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Investigation of External Quantum Efficiency of GaN-based Micro-LEDs

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Abstract: GaN-based micro-sized light-emitting diodes (micro-LED) has gradually become the main light source in many optoelectronic devices such as visible light communications and next-generation displays. Low external quantum efficiency (EQE), caused by non-radiative recombination and quantum confined Stark effect (QCSE), is the main bottleneck in applications of micro-LEDs. In this report, the reasons for low EQE of micro-LEDs are discussed, and the physical characteristics of micro-LEDs are analyzed and several optimal methods are suggested to improve EQE.

Key words: light extraction efficiency (LEE); internal quantum efficiency (IQE); EQE; micro-LED; size effect

GaN 基 Micro-LED 的外量子效率研究

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摘　要：基于氮化镓材料的微型发光二极管(micro-LED)已逐渐成为可见光通信和下一代显示器等许多光电器件的主要发光源。由非辐射复合和量子限制斯塔克效应(QCSE)引起的低外量子效率(EQE)是微型发光二极管应用开发过程中的主要瓶颈。文章讨论了微型发光二极管低EQE的成因，分析了其物理特性，并提出了改善其EQE的优化方法。

关键词：光萃取效率；内量子效率；外量子效率；微型发光二极管；尺寸效应

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0 Introduction

LEDs are the optoelectronic devices converting electrical energy into light energy. Micro-LEDs refer to miniaturized LEDs with a general device size of below 100 μm. GaN-based micro-LEDs have many benefits, such as high resolution, high contrast, long life time and fast response speed[1]. Therefore, they have received much more attention, and are expected to become the main platform of next generation displays.

Generally, EQE is the most important performance indicator of LEDs and is defined as the ratio of the photons emitted from the LED to electrons injected into the active layer of LEDs, which is expressed by Eq. (1):

$$EQE = IQE \times LEE \tag{1}$$

EQE is associated with LEE and IQE, where LEE is photons emitted externally from the device over photons generated internally by recombination and IQE is the ratio of radiative recombination divided by total ratio of recombination (radiative and nonradiative). IQE can also be explained by classic *ABC* model[2]:

$$IQE = \frac{Bn^2}{An + Bn^2 + Cn^3} \tag{2}$$

In which, coefficient A represents non-radiative recombination (for example, Shockley-Read-Hall

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Recombination (SRH)), coefficient B represents the radiation recombination, coefficient C represents the Auger recombination, and n is the carrier concentration of quantum well. Currently, it is reported that the peak EQE of InGaN/GaN micro-LEDs is usually less than 15%[3-4]. There are several physical mechanisms limiting EQE of GaN-based micro-LEDs, such as non-radiative recombination and quantum confined Stark effect (QCSE).

Olivier et al. showed that the Auger recombination coefficient is barely influenced by the size of micro-LEDs and remains a constant as shown in Fig. 1(a), but Shockley-Read-Hall (SRH) recombination increases when the size of micro-LEDs decreases, as shown in Fig. 1(b) [3]. Therefore, when the size (d) of micro-LEDs decreases, the EQE decreases due to the non-radiative recombination of SRH originated from surface defects. So, great efforts are required to inhibit the non-recombination rates at the surface.

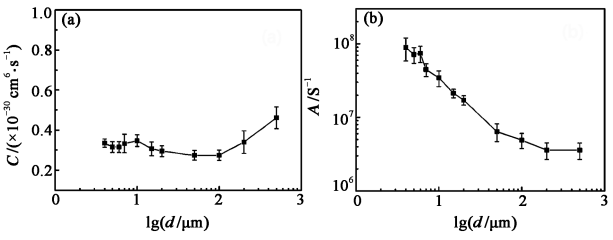


Fig. 1　(a) Auger recombination coefficient; (b) SRH recombination coefficient in different LED sizes[3], with the permission of AIP publishing

The reactive ion etching (RIE) or inductive coupled plasma (ICP) etching process is used to fabricate the mesa structure of micro-LED, which lead to the sidewall defects at the surface of the active layers. The number of sidewall defects affects the non-radiative recombination process, and the more defects there are, the more non-radiative recombination exists in the device[4]. P/A (Perimeter/Area) is the ratio between perimeter and area of mesa. It reveals the ratio of sidewall area to overall area, that is, the proportion of sidewall defects to overall defects. For traditional LEDs with large mesa sizes, it does not greatly sacrifice the performance of LEDs, even if the surface non-radiative recombination exists. Because the P/A of traditional LEDs is much smaller than that of micro-LEDs, when the chip size decreases, the ratio of sidewall defects to overall defects will increase, eventually leading to a continued decrease in EQE[5-8].

