Novel Electrode Design for Integrated Thin-Film GaN LED Package With Efficiency Improvement

Yao-Jun Tsai, Re-Ching Lin, Hung-Lieh Hu, Chen-Peng Hsu, Shih-Yi Wen, and Chi-Chin Yang

***Abstract*— This letter proposes a novel electrode structure for thin-GaN LED applications. The structure enhances light extraction and wall-plug efficiency in thin-GaN LEDs. To enhance light extraction in thin-GaN LEDs and solve current crowding effects caused by electrodes composed of metal, conventional n-GaN electrodes were replaced with ITO conductive films because of their high optical transparency. Simulation results show that the thin-GaN LEDs that use ITO as the nonshielded electrode have a more uniform current density distribution on the n-GaN surface and a higher average internal quantum efficiency than conventional metal electrodes. Furthermore, when a current of 200 mA was applied, the thin-GaN LEDs using the proposed electrode had a 40% increase in light-output power and a significant decrease in chip temperature compared to the use of conventional electrodes. The results indicate that the nonshielded ITO electrode design enhances the light extraction efficiency and avoids the accumulation of heat because of its uniform current density distribution.**

***Index Terms*— LED, nonshielding electrode, thin-film package LED (TFP LED).**

I. Introduction

Recently, LEDs with a vertical structure, or vertical LEDs (VLEDs), have been widely researched as a high-potential replacement for conventional LEDs manufactured with sapphire substrates. In conventional LEDs with sapphire substrates, p- and nelectrodes must be placed on the same side, and, consequently, current and heat crowding around the electrodes result in lower internal quantum efficiency (IQE) because of the insulating sapphire substrates [1]–[2]. VLEDs, however, allow an epitaxial layer to form between two metal electrodes to adhere to submount substrates. Because currents travel to the submount substrates vertically through n-GaN, VLEDs have a more uniform current density distribution and can be operated at higher injection powers compared with conventional structures [3]–[4]. However, metal electrodes in VLEDs shield the light that is emitted by the multiple quantum wells (MQWs), reducing light extraction efficiency and increasing the current crowding effect [5]–[6].

This letter proposes a thin-film-packaging (TFP) LED structure packaging LED epitaxial thin-films on Si substrates with through-silicon vias (TSV) by employing the flip chip method and a laser lift-off process. In addition, n-GaN electrodes were replaced with ITO thin films to prevent light from being shielded by the electrodes. Regarding TFP LEDs and conventional VLEDs, analyses using simulation software were conducted comparing the distribution of current density and IQE. Finally, this letter discusses the light emissions and thermal characteristics of the two LED types.

Manuscript received November 8, 2012; revised January 17, 2013; accepted January 22, 2013. Date of current version March 7, 2013. This work was supported in part by the Ministry of Economic Affairs, and in part by the Electronics and Optoelectronics Research Laboratories of the Industrial Technology Research Institute, Taiwan.

The authors are with the Electronics and Opto-Electronics Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan (e-mail: tsaiyaojun@itri.org.tw; rechinglin@itri.org.tw; fredhu@itri.org.tw; CPHsu@itri.org.tw; wenshihyi@itri.org.tw; chichin@itri.org.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2013.2244078

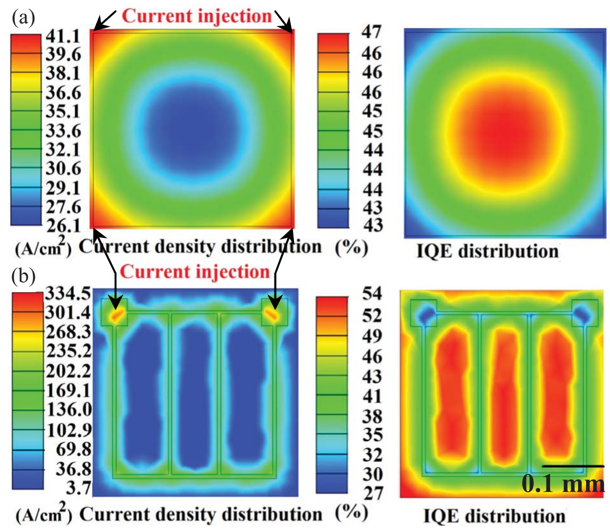

Fig. 1. Current density and IQE simulation results taken from (a) TFP LED and (b) original VLED.

