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A Screen Printed Sn-Based Dicing-Free Metal Substrate Technology for the Fabrication of Vertical-Structured GaN-Based Light-Emitting Diodes

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1. Introduction

GaN-based light-emitting diodes (LEDs) have continuously attracted many interests to expand their applications into high brightness area such as flashlight, backlight source for liquid crystal display (LCD), and even solid-state lighting recent years [1], [2]. The most crucial issue for conventional sapphire substrate GaN-based LEDs (regular LEDs) applied to high brightness applications lies on the severe current-crowding effect accompanied with inherent joule heat accumulation. To alleviate this, substrate transfer techniques by means of laser lift-off (LLO) in conjunction with wafer bonding or thick electroplated-metal-substrate have been reported for the fabrication of vertical GaN-LEDs [2-4]. The electroplated-metal-substrate is adorable for its simplicity of fabrication processes, yet a large thickness (30~80 μm) is highly demanded to provide enough mechanical sustainability after sapphire removal and for die attaching processes. It is thus inevitable to confront metal cutting issues. For the avoidance of thick-metal-cutting, Chen *et al.* developed a dicing free metal substrate technology for the fabrication of vertical GaN-LEDs through the use of selective electroplating nickel (Ni) substrates with patterned LLO, and stimulating results have been reported [4].

However, it is still time-consuming to grow thick metal substrate using selective electroplating technology. For the pursuit of high production throughput, simplification of the fabrication process, and reserving the merits of using metal substrates, a dicing free metal substrate technology using Sn-based solder screening printing techniques with patterned laser lift-off (LLO) for the fabrication of vertical LEDs (VM-LEDs) was proposed and demonstrated in this work. Electrical and optical characteristics of the prepared VM-LEDs are presented and discussed. Comparisons with that of regular LEDs are also made.

2. Sample preparation

Samples prepared in this work were epitaxially grown on sapphire by metal-organic chemical vapor deposition. The p-GaN was 0.15 μm thick and 3×1017 cm^{-3} doped, while for n-GaN were 3 μm and 4×1018 cm^{-3}, respectively. Note that oxidized Ni(2.5 nm)/Au(3.5 nm) as an ohmic contact, and Ti(15 nm)/Al(400 nm)/Ti(100 nm)/Au(200 nm) as an adhesive and mirror reflector layer were deposited sequentially on p-GaN layer by E-beam evaporator.

To pursue dicing free, a photolithography process using thick SU8-3010 photoresist was employed to defined the device region (960×910 μm^2) with a cutting-way width of 90 μm, followed by deposing on patterned Ni (5 μm)/Au (150 nm) barrier/wetting layers preventing Sn from reacting with the structure underneath during the reflow process. After that, using 100-μm-thick stencil plate aligned to patterned wetting layer, the Sn-based solder paste was screen-printed, defining the volume and localization in the meantime [Fig. 1(a)]. Afterwards, a rapid thermal reflow treatment was performed at 210-230 °C for 90s and the patterned Sn-based metal substrates formed. Note that, the melting point, reflow temperature, and thermal conductivity of the Sn-based substrate could be increased via a suitable change in its alloy composition [5]. Prior the patterned LLO, samples were glued to glass temporal substrate with polyamide [Fig. 1(b)]. Removal of u-GaN with inductively coupled plasma, surface treatments with KOH, and the formation of n-side metal pad (Fig. 1(c)) were sequentially performed for the fabrication of the proposed VM-LEDs [6]. Note that regular LEDs, as shown in Fig. 1(d), of the same chip size with two electrodes on the same side of the device were also fabricated with the same wafer for comparison.

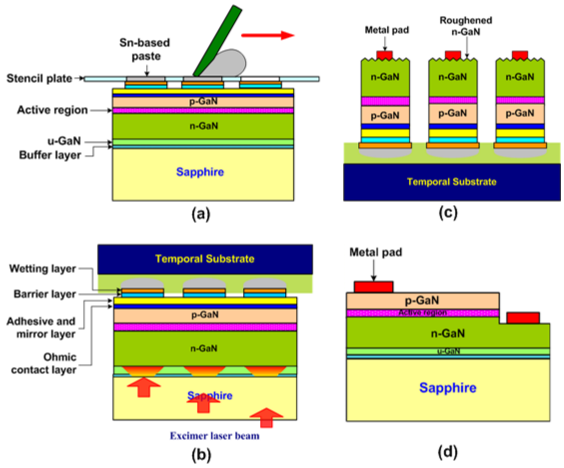

Fig. 1 The key fabrication processes of the proposed screening printed metal substrate technology. (a) Solder paste screen printing, (b) patterned LLO process, (c) the fabricated VM-LEDs, and (d) The schematic cross section of a regular GaN-based LEDs.

