Theoretical analysis of enhanced light output from a GaN light emitting diode with an embedded photonic crystal*

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Abstract: The enhancement of the light output of an embedded photonic crystal light emitting diode is investigated based on the finite-difference time-domain modeling. The embedded photonic crystal (PC) lattice type, multi-layer embedded PC, distance between the multiple quantum well and the embedded PC are studied. It is found that the embedded one dimensional PC can act as well as embedded two dimensional PCs. The emitted light flux in the up direction can be increased by a new kind of multi-layer embedded PC. Also, we show that the light output in the up direction for the LED with both surfaces and embedded PC could be as high as five times that of a conventional LED.

Key words: photonic crystal; light emitting diode; finite-difference time-domain modeling
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1. Introduction

GaN based light emitting diodes (LED) have not only been widely used for full color displays and liquid display back lighting, but are also promising for general lighting with the advantages of long life, small size and low energy consumption[1]. With the development of growth technology, the internal quantum efficiency of the LED has been improved to about 80%[2]. Low extract efficiency, which is only about 4% because of the total internal reflection at the interface between GaN and air, is still an important factor which limits the performance of the high power LED.

Photonic crystals (PCs) have been investigated in LEDs to improve the extract efficiency for several years[3]. Normally, PCs are fabricated on the surface of the LEDs[3−6]. Although PCs can improve the extract efficiency of LEDs to some extent, as David pointed out[7], the real GaN is 3–5 μm thick, and behaves like a multi-mode waveguide. Low order modes are located in the middle of the waveguide, which is badly coupled with the PCs upwards or downwards. David[7] and Matioli[8] have experimentally demonstrated that light output is improved with the help of a one layer PC embedded in the GaN epitaxial layer.

In this paper, a new kind of multi-layer embedded PC-LED is proposed and different kinds of embedded PC-LED are investigated in detail. We numerically analyze the emitted flux in the up direction as a function of embedded PC lattice types, embedded PC layer numbers and the distance from the multiple quantum well (MQW) layer to the embedded PC layer. In the end, we show that the improved emitted flux in the up direction is as high as 5 fold in the LED around normalized frequency 1 with both surface and embedded PCs. These results are helpful in the fabrication of GaN embedded PC-LEDs.

2. Simulation methods

Finite-difference time-domain modeling (FDTD) has been widely employed to investigate the light extraction efficiency in the PC-LED[9−11]. In this paper, we use FDTD software Meep, developed by MIT, to investigate the output power of different kinds of embedded PC-LED with perfectly matched layers. To save the simulation time, we neglect the sapphire substrate in the simulation. The simulation domain is $7a \times 7a$ in plane, $10a$ in the vertical direction, where a is the lattice constant of the embedded PC. The refractive index of GaN is 2.5. A Gaussian source is located in the middle of the MQW layer, whose normalized frequency a/λ is centered at 1 and where the bandwidth is 1. The wavelength λ is set to 500 nm. In the simulation, the typical thickness of P-GaN, MQW and GaN (including N-GaN and GaN buffer) is taken as 200 nm, 100 nm, 3 μm, which is $0.4a$, $0.2a$, $6a$, respectively. The term relative enhanced fold R, which is defined as the ratio of the emitted flux in the up direction of the PCLED to the conventional LED, is used in the following simulation to make comparison.

