Strong light extraction enhancement in GaInN light-emitting diodes by using self-organized nanoscale patterning of *p*-type GaN

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We report on a self-organized nanoscale patterning method by using oblique angle deposition to enhance the light extraction in a GaInN light-emitting diode (LED). The method offers one-step processing with good controllability of the feature size and density of the nanopatterns by varying the deposition angle during oblique angle deposition, eliminating the need for photolithography and annealing. A 5-nm-thick silver (Ag) film, when deposited by using oblique angle deposition, spontaneously forms a nanoscale island-like morphology on the substrate. This method is used to texture *p*-type GaN with nanoscale features, which results in increased light extraction from a GaInN LED. At 100 mA, the nanotextured LED shows a 46% higher light output than a standard LED with unpatterned (planar) *p*-type GaN. © *2011 American Institute of Physics*. [doi:10.1063/1.3554426]

In recent years, the field of semiconductor optoelectronics has seen tremendous technological and commercial progress. This rapid advancement is fueled mainly due to the promise of solid-state lighting, which is made possible by high-performance III-Nitride based light-emitting diodes (LEDs). Solid-state light sources are increasingly being used for applications ranging from low-power indicators to high-power illumination due to their advantages (e.g., higher efficiency, spectral and temporal control, longer lifetime, and robustness) over conventional light sources.

However, to successfully compete in the illumination market with conventional lighting technologies, LED efficiency has to further improve. Fundamentally, the ability of the semiconductor LED to convert electricity into light, quantified by the internal quantum efficiency—η_{IQE}, and the ability of efficiently extracting the generated light from within the semiconductor to the outside ambient, quantified by the light-extraction efficiency—η_{LEE}, are the two most important performance parameters of a LED. A planar GaN LED has a light-extraction efficiency of about 26%.[1] A major obstacle in achieving high light-extraction efficiency is posed by the high refractive index of the semiconductor material compared to the air ambient. The refractive index of GaN is 2.5 at 460 nm whereas that of air is 1.0. This causes as much as 18% of light to reflect back into the semiconductor at normal incidence. The critical angle of total internal reflection for GaN-air interface is merely 23° and severely limits the extraction efficiency of a GaN based LED.

Over the past few decades, a significant amount of research has addressed ways to improve light-extraction efficiency.[2] Various methods, including chip shaping,[3] contact geometry designs,[4] growth on patterned sapphire substrates,[5,6] photonic crystals,[7,8] graded-refractive-index antireflective contacts,[9] and micro or nanoscale texturing of light extracting surfaces[10,11] have been reported. Typically, the texturing of a surface involves additional lithography, deposition, etching, and high temperature processing steps. In photolithography, the feature size is limited by the wavelength used and is unsuitable for nanoscale patterning. Electron-beam lithography, although capable of producing nanoscale features, is unsuitable for high-throughput mass-production. Other techniques that use metal masks, such as e-beam deposited Ni, require a high temperature annealing step to form nanoscale islands and typically use a dielectric layer underneath the metal mask in order to prevent metal-migration into the semiconductor during annealing.

In this letter, we report a method of nanoscale patterning by using oblique angle deposition. We use this method to create a nanoscale texture on the *p*-side of a GaInN LED. As-deposited Ag metal is used as an etch mask in this method. The LED with *p*-side nanotexture shows strong improvement in light-output power over the LED with planar *p*-side. The experimental details and measurement results are discussed next.

A unique feature of oblique angle deposition is the ability to form self-organized nanostructures due to random growth fluctuations and self-shadowing effect. The details of this deposition technique are discussed elsewhere.[12] This method allows the controllability of feature size and density by varying the deposition angle during oblique angle deposition. Therefore, additional photolithography and annealing steps for nanoscale patterning are eliminated. When a thin film of Ag is deposited on a substrate by using oblique angle deposition, it spontaneously forms self-organized nanoscale island-like features. It has been reported that an Ag thin film grows as isolated islands up to critical thickness, above which the film coalesces.[13] Figure 1 shows the scanning electron micrographs of nanostructures with different feature

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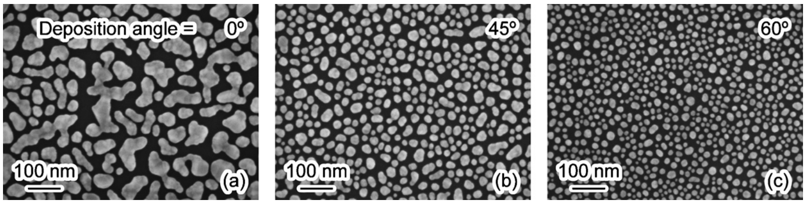

FIG. 1. Scanning electron micrographs of 5 nm Ag deposited on Si substrate by using oblique angle deposition at deposition angles of (a) 0°, (b) 45°, and (c) 60°.

sizes formed by oblique angle deposition. The nanostructures were obtained by deposition of 5 nm Ag on a Si substrate at (a) 0°, (b) 45°, and (c) 60° angles. It is evident from the figure that the size of Ag islands can be controlled by varying the deposition angle.

