Low-resistance ohmic contacts to p-type GaN achieved by the oxidation of Ni/Au films

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A contact has been developed to achieve a low specific contact resistance to p-type GaN. The contact consisted of a bi-layer Ni/Au film deposited on p-type GaN followed by heat treatment in air to transform the metallic Ni into NiO along with an amorphous Ni–Ga–O phase and large Au grains. A specific contact resistance as low as $4.0 \times 10^{-6} \Omega \text{cm}^2$ was obtained at 500 °C. This low value was obtained by the optimization of Ni/Au film thickness and heat treatment temperatures. Below about 400 °C, Ni was not completely oxidized. On the other hand, at temperatures higher than about 600 °C, the specific contact resistance increased because the NiO detached from p-GaN and the amount of amorphous Ni–Ga–O phase formed was more than that of the sample annealed at 500 °C. The mechanism of obtaining low-resistance ohmic contacts for the oxidized Ni/Au films was explained with a model using energy band diagrams of the Au/p-NiO/p-GaN structure.

I. INTRODUCTION

Group III nitride semiconductors have attracted great attention in recent years owing to the successful commercialization of light emitting diodes from ultraviolet to visible range$^1$–$^5$ and the development of laser diodes with a lifetime longer than 10,000 h.$^6$ Meanwhile, various kinds of devices based on these materials have also been developed, including ultraviolet photoconductive$^7$–$^8$ and ultraviolet photovoltaic detectors,$^9$ heterojunction phototransistors,$^{10}$ metal-semiconductor field effect transistors,$^{11}$ heterostructure field effect transistors,$^{12}$ modulation doped field effect transistors,$^{13}$ and heterojunction bipolar transistors.$^{14}$ Low-resistance ohmic contact to GaN is essential to the performance of these devices.

Previous studies have demonstrated ohmic contact to n-GaN with specific contact resistance ($\rho_c$) as low as $10^{-6}–10^{-8} \Omega \text{cm}^2$ by using Ti/Al/Ni/Au$^{15}$ or Ti/Al/Pt/Au$^{16}$ contacts with proper surface pretreatment of GaN. Currently, Ti/Al based metallization schemes are widely used for n-GaN contacts. The formation of the reaction products such as Al–Ti intermetallics,$^{17}$–$^{18}$ TiN$^{19}$–$^{20}$ and AlN$^{19,20}$ was proposed to explain the mechanism of obtaining low $\rho_c$. However, low-resistance ohmic contact to p-GaN so far has had little success with reported $\rho_c$ values greater than $10^{-4} \Omega \text{cm}^2$. These higher values are inappropriate for high performance devices having small contact areas.

