Highly low resistance and transparent Ni/ZnO ohmic contacts to $p$-type GaN

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We report on a promising Ni (5 nm)/Al-doped ZnO (AZO) (450 nm) metallization scheme for low resistance and transparent ohmic contacts to $p$-GaN ($5 \times 10^{17}$ cm$^{-3}$). It is shown that the as-deposited Ni/AZO contact shows a nonohmic characteristic due to the insulating nature of the as-deposited AZO. However, annealing the contacts at 450 and 550 $^\circ$C for 2 min in air ambient results in linear current–voltage characteristics, giving a specific contact resistance of $1.01 \times 10^{-5}$ and $8.46 \times 10^{-6}$ $\Omega$ cm$^2$, respectively. It is further shown that annealing the contact at 550 $^\circ$C for 5 min produces a specific contact resistance of $6.23 \times 10^{-6}$ $\Omega$ cm$^2$. The light transmittance of the contacts annealed at 550 $^\circ$C for 2 min is measured to be higher than 76% at wavelengths in the range of 400–550 nm. It is shown that the Ni/AZO contact could be a suitable scheme for high-performance optical devices. © 2003 American Institute of Physics.

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III–V nitrides based light emitting diodes (LEDs) operating in the green, blue, and ultraviolet range of optical spectra are of great technological importance. In order to further improve such devices, it is essential to develop highly reliable ohmic contacts to $p$-GaN, especially for high power LED operation. Thus, to fabricate high-quality ohmic contacts to $p$-GaN, various metallization schemes, such as Ni/Au, Pt/Ni/Au, Ni/Pt/Au, Ti/Pt/Au, Pd/Au, and Pt/Au, have been extensively investigated. Ho et al., investigating Ni/Au contacts to $p$-GaN, reported that the contact schemes can produce specific contact resistances in the range of $10^{-5}–10^{-6}$ $\Omega$ cm$^2$ when annealed at temperatures of 400–600 $^\circ$C in air ambient. The high conductivity and transparency of the oxidized Ni/Au contacts made it possible for a current spreading ohmic contact system for GaN-based LEDs. The main concept of the oxidized Ni/Au scheme is to form $p$-type NiO (with Ni vacancies and/or oxygen interstitials) to be in contact with $p$-GaN. However, Au-based contacts generally have poor thermal stability, leading to poor device reliability. Furthermore, the optical and electrical properties of the Au-based contacts have shown to be strongly dependent on the thickness of the Au layer. Thus, in order to obtain reliable ohmic contacts, transparent conducting oxides, such as indium tin oxide (ITO), have been employed. Horng et al., investigating low resistance and transparent Ni/ITO contacts to $p$-type GaN, showed that the use of ITO (250 nm) is fairly effective in improving the electrical and optical properties. They attributed the improved ohmic properties to the formation of NiO phase and the diffusion of indium into GaN. In this work, we investigate the Ni/ZnO scheme for use in fabricating low resistance and transparent ohmic contacts to $p$-GaN ($5 \times 10^{17}$ cm$^{-3}$). It is shown that the Ni/ZnO contacts yield very low specific contact resistances in the range of $10^{-5}–10^{-6}$ $\Omega$ cm$^2$ when annealed at 450 and 550 $^\circ$C, and transparency of 76%–83% at wavelengths of 400–550 nm.

Metalorganic chemical vapor deposition was used to grow a 2.0-m-thick unintentionally doped GaN layer on a (0001) sapphire substrate, on which a 1.0 $\mu$m-thick $p$-GaN:Mg layer ($n_p = 5 \times 10^{17}$ cm$^{-3}$) was grown. The $p$-GaN layer was ultrasonically degreased with trichloroethylene, acetone, methanol, and ethanol for 5 min in each step, and then rinsed with de-ionized water. After the buffered oxide etch treatment, circular transmission line model (CTLM) patterns were defined by the standard photolithographic technique to measure specific contact resistance. The outer dot radius was 75 $\mu$m and the spacings between the inner and the outer radii were varied from 4 to 25 $\mu$m. Ni (5 nm)/Al-doped ZnO (AZO) (450 nm) films were then deposited on the GaN by an electron beam vapor evaporation (PLS 500 model) and a sputtering system, respectively. Some of the samples were subsequently annealed at 450 and 550 $^\circ$C for 2–5 min under $N_2$ and air ambient in a rapid thermal annealing system. $I$–$V$ measurements were performed using a parameter analyzer (HP 4155A). Auger electron spectroscopy (AES) was carried out using a PHI 670 Auger microscope with an electron beam of 10 keV and 0.0236 $\mu$A. X-ray photoemission spectroscopy (XPS) (PHI 5200 model) was performed using an Al$K_{\alpha}$ x-ray source in an UVH system with a chamber base pressure of $\sim 10^{-10}$ Torr. The Ni/AZO film was also deposited onto quartz substrate and subsequently annealed at the same condition as those for $I$–$V$ measurements to determine light transmittance.

