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Low-resistivity and transparent indium-oxide-doped ZnO ohmic contact to *p*-type GaN

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We report on the indium-oxide-doped ZnO (IZO) transparent ohmic contact to the *p*-GaN. The IZO transparent ohmic contact layer was deposited on *p*-GaN by e-beam evaporation. The transmittance of an IZO film with a thickness of 250 nm was 84%–92% for the light in the wavelength range of 400 and 600 nm. In addition, the IZO contact film yielded a low specific contact resistance of $3.4\times10^{-4}\ \Omega\ \mathrm{cm}^2$ on *p*-GaN when annealed at 600 °C for 5 min under a nitrogen ambient. Auger electron spectroscopy and x-ray photoemission spectroscopy analyses of the IZO and *p*-GaN interface indicated that Ga atoms had out-diffused and an InN phase was formed at the interface region after the thermal annealing process, resulting in a decrease in contact resistance. The light output power of a light-emitting diode (LED) with an IZO ohmic contact layer was increased by 34% at 83 mW of electrical input power compared to that of a LED with a Ni/Au ohmic contact layer. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1826231]

As the brightness of GaN-based light-emitting diodes (LEDs) has increased, GaN-based compound semiconductors have recently attracted considerable interest for their application fields such as displays, traffic signals, backlight, and exterior lighting.[1,2] The fabrication of high-quality ohmic contacts with a low resistance, high thermal stability, and high transparency, is of great importance in improving the efficiency of the light output of LEDs. Thin film metals with large work function have been widely studied as contact materials to *p*-GaN in LEDs. The oxidation of a Ni/Au thin film is commonly used as an ohmic contact to *p*-GaN.[3,4] However, LEDs using this contact material suffer from low external quantum efficiency due to the low transmittance of the metal layers for the emitted light. Therefore, in order to improve the light extraction efficiency of LEDs, transparent ohmic films need to be extensively investigated. Recently, indium tin oxide (ITO) films on *p*-GaN were employed as a transparent ohmic layer but they showed Schottky behavior even after thermal annealing.[5] Insertion of a Ni layer between the ITO and *p*-GaN was, however, very effective in improving the electrical and optical properties.[6,7]

The indium-oxide-doped ZnO (IZO) is one of the transparent conducting oxides which have high transparency and good electrical conductivity. Even though the work function of IZO is decreased slightly with increasing doping concentrations of the In_2O_3 in the ZnO, the work function of the IZO is still higher than that of an ITO by 0.6 eV.[8,9] In this study, we investigated an IZO scheme for a transparent and low resistance contact layer on *p*-GaN ($3\times10^{17}\ \mathrm{cm}^{-3}$). The results show that the IZO contact yields a very low specific contact resistance of $3.4\times10^{-4}\ \Omega\ \mathrm{cm}^2$ when annealed at 600 °C for 5 min under a nitrogen ambient, and has a transparency of 84%–92% at wavelengths in the range of 400–600 nm. In addition, the light output power of the LED with an IZO *p* contact was improved by 34% compared to that of a LED using a Ni/Au film at 83 mW input power.

A *p*-GaN layer with a thickness of 1.2 μm was grown on a *c*-plane sapphire substrate by metalorganic chemical vapor deposition and showed a hole concentration of $3\times10^{17}\ \mathrm{cm}^{-3}$ and hole mobility of $7\ \mathrm{cm}^2/\mathrm{V\,s}$. An IZO layer with a thickness of 250 nm was deposited on the *p*-GaN layer by e-beam evaporation using a ZnO source containing 3 wt% In_2O_3. The samples were then annealed at 600 °C under a nitrogen ambient in a rapid thermal annealing system (AST™). The specific contact resistance was measured by means of circular transmission line method (*c*-TLM) patterns, which were formed by photolithography and lift-off techniques.[10] The inner dot radius was 200 μm and the spacing between the inner and the outer radii varied from 5 to 50 μm. To characterize the extent of interdiffusion between the IZO layer and the *p*-GaN film, Auger electron spectroscopy (AES) analysis was performed using a PHI 670 Auger microscope with an electron beam energy of 10 keV and current of 0.029 μA. X-ray photoemission spectroscopy (XPS) (PHI 5200 model) study was also carried out using an Al $K\alpha$ x-ray source.

