Graded refractive index structures boost LED emission by up to 131%

Total internal reflection effects have been reduced with five layers of titanium-silicon dioxide dielectric.

Researchers in the USA and South Korea have used patterned layers of titanium-silicon dioxide (TiO_2/SiO_2) dielectrics to enhance light output from indium gallium nitride (InGaN) light-emitting diodes (LEDs) by up to 131% [Ahmed N. Noemaun et al, J. Appl. Phys., vol110, p054510, 2011].

The layers work by stepping down the refractive index of the material through which light passes from the high value of 2.47 for GaN to 1 for air. Patterning of the graded refractive index (GRIN) coating allows light to be extracted from the side walls of the dielectric structures.

In the absence of such dielectric layers the large difference in refractive index reduces the angles at which light can emerge from an GaN/air interface to within 24° to the surface normal. Light hitting at greater angles (24–90°) is reflected back into the device, a situation called total internal reflection (TIR).

The researchers from Rensselaer Polytechnic Institute, Samsung LED and Pohang University of Science and Technology developed the GRIN technology using 1mm x 1mm 445nm-wavelength nitride semiconductor LEDs grown on c-plane sapphire using metal-organic chemical vapor deposition (MOCVD). The LED layers were lifted-off the underlying sapphire substrate using a 248nm krypton fluoride excimer laser beam.

The separated GaN surface was a nitrogen-face. Two reference LED types consisted of devices with no passivation and planar GaN N-face, and devices with roughened surfaces created through wet etching with 10%-by-weight potassium hydroxide solution for 4 minutes at 50°C.

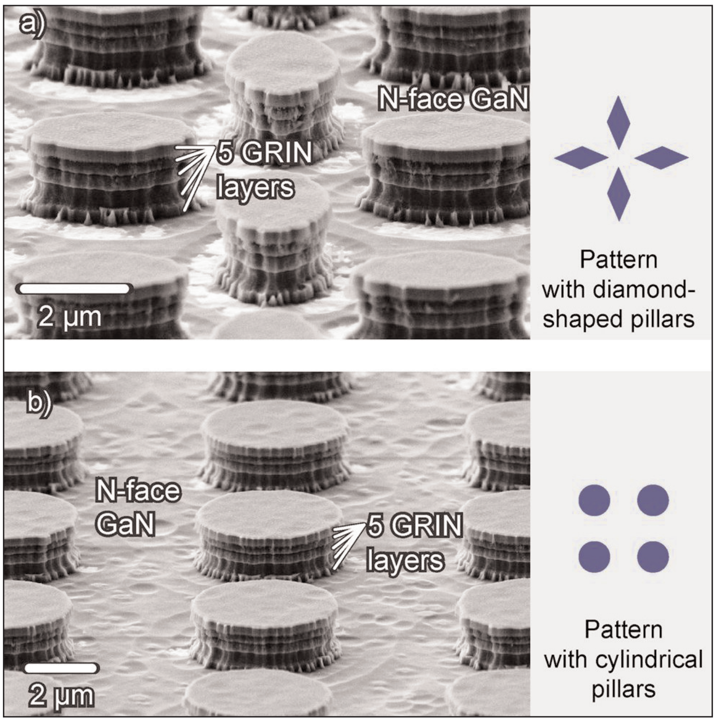

Figure 1. Scanning electron micrographs (SEMs) of (a) an array of diamond-shaped pillars and (b) an array of cylindrical pillars etched under 1kW ICP power and 400W RIE power with 60sccm of CHF_3 at 15mTorr and 50°C.

Table 1. Thickness and refractive index of each layer in the graded-refractive-index stack is controlled by the power applied to the TiO_2 and SiO_2 targets and the deposition time.

Layer number	Power applied to target TiO_2	Power applied to target SiO_2	Deposition time	Measured layer thickness	Measured refractive index
1	200W	0W	240min	333nm	2.47
2	200W	50W	180min	331nm	2.26
3	200W	100W	120min	323nm	1.99
4	200W	150W	90min	330nm	1.83
5	0W	200W	120min	260nm	1.46

