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Optimization design of holographic photonic crystal for improved light extraction efficiency of GaN LED

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ABSTRACT

A study on improved light extraction efficiency (LEE) of LEDs with photonic crystals formed by holographic lithography (HL) was present. The propagation and extraction of light in LEDs were simulated using FDTD method for LED structures with top HL PC and embedded HL PC respectively. By optimizing the design parameters of the HL PC, the best value of 88.3% enhancement of LEE were obtained. Result also revealed that the scattering and diffraction of photonic lattices play a more important role in the increased light extraction of HL PC LEDs than photonic band gap effects.

1. Introduction

GaN-based LEDs play an important role recently in many fields, since they can be widely used in medical operations, traffic lights, mobile devices, flat panel displays, general lighting, and many other fields. However, external quantum efficiency of LEDs is still not high enough to realize LED-based solid state lighting, even the internal quantum efficiency is relatively high [1,2]. The external quantum efficiency is mainly limited by low light extraction efficiency (LEE). And one of the primary reasons for low LEE is the total reflection at the interface of the semiconductor and the outer medium. In order to improve the LEE, a number of approaches have been applied, such as LEDs grown over patterned sapphire substrates, shaped LED ships, photon recycling, coupling to surface plasmon modes [3], surface roughening [4] and photonic crystals [5–8]. The aims of surface roughening and photonic crystals

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used in LEDs are both to avoid total internal reflection and prevent the lateral propagation of light-waveguide effect. Though the randomizing light reflection at roughed surface destroyed the light propagation in straight paths and made light escaped from the LEDs through the critical cone, yet it provides little control on the direction of the light emission, which result in Lambertian radiation patterns. Compared with surface roughening method, PCs used in LEDs have been researched in many works and demonstrated to provide superior light extraction and directional light emissions. Most studies used 2-D PCs with regular circle columns formed by RIE or electron beam lithography. Since the holographic lithography (HL) approach for PCs fabrication has its unique advantages such as one step recording in large scale [9,10], which made the industrialization of production low cost and easy; And holographic structures usually have irregular atoms or columns, the light propagation properties of PCs are closely related to their specific structures [11,12], we may expect some difference in light extraction behavior between LED structures with regular and holographic photonic crystals.

The fabrication of a PC on the top of an LED degrades the Ohmic contact between the P-GaN and the Ohmic metals, and the low interaction of the PCs with some of the guided modes limits the potential enhancement in extraction efficiency, as these modes are not well diffracted by shallow PCs due to their poor overlap with the etch region [13]. Thus LEDs with embedded PC inserted below the active layer were researched to improve the light extraction efficiency [14]. The embedded PC was fabricated in highly conductive N-GaN cladding, and both p-type and n-type Ohmic performance were not degraded. To fully utilize the advantage of an LED with embedded PC, structures of LEDs with top or embedded PCs are researched. In our study, we used the finite-difference time-domain (FDTD) method to study the light extraction characteristics of LEDs with various PC structures formed by holographic lithography and compared the improved enhancement results. The HL PC structures were introduced in Section 2; the enhancements of light extraction of LEDs with top and embedded HL PCs were analyzed and compared in Section 3, We also analysized the distribution of band gap for HL PC structures using the plane wave method (PWM) [15] with the wave number of 729 in Section 3, to demonstrate the point that the increased light extraction of HL PC LEDs was mainly due to lattices scattering and diffraction more than photonic band gap effects.

2. Structures and FDTD method

In our analysis, there are two steps carried out to fabricate holographic PCs onto the LED structures: (1) Fabricating triangular pattern in photo resist layer using holographic lithography; (2) Transferring the pattern into GaN layer. We used an interference technique of three non-coplanar beams (ITNB) to fabricate the 2-D triangular lattices. The intensity distribution of the holographic structure we adopt can be expressed as [16]

$$I = 3 + \cos\left[\frac{2\pi}{\sqrt{3}a}(2y)\right] + \cos\left[\frac{2\pi}{\sqrt{3}a}\left(\frac{-3}{\sqrt{3}}x + y\right)\right] + \cos\left[\frac{2\pi}{\sqrt{3}a}\left(\frac{-3}{\sqrt{3}}x - y\right)\right]. \quad (1)$$

By controlling the exposure intensity, introducing an intensity threshold I_t, (here $I_t\ \varepsilon(1.5, 6)$ for Eq. (1)), which is a specific value the region with light intensity below it can be removed and the region above it will remain due to photo polymerization for negative photoresist, we may wash away the region of $I < I_t$ to get a normal structure. By filling this structure with a material of high dielectric constant and then removing the template, an inverse structure can be obtained [17]. In our situation, we used the inverse structure which means that the dielectric constant distribution $\varepsilon(x, y)$ of result lattice should be 1 in the region $I(x, y) > I_t$, represented by the white part (air); and 5.86 in the region $I(x,y) < I_t$, represented by black part (GaN with the refractive index of 2.42 at a wavelength of 465 nm). To find the difference between the holographic structures and the regular ones, we chose several lattices shown in Fig. 1 for investigation, here (a), (b) and (c) are the shape and size of the cross section of air columns with different intensity threshold I_t and filling ratio *FR*. The relation between I_t and *FR* of the air column is shown in Fig. 2, to optimize the structures so as to maximize the LEE of LEDs, the effect of different threshold and corresponding *FR* has been examined.

Light extraction characteristics of LEDs with various PC structures formed by holographic lithography were studied using FDTD method with the calculation domain shown in Fig. 3. The simulated LED