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Effects of the microstructure slab with pillars on light extraction of GaN light-emitting diode*

Li Yan(李 岩)[a)b)†], Zheng Rui-Sheng(郑瑞生)[a)], Feng Yu-Chun(冯玉春)[a)], Liu Song-Hao(刘颂豪)[b)], and Niu Han-Ben(牛憨笨)[a)]

[a)] *Key Laboratory of Optoelectronic Devices and Systems (Shenzhen University), Ministry of Education, Institute of Optoelectronics, Shenzhen University, Shenzhen 518060, China*

[b)] *College of Optoelectronic Information of South China Normal University, Guangzhou 510631, China*

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The positive z direction relative light extraction efficiency of GaN light-emitting diodes with microstructure slab is calculated by three-dimensional finite-difference time-domain method, where the microstructure slab consists of a graphite lattice of pillars. The results show that the two-dimensional graphite-arranged pillars suppress light extraction. When there is a thick pillar in the middle of the pillars, the structure can enhance light extraction of the light-emitting diodes. The tower-like pillars, which are thin on the top of the pillars and thick on the bottom of the pillars, benefit the light extraction when the angle of the tower-like pillars is proper.

Keywords: photonic crystal, light-emitting diodes, GaN
PACC: 4220, 4270Q

1. Introduction

Light-emitting diodes (LEDs) have the potential to be low-cost and long lifetime solid-state lighting source for applications as varied as room lighting to displays.[1,2] Unfortunately, there is a significant discrepancy between the high internal efficiency and poor external efficiency of LEDs. Most of the generated light is never emitted from LEDs, but is lost to guided modes within the high dielectric material. Depending on the Snell law, the extraction efficiency of the conventional planar LEDs can be as poor as $1/(4n^2) \approx 1/50$, where n=3.5 is the refractive index of the LEDs cladding material. A number of schemes,[3−6] such as surface roughness, resonant cavities and surface plasmon, etc., attempted to overcome the poor extraction efficiency of LEDs, and all these methods allow up to 30% external efficiency LEDs.

Since it was suggested that the photonic crystal (PC) structure can enhance light extraction efficiency,[7] rapid progress[8−10] has been made mainly in the enhancement of light extraction by two-dimensional (2D) PCs from GaAs/GaAlAs or InGaAsP/InP LED, which are expected to emit red light or infrared light. Recently, there is a breakthrough in III-nitride LEDs, the nanofabrication of PCs on InGaN/GaN LEDs is reported.[11,12] This is crucial for improvement of the extraction efficiency of the blue/green and ultraviolet LEDs based on III-nitride wide band gap semiconductors.

All the works involve a 2D PC consisting of a triangular lattice of holes. However, an expected problem with this kind of microstructure is the surface recombination at sidewalls of holes, which degrades the internal efficiency.[13] In this paper, we discuss the effects of a microstructure slab, which consists of dielectric pillars in air, on light extraction of GaN LED. This kind of microstructure is expected to get photonic band gaps (PBGs) easily for small refractive index material and minimize the surface recombination.[14,15]

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†E-mail: g_yjsh@szu.edu.cn

2. The relative light extraction efficiency of the PC LED

Figure 1(a) shows a simplified model of an ordinary planar LED with uniform GaN material cladding. Figure 1(b) shows a simplified model of a LED with a graphite lattice of dielectric pillars, like 2D PCs, etched in GaN cladding, we call it the PC LED model. The width L_x and L_y of the ordinary LED model are the same as that of the PC LED model, they are L_x=5276.7nm, L_y=4737.0nm. The thickness of the active region of the two models is 40 nm. The lattice constant and the pillars radius of the PCs in Fig.1(b) are a=298.1nm, r=89.4nm respectively. The notations L and h in Fig.1 denote the thickness of the LED cladding and the height of the dielectric pillars respectively. The permittivity of the semiconductor in cladding layer and active region are 5.8, 5.4 respectively.[16] Here, we only show the X–Z plane of the ordinary LED in Fig.1(a).