II. Simulation and Experiments

SpeCLED was adopted to simulate the distribution of the current density and IQE in the TFP LEDs, which use nonshielded electrodes, and in the conventional VLEDs that use shielded electrodes. Fig. 1 shows the results of the simulation. A light-emitting area of $0.36\times$ 0.36 mm^2 and a grid of 10 $\times$ 10 were established for both the TFP LEDs and VLEDs. The GaN LEDs (λ_p = 455 nm) are mounted on (100) Si substrate. The structure consisted of a 2.5 μm-thick Au&Sn bonding metal, a 0.3μm-thick Mg-doped GaN layer, an InGaN/GaN MQW stack, a 3μm-thick Si-doped GaN layer and a 400 nm-thick ITO layer (TFP LED) or a 1μm-thick Au electrode (VLED). The injection current is set at 50 mA. The results show a uniform distribution of the current density for TFP Because current crowding was prevented by replacing n-GaN electrodes with ITO thin films Correspondingly, the distribution graph shows a uniform distribution of the IQE in the TFP. A nonuniform distribution of the IQE is frequently observed in VLEDs because

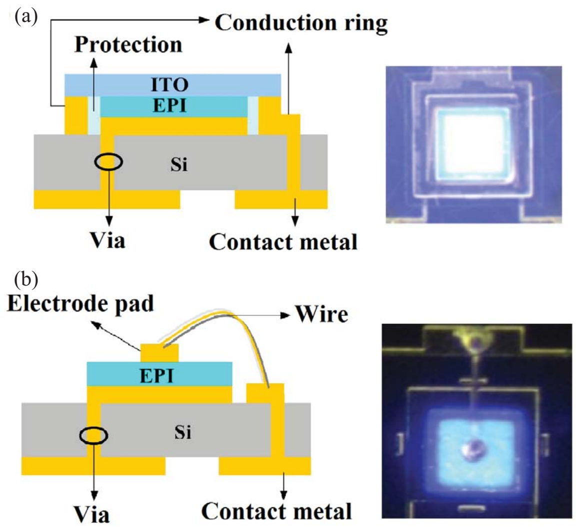

Fig. 2. Schematic diagram and photographs of TFP LED (a) without wire bond, and (b) with wire bond.

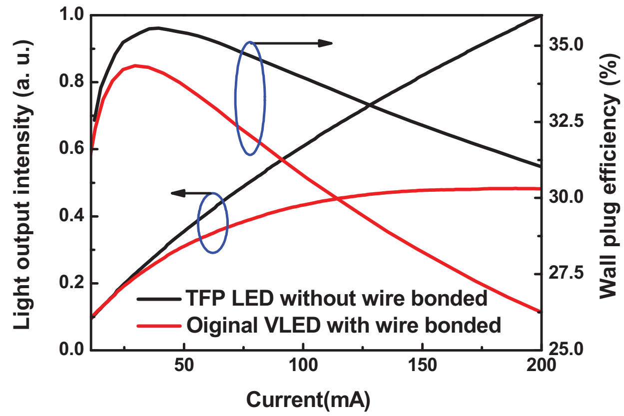

Fig. 3. Light output powers and wall-plug efficiency as a function of injection current for the TFP LED and original LED.

of crowded currents around the electrodes. Based on the results shown in Fig. 1, the current density in the TFP LEDs ranged from 25 – 40 A/cm^2 (Fig. 1 (a)), whereas the current density in the VLEDs ranged from 4 – 340 A/cm^2 (Fig. 1(b)). The VLEDs show a significant current crowding effect that reduces their IQE, life expectancy, and reliability. Fig. 1 (b) shows high-density current crowding around the metal electrodes and a decrease in the IQE around these electrodes.

Fig. 2 (a) shows the schematics of a TFP LED. This structure has no bonding wire, and ITO transparent conductive films were adopted to replace the n-GaN metal electrodes. The films were connected to the contact metal using conduction rings. The fabrication process of the TFP LED was as follows.

Prepared LED dies were mounted on a TSV substrate using metal bonding, and the sapphire substrate was removed using a laser lift-off process to complete an n-side-up thin GaN LED structure with a light-emitting area of 0.36× 0.36 mm^2 In order to avoid bonding problems in the vertical direction between epitaxial layer and substrate, the PTS (Planarized Thermally Stable) technology was adopted to fabricate a planarizing protection layer **[7]**. The planarized protection layer improves the reliability of electrical connection between conduction ring, epitaxial layer and ITO. Next, a protective insulating layer was coated on the side of the epitaxial layer, and conduction rings were produced to enable connection with the metal contact of the TSV substrate. Thereafter, the ITO transparent conductive films that were deposited on n-GaN contacted the conduction rings to uniformly distribute the injection current on the n-GaN surface through the ITO films. Fig. 2 (b) shows a conventional VLED structure. In this structure, n-GaN electrodes were connected with the contact metal of the n-Gan via gold wires. Extraction was affected because the light was shielded by both the n-GaN metal and gold wires. In the conventional GaN film transformation process in VLED fabrication, metal bonding and laser lift-off techniques were adopted. Metal electrodes were deposited on the surface of the n-GaN following the removal of the sapphire substrates, and the n-GaN electrodes were connected to the TSV conduction via using wire bonding.

