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Fabrication and Characterization of Flip-Chip Power Light Emitting Diode with Backside Reflector

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Abstract—***The electrical, optical, and thermal characteristics of flip-chip (FC) GaN-based light-emitting diodes (LEDs) with and without backside aluminum (Al) reflector have been investigated. The LEDs were mounted on the silicon (Si) sub-mounts which have superior thermal conductivity (150 W/m·K), and the Au stub bumps were used as the interconnecting metal to achieve the FC bonding process. Compared with the conventional FC-free LED, the light extraction and thermal conduction of FC LED have been improved and no significant degradation of forward and reverse I–V characteristics are observed. Moreover, adding a backside Al reflector can further enhance upward light emission. The optimum numbers of Au stub bumps are 24, that is, the optimum total area of Au stub bumps is about 22.8×10^4 μm^2 for a 1 mm×1 mm LED chips.***

Index Terms—**Au stub bumps, flip-chip, light-emitting diodes, thermal performance.**

I. INTRODUCTION

The high power gallium nitride (GaN) based light-emitting diodes (LEDs) are of great technological importance for the achievement of solid-state lighting [1]-[4]. In order to achieve solid-state lighting, it is important to attain significant improvement of the light output of LEDs. Since most GaN-based LED related epitaxial grown devices choose sapphire as substrate which thermal conductivity are only 35 W/m·K. With the increase of input power, the thermal problem is becoming more and more important causing negative effect on the optical performance, reliability, and lifetime [5]-[6]. In order to solve the thermal problem, it has become essential to adopt high-power chip structures such as the flip-chip configuration (FC LED) [7]–[10]. Flip-chip (FC) LED means that the LED chip is flipped over and mounted on various heat-sink sub-mounts. The light from the active layer emits through the backside of transparent sapphire substrate, therefore, no attenuation of light is made by the semi-transparent metal electrode. Moreover, p-type electrodes should be good reflectors having high reflectance and low contact resistivity, or a thick backside metal reflector should be deposited on the p-layer to enhance upward light emission. The level of current injection in FCLED can be increased by the use of a thick p-electrode with negligible sheet resistance and efficient heat dissipation through the sub-mount. The heat generated in the LED will flow directly through the interconnecting metal bumps between the LED chip and the sub-mount to improve the thermal conduction. Thus, FC LED structure can achieve high power and high brightness performance. Conventional FC bonding methods include thermo compression bonding using high force and heat, but problems such as reliability can be caused by the high force and temperature required by this process. Adhesives are an attractive alternative, however it needs to apply adhesive on the chip or sub-mount surface reduced the effectiveness and will add cost of this process in high volume production. Thermo sonic bonding used in this study is a thermo compression process which is aided by ultrasonic vibration of the chip during bonding. With ultrasonic vibration providing energy to interface, the need of force and temperature can be reduced [11]. Low force and temperature makes it particularly useful for fragile materials such as epi-layers of LEDs. This bonding process also provides a short time that means high yield rate can be beneficial for mass production. In order to properly develop FC LED structures for specific applications, it is important to accurately understand the characteristics of LEDs. In this work, the electrical, optical, and thermal performances of high power GaN-based FC LED have been studied experimentally. Silicon (Si) is used as sub-mount which has high thermal conductivity of 150 W/m·K, and Au stub bump as the interconnecting metal by thermo sonic bonding to achieve the FC process. Au stub bump has very high thermal conductivity (291 W/m·K), therefore, it can also provide a good spreading path to transmit the heat to the sub-mount. However, without enough spreading paths, the junction temperature of LED cannot be reduced, or even more, are higher than conventional FC-free LED. There are few works reported on the optimum numbers of Au stub bump for silicon sub-mount FC LEDs. In our previous work [12], we showed that the thermal performance of the FC LEDs can only be improved when using at least 6 Au stub bumps as interconnected metals, and can be improved with increasing numbers of Au stub bumps (8~20). However, the thermal performance of the FC LED with more Au stub bumps (>20) is not understood. In order to balance cost, yield, and spreading heat ability, the optimum numbers of Au stub bump has been investigated for FC LED in this work. Moreover, a high-reflectance backside aluminum (Al) reflector is deposited surround the p-contact pad to enhance upward light emission of FC LED. The investigation was carried out by combining electrical, optical, and thermal measurement.

