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RESEARCH ARTICLE

Light emitting enhancement and angle-resolved property of surface textured GaN-based vertical LED

Zhe Liu[1] · **Chuanrui Zhu**[1] · **Yujin Wang**[1] · **Yan Shen**[2] · **Haifang Yang**[1] · **Changzhi Gu**[1,3] · **Junjie Li**[1] · **Baoli Liu**[1] · **Xiangang Xu**[2]

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Abstract The performances of GaN-based vertical light emitting diodes with surface texture of GaN cones were studied. The cones were fabricated by inductively coupled plasma reactive ion etching with Cr mask, which can enhance the light intensity by about 95 % at injection current of 350 mA. Angle and wavelength-resolved far-field spectra were measured, and the maximum light enhancement lies at about ±15°–50° respect to normal direction. This is because of the successive reflection of light by the sidewall of cones, which can be concluded from the far-field pattern that the Fabry-Perot like resonance of patterned LED disappears compared to the original device. The polarization property of patterned LED was also analyzed, which can explain the increasing of enhancement ratio with injection current.

Keywords Vertical light emitting diode · GaN cone · Light enhancement · Angle-resolved spectrum

Introduction

GaN-based light emitting diodes (LEDs) have achieved great progress to be a promising light source in future due to its advantages of reliable performance, energy saving and long lifetime. To be widely applied in daily life, especially in lightening area, the LEDs should have large efficiencies, both internal quantum efficiency (IQE) and light extraction efficiency (LEE). Up to now the IQE can be improved to a high level for the best commercial LEDs by good epitaxy [1]. Meanwhile, in order to get high LEE, people made a lot of efforts to eliminate the flat surface of LED including surface roughening [2, 3], photonic crystals (PCs) [4–6], placing other materials on surface [7–9], or substrate patterning [10–12]. Nowadays the LEDs have become a smart and ultra-efficient solid-state lighting source, which has large potentials to increase human productivity [13].

The vertical LED (VLED), which has an n-side-up structure fabricated by laser lift-off process, is a high power lighting device that can be used for ordinary lighting or street lamp [14], with better current spreading effect and heat dissipation. It has a mirror on p-side, which can reflect the downward light back to the top, thus the luminance of VLED is much larger than traditional p-side-up LED. The illumination intensity of VLEDs can be measured by either integrating sphere, or detectors at different positions above the device. By integrating sphere, the light intensity and electroluminescence spectra can be easily measured as an average of the whole space, which characterizes the output power and spectra property of the device. Meanwhile, the angle-resolved far-field spectra, which are measured by detectors in different positions around the LED, can fix the radiation pattern in different directions [15], and this is important for applications in illuminations [16] and display [17]. However, studies on angle resolved far-field property with respect to the orientation of the pattern array and polarization of output light have rarely been reported up to now.

In this work, GaN cones were fabricated on the surface n-GaN layer of VLEDs by inductively coupled plasma reactive ion etching (ICP-RIE) method. The light emitting

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✉ Haifang Yang
hfyang@iphy.ac.cn

✉ Changzhi Gu
czgu@iphy.ac.cn

[1] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

[2] State Key Laboratory of Crystal Materials, Shandong University, 27 South Shanda Road, Jinan, Shandong 250100, China

[3] Collaborative Innovation Center of Quantum Matter, Beijing, China

enhancement reached 95 % at injection current of 350 mA. The angle-resolved far-field property was also studied, which showed a Fabry-Perot like resonance of VLED because of the reflecting mirror at the bottom of the chip. The surface patterned VLED had an ultramost light enhancement at about ±15°–50° respect to the normal direction, and the enhancement factors of s and p polarized light were nearly the same.

Fabrication

The LED chips were grown on *c*-plane sapphire substrate by metal-organic chemical vapor deposition. The sapphire substrate was removed by laser-lift-off process with 248 nm laser [18], and the LED chips were bonded by AuSn alloy with high pressure onto silicon substrate, on which Ag film was deposited in advance as a reflect mirror. The cross-section of the device is shown in Fig. 1a. The top n-GaN layer has a thickness of 8 μm, with n-electrode on the surface. The device has an emitting peak wavelength of 455 nm (Fig. 1b), and the size of the chip is 1 mm × 1 mm.

