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Investigation of InGaN/GaN power chip light emitting diodes with TiO_2/SiO_2 omnidirectional reflector

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Abstract
Enhancements of light extraction of GaN-based power chip (PC) LEDs with and without rough surface on p-GaN and TiO_2/SiO_2 omnidirectional reflector (ODR) on the bottom are presented. Motivated by phosphor-conversion white light applications, the peak-emitting wavelength of our studied PC LEDs is chosen to be 455 nm and the fabricated ODR is designed for the same wavelength regime. At a driving current of 350 mA and a chip size of 1 mm × 1 mm on a TO-can package, the light output power of the PC LED with ODR on the bottom and pit type of rough surface on p-GaN is enhanced by 67% when compared with the same device without ODR and rough surface. Furthermore, by examining the radiation patterns, the PC LED with the ODR and rough surface shows stronger enhancement around the vertical direction. Our results provide promising potential to increase output powers of commercial light emitting devices, especially for white light applications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Impressive recent developments of high brightness gallium-nitride (GaN)-based light-emitting diodes (LEDs) have made possible their use in large size flat-panel displays [1, 2]. There is still a great need to improve the internal as well as external quantum efficiency to increase their light output power in order to further drive down the total cost of LED modules. However, it is well known that LEDs are inherently inefficient because photons generated by spontaneous emission within the device are emitted in all directions with random polarizations. To improve the external quantum efficiency and the output power of conventional LEDs, light emitted downward toward the substrate should be reflected upward in order to contribute to useable light output [3–6].

In general, metallic mirrors can reflect light efficiently over a broad range of wavelengths at arbitrary incidence angles. However, metallic mirrors cannot be perfect because of the absorption variance for different wavelengths [7]. Among metallic reflectors, Ag and Al are known to have good reflectivity with low absorption in the blue wavelength region, but they usually suffer from poor mechanical adhesion and thermal instability, namely, agglomeration and the formation of voids during post-deposition annealing. Therefore, these problems still need to be further resolved for commercial purposes. In addition, a recent work has indicated that light absorption by metallic mirrors becomes more severe when the thickness of the device is reduced [8]. As a result, a distributed Bragg reflector (DBR) that is composed of optical materials can be used to avoid the absorption instability problem [9]. They have many advantages, such as low optical loss, high reflectance and high mechanical robustness, compared with

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their metallic counterpart [10]. However, the high reflectance of a DBR can only be achieved at a given incidence angle and light polarization.

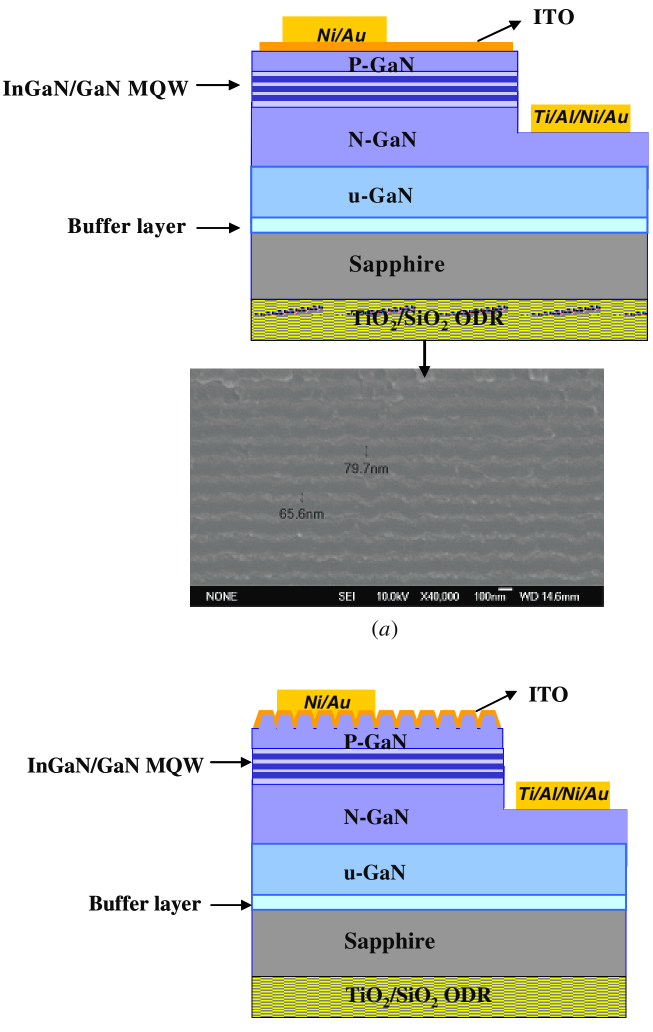
Total reflection of light with an arbitrary polarization at an arbitrary incidence angle onto a periodic structure can be realized with the existence of a complete photonic band gap (CPBG) at the wavelengths of interest [11]. A one-dimensional periodic dielectric structure possessing this characteristic is known as an omnidirectional one-dimensional photonic crystal (1D PhC) [7]. Since there are no allowed photon propagation states for wavelengths within the CPBG, an omnidirectional reflector (ODR) made from such a 1D PhC can totally reflect the light with wavelength in the CPBG at any incidence angle and polarization. Therefore, compared with a DBR mirror, a substantially higher reflectance can be achieved. In our previous work, we have demonstrated a 31% enhancement in the extracted light intensity for a flip-chip LED with a TiO_2/SiO_2 ODR compared with the same device with an Al mirror instead [12].

