APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 18 1 NOVEMBER 2004

High-power and reliable operation of vertical light-emitting diodes on bulk GaN

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(Received 24 May 2004; accepted 30 August 2004)

InGaN/GaN light-emitting diodes (LEDs) with lateral and vertical geometries have been fabricated on free-standing GaN substrates. Current spreading was significantly enhanced in the vertical LED, leading to a reduced series resistance of 7 Ω compared to 12.2 and 14.2 Ω for the lateral LEDs on GaN and sapphire, respectively. As a result, the light output and power conversion efficiency of the vertical LED on GaN were greatly improved at high injection currents. The vertical LED was subjected to a stress test at 400 mA and showed minimal degradation of optical power, whereas the same stress resulted in the destruction of the lateral LED on sapphire due to increased current crowding and self-heating. However, lateral LEDs on sapphire with optimized current spreading exhibited excellent reliability, indicating the presence of a high density of dislocations ($\sim 10^9$ cm^{-2}) in the heteroepitaxial device does not accelerate LED degradation at current densities up to 700 A/cm^2. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1810631]

GaN-based short wavelength light-emitting diodes (LEDs) can be used in conjunction with downconversion phosphors to produce white light, and hold significant promise for next generation lighting technology.[1–3] However, a substantial decrease in cost and increase in luminous power must be achieved before the LEDs can compete with fluorescent and other high-efficiency lighting sources. In order to meet the cost and performance targets, it is essential to drive the LEDs at much higher current densities without sacrificing emission efficiency and operating lifetime.[3] Most commercially available blue and ultraviolet (UV) LEDs are grown on sapphire and are not suitable for high power operation for a few reasons. First, LEDs grown heteroepitaxially on sapphire contain a high density of threading dislocations due to large lattice and thermal expansion mismatch between sapphire and III nitrides. The dislocations may accelerate device degradation particularly at high pump currents. Second, LEDs on sapphire are normally fabricated in a lateral device configuration—both *n*- and *p*-type electrodes are located on the side of the epitaxial structure—due to the insulating substrate. Current spreading in the lateral device relies on the use of a semitransparent contact which covers the entire *p*-GaN. Mismatch between the semitransparent contact and *n*-GaN layer may lead to severe current crowding at high currents.[4–6] Finally, sapphire has a rather poor thermal conductivity, limiting heat dissipation and therefore drive current density.

The use of conducting SiC substrates enables vertically structured LEDs and alleviates the current crowding limitations. However, like the case for LEDs on sapphire, the lattice mismatch between SiC and III nitrides results in a large number of dislocations in the device structure. Another drawback is that LEDs on SiC normally exhibit a high series resistance due in part to the resistive buffer layer which is mandatory in the epitaxial growth.[7] In addition, doped SiC is typically opaque, decreasing the LED efficiency due to the absorption of downward light by the substrate.

It is clear that high-quality bulk GaN is an ideal substrate material for nitride LEDs. Pure GaN crystal is five times more thermally conductive than sapphire, and essentially optical transparent at visible and near-UV wavelengths. Electrically conductive GaN substrates would allow fabrication of vertical geometry LEDs capable of much higher current operation. The vertical structure also facilitates device processing, cleavage, and packaging. Our previous work showed that homoepitaxy of LED structures on bulk GaN yielded much higher material quality compared to their counterparts on sapphire. As a result, the LEDs exhibited greatly improved electrical characteristics and optical efficiency.[8,9]

In this work, we report on fabrication of lateral or vertical LEDs on sapphire and free-standing GaN substrates. The electrical and optical characteristics of the LEDs at high injection currents are evaluated. The vertical devices show superior reliability under 400 mA stress test, largely due to more uniform current spreading.

Near-UV (405 nm) InGaN/GaN multiple-quantum-well (MQW) LEDs with an identical structure were grown on sapphire and bulk GaN substrates using low-pressure metal-organic chemical vapor deposition. The bulk GaN was produced using hydride vapor phase epitaxy[10] and had a resistivity of $\sim 0.03\ \Omega$ cm. The detailed LED structure can be found elsewhere.[8] Top-emitting LEDs with a size of $300\ \mu\text{m} \times 300\ \mu\text{m}$ were fabricated using standard photolithography and BCl_3/Cl_2 inductively coupled plasma etching.[5] Ni/Au (5 nm/6 nm) was deposited as the semitransparent *p*-type ohmic contact. To produce conventional lateral LEDs on sapphire and GaN, the *p*-GaN and active layers were partially etched and Ti/Al metallization was formed on the exposed *n*-GaN, whereas a full-area Ti/Al contact was formed on the N-face of the GaN substrate as the *n*-type electrode of vertical LEDs. The samples were annealed at 550 °C for 3 min in air. The vertical LEDs have a ~20% larger emitting area compared to the lateral LEDs because the mesa structure is not needed. The current–voltage ($I-V$) and light output–current ($L-I$) characteristics of the LEDs were measured using a Keithley 238 current source measurement unit and a silicon photodiode-array

