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Formation of Sb-Doped SnO_2 p-Type Ohmic Contact for Near-UV GaN-Based LEDs by a CIO Interlayer

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A Cu-doped In_2O_3 (CIO) interlayer was introduced to enhance the electrical and optical properties of Sb-doped SnO_2 (ATO) p-type electrodes grown by pulsed laser deposition. CIO (2.5 nm)/ATO (250 nm) contacts become ohmic with specific contact resistance of $2.1 \times 10^{-3}\ \Omega\ cm^2$ and give transmittance of ~81% at 400 nm, when annealed at 630°C for 1 min in air. Near-UV (400 nm) GaN-based light-emitting diodes (LEDs) fabricated with the CIO/ATO p-electrodes give forward-bias voltage of 3.91 V at injection current of 20 mA and show much higher output power compared to LEDs with conventional Ni/Au p-electrodes.
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High-brightness GaN-based light-emitting diodes (LEDs) are of potential importance for solid-state lighting application. For this purpose, the improvement of the luminous efficiency of LEDs is a key factor to be achieved.[1] To increase the luminous efficiency, low-resistance and highly transparent ohmic contacts to p-type GaN should be developed.[1-3] Transparent conducting oxides (TCOs) have been regarded as potential p-type electrodes, because of their good transparency and moderate resistance.[4,5] Among various TCOs, indium tin oxide (ITO) is known to be a good p-contact candidate (or a p-type current spreading layer) for GaN-based LEDs because it has good conductivity and high-transmittance. Indeed, it was shown that ITO-based contacts could serve as promising p-type electrodes for high-performance GaN-based LEDs.[2,6,7] However, ITO has some drawbacks, such as thermal instability and the exhaustion of indium.[4,8-10]

Impurity (Sb or F)-doped tin oxide (SnO_2) is an n-type semiconductor having a wide bandgap of 3.6 eV and it has been considered as promising TCOs,[11] which may replace ITO, because of its high thermal and chemical stability. Thus, Sb- or F-doped SnO_2 was used in photovoltaic cells and transparent electrodes.[12] Our group[4] also investigated the electrical and optical properties of pulsed-laser-deposited (PLD) Sb-doped SnO_2 films (ATO) and showed that their electrical and optical properties sensitively depend on the oxygen partial pressure. LEDs fabricated with the ATO contacts produced reasonably good performance. In this work, we have attempted to further improve the electrical and optical properties of ATO-based p-type contacts by introducing Cu-doped indium oxide (CIO) thin layers. It was shown that the CIO/ATO p-contacts give good electrical behaviors when annealed at 630°C in air. Near-UV (400 nm) LEDs with the CIO/ATO p-contacts produce much better output power compared to those with conventional Ni/Au contacts.

1.0 μm thick Mg-doped GaN layers (with a carrier concentration of $4 \times 10^{17}\ cm^{-3}$) were grown using a metallorganic chemical vapor deposition system. 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.[13] Circular transfer length method (CTLM) patterns were defined by the standard photolithographic technique for measuring specific contact resistance. The inner dot radius was 120 μm and the spacing between the inner and outer radii varied from 4 to 25 μm. CIO (2.5 nm thick) films were then deposited on the samples by e-beam evaporation, on which ATO films (250 nm thick) were deposited by PLD using a sintered SnO_2 target containing 5 atom % Sb. Growth chamber was evacuated to 1.3×10^{-4} Pa. Working pressure was maintained to be 4 Pa by monitoring oxygen gas from a leak valve. To deposit the ATO films, the target was ablated using KrF excimer laser (wavelength of 248 nm; pulse width at half maximum of 25 ns) with energy density of 3.75 J/cm^2 at a repetition rate of 5 Hz. For comparison, a single ATO (250 nm) layer was also deposited. Some of the samples were rapid thermal annealed at 530 and 630°C for 1 min in air. Current-voltage (*I-V*) measurements were performed using a parameter analyzer (HP 4155A) and the transmittance of the samples was measured using a high-resolution UV-VIR-NIR spectrophotometer (Varian Carry 500). Auger electron spectroscopy (AES) was used to investigate interfacial reactions at the contact/GaN interfaces. Furthermore, multiple-quantum-well near-UV (400 nm)-LEDs were fabricated with CIO (2.5 nm)/ATO (250 nm) and conventional Ni (5 nm)/Au (5 nm) p-contacts, and their electrical and optical properties were characterized.

