Performance Enhancements of Flip-Chip Light-Emitting Diodes With High-Density n-Type Point-Contacts

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***Abstract*— Novel gallium nitride-based flip-chip light-emitting diodes (FCLEDs) with high-density distributed n-type point-contacts were designed and fabricated. With high density and uniformly distributed n-type point-contacts, the point-contact (PC) FCLEDs had higher light output power (LOP) by 18% over the reference flip-chip LED with conventional contacts fabricated from the same wafer. The forward voltage of the PC-FCLEDs was 0.16 V lower than the reference FCLED and the wall-plug efficiency was increased by 24% at the same current level. The maximum LOP of the PC-FCLEDs measured at 2.4 A was 43% more than the maximum obtained by the reference LED at 1.8 A. It was also found that the PC-FCLEDs suffered lower efficiency droop. The optical performance improvement of the PC-FCLEDs is attributed to an increase of the light extraction and the uniform carrier distribution, which results from the small and high density deeply etched holes and PCs. The electrical performance was enhanced through a minimized lateral current spreading distance.**

***Index Terms*— Flip-chip, gallium nitride (GaN), light-emitting diodes (LEDs), point-contact (PC), point-contact flip-chip LED (PC-FCLED).**

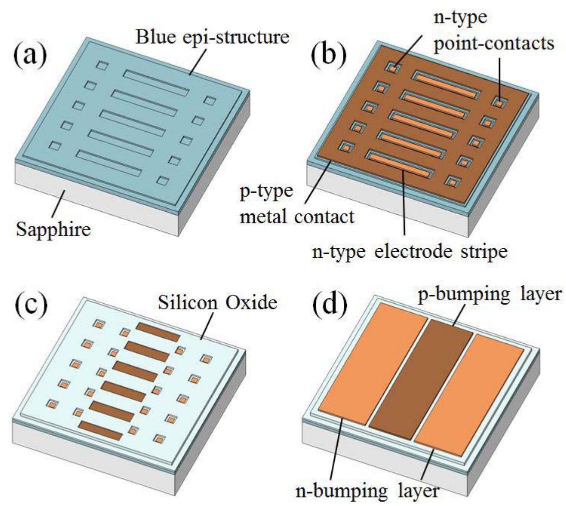

Fig. 1. The fabrication process of the PC-FCLEDs: (a) Mesa and n-contact definitions. (b) n- and p-contact metal formation. (c) Oxide deposition for passivation and isolation of n- and p-electrodes. (d) Evaporation of p and n-bumping layers.

I. Introduction

The development of gallium nitride-based light-emitting diodes (LEDs) for solid-state lighting has been remarkable in the past few years due to their significant advantages, such as high luminous efficacy and extremely long lifetime compared to traditional light sources [1], [2]. The application of LEDs toward general lighting requires even higher brightness and wall-plug efficiency (WPE), especially at high current injection.

Flip-chip LEDs (FCLEDs) are very promising for high power solid-state lighting [3]. The thick p-type metal contact at the bottom not only improves current spreading over the p-GaN layer, but also reflects downward propagating light upward for better extraction. However, the optical and electrical performances of FCLEDs are still limited by light trapping in the bulk substrate, severe current crowding effect near the n-type contact and efficiency droop at high current injection. Better light extraction can be improved via the use of surface texture or a patterned substrate [4]. Current crowding and efficiency droop can be minimized by growing a more conductive GaN layer, modifying the mesa geometry or electrode patterns [5]–[7].

In this letter, we report a novel device structure which enhances both current spreading and light extraction simultaneously by using high-density n-type point-contacts. The finely distributed contacts on the n-type GaN layer shorten the lateral current spreading distance in the semiconductor. This reduces the overall series resistance and hence the forward voltage of the device without penalty to the light-emitting area. Meanwhile, the light output power (LOP) was significantly improved by small and high-density deeply etched contact holes. Suppression of efficiency droop was also observed, attributed to the uniform carrier distribution.

