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Polarized light emission from photonic crystal light-emitting diodes

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We have experimentally studied polarization characteristics of the two-dimensional photonic crystal (PhC) light-emitting diodes (LEDs) using an annular structure with square lattice and observed a strong polarization dependence of the lattice constant and orientation of the PhC. The extracted light from the GaN PhC LEDs has P/S ratios of 5.5 ($\sim$85% polarization light) for light propagating in the ΓX direction and 2.1 ($\sim$68% polarization light) for the ΓM direction, respectively. Based on the couple mode theory, the dependence of polarization behaviors on different lattice constant and orientation was found to be in good agreement with theoretical discussion. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2938885]

Light-emitting diodes (LEDs) have become ubiquitous in illumination and signal applications as their efficiency and power level improve. While the improvement of the basic characteristics will benefit the replacement of the conventional light sources, further improvement in other characteristics can bring about unique applications. One notable example is the polarized light emission which is highly desirable for many applications,[1] e.g., backlighting for liquid crystal displays and projectors. Several authors have reported polarized light emission for LED structures grown on nonpolar or semipolar GaN substrates.[2,3] In the present study, we investigate the approach employing photonic crystals (PhCs) which do not require the growth on different orientation of sapphire or GaN substrates nor using specific wafer orientations. PhC has been widely studied in recent years[4–8] for the enhancement of LED efficiency, but polarized light emission using PhC has not been investigated.

Due to valence band intermixing, the side emission of light from quantum well (QW) structure is predominantly polarized in the TE direction (along the wafer plane). The observed polarization ratio has been reported to be as high as 7:1 for GaN/InGaN QWs.[9] For common GaN LED structures grown along the c axis, access to this polarized light can only be gained by measurements taken from the edge of the sample.[10,11] In this work, we use the PhC structure to access the polarized emission and measured their orientation dependence using a especially designed PhC structure to extract the waveguided light. It is found that the PhC can behave as a polarizer to improve the P/S ratio of the extracted electroluminescence (EL) emission. The results of the P/S ratio for light propagating in different lattice orientation were found to be consistent with the results obtained using the PhC Bloch mode coupling theory.

The GaN-based PhC LED samples used in the present work are the same as described before.[7,8] Figure 1 shows the cross-sectional view of the GaN blue PhC LED structure, where an annular PhC region with an inner/outer diameter of 100/200 μm was fabricated. The lattice constants a and hole diameters d of square lattice are 260 nm and 180 nm, respectively, wherein the etch depth is 120 nm, the same as in Ref. 8. The orientation of the PhC is fixed in space and the ratio of hole diameter d to lattice constant a is also fixed to 0.7 to provide the consistent band structure.

The polarization properties of the GaN blue PhC LEDs were measured at room temperature using a scanning optical microscopic system, the same as in Refs. 7 and 8. Figure 2(a) shows EL CCD image for the sample with square lattice constant $a=260$ nm corresponding to $a/\lambda=0.553$. Inset in Fig. 2(a) are the photoluminescence (PL) CCD image and the reduced Brillioun zone. The observed light emission is from the light propagation along the ΓM and ΓX directions as reported before.[8] Furthermore, the extraction enhancement of the PhC LED chips was determined to be above 100% by mounting the dies on TO packages and using an integration sphere with Si photodiode, when compared to the GaN-based LED chips without PhC. A polarizer (Newport, 10LP-VIS-B)

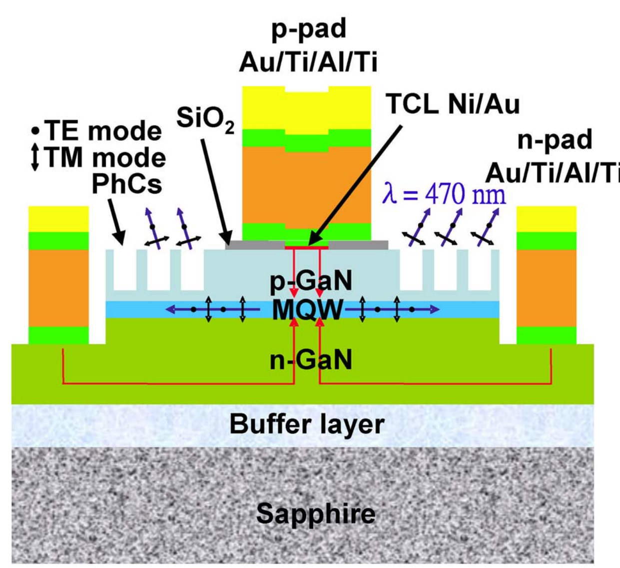

FIG. 1. (Color online) Schematic of the cross section of the annual structure of GaN PhC LED used in this work.

