Optimization of top polymer gratings to improve GaN LEDs light transmission

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We present a grating model of two-dimensional (2D) rigorous coupled wave analysis (RCWA) to study top diffraction gratings on light-emitting diodes (LEDs). We compare the integrated-transmission of the non-grating, rectangular-grating, and triangular-grating cases for the same grating period of 6 μm, and show that the triangular grating has the best performance. For the triangular grating with 6-μm period, the LED achieves the highest light transmission at 6-μm grating bottom width and 2.9-μm grating depth. Compared with the non-grating case, the optimized light transmission improvement is about 74.6%. The simulation agrees with the experimental data of the thin polymer grating encapsulated flip-chip (FC) GaN-based LEDs for the light extraction improvement.

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In general, GaN solid-state lighting is very critical for future energy conversion. It is a very hot research area and revolutionizes the lighting industry, and is being called "the next generation light sources". Customers worldwide use light-emitting diode (LED) chips to replace traditional bulb technology with solid-state products that provide a powerful and energy-efficient source of blue, green, or white lights. Growth in the high-brightness LED market in the next few years will be driven by lighting, display backlighting, and automotive applications. LEDs are the advanced form of a lamp, and its development can and will continue until all power levels and colors are realized. However, low external quantum efficiency is one of the biggest obstacles for the GaN LED development. Because of the high refractive index of GaN-related material and/or indium tin oxide (ITO) top contact layers, only a few percentage of internal light escapes and is collected outside. Most of the light generated in the active layer experiences total internal reflection and loss in the device material. A common way to solve this light trapping is to form nano/microstructures at the light extraction surface or the bottom reflective layer of the LEDs[1−5]. It has been shown that the micro-sized patterning of the ITO top transparent electrode[6,7] or one-dimensional (1D) nano-patterned structure results in an enhancement of light extraction compared with conventional LEDs (C-LEDs)[8].

For commercial applications, low cost and simplicity in fabrication are desired. It has been demonstrated by Peking University in 2008 that 31.9% of the light extraction enhancement was achieved by using the triangular patterned encapsulated flip-chip (FC) GaN LEDs compared with C-LEDs[9]. In this design, the surface gratings and the encapsulation of a polymer can be simultaneously accomplished in a single procedure. Therefore, it can realize thin and low-cost LED package. Based on this work, we utilize the two-dimensional (2D) rigorous coupled wave analysis (RCWA)[10,11] to GaN-based LED grating model and study top polymer diffraction grating on GaN-based LED grating model design. We also provide a design guideline for the improvement of the LED light extraction and optimize the micro-patterned polymer top grating design. To keep the comparison simple, we still keep the simulation grating period fixed to 6 μm according to our initial experiment[9].

The core algorithm of the model is based on RCWA and enhanced with modal transmission line theory. RCWA represents the electromagnetic fields as a sum of coupled waves[10,11]. A periodic permittivity function is represented using Fourier harmonics. Each coupled wave is related to a Fourier harmonic, allowing the full vectorial Maxwell's equations to be solved in the Fourier domain. Currently, plane wave incidence is assumed and the material is assumed lossless to simplify the calculation. The schematic diagrams of the top grating lattices for the simulation are shown in Fig. 1 with flat interface (non-grating), rectangular interface, and triangular interface. The plane wave is incident from semi-infinite homogenous polymer (refractive index is 1.5) to semi-infinite homogenous air (refractive index is 1.0). The incident angle θ upon the normal of the grating varied from 0° to 90°. The simulation is performed at 460-nm wavelength according to the GaN LED experimental spectra[9]. For each incident angle θ, we calculate the −20 to +20 order diffraction efficiency. The total power transmission is calculated at the end of simulation by summing all the diffraction modes. In the initial simulation (Fig. 2), we calculate three cases according to Fig. 1, in which the cases of Figs. 1(b) and (c) are grating period $\Lambda = 6$ μm, grating height $d = 4$ μm, and grating bottom width $w = 3$ μm. Our simulation shows that the critical angle

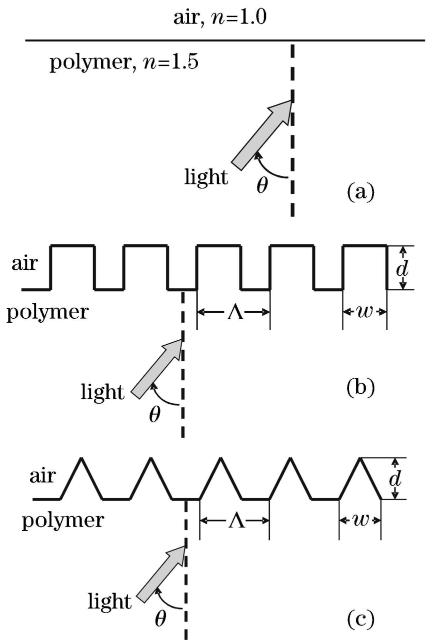

Fig. 1. Simulation schematic diagrams of the top grating lattices. (a) Flat interface (non-grating); (b) rectangular interface; (c) triangular interface.

