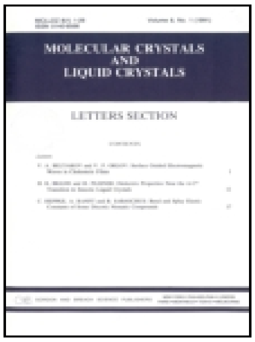

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Improved Light Extraction of GaN-based LED with Patterned Ga-doped ZnO Transparent Conducting Layer

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ABSTRACT
In this study, patterned Ga-doped ZnO transparent conducting layers were made to increase the light-extraction efficiency of GaN-based LEDs. The patterns were designed by different side length, spacing and depth of the concave squares. Simulations and experiments were taken to study the light output powers of LEDs made by patterned transparent conducting layers. The area of the vertical sidewalls of the patterns is thought to have important effect on the light extraction of LEDs. With bigger sidewalls, the escape possibility of photon can be increased. Compared with conventional LEDs with planar Ga-doped ZnO transparent conducting layers, the light output power can be increased by 8.9% via using 10μm side length, 5μm spacing and 400 nm depth concave square patterns, which is basically consistent with the simulated results.

KEYWORDS
LED; light extraction; patterned surface; Ga-doped ZnO

1. Introduction

Nowadays, GaN-based light emitting diodes (LEDs) have achieved dramatic development due to their widely applications in traffic signals, backlighting sources for display and solid-state lighting [1,2]. Transparent conducting layers (TCLs), such as indium tin oxide (ITO, Sn doped In_2O_3) has been widely used to improve the current spreading of p-GaN due to its high transmittance (>80%) in the visible region and low electrical resistivity ($\sim 10^{-4}\Omega$cm) [3]. However, it is widely believed that indium shortage may occur in the future and indium will soon become a strategic resource in the world. Recently, zinc oxide (ZnO) has attracted much attention. Impurity such as Al, In and Ga doped ZnO is thought to be a possible alternative for ITO because of its similar optical and electrical characteristics as compared to ITO [4].

It is well known that the external quantum efficiency of LED is usually limited by total internal reflection [5]. Due to the large difference in the refractive index, the critical angle of total internal reflection at GaN-air interface is very small. The photon can not pass through and is entirely reflected if the incident angle is greater than the critical angle. In order to improve the light-extraction efficiency (LEE), as an effective technique, patterned surface have been used because it can change the light propagation path and reduce the total internal reflection

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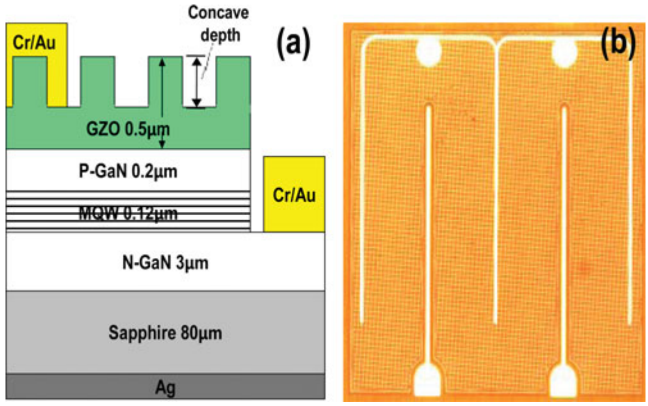

Figure 1. (a) Schematic device structure with cross-section view, (b) the top-view graph of the LED chip with patterned GZO surface. The chip size is 1×1 mm^2.

[6,7]. Sheu [8] have studied the periodic textured Ga-doped ZnO (GZO) surface and found the light output power was increased by 48.9% as compared with planar GZO surface. Lim [9] used HCL aqueous solution to create GZO pyramids and found the output power was increased by 26.5% for patterned GZO/Ni/Au and 21.5% for Ni/Au/patterned GZO.

In this study, patterned GZO TCLs have been used to improve the light extraction efficiency of LEDs. Patterns were designed by different side length, spacing and depth of the concave squares. Optical simulation software (Tracepro) was used to simulate the luminescence properties of LEDs with these patterned GZO TCLs. At the same time, the corresponding LEDs were made to verify the simulated results.

