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Size effect on optical performance of blue light-emitting diodes

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Abstract: In this paper, size effects on optical performance of blue light-emitting diodes (LEDs) are investigated. The essential physical mechanism is studied by fabricating LEDs with various sizes of the active area and testing optical characteristics. It is found that micro-LEDs have better light extracting efficiency and thermal dissipation compared with broad-area LEDs, which is likely due to the small ratio of perimeter and active area. Furthermore, micro-LEDs are more beneficial for displays due to the stable wavelength under the low pulse width modulation (PWM) current density.

Key words: micro-LED; size dependence; light extract efficiency; strain relaxation

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1. Introduction

Recently, micro-LED displays have been developing rapidly owing to their high dynamic range (HDR), high contrast ratio (CR), thin profile and low power consumption. Furthermore, with the growing interest in augmented reality (AR) and virtual reality (VR), the micro-LED displays with high pixels per inch (PPI) are strongly demanded, which means the ever-smaller LEDs are required. Generally, the size of micro-LEDs is smaller than 50 μm. Some groups have found that the micro-LEDs have higher nonradiative recombination, shorter response time[1–4] and higher performance in visible light communication (VLC)[5, 6]. To the conventional LEDs, surface recombination is ignored commonly because of the broad active area. However, with the decrease of LEDs' size, the effect of surface recombination should be paid attention to, especially the micro-LEDs with small active area and high perimeter area ratio. Studies show that the size of the active area affects the photoelectric property of micro-LEDs such as the light extract efficiency[7], the wavelength shift[8] and the efficiency droop[9]. It is meaningful to calculate the size effects and give a proposal on micro-LEDs fabrication.

In this study, a series of GaN-based LED chips with the same epilayer structure but different sizes were fabricated and the size effects of LEDs on the opto-electrical properties are further researched. In general, the micro-LED displays are driven by the constant current source with pulse width modulation. So we tested the external quantum efficiency, peak wavelength, full width at half maximum (FWHM) and other optical characteristics of these LEDs with different sizes driven by the direct current (DC) and PWM. It is found that these factors vary with the size of LEDs, which may be caused by stress release, surface recombination and thermal dissipation in different LEDs. The LED310 and the Agilent 33220A are used as DC and PWM power, respectively. The optical performance is tested by the integrating sphere and the HAAS-2000.

2. Experimental details

To eliminate machining errors, InGaN LED chips with seven different sizes were fabricated on the same epilayer structure for investigation. An optical micrograph of the fabricated LEDs with different dimensions is shown in Fig. 1. These chips all have a square active area with side length (D) ranging from 20 to 120 μm (20, 30, 40, 60, 80, 100, 120 μm respectively). Correspondingly, the size of the active area (S), the ratio of the perimeter (L) and the active area (S), the ratio of electrode area (L_E) and the active area (S) are shown in Table 1. The main fabrication procedures of these LED chips with different sizes are as follow: cleaned the wafer, then formed the LEDs mesa structure by the photolithography and inductively coupled plasma (ICP) etching technique. Afterwards, these LEDs were isolated from each other using ICP etching technique. Thereafter, a silicon dioxide (SiO_2) passivation layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) and holes were formed at certain sites to support electrode connection by photolithography and buffered oxide etching (BOE). Finally, the metal layers were deposited by electron-beam evaporation and patterned by a lift-off procedure. The yellow areas in Fig. 1 are the electrodes.

3. Results and discussion

The J–V characteristics of micro-LEDs of varying sizes are plotted in Fig. 2. It is found that the LED of the smaller size exhibits the higher turn-on voltage and series resistance, which is ascribed to the larger dry-etching damage and the poor p-contact quality[8].

Fig. 3 shows the normalized external quantum efficiency (EQE) varying with current density of different LEDs. The EQE of seven different micro-LEDs shows a decreasing tendency with the increase in current density, which is called efficiency droop (ED).

