Graded-refractive-index structures on GaN-based light-emitting diodes for light-extraction-efficiency enhancement and far-field-emission control

by

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ABSTRACT

Light-emitting diodes (LEDs) represent the next generation of lighting and illumination sources. There are many challenges yet to be solved for nitride-based LEDs such as enhancing the internal quantum efficiency and enhancing the light-extraction efficiency (LEE). Both challenges need to be overcome to obtain highly efficient devices.

Semiconductor materials used for LEDs have large refractive indices ($n = 2.5$ to 3.5) in contrast to air ($n = 1.0$) or encapsulant materials ($n \approx 1.5$), resulting in total internal reflection losses and high Fresnel reflection losses at semiconductor−air and semiconductor−encapsulant interfaces thereby limiting light extraction. Frequently, single-layer anti-reflection (AR) coatings are used in optical devices to eliminate reflection. However such single-layer coatings eliminate reflection at only a single wavelength and angle of incidence.

In this dissertation, we demonstrate that broadband omni-directional AR characteristics are attainable by grading the refractive index of the AR coating from the substrate index to the ambient index. Furthermore, micro-patterning of graded-refractive-index (GRIN) coatings deposited on top of GaInN LEDs is demonstrated to enhance light-output power through the extraction of light that would otherwise be waveguided. Three-dimensional ray-tracing simulations for GRIN micro-pillars on GaInN LEDs predict a LEE enhancement of 85% over uncoated LEDs when the pillar height is half the pillar diameter. The theory, simulation, and fabrication steps needed to realize such a device are developed.

In Chapter 1, a review of LED fundamentals is given. Furthermore, modern methods to achieve high light-extraction efficiency for LEDs are discussed.

In Chapter 2, the fabrication and characterization of GRIN multi-layer structures are discussed. A method to achieve tunable-refractive-index coatings using co-sputtering is demonstrated. Ellipsometry, reflectance, and transmittance measurements of the GRIN coatings demonstrate that they are optically transparent. Scanning electron micrographs and atomic force micrographs of the GRIN coatings demonstrate that they have smooth layer interfaces and surfaces.

In Chapter 3, light-extraction efficiency calculations and simulations are described for unpatterned (non-textured) LEDs and micro-patterned GRIN structures on GaInN

LEDs. Ray-tracing simulations are used to investigate the effects of GRIN micro-patterns on LEDs including their effects on the light-extraction efficiency and the far-field-emission pattern of LEDs.

In Chapter 4, simulations of far-field-emission patterns for GRIN micro-pillar arrays on GaN-based LEDs are described; the arrays are optimized by a genetic algorithm. The algorithm, guided by a desired far-field-emission pattern, determines pillar diameter and spacing as well as the refractive index and height of each layer of a pillar. Simulated far-field-emission patterns of GRIN micro-pillar arrays placed on three common LED configurations show a peak emission intensity directed at angles between 20° to 60° from the surface normal. Light out-coupling through the GRIN micro-pillar sidewall changes the LED-emission directionality while enhancing light-extraction efficiency. Tailoring of far-field-emission patterns is demonstrated by using ray-tracing simulations for GRIN micro-pillar arrays on GaN LEDs.

In Chapter 5, fabrication methods for realizing micro-patterned GRIN structures on GaInN LEDs are introduced. Indium-tin oxide (ITO) etching by inductively-coupled plasma (ICP) and reactive ion etching (RIE) is optimized. Dry etching of SiO_2, TiO_2 and TiO_2−SiO_2 by ICP−RIE using a photoresist mask is performed. Dry etching of GRIN TiO_2−SiO_2 using ITO as a hard mask is optimized.

In Chapter 6, the photoluminescence, electroluminescence, and far-field-emission-pattern measurements of LEDs with GRIN micro-pillar arrays are presented. LEDs with GRIN micro-pillar arrays have a bi-lobe-shaped far-field pattern. Five-layer GRIN TiO_2−SiO_2 micro-pillars on vertical-structure thin-film GaN laser lift-off (LLO) LEDs show a LEE enhancement of 73% over uncoated LED wafers. A waveguide LED is developed and the photoluminescence measurements for the micro-patterned GRIN $(TiO_2)_x(SiO_2)_{1-x}$ coatings on top of GaInN LEDs show LEE enhancements 40% over unpatterned LEDs. Electroluminescence (EL) measurements for the micro-patterned GRIN $(TiO_2)_x(SiO_2)_{1-x}$ coatings on top of GaInN LEDs show LEE enhancements 45% over unpatterned LEDs. Position-dependent EL measurements for micro-patterned TiO_2 and TiO_2−SiO_2 coated LEDs are performed. The GRIN TiO_2−SiO_2 micro-pillars on GaN show a measured peak LEE enhancement of 35% and 43% for pillars forming square and triangular lattices, respectively, compared to planar GRIN coated references. ITO on

GRIN micro-pillar arrays with 3 μm and 6 μm diameter pillars on vertical-structure thin-film GaN LLO LEDs show a LEE enhancement of 48% and 41%, respectively, compared to a planar GRIN coated LED. A peak emission angle close to 35° is observed for the two GRIN micro-pillar arrays on the GaN LEDs.