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Light Extraction in GaInN Light-Emitting Diodes using Diffuse Omnidirectional Reflectors

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A theoretical and experimental analysis of light extraction in GaInN light-emitting diodes (LEDs) employing diffuse omnidirectional reflectors is presented. The diffuse omnidirectional reflector consists of GaN, a Ni/Au current spreading layer, a SiO_2 layer roughened by Ar ion etching, and a Ag layer. Randomly distributed polystyrene spheres are used as an etch mask. The diffusely reflected power is enhanced by two orders of magnitude for a roughened reflector surface compared with a planar surface. The GaInN LEDs with diffuse omnidirectional reflectors show a higher light output ($>3.3\%$) and a lower angular dependence of emission than LEDs with specular reflectors. The enhancement is attributed to reduced trapping of light within the high-index GaN semiconductor.
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GaN-based light-emitting diodes (LEDs) provide a higher performance in the ultraviolet and short-wavelength part of the visible spectrum than any other material system. However, there is still a great need for improvement of the light-extraction efficiency as well as the internal quantum efficiency. There are several ways to obtain high extraction efficiency including shaping of LED dies,[1] flip-chip mounting,[2] roughening of the top LED surface,[3] and introducing highly reflective omnidirectional reflectors (ODRs).[4,5] Electrically conductive specular ODRs comprising the GaInN epilayer, a quarter-wave-thick low-refractive index layer, and a metal have been demonstrated to have higher light output than LEDs with a Ag reflector.[6,7]

An important problem facing high extraction efficiency is the occurrence of trapped light within a high-index semiconductor.[8] Waveguided optical modes in the semiconductor cannot be extracted into the surrounding medium except through the side surfaces of the die. This problem is particularly severe for large refractive index differences between the semiconductor and the surrounding medium. The critical angle of total internal reflection of the semiconductor-air interface is given by $\theta_c = \sin^{-1}(1/n_s)$[8], where n_s is the semiconductor refractive index. The critical angle for the GaN ($n \approx 2.4$ at 470 nm) /air ($n \approx 1$) interface is $\sim 24°$, and thus most of the light emitted by the active region is trapped inside the GaN. The trapped light is repeatedly reflected as shown in Fig. 1a and can be reabsorbed by the active region or by the low-reflectivity metal electrodes. However, if waveguided light is reflected diffusively at the reflector, light may be scattered to angles inside the escape cone, and thus could be extracted out of the waveguide, as shown in Fig. 1b. Therefore, light extraction of waveguided modes can be enhanced by cladding the waveguide with a diffuse (Lambertian) reflector rather than a specular reflector. Real reflectors were recently shown to have both a diffuse as well as a specular component.[9] In our present work, we refer to surface-roughened reflectors as *diffuse* reflectors and reflectors without a surface-roughening process as *specular* reflectors.

In this work, enhancement of light extraction in GaInN LEDs employing diffuse ODR is presented. Randomly distributed polystyrene spheres (PSS) serve as mask for Ar ion etching used to roughen the reflector surface. The ideal diffuse reflector, also called the Lambertian reflector, has a cosine θ dependence of the reflected intensity where θ is the polar angle. It is shown that the diffusely reflected power is enhanced by two orders of magnitude for a roughened reflector surface. GaInN LEDs with diffuse ODR show a 3.3% higher light-output power and more uniform light distribution than LEDs with specular reflectors. Ray-tracing simulations confirm that the light-extraction efficiency is enhanced by diffuse ODR.

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Experimental

The GaInN LED structure was grown by metallorganic 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, a p-type GaN upper cladding, and a highly doped GaN contact layer. LED mesa structures were obtained by standard photolithographic patterning followed by chemically assisted ion-beam etching using Cl_2 and Ar to expose the n-type cladding layer. After 10 min dip in aqua regia solution to remove native oxide on p-type GaN, Ni/Au (50/50 Å) was deposited and annealed at 500°C in an O_2 ambient. A quarter-wave-thick SiO_2 layer was deposited on the annealed Ni/Au layer using plasma-enhanced chemical vapor deposition. Methanol solutions containing 445- and 740-nm-diam PSS were dropped on the clean SiO_2 surface. The PSS, distributed randomly by a spin-on process, were used as an etch mask. Ion-beam etching was performed using Ar ions with an ion energy of 600 eV and an ion-beam current of 20 mA for 3 min. An array of circular micro-openings was patterned on the roughened SiO_2 by HF etching, thereby exposing the conductive Ni/Au layer. Ag (1000 nm) was deposited by electron-beam evaporation on the SiO_2. The Ag perforates the SiO_2 and forms an array of microcontacts to the Ni/Au layer.

