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Formation of High-Quality Ag-Based Ohmic Contact to p-Type GaN for UV LEDs Using a Tin-Zinc Oxide Interlayer

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We report on the formation of high-quality ohmic contacts to p-GaN ($N_a = 4 \times 10^{17}/cm^3$) for UV flip-chip light-emitting diodes (LEDs) using a tin-zinc oxide (TZO) interlayer. It is shown that the TZO (2.5 nm)/Ag (250 nm) contacts produce contact resistivity of $1.58 \times 10^{-4}\ \Omega\ cm^2$ and reflectance of 76% at 405 nm when annealed at 530°C. Near-UV LEDs made with the annealed TZO/Ag p-contacts give forward-bias voltage of 3.26 V at 20 mA, and higher output power than those with single Ag contacts. Based on transmission electron microscopy and electrical results, possible ohmic formation mechanisms are discussed.
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GaN-based semiconductors are of great technological importance for their applications in solid-state lighting.[1,2] For the realization of solid-state lighting, the fabrication of high-brightness light-emitting diodes (LEDs) is crucial. It was shown that LEDs with flip-chip configuration were more effective in enhancing light-extraction efficiency as compared with top-emitting LEDs.[3,4] This is because for flip-chip LEDs, light is extracted through transparent sapphire substrates rather than semitransparent p-type current spreading layers. Flip-chip LEDs require metallic reflectors, such as Ag, Al, and Rh. Among them, Ag is the most common reflector for GaN-based flip-chip LEDs because it produces good ohmic characteristic on p-GaN and has high reflectivity at ultraviolet-visible regions.[3] However, Ag reflector undergoes thermal degradation, such as agglomeration and formation of voids upon annealing, which leads to the degradation of LED performances.[3-5] To overcome such problems, thin interlayers have been introduced between Ag and p-GaN. For example, Kim et al.[6] added indium-tin oxide (ITO)/Ni/Au multilayers between Ag and GaN. Their Ag-based contact layer produced reflectance of 82.5% at 460 nm after annealing. Gessmann et al.[7] introduced a 55-nm-thick ITO interlayer between Ag and GaN. The ITO-based contacts gave much higher forward-bias voltage than that of conventional Ni/Au contacts. However, the former produced higher light output power compared with the Ni/Au contacts due to their higher light extraction. Recently, Song et al.[8,9] showed that Mg- or Cu-doped indium oxide/Ag contacts yielded reflectivity of ~90% at 460 nm and specific contact resistance of $\sim 10^{-5}\ \Omega\ cm^2$ upon annealing at 530°C. In this work, we have investigated low resistance and reflective p-type Ag-based contacts for UV LEDs using tin-zinc oxide (TZO) interlayers. It is shown that the TZO/Ag contact gives ohmic behavior with specific contact resistance of $1.58 \times 10^{-4}\ \Omega\ cm^2$ and reflectivity of 76% at a wavelength of 405 nm, when annealed at 530°C for 1 min in air.

1.0-μm-thick Mg-doped GaN layers ($N_a = 4 \times 10^{17}\ cm^{-3}$) were grown by metallorganic chemical vapor deposition. The samples were then ultrasonically degreased using trichloroethylene, acetone, methanol, and deionized (DI) water for 5 min in each step, followed by N_2 blowing. Prior to photolithography, the samples were treated with a buffered oxide etch (BOE) solution for 20 min and rinsed in DI water.[10] Circular transfer length method (CTLM) patterns were defined by the standard photolithographic technique for measuring 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. 2.5- or 5-nm-thick tin-zinc oxide (TZO)/Ag (250 nm) layers were deposited by electron-beam evaporation using a ZnO target with 30 atom % SnO_2. For comparison, a single Ag (250 nm) layer was also deposited. Some samples were rapid thermal annealed at temperatures of 330–530°C for 1 min in air.