The evident quantum confinement Stark effect (QCSE), which is the intrinsic characteristics of the GaN material itself, is another reason for low EQE of micro-LEDs. At present, InGaN/GaN LEDs are mainly fabricated with GaN wafer grown on [0001], generating a strong spontaneous polarization and piezoelectric polarization effect in multiple quantum wells (MQWs). The polarized electric field causes energy band to bend, and wave functions of holes and electrons do not coincide, which is called QCSE. The radiation recombination rate of InGaN/GaN MQWs can be reduced by QCSE[9].

1　Solution for Increasing EQE of Micro-LEDs

There are several approaches for increasing EQE of micro-LEDs. Roughly, according to Eq. (1) and (2), we can consider improving the EQE of micro-LED by improving LEE with optimized device structure, and by increasing IQE with reduced non-radiative recombination and with weaker QCSE, enhancing radiative recombination.

Hwang et al. deposited an omni-directional reflector (ODR) structure on the sidewall of micro-LEDs by ion beam deposition to improve the light extraction efficiency of the micro-LEDs[5]. The peak EQE of the 10 μm×10 μm micro-LED is remarkably 40.2%. The ODR structure is mainly composed of silicon dioxide (SiO_2), tantalum pentoxide (Ta_2O_5) and aluminum oxide (Al_2O_3). SiO_2 and Ta_2O_5 are alternately overlapped, and finally Al_2O_3 is deposited on the outermost layer. The well-designed ODR structure reflects the light in the micro-LEDs, ultimately improving the EQE of the device. The simulation work by Yan Gewei,

et al. also demonstrated to improve the LEE of micro-LEDs by using a similar structure[10]. In Fig. 2, AlGaN/GaN superlattice distributed Bragg reflector (SL DBR) plays as the p-type electron blocking layer in a GaN-based micro-LED. SD A, SD B, and SD C correspond to the 2, 4, and 6 pairs of DBRs in micro-LED devices. Fig. 3 shows that the EQE of SD C is 18.5% higher than that of Ref, and LEE increase with the number of DBR pairs. Ley et al. tried to use a fully covered electrode structure to reflect light, which also achieved the effect of improving LEE [11]. As shown in Fig. 4～5, using Al/Ni/Au electrodes as a reflective layer unexpectedly makes the EQE of a 2 μm micro-LED exceed that of a 100 μm device.

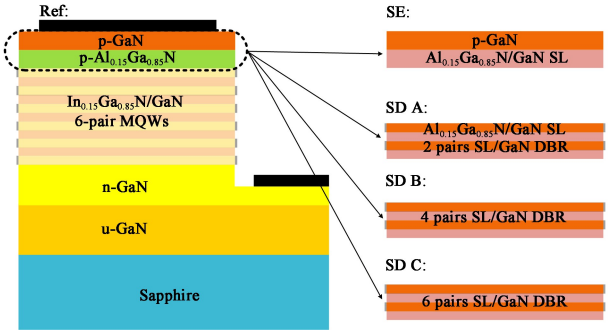


Fig. 2 Schematic diagram of micro-LEDs

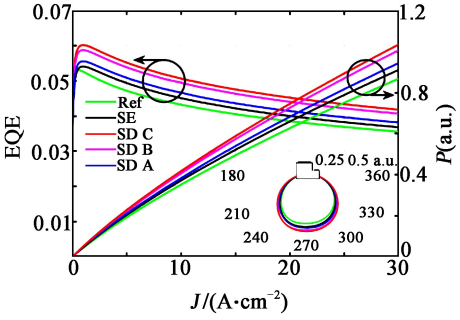


Fig. 3 The EQE and output power as a function of current density[10]