For comparison, LEDs with a specular ODR were fabricated on the same wafer piece. All the fabrication processes were done at the same time with the LEDs with a diffuse ODR except for the roughening of the SiO_2 surface. During the roughening process, the LEDs with a specular reflector were covered using photoresist. Figure 2 shows schematic cross-sectional views of the GaInN LEDs with ODRs. The device structures show both the diffuse and the specular reflector (GaN/oxidized Ni/Au/SiO_2/Ag ODRs) with a high index medium (GaInN LED) and a low index medium (sapphire and/or air). The structures shown in Fig. 2a and b are virtually the same structures as the conceptual structures shown in Fig. 1a and b, respectively. The chip dimensions are 300 × 300 μm. The radius of the circular microcontacts is 2 μm. The microcontact array covers only about 2% of the entire backside lit area of the LED chip. The n-type contact for the samples was fabricated by electron-beam evaporation of Ti/Al/Ni/Au. Ray-tracing simulations on the structures described above were performed using Light Tools software to estimate the change in light-extraction efficiency. In the simulations, both diffuse ODR and specular ODR were used. In order to measure the angular dependence of the reflected power of the mirrors with and without the roughening process, a 10 mW He-Ne laser emitting at 632.8 nm was used.

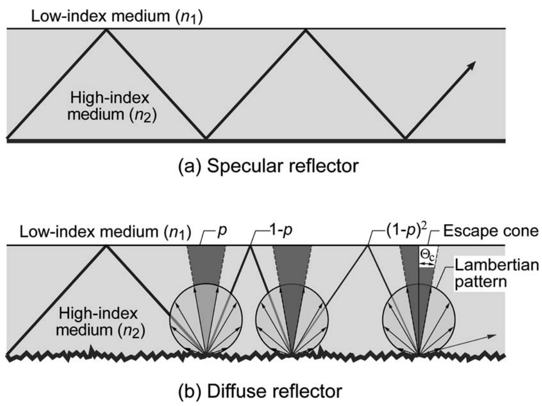

Figure 1. (a) Optical ray propagating in epilayer guided by specular reflector at lower and top interface. (b) Optical ray propagating in epilayer clad by a diffuse reflector at the lower interface. n_1 and n_2 are refractive indices of medium 1 and 2, respectively, and p is the probability of light extraction following a reflection event.

Results and Discussion

Consider an optical ray propagating in a semiconductor guided by a specular reflector and a partially diffuse reflector at the semiconductor/reflector and the semiconductor/air interfaces, as shown in Fig. 1a and b, respectively. If light is reflected specularly, the light outside the escape cone propagates in the waveguide. If the light is reflected diffusely by the reflector, part of the reflected light propagates at angles less than the critical angle of total internal reflection θ_c, and thus can be extracted out of the waveguide. The probability of light extraction following a reflection event is given by[9]

$$p = R\frac{P_{\text{diff}}}{P_{\text{diff}} + P_{\text{spec}}}\frac{\int_0^{\theta_c} I_{\text{diff}} \cos\theta \sin\theta 2\pi d\theta}{\int_0^{\pi/2} I_{\text{diff}} \cos\theta \sin\theta 2\pi d\theta} \quad [1]$$

where R is the reflectivity, P_{diff} and P_{spec} are the powers of diffuse and specular reflection, respectively, and I_{diff} is the intensity of diffuse reflection along the normal direction. If, after N reflection events, the intensity in the waveguide has decreased to 1/e of its original value, then $(1 - p)^N = 1/\text{e}$. Considering Snell's law for the critical angle of total internal reflection and assuming $R = 1$ in Eq. 1, N is given by[9]

