Polarization of light emission by 460 nm GaInN/GaN light-emitting diodes grown on ⟨0001⟩ oriented sapphire substrates

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Measurements on the polarization of top- and side-emitted light as a function of direction are performed for 460 nm GaInN unpackaged and packaged light-emitting diode (LED) chips with a multiquantum well (MQW) GaInN/GaN active region grown on (0001) oriented sapphire substrates. Side emission is found to be highly polarized with the electric field in the plane of the MQW. Intensity ratios for in-plane to normal-to-plane polarization reach values as high as 7:1, while the total intensity for the in-plane polarization is more than twice as large compared to the normal-to-plane polarization. Despite these measured polarization characteristics, conventional packaged LEDs are found to be virtually unpolarized due to packaging. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2757594]

Light-emitting diodes (LED) that emit polarized light would be highly desirable for many applications, including sensing, imaging, and liquid crystal display backlighting.[1–5] Previously it has been reported that nonpolar or semipolar GaInN growth for LED structures leads to partially polarized output.[6–10] In addition, measurements of blue GaInN LEDs on (0001) oriented sapphire substrates that considered total emission over the angular range from 0° (normal to surface) to 90° (parallel to surface) showed polarization ratios of up to 1:1.8.[11] However, a complete analysis of the polarization characteristics of emission from conventional polar GaInN LEDs has not yet been performed. In this letter, the results of angle-dependent polarization measurements which individually treat top- and side-emitted light over nearly the complete range of emission angles are reported for unpackaged and packaged 460 nm GaInN LEDs.

The LEDs under consideration emit at 460 nm and consist of GaInN epitaxial layers grown on (0001) oriented sapphire substrates. The GaInN LED structure is grown by metal-organic chemical vapor deposition and consists of a 2 μm thick undoped GaN buffer layer, an *n*-type GaN lower cladding layer, a GaInN/GaN multiple quantum well active region, a *p*-type GaN upper cladding, and a highly doped *p*-type GaN contact layer. LED mesa structures are obtained by standard photolithographic patterning, followed by chemically assisted ion-beam etching using Cl_2 and Ar to expose the *n*-type cladding layer. The Ohmic contact for *n*-type GaN is Ti/Al/Ti/Au annealed at 650 °C for 1 min. Then, AgCu alloy (2 nm)/indium tin oxide (200 nm) is deposited on *p*-type GaN by electron-beam evaporation and annealed at 500 °C under O_2 ambient to form transparent Ohmic contact to *p*-type GaN. After processing, the sapphire substrate is thinned to approximately 80 μm thickness and then diced into individual LED chips 200×450 μm^2 in size. The polarization characteristics of these bare unpackaged chips are then measured. For comparison, the polarization characteristics of conventionally packaged LEDs are also measured.

The position of the LED in the measurement setup is shown in Fig. 1. The LED chip is placed on the corner of an absorbing sample holder so that two sides overhang the holder. The emission of the LED chip is measured along a direction given by the azimuthal angle θ and zenith angle ϕ. The chip is aligned so that the side with the *p* contact overhangs the sample holder and is oriented in the $\theta=0$ direction. For every measurement direction, the intensity of two polarizations is measured—the polarization which lies in the plane of the quantum wells and is orthogonal to the measurement direction, and the polarization orthogonal to it. These polarizations are termed the in-plane polarization and normal-to-plane polarization, respectively, because of their orientation when ϕ for the measurement direction is 90°. Figure 2 shows the orientation of the polarization vector for each with respect to the quantum well plane. The *c* axis of the sapphire substrate is perpendicular to the quantum well plane.

The intensities of the two polarizations are measured as a function of angle for six separate LED chips. For each chip, θ was swept from 0° to 90° in 5° steps, while ϕ was

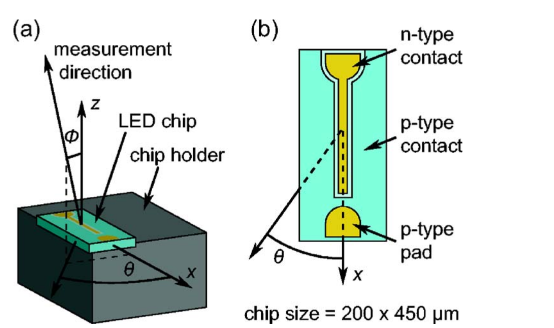

FIG. 1. (Color online) Schematic of LED position during measurement (a) and top view of LED (b). The LED chip slightly overhangs the sample holder which allows measurement of nearly all side emissions.

