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Indium as an efficient ohmic contact to N-face *n*-GaN of GaN-based vertical light-emitting diodes

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We propose indium (In), a low work function and nitride-forming element, as an efficient ohmic contact layer to N-face *n*-GaN. While conventional Al-based ohmic contacts show severe degradation after annealing at 300 °C, In-based ohmic contacts display considerable improvement in contact resistivity. The annealing-induced enhancement of ohmic behavior in In-based contacts is attributed to the formation of an InN interfacial layer, which is supported by x-ray photoemission spectroscopy measurements. These results suggest that In is of particular importance for application as reliable ohmic contacts to *n*-GaN of GaN-based vertical light-emitting diodes. © *2011 American Institute of Physics*. [doi:10.1063/1.3662421]

GaN-based light-emitting diodes (LEDs) are expected to replace incandescent and fluorescent light bulbs for solid-state lighting in which the use of highly energy-efficient, longer-lasting, versatile light sources would bring considerable energy savings to human life.[1] GaN-based vertical LEDs fabricated by laser lift-off (LLO) process are very promising candidates for deployment in solid-state lighting products owing to their low thermal resistance and high extraction efficiency.[2–5] However, the high-yield production of reliable vertical LEDs are still challenging.[6] One of the major barriers is to achieve low-resistance ohmic contacts with long-term stability to N-face *n*-GaN which is the top epilayer of GaN-based vertical LEDs by LLO. While conventional Al-based ohmic contacts such as Ti/Al and Cr/Al lead to low contact resistivities on the N-face *n*-GaN layer at the as-deposited conditions, they suffer from thermal degradation during the passivation and curing process of the devices at 200–300 °C.[7–9] Although metallization schemes including TiN/Al,[10] CrB_2/Ti/Al,[11] and Al-Ga/Ti/Al,[12] or surface treatments[13,14] have been reported to improve the thermal stability, none of them are free from the thermal degradation. In a thermodynamic point of view, the prevention of the thermal degradation in Al-based ohmic contacts to N-face *n*-GaN is unfavorable,[8,9] suggesting that a thermally stable metallization scheme beyond Al-based contacts should be invented.

In this letter, we propose that indium is an efficient ohmic contact layer to N-face *n*-GaN of GaN-based vertical light-emitting diodes. Direct comparison of current-voltage characteristics between Al and In contacts to N-face *n*-GaN clearly shows that In contacts have no thermal degradation and exhibit even better ohmic behavior after annealing at 300 °C. X-ray photoemission spectroscopy (XPS) measurements reveal that interfacial reactions between In and GaN play a critical role in the formation of the ohmic contacts.

Previous studies[9,15] have shown that the ohmic contacts between Al and N-face *n*-GaN deteriorated with the formation of AlN at the interface. The large bandgap of AlN (6.2 eV) and the polarization-induced upward band bending at the AlN/GaN interface impede the transport of electrons across the interface [Fig. 1(a)]. We have expected that In can replace Al for ohmic contacts to N-face *n*-GaN. Like Al, In has a low work function (4.1 eV) (Ref. 16) and is a nitride-forming element on GaN.[17] The formation of InN at the interface between In and N-face *n*-GaN can improve the ohmic contact characteristic. Since the bandgap of InN is as small as ∼0.7 eV and the piezoelectric polarization (pointing down to the substrate) in InN is much larger than the spontaneous polarization (pointing up to the surface), the interfacial band banding is expected to be benign for electron transport [Fig. 1(b)].

In order to demonstrate our concept, we have prepared Al and In contacts on N-face n-GaN of vertical InGaN/GaN LEDs which were fabricated using a Au-Sn wafer bonding and LLO process. After removing the 500-nm-thick undoped GaN layer by dry etching, metal deposition onto the top N-face *n*-GaN was carried out using an electron-beam evaporator at base pressure of 5×10^{-7} Torr. Specific contact resistivities of the contacts were evaluated using the transmission line method. Current-voltage ($I-V$) characteristics of the contacts were measured before and after annealing at 150 and 300 °C for 1 min in N_2 ambient.