II. Experiment

The fabrication process of the (point-contact FCLED) PC-FCLEDs is shown in Fig. 1. Both the PC-FCLEDs and reference FCLED (ref-FCLED) were fabricated on the same GaN epi-wafer. Blue LED GaN epi grown on a planar sapphire substrate by metalorganic chemical vapor deposition (MOCVD) with a peak emission wavelength of 450 nm was used in this study. 1×1 mm^2 LED mesas,

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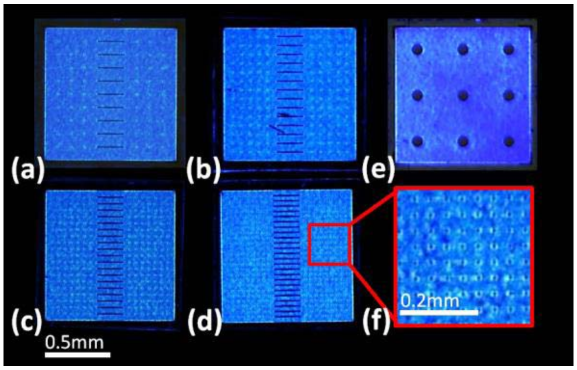

Fig. 2. The light emission images of the four different designs of PC-FCLEDs with point-contact pitch (a) 100 μm, (b) 67 μm, (c) 50 μm, and (d) 40 μm. (e) The image of ref-FCLED. (f) The magnified view of point-contact holes.

with 11×11 μm^2 point-contact holes in the PC-FCLEDs, as shown in Fig. 1(a), were patterned by photolithography and then etched down to the n-type GaN by inductively coupled plasma (ICP) etching. 115 nm electron-beam evaporated ITO was deposited on the p-type GaN surface, followed by annealing in an atmospheric ambient at 600 °C for 5 minutes. Then, Cr/Al/Ti/Au (10/120/50/50 nm) metal layers were evaporated to form the reflective p-type metal contacts and n-type electrodes shown in Fig. 1(b). 500-nm thick oxide was later deposited by plasma enhanced chemical vapor deposition (PECVD) for passivation and isolation of the p- and n-electrodes, followed by contact holes opening by buffer oxide etchant (BOE) wet etching, as shown in Fig. 1(c). Finally, Ti/Al/Ti/Au (30/120/50/50 nm) was evaporated to connect all n-type point-contacts, forming p and n-bumping layers for flip-chip bonding, as shown in Fig. 1(d).

After lapping and polishing the substrate down to 100 μm, the devices were cut into LED dies by scribing and breaking. The small dies were then flipped onto silicon submounts with aluminum interconnects and ball shaped indium bumps. After that, thermal-compression bonding was performed by SET FC-150 bonder to complete the flip-chip process. Eventually, the FCLEDs were mounted and wire-bonded onto LED packages without silicone encapsulation. The electrical and optical properties of the FCLEDs were measured by HP 4155A, LED auto-prober and SphereOptics SMS-500.

III. Results and Discussion

The light emission images of four different PC-FCLEDs (Fig. 2(a,b,c,d)) and ref-FCLED (Fig. 2(e)), all captured at 10 mA, are shown in Fig. 2. While the size of individual point-contact is the same, the pitch and thus density of the point-contacts vary among the PC-FCLEDs (see Table I for more details). Light emission is more intense in the vicinity of the point contacts, as displayed in Fig. 2(f). This is due to enhanced light extraction enabled by the deep edges of the point-contact holes than a flat GaN surface. In addition, arrays of dark stripes are present in the PC-FCLEDs. These are actually n-type electrodes stripes that are dedicated to enhance current spreading in the regions that cannot be accessed by n-type point-contacts due to the coverage of p-bumping layer.

