

Linearly polarized emission from GaInN light-emitting diodes with polarization-enhancing reflector

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Abstract: A polarization-enhancing reflector design, which is matched to the emission characteristics of GaInN/GaN 460 nm light-emitting diodes grown on (0001) oriented sapphire substrates, is reported. Side-emitted light from these devices is known to be highly polarized with the electric field in the plane of the active region. Through selective rotation of polarization by the reflector, the in-plane polarized side-emitted light is directed upwards with a single dominant linear polarization. Polarization ratios as high as 3.5:1 are measured in the farfield, and the average polarization ratio is 1.9:1. If only light that strikes the reflector is considered, the polarization ratio is 2.5:1. The concept of the polarization-enhancing reflector and the numerical algorithm used to generate the optimized shape are also described.

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1. Introduction

High efficiency and power, long lifetime, small size, and the wide range of wavelengths available are reasons why light-emitting diodes (LEDs) are becoming increasingly important in areas such as sensing and imaging [1,2], general illumination [3,4], and liquid crystal display (LCD) backlighting [5]. A key benefit provided by LEDs is the ability to tune properties such as wavelength or color temperature to meet the needs of specific applications [6]. However, the control of one property in particular – the optical polarization – has remained elusive. Polarized LEDs would be extremely useful for LCD backlighting [7-10] and also for imaging [11,12] and communications [13].

Previously it has been reported that the light emitted in certain directions by GaInN LEDs epitaxially grown on (0001) oriented sapphire substrates shows some degree of polarization [14]. Polarization effects have also been demonstrated with LEDs grown on non-polar or semi-polar substrates [15-18]. Our own studies of GaInN LEDs on (0001) sapphire substrates with multiple quantum well (MQW) active regions emitting at 460 nm revealed that light emitted from the side facets of the LED chips is dominantly polarized in the plane of the quantum wells, with values as high as 7:1 for the ratio of in-plane polarized light to normal-to-plane polarized light [19]. However, despite the measured polarization characteristics of unpackaged chips, conventional packaged LEDs were found to be completely unpolarized. This is attributed to the use of reflectors which do not preserve the inherent polarization properties of the LED chips. The reflectors typically exhibit continuous rotational symmetry and simply take the rays emitted in different directions and reflect them upwards. When two orthogonally polarized beams of equal intensity are combined, the result is unpolarized light.

2. Concept and algorithm for determining reflector shape

Previously we have shown that the encapsulation of a light source can be designed to extract polarized light even from a completely unpolarized light source [20]. Here a similar approach is used to realize a fundamentally new reflector shape tailored to exploit the polarization characteristics of light emitted from the side facets of GaInN LEDs, in order to directly generate vertically emitted (i.e. normal to the plane of the LED chip) polarized light. This novel reflector design varies the optical path based upon the direction of light emission; all light emitted by the LED that is incident on the reflector is directed upwards; however, depending upon the direction of the emitted light, the polarization may also be rotated by some angle. This concept is illustrated in Fig. 1. Through the selective polarization rotation, all side emitted light – which is initially polarized in the plane of the quantum wells – is polarized along a single direction when it leaves the reflector.

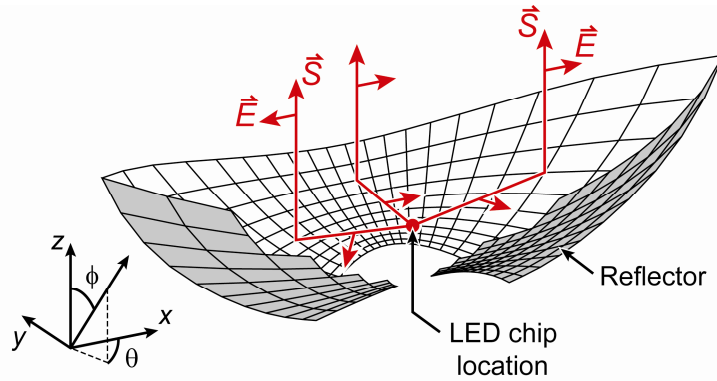


Fig. 1. Illustration of the polarization-enhancing reflector concept. Light emitted by the LED chip is primarily polarized in-plane; the reflector selectively rotates the polarization of side emitted light to convert in-plane polarized light to x -polarized light traveling upwards.

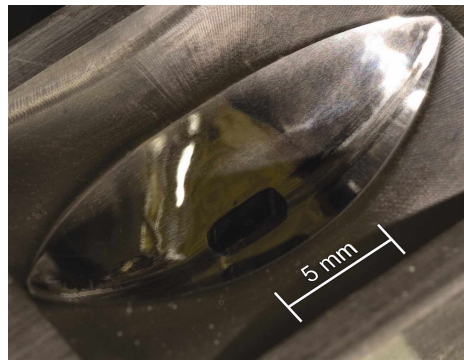


Fig. 2. Photograph of polarization-enhancing reflector shape.

