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Highly Reflective and Low Resistance Indium Tin Oxide/Ag Ohmic Contacts to p-Type GaN for Flip-Chip Light Emitting Diodes

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We report on the formation of high-quality Ag contacts to p-GaN by using indium-tin oxide (ITO) interlayers. The ITO (2 nm)/Ag (200 nm) contacts give specific contact resistances of 3.26–4.34 × 10^{-4} Ω cm^2 when annealed at 330–530°C for 1 min in air. The reflectance of the ITO (2 nm)/Ag (200 nm) is measured to be 85% at 405 nm, which is much better than that of the ITO (55 nm)/Ag (200 nm) and the single Ag contacts. Light-emitting diodes fabricated with the ITO (2 nm)/Ag (200 nm) contact gives much higher output power than those with the ITO (55 nm)/Ag and single-Ag reflective contacts.
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High-brightness GaN-based blue and ultraviolet light-emitting diodes (LEDs) are of great technological importance for their application in solid-state lighting. The fabrication of high-brightness LEDs requires high light-extraction efficiency as well as high internal efficiency in LED structures. Flip-chip LEDs, where emitted light is extracted through the transparent sapphire substrate, have been demonstrated as one of the promising ways to achieve high light-extraction efficiency, as compared with conventional top-emitting LEDs.[1-3] Thus, in this connection, ohmic contacts having highly reflective as well as low contact resistivity are essential for flip-chip LED applications. The most common Ni/Au ohmic contact is a poor reflector at visible wavelengths, e.g., only 31% at 470 nm.[2] An Ag layer is very attractive due to its high reflectance of ~92% at 470 nm.[2,4] However, the Ag contact has poor adhesion and agglomeration problems when annealed at elevated temperatures.[2-5] Thus, to realize reliable Ag-based ohmic contacts to p-type GaN, a variety of different schemes, such as Cu-doped indium oxide/Ag,[6] Ni/Ag,[7] Mg-doped indium oxide/Ag,[8] Ni/Au/indium tin oxide (ITO)/Ag,[9] Cu–Ni solid-solution/Ag,[10] Zn–Ni solid-solution/Ag,[11] and Ni/Au/Ag,[12] have been investigated to date. For example, Gessmann et al.[3] investigated omnidirectional reflector (ODR) to increase extraction efficiency and showed that LEDs made with ODR [consisting of GaN, a quarter-wave interlayer of ITO (55 nm), and Ag (200 nm)] give somewhat higher extraction efficiency than those made with conventional Ni/Au contacts. However, their forward voltage and series resistance were much higher than those of the conventional LEDs. In this work, we introduced a thin ITO interlayer to stabilize the Ag reflector and to improve its electrical properties. It is shown that ITO (2 nm)/Ag (200 nm) contacts become ohmic with the specific contact resistance is as low as ~10^{-4} Ω cm^2 when annealed at 330 and 530°C for 1 min in air. Near UV (405 nm) GaN-based LEDs were fabricated using the ITO/Ag reflective contacts give forward-bias voltage of ~3.3 V at of 20 mA.

Metallorganic chemical vapor deposition was used to grow 2 μm thick unintentionally doped GaN layers on sapphire (0001) substrates. This was followed by the growth of 1 μm thick GaN:Mg layer ($n_a = 5 \times 10^{17}$ cm^{-3}). The GaN layers were ultrasonically degreased with trichloroethylene, acetone, and methanol for 5 min in each step, and then rinsed with deionized (DI) water. After cleaning the samples using a buffered oxide etch (BOE) solution for 20 min, the GaN layers were blown dry by nitrogen gas. Circular transfer length model (CTLM) patterns were defined by the photolithographic technique to measure the specific contact resistance. The inner dot radius was fixed to be 120 μm and the spacing between the inner and outer radii varied from 4 to 24 μm. ITO and Ag films were successively deposited by electron-beam evaporation. For comparison, single Ag (200 nm) and ITO (55 nm)/Ag (200 nm) contacts were also prepared. Some of the samples were rapid-thermal-annealed (RTA) at 330 and 530°C for 1 min in air. Current-voltage (*I-V*) measurements were carried out using a parameter analyzer (HP 4155A). The film morphologies of the samples were characterized by scanning electron microscopy (SEM, Hitachi S-4700). Furthermore, InGaN/GaN multiple-quantum-well (MQW) near UV (405 nm) LEDs (300 × 300 μm in chip size)[13] were fabricated using Ti (300 nm)/Al (800 nm) and ITO/Ag contacts for n-type and p-type electrodes, respectively.

