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Visible Light-Emitting Diodes with Thin-Film-Flip-Chip-Based Wafer-Level Chip-Scale Package Technology Using Anisotropic Conductive Film Bonding

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***Abstract*—Demonstrated is advanced device and packaging architecture of visible GaN-based light-emitting diodes (LEDs) combining thin-film flip-chip (TFFC) devices and wafer-level chip-scale package (WLCSP) with through-silicon-via (TSV) and wafer-to-wafer alignment bonding. Also, a new interconnect technique for LEDs is introduced using an anisotropic conductive film with metal balls. Thermal rollover in light output vs. current characteristics is not observed up to 700 mA. A forward voltage at 350 mA is 3.06 V. The architecture can facilitate excellent heat removal through a TSV-formed Si wafer in addition to expected benefits of easy integration of Si-based devices in lighting modules. Light-output power at 350 mA increases by 11.1% compared to that of conventional flip-chip LEDs. A Lambertian-like emission pattern is also achieved.**

***Index Terms*—anisotropic conductive film (ACF), light-emitting diodes (LEDs), thin film flip chip (TFFC), through-silicon via (TSV), wafer-level chip-scale package (WLCSP).**

I. Introduction

Further improvement in quantum efficiencies while resolving technical issues associated with manufacturing costs is critical for continued expansion of light-emitting diodes (LEDs) to various applications as dominant lighting sources [1],[2]. For such purposes, flip-chip (FC) LEDs [3], thin-film flip-chip (TFFC) LEDs [4], and wafer-level package (WLP) technology [5] have been introduced. Further advancement in device fabrication and packaging, however, are required to provide a better technology platform for solid-state lighting.

In the present study, we propose to integrate four different device and packaging technologies. Two of them include TFFC for the highest light-extraction efficiency [6], and wafer-level chip-scale package (WLCSP) as an advanced cost-saving package. WLCSP is a technology for packaging of devices and circuits at the wafer-level instead of the traditional process of assembling individual devices in packages after dicing them from a wafer [7],[8]. We also employ two other techniques. Through-silicon-via (TSV) technology, which enables a vertical connection of two or more chips, is a promising solution to realize 3-D integration and to construct device architectures with increased efficiencies and improved performance characteristics used in silicon (Si) technology [9]. A TSV-formed Si substrate is employed for low cost, high thermal conductivity, and easy integration of Si-based devices. Finally, a new wafer-to-wafer (W2W) alignment bonding technique is introduced. Previous bonding techniques [10] are difficult to be applied in TFFC-based WLCSP (TFFC-WLCSP) due to high cost, low productivity, and voids formed between wafers during the bonding. A new interconnect technique is introduced using an anisotropic conductive film (ACF) as a one-step bonding material for the W2W-alignment bonding. ACF is an epoxy adhesive system used in electronics industry to make electrical and mechanical connections between drive electronics and substrates [11]. The ACF is filled with conductive particles (metal balls) that provide electrical interconnection between pads through the film only in a vertical (z) direction. The conductive particles are distributed far apart in the film, making the ACF not electrically conductive along in-plane (x and y) directions. ACF offers cost-saving yet effective interconnects, substituting conventional mechanical connectors or soldering interconnects. Furthermore, the ACF provides additional and possibly more important benefits in TFFC-based WLCSP, including simple process steps, high productivity, and the prevention of voids, which is critical in a laser lift-off (LLO) process.

II. Device and Packaging Structure and Process

LED structure grown on a (0001) sapphire substrate consists of a 5-μm-thick unintentionally-doped GaN layer (GaN:ud, 5 μm), a 4-μm-thick Si-doped n-type GaN layer (n-GaN:Si, 4 μm), five-period InGaN/GaN multiple quantum wells (MQWs), and a p-GaN:Mg layer (0.3 μm). For fabrication of TFFC-WLCSP LEDs, hole-type mesas were first formed for n-contact electrode until the n-GaN layer was exposed using inductively-coupled plasma reactive-ion etching (ICP-RIE).

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An indium-tin-oxide (ITO) film was deposited by sputtering as a transparent conductive electrode on *p*-GaN, and then annealed to reduce contact resistance. Reflective Ag/Ni/Pt metal layers were deposited by sputtering on the ITO/*p*-GaN. A SiO_2 layer (0.7 μm) was deposited by plasma-enhanced chemical vapor deposition (PECVD) to passivate the side walls of mesa. Ti/Ni/Au metals were then deposited on *p*- and *n*-contacts as bonding pads.

We adopted TSV formed on a Si wafer (thickness ~ 250 μm) as a bonding substrate. Fabrication process of the TSV started with deposition of a SiO_2 layer (1 μm) on the backside of Si wafer by PECVD as an etch-stop layer for via etching. TSV holes having a diameter of 200 μm each with an aspect ratio of 1.25 were formed by deep RIE. After removal of the SiO_2 layer on the backside of Si, another SiO_2 film (0.8 μm) was formed by thermal oxidation for side-wall insulation. Ti/Cu/Ni/Au metals were deposited by sputtering and electroplating for both *p*- and *n*-type contact metals, completing the process of TSV shown in lower part (in a dotted rectangle) of Fig. 1(a).