The reflector shape is determined using the following algorithm. In the calculations, the light source is assumed to be located at the origin and emit light polarized in the quantum well plane. The reflector shape is defined in terms of a rectangular grid of points in spherical coordinates in which the azimuthal angle θ and zenith angle ϕ for each point are fixed and are spaced at regular intervals. The radial coordinate r for each point on the grid is initially unknown. By grouping three points on the grid, a triangle is formed. The r -values for these three points are then optimized in order to maximize the figure of merit, which is chosen to be the product of (1) transmission through a linear polarizer lying in the xy -plane above the reflector which allows x -polarized light to pass and (2) $|\cos(\phi_{\text{final}})|$, where ϕ_{final} is the zenith angle of the propagation direction for a beam after reflection. This figure of merit ensures that the light which leaves the reflector has the desired polarization and travels in a close-to-vertical direction. It would be possible to change the figure of merit in order to tailor the far-field emission pattern of the final device. Once one triangle has been found, it is possible to form a new triangle by selecting a single new point, which is again optimized. This process is continued until the entire reflector shape is determined. The optimized reflector shape was calculated for beams that are emitted with zenith angles between $\phi = 72^\circ$ and $\phi = 126^\circ$. For ϕ greater than 126° , the reflector shape is linearly extrapolated from calculated points; for ϕ less than 72° , light rays do not strike the reflector. The reflector is fabricated from aluminum by a computer controlled milling machine and then extensively polished by hand to give the surface a specular optical finish. A slot is machined in the center at the bottom in order to facilitate mounting of the LED chip. A photograph of the reflector and a wireframe view are shown in Fig. 2 and Fig. 3, respectively.

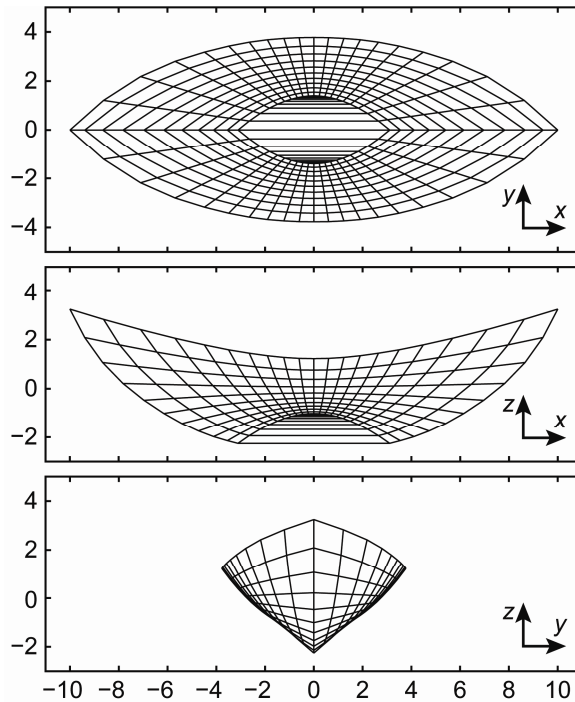


Fig. 3. Wireframe view of the polarization-enhancing reflector. The LED position is at the origin. The units are millimeters.

3. Methods

The GaInN LED chip used to test the reflector emits at 460 nm and has an area of $200 \times 450 \mu\text{m}^2$. The LED structure is grown by metal-organic chemical vapor deposition on (0001) oriented sapphire substrates and consists of a $2 \mu\text{m}$ 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 which is annealed at 650°C for 1 min. Then, AgCu alloy (2nm) / ITO (200 nm) is deposited on p-type GaN by electron-beam evaporation and annealed at 500°C under O_2 ambient to form a transparent Ohmic contact to p-type GaN. After processing, the sapphire substrate is thinned to approximately $80 \mu\text{m}$ thickness and then diced into individual LED chips.

The chip is mounted on the tip of a pin which has been flattened to make a level surface for mounting and is held in place with a small amount of adhesive. The flattened pin tip is circular in shape and approximately $180 \mu\text{m}$ in diameter, which allows the edges of the chip to overhang. The pin which serves as the LED chip holder is fixed in place and the reflector cup is positioned on a 3-axis stage so the pin protrudes through the slot in the base of the reflector. The position of the reflector with respect to the LED chip is optimized using a large-area (25 mm diameter) photodetector and polarizer located approximately 40 mm above the top of the reflector. This detector position allows the capture of nearly all light emitted in vertical and close-to-vertical directions.

