Enhanced Luminescence of InGaN-Based 395 nm Flip-Chip Near-Ultraviolet Light-Emitting Diodes with Al as N-Electrode *

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High-reflectivity Al-based n-electrode is used to enhance the luminescence properties of InGaN-based 395 nm flip-chip near-ultraviolet (UV) light-emitting diodes. The Al-only metal layer could form the Ohmic contact on the plasma etched n-GaN by means of chemical pre-treatment, with the lowest specific contact resistance of $2.211\times10^{-5}\,\Omega\cdot cm^2$. *The Al n-electrodes enhance light output power of the 395 nm flip-chip near-UV light-emitting diodes by more than 33% compared with the Ti/Al n-electrodes. Meanwhile, the electrical characteristics of these chips with two types of n-electrodes do not show any significant discrepancy. The near-field light distribution measurement of packaged chips confirms that the enhanced luminescence is ascribed to the high reflectivity of the Al electrodes in the UV region. After the accelerated aging test for over 1000 h, the luminous degradation of the packaged chips with Al n-electrodes is less than 3%, which proves the reliability of these chips with the Al-based electrodes. Our approach shows a simplified design and fabrication of high-reflectivity n-electrode for flip-chip near-UV light emitting diodes.*

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GaN-based light-emitting diodes (LEDs) have attracted tremendous attention and undergone rapid development over the past two decades. A combination of GaN-based blue LEDs and yellow phosphor is the most successful and commercial scheme to generate white light. However, such an approach suffers from high color temperature and low color-rendering index.[1] Then a combination of GaN-based near-UV LEDs and red/green/blue phosphors is proposed and confirmed to be the most promising scheme of developing next-generation white LEDs.[2,3] Near-UV irradiation around 395 nm is preferred since the red/green/blue phosphors show stronger excitation at this wavelength.[4] Moreover, with the advantages of low power consumption and being environmentally friendly, the 395 nm GaN-based near-UV LEDs have been gradually substitutable for mercury lamps as the light source for different UV curing applications. Although the 395 nm GaN-based near-UV LEDs are now available for commercial production, researchers are still developing different techniques to further improve their performance.

In recent years, flip-chip configuration has been considered to be the best approach to develop high power and high brightness GaN-based LEDs. Compared with the normal chips, the elimination of substrates and wire bonds in flip-chip design lead to higher extraction efficiency and greater versatility in attachment of optics.[5,6] The better heat dissipation properties of flip-chip LEDs can reduce thermal resistance and junction temperature, which may improve their internal quantum efficiency and lifetime. Reflective electrodes are preferred in the flip-chip LEDs, which may enlarge the light extraction efficiency.[7] At present, various metal layers have been reported as the Ohmic contacts on n-GaN, such as Cr/Ti/Al, Ti/Al/X/Au(X∼Ti, Ni, Mo, Pd and Pt).[8–11] Although these metallization schemes can form low-resistance Ohmic contacts on n-GaN, they exhibit low reflectivity in the UV region. Motivated by the attempts to further improve the light extraction efficiency of GaN-based near-UV LEDs, we try to develop a new metallization scheme with high reflectivity, as well as forming the Ohmic contacts on n-GaN. In this work, we design and fabricate 395 nm InGaN-based flip-chip LEDs with Al-only n-electrodes.

The InGaN-based near-UV LED samples were all grown by metal–organic chemical vapor deposition (MOCVD) on 2-inch *c*-plane patterned sapphire substrates. The epitaxial structure consists of a 15-nm-thick GaN nucleation layer, a 1.5-μm-thick undoped GaN layer, a 2-μm-thick n-GaN, an $In_{0.05}Ga_{0.95}N$/GaN multiple-quantum-well (MQW) active region, a 40-nm-thick p-AlGaN electron blocking layer, and a 0.2-μm-thick p-GaN. The MQW active region consists of 13 pairs of 3-nm-thick $In_{0.05}Ga_{0.95}N$ well layers and 13-nm-thick GaN barrier layers grown at 880℃. After the epitaxial growth, mesa etching was performed to expose the n-GaN layer.