To form control groups, the TFP LEDs and VLEDs were packaged on metal core PCBs (MCPCBs). Light emission was measured using integrating spheres at room temperature, and the transient thermal resistance was measured using the T3Ster Master System. In a thermal equilibrium state and by injecting a current of 50 mA into the TFP LEDs and VLEDs, a thermal infrared image analysis was performed to analyze the distribution of the surface temperature.

III. Results and Discussion

Fig. 3 shows the relationship between the output power and wall-plug efficiency of the TFP LEDs and VLEDs with various injections current. When a current greater than 40 mA was injected, the VLEDs showed significant signs of current droop, and the TFP LEDs, because they did not have bonding wires, demonstrated superior output power and wall-plug efficiency compared to the VLEDs. The output power of the TFP LEDs increased with the injection current, and, at 200 mA, no significant sign of current droop was observed. This was because, in the TFP LEDs, highly efficient light extraction was achieved through the nonshielded ITO films adopted as the n-GaN electrodes, whereas the metal wires and electrodes in the conventional VLEDs shielded the light and lowered the efficiency of light extraction, and unextracted light was absorbed and converted into heat by the epitaxial layers [8]. Fig. 4 summarizes the results of the thermal resistance analysis for the TFP LEDs and VLEDs. The thermal resistance of the TFP LEDs and VLEDs between the epitaxial layers and submount substrates was measured as 18 and 20.5 kW, respectively. The epitaxial layer was the primary cause of the thermal resistance difference between the TFP LEDs and VLEDs because heat spreading by ITO and the conduction ring is more efficient than through the thin bond wire. Consequently, the thermal resistance of VLEDs, which have bonding wires, increased.

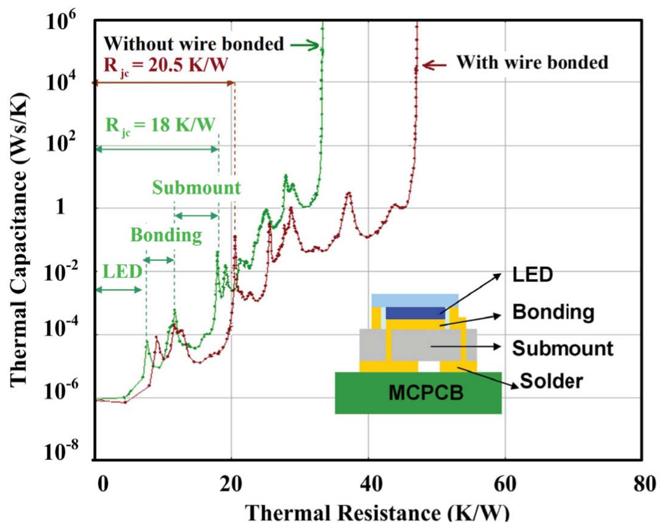

Fig. 4. Thermal resistance measured by T3ster and compared with the TFP LED and original VLED.

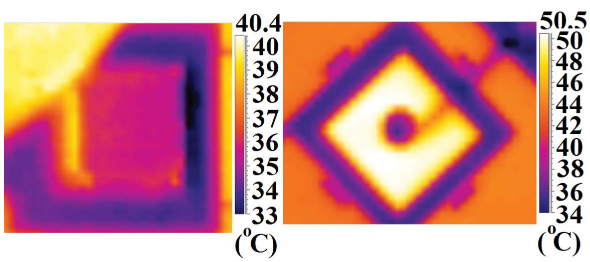

Fig. 5. Surface temperature distribution at an injection current of 50 mA for the LEDs with (a) TFP LED without electrode shielding and (b) original VLED with electrode shielding.