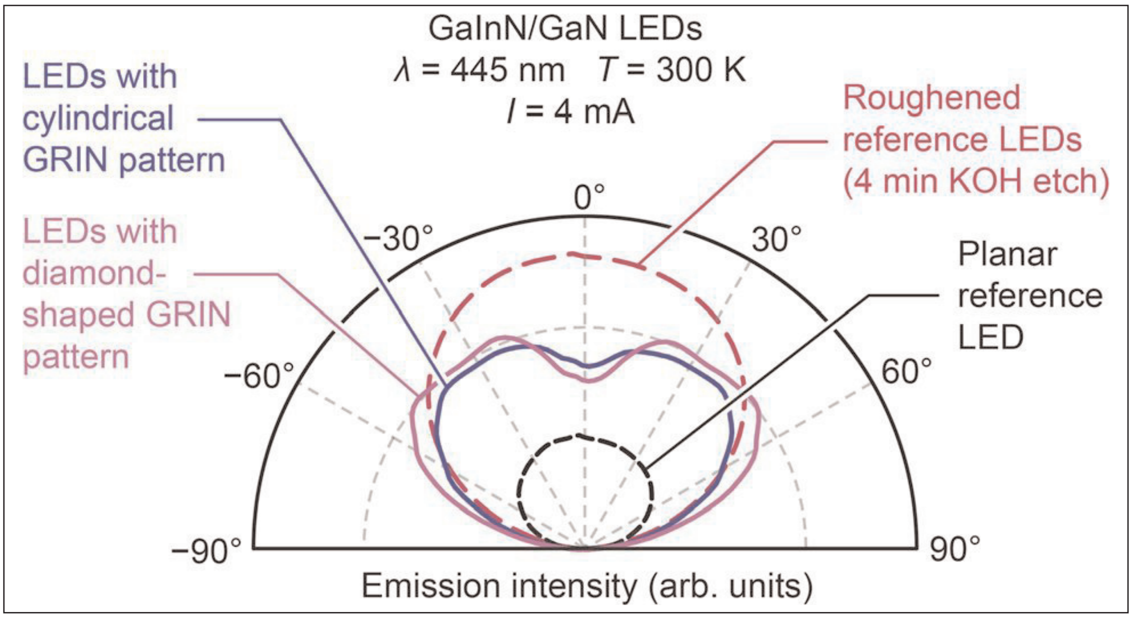

Figure 2. Far-field emission intensity of planar reference LEDs, KOH-roughened reference LEDs, LEDs with GRIN cylindrical patterns of 2μm diameter, and LEDs with GRIN diamond-shaped patterns with 4.7μm longer diagonal and 2μm shorter diagonal.

For the devices with GRIN structures, a series of layers with varying thickness and refractive index were applied by sputtering combinations of titanium (TiO_2) and silicon (SiO_2) dioxide (Table 1). The chamber pressure was 2mTorr and was subjected to a 10/0.5 standard cubic centimeter (sccm) flow of argon/oxygen. The substrate plasma was generated at 100V bias.

The GRIN layers were followed by a 127nm layer of indium tin oxide (ITO), which was used as the hard mask for the patterning of the GRIN layers. Photolithography was carried out using a Shipley S1813 photoresist and the pattern transferred to the ITO mask using a methane/hydrogen/chlorine inductively coupled plasma reactive ion etch (ICP-RIE). Having formed the hard mask, the TiO_2–SiO_2 layers were patterned with trifluoromethane (CHF_3), again using ICP-RIE. The etch residues were removed using a 30 minute 80°C dip consisting of a photoresist stripper.

The tilt angle of the resulting pillars of dielectric was less than 5°. The patterns were either cylindrical or diamond-shaped pillars (Figure 1). These patterns were designed using theoretical calculations involving ray tracing.

Although the patterning increased the forward voltage of the devices, improved light output up to 131% was achieved. Patterning of GRIN layers on LEDs could also be used to convert trapped modes of light inside a semiconductor into designable modes with desirable properties, such as preferential direction of emission and polarization of light

Although the patterning increased the forward voltage of the devices, improved light output up to 131% was achieved (Table 2). The planar and roughened far-field emission patterns are described as 'Lambertian', with peaks at 0°, while the emission for cylindrical and diamond patterned GRIN layers peaks at an off-surface normal direction between 25° and 55° (Figure 2). The researchers comment: "The strong side emission is consistent with our expectations resulting from theoretical calculations."

The researchers suggest that patterning of GRIN layers on LEDs could also be used "to convert trapped modes of light inside a semiconductor into designable modes with desirable properties, such as preferential direction of emission and polarization of light."

Financial support came from a wide range of sources: Samsung LED Co, the Korean Ministry of Knowledge Economy through International Collaborative R&D Program, and the USA's Sandia National Laboratories, National Science Foundation, Department of Energy, Department of Defense, NY State Energy Research and Development Authority (NYSERDA), Magnolia Solar Inc and Raydex Technology Inc. ■

http://link.aip.org/link/doi/10.1063/1.3632072

Author: Mike Cooke

Table 2. Performance results for some of the devices compared at 4mA.

Type	Spacing	Dimensions	Improvement in light output	Forward voltage
Planar			0%	2.64V
Roughened			124%	2.7V
Cylinder GRIN	2μm	2μm diameter	104%	2.67V
Diamond GRIN	4μm	2μm x 4.7μm diagonals	131%	2.67V