Emission pattern control and polarized light emission through patterned graded-refractive-index coatings on GaInN light-emitting diodes

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Abstract: Patterned graded-refractive-index (GRIN) coatings that offer the controllability of far-field emission pattern and polarization properties of GaInN light-emitting diodes (LEDs) are investigated. Compared with a planar reference LED, the light-output power of an LED with patterned GRIN coatings (GRIN LED) is enhanced by about 69%. Furthermore, the GRIN LED has bidirectional emission peaks at about 45° off-surface-normal and *polarized* light emission with the maximum polarization ratio occurring at the same angle, i.e. the intensity maximum and the polarization-ratio maximum coincide. The large off-surface-normal emission of the GRIN LED results from the strong light extraction through the sidewalls of the GRIN pillars, which is in good agreement with results predicted from ray-tracing simulations.

OCIS codes: (230.3670) Light-emitting diodes; (310.4165) Multilayer design.

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The high efficiency of light-emitting diodes (LEDs) already provides energy savings in a number of lighting applications [1–3]. Moreover, LEDs fundamentally offer new

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functionalities such as the control of color temperature, dimming, pulsation, far-field emission pattern, and even polarization, which have not been possible in traditional lighting sources [4]. Such optically functional light sources (i.e., LEDs) can provide tremendous benefits in general lighting, automobiles, and liquid-crystal display (LCD) backlighting [5]. On the other hand, crystallographic wet chemical texturing of the N-face GaN surface is currently a most popular technique to enhance the light-extraction efficiency (LEE) of GaInN LEDs. However, such random texturing does not provide such new functionalities, specifically, the control of far-field emission pattern and polarization. This is because the random surface features result in mixing of the emitted light rays and averaging of light with different polarizations [6,7]. Thus, technical approaches that cannot only improve the light extraction in GaInN LEDs, but also offer controllability of the far-field emission pattern and polarization, are highly desirable.

In this paper, we present an approach which will not only enhance the LEE of GaInN LEDs, but also offer controllability of their far-field emission pattern and polarization of light emission. This is achieved by patterned graded-refractive-index (GRIN) coatings on the top surface of an LED chip. The coatings are composed of patterned GRIN micro-pillars with a well-defined planar geometric shape, such as circular and rhombus shapes. Each GRIN micro-pillar is composed of five dielectric layers of TiO_2-SiO_2 mixture with a decreasing TiO_2 / SiO_2 volume ratio as the pillar height increases, thus resulting in a decreasing refractive index as the pillar height increases. It is shown that the patterned GRIN micro-pillars can make the surface of the LED chip optically functional, i.e., when properly designed, the far-field emission pattern and the polarization of emitted light can be tailored, showing increased light emission and polarization in desired directions.

Thin-film 1×1 mm^2 GaInN LEDs (N-face up) emitting at 445 nm (planar LEDs) are used as a reference device. The crystallographically wet chemically etched LEDs (wet-etched LEDs) have a roughened N-face GaN surface textured by using an aqueous 10% KOH (weight ratio) solution at 50 °C in which the samples are immersed for 4 min. To fabricate the five-layer GRIN coatings (GRIN LEDs), a varying composition of TiO_2 and SiO_2 is sputter-deposited on the N-face GaN surface of thin-film LEDs. The electrical powers applied to the two sputtering targets are carefully adjusted for each layer so that the desired refractive index of each layer is achieved. The total thickness of the GRIN-layer stack is around 1.6 µm, with each layer thickness around 300 nm. Rhombus-shaped GRIN pillars are arranged in a hexagonal pattern with the pillars having a longer diagonal of 4.7 µm, a shorter diagonal of 2 µm, and spacing between pillars of 2 µm. The detailed fabrication procedure was described in the literature [8,9]. A top-view scanning electron micrograph of an array of rhombus-shaped GRIN micro-pillars with smooth, vertical sidewalls fabricated on the N-face GaN surface of a thin-film LED is shown in Fig. 1(a). And a cross-section-view focused ion beam micrograph of a GRIN micro-pillar on the N-face GaN surface of a thin-film LED revealing the five-layer GRIN layers is shown in Fig. 1(b). The far-field emission pattern of the LED chip is measured using a lab-made setup with a blue-enhanced Si PIN photo-detector moved by a rotating arm similar to a goniometer. When measuring the polarization emission intensity, a polarizer is added in front the photo-detector.