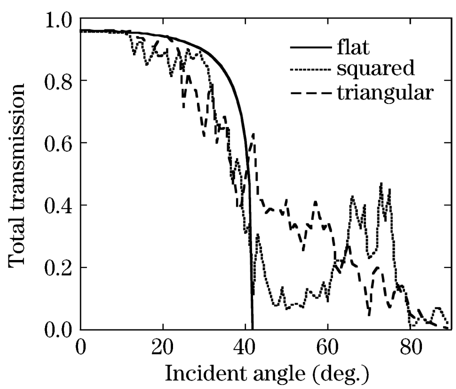

Fig. 2. Comparison of transmission for non-grating (flat), squared-grating, and triangular-grating cases.

is $\theta_c = 42°$ for the non-grating case. For the incident angle above the critical angle of 42°, there is no light transmission for the non-grating case, which agrees with Fresnel's law. In the rectangular and triangular cases for comparison, the transmittance is a little lower for the incident angle below the critical angle. However, the transmittance of the gratings is significantly increased for the incident angle above the critical angle, since a grating can extract some trapped light. The total transmission is the transmittance integrated over the entire region of θ from 0° to 90°, which are 21.79%, 31.60%, and 34.13% for the non-grating case, the squared-grating case, and the triangular-grating case, respectively. Improvements of about 45% (squared) and 56.6% (triangular) are obtained over the non-grating case. This means the triangular-grating has a higher total transmitting diffracting effect than that of the squared grating. In the previous experiment[9], the enhancement factor of light extraction for the triangular grating ($\Lambda = 6$ μm, $d = 4$ μm, and $w = 3$ μm) was 31.9%, which should include light transmission from GaN layer to polymer and from polymer to air. Our above simulations only consider the polymer to air transmission. If we include GaN to polymer transmission efficiency in the simulation, the total transmission from GaN layer to air should be 8.40% with triangular grating and 6.41% without grating, which is about 31.1% improvement. Our triangular-grating simulation results agree with the experimental data presented in Ref. [9] very well.

Increasing the top grating transmission will directly improve the total light extraction of LEDs. To keep the simulation time short and simplify the problem, we still focus on the polymer grating calculation for our design optimization. Figure 3 shows the simulation results of the transmission versus the incident angle for the triangular-grating case. The grating period is 6 μm, and the grating depth is 4 μm. The bigger the grating bottom width, the more light transmits at an incident angle above the non-grating-case critical angle and the less light transmits at an incident angle below the non-grating-case critical angle. To understand the total transmission efficiency, we integrate the transmittance over the incident angle and normalize the integration. The final results of the optimized triangular grating for period $\Lambda = 6$ μm are shown in Fig. 4. At a small value of the grating height d, the transmittance improvement at the large incident angle is dominating. At the largest d value the transmittance improvement at the large incident angle is almost equal to the transmittance degradation at the small incident angle; therefore the total efficiency will not be improved any more with the further increase of the grating height d.

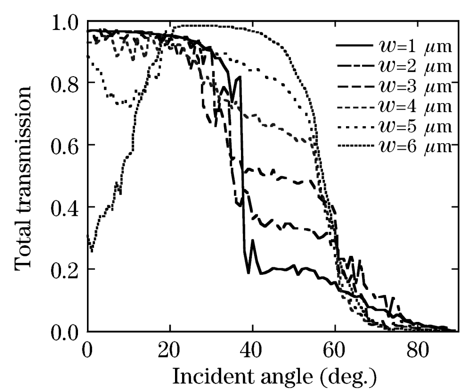

Fig. 3. Simulation results of the light transmission for the triangular-grating case. $\Lambda = 6$ μm, $d = 4$ μm.

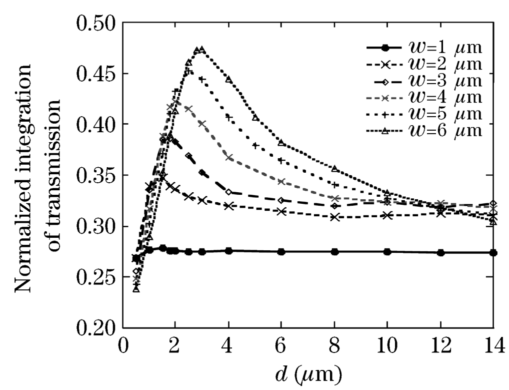

Fig. 4. Light transmission versus grating height for different grating bottom widths of polymer grating at the period of 6 μm.

There exists an optimal value in the grating depth design. We can clearly see that the 6-μm grating width and the 2.9-μm grating depth provide the highest light extraction rate. Compared with the non-grating case, the maximum light enhancement is about 117% for the triangular-grating case, which is much better than 56.6% of the non-optimized case in Fig. 2. Our data clearly shows that the diffraction of the grating improves the overall light extraction of the GaN LEDs.

Even though our simulation is only performed at one grating period value (6 μm), this is a very representative and informative case, which enlightens several design guidelines for the GaN LED grating clearly. Firstly, at the same grating period, the triangular grating has the best performance compared with the non-grating and squared-grating cases. Secondly, for the triangular grating, the grating bottom width (w) should be set to the grating period (Λ) to obtain the highest light extraction efficiency. Thirdly, the light transmission coefficient of triangular gratings varies according to either w or d variation, which changes the light incident angle at the interface and modifies the total light extraction. The gratings can greatly improve light extraction above the non-grating-case critical angle, but decrease the light extraction below the non-grating-case critical angle. Overall, there is an optimzation point for the design. Fourthly, our triangular grating experimental data[9] is right on our simulation chart Fig. 4. This shows that our experimental results can be further improved. Finally, there are also other parameters, such as grating period and polymer material index (can be equal to 1.5, 1.4, or even 1.3) can be considered in our future simulations to further improve the light extraction beyond this work.

In conclusion, we compare the flat interface (non-grating), rectangular-grating, and triangular-grating cases, and show that the triangular grating has the best performance. For the triangular grating with a 6-μm period, the LEDs have the highest light transmission, which reaches the maximum output at 6-μm width and 2.9-μm grating depth. Compared with the non-grating case, the maximum light transmission improvement for just the grating is about 117%. If we include the GaN layer in the simulation, the total light transmission is about 11.19%, which is an improvement of about 74.6% upon the non-grating case.

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