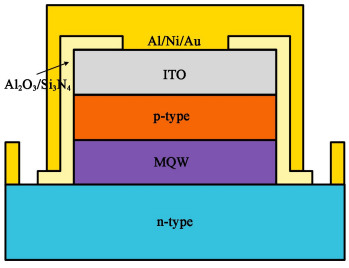


Fig. 4 Simplified device schematic diagram of micro-LED

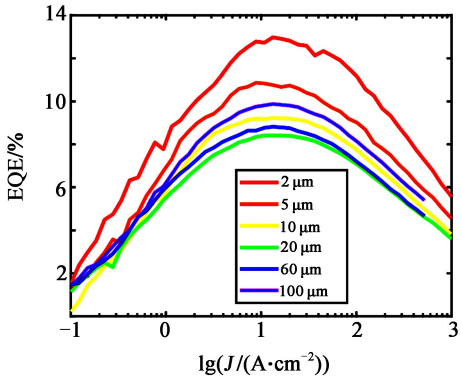


Fig. 5 The EQE as a function of current density for micro-LEDs with different sizes

Wong et al. proposed to use a passivation layer to optimize device characteristics and enhance the property of micro-LEDs[12]. As stated in the previous section, the etching defects on sidewall will cause the increase of surface non-radiative recombination. Therefore, the silicon dioxide passivation layer is deposited on micro-LEDs' sidewall using atomic-layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD), mainly to reduce non-radiative recombination and to enhance IQE of micro-LEDs. Further, LEE could be improved by using sidewall passivation layers, too. LEE is increased by allowing a larger critical angle, because the refractive index of gallium nitride is higher than that of the deposited passivation layer of 100 μm×100 μm and 20 μm×20 μm devices with different sidewall passivation methods is shown in Fig. 6. LED-1 stands for micro-LEDs without sidewall passivation, and no contact holes are required. LED-2 represent micro-LEDs by passivated by ALD and inductive coupled plasma (ICP) dry etching is used to open contact holes. LED-3 represents micro-LEDs with PECVD sidewall passivation and wet etching with HF is used to open the contact holes. LED-4 are marked as micro-LEDs with ALD sidewall passivation, and wet etching is used to open the contact holes. For 100 μm devices, there is no obvious improvement in EQE with passivation layers, while the EQE improvement of 20 μm devices is clear. The P/A

value of the 20 μm device is 0.2, which is 5 times higher than that of the 100 μm device. It means that the proportion of sidewall etch defects in the 20 μm device is also five times that of the 100 μm device. It results in that adding passivation layers lead to pronounced EQE improvement for small-sized micro-LEDs.

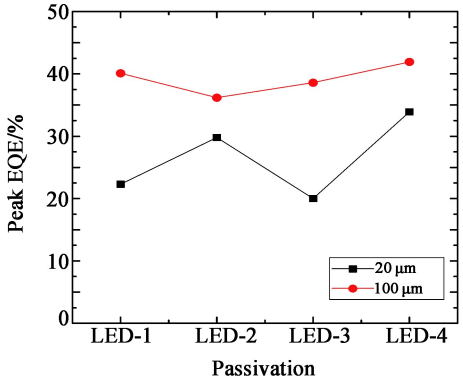
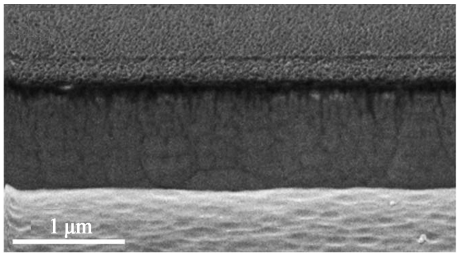
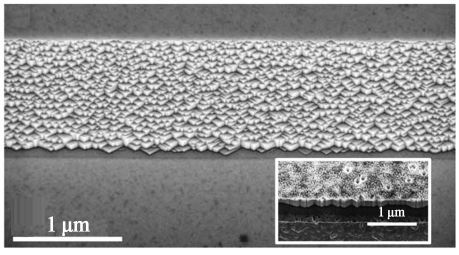