Figure 2 shows *I-V* curves of 200 nm thick Al and In contacts to N-face *n*-GaN as a function of annealing temperature. At the as-deposited conditions, both contacts show linear $I-V$ curves. It is noted that the lower contact resistivity was obtained from the In contact. After annealing, the Al contact exhibits degradation in *I-V* curves [Fig. 2(a)], while the In contact displays improvements [Fig. 2(b)]. This stark contrast is highlighted in Fig. 2(c). The thermal degradation in the Al contact is consistent with the previous result.[9]

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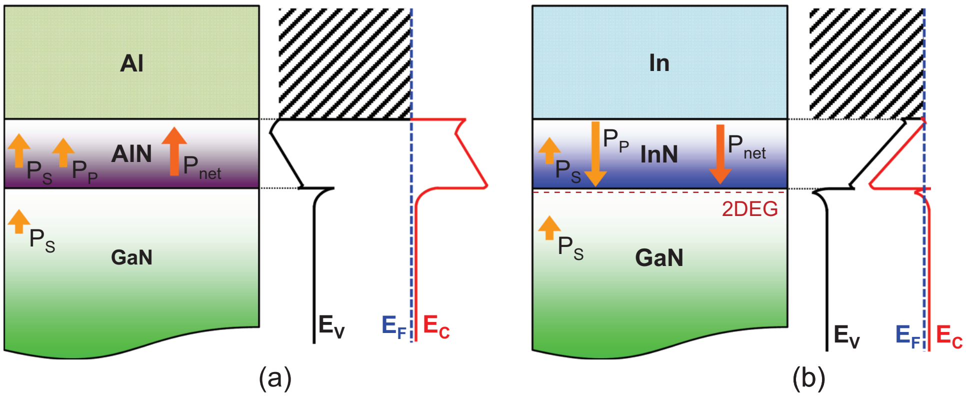

FIG. 1. (Color online) Schematic band diagrams for (a) Al/AlN/N-face *n*-GaN and (b) In/InN/N-face *n*-GaN structures. P_S and P_P denote spontaneous polarization and piezoelectric polarization, respectively. For an InN epilayer on N-face *n*-GaN, P_S is calculated to be $-0.032\ \mathrm{C/m^2}$ and P_P is $0.241\ \mathrm{C/m^2}$.

However, the annealing-induced reduction of contact resistivity in the In contact is surprising because none of previous metallization schemes showed such an improvement in contact resistivity. After annealing at 300 °C, the contact resistivity of the In contact was as low as $2.2 \times 10^{-5}\ \Omega\ \mathrm{cm}^2$.

In XPS measurements, the change in interfacial band bending at the metal/GaN interface with annealing can be determined by monitoring the shift of a core level peak from the underlying GaN. Figure 3(a) shows Ga $2p_{3/2}$ core level spectra for a 10 Å thick In contact to N-face *n*-GaN before and after annealing at 300 °C. The peak shifts toward the higher binding energy by 0.13 eV after annealing at 300 °C. The shift means that interfacial band bending between In and GaN decreases. This corresponds to the reduction of the effective potential barrier height for the transport of electrons across the interface, consistent with the results in Fig. 2.

