第35卷第6期
2006年6月

光 子 学 报
ACTA PHOTONICA SINICA

Vol. 35 No. 6
June 2006

Influence of Disordered Photonic Crystal on Light Extraction of a Kind of Light-emitting Diode Model*

Li Yan[1,2], Zheng Ruisheng[1], Feng Yuchun[1], Liu Songhao[2], Niu Hanben[1]

1 *Key Laboratory of Optoelectronic Devices and Systems (Shenzhen University), Ministry of Education. Institute of Optoelectronics, Shenzhen University, Shenzhen* 518060

2 *College of Optoelectronic Information of South China Normal University, Guangzhou* 510631

Abstract The effects of cylinder site displacements (site randomness) and cylinder radius variations (size randomness) on photonic band gaps of the photonic crystals, which consist of a graphite lattice of dielectric cylinders, have been discussed by the Order-N method with a supercell technique. The numerical result shows that the variation of the photonic band gaps for the E polarization mode is far more sensitive to disorders with a size randomness than with a site randomness. Furthermore, the influence of the disorder on light extraction of a GaN light-emitting diodes model, which has a disordered photonic crystal slab, has been investigated by three-dimensional finite-difference time-domain method. The numerical result shows that the influence of the disorder is small on light extraction of this light-emitting diodes model, and the influence is random.

Keywords Disordered photonic crystal; Photonic band gaps; Light-emitting diodes; GaN

CLCN O482.3; TN312+.8 **Document Code** A

0 Introduction

Light-emitting diodes (LEDs) have the potential to be low-cost and long lifetime solid-state lighting source for many applications[1~3]. But there is a significant discrepancy between the high internal efficiency and poor output efficiency of LEDs. Most of the generated light is never emitted from LEDs, but is lost to guided modes within the high dielectric material. Since it has been suggested that the photonic crystal (PC) structure can enhance light extraction efficiency, a rapid progress was made in enhancement of light extraction by two dimensional PC from GaAs/GaAlAs or InGaAsP/InP LED[4,5]. Recently, there is a breakthrough in nanofabrication of PCs on the blue/green and ultraviolet LEDs based on III-nitride wide band gap semiconductors, which are crucial for many important applications[6].

In the fabrication of PCs, nonuniformities inevitably occur, especially when the crystals are of micrometer and submicrometer sizes, such as, the deviation of crystal cylinders (holes) from their periodic sites, fluctuation of cylinders (holes) radius, etc. These disorders may affect the properties of PCs significantly. So the disordered PCs have also been extensively discussed[7~9].

Most of the research works involve 2D PC consisting of a triangular lattice of holes. In this paper, it is given a 2D PC consisting of a graphite lattice of cylinders and a GaN LED model with a graphite-arrangement pillars slab, where this kind of PCs structure is expected to get photonic band gaps (PBGs) easily for small refractive index material and minimize the surface recombination. The influence of the disorder on the PBGs of the PCs and on light extraction of the PC LED model has been discussed.

1 Effects of the size randomness and the site randomness on PBGs

Fig. 1 shows schematic plots of a unit cell of the PCs, which consists of a graphite lattice of dielectric cylinders in air. The side length of the unit cell is 1.732a, the radius of cylinders in the unit cell is $r_0 = 0.3\,a$. a is the lattice constant of the graphite lattice . The white and black color

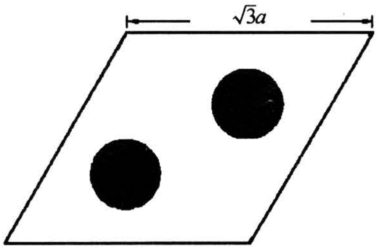


Fig. 1 The unit cell of the photonic crystal with a graphitelattice of dielectric cylinders

---

* Supported by the National Natural Science Foundation of China (No. 60376003), Guangdong Province's Keystone Breakthrough Program (No. ZB2003A07) and Shen Zhen Science and technology Program (Grant No. 2002-K1-65)

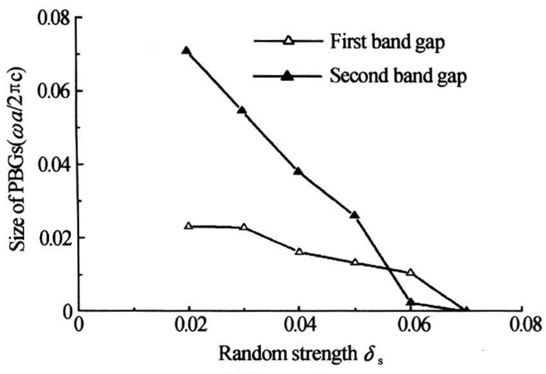
Tel: 0755-26733319 Email: g_yjsh@szu.edu.cn

