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Low Operation Voltage of Nitride-Based LEDs with Al-Doped ZnO Transparent Contact Layer

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We have developed nitride-based multiquantum well light-emitting diodes (LEDs) with E-beam evaporated Al-doped ZnO (AZO) transparent contact layers (TCLs). With 20 mA injection current, it was found that forward voltages were 3.32, 3.33, and 4.91 V, while output powers were 10.1, 11.8, and 6.0 mW for the indium-tin-oxide LED, E-beam evaporated AZO LED, and sputter-evaporated AZO LED, respectively. The low operation voltage of the E-beam evaporated AZO LED is attributed to the deposition of low-resistivity TCLs, and the elimination of plasma damage in the p-GaN layer is attributed to use of the E-beam evaporated AZO. The high output power of the E-beam evaporated AZO LED is due to the enhancement of light extraction resulting from the high refractive index of AZO TCL.
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III-nitride-based materials have recently emerged as important semiconductor materials, leading to the realization of high-performance light emitters from the UV to blue and green spectral regions.[1,2] For example, GaN-based blue and green light-emitting diodes (LEDs) have already been extensively used in full-color displays, and they are highly efficient light sources for traffic light lamps. UV emitters are of interest for fluorescence-based chemical sensing, flame detection, and possibly optical storage. These nitride-based LEDs are also potentially useful for solid-state lighting. To realize solid-state lighting, however, further improvement of the output efficiency of these LEDs is necessary. It has been demonstrated that several methods can be used to improve output efficiency of GaN-based LEDs, such as textured surfaces,[3-5] highly transparent p-contact layers,[6,7] proper substrate design,[8] and flip-chip packaging.[9] Because photons generated in the active region will be partially absorbed by the p-contact layer and partially lost from total internal reflection, it is necessary to increase the transmittance of the p-contact layer. It has been shown that the output power of nitride-based UV/blue/green LEDs with indium-tin-oxide (ITO) p-contact is much larger than that with conventional Ni/Au p-contact.[6,7] It is well known that Al-doped ZnO (AZO) is a wide-bandgap material. It has similar electrical and optical properties as ITO, but it is a nontoxic material which has high temperature stability and costs less to mass produce.[10] There are some reports on ZnO transparent contacts to p-GaN. A nonohmic contact with a rectifying property has been demonstrated when AZO is deposited directly onto p-GaN.[10-13] Therefore, it is necessary to change such a rectifying contact into ohmic with low operation voltage of LED devices by inserting a Ni, Ni/Au, or NiO_x contact layer between the AZO and p-GaN layers. Lim et al. have shown a very low specific contact resistance of $3.4 \times 10^{-4}\ \Omega\ cm^2$ by using indium-oxide-doped ZnO (IZO) on p-GaN without an insert layer.[14] Although the contact resistance was low, the operation voltage of the LED with an IZO transparent contact layer (TCL) was still high, 4.3 V at 20 mA, ~0.75 V higher than that of the LED with Ni/Au TCL. Recently, Nakahara et al. have shown Ga-doped ZnO TCLs for nitride-based LED; by use of molecular beam epitaxy.[15] It has been also shown that the LEDs with Ga-doped ZnO TCLs had the lowest forward voltage, 3.5 V at 20 mA. In this study, we report the fabrication of nitride-based LEDs with E-beam evaporated AZO TCLs. We show that by using the E-beam evaporated AZO process without an insert layer, low contact resistance, high transmittance, and low operation voltage comparable to ITO TCLs can be achieved. The E-beam evaporated process is an inexpensive and simple method and is useful to those who work in LED industries.

