UV-transparent glass electrodes for high-efficiency nitride-based LEDs

Tae Geun Kim and Tae Ho Lee

Aluminum gallium nitride LEDs with glass electrodes can deliver high luminous efficiency in the UV region owing to low contact resistance and high transmittance.

Nitride-based UV LEDs are promising replacements for conventional UV lamps because of their higher energy efficiency, longer lifetime, and greater reliability. However, the external quantum efficiency of UV LEDs is currently much lower than that of visible LEDs. This difference is mainly due to the light absorption that occurs in the p-type gallium nitride (p-GaN) contact layer and the metal electrode layers. In deep-UV LEDs, absorption becomes an even greater problem.

One possible solution to this fundamental issue is to obtain a direct ohmic contact to p-type aluminum gallium nitride (p-AlGaN). This can be achieved using UV-transparent conductive electrodes (TCEs), thus avoiding absorption and increasing device efficiency. Prior to our work, no solution had been found to overcoming the trade-off between high electrical conductivity and high optical transmittance. Indeed, these properties have generally been considered mutually exclusive. In recent years, some groups have reported the use of metal nanowires, metal nanomeshes, graphene, carbon nanotubes, metal oxides, and conductive polymers as replacements for conventional indium tin oxide (ITO), but these efforts are still under way.

We have proposed a universal method for producing TCEs using wide bandgap (WB) materials such as silicon oxides and nitrides. Glass-based TCEs (G-TCEs) enable effective current injection from a metal to a WB semiconductor (e.g., p-type AlGaN under bias) via conducting filaments (CFs) that are formed by the electrical breakdown (EBD) that occurs in the G-TCE. In these devices, high transmittance is maintained even in the deep-UV region (i.e., more than 95% at a wavelength of 280nm). To achieve this, we developed a G-TCE using aluminum nitride (AlN) as a unique solution and implemented the resultant electrode within an LED structure. We also demonstrated its feasibility for use in such a device and its superiority in terms of...
both blue and near-UV LEDs, particularly those with a p-AlGaN top layer, compared with a conventional ITO layer.

Figure 1(a) shows a schematic of our lateral-type AlGaN LEDs with AlN-based G-TCEs. We designed a tripod-shaped p-metal chromium/nickel (Cr/Ni) pad, with 55 metal dots beneath it, to enable the formation of CFs during the EBD process. This pad also enables us to easily observe the current-spreading effect under low-current operation. Figure 1(a) shows that current can be injected via CFs that form in the AlN TCE and can then spread out via thin indium tin oxide (ITO) buffer layers.

We measured the current–voltage (I–V) curves of our devices (i.e., AlN-based G-TCEs deposited on LED wafers) before and after EBD. These experiments were performed in air and at room temperature. We swept direct-current (DC) voltage from 0 to 6V (with a ramp rate of 0.1V per second) using a two-point-probe contact between the metal pad and the ITO buffer layer. This led to the formation of CFs in the G-TCE. Initially, the TCE maintained a high resistance state (HRS), but we observed a steep increase in the current level at ~4V (i.e., the voltage at which EBD occurs). To prevent any damage to the device, we imposed a compliance current of 10mA. In the second DC voltage sweep, we found that the current level increased linearly, reaching a maximum compliance current (10mA) at below 0.5V. This abrupt transition (from an HRS to a low-resistance state) occurs as a result of the formation of CFs in the G-TCE, which causes the current level to increase from a few pA to ~100mA at 1V. We also obtained conductive atomic force microscopy images at 1V from the AlN-based G-TCE before and after the EBD, and after removal of the Cr/Ni pad, as shown in the inset of Figure 1(b). Our results indicate that the CFs are formed stably in the AlN-based G-TCE after the EBD process.

Our investigations determined that both the lower forward voltage and reverse leakage current were reduced (by 3.7 and 30.2%, respectively) for the LEDs with AlN-based G-TCEs when compared with those based on reference ITOs: see Figure 2(a). We also observed a higher light output power (by 8.6%), as shown in Figure 2(b). Finally, we measured the light emission images for LEDs with AlN-based G-TCEs, 100nm-thick ITOs, and 10nm-thick ITOs at 20mA and 50mA: see Figure 2(c). Of these, we observed the brightest light emission in LEDs with AlN-based G-TCEs.

In summary, we have proposed a new concept of G-TCEs, based on an AlN-based thin film, which achieve high transmittance and low contact resistance. We have also successfully demonstrated its validity at the device level by applying the G-TCEs in nitride-based LEDs that operate from the visible to the near-UV range (365–450nm). Our G-TCE concept is a unique approach capable of making direct ohmic contact with p-AlGaN while maintaining high optical transmittance in even the UV region. We believe that this technology has wide application in organic/inorganic WB semiconductors, and will thus enable performance breakthroughs in a wide range of optoelectronic devices (e.g., deep-UV LEDs, solid-state lighting, displays, and...
solar cells). Our recent work on the application of this approach for the development of deep-UV LEDs will be reported shortly.

The authors acknowledge financial support from the National Research Foundation of Korea grant, funded by the Korean government (2016R1A3B1908249).

Author Information

Tae Geun Kim and Tae Ho Lee
School of Electrical Engineering, Korea University
Seoul, Republic of Korea

Tae Geun Kim is a professor of electrical engineering. His research is in the field of display and solid-state lighting devices such as transparent electrodes, oxide thin-film transistors, and LEDs.

References


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