Figure 1 shows the typical *I-V* characteristics of the ITO/Ag contacts to p-GaN as a function of the annealing temperature. For the ITO (55 nm)/Ag (200 nm) contacts (Fig. 1a), all the samples exhibit nonlinear *I-V* characteristics, although annealing improves their *I-V* behaviors. For the ITO (2 nm)/Ag (200 nm) contacts (Fig. 1b), annealing results in ohmic behaviors. The specific contact resistance was determined from plots of the measured total resistance *vs.* the spacing between the CTLM pads (as shown in Fig. 1c).[14] Measurements showed that the specific contact resistances as low as 4.34 × 10^{-4} and 3.26 × 10^{-4} Ω cm^2 are obtained from the ITO (2 nm)/Ag (200 nm) contacts annealed at 330 and 530°C, respectively. It should be noted that ITO (5 nm)/Ag (200 nm) contacts gave near linear *I-V* behavior upon annealing at 330 and 530°C. In other words, the electrical properties of the ITO/Ag contacts became degraded when the thickness of the ITO interlayer exceeded 5 nm. This implies that there exists an optimum thickness of the ITO layer for forming ohmic contacts to p-GaN.

To investigate mechanical adhesion between the contact layer and p-GaN, SEM examination (not shown) was made of the ITO (2 nm)/Ag (200 nm) and single Ag (200 nm) layers that were annealed at 530°C. It was shown that for the single Ag contact, numerous voids were formed at the Ag/GaN interface. In addition, the single Ag layer experienced serious surface degradation. However, the Ag contact with the ITO interlayer exhibited fairly smooth surface morphology with virtually no interfacial voids.

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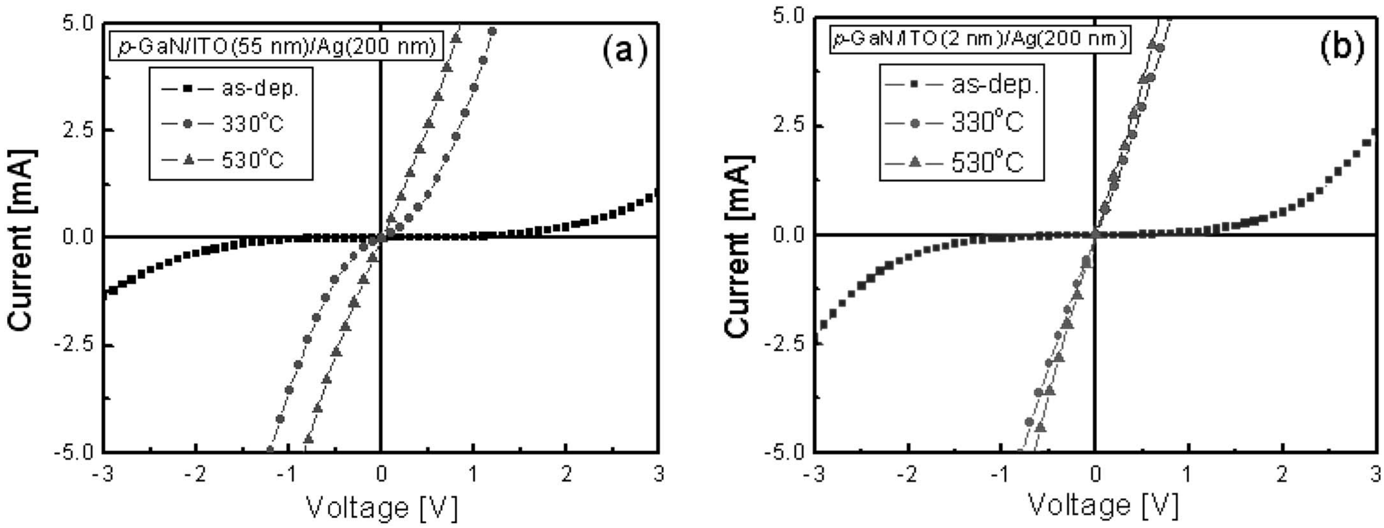