Samples used in this study were all grown by metallorganic chemical vapor deposition.[6,7] To evaluate the properties of the contacts themselves, we first prepared thick p-GaN samples by depositing a 30 nm thick, low-temperature GaN nucleation layer followed by a 2 μm thick, Mg-doped GaN epitaxial layer on top of the c-face (0001) sapphire substrates. We subsequently deposited a Si-doped n^+-$In_{0.23}Ga_{0.77}N$/GaN (5 Å/5 Å) short-period superlattice (n^+-SPS) structure on top of the p-GaN layer. By growing such an n^+-SPS structure on top of the p-GaN cap layer, one could achieve good "ohmic" contact through tunneling when the n^+(SPS)–p(GaN) junction was properly reverse biased. Recently, we have demonstrated low-operation-voltage, nitride-based LEDs with ITO TCL by using an n^+-SPS tunneling contact layer.[6,7] We used transparent AZO to replace ITO as the p-contact material. We then either deposited a 250 nm thick E-beam evaporated AZO film or 230 nm thick E-beam evaporated ITO contact onto the samples. The deposition rate of AZO was 8 nm/min. Deposition temperature was 400°C for the E-beam evaporated AZO contacts. Al content was 5% in AZO. In contrast, the sputtering-evaporated AZO contacts deposited by dc sputtering at room temperature. Details of the deposition of the AZO layer by sputtering can be found elsewhere.[10,11] These three contact materials were also deposited onto double-side-polished sapphire. Figure 1 shows the transmission spectra of the three different kinds of contact layers. In this figure, the transmittance of each film was normalized with respect to the transmittance of the double-side-polished sapphire. It can be seen clearly that AZO has similar transmittance as ITO. At 455 nm, it was found that the transmittances were 90, 93, and 91% for the ITO, E-beam evaporated AZO, and sputtering-evaporated AZO, respectively. This suggests that AZO is indeed optically suitable to serve as the upper contact of nitride-based LEDs. The electrical properties of these three contacts on GaN samples were then measured by an HP4156C semiconductor parameter analyzer. Figure 2 shows the current–voltage (*I-V*) characteristics of ITO and AZO contacts on p-GaN and n^+-SPS structure. It was found that we could achieve a nonohmic contact with a rectifying property when we deposited AZO by using the dc sputtering. However, we could change such a rectifying contact into an ohmic contact with a specific contact resistance of $4.09 \times 10^{-2}\ \Omega\ cm^2$ by using E-beam evaporated AZO. As shown in Table I, the resistivity of the ITO sample was $2.66 \times 10^{-4}\ \Omega\ cm^2$. In contrast, the resistivity of the E-beam evaporated AZO sample could reach $3.80 \times 10^{-4}\ \Omega\ cm^2$, which was at least 1 order of magnitude lower than that observed from sputtering-evaporated AZO.

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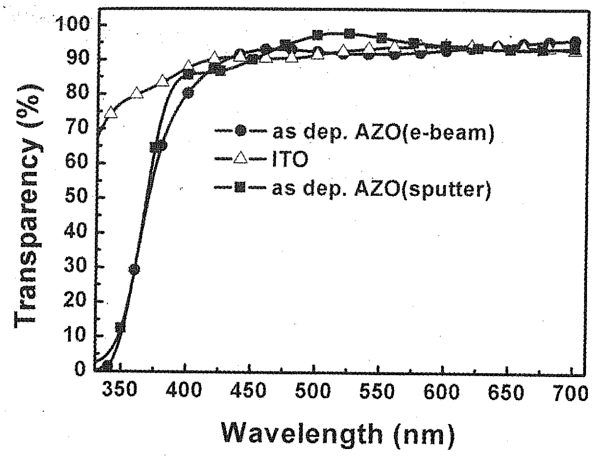


Figure 1. Transmission spectra of ITO, AZO (E-beam), and AZO (sputter) deposited on double-side-polished sapphire.

These results revealed that the E-beam evaporated AZO contact can serve as a suitable TCL for the fabrication of GaN-based light-emitting devices.

