Performance of InGaN–GaN LEDs Fabricated Using Glue Bonding on 50-mm Si Substrate

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***Abstract*—Vertical InGaN–GaN light-emitting diodes (LEDs) epitaxial films were successfully fabricated on a 50-mm Si substrate using glue bonding and laser liftoff technology. A high-temperature stable organic film, rather than a solder metal, was used as the bonding agent. It was found that the light output of the vertical InGaN LED chip exceeded that of the conventional sapphire-substrate LEDs by about 20% at an injection current of 20 mA. The vertical InGaN LEDs operated at a much higher injection forward current (280 mA) than sapphire-substrate LEDs (180 mA). The radiation pattern of the vertical InGaN LEDs is more symmetrical than that of the sapphire-substrate LEDs. Furthermore, the vertical InGaN LEDs remain highly reliable after 1000 h of testing.**

***Index Terms*—Glue bonding, InGaN–GaN, laser liftoff, light-emitting diodes (LEDs).**

I. INTRODUCTION

HIGH-BRIGHTNESS GaN-based light-emitting diodes (LEDs) have attracted considerable attention for their versatile applications in mobile phones, full-color displays, and lighting [1]. Although the development of these GaN-based LEDs is very successful, the poor conductivity of p-GaN limits the performance of LEDs because of current crowding [2]. This problem can be solved using a thin Ni–Au layer or a highly transparent (>80%) indium tin oxide (ITO) layer as a current spreading layer [3]–[4]. However, the poor electrical characteristics (electrical resistivity $= 10^{11}$–$10^{16}\ \Omega\cdot$cm) of the nonconducting sapphire substrate necessitate the need for p- and n-metal electrodes on the top surface of the devices. Hence, some of the active layers in the n-contact region are sacrificed. Moreover, the heat dissipation of the sapphire substrate is also poor, so the GaN-based LEDs are generally operated at low injection current. These problems can be solved by transferring GaN LEDs onto Si [5], [6] or Cu substrates [7]. Much of this investigation is focused on the intermetallic bonding. In this work, an n-side-up InGaN LED with vertical electrodes was fabricated by glue bonding. A high-temperature stable organic film is utilized as the bonding agent to prevent any possible reaction with the metal reflector.

II. DEVICE FABRICATION

We used 50-mm sapphire-substrate LEDs and Si substrates. The InGaN–GaN films were grown on a sapphire substrate by low-pressure metal–organic chemical vapor deposition. The LED structures comprise a 0.3-μm-thick Mg-doped GaN, an InGaN–GaN multiple quantum well, a 2-μm-thick Si-doped GaN, a 2-μm-thick undoped GaN layer film, and a GaN buffer layer on sapphire substrate. The mirror system is composed of an ITO p-side contact layer, an Al_2O_3 low index layer, and an Al metal layer deposited on the surface of the Mg-doped GaN. Using a comprehensive load of 10 kg/cm^2, this LED wafer was bonded to a metal dot-array silicon substrate which was covered with a high-temperature stable organic film by the spin dry process. The organic film is a polycyclic aromatic hydrocarbon (C_8H_6), composed of a benzene ring fused to a cyclobutene ring. It was then cured at 200 °C for 60 min.

The InGaN LED wafer was subsequently bonded to a Si substrate. By exposing the sapphire substrate to a frequency-tripled Nd: YAG 1 mm^2 spot, 355-nm laser [8] with 170-mJ energy, the GaN was locally decomposed at the GaN and sapphire boundary. After scanning the GaN surface through sapphire substrate, the sapphire substrate was successfully separated. No peeling or cracking was observed on the bonded sample, indicating that the bond strength was sufficiently strong to endure the sapphire substrate removing process. The n-GaN roughening surface was obtained by subjecting the undoped GaN to boiling KOH solution and using inductively coupled plasma to remove undoped GaN until the Si-doped GaN was exposed. The Ti–Al–Pt–Au dots with a diameter of 100 μm and Ti–Au were deposited onto the n-side (n$^+$-GaN contact layer) and the underside of the Si substrate. Fig. 1 presents the structure and the roughened surface of the vertical InGaN LEDs. Finally, as shown in Fig. 2, the vertical InGaN LEDs was successfully cut into isolated devices, each with an area of $300 \times 300\ \mu$m^2. The ability of the interface to remain stable and uninterrupted through the dicing process again indicates that the interfaces was sufficiently high.