Next, we discuss a LED fabrication procedure to texture the *p*-type GaN surface of the LED by using Ag islands as the etch mask. It is expected that the nanotextured *p*-type GaN surface leads to improved light-output characteristics of the LED. The GaInN LEDs emitting at 460 nm were grown on a *c*-plane (0001) sapphire substrate by using a single-wafer Aixtron MOVPE system. The LED epitaxial structure consists of an undoped GaN layer (2 μm), a Si-doped *n*-type GaN layer (3 μm), a three-period GaInN/GaN multiple-quantum-wells (MQWs) active region, an undoped GaN spacer layer, a Mg-doped *p*-type AlGaN electron blocking layer (EBL) (35 nm), and a Mg-doped *p*-type GaN (150 nm). The wafers were annealed at 800 °C for 1 min under N_2 ambient for *p*-type GaN dopant activation. The standard LED fabrication process involves the following steps: Mesas of 1×1 mm^2 device area are defined by using standard photolithography and then etched by inductively coupled plasma reactive ion etching (ICP/RIE) (500/100 W) by using Cl_2/BCl_3 [50/20 SCCM (SCCM denotes cubic centimeter per minute at STP)] for 90 s. This is followed by electron-beam deposition of *n*-contact metal (Ti/Al/Ti/Au–30/120/40/50 nm), *p*-contact metal (semitransparent Pd–10 nm), and bonding metal (Ti/Au–20/300 nm) with appropriate photolithography steps preceding each metal deposition step. As-deposited Pd is known to form good nonalloyed electrical contacts to *p*-type GaN due to its high work function.[14,15]

Two representative samples, (a) Reference-LED and (b) Nanotextured-LED, are fabricated. The Reference-LED is fabricated by using the standard LED fabrication process as described above. The Nanotextured-LED is also fabricated by using the same standard LED fabrication process except for additional nanotexturing steps between the *p*-contact metal photolithography and deposition. Following the *p*-metal photolithography step, 5 nm Ag is deposited at 60° deposition angle by using oblique angle deposition. The wafer is then etched for 15 s in ICP/RIE by using the same power (500/100 W) and gas chemistry of Cl_2/BCl_3 (50/20 SCCM) as the mesa etch recipe. The Ag mask is then removed by using 70% $HNO_3:H_2O$ (1:1). The remaining fabrication steps, starting from the *p*-contact metal deposition, are the same as in the Reference-LED fabrication. Figure 2 shows the sequence of the additional steps in the Nanotextured-LED fabrication process required to perform the nanoscale texturing of the *p*-type GaN. Note that unlike most other nanoscale patterning methods, this approach does not require deposition of sacrificial layers or high temperature annealing.

Figure 3(a) shows scanning electron micrographs of a fully fabricated LED with nanotextured *p*-type GaN. A magnified view of the top surface of *p*-type GaN is shown in Fig. 3(b) and nanoscale texture on the *p*-side of the LED is clearly visible. Figure 3(c) shows the cross-sectional scanning electron micrograph of the nanotexture. The lateral features size in the nanotexture is 30–60 nm and the etch depth is ~50 nm.

The two types of LEDs are characterized by using an Agilent 4156B semiconductor parameter analyzer. The light-output power (*L*) is measured as a function of current (*I*) from 0 to 100 mA (pulsed mode, 1% duty cycle, 500 μs pulse width), in steps of 0.1 mA. Figure 4 shows the *L-I* plots of the Reference-LED and the Nanotextured-LED. Each plot is the average of 10 devices measured in a quarter of a 2 in. wafer. Compared to the Reference-LED, the Nanotextured-LED shows improved light-output characteristics. At a current of 100 mA, the Nanotextured-LED shows 46% higher light-output as compared to the Reference-LED. The inset in Fig. 4 shows optical microscopic images of the representative LEDs from the two samples at 20 mA. The Nanotextured-LED is visibly brighter than the Reference-LED. This result shows that the light-extraction efficiency of a GaInN LED significantly improves when the *p*-side is tex-

