Metallization scheme for highly low-resistance, transparent, and thermally stable Ohmic contacts to p-GaN

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We report on a promising metallization scheme for high-quality Ohmic contacts to surface-treated p-GaN: Mg (2–3 × 1017 cm–3). It is shown that the as-deposited Pt/Ru contact produces a specific contact resistance of 7.8(2.2) × 10–4 Ω cm2. However, annealing of the contact at 600 °C for 2 min results in a resistance of 2.2(2.0) × 10–4 Ω cm2. It is also shown that the light transmittance of the annealed contact is 87.3% at 470 nm. Furthermore, the surface of the contact annealed at 600 °C for 30 min is found to be very smooth with a rms roughness of 0.8 nm. These results strongly indicate that the Pt/Ru can be a suitable scheme for the fabrication of high-performance laser diodes or other devices. © 2000 American Institute of Physics. [S0003-6951(00)00220-5]

Due to the successful development of GaN-based devices, such as blue light-emitting diodes, metal–semiconductor field-effect transistors, high electron mobility transistors, and laser diodes (LDs),1–5 the fabrication of high-quality Ohmic contacts with low resistance, thermal stability, and high transparency, is of great technological importance. In fact, the high contact resistance of p-GaN is one of the major problems in the realization of long-lifetime cw operation of GaN-based optical devices. It is, therefore, crucial to develop high-quality Ohmic contacts on p-GaN to enhance device performance.

For Ohmic contacts to p-GaN, there are two main obstacles, namely, (i) a difficulty in growing heavily doped p-GaN (>1018 cm–3); and (ii) the absence of appropriate metals which have a work function larger than that of p-GaN (6.5 eV).6 Most of the contact metallization schemes for p-GaN have been reported to Au-based schemes such as Ni/Au,7–9 Pt/Au,10 Cr/Au,11 Pd/Au,11 Ni/Cr/Au,12 Ni/pt/Au,13–14 and Pt/Ni/Au.15 However, Au-based contacts generally have poor thermal stability, leading to poor device reliability. Several groups have attempted to achieve thermally stable and low-resistance Ohmic contacts on p-GaN using Au-free contact schemes. Cao et al.16 showed that thermally stable Ohmic contacts to p-GaN are obtained using W and WSi2 schemes. However, the W-based contacts produced rather a high contact resistance of ∼10–2 Ω cm2, indicating that these schemes are not suitable for the application of LDs. Suzuki et al.,17 investigating Ta/Ti Ohmic contacts to p-GaN (N a~7 × 1017 cm–3), demonstrated that the contacts are Ohmic with a contact resistance of 3 × 10–2 Ω cm2 when annealed at 800 °C for 20 min in vacuum (∼4 × 10–4 Pa). However, the contacts were found to experience atmospheric degradation.

Native oxide on p-GaN is detrimental to Ohmic properties. It is, therefore, important to remove the native oxide thoroughly for achieving low resistance and thermally stable Ohmic contacts. In our previous work,18 we showed that the two-step surface treatment effectively removes the native oxide and increases a near-surface carrier concentration. In this letter, we report on a metallization scheme for the formation of low resistance and highly transparent Ohmic contacts to p-GaN, which was two-step surface treated using a buffered oxide etch (BOE).

Metalorganic chemical-vapor deposition (Emcore DGA125TM) was used to grow a 2-μm-thick unintentionally doped GaN layer on a (0001) sapphire substrate. This was followed by the growth of 0.5-μm-thick p-GaN:Mg (2–3 × 1017 cm–3). The GaN layers were ultrasonically degreased with trichloroethylene, acetone, methanol, and ethanol for 5 min in each step, and then rinsed with deionized water. Prior to the fabrication of transmission line method (TLM) patterns, mesa structures were patterned by inductively coupled plasma etching (Oxford Plasma 100) using Cl2/Ar/H2. The mesa-patterned layers were then ultrasonically boiled in BOE for 20 min. After the chemical treatment, the TLM patterns were defined by a photolithographic technique. The pads were 100×200 μm2 in size and the spacings between the pads were 5, 10, 15, 20, 25, and 35 μm. Prior to deposition of the metal films, the TLM-patterned layers were dipped into BOE for 30 s. The Pt (20 nm)/Ru (50 nm) films were then deposited on the p-GaN by electron-beam evaporation (PLS 500 model). The sample was then heat treated under a N2 ambient at a temperature of 600 °C for 2 min in the rapid thermal anneal system (AST). Current–voltage (I–V) measurements were carried out using a parameter analyzer (HP 4155A). To investigate the extent of interdiffusion between the metal layers and the p-GaN, Auger electron spectroscopy (AES) was performed using a PHI 670 Auger microscope with an electron beam of 10 keV and 0.0236 μA. X-ray diffraction (XRD) measurement (using Cu Kα radiation) was carried out using a Rigaku diffractometer to investigate interfacial reaction products formed during annealing. Light transmittance was measured using an UV-visible spectrometer (UVIKON spectrometer 922).

