Highly transparent and low resistance gallium-doped indium oxide contact to \textit{p}-type GaN

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We report on a transparent gallium-doped indium oxide (GIO) ohmic contact to the \textit{p}-GaN. The GIO contact film yielded a low specific contact resistance of $8.1 \times 10^{-5}$ $\Omega$ cm$^2$ on \textit{p}-GaN when annealed at 600 °C under a nitrogen ambient. The low specific contact resistance can be attributed to the formation of acceptorlike Ga vacancies and an In$_x$Ga$_{1-x}$N phase at the interface between the GIO and \textit{p}-GaN films. The forward voltage of a light-emitting diode (LED) with a GIO ohmic layer was slightly increased by 0.2 V compared to that of a LED with a standard Ni/Au contact. However, a light transmittance of 85.7%, which was higher than that of indium tin oxide, was observed in the GIO film at a wavelength of 470 nm after thermal annealing at 600 °C. These results suggest that the GIO contact scheme is suitable for use as a highly transparent and low specific contact resistance contact layer for \textit{p}-GaN.

The overall performance of GaN-based light-emitting diodes (LEDs) is strongly affected by contact resistance and the light transmission efficiency of \textit{p}-ohmic contact materials. However, a low contact resistance is difficult to achieve, because the hole concentration of \textit{p}-GaN in most of the cases is less than $10^{18}$ cm$^{-3}$ due to the low activation efficiency of the deep acceptor Mg atoms in \textit{p}-GaN. To date, various attempts have been made to reduce contact resistance, including a surface treatment using boiling aqua regia, the deposition and annealing of high work function metals, and the growth of AlGaN/GaN superlattices. The focus of these methods has been on attaining a low specific contact resistance to \textit{p}-GaN. It is, however, necessary to improve the light extraction efficiency by increasing the light transmittance of \textit{p}-ohmic contact materials. Indium tin oxide (ITO) films on \textit{p}-GaN were recently employed as a transparent ohmic layer but Schottky behavior was observed even after thermal annealing. Even though Ni or Ni/Au interlayers between ITO and \textit{p}-GaN greatly lowered the contact resistance, the forward voltage of an LED using such an interlayer was still higher than that for an LED using a Ni/Au layer as the \textit{p}-electrode.

Gallium-doped indium oxide (GIO) is also a good conducting oxide, and has a high transparency in the visible spectral region, a high electrical conductivity, and a high work function. In this study, we investigated the GIO ohmic scheme as a transparent and low resistance contact layer on \textit{p}-GaN. It is shown that the GIO contact yields a low specific contact resistance of $8.1 \times 10^{-5}$ $\Omega$ cm$^2$ when annealed at 600 °C for 1 min under a nitrogen ambient. In addition, the forward voltage of the LED with a GIO \textit{p}-contact was increased by only 0.2 V compared to that of an LED with a Ni/Au contact, while a high light transmission of 85.7% was maintained at a wavelength of 470 nm. A \textit{p}-GaN layer with a thickness of 1.2 $\mu$m was grown on a $c$-plane sapphire substrate by metalorganic chemical vapor deposition and the resulting film showed a hole concentration of $2 \times 10^{17}$ cm$^{-3}$ and hole mobility of 7 cm$^2$/V s. A GIO layer with a thickness of 200 nm was deposited on the \textit{p}-GaN layer by electron-beam evaporation of an In$_2$O$_3$ source containing 5 at.% Ga$_2$O$_3$. The samples were then annealed at 600 °C for 1 min under a nitrogen ambient in a rapid thermal annealing (RTA) system. The specific contact resistance was measured using circular transmission line method (c-TLM) patterns, which were formed by photolithography and lift-off techniques. The inner dot radius was 200 $\mu$m and the spacing between the inner and the outer radii varied from 5 to 50 $\mu$m. To characterize the extent of interdiffusion between the GIO layer and the \textit{p}-GaN film, an x-ray photoemission spectroscopy (XPS) (PHI 5200 model) study was performed using an Al $K\alpha$ X-ray source.

A postdeposition annealing of a GIO film on \textit{p}-GaN under a nitrogen environment was performed to examine the effect of thermal annealing on electrical conductivity and the light transmittance of the GIO layer. The resistivity of the GIO film was decreased with increasing annealing temperature and a resistivity of $1.4 \times 10^{-3}$ $\Omega$ cm was obtained at an RTA temperature of 600 °C. This result can be attributed to the increase in grain size and carrier mobility in the GIO film by RTA. However, the GIO film annealed at 700 °C for 1 min showed an increased resistivity of $2 \times 10^{-3}$ $\Omega$ cm due to the formation of oxygen vacancies which act as scattering centers. Therefore, it would be expected that the uniform current spreading in the \textit{p}-GaN layer would be improved by thermal annealing of the GIO film, due to the increase in conductivity. We also measured the light transmittances of the annealed GIO films on \textit{p}-GaN by means of an ultraviolet/visible spectrometer in visible light region. The light transmittance at a wavelength of 470 nm was increased with increasing annealing temperature, which can be attributed to the crystallization of the GIO film and the increased size of the crystalline grains. The light transmittance of the GIO...
film was determined to be 85.7% at a wavelength of 470 nm, after annealing at 600 °C.

