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Brief Communication

Effects of Different n-Electrode Patterns on Optical Characteristics of Large-Area p-Side-Down InGaN Light-Emitting Diodes Fabricated by Laser Lift-Off

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Large-area p-side-down InGaN light-emitting diodes (LEDs) $1000 \times 1000\,\mu m^2$ in size have been fabricated by laser lift-off (LLO). The p-side-down LEDs with different geometric patterns of n-electrodes were fabricated to investigate electrode pattern-dependent optical characteristics. The current crowding effect was observed in the large-area p-side-down InGaN LLO-LEDs. A LED with a well-designed n-electrode pattern shows a uniform distribution of light emission and a higher output power due to uniform current spreading. The output power saturation induced by the current crowding effect was investigated. In the absence of a transparent contact layer for current spreading, the n-electrode pattern has a marked influence on the current distribution and the consequent light output power of the large-area p-side-down LEDs.
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KEYWORDS: GaN LEDs, laser lift-off (LLO), wafer bonding, large-area light-emitting diode (LED)

GaN-based devices such as light-emitting diodes (LEDs), laser diodes (LDs), and field-effect transistors (FETs) with high-power operation have attracted considerable interest and have been significantly developed. In particular, GaN-based LEDs are being marketed and used for a variety of applications, including traffic signals, full-color displays, back lighting in liquid-crystal displays, and white LEDs. Recently, high-efficiency white LEDs made with blue LEDs and phosphors have received much interest because the replacement of fluorescent lamps could be realistic in the near future.[1–4] However, for illumination applications, where dozens, hundreds or even thousands of lumens are required from a single light source, this goal can hardly be realized by simply accumulating appropriate numbers of conventionally sized (about $350 \times 350\,\mu m^2$) LEDs. Therefore, a single LED chip must be enlarged to provide higher light output power. For GaN-based LEDs epitaxially grown on sapphire, the chip size is restricted by the low thermal conductivity of the sapphire and the low conductivity of the p-type GaN. In recent papers,[5–9] p-side-down GaN laser-lift-off LEDs (LLO-LEDs) on Cu substrates have been reported to have superior performance over the conventional p-side up LEDs on sapphire due to the elimination of the constraints of the sapphire substrate and p-GaN. Large-area p-side-down LLO-LEDs of $1000 \times 1000\,\mu m^2$ in size on Cu substrates were also demonstrated in our previous report.[10] In the p-side-down LLO-LED configuration, the n-GaN layer serves as a better current spreading layer than the p-GaN layer in the p-side-up configuration on a sapphire substrate due to the higher electron mobility and greater thickness of the n-GaN layer. However, the influence of the n-electrode pattern on current spreading in the p-side-down LLO-LEDs was not investigated. Since the light emission intensity is directly proportional to the current density,[11] a uniform current distribution in a n-GaN layer to provide a uniform light emission pattern is necessary. In this work, wafer bonding and LLO techniques were used to fabricate large-area p-side-down LLO-LEDs of $1000 \times 1000\,\mu m^2$ in size. Four different geometric n-electrode patterns were deposited on n-GaN without a transparent contact layer. We first observe and study the current crowding effect in the p-side-down GaN LLO-LEDs under high current injection levels. The light emission patterns of LEDs with different n-electrode patterns are compared. The electrode-pattern-dependent light output power is also discussed.