Received date: 2005-07-06

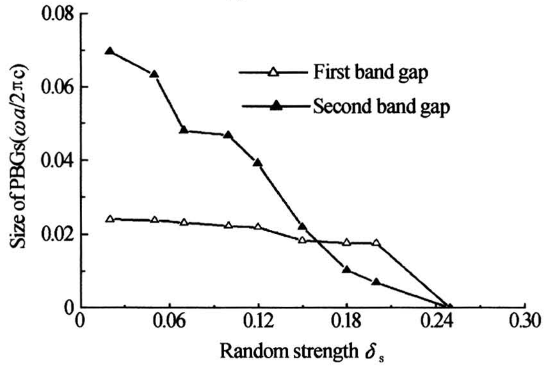
represent dielectric materials with permittivity[10] $\varepsilon_1=1$ and $\varepsilon_2=5.8$, respectively.

When the size and the position of the cylinders have a random fluctuation, a supercell technique will be used to compute the variation of the size of the PBGs. In this calculation, the supercell consists of 10 × 10 unit cells shown in Fig. 1. The geometry structure of the supercell is still a parallelogram. The disordered PCs are described by the random strength[7]. For an original periodic crystal with a lattice constant of a and the cylinders radius of r_0, in the size randomness, the cylinders are arrayed in the original lattice sites, while the radius of the jth cylinder is given by $r_j=r_0+\delta_j a$, where δ_j is a random variable uniformly distributed over $|\delta_j|\leqslant\delta_s$. Here, δ_s is the random strength of the disordered system. For the disordered crystal with a site randomness of strength δ_s, every cylinder keeps its radius r_0, while the x and y components of the position of the jth cylinder in the disordered crystal is given by $x=x_j+\delta_j a$ and $y=y_j+\delta_j a$. The variation of PBGs is computed by the Order-N method[11]. In the computation, it uses $\omega a/(2\pi c)$ as the frequency unit, where ω is the angular frequency and c is the free-space light speed.

The size of the E polarization PBGs for the disordered PCs varied with the random strength δ_s is shown in Fig. 2, where Fig. 2 (a) is for the size randomness while Fig. 2 (b) for the site randomness. The curve —△— and the curve —▲— in the figures show the size of the first and second E polarization PBG, respectively.



(a)Size randomnes



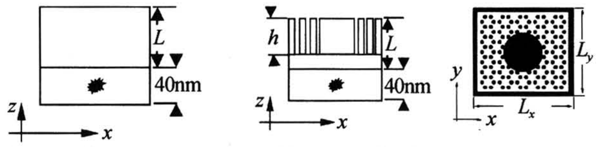
(b)Site randomnes

Fig. 2 The size of the E polarization PBGs varies with the random strength δ_s

In Fig. 2, it can be seen that the size of the second PBG is much bigger than that of the first PBG. With increasing the random strength, all the sizes of the PBGs are reducing. Comparing Fig. 2 (a) with Fig. 2 (b), when the random strength reaches 0.07 in Fig. 2 (a), the first and second PBGs are closed up, however, until the random strength reaches 0.25 in Fig. 2 (b), the first and second PBGs don't close up yet. This result denotes that the variation of the PBGs for the E polarization mode of the PCs is far more sensitive to disorders with a size variation than with a site displacement.

2 Influence of disorder PCs on light extraction of GaN PC LEDs

Fig. 3 (a) shows a simplified model of an ordinary LED with uniform GaN material cladding. Fig. 3 (b) shows a simplified model of a middle pillar PC LED, where a graphite lattice of dielectric cylinders with a thick pillar in the middle etches in GaN cladding. If the cylinders, which surround the thick middle pillar, have fluctuation of radius or deviation from their periodic sites, it is called the disordered middle pillar PC LED. The parameters for two models are $L_x=5276.7$ nm, $L_y=4737.0$ nm, $a=298.1$ nm, $r_0=89.4$ nm, the thicknesses of the active region are all 40 nm. The permittivity of the semiconductor in cladding layer and active region are 5.8, 5.4, respectively[10]. The radius of the thick pillar is $R=m\times a+r_0$, where m is a positive fig. The notations L and h in Fig. 3 denote the thickness of the LED cladding and the height of the dielectric cylinders, respectively. Here, it only shows the X-Z plane of the ordinary LED in Fig. 3(a).

