Formation of low resistance Pt ohmic contacts to p-type GaN using two-step surface treatment

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Two-step surface treatment is introduced to obtain low resistance Pt contacts to p-type GaN. The first step is performed after the mesa etching process using buffered oxide etch (BOE) and ammonium sulfide [(NH$_4$)$_2$S$_2$]. This is followed by the second step using BOE. The Pt contact, that was simply BOE treated, yields $2.1(\pm0.9) \times 10^{-2} \ \Omega \text{cm}^2$. However, the contact which was treated sequentially using ultrasonically boiled BOE (10 min) and boiled (NH$_4$)$_2$S$_2$ (10 min), produces a specific contact resistance of $2.0(\pm3.5) \times 10^{-3} \ \Omega \text{cm}^2$. To the best of our knowledge, this is the lowest contact resistance reported hitherto for the contacts on p-GaN. The effective Schottky barrier heights (SBHs) of the differently surface-treated contacts were determined using the Norde and current–voltage methods. It is shown that the SBHs are dependent upon the surface treatment conditions. © 1999 American Vacuum Society. [S0734-211X(99)03506-4]

GaN and III–V nitride layers have been extensively investigated, since the realization of short-wavelength light-emitting diodes (LEDs) and laser diodes (LDs)\textsuperscript{1,2} and the demonstration of metal–semiconductor field effect transistors (MESFETs)\textsuperscript{3} and heterojunction bipolar transistors (HBTs).\textsuperscript{4} Low resistance and thermally stable ohmic contacts are crucial for improving such device performance. However, there are some obstacles, such as difficulty in increasing p-GaN near-surface carrier concentrations and the absence of metals having a work function larger than that of p-GaN (sum of band gap of 3.4 eV and electron affinity of 4.1 eV),\textsuperscript{5} which makes it difficult to achieve low resistance ohmic contacts to p-GaN. Jang et al.,\textsuperscript{6} investigating ohmic contacts to p-GaN using a Ni/Pt/Au metallization scheme, showed that the metal contact was ohmic with a contact resistance of $2.1 \times 10^{-2} \ \Omega \text{cm}^2$ when annealed at 500 °C for 30 s in a flowing Ar atmosphere. Mori et al.,\textsuperscript{7} investigating ohmic contacts on p-GaN using Pt, Ni, Au, and Ti single layers, showed that the as-deposited Pt contact was ohmic with a specific contact resistance of $1.3 \times 10^{-2} \ \Omega \text{cm}^2$. Cao et al.,\textsuperscript{8} investigating thermal stability of W and WS$_x$ contacts on p-GaN, reported a specific contact resistance of $\sim 10^{-2} \ \Omega \text{cm}^2$ for the 300 °C annealed WS$_x$.

To achieve low resistance ohmic contacts to p-GaN, surface treatments using the solutions of KOH and HNO$_3$ :HCl (1:3) have been performed.\textsuperscript{5,10} Lee et al.,\textsuperscript{5} employed KOH to modify surface conditions and showed that for Pt/Au contacts, the surface treatment leads to a decrease in the specific contact resistance up to $7.1 \times 10^{-3} \ \Omega \text{cm}^2$. Kim et al.,\textsuperscript{10} used HNO$_3$ :HCl (1:3) to modify surface conditions and showed that for Pt/Au ohmic contacts to p-GaN, the surface modification results in a specific contact resistance of $4.1 \times 10^{-4} \ \Omega \text{cm}^2$. They attributed the low resistance to the removal of a native oxide layer that inhibits hole transport from the metal to p-GaN.

In this article, we report on the formation of low resistance Pt contacts to p-GaN by a two-step surface treatment technique using buffered oxide etch (BOE) and ammonium sulfide [(NH$_4$)$_2$S$_2$]. It is shown that specific contact resistances and Schottky barrier heights depend sensitively on the surface-treated conditions.