The difficulties in achieving low-resistance ohmic contacts to p-GaN are due to the fact that the carrier concentration of p-GaN cannot be increased to a degenerate level during epitaxial growth, and a practical metal with a higher work function than that of p-GaN is not available. Mg is typically used as a p-type dopant with an activation energy of about 170 meV,$^{21,22}$ which is very low compared to other acceptors. However, this activation energy is still too high, implying that only about 1% of Mg dopants ionize at room temperature when the doped Mg concentration is $10^{20} \text{cm}^{-3}$. Meanwhile, the formation of Mg–H complexes further reduces the carrier concentration. Therefore, the carrier concentration of the p-GaN layer is limited to a value less than mid $10^{18} \text{cm}^{-3}$.$^{1,23}$ Diffusion$^{24,25}$ and ion implantation$^{26–29}$ were studied to increase the carrier concentration, but did not reveal any significant improvement. Metals with a high work function were chosen to obtain low-resistance ohmic contacts, e.g., Au,$^{30,31}$ Ni,$^{30,32}$ Pd,$^{33}$ Pt,$^{30,34}$ Ni/Au,$^{34–39}$ Pt/Au,$^{34,38}$ Cr/Au,$^{37}$ Pd/Au,$^{37,38,40}$ Pd/Pt/Au,$^{34}$ Ni/Cr/Au,$^{35}$ Ni/Pt/Au,$^{41,42}$ and Pt/Ni/Au.$^{42,43}$ The semiconductor’s surface condition prior to metal deposition also influenced the contact. A very thin layer of native oxide could severely degrade it. Conversely, the reduction of surface contamination also reduced $\rho_c$.$^{36,40}$ Unfortunately, the lowest reported value of $\rho_c$ with proper surface pretreatment of p-GaN was only $4 \times 10^{-4} \text{cm}^2$. Since using a metal with a high work function cannot obtain an ohmic contact of the required quality, the concept of solid phase reaction proposed by Sands, Marshall, and Wang$^{45}$ was employed. This approach incorporated p-type dopants into the semiconductor superficial layer to produce a low-resistance contact. Mg and Zn were categorized to shallow p-type doping elements, hence, these dopants were added into the contact metal. Although metallization schemes including Au/Mg/Au,$^{31}$ Ni/Mg/Ni/Si,$^{45}$ Ni/Au–Zn,$^{36,47}$ and Cr/Au–Zn,$^{47}$ were investigated, no evi-
dopant progress was made in decreasing $\rho_c$ with $\rho_c$ limited to $10^{-3}$ $\Omega$ cm$^2$ range. Recently, Suzuki et al. proposed that metals having strong binding energies with hydrogen atoms can make low-resistance ohmic contacts to $p$-GaN because the metals can attract the hydrogen atoms from $p$-GaN at high temperatures to increase the hole concentration of $p$-GaN. The use of Ta/Ti as the metal contact obtained a $\rho_c$ as low as $3 \times 10^{-5}$ $\Omega$ cm$^2$. Unfortunately, this contact is unstable in air.

Another approach to achieving low-resistance ohmic contact is through semiconductor band gap engineering. Small band gap semiconductors can promote thermionic emission of carriers. Thus thin, heavily doped cap layers of small band gap semiconductors have been applied to various devices to obtain low contact resistance InN, having a lower band gap than GaN and AlN, should produce a lower contact resistance when a layer of InN or InGaN is built on GaN.

The creation of low-resistance ohmic contact is attributed to the formation of $p$-type NiO. Cross-sectional transmission electron microscope analysis revealed that the as-deposited Au film converted into discontinuous islands connected with $p$-GaN. Besides crystalline NiO, an amorphous Ni–Ga–O phase was also present at the interface between the contact and $p$-GaN. These results suggest that the crystalline NiO and/or amorphous Ni–Ga–O phase may play a significant role in lowering ohmic contact resistance to $p$-GaN. NiO, which is a $p$-type semiconductor, may serve as a medium between $p$-GaN and metal in forming ohmic contacts. In this investigation, we achieve $\rho_c$ with a value as low as $4 \times 10^{-6}$ $\Omega$ cm$^2$ by adjusting the Ni/Au thickness. In order to understand the mechanism for obtaining low contact resistance to $p$-GaN, a model based on energy band diagram is also proposed to explain the results which will be discussed below.

II. EXPERIMENTAL PROCEDURES

The GaN samples used in this study were grown by a low pressure metalorganic chemical vapor deposition method on (0001) sapphire substrates. The substrates were cleaned with organic solvents before loading into the chemical vapor deposition system. A thin GaN nucleation layer was initially grown on sapphire at low temperatures, followed by a 2-$\mu$m-thick undoped GaN and 2-$\mu$m-thick Mg doped GaN at about 1000°C. During GaN growth, trimethylgallium, ammonia, and bis-cyclopentadienyl magnesium were used as Ga, N, and Mg sources, respectively. The carrier gas was H$_2$. The undoped GaN was inherent $n$-type with carrier concentration of $1 \times 10^{17}$ cm$^{-3}$, and the hole concentration of the Mg doped $p$-GaN was $2 \times 10^{17}$ cm$^{-3}$ after heat treating in a nitrogen atmosphere. The average surface roughness measured with a stylus surface profiler was below 10 nm. The GaN epilayers measured had about 200 arcsec of full width at half maximum of (0002) diffraction in the rocking curve x-ray diffraction (XRD) analysis.

