Ti and Al had extensive alloying. These (Ti, Al) phases had resistivity higher than that of Ti. Resistivity decreased with the Al fraction in the phase. Also (Ti, Al) phases are known to have a low work function. Hence, it was clearly evident that the reaction between Al and Ti and the consequent formation of Al\textsubscript{1-x}Ti\textsubscript{x} alloys were responsible for the low contact resistance of the present microstructure.

C. Overall Ti/Al/Ti/Au microstructure analysis

Both the AES and the XRD studies of the present microstructure suggest that the reaction mechanism underlying the formation of the Ohmic contact involved the reaction between Ti and Al. It can be explained based on the Ti–Al phase diagram. Probably the reaction between Ti and Al started at lower temperature (250 – 300 °C) with the formation of Al\textsubscript{2}Ti and α-Ti as the primary products. Among them, although the α-Ti phase could dissolve a small amount of oxygen, it could still be in the pure Ti phase. As the phase diagram shows in Fig. 6, thermodynamically stable phases at 800 °C were Ti\textsubscript{3}Al and possibly other (Ti, Al) products. Although Ti\textsubscript{2}Al does not appear in the phase diagram, the presence of this product in the microstructure could not be ruled out. Notably, as there are always significant differences between bulk and the thin-film reactions, products that were not thermodynamically favorable in the bulk, could appear in thin-film reactions. However, bulk reactions were far more easier to be thermodynamically possible.

The presence of the (Ti, Al) phases in the neighborhood of the GaN interface proved to be highly important in lowering the resistance of the present contacts. Indication of the formation of the TiN phase in the microstructure was obvious. Considering the enthalpies of formation of GaN and TiN, which are –110 and –336 kJ per g atom, respectively, the formation of TiN in the microstructure upon alloying appeared justified. With the TiN formed at the interface extracting N from the GaN lattice, a heavily doped degenerate interface layer resulted from the generation of nitrogen vacancies. The latter acted as n-type dopant atoms in GaN. The present contact metallization had a pronounced tunneling effect. In other words, field emission was the dominant current transport mechanism across these contacts.

VI. THERMAL STABILITY

The thermal stability of the Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/300 Å) microstructure annealed at 750 °C for 30 s was critically studied. For this study, contacts were thermally stressed at 400 °C for 24 h. TLM and I–V characteristic studies were made before and after heat treatment. From the I–V characteristic curves of the contacts shown in Fig. 7, it was quite evident that the contacts showed insignificant degradation after aging at 400 °C for 24 h. The total resistance versus gap spacing of the contacts annealed at 750 °C was also studied. The results are presented in Fig. 8. From Fig. 8 it is also apparent that there was insignificant change in the contact resistance due to thermal stressing.

TLM studies yielded a contact resistivity in the range of $3.40 \times 10^{-6} \Omega \text{cm}^2$ before heat treatment and $3.15 \times 10^{-5} \Omega \text{cm}^2$ after heat treatment. Thus, the contact resistivity of the contacts improved slightly rather than being deteriorated after heat treatment. They showed very high thermal stability. The failure of the Al-based contacts stemmed from the high-temperature Al melting and bending to ball up, resulting in a rough surface. Based on the x-ray diffraction analysis of the present microstructure, it was the Ti layer on the top of the Al layer that appeared to be actually responsible for the exceptional thermal stability of the contacts. During annealing, a portion of the Al in-diffused and out-diffused through Ti layers above and below it, forming (Ti, Al) compounds. Some, or all, of these compounds contributed to the low resistance of the contacts. (Ti, Al) alloys are
known to have a low work function. During annealing, the Ti layer on top of the Al layer also tied up excess Al. Thus, there was little or no Al left to melt or ball up during heat treatment. Further, as the excess Al was tied up with Ti, and thus none could reach the contact surface in appreciable amounts, the probability of formation of an Al– or Ti–oxide layer was considerably reduced. This definitely provided the contact with a better thermal stability, as observed from the behavior of contacts after long-term heat treatment. A small improvement in contact resistivity after long-term heat treatment might be attributed to additional diffusion of Al into the two Ti layers and to further in-diffusion of Ti onto GaN forming TiN and nitrogen vacancies. The resistivity saturation effect was observed for Al$_2$N$_3$ alloys; where there occurred a decrease in resistivity of the alloy with increasing Al component in the alloy, until a point was reached where there was no further decrease in the resistivity. As one can see from the (Ti, Al) phase diagram (see Fig. 6), the reaction between Ti and Al started at a fairly low temperature with Ti reacting with Al and forming Al$_2$Ti. With increasing alloying temperature, the reaction between Ti and Al continued to proceed. These reactions were key to the success of the present contact metallization. The phases thus formed were thermodynamically stable at higher temperatures, which contributed to the thermal stability of the present contacts.