To pattern VLED with cone structures, Cr masks were first fabricated on the GaN layer by electron beam lithography and lift-off method. Then the chips were etched by ICP-RIE system with reactive gas of BCl_3 and Cl_2 (10 sccm : 50 sccm). The chamber pressure was 12 mTorr, the RF power was 75 W and the ICP power was 300 W. The etching parameters were optimized so that the etching sidewall was inclined in order to form cone shapes. After etching, the Cr masks were finally removed by wet etching in $Ce(NH_4)_4(NO_3)_6$ solution. Figure 1c gives SEM images of GaN cones with period of 550 nm and height of 1 μm. The taper angle of the cones is about 30°, which is close to the optimized angle by simulation [19]. The size of the cone pattern is 1 mm × 1 mm, which covers the whole surface of VLED.

Measurements and simulations

The output power of the VLED was measured by an integrating sphere in combination with a spectrometer (MAYA 2000 PRO), and the light intensity under different injection current was obtained. Figure 2a shows the output power as a function of injection current for the original and patterned VLEDs. When the injection current is 350 mA (the normal working current condition of VLEDs), the patterned VLED chip shows a power enhancement of 95 % compared with the original VLED chip. It should be noted that the enhancement ratio increases with injection current, which will be explained at the end of part III. From the I-V curves given in Fig. 2b, the forward voltages of original VLED and patterned VLED at an injection current of 100 mA are 3.1 and 3.08 V, respectively. Furthermore, the leakage currents of both VLEDs were below 0.01 μA (data not shown in this figure), which indicates that the surface structures do not cause deterioration of electrical properties.

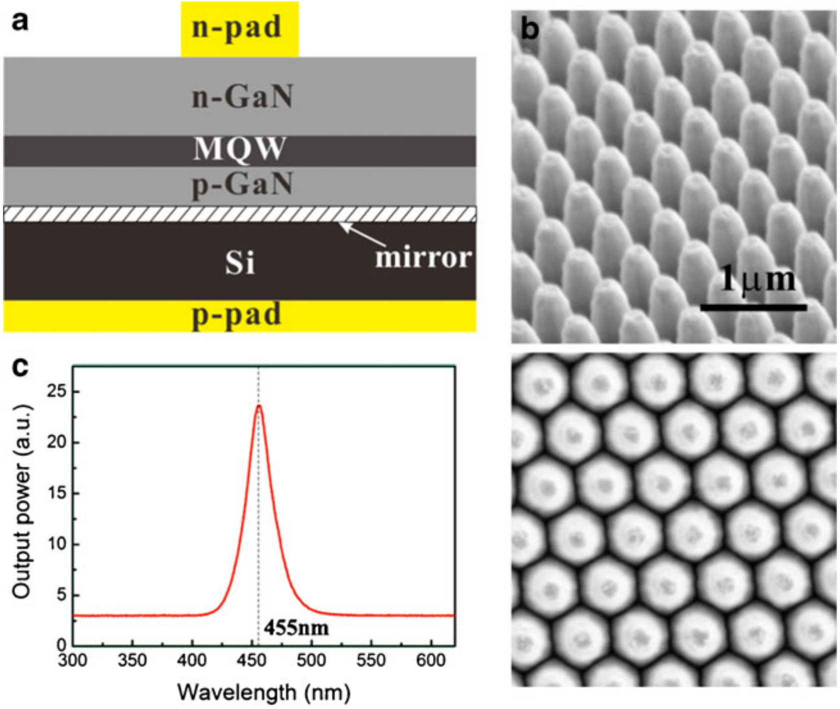

Fig. 1 **a** Schematic cross-section of the VLED device; **b** Electroluminescence spectrum of original LED; **c** Side view (*top*) and top view (*bottom*) of cone structures on surface n-GaN layer