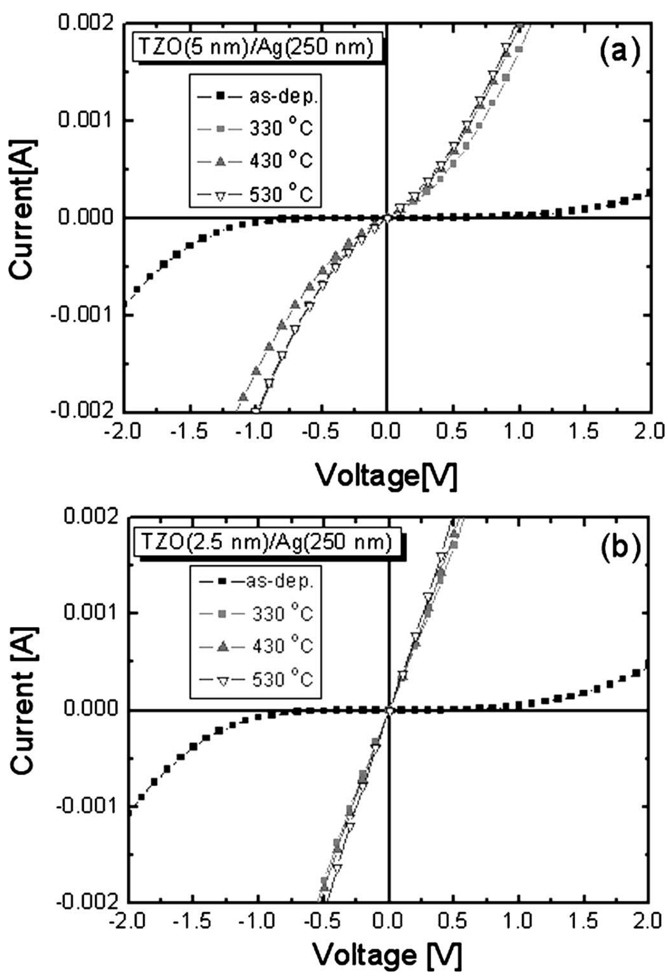

Figure 1. Typical I-V characteristics of the TZO/Ag contacts as a function of the annealing temperature, measured on the 4-μm-spaced pads.

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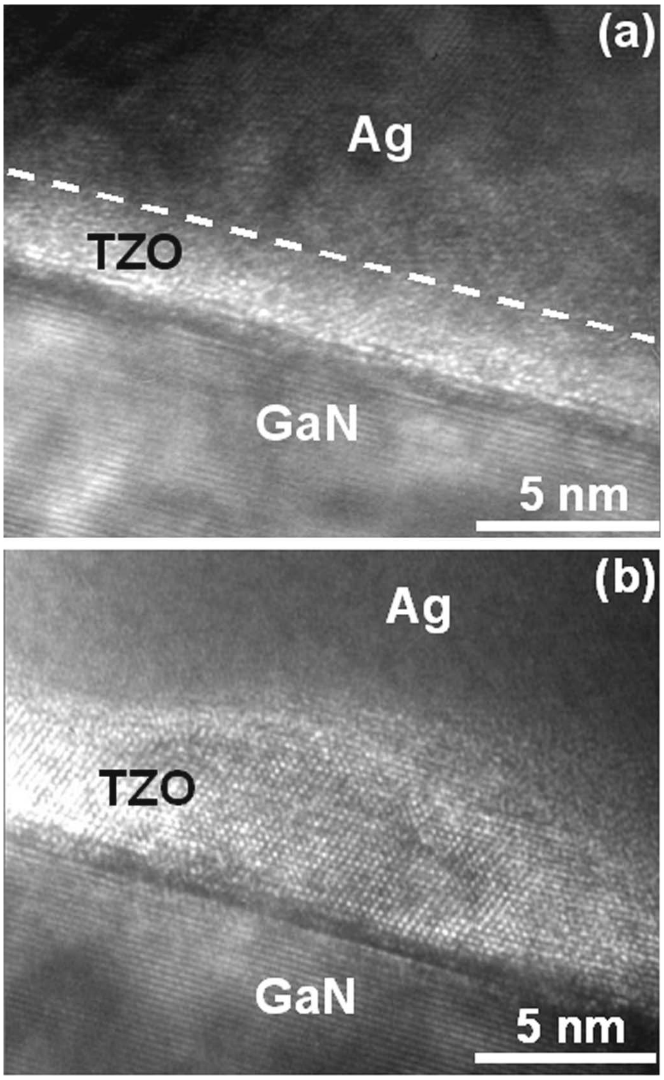

Figure 2. Cross-sectional STEM high-resolution lattice images obtained from the interface regions including the contact scheme and GaN (a) before and (b) after annealing.