Nitride-based LEDs with ITO and AZO film as the upper contacts were also fabricated. LEDI has deposited ITO TCL. LEDII has deposited AZO TCL using the E-beam evaporating system. LEDIII has deposited AZO TCL using the dc sputtering system. The structure of the LEDs consists of a 30 nm thick GaN nucleation layer, a 4 μm thick Si-doped GaN n-cladding layer, an InGaN/GaN multiquantum well (MQW) active region, a 50 nm thick Mg-doped $Al_{0.15}Ga_{0.85}N$ p-cladding layer, a 0.2 μm thick Mg-doped GaN layer, and a Si-doped n^+-InGaN/GaN SPS structure. The MQW active region consists of six periods of 3 nm thick $In_{0.23}Ga_{0.77}N$ well layers and 15 nm thick GaN barrier layers. Details of the LED structures can be found elsewhere.[6,7] For these LEDs, we deposited a 0.2 μm thick p-GaN layer directly on top of the p-type $Al_{0.15}Ga_{0.85}N$ at 850°C. The surface morphology of the LED was rough. As shown in the inset of Fig. 4, the cross-sectional view transmission electron microscopy (TEM) image of p-GaN layer was rough with V-pits. Such a rough surface could be attributed to the fact that Ga atoms might not have enough energy to migrate to proper sites at low temperatures. Thus, the lateral growth rate of GaN will become smaller due to the smaller Ga diffusion length at low temperatures.[16] The as-grown samples were then furnace annealed at 740°C in N_2 ambient to activate Mg in the p-type $Al_{0.15}Ga_{0.85}N$ and p-type GaN layers. The surface of the samples was then partially etched until the n-type GaN layer was exposed. ITO and AZO were subsequently evaporated onto the sample sur-

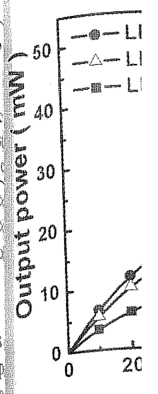
Table I. Hall measurement result of ITO, AZO (E-beam), AZO (sputter) films and specific contact resistance.

Sample	Resistivity (Ω cm)	Concentration (cm^{-3})	Specific resis… (Ω…
ITO	2.66×10^{-4}	1.51×10^{21}	2.20…
AZO (E-beam)	3.80×10^{-4}	5.60×10^{20}	4.09…
AZO (sputter)	4.00×10^{-3}	2.00×10^{20}	None

face to serve as the upper contact. The Cr/Pt/Au contact was ited onto the exposed n-type GaN layer to serve as the n-typ trode. The two 2 in. epi-wafers were then lapped down to 90 μm. We then used scribe and break to fabricate 350 × 3 InGaN/GaN LED chips.

Figure 3 shows forward *I-V* and dynamic resistance cha tics of the fabricated nitride-based LEDs. It was found that eration voltage measured from the LED with sputtering eva AZO was much higher than those measured from the oth LEDs. It was also found that E-beam evaporated AZO could cantly reduce the LED operation voltage. The 20 mA forwa ages measured from LEDI, LEDII, and LEDIII were 3.32, 3. 4.91 V, respectively. Compared with the LEDI and LED larger 20 mA forward voltage measured from the LEDIII co attributed to the larger specific contact resistance be sputtering-evaporated AZO and the underneath n^+-SPS struct shown in Fig. 2. There are two reasons that account for the l operation voltage of LEDs with E-beam evaporated AZO. F lower E-beam evaporated AZO layer resistivity could resu smaller contact resistance and a better current spreading. Th 20 mA forward voltage and the dynamic resistance were both lar for ITO LED. Second, it is well known that the electrical acteristics of p-GaN change its resistivity into semiconducto the plasma damage.[17,18] The worsened *I-V* characteristic sputtering-evaporated AZO contact that is attributed to the p layer was damaged by plasma in the sputter system. As a resu can eliminate the plasma damage by using the E-beam evapo system to obtain the low operation voltage of the LEDs.

Sputtering-evaporated AZO contacts were deposited by dc tering result in a larger p-layer resistivity, a large AZO resisti larger p-contact resistance, and a worse current spreading. N form current spreading leads to current crowding in localized of the device. Thus, LEDIII will have a severe heating effect. S self-heating can degrade the output power of the LED. A signi difference in the performance of LEDs with various TCLs c found in its intensity-current (*L-I*), characteristics shown in F With 20 mA injection current, it was found that the output p were 10.1, 11.8, and 6.0 mW for the LEDI, LEDII, and LE



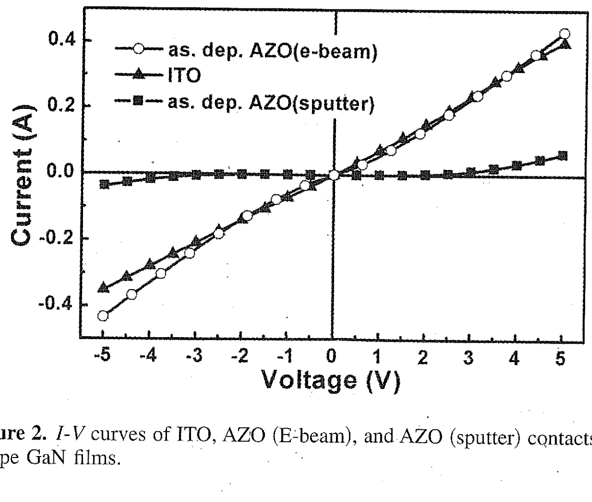


Figure 2. *I-V* curves of ITO, AZO (E-beam), and AZO (sputter) contacts on p-type GaN films.