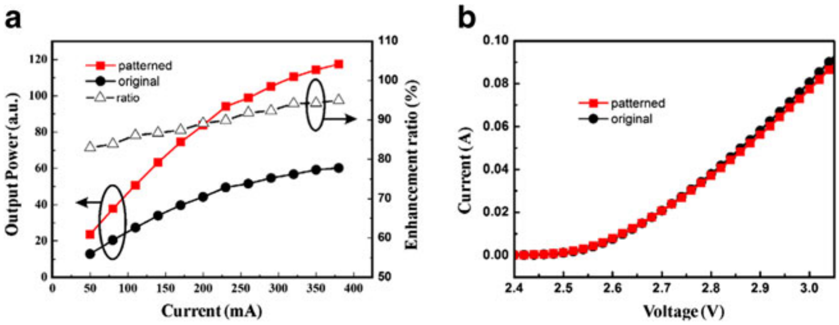

Fig. 2 **a** Output Power of the patterned and original VLED and light enhancement ratio as a function of injection current; **b** Forward I-V characteristics of both kinds of VLED

To measure the far-field property of VLED, we present a setup consisting of an optical fiber on a rotating arm (Fig. 3a), which can collect the output signal in various angles. The distance between the fiber and LED sample is 30 cm, the fiber aperture is 3 mm, and the scanning step is 5° from −90° to 90°. Spectra at each angle point can be collected by a spectrometer connected to a fiber, and the light intensity was integrated over wavelength. The hexagonal lattice has two kinds of symmetry axis, so the angle-resolved spectra along the two axes were both measured and the results are shown in Fig. 3b. The original VLED displays a typical Lambertian source, of which the angle-resolved curve appears to be circular according to the formula: $I(\theta)=I_0\cos\theta$, where I_0 is the light intensity in vertical direction. For patterned VLED, there's a minimum value along the normal direction, and the light emitting intensity reaches a peak value at the angle of ±15°. This demonstrates that the cones increase light escaping from the side walls of the etched patterns much more than from the top. There are very small differences between the red and blue curves from −15° to +15°, which is resulted by the different symmetry along the two axes.

Figure 3c and d show the angle-resolved far-field spectra of the original VLED and patterned VLED (on yOz plane), respectively. In Fig. 3c, there are wrinkles in the far-field spectrum. The wrinkles come from interference of light reflected by Ag mirror and GaN-air interface, and light that emitted from MQW both upward and downward. This is similar to Fabry-Perot resonance [20] but with some differences. The schematic of the Fabry-Perot like resonance in VLED is shown in Fig. 4a. The reflection rate for Ag mirror is constant instead of an angle sensitive reflectivity. Meanwhile, the MQW can radiate light both upward and downward, so there are two terms for both directions. For simplicity, the thickness of MQW