Current-voltage (I-V) measurements were performed using a parameter analyzer (HP 4155A) and reflectance measurements were done using a high-resolution UV-VIR-NIR spectrophotometer (Varian Carry 500). Furthermore, near-UV LEDs were fabricated using the TZO/Ag contacts and their electrical and optical properties were characterized.

Figure 1 shows the typical I-V characteristics of the TZO/Ag contacts as a function of the annealing temperature, measured on the 4-μm-spaced pads. It is shown that regardless of annealing treatments, the 5-nm-thick TZO/Ag contacts produce nonlinear I-V behavior (Fig. 1a). For the 2.5-nm-thick TZO layer/Ag contacts, however, their I-V characteristics became considerably improved when annealed at temperatures of 330–530°C (Fig. 1b), indicating the formation of ohmic contacts. Specific contact resistance was determined from the plots of the measured total resistances vs the spacing between the CTLM pads.[11] The least-square method was used to fit a straight line to the experimental data. Measurements show that the TZO (2.5 nm) interlayer/Ag (250 nm) contacts yield specific contact resistance of $1.58 \times 10^{-4}\ \Omega\ cm^2$ after annealing at 530°C.

Interfacial reactions between contacts layers and GaN were characterized by scanning transmission electron microscopy (STEM). Figure 2 exhibits cross-sectional STEM high-resolution lattice images obtained from the interface regions including the contact

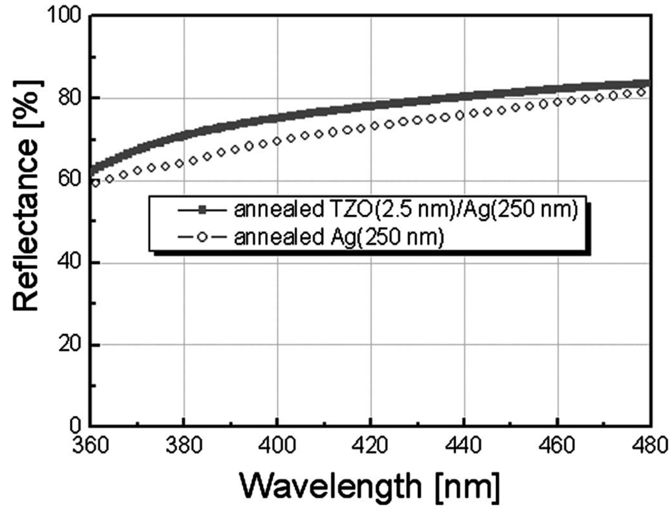

Figure 3. Optical reflectance of the Ag layers with and without the 2.5-nm-thick TZO interlayer, which were annealed at 530°C.

scheme and GaN before and after annealing at 530°C. There is a thin amorphous TZO layer in the as-deposited sample, Fig. 2a. It is, however, shown that the TZO film was broken into TZO nanodots (10–25 nm in size), Fig. 2b. Thus, the TZO and Ag are in contact with p-type GaN at the interface, indicating the formation of inhomogeneous contacts on p-GaN.

Figure 3 shows the optical reflectance of the Ag contacts with and without the 2.5 nm thick TZO interlayer, which were annealed at 530°C. (For convenience, reflectance measurements were made of the samples deposited on glass substrates.) The TZO/Ag contact gave better reflectance as compared with the single Ag contact across the whole 360–480 nm wavelength region. For example, the reflectance at 405 nm was measured to be 76 and 70.6% for the samples with and without the interlayers, respectively.

SEM results (not shown) exhibited that unlike the single Ag contacts, the Ag contacts with the TZO interlayer remained stable without interfacial voids and consequently revealed smooth surface morphology when annealed at 530°C. This indicates that the TZO interlayer effectively delays the agglomeration of the Ag capping layer.

Figure 4a shows the I-V characteristics of multiquantum-well near-UV (405 nm) LEDs fabricated with the TZO (2.5 nm)/Ag (250 nm) and single Ag p-type contacts, which were annealed at 530°C. The LEDs made with the TZO/Ag contacts show better performance compared with that with the single Ag contact. For example, the LEDs with the TZO/Ag contacts give forward-bias voltage of 3.26 V at 20 mA and series resistance of 9.21 Ω. However, the LEDs with the Ag contacts showed forward-bias voltage of 3.42 V at 20 mA and series resistance of 11.08 Ω.