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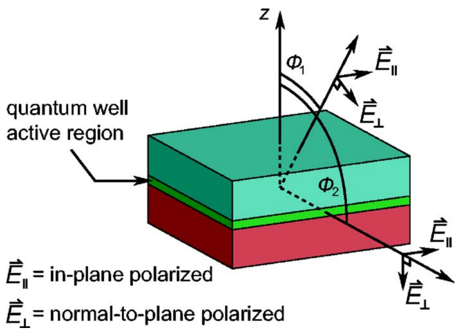

FIG. 2. (Color online) In-plane and normal-to-plane polarizations for two different zenith angles ϕ_1 and ϕ_2. The c axis is parallel to the z direction.

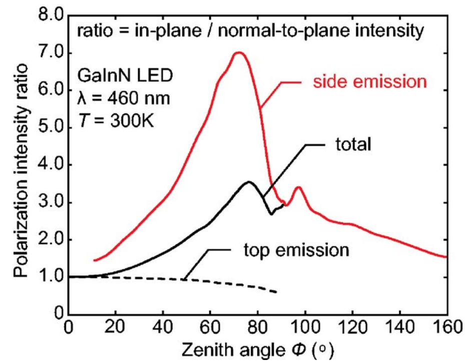

FIG. 4. (Color online) Ratio of in-plane polarization to the orthogonal polarization for total, top-emitted, and side-emitted lights.

varied from 0° to 160° in steps of 2°. Figure 3 shows the total measured intensity for both polarizations as a function of the angle ϕ for a representative LED sample. The intensities have been averaged over all the θ values considered. Figure 3 also shows the top emission and side emission separately. The top emission intensity versus ϕ has been calculated with a ray tracing simulation and has an approximately Lambertian shape, i.e., a $\cos(\phi)$ dependence. The calculated top emission curve is scaled so that emission in the $\phi=0$ direction is entirely composed of top emission. Side emission is found by subtracting the top emission from the total measured intensity. Side-emitted light consists of light that is waveguided in the GaN epitaxial layers and is emitted from GaN at the facet, and light which is emitted into the sapphire substrate and then escapes from the sapphire side facet. Light emitted into the sapphire has polarization characteristics similar to that of top emission and produces the asymmetry of side emission above and below 90°. Comparing the results for the in-plane and normal-to-plane polarizations, it is evident that side emission is much stronger for in-plane polarized light. When considering emission angles above $\phi=90°$, the peak intensity value for in-plane polarized side emission

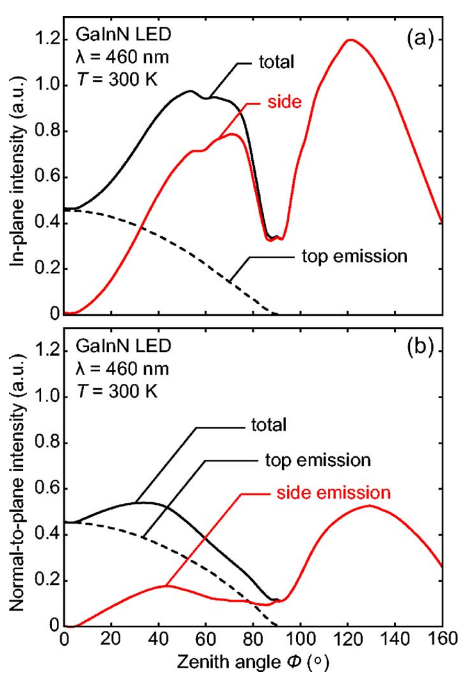

FIG. 3. (Color online) Total intensity and intensities of top emitted and side emitted passing through the polarizer when aligned in plane (a) and normal to plane (b).

is 1.73 times the peak intensity for in-plane polarized top emission. In contrast, the peak intensity for normal-to-plane polarized side emission only is 0.39 times the peak value for normal-to-plane polarized top emission.