Figure 1 shows current–voltage characteristics of the IZO contacts to *p*-GaN. When the IZO sample was annealed at 600 °C for 1 min, the IZO contact resistance was improved compared to that of the as-deposited sample. An IZO contact annealed at 600 °C for 5 min showed a great improvement in $I-V$ characteristics. Specific contact resistances were calculated from plots of the measured resistances versus the spacings between the c-TLM pads. The specific contact resistance was determined to be 8.3×10^{-2}, and $3.4\times10^{-4}\ \Omega\ \mathrm{cm}^2$ for contacts annealed at 600 °C under a nitrogen ambient for 1 and 5 min, respectively. It is worth noting that a longer thermal annealing process leads to a reduction in the specific contact resistance by more than two orders of magnitude compared to that of the as-deposited contact. We also measured the light transmittance of a Ni/Au and an IZO thin film on *p*-GaN by means of a UV/visible spectrometer in the light in the visible region. The *p*-GaN sample was

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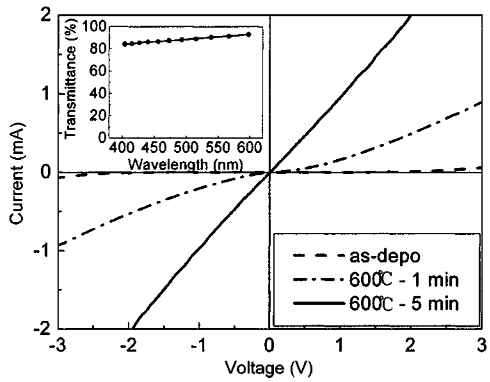

FIG. 1. $I-V$ characteristics of the IZO contacts to p-GaN before and after annealing process. The inset shows the light transmittance for an IZO sample annealed at 600 °C for 5 min.

used as a reference to calibrate the light transmittance measurement. The light transmittance was found to be 84%–92% for an annealed IZO (250 nm) contact in the wavelength range of 400 and 600 nm, as shown in the inset of Fig. 1. The low specific contact resistance and high transmittance of the annealed IZO contacts to p-GaN suggest that annealed IZO would be suitable for use as a transparent contact to p-GaN of a highly efficient GaN-based LED.

The in-depth Auger profiles of the as-deposited and annealed IZO contact layers on p-GaN were examined and these data are as shown in Fig. 2. Figure 2(a) shows that no interdiffusion occurs between the IZO thin film and p-GaN layer for an as-deposited sample and that the In atoms are uniformly distributed in the IZO thin film. On the other hand,

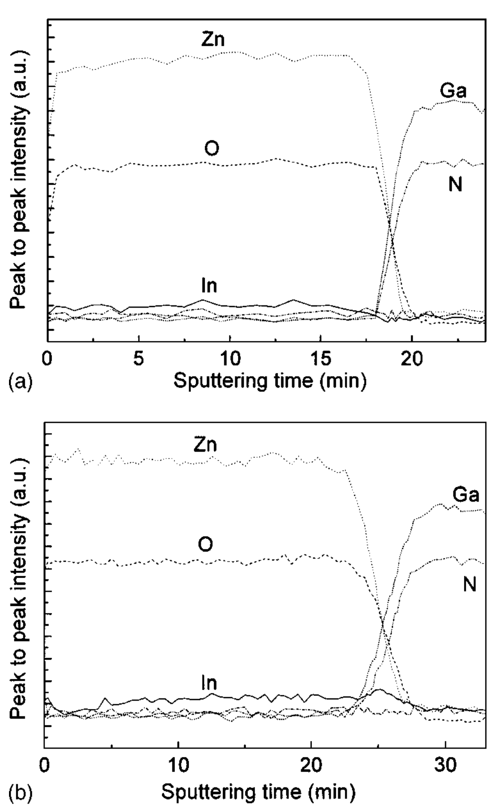

FIG. 2. AES depth profile of the IZO contacts to p-GaN: (a) for the as-deposited sample, the layers of IZO and p-GaN are well defined indicating no significant interdiffusion between them, (b) for the annealed sample, In atoms have accumulated near the interface, and a diffusion tail for Ga atom is observed.

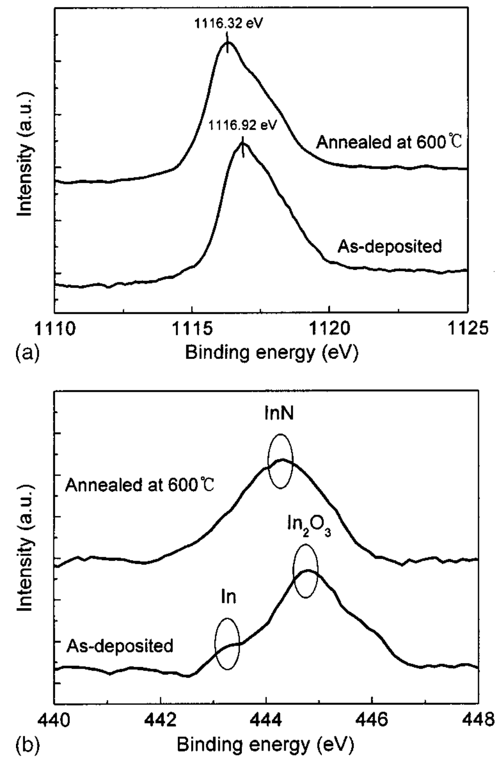

FIG. 3. XPS spectra of (a) In 3d core levels of IZO film/p-GaN interfaces before and after annealing process, (b) Ga 2p core levels of IZO film/p-GaN interfaces before and after annealing.