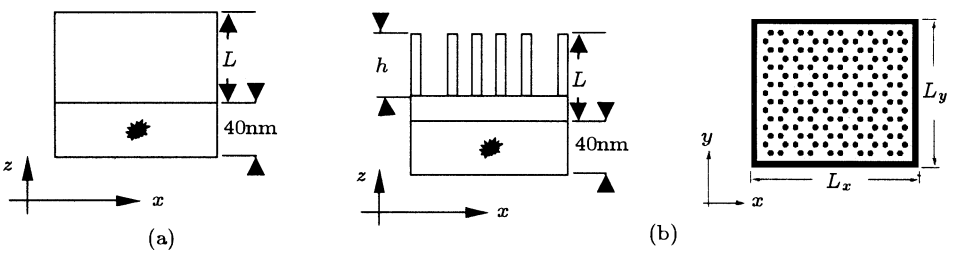


Fig.1. Schematic diagram of the simplified LEDs with the width, L_x=5276.7nm, L_y=4737.0nm and a 40nm thickness active region. (a) A simplified model of an ordinary planar LED. (b) A simplified model of LED with graphite-arranged pillars etched in GaN cladding.

Since we are concerned about the effects of the pillars slab on light extraction from the positive z direction of the LED, the optical energy extracted from a LED is computed in a fixed plane which is above the LED and perpendicular to the z axis by the three-dimensional finite-difference time-domain (FDTD) method. In the FDTD calculation, a point dipole source with emission spectrum from 455nm to 485nm, which is in the PBG produced by the 2D PC pillars, is put in the middle of the active region, and the uniaxial perfectly matched layer (UPML), which surrounds the model, is employed as the absorbing boundary condition. When the optical output energy of the PC LED has been divided by that of an ordinary LED which has the same L, L_x, L_y with the PC LED, the relative light extraction efficiency of the PC LED can be given. Considering that the pillars may inhibit the emission of radiation, in our discussion, the pillars in the cladding of the LED.

The relative light extraction efficiency of the PC LED in Fig.1(b) is shown in Fig.2, where $L-h$=40nm. We denote this situation as light extraction varying with absolute height of the pillars. The relative light extraction efficiency varies only with h as shown in Fig.3, where L=500nm. We denote this situation as light extraction varying with relative height of the pillars.

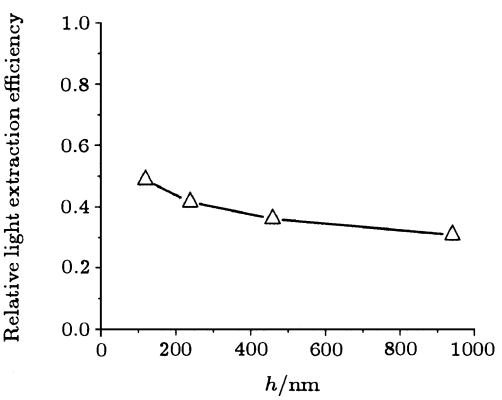


Fig.2. Relative light extraction efficiency of the PC LED varying with L and h, where $L-h$=40nm.

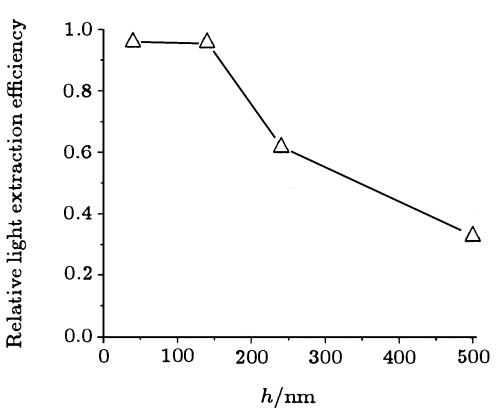


Fig.3. Relative light extraction efficiency of the PC LED varying only with h, where L=500nm.