Fig. 6　The peak EQE of 100 μm × 100 μm and 20 μm × 20 μm devices when using different sidewall passivation methods[12]

Besides, chemical treatments are used to suppress surface defects on the sidewalls, leading to decreased non-radiative recombination coefficient of the sidewalls and occurring improve IQE[13]. The comparison of the sidewalls of mesa before and after the potassium hydroxide (KOH) treatment is shown in Fig. 7. The sidewalls of the mesa after KOH treatment are scaly, which removes the sidewall etching defects that cause leakage current. In this way, chemical treatment reduces non-radiative recombination, and improves micro-LEDs' IQE. Furthermore, the scaly rough and uneven sidewalls can also improve the LEE of micro-LEDs and the overall EQE. Comparisons on the EQE of micro-LEDs devices of different sizes with or without KOH treatment indicate that, the peak EQE of micro-LEDs without KOH treatment decreases with the decreasing device size, while the peak EQE of micro-LEDs after KOH treatment hardly changes (see Fig. 8). This is due to the KOH chemical treatment that increases the EQE of small-size devices, making it the same level EQE as large-size devices.



(a)　SEM image before KOH chemical treatment



(b)　SEM image after KOH chemical treatment[13]

Fig. 7　Comparison of the sidewalls of mesa before and after the potassium hydroxide (KOH) treatment

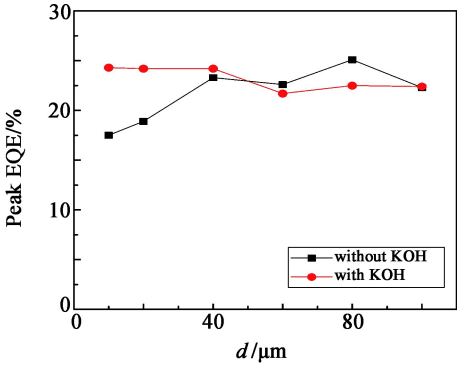


Fig. 8　The relationship between peak EQE and micro-LED size without KOH treatment and with KOH treatment[13]

Using buried tunnel junctions (TJ) is another effective method to improve EQE[8,14-15]. Thus, the current being injected into the active layer of micro-LEDs can be better controlled, thereby reducing carriers reaching to the edge of the mesa. This approach was applied to GaN-based micro-LEDs with the buried tunnel junction method[16]. Fig. 9(a) shows the peak EQE of 40 μm × 40 μm (square dot) and 100 μm × 100 μm (round dot) micro-LEDs in different structures. Fig. 9(b) shows the voltage at an injection current density of 20 A/cm^2 for the standard LED and TJ LED with different sizes. Standard LEDs represent LEDs without a TJ structure, with indium tin oxide

(ITO) but no superfluous n-GaN epitaxial layers. LED-1, LED-2 and LED-3 have TJ structure, which replaces ITO, and their silicon concentration is different. According to Fig. 9(b), it can be seen that regardless of the size of the LED, if a tunnel junction is used, the forward voltage will increase. In fact, the ionization efficiency of Mg-doped p-GaN layers is low, thus leading to an increase in the overall micro-LEDs' resistance[16]. The carrier tunneling probability will be reduced because the extremely low doping efficiency of the p-GaN layer decreases the electric field in reverse biased p-GaN/n-GaN junction[17-18]. So, the device in the tunnel junction requires more bias to generate an extra electric field to promote carrier tunneling effect. However, EQE has been greatly improved. The EQE of TJ structure micro-LEDs reaches 34%, thanks to the replacement of ITO by n-GaN, which increases the light extraction efficiency (see Fig. 9(a)).