The specific contact resistance was characterized by current–voltage ($I$–$V$) measurements based on the circular transmission line model (CTLM).53 For the CTLM measurement, the total resistance, $R_t$, between two contacts separated by a circular gap is given by Eq. (1)

$$R_t = \frac{R_{sh}}{2\pi} \left[ \ln \frac{R}{r} + L_1 \left( \frac{1}{R} + \frac{1}{r} \right) \right],$$

where $R_{sh}$ denotes the sheet resistance of $p$-GaN, $R$ and $r$ represent the radius of the outer and inner circular contact, respectively, and $L_1$ is the transfer length. The total resistance was measured for various spacings and plotted as function of $\ln(R/r)$. The least squares curve fitting method was used to obtain a straight line plot of $R_t$ vs $\ln(R/r)$ data. The slope leads to $R_{sh}$, and the intercept at $\ln(R/r)=0$ is $R_{sh} \cdot L_1/r \pi$, giving $L_1$. Thus, the specific contact resistance, $\rho_c$, can be obtained by Eq. (2)

$$L_1 = \sqrt{\frac{\rho_c}{R_{sh}}}.$$
To determine the same temperatures in either an air or oxygen atmosphere.

![Image](Image.png)

**FIG. 1.** CTLM $I–V$ measurement of Ni (5 nm)/Au (5 nm) contacts to $p$-GaN heat treated at 500 °C for 10 min in air. The spacing is 14 μm. The inset at lower right indicates the pattern of CTLM measurement.

The temperature range of about 300–600 °C. Figure 1 displays the results of $I–V$ measurement for the samples with Ni (5 nm)/Au (5 nm) contacts heat treated in air. There were no obvious differences in $R_t$ for the samples heat treated at the same temperatures in either air or oxygen atmosphere.

To determine $\rho_c$, data on $R_t$ obtained from Fig. 1 were plotted as a linear function of $\ln(R_t)$ in Fig. 2. The slopes produced closely resembled each other. The difference in the $R_{sh}$ values obtained from CTLM measurements and those from Hall measurements was less than 8.7%. Hence, we believe that $\rho_c$ obtained from our CTLM analysis appears to be reliable.

The $I–V$ curves of the samples heat treated in air at temperatures below approximately 350 °C showed a nonlinear behavior which was similar to those heat treated in nitrogen. In addition, the $\rho_c$ of many samples could not be obtained because $R_t$ did not exhibit a linear function with respect to $\ln(R_t)$. This phenomenon could result from incomplete and/or inhomogeneous oxidation of Ni. Certainly, XRD analysis indicated that large amounts of Ni still existed in the contact layers. Under such condition, $\rho_c$ was determined to be in the range of $10^{-1}–10^{-2}$ Ω cm² when $R_t$ was defined at 0.5 V forward bias that current flows into the center circular contacts.