From Fig.2, one can observe that the relative light extraction efficiency is smaller than 1; moreover, the relative light extraction efficiency is descending with the rising height of the pillars, but its descending speed decreases. In Fig.3, the result shows that the relative light extraction efficiency trends to 1 when the relative height of the pillars decreases. This means that the light extraction efficiency of the PC LED trends to that of the ordinary LED when the relative height of the pillars decreases. It is not difficult to understand this result, because the PC LED trends to an ordinary planar LED when the relative height of the pillars decreases.

These results imply that the microstructure of pillars suppresses the light extraction.

The reason why the optical output energy of the PC LED is smaller than that of the ordinary LED can be given by the spatial distribution of the electric-field intension. The spatial distribution of the electric-field intension is shown in Fig.4, where Fig.4(a) and Fig.4(b) show the distribution of the ordinary LED with the thickness of cladding layer, L=980nm, in the X–Y plane and in the X–Z plane respectively. Fig.4(c) and Fig.4(d) show the distribution of the PC LED with the thickness of cladding layer, L=980nm, the height of the pillars, h=940nm, in the X–Y plane and in the X–Z plane respectively. Contrasting Fig.4(a) with Fig.4(c), one can observe that the area of the light extraction for the planar LED is far bigger than that for the PC LED. At the same time, contrasting Fig.4(b) with Fig.4(d), one can see clearly that the pillars confine light to the z direction. We can explain the reason as follows: because the emission spectrum is in the PBG, when the light reaches the microstructure slab, it cannot spread laterally; the only direction that the light can spread is along the z direction. Thus, a small part of the light whose direction is along the positive z direction can escape from the LED, but most parts of the light are reflected and absorbed by the UPML boundary. From Fig.4, it seems that the pillars reduce the area of the light extraction, and the higher the height of the pillars are, the smaller the area of the light extraction is. This reason induces that the optical output energy of the PC LED is smaller than that of the ordinary LED, and the relative light extraction efficiency of the PC LED descends with the rising of the height of the pillars.

Since a small area of light extraction results in small output energy for the PC LED, a new PC LED model with a thick GaN pillar in the middle of the pillars region is shown in Fig.5. We call it the middle pillar PC LED. The radius of the thick middle pillar is $R = m \times a + r$, where m is a positive number.

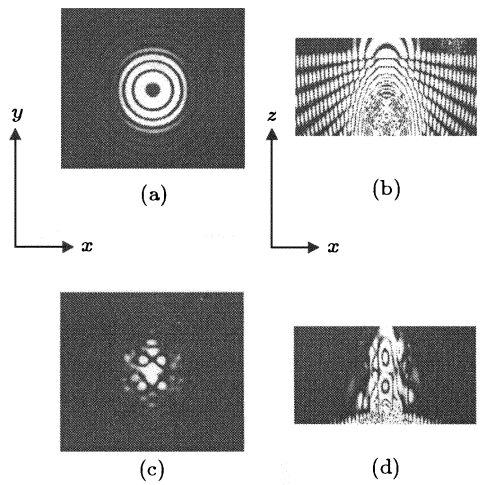


Fig.4. Electric-field intension distributes in the X–Y plane and in the X–Z plane, respectively. (a) The distribution of the ordinary LED in the X–Y plane. (b) The distribution of the ordinary LED in the X–Z plane. The thickness of cladding layer of the ordinary LED is L=980nm. (c) The distribution of the PC LED in the X–Y plane. (d) The distribution of the PC LED in the X–Z plane. The thickness of cladding layer and the height of the PC pillars are L=980nm, h=940nm respectively.