Next, W2W-alignment bonding between TSV-formed Si and FC-LED wafers was carried out using an ACF. Then, LLO process was performed using 248-nm line of a KrF excimer laser to separate the sapphire substrate that was used in epitaxial growth. After LLO, a GaN:ud layer was further etched to expose an *n*-GaN layer by ICP-RIE. Surface texturing by photo-electrochemical (PEC) etching was subsequently carried out using KOH-based solution.

III. Results and Discussion

Fig. 1(a) shows a schematic cross-sectional structure of TFFC-WLCSP LED architecture, where ACF is used for interconnection with metal balls between TFFC-LED and TSV-formed wafers. The pressed metal balls in a vertical (z) direction between metal pads serve as the electrical interconnection only in a vertical direction, not lateral directions. We believe that LEDs with such structure is the first one ever demonstrated. Fig. 1(b) and (c) show scanning electron microscopy (SEM) images of a fabricated chip and a textured N-face surface of *n*-GaN. Fig. 1(d) is an image of the opposite side of a TFFC-WLCSP LED, where TSV and anode/cathode metal contacts are formed. Fig. 1(e) shows an LED in operation. For high-power LEDs, thermal conductivity and cost of a package material are important selection factors. Alumina (Al_2O_3) and AlN used as a commercial package material have drawbacks of lower thermal conductivity and higher cost than Si, respectively. High thermal conductivity of Si (~140 W/mK vs. ~30 W/mK of Al_2O_3) secures efficient heat removal for stable LED junction temperature during the operation. In addition, via holes in TSV provide space to overflow the resin of ACF because the thickness of ACF before boding ~ 15 μm decreases to ~ 4 μm after bonding. Lastly, it is also easier to embed Si-based devices required in lighting modules, including as resistors, Zener diodes, and field-effect transistors (FETs).

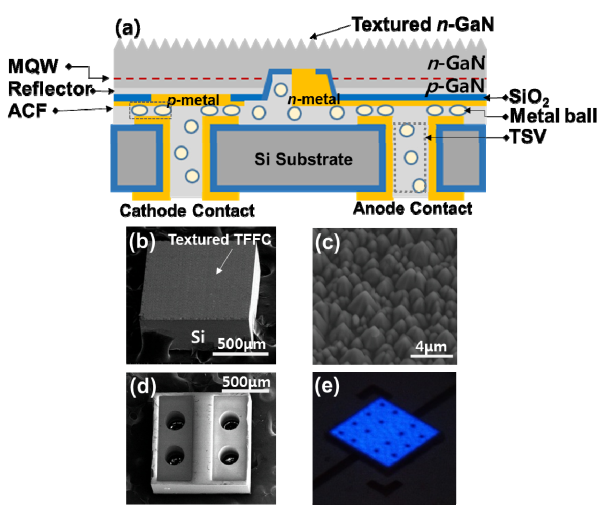

Fig. 1. (a) Schematic cross-sectional structure of a light-emitting diode (LED) using thin-film flip-chip (TFFC) and wafer-level chip-scale package (WLCSP), scanning electron microscope images of (b) a fabricated chip, (c) a textured *n*-GaN surface, and (d) the opposite side of chip, and (e) optical microscope image of device in operation.

Fig. 2 shows W2W-alignment bonding process using an ACF. An ACF is first attached on a TSV-formed Si wafer, a base substrate, by lamination process. For the lamination, heat is applied to the ACF at ~90 °C for 2 sec (Fig. 2(a)). The ACF-attached Si wafer is then placed on a plate in an alignment module. The other wafer with LEDs on a sapphire substrate is placed in position over the base substrate and the two sides are then aligned in the bonding module. A spacer is inserted between two wafers to prevent them from bonding before the alignment (Fig. 2(b)). After alignment, a bonding is made between the wafers by thermal compression (Fig. 2(c)). The ACF used in this study contains metal balls (with thermal conductivity of ~300 W/mK) having a diameter of ~4 μm with an areal density of ~5.2×10^3 mm^{-2}. A higher metal density than normally used ACF is intended for the good contact characteristics. A pressure of 2 MPa while heating at 180 °C was applied for 60 sec. for the bonding. ACF bonding technique can provide dual functions of interconnection, which enables interconnects of all chips with self-alignment in a wafer level without additional step and under-fill for a void-free structure, which can prevent cracks generated by laser thermal

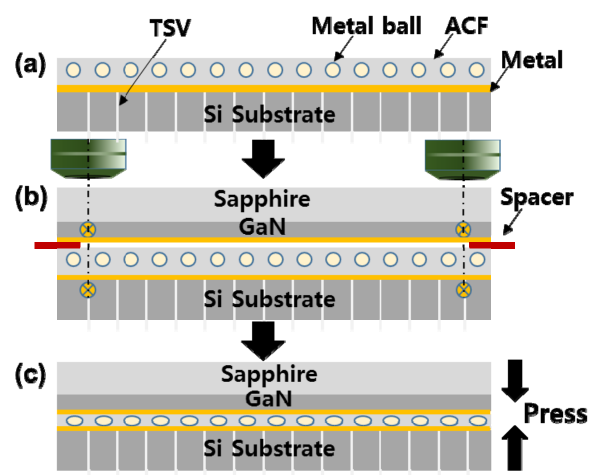

Fig. 2. Fabrication process flow for wafer-to-wafer (W2W) alignment bonding between a TSV-formed Si wafer and a fabricated FC-LED wafer using an anisotropic conductive film (ACF).