Figure 3 displays the variation of $\rho_c$ as a function of heat treatment temperature in air for Ni/Au contacts with various combinations of Ni/Au thickness. This figure does not contain those contacts with asymmetric $I–V$ curves. The slopes of the curves reveal that $\rho_c$ heavily depended on both heat treatment temperature and Ni/Au film thickness. In general, $\rho_c$ initially decreased with increasing heat treatment temperature, and subsequently increased. A minimum $\rho_c=4×10^{-6}$ Ω cm² was obtained for the Ni (5 nm)/Au (5 nm) contact heat treated at 500 °C. Another contact Ni (20 nm)/Au (20 nm), also heat treated at 500 °C, also exhibited low $\rho_c=8×10^{-6}$ Ω cm², as shown in Fig. 3(b). Apparently, low-resistance ohmic contact could be achieved when the Ni and Au layers were of equal thickness and heat treated at 500 °C. XRD analysis on these two samples indicated that the Ni constituent of the Ni/Au films transformed completely into NiO after the heat treatment, while the Au remained in the metallic phase. Our recent cross-sectional TEM observation found that the as-deposited metallic Ni/Au films were reconstructed as a film comprising of a mixture of crystalline NiO, Au, and amorphous Ni–Ga–O phases after being heat treated at 500 °C. A few small voids adjacent to GaN were also found. The as-deposited Au film became discontinuous islands on the top of $p$-GaN. The NiO formed a continuous film in the outer region which covered the Au islands and amorphous Ni–Ga–O phase. Observation revealed a large percentage of GaN surface area was still in direct contact with NiO. The transformation brought about a specific relationship of crystal orientation between the crystalline NiO, Au islands, and $p$-GaN. This relationship is NiO(111)//Au(111)//GaN(0002) and NiO[1 1 0]//Au[1 1 0] //GaN[1 1 2 0], as shown in Fig. 4. The NiO and Au were epitaxially formed on $p$-GaN with sharp interfaces. This process formed a $p$-$p$ type heterojunction of GaN and NiO. The reduction of specific contact resistance could be related to the formation of NiO because Au alone could not form low-resistance ohmic contact to $p$-GaN, and the amorphous Ga–Ni–O phase was considered to be insulating currently. Therefore, the minimum value of $\rho_c$ at 500 °C shown in Figs. 3(a) and 3(b) could be due to the optimal phase distribution among NiO and Au. For temperatures below 400 °C, the TEM observation showed the percentage of NiO was not optimized. On the other hand, there was an increase of $\rho_c$ when the temperature was higher than about 600 °C.

![Image](Image.png)

**FIG. 2.** The dependence of $R_t$ on $\ln(R_t/r)$ for the oxidized Ni (5 nm)/Au (5 nm) contacts to $p$-GaN.
due to the fact that oxidized Ni/Au film contained many larger voids and much more amorphous Ni–Ga–O phase. The voids between NiO and p-GaN grew with increasing temperature, separating NiO from p-GaN. This leaves almost only the Au islands in contact with p-GaN. These results hint that the formation of NiO is the reason for obtaining low $\rho_c$ to p-GaN and the amorphous Ni–Ga–O phase may have a detrimental effect.

IV. DISCUSSION

To understand the mechanism for forming low-resistance ohmic contacts, a single Ni film with a thickness of 20 nm was deposited and heat treated in air. The results of $\rho_c$ versus temperature are shown in Fig. 3(b). The oxidized Ni contacts displayed ohmic characteristics, revealed in the $I–V$ measurements, although the value of $\rho_c$ was high (about 10$^{-1}$ $\Omega$ cm$^2$). The resistivity of oxidized Ni films was too high to be measured by the conventional four-pointprobe analysis. Once an Au layer was added to the as-deposited Ni films, the oxidized Ni/Au films became conductive. We believe that the Au layer forms islands which disperse in the NiO matrix to enhance the conductivity of oxidized films. The presence of Au itself does not necessarily contribute to the reduction of $\rho_c$ for the oxidized Ni/Au ohmic contact. Thus the lowering of interface resistance between the oxidized Ni/Au contact and p-GaN can be attributed to the formation of NiO. The high $\rho_c$ for the oxidized Ni contact, compared to those with Au, are due to the high resistivity of the NiO which prevents the current from spreading uniformly over the CTLM contact. The actual contact area for current flow across the interface is much smaller than the nominal circular contact area. Therefore, the real interface impedance could be much lower than the measured value.

