Effect of an indium-tin-oxide overlayer on transparent Ni/Au ohmic contact on p-type GaN

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(Received 2 October 2002; accepted 11 November 2002)

We report a low-resistant, thermally stable, and transparent ohmic contact on p-type GaN using an indium-tin-oxide (ITO) overlayer on Ni/Au contact. Ni (20 Å)/Au (30 Å)/ITO (600 Å) contact with preannealing at 500 °C before ITO deposition showed lower contact resistivity by one order of magnitude than the contact without the preannealing. The preannealing produced NiO, acting in the role of diffusion barrier for outdiffusion of N and Ga atoms and indiffusion of In during the subsequent post-annealing. Thus, the formation of Au–In solid solution was effectively suppressed, resulting in the decrease of contact resistivity and enhancement in thermal stability. © 2003 American Institute of Physics. [DOI: 10.1063/1.1534630]

The achievement of high-quality and reliable ohmic contacts is crucial for GaN-based optoelectronic devices, such as light-emitting diodes (LEDs), photodetectors, and laser diodes.1 For p-type GaN, low-resistant ohmic contacts (<10−4 Ω cm2) were obtained using Ni/Au,2 Pt/Au,3 and Ru/Ni.4 Among these contacts, the Ni/Au bilayer contact is commonly used as a transparent ohmic contact on p-type GaN due to its low contact resistivity and high transparency.2 However, the thin layer thickness of the contact (<100 Å) limits current spreading as well as thermal stability.5

Indium tin oxide (ITO) is one of the promising electrodes on p-type GaN due to high transparency (>80%) and good conductivity (~104 Ω−1 cm−1). In general, ITO films on p-type GaN showed Schottky behavior even after thermal annealing due to low hole concentration.6 While many attempts have been made to find a way to lower the contact resistivity on p-type GaN using ITO, the contact resistivity was still high for the p-electrode of GaN-based LEDs.7 The Ni layer in the Ni/Au contact is easily transformed into NiO when the contact was annealed at a moderate temperature (~500 °C) under O2 ambient.8 The NiO has higher work function by 0.3 eV than ITO (4.7 eV)9 and showed a good diffusion barrier for both Ga and N atoms.10 Thus, high-transparent, low-resistant, and thermally stable ohmic contacts to p-type GaN could be obtained by using an ITO overlayer on the Ni/Au contact.

In this letter, we report an oxidized Ni/Au/ITO ohmic contact with a low resistance, high transparency and good thermal stability on p-type GaN. In order to find the effect of oxidation of contact metals on the improvement of electrical properties, the Ni/Au layers were annealed under O2 ambient, followed by deposition of the ITO overlayer. The microstructure at the interface of the contact with p-type GaN was analyzed by x-ray diffraction (XRD) and secondary ion mass spectroscopy (SIMS). From this, the contact formation mechanism of transparent Ni/Au/ITO ohmic contact on p-type GaN is proposed.

GaN films used in this study were grown by metalorganic chemical vapor deposition on the c-plane sapphire substrate. A p-type GaN layer with a thickness of 1.2 μm was grown. The electron concentration was 2×1017 cm−3 and electron mobility was 8 cm2/V s, determined by Hall measurements.

For the evaluation of contact resistivity on p-type GaN, a mesa structure was formed, followed by dipping the sample into boiling aqua regia solution (HCl:HNO3 = 3:1) to remove surface oxides formed on GaN.11 TLM pads were patterned by photoresist. Ni (20 Å) and Au (30 Å) metals were deposited in sequence by electron-beam evaporator.