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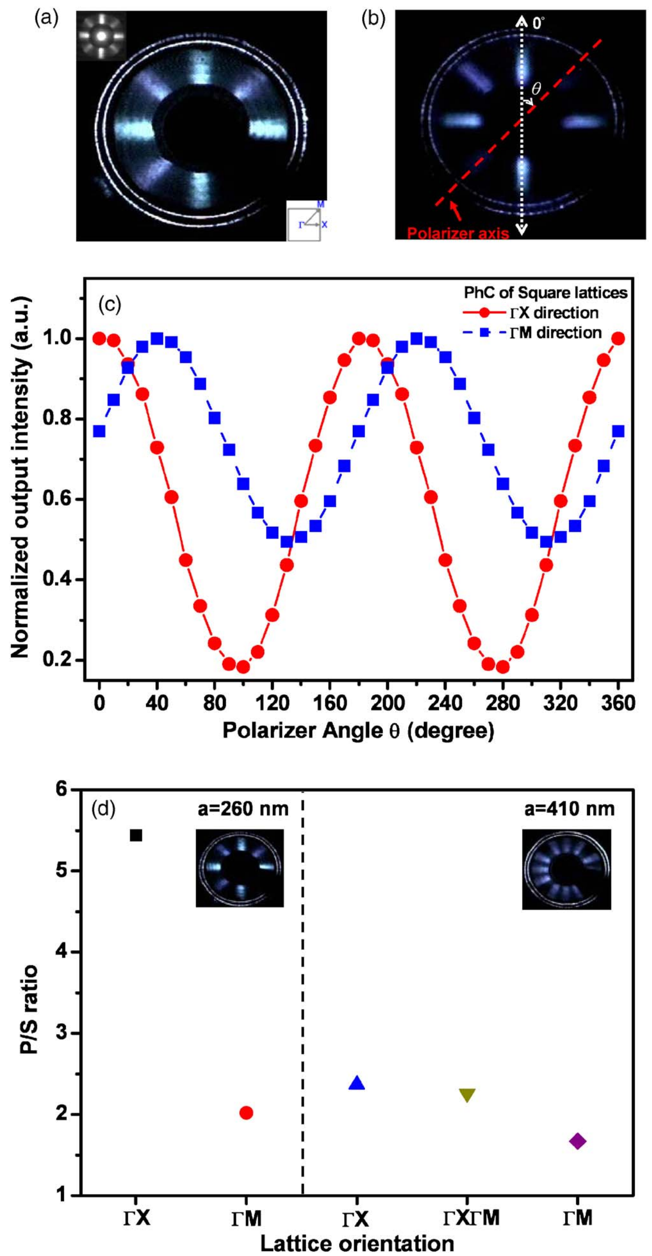

FIG. 2. (Color online) (a) CCD EL images for lattice constants $a=260$ nm, inset of the PL CCD image, and the reduced Brillouin zone. (b) CCD EL images show polarization properties; the red line indicates the polarization axis of the polarizer. (c) Spectrally integrated EL intensity of the GaN PhC LED as a function of polarizer angle θ. (d) P/S ratio of different lattice constant as a function of orientation direction.