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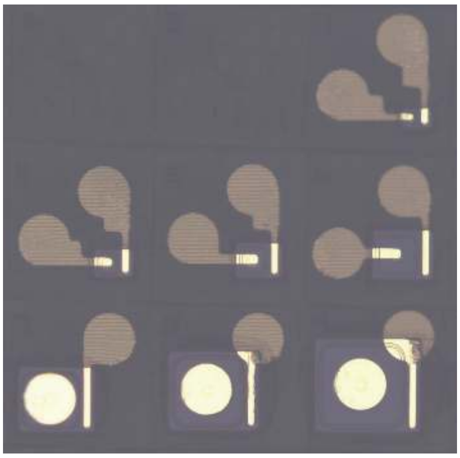

Fig. 1. (Color online) Optical micrograph of LEDs. The sizes of active area range from 20 to 120 μm.

Table 1. The geometric parameters of LEDs.

D (μm)	S (μm^2)	L/S	L_E/S
20	400	0.2	0.351
30	900	0.13	0.322
40	1600	0.1	0.172
60	3600	0.067	0.168
80	6400	0.05	0.601
100	10000	0.04	0.382
120	14400	0.033	0.267

$$\eta_{ext} = \eta_{int}\eta_{extration} = \frac{P/(hv)}{I/e}. \tag{1}$$

From Eq. (1), the EQE is determined by two factors: the internal quantum efficiency (IQE) and the light extract efficiency (LEE). Dai *et al.*[10] found that there was an enhancement of internal quantum efficiency in InGaN micro-LEDs due to partial strain relaxation in the microstructures. However, Demaneot *et al.*[11] found that the strong strain relief was shown to nanometer-size structure, which is much smaller than those considered here. Thus, an increase in light extract efficiency is more likely to contribute to the increase in EQE. Fig. 4 shows the normalized EQE varying with chip size at 100, 300, and 500 A/cm^2. With the chip size decreasing from 120 to 80 μm, the EQE improves at same current density. As Table 1 shows, the ratio of electrode area and chip area (L_E/S) increases when the chip size changes from 120 to 80 μm, which means the electrodes of smaller chips block more light and the EQE becomes less as a result. Meanwhile, the ratio of the perimeter and active area (L/S) increases as the size of LEDs decreases, indicating more light could be extracted from the sidewall. When the chip size further decreases to 20 μm, the EQE decreases at certain current density, although the LEDs have similar values of L_E/S as the chip size is 60 versus 40 μm or 30 versus 20 μm. The possible reason for this is that the surface recombination plays a dominant role compared to sidewall light emission under the circumstances of large L/S. As for the smaller LEDs, there will be more surface recombination[12] induced by etching damage and impurities during fabrication even though SiO_2 layer could passivate the chip sidewall, which is also the reason for the voltage rising[8].

Peak wavelength (λ_p) is plotted in Fig. 5(a) as a function

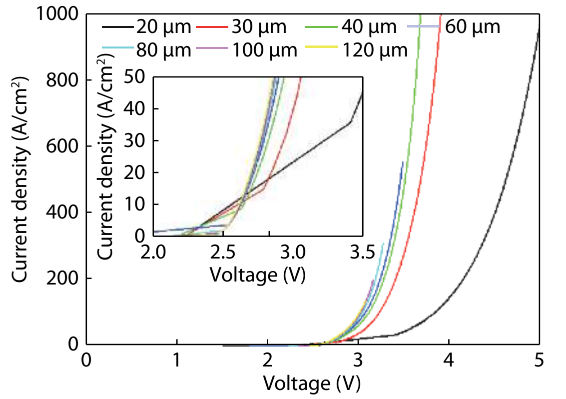

Fig. 2. (Color online) J–V characteristics of micro-LEDs with different sizes.

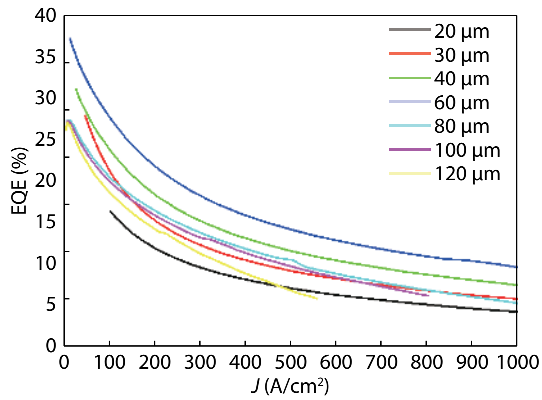

Fig. 3. (Color online) Normalized EQE vary with forward current density of micro-LEDs with different sizes.