2. Experiment

The GaN-based LED wafers used in this study were grown on (0001) sapphire by metal organic chemical vapor deposition (MOCVD) [8,10]. The peak emission wavelength of these wafers was approximately 460 nm. After deposition, the GaN wafers were dipped in HCL solution for 10 min to remove the oxide layer from the surface of p-GaN, and ultrasonically cleaned with acetone and isopropyl alcohol for 10 minutes. Afterwards, 500 nm GZO thin

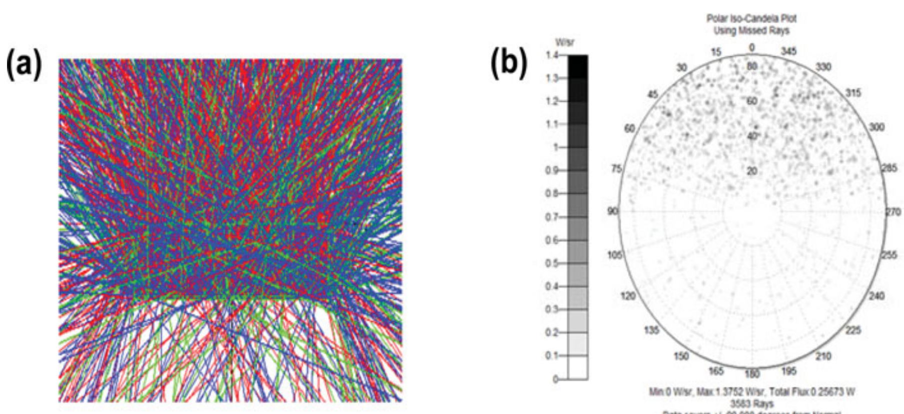

Figure 2. (a) Ray tracing of simulated LED with GZO TCL, (b) Polar ISO-Candela Plot (using missed Rays) of LED with unpatterned GZO TCL

Table 1. Parameters of the LED material properties.

Material	Refractive index	Absorption coefficient (mm^{-1})
Sapphire	1.71	0
n-GaN	2.5	8
MQWs	2.5	8
p-GaN	2.5	8
GZO	2.008	0.01

films were deposited on GaN surface by RF magnetron sputtering using a GZO (0.6 wt.% Ga_2O_3) target, which was purchased from ULVAC, Inc. The GZO target with 0.6 wt.% Ga_2O_3 is widely used in the electrodes of solar cell. The resistivity of the GZO thin films was about $5\times10^{-4}\Omega\cdot$cm and the light transmittances of these films were above 90% in the visible region. Different patterned surfaces of GZO were made by conventional lithography process before LED process. Ion beam etching was used to fabricate different concave depths of the patterns on GZO surface. The etching atmosphere is argon and the etching rate is 14 nm/min. LED chips using these patterns were fabricated by standard LED chip process [4,8] with a chip size of 1 × 1 mm^2. The cross-section and top-view graph of patterned LED is shown in Fig. 1(a) and (b). The optical transmittance and output power of the LEDs were measured using a UV/VIS spectrophotometer (U-3000 spectrophotometer) and IPT6000 LED chip-prober.

3. Simulation

Tracepro was used in this simulation. Patterned sapphire substrate (PSS) was used in this experiment. The bottom of the LED is Ag layer, which was defined as mirror surface, and the light reflectivity was set to be 98%. The upper and lower surfaces of MQW layer was defined as the light emitting area. As shown in Fig. 2(a), the image is complex with too many lines (each line has different colors). These lines represent the tracing rays, which were used to simulate the light tracing. The total luminous power was set to be 1 watt with 10000 tracing ray numbers. The thickness of the GZO thin films is 500 nm. On the top of the GZO layer, there is an absorbing surface, which was used to collect the numbers of tracing rays. The luminous flux of LED was calculated by the polar ISO-candela plot, which is a build-in function of TracePro software. For example, as seen in Fig. 2(b), 3583 tracing rays was collected and the simulated total flux (light output power) was 0.25673W for LED with unpatterned GZO surface. The refractive index and absorption coefficient of these materials were summarized in Table 1. The details of patterns used in this simulation and the simulated results for LED with patterned GZO surface will be discussed below.