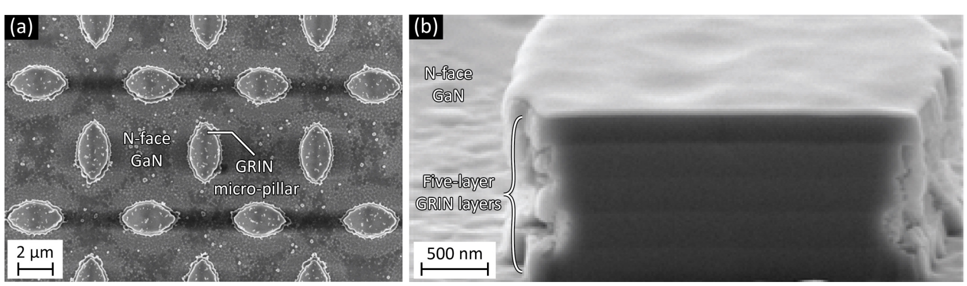

Fig. 1. (a) Top-view scanning electron micrograph of an array of rhombus-shaped GRIN micro-pillars on the N-face GaN surface of a thin-film GaInN LED. (b) Cross-section-view focused ion beam micrograph of a GRIN micro-pillar on the N-face GaN surface of a thin-film GaInN LED.

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The schematic of the GRIN micro-pillar is shown in Fig. 2 along with light rays that are extracted through the pillar. The GRIN pillar consists of five layers with a decreasing refractive index as the pillar height increases. The bottom layer is refractive-index-matched to the GaN layer so that the coupling loss at the interface is minimized. For the planar LED, only one interface exists between the LED semiconductor and air, and there is a substantial amount of total-internal-reflection (TIR) due to the large refractive-index contrast between the semiconductor (n = 2.47) and air (n = 1). However, if the LED top surface is coated with GRIN pillars, additional interfaces are introduced, which include the interfaces between the sidewall of each layer and air, and the interface between the top surface of the top layer and air. The light escape cone has now increased, because it encompasses both the original escape cone and the escape cones associated with the pillar sidewalls. Each layer in the GRIN pillar extracts light incident on the layer's surface at a specific range of incident angles. In a multilayer GRIN pillar structure, the relatively large critical angle at each GRIN layer interface allows light rays entering the pillar to (i) refract into the subsequent GRIN layer; or (ii) strike the sidewall at near-normal angles of incidence; and (iii) finally get extracted through the pillar sidewall, as shown in Fig. 2. We can see that the pillar sidewall can simultaneously (i) out-couple what would otherwise be TIR modes ("conventional TIR modes") and (ii) affect the directionality of light-emission.

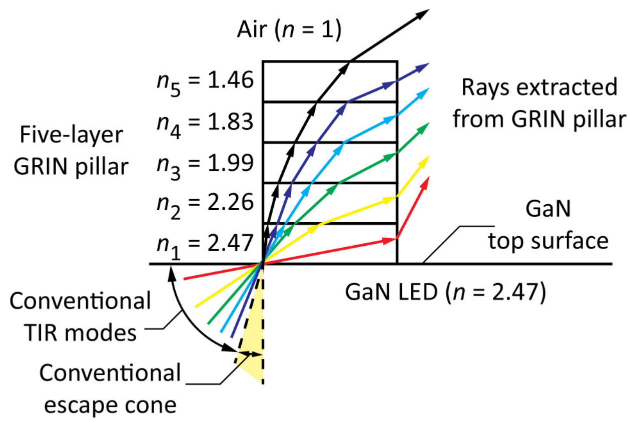

Fig. 2. Schematic of the GRIN pillar on the top surface of a GaInN LED and illustration of light rays that are extracted through the pillar.