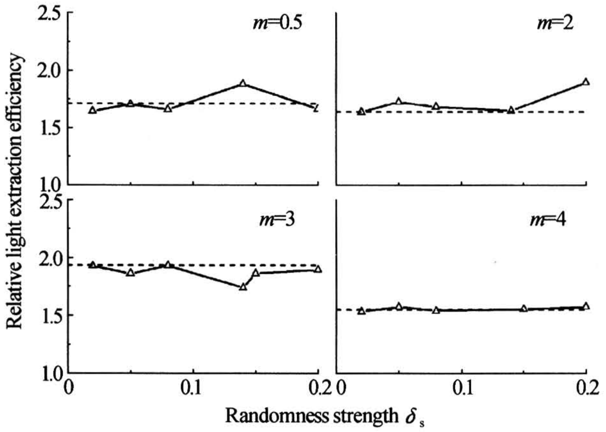


(a)The ordinary LED model (b)The middle pillar PC LED model

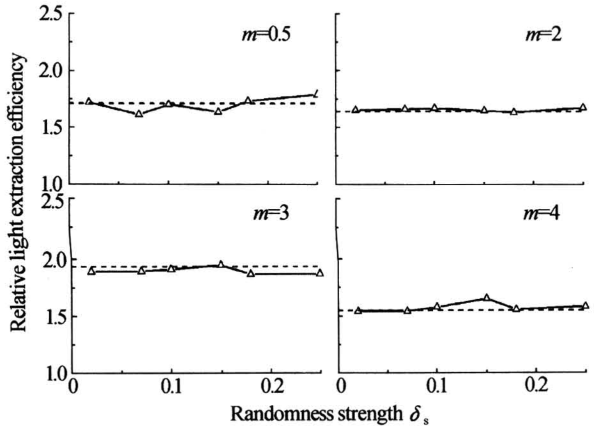
Fig. 3 The simplified LED mode

When a point dipole source with emission spectrum from 455 nm to 485 nm is in the middle of the active region, where the emission spectrum is in the second E polarization PBG produced by the original PCs, one can calculate the output energy of the LED in a fixed plane which is above the LED and perpendicular to z axis by three dimensional finite-difference time-domain method. In the computation, the uniaxial perfectly matched layer, which surrounds the model, is employed as the absorbing boundary condition. After the optical output energy of the middle pillar PC LED is divided by that of the ordinary LED, the relative light extraction efficiency (RLEE) of the middle pillar PC LED can be given. The RLEE of the disordered middle pillar PC LED can also be given by the same way. Thus, comparing the RLEE of the middle pillar PC LED with that of the disordered one, the influence of disorder on light extraction of the middle pillar PC LEDs can be given.

Choose $L=520$ nm and $h=480$ nm, the RLEE varied with the random strength are shown in Fig . 4 . In Fig. 4, the curves —△— show the RLEE of the disordered middle pillar PC LED, and the dash lines show their counterparted without disorder, with the radius of the middle pillar $m=0.5$, 2, 3, 4, respectively. From Fig. 4 it can be seen that all the RLEE are bigger than 1. When $m=3$, the RLEE is the biggest whether for the disordered model or without disorder one.



(a)Size randomness



(b)Site randomness

Fig. 4 The relative light extraction efficiency varies with the random strength

Comparing the RLEE of the disordered middle pillar PC LED with that of without disorder, namely, comparing the curve —△— with the corresponding dash line, it can be found that the curve —△— varies randomly around with the dash line due to the disorders. This result denotes that the influence of the disordered PCs to light extraction of this LED model is random. When defining the ratio of offset of the RLEE as $\gamma=(\eta_{\mathrm{rest}}-\eta_m)/\eta_m$, where η_m is the RLEE of the middle pillar PC LED, η_{rest} is the greatest RLEE of the disordered model relative to η_m. It can be found in Fig. 4 (a) that the $|\gamma|$ brought by the size randomness are no more than 11% in most cases, and the $|\gamma|$ in Fig. 4 (b) brought by the site randomness are no more than 6% in most cases. This result denotes that the variation of the RLEE brought by the size randomness is bigger than that by the site randomness. This result is coincident with the situation that the variation of the PBGs is much sensitive to disorders with a size randomness than with a site randomness.

One remarkable thing to note is the relation between the RLEE of the disordered middle pillar PC LED and the PBGs. From Fig. 2(a), one can see that when the random strength δ_s for the size randomness is greater than 0. 07, the first and second E polarization PBG are closed up. But from Fig. 4 (a), one can find that the RLEE doesn't change obviously even though the random strength δ_s is greater than 0. 07. In the same fashion, from Fig. 2 (b), it can be seen that when the random strength δ_s for the site randomness is greater than 0. 25, the first and second E polarization PBG are closed up. But from Fig. 4(b), one can also find that the RLEE doesn't change obviously even though the random strength δ_s is close to 0. 25. This phenomenon denotes that although PBGs can be used to block the guided mode within the high dielectric material of LEDs, so as to enhance the light extraction of LEDs, but the influence of the PBG is limited in this LED model, therefore, the effect of the disordered PCs on light extraction of this LED model is limited and random.

