Enhanced light extraction efficiency of vertical light emitting diode by hemispherical and pyramidal pattern surface texture

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A quantitative investigation of light extraction efficiency for hemispherical and pyramidal pattern surface textured GaN based vertical light emitting diode (VLED) was reported by various distance and size ratios. There is a significant increase in light extraction efficiency because of increase number of random scattering of textured surface. Hemisphere pattern surface always gives the 30% better enhancement than pyramid type pattern. We also showed the efficiency dependency on the reflectivity of GaN/metal interface. Furthermore, a linear diffraction grating with certain grating period can eliminate the distance and size ratio dependency on output power which can be considered as an integrated surface texture.

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1. Introduction

GaN based light emitting diodes have been developed rapidly for many applications such as full color display, solid state lighting, backlighting in liquid crystal displays [1, 2]. In recent years, blue GaN LED together with yellow phosphor is one of the key component for high efficiency white LED. Although LED market is growing fast, further improvement of light output power is required for future demand. Only 4 % of emitted light from active layer can escape from LED because of low escape cone (24^{o}) at the GaN-air interface [3]. In this case texture the surface is an efficient way to improve the light output power because of multiple chances of light escape from the surface. However, vertical LED on metal substrate shows many excellent performances over lateral LED such as vertical current path for low operation voltage, better current spreading, higher heat dissipation, better light extraction, higher driving current density, flexible chip size scaling and good reliability [4, 5, 6]. In addition, various types of texture can be easily formed on the comparatively thick n-side up VLED. Periodically pattern micro structures such as hemisphere holes [7], pillar [8], air prism array [9, 10], photonic crystal [11], and hexagonal cone [12] have been successfully demonstrated in producing improved light output. In addition to one-step texture two-step surface patterning, combines with micro and sub micro structures also investigated [13, 14]. Considering these, optimization of surface textured VLED is an indispensable issue for best light extraction.

In this work, we represent a simulation analysis on texture surface VLED of different distance to size (D/S) ratios. Extraction efficiency of VLED with hemisphere and pyramid type texture surface was analyzed at three different sizes 0.1, 0.5, 2.0 μm respectively. Results showed that for more efficiency more compact pattern is required. There is no dependency of output power on the size of pattern. We also took this investigation considering different reflectivity of GaN/metal interfaces 100% and 80% respectively because reflectivity becomes more important in textured surface VLED. Furthermore, applying a linear grating on hemisphere pattern surface with a certain nano scale grating period can solve the problem of making compact pattern.

Simulation was realized by Light Tools™ commercial package which is a 3D ray tracing tools required for optical design and engineering [15]. It allows you to set up, view, modify and analyze optical system graphically.

2. Structural model

To analyze the LED, geometrical structure for vertical LED is presented in Table 1. As conductive metal substrate is used for VLED, Si metal is used as substrate with refractive index 3.42 and dimension $1000\times1000\times100\mu m^2$.

Table 1 shows the structural parameters of GaN based LED with thickness 4 μm. As the thickness of the GaN, AlGaN, N-GaN, MQW, P-GaN is very small compared to the surface size of LED we can ignore the photons that escape from four sides. Furthermore, total internal reflection also can be ignored as the indices of these layers are similar.

The surface source with lambertian intensity distribution is used as an emitter without the need of any additional features. The size of the source matches the size of the

LED. After simulation the extraction efficiency of planar vertical LED was found to be 21.63%.

Table 1. Parameter of each layer of the simulated VLED.

Chip size: $1000 \times 1000 \mu m^2$

Layer	Thickness(μm)	Refractive Index
Silicon	100	3.42
P-GaN	0.05	2.45
MQW	0.1	2.54
N-GaN	2.0	2.42
AlGaN	0.05	2.40
GaN	2.0	2.40

3. Theory of escape cone and reflectivity

In the vertical injection LED, power efficiency mainly controlled by two interfaces, one is GaN/air interface and another is GaN/metal interface. The main reason for low extraction efficiency of LED is total internal reflection (TIR) of light at the semiconductor-air interface which results from the high refractive index difference between the semiconductor and air. According to Snell's law, critical angle [$\theta_c = \sin^{-1}(n_{air} / n_{GaN})$] in case of GaN (n_{GaN}=2.5) and air (n_{air}=1.0) interface is 24° [16]. So any light ray incident from MQW with an angle more than 24° on the GaN-air interface will be trapped inside the semiconductor. Fig. 1. Shows how a ray of light incident greater than critical angle trapped inside the semiconductor.

