ABSTRACT

W and WSi ohmic contacts on both p- and n-type GaN have been annealed at temperatures from 300 - 1000 °C. There is minimal reaction (< 100 Å broadening of the metal/GaN interface) even at 1000 °C. Specific contact resistances in the $10^{-2}$ Ω·cm$^2$ range are obtained for WSi on Si-implanted GaN with a peak doping concentration of $5 \times 10^{19}$ cm$^{-3}$, after annealing at 950 °C. On p-GaN, leaky Schottky diode behavior is observed for W, WSi, and Ni/Au contacts at room temperature, but true ohmic characteristics are obtained at 250 - 300 °C, where the specific contact resistances are in the $10^{-2}$ Ω·cm$^2$ range. The best contacts for W and WSi are obtained after annealing for periods of 30 - 120 secs. The formation of β-W2N interfacial phases appears to be important in determining the contact quality.
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I. INTRODUCTION

One of the life-limiting factors in GaN laser diodes to date has been the p-ohmic contact.\(^{(1)}\) Due to the relatively poor specific contact resistances (\(R_c\)) achievable, the metallization will heat-up as current flows across the p-n junction, leading to metal migration down threading dislocations and eventual shorting of the junction.\(^{(1)}\) Removal of the dislocations, such as in epitaxial lateral overgrowth structures, will greatly extend the device lifetime.\(^{(1)}\) There are a number of contributing factors to the high \(R_c\) values for contacts on p-GaN, including:

(i) The absence of a metal with a sufficiently high work function (the bandgap of GaN is 3.4 eV, and the electron affinity is 4.1 eV, but metal work functions are typically \(\leq 5\) eV).

(ii) The relatively low hole concentrations in p-GaN due to the deep ionization level of the Mg acceptor (\(~170\) meV).

(iii) The tendency for the preferential loss of nitrogen from the GaN surface during processing, which may produce surface conversion to n-type conductivity.

In the search for improved contact characteristics, a wide variety of metallizations have been investigated on p-GaN besides the standard Ni/Au\(^{(2-7)}\) including Ni\(^{(4,5,8)}\) Au\(^{(4,7,9,10)}\) Pd\(^{(4)}\) Pd/Au\(^{(11,12)}\) Pt/Au\(^{(6)}\) Au/Mg/Au\(^{(9,13)}\) Au/C/Ni\(^{(14)}\) Ni/Cr/Au\(^{(12,15)}\) and Pd/Pt/Au.\(^{(6)}\) This area has been reviewed recently by Mohney and Lau\(^{(16)}\) and by Liu and Lau.\(^{(17)}\) Typically Ni, Pd or Pt is the metal in direct contact with the GaN, and the structure is annealed at 400 - 750 °C. This produces contact resistances in the \(10^1 - 10^3\) \(\Omega\)-cm\(^2\) range. For higher temperatures severe degradation in contact morphology is observed, usually resulting from the formation of the metal gallides.\(^{(16)}\)
For n-type ohmic contacts, the most popular metallization schemes have been those based on Al/Ti/n-GaN, often with overlayers of Au/Ni.\(^\text{(16,17)}\) It is believed that diffusion of Al to the metal/GaN interface is a critical step in forming the lowest specific contact resistance, and that TiN formation produces a high concentration of nitrogen vacancies that lead to \(n^+\) doping level and lower \(R_c\) values.\(^\text{(17)}\) We have previously reported that both W and WSi\(_x\) on \(n^+\) epi GaN layers (\(n \sim 10^{19} \text{ cm}^{-3}\)) produce reasonable contacts (\(R_c \sim 8 \times 10^{-5} \Omega\cdot\text{cm}^2\)), but extremely stable behavior\(^\text{(18,19)}\) - annealing at 1000 °C led to a shallow reacted region of \(\leq 100 \text{ Å}\), and in junction field-effect transistor structures these contacts can withstand implant activation anneals at 1100 °C.\(^\text{(20)}\)

In this paper we report an investigation of W and WSi\(_x\) contacts on p-GaN, and of W on Si-implanted, \(n^+\) GaN. The annealing temperature dependence of the current - voltage (I-V) characteristics and contact morphology have been examined over the temperature range 300 - 1000 °C.