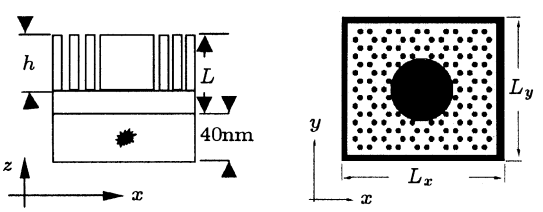


Fig.5. Schematic diagram of the middle pillar PC LED. The radius of the thick middle pillar is $R = m \times a + r$.

When we choose L=520nm, h=480nm, the relative light extraction efficiency of the middle pillar PC LED, which varies with m, is shown in Fig.6. One can observe in Fig.6 that the relative light extraction efficiency is greater than 1, which means that the optical output energy of the middle pillar PC LED is greater than that of the ordinary LED. In addition, the results show that there is very different relative light extraction efficiency if the thick middle pillar has different radius. The curve shows an evident tendency that the relative light extraction efficiency descends with the rising of the middle pillar radius m, but it jumps up when the radius is about $R = 3a + r$. Moreover, the relative light extraction efficiency is the biggest when m=3.

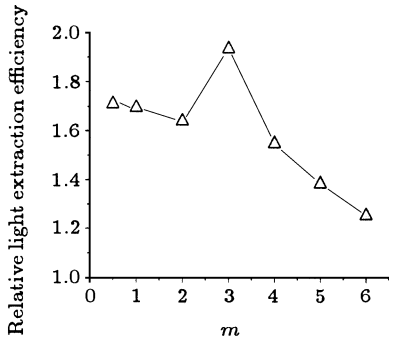


Fig.6. Relative light extraction efficiency of the middle pillar PC LED varies with m. The parameters of the model are L=520nm, h=480nm.

The main reason for this phenomenon is scattering, which can be explained qualitatively as following: according to the Snell law, the critical angle of total reflection from GaN to vacuum is about 24.5°. Thus, total reflection occurs when the light ray reaches outside the circle area ($R = 0.49a + r$) on the surface of the LED. This result indicates that the light output energy does not ascend any more with the rising of the radius of the middle pillar when the radius is bigger than m=0.5. In addition, the bigger the radius of the middle pillar is, the much more the middle pillar PC LED tends to the ordinary LED. This implies that the relative light extraction efficiency will trend to 1 with the rising of the radius of the middle pillar. The relative light extraction efficiency sharply increases at m=3, this effect must be due to sharp enlargement of the diffraction limit for this structure. The effect of the cylinders, which surround the thick middle pillar, is to block the light propagating laterally. These results can be seen clearly by comparing the figures of Fig.7 with each other. Figs.7(a), (b) and (c) are spatial distribution of the electric-field intension of the middle pillar PC LED in X–Y plane, the radius of the middle pillar are m=0.5, 3, 5 respectively.

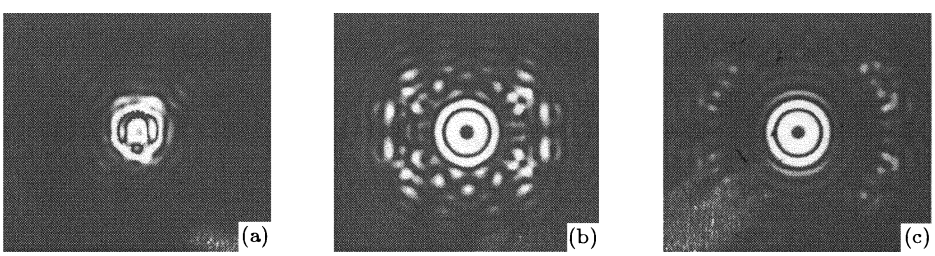


Fig.7. The distribution of the electric-field intension of the middle pillar PC LED in X-Y plane. (a), (b) and (c) are the spatial distribution with radius of the middle pillar, m=0.5, 3, 5, respectively.