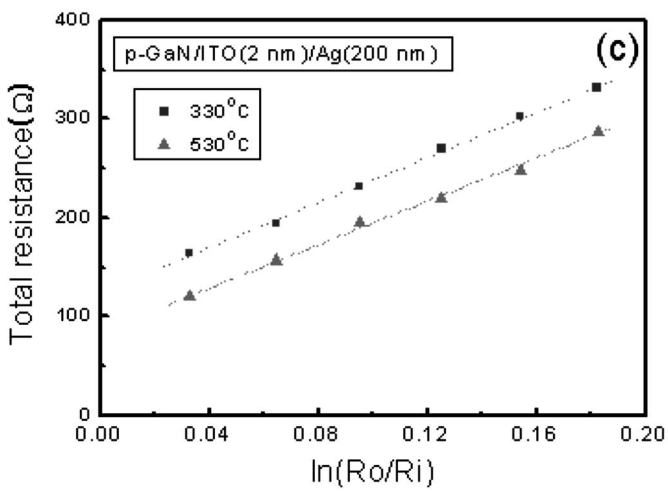

Figure 1. The typical *I-V* characteristics of (a) the ITO (55 nm)/Ag (200 nm contacts and (b) the ITO (2 nm)/Ag (200 nm) contacts as a function of the annealing temperature. (c) Relation between the total resistance and the pad spacing, where R_o is the outer radius and R_i is inner radius.

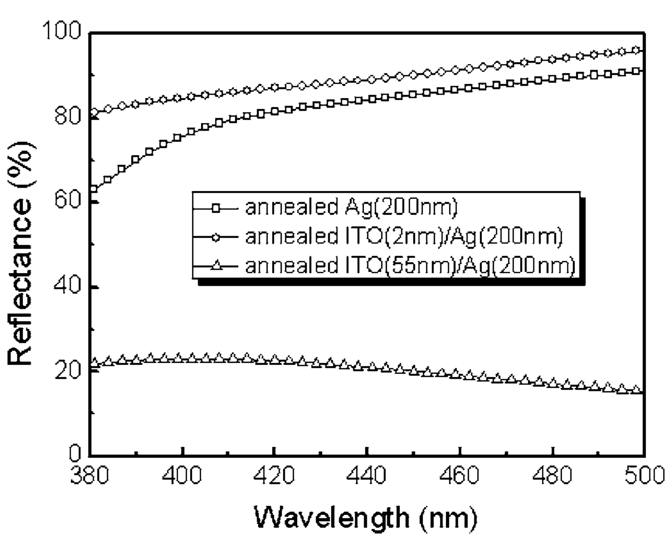

Figure 2. The light reflectance of the ITO (2 nm)/Ag (200 nm), ITO (55 nm)/Ag (200 nm), and single Ag (200 nm) contacts, which were annealed at 530°C.

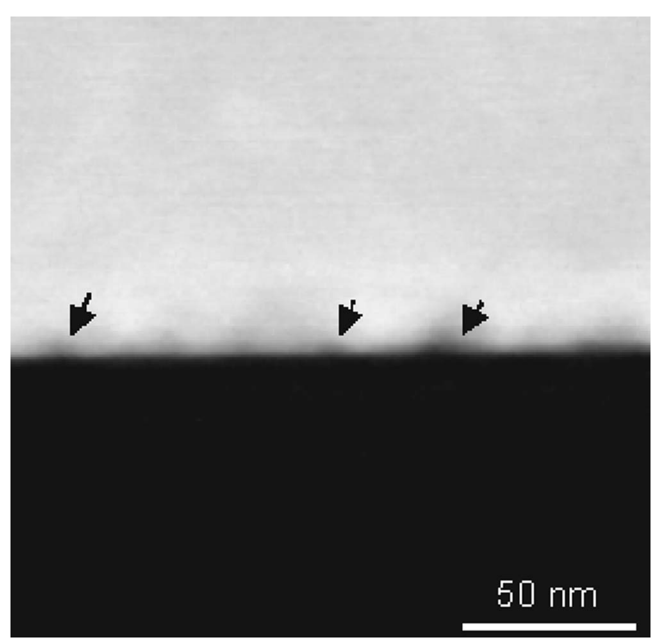

Figure 3. A cross-section STEM *z*-contrast image obtained from the ITO/Ag sample after annealing at 530°C.