Figure 4b shows the light output-current (L-I) characteristics of LEDs made with the TZO/Ag and single Ag contacts as a function of the forward drive current. The LEDs with the TZO/Ag contacts exhibits better light output performance than the LEDs with the Ag contacts. This is consistent with the combined results of their reflectance and series resistances.

The annealing temperature dependence of the electrical properties of the TZO/Ag contacts could be explained as follows. First, the anneal-induced improvement can be associated with the conversion of resistive TZO into conducting crystalline phase after annealing at 530°C.[d] Second, the improvement may be related to the formation of inhomogeneous barriers at the contact scheme/GaN interface due

[d]Measurements showed that the resistivity of the as-grown TZO layer was significantly reduced from $\sim 10^{-2}$ to $\sim 10^{-3}\ \Omega$ cm, when annealed at 530°C.

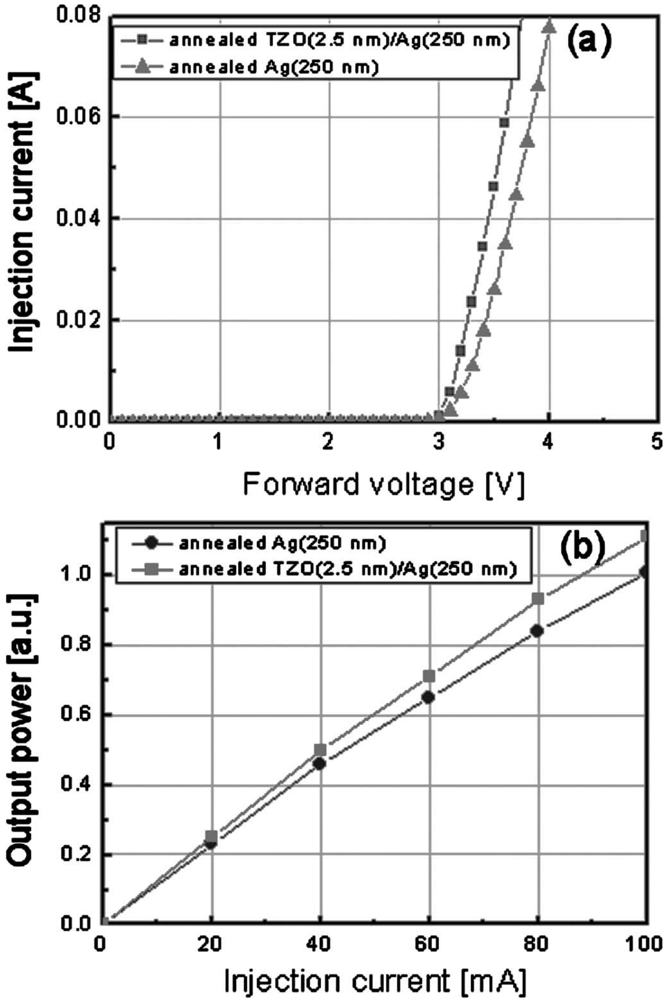

Figure 4. (a) I-V characteristics of multiquantum-well near-UV (405 nm) LEDs fabricated with the TZO (2.5 nm)/Ag (250 nm) and single Ag p-type contacts, which were annealed at 530°C. (b) L-I characteristics of LEDs made with the TZO/Ag and single Ag contacts as a function of the forward drive current.

to the breaking up of the TZO film, as shown by the STEM (Fig. 2b). According to the electronic transport theory at the metal/semiconductor (MS) interface with inhomogeneous Schottky barriers,[12] the presence of the TZO nanodots and the difference of the Schottky barrier heights between Ag/GaN and TZO/GaN could result in an increase in the electric field at the MS interface. An increase of the electric field was shown to cause barrier height to be lowered and consequently the reduction of specific contact resistance.[13-16] Another factor could be attributed to the formation of Ag–Ga solid-solution,[17] which produces deep acceptor-like Ga vacancies near the GaN surface region beneath the contact layer, resulting in an increase in carrier concentration at the surface region[10,18,19] and so the reduction of the Schottky barrier height. The poor I-V behavior of the 5-nm-thick TZO/Ag contacts may be attributed to the fact that the TZO interlayer remained unbroken, as confirmed by electron microscopy. As described above, to produce ohmic behavior, the interlayer should be broken into nanodots, which allow the formation of inhomogeneous barriers and Ag–Ga solid-solution.