To compare the electrical characteristics of Al and Ti/Al contacts on plasma etched n-GaN, several regions of the wafer were kept for definition of the circular transmission line method patterns with 10–50 μm

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gaps. The etched n-GaN samples were extra treated with 40% KOH solution for different times at 60℃. Then the Al (2000 nm) and Ti/Al (50 nm/2000 nm) layers were deposited on these regions, respectively, which were finally cleaved into pieces for annealing at various temperatures from 200℃ to 700℃ in N_2 for 30 min. We measured the current–voltage (I–V) curves of these two different contacts on etched n-GaN samples to obtain the specific contact resistances.

For fabricating the LED chips, a 100-nm-thick indium-tin-oxide (ITO) was deposited on the p-GaN by e-beam evaporation and annealed under ambient nitrogen at 550℃ for 30 min. Next, Ni/Ag/Ni/Ti/Au (1 nm/200 nm/200 nm/200 nm/400 nm) layers were deposited on ITO as the reflective p-electrode. The Al (2000 nm) and Ti/Al (50 nm/2000 nm) layers were deposited onto the n-GaN layer as n-electrodes, respectively. These two n-type contacts were both annealed in N_2 at 500℃ for 30 min. After that, we additionally deposited Ti/Ni (50 nm/ 300 nm) layers on both the annealed p-electrodes and n-electrodes to enhance the adhesion of bonding pads. A 100-nm-thick SiN_X was deposited over the wafer by plasma-enhanced chemical vapor deposition as the passivation layer. Finally, 3000-nm-thick AuSn bonding pads were fabricated on the p-electrodes and n-electrodes by thermal evaporation.

After thinning and polishing processes of the sapphire substrates, all the wafers were finally scribed and broken to form 350 μm×350 μm chips. All measurements of the LED chips were performed at room temperature.

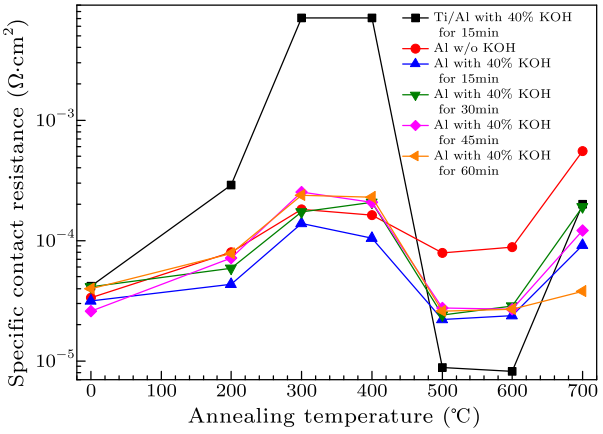

Fig. 1. The specific contact resistances of Al and Ti/Al contacts on n-GaN as a function of the annealing temperature.

The Al and Ti/Al contacts all exhibited linear $I-V$ characteristics before and after annealing, indicating the formation of the Ohmic contacts on the plasma etched n-GaN. The specific contact resistances were then calculated and compared in Fig. 1. Both Al and Ti/Al contacts showed low specific contact resistances with the annealing temperatures ranging from 500℃ to 600℃. The pre-treatment to the surface of etched n-GaN with 40% KOH solution could significantly reduce the specific contact resistances of Al contacts at annealing temperatures higher than 500℃. Moreover, the pre-treatment time might affect the specific contact resistances of annealed Al contacts. Previous reports have proved that Al could form the Ohmic contacts on as-grown n-GaN epilayers.[12–14] The pre-treatment with KOH solution herein was thought to remove native oxides formed on n-GaN surface after mesa etching, which enabled formation of low-resistance Ohmic contacts on etched n-GaN.[15] For Al contacts on the etched n-GaN samples, the minimum specific contact resistance was $2.211\times10^{-5}\,\Omega\cdot\mathrm{cm}^2$ after annealing at 500℃. For Ti/Al contacts on the etched n-GaN samples, the minimum specific contact resistance could reach $8.161\times10^{-6}\,\Omega\cdot\mathrm{cm}^2$ after annealing at 600℃. Since the specific contact resistances of the annealed Al and Ti/Al electrodes varied slightly in the range of 500℃–600℃, the annealing temperature of the two types of n-electrodes was set at 500℃, and the pre-treatment time of KOH solution was set at 15 min during the fabrication of LED chips.