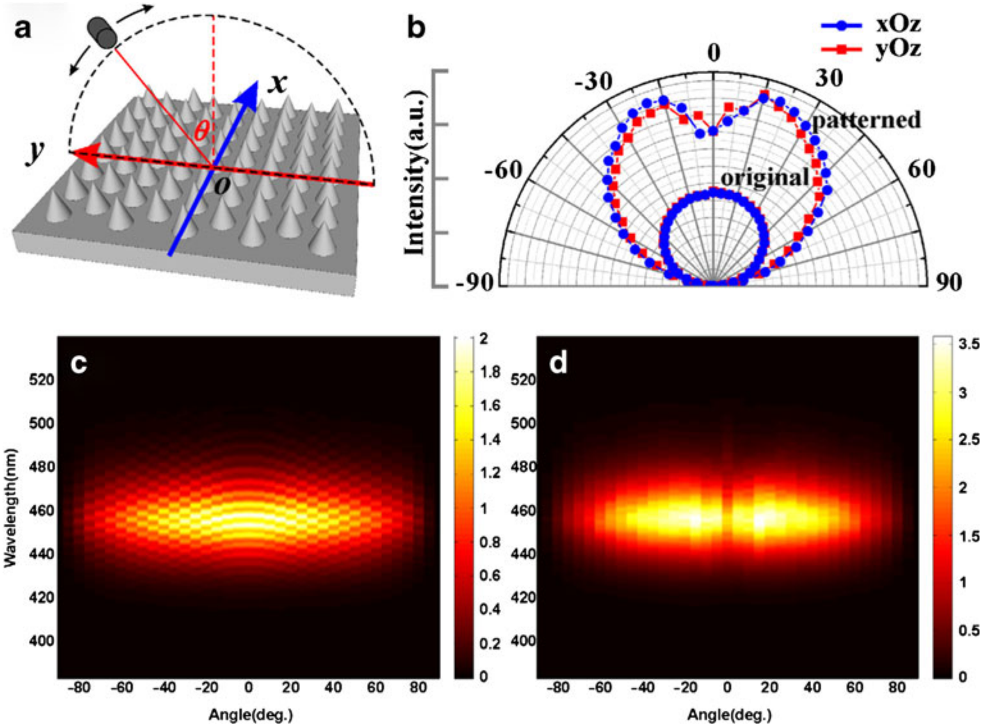

Fig. 3 **a** Schematic setup for measuring the angle-resolved far-field intensity of VLED; **b** Far-field intensity distribution of original and patternd VLED on both planes; **c** and **d** Angle-resolved far-field spectra of original VLED and patterned VLED (on yOz plane)

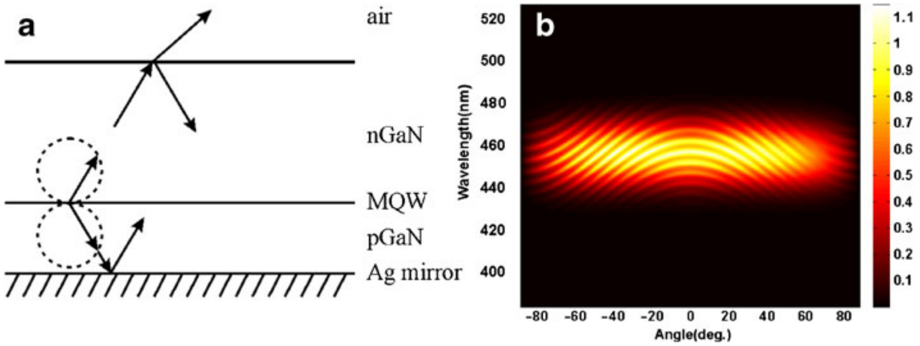

Fig. 4 **a** Schematic of light interference in VLED; **b** Calculated angle-resolved far-field spectrum of original VLED

is approximated to be zero. We give the expression of light complex amplitude as follows:

$$\tilde{U} = \frac{Ate^{i\delta_h}\left(1 + r'e^{i\delta_{dd}}\right)}{1 - rr'e^{i\delta_{hdhd}}} \tag{1}$$

Here, *t* and *r* are transmittivity and reflectivity at GaN-air interface, respectively, *r*' is reflectivity of Ag mirror, δ is phase changes between interfaces ($\delta_{hdhd} = \frac{2\pi n(h+d+h+d)}{\lambda}\cos\theta$), the subscript *d* is the distance between MQW and Ag mirror, and *h* is distance between MQW and GaN-air interface. The two terms in the bracket represents light emitting upwards and downwards, respectively. Figure 4b shows the 2D spectrum calculated by Eq. (1), which fits well with the far-field spectrum in Fig. 3c. The small differences between calculation and measurement come from the deviations of ideal conditions (Lambertian source and Gaussian function in frequency domain) in real LEDs.

In Fig. 3d, there are no wrinkles in the angle-resolved spectrum of patterned VLED. This is because the light that incident into the cones is reflected successively by the sidewalls, and after each reflection the departure angle decreases. Finally the departure angle is smaller than critical angle of GaN (about 23.5°), and most of the light can exit instead of trapped in the cones [7]. A similar hemiellipsoid structure was also studied which can extract light beyond light escape cone into the air, and the extraction efficiency saturates with structure diameter increasing [21]. This indicates that the surface textured structure can affect the angle-resolved far-field pattern in two ways. On one hand, the light within light escape cone which can escape directly is diffracted successively by sidewalls thus it finally emits out with large angles. On the other hand, the light beyond escape cone which was stopped in original LED is diffracted less times. This results in the low light extraction efficiency in vertical direction.