In this paper, we report enhanced light extraction of nitride-based power chip (PC) LEDs with and without a TiO_2/SiO_2 ODR on the bottom and a rough surface on the p-GaN. At a driving current of 350 mA with a chip size of 1 mm × 1 mm on the TO-can package, the light output power of our PC LED with ODR on the bottom and pit type of rough surface on p-GaN is enhanced by 67% when compared with the same device without ODR and rough surface. Improvement in the light output power of the device is attributed to better reflectivity, much lower absorption loss of the ODR and strong scattering effect by rough surface (external quantum efficiency).

2. Experiments

Figure 1 shows the schematic structures of two types of PC LEDs with TiO_2/SiO_2 ODR. In our study, both types are fabricated in order to investigate the influence of the ODR and the rough surface on the LED output power performance. LED I consists of a Ni/Au p-electrode, ITO transparent layer, LED epitaxial layers, a smooth surface, a Ti/Al/Ni/Au n-electrode and a TiO_2/SiO_2 ODR on sapphire substrate, as shown in figure 1(*a*). LED II is similar to type I, but the top emitting p-GaN surface is roughened, as shown in figure 1(*b*).

Our GaN-based LED samples are grown by metal-organic chemical vapor deposition (MOCVD) with a rotating-disc reactor (Emcore) on a c-axis sapphire (0 0 0 1) substrate at the growth pressure of 200 mbar. The LED structure consists of a 50 nm thick GaN nucleation layer grown at 500 °C, a 2 μm undoped GaN buffer, a 2 μm thick Si-doped GaN buffer layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 °C, a 50 nm thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C, and a Mg-doped p-GaN contact layer grown at two different temperatures. The MQW active region consists of five periods of 3 nm/7 nm thick $In_{0.21}Ga_{0.79}N$/GaN quantum well layers and barrier layers.