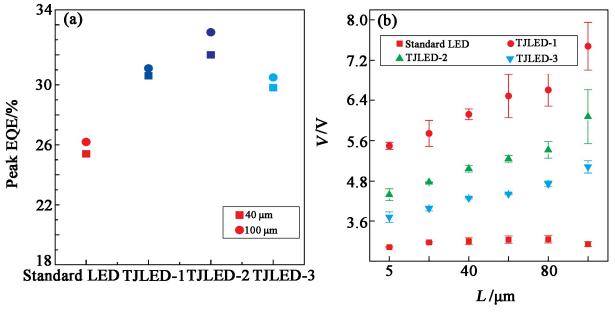


Fig. 9 (a) The peak EQE of 40 μm×40 μm (square dot) and 100 μm×100 μm (round dot) micro-LED in different structures; (b) Voltage at an injection current density of 20 A/cm^2 for the standard LED and TJLED with different sizes[16]

As we all know, GaN-based heterojunctions along polarity orientation have inherent piezoelectricity and spontaneous polarization[19-20]. Hence, InGaN/GaN-based MQWs have a grand QCSE, which will severely reduce the IQE of GaN-based micro-LEDs[21]. A direct way to solve this effect is to epitaxial grow MQWs on semi-polar or non-polar planes by MOCVD[22-24]. Normalized EQE of *m*-plane and *c*-plane micro-LEDs is shown in Fig. 10(a). The EQE droop effect of *c*-plane LED is more obvious than that of *m*-plane LED[24]. This is because the *m*-plane surface suppresses QCSE, which makes the distribution of carrier concentration in the quantum well more uniform[25]. As current density raises, EQE droop decreases, thanks to the *m*-plane substrates suppress QCSE and improve radiation recombination. As shown in Fig. 10(b), the *c*-plane and *m*-plane micro-LED devices exhibited peak wavelength shift of 11.81 nm and 8.12 nm from 1～500 A/cm^2. The effect of non-polar surface substrate on wavelength stabilization is demonstrated[24]. As shown in Fig. 10(c), the high density of stacking faults during epitaxy results in a much narrower full wavelength at half maximum (FWHM) for *c*-plane than *m*-plane micro-LED devices[24]. However, high-quality semi-polar and non-polar GaN-based micro-LEDs should be grown on substrates with special crystal orientations, which makes them unsuitable for mass production[26]. Therefore, micro-LEDs are still based on [0 0 0 1] oriented substrates for epitaxial

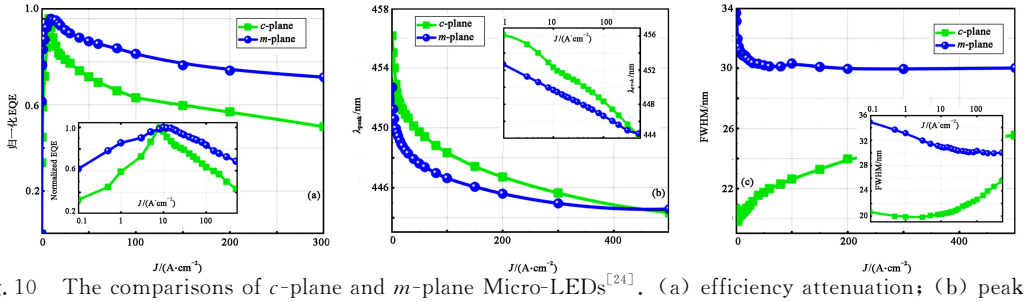


Fig. 10 The comparisons of *c*-plane and *m*-plane Micro-LEDs[24]. (a) efficiency attenuation; (b) peak wavelength shift; (c) full width at half maximum (FWHM)

growth because they are easier to fabricate, such as [0001] oriented Si[27-28] and sapphire substrates[29]. At this stage, this is still the inevitable factor that generates polarization-inducing electric fields and QCSE in MQW.

2 Conclusion

In summary, we reviewed the basic reasons for low quantum efficiency of micro-LEDs in small sizes, such as the increase of non-radiative recombination resulted by sidewall etching defects, and QCSE phenomenon that limits the carrier concentration of MQWs. We can optimize its EQE through such methods as ODR, DBR, passivation layer, chemically treatment of the etching mesa sidewall, using tunnel junction instead of ITO, and epitaxial growth on non-polar or semipolar plane. We believe that there are many methods for optimizing micro-LEDs' EQE waiting to be explored, encouraging researchers to produce high-performance micro-LEDs.

3 Acknowledgements

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