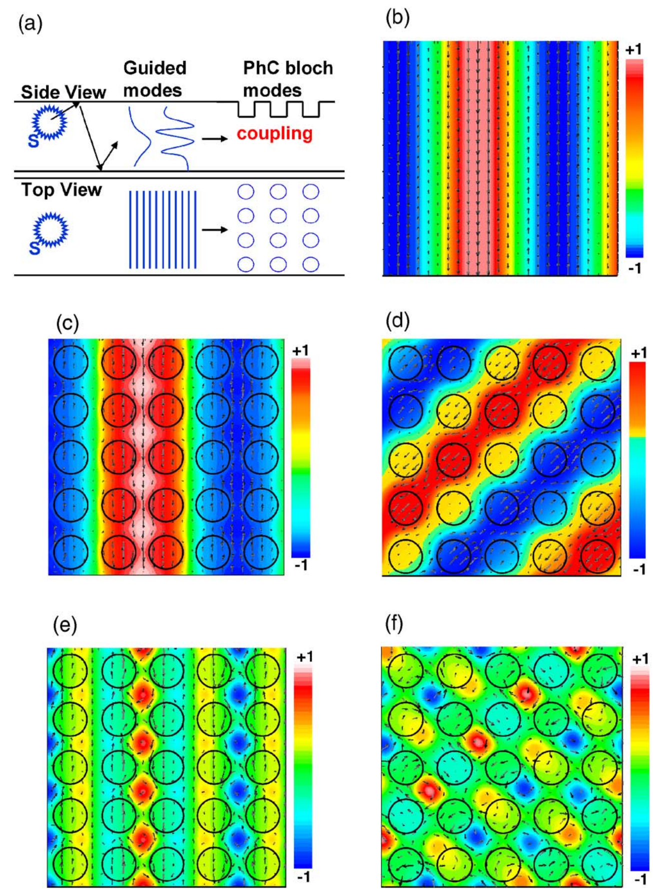

FIG. 3. (Color online) (a) Schematic of the light generating, propagating, and coupling to PhC Bloch modes. Electromagnetic field distributions for a waveguiding mode in the (b) plane slab guide mode and PhC Bloch modes in the (c) ΓX and (d) ΓM directions of the frequency $a/\lambda=0.553$ and in the (e) ΓX and (f) ΓM directions of the frequency $a/\lambda=0.872$, respectively. Arrows indicate the electric field vectors in the plane, and black circles indicate the locations of lattice points.

was placed on the GaN blue PhC LEDs for the EL measurements. Figure 2(b) presents CCD image of room temperature EL for samples biased at a drive current of 20 mA. The red dashed line indicates the polarization axis for the polarizer. Since the polarization direction of the light is perpendicular to its propagation directions, the light propagated in the direction align with the axis of the polarizer will be blocked. The luminescent signal emitted by the sample was collected by the 40× objective lens of the confocal microscope and was transferred to a monochromator for μ-PL measurement through an optical fiber with a core diameter of 600 μm. Figure 2(c) shows the EL intensity as a function of the orientation of the polarizing filter placed between the GaN blue PhC LED and the spectrometer, at a drive current of 20 mA. The intensity at various angles was determined from image taken under the same bias condition. Thus the polarization for different propagation direction can be determined, as shown in Fig. 2(c). It can be seen that there is a periodic variation of the EL intensity with angular orientation of the polarizer. This indicates that the light collected from the PhC LED is partially polarized, and the P/S ratios (defined as $P/S=I_{\max}/I_{\min}$) were 5.5 and 2.1 for square lattice ($a=260$ nm) in the ΓX and ΓM directions, respectively, as shown in Fig. 2(d). Figure 2(d) also shows the P/S ratio measured in other samples with different period. For square-lattice PhC LEDs, P/S ratio in ΓX orientation is larger than those in other orientations despite the lattice constants. In addition, for the same orientations, PhC LEDs with shorter lattice constant have higher P/S ratio.

The experimental results described above can be explained by examining the electromagnetic field distributions of PhC Bloch modes. Field distributions of Bloch modes were calculated by plane wave expansion (PWE) method using the structure with PhC sandwiched in between air and GaN materials. Figure 3(a) schematically shows the device structure where light is generated and extracted through PhCs. Due to the valence band mixing effects in QWs, guided light propagating in the GaN slab is nearly linear polarized in the transverse direction, as shown in Fig. 3(b). For PhC $a/\lambda=0.553$, the field distributions for propagation in ΓX and ΓM directions are shown schematically in Figs.

