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Low Resistance CrB_2/Ti/Al Ohmic Contacts to N-face n-GaN for High Power GaN-Based Vertical Light Emitting Diodes

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We investigated the effect of a CrB_2 interlayer on the electrical properties of Ti/Al contacts to N-face n-type GaN for high performance vertical light emitting diodes. Before annealing, both CrB_2 (30 nm)/Ti (30 nm)/Al (200 nm) and Ti (30 nm)/Al (200 nm) contacts produce ohmic behaviors with a contact resistivity of 1.92×10^{-4} and 1.99×10^{-4} Ω cm^2, respectively. Unlike the Ti/Al contacts, however, the CrB_2/Ti/Al contacts remain ohmic with a contact resistivity of 8.30×10^{-4} Ω cm^2 even after annealing at 250°C for 1 min in N_2 ambient. X-ray photoemission spectroscopy and secondary-ion mass spectrometry examinations are performed to describe the ohmic formation behavior.
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For the application of light emitting diodes (LEDs) to solid-state lighting, high power and high efficiency vertical injection GaN-based LEDs fabricated by wafer bonding (or electroplating) combined with a laser lift-off (LLO) process have been extensively investigated.[1-6] One of the main parameters that n-type side-up vertical LEDs yield relatively low light output is related to the difficulty in obtaining highly reliable p-type and low resistance n-type ohmic electrodes. For n-type contacts, conventional LEDs require n-ohmic contacts to Ga-face GaN, which can be easily formed using either Ti- or V-based schemes,[7-11] while vertical LEDs require the development of high quality ohmic contacts to N-face n-GaN.[12-14] N-face ohmic contacts was difficult to form.[12-19] For example, Jang et al.,[15] investigating Ti/Al-based contacts to metallorganic chemical vapor deposition grown Ga- and N-face n-GaN, reported that Ti/Al contacts to Ga-face n-GaN are ohmic when annealed at 700°C, while contacts to N-face n-GaN produces nonohmic behavior. The poor electrical characteristics were attributed to the absence of a polarization-induced two-dimensional electron gas (2DEG) formed at the AlN/GaN interface due to the opposite direction of spontaneous polarization built from the bulk to the surface.[16] Jeon et al.,[17] investigating the electrical characteristics of Ti/Al contacts to N-polar n-GaN films prepared by an LLO process, showed that the contacts were electrically degraded when annealed at 300°C. To improve the electrical behavior of Ti/Al contacts to LLO-prepared N-face n-GaN, Jang et al.[14] introduced a 5 nm thick Pd interlayer at the interface between Ti and n-GaN. Compared to Ti/Al contacts, the Pd/Ti/Al contacts produced a much lower contact resistance and a better thermal stability when annealed above 450°C. The improvement was ascribed to the presence of stable AlN at the interface due to the insertion of the Pd interlayer. Very recently, Jeon et al.,[18] investigating the temperature dependence of the electrical properties of TiN/Al and Ti/Al contacts to LLO-prepared N-face n-GaN, reported that both the contacts were electrically degraded upon annealing at temperatures of 300–500°C. They attributed the electrical degradation to the formation of deep acceptor-like Ga vacancies near the n-GaN surface region caused by the out-diffusion of Ga.[18] This result implies that the Ga out-diffusion would be a main difficulty in forming low resistance ohmic contact to N-face n-GaN. In this work, we have investigated the effect of CrB_2 interlayer on the electrical properties of Ti/Al contacts to N-face n-GaN. CrB_2 was chosen because it has a small work function of ~3.18 eV [20] and may serve as a barrier to the out-diffusion of Ga atoms from the n-GaN. Both Ti (30 nm)/Al (200 nm) and CrB_2 (30 nm)/Ti (30 nm)/Al (200 nm) contacts produce ohmic behaviors. Unlike the Ti/Al contacts, however, the CrB_2/Ti/Al contacts remain ohmic even after annealing at 250°C.

N-face n-GaN samples were prepared from LED wafers consisting of ~0.15 μm thick p-GaN, a multiple quantum-well layer, 4 μm thick n-GaN ($n_d = 5 \times 10^{18}$ cm^{-3}), 2 μm thick undoped GaN, and a sapphire substrate. Before an LLO process, the wafer was bonded to a Si wafer using a Au–Sn alloy by thermal compression at 300°C. The LLO process was then performed using a KrF excimer laser (248 nm) to separate the sapphire substrate, followed by HCl:deionized (DI) water (=1:2) cleaning for 5 min to remove Ga droplets. The undoped GaN layers were then etched by an inductively coupled plasma reactive ion etching system to expose the n-GaN layer. To investigate the contact resistivity of the samples, circular transfer length method (CTLM) patterns were defined using the standard photolithography and lift-off techniques. The outer dot radius of the CTLM patterns was 200 μm and the spacing between the inner and outer radii changed from 5 to 40 μm. Before metal deposition, the samples were cleaned by HCl:DI water (=1:2) solution for 1 min and rinsed with DI water for 5 min. 30 nm thick CrB_2 films were electron-beam evaporated on the n-GaN layers using a CrB_2 target on which Ti (30 nm)/Al (200 nm) layers were deposited. For comparison, Ti (30 nm)/Al (200 nm) films were also prepared. Some of the samples were rapid thermal annealed at 250°C for 1 min in N_2 ambient. The temperature was chosen because during a chip fabrication process, LEDs undergo an annealing process at ~250°C. Furthermore, annealing above 300°C should be avoided because it causes LLO-prepared LEDs/metal supporter to get deformed. Current–voltage (*I-V*) data were measured at room temperature using a parameter analyzer. Secondary-ion mass spectrometry (SIMS) and X-ray photoemission spectroscopy (XPS) examinations were performed to understand the electrical degradation phenomena.