Figure 1 shows I–V characteristics for the Pt/Ru contacts on p-GaN. The as-deposited contact exhibits near-linear I–V behavior. The contact annealed at 600 °C, however, shows a linear characteristic. Specific contact resistances were measured from plots of the measured resistances versus the spacings between the TLM pads. The least-square
method was used to fit a straight line to the experimental data. The specific contact resistance was measured to be $7.8(\pm 2.2) \times 10^{-4} \, \Omega \, \text{cm}^2$ for the as-deposited contacts and $2.2(\pm 2.0) \times 10^{-6} \, \Omega \, \text{cm}^2$ for the $600 \, ^\circ\text{C}$ contacts. It is noteworthy that the annealing results in a drastic reduction in the specific contact resistances by more than two orders of magnitude.

The low specific contact resistance observed in the as-deposited sample can be attributed to the combined effects of the high work function of Pt in contact with $p$-GaN, the effective removal of the native oxide on the surface, and an increase in the carrier concentration near the surface of the $p$-GaN layers (due to the surface treatment). The further improvement in the contact resistance of the $600 \, ^\circ\text{C}$ sample may be related to additional factors, such as the formation of interfacial reaction products and an increase in the contact area between the metal films and the GaN due to the interfacial reactions. As will be described later.

Figure 2 shows Auger depth profiles of the Pt/Ru contacts on $p$-GaN. As for the as-deposited contact, there is no obvious evidence for interdiffusion between the metal layers and the GaN, Fig. 2(a). However, for the $600 \, ^\circ\text{C}$ contact [Fig. 2(b)], a small amount of Ga diffuses into the Pt layer, being indicative of the possible formation of Ga–Pt reaction products. However, there is no clear evidence for the outdiffusion of nitrogen into the metal layers. This indicates that the Pt layer (and/or Ga–Pt alloy layers) on the GaN may prevent the formation of nitrogen vacancies which are detrimental to $p$-type Ohmic contact performance. It is also worth noting that there is no evidence for the presence of oxygen at the interfaces between the metal layers and the GaN, as is evident from the Auger spectral results of the as-deposited and annealed contacts [Figs. 2(c) and 2(d), respectively]. This indicates that the native oxide is effectively removed by the surface treatment.

To investigate the interfacial reaction products formed during the thermal annealing process, XRD analysis was performed on the contact annealed at $600 \, ^\circ\text{C}$ for 2 min (Fig. 3). The XRD plot shows the characteristic diffraction peaks of Pt, Ru, Al$_2$O$_3$, and GaN. In addition, as expected from the AES result [Fig. 2(b)], there are extra peaks, being indicative of the formation of a new interfacial phase. This phase is identified to be Ga$_3$Pt$_5$: (201) $(2\theta = 31.4^\circ)$, (022) $(52.9^\circ)$, and (511) $(64.2^\circ)$.

The surface morphology of the as-deposited and annealed Pt/Ru contacts was characterized using atomic-force microscopy (AFM) and scanning electron microscopy (SEM). The AFM and SEM results show that the surfaces of the as-deposited and $600 \, ^\circ\text{C}$ contacts are very smooth with a rms roughness of 0.9 nm. It is worth noting that annealing of the contact at $600 \, ^\circ\text{C}$ for 30 min causes no degradation in the surface morphology; the surface is remarkably smooth with a rms roughness of 0.8 nm. In addition, electrical measurements show that the prolonged annealing does not seriously affect the electrical property of the contacts. For example, the sample annealed for 30 min produces a contact resistance...
of 3.8(±2.0)×10⁻⁶ Ω cm², which is comparable to that of the sample annealed for 2 min [2.2(±2.0)×10⁻⁶ Ω cm²]. These AFM and electrical results indicate that the Pt/Ru scheme does not critically suffer from thermal degradation during annealing at 600 °C.

Based on the results obtained using the XRD and AES measurements, the thermal stability of the Pt/Ru contacts may be explained as follows. First, the stability may be due to the effective removal of a native oxide layer on GaN during annealing at 600 °C. These AFM and electrical results indicate that the Pt/Ru scheme does not critically suffer from thermal degradation during annealing at 600 °C.

In summary, we report a highly promising Pt/Ru Ohmic contact on p-GaN:Mg (2–3×10¹⁷ cm⁻³), which was surface treated using BOE. Both the as-deposited and annealed contacts showed high-quality Ohmic behavior with very low resistance, thermal stability, and high light transmittance. These results strongly indicate that Pt/Ru can be a suitable metallization scheme for the fabrication of high-performance LDs or other devices.

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