A Sn-based metal substrate technology for the fabrication of vertical-structured GaN-based light-emitting diodes

Hon-Yi Kuo, Shui-Jinn Wang, and Pei-Ren Wang
Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan, Republic of China

Kai-Ming Uang and Tron-Min Chen
Department of Electrical Engineering, Wu Feng Institute of Technology, Chiayi 621, Taiwan, Republic of China

Hon Kuan
Optoelectronics Center of Far East University, Tainan 744, Taiwan, Republic of China

(Received 1 October 2007; accepted 17 December 2007; published online 14 January 2008)

Through the use of tin (Sn) based solder balls and patterned laser lift-off technique, a metal substrate technology was proposed for the fabrication of vertical-structured metal substrate GaN-based light-emitting diodes (VM-LEDs). Advantages including the merits of metallic substrate and simplifying the fabrication processes of vertical-structured GaN-based LEDs were demonstrated. As compared to conventional sapphire substrate GaN-based LEDs, the fabricated VM-LEDs with an emission area of $620 \times 620 \, \mu m^2$ show an increase in light output power about 145.36% at 350 mA with a significant decrease in forward voltage from 4.51 to 3.46 V.

Recently, continuous efforts have been made to develop high power and high efficiency white light GaN-based light-emitting diodes (LEDs) for the applications of flashlight, backlight source for liquid crystal display, and even solid-state lighting. To solve the severe current-crowding effect and heat accumulation issues due to insulating sapphire substrate used in conventional p-side up GaN-based LEDs (namely, regular LEDs), substrate transfer techniques by means of laser lift-off (LLO) with wafer bonding or electroplating have been reported for the fabrication of vertical-structured GaN-based LEDs. Lately, the author’s groups demonstrated the use of selective electroplating nickel (Ni) substrates with patterned LLO for the fabrication of vertical-structured metal-substrate GaN-based light-emitting diodes (VM-LEDs). Advantages including avoidance of metal cutting and better electrical and optical characteristics in comparison with regular LEDs have been presented.

To package high performance LED chips, tin-based solder materials have been widely adopted as a substitute for conventional epoxy or conductive glue used in the die-attaching process for its superior thermal and electrical characteristics. In this paper, to simplify the device fabrication processes of VM-LEDs with high throughput, cost effectiveness, and environmental friendliness, a metal substrate technology using tin (Sn) based solder balls with a nickel barrier layer and a Au wetting layer was proposed and demonstrated. Electrical and optical characteristics of the fabricated VM-LEDs were reported and compared to those of regular LEDs as well.

Figures 1(a) and 1(b) illustrate schematically the layer structure and key fabrication processes of the VM-LEDs using the proposed metal substrate engineering. Here, lead-free Sn-based (a Sn–Ag–Cu–Au alloy) solder balls were employed for the implementation of dicing free metal substrates. The samples prepared in this work were epitaxially grown on sapphire substrate by metal-organic chemical vapor deposition. For the details of the layer structure, please refer to Ref. 6. Note that oxidized Ni(2.5 nm)/Au(3.5 nm), Ti(15 nm)/Al(400 nm)/Ti(100 nm)/Au(200 nm), and Ni(200 nm)Au(200 nm) metal systems were deposited sequentially on p-GaN layer by e-beam evaporator to serve as Ohmic contact, adhesive/mirror layer, and barrier/wetting layer, respectively.

To pursue dicing free, a photolithography process using thick SU8-2035 photore sist was employed to define the device region ($750 \times 750 \, \mu m^2$) with a cutting-way width of 90 $\mu m$, followed by a selective electroplating process to form 10-$\mu m$-thick Ni metal frames over the entire cutting-way region under a constant current of 1.7 A for 10 min. After that, Sn-based solder balls (350 $\mu m$ in diameter) were placed within each device region and a rapid-thermal (RT) reflow process was autolifted after the RT reflow treatment at 280–300 °C for 90 s was conducted. Note the increasing rate of temperature was kept at 1.7 °C/s. After that, the samples were cooled at a rate of −0.5 °C/s and the patterned Sn-based metal substrates formed. It should be mentioned here 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 to accommodate surface mount technology used for LED applications.

