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Fabrication of High Performance GaN-Based Vertical Light-Emitting Diodes Using a Transparent Conducting Indium Tin Oxide Channel Layer

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We fabricate blue GaN-based vertical light-emitting diodes (LEDs) using transparent insulating SiO_2 and conducting indium tin oxide (ITO) channel layers connected to the passivation layer by a combined process of electroplated deposition and a laser lift-off technique. It is shown that unlike the SiO_2 layer, the ITO layer effectively serves as current spreading and injection layers. LEDs fabricated with the ITO channel layer exhibit a slightly higher reverse current when the voltage exceeds −10 V. However, LEDs fabricated with the ITO layer produce higher output power (by ~20% at 100 mA) compared to LEDs with the SiO_2 layers.
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To realize solid-state lighting through GaN-based light-emitting diodes (LEDs),[1-3] it is essential to improve the external quantum efficiency (EQE) as well as the internal quantum efficiency. The low EQE of GaN-based LEDs is due in part to the large refractive index of GaN-based epitaxial layers. According to the total internal reflection theory, the critical angle for the light generated at the active region consisting of GaN-based layers is approximately 23°.[4] This indicates that only a small fraction of the generated light can be extracted, leading to the low EQE of such LEDs. Thus, to improve the EQE, various approaches, such as patterned sapphire substrate,[5] etched undercut sidewall,[6] surface roughening,[7] photonic crystal (PhC),[8,9] and surface plasmon techniques,[10] have been investigated. For example, Xu et al.[9] reported on the improvement of light extraction in GaN-based LEDs by using double PhCs. The simulation results using a three-dimensional finite-difference time domain showed that the light output of the LEDs fabricated with double PhCs could be enhanced by factors of 3.2 and 1.39, as compared to LEDs made without PhCs and with single PhCs, respectively. Furthermore, it is well known that GaN-based lateral-type LEDs fabricated on sapphire substrates are not suitable for solid-state lighting applications because of the poor heat dissipation due to the low thermal conductivity of the sapphire substrates. Thus, to effectively release the generated heat, a GaN-based vertical-type LED configuration[11,12] was developed, where LED epitaxial layers were separated from the sapphire substrate by a laser lift-off (LLO) technique and then transferred onto the electrically and thermally conducting support. Compared to lateral-type LEDs, vertical-type LEDs have several advantages, such as better current injection, excellent heat dissipation, and resistance to electrostatic discharge damage. The surface roughening of n-GaN and reflective contacts to p-GaN improved the output power of vertical-type LEDs.[13-15] For example, Fujii et al.[13] combined the LLO process with photo-electrochemical etching to produce conelike structures on the n-GaN surface of vertical LEDs. It was shown that the roughening caused an increase (over 100%) in the light extraction efficiency as compared to that of vertical LEDs without a patterned structure. In this work, to fabricate high performance vertical-type LEDs, transparent conducting indium tin oxide (ITO) and transparent insulating SiO_2 films were used as channel layers that were connected to the passivation layer. Unlike the SiO_2 layer, the ITO layer effectively served as current spreading and injection layers. Further, the light output power of the LEDs fabricated with the ITO channel layers (LED-II) was enhanced by ~20% at a driving current of 100 mA as compared to that of the LEDs with the SiO_2 channel layers (LED-I).