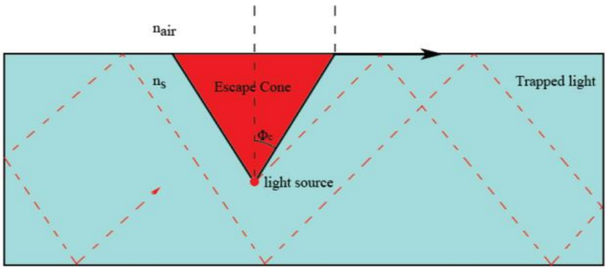

Fig. 1. Illustration of escape cone.

Surface texture is an important method in enhancing light extraction efficiency. The enhancement in light extraction is attributed to the multiple chances for lights to escape from the cone through surface texture. However, surface texturing is difficult for lateral LED because the top p-GaN layer is too thin for texturing and sensitivity of p-GaN to electrical deterioration and plasma damage. Any engineering on thin p-GaN layer can affect the underneath MQW. In case of VLED, all the surface engineering occurs on n-GaN layer (>2 μm) which is much thicker than p-GaN. So texture engineering on n-GaN layer will not affect the underneath MQW.

The reflectivity of metal/GaN layer plays an important role to enhance the extraction efficiency of light. The reflectivity at the metal/semiconductor interface can be calculated by using the formula (1) [17] for reflection of a wave perpendicularly incident from media 1 onto the plane boundary of a solid with refractive index n. The ratio R of reflected-to-incident irradiance is given by Fresnel expression

$$R = \frac{(n_s - n_m)^2 + k_m{}^2}{(n_s + n_m)^2 + k_m{}^2} \tag{1}$$

where n_s the refractive index of semiconductor, n_m is the refractive index of metal, and k_m is extinction coefficient of metal. Greater reflectivity at the semiconductor/metal interfaces gives more light output power of LED.

Fig. 2 shows the schematic cross sectional view of GaN based vertical light emitting diode with hemisphere and pyramid shape.

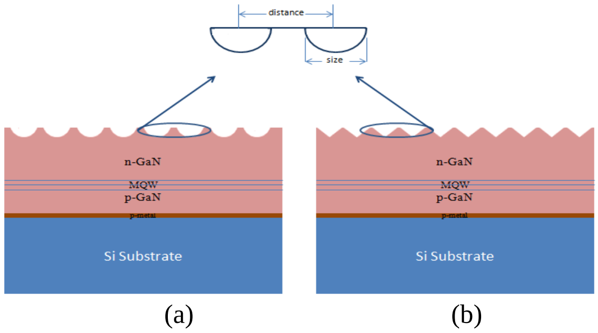

Fig. 2. Schematic structure of (a) hemisphere and (b) pyramid shape surface texture VLED.

4. Result and discussion

Fig. 3 shows the change of extraction efficiency (EE) with distance/size(D/S) parameter (relation of placement between pattern and its size) of textured VLED with R=100% at the GaN/metal interfaces. Patterns are distributed in hexagonal packing because it is more effective due to larger fill factor and redirecting of light rays. Two types of textured pattern were analyzed i.e. hemisphere and pyramid, at three different radius (for hemisphere) and side width (for pyramid) 0.1, 0.5, 2.0 μm.

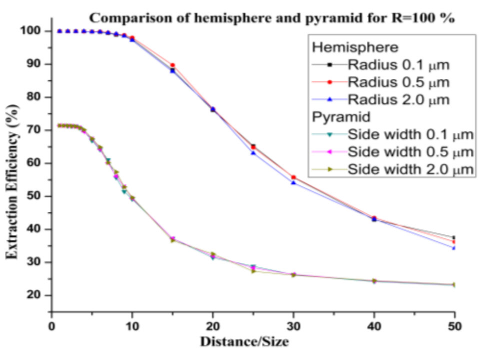

Fig. 3. Extraction efficiency of hemisphere and pyramidal pattern surface at different sizes as a function of distance/size of the texture at reflectivity R=100%.

As shown in Fig. 3, EE increase significantly by texturing the surface, up to 100% for hemisphere and 72% for pyramid whereas it is only 21.93% for planar VLED.

Fig. 4 shows the change of extraction efficiency (EE) with distance/size parameter of textured VLED with R=80% at the GaN/metal interfaces at the same radius (hemisphere) and side width (pyramid) as in Fig. 3. In this case, EE increase up to 44% for hemisphere and 30% for pyramid whereas in case of planar surface it was only 15.4%. The dots show the total efficiency experimental data extracted from different references for hemisphere [7, 14] and pyramidal [19] structures as mentioned in Fig. 4. The simulation results repeat the tendency of experimental data but not the same because the shape is not exactly pyramidal. Therefore, we can conclude that for better EE it is essential to increase the reflectivity of GaN/metal interfaces because 20% increase in reflectivity results in more than 2 times increase in EE.