A LED structure was grown by metal organic chemical vapor deposition on a (0001) sapphire substrate. The LED structure consists of a 4-μm-thick Si-doped GaN layer, a multi-quantum-well (MQW) region consisting of five pairs of $In_{0.25}Ga_{0.75}$ N wells (3 nm) and GaN barriers (10 nm), and a 0.1-μm-thick Mg-doped GaN layer. The original LED wafer with a back surface polished sapphire substrate was cleaved to a size of $1.5 \times 1.5\,cm^2$. Si_xN_{1-x} film was deposited on the samples and then patterned Si_xN_{1-x} serving as etching masks were defined by a standard photolithographic and etching process. Mesas $1000 \times 1000\,\mu m^2$ in size were formed by inductively coupled plasma reactive ion etching. Ni/Au/Ni (20 nm/20 nm/150 nm) layers were then deposited on the defined mesas. The first Ni/Au layer is used to form the p-GaN contact and the final Ni layer serves as the bonding metal. The LED sample with a structure of sapphire/GaN-LED/Ni/Au/Ni was then bonded with a Ni-coated Cu substrate by fixting in argon atmosphere at 400°C for 30 min. The bonded structure was then subjected to the LLO process. A KrF excimer laser with a wavelength of 248 nm and a pulse width of 25 ns was used to separate the sapphire substrate from the epitaxial LED structure. The laser with a beam size of $1.2 \times 1.2\,mm^2$ was incident from the polished back surface of the sapphire substrate onto the sapphire/GaN interface. In this process, the beam size of the KrF laser was larger than of LEDs. Therefore, the laser irradiation on the sapphire/GaN interface was uniform. After the LLO process, the n-GaN/MQW/p-GaN/Ni/Au/Ni structure was transferred onto the Cu substrate as shown in Fig. 1(a). Finally, Ti/Al layers with different patterns were deposited on the n-GaN layers as an n-type contact without additional transparent contact layers. The top view of the LED devices with four different n-electrode patterns is shown in Fig. 1(b). The diameter of the circular electrodes and the width of the linear electrodes in the four types of LEDs are 120 and 20 μm, respectively. In *LED b*, the length of the linear electrodes is 700 μm. The cross-shaped

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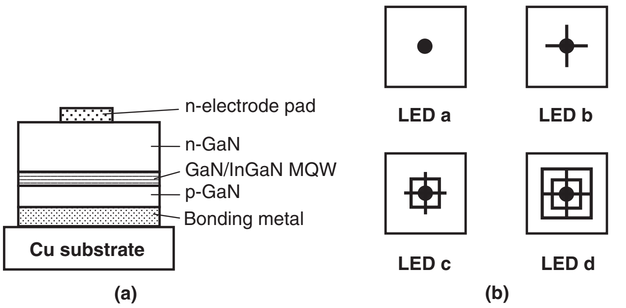

Fig. 1. (a) Schematic structure of p-side-down LLO-LED on copper substrate. (b) Top view of *LED a*, *LED b*, *LED c* and *LED d* with different n-electrode patterns.

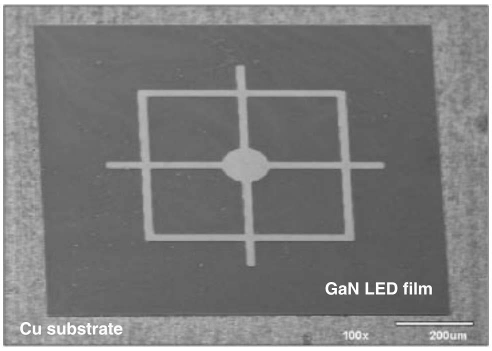

Fig. 2. SEM image of *LED c* on Cu substrate.

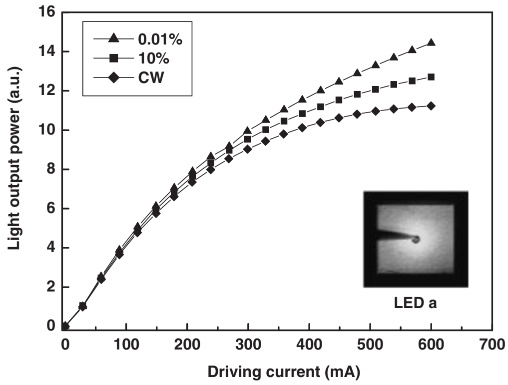

Fig. 3. Light output power as a function of driving current for cw and pulse operation of *LED a*. The inset shows the micrographic surface light emitting pattern of *LED a*.

electrodes in *LED c* and *LED d* have the same dimension as in *LED b*. In *LED c*, the width of the square electrode is 520 μm. In *LED d*, the width of the inner and outer squares is 350 and 700 μm, respectively.