II. EXPERIMENTAL

P-type (\(N_A = 10^{18} \text{ cm}^{-3}\)), Mg-doped GaN layers 1 \(\mu\)m thick were grown on \(\text{Al}_2\text{O}_3\) substrates by Molecular Beam Epitaxy using solid Ga and rf plasma-activated \(\text{N}_2\).\(^\text{(21)}\) Strong cathodoluminescence was observed at \(~385 \text{ nm}\), with very little deep level emission. Undoped GaN layers \(~3 \mu\text{m}\) thick were grown on \(\text{Al}_2\text{O}_3\) by Metal Organic Chemical Vapor Deposition. These samples were implanted with 100 keV \(\text{Si}^+\) ions at a dose of \(5 \times 10^{15} \text{ cm}^{-2}\), and annealed with AlN caps in place to 1400 °C for 10 secs.\(^\text{(22)}\) This produced a peak \(n\)-type doping concentration of \(~5 \times 10^{20} \text{ cm}^{-3}\). W or WSi\(_{0.45}\) layers \(~1000 \text{ Å}\) thick were deposited using an MRC501 sputtering system. The sample position
was biased at 90 V with respect to the Ar discharge. Prior to sputtering, the native oxide was removed in a 20:1 H$_2$O:NH$_4$OH solution. Transmission line patterns were defined by dry etching the exposed metal with SF$_6$/Ar, and forming mesas around the contact pads using BCl$_3$/N$_2$ dry etching to confine the current flow. For comparison, on the p-GaN, Au(1000 Å)/Ni(500 Å) was deposited by e-beam evaporation, defined by lift-off and mesas formed by dry etching. Both n- and p-type samples were annealed for 60 secs (in some experiments this was varied from 30 - 300 secs) at 300 - 1000 °C under flowing N$_2$.

III. RESULTS AND DISCUSSION

A. p-GaN

From Fermi - Dirac statistics we can calculate the Fermi level position $E_F$ for p-GaN containing $10^{18}$ acceptors cm$^{-3}$ as a function of absolute temperature $T$, from

$$
\frac{1}{1 + 2 \exp((E_a - E_F)/kT)} = N_V \exp(-(E_F - E_V)/kT)
$$

where $N_A$ is the acceptor concentration, $E_a = 171$ meV for Mg in GaN and $N_V$ is the valence band density of states. Using this relation, we calculated the ionization efficiency for Mg as a function of sample temperature, as shown in Figure 1. Since the hole concentration in the p-GaN will increase rapidly with temperature, we would expect better ohmic contact properties.

Figure 2 shows annealing temperature dependence of the I-V characteristics of the Ni/Au, W and WSi on p-GaN, with the measurements made at 25 °C in all cases. Note that for the optimum anneal temperatures (700 °C for Ni/Au and W, and 800 °C for WSi$_3$), the contacts are not ohmic, but are more accurately described as leaky Schottky...
diodes. In the case of W and WSi, we assume that annealing above the optimum temperature produces loss of N\textsubscript{2} and poorer contact properties.

The contact morphology on the W and WSi metallization remained featureless to the highest temperature we investigated. This is in sharp contrast to the case of Ni/Au, as shown in Figure 3. For the latter metallization, islanding is quite severe after 700 °C annealing due to reaction of the Ni with the GaN.\textsuperscript{(23-25)}

From the earlier discussion, we would expect the contact properties to improve at elevated temperatures because of the increased hole density and more efficient thermionic hole emission across the metal - GaN interface. Figure 4 shows the I-V characteristics for the 700 °C (Ni/Au and W) or 800 °C(WSi) annealed samples, as a function of the measurement temperature(25 - 300 °C). For the Ni/Au, the contacts become ohmic at \textgtr 200 °C, while for W and WSi this occurs at 300 °C. Table I shows the R\textsubscript{c} values at 300 °C are 9.2×10\textsuperscript{-2} Ω-cm\textsuperscript{2} (Ni/Au), 6.8×10\textsuperscript{-2} Ω-cm\textsuperscript{2} (W) and 2.6×10\textsuperscript{-2} Ω-cm\textsuperscript{2} (WSi). The TLM measurements showed that the substrate sheet resistance is reduced from 1.39×10\textsuperscript{4} Ω/□ at 200 °C, to 8470 Ω/□ at 250 °C and 4600 Ω/□ at 300 °C, indicating that the increased hole concentration plays a major role in decreasing R\textsubscript{c}.