GaN-based epitaxial layers for blue vertical-type LEDs were grown on a (0001) sapphire substrate by metallorganic chemical vapor deposition. The vertical LED epilayer stacks consisted of a 30 nm thick GaN nucleation layer, a 2.5 μm thick GaN undoped layer, a 2 μm thick Si-doped n-GaN layer, an active region with five periods of InGaN/GaN multiquantum wells (MQWs), 0.1 μm thick Mg-doped AlGaN, and a 0.2 μm Mg-doped p-GaN layer. The device fabrication steps are as follows: First, the samples were immersed into boiling aqua regia ($HCl:HNO_3 = 3:1$) for 10 min and rinsed in running deionized (DI) water. Before lithography, the samples were ultrasonically degreased using acetone, methanol, and DI water for 5 min each per step, followed by N_2 blowing. After the cleaning process, the channel layers were formed on the p-GaN using SiO_2 and ITO by lithography, and then the square mesa structure (500 × 500 μm) was fabricated using an inductively coupled plasma (ICP) etcher for electric isolation. (A channel layer means that the layers serve as current spreading and injection layers.) The ICP process was used to etch away the p-GaN, MQWs, and n-GaN to expose the sapphire surface. A SiO_2 passivation layer that was used to protect the devices was deposited by plasma-enhanced chemical vapor deposition. Next, an ITO (20 nm) contact layer was deposited by radio-frequency-magnetron sputtering. A Ti/Ni (50 nm/100 nm) capping layer, a Ni/Ag/Ni (1 nm/200 nm/50 nm) reflector, and a Cu (500 nm) seeding layer were deposited on the p-GaN by an electron beam system. After annealing at 400°C for 1 min in N_2 ambient, a 70 μm thick Cu supporting layer was deposited by electroplating. Subsequently, an LLO process was performed using an ArF excimer laser operated at a wavelength of 193 nm. The back surface of the transparent sapphire was irradiated by the laser beam; the irradiation caused the separation of the sapphire substrate from the LED structure. The separated LED structures were transferred onto the electroplated Cu support with the reflector and channel layers, where an undoped GaN epilayer was exposed to air. The undoped GaN was etched off to expose the n-GaN layer by wet chemical etching and ICP. A heated KOH solution was then used to roughen the n-GaN surface. A Cr/Al/Ti/Au film (n contact) and a Ti/Au film (p contact) were then deposited onto the roughened n-GaN surface and the back surface of the electroplated Cu support, respectively. Figure 1a and b shows vertical LED structures with transparent insulating SiO_2 and transparent conducting ITO channel layers, respectively (referred to here as LED-I and LED-II, respectively), where the top n-GaN surfaces were roughened by wet etch-

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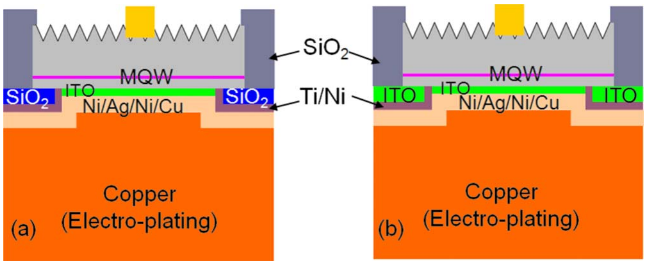

Figure 1. (Color online) Schematic diagram of (a) vertical-type configuration LEDs fabricated with SiO_2 channel layers (LED-I) and (b) LEDs with ITO channel layers (LED-II).

ing. GaN-based vertical LED samples were then cut into chips and encapsulated into standard LED lamps, and their electrical and optical characteristics were characterized.

Figure 2 shows the typical forward current–voltage characteristics of LEDs fabricated with the SiO_2 and ITO channel layers (i.e., LED-I and LED-II, respectively). The forward voltages of LED-I and LED-II were 3.25 and 3.22 V, respectively, at an injection current of 80 mA. It is evident that the forward voltages gradually increase with increasing injection current up to 500 mA. LED-II shows a lower forward voltage across the whole current range of 0–500 mA. The better electrical property of LED-II could be attributed to the reduction in the current density due to the increased contact region by the use of the transparent conducting ITO channel layer. The ITO channel layer enables better lateral current spreading and vertical current injection. The forward voltage of LED-II becomes saturated when the current exceeds 500 mA. Considering that vertical LEDs require high electrical efficiency and reliability, this suggests that the conducting ITO layer serves as an effective channel layer for fabricating high power vertical LEDs. The typical reverse characteristics of LED-I and LED-II are shown in the inset of Fig. 2. Both the samples show almost the same reverse current up to −10 V. As the voltage exceeds −10 V, LED-II begins to show a slightly higher reverse current. However, a comparison of the reverse characteristics shows that the use of the ITO layer would not degrade the performance of vertical LEDs, as described below.