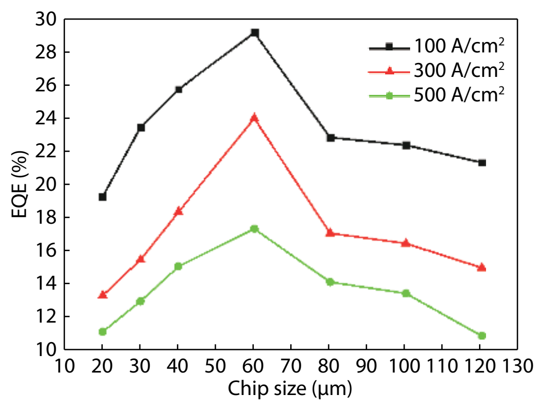

Fig. 4. (Color online) Normalized EQE vary with chip size at 100, 300, and 500A/cm^2.

of current density. At the same current density, the different peak wavelength is observed in these seven micro-LEDs even though they are grown on the same epilayer. It is found that the blue shift of the peak wavelength occurs with decrease of chip size, which attributes to the increasing bandgap caused by strain release[13]. For all devices, blueshift of the peak wavelength with increasing current density is observed under the low current density. The band-filling effect and screening of the quantum confined Stark effect[14, 15] contribute to this phenomenon. While redshift of the peak wavelength occurs under the higher current density, attributed to the bandgap shrink effect[16, 17] at high junction temperature. λ_{p0} is identified as the peak wavelength at 100 A/cm^2, and $\Delta\lambda_p$

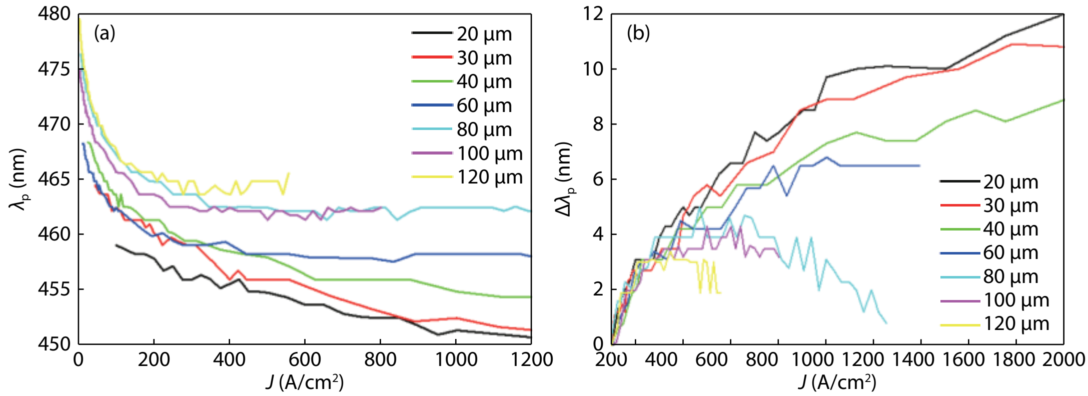

Fig. 5. (Color online) (a) Peak wavelength and (b) change of peak wavelength vary with forward current density of micro-LEDs with different sizes.

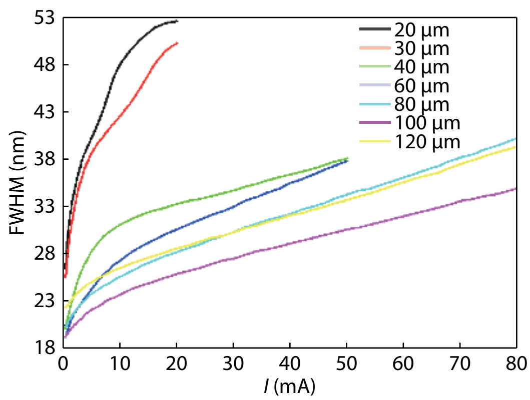

Fig. 6. (Color online) Full width at half maximum (FWHM) varying with forward current of micro-LEDs with different sizes.

refers to the change of peak wavelength which can be calculated by the equation $\Delta\lambda_p = |\lambda_p - \lambda_{p0}|$. The current density dependence of $\Delta\lambda_p$ for the different LEDs is plotted in Fig. 5(b). It is revealed that the maximum value of $\Delta\lambda_p$ increases as the chip size decreases. For instance, $\Delta\lambda_p$ is 3.4, 6.8, 13.2 nm, at the chip size of 120, 60, 20 μm, respectively. For the broad-area LEDs, the junction temperature increase for the poor thermal dissipation, then resulting in redshift of the peak wavelength at the lower current density.

