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<td>Zhang, Q; Li, KH; Choi, HW</td>
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Polarized Emission from InGaN Light-emitting Diode with Self-assembled Opal Coating

Q. Zhang, K.H. Li, Student Member, IEEE and H.W. Choi, Senior Member, IEEE

Abstract—The polarization behaviors of light emission from InGaN light-emitting diodes (LEDs) with nanosphere opal coatings have been studied. The close-packed nanosphere opal films are self-assembled with 220 nm polystyrene nanospheres onto the LEDs. Optical transmission properties of the TE and TM polarized light have been measured as a function of detection angle; an integrated p/s ratio of 2.16 has been obtained at the detection angle of 70°. The polarization of light propagating through the opal film is strongly related to the photonic bandgap of the three-dimensional photonic crystal and is also dependent upon the angle of incidence. Theoretical calculations by the transfer matrix method are found to be consistent with the measured results.

I. INTRODUCTION

PHOTONIC crystals are currently attracting much attention for their possible capabilities to confine, control and route photons on a scale commensurate with nanometer [1]. In these structures, propagation of light is forbidden along certain directions due to diffraction effects in a range of wavelength, known as a stop band. Being a representative three-dimensional (3D) photonic crystal, the opal crystal structure consisting of identical nanometer to micrometer-sized dielectric spheres closely packed into a face-centered cubic lattice (fcc) has been reported to be coupled with linearly polarized light [2]. The complex interaction of polarized light with opal photonic crystal has thus been established. However, there is a lack of study discussing the potential of employing opal coating to generate polarized light from light-emitting diodes (LEDs). Polarized light emission from LEDs is desirable for many applications, such as LCD backlighting [3], anti-glare reading lamps [4] and 3-D projection displays [5]. Since conventionally packaged LEDs are regarded as un-polarized light sources [6], several approaches have been proposed to achieve polarized light emission, including using special reflectors [7] and nano-gratings [8]. Previously, we have demonstrated the use of fluorescent nanosphere opal coating as color conversion agent to produce polychromatic light on InGaN LEDs [9]. Now we attempt to develop the possibility of nanosphere opal coating on LEDs to obtain polarized light emission.

In this paper, we investigate the polarization behaviours of light emitted from blue InGaN LEDs with nanosphere opal coating. A close-packed fcc opal film is fabricated by self-assembly with polystyrene nanospheres on the top surface of LED. Angle- and polarization-resolved transmission spectra are examined to learn the polarization dependence of opal film structure. Theoretical calculation is also conducted to predict the behaviours.

II. EXPERIMENTAL DETAILS

The GaN-based wafers used in this study are grown on c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD), with InGaN/GaN multi-quantum wells emitting blue light at ~450 nm. The LEDs devices with emission area of 200 μm x 500 μm are fabricated using standard micro-fabrication process [10]. The chips diced by ultraviolet (UV) nanosecond laser are then mounted onto TO-header, followed by wire bonding process without encapsulation. Polystyrene nanospheres suspended in deionized water with mean diameter of 220 nm are deposited onto the entire p-mesa surface of LED using a micro-pipette. Mild spin-coating process is applied to establish a well-ordered opal film with uniform thickness and close-packed arrangement. Surface morphology of opal photonic crystal captured by field-emission scanning electron microscopy (FE-SEM) is shown in Fig. 1. Cracks and dislocations can be observed in the opal structures shown in the inset of Fig. 1, which is the intrinsic limitation of self-assembled crystals [11].

To investigate the optical performance of opal photonic crystal, an angular transmission measurement is conducted, as illustrated in the schematic diagram in Fig. 2. The opal-
coat LED mounted horizontally is operated under injection current of 10 mA. An optical fiber mounted together with a rotatable polarizer is rotated with fixed separation of 5 cm. The light component perpendicular and parallel to the incident plane is defined as TE and TM modes respectively. The emitted signals dispersed by an Acton SP2500A 500 nm spectrograph are then detected by a Princeton Instrument PIXIS open-electrode charge-coupled device camera. Emission spectra of both TE and TM modes are collected at 5° steps over an angular range of 70° at room temperature. For comparison, an uncoated LED is measured alongside.