The above discussion indicates that the effective configuration of oxidized Ni contact to p-GaN may be regarded as a Au/p-NiO/p-GaN junction since the probes used in $I–V$ measurement are gold plated tungsten needles. Figure 5 displays the equilibrium energy band diagram of the Au/p-NiO/p-GaN junction based on the electron affinity rule. The parameters adopted to construct this energy band diagram, such as electron band gap ($E_g$), electron affinity ($\chi$), and dielectric constant ($\varepsilon$), etc. are listed in Table I which is explained below. The Fermi level is assessed as about 0.13 eV above the top of the valence band at 300 K. For NiO, the carrier concentration at 500°C was estimated to be 1 x 10$^{16}$ cm$^{-3}$, a figure extrapolated from the high temperature data measured by Peterson and Wiley. The temperature of 500°C was chosen for the calculation of hole concentration of NiO because the minimum $\rho_c$ is obtained by heat treating at this temperature and then rapidly quenching down to room temperature. Also, the diffusion is negligible at such a temperature. The Fermi level is assessed as about
0.5 eV above the top of the valence band for undoped NiO. From these parameters, the conduction band and valence band offsets, $\Delta E_c$ and $\Delta E_v$, can be determined to be 2.7 and 2.1 eV, respectively. The total built-in potential ($V_{bi}$) across the p-NiO/p-GaN isotype heterojunction is assumed to be equal to the work function difference between the p-GaN and p-NiO before any junction is formed. Figure 5(a) displays that $V_{bi} = 2.47$ V which is equal to the sum of the partial built-in potentials in p-GaN and p-NiO, respectively, as indicated in Eq. (3)

$$V_{bi} = V_{GaN}^{bi} + V_{NiO}^{bi},$$

(3)

where $V_{GaN}^{bi}$ and $V_{NiO}^{bi}$ are the potentials induced at equilibrium in p-GaN and p-NiO, respectively. Following Cseraeny’s concept, the relationship between $V_{GaN}^{bi}$ and $V_{NiO}^{bi}$ is derived as

$$\frac{\exp(-qV_{NiO}^{bi}/kT)}{\exp(qV_{GaN}^{bi}/kT)} + 1 = \frac{[p]_{GaN}}{[p]_{NiO}},$$

(4)

where $[p]$ is the hole concentration, $k$ the Boltzmann constant, $q$ the electronic charge, and $T$ absolute temperature. Here, the hole concentration is used to replace the dopant concentration. $V_{GaN}^{bi}$ and $V_{NiO}^{bi}$ can be obtained by combining Eqs. (3) and (4) and applying the data shown in Table I. Calculation shows them to be equal to 0.055 and 2.415 V, respectively. Besides, the transition width ($\Delta X$) in p-NiO and p-GaN is derived as Eq. (5)

$$\Delta X = \frac{2\pi}{\varepsilon} \sqrt{\frac{V_{bi}}{q\cdot[p]}}.$$  

(5)

The above results of p-GaN/p-NiO isotype heterojunction are summarized in Table II. For the interface between Au and p-NiO, an ideal ohmic contact is formed because the work function of Au ($\Phi_{Au} = 5.10$ eV) is larger than that of p-NiO (4.9 eV), as shown in Fig. 5(a). For a thick p-NiO connected to p-GaN, the situation resembles that of Fig. 5(b). The p-NiO and p-GaN surface bands bend upwards and downwards, respectively, at the p-GaN/p-NiO interface. A deep notch for holes in p-NiO exists close to p-GaN where great amounts of holes are trapped because the top of the valence band is positioned above the Fermi level. Under forward bias condition, with a current injection into p-GaN from Au as defined herein, holes flowing from p-NiO toward p-GaN encounter a barrier at p-GaN surface resulting from the built-in potential in p-GaN. The barrier height is equal to $(E_{GaN}^{bi} - E_{NiO}^{bi}) + qV_{GaN}^{bi} = 0.185$ eV. The impedance at this interface could be very small because the barrier height is relatively low. The p-NiO/p-GaN interface impedance will abruptly decrease when the applied forward voltage reaches a level where the valence band bottom is higher than the Fermi level of p-NiO at the interface. By further increasing the bias, holes can inject into p-GaN from the notch in p-NiO freely. Meanwhile, a large portion of applied voltage is also consumed in the p-NiO to develop an electrical field there because of its high resistivity. The impedance increases.