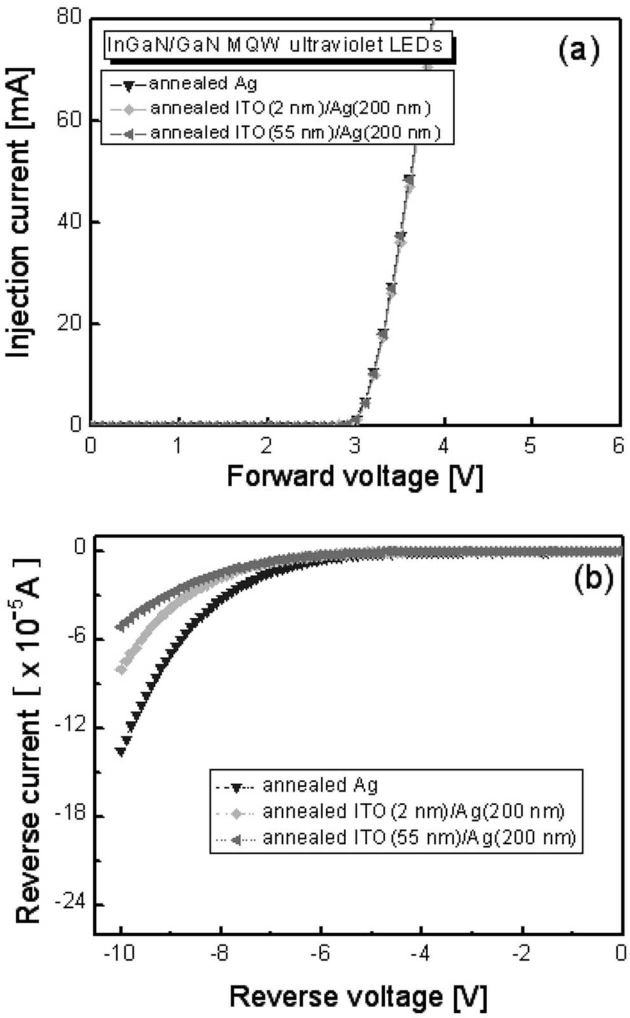

Figure 4. (a) Forward and (b) reverse electrical characteristics of near UV LEDs fabricated with the single Ag and ITO/Ag ohmic contacts, which were annealed at 530°C.

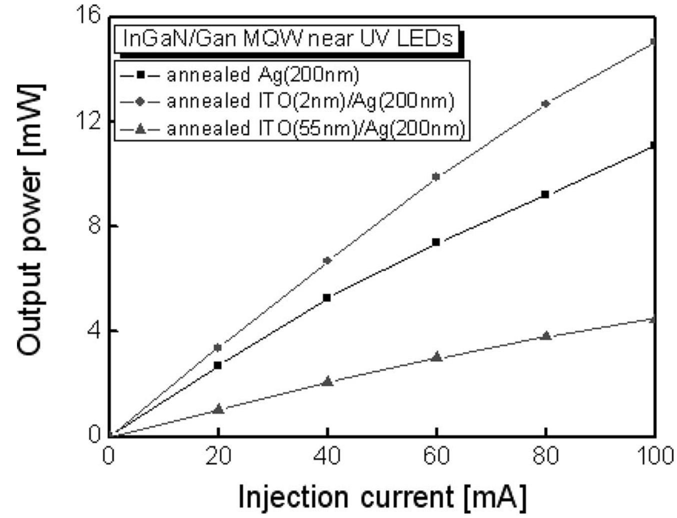

Figure 5. The light output-current (*L-I*) characteristics of the LEDs fabricated with the Ag ohmic reflectors with and without the ITO interlayers (annealed at 530°C) as a function of the forward drive current.

Figure 2 shows the light reflectance of the ITO (2 nm)/Ag (200 nm), ITO (55 nm)/Ag (200 nm) and single Ag (200 nm) contacts, which were annealed at 530°C. It is found that the Ag reflector with the ITO (2 nm) interlayer produces much higher reflectance than the other samples across the whole 380–500 nm wavelength region. For example, the reflectance of the ITO (2 nm)/Ag (200 nm), ITO (55 nm)/Ag (200 nm), and single-Ag (200 nm) layers was measured to be 85, 23, and 77% at wavelength of 405 nm, respectively. The results show that the ITO layer thickness is a crucial factor for obtaining high reflectance.

