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Analysis on the effect of amorphous photonic crystals on light extraction efficiency enhancement for GaN-based thin-film-flip-chip light-emitting diodes

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ABSTRACT

This work showed the liquid-like amorphous photonic crystals (PhCs) can effectively enhance the light extraction efficiency of GaN-based thin-film-flip-chip light-emitting diodes (TFFC LEDs) by the light scattering effect. The finite-difference time-domain (FDTD) method was employed to analyze the light scattering characteristics, numerical studies revealed that the amorphous PhCs can provide omnidirectional scattering, and the transmittances of amorphous PhCs is superior to that of triangular lattice PhCs when the incident angle is in the region $20° \leq \theta \leq 35°$. The influence of p-GaN layer thickness and the amorphous PhCs feature size on the light extraction efficiency was also studied by 3D-FDTD method systematically. For the proposed amorphous PhCs structure in n-GaN layer, the light extraction efficiency is enhanced by a factor of 1.49 as compared to conventional TFFC LEDs, which shows 1.07 times enhancement in comparison to that of triangular lattice PhCs.

1. Introduction

Recently, high performance GaN-based light-emitting diodes (LEDs) have attracted much attention for use in back lighting in large liquid-crystal displays [1] and general lighting [2]. GaN-based LEDs are promising candidates for the application of next-generation general lighting source because their wall-plug efficiency is comparable to conventional fluorescent lamps [3]. In general, the conventional GaN-based LEDs are grown on a sapphire substrate and emit photons from the p-side indium-tin-oxide (ITO) contact. The top-emitting configuration results that a considerable fraction of light is absorbed by the metal contacts, and it still has severe current-crowding and heat-conducting problems at high current injection due to poor thermal conductivity of sapphire. A flip-chip LEDs (FC LEDs) [4,5] configuration that can simultaneously satisfy thermal management and light extraction has been developed. A typical FC LEDs chip is commonly bonded to a submount with high thermal conductivity, and downward-propagating light can be reflected upward by placing a reflector (e.g. silver) on the p-GaN layer [6,7]. Recently, improvements in the nitride light emitters efficiency can also be achieved by thin-film-flip-chip (TFFC) structure, it can be fabricated with the help of FC and laser lift-off (LLO) technique [8,9]. The thickness of TFFC LEDs is ~1 μm [10,11], which can also reduce the number of waveguide modes. This method has been proven to be effective in boosting the optical power.

For illumination applications, GaN-based TFFC LEDs is still necessary to further improve output efficiency. It has been found that efficiency of GaN-based LEDs is mainly limited by external quantum efficiency also known as light extraction efficiency (LEE) [12,13]. The limitation occurred in LEE of GaN-based LEDs is attributed to the large refractive index difference between GaN and air/epoxy resin [14]. Large portion of generated photons in the active region are trapped inside the LEDs device by total internal reflection at the interface. As a result, currently the major challenge associated with light extraction is enhancing the LEE of LEDs. Several approaches have been proposed to extract the light confined in waveguide modes, including surface roughness [15–17], photonic crystals (PhCs) and so on. The rough-surface thin-film LEDs can offer high LEE (~80%) for an encapsulated device [18], but it offers no control over the direction of the emitted light, resulting in a Lambertian far field emission. Using 2D PhCs is an effective approach for improving the LEE of LEDs [19–23]. It has been proven that the bandgap of PhCs can inhibit the light emission into guided modes and hence increasing the LEE of LEDs in which the PhCs penetrates through the entire device [24]. However, this approach is difficult to achieve a high performance working device when the PhCs penetrates through the active layer

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[25]. Most scientific efforts have therefore focused on the diffractive properties of PhCs [25–27]. In this scheme, PhCs can be used to diffract guided modes confined in LEDs into air. In general, the PhCs are located on the surfaces of the LEDs and do not penetrates through the active layer, and current injection is less problematic. Compared with triangular lattice PhCs, the amorphous PhCs can provide omnidirectional scattering.

In this work, the influence of the amorphous PhCs on the LEE of TTFC LEDs was first studied by using the three-dimensional finite difference time domain (3D-FDTD) method [28], the FDTD method has also been used to analyze the efficiency of superluminescent diodes [29,30]. The light scattering characteristics of liquid-like amorphous PhCs were analyzed by FDTD method, numerical studies revealed that the liquid-like amorphous PhCs can provide larger LEE than triangular lattice PhCs. The influence of p-GaN layer thickness and the amorphous PhCs feature size on LEE was also systematically studied by 3D-FDTD method.

2. Numerical model and numerical method

A schematic diagram of the TFFC LEDs structure is shown in the Fig. 1(a). The typical TFFC LEDs is multi-layer planer structure with a silver reflector, a P-GaN layer, a multiple quantum wells (MQWs) layer and an N-GaN layer. The liquid-like amorphous PhCs is located on the top surface of the N-GaN layer. Our liquid-like amorphous PhCs are different from that quasi PhCs [31–33] and Archimedean PhCs [34], which is lack of symmetry. We distributed the cylindrical air holes as a snapshot of atoms in a liquid by the use of the Metropolis Monte Carlo method [35] with a repulsive interatomic force. Fig. 1(b) shows the refractive index distribution of the amorphous PhCs, which has only short-range order but no long-range order. And the average distance of adjacent air holes is equal to a. As illustrated in Fig. 1(c), the modulus of the Fourier transform of amorphous PhCs shows an isotropic ring pattern, which has no Bragg peaks [36].