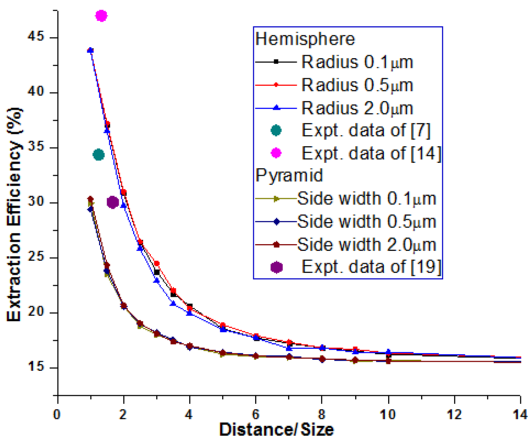

Fig. 4. Extraction efficiency of hemisphere and pyramidal pattern surface at different sizes as a function of distance/size of the texture at reflectivity R=80%.

Both in Fig. 3 and Fig. 4 it is shown that there is a weak dependence of light extraction efficiency on sizes of hemisphere and pyramid but strong dependence on the variation of distance/size parameter. For better efficiency compact pattern is required. This is because as the D/S increase, number of hemisphere/pyramid pattern decrease. Thus random scattering probability decreases.

However, decreasing characteristics are different for reflectivity 100% and 80% for both patterns. For R=100% almost no change in EE until D/S parameter changes to 5 but for R=80% EE decreases mostly up to D/S parameter 5. As we know light rays those cannot escape from the top surface are go out through the back surface or absorbed by the structure through non-radiative recombination. In case of 100% reflectivity there is no way of light to go out through back surface. So photons reflected back again and again from back surface and at last escape through the texture top surface, But for larger value of D/S very little number of pattern remain on the surface. In this case they cannot go out through the back surface or the top surface and consequently absorbed by the structure. However, for 80% reflectivity, photons from the MQW cannot escape through the top surface; a large portion of them can go out by the back surface at first chance. Thus EE decreases rapidly with small change in D/S parameter. However, the latter case is more practical because 100% reflectivity in not possible in real case and 80% reflectivity can be possible if we use Ag based reflective p-contact [18]. So we can conclude that more compact pattern is necessary for better device performance.

Fig. 5 shows the efficiency of hemisphere pattern surface as a function of D/S by applying an additional linear grating on it. Analysis was taken on different grating period at 100nm, 200nm and 400 nm respectively. General grating equation is often referred to as

$$\sin\theta_d - \sin\theta_i = m\frac{\lambda / n}{\Lambda} \qquad (2)$$

where, θ_i is angle of propagated light incident on the texture surface and θ_d is the angle of diffracted light from the surface normal, m is the diffraction order, λ is free space wavelength, n is the refractive index of medium and Λ is spatial period of the scattering sites i.e. grating period. The value of diffraction order can be $m = 0, \pm1, \pm2, \ldots\ldots$.

If $\Lambda >> \lambda$, many diffraction order m are possible and thus efficiency can increase. However, maximum propagating order is limited to < 90^o. When this angle is exceed diffraction angle is no longer possible.

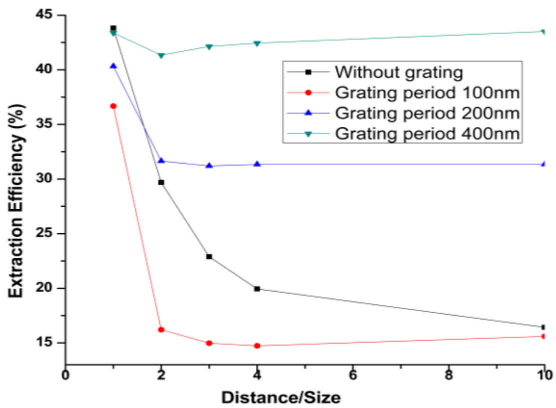

Fig. 5. Effect of grating period on the efficiency of hemisphere texture surface as a function of distance/size parameter.

Above result indicate that, for grating period 100 nm, EE is even less than without grating because in this case only m=0 is worked. For grating period 400 nm, larger m is propagated that is why we get better efficiency. Moreover, in this case D/S dependency does no longer exist and we can get almost constant efficiency as a function of D/S.

5. Conclusions

In this work, surface textured GaN based vertical light emitting diode was designed and simulated. Texturing surface with hemispherical and pyramidal pattern at different placement between patterns was analyzed separately. We also investigate this structure at two different reflectivity 100% and 80% of GaN/metal interfaces and three different sizes of the pattern. Results show that extraction efficiency depends strongly on the placement between the pattern and it is independent on the size of the pattern. There is an exponential decrease in efficiency as distance/size ratio increase. Texture surface gives 2.8 times and 2.0 times enhancement of efficiency for hemisphere and pyramid pattern respectively with R=80%. Hemispherical pattern always gives 30% more enhancement than pyramid. In addition to this applying a linear grating at a certain grating period can solve problem about the dependence of light output power on distance/size ratio.

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