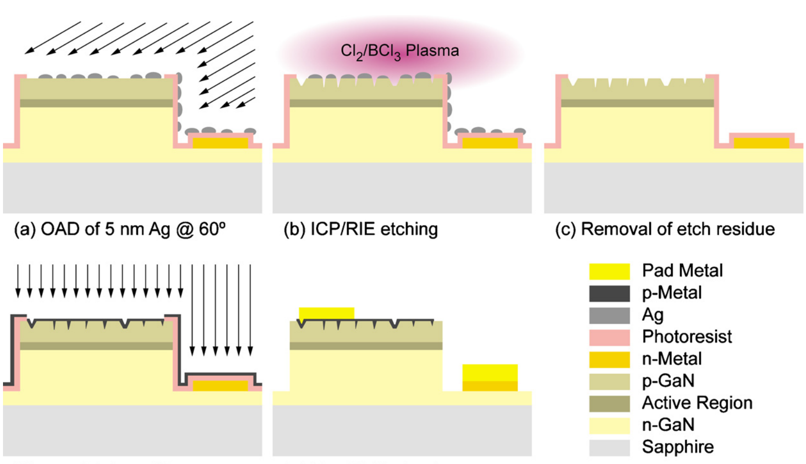

FIG. 2. (Color online) Schematic fabrication process flow of the nanotextured *p*-type GaN mesa of a GaInN LED.

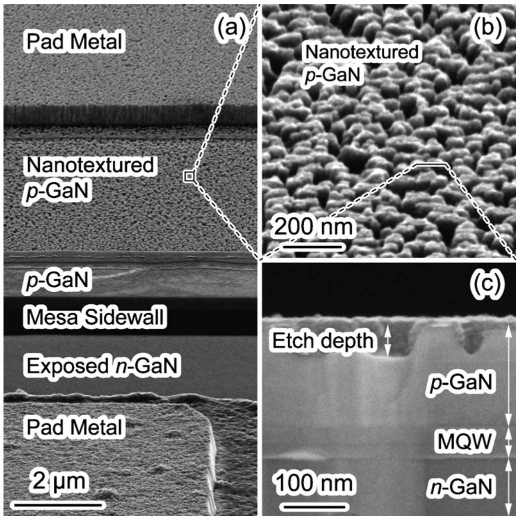

FIG. 3. Scanning electron micrographs of (a) the nanotextured *p*-type GaN mesa of a GaInN LED; (b) top view of the nanotextured *p*-type GaN; (c) cross-sectional view of nanotextured *p*-type GaN.

tured by using a simple self-organized nanoscale texturing technique enabled by oblique angle deposition. The average *I-V* characteristics of the LEDs are also shown as an inset in Fig. 4. The increase in the series resistance of the Nanostructured-LED is observed, which, we propose, is attributed to the increased contact resistance and current

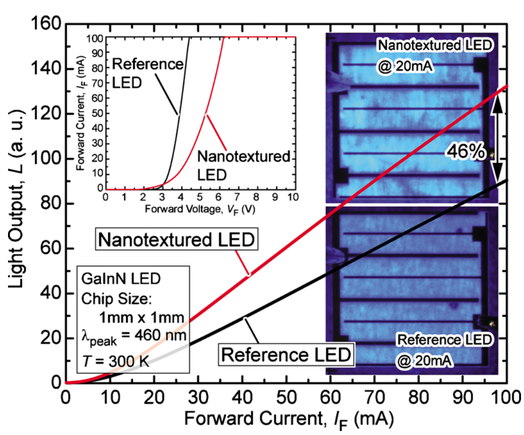

FIG. 4. (Color online) Light-output power vs forward current plots of reference and nanotextured LEDs. The inset shows the forward current vs forward voltage characteristics of the LEDs. The photographs of the illuminated LEDs at 20 mA are shown in the background.

crowding effect due to the reduction in the effective ohmic contact area and can be mitigated by the optimization as a further work.[16]

In summary, we have demonstrated a method for nanoscale patterning by using oblique angle deposition. The feature size and density of the nanopatterns can be controlled by varying the deposition angle during oblique angle deposition, eliminating the need for photolithography and annealing. The *p*-type GaN surface of a GaInN LED was nanotextured and deposited with a semitransparent Pd contact. The LED with nanotextured *p*-type GaN shows a 46% improvement in light-extraction efficiency over a standard planar *p*-type GaN LED.

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