II. EXPERIMENTAL

The GaN-based LEDs with the emission wavelength of 456 nanometer (nm) used in this paper were grown by metal organic chemical vapor deposition (MOCVD) on c-face sapphire (0001) substrates. After the epitaxial layers were grown, indium–tin–oxide (ITO) transparent conductive layer (2400 Å) was deposited by E-beam evaporator on the epitaxial layers, and then partially etched by inductively coupled plasma (ICP) until n-type GaN layer for mesa formation. The silicon dioxide (SiO_2) was deposited by PECVD (1100 Å) on the surface of wafer to avoid the backside Al reflector diffusing downward and degrading the contact resistance [13]. Then, Cr (30 nm)/Au (1.2 µm) was deposited by E-beam evaporator and annealed at 270 °C for 30 min used as a contact metal layer. The sapphire substrate was grinded to 150 micrometer (µm) thick and cut into power size chips with laser, in 1 mm × 1 mm after depositing aluminum (Al) of thickness 500 nm as backside reflector to reflect the light emitted downward through the p-type contact in our FC LED structure. Fig. 1(a)-(d) show the Cr/Au contact metal pattern with different geometry. For fabricating p-Si (100) sub-mount (thickness 525 µm), the SiO_2 layer (300 nm) was deposited by PECVD after the sub-mount had been cleaned. Using photolithography process, Ti/Au (15 nm/100 nm) metal electrode was deposited by E-beam evaporator. Au stub bumps with about 110 µm diameter and 85 µm height (including tail height) as shown in Fig. 2(a) were then implanted on the sub-mount by wire bonder (Kulicke and Soffa 4522 series manual). The heating temperature of the wire bonder hotplate was set to 180 °C to let Au stub bumps have better adhesion on sub-mount. Fig. 2(b) clearly describes, for example, the arrangement of 24 Au stub bumps on designed sub-mount where n and p represent the negative and positive electrode, respectively. In this design, the number of Au bumps on n-pad is 4. Keeping in mind that the heat is generated from p-GaN layer, more Au bumps were placed beneath the p-electrode to dissipate heat effectively. The total number of Au bumps placed on p-pad and n-pad is 20, 24, and 36 for three different configurations, respectively. Furthermore, the arrangement of 24 Au bumps is designed two patterns, referred to as “n-pad not connection” and “n-pad connection”, in order to realize the effect caused by the separation of electrical property and heat dissipation. The sub-mount with implanted Au stub bumps was then put on the hotplate of Ultrasonic-FC Bonder which is made by Industrial Technology Research Institute (ITRI, Taiwan). The temperature of hotplate was set to 180 °C. The flip-chip bonding was implemented by appropriate ultrasonic power and force of Ultrasonic-FC Bonder. Finally, silver adhesive was used to attach LED on the COP (chip on plate) package in order to understand the effect of light extraction with respect to chip structure after packaging. In the electrical (I–V) and optical (EL, LI) characteristics measurements for LEDs with and without the FC sub-mount (referred to as FC LED and FC-free LED), Keithley 2410 and *integrating sphere* were used, respectively. The forward voltage was analyzed based on the measured forward current versus voltage curves. The thermal infrared microscopy (FLIR SC620) was used to measure the average surface temperature for LED samples.

