Interdigital Structure Enhanced the Current Spreading and Light Output Power of GaN-Based Light Emitting Diodes

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ABSTRACT In this manuscript, blue light emitting diodes (LEDs) with comb-shaped mesa and interdigital electrodes structure based on gallium nitride (GaN) are presented. This kind of LEDs have showed higher light output power and more efficient current spreading, comparing with a reference large-area LED. For the optimized LED structure, the light output power and external quantum efficiency, considering the actual emission area, reach to 600 mW and 73% at a forward current of 350 mA. The experimental results are consistent with the predictions of current expansion equations. The comb-shaped mesa structure decreases the total internal reflection (TIR) and the interdigital electrodes improve the current crowding effect, as validated from the electrical and optical tests. Therefore, the efficiency and reliability of the LED devices have been significantly enhanced by reducing the transverse current path. This work should be of guiding significance for structural design of large-area/high-power optoelectronic devices.

INDEX TERMS Light emitting diodes, current spreading, light output power.

I. INTRODUCTION

Gallium nitride (GaN)-based wide-band-gap semiconductors and devices have attracted great interests in optoelectronic device applications. GaN-based LEDs with advantages of high luminous efficiency, compact design, long lifetime and environmental friendly have been widely applied in smart lighting and display systems, such as, full color, traffic and general illumination [1]–[3].

Over the last decade, considerable progresses have been achieved in the development of high-power and high-efficiency LEDs, which require high current injection to sustain its normal operation [4]. However, at a high injection current, current crowding effect caused by non-uniform current distribution in large-area LED degrades the device performance significantly [5]–[7]. In addition, the total internal reflection (TIR), due to the refractive index steps between each layer from the sapphire substrate, GaN-layer (n = 2.48), to indium-tin-oxide (ITO), and air, decreases the light extraction of large-area LEDs [8]. Researchers are now focusing on improving the efficiency of high-power LEDs [9]–[14]. Cho et al. used a buried n(+)−p(+) GaN tunnel junction prepared by plasma-assisted molecular beam epitaxy (MBE) to decrease the contact resistance and improve the current spreading [15]. Lee et al. adapted a surface GaN p-n junction that was formed through selective area regrowth of a n-type InGaN/GaN multiple quantum well (MQW) structure, serving as the carrier injector to increase current spreading between the p-GaN and MQWs [16]. However, plasma-assisted MBE and selective growth techniques are too complicated and expensive to be applied to mass production. Moreover, the GaN tunnel junction suffered from the tradeoff between transmittance and carrier concentration, which limits the device performance and increases the costs of fabrication.
To enhance light extraction by reducing the TIR, Lee et al. added texture to the side wall and surface of the device by using wet-chemical and inductively coupled plasma (ICP) etching [17], [18]. However, it is still difficult to reduce TIR and improve current distribution for large-area LEDs. Although vertical LED is considered as a good alternative to solve the current crowding issue and improve the output power for high-power and high-efficiency lighting applications [19], it also costs high because of complicated bonding processes required [20]. By researching previously published literatures of interdigits and MESAs of GaN [21]–[32], we noticed there is still no systematic and in-depth studies on the mechanism of mesa size and structures. Particularly, the major problem of the high-power LEDs is the current crowding under high current injection. Therefore, our work focuses on finding better solution to improve the light extraction efficiency and current crowding for high-power LEDs.

Here in this work, we first present a series of LED with interdigital electrodes and comb-shaped mesa of different width, but in same device size (635um) of square shape for each device. As illustrated in Fig. 1, for the large structure, the most part of light generated from the active region could be totally reflected due to a large refractive index of the material, and eventually trapped in the device. The optimized interdigital structure not only effectively reduces the length of horizontal optical path in the LED, but also greatly increases the chance of side wall light emission. By measuring the electrical and optical performances, we demonstrated that the LED with interdigital structure show more uniform current spreading and higher light emission than the reference LED, which is a large-area LED. With relatively simple processes, these interdigital structures could be simply and economically fabricated in large scale manufacturing to mitigate the current crowding through more current paths, leading to higher efficiency of current injection into the MQW. As a result, the light output power and external quantum efficiency of the LEDs are remarkably increased due to the decreasing of the light propagating distance within the devices.