3. Principles of embedded photonic crystal LED to improve light output

First, we studied why the embedded PC could improve the output light in the up direction. Figure 1 illustrates the effects of the embedded PC-LED by the schematic drawing of the cross section of LED. It shows that the PC layer has a relatively lower effective refractive index, so the thin LED layer on the top behaves like a slab waveguide. As David pointed out[2], a thick top layer supports several guided modes, but a thinner top layer supports fewer guided modes. With the help of the lateral epitaxial overgrowth, it is possible to grow a very thin LED layer on the embedded PC[2]. A too thin top layer could only support a very weakly guided mode and most of the energy would be leaked to air, which is theoretically demonstrated in Fig. 2. The relative enhanced fold R of three structures with different distances d from the MQW to the PC layer is shown. As d increases, the R decreases, which agrees with David's ex-

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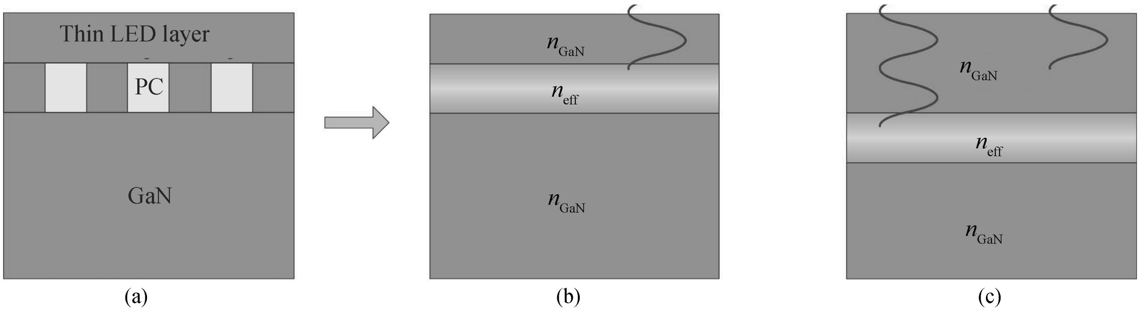

Fig. 1. (a) Schematic drawing of a cross section of the embedded PCLED. (b) Schematic drawing of the embedded low refractive index layer, which is equivalent to the embedded PC. The top thin LED layer is as thin as a single mode waveguide. (c) Schematic drawing of the embedded low refractive index layer, which is equivalent to the embedded PC. The top thin LED layer is as thick as a multi mode waveguide.

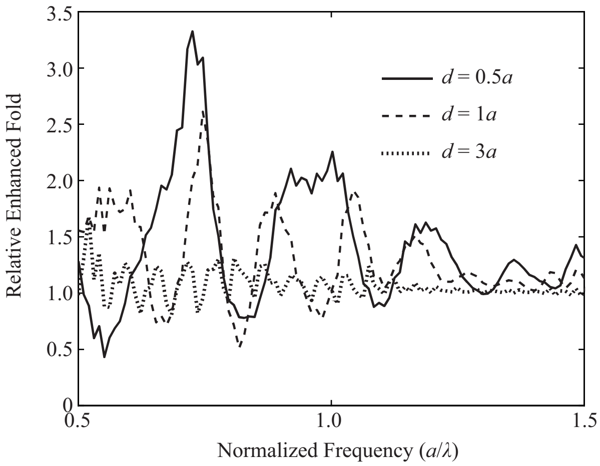

Fig. 2. A comparison of R of LEDs with different thicknesses d from MQW to embedded PC.

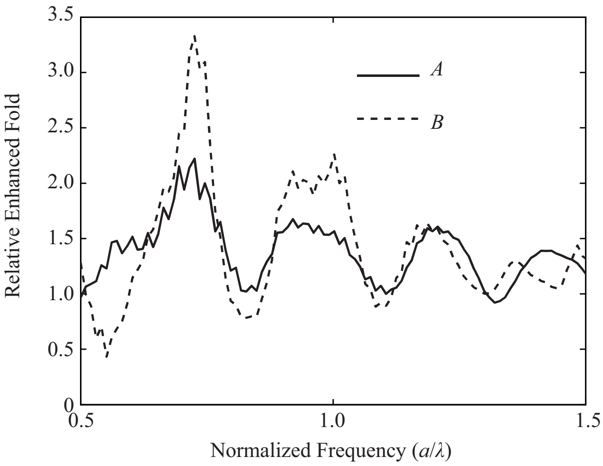

Fig. 3. A comparison of R of two structures. (A) Thin LED. (B) E1DPC-LED. The thickness of the top thin LED layer on the E1DPC is the same as the thickness of the thin LED in (A).