3(c) and 3(d), respectively, where the arrows indicate the electric field vectors in the plane, and black circles indicate the locations of holes. The individual electric field distributions are complicated, resulting in complicated polarization pattern. It can be seen that the field distribution in the Γ*X* orientation has linearlike polarization behavior, and those in the Γ*M* orientation has circularlike polarization.[12] This behavior can be inferred from the arrangement of the atoms relative to the propagation direction. For the Γ*X* direction, the propagating wave sees the same atom arrangement in the planes perpendicular to the propagating direction from one lattice plane to plane, while in the Γ*M* direction, the field distribution sees an alternately displaced atom arrangements from plane to plane. Such a staggered atom arrangement will tend to generate the field components normal to the polarization plane. Based on the couple mode theory, the polarization behavior of extracted light can follow the Bloch modes in PhCs and reveal the similar polarization characteristics. Therefore, the P/S ratio of light extracted through the Γ*X* orientation would be higher than through the Γ*M* orientation. From the Bloch mode patterns in Fig. 3, the experimental polarization results can be realized and consistent with the above discussion.

At $a/\lambda = 0.872$, the field distribution in the Γ*X* orientation also has more linearlike than circularlike behavior, and those in the Γ*M* orientation have stronger circularlike polarization, as shown in Figs. 3(e) and 3(f). The degree of the polarization appears to be much weaker than that for $a/\lambda = 0.553$. In order to discuss this observation, the P/S ratio as a function of normalized frequency was calculated. We employ the PWE method to calculate the polarization properties (P/S ratio) of the leaky modes in the Γ*X* directions as a function of normalized frequency. In the calculation, the polarization of the generated light is assumed to be TE polarized. The calculation was carried for each band along the Γ*X* direction up to the light line where the light becomes guided and its polarization is then the same as they were generated. As can be seen in Fig. 4, the trend of the P/S ratio decreases with normalized frequency although the trend within each band is not uniform depending on the field distribution. Details of this discussion will appear in later publication. It can also be seen from Fig. 4 that by varying the fill factor of the lattice constant, the PhC can be designed to have higher extraction efficiency for TE polarization while discriminating the TM polarization. In such case, a very high P/S ratio ($>10^2$) can be achieved. The maximum efficiency for the polarized emission that can be obtained in such case is equal to the TE portion of the total emission which is as high as 88% for a 7:1 P/S ratio.

In conclusion, we have experimentally demonstrated that surface emitted polarized light from GaN blue PhC LEDs. A P/S ratio of 5.5 (~85% polarization light) has been observed. The polarization characteristics are theoretically discussed by couple mode theory. At lower normalized frequency, PhC LED has better polarization property, and lattice orientation not only affects the extraction efficiency but also P/S ratio of radiative light. This polarization behavior suggests an efficient means to design and control the GaN blue PhC LEDs for polarized light emission.

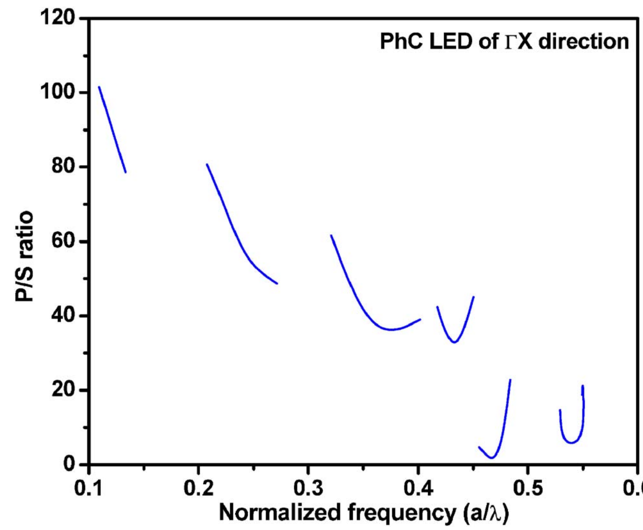

FIG. 4. (Color online) P/S ratio of PhC Bloch leaky modes in the Γ*X* direction as a function of normalized frequency.

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