Prior to the patterned LLO process, the sample was glued to a temporal silicon (Si) substrate with polyamide. Through the use of a mask to define both size ($620 \times 620 \, \mu m^2$) and shape of excimer laser beam (248 nm) and an alignment to the patterned Sn-based metal substrate, the patterned LLO process [Fig. 1(a)] was performed at a reac-
tive energy of 850 mJ/cm². It should be noted that the area ratio of the laser beam size also the size of the device emission area to the chip size i.e., device region was kept to be less than 0.82 in the present work to prevent the edge of epitaxial structure from irregular breach or flaw during the fabrication of device. The sample was then heated to about 40 °C for 10 min to remove the sapphire substrate. To remove the u-GaN, an inductively coupled plasma dry-etching process was conducted. For better light extraction and the contact characteristics, a surface treatment with 6 mol KOH solution at 60 °C for 90 s was also made. After the surface of the exposed n-GaN was cleaned with HF and diluted HCl:H₂O (1:1) solution for 1 min, a metal contact pad comprised of Ti–Al–Ti–Au was deposited by e-beam evaporator. Finally, the temporal silicon substrate was replaced with a blue tape and the fabrication of the proposed n-side up VM-LED chips with Sn-based metal substrates was completed. Note that regular LEDs, as shown in Fig. 1(c), of the same chip size with two electrodes on the same side of the device were also fabricated with the same wafer for comparison.

Figure 2(a) shows that top view of the oval-like patterned Sn-based metal substrate due to its cohesion. Figure 2(b) shows the cross-sectional structure of the sample before patterned LLO. Flat and smooth interface between GaN epitaxial layer and metal layers was observed. By energy dispersive x-ray spectrum analysis, Ni/Au layer was proved to effectively prevent Sn from reacting with the structure underneath during the reflow process. Figure 2(c) shows the top view of the exposed n-GaN. An even GaN surface was obtained. Figure 2(d) reveals that the Ni metal frames were completely self-removed after the RT reflow treatment.

The comparison of current-voltage (I-V) characteristics of the fabricated VM-LEDs and regular LEDs with the same chip size were shown in Fig. 3. It is seen that, at an injection current of 350 mA, the forward voltage (V₉) of the proposed VM-LEDs are 3.46 V, which is comparably good with previous works reported by Chen et al. and Lin et al. in spite of the smaller chip size, while that of the regular one is 4.51 V. As compared with regular LEDs, the reduction in V₉ of the n-side up VM-LEDs should be attributed to the con-
considerable improvement in current spreading and the realization of a much shorter vertical conduction path between the two electrodes (~4 μm in this work).1–6 It is noted that the incremental series resistance [(dV/dI)−1] of the VM-LEDs is about 1.0 Ω at 350 mA, which is about 1/3 that of regular LEDs at the same current. The inset of Fig. 3 shows the typical reverse characteristics of VM and regular LEDs. It is seen that the VM-LED has a relatively inferior reverse characteristic. This might be attributed to the LLO process that increases the density of screw dislocations, which penetrated through the MQW region, and/or causes damages to the periphery of the device.8 Optimization of the LLO process to minimize the damage to the epilayer and utilization of suitable passivation to VM-LEDs are now underway.

Figure 4 shows the typical light output power–current (Lop−I) characteristics of VM-LEDs and regular LEDs. The proposed VM-LED was found having an increase in light output power (i.e., ΔLop/Lop) of about 145.36% over that of regular LEDs at 350 mA. The power conversion efficiency (λ=P_o/I, i.e., the ratio of optical output power P_o to input electrical power I) of the VM-LEDs at 350 mA is about 3.20× that of regular 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.4 Through curve fitting for both the Lop−I curves at high injection currents (blue solid lines), it was found that the dependence of light output power of the VM and regular LED on the injection current can be expressed as Lop∝I^0.71 and Lop∝I^0.56, respectively. As we expected, the light output power of the VM-LED exhibited a better response under high injection currents. Note that the improvement in ΔLop/Lop and λ are comparably good with previous works, indicating that the present Sn-based substrate technology would be attractive for thin GaN-based LED fabrication.4,5

The dependence of peak wavelength (λp) on injection current of both VM and regular LEDs was also plotted in the inset of Fig. 4. Under low injection currents, the band-filling effects dominated and led to the blueshift in λp for both the VM and regular LEDs.9–11 As the injection current was further increased, accumulation of Joule heating attributed to series resistance and nonradiative recombination of carriers results in a strong redshift and the blueshift from the band filling effect was overridden.10 One observes that the prevailing of the redshift occurred at 170 and 280 mA for the regular and VM-LEDs, respectively. It reveals that a relatively slight accumulation of Joule heating of the VM-LEDs was achieved.

In summary, a metal substrate technology using Sn-based solder balls and patterned laser LLO technique for the fabrication of VM-LEDs has been proposed and stimulating experimental results have been demonstrated. As compared to regular LEDs, the proposed VM-LEDs have been shown to have an enhancement in Lop about 145.36% and a Vf drop of 1.05 V at 350 mA, which provides an improvement in the power conversion efficiency by about 3.20× that of regular LEDs. It is expected that the proposed Sn-based metal substrate technology would be a potential candidate for the fabrication of high power GaN-based LEDs for solid-state lighting in the near future.

This work was supported by the National Science Council (NSC) of Taiwan, Republic of China, under Contract No. NSC 95-2215-E-006-014 and the Landmark Project Grant for NCKU’s Top-University Project.