Two types of contacts were prepared. One sample was prepared by preannealing the Ni/Au metals at 500 °C under O2 ambient, followed by depositing ITO (600 Å) film by rf magnetron sputtering ("preannealed" contact). The other sample was sequentially deposited with ITO (600 Å) without the preannealing of the Ni/Au ("nonannealed" contact). The ITO target composed of 90 wt % In2O3 and 10 wt % SnO2 was used to obtain ITO films with high conductivity.12 For a reference, the sample of Ni (20 Å)/Au (30 Å) contact was prepared ("Ni/Au" contact). The summary of sample preparation is given in Table I. All samples were annealed in the temperature range of 300~600 °C for 1 min under O2 ambient by rapid thermal annealing. Current–voltage characteristics of the contacts were examined by the four-point-probe measurements.

Figure 1 shows the specific contact resistivities of samples as a function of annealing temperature. The contact resistances (Rc) in the unit of Ωmm and the sheet resistance (Rs) in the unit of Ω/□ were determined from the intercept of the y-axis and the slope of resistances at 0 V with the interspacings. The specific contact resistivity (ρc) was calculated by the method of current–voltage characteristics of the contacts at the four-point-probe measurements.

<table>
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<th>Notation</th>
<th>Deposition step</th>
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<tr>
<td>Preannealed contact</td>
<td>Ni(20 Å)/Au(30 Å)+O2 annealing at 500 °C + ITO (600 Å)</td>
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<tr>
<td>Nonannealed contact</td>
<td>Ni (20 Å)/Au (30 Å)+ ITO (600 Å)</td>
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<tr>
<td>Ni/Au contact</td>
<td>Ni (20 Å)/Au (30 Å)</td>
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lated by $\rho_c = R_c^2 / R_i$. The minimum contact resistivities of the contacts were obtained at 500 °C, summarized in Table II. The contact resistivity in the preannealed contact ($2.0 \times 10^{-4} \, \Omega \, \text{cm}^2$) is comparable to the Ni/Au contact ($1.9 \times 10^{-4} \, \Omega \, \text{cm}^2$). Note that the contact resistivity of the pre-annealed contact is lower than that of the nonannealed one ($8.8 \times 10^{-4} \, \Omega \, \text{cm}^2$). This means that the preannealing of the Ni/Au layers under O2 ambient is effective in reducing contact resistivity on p-type GaN.

Figure 2 shows the change of contact resistivity for the three samples as a function of annealing time at 500 °C. After annealing for 24 h, the value of contact resistivity is $7.7 \times 10^{-4} \, \Omega \, \text{cm}^2$ for the preannealed contact, while those of nonannealed and Ni/Au samples are $8.3 \times 10^{-3} \, \Omega \, \text{cm}^2$ and $1.1 \times 10^{-2} \, \Omega \, \text{cm}^2$, respectively. This result indicates that the thermal stability of the contacts using ITO overlayer is superior to that of the Ni/Au contact, and that the preannealing of the Ni/Au layers is the most effective in enhancing the thermal stability.

Figure 3(a) displays the XRD profiles of the three samples before annealing. The peak corresponding to Ni appears in both the nonannealed and Ni/Au contacts. However, for the preannealed contact, a NiO peak appears instead of a Ni one, indicating that Ni transformed to NiO during the preannealing under O2 atmosphere. The XRD profiles after annealing at 500 °C for 1 min are displayed in Fig. 3(b). The intensity of Au (111) increases after annealing in both the preannealed and Ni/Au contacts, indicating enhancement in the crystallinity of the Au layer. A NiO peak is observed in both the preannealed and Ni/Au contacts. For the nonannealed contact, Au (111) peak moves to higher angle. This is due to the formation of Au–Ni solid solution because the atomic radius of Ni (1.24 Å) is smaller than that of Au (1.44 Å). It can be found that the peak of the Au–Ni solid solution can be separated two components. The atomic radius of In (1.62 Å) is larger than that of Ni and Au. Thus, it is suggested that the indiffusion of In atoms to the Au–Ni solid solution shifts the peak toward lower angle, resulting in the two components. Meanwhile, the position of Au (111) peak is not changed in the preannealed contact. This provides the evidence that the NiO produced during the preannealing of the Ni/Au contact acted as a diffusion barrier for the indiffusion of In from ITO.