Figure 1 shows *I-V* characteristics of CrB_2 (30 nm)/Ti (30 nm)/Al (200 nm) and Ti (30 nm)/Al (200 nm) contacts on N-face n-GaN before and after annealing at 250°C. Before annealing, both the CrB_2/Ti/Al and Ti/Al samples exhibit ohmic behaviors. The specific contact resistance was determined from plots of the measured resistance vs the spacing between the CTLM pads. Measurements showed that the specific contact resistivity was 1.92×10^{-4} and 1.99×10^{-4} Ω cm^2 for the as-deposited CrB_2/Ti/Al and Ti/Al contacts, respectively. Upon annealing, however, the Ti/Al contacts become nonohmic, while the CrB_2/Ti/Al contacts remain ohmic. The specific contact resistivity of the annealed CrB_2/Ti/Al contacts was 8.30×10^{-4} Ω cm^2.

To characterize the chemical bonding states of Ga, XPS examinations were performed on the CrB_2/Ti/Al and Ti/Al samples before and after annealing at 250°C. Figure 2 shows the Ga 2p core levels obtained from the contacts/GaN interface regions. XPS core level

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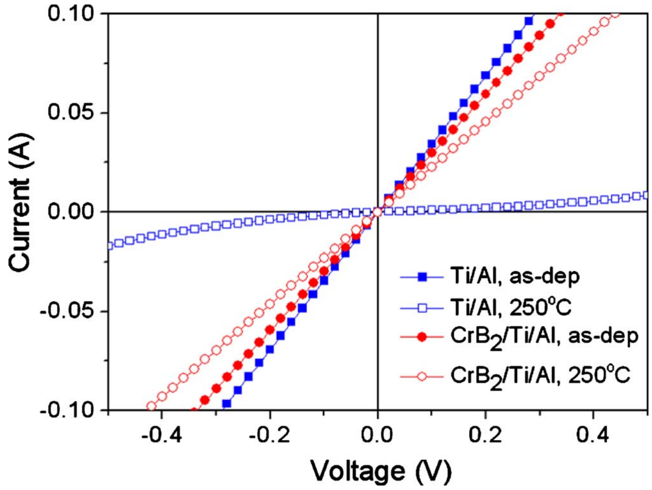

Figure 1. (Color online) *I-V* characteristics of CrB_2 (30 nm)/Ti (30 nm)/Al (200 nm) and Ti (30 nm)/Al (200 nm) contacts on N-face n-GaN before and after annealing at 250°C.

peak fittings were performed with Shirley-type background and Lorentzian–Doniac–Sunsic curves convoluted with Gaussian profile. For the Ti/Al contact, the Ga 2p core level moved toward the lower binding energy side by 0.20 eV after annealing (Fig. 2a). This indicates that the upward band bending increases upon annealing, leading to an increase in the Schottky barrier for the Ti/Al contacts. For the CrB_2/Ti/Al samples (Fig. 2b), the Ga 2p core level moved slightly toward the lower binding energy side by 0.08 eV after annealing. This indicates that the band bending is negligible, leading to a slight change in the Schottky barrier height for the CrB_2/Ti/Al contacts. The normalized N/Ga atomic ratios were also obtained from the integral intensity of the XPS N 1s peak against the Ga 2p peak (Ga–N bond) with reference to those of the as-deposited samples. Measurements showed that the normalized ratio was 1.04 ± 0.02 and 1.01 ± 0.01 for the Ti/Al and CrB_2/Ti/Al samples, respectively. This shows that unlike the CrB_2/Ti/Al sample, the N-face n-GaN surface region of the Ti/Al sample is Ga-deficient, indicating that Ga vacancies are generated at the n-GaN surface region.

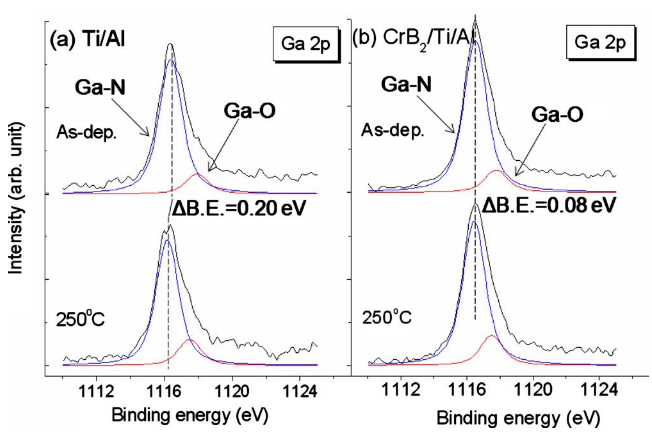

Figure 2. (Color online) The Ga 2p core levels obtained from the contacts/GaN interface regions before and after annealing at 250°C.