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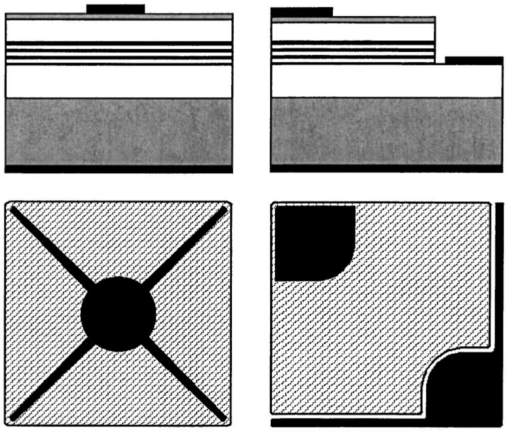

FIG. 1. Schematic cross sections and top contact patterns of the lateral and vertical LEDs on sapphire or GaN substrates.

fiber-optic spectrometer. The LEDs were then stressed at 400 mA for up to 24 h. The tests were performed on wafer level at ambient temperature. The evolution of optical power of the LEDs was recorded.

Figure 1 (top) shows schematic cross sections of the vertical LED on GaN and lateral LED on GaN or sapphire. The corresponding top contact patterns are shown in Fig. 1 (bottom). Finger projections are added to the bond pads to alleviate current crowding by reducing current spreading distances. The lateral device has a conventional asymmetric structure similar to most commercially available nitride LEDs grown on sapphires. The current spreading length in the lateral devices, which is the length where the current density drops to $1/e$ value of that at the mesa edge, can be estimated by using[4]

$$L_s = (r_c + \rho_p t_p)^{1/2}\left(\frac{\rho_n}{t_n} - \frac{\rho_t}{t_t}\right)^{-1/2},$$

where ρ_p, ρ_n, ρ_t, t_p, t_n, and t_t are the resistivity and thickness of the p-GaN, n-GaN, and semitransparent p-contact layers, r_c is the specific contact resistance of the p contact. For the measured values of $\rho_p = 2.7\ \Omega$ cm, $t_p = 0.2\ \mu$m, $\rho_n/t_n = 26\ \Omega$, $\rho_t/t_t = 18\ \Omega$, $r_c = 5 \times 10^{-3}\ \Omega\ \text{cm}^2$ for the LED on sapphire, L_s has a value of about 250 μm, which is close to the length of a typical lateral current path in this LED, indicating current crowding at the mesa edge. On the contrary, current tends to crowd toward the p-type bond pad in the lateral LED on GaN due to the conductive substrate. The finger projections significantly enhance current spreading in the n-GaN layer, and thus the current uniformity particularly in the LED on sapphire. In contrast, the vertical LED has a symmetric structure. The lateral current paths in the n-GaN and semitransparent contact are eliminated or considerably reduced, leading to a much more uniform current distribution and light emission. Note that uniform current spreading in the lateral LEDs can be achieved by optimizing the transparent contact to meet $\rho_t/t_t = \rho_n/t_n$.[4,5] However, this may not prevent current crowding at high currents due to different temperature dependence of ρ_t and ρ_n.

Figure 2 presents typical forward I–V characteristics of the LEDs. The series resistances of the vertical LED on GaN, the lateral LEDs on GaN and sapphire are 7, 12.2, and 14.2 Ω, respectively. The high series resistances in the lateral devices can be attributed to the high spreading resistances in the n- and p-type current spreaders. The forward voltage of the vertical LED at 200 mA is 4.5 V compared to 5.8 V for the lateral LED on sapphire. With a much lower series resistance, and therefore a reduced thermal load, the vertical LED is expected to have an increased power conversion efficiency and lifetime when operating at high currents. The inset of Fig. 2 shows that low-bias leakage currents are substantially reduced in the LEDs on GaN, suggesting much better material quality yielded by the homoepitaxy.[8,9]

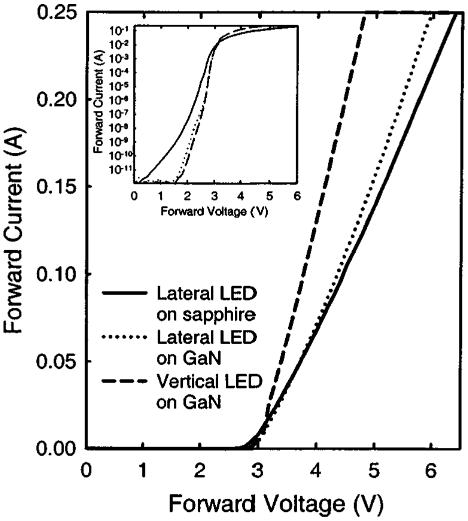

FIG. 2. Forward I–V characteristics of the lateral and vertical LEDs on sapphire or GaN. The inset shows the same data plotted on a log–log scale.