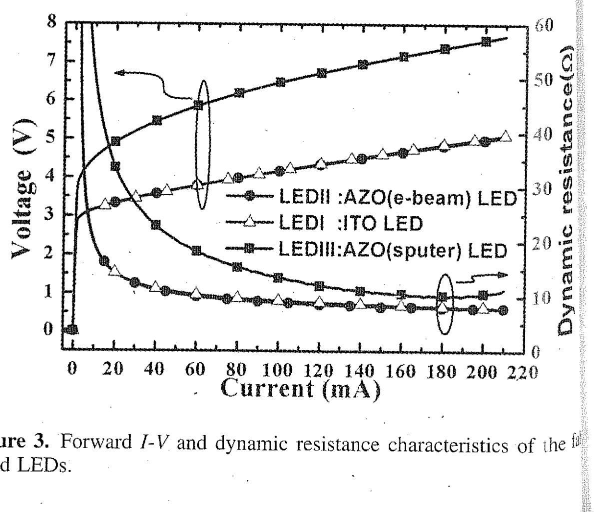
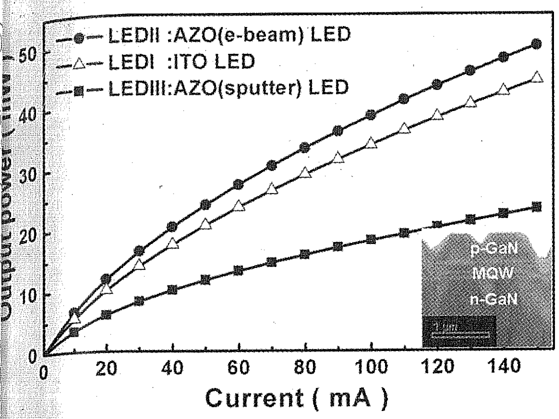


Figure 3. Forward *I-V* and dynamic resistance characteristics of the fa cated LEDs.



[...]e 4. *L-I* characteristics of the fabricated LEDs. The inset shows elec[...]minescence spectra of the fabricated LEDs with a 20 mA dc injection [...]nt. The cross-sectional view TEM image of the LED with the rough [...]e is shown in the inset.

[...]ctively. Compared with ITO LED, the 20 mA output power [...]enhanced by 16.8% for the E-beam evaporated AZO TCL LED. [...]is attributed to the high refractive index of AZO TCL that [...]nces the escape probability of photons generated in the MQW [...]e LED. ZnO-based TCLs with high refractive index of around [...]would render more advantage when a roughening process is [...]rmed on the surface. In other words, because packaged LEDs [...]generally encapsulated using epoxy with a refractive index of [...]nd 1.5, further improvement in light extraction by means of [...]ce roughening performed on ITO TCL would thus be minor, [...]use the typical refractive index of an ITO film prepared by our [...]am evaporator is around 1.7.

Conclusion

[...]O (230 nm) and AZO (250 nm) films were deposited onto [...]le-side-polished sapphire, p-GaN layers with n^+-InGaN/GaN [...]structures and nitride-based LEDs. It was found that E-beam [...]orated AZO could provide an extremely high transparency (i.e., [...]at 455 nm) and a reasonably small $4.09 \times 10^{-2}\ \Omega\ cm^2$ specific [...]ct resistance. We enhanced the 20 mA output power by 16.8%, [...]mpared to the ITO LEDs, for the E-beam evaporated AZO TCL [...] The 20 mA forward voltage of the LED with E-beam evapo[...] AZO TCL was almost the same as the LED with ITO TCL. These results revealed that the E-beam evaporated AZO contact can serve as a suitable TCL for the fabrication of nitride-based light-emitting devices.

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