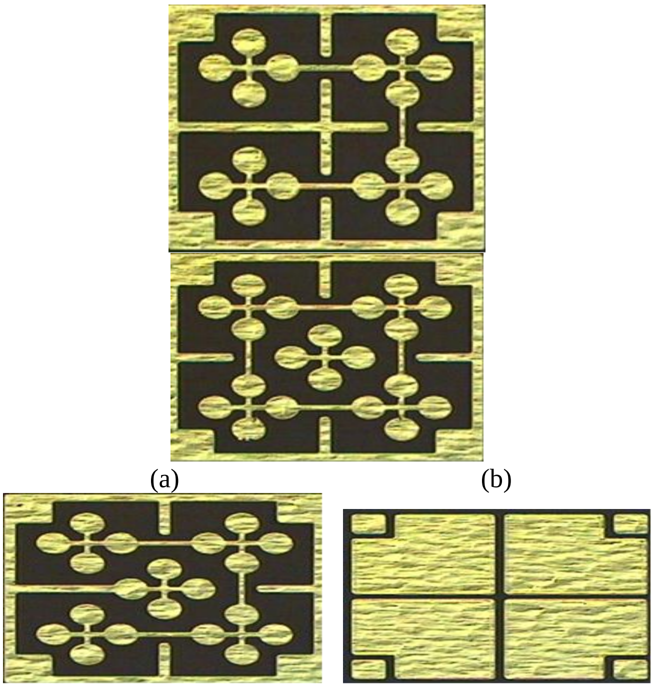
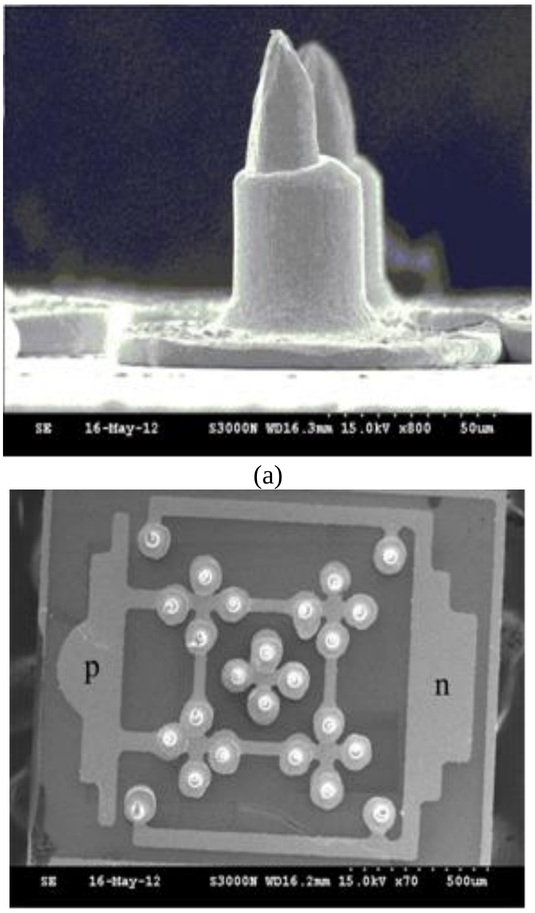


Fig.1 Cr/Au contact metal pattern with different geometry of LED for (a) 20 Au stub bumps, (b) 24 Au stub bumps (n-pad not connection) (c) 24 Au stub bumps (n-pad connection) (d) full plane p-pad (36 Au stub bumps).

III. RESULTS AND DISCUSSION

A. The electrical characteristics

In order to realize the effect of FC bonding process on the electrical characteristics, the forward and reverse current–voltage (I–V) curves were measured for FC LEDs without backside Al reflector and conventional FC-free LEDs as shown in Fig. 3 (a) and (b). No significant degradation of forward and reverse I–V characteristics were observed from the measurement. The induced series resistance and minor degradation caused by FC processes were responsible for the shift of forward voltage (V_F) as compared to FC-free LED. The forward voltage (V_F) of 3.58 V at 350 mA injection current was observed for FC-free LED, while the forward voltage (V_F) of 3.68 V, 3.83 V, 3.96 V, and 4.28 V was observed at 350 mA after FC process. Similarly, the reverse leakage current is increased after FC process but still far below the standard value of 1 μA at -5 V except for FC LED with 36 Au stub bumps (not shown). While too many Au stub bumps are implanted on sub-mount, the contacts of Au stub bumps become poor and hence the leakage current becomes larger than standard value.



(a)

(b)

Fig. 2 (a) SEM image of Au stub bumps on submount with diameter of 110 μm and height of 85 μm, (b) Arrangement of 24 Au stub bumps (n-pad not connection) on designed sub-mount where n and p represent the negative and positive electrode, respectively.