Figure 1 shows current-voltage (I-V) characteristics of a GIO contact layer on p-GaN. When the GIO/p-GaN sample was thermally annealed under a nitrogen ambient, the GIO ohmic contact was improved, showing a linear ohmic behavior at 600 °C for 1 min. However, the I-V curve became nonlinear again when the annealing temperature was further increased to 700 °C. The specific contact resistance was calculated from plots of the measured resistances versus the spacings between the c-TLM pads. The specific contact resistance was determined to be 8.1×10⁻⁵ Ω cm². These results suggest that the GIO contact scheme is suitable for use as a highly transparent and low specific contact resistance contact layer for p-GaN.

The in-depth XPS profiles of the as-deposited and annealed GIO contact layers on p-GaN are shown in Fig. 2. Figure 2(a) shows that interdiffusion does not occur between the GIO film and a p-GaN layer in the as-deposited sample. On the other hand, when annealed at 600 °C, a small amount of Ga atoms outdiffuse into the GIO film, as shown in Fig. 2(b). These results indicate that the thermal annealing process which was used to obtain a good GIO ohmic contact to a p-GaN layer also produces Ga vacancies near the surface of the p-GaN. The outdiffusion of Ga atoms from p-GaN is reported to produce acceptorlike Ga vacancies near the p-GaN surface region and this results in an increase in hole concentration and a decrease in contact resistance.¹²

To characterize the chemical bonding state of the GIO/p-GaN ohmic scheme, an XPS analysis was performed on the bulk p-GaN film and at the GIO/p-GaN interface, after an annealing at 600 °C in a nitrogen ambient. It is known that the binding energies of the N 1s core-level peak are 396.6 eV for InN and 397.5 eV for the GaN.¹³,¹⁴ The XPS spectrum (a) in Fig. 3 shows a N 1s core-level peak at 397.5 eV, indicating that only the GaN compound is present on the surface of the bulk p-GaN film. For the annealed GIO/p-GaN interface, however, it is noteworthy that the binding energies of the N 1s core-level peaks at 397.5 and 396.6 eV indicate the presence of GaN and InN compounds, respectively, as shown in the XPS spectrum (b) in Fig. 3. InN or InₓGa₁₋ₓN compound, formed at the surface of a p-GaN film, is known to induce large piezoelectric polarization fields and a valence-band discontinuity, leading to the accumulation of holes at the surface of the p-GaN film.¹⁵,¹⁶ Therefore, the formation of InN or InₓGa₁₋ₓN compound appears to reduce contact resistance by increasing the hole concentration near the interface thus decreasing the width of the tunneling barrier. Therefore, high transparency, low resistivity, and low contact resistance could be achieved in the GIO contact scheme on p-GaN, leading to a low total series resistance and possibly uniform current spreading in the LEDs.

To demonstrate the GIO contact scheme on the p-GaN layer for improving hole injection and current spreading, we fabricated InGaN/GaN multiquantum-well LEDs with a dimension of 300×300 μm². Figure 4 shows the I-V characteristics of the LEDs with different p-ohmic contacts. The forward voltage, measured at a 20 mA injection current, was 3.60 V and 3.80 V for Ni/Au and GIO contacts to p-GaN, respectively. It is noteworthy that the forward voltage of the LED with a GIO ohmic layer was slightly higher by 0.20 V compared to the Ni/Au ohmic contact layer.
than that of the LED with a standard Ni/Au contact. The GIO contact scheme is better than the ITO $p$-electrode which showed a higher forward voltage of 2 V than a Ni/Au contact at an injection current of 20 mA and a lower light transmittance of 83% at 465 nm. The GIO contact was comparable to the ITO contact with the insertion of a $p$-In$_{0.1}$Ga$_{0.9}$N film between ITO and $p$-GaN layers, which showed an increase in forward voltage by 0.22 V compared to a Ni/Au contact at an injection current of 20 mA. These results show that the GIO contact scheme is a potentially promising ohmic scheme for highly efficient and high output-power GaN-based LEDs.

In summary, GIO ohmic schemes were investigated for use as highly transparent and low resistance ohmic contacts to $p$-GaN. The GIO contact annealed at 600 °C for 1 min in a nitrogen ambient showed a low specific contact resistance of $8.1 \times 10^{-5}$ Ω cm$^2$ and a high light transmittance of 85.7% at a wavelength of 470 nm. The decrease in contact resistance of the annealed GIO layer on $p$-GaN can be attributed to the formation of the acceptorlike Ga vacancies and InN or In$_x$Ga$_{1-x}$N phase at the interface between the GIO and $p$-GaN films.

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