For comparison, a standard sapphire-substrate LED with an ITO current spreading layer was prepared from the same InGaN–GaN LED epitaxial material. The samples described herein were only cut into chips without encapsulation.

III. RESULTS AND DISCUSSION

The vertical InGaN LED devices are easier to process and have advantages over conventional sapphire-based LEDs. The dicing process for vertical InGaN LED devices can replace the complicated process of dry etching to mesa, laser scribing and breaking of the sapphire-based LEDs. The light-emitting area is increased by 15% because only a single electrode is present on the topside of vertical InGaN LED devices, as shown in Fig. 3.

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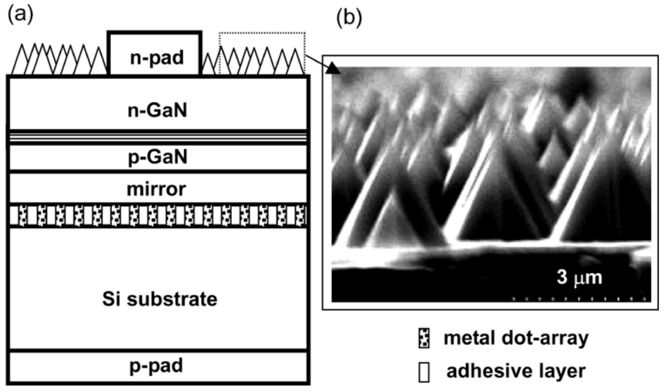

Fig. 1. (a) Schematic illustration of the vertical InGaN LED structure. (b) Scanning electron miscroscope (SEM) image of roughened surface.

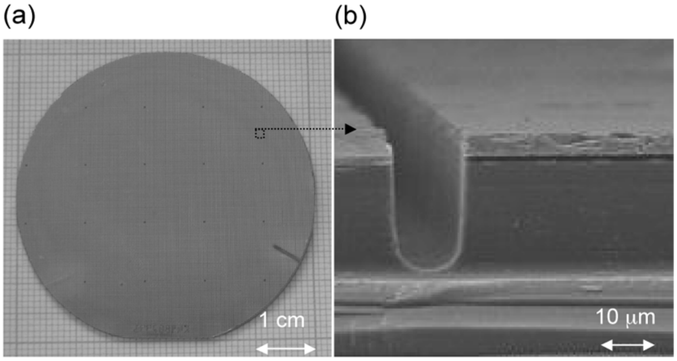

Fig. 2. (a) Image of an InGaN LED wafer bonded on a 50-mm diameter Si substrate. Wafer was successfully cut into isolated devices with an area of 300 × 300 μm^2. (b) SEM image of the cross section of the LED structure after dicing process.