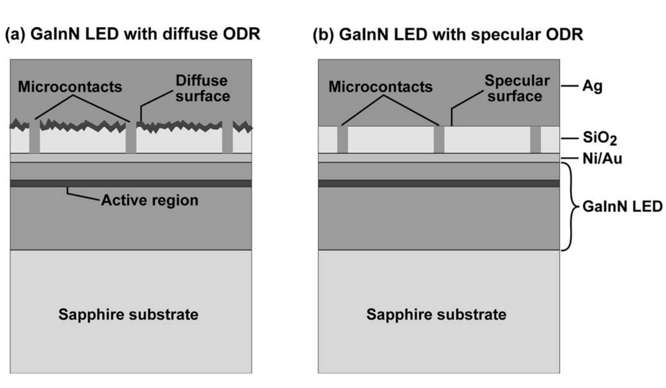

Figure 2. Schematic cross-sectional view of GaInN LED with (a) diffuse ODR and (b) specular ODR.

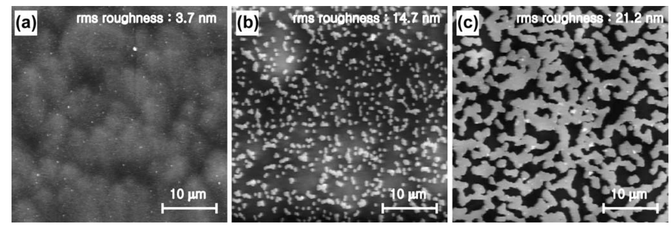

Figure 3. Atomic force microscopy (AFM) images of (a) a SiO_2 surface before Ar-ion etching, and after Ar-ion etching using (b) 445-nm- and (c) 740-nm-diam PSS masks. The rms roughness is (a) 3.7 nm, (b) 14.7 nm, and (c) 21.2 nm.

$$N = -\left[\ln\left(1 - \frac{P_{\text{diff}}}{P_{\text{diff}} + P_{\text{spec}}}\frac{n_2^2}{n_1^2}\right)\right]^{-1} \quad [2]$$

where n_1 and n_2 are the refractive indices of the semiconductor and the surrounding medium, respectively. Note that low values of N are desirable to minimize absorption losses, which can be achieved by maximizing the diffuse component of the reflectivity.

In order to measure the change of surface roughness of the SiO_2 low-index layer caused by ion etching, atomic force microscopy (AFM) measurements were performed. Figure 3 shows AFM images of the SiO_2 surface before and after ion etching using 445- and 740-nm-diam PSS as etch masks. The rms roughness of SiO_2 before Ar ion etching is 3.7 nm. After ion etching, the rms roughness increases to 14.7 and 21.2 nm for samples masked with 445 and 740 nm PSS, respectively.

Figure 4 shows the angular dependence of reflected power measured on partially diffuse reflectors fabricated by ion etching, and a Ag specular reflector. The incident angle θ_i of the He-Ne laser was 40° and the reflected power was measured from −90 to 90°, as shown in the inset of Fig. 4. The figure clearly shows that the roughened reflectors have a specular as well as a diffuse component of reflectivity while the specular reflector has only a specular component. Note that the diffusely reflected power is enhanced by two orders of magnitude by the roughening of the reflector surface. Fitting of a theoretical model[9] to the experimental data reveals that the diffuse ratio $P_{\text{diff}}/P_{\text{total}}$ is 42.8% for the 740 nm diffuse reflector and 38.1% for the 445 nm diffuse reflector. For the Ag specular reflector, the diffuse ratio $P_{\text{diff}}/P_{\text{total}}$ is only 0.35%.