The SIMS depth analysis was carried out to find interfacial reactions during annealing, displayed in Fig. 4. It is found that Au atoms indiffuse and Ni ones outdiffuse in the annealed Ni/Au contact. In the nonannealed contact, In and O atoms indiffuse through the Ni/Au layers into GaN, and both Ga and N atoms outdiffuse simultaneously. The indiffusion of In atoms is especially pronounced. This provides the evidence on the formation of Au–In solid solution, consistent with the XRD result. It is noteworthy that both the In indiffusion and the outdiffusion of Ga and N atoms are sig-

<table>
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<th>TABLE II. Minimum contact resistivities for all samples.</th>
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<td>Sample</td>
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<tr>
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<tr>
<td>Preannealed contact</td>
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<tr>
<td>Nonannealed contact</td>
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<td>Ni/Au contact</td>
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Fig. 3. XRD profiles of all the samples (a) before and (b) after annealing at 500 °C for 1 min. [● : NiO (111), □ : Au (111), ○ : Ni (111), △ : Au–Ni solid solution, ▲ : Au–Ni–In solid solution].
significantly suppressed in the preannealed contact. This is attributed to the formation of NiO during the preannealing of Ni/Au contact, as shown in Fig. 3, acting as a diffusion barrier against the indiffusion of In atoms. Consequently, the contact resistivity and thermal stability are simultaneously enhanced, as shown in Figs. 1 and 2.

In order to examine the feasibility of the Ni/Au/ITO contacts to GaN-based optical devices, the light transmittance of the contacts was measured. Figure 5 shows the transmittance at the wavelength of 470 nm as a function of annealing temperature. The transmittance increases with the annealing temperature. The transmittance of the preannealed contact is higher than those of the nonannealed and Ni/Au contacts through all annealing temperatures. The light transmittance of the preannealed contact after annealing at 500 °C is evaluated to be 90.3%, while the transmittances of the nonannealed and Ni/Au contacts are 83.7% and 85.0%, respectively. This value is comparable to the highest value reported for p-type GaN. Therefore, it is suggested that the preannealed Ni/Au/ITO contact could be a promising candidate for a transparent ohmic contact to GaN-based LEDs.

Based on these experimental observations, the low contact resistivity and the good thermal stability of the transparent Ni/Au/ITO ohmic contact could be explained. When the nonannealed sample was annealed under O₂ atmosphere, Au indiffused through the Ni layer to the interface of p-type GaN, resulting in a decrease of contact resistivity. Simultaneously, In atoms from ITO layer also indiffused into Au, forming an Au–In solid solution. The work function of the Au–In solid solution is decreased with the quantity of In atoms and the decrement is 0.7 eV in the Au–In (1:1) solid solution. Thus, the barrier height for transport of holes could be increased, leading to the increase in contact resistivity. Meanwhile, there was no reaction between Au and In in the preannealed sample because of the formation of NiO between Ni/Au and ITO layers, acting as a diffusion barrier to In atoms. Thus, the formation of Au–In solid solution effectively restrained, resulting in the decrease in contact resistivity and the enhancement of thermal stability. The higher transmittance in the preannealed contact originated from the improvement in the crystallization of ITO owing to the diffusion barrier of NiO.

In conclusion, low-resistive, high transparent, and thermally stable ohmic contact on p-type GaN was achieved using ITO overlayer on preannealed Ni/Au contact. After annealing at 500 °C under O₂ ambient, a specific contact resistivity as low as 2.0×10⁻⁴ Ω cm² was obtained. The light transmittance at the wavelength of 470 nm was as high as 90.3%. The thermal stability was much better than the Ni/Au contact. The preannealed Ni/Au contact using ITO overlayer could be a promising p-electrode for a transparent ohmic contact to GaN-based LEDs.

This work was performed through project for “National Research Laboratory” supported by the Korea Institute of Science and Technology Evaluation and Planning (KISTEP).