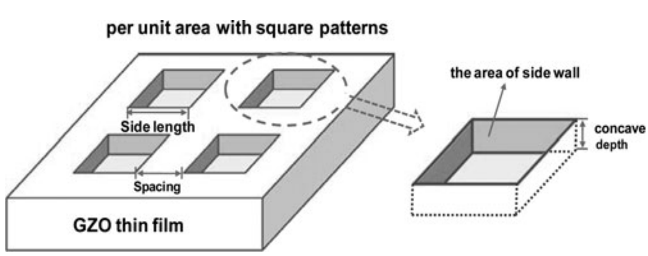

Figure 3. Schematic diagram of the concave square patterns.

Table 2. Light output powers of simulated and experiment results of LEDs with different TCL patterns measured at 350 mA.

	Unpatterned device	Device-A	Device-B	Device-C	Device-D
Simulated results (mW)	256.7	266.5	264.4	275.5	273.4
Increase (%)	/	3.8	2.9	7.3	6.5
Experiment results (mW)	223.8	229.3	224.9	240.2	233.6
Increase (%)	/	2.4	0.5	7.3	4.3
Area of sidewall per unit area (arb. unit)	/	1.125	1 (ref.)	2	2.25

4. Result and discussion

The schematic diagram of the patterned GZO surface is shown in Fig. 3. Different side length and spacing (5 and 10 μm) were used in this experiment. The side length means the side length of one square. The spacing means the distance between two squares. The side wall means the vertical area of the concave squares. The area of side wall per unit area means the total area of the sidewall in per unit area, which can be calculated by multiply the numbers of square in per unit area by the sidewall area of one square. The simulated results of LED with different patterns were summarized in Table 2. The concave depth of the patterns was 300 nm. LEDs with 10 μm side length and 10 μm spacing patterns were labeled as Device-A. LEDs with

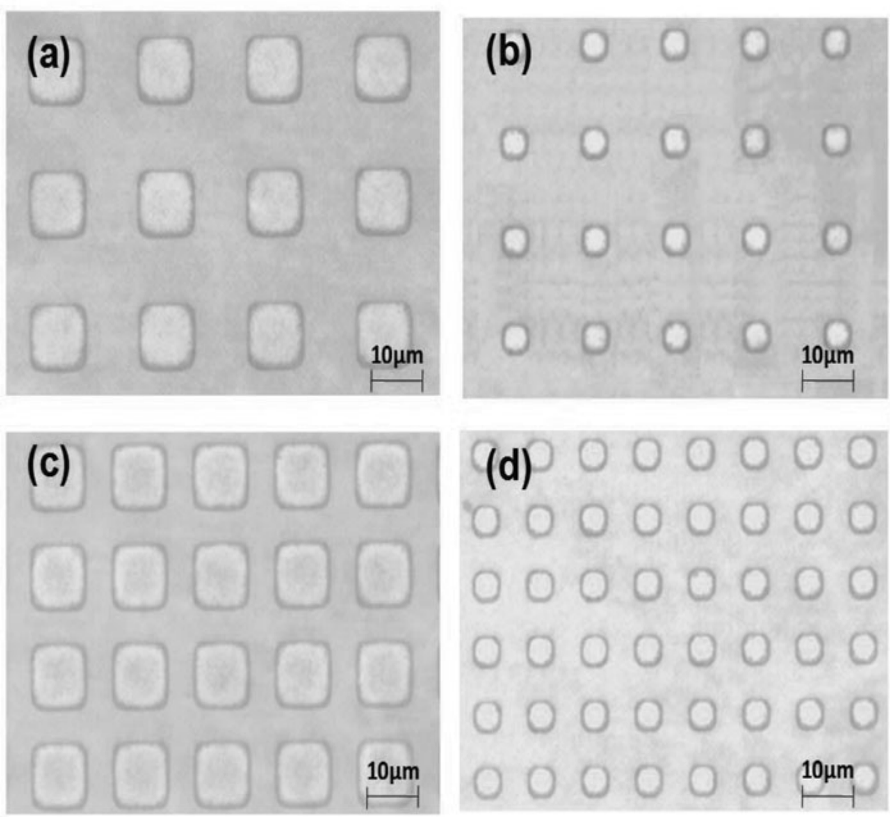

Figure 4. Top-view graph of patterned GZO surface by optical microscope with 10 μm side length and 10 μm spacing (a), 5 μm side length and 10 μm spacing (b), 10 μm side length and 5 μm spacing (c), 5 μm side length and 5 μm spacing (d).