Figure 1 shows the electrical characteristics of as-deposited single ATO films (250 nm thick) as a function of the annealing temperature. The ATO films were deposited on glass substrates and then annealed at different temperatures for 1 min in air. Hall concentrations of the films were measured using the van der Paaw geometry. As the annealing temperature increases, the carrier concentration increases due to dopant activation, leading to the reduction of the resistivity. For example, the ATO film annealed at 630°C gives a minimum resistivity of $2.6 \times 10^{-3}\ \Omega$ cm.

Figure 2 shows the typical *I-V* characteristics of the CIO/ATO p-contacts as a function of the annealing temperature. It is shown

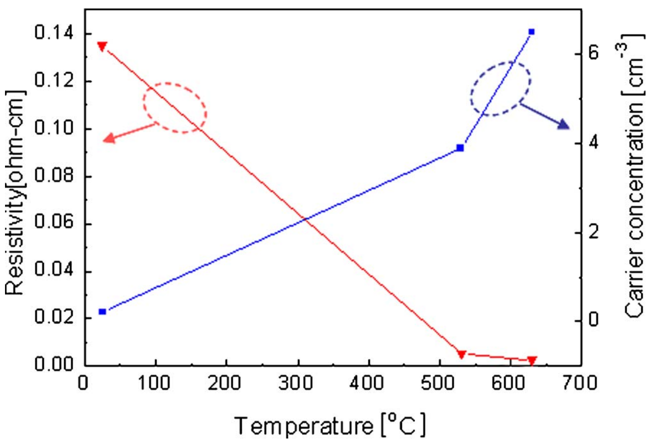

Figure 1. (Color online) The electrical characteristics of as-deposited single ATO films (250 nm thick) on a glass substrate as a function of the annealing temperature.

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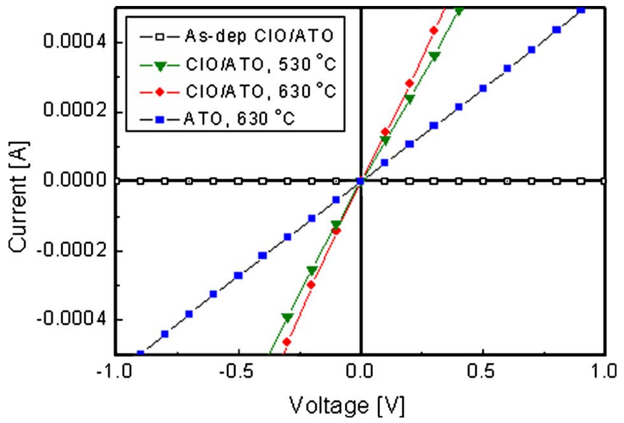

Figure 2. (Color online) The typical *I-V* characteristics of the CIO/ATO p-contacts as a function of the annealing temperature.

that the *I-V* characteristics of the CIO/ATO p-contacts are considerably improved upon annealing, indicating the formation of ohmic contacts. When the temperature exceeds 630°C, however, the electrical behavior of the CIO/ATO p-contacts became somewhat degraded (not shown). The CIO/ATO p-contacts produce the specific contact resistance of $2.1 \times 10^{-3}\ \Omega\ \mathrm{cm}^2$ after annealing at 630°C. It is shown that all of the annealed CIO/ATO p-contacts show better electrical characteristics compared with the annealed ATO single p-contact. This indicates that the CIO interlayer is important for the improvement of the ohmic behavior of the ATO-based contacts.

Figure 3 shows the transmittance of the CIO/ATO films deposited on sapphire substrates before and after annealing at 630°C. Compared with the as-deposited sample, the annealed samples give higher transmittance across the whole wavelength region of 300–600 nm. Low transmittance of the as-deposited samples may be associated with the formation of oxygen deficient phases in ATO films, such as SnO and Sn_3O_4, as demonstrated previously by Hong et al.[4] As the annealing temperature increases, the absorption edge shifts toward the short wavelength region due to Burstein–Moss shift,[14,15] which results in an increase of transmittance at the short wavelength region. For example, the transmittance was measured to be 33, 77, and 81% around 400 nm for the as-deposited, 530°C annealed and 630°C annealed CIO/ATO p-electrodes, respectively.