TABLE I
Specifications of Ref-FCLED and PC-FCLEDs

	Effective Light-Emitting Area	Number of point-contacts	Point-contact pitch
Ref-FCLED	0.93 mm^2	9	350 µm
PC-FCLED (A)	0.97 mm^2	54	100 µm
PC-FCLED (B)	0.95 mm^2	140	67 µm
PC-FCLED (C)	0.92 mm^2	266	50 µm
PC-FCLED (D)	0.89 mm^2	432	40 µm

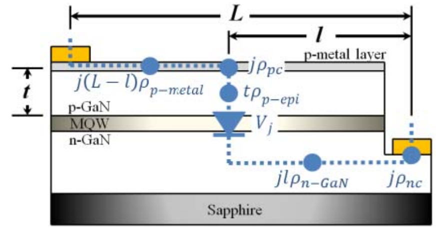

Fig. 3. The equivalent circuit model of a unit of an FCLED.

Table 1 shows the specifications of the ref-FCLED and PC-FCLEDs. The difference in the effective light-emitting area of the PC-FCLEDs and ref-FCLED is insignificant. By using small size point-contacts (10×10 μm^2) and electrode stripes instead of regular size contacts (90 μm in diameter) in ref-FCLED, current can be uniformly redistributed without sacrificing the effective light-emitting area.

Referring to the study by Venugopalan *et al.*, the forward voltage of FCLEDs is the sum of the voltage drops in the p-type and n-type contacts ($j\left(\rho_{\mathrm{pc}}+\rho_{\mathrm{nc}}\right)$), the reflective p-type metal layer ($j\left(L-l\right)\rho_{p-\mathrm{metal}}$), the p-type and n-type epi layers ($j\left(l\rho_{n-\mathrm{GaN}}+t\rho_{p-\mathrm{epi}}\right)$), and in the p-n junction (V_j), as shown in Fig. 3 [8].

where j is the current density,ρ_{pc} and ρ_{nc} are the resistivity of the respective contacts, $\rho_{p-\mathrm{metal}}$ is the lateral resistivity of the reflective p-type metal layer, $\rho_{n-\mathrm{GaN}}$ and l are the lateral resistivity of the n-type GaN and effective length of the lateral current spreading path through the n-type GaN, $\rho_{p-\mathrm{epi}}$ and t are the vertical resistivity and thickness of the p-type GaN, respectively, and L is the lateral current spreading distance between the p and n-bumps. One advantage of FCLEDs is that the resistivity of the reflective p-type metal layer ($\rho_{p-\mathrm{metal}}$) is significantly low, resulting in a lower forward voltage. In this study, high density and small n-type point-contacts minimizes the lateral current spreading distance L and l to scale so that both the terms $j\left(L-l\right)\rho_{p-\mathrm{metal}}$ and $jl\rho_{n-\mathrm{GaN}}$ are minimized in proportion and it ultimately reduces the forward voltage. Moreover, current crowding effect is reduced by uniformly distributed n-type point-contacts on the entire PC-FCLED.

The forward voltage of all of the FCLEDs is shown in Fig. 4(a). Except PC-FCLED (A), all of the PC-FCLEDs have lower forward voltage than the ref-FCLED. PC-FCLED (B), although having a slightly smaller total n-contact area than ref-FCLED, exhibits a forward voltage lower than ref-FCLED. Forward voltage drops further as the number of point-contact increases. In particular,

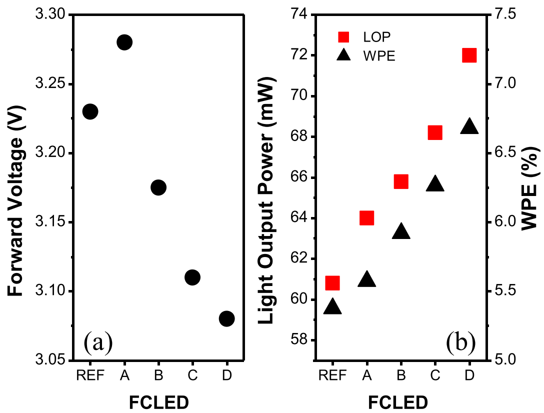

Fig. 4. (a) Forward voltage, (b) light output power and wall-plug efficiency of the ref-FCLED and PC-FCLEDs measured at 350 mA.