A scanning electron microscope (SEM) image of *LED c* on a Cu substrate is shown in Fig. 2. Complete and smooth LED films on Cu substrates without peeling or cracks were observed despite the large difference in thermal expansion coefficients of GaN (4.4×10^{-6} K^{-1}) and Cu (16.9×10^{-6} K^{-1}). A smooth and well-adhesing bonding interface was also obtained. These results are essential for providing good optical and electrical characteristics for the LLO-LEDs. In Fig. 3, the light output–current (*L–I*) characteristics of *LED a* under cw and pulse operations with varying duty cycles are compared. The peak wavelength of the LED was 456 nm with a driving current of 100 mA under cw operation. Under the same driving current operation, the light output power increased as the operation duty cycle was decreased from cw to 0.01% as shown in the figure. The output power saturation is also less pronounced as the duty cycle is decreased. The inset shows the micrographic surface light emission pattern of *LED a* driven at 100 mA. The injected current crowded near the electrode, resulting in an area with a higher current density corresponding to the brighter area around the circular contact indicated by the surface light emission pattern of *LED a*. The crowded current could induce thermal and carrier over flow effects[12] which saturate and decrease the output power of the LEDs. The thermal effect induced by current crowded around the electrode is one reason for the power saturation of *LED a* as suggested by the *L–I* characteristics for different operation duty cycles.

In order to reduce the current crowding effect and investigate the influence of the n-electrode pattern on optical characteristics, LLO-LEDs with different n-electrode patterns were fabricated. The n-electrode patterns of *LEDs a–d* are shown in Fig. 1(b). Surface light emission patterns of the four LEDs with different n-electrode are shown in Fig. 4. The light emission patterns were obtained and analyzed at a driving current of 450 mA using a near-field microscope with a charge-couple device and a video analyzer (Beam-View Analyzer, Coherent) linked to a computer. The solid curves at the bottom of the images stand for the relative light output intensity measured along the dashed lines. The light intensity was normalized with the peak values, normally appearing at the edges of the circular electrodes in the four LEDs. In Fig. 4(a), the light emission close to the circular electrode shows great intense intensity, which reveals that the injection current crowded around the electrode pad. As shown by the relative intensity curve, the output power drops to $1/e$ of the maximum value as the distance from the edge of the circular electrode increased to about 190 μm. In the absence of a transparent contact layer for current spreading, the n-electrode of *LED a* is insufficient to provide uniform current spreading in the large-area p-side-down LEDs configuration. In Fig. 4(b), more intense light emission around the extended cross-shaped electrode is observed. With the cross-shaped electrode for enhancement of current spreading, the distribution of light emission was more uniform compared with that of *LED a*, as shown by the relative intensity curve. The extended cross-shaped electrode improved the current spreading over the large-area mesa and consequently provided a more uniform light emission pattern. The light emission patterns of the LEDs with two other electrodes are shown in Figs. 4(c) and 4(d). The light intensity of *LED d* showed a uniform distribution from the center to the edge of the mesa. In contrast, the light intensity of *LED c* decreased near the edge of the mesa. The light emission pattern of *LED d* is more uniform than that of *LED c*, in which a more intense emission appeared inside the square electrode.

The *L–I* characteristics of the LEDs with four different n-electrode patterns under cw operation are shown in Fig. 5. The insets show the micrographic top view of the four LEDs driven at 100 mA in the sequence *LED d*, *LED c*, *LED b*, and *LED a* from top to bottom. The output power measurement was performed from the upper side of the chip using a