Figure 3 shows a cross-sectional scanning transmission electron microscopy (STEM) *z*-contrast image obtained from the ITO/Ag sample after annealing at 530°C. It is evident that an amorphous ITO continuous film was broken into ITO nanodots (5–18 nm in size,) (indicated by the arrows). The breaking-up of thin films was also commonly observed in other (2–3 nm thick) oxide thin films.[6,15] Such breaking up results in the formation of inhomogeneous barrier heights on p-GaN.

Figure 4 shows the *I-V* characteristics of near-UV LEDs fabricated with the single Ag and ITO/Ag ohmic contacts, which were annealed at 530°C. It is found that both the LEDs with the Ag contacts with and without the ITO interlayers give a forward voltage of ~3.3 V at an injection current of 20 mA and series resistance of 6.6 Ω, Fig. 4a[f] In addition, the reverse current characteristics of the LEDs with and without the ITO interlayers are shown in Fig. 4b. It is noted that the reverse characteristic becomes improved when the ITO interlayer is inserted. The occurrence of a large leakage current in LEDs made with the single Ag contact was attributed to the indiffusion of Ag into the active region of LEDs.[16] This indicates that the ITO interlayer serves effectively as a barrier for the indiffusion of Ag.

Figure 5 shows the light output-current (*L-I*) characteristics of the LEDs fabricated with the Ag ohmic reflectors with and without the ITO interlayers (annealed at 530°C) as a function of the forward drive current. (The output power was measured from LED chips, but not from encapsulated LEDs. LEDs were emitting directly into air.) The LED with the ITO (2 nm)/Ag contact gives much higher output power than those with the ITO (55 nm)/Ag and Ag reflective contacts. The results are consistent with the combined results of their reflectance and *I-V* characteristics.

The electrical characteristics of the ITO (2 nm)/Ag (200 nm) contacts became considerably improved upon annealing. The anneal-induced improvement could be explained as follows. First, the improvement can be related to the transformation of resistive ITO into conducting crystalline oxide after annealing. Second, it could be associated with the formation of Ag–Ga solid-solution,[17] which produces deep acceptor-like Ga vacancies near the GaN surface region under the contacts, resulting in an increase in carrier concentration at the surface region[18-20] and so the reduction of the Schottky barrier height. In addition, the improvement may be related to the formation of inhomogeneous Schottky barriers at the contact scheme/GaN interface due to the breaking-up of the ITO film, as shown in Fig. 3. The electronic transport theory at the metal/semiconductor (MS) interface with inhomogeneous Schottky barriers[21] indicates that the presence of the ITO nanodots and the difference of the Schottky barrier heights between Ag/GaN and ITO/GaN could lead to an increase of the electric field at the MS interface. It was shown that the increase of the electric field causes a lowering of barrier heights and consequently the reduction of specific contact resistance.[22-25] It was shown that the ITO (thicker than 5 nm)/Ag contacts yielded poor *I-V* behavior. This may be related to

[f] It should be noted that the LEDs fabricated with the annealed Ag-single contacts showed a wide variation of their electrical properties. In other words, the LEDs with the annealed single-Ag contacts gave sometimes reasonably good electrical behaviors, but sometimes pretty poor properties.

the fact that the thick ITO interlayer remained unbroken, as confirmed by STEM. As described previously, to form ohmic contacts, the interlayer should be broken into nanodots, resulting in the formation of inhomogeneous barriers and Ag–Ga solid solution.

In summary, we investigated the ITO/Ag contacts for the formation of low resistance and highly reflective ohmic contacts to p-GaN for high-performance flip-chip LEDs. The ITO (2 nm)/Ag (200 nm) contacts became ohmic with specific contact resistance of $3.26 \times 10^{-4}\ \Omega\ cm^2$ when annealed at 530°C for 1 min in air. However, the 55-nm thick ITO/Ag (200 nm) contacts remained nonlinear even after annealing. The reflectance of the ITO (2 nm)/Ag (200 nm) was measured to be 85% at 405 nm, which is much better than those of the ITO (55 nm)/Ag (200 nm) and the single Ag contacts. LEDs made with the ITO (2 nm)/Ag (200 nm) contact yielded much higher output power than those with the ITO (55 nm)/Ag and the single Ag contacts. These indicate that the 2-nm thick ITO/Ag contact could be a promising p-type ohmic electrode for the fabrication of high-performance GaN-based flip chip LEDs.

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