### Table I. Properties of p-GaN and p-NiO at room temperature.

<table>
<thead>
<tr>
<th>Semi-conductor</th>
<th>$E_c$ (eV)</th>
<th>$\chi$ (eV)</th>
<th>$E_v - E_c$ (eV)</th>
<th>$[p]$ (cm$^{-3}$)</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-GaN</td>
<td>3.4$^a$</td>
<td>4.1$^b$</td>
<td>0.13</td>
<td>$2 \times 10^{17}$</td>
<td>10.4$^c$</td>
</tr>
<tr>
<td>p-NiO</td>
<td>4.0$^d$</td>
<td>1.4$^e$</td>
<td>0.5$^f$</td>
<td>$1 \times 10^{16}$</td>
<td>11.9$^g$</td>
</tr>
</tbody>
</table>

$a$Reference 61.  
$b$References 62 and 63.  
$c$Reference 64.  
$d$Reference 58.  
$e$References 65 and 66.  
$f$References 58 and 59.  
$g$Reference 67.
with increasing reverse bias because of the barrier and the resistive NiO layer. Consequently, the $I$–$V$ curves are not considered to be symmetric with respect to applied bias. In addition, the total contact resistance could be unable to reach a very low value when the thickness of the $p$-NiO layer is greater than $\Delta X_{\text{NiO}}$.

In our experiments, the oxidized Ni contact is about 33 nm, i.e., markedly smaller than the calculated value of $\Delta X_{\text{NiO}} = 571$ nm. The electrical property is completely different from that predicted in Fig. 5(b). The energy band diagram is shown in Fig. 5(c). Again, there is a hole notch at the heterojunction because of the large band offset between $p$-NiO and $p$-GaN. An additional small barrier exists at the Au/$p$-NiO interface except that one at $p$-NiO/$p$-GaN interface as described previously. The barrier height is 0.3 eV resulting from the band discontinuity at the Au/$p$-NiO interface. Although the band diagram is more complicated because the interaction between Au and $p$-GaN cannot be neglected, similar qualitative trends are still valid. With forward bias, holes can easily overcome the barriers by thermonic-field emission to inject into $p$-GaN from $p$-NiO. When the bias becomes negative, electrons can tunnel through the Au/$p$-NiO interface barrier and inject into the notch to recombine with holes. The contact resistance could be quite low because the notch provides a recombination center for carriers. This is the reason that the $I$–$V$ curve is linear for the oxidized Ni contact.

As the above discussion shows, the lowest $\rho_c$ was obtained at 500 °C for the oxidized Ni/Au contact. At this temperature, Au, NiO, and the amorphous Ni–Ga–O phase are present. The contact angle of Au islands to $p$-GaN is about 120°–140°, developing an Au island undercut edge profile. NiO frequently occupies the undercut space, as shown in Fig. 4. The Au/thin $p$-NiO/p-GaN model is valid under such condition. The arrow in Fig. 4 indicates an Au/thin $p$-NiO/p-GaN region with an ultrathin $p$-NiO layer. In addition, the Au islands are uniformly distributed in the contact, greatly enhancing its conductivity. Combining these effects produces low-resistance ohmic contacts.

## V. SUMMARY

This study has developed an ohmic contact to $p$-GaN with specific contact resistance as low as $4 \times 10^{-6}$ Ω cm$^2$ by the oxidation of Ni (5 nm)/Au (5 nm) bilayer film in air or oxygen at 500 °C. The oxidized Ni/Au contact comprises Au, NiO, and amorphous Ni–Ga–O phases. The NiO and Au epitaxially build on $p$-GaN with sharp interfaces. Finally, we proposed a model based on Au/$p$-NiO/p-GaN heterostructure to explain the low-resistance ohmic behavior.

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