It is known that light emission from planar LEDs without surface texture is Lambertian with decreasing angular intensity from the surface normal. Light emission from wet-etched LEDs is also Lambertian and thus offers little controllability in terms of the light emission directionality. However, the GRIN LED can have strong off-surface-normal emission due to the light extraction from the sidewalls of GRIN pillars. Furthermore, the refractive index profile and the structure of the GRIN pillar will directly impact the far-field emission pattern. For example, for LEDs coated with GRIN pillars with a given refractive index profile, larger spacing between pillars will have less light rays re-enter neighboring pillars, thus resulting a stronger off-surface-normal emission. This is confirmed by ray-tracing simulation. Figure 3 shows the far-field emission patterns for LEDs coated with GRIN pillars with different diameter (d) and spacing (s) as simulated by ray tracing. The GRIN pillars have the same refractive index profile and thickness as previously mentioned. For simplicity, the GRIN pillars have a planar shape of a circle. As shown in Fig. 3, the GRIN LEDs have bidirectional emission peaks, with the peak emission angle increases from 30° off-surface-normal to 60° off-surface-normal as the pillar diameter and spacing increases, which is a clear indication of the stronger off-surface-normal emission. Thus, careful design of height, size, and refractive index of each layer of the GRIN pillar allows not only to enhance light-extraction (by eliminating the conventional TIR modes) but also to tailor other LED characteristics such as

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the far-field emission pattern and, as will be shown below, the polarization properties of LEDs [10].

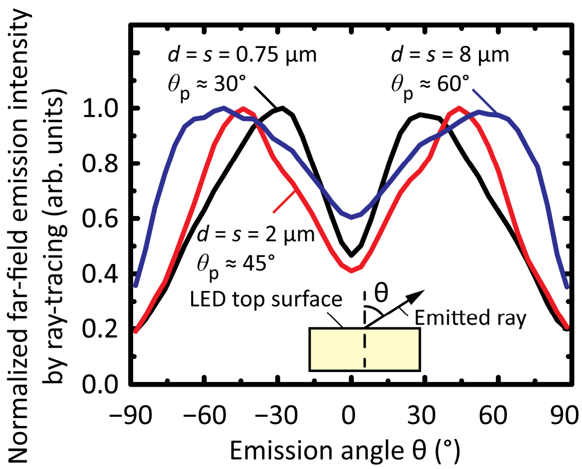

Fig. 3. Far-field emission intensity as a function of the emission angle for LEDs coated with GRIN pillars with different pillar diameter and spacing as simulated by ray tracing.

Figure 4 shows the measured far-field emission pattern of a planar LED, a wet-etched LED, and a GRIN LED. We find that the experimental results agree well with the simulation results. The planar LED shows a Lambertian far-field emission pattern with decreasing angular intensity from the surface normal. The wet-etched LED also shows a Lambertian far-field emission pattern and an about 72% enhancement in light-output power (LOP) compared to the planar LED. The GRIN LED has bidirectional emission peaks at about 45° off-surface-normal, in addition to about 69% enhancement in LOP which is very comparable to that of the wet-etched LED. Compared with the planar LED and the wet-etched LED, the far-field emission pattern of the GRIN LED show strong off-surface-normal light emission, which is a clear indication of the strong light extraction from the sidewalls of GRIN pillars. Furthermore, the far-field emission pattern of the GRIN LED can be tailored by adjusting the peak emission angle. For example, a larger spacing between pillars will have less extracted light rays re-entering a neighboring pillar [10], resulting in a larger off-surface-normal peak emission angle. We can see that compared with the wet-etched LED, the GRIN LED offers both high LEE and controllability of the far-field emission pattern.

