Low-resistance ohmic contacts to p-type GaN

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Low-resistance ohmic contacts with high transparency to p-type GaN have been developed by oxidizing Ni/Au thin films. Compared to the metallic Ni/Au contacts, the oxidized Ni/Au contacts exhibited lower specific contact resistance and much improved transparency. The transparency was from 65% to 80% in the wavelength of 450–550 nm. A specific contact resistance below 1.0 \times 10^{-4} \, \text{\Omega}\,\text{cm}^2 was obtained by oxidizing Ni(10 nm)/Au(5 nm) on p-type GaN. The mechanism of low-resistance ohmic contact could be related to the formation of NiO.

The group III nitrides, especially GaN, are attractive materials for optoelectronic devices because of the success in commercialization of blue light emitting diodes. Other devices including laser diodes, ultraviolet photoconductive detectors, ultraviolet photovoltaic detectors, metal–semiconductor field effect transistors, etc., also have been studied. Ohmic contact to GaN is very important because of the performance of these devices such as operating voltage is strongly influenced by the contact resistance. A very low-resistance ohmic contact to n-type GaN has been demonstrated using Ti/Al/Ni/Au. However, no satisfying ohmic contacts to p-type GaN have been developed so far. Various metal contacts were applied to p-type GaN, such as Au, Ni, Ti, Pt, W, WSi, Ni/Au, Pt/Au, Cr/Au, Pd/Au, Au/Mg/Au, Ni/Cr/Au, Ni/Pt/Au, Ni/Au–Zn, Ni/Mg/Ni/Si, etc., but all of the reported specific contact resistance are in the range from 2.1 \times 10^5 to 9.6 \times 10^{-4} \, \text{\Omega}\,\text{cm}^2. These values are too high for high performance devices. Low contact resistance to p-type GaN is difficult to obtain because of the difficulty to achieve high hole concentrations in p-type GaN and the lack of metals with high work function compared to the band gap and electron affinity of GaN. One approach to achieve low-resistance ohmic contact is through semiconductor band gap engineering. Lin, Huang, and Morkoc found that the hole concentration of NiO films prepared by sputtering deposition can be as high as 1.3 \times 10^{19} \, \text{cm}^{-3} which is about one to two orders higher than that of common p-type GaN films. The high carrier concentration of NiO makes a metal easy to achieve an ohmic contact on it. The Ni ion vacancies which provide holes can be introduced during the oxidation of Ni. Therefore, the NiO films obtained by the oxidation of Ni films are p-type. The authors tried to use p-type NiO produced by oxidation of a Ni film as a medium between p-type GaN and metal to form ohmic contacts.

The GaN samples used in this study were grown by low pressure metalorganic chemical vapor deposition (MOCVD) method on (0001) sapphire substrates. The substrates were cleaned with organic solvents before loading into MOCVD system. A GaN nucleation layer was first grown on sapphire at low temperatures, followed by the growth of 2-\mu-m-thick undoped GaN and 2-\mu-m-thick Mg doped GaN at high temperatures. The undoped GaN was inherent n-type with carrier concentration of 1 \times 10^{17} \, \text{cm}^{-3}, while the hole concentration of the Mg doped GaN was of 2 \times 10^{13} \, \text{cm}^{-3} after heat treating in nitrogen atmosphere. The GaN epilayers displayed average surface roughness is smaller than 100 Å measured by a stylus surface profile meter. The specific contact resistance was characterized using a circular transmission line model (CTLM). The metallized samples were heat treated with a conventional hot wall furnace with flow of nitrogen, forming gas, oxygen, or air. The crystal structure and optical transparency of the films deposited on glass substrates were characterized with a thin-film XRD system and a double beam spectro-photometer, respectively. The resistivity of films was analyzed by the conventional four-point probe method.

For the metallic Ni/Au contacts to p-type GaN, the current–voltage (I–V) curves were rectified at high biases in the as-deposited samples and remained the same upon heat treatment at all experimental temperatures, e.g., 350–800°C, in nitrogen or forming gas. A typical result is shown in Fig. 1. On the contrary, when the samples were heat treated in air, the I–V curves became linear, which indicates the formation of an ohmic contact. Meanwhile, a steeper slope of the I–V curve was observed for samples heat treated in air than those heat treated in nitrogen or forming gas. This indicates lower specific contact resistance can be obtained by heat treating Ni/Au contacts in air. The same results were obtained when air is replaced by pure oxygen. Figure 2 shows the specific
contact resistance of Ni/Au contacts heat treated at various temperatures in air. In the temperature range between 300 and 600 °C, the specific contact resistance decreased first and then went up. A minimum value of $1.0 \times 10^{-4}$ Ω cm$^2$ was obtained at 400 °C. To our knowledge, this is the lowest value reported for ohmic contact to $p$-type GaN. On the contrary, Ni/Au contacts with various thickness combination heat treated in inert ambient such as nitrogen only had contact resistance in the range of about $10^{-2}$ – $10^{-1}$ Ω cm$^2$. At temperatures lower than 300 °C, specific contact resistance of oxidized Ni/Au could not obtain because the total resistance from $I$–$V$ curve did not monotonically increase with gap spacing. It could be resulted from incomplete and/or inhomogeneous oxidation of Ni. On the other hand, the Ni/Au contact converted to resistive when temperature was higher than 700 °C. XRD analysis indicated that the Ni constituent of Ni/Au film transformed to NiO after heat treating in air or pure oxygen, but Au remained in metallic state, as shown in Fig. 3. Thus, the reduction of specific contact resistance could be due to the formation of NiO because Au cannot form low-resistance ohmic contact to $p$-type GaN.$^7, 8$