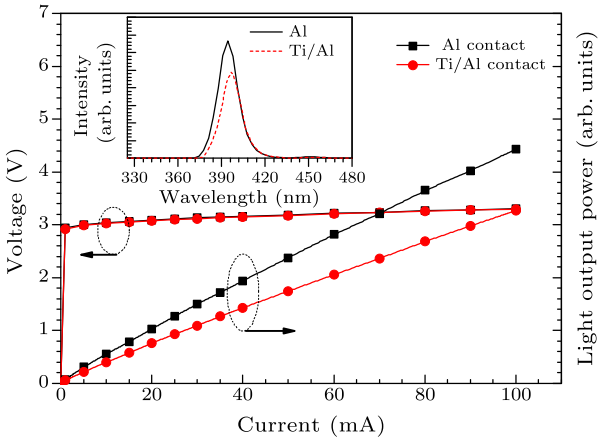

Fig. 2. LOP I–V curves of the UV LEDs with Al and Ti/Al as n-electrodes. The inset shows the EL spectra of these LEDs.

Figure 2 shows the light output power (LOP) and voltages of the fabricated near-UV LED chips with Al and Ti/Al n-electrodes as a function of the injection current. The electrical characteristics of these two chips do not show any significant discrepancy. Under a driving current at 20 mA, the forward voltages of these two chips were both around 3.13 V. The output power of bare LED chips was measured from the substrate side. It was found that LOP of the two sets of chips both increased linearly with the injection current, and the LEDs with Al taken as n-electrode could enhance the output power by more than 33% compared with those with Ti/Al as n-electrode. The inset shows the electroluminescence (EL) spectra of the fabricated LEDs at an injection current of 80 mA. The slight difference between the peak wavelengths of these two LEDs arises from the indium-composition fluctuation in the MQW active region.

We also measured the reflection spectra of the Al and Ti/Al films. During the deposition of n-electrodes

for near-UV LED chips, the double-polished sapphire substrates were also used for reflectivity measurement, and the metal films on sapphire were annealed simultaneously with the LED chips. As demonstrated in Fig. 3, the reflectivity of Al electrodes can reach 87%, which is much higher than that of the Ti/Al electrodes. During the annealing process, the Ti-Al alloys form owing to the inter-diffusion between the separate metal layers on n-GaN. The reflectivity measurement indicates that the Ti-Al alloy electrode cannot reflect the UV light as efficiently as the Al electrode. Thus the Al electrode with higher UV reflectivity can contribute to the enhanced LOP of the near-UV LED chips due to better light extraction efficiency.

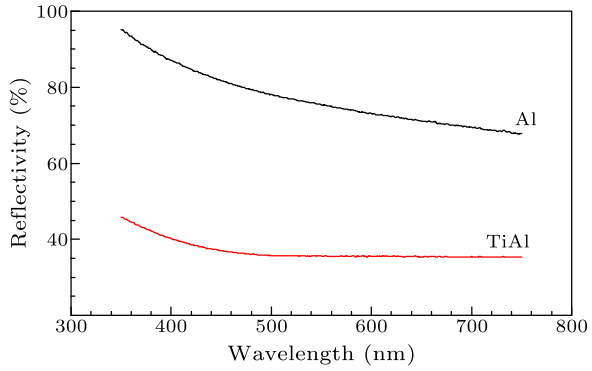

Fig. 3. The reflection spectra of the Al (2000 nm) and Ti/Al (50 nm/2000 nm) films on the double polished sapphire substrate.