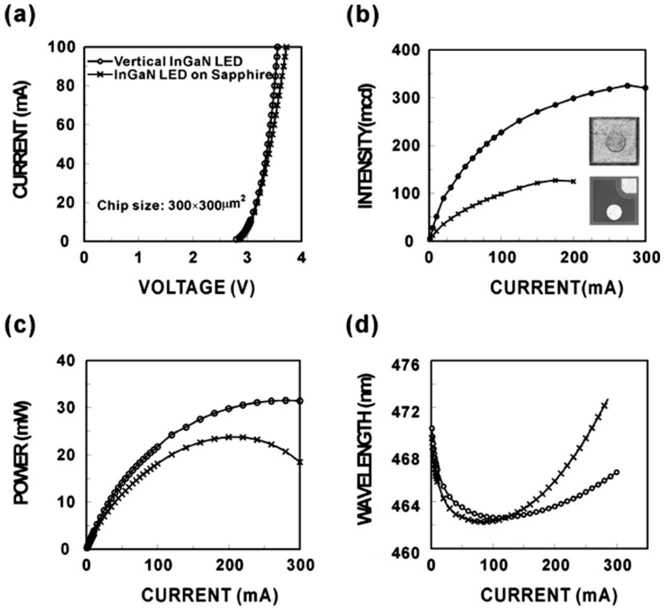

Fig. 3. Performances of vertical and conventional InGaN LEDs. (a) I–V characteristics. (b) Effects of injection current on the luminous intensity. (c) Effects of injection current on the light output. (d) Peak spectral wavelength as a function of dc drives current.

Fig. 3(a) plots the current against voltage (I–V) of LEDs with an area of 300×300 μm^2. The vertical InGaN LEDs exhibited normal p-n diode behavior with a forward voltage of 3.2 V at 20 mA, which were similar to conventional LEDs, indicating that neither wafer bonding nor the device process degrades the performance of LEDs. Furthermore, the organic film does not affect the electrical conductivity between the device contact (p-side) and metal dot-array Si substrate.

Fig. 3(b) depicts the effects of injection current on the luminous intensity of the vertical and conventional InGaN LEDs. During optical testing, the LEDs were put onto a copper plate with the collection angle at about 27°. The light intensity of the vertical InGaN LED chip is 2.8 times that of the conventional LEDs at an injection current of 20 mA. As presented in Fig. 1, this difference is caused by the improvement of the emission of light from the vertical InGaN LEDs by using only one electrode, reflecting the downward-traveling light by the mirror, and roughening the n-GaN surface. Furthermore, the current can spread uniformly without an n-metal layer (Ni–Au) or a transparent layer (ITO), because the vertical LED structure was p-side-down and n-side-up, with an n-metal electrode. Accordingly, the vertical InGaN LEDs do not exhibit the current crowding problem on the top emission area. Therefore, the emission of light is better than that of the conventional sapphire-based LEDs. The light output of the vertical InGaN LEDs (6.8 mW at 465 nm) exceeds the sapphire-based LEDs (5.7 mW at 464 nm) by about 20% at 20 mA, as shown in Fig. 3(c).

Fig. 3(c) also reveals that vertical InGaN LEDs can be operated with an injection forward current of 280 mA, which is 100 mA greater than sapphire-substrate LEDs, because the thermal conductivity of Si (168 $\mathrm{Wm^{-1} \cdot K^{-1}}$) is 4.8 times higher than that of sapphire (35 $\mathrm{Wm^{-1} \cdot K^{-1}}$). However, this improvement in heat dissipation is not as large as expected because the thermal conductivity of the organic film (0.29 $\mathrm{Wm^{-1} \cdot K^{-1}}$) was poor. The thermal impedance of the sapphire-based LEDs is about 2.9 times than that of vertical InGaN LEDs. The effects of heat dissipation on the performance of LEDs are plotted as a peak shift as a function of dc drive current. As shown in Fig. 3(d), when the dc drive current increased from 100 to 200 mA, the emission peak wavelengths of the sapphire-based LEDs shifted toward longer wavelengths, from 462.3 to 465.1 nm, whereas that of vertical InGaN LEDs on the Si substrate shifted from 462.6 to 463.5 nm. From the shift in emission wavelength and assuming a wavelength shift with a temperature of 0.03 (nm/°C) [9], we estimate the rising junction temperature of the sapphire-based LEDs and vertical InGaN LEDs is 93 °C and 30 °C from 100 to 200 mA, respectively. These peak shifts were caused by Joule heating [10]. Evidently, this Si wafer bonding technique reduced the Joule-heating problem of conventional sapphire-based LEDs.