The intensity ratio of in-plane to normal-to-plane polarization as a function of ϕ is shown in Fig. 4, which is calculated by dividing the curves shown in Fig. 3. For combined top and side emission, the ratio has a peak value of 3.55, while the ratio peak for side emission is 7.01. Top emission is slightly polarized in the normal-to-plane direction, due to the difference in reflection coefficient for the two polarizations. In-plane polarized light which is emitted from the top of the device is transverse electric (TE) polarized with respect to the interface, whereas normal-to-plane polarized light is transverse magnetic (TM) polarized. The lower reflection coefficient for TM at the air-semiconductor interface compared to TE accounts for the intensity ratio of top-emitted light. The integrated polarization ratio $R_{\text{integrated}}$, defined as,

$$R_{\text{integrated}} = \frac{\int_{0°}^{90°}\int_{0°}^{160°} I_{\parallel}(\theta,\phi)|\sin(\phi)|\,d\phi\,d\theta}{\int_{0°}^{90°}\int_{0°}^{160°} I_{\perp}(\theta,\phi)|\sin(\phi)|\,d\phi\,d\theta}, \quad (1)$$

where $I_{\parallel}$ and $I_{\perp}$ are the angle-dependent in-plane and normal-to-plane measured intensities, was also calculated from the measured data. Out of the six LED samples, the maximum and minimum $R_{\text{integrated}}$ were 2.34 and 2.10, respectively. The average integrated polarization ratio over all samples is 2.19. If only side emission is considered, the average integrated polarization ratio is 2.81.

Wurtzite crystal structure, especially combined with strain, leads to a polarization anisotropy in optical gain for bulk GaN.[12] The active region material in our case is strained wurtzite-structure GaInN, which likely contributes to the polarization characteristics present in the unpackaged blue GaInN LED. In addition, the specific active region structure—including the emission wavelength—plays a role in determining the polarization dependence of interband optical transitions in the quantum well active region.[11] The design of the LED structure can also affect the overall polarization of the output. For example, surface roughening used to extract guided modes by scattering light actually randomizes the light polarization and direction and will reduce the polarization characteristics of emitted light.

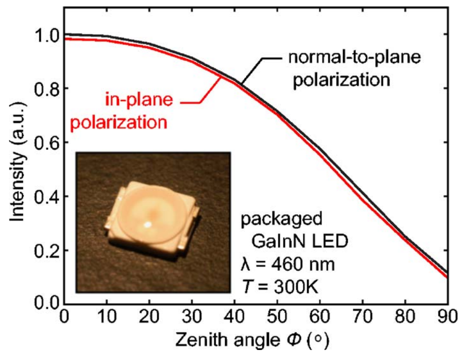

FIG. 5. (Color online) In-plane and normal-to-plane intensities for a packaged LED. The inset shows a photograph of the measured device.

Despite the pronounced polarization characteristics shown above, LEDs have generally been considered to be unpolarized sources. When two orthogonally polarized rays are combined, the result is unpolarized light. Conventional LED packaging—which uses rotationally symmetric reflector cups and encapsulants—performs exactly this sort of mixing of rays and averaging. Figure 5 shows a measurement of in-plane and normal-to-plane intensities for a packaged blue GaInN LED. The curves are approximately Lambertian in shape and have virtually identical intensities, which yields an integrated polarization ratio of 1.0, indicating that the light is unpolarized.

In conclusion, we have demonstrated that side-emitted light from 460 nm GaInN multiple quatum well LEDs is highly polarized in the plane of the quantum wells. The intensity ratio of in-plane polarization to normal-to-plane polarization has a peak value as high as 7:1. On average, overall intensity of the in-plane polarization is 2.19 times higher than that of the normal-to-plane polarization. Conventional LED packaging structures eliminate this inherent polarization effect because their rotationally symmetric structures act to average the light rays emitted in different directions.

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