There was not a strong dependence of the room temperature I-V characteristics on annealing time. An example is shown in Figure 5 for W/p-GaN, annealed at 700 °C. There is little change in the characteristics for 30 - 120 secs, but the contacts become more rectifying for longer times.

B. n-GaN

Figure 6 shows the annealing temperature dependence of R\textsubscript{c} for W contacts on Si-implanted GaN. The specific contact resistance improves with annealing up to \textless 950 °C,
which appears to correspond to the region where the $\beta$-$W_2N$ interfacial phase is formed. Cole et al. reported that W and WSi contacts on GaN annealed in the range 750-850 °C showed the minimum degree of metal protrusion in the interfacial regions devoid of the $\beta$-$W_2N$ phase, whereas at lower annealing temperatures the horizontal spatial extent of this phase was smaller and allowed more protrusions to develop. The excellent structural stability of the W on GaN is shown in the SEM micrographs of Figure 7, where a sharp interface is retained after 750 °C annealing.

IV. SUMMARY AND CONCLUSIONS

One of the emerging applications for GaN is in ultra-high power electronic switches, where thermal stability of the contact metallization will be of paramount importance. Tungsten-based contacts on both n- and p-type GaN offer superior thermal stability to the standard metalization used in photonic devices, Ti/Al and Ni/Au, respectively.

ACKNOWLEDGEMENTS

The work at UF is partially supported by a DARPA/EPRI grant (E. R. Brown/J. Melcher) and by an NSF grant (DMR-9732865) monitored by L. D. Hess. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin company, for the US Department of Energy under contract No. DEAC04-94AL85000.
References


Figure Captions

Figure 1. Ionization efficiency of Mg acceptors in GaN, and Fermi level position for GaN containing $10^{18}$ cm$^{-3}$ Mg acceptors, as a function of temperature.

Figure 2. Annealing temperature dependence of I-V characteristics of WSi, W and Ni/Au contacts on p-GaN (60 sec anneal times).

Figure 3. SEM micrographs of Ni/Au contacts on p-GaN after 60 secs anneals at either 400 °C (top left) or 700 °C (top right), or W contacts after similar annealing at 400 °C (bottom left) or 900 °C (bottom right).

Figure 4. Measurement temperature dependence of I-V characteristics of Ni/Au, W or WSi$_x$ contacts on p-GaN.

Figure 5. Annealing time dependence at 700 °C of I-V characteristics from W contacts on p-GaN.

Figure 6. Annealing temperature dependence of $R_c$ for W contacts on Si-implanted GaN.

Figure 7. SEM micrographs of W contacts on Si-implanted GaN after annealing at 750 °C.
Table I. Temperature-dependent contact data for p-GaN.

<table>
<thead>
<tr>
<th>Contact</th>
<th>Measurement temperature (°C)</th>
<th>Specific contact resistance (Ω·cm²)</th>
<th>Contact resistivity (Ω·mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/Au</td>
<td>200</td>
<td>0.125</td>
<td>415.7</td>
</tr>
<tr>
<td>Ni/Au</td>
<td>250</td>
<td>0.121</td>
<td>319.5</td>
</tr>
<tr>
<td>Ni/Au</td>
<td>300</td>
<td>0.092</td>
<td>205.9</td>
</tr>
<tr>
<td>W</td>
<td>300</td>
<td>0.682</td>
<td>758.4</td>
</tr>
<tr>
<td>WSi</td>
<td>300</td>
<td>0.026</td>
<td>1728.3</td>
</tr>
</tbody>
</table>
Mg in GaN $1 \times 10^{18}$ cm$^{-3}$

$E_A - E_V = 171$ meV
Au/Ni/p-GaN

W/p-GaN

WSi/p-GaN

Voltage (V)

Current (A)
Au/Ni/p-GaN

W/p-GaN

WSi/p-GaN
700 °C annealed

- • 30 s
- ○ 1 min
- △ 2 min
- ▼ 3 min
- ■ 5 min

W/p-GaN

Voltage (V)

Current (A)

-2 x 10^-5
-1 x 10^-5
0
1 x 10^-5
2 x 10^-5
2
1
0
-1
-2
W/Si-implanted GaN
30 second anneals

$R_c$ (ohm-cm$^2$)

Temperature (°C)