Enhanced Light Extraction in GaInN Light-Emitting Diode With Pyramid Reflector

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***Abstract*—GaInN light-emitting diodes (LEDs) that employ a reflector consisting of an array of three-dimensional (3-D) SiO_2 pyramids and a Ag layer are demonstrated to have enhanced light extraction compared with GaInN LEDs with planar Ag reflector. Ray tracing simulations reveal that the pyramid reflector provides 14.1% enhancement in extraction efficiency. Consistent with the simulation, it is experimentally demonstrated that GaInN LEDs with the pyramid reflector show 13.9% higher light output than LEDs with a planar Ag reflector. The enhancement is attributed to the appearance of an additional escape cone for light extraction enabled by the 3-D pyramid reflector.**

***Index Terms*—GaN, light extraction, light-emitting diode (LED), reflector.**

I. Introduction

THE III–V nitrides provide very high internal quantum efficiencies in the short wavelength part of the visible spectrum and the near-ultraviolet spectrum. However, there is still a great need for improvement of light-extraction efficiency in III–V nitride light-emitting diodes (LEDs). Several methods have been demonstrated to yield a high light-extraction efficiency including shaping of LED dies [1], flip-chip mounting [2], roughening of the top LED surface [3], photonic crystals [4], and reflectors with high reflectivity [5]–[8].

An important problem facing light-extraction efficiency in LEDs is the occurrence of light that is trapped within the high-index semiconductor, due to total internal reflection (TIR). Trapped light is repeatedly reflected by TIR at the semiconductor/external medium interface or by a planar reflector. The optical output will continuously decrease due to mirror losses and re-absorption in the active region.

II. Device Structure and Optical Simulation

In this work, a new type of reflector with a 3-dimensional (3-D) structure, namely, a pyramid reflector consisting of an array of SiO_2 pyramids and a Ag layer, is used to increase the extraction efficiency of GaInN LEDs. The enhancement in light extraction is attributed to an additional escape cone that is enabled by the change in propagation direction of light rays when reflected by the pyramid reflector.

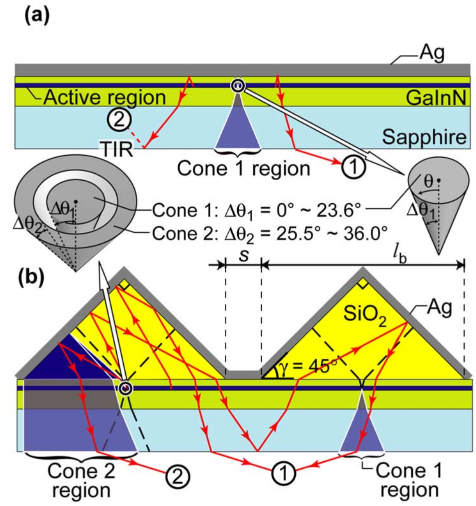

Fig. 1. Optical model and ray traces of (a) a conventional GaInN LED with a planar Ag reflector and (b) a GaInN LED with a pyramid reflector.

The optical model and ray traces for a conventional GaInN LED with a planar reflector are shown in Fig. 1(a). The escape cone of this LED is shown by Cone 1 with polar angle range $\Delta\theta_1 = 0°–23.6°$ calculated from Snell's law. The rays of light lying inside Cone 1 region, e.g., Ray 1, can be extracted into free-space. However, the rays of light lying outside Cone 1 region, e.g., Ray 2, are trapped by TIR. Fig. 1(b) shows the optical model and ray traces of a GaInN LED with a pyramid reflector consisting of a SiO_2 pyramid array and a Ag layer. The pyramids have a side slope $\gamma = 45°$. Cone 1 is still an escape cone for the structure with the pyramid reflector. Furthermore, there is an additional cone, Cone 2 with polar angle range $\Delta\theta_2$, from which the light propagation direction is changed to the range of $\Delta\theta_1$ after reflecting from the pyramid reflector so that light rays lying inside Cone 2, e.g., Ray 2, can be extracted to free-space. This case is shown in Fig. 1(b) by the Cone 2 region. Snell's law shows that Cone 2 has a polar angle range of $\Delta\theta_2 = 25.5°–36.0°$. Therefore, the pyramid reflector can improve the light-extraction efficiency.

An optical ray-tracing simulation is performed on both a GaInN LED with a pyramid reflector and a LED with a planar Ag reflector. In the simulation, the pyramid's base length is $l_b = 3.5\ \mu$m, and the spacing is $s = 2.0\ \mu$m. The square-shaped 100-μm-thick GaInN LED chip has a lateral dimension of $300 \mu\text{m} \times 300\ \mu$m. The following optical parameters at wavelength $\lambda = 400$ nm are used for the ray-tracing simulation:

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Color versions of Figs. 1–4 are available online at http://ieeexplore.ieee.org.