From Fig. 4 one can also see that with increasing the radius of the middle pillar, the variation of the RLEE is reducing, namely, the curve that the RLEE varies with random strength trends to a straight line. The reasons are that, with increasing m, the disordered middle pillar PC

LED trends to an ordinary LED, at the same time, the decrease of the amount of the PC cylinders makes that the disorder has smaller influence to the RLEE.

3 Conclusion

It has discussed the effects of the fluctuation of the cylinders radius and the cylinders site random displacement on PBGs for the PCs, which consists of a graphite lattice of dielectric cylinders in air. The numerical result shows that the variation of the PBGs for the E polarization mode is far more sensitive to disorders with a size randomness than with a site randomness. Furthermore, it has discussed the influence of disordered PC to light extraction of a GaN LEDs model. The disordered PCs slab, where the original PCs consist of a graphite lattice of dielectric cylinders with a thick pillar in the middle, is etched in the cladding of the GaN LEDs model. The numerical result shows that the disorder has smaller influence on the light extraction of this LED model, and the influence is random.

Reference

1 Lin Y F, Liu X D, Liu X, *et al*. The analysis of voxel attributes in three-dimensional volumetric display system based on the rotation of a two-dimensional display panel. *Acta Photonica Sinica*, 2004, **33**(4): 476～480

2 Liu J, Liu C Y, Yang Y Y, *et al*. The novel light emitting diode (LED) sources system for animal cell or tissue culture. *Acta Photonica Sinica*, 2004, **33**(2): 151～154

3 Wang Y D, Zhong H J, Li Y D. *Acta Photonica Sinica*, 2000, **29**(Z01): 357～360

4 Fan S H, Villeneuve P R, Joannopoulos J D, *et al*. High extraction efficiency of spontaneous emission from slabs of photonic crystals. *Physical Review Letters*, 1997, **78**(17): 3294～3297

5 Boroditsky M, Krauss T F, Coccioli R, *et al*. Light extraction from optically pumped light-emitting diode by thin-slab photonic crystals. *Applied Physics Letters*, 1999, **75**(8): 1036～1038

6 Oder T N, Kim K H, Lin J Y, *et al*. III-nitride blue and ultraviolet photonic crystal light emitting diodes. *Applied Physics Letters*, 2004, **84**(4): 466～468

7 Li Z Y, Zhang X D, Zhang X Q. Disordered photonic crystals understood by a perturbation formalism. *Physical Review B*, 2000, **61**(23): 15738～15748

8 Hughes S, Ramunno L, Young J F, *et al*. Extrinsic optical scattering loss in photonic crystal waveguides: role of fabrication disorder and photon Group velocity. *Physical Review Letters*, 2005, **94**(3): 033903/1～4

9 Frei W R, Johnson H T. Finite-element analysis of disorder effects in photonic crystals. *Phys Rev B*, 2004, **70**(16): 165116/1～11

10 Madelung O. Semiconductors-Basic Data. Berlin: Springer Press, 1996

11 Ward A J, Pendry J B. A program for calculating photonic band structures, Green′s functions and transmission/reflection coefficients using a non-orthogonal FDTD method. *Computer Physics Communications*, 2000, **128**(3): 590～621

一种发光二极管模型中无序光子晶体对光输出影响的研究

李　岩[1,2]　郑瑞生[1]　冯玉春[1]　刘颂豪[2]　牛憨笨[1]

(1 教育部光电子设备与系统重点实验室(深圳大学),深圳大学光电子学研究所,深圳 518060)

(2 华南师范大学信息光电子科技学院,广州 510631)

收稿日期:2005-07-06

摘　要　利用 Order-N 算法及超晶格技术讨论了位置无序及尺寸无序对石墨点阵柱状光子晶体光子带隙的影响．计算结果表明,对于电场偏振模,光子带隙对尺寸无序更加敏感．在此基础上,利用三维时域有限差分方法进一步讨论了无序光子晶体对石墨点阵柱状中心柱光子晶体 GaN 发光二极管模型光输出效率的影响．计算结果表明,无序对这种光子晶体发光二极管模型光输出效率的影响较小,且这种影响也是随机的

关键词　无序光子晶体;光子带隙;发光二极管;氮化镓

Li Yan　was born in October of 1967. He got his B. S. (Physics) and M. S. (Physics) degree from Northwest University in 1989 and in 1996, respectively. He got his PH. D degree from Xi′an Institute of Optics & Precision Mechanics of CAS in 2004. His current research interest is the photonic crystal and semiconductor optical amplifier.