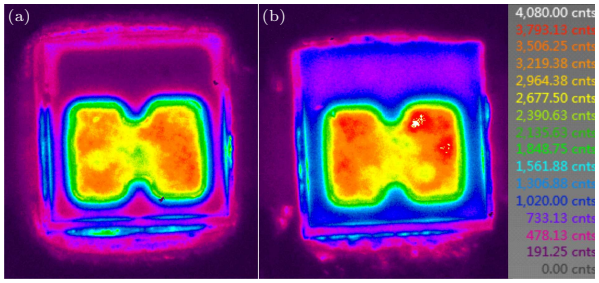

Fig. 4. The near-field light distribution of the packaged chips with (a) Ti/Al and (b) Al as n-electrodes.

Furthermore, these near-UV LED chips with the two types of n-electrodes were flip-chip bonded on ceramic sub-mounts. We used a Spiricon SP620U profiling camera to capture the light near-field distribution of the packaged LED chips. As shown in Fig. 4, under the same injection current, more UV photons could emit from the n-GaN zone of the LED chips with Al as n-electrode owing to the higher reflectivity, consistent with the above test results and analysis. We also examined the far-field emission patterns of these two types of LED chips by angular-resolved EL measurement. Figure 5 compares the measured far-field patterns of the LED chips with Al or Ti/Al electrodes at 80 mA. Obviously, the near-UV emission from the packaged LED chips with Al electrodes exhibited higher intensity than those with Ti/Al electrodes.

To evaluate the reliability of the packaged LED chips with Al or Ti/Al as n-electrodes, accelerated aging tests were conducted at forward current 80 mA for over 1000 h at room temperature. Behavior of optical power during the tests, averaged 10 samples for each type, is shown in Fig. 6. Increasing with aging time, the output powers of these two types of LED chips both decreased slightly. The luminous degradation of the packaged chips with Al n-electrodes was less than 3%, which proved the reliability of these chips with the Al-based electrodes.

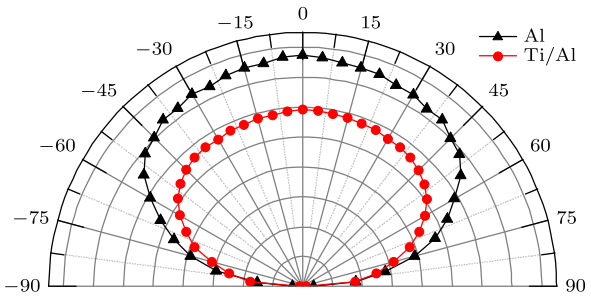

Fig. 5. Measured far-field emission patterns of the packaged chips with Al or Ti/Al as n-electrodes.

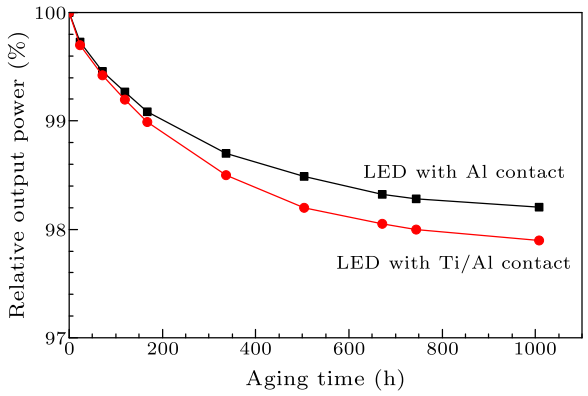

Fig. 6. Normalized output power of the packaged chips submitted to accelerated aging tests under 80 mA.

In conclusion, we have utilized an Al-based n-electrode to enhance the luminescence properties of InGaN-based 395 nm flip-chip near-UV light-emitting diodes. By means of the pre-treatment to etched n-GaN with diluted KOH solution, we achieved heat-stable and low-resistance Al-only Ohmic contacts on etched n-GaN. Although the Ti/Al electrodes provided a lower specific contact resistance than Al electrodes, the I–V characteristics of the near-UV LED chips with these two types of electrodes are very similar. The Al electrodes could improve light output power of 395 nm near-UV LED chips by more than 33%, which is ascribed to the higher reflectivity of the Al in UV region. After flip-chip bonding, the packaged LED chips with Al electrodes still show higher output power and equivalent reliability. Our work indicates a simplified design and fabrication of high-reflectivity n-electrode for flip-chip near-UV light emitting diodes.

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