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TABLE I
SIMULATION OF LIGHT-EXTRACTION EFFICIENCY OF THE GaInN LED WITH A PYRAMID REFLECTOR WITH DIFFERENT PYRAMID SLOPE ANGLES γ AND LIGHT-EXTRACTION ENHANCEMENT COMPARED WITH THE LED WITH A PLANAR Ag REFLECTOR. THE PLANAR REFLECTOR HAS $\gamma = 0°$. (NA = Not Applicable)

γ(°)	Extraction Efficiency (%) [Enhancement (%)]		
	Side Wall	Bottom Surface	Total
0	11.7 [NA]	14.5 [NA]	26.2 [NA]
20	11.6 [–0.8]	18.0 [24.1]	29.6 [13.0]
30	11.4 [–2.6]	18.5 [27.6]	29.9 [14.1]
40	11.4 [–2.6]	18.1 [24.8]	29.5 [12.6]
50	11.2 [–4.3]	16.5 [13.8]	27.7 [5.7]

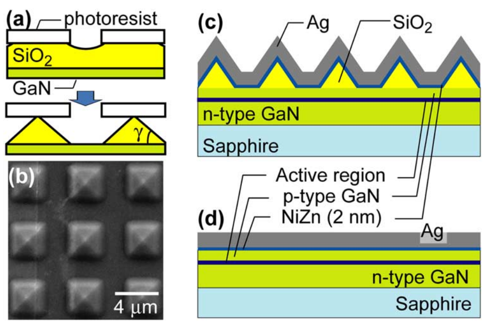

Fig. 2. (a) Isotropic wet chemical etching of SiO_2 to form pyramid pattern. (b) Top view scanning electron micrograph of SiO_2 pyramid pattern. (c) GaInN LED with pyramid reflector. (d) GaInN LED with planar Ag reflector.

$n_{\mathrm{SiO2}} = 1.47, n_{\mathrm{GaN}} = 2.5, n_{\mathrm{sapphire}} = 1.79, n_{\mathrm{Ag}} = 0.173$ are the refractive indices of SiO_2, GaN, sapphire, and Ag, respectively; $\alpha_{\mathrm{GaN}} = 150\ \mathrm{cm}^{-1}$ is the absorption coefficient of GaN, $k_{\mathrm{Ag}} = 1.95$ is the extinction coefficient of Ag. Different slope angles γ are simulated to find the optimal condition for the pyramid reflector. The simulation results, given in Table I, show that the pyramid reflector significantly increases the LED's bottom emission. With a pyramid slope angle of $\gamma = 30°$, the device has the highest bottom emission enhancement, 27.6%, and total emission enhancement, 14.1%.

III. DEVICE FABRICATION

To demonstrate the viability of our new concept, GaInN LEDs emitting at 400 nm that employ a pyramid reflector are fabricated. The GaInN LED structure was grown by metal-organic chemical vapor deposition on a c-plane sapphire substrate and consists of a 3-μm-thick n-type GaN buffer layer, an n-type GaN lower cladding layer, a GaInN–GaN multiple quantum-well active region, and a p-type GaN upper cladding layer. The LED mesa structure is obtained by standard lithographic patterning followed by chemically assisted ion-beam etching using Cl_2 and Ar to expose the n-type cladding layer. A 1.4-μm-thick SiO_2 layer is deposited on the wafer piece by plasma enhanced chemical vapor deposition. An array of SiO_2 pyramids on the p-type mesa is obtained by 13-min etching in buffered oxide etchant (BOE) after the lithography. BOE starts the etching on the exposed SiO_2 between the photoresist-covered areas, as indicated in Fig. 2(a), and continuously moves deeper both vertically and horizontally. This process creates an array of SiO_2 pyramids with $\gamma \approx 25°$ on the p-type GaN mesa. A scanning electron micrograph top view of the pyramid pattern is shown in Fig. 2(b).

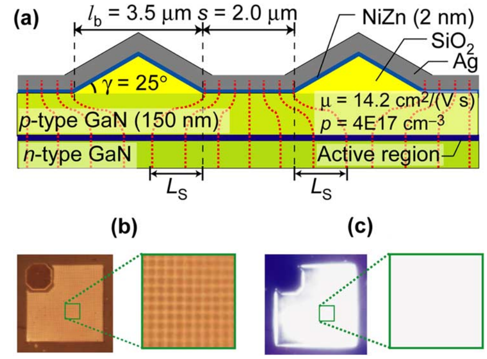

Fig. 3. (a) Current-spreading effect in p-type GaN layer for LED with pyramid reflector. (b) and (c) Micrographs of GaInN LED with pyramid reflector when the device is "off" and "on," respectively. The micrographs are taken from the back side of the device through the sapphire substrate.

The variation of the slope angle is within 5° for the same recipe from sample-to-sample. For each sample, all the pyramids have no obvious differences in slope angle. Each SiO_2 pyramid has a square base with width $l_b = 3.5 \mu$m. The spacing between the pyramids is $s = 2.0\ \mu$m. The height of the pyramids is 0.8 μm. After pyramid formation, 2 nm of NiZn (10 wt% of Zn) and 600 nm of Ag are deposited onto the pyramid patterned p-type mesa followed by annealing at 500°C in an O_2 ambient for 1 min to form ohmic contacts. Finally, the n-type contact is formed on the device with Ti–Al–Ni–Au to finish the device fabrication. The schematic of the GaInN LED with a pyramid reflector is shown in Fig. 2(c). As a comparison, a reference sample with a planar Ag reflector is fabricated from the same wafer piece, as shown in Fig. 2(d).