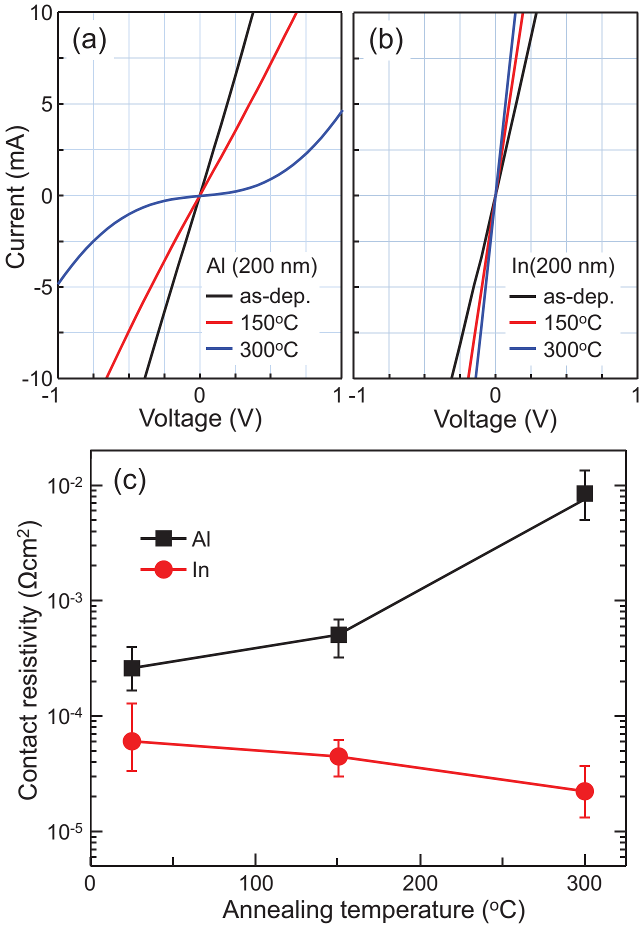

FIG. 2. (Color online) (a) and (b) Typical $I-V$ curves of Al (200 nm) and In (200 nm) contacts to N-face *n*-GaN before and after annealing. (c) Contact resistivities of the Al and In contacts as a function of annealing temperature.

Figure 3(b) shows In $3d_{5/2}$ core level spectra for the 10 Å thick In contact to N-face n-GaN. After annealing at 300 °C, the full width at half maximum of the peak increased from 1.77 eV to 1.84 eV. To identify the change in chemical bonding states of In, the In $3d_{5/2}$ spectra were deconvoluted. With careful fitting, it was found out that the peaks consist of three components: In-In, In-N, and In-O bonds. The binding energy differences between deconvoluted peaks, 1.5 ± 0.05 eV ($= E_{\text{In-O}} - E_{\text{In-In}}$) and 0.5 ± 0.05 eV ($= E_{\text{In-N}} - E_{\text{In-In}}$), are in good agreement with the previous results.[18,19] At the as-deposited condition, the existence of the In-N bond indicates the interfacial reaction of In with GaN. As the portion of the In-N peak increases with annealing, the peak shift toward the high binding energy is accompanied.

The dependence of contact resistivity on annealing temperature in the In contact on N-face *n*-GaN can be explained by the formation of the InN interfacial compound, based on the experimental results. A large number of N vacancies which are effective donors in GaN have been formed at the surface of the dry-etched GaN.[20] In addition, the formation of the InN interfacial layer creates more N vacancies in GaN, enhanced the ohmic behavior. Thus, the contact resistivity of the as-deposited In contact is lower than that of the as-deposited Al contact although the work functions of In and Al are very close to ∼4.1 eV.[16] Upon annealing, a considerable portion of N vacancies is annihilated out by the compensation with N atoms from the bulk GaN and ambient.[8] However, the enriched formation of the InN interlayer with annealing overcomes the annihilation of N vacancies and increases the carrier concentration near the interface, leading to the lower contact resistivity for the In contact.

To confirm that In is an efficient ohmic contact layer to N-face *n*-GaN, we have employed Ti/Al as the overlayer. Figure 4 shows *I-V* curves of Ti/Al and In/Ti/Al contacts to N-face n-GaN before and after annealing. For the reference Ti/Al contact, thermal degradation is observed, which is consistent with the previous reports.[7,10–14] The contact resistivity drastically increase from $6.9 \times 10^{-5}\ \Omega\ \mathrm{cm}^2$ to $7.4 \times 10^{-3}\ \Omega\ \mathrm{cm}^2$ after annealing at 300 °C. For the In/Ti/Al contact, the annealing reduces the contact resistivity from $1.8 \times 10^{-4}\ \Omega\ \mathrm{cm}^2$