Metalorganic chemical vapor deposition (Emcore DgN125TM) was used to grow a 2-μm-thick unintentionally doped GaN layer on a (0001) sapphire substrate. This was followed by the 1-μm-thick p-GaN:Mg ($n_d=1.8 \times 10^{17} \ \text{cm}^{-3}$). The GaN layer was ultrasonically degreased in trichloroethylene, acetone, methanol, and ethanol, and rinsed in deionized (DI) water for 5 min. Prior to the fabrication of transfer length method (TLM) patterns, mesa structures were patterned by inductively coupled plasma etching (Oxford Plasma 100) using Cl$_2$/Ar/H$_2$. The first step surface treatment was performed after the mesa etching process. The mesa-patterned layers were chemically treated by four different conditions: (i) not treated (termed here “A-treated”); (ii) ultrasonically boiled in BOE solution for 10 min (B); (iii) ultrasonically boiled in (NH$_4$)$_2$S$_2$ solution for 10 min (C); and (iv) first ultrasonically boiled in BOE for 10 min and then boiled in (NH$_4$)$_2$S$_2$ for 10 min (D). The conditions are summarized in Table I. After the first step treatment, TLM patterns were defined by a photolithographic technique. The size of the pads was $100 \times 200 \ \mu\text{m}^2$ and the spacing between the pads was 5, 10, 15, 20, 25, and 35 μm. After the TLM patterning, the second step treatment was performed. All the TLM-patterned layers were dipped into BOE for 30 s. Metalization patterns were defined using a lift-off technique. The samples were then rinsed in DI water, blown dry by N$_2$, and immediately loaded into an electron-beam evaporation chamber (PLS 500). The thickness of the Pt films was 25 nm. Current–voltage (I–V) data were measured at room temperature using a parameter analyzer (HP 4155A) and Schottky barrier heights (SBHs, $\phi_s$) were calculated using the Norde\textsuperscript{11} and I–V methods.\textsuperscript{7–14}
Figure 1(a) shows the $I-V$ characteristics of the various surface-treated Pt contacts on $p$-GaN. The A-treated Pt contact reveals nonlinear $I-V$ behavior. The $I-V$ behavior of the B-treated contact is fairly similar to that of the C-treated one. The D-treated contact shows a linear $I-V$ characteristic. Specific contact resistances were determined from a plot of the measured resistances versus the spacings between the TLM pads. The least squares method was used to fit a straight line to the experimental data. Figure 1(b) shows a plot of the resistance as a function of the spacing for the surface-treated samples. The specific contact resistance was determined to be $2.1(\pm0.9) \times 10^{-2}$ $\Omega$ cm$^2$ for the A-treated sample, $3.7(\pm3.5) \times 10^{-3}$ $\Omega$ cm$^2$ for the B-treated sample, $3.8(\pm3.0) \times 10^{-3}$ $\Omega$ cm$^2$ for the C-treated sample, and $2.0(\pm3.5) \times 10^{-2}$ $\Omega$ cm$^2$ for the D-treated sample. It is worth noting that the D treatment resulted in a dramatic reduction (by about three orders of magnitude) in the specific contact resistance as compared to that of the A treatment. The result

<table>
<thead>
<tr>
<th>Treatment</th>
<th>The first step treatment condition (performed after the mesa etching)</th>
<th>The second step treatment condition (performed before the metal deposition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Not treated</td>
<td>Dipped in BOE for 30 s</td>
</tr>
<tr>
<td>B</td>
<td>Ultrasonically boiled in BOE for 10 min</td>
<td>Dipped in BOE for 30 s</td>
</tr>
<tr>
<td>C</td>
<td>Ultrasonically boiled in (NH$_4$)$_2$S$_x$ for 10 min</td>
<td>Dipped in BOE for 30 s</td>
</tr>
<tr>
<td>D</td>
<td>First ultrasonically boiled in BOE for 10 min and then boiled in (NH$_4$)$_2$S$_x$ for 10 min</td>
<td>Dipped in BOE for 30 s</td>
</tr>
</tbody>
</table>

Fig. 1. (a) $I-V$ characteristics of the various surface-treated Pt contacts on $p$-GaN. (b) Plot of the resistance as a function of the spacing for the not-treated, BOE-treated, (NH$_4$)$_2$S$_x$-treated, and BOE/(NH$_4$)$_2$S$_x$-treated samples.

Fig. 2. Plots of (a) $F(V)$ vs $V$ and (b) $I/[1-\exp(-qV/kT)]$ vs $V$ for the various surface-treated samples.
of the A-treated sample is comparable to that reported by Mori *et al.*\(^7\).

In order to determine the effective SBH of each contact, the Norde method\(^11\) was employed. The method involves a Norde function, \(F(V)\), being plotted against \(V\). \(F(V)\) is given by\(^11\)

\[
F(V) = \frac{vT}{2} \frac{kT}{q} \ln \left( \frac{I(V)}{AA**T^2} \right),
\]

(1)

where \(A\) is the contact area, \(A**\) is the effective Richardson constant, defined by \(A** = (4\pi qk^2m^*_h)/h^3\). The value of \(A**\) was calculated to be 104 A cm\(^{-2}\) K\(^{-2}\) assuming the effective hole mass (\(m^*_h\)) of 0.8\(m_e\) for the p-GaN.\(^12\) It is known that the measured SBHs is not significantly affected by the variation of \(A**\).\(^13\) Thus, a value of 104 A cm\(^{-2}\) K\(^{-2}\) was used for \(A**\) to calculate SBHs. The effective SBH (\(\phi_b\)) is given by

\[
\phi_b = F(V_{\text{min}}) + \frac{V_{\text{min}}}{2} \frac{kT}{q},
\]