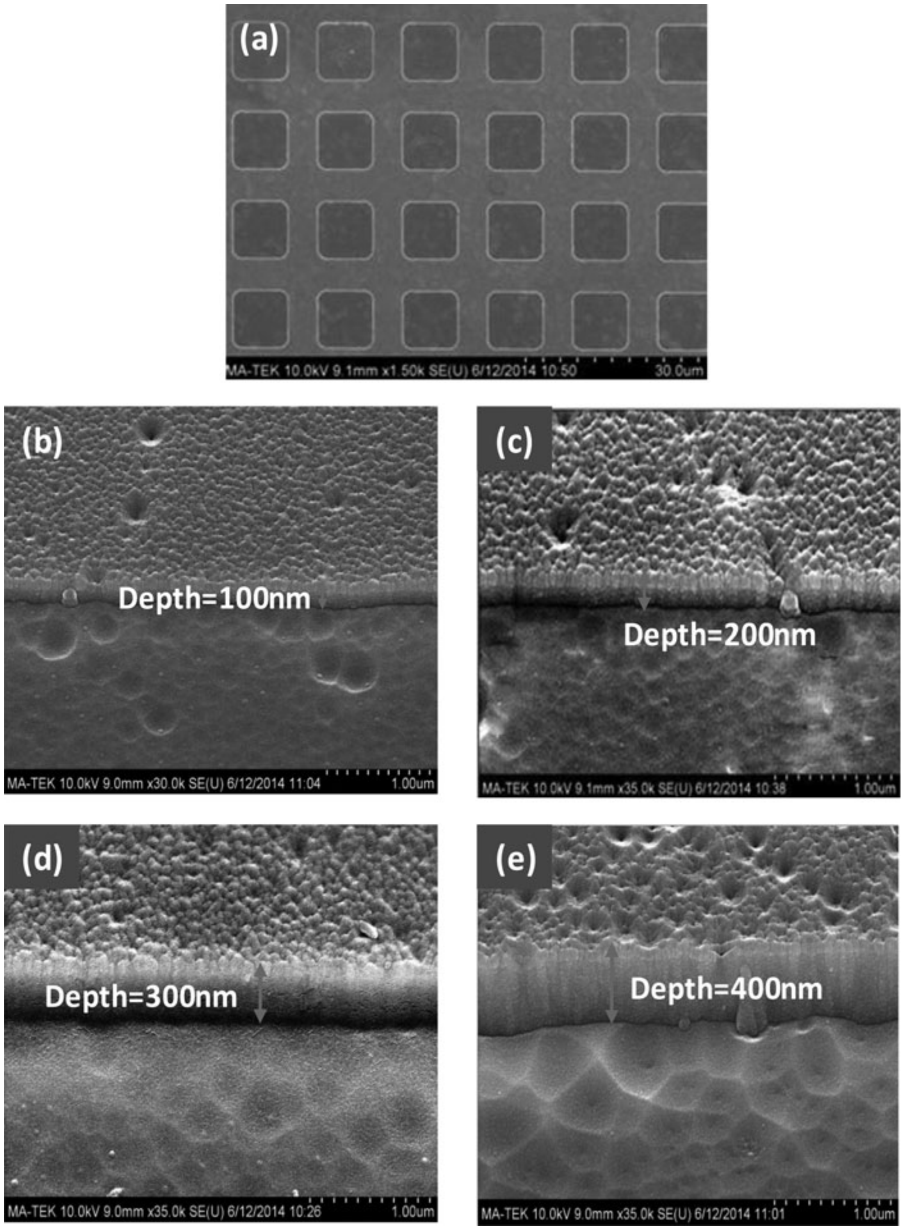

Figure 5. SEM images of (a)top-view patterned GZO surface, patterns with (a)100 nm etching depth, (b)200 nm etching depth, (c)300 nm etching depth, (d)400 nm etching depth.

5 μm side length and 10 μm spacing patterns were labeled as Device-B. LEDs with 10 μm side length and 5 μm spacing patterns were labeled as Device-C. LEDs with 5 μm side length and 5 μm spacing patterns were labeled as Device-D. Compared with unpatterned device, the highest increasing rate of 7.3% was obtained by Device-C, whereas the lowest increasing rate was 2.9% by Device-B. The simulation results indicate that patterns with bigger side length and smaller spacing are beneficial for the improvement of light extraction.