Next, the 3-D FDTD method was employed to calculate the LEE of the TFFC LEDs. The thickness of total GaN layer included the P-GaN layer, MQWs layer and N-GaN layer was set to 700 nm, the thickness of silver layer was set as 200 nm, and the lateral dimension of the computational domain was set as 8 μm in the simulation. The complex refractive index of GaN material was assumed to $2.5 + 0.0013i$ at the wavelength of 460 nm [37]. In addition, the homogeneous mesh was used during the simulation, and the grid was set to $\Delta x = \Delta y = \Delta z = 10$ nm. Furthermore, a perfectly matched layer (PML) enclosing the entire simulation domain was used to absorb outgoing waves.

It has been proven that the electron-hole-recombination can classically be represented by a dipole. The conventional InGaN/GaN quantum well grows along the *c*-axis (*z* direction), and it is polar and can be modeled by a uniform distribution x and y polarization orientation dipoles placed in the MQWs plane that is perpendicular to the growing axis (z direction). In the *z* direction, the dipole source is located in the middle of the MQWs layer. In the *x*–*y* plane, the typical locations of the dipole sources in the PhCs or amorphous PhCs TFFC LEDs are shown in Fig. 2. And thus, there are 6 kinds of dipole source states in the 3D-FDTD simulation, the result of Pan [38] proved that that the accurate averaged efficiency can be obtained by these typical dipole sources. Nevertheless, the FDTD intrinsically is a coherent simulation method. In order to avoid generating an unphysical coherent effect between different dipole sources, only one dipole source was located in the MQWs plane once in the simulation. And the center wavelength of the dipole source in the FDTD simulation is 460 nm.

In the FDTD simulation, the LEE of one dipole can be calculated from the power flux extracted from the LEDs with respect to the overall emitted power from the dipole source

$$\eta_{extr} = P_{out}/P_{source} \quad (1)$$

where P_{out} is the power flow integrated over a plane just above the LEDs structure and P_{source} the integrated power flux through the closed surface enclosing the source. And thus, the LEE of LEDs can be obtained by

$$\eta = \frac{\sum_{n=1}^{N} \eta_{extr}^{n}}{N} \quad (2)$$

where N is the number of dipole source states. Finally, the LEE enhancement factor F is defined as follows:

$$F = \eta/\eta_0 \quad (3)$$

where η is the vertical LEE of the LEDs while η_0 is the LEE of planar TFFC LEDs.

3. Numerical analysis and discussion

3.1. Influence of gap distance d between the active layer and reflector on LEE for planar TFFC LEDs

Note that in the TFFC LEDs, the MQWs layer is placed close enough to the silver reflector (∼100 nm). The light emitted from QWs will interfere with the reflected waves, and such interference can modulate the radiation's profile. It is important for high performance TFFC LEDs to choose an appropriate gap distance between the active layer and reflector. To systematically study the interference effect, we first calculated the LEE of the TFFC LEDs structure while varying the positions of the dipole sources from

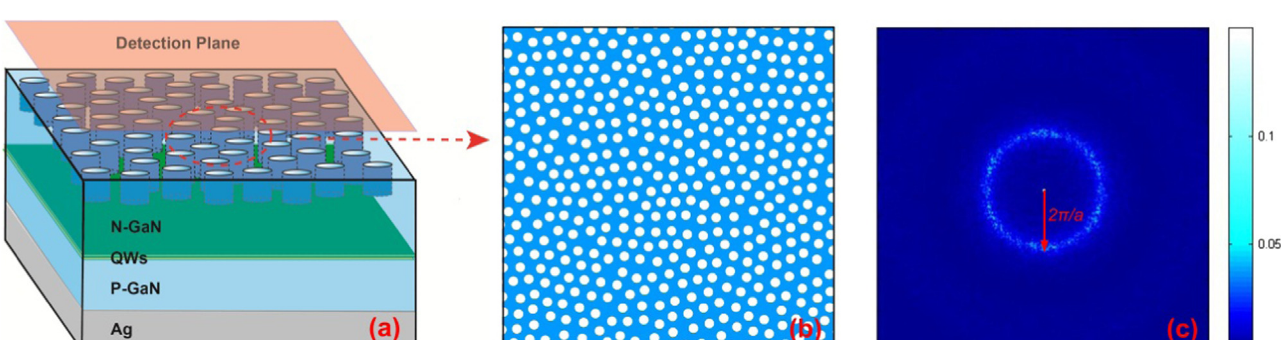

Fig. 1. (a) The schematic diagram of TFFC LEDs structure, The thickness of total GaN layer included the P-GaN layer, MQWs layer and N-GaN layer is 700 nm, the thickness of silver layer is set as 200 nm, and the center wavelength of the dipole source in the FDTD simulation is 460 nm. The detection plane is set as 460 nm away from the emission surface of n-GaN. (b) Schematic view of the transverse cross section in the amorphous PhCs region. (c) Spatial Fourier spectrum of the structure (b).