when annealed at 600 °C, a small amount of Ga atoms diffuse into the IZO thin film and In atoms accumulate at the interface between the IZO film and p-GaN layer, as shown in Fig. 2(b). These results indicate that the thermal annealing process used in preparing an IZO thin film on a p-GaN layer can produce Ga vacancies near the surface of the p-GaN, which would result in an increase in hole concentration and a decrease in contact resistance, because the out-diffusion of Ga atoms from p-GaN could create deep acceptor-like Ga vacancies near the p-GaN surface region.[11,12] In addition, In atoms that accumulate at the interface may increase the carrier concentration in the ZnO film near the interface.[8,9]

To characterize the chemical bonding state of Ga and In, XPS analysis of an IZO contact to p-GaN was adopted, both before and after the annealing process at 600 °C. Figure 3(a) shows the Ga 2p core levels at the IZO/p-GaN interfaces before and after the thermal annealing process. It is evident that the Ga 2p core level for the annealed sample shifted toward the lower energy side by 0.6 eV compared to that of the as-deposited sample. This could indicate a reduction in the Schottky barrier height for hole injection from metal to p-type GaN, resulting in a low specific contact resistance.[13] Figure 3(b) shows the In 3d core level peaks at the IZO/p-GaN interfaces before and after annealing. The In 3d core level peak is 443.7 eV for pure In, 444.3 eV for In–N phase, and 444.6 eV for In–O phase.[14,15] For an as-deposited sample, the In 3d core level indicates the presence of both In_2O_3 and a small amount of In metal. For the annealed sample, however, the In 3d core level at the interface is shifted toward the lower energy side, indicating that an In–N phase is formed at the interface of the IZO and p-GaN. The larger lattice mismatch between InN and GaN films may cause the strain induced and spontaneous polarization fields in InN phase and p-GaN, leading to the interfacial hole

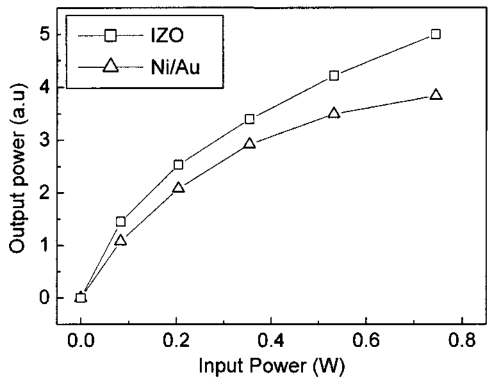

FIG. 4. Power efficiency (output power/input power) for LEDs with an IZO thin film as a transparent layer and a conventional LED. The light output power for LED with IZO film was increased by 34% at 83 mW of input power compared to that of the LED with a Ni/Au layer.

accumulation.[16,17] Therefore, the formation of an In–N phase seems to reduce the contact resistance by increasing the hole concentration near the interface and decreasing the depletion width of the Schottky junction, which enhance the tunneling transport from the IZO to the p-GaN layer.

GaN LEDs with a chip size of 300×300 μm were fabricated by using an IZO film and a Ni/Au layer for use in a comparative study. The operating voltage of a LED with an IZO layer was 4.3 V at 20 mA, an increase of 0.75 V at 20 mA compared to that of a LED with a Ni/Au layer. The light output power of the LED with an IZO layer, however, exceeded that of the LED with a Ni/Au contact to p-GaN. In Fig. 4 the light output powers of LEDs, prepared using the two different ohmic schemes, IZO and Ni/Au, were compared as a function of electrical input power. The light output power of the LED with IZO p contact was 1.45 mW at an 83 mW input power, which is larger by 34% than that of the LED prepared using a Ni/Au film. The enhancement of light output power could be attributed to the high light transmittance of the annealed IZO film compared to that of the Ni/Au layer.

In summary, transparent ohmic schemes of IZO thin films were investigated for the formation of transparent ohmic contacts to p-GaN. Contacts annealed at a temperature of 600 °C for 5 min under a nitrogen ambient produced low specific contact resistance of 3.4×10^{-4} Ω cm^2. AES and XPS studies of the interface between the IZO and p-GaN showed that the improvement of contact resistance of an annealed IZO film on p-GaN would be attributed to an increase in hole concentration due to the out-diffusion of Ga and the formation of an In–N phase at the interface. The light transmittance of the annealed IZO film was 87.2% at 470 nm. The light output power for the LED with an IZO film was increased by 34% at an input power, compared to that for LED with a Ni/Au film.

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