As shown in Fig. 6, full width at half maximum (FWHM) shows strong dependence on the chip size. The change of the FWHM is conspicuous for the small-size LED as the current increases, and it attributes to the junction temperature[18] rising caused by the current crowding effect.

The pulse width modulation is adopted in the driving circuit of the LED displays generally. The PWM is a modulation technique for generating variable width pulses to represent the amplitude of an input analog signal or wave. Hence, the LED can be dimmed by the change of duty cycle. For LED displays, the stability of the domain wavelength (λ_d) is significant since humans can recognize color differences when the domain wavelength changes more than 0.1 nm. Therefore, the domain wavelengths of these seven different-size micro-LEDs are all tested under two different current density (100 and 500 A/cm^2) driven by the PWM and the modulation frequency is 5 MHz. The effective current density is adjusted by the duty cycle from 90% to 10%. λ_{d0} is identified as the domain wavelength when the duty cycle is 90%, and $\Delta\lambda_d$ refers to the change of the domain wavelength which can be calculated by the equation $\Delta\lambda_d = \lambda_d - \lambda_{d0}$. The duty cycle dependence of $\Delta\lambda_p$ for the different LEDs is plotted in Fig. 7. As shown in Fig. 7(a), the modulation current density is 500 A/cm^2 and the λ_d of the broad-size LEDs is more stable, which is due to the redshift of wavelength caused by the junction temperature rising. However, when the modulation current density changes to 100 A/cm^2 (Fig. 7(b)), the λ_d of the small-size LEDs is more stable. At the lower current density, the current injection in the small-size LEDs is much lower than the broad-size LEDs. Therefore, for small-size LEDs, the band-filling effect reduces and the domain wavelength changes slowly, which are more beneficial for displays.

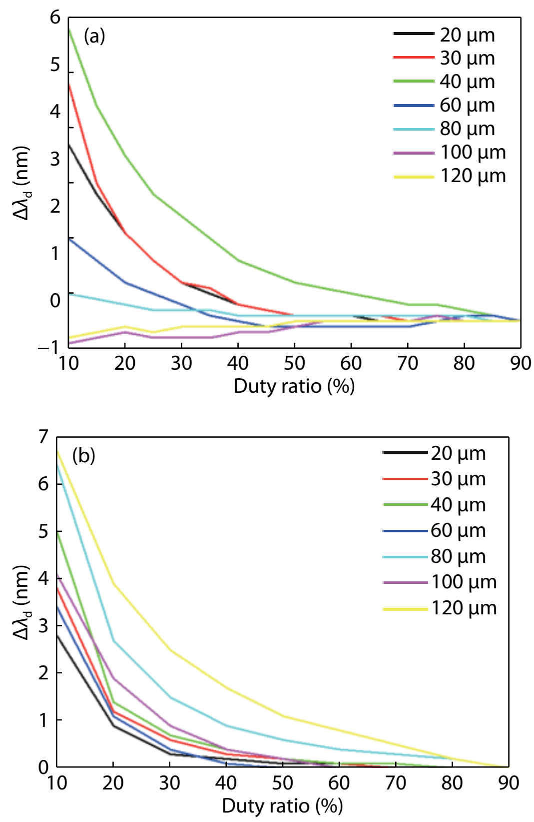

Fig. 7. (Color online) Current density dependence of $\Delta\lambda_d$ driven by PWM at (a) 500 and (b) 100 A/cm^2 of micro LEDs with different sizes.

4. Conclusion

In summary, we have investigated size effects on the optical performance of seven different-size LEDs. We find that smaller LEDs have great thermal dissipation and light extract efficiency. Besides, the surface recombination has an effect on EQE performance. At the low current density driven by PWM, the small-size LEDs have more stable wavelength because of the less carrier injection. That means micro-LED displays not only have higher PPI but have great wavelength stability.

Acknowledgments

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