The polarization property of patterned VLED is measured by placing a polaroid before the detector. In Fig. 5a, the original VLED shows different light intensity for s and p polarization, which is caused by the InGaN MQW [22]. For the patterned VLED, the output power is enhanced in different ratios for different directions, which is shown in Fig. 5b (the curves from −90° to 0° are not shown here). The enhancement factor is defined as:

$$factor(\theta) = \frac{I_{patterned}(\theta) - I_{original}(\theta)}{I_{original}(\theta)} \tag{2}$$

in which *I*(θ) is the light intensity at angle θ. At the point of θ = 0°, the enhancement factor is only 0.5. The maximum factor lies between 15° to 45°, which is over 1.0 for both s and p polarization. This is different from PC LED, of which the light enhancement factor is polarization dependent [23, 24]. For 1D or asymmetry 2D photonic crystals, the diffraction for different polarizations mainly depends on band structures, and the light output may be enhanced of one polarization but suppressed of the other. But in this paper, the peak wavelength is smaller than the period of cones, so it is out of

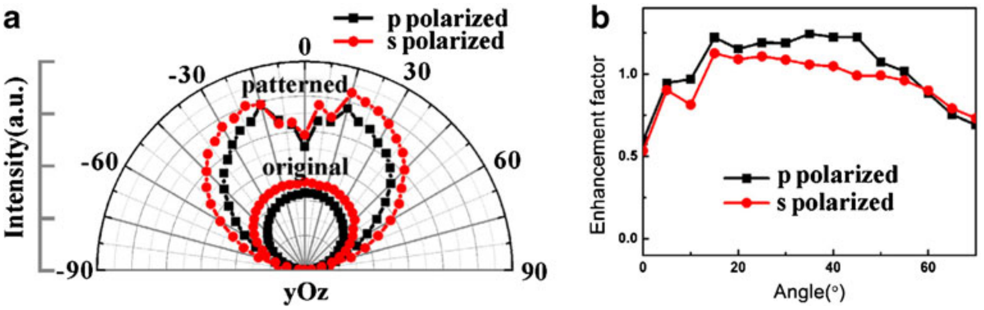

Fig. 5 **a** Angle-resolved far-field intensity of s and p polarized light; **b** Enhancement factor for s and p polarized light

the bandgap of planar periodic array, and the guiding modes are coupled out because of reflection of cones rather than bandgap.

Compared to random surface roughening structures, the mechanism of light enhancement here is also different. When scattered by random structures, the far-field emission pattern is of the same shape with flat LED [25]. This is because the light scattered by random structures is also random for all directions and polarizations. But for the periodic structures, interference effect between different units occurs so there's a specific pattern of the far-field spectrum, and the enhancement for different polarizations is almost the same because the cones is of high symmetry. Since the light extraction is resulted on avoiding TIR instead of waveguide coupling, both s and p polarized light can be extracted simultaneously, so the cone textured VLED can have more promising light extraction effect.

As mentioned above, the enhancement ratio increases with injection current from 83 % at 50 mA to 95 % at 350 mA in Fig. 2a. It has been reported that the components of different polarizations can be changed by injection current, because of polarization switching caused by high state occupation above $k = 0$ in case of high injection current [26]. In Fig. 5a the intensity of s polarization component is larger than p polarization, which is accordance with Ref. [22]. Here, the enhancement factor can be rewritten as:

$$factor = \frac{f_s I_s + f_p I_p}{I_s + I_p} \tag{3}$$

Here f_s and f_p represent the enhancement factor of s and p polarization components, while I_s and I_p are the intensities. We define R to be the intensity ratio of I_s/I_p, and Eq. (3) can be derived into:

$$factor = f_s + \frac{f_p - f_s}{R + 1} \tag{4}$$

Since the intensity ratio R decreases with increasing injection current increasing [26] and $f_p > f_s$ (see Fig. 5b), the enhancement factor increases with injection current as we mentioned at the beginning of part III. This indicates that the changing of enhancement ratio with injection current can be different by diverse surface structures.

Summary

In conclusion, GaN circular cones were fabricated on n-side surface of VLED by ICP-RIE etching. The light intensity of patterned VLED was enhanced by about 95 % at injection current of 350 mA compared with original VLED with flat surface. The angle-resolved spectra of the original VLED showed Fabry-Perot like resonance, while the resonance disappeared for patterned devices because the cone structures lead to light rearrangement on the surface. The cone structures result in nearly equal light enhancement to different polarizations of light. These results indicate that the nano-cones can effectively increase the light extraction efficiency, and make full use of different components of light, which can also be used in other optical devices such as organic LEDs and solar cells.

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