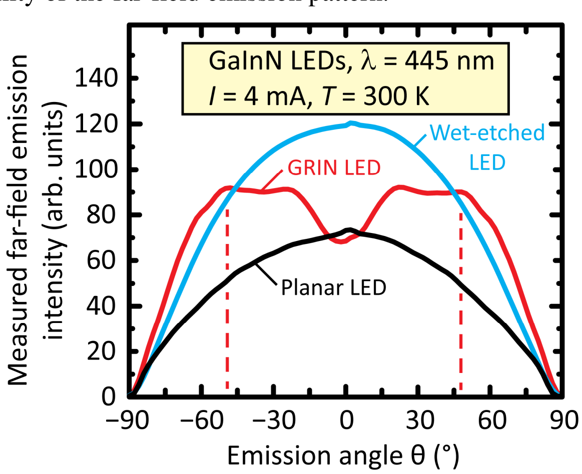

Fig. 4. Measured far-field emission intensity as a function of the emission angle for a planar LED, a crystallographically wet-etched LED, and a GRIN LED.

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Furthermore, the unique characteristic of the GRIN LED, i.e., the strong light extraction from the sidewalls of GRIN pillars, will change the polarization properties of LEDs. Figure 5 shows the measured transverse electric (TE) and transverse magnetic (TM) polarization intensity as a function of the emission angle from a planar LED, a wet-etched LED, and a GRIN LED. We define the degree of polarization as:

$$Degree\ of\ \ polarization = \frac{\left| I_{\mathrm{TE}} - I_{\mathrm{TM}} \right|}{I_{\mathrm{TE}} + I_{\mathrm{TM}}} \tag{1}$$

where I_{TE} and I_{TM} are the emission intensity of TE-polarized and TM-polarized light, respectively. As shown in Fig. 5, for the planar LED, the degree of polarization at first increases as the emission angle increases, reaches its maximum at around 80° off-surface-normal, and then decreases as the emission angle increases. While for the wet-etched LED, the TE and the TM polarization intensity stays almost the same over the entire range of angles of emission. As for the GRIN LED, the degree of polarization at first increases as the emission angle increases, reaches its maximum at around 45° off-surface-normal, which coincides with the angle with its peak emission intensity, and then decreases as the emission angle increases.