Fig. 4 shows the forward I–V characteristics of the FC-free LED and FC LED with backside Al reflector and with different numbers of Au stub bumps. The forward voltage (V_F) of 3.58 V at 350 mA injection current was observed for FC-free LED, while the forward voltage (V_F) of 3.76 V, 3.85 V and 3.87 V was observed at 350 mA for FC LED with 20, 24 (n-pad not connection), and 24 (n-pad connection) of Au stub bumps. The measured forward voltages (V_F) of FC LED with backside Al reflector are comparable to that of FC LED without backside Al reflector. We suggest that the backside Al reflector is deposited surround the p-contact pad and hence do not further increase the series resistance. Similarly, the reverse leakage current (not shown) is also increased after FC process, but still far below the standard value of 1 μA at -5 V.

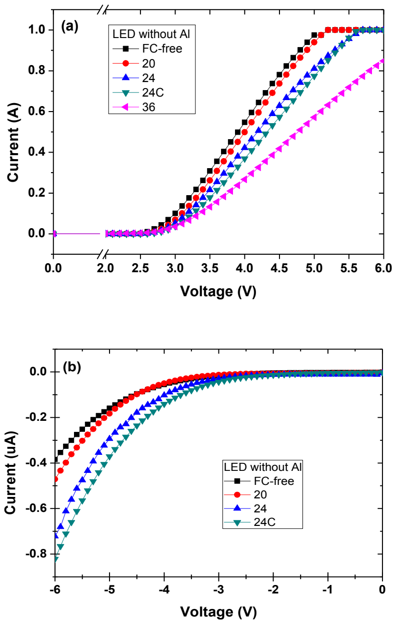


Fig. 3 (a) Forward and (b) reverse I–V characteristics of the FC-free LED and FC LED with different numbers of Au stub bumps and without backside Al reflector.

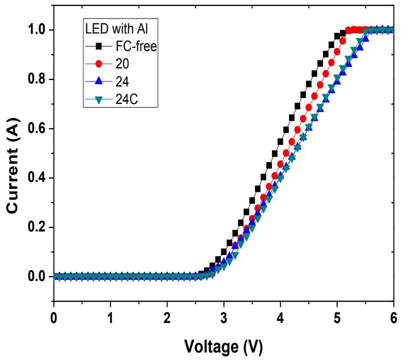


Fig. 4 Forward I–V characteristics of the FC-free LED and FC LED with different numbers of Au stub bumps and with backside Al reflector.

B. The optical characteristics

Fig. 5 shows electroluminescence (EL) spectra taken through the FC-free LED and FC LED with and without backside Al reflector and with 20 of Au stub bumps at 350 mA injection current. A single peak emission at around 456 nm with full-width-at-half-maximum (FWHM) of around 26 nm was observed. The EL intensity of FC LED without backside Al reflector at operating current of 350 mA is 122.7% of that of FC-free LED, while the EL intensity of FC LED with backside Al reflector is 142.6% of that of FC LED without backside Al reflector. It is apparent that the light output efficiency of FC LED has been improved. Moreover, adding a backside Al reflector can further enhance upward light emission. FC LED means that the LED chip is flipped over and mounted on heat-sink sub-mount. Compared with the conventional FC-free LED, the light from the active layer emits through the transparent sapphire substrate, therefore, no attenuation of light is made by the metal electrode. The design of metal electrode geometry can be larger and more symmetry. The light output intensity and emission wavelength of FC-free LED and FC LED without backside Al reflector and with 20 of Au stub bumps were measured at current ranging from 10 to 1000 mA as shown in Fig. 6. The light output intensities were 8.5 and 11.2 mW at operating current of 350 mA, respectively. The light output intensity of FC LED is larger than FC-free LED which means that its junction temperature was higher compared to that of FC-free LED. However, the red-shift of emission wavelength of FC-free LED is more apparent, changing from 456.75 to 464.99nm at currents ranging from 100 to 1000 mA. The red-shift of FC LED is less apparent, changing from 456.51 to 461.02 nm, which means that the thermal problem is reduced. It is concluded that FC LED mounted on Si sub-mount could effectively improve both thermal conduction and the light output efficiency.