3. Influence of the tower-like pillars

It is well known that instead of straight micropillars etched in semiconductor cladding, tower-like micropillars, which are thin on the top and thick on the bottom,[13] are much realistic in practice. Then we discuss the situation that the relative light extraction efficiency of the PC LED with tower-like pillars, which we call the tower-like PC LED, varies with angle β. β is a angle between the slant face of the tower-like pillars and the negative direction of the z axis.

The tower-like PC LED model is the same as the PC LED model in Fig.1(b) except for the shape of the pillars, which are tower-like pillars for the tower-like PC LED model, but straight pillars for the PC LED model. They have the same L_x, L_y and thickness of the active region. L and h of the tower-like PC LED are 520nm and 480nm respectively. Other parameters of the tower-like pillars are shown in Table 1.

Table 1. Parameters of the tower-like pillars.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Top radius/a	0.2	0.2	0.2	0.2	0.2	0.2
Bottom radius/a	0.25	0.30	0.35	0.40	0.45	0.50
β/(°)	1.94	3.88	5.80	7.72	9.61	11.49

The relative light extraction efficiency of the tower-like PC LED varies with β, as shown in Fig.8. Two features can be observed in this figure. First, the relative light extraction efficiency is smaller than 1 and descends with rising β in the mass. Second, the curve is protuberant at about 5.80°. The biggest relative light extraction efficiency is 0.3895. In addition, in Fig.2 the relative light extraction efficiency is 0.3610 when L=500 nm and h=460 nm. Comparing the two relative light extraction efficiencies, we can find that although L and h in Fig.8 are bigger than that in Fig.2, when there is a proper value of β, the relative light extraction efficiency of the tower-like PC LED is bigger than that of the PC LED. On the side of enlarging the light extraction of LED, this result implies that the tower-like pillars benefit light extraction when there is a proper angle.

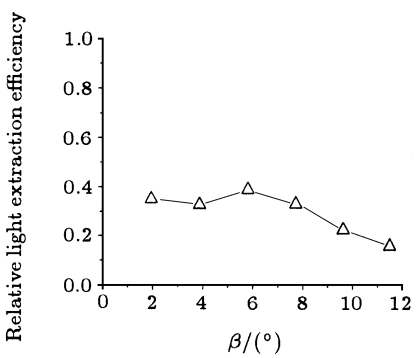


Fig.8. Relative light extraction efficiency of the tower-like PC LED varies with β. The parameters of the tower-like PC LED are L=520nm and h=480nm.

Because the relative light extraction efficiency of the tower-like PC LED is smaller than that of the ordinary LED, based on the same reason, we study the tower-like middle pillar PC LED, which is tower-like PC LED with a thick GaN pillar in the middle of the pillars region. The radius of the thick middle pillar is $R = m \times a + r'$, where r' is the bottom radius of the tower-like pillars.

The relative light extraction efficiency of the tower-like middle pillar PC LED is shown in Fig.9, where L, h, the top radius and the bottom radius of the tower-like pillars are 520nm, 480nm, 0.20a and 0.35a respectively. Contrasting Fig.9 with Fig.6, one can see that except the same characters as those of the middle pillar PC LED, such as that the relative light extraction efficiency is bigger than 1, the relative light extraction efficiency is the highest when m=3, etc., the tower-like middle pillar PC LED has two special characters. First, the relative light extraction efficiency is bigger than that of the corresponding middle pillar PC LED except the case m=0.5. This implies again that the tower-like pillars benefit light extraction when the angle β is proper. Second, with variety of m, the relative light extraction efficiency has a wavelike change. This character is very different from that of the middle pillar PC LED, which has the trend that the relative light extraction efficiency descends with rising m in the mass.