3. Results and discussion

The surface morphologies of the sample at specific processing stages were obtained from scanning electron microscopy (SEM) and optical microscope (OM) and shown in Fig. 2. Figure 2(a) showed the top-view image of the sample after screen printing. The volume was well controlled and the solder paste was properly localized using the stencil plate aligned to the patterned wetting layer. Figure 2(b) showed the top-view image of the sample after the reflow process, and Fig. 2(c) revealed the 3-D profile of the unit substrate characterized with the confocal microscope. Square and uniform patterned Sn-based substrates were attained. The tilt-view image of the exposed n-GaN after patterned LLO processes was shown in Fig. 2(d). One observed the exposed n-GaN surface was even and flat, indicating the proposed Sn-based substrate sustained the epi-layers nicely through the fabrication processes.

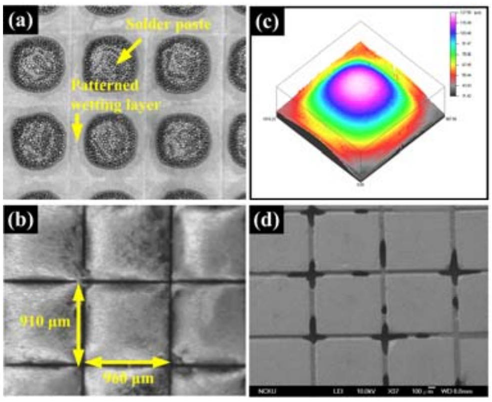

Fig. 2 SEM and optical microscope OM images of samples at some processing states. (a) Top-view image of the sample after screening printing of Sn-based solder paste. (b) Top-view image of the patterned Sn-based substrates after reflow process. (c) 3-D profile of the unit Sn-based substrate. (d) Tilt-view image of the exposed n-GaN after patterned LLO.

Both the current-voltage (*I-V*) and light output-current (*L-I*) characteristics of the fabricated LEDs were measured by an LED tester. VM-LEDs prepared with the proposed screen printing metal substrate technology show comparably much better than regular LEDs, indicating the feasibility of the new metal substrate technology proposed in this work. The comparisons of the typical *I-V* characteristics of the fabricated and regular LEDs were shown in Fig. 3. Since the vertical structure allows a much shorter conduction path between electrodes and a lees current crowding, a considerable reduction in forward voltage drop of 1.62 V ($\Delta V_F/V_F$=25.67%) at 350 mA was obtained.

Figure 4 shows the comparison of typical *L-I* characteristics of VM-LEDs and regular LEDs. At 350 mA, it is seen that a significant improvement in Lop by 226.64% (i.e., $\Delta L/L$) was obtained from VM-LEDs. These improvements should be mainly attributed to the fact that the vertical structure itself provides better current spreading, less series resistance, larger light extraction area benefiting from single electrode on top n-GaN, surface roughening on n-GaN layer, and higher light reflection [7]. Based on our results, note that VM-LEDs prepared by the proposed screen printed metal substrate technology also exhibit comparable good in reliability performance test. Results of the device performance after 168 hr continuously operation at 350 mA will be reported and discussed.

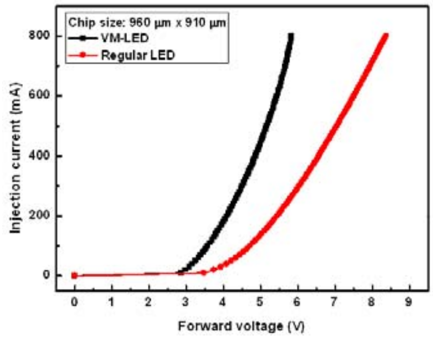

Fig. 3 Comparisons of the typical *I-V* characteristics of VM-LEDs and regular LEDs.

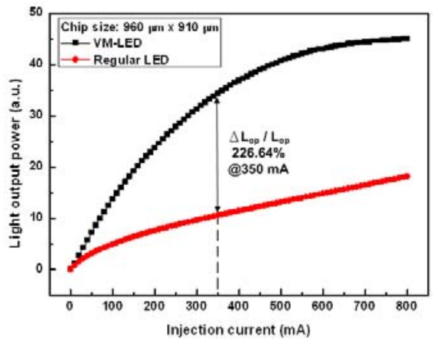

Fig. 4 Comparisons of the typical L_{op}-*I* characteristics of VM-LEDs and regular LEDs.

4. Conclusion

In summary, the novel dicing free metal substrate technology using Sn-based solder screening printing and patterned laser lift-off (LLO) technique for the fabrication of VM-LEDs has been proposed and stimulating experimental results have been demonstrated. As compared to lateral-conducting regular LEDs, the proposed VM-LEDs with a surface roughening have been shown having an enhancement in Lop about 226.64% at 350 mA. It is expected that the proposed screen printed Metal Substrate technology would be a potential candidate for the fabrication of high power and cost-effective GaN-based LEDs for solid-state lighting.

Acknowledgements

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