VII. CONCLUSION

In conclusion, an important feature of the present investigation is the realization that very good Ohmic contact can be made to n-GaN with composite metal layers of Ti/Al/Ti/Au that were, respectively, 30, 100, 30, and 30 nm thick. For films doped to $5 \times 10^{17} \text{cm}^{-3}$, $\rho_s = 3.0 \times 10^{-6} \Omega \text{cm}^2$ with an uncertainty of $\pm 5\%$. In Table II the results from the present investigation are compared with those from previous Ti/Al-based contacts.$^8$–$^{17}$ It can be seen from Table II that, with the exception of the results of Fan et al.,$^1$ all others obtained for a doping level of $5 \times 8 \times 10^{17} \text{cm}^{-3}$ have higher resistivity values. The contact resistivity obtained by Burn et al.$^8$ is much lower. However, it corresponds to a very heavy doping level: $N_d = 4 \times 10^{20} \text{cm}^{-3}$.

The most striking feature of the present investigation is the demonstration of the fundamental physics underlying the realization of the low contact resistivity. We believe that the key to the success of the present contact was the Ti layers on both sides of the Al layer. As shown in Fig. 9, upon annealing, there occurred both in-diffusion and out-diffusion of the first 30-nm-thick Ti layer (e.g., the Ti layer in intimate contact with the GaN film). The in-diffusion led to the formation of TiN, while the out-diffusion led to the formation of (Ti, Al) alloys. TiN is metallic in nature and has a low work function. Therefore, the formation of a TiN interfacial layer was not detrimental to the Ohmic contacts. In fact, as the formation of TiN accompanied the generation of nitrogen vacancies causing heavy doping of GaN, the effective barrier was thinned (see Fig. 10), and hence, the current conduction in the form of tunneling was facilitated through the junction. The second Ti layer, also 30 nm thick, in-diffused and out-diffused during annealing. Due to the presence of the 30-nm-thick Au layer, the magnitude of the out-diffusion was probably marginalized, and that of the in-diffusion was much higher than the out-diffusion. The in-diffusion led to the formation of (Ti, Al) alloys with the remaining Al content. Consequently, both Al and the Ti (from the second Ti layer) were almost fully consumed, and none of them was left to appear on the contact surface to form oxides.

More specifically, the second Ti layer formed on the top of the traditional Ti/Al contact enhanced the tying up of the excess Al. So, it could not form a mottled contact. Some of the additional (Ti, Al) intermetallic alloys that were formed

![FIG. 8. Total resistance vs gap spacing plot for the TLM measurement of contact resistivity of the Ti/Al/Ti/Au-GaN Ohmic contact annealed at 750 °C for 30 s before and after thermal stressing. The small solid squares are the actual data for resistance after thermal stressing. The solid line is the least-square fit for the annealed data.](image-url)
As noted by Wu, metallization tends to be oxidized even at room temperature. It may be noted that neither Al- nor Ti-only annealed metatllization is suitable for Ohmic contacts. The Al-only metallization tends to yield wide-band-gap AlN at the interface, and as a result, the barrier in GaN may be lowered due to the potential drop across the AlN, as in the case of metal–insulator–semiconductor structures. However, the Ti-only metallization tends to be oxidized even at room temperature. As noted by Wu et al., even at relatively lower temperatures, the Al surface oxidizes forming mostly polycrystalline. A coating of the lowly conductive sapphire thus grown surface oxides and the creation of a shallow damaged layer. That the RIE etch process indeed reduces the contact resistance Ohmic contacts to $n$-GaN.

A factor that could further improve the contact resistance of our contacts is the reactive ion etching of the TLM mesas. The improvement would arise from the removal of the as-grown surface oxides and the creation of a shallow damaged layer. That the RIE etch process indeed reduces the contact resistance is evident from a recent investigation reported elsewhere.

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