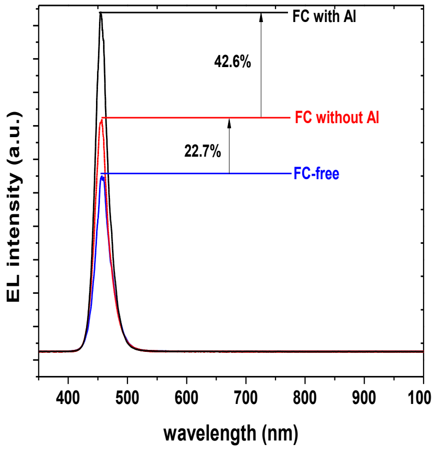


Fig. 5 EL intensity of the FC-free LED and FC LED with 20 of Au stub bumps.

Refer to our previous report [12], the thermal performance of the FC LEDs without backside Al reflector can only be improved when using at least 6 Au stub bumps as interconnected metals, and can be improved with increasing numbers of Au stub bumps (8~20). However, the thermal performance of the FC LED with more Au stub bumps (>20) is not understood. In this study, the EL intensity of the FC-free LED and FC LED with different numbers of Au stub bumps (20~36) at operating current of 350 mA is shown in Fig. 7. A single peak emission at around 456 nm was also observed. The EL intensity of FC LED with 20 and 24 of Au stub bumps is similar. As the numbers of Au stub bumps is further increased, the EL intensity starts to degrade. It means that the optimum numbers of Au stub bumps is 20~24. While too many Au stub bumps (>24) are implanted on sub-mount, the light output intensity can not be further improved, but the electrical characteristics becomes degraded (the leakage current becomes larger than standard value).

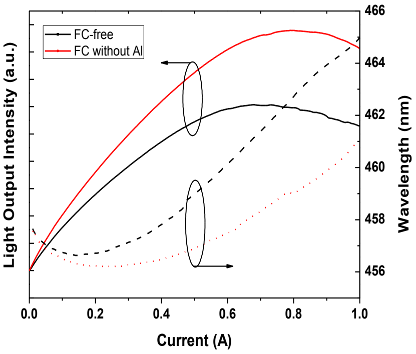


Fig. 6 Light output intensity and emission wavelength of FC-free LED and FC LED without backside Al reflector and with 20 of Au stub bumps.

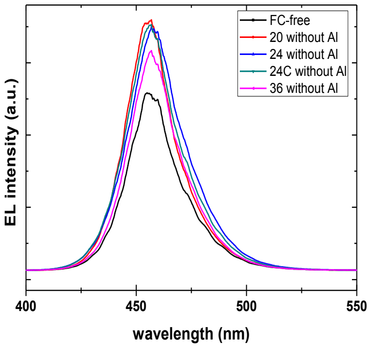


Fig. 7 EL intensity of the FC-free LED and FC LED with different numbers of Au stub bumps.

The light output power of FC-free LED and FC LED with different numbers (20~36) of Au stub bumps were measured at current ranging from 10 to 1000 mA as shown in Fig. 8. The light output power of FC LED with different numbers of Au stub bumps is larger than that of FC-free LED. For FC LED, the light output power is increased with the numbers of Au stub bumps except for 36 of Au stub bumps. The maximum intensity of FC LED with 24 of Au stub bumps was increased 76% than that of FC-free LED, and the operation current corresponding to maximum light intensity can be increased from 690 mA to 900 mA. At much higher operation current, the light output power is decreased for all LED. Furthermore, the more the numbers of Au stub bumps, the larger the decrease of the light output power. In this study, the most appropriate numbers of Au stub bumps is 24.

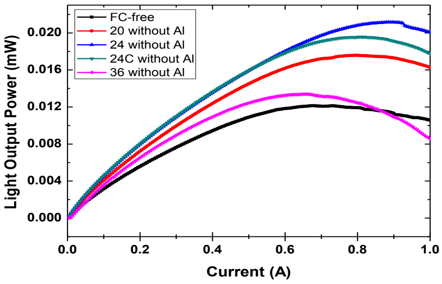


Fig. 8 Light output intensity of FC-free LED and FC LED with different numbers of Au stub bumps