To characterize the interfacial reactions, SIMS depth profile examinations were made of the Ti/Al and CrB_2/Ti/Al samples on the N-face n-GaN before and after annealing at 250°C (Fig. 3). For both the as-deposited samples, Ti and Al profiles reveal well-defined individual layers, indicating the absence of interfacial reactions at room temperature. A comparison of the Ga profiles shows that for the Ti/Al samples, Ga atoms are out-diffused into the n-electrodes after annealing (as indicated by the arrow). However, the Ga out-diffusion is less significant in the CrB_2/Ti/Al samples (as indicated by the arrow). This indicates that the CrB_2 layer serves as a diffusion barrier to the out-diffusion of Ga atoms, which is consistent with the XPS results (Fig. 2).

The *I-V* results showed that both the as-deposited CrB_2/Ti/Al and Ti/Al samples produced good ohmic behaviors. The nonalloyed ohmic formation could be the result of reactive ion etching,[21,22] leading to the generation of numerous donorlike surface defects such as V_N or O_N at the n-GaN surface region. As for the Ti/Al-based contacts to Ga-face n-GaN, which were annealed at temperatures in the range 400–900°C, ohmic formations were explained in terms of the generation of N vacancies and 2DEGs at the AlN/GaN interface caused by the formation of interfacial AlN[7,15,23] and additional N vacancies due to the occurrence of TiN.[24] For the Ti/Al-based contacts to N-face n-GaN, the electrical degradation at 600–900°C was related to the absence of a polarization-induced 2DEG.[15] In the present work, the Ti/Al contacts underwent significant electrical degradation when annealed at 250°C. The low temperature degradation cannot be explained by the generation of interfacial AlN and TiN phases. Alternatively, the degradation could be related to the presence of Ga vacancies near the n-GaN surface region[18] occurring in consequence of Ga out-diffusion. Ga atoms were dominantly out-diffused into the metal electrodes due to the lower formation energy of Ga vacancy compared to that of N vacancy in n-GaN.[25] This seems to be consistent with the solubility (~14 wt % at ~250°C) of Ga in Ti (obtained by extrapolating from the phase diagram).[26] The acceptor-like Ga defects could cause an electrical compensation in the n-GaN, decreasing the electron concentration and so increasing the effective Schottky barrier height. However, the CrB_2/Ti/Al contacts remained ohmic after annealing, although somewhat electrically degraded. Based on the XPS and SIMS results (Fig. 2 and 3), the relatively stable electrical behavior could be explained by the fact that the CrB_2 interlayer hampers the Ga out-diffusion by serving as a diffusion barrier.

To summarize, we investigated the effect of the CrB_2 interlayer on the electrical properties of Ti/Al contacts to N-face n-GaN. Be-

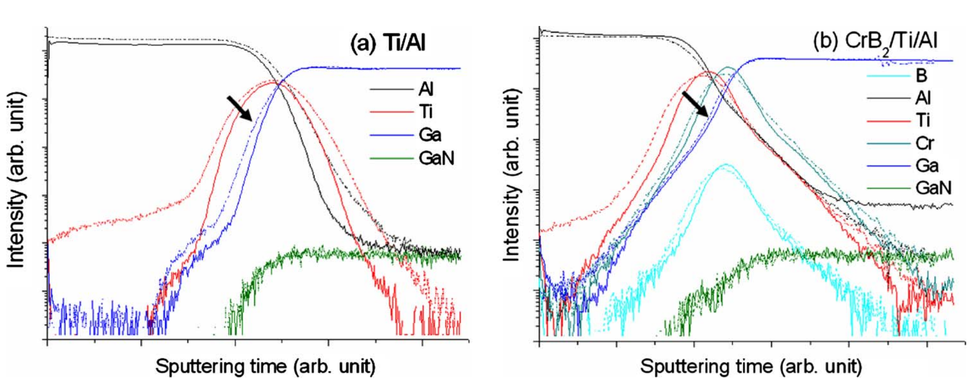

Figure 3. (Color online) SIMS depth profiles of the (a) Ti/Al and (b) CrB_2/Ti/Al samples on the N-face n-GaN before and after annealing at 250°C.

fore annealing, the CrB_2/Ti/Al contacts exhibited electrical characteristics similar to those of Ti/Al contacts. Unlike the Ti/Al contacts, the CrB_2/Ti/Al samples produced ohmic behavior when annealed at 250°C. Based on the XPS and SIMS results, the annealing dependence of the electrical properties was described in terms of the outdiffusion of Ga. The results show that the use of CrB_2 interlayers is fairly effective in forming low resistance ohmic contacts to N-face n-GaN for the fabrication of high power vertical LEDs.

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