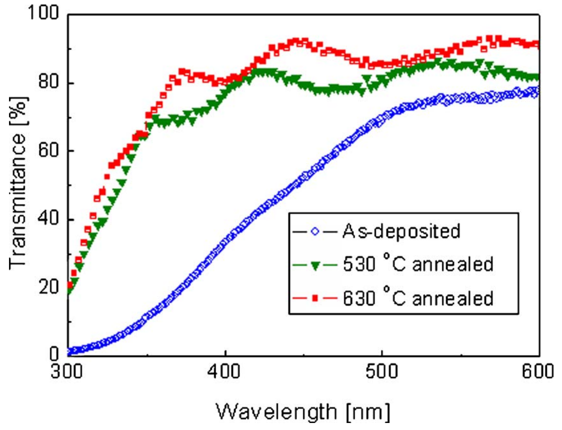

Figure 3. (Color online) The transmittance of the CIO/ATO p-contacts before and after annealing at 630°C.

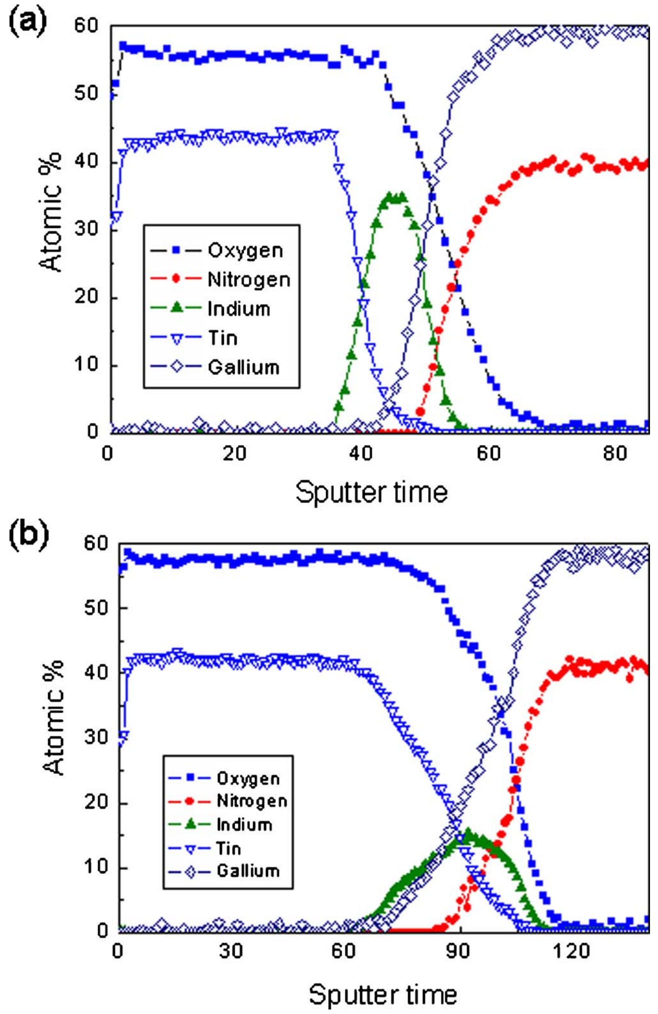

Figure 4. (Color online) The AES depth profiles of the CIO/ATO p-contacts before and after annealing at 630°C. Cu and Sb were not detected due to their small amounts.

Interfacial reactions between the contact and p-GaN layers were characterized by AES. Figure 4 shows the AES depth profiles of the CIO/ATO p-contacts before and after annealing at 630°C. Cu and Sb were not detected due to their small amounts. For the as-deposited sample (Fig. 4a), each layer is well defined, indicating the absence of significant intermixing. For the annealed sample (Fig. 4b), however, some amount of Ga was outdiffused toward the contact layers. This behavior is in agreement with the results observed previously by Song et al.[2,16] In addition, some amounts of indium and oxygen seem to indiffuse into the GaN.

The annealing-induced improvement of the electrical properties of the CIO/ATO contacts may be explained as follows. First, it could be related to the fact that as-deposited amorphous ATO films become crystallized and conductive after annealing, as shown in Fig. 1. (Note that a CIO film gives the sheet resistance of 26.8 Ω/sq when annealed at 630°C, while a reference ITO film yields 24.3 Ω/sq.) High conductivity of the ATO film leads to the improvement of lateral current spreading in the contacts and hence enhances electrical performance. Second, it may be due to the outdiffusion of Ga atoms, as shown Fig. 4. Song et al.[2] reported that the outdiffused Ga atoms participate in the formation of Ga-based oxides (e.g., Ga–Cu–In–O complex) having high workfunction and cause the formation of Ga-related defects near the interface region.[17] The interfacial conductive oxide may lower the Schottky barriers. Furthermore, the Ga-related deep defects near the interface may introduce tunneling and hopping of carriers as suggested by Leem et al.[18] However, the precise mechanisms are under investigation at the moment.