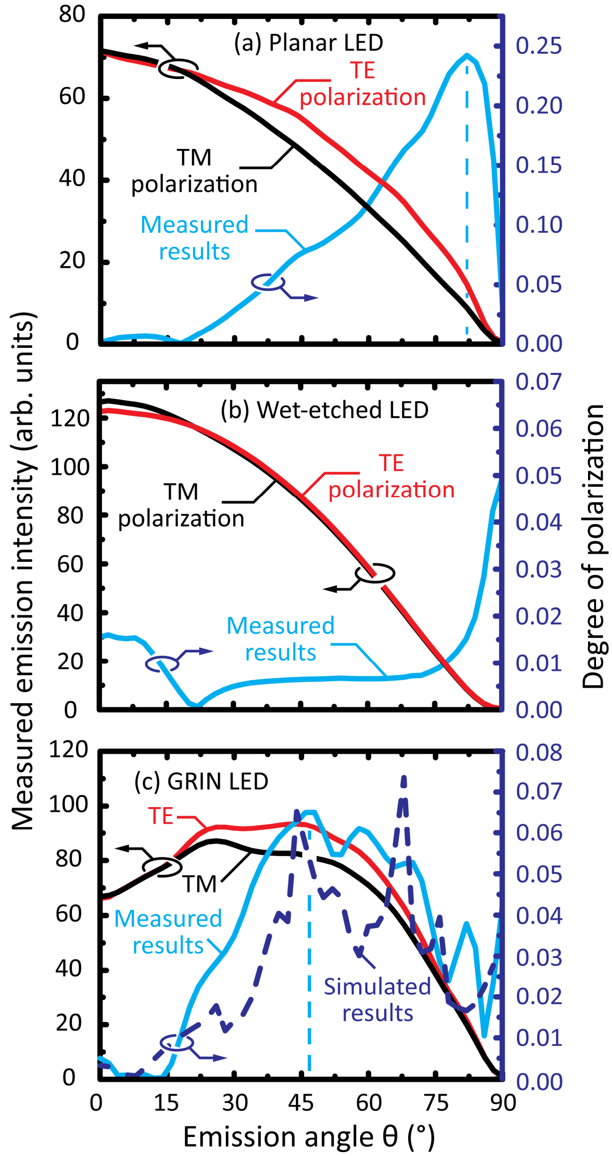

Fig. 5. Measured TE and TM polarization intensity as well as the degree of polarization as a function of the emission angle for (a) a planar LED, (b) a crystallographically wet-etched LED, and (c) a GRIN LED (the dashed line shows the results simulated by rigorous coupled wave analysis).

For the planar LED, the degree of polarization peak occurs at a large angle (80°) off-surface-normal. This indicates that the high degree of polarization mainly comes from the side emission of the planar LED consistent with results reported in the literature [11]. The light emitted from the side of the LED consists of light that is waveguided in the GaN epitaxial layers and is emitted from GaN at the facet. And it was found that the side emission is stronger for the TE-polarized light [11,12]. However, for the wet-etched LED, the random surface feature mixes and averages light rays so that the polarization of emission gets randomized, therefore showing completely unpolarized emission. As for the GRIN LED, the degree of polarization peak coincides with the emission intensity peak at about 45° off-surface-normal. This indicates the polarized emission results from the light extracted through the sidewalls of GRIN pillars as well. The TE-polarized light rays, which would have been waveguided in the GaN epitaxial layers and eventually be emitted from the sidewall of the LED chip, will now be extracted through the sidewalls of GRIN pillars. As a result, the emission with the maximum intensity is also stronger for the TE-polarized light, and the degree of polarization peak coincides with the emission intensity peak at about 45° off-surface-normal. The polarization property of the GRIN LED is also simulated by rigorous coupled wave analysis, and the simulated results show very similar trend with the measured results. Especially, the degree of polarization peak at about 45° off-surface-normal is reproduced, as shown in Fig. 5(c). Besides, the strong light extraction from the sidewalls of GRIN pillars reduces the absorption loss during the waveguiding and thus results in higher polarized emission intensity. Furthermore, this suggests that the polarized emission from the GRIN LED can be tailored together with their far-field emission pattern. As a result, when compared with the wet-etched LED, the GRIN LED shows polarized emission over the entire range of angles. And when compared with the planar LED, the degree of polarization peak of the planar LED occurs at about 80° off-surface-normal, where the emission intensity is very low; while the degree of polarization peak of the GRIN LED occurs at about 45° off-surface-normal, where the emission intensity is also at its peak.

In summary, patterned GRIN coatings that offer the controllability of far-field emission pattern and polarization properties of GaInN LEDs are investigated. Compared with the planar reference LED, the LOP of the GRIN LED is enhanced by about 69% with an array of rhombus-shaped GRIN pillars with a longer diagonal of 4.7 μm, a shorter diagonal of 2 μm, and spacing between pillars of 2 μm on the LED top surface. In addition, the GRIN LED has bidirectional emission peaks at about 45° off-surface-normal and *polarized* light emission with the maximum polarization ratio occurring at the same angle, i.e. the intensity maximum and the polarization-ratio maximum coincide. The large off-surface-normal emission of the GRIN LED results from the strong light extraction through the sidewalls of the GRIN pillars, which is in good agreement with results predicted from ray-tracing simulations. Furthermore, it is shown that the far-field emission pattern and the polarization of emission can be tailored by carefully designing the structure and spacing of the GRIN pillars.

Acknowledgments

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