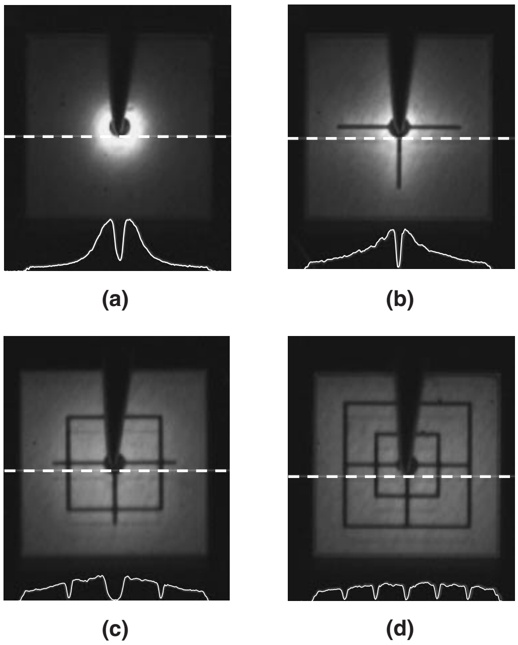

Fig. 4. Light emission patterns of p-side-down LLO-LEDs (driven at 450 mA) with four different geometric n-electrode patterns: (a) *LED a*, (b) *LED b*, (c) *LED c*, and (d) *LED d*. The solid curves at the bottom of the images stand for the relative light output power measured along the dashed lines.

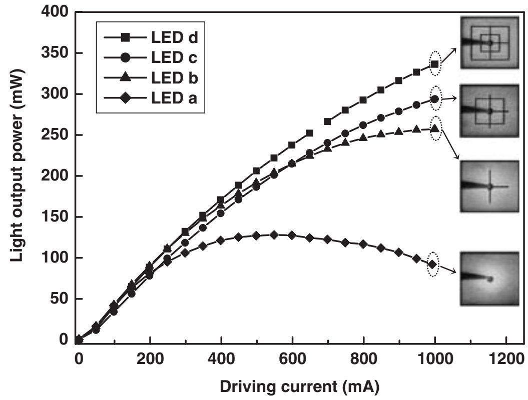

Fig. 5. Light output power as a function of the cw driving current for the LEDs with different n-electrode patterns. The insets show the micrographic top view of the four LEDs driven at 100 mA in the sequence *LED d*, *LED c*, *LED b*, and *LED a* from top to bottom.

large-area Si photodiode placed 5 mm above the samples. The light output power of the LEDs showed a linear increase as the driving current was increased to 250 mA. The light output power of the four LEDs is also approximately equal when the driving current was below 250 mA. The injection current is supposed to spread uniformly over the mesas on the four LEDs, which results in equal light output power when the driving current was below 250 mA. As the driving current was increased above 250 mA, the light output power of *LED a* began to saturate and decreased due to the carrier overflow effect and the thermal effect caused by the high current density distributed around the circular electrode corresponding to the discussion for Fig. 3. In *LED b*, the output power saturation was also observed under a current injection level above 600 mA. *LED d* showed superior *L–I* characteristics compared with the other LEDs due to its well-designed electrode pattern for providing uniform current spreading as indicated in Fig. 4(d), which consequently reduced the thermal and carrier overflow effects caused by localized high injection current density. As the injection current was driven at 1000 mA, the light output power of *LED d* was 1.15, 1.30 and 3.15 times larger than that of *LED c*, *LED b* and *LED a*, respectively. The different light output powers among the four LEDs as the driving current increased to 1000 mA is caused by different current densities in the active region of each LED, which depend on the distribution of the injected current over the LEDs, resulting in carrier over flow and thermal effects at different levels and consequently different external quantum efficiencies.[13] The results indicate that the patterns of n-electrodes have a marked influence on the light output power.

In summary, we observe and report the effect of n-electrode patterns on the optical characteristics of large-area p-side-down LLO LEDs. The light emitting patterns showed an obvious current crowding effect in the LEDs with poorly designed n-electrode patterns. The LEDs with well-designed n-electrode pattern showed a uniform distribution of light emission and a higher output power due to uniform current spreading. The geometric pattern of the n-electrode has a marked influence on the current distribution and the light output power of the large-area p-side-down LEDs without transparent contact layers. The LED with a well-designed n-electrode shows about a 4-fold increase in the light output power over a LED with a single circular n-electrode centered on the mesa. In the large-area p-side-down LEDs, the light output power and light emission pattern depends on the geometric pattern of the n-electrode. The LEDs employing the well-designed n-electrode pattern show superior *L–I* characteristics compared with the other LEDs because the well-designed electrode pattern provides uniform current spreading.

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