Fig. 4 displays the radiation pattern of the conventional LEDs and vertical InGaN LED chips. It shows that the radiation pattern of the vertical InGaN LED chip is more symmetrical than that of sapphire-based LEDs, which could be attributed to the distribution of the electrodes. The view angle (half-center brightness or 50% of the full luminosity) of the vertical InGaN LED chip is smaller than that of sapphire-based LEDs, since the vertical InGaN LEDs were designed to have greater extraction efficiency using only one electrode, reflecting downward light,

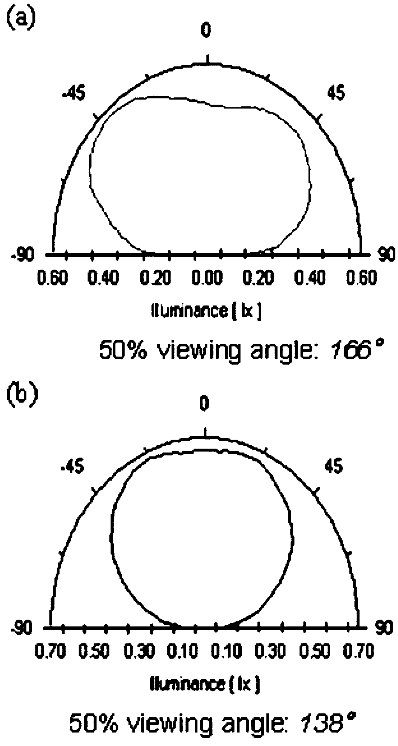

Fig. 4. Radiation patterns of (a) sapphire-based LEDs and (b) vertical InGaN LEDs.

and have a rougher n-GaN surface. Accordingly, most light is easily reflected upward. Additionally, the vertical InGaN LEDs were fabricated by replacing the transparent sapphire substrate with a Si substrate. Thus, only a few photons could be emitted from the side, i.e., improved efficiency.

A life test was performed on the vertical InGaN LEDs at a forward current of 50 mA at 55 °C. The voltage variation was under 3% and the output luminescent intensity did not degrade after 1000-h testing, as presented in Fig. 5.

IV. CONCLUSION

In summary, vertical InGaN–GaN LEDs were successfully fabricated on 50-mm diameter Si wafers using wafer bonding and laser liftoff technology. This bonding method enabled the emission of light from the vertical InGaN LED device to be improved such that a single electrode could be used and the light could be reflected downward using a mirror and rougher n-GaN surface. Hence, the light output of the vertical LED chip is 20% greater than that of conventional sapphire-substrate LEDs at 20 mA. The radiation pattern of the vertical InGaN LED chip is more symmetrical than that of sapphire-based LEDs, and the power angle of the vertical InGaN LED chip is smaller than that of sapphire-based LEDs. The vertical LEDs could be operated at a much higher injection forward current (280 mA) than sapphire-substrate LEDs (180 mA) because the sapphire substrate was replaced with a Si substrate. Additionally, the performance of the vertical InGaN LEDs did not degrade during 1000 h of testing.

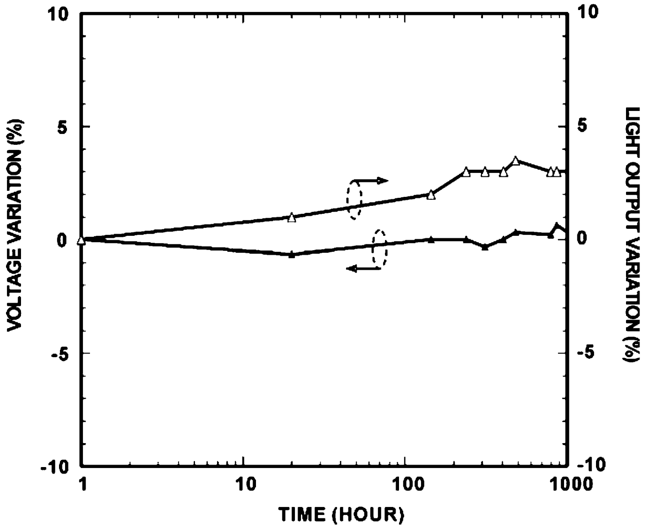

Fig. 5. Reliability test of vertical InGaN LEDs under stress condition of 55 °C and 50 mA.

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