IV. CURRENT-SPREADING EFFECT ANALYSIS

Since the SiO_2 pyramids are insulators, the current can only flow into p-type GaN through the space between the pyramids. This lowers the effective contact area of the p-type GaN by a factor of $f = 1 - l_b^2/(l_b + s)^2$, which for our geometry $f = 0.595$. The p-type GaN layer functions as the current-spreading layer. The current flow is shown by the dotted red line in Fig. 3(a). The current spreads into the region underneath the SiO_2 pyramid pattern with a current-spreading length, L_S, which can be calculated by [9]

$$L_S = \sqrt{\frac{t\, n_{\mathrm{ideal}}\, k\, T}{\rho\, J_0\, e}}, \qquad \text{with } \rho = \frac{1}{\mu_p\, e\, p} \tag{1}$$

where t is the thickness of the current spreading layer; n_{ideal} is the diode-ideality factor, k is the Boltzmann constant, T is the temperature, J_0 is the current density at the top interface of the current-spreading layer. For our devices, the p-type GaN has a thickness $t = 150$ nm, a hole concentration $p = 4 \times 10^{17}$/cm^3, and a hole mobility $\mu_p = 14.2$ cm^2/(V s). The ideality factor is measured to be $n_{\mathrm{ideal}} = 4.5$. The area of the LED is $S = 300\ \mu\mathrm{m} \times 300\ \mu$m. Neglecting the area of the n-type contact, the current density J_0, that flows into p-type GaN layer from Ag contact is $J_0 = I_0/(Sf)$, where I_0 is the total injection current. The current-spreading lengths with different injection current levels are calculated and listed in Table II. The current-spreading length is comparable with the dimension of a

TABLE II
CALCULATED CURRENT SPREADING LENGTHS L_S OF THE p-TYPE GaN LAYER AT DIFFERENT INJECTION CURRENT LEVELS I_0

I_0 (mA)	L_S
10	2.92
20	2.06
50	1.30

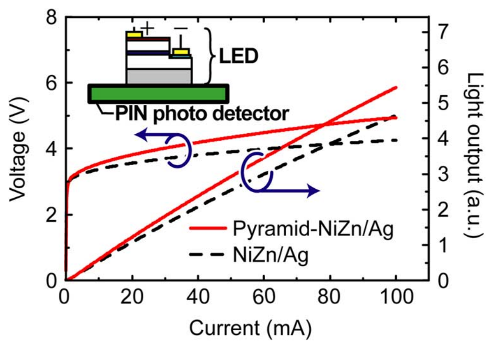

Fig. 4. Light output versus injection current and forward voltage versus current for GaInN LED with pyramid Ag reflector and planar Ag reflector.

single SiO_2 pyramid. This yields reasonable current spreading beneath the SiO_2 pyramid pattern. The micrograph in Fig. 3(b) clearly shows the SiO_2 pyramid array when the device is "off." The micrograph in Fig. 3(c) clearly shows uniform light intensity over the whole active region when the device is "on." This confirms our contention that the GaInN LED with pyramid reflector has good current spreading beneath the SiO_2 pyramids.

V. DEVICE CHARACTERIZATION

The electroluminescence intensity from the back side of the LED was measured directly on a large-size (10×10 mm^2) Si p-i-n photodetector biased at -5.0 V. A typical light-output-versus-current characteristic of the LEDs is shown in Fig. 4. The light-output power of the GaInN LEDs with the pyramid reflector is significantly higher than that of the LEDs with the planar Ag reflector. At an injection current of 20 mA, 13.9% enhancement of the light output is obtained. This improvement is consistent with the simulation result of 14.1%. We attribute the increased light output of the LEDs with pyramid reflector to higher light-extraction efficiency mainly due to an additional escape cone enabled by the 3-D structure of the pyramid reflector. Fig. 4 also shows typical current-versus-voltage characteristics of the GaInN LEDs. The forward voltage at 20 mA is 3.77 V for the LEDs with the pyramid reflector and 3.52 V for the LEDs with the planar Ag reflector. The higher forward voltage is attributed to the smaller contact area for p-type GaN with the pyramid pattern. It is anticipated that the light output of the GaInN LEDs with pyramid reflector can be further increased, while simultaneously decreasing the forward voltage by optimizing the spacing and size of pyramids.

VI. CONCLUSION

In summary, GaInN LEDs with a pyramid reflector consisting of an array of SiO_2 pyramids and a Ag layer on p-type GaN is demonstrated to have 13.9% enhancement of light output compared with conventional GaInN LED with a planar Ag reflector. Ray-tracing simulations reveal that the pyramid reflector provides 14.1% enhancement of extraction efficiency in GaInN LEDs, which is consistent with our experimental result, an enhancement of 13.9%. The enhancement is attributed to an additional escape cone for light extraction enabled by the change in propagation direction of light rays reflected by the 3-D pyramid reflector. The current spreading length is calculated to be a few micrometers, thereby enabling good current spreading beneath the SiO_2 pyramids.

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