Enhanced light extraction from a GaN-based green light-emitting diode with hemicylindrical linear grating structure

Yuanhao Jin, Fenglei Yang, Qunqing Li, Zhendong Zhu, Jun Zhu, and Shoushan Fan

Department of Physics and Tsinghua-Foxconn Nanotechnology Research Center, Tsinghua University, Beijing 100084, China

State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing 100084, China

Abstract: Significant enhancement in the light output from GaN-based green light-emitting diodes (LEDs) was achieved with a hemicylindrical grating structure on the top layer of the diodes. The grating structure was first optimized by the finite-difference time-domain (FDTD) method, which showed that the profile of the grating structure was critical for light extraction efficiency. It was found that the transmission efficiency of the 530 nm light emitted from the inside of the GaN LED increased for incidence angles between 23.58° and 60°. Such a structure was fabricated by electron-beam lithography and an etching method. The light output power from the LED was increased approximately 4.7 times compared with that from a conventional LED. The structure optimization is the key to the great increase in transmission efficiency. Furthermore, the light emitted from the edge of the LED units could be collected and extracted by the grating structures in adjacent LED units, thus enhancing the performance of the whole LED chip.

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References and links

1. Introduction

GaN is a promising material for blue-green light emitting diodes (LEDs) and white light sources and has attracted considerable attention because of numerous applications [1–4], particularly in the areas of LCD screen backlighting [5] and general illumination [6]. However, the transmission efficiency of LEDs is limited by several factors, including the high refractive index of p-GaN (approximately 2.52) [7]. Therefore, the critical angle of 23.58° at the interface of p-GaN and air limits the external quantum efficiency (EQE) of conventional GaN-based LEDs to only a few percent [8]. Photons emitted beyond this angle undergo total internal reflection (TIR) at the interface and thus become internally confined.

Several methods have been proposed to enhance the light extraction efficiency of LEDs, such as texturing the emitting surface [9–11], using a patterned substrate [12], and generating photonic crystals in LEDs [13]. However, improvements in GaN LEDs using these methods have been limited to factors of 1.5–2 times [14–19], despite much higher increases being predicted theoretically. This is partly because the unoptimized vertical design of the LEDs does not achieve maximum interaction of the guided modes with the designed photonic crystal structure, and also because of the use of nonoptimal lattice constants.

Here, a GaN LED light enhancement structure is presented. It was found that a linear grating on the top layer of the diodes with optimized parameters and profile can significantly enhance the light output of GaN-based green light-emitting diodes. The hemicylindrical grating (HG) structure is fabricated by electron beam lithography (EBL) and reactive ion etching (RIE). The light output power of the fabricated LED is increased approximately 4.7 times compared with that of a conventional LED. The improved performance comes from the increased transmission efficiency of the light at angles between 23.58° and 60°. Furthermore, it is demonstrated that this structure could guide the light from the edges of neighboring LEDs to radiate in the vertical direction with high efficiency. This application could allow full utilization of the light radiated from the edges of LEDs.

2. Simulation

In this study, the finite-difference time-domain (FDTD) method was employed to simulate the light transmission efficiency of the LED with a linear grating structure on the p-GaN layer, using the Fullwave function of commercial Software Rssoft. Figure 1 shows the model of a GaN LED unit with a linear grating. Three kinds of linear gratings with different profiles were calculated, including a rectangle grating (RG), a hemicylindrical grating (HG), and a concave...
hemicylindrical grating (CHG), with an unstructured planar LED as a reference. An additional transparent conducting layer of Ni(2 nm)/Au(5 nm) was put on top of the GaN structures in order to reflect the real conditions in the experiment. It is assumed that TE and TM mode light with a wavelength of 530 nm was emitted from the top of the multi quantum well (MQWs) layer in the GaN LED unit as constant light sources and transmitted to the GaN/air interface, separately. The thickness of the p-GaN epitaxial-layer is set to 0.5 μm for the situation of planar LED, with its refractive index as 2.4. The refractive index values of Au / Ni layers are 0.402 + 2.54i and 1.75 + 3.19i. The period boundary condition in the lateral direction was set and the simulation cell was shown in the left side of Fig. 1 for each kind of gratings. The spatial grid is 5nm × 5nm × 5nm and the temporal discretization is 12 attosecond. We choose to terminate the simulation at 1.85 picoseconds in order to allow the change of the energy decay to a negligible level (35dB) to ensure simulation convergence. The transmission efficiency of TE and TM light was calculated separately. The total transmission is the sum of these two polarization. The grating period and duty cycle for these three gratings were optimized based on the total transmission efficiency. The grating period and duty cycle for these three gratings were optimized based on the total transmission efficiency.