Figure 5 shows the *I-V* characteristics of near-UV (400 nm) LEDs fabricated with the CIO/ATO p-contacts, which were annealed

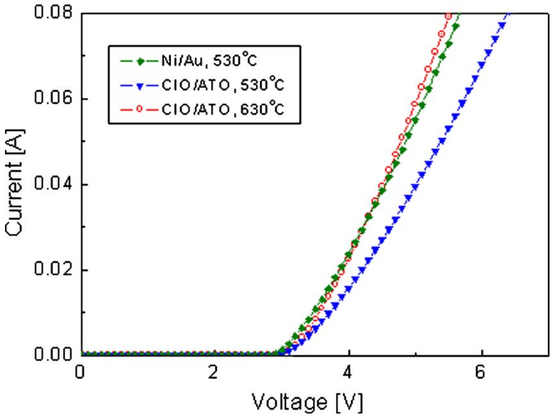

Figure 5. (Color online) The *I-V* characteristics of near-UV (400 nm) LEDs fabricated with the CIO/ATO p-contacts, which were annealed at different temperatures. For comparison, near-UV LEDs with Ni/Au contacts annealed at 530°C were also prepared.

at different temperatures. For comparison, near-UV LEDs with Ni/Au contacts annealed at 530°C were also prepared. LEDs with the 630°C-annealed CIO/ATO p-contacts and Ni/Au p-contacts exhibit similar electrical characteristics. For example, the LEDs with the 630°C-annealed CIO/ATO and Ni/Au p-contacts produce forward-bias voltage of 3.91 and 3.87 V at an injection current of 20 mA and series resistance of 26.5 and 29.22 Ω, respectively. The LEDs with the 530°C-annealed CIO/ATO p-contacts give 4.2 V at 20 mA and series resistance of 36.7 Ω. LEDs with the as-deposited CIO/ATO p-contacts show poor characteristics.

Figure 6 shows the light output-current (L-I) characteristics of LEDs fabricated with the annealed CIO/ATO and Ni/Au p-contacts as a function of the forward drive current. All LEDs with the CIO/ATO contacts show better light output performance compared to the LEDs with the Ni/Au contacts. For example, LEDs with the 530 and 630°C-annealed CIO/ATO p-contacts show the improvement of the output power at 20 mA by 67 and 82% compared to the Ni/Au contacts, respectively.

In summary, PLD-prepared ATO films were investigated as p-contacts for GaN-based near-UV LEDs. A CIO thin interlayer was used to improve electrical characteristics of the ATO contacts. The contact resistivity and transmittance of the CIO/ATO scheme were measured to be 2.1×10^{-3} Ω cm^2 and 81% at 400 nm upon annealing at 630°C. Near-UV (400 nm) LEDs fabricated with the CIO/ATO p-contacts showed enhanced output power at injection currents in the range of 20–100 mA compared to LEDs with conventional Ni/Au contacts. These results show that the PLD-deposited ATO film combined with a CIO interlayer may serve as a potential p-type electrode for the fabrication of high-performance short-wavelength GaN-based LEDs.

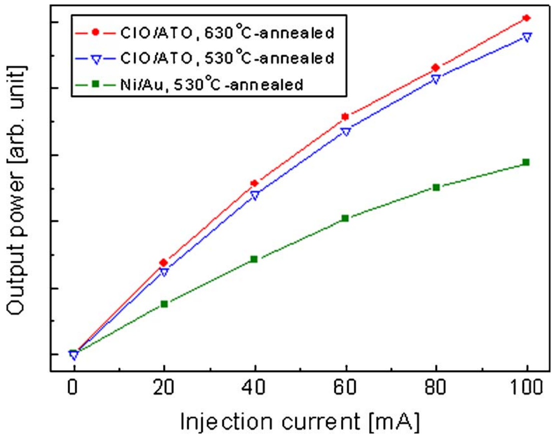

Figure 6. (Color online) The light output-current (L-I) characteristics of LEDs fabricated with the annealed CIO/ATO and Ni/Au p-contacts as a function of the forward drive current.

Acknowledgments

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