In summary, we have investigated the TZO/Ag contacts to form low resistance and reflective ohmic contacts to p-GaN for near-UV LEDs. It was shown that the TZO (2.5 nm)/Ag (250 nm) contacts become ohmic with specific contact resistance of $\sim 10^{-4}\ \Omega\ \text{cm}^2$ and reflectance of 76% at 405 nm upon annealing at 530°C for 1 min in air. Near-UV LEDs fabricated with the TZO/Ag p-type contact layers gave forward-bias voltage of 3.26 V at 20 mA, which is better than that with the single Ag contacts. As a result, the output power was higher in the LEDs with the TZO/Ag contacts than that with the Ag contact. This indicates that the TZO/Ag may be potentially promising for the fabrication of high-brightness UV FCLEDs.

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References

1. S. Nakamura, T. Mukai, and M. Senoh, *Appl. Phys. Lett.*, **64**, 1687 (1994).
2. D. A. Steigerwald, J. C. Bhat, D. Collins, R. M. Fletcher, M. O. Holcomb, M. J. Ludowise, P. S. Martin, and S. L. Rudaz, *IEEE J. Sel. Top. Quantum Electron.*, **8**, 310 (2002).
3. D. L. Hibbard, S. P. Jung, C. Wang, D. Ullery, Y. S. Zhao, H. P. Lee, W. So, and H. Liu, *Appl. Phys. Lett.*, **83**, 311 (2003).
4. J. J. Wierer, D. A. Steigerwald, M. R. Krames, J. J. O'Shea, M. J. Ludowise, G. Christenson, Y.-C. Shen, C. Lowery, P. S. Martin, S. Subramanya, W. Gotz, N. F. Gardner, R. S. Kern, and S. A. Stockman, *Appl. Phys. Lett.*, **78**, 3379 (2001).
5. D.-S. Leem, J.-O. Song, H.-G. Hong, J. S. Kwak, Y. Park, and T.-Y. Seong, *Electrochem. Solid-State Lett.*, **7**, G219 (2004).
6. S. Y. Kim and J.-L. Lee, *Electrochem. Solid-State Lett.*, **7**, G102 (2004).
7. T. Gessmann, Y.-L. Li, E. F. Schubert, J. W. Graff, and J. K. Sheu, in *Light-Emitting Diodes: Research, Manufacturing, and Applications VII*, E. F. Schubert, H. W. Yao, K. J. Linden, and D. J. McGraw, Editors SPIE, Bellingham, WA (2003).
8. J.-O. Song, J. S. Kwak, and T.-Y. Seong, *Appl. Phys. Lett.*, **86**, 062103 (2005).
9. J.-O. Song, D.-S. Leem, J. S. Kwak, O. H. Nam, Y. Park, and T.-Y. Seong, *IEEE Photonics Technol. Lett.*, **16**, 1450 (2004).
10. J.-S. Jang, S. J. Park, and T.-Y. Seong, *J. Vac. Sci. Technol. B*, **17**, 2667 (1999).
11. G. S. Marlow and M. B. Das, *Solid-State Electron.*, **25**, 91 (1982).
12. R. T. Tung, *Phys. Rev. B*, **45**, 13509 (1992).
13. S. K. Lee, C. M. Zettering, M. Ostling, I. Aberg, M. H. Magnusson, K. Deppert, L. E. Wernersson, L. Samuelson, and A. Litwin, *Solid-State Electron.*, **46**, 1433 (2002).
14. J.-O. Song and T.-Y. Seong, *Appl. Phys. Lett.*, **85**, 6374 (2004).
15. E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts*, p. 39, Clarendon Press, Oxford (1988).
16. J. I. Sohn, J.-O. Song, D.-S. Leem, S. Lee, and T.-Y. Seong, *Electrochem. Solid-State Lett.*, **7**, G179 (2004).
17. J.-O. Song, J. S. Kwak, Y. Park, and T.-Y. Seong, *Appl. Phys. Lett.*, **86**, 062104 (2005).
18. V. M. Bermudez, D. D. Koleske, and A. E. Wickenden, *Appl. Surf. Sci.*, **126**, 69 (1998).
19. J.-O. Song, D.-S. Leem, and T.-Y. Seong, *Appl. Phys. Lett.*, **83**, 3513 (2003).