![Figure 1](image)

Fig. 1. Cross-sectional views of the GaN LED with four configurations, left side is the total view of the grating and the right side is the cell of the FDTD simulation: (1) conventional planar LED, (2) LED with rectangle grating (RG) on top of the p-GaN layer, (3) LED with a concave hemicylindrical grating (CHG) on top of the p-GaN layer, (4) LED with a hemicylindrical grating (HG) on top of the p-GaN layer. Light is emitted from the MQW layer and θ is the incidence angle.

Figure 2 shows the simulation results of the transmission efficiency of the light from inside of the GaN LED as a function of the incidence angle. In Fig. 2(a), we can see that for the planar GaN sample, the critical angle is 23.58° at the p-GaN/air interface and that no light was transmitted from the inside of the GaN LED at angles greater than 23.58°. For the
rectangular linear grating structure with the period of 460nm (line width of 320nm and height of 160nm), the transmission at angles between 0° and 23.58° is obviously degraded, but the light can be transmitted at angles between 23.58 and 60°. For the HG structure, the transmission at angles between 0° and 23.58° is somewhat less than that in planar GaN, but at angles between 23.58° and 60° the transmission increased significantly. For the concave HG structure, the situation is similar, in that the transmission is suppressed at angles between 0° and 23.58° but the transmission at angles between 23.58° and 65° is increased. Both of the HG structure and concave HG structure are with the same parameter, including the period of 460nm, the diameter of 320nm and the height or depth of 160nm. The areas below the transmission line in Fig. 2(a) represent the total transmission efficiencies, which are 47.7, 37, 30, and 24 for the HG structure, the CHG structure, the RG structure, and the planar structure, respectively. These results indicate that the total transmission efficiency for the HG-structured, CHG-structured, and RG-structured GaN is about 1.99, 1.54, 1.25 times that of the unstructured GaN, respectively. Thus, the HG structure is more suitable for enhancing the light extraction of LEDs.

The optimized parameters of the HG structures were determined as follows. We scanned the diameter of the hemicylinder from 200 nm to 380 nm, with a step of 20 nm for the period of the grating as 420 nm, 440 nm, 460 nm, 480 nm and 500 nm, separately. The total transmission efficiency was calculated, and for each period the diameter with the largest transmission efficiency was selected. In Fig. 2(b), the largest transmittances for different periods are presented in polar coordinates, with the unstructured LEDs as reference. From the area under the transmittance line, the total transmission efficiencies could be calculated as 30.7 for the period of 500nm, 47.5 for the period of 480nm, 47.7 for the period of 460nm, 47.4 for the period of 440nm and 32.6 for the period of 420nm. We found that the best results occur with the HG structures with a period of 460 nm and an optimized cylinder diameter of 320 nm.

3. Device fabrication

To fabricate the HG-structured LEDs, a GaN LED wafer was employed, which consisted of a 200 nm p-type GaN layer, a layer of InGaN/GaN quantum wells, an n-type GaN layer, and a GaN buffer layer. The peak emission wavelength of the LED is centered at 530 nm. Nanogratings were formed by EBL and transferred to the p-GaN layer by RIE [18]. After the fabrication of the nanostructures, the GaN wafer was used to fabricate LEDs using standard processes with a mesa area of 1 mm². A transparent conducting layer (TCL) of Ni (2 nm) and Au (5 nm) was deposited on the p-GaN grating. Ni (5 nm)/Au (100 nm) electrodes were then fabricated by photolithography exposure and electron-beam evaporation on the n-GaN layer.
and TCL, as n- and p-pads, respectively. For comparison, a standard LED device was fabricated with a TCL directly deposited on the p-GaN layer; otherwise the fabrication processes were the same as those used for the HG-structured LED. Figure 3(a) shows a cross-sectional view of the fabricated HG GaN LEDs.

To obtain hemicylindrical gratings on the surface of the p-GaN layer, RIE etching parameters were adjusted carefully. In conventional etching of GaN, much attention is focused on obtaining a very straight edge. In this study, it was intended that lateral etching would vary gradually while the longitudinal etching proceeded. Thus, the etching conditions were adjusted to a mixed etching gas of Cl₂ and Ar with flow rates of 10 and 25 sccm, respectively, a chamber pressure of 2 Pa, and a plasma power of 70 W. Figure 3(b) shows a cross-sectional view of the hemicylindrical grating being etched with the modified conditions. It can be seen that the average depth of the hemicylindrical structures is about 160 nm, with a diameter of 320 nm and a period of 460 nm. All of these parameters strictly satisfy the hemicylindrical grating requirements, which are optimized in the simulation.