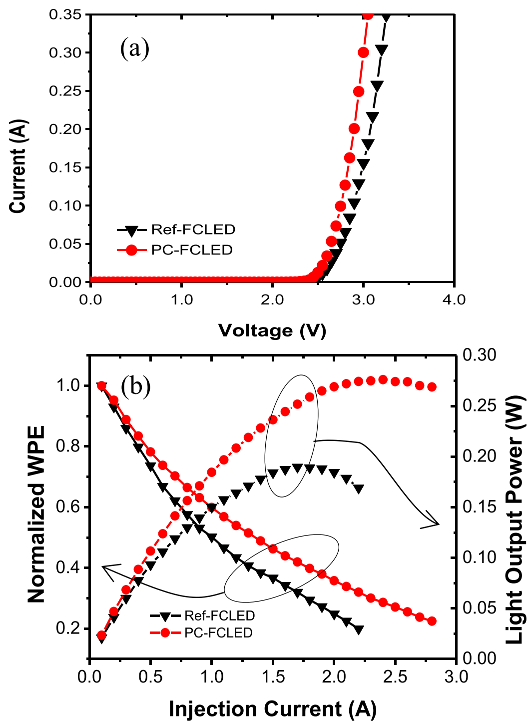

Fig. 5. Comparison of (a) I-V and (b) L-I curves and normalized WPE of PC-FCLED (D) and ref-FCLED.

the forward voltage of PC-FCLED (D) was as low as 3.07 V at 350 mA, which is 0.16 V lower than the ref-FCLED. These observations show that breaking down big electrodes into high-density point contacts can indeed reduce the series resistance by shortening the lateral current spreading distance. When the total n-contact area becomes too small, however, voltage drop across the contact resistance becomes the dominant factor. As a result, PC-FCLED (A) has the highest forward voltage due to its considerably reduced n-contact area.

Fig. 4(b) shows the comparison of the LOP and WPE of the FCLEDs. All of the PC-FCLEDs achieved higher LOP and WPE than the ref-FCLED. The LOP of PC-FCLED (D) was measured to be 72 mW at 350 mA, 18% more optical output power compared with the ref-FCLED. The WPE was increased by 24% at the same current level. The increase of the LOP and WPE is mainly attributed to (1) the improvement of light extraction via the large number of n-type point-contact holes, (2) more uniform carrier distribution on the entire chip via the high density n-type point-contacts, and (3) the shortened lateral current spreading distance.

The I-V and L-I curves of PC-FCLED (D) and ref-FCLED in Fig. 5(a) and 5(b) were measured by pulsed current input to minimize heat generation. While the LOP of ref-FCLED saturates at 1.8 A, PC-FCLED can be pumped to over 2.4 A before the LOP peaks at 278 mW, 43% higher than the maximum LOP of ref-FCLED. Comparing the normalized WPE, the PC-FCLED showed lower efficiency droop. The ref-FCLED had 75% WPE degradation from 100 mA to 2 A, whereas The PC-FCLED, however, had only 64% WPE degradation. This efficiency droop reduction is attributed to the uniform carrier distribution, which effectively suppresses the local Auger recombination and carrier overflow in the active region [9]. These results underscore the potential of PC-FCLEDs in ultra-high power applications.

IV. Conclusion

High performance flip-chip LEDs with high-density n-type point-contacts were fabricated. At 350 mA injection current, the PC-FCLEDs were demonstrated to produce 18% more LOP and had 24% higher wall-plug efficiency compared to the reference FCLED. The maximum LOP of the new design was 278 mW at 2.4 A, 43% more than the maximum value obtained from the reference chip at 1.8 A. The PC-FCLEDs also suffered lower efficiency droop. The optical and electrical enhancement is attributed to improved light extraction efficiency, uniform carrier distribution and minimized lateral current spreading distance.

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