II. DEVICE STRUCTURE AND FABRICATION

The GaN-based LED epitaxial layers were grown on patterned sapphire substrates (PSS) by using metal-organic chemical vapor deposition (MOCVD) technique. As shown in Fig. 2 (a), the epitaxial structure includes of, 3.6-µm-thick undoped GaN layer, a 2.6-µm Si-doped n-GaN layer, 3-period undoped InGaN (3 nm) / GaN (40 nm) MQW layer, 6-period InGaN (2 nm)/GaN (9 nm) MQW (this is served as a function of generating V-shaped pits at the early growth stage, which can restrain the carriers, allow holes and electrons to recombine, and increase the probability of radiation recombination [33]), and 10-period InGaN (3 nm) / GaN (10 nm) MQW layer (designed to emit lights at 460nm), 22-nm-thick undoped AlGaN electron barrier layer (EBL), and 16-nm Mg-doped p-GaN layer. Prior to device fabrication, the GaN-based epi-wafers were processed in the following sequences: (1) ultrasonically cleaned in acetone and isopropanol mixture for 30 mins; (2) dipped in sulfuric acid peroxide mixture (H2SO4:H2O2 = 3:1) for 30 mins to remove the native oxides; (3) dipped in KOH solution subsequently at 80°C for 10 mins to neutralize the remaining acid on the surface; (4) rinsed by deionized water cleaning and finally dried by nitrogen gas blowing. Atomic force microscope (AFM) was used to examine the surface morphology, as shown in Fig. 2 (b). We can see that the p-GaN surface was smooth, and the roughness represented by root-mean-squared (RMS) in a 10 × 10 µm2 area is 0.65 nm. Then, a 220 nm thick ITO film was deposited immediately on the p-GaN surface by optical thin film coating (OTFC-900 CB) system with a working pressure of 10E-6 Torr. To form the comb-shaped mesa, partial ITO film was etched away by using ion beam etching (IBE, A-150). After annealing at 550 °C for 20 mins under atmosphere, good electric contact between ITO and p-GaN formed. The interdigital array structures of each device were formed by Cl2/BCl3 -based inductively- coupled plasma (ICP, Sigma i2L) etching, and then the n- and p-electrodes of Cr (70 nm) /Al (500 nm) /Ti (50 nm) /Au (200 nm) metal films were deposited by electron beam evaporator (IBE, Ei-5z), followed by annealing at 250 ° in nitrogen atmospheres for 15 min to form good n- and p-type Ohmic contacts. TLM structures were formed on a separate sample to evaluate the contact resistances, as illustrated in Fig. 3, which is 8.21 × 10−4Ω·cm2 for the n-type electrode and 9.86 × 10−4Ω·cm2 for p-type electrode, respectively. At the end, a SiO2 passivation layer of 270 nm was deposited by plasma enhanced chemical vapor deposition (PECVD, SYSTEM-100) to isolate the p-electrode from the n-electrode. The p-electrode was set at the center of the chip,
and the n-electrodes were symmetrically set at both sides of the p-electrode. Fig. 4 shows the 3D structures of the reference LED (a) and the LEDs with mesa widths of 191.67, 80.83 and 30.45 µm (b-d), and their top-view images (e-h) of scanning electron microscopy (SEM, NOVA, NANOSEM-450), which labeled as reference, LED-I, LED-II and LED-III, respectively.

A constant ±5 V voltage power supply with output current in a range of 0 to 600 mA was applied to drive each un-encapsulated LEDs. The current-voltage (I-V) curves were measured using a semiconductor parameter analyzer, mounted on a high-precision probe table (Keithley4200, Suss-PM8). The electroluminescence (EL) spectral characteristics of the LEDs were collected at ambient temperature by using TLM pads with gaps of 10, 20, 30, 40, 50, and 60 µm. The insets are the fitting curves of the specific contact resistances.