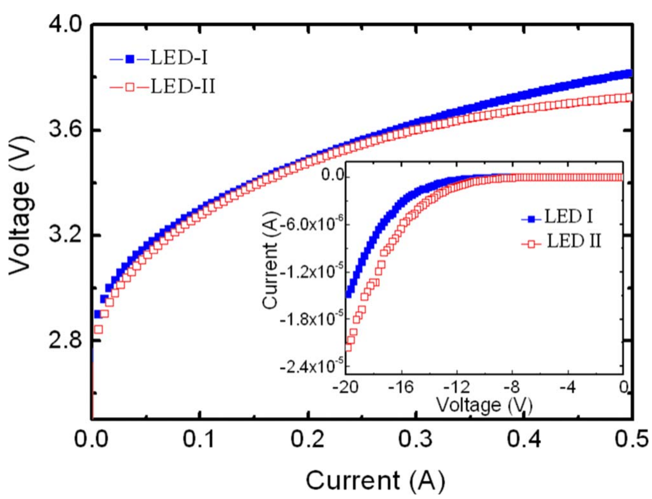

Figure 2. (Color online) The forward current–voltage characteristics of LEDs fabricated with the SiO_2 and ITO channel layers (i.e., LED-I and LED-II, respectively). The forward voltages of LED-I and LED-II are 3.25 and 3.22 V, respectively, at an injection current of 80 mA.

Figure 3 shows the light output power of LED-I and LED-II as a function of the driving current. LED-II exhibits higher output power than LED-I across the whole current range. For example, the light output powers (at a driving current of 100 mA) of LED-I and LED-II are 46.3 and 55.6 mW, respectively; LED-II produces the output power higher (by about 20%) than that of LED-I. The higher light output of LED-II could be ascribed to the fact that the conducting ITO channel layer causes better current spreading and injection.

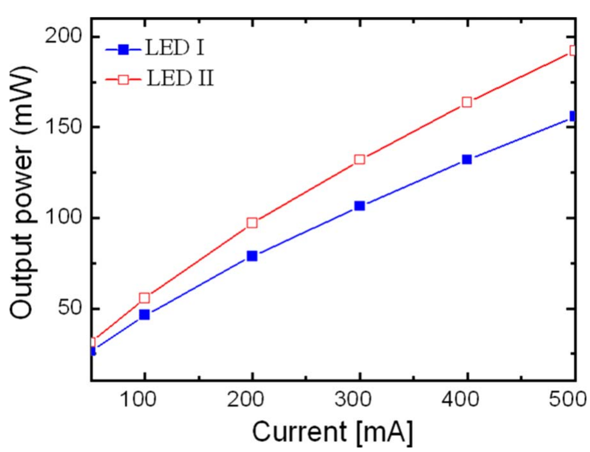

Figure 3. (Color online) Light output power of LED-I and LED-II as a function of the driving current. LED-II exhibits higher output power than LED-I across the whole current range.

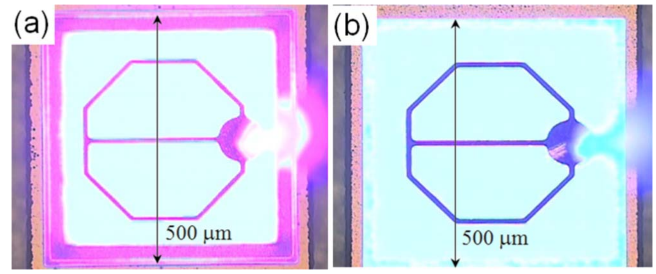

Figure 4. (Color online) The surface-emitting characteristics (at a driving current of 200 μA) of (a) LED-I and (b) LED-II. A comparison shows that LED-II is apparently brighter than LED-I.

To investigate the current spreading and injection efficiency of LED-I and LED-II, their surface-emitting behaviors were characterized. Figure 4 shows the surface-emitting characteristics (at a driving current of 200 μA) of LED-I and LED-II. A comparison shows that LED-II is apparently brighter than LED-I. This indicates that the transparent conducting ITO channel layer effectively serves as current spreading and injection layers, resulting in the enhancement of the electrical and optical performance of LED-II.

In summary, we investigated the effect of the transparent conducting and insulating channel layers on the electrical performance of GaN-based vertical-type configuration LEDs. It was shown that blue LEDs fabricated with SiO_2 and ITO channel layers (LED-I and LED-II) exhibited forward-bias voltages of 3.25 and 3.22 V at a driving current of 80 mA, respectively. Both LED samples yielded the same reverse currents, although LED-II gave a slightly higher current when the voltage exceeded −10 V. The light output power (at 100 mA) of LED-II improved by about 20% as compared with that of LED-I. These results indicate that the transparent conducting ITO layer is a promising channel layer for high performance vertical LEDs.

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