### III. RESULTS AND DISCUSSION

The degree of polarizations is generally defined as the intensity ratio of TM mode to TE mode of transmitted light, so-called p/s ratio. Fig. 3 shows the measured value of p/s ratio under varying detection angles. For the detection angle smaller than 30°, the p/s ratios of both coated and uncoated LEDs are close to unity, meaning that output intensities of both TM and TE modes are similar to each other. The p/s ratio for coated LED increases gradually beyond 30° and reaches the highest value of 2.16 at θ = 70°, while that for uncoated LED just slightly increases. This result implies that emitted light from LED is partially polarized at larger detection angle after propagating through the opal film.

To understand the polarization mechanism of opal film, transmission spectra at θ = 0° and 55° are examined, as plotted in Fig. 4(a) and Fig. 4(b) respectively. It can be seen that both TM and TE modes are nearly the same at θ = 0°, resulting in mild polarization effect. On the other hand, the observation of relatively large transmission difference at θ = 55° greatly enhances the polarization ratio. Moreover, the sudden dips centered at ~500 nm and ~440 nm are detected at θ = 0° and 55° respectively. Since opal film acts as 3D photonic crystal which forbids a certain range of frequencies to propagate for each direction of propagation, the dips shown in the plots can be regarded as forbidden band, namely photonic bandgap. The TE mode at θ = 55° shows a strong coupling to the photonic crystal, resulting in a drastic suppression of the propagating light.

To study the polarization behaviors, a 3D simulation based on transfer matrix method (TMM) is performed and the model of closed-packed opal film with dielectric constant of 2.46 is constructed along the (111) plane. Fig. 5 shows the calculated TE and TM transmissivities together with their p/s ratio at three different incident angles. The normalized frequency mentioned in plots is in the range of 0.57-0.79, corresponding to a wavelength range of 394-546 nm. At normal incident angle φ = 0°, the transmissivities of TE and TM modes are nearly identical, with a 43 nm-width (defined as width at half minimum) pronounced dip between 495 and 538 nm. This result in a near-unity p/s ratio. At φ = 40°, a maximum of p/s ratio at 484 nm is observed, attributed to sudden increase of TM mode transmissivity.

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**Fig. 2.** Schematic diagram of experimental setup, where θ is the detection angle. The device surface plane is shaded yellow, perpendicular to the blue shaded incident plane. Arrows labeled TM and TE indicate the direction of light polarizations while the vector k shows the propagation direction of wave.

**Fig. 3.** Measured p/s ratio as a function of detection angle θ for LEDs with and without an opal coating.

**Fig. 4.** Measured transmissivity of TE and TM modes for LED with opal coating at (c) θ = 0° and (d) θ = 55°.
The TM waves are found to couple to symmetric photonic crystal modes with narrowed stop band. This observation mainly originated from the different symmetries of the opal eigenmodes [12]. The TM waves are found to couple to symmetric photonic crystal modes while the TE waves couple to anti-symmetric modes with respect to the mirror plane [13]. Therefore, as the incident light steer away from the normal direction, stop band of TM wave becomes narrowed dramatically with increasing angle but TE wave maintains a relatively wide band [14]. With a further increase of the incident angle to 55°, two minima are obtained from TE modes, giving rise to two separate maxima of p/s ratio at 409 and 437 nm; this occurs when specular conditions for reflectance are satisfied for both the (111) and (200) planes [15]. The large transmission contrast also promotes the polarization effect, resulting in higher value of p/s ratio. However, only a single peak center at 437 nm is observed from our experiment. This may be attributed to the fact that light emitted from the blue LED at shorter wavelength is too weak to be detected, as well as the imperfect arrangement of the self-assembled opal structure induced by randomly-distributed dislocations weakens the transmission spectra.

IV. CONCLUSION

The polarization dependence of nanosphere opal coating on GaN LED has been studied. Angular transmission spectra have been measured for TE and TM modes. TMM calculation has also been carried out to explain the polarization behavior of light propagating through opal film. This demonstrated the potential of employing nanosphere opal coating to generated polarized light in addition to converting color.

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REFERENCES