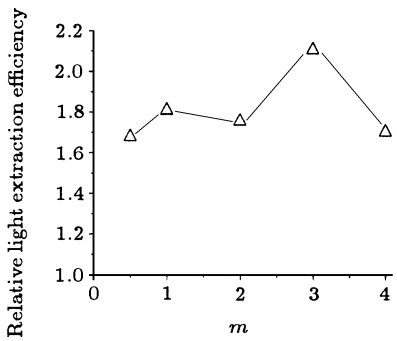


Fig.9. Relative light extraction efficiency of the tower-like middle pillar PC LED vary with m. The parameters, L, h, the top radius and the bottom radius of the tower-like pillars are 520nm, 480nm, 0.20a and 0.35a respectively.

4. Conclusion

In conclusion, we have discussed the effects of the microstructure slab on light extraction of GaN LED in positive z direction, where the slab consists of a graphite lattice of pillars. The results show that the PCs slab of graphite arrangement GaN pillars can stop light propagating laterally, but it suppresses light extraction simultaneously. When there is a thick GaN pillar in the middle of the slab, the light extraction of the LED is bigger than that of the ordinary LED due to scattering. In addition, because the tower-like pillars are much realistic in fabricating PCs, we have discussed the effect of the tower-like pillars on light extraction of the GaN LED, the results show that the tower-like pillars have small influence on light extraction, when there are proper angles, the tower-like pillars benefit the light extraction. Based on this calculating result, we can use a lower standard in fabricating PCs. When the radius of the middle pillar is $3a + r$, the relative light extraction efficiency is the highest for either the middle pillar PC LED or the tower-like middle pillar PC LED.

References

[1] Krames M R, Amano H, Brown J J and Heremans P L 2002 *IEEE J. Selected Topics in Quantum Electronics* **8** 185

[2] Gu P F, Chen H X, Qin X Y and Liu X 2005 *Acta Phys. Sin.* **54** 773 (in Chinese)

[3] Delbeke D, Bockstaele R, Bienstman P, Baets R and Benisty H 2002 *IEEE J. Selected Topics in Quantum Electronics* **8** 189

[4] Royo P, Stanley R P and Ilegems M 2001 *J. Appl. Phys.* **90** 283

[5] Vuckovic J, Loncar M and Scherer A 2000 *IEEE J. Quantum Electron.* **36** 1131

[6] Xu X M, Peng J C, Li H J, Qu S, Zhao C J and Luo X H 2004 *Acta Phys. Sin.* **53** 286 (in Chinese)

[7] Fan S H, Villeneuve P R, Joannopoulos J D and Schubert E F 1997 *Phys. Rev. Lett.* **78** 3294

[8] Erchak A A, Ripin D J, Fan S H, Rakich P, Joannopoulos J D, Ippen E P, Petrich G S and Kolodziejski L A 2001 *Appl. Phys. Lett.* **78** 563

[9] Rattier M, Krauss T F, Carlin J F, Stanley R, Oesterle U, Houdre R, Smith C J M, De La Rue R M, Benisty H and Weisbuch C 2002 *Opt. Quantum Electron.* **34** 79

[10] Boroditsky M, Vrijen R, Krauss T F, Coccioli R, Bhat R and Yablonovitch E 1999 *J. Lightwave Technol.* **17** 2096

[11] Oder T N, Kim K H, Lin J Y and Jiang H X 2004 *Appl. Phys. Lett.* **84** 466

[12] Chen L and Nurmikko A V 2004 *Appl. Phys. Lett.* **85** 3663

[13] Baba T, Inoshita K, Tanaka H, Yonekura J, Ariga M, Matsutani A, Miyamoto T, Koyama F and Iga K 1999 *J. Lightwave Technol.* **17** 2113

[14] Baba T and Matsuzaki 1996 *J. Appl. Phys.* **35** Part 1 1348

[15] Boroditsky M, Gontijo I, Jackson M, Vrijen R, Yablonovitch E, Krauss T, Cheng C C, Scherer A, Bhat R and Krames M 2000 *Journal of Applied Physics* **87** 3497

[16] Madelung O 1996 *Semiconductors—Basic Data* (Berlin: Springer)