III. RESULTS AND DISCUSSION

Fig. 5 (a) displays the I-V characteristics obtained from the reference LED, LED-I, LED-II and, LED-III. The three types of LEDs show excellent electronic performance, as proved by the sharp I-V curves. All the LEDs exhibit a turn-on voltage of approximately 2.5V. The forward voltage of the reference LED was slightly higher than that of other LEDs because the interdigital LED has more contact area so that its resistance is small. In Fig. 5 (b), the leakage current of the four devices with different structures is about 5E-10 A, which is small enough to consider the devices being reliable. As shown in the inset, the typical current densities measured at 3V are 0.315, 0.342, 0.501, and 1.19 A/mm², respectively for reference LED and three interdigital LEDs. Here, the current density defined as the total inject current divided by total mesa area. LED-III has a current density of 3.7 times higher than that of the reference LED, while the total mesa area of Ref-LED is only 1.7 times of LED-III. As the mesa width reducing, the current density increases dramatically because of current crowding relieved. Current crowing generally happens at the p-n junction interface [34], [35]. One way to improve the current spreading uniformity is to reduce the lateral current path, as modelling analyzed by Kim et al. [36]. Also, based on the simulation by Guo and Schubert [6], current crowding effect should be greatly reduced when the current path is comparable to or less than the current spreading length.

To verify the relationship between the current crowding effect and the mesa width, the current spreading length (Ls), defined as the length where the current density decays to 1/e [6], [36] of the value at the edge of p-n junction, could be calculated according to formula (1):

$$L_s = \sqrt{\left(\rho_c + \rho_{p}\rho_p\right) t_n / \rho_n}$$

where, $\rho_c$ is the contact resistance of the transparent extension layer; $\rho_p$ and $t_p$ are the resistivity and thickness of p-contact layer; $\rho_n$ and $t_n$ are the contact resistivity and thickness of the n-contact layer, respectively. These resistances of the device were measured by Hall method at room temperature:

$$\rho_n = 1/eN_D \quad \mu_n = 0.01\Omega \cdot cm, \quad N_D = 10^{18} cm^{-3},$$
$$\mu_n = 600cm^2/Vs.$$ 
$$\rho_p = 1/eN_A \quad \mu_p = 4.16\Omega \cdot cm, \quad N_A = 10^{17} cm^{-3},$$
$$\mu_p = 15cm^2/Vs.$$ 
$$t_n = 3\mu m, \quad t_p = 0.1\mu m, \quad w = 650\mu m.$$ 
$$\rho_c = 0.08\Omega \cdot cm, \quad \text{thus, } L_s = 12.19\mu m.$$

**FIGURE 3.** I-V characteristics of (a) n- and (b) p- contacts tested at room temperature by using TLM pads with gaps of 10, 20, 30, 40, 50, and 60 µm. The insets are the fitting curves of the specific contact resistances.

**FIGURE 4.** 3D-structures (a-d) and Top-view SEM images (e-h) of reference, LED-I, LED-II, and LED-III, respectively.

**FIGURE 5.** (a) I-V characteristics, (b) Leakage currents of reference LEDs and optimized LEDs. The inset in (a) is the current density for different LEDs.
Therefore, current density distribution $J(x)$ can be expressed as [6]:

$$J(x)/J(0) = \exp(-x/L_s)$$

(2)

where, $J(0)$ is the current density at the position of mesa edge, $x$ is the distance from the edge to the mesa center. As the mesa width reduced, current lateral path cuts down to the level comparable to current spreading length, and then the current crowding effect also eliminated. For LED-III, the lateral current path from the mesa edge to mesa center is about 15 $\mu$m, which actually is comparable the spreading length ($L_s = 12.19 \mu$m).