perimental results[2]. Also, as shown in Fig. 3, we calculate the relative enhanced fold R of two structures in comparison with a conventional LED. The thickness of GaN, MQW and P-GaN is $6a$, $0.2a$, $0.4a$, respectively. To understand the scattering of the PC layer: (A) a thin LED, the thickness of GaN, MQW and P-GaN is separately $0.5a$, $0.2a$ and $0.4a$; (B) an embedded one dimensional photonic crystal (E1DPC) LED, the distance from the PC layer to MQW layer is $0.5a$, that is to say, the thin LED layer on the embedded PC has the same thickness as the thin LED in (A). The minor peaks in Fig. 3 are due to the Fabry–Perot interference. The output of the E1DPC-LED is larger than the thin LED, which means that not only the thin slab gives more opportunity for the light to leaky, but also the PC pattern scatters the light in different directions to escape from the GaN waveguide.

4. Simulation results of different embedded PCLEDs

Figure 4 presents six different configurations of LEDs: (a) is a conventional LED; (b) is a conventional surface PC-LED; (c) is an embedded square lattice PC-LED; (d) is an E1DPC-LED, with groove width $w = 0.8a$; (e) is an embedded two layer 1DPC-LED, with air hole diameter $d = 0.8a$; (f) is an LED with both surface and embedded PCs. The embedded PC could be realized in the following process[7]: after the deposition of the GaN epitaxial layer, the PC pattern is realized by electron beam exposure and ICP etching; then N-GaN, the active region and P-GaN are grown on the top of the pattern by later epitaxial overgrowth. For the two-layer embedded PC, a thin GaN epitaxial layer is deposited by later epitaxial overgrowth, and another PC pattern is realized on the thin epitaxial layer before growing the N-GaN.

Figure 5 shows the relative enhanced fold R of configuration (c) and configuration (d). It indicates that the embedded square PC and the E1DPC have nearly the same effects on the emitted flux in the up direction around normalized frequency 1 (λ = 500 nm). This could be explained as follows: although the E2DPC and the E1DPC have different patterns in plane, they have similar filling factors, which means they have nearly the same scattering ability in the vertical direction.

5. Simulation results of different embedded PCLEDs

As it is difficult to improve the efficiency by changing the pattern in plane, we propose a multi-layer E1DPC, shown in Fig. 4(e), in which the dielectric rods of the neighbor layer are mutually perpendicular, to enhance the light scattering in