Figure 1 shows $I$–$V$ characteristics for the Ni/AZO contacts on $p$-GaN after annealing at temperatures of 450 and 550 $^\circ$C for 2 min in air ambient, measured between ohmic pads with a spacing of 8 $\mu$m. Due to the insulating nature of the as-deposited AZO, the as-deposited Ni/AZO contact revealed rectifying $I$–$V$ behavior. Annealing the contacts, however, results in linear $I$–$V$ characteristics, indicating the
formation of high-quality ohmic contacts. Specific contact resistance was determined from plots of the measured total resistance versus the spacings between the CTLM pads. The least square curve-fitting method was used to fit a straight line to the experimental data. The specific contact resistance was measured to be $1.01 \times 10^{-5}$ and $8.46 \times 10^{-6}$ $\Omega \text{cm}^2$ for contacts annealed at 450 and 550 °C, respectively. It is worth noting that annealing causes a dramatic reduction in the specific contact resistance. These values are lower than those previously reported for thick Ni/Au ohmic contacts to p-GaN.4

Figure 2 shows the $I–V$ characteristics of the Ni/AZO contacts which were annealed at 550 °C for 5 min in air and N$_2$ ambient. It is evident that annealing in air ambient shows much better $I–V$ characteristic, compared to that annealed in N$_2$ ambient. The specific contact resistance of the air-annealed sample was measured to be $6.23 \times 10^{-6}$ $\Omega \text{cm}^2$, which is lower than that of the 2 min annealed sample (Fig. 1). Similar ambient dependence of $I–V$ characteristics was observed in Ni/Au and Ni/ITO contacts by Ho et al.4 and Horng et al.,14 respectively.

In order to investigate interfacial reactions between the Ni and the AZO films, XPS examination was made of the as-deposited and annealed samples. The air-annealed Ni/AZO contact (550 °C for 2 min) produced a specific contact resistance of $8.46 \times 10^{-6}$ $\Omega \text{cm}^2$. Figure 3 shows the Ni $2p$ core level peaks for the AZO/Ni/p-GaN interfaces before and after annealing. For the as-deposited sample, the Ni $2p$ core level is slightly asymmetric with a weak shoulder on the high-energy side of the main peak. This indicates the presence of a small amount of NiO, Fig. 3(a). For the annealed sample, the Ni $2p$ core level is shifted toward the high-energy side. It is evident that the Ni $2p$ core level peaks corresponding to NiO and Ni–Ga phases are present,15 Fig. 3(b). It is known that the Ni $2p$ core level peak is expected to be at 852.6 eV for pure Ni, at 853.5 eV for Ni–oxide, and at 852.9 eV for the Ni–Ga compound.17 Thus, a comparison shows that for the annealed sample, a Ni–Ga phase is also formed in addition to NiO. However, the Ni–Ga interfacial phase may be very thin and discontinuous. Structural details of interfacial reactions between the Ni/AZO and the GaN as a function of annealing temperature and time are under investigation.

To investigate the extent of interdiffusion between the metal films and the p-GaN, AES analysis was performed, Fig. 4. For the as-deposited sample (not shown), there is no obvious evidence for interdiffusion between the metal films and the GaN. For the sample annealed at 550 °C for 2 min in air ambient, a small amount of Ni diffused into the p-GaN, indicating the possibility that Ni reacts with Ga to form compound phases during annealing, as expected from the XPS result (Fig. 3).

The light transmittance of the annealed Ni (5 nm)/AZO (450 nm) contact is shown in the inset of Fig. 4. The transmittance was measured to be 76% (at 470 nm). This is lower than the highest value (88%) reported for a very thin Ni (2 nm)/Au (6 nm) contacts to p-GaN.5 The Ni/Au contacts, however, exhibited a poor specific contact resistance of $2.4 \times 10^{-2}$ $\Omega \text{cm}^2$, which is far higher than that of the present Ni/AZO contact (Fig. 1). Furthermore, our preliminary results showed that the optimization of the film thickness and annealing temperature leads to the better electrical and optical properties of the Ni/AZO contacts.

It was shown that the electrical properties of the Ni/AZO contacts are dramatically improved upon annealing. Based...
on the XPS and AES results, the annealing dependence behavior could be explained as follows. First, the improvement could be attributed to the formation of highly conductive NiO, which has $p$-type conductivity, as well described by Horng et al.\textsuperscript{14} Second, it might be associated with the presence of unevenly distributed interfacial gallide phase,\textsuperscript{18,19} as noted from the AES and XPS results. The formation of gallide phases causes Ga vacancies to be generated near the GaN surface, which are known to serve as deep acceptors.\textsuperscript{20} Finally, the reduced contact resistance may also be related to an increase in the contact area between the contact schemes and the GaN due to the interfacial reactions.

To summarize, we investigated the Ni/Al-doped ZnO (AZO) schemes for use in producing low resistance and transparent ohmic contacts to $p$-GaN ($5 \times 10^{17}$ cm$^{-3}$). It was shown that the contacts annealed at 450 and 550 °C for 2 min in air ambient results in a very low specific contact resistance of $1.01 \times 10^{-5}$ and $8.46 \times 10^{-6}$ Ω cm$^2$, respectively. The light transmittance of the contacts annealed at 550 °C for 2 min was measured to be higher than 76% at wavelengths of 400–550 nm. Based on the XPS and AES results, ohmic formation mechanisms for the Ni/AZO contacts were briefly described.

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