Next, to verify the effect of interdigital mesa structure on optical characteristics, we tested the current-dependence of EL-spectra at 200 $\mu$A, 400 $\mu$A, 600 $\mu$A, 800 $\mu$A, and 1000 $\mu$A for all LED under stable conditions. As shown in Fig. 6, all the spectra collected from the LEDs not only have the same shape, but also keep the emission peak positions almost no change, indicating a good stability of peak wavelength at various injection currents. The full widths at half maximum (FWHM) of the emission peaks for all LEDs are around 14 nm. However, as the mesa width narrows, the luminous intensity of LED-III is obviously higher than that of the reference large-area LED and the other three interdigital structure LEDs, as in Fig. 7 (a). All these results clearly demonstrate the excellent electrical and optical performances of the LED with small mesa structure.

With such kind of interdigital mesa structure, in order to increase the current injection rate, we designed the p-electrodes at the middle of mesa top, and the n-electrodes at the middle between each mesa. The light emission was partly blocked by the metal p-electrodes on the top of each mesa. Therefore, to accurately evaluate the light characteristics of LEDs with different mesa structures, we should consider the actual light-emitting area which is the area of the mesa minus the area of the p-electrode. In Table 1 are summarized the width of mesa, p-electrode perimeter (P) and area (A), total emitting area, actual emitting area, effective fill factor of the reference LED and LEDs. The P/A ratios are also listed in Table 1, to better understand the effect of the peripheral and areal components. In fact, we can clearly see a reduction in the ON-resistance from LED-I to LED-III. The total emitting area defined as the mesa area of p-GaN layer for one device, while, the actual emitting area corresponds to the total emitting area excluding the p-electrode area. The effective filling factor is the ratio of actual emitting area to the total emitting area.

Fig. 7 (a) shows the EL-spectra at 1mA of the four LEDs. All the EL peaks locate at the same wavelength of about 455 nm, but the LED III shows obviously the highest EL intensity, and the reference LED the lowest. This trend agrees well with the output power results, as shown in Fig. 7 (b), which are the integrations of EL in all direction and corrected by the effective filling factors. EL intensity is proportional to injection current, therefore, such an enhancement should be resulted from the reduction of current crowding effect [5]. The small mesa structure of LED-III should benefit mostly the current diffusing from the n-GaN layer to the MQWs. Particularly for high injection current, the output powers of the interdigital LEDs are significantly higher than that of the reference large-area LED and with increasing with the mesa width reducing. For example, at an injection current of 350 mA, the output powers were 224 mW, 315 mW and 604 mW for LED-I, LED-II, LED-III, respectively, much higher than that of reference LED (181 mW). By the way, in Fig. 7 (b), LED-II and LED-III shows a slightly earlier drooping effect, probably due to the non-uniformity of the epitaxial wafer itself and some uncertain factors during the tests. In general, as the LED junction temperature increases, carrier confinement in MQWs becomes less efficient, and leads to radiant power premature saturation for traditional large-area LED [7]. While, for interdigital LEDs the output power increases steadily with current and shows no saturation up to 600 mA. Fig. 7 (c) shows the EQE as a function of injection current for all the
TABLE 1. Width of mesa, emitting area, and effective fill factor for the reference LED and interdigital LEDs.

|               | Width of mesa (µm) | p-electrode perimeter (µm) | p-electrode area (µm²) | P/A (perimeter/area) | Total emitting area (µm²) | Actual emitting area (µm²) | Effective fill factor (%) |
|---------------|--------------------|----------------------------|------------------------|----------------------|---------------------------|-----------------------------|---------------------------|
| Ref LED       | 635                | 2154                       | 18789                  | 0.115                | 390079                    | 371290                      | 95                        |
| LED-I         | 192                | 3074                       | 23289                  | 0.132                | 363979                    | 340690                      | 93                        |
| LED-II        | 81                 | 6540                       | 40449                  | 0.162                | 312019                    | 271570                      | 87                        |
| LED-III       | 30                 | 12900                      | 65949                  | 0.196                | 233179                    | 167230                      | 72                        |

FIGURE 8. Heating distribution image of (a) reference LED, (b) LED-I, (c) LED-II, and (d) LED-III.