The distribution of light-output power from LEDs, calculated using three-dimensional ray-tracing simulation, is shown in Fig. 5. The square-shaped 200-μm-thick GaInN LED chip with lateral dimensions of 300 μm × 300 μm is located at the center of the

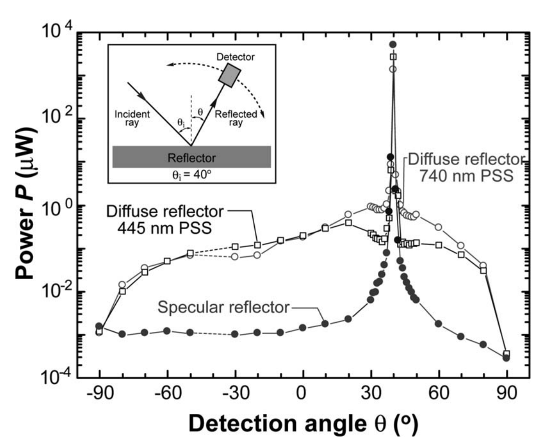

Figure 4. Angular dependence of reflected power measured from diffuse reflectors fabricated by Ar ion etching using 445-nm- and 740-nm-diam PSS as etch masks, and Ag specular reflector.

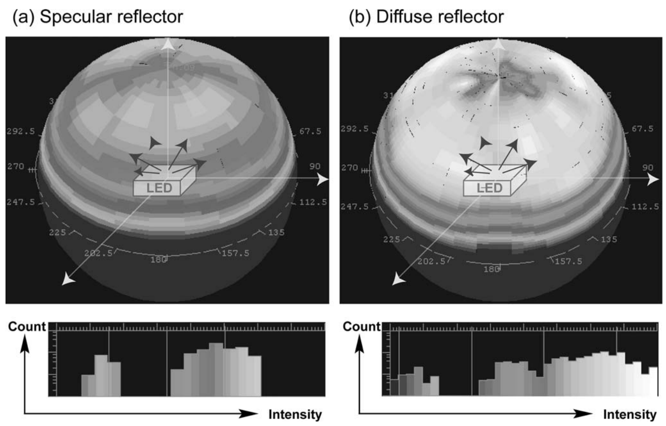

Figure 5. Light intensity distribution of (a) LED with specular ODR, and (b) LED with diffuse ODR, calculated by ray tracing simulation.

sphere. The following optical parameters of the device structure were used for the ray-tracing simulation: $\lambda = 470$ nm, $n_{SiO_2} = 1.46$, $n_{GaN} = 2.4$, $n_{sapphire} = 1.8$, $n_{Ag} = 0.151$, the absorption coefficient of GaN $\alpha_{GaN} = 150\ cm^{-1}$, and the extinction coefficient of Ag $k_{Ag} = 2.48$. The distribution of light-output power of the LED with a diffuse reflector is more uniform than that of the LED with specular one. The light extraction from the top of the LED with a diffuse reflector is 30.7%, larger than that from the LEDs with a specular reflector, 22.7%. However, the side-emission of the LED with a diffuse reflector is 17.8%, slightly lower than that of the LED with specular reflector, 19.1%, due to fewer waveguided optical modes inside the high-index semiconductor. Note that the difference in side-emission power between the two samples is relatively small because of optical loss occurring during the multireflection events in the LEDs with specular reflectors. Considering the optical loss by an absorptive metal contact, which is not taken into account in the simulation, the decrease of side-emission power by using a diffuse reflector should be even lower. The overall light extraction obtained from the simulation is 41.8 and 48.5% for the LED structure with specular ODR and diffuse ODR, respectively.

Figure 6 shows the average light-output power from the backside of 30 representative LED chips as a function of detection angle. A blue-enhanced Si PIN photodetector with a ~1-mm-diam aperture was used. The standard deviation between the individual value of light-output power at all the detection angles is in the range of

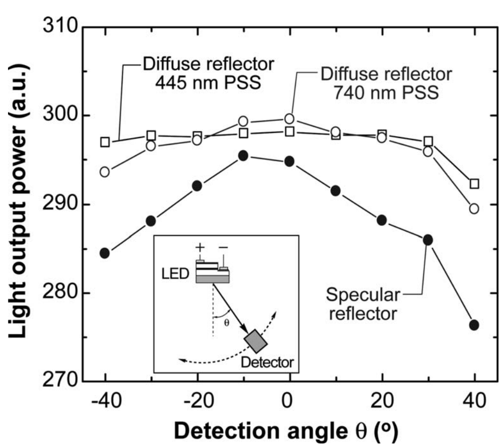

Figure 6. Light-output power through sapphire substrate of LEDs as a function of detection angle θ. The data points correspond to averages of 30 devices.