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damage during LLO. The W2W-alignment bonding technology using a lamination method with ACF is a promising technology for the interconnection of the entire chip, which offers advantages in cost, alignment accuracy, larger diameter semiconductor manufacturing, and mass production.

Fig. 3 compares light output power-current-voltage (*L-I-V*) curves of LEDs fabricated with a conventional FC-structure and a TFFC-WLCSP-structure. The light output power of TFFC-WLCSP LEDs is higher than that of FC-LEDs, with an improvement of 11.1% at a forward current of I = 350 mA. Forward voltages at 350 mA are 3.04 V, and 3.06 V for FC-LEDs and TFFC-WLCSP LEDs, respectively. The forward voltage of the TFFC-WLCSP LEDs is slightly higher than that of FC-LEDs by ~0.02 V, which is small enough to be ignored in practical devices. The interconnects with metal balls in the ACF do not cause large contact resistance. The improved light-output-power characteristics of the TFFC-WLCSP LEDs compared to FC-LEDs are due to improved light extraction efficiency by roughening of n-GaN surface. In the case of FC-LEDs, it is difficult to further enhance the light extraction efficiency through patterning/texturing except patterned sapphire substrates. The TFFC-LEDs also have advantages over vertical-injection thin-film LEDs in light extraction, avoiding absorption by a top-contact and wire bond pads. Furthermore, thermal rollover of output power is not observed up to I = 700 mA. This suggests that heat generated in the LED is effectively removed through the TSV-formed Si wafer, which has a higher thermal conductivity than sapphire by the factor of three in magnitude.

Fig. 4 compares radiation patterns of TFFC-WLCSP LEDs and FC-LEDs. The TFFC-WLCSP LEDs have a Lambertian-like emission pattern due to the thin-film structure and surface roughening, which disrupts a waveguide formed by air/GaN and GaN/sapphire interfaces. It can effectively enhance out-coupling and significantly reduce the amount of side emission. The emission pattern of conventional FC-LEDs spreads in lateral directions and exhibits a considerable amount of side emission.

IV. Conclusion

We present visible light-emitting diode (LEDs) with thin-film flip-chip (TFFC)-based wafer-level chip-scale package (WLCSP) as an advanced packaging structure. We also introduce an anisotropic conductive film (ACF) as a bonding material used in wafer-to-wafer (W2W) alignment bonding. Especially, W2W-alignment bonding technology by a lamination method with ACF is developed for the interconnection of the entire chips on wafers, which differentiate this study from conventionally used methods. We confirm that thermal rollover does not occur up to 700 mA and current flow through ACF is not limited. Developed technology also offers advantages of easy embedment of Si-based devices to enhance the degree of freedom in designing general lighting modules. Light-output power of TFFC-WLCSP LEDs is higher than that of conventional FC-LEDs by 11.1%. A Lambertian-like emission pattern is achieved, which is suitable for the applications of automotive headlamps and projection systems.

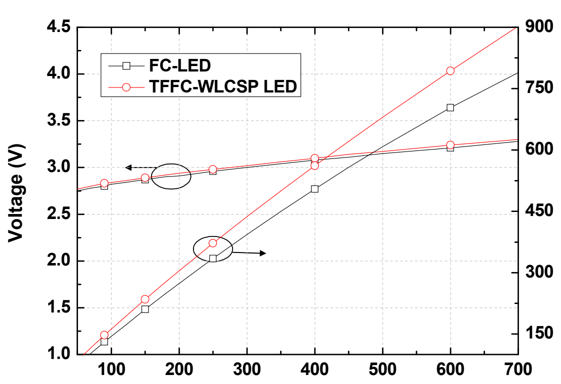

Fig. 3. *L-I-V* characteristics of FC-LEDs and TFFC-WLCSP LEDs.

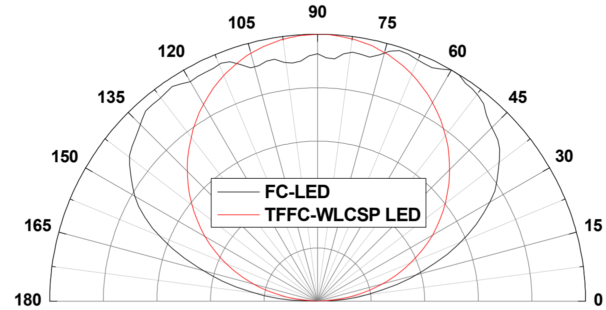

Fig. 4. Normalized radiation patterns of FC-LEDs and TFFC-WLCSP LEDs at a forward current of 350 mA.

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