The films heat treated in nitrogen or forming gas exhibited pale golden tinct and the transparency is lower than 40%. On the contrary, the oxidized films were transparent. The transparency spectra are shown in Fig. 4. The improvement in transparency was caused by the transformation of Ni to NiO, which has a wide band gap of about 4 eV.$^{26}$ Resistivity measurement (Table I) revealed that the oxidized films still possessed good conductivity, though the values are about two to four times higher than those of the samples treated in nitrogen. Furthermore, specific contact resistance as small as $8.2 \times 10^{-6}$ Ω cm$^2$ was obtained with oxidized Ni(20 nm)/Au(20 nm) contacts, but the value is beyond the accuracy of the CTLM analysis because of the poor conductivity of $p$-type GaN. The specific contact resistance was definitely smaller than $1 \times 10^{-4}$ Ω cm$^2$ without any doubts by comparing the slopes of $I$–$V$ curves.

In order to understand the mechanism of ohmic contact, pure Ni, instead of Ni/Au, with a thickness of 20 nm was used for comparison. However, the conductivity of the oxidized Ni films was poor. This result also showed that the
addition of Au layer improving the conductivity of oxidized Ni/Au contact. The specific contact resistance of the oxidized Ni contact was only about 0.1 Ω cm\(^2\), but its \(I-V\) curve displayed a linear relationship indicating that the interface of NiO/p-GaN is ohmic with small impedance. The measured high specific contact resistance may be due to the high resistivity of the NiO film so that the current cannot uniformly spread over the CTLM pad. Barcz, Turos, and Wielunksi\(^{27}\) and Raiden, Neugebauer, and Sigsbee\(^{28}\) reported that Ni tends to penetrate Au film through defects to surface to react with oxygen in the Ni/Au bilayer structure. The authors believed that the same phenomena occurred in the GaN/Ni/Au system. The Ni atoms diffused out to surface and formed NiO, while Au still remained in metallic state. The thickness of both as-deposited Ni and Au layers is very thin. The condition tended to break the thin Au film during NiO formation. The Au film might reconstruct its morphology into networks or discontinuous small pieces, or between the two extreme cases. The high conductivity of the oxidized Ni/Au could be easily understood for the former case. As to the later case, the Au particle’s shape may change to granular because of surface tension. The out diffusion of Ni atoms induced the Au particles migrating toward GaN surface due to the Kirkendall effect. Besides, the volume percentage of Au in the oxidized films is about 23% by a calculation basing on bulk density of Au, Ni, and NiO. Thus, the authors speculated the oxidized Ni/Au film containing Au particles embedded in NiO matrix. The conduction mechanism under such conditions may be similar to that of a cermet,\(^{29}\) where current flow by electron tunneling among Au particles inside NiO. This configuration also illustrates the conductive behavior of the oxidized Ni/Au film. To form a low-resistance ohmic contact requires not only a highly conductive contact material but also low interface resistance between the contact and semiconductor. The oxidized Ni/Au film made low-resistance ohmic contact to \(p\)-type GaN by creating the low impedance interface resulting from the formation of NiO and by building the highly conductive composite film with the presence of Au phase. Finally, the whole contact produced a low-resistance ohmic contact to \(p\)-type GaN. The actual contact may regard as a Au/p-NiO/p-GaN conjunction.

In summary, the authors have demonstrated an ohmic contact to \(p\)-type GaN with specific contact resistance lower than \(1.0 \times 10^{-4}\) Ω cm\(^2\) by the oxidation of Ni/Au thin films. This value is lower than all previously published data. Au remained in metallic state but Ni transformed to NiO during heat treatment in air or oxygen. The oxidized contact was transparent when the thickness of the deposited Au layers was thin. The high conductivity of the oxidized Ni/Au films was referred to the constituent Au, while the low interface resistance between the oxidized Ni/Au film and \(p\)-type GaN was attributed to the formation of \(p\)-type NiO. With the combination of the two effects, very low-resistance ohmic contact to \(p\)-type GaN was created.

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**Table I.** The electrical properties of Ni(10 nm)/Au(5 nm) deposited on glass heat treated in different atmosphere and temperature for 10 min.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sheet resistance (Ω cm(^2))</th>
<th>Resistivity (μΩ cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-deposited</td>
<td>11.87</td>
<td>18</td>
</tr>
<tr>
<td>N(_2), 400 °C</td>
<td>15.94</td>
<td>23</td>
</tr>
<tr>
<td>N(_2), 500 °C</td>
<td>16.82</td>
<td>24</td>
</tr>
<tr>
<td>N(_2), 600 °C</td>
<td>22.17</td>
<td>32</td>
</tr>
<tr>
<td>Air, 400 °C</td>
<td>27.07</td>
<td>58</td>
</tr>
<tr>
<td>Air, 500 °C</td>
<td>38.94</td>
<td>81</td>
</tr>
<tr>
<td>Air, 600 °C</td>
<td>24.16</td>
<td>52</td>
</tr>
</tbody>
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