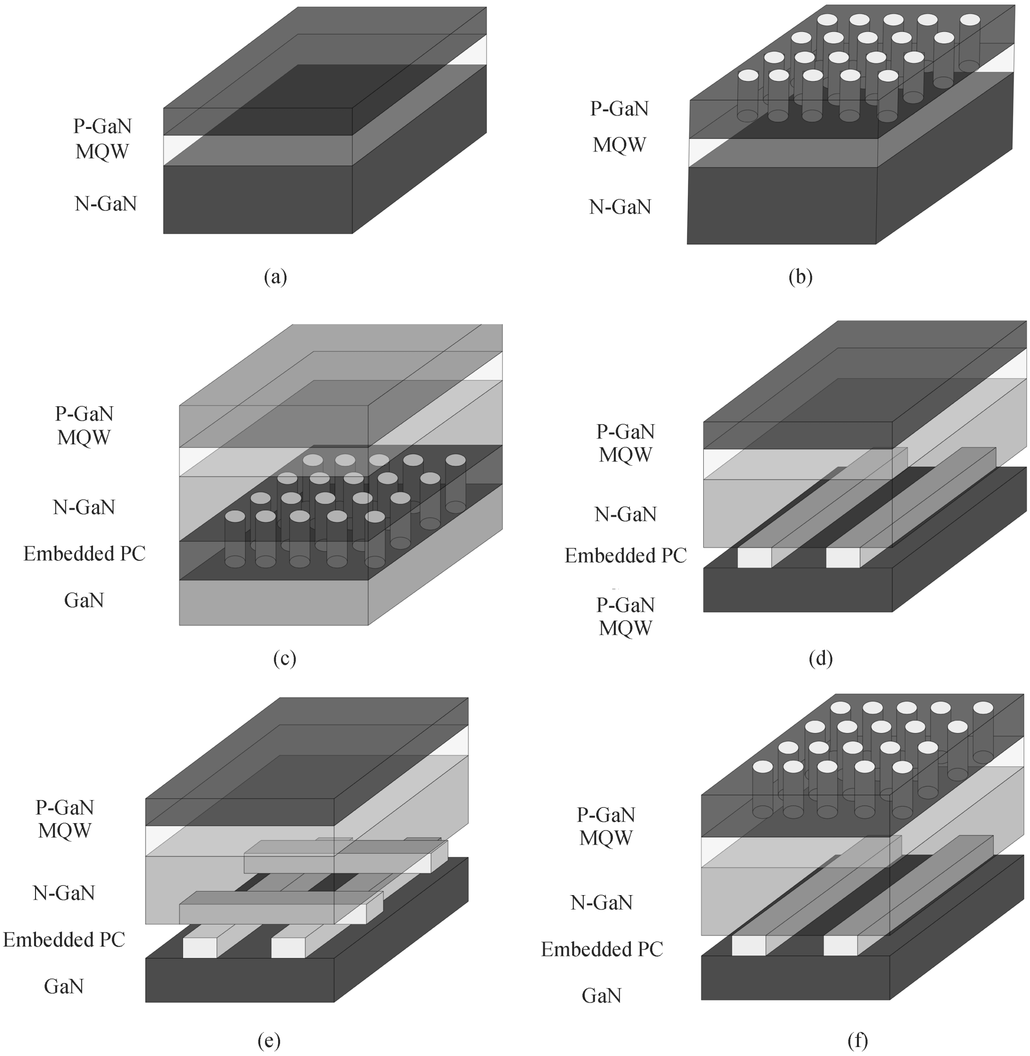

Fig. 4. Schematic drawing of different LED configurations.

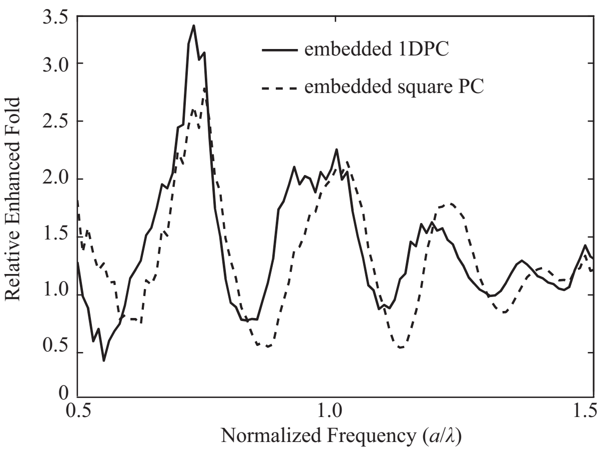

Fig. 5. A comparison of R of configuration (c): embedded square PC and configuration (d): E1DPC.