0.3-2.0 (average: 1.1) using the units of the ordinate of Fig. 6. For the LEDs with specular reflector, the light-output power is highest around normal emission and decreases rapidly as $|\theta|$ increases. For the LEDs with diffuse reflectors, the distribution of light-output power is more uniform. In addition, the light-output powers from the LEDs with diffuse reflectors are higher than those from the LEDs with specular ones at all the detection angles. This is consistent with the ray-tracing simulation result. The total light-output power from the LEDs over the solid angle is given by

$$P_{total} = \frac{r^2}{A}\int_{\theta} P(\theta)2\pi \sin\theta d\theta \qquad [3]$$

where r is the distance between the LED and the detector, and A is the area of the aperture in front of the detector. The LEDs with diffuse reflectors show higher total light-output power by 3.2 and 3.3% for the 445 and 740 nm PSS sample, respectively, than the LEDs with specular reflectors in the entire measured range (−40 to +40°). Because light-output power of the LED with specular reflector decreases with $|\theta|$ more rapidly than that of the diffuse ODR-LED, the total increase in light-output is expected to be much higher than 3.3%. Furthermore, because the LED chip emits light isotropically, only half of the light emitted by the active region is directed toward the reflector. Therefore, the effective enhancement of light reflected by the diffuse reflector is at least two times larger (>6.6%) than the measured enhancement. The enhancement of light output by using diffuse reflectors is attributed to the reduction of trapped waveguided light within the high-index GaN semiconductor.

Conclusion

We presented the enhancement of light extraction in GaInN LEDs employing a diffuse ODR rather than specular ODR. The diffuse ODR consists of GaN, an oxidized Ni/Au current spreading layer, a SiO_2 layer roughened by Ar ion etching, and an Ag layer. Randomly distributed PSS with diameters of 445 and 700 nm are used as etch masks. It is shown that the diffusely reflected power is enhanced by two orders of magnitude by roughening the reflector surface. Ray-tracing simulation reveals that light extraction increases by using a diffuse ODR rather than a specular ODR. Thirty representative LEDs with diffuse reflectors show higher light-output by at least 3.2 and 3.3% for the 445 and 740 nm PSS sample, respectively, than the LEDs with specular reflectors. This is attributed to reduced trapping of light within the high-index semiconductor.

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References

1. M. R. Krames, M. Ochiai-Holcomb, G. E. Höfler, C. Carter-Coman, E. I. Chen, M. G. Craford, T. S. Tan, C. P. Kocot, M. Hueschen, J. Posselt, B. Loh, G. Sasser, and D. Collins, *Appl. Phys. Lett.*, **75**, 2365 (1999).
2. J. J. Wierer, D. A. Steigerwald, M. R. Krames, J. J. O'Shea, M. J. Ludowise, G. Christenson, Y.-C. Shen, C. Lowery, P. S. Martin, S. Subramanya, W. Götz, N. F. Gardner, R. S. Kern, and S. A. Stockman, *Appl. Phys. Lett.*, **78**, 3379 (2001).
3. T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, *Appl. Phys. Lett.*, **84**, 855 (2004).
4. Y. Fink, J. N. Winn, S. Fan, C. Chen, J. Michel, J. D. Joannopoulos, and E. L. Thomas, *Science*, **282**, 1679 (1998).
5. T. Gessmann, E. F. Schubert, J. W. Graff, K. Streubel, and C. K. Arnutsch, *IEEE Electron Device Lett.*, **24**, 683 (2003).
6. T. Gessmann, Y.-L. Li, E. F. Schubert, J. W. Graff, and J. K. Sheu, *Proc. SPIE*, **4996A**, 139 (2003).
7. J. K. Kim, T. Gessmann, H. Luo, and E. F. Schubert, *Appl. Phys. Lett.*, **84**, 4508 (2004).
8. E. F. Schubert, *Light-Emitting Diodes*, p. 119, Cambridge University Press, Cambridge, U.K. (2003).
9. Y. Xi, J. K. Kim, F. Mont, Th. Gessmann, H. Luo, and E. F. Schubert, *Appl. Phys. Lett.*, Submitted.