As shown in Fig. 5, the infrared temperature measurement showed a surface temperature of 34.3 and 49.0 °C for the TFP LEDs and VLEDs, respectively, matching the results of the thermal resistance analysis. The light emitted by MQW in the conventional VLEDs was reflected or absorbed by the metal electrodes. Reflected light entered the epitaxial layer and was converted to heat through accumulation in the GaN thin films. Light absorbed by metal was converted to heat through accumulation on the LED chip surface. The TFP LEDs were highly effective regarding light extraction because no light was shielded by metal Besides, the conduction ring and the contact metal of TFP LED provide two channels for heat transfer from the EPI to ITO then to the submount substrate. Therefore, the reduction of heat accumulation significantly enhanced the optical and thermal characteristics of the TFP LEDs.

A comparison of the measured results between the TFP LEDs and VLEDs suggested that the light-shielding metal electrodes reduced the efficiency of light extraction, increased heat accumulation, and shortened the life expectancy of LEDs. Furthermore, bonding wires in LED dies alter the uniformity and forms of phosphor distribution, and any alteration in the phosphor distribution changes the correlated color temperature (CCT) [9]. Therefore, TFP LEDs, which do not possess light-shielding metal, are an excellent electrode design that enhances the reliability of the color-mixing processes.

IV. Conclusion

This letter developed a novel electrode structure using thin films to manufacture LEDs. In the TFP LEDs, the proposed electrode design, using ITO transparent conductive films as nonshielded n-GaN electrodes, enhanced the light extraction efficiency and lightoutput power. In addition, the uniform current density distribution in the design enhanced the IQE of the epitaxial layers and reduced heat accumulation. The optical and thermal characteristics were improved, and, accordingly, the wall plug efficiency was increased. Color temperature and lumen as critical factors in LED lighting products, are determined by the quality of the phosphor distribution. The structure of the TFP LEDs, which have no bonding wires, proposed in this letter enable a uniform distribution of phosphor on the surface of the LED chip. By adopting this design, the distortion of phosphor can be prevented, and improved stability for LED color temperature is expected. Furthermore, gold consumption in producing TFP LEDs and VLEDs is 2.8×10^{-7} g and 1.9×10^{-5} g, respectively. The TFP LEDs, which have no bonding wires, are more economical than the VLEDs in their manufacturing process and can replace conventional VLEDs.

References

[1] I. Y. Evstratov, V. F. Mymrin, S. Y. Karpov, and Y. N. Makarov, "Current crowding effects on blue LED operation," *Phys. Status Solidi (c)*, vol. 3, no. 6, pp. 1645–1648, Jan. 2006.

[2] K. A. Bulashevich, I. Y. Evstratov, V. F. Mymrin, and S. Y. Karpo, "Current spreading and thermal effects in blue LED dice," *Phys. Status Solidi (c)*, vol. 4, no. 1, pp. 45–48, Jan. 2007.

[3] D. S. Wuu, S. C. Hsu, S. H. Huang, and R. H. Horng, "Vertical-conducting p-side-up GaN/mirror/Si light-emitting diodes by laser lift-off and wafer-transfer techniques," *Phys. Status Solidi (A), Appl. Res.*, vol. 201, no. 12, pp. 2699–2703, Sep. 2004.

[4] J. S. Ha, *et al.*, "The fabrication of vertical light-emitting diodes using chemical lift-off process," *IEEE Photon. Technol. Lett.*, vol. 20, no. 3, pp. 175–177, Feb. 1, 2008.

[5] G. Elger, M. Hutter, H. Oppermann, R. Aschenbrenner, H. Reichl, and E. Jager, "Development an assembly process and reliability investigations of flip-chip LED using the ausn soldering," *Microsyst. Technol.*, vol. 7, nos. 5–6, pp. 239–243, Jan. 2002.

[6] K. N. Tu and K. Zeng, "Tin-lead (SnPb) solder reaction in flip chip technology," *Mater. Sci. Eng.*, vol. 34, no. 1, pp. 1–58, Jul. 2001.

[7] A. Krishnamoorthy, *et al.*, "Solution processable passivation layer for active matrix thin film transistirs on rigid and flexible substrates,"in *Proc. SID Symp. Dig. Tech. Papers*, vol. 39, May 2008, pp. 140–142.

[8] R. H. Horng, R. C. Lin, Y. C. Chiang, B. H. Chuang, H. L. Hu, and C. P. Hsu, "Failure modes and effects analysis for high-power gan-based light-emitting diodes package technology," *Microelectron. Rel.*, vol. 52, no. 5, pp. 818–821, May 2012.

[9] B. Wu, X. Luo, H. Zheng, and S. Liu, "Effect of gold wire bonding process on angular correlated color temperature uniformity of white light-emitting diode," *Opt. Express*, vol. 19, no. 24, pp. 24115–24121, Nov. 2011.