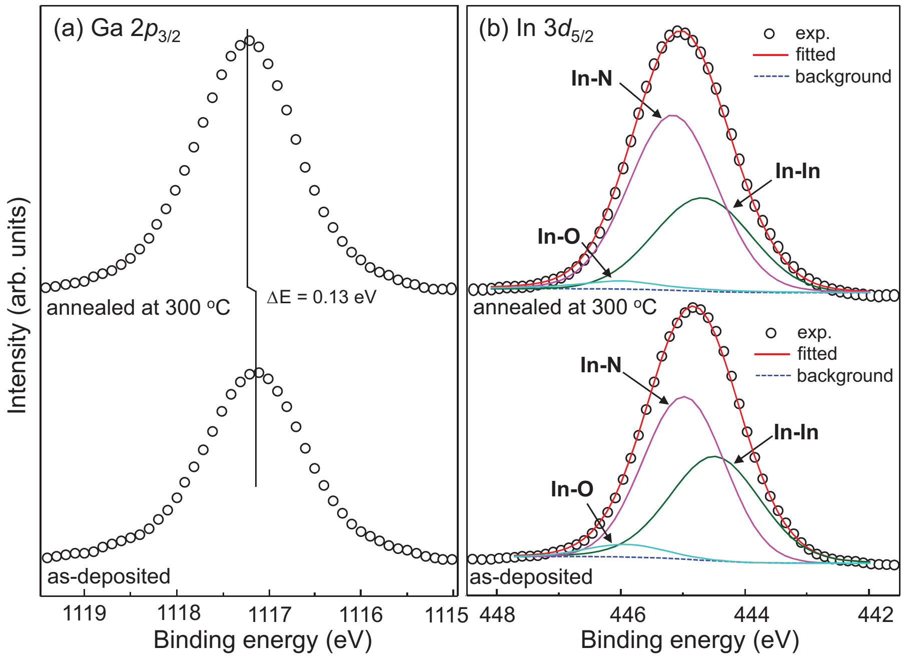

FIG. 3. (Color online) XPS spectra of (a) Ga $2p_{3/2}$ (b) In $3d_{5/2}$ core levels for as-deposited and 300 °C-annealed In (10 Å) contacts on N-face *n*-GaN. All In$3d_{5/2}$ peaks were fitted using a Shirley background and mixed Lorentzian–Gaussian line shapes.

to 1.2×10^{-5} Ω cm^2. The more pronounced improvement of contact resistivity in the In/Ti/Al contact than in the In contact is attributed to our prediction that the Ti/Al overlayer can promote the reaction with In and GaN to form an InN interfacial layer. Even after annealing at 450 °C, the In/Ti/Al contact shows no degradation, indicating that the Ti/Al overlayer prevents the decomposition of the InN interlayer and persistently assists the formation of InN at the higher temperature. We suggest that Ti/Au, Cr/Au, Ni/Au, or Pt/Au can be also used for the overlayer.

In conclusion, we have demonstrated that low resistance ohmic contacts to N-face *n*-GaN are achieved using In. While conventional Al-based contacts showed severe degradation after annealing at 300 °C, In-based contacts displayed considerably improved ohmic behaviors after annealing. The origin of the ohmic contact formation and the annealing-induced improvement was discussed with the formation of an interfacial InN layer. Our results prove that In-based ohmic contacts can be utilized as reliable electrodes to N-face *n*-GaN of GaN-based vertical LEDs for solid-state lighting.

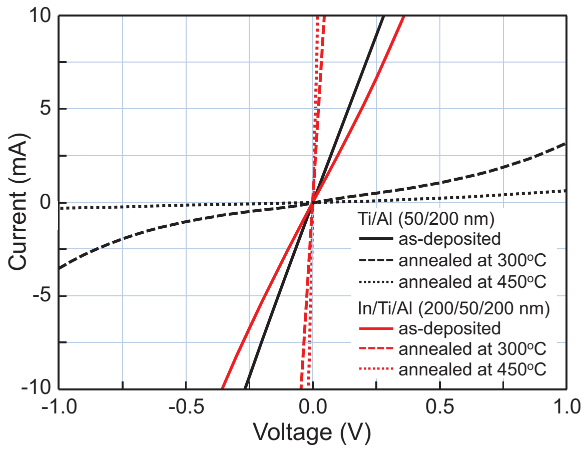

FIG. 4. (Color online) Typical $I-V$ curves of Ti/Al (50/200 nm) and In/Ti/Al (200/50/200 nm) contacts to N-face *n*-GaN before and after annealing at 300 °C and 450 °C.

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