4. Experimental results and discussion

The optical properties of the HG-structured LEDs were investigated by electroluminescence (EL) spectroscopy. Figure 4(a) shows the EL spectra of the LEDs both with and without the HG structure operating at a forward injection current of 10 mA. Both devices exhibited similar EL spectra, which demonstrate that the HG structure fabricated on the p-GaN layer did not affect the MQW quality. However, the EL intensity was enhanced approximately 4.7 times for the device with the HG structure compared with that of the standard LED. Figure 4(b) represents the forward current-voltage (I-V) characteristics of the LEDs both with and without the HG structure. It is clear that the electrical characteristics of the two types of LEDs are the same, indicating that the HG structures and their fabrication processes did not alter the electrical properties of the LED. The inset in Fig. 4(b) shows the light output power versus injection current (L-I) characteristics of these two kinds of LED units. The enhancement of the output power of the HG-structured LED increased as the injection current increased.
Fig. 4. (a) EL spectra from standard and HG-structured LEDs at an injection current of 10 mA. (b) I-V characteristics of standard and HG-structured LEDs. The inset shows the characteristics of light output power versus injection current.

Optical microscopy images of the LEDs both with and without the HG structure at an injection current of 10 mA are shown in Fig. 5. In order to obtain an accurate comparison, the images were taken using the same camera settings. Figure 5(a) shows the luminescence image of the standard LED, while Fig. 5(b) depicts the image of the LED with the HG structure. The LED patterned with the HG structure is much brighter than the conventional LED under the same current injection.

The increased brightness of the HG-structured LED could be explained by the transmission of the 530 nm green light emitted from the LEDs being increased at incidence angles between 23.58° and 60°. The experimental results of the devices were much better than the simulation data, which showed that the total transmission of the HG-structured LEDs should be approximately two times that of the unstructured ones. The higher enhancement achieved experimentally arises from the final extraction of light that is emitted at larger angles after being reflected several times between the substrate and p-GaN surface. Thus, the HG structure could extract more light from internal emission than was predicted theoretically.

Fig. 5. Optical microscopy images of LEDs (a) without and (b) with the HG structure. Both are operated at an injection current of 10 mA.

Furthermore, it was noted that the light emitted from the edge of the LED could be collected and extracted by the HG structure of adjacent LED units, as suggested in Fig. 6(a) and Fig. 6(c). Figure 6(a) is an optical microscopy image of two adjacent HG-structured devices, in which only the left device was powered with an injection current of 20 mA. It can be seen that there is also light emitted from the adjacent device on the right. From the EL...
spectra of these two units (Fig. 6(b)), we can see that the intensity of the light emitted from the right adjacent unit is about half of the left unit.

The adjacent devices are electrically isolated, which can be seen in Fig. 6(c). It was also noted that the unpowered units were totally dark if they were not structured with HG even when their neighbors were bright powered LED units. This confirms that the HG structure on the adjacent LED unit extracted the light emitted from the edge of the powered unit, and emitted the light perpendicularly. In our experiment, the phenomenon could be observed between the two adjacent LED units with a minimum distance of 10 micrometers. And the light could also be extracted by the third LED unit, with the maximum distance of 1020 micrometers from the powered LED unit (with the LED unit size of 1mm square). Therefore, the HG structure could allow full utilization of the light from the edges of LEDs, improving the light-emitting properties of the whole chip.

4. Conclusion

In conclusion, GaN LEDs containing a HG structure on a p-GaN layer were fabricated and their EL properties were studied. Significant enhancement in the light output from GaN-based green light-emitting diodes was achieved. The grating structure was first optimized by the finite-difference time-domain (FDTD) method and simulation results showed that the profile of the grating structure is critical for the light extraction efficiency. A hemicylindrical grating structure (HG) was fabricated by electron beam lithography (EBL) and reactive ion etching (RIE). At an injection current of 10 mA, the light output power of the HG-structured LED was enhanced approximately 4.7 times compared to that of the unstructured LED. The enhancement was caused by increased light extraction between the emergent angles of 23.58° and 60°. Furthermore, it is demonstrated that this structure could guide the light from the
edges of neighboring LEDs to radiate in the vertical direction with high efficiency. This application could thus allow full utilization of the light radiated from the edges of LEDs.

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