C. The thermal performance

The average surface temperature (or the junction temperature) is a critical parameter and affects the internal efficiency, reliability, and lifetime of optoelectronic devices [14]. The chip can be survived under an ambient temperature more than 300 °C, since the traditional fabrication of LEDs is often processed above 400 °C. Fig. 9 shows the average surface temperature and emission wavelength of FC-free LED and FC LED with 20, 24 (n-pad not connection) of Au stub bumps measured at currents ranging from 100 to 1000 mA. Both the red-shift of emission wavelength and the increase of average surface temperature are reduced for the FC LED, especially for FC LED with 24 of Au stub bumps. The average surface temperature of FC LED with 24 of Au stub bumps is 56.4 °C and 83.3 °C at operation current of 350 mA and 700 mA, respectively. From SEM photograph (not shown), it was found that the surface of Au stub bumps does not completely adhere very well. The obvious voids and cracks were observed on the sub-mount and LED side. The main reason of these cracks and voids is the different tail height of each Au stub bump which is unavoidable during Au stub bumps implantation. It will induce force and ultrasonic power imbalance in FC bonding process. Therefore, the thermal spreading paths have not achieved saturation stage, and the average surface temperature will still have great reduce when we used 24 Au stub bumps compared to 20 Au stub bumps [12]. Replotted from Fig. 9, the average surface temperature of FC-free LED and FC LED versus numbers of Au stub bumps or total area of Au stub bumps measured at different currents (300, 600, 900 mA) is shown in Fig. 10. The more the numbers of Au stub bumps, the more the decrease of the average surface temperature. The optimum total area of Au stub bumps is about 22.8×10^4 µm^2.

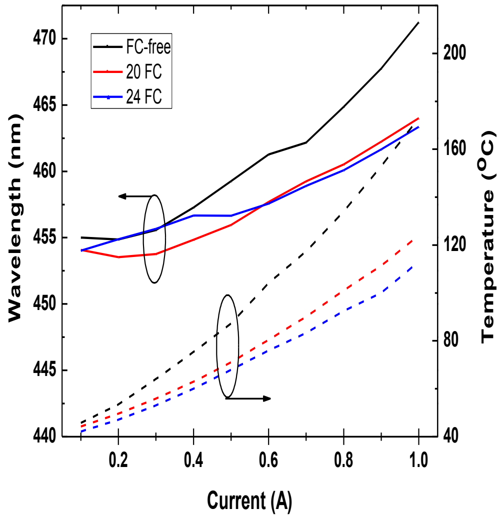


Fig. 9 The emission wavelength and average surface temperature of FC-free LED and FC LED with different numbers of Au stub bumps.

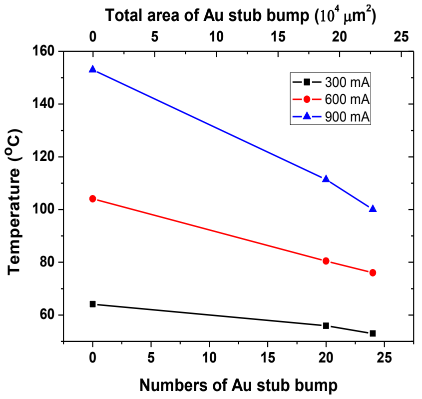


Fig. 10 The average surface temperature of FC-free LED and FC LED versus numbers of Au stub bumps or total area of Au stub bumps measured at different currents (300, 600, 900 mA).

IV. CONCLUSION

The electrical, optical, and thermal performance of high power GaN-based FC LED with and without backside Al reflector have been studied experimentally. The electrical characteristics of the FC LED on Si sub-mount and conventional FC-free LED are similar, no significant degradation of forward and reverse I–V characteristics was observed from the measurement. Compared with the conventional FC-free LED, the light output efficiency of FC LED has been improved. Moreover, adding a backside Al reflector can further enhance upward light emission. With a continuous increase of the numbers of Au stub bumps, the optical and thermal performance of the FC LED can be improved. However, while too many Au stub bumps is used, the performance starts to degrade. For the thermal performance, both the red-shift of emission wavelength and the increase of average surface temperature are reduced for the FC LED, especially for FC LED with 24 of Au stub bumps. It is concluded that the optimum numbers of Au stub bumps are 24, that is, the optimum total area of Au stub bumps is about 22.8×10^4 µm^2 for a 1 mm × 1 mm LED chips.

V. ACKNOWLEDGMENT

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