In order to verify the simulated results, LED chips with the patterned GZO TCLs were made. Fig. 4 shows the top-view graph of the GZO patterns used in the experiment. These patterns were in accordance with the simulation conditions. For each pattern, 6 chips were

Table 3. Light output powers of simulated and experiment results of LEDs with different TCL concave depths measured at 350 mA.

Concave depth (nm)	Unpatterned device	100	200	300	400
Simulation results (mW)	256.7	259.2	269.1	275.5	277.6
Increase (%)	/	1.0	4.8	7.3	8.1
Experiment results (mW)	223.8	226.7	233.4	240.2	243.9
Increase (%)	/	1.3	4.3	7.3	8.9
Area of sidewall per unit area (arb. unit)	/	0.33	0.67	1 (ref.)	1.33

randomly selected in the LED wafer and the light output power was measured. The mean value of light output powers were calculated and summarized in Table 2. With an injection current of 350 mA, the light output powers are 240.2 mW for device-(c), which is 7.3% larger than that of unpatterned device. This result is coincidently consistent with the simulated result (7.3%). The photon extraction occurs at the etched GZO sidewall, whereas the unpatterned device has no such sidewall due to the planar surface of GZO thin film [8].

The patterned surface can disturb the original incident angle; result in the scatter of light at the sidewalls of the patterns. Therefore, the increase of light output power can be attributed to the sidewalls of the patterns. The sidewall areas of the four patterns in per unit area were calculated in Table 2 and the sidewall areas in per unit area of Device-B was used as reference. It is found that the sidewall areas of Device-C and D is 100% and 125% larger than that of Device-B in per unit area; this means the probability of photon escape of Device-C and D is much higher than that of Device-B. In contrast, the light output power of Device-B is 224.9 mW, which is only 0.5% larger than that of unpatterned device. This increased value is much lower than the simulated result (2.9%). It was caused by the inaccuracy of lithography process in our experiment. As seen in Fig. 4(b) and (d), the side length of the patterns is a bit smaller than 5 μm thus the sidewall areas were also decreased compared with the simulated results. Nevertheless, the trend of the experimental results is basically consistent with the simulation results. Among these four patterns, patterns with 10 μm side length and 5 μm spacing has the best light extraction efficiency.

To further understand the effect of the patterned GZO surface on the light extraction of LED, different concave depths on the same pattern were made. As seen in Fig. 5(a), patterns with 10 μm side length and 5 μm spacing were selected and the concave depths were 100, 200, 300 and 400 nm. The SEM images of the patterns etched by different concave depths were shown in Fig. 5(b-d). The simulated and experimental results were summarized in Table 3. It is found that the light output power increases with the increase of etching depth. With an injection current of 350 mA, the light output power of LED made by patterned GZO with 400 nm etching depth were 243.9 mW, which was 8.9% larger than that of unpatterned device. However, the light output power of LED made by patterned GZO with 100 nm etching depth was increased only by 1.3% as compared with the unpatterned device. The sidewall areas were also calculated to account for the increase of light output power. Patterns with 300 nm etching depth were used as reference. It can be found that the sidewall area of the patterns with 400 nm etching depth is 33% larger than that of the pattern with 300 nm etching depth. As a consequence, it resulted in higher light output power.

5. Conclusions

In conclusion, LEDs with patterned GZO TCLs were made. The patterns were designed by different side length, spacing and depth of the concave squares. The simulation results indicated that bigger side length and smaller spacing are beneficial for the enhancement of light extraction. By comparison of the four patterns, Device-C has the highest light output power. With an injection current of 350 mA, the light output power of Device-C can be increased by 7.3% compared with that of the unpatterned device. Moreover, from the investigation of the concave depth of the patterns, the light output power can be further increased to 8.9% by increasing the concave depth to 400 nm as compared with that of the unpatterned device. The area of sidewalls is thought to have important effect on the light extraction of LEDs. With bigger sidewalls, the escape possibility of photon can be increased. The simulation work here is very meaningful because the experiment results are basically consistent with the simulation results. Therefore, a reasonable design of the pattern structure is important for the improvement of light extraction efficiency.

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