The EQE of LEDs is given by the following formula [37]:

$$EQE = \frac{P_{out}/E_{phot}}{I/q}$$

where, $P_{out}$ is the light output power, $E_{phot}$ is photon energy, $I$ is injection current, and $q$ is charge. The typical EQE of LEDs quickly increases to a peak value at a current of about 50 mA and then slowly decreases with the injection current further increasing. This trend of efficiency droop is similar to that for conventional GaN-based blue LEDs [38]. However, the light output power of LED-III is 3.3 times higher than that of the reference LED, and its EQE reaches 73% at 350 mA. This can be attributed to the enhanced sidewalls emission rate and uniform current spreading [39], [40].

The reduction of current crowding in this interdigital mesa structure benefits the uniform distribution of current in the LEDs. Otherwise, poor current spreading could lead to self-heating effect in the devices. Self-heating inevitably impacts luminal performance, which starts to deteriorate beyond 50 °C [41]. For large injection currents, the current spreading effect is reflected by the peak wavelength shifts, as shown in Fig. 7 (d). LED-III shows the least the spectral blue shift which is caused by the band-filling effect and the least red shift with current up to 600 mA, or in other words, the smaller self-heating effect, comparing to others. The reference LED presents the largest red shift, which could be caused by thermal effect at the junction [42], [43]. To verify this hypothesis, we took the heat distribution image under working condition with an infrascope temperature mapping microscope. As shown in the Fig. 8, the thermal distribution image test was performed on a heated platform of 75 °C on purpose of testing the uniformity of heat distribution. The temperatures at the probe contacts are significantly higher than the surrounding temperature. So, the temperature noted in Fig. 8 is the average temperature. For the reference LED, the heat-emission image exhibits significant current crowding at a driven current of 350 mA. While, LED-III shows a very uniform heat distribution at the same injection current due to the uniformity of current distribution. This result demonstrates that the current spreading can be improved by reducing current crowding, as in the interdigital LEDs with small mesa area. Therefore, we understand that current crowding is a key impact on the light output power of LED with large structure. It is also noticed that light emission of the LEDs is stronger from the top than from the side, because the TIR effect at the top surface of chip is reduced (thus, light travel distance within a chip is reduced, and the lights reflected from the surface could emit via the sidewalls) [44].

These results also show the importance of developing efficient thermal management schemes for high power LED. In this work, we designed the LED-III with 30 µm of mesa width and 10 µm of electrode width, which ensure the current diffusion path similar to the current spreading length and conducive to improvement the optical performance. Indeed, interdigital structure reduces the effective light-emitting area. However, the reduced area is only a small portion, which could be over compensated by increasing the light-emitting efficiency of the side walls. Of course, if further reduce the mesa width, the effective illuminating area dramatically decreases and the etch-damaged area also increases, leading to lower internal quantum efficiency due to more non-radiative recombination of the sidewall carriers. The light extraction efficiency is equal to the product of the internal quantum efficiency and the external quantum efficiency, a decrease in internal quantum efficiency results in a decrease in light extraction efficiency. The relationship between effective light-emitting area, etching damage and light extraction efficiency requires extra experiments to clarify and optimize.

IV. CONCLUSION

We investigated experimentally the optical and electrical performance of LEDs with different mesa width. The results
demonstrate that the LEDs with interdigital structure exhibited higher light output power and better current spreading than that of the LED with large emitting area. This is because that the interdigital array mesa structures can mitigate the current crowding through short current paths, and as a result, the current can be effectively injected into the MQW, enhancing the light output power and external quantum efficiency. For the LED with the smallest mesa width of 30 μm, the current density is 3.7 times higher than that of reference LED, and its light emission output power reached to 600 mW with an external quantum efficiency of 73% at a driving current of 350 mA. This is a promising novel structure for high-power LED devices, since no light output power saturation of optimized LED-III is observed at a high injection current up to 600 mA. For a fixed current, the increasing of optical output power is due to more electrical power was transferred into optical radiation, instead of thermal effect in the devices. This kind of design can be adopted in various GaN-based optical devices to reduce the current crowding, especially, improve the path of light emission, and increase the optical output power.

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