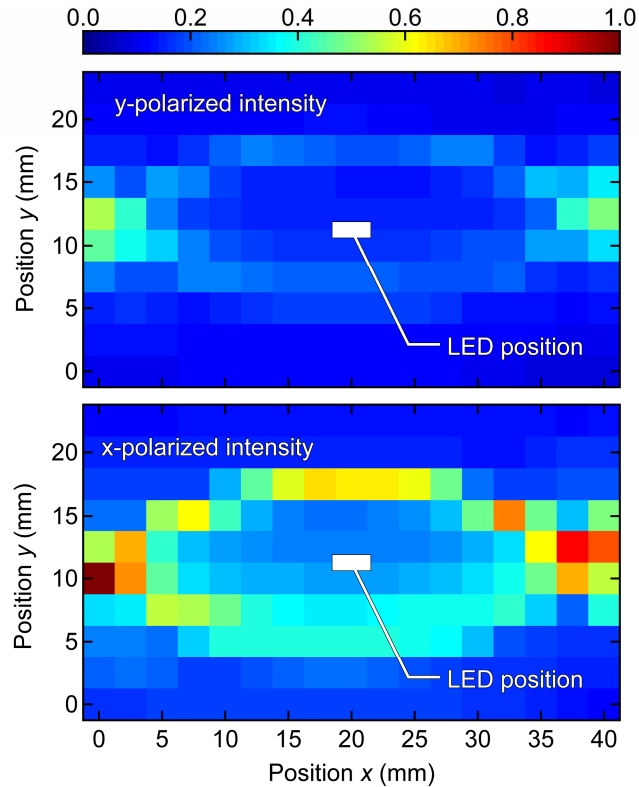


Fig. 4. Measured intensity of x -polarized and y -polarized light as a function of position.

4. Results and discussion

The reflector position is adjusted in order to maximize the polarization ratio, defined as the ratio of intensity with the polarizer aligned in the x -direction to the intensity with the polarizer aligned in the y -direction. The intensity of x -polarized and y -polarized light is also measured in the absence of the reflector in order to determine the polarization ratio for only that light which strikes the reflector. The total polarization ratio, which combines reflected and directly emitted (i.e. light not striking the reflector) light, is measured to be 1.9:1, while ratio for reflected light only is 2.5:1. Due to the detector position and its large area, this may be considered the average polarization ratio for light traveling in the vertical direction. By comparison, an unpackaged or conventionally packaged LED has a ratio of 1:1 for vertically emitted light [19].

Measurements of the x - and y -polarization intensities as a function of position above the reflector are also performed. A detector with a 2.5 mm aperture is scanned over a 22.5×40 mm² area in the xy -plane above the reflector. This measurement reveals the farfield emission pattern of the LED with reflector. Figure 4 shows the measured intensity as a function of detector position for both polarizations. Figure 5 shows the ratio of the two polarizations. The peak ratio observed is approximately 3.5:1 and there are several points which have ratios above 3:1. Figures 4 and 5 reveal an asymmetry in both the intensity and ratio as a function of position; this difference is likely due to an asymmetry in the reflector itself. The fabrication method used relies heavily on work done by hand and does not produce a perfect result. When the reflector is examined, the surface does appear specular in general, but close inspection reveals some non-specular regions where the finish is compromised by small scratches as well as regions where the reflector shape deviates from the intended shape. This indicates that the performance would be further increased through the use of improved methods in the manufacture and polishing of the reflector. It would also be possible to increase performance

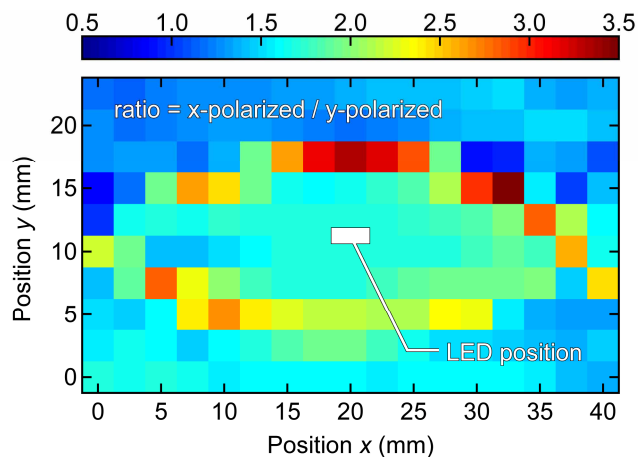


Fig. 5. Ratio of x -polarized to y -polarized light as a function of position.

by designing a deeper reflector that reflects light with $\phi < 72^\circ$, which would allow the capture of more highly-polarized side emission. As a result, the maximum values measured for the polarization ratio should be taken as an indicator of the performance potential of the reflector. The combination of side-emitting LEDs and the polarization-enhancing reflector could lead to highly polarized and highly efficient light sources useful for LCD backlighting and other applications.

5. Conclusion

In conclusion, we have demonstrated a reflector design tailored to take advantage of the inherently polarized emission characteristics of GaInN LEDs in order to make a light source that emits predominantly linearly polarized light. Measurements show that reflected light traveling in close-to-vertical directions has an intensity ratio of desired-polarization-to-undesired-polarization of 2.5:1, while the combination of reflected and directly emitted light is polarized with an average ratio of 1.9:1. In addition, a scan of the farfield emission pattern shows local polarization ratios as high as 3.5:1. The reflector design and the concept of providing a different optical path dependent upon the direction and polarization of light through selective polarization rotation are both promising for the development of polarized light sources that are highly desirable for specific applications, such as LCD backlighting.

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