The output power of the LEDs as a function of injection current measured in cw mode is shown in Fig. 3. The homoepitaxial LEDs greatly outperform the LED on sapphire at high injection levels. The light output of the lateral LEDs on sapphire and GaN saturates at ~200 and 400 mA, respectively. This can be attributed to enhanced current crowding and self-heating effects, which are even more pronounced in the LED on sapphire due to the poor thermal conductivity of sapphire. As the LED junction temperature increases, carrier confinement in the MQWs becomes less efficient, leading to premature saturation of the radiant power. In sharp contrast, the output power of the vertical LED on GaN increases

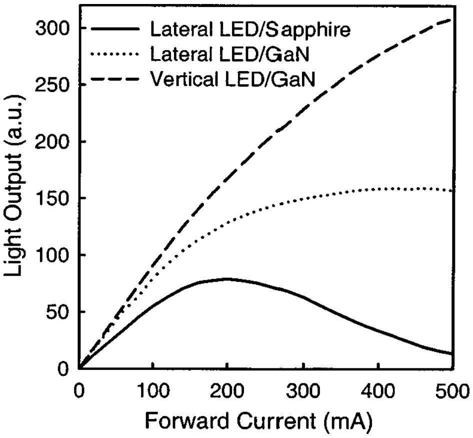

FIG. 3. Light output of the LEDs as a function of injection current in cw mode.

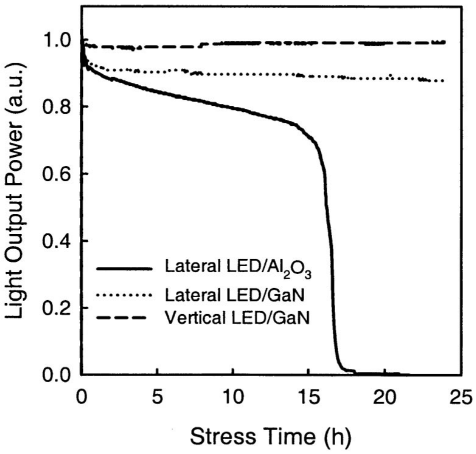

FIG. 4. Normalized optical power of the LEDs as a function of stress time.

steadily with increasing current and shows no saturation up to 500 mA, which is 25× higher than standard rated current for most commercially available blue LEDs of similar size. At this current, the vertical LED chip has an output power of 35 mW, and a power conversion efficiency 2× and 28× higher than the lateral LEDs on GaN and sapphire, respectively. These results illustrate the critical need for developing efficient thermal management schemes for high power LED packages. At 20 mA, the lateral and vertical LEDs on GaN have similar light output, but are 50% brighter than the LED on sapphire, mainly due to improved internal quantum efficiency.

To investigate the reliability of the LEDs operating at high currents, the devices were subjected to stress tests at 400 mA for 24 h. The average current density in the lateral LEDs was 620 A/cm^2, and localized current densities could be much higher due to nonuniform current spreading. Figure 4 shows the variation of light output as a function of stress time. The optical power of the vertical LED is essentially unchanged ($<1\%$ decrease), suggesting excellent reliability. The lateral LED on GaN exhibits a gradual degradation and a 12% decrease after 24 h stress. The light output L is roughly an exponential function, i.e., $L=L_0\exp(-\beta t)$, and the value of the degradation rate β is determined to be $1.9\times10^{-3}\ h^{-1}$. The lateral LED on sapphire also shows a gradual decay during the first 15 h, though with a much higher rate of $1.4\times10^{-2}\ h^{-1}$. Further stress leads to a nearly catastrophic failure. The drastic drop in light output is accompanied by the destruction of the *p*-type contact, suggesting that the device failure is probably due to contact degradation at high temperatures but rather due to defect generation in the LED structure.

To gain further insight into the stress failure mechanism, symmetrical lateral LEDs with an *n*-electrode ring surrounding the mesa were also fabricated on sapphire, and stressed under the same conditions. Current spreading was greatly improved in these LEDs and optical degradation was less than 5% after the stress. This finding suggests that the high-density pre-existing dislocations ($\sim10^9\ cm^{-2}$) in the heteroepitaxial LEDs do not drive the degradation of light output power at current density up to $\sim700\ A/cm^2$.[11] It also confirms a previous report that threading dislocations in GaN and its alloys have much lower mobility compared to those in conventional III–V materials.[12] It is worthy to mention that GaN-based laser diodes (LDs) typically operate at even higher current densities (in the kA/cm^2 range), and therefore may be more sensitive to the presence of the dislocations.[13,14] Homoepitaxy of LD structures on a low-defect GaN substrate should have a significant positive impact on the device lifetime.

In summary, lateral and vertical geometry LEDs have been fabricated on bulk GaN substrates. Compared to conventional lateral LEDs on sapphire, the vertical device has a reduced series resistance, improved current spreading and heat dissipation. As a consequence, the power conversion efficiency is increased by a factor of 28 at 500 mA. The LED has proven to be reliable when stressed at 400 mA. If low-cost flawless bulk GaN eventually becomes available, the homoepitaxially grown nitride LEDs, combined with advanced light extraction and packaging, can be used for developing high brightness and cost-efficient solid-state lighting sources.

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