(2)

where \(F(V_{\text{min}})\) is the minimum value of \(F(V)\) and \(V_{\text{min}}\) is the corresponding voltage. Figure 2(a) shows a plot of \(F(V)\) vs \(V\) for the various surface-treated samples. The calculations showed that the SBH is 0.37(±0.015) eV for the A-treated contact, 0.33(±0.015) eV for the B- and C-treated contacts, and 0.30(±0.01) eV for the D-treated contact.

To compare the barrier heights, we also employed the \(I-V\) method.\(^7,14\) Figure 2(b) shows a plot of \(I/I_{\text{sat}}(1 - \exp(-qV/kT))\) vs \(V\) for the surface-treated samples. The measurements showed that the SBHs are in the range of 0.43(±0.015)–0.49(±0.01) eV, depending on the surface treatment. It is noted that these values are higher than those obtained by the Norde method. Our SBH of the A-treated sample is comparable to a value reported by Mori *et al.*\(^7\) who also obtained their SBH using \(I-V\) results. The SBHs obtained from both the methods are listed in Table II.

The precise mechanism for the surface-treatment dependence of the specific contact resistance is not clear at the moment. However, a few points could be brought into discussion for possible mechanisms. First, the reduction in the contact resistance could be attributed to the effective removal of the native oxide on the surface.\(^10\) Kim *et al.*\(^10\) investigating the surface treatment effect on Pd/Au ohmic contacts to p-GaN, showed that the oxide layer has a critical effect on the formation of low resistance ohmic contacts. Second, the surface treatments could result in an increase in the carrier concentration near the surface of the p-GaN layers. In this work, Hall measurements were made for the A- and D-treated GaN layers before the metal deposition. Indeed, it was shown that the D treatment leads to an increase (by about a factor of 10) in the carrier concentration as compared to the A treatment. Third, the improvement in the contact resistance may be associated with an increase in the contact area between the metal and the p-GaN layer,\(^15\) since the surface treatment may cause the roughening of the layer surface. Therefore, we suggest that the improvement in the specific contact resistance could be due to either the removal of the native oxide, an increase in the carrier concentration, an increase in the contact area, or their combined effects.

In summary, the effects of the surface treatment on the ohmic properties of the Pt contacts to p-GaN:Mg (1.8 × 10\(^{17}\) cm\(^{-3}\)) were investigated. Prior to the metal deposition, the two-step surface treatment was performed to modify the surface structures of the p-GaN layers: First, the layers were treated using boiled BOE and (NH\(_4\))\(_2\)S\(_2\) solutions; second, all the layers were then dipped into BOE. The measurements showed that the specific contact resistance was highly sensitive to the surface-treated conditions. The not-treated sample produced 2.1(±0.9) × 10\(^{-2}\) Ω cm\(^2\), while the BOE/(NH\(_4\))\(_2\)S\(_2\)-treated contact yielded 2.0(±3.5) × 10\(^{-3}\) Ω cm\(^2\). This indicates that the two-step surface treatment is a promising technique for obtaining high quality ohmic contacts to p-GaN. The effective SBHs determined by the Norde and \(I-V\) methods were in the range of 0.30–0.37 and 0.43–0.49 eV, respectively, depending on the treatment.

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**Table II. Summary of the electrical characteristics of the two-step surface-treated Pt contacts of p-GaN.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Specific contact resistance (R_c) (Ω cm(^2))</th>
<th>Schottky barrier height (SBH) (\phi_b) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.1(±0.9) × 10(^{-2})</td>
<td>0.37(±0.015)</td>
</tr>
<tr>
<td>B</td>
<td>3.7(±3.5) × 10(^{-3})</td>
<td>0.33(±0.015)</td>
</tr>
<tr>
<td>C</td>
<td>3.8(±3.0) × 10(^{-3})</td>
<td>0.33(±0.015)</td>
</tr>
<tr>
<td>D</td>
<td>2.0(±3.5) × 10(^{-3})</td>
<td>0.30(±0.020)</td>
</tr>
</tbody>
</table>

\(^8\) SBH (\(\phi_b\)) was calculated from the ideal \(I-V\) relation given by (see Refs. 7 and 14) \(I = I_o \exp(qV/kT)(1 - \exp(-qV/kT))\), where \(I_o = AA**T^2 \exp(-\phi_b/kT)\). A is the contact area, \(A**\) the effective Richardson constant, and \(n\) the ideality factor.