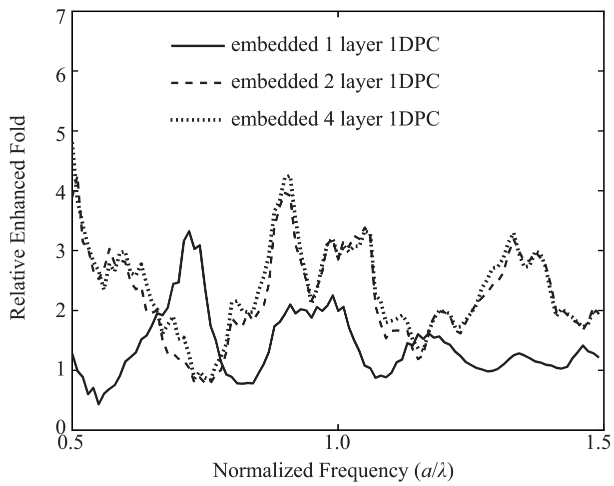

Fig. 6. A comparison of R of multi layer embedded photonic crystals.

the vertical direction and thus improve the light output. Figure 6 shows the R of LEDs with different numbers of embedded PCs. It is obvious that a one layer embedded photonic crystal can double the light extract efficiency. R is much higher as the embedded layer number is increased to two. This is because the dielectric rods of the second layer are placed in a different direction compared to the first layer. The different refractive index can scatter more, light which the first layer misses, as

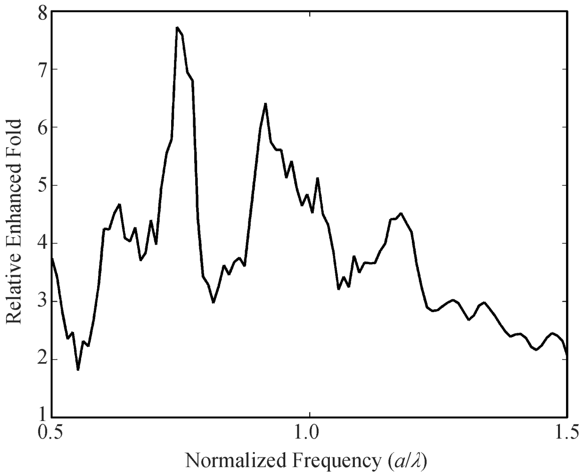

Fig. 8. *R* of configuration (f): an LED with both surface and embedded PCs.

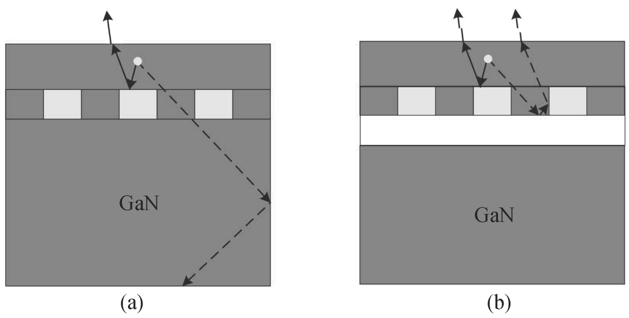

Fig. 7. Schematic drawing of light scattering in (a) a one-layer E1DPC and (b) a two-layer E1DPC.

shown in Fig. 7. But as the embedded layer is increased again, the added layers play the same role as the first or second one, so the light output cannot increase.

Figure 8 shows the R of configuration (f), the LED with both surface and embedded photonic crystals. For the part around frequency 1 (λ = 500 nm), the enhanced flux in the up direction is five times that of the conventional LED. This indicates that it is possible to increase the light output significantly with both surface and embedded photonic crystals.

6. Conclusion

In summary, the principles of enhancement of the embedded PCs are investigated. Both the leaky mode effect in the thin slab and the scattering of the embedded PC pattern play a great part in the extraction of the light. Based on these principles, several different structures, such as embedded PC lattice types, embedded multi-layer PCs, LEDs with both surfaces and embedded PCs were analyzed. The simulation results indicate that an embedded 1DPC can act as well as a 2DPC and it is possible to improve the light output with an embedded multi 1DPC layer which can enhance the scattering of the light in the vertical direction. Also, they show that the light output in the up direction for an LED with both surface and embedded PCs could be as much as five times that of a conventional LED. This study will be very useful in the fabrication of embedded PCLEDs.

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