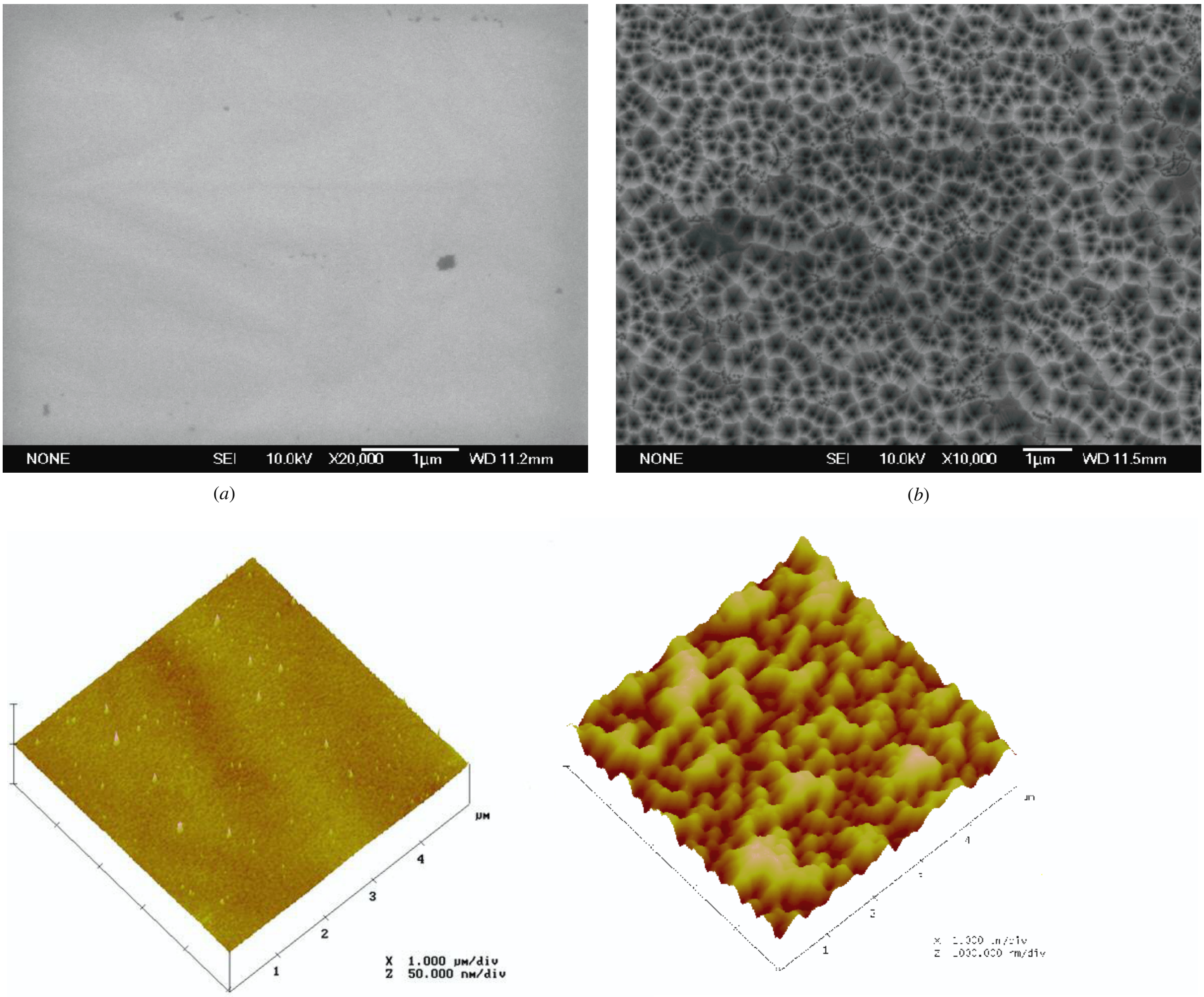
(*a*)

(*b*)

Figure 1. Schematic diagram of PC LEDs of (*a*) smooth surface and (*b*) pit rough surface with TiO_2/SiO_2 ODR fabricated at the sapphire bottom. The inset to (*a*) shows the SEM picture of the TiO_2/SiO_2 ODR.

For LED I, a 0.2 μm thick Mg-doped p-GaN smooth surface contact layer is grown at 1050 °C to form a smooth surface as shown in the SEM picture of figure 2(*a*). The smooth condition of surface morphology can be evaluated by figure 2(*c*) which is the corresponding AFM image possessing a root mean square (RMS) roughness of 0.5 nm for the p-GaN cap. For LED II, a 0.5 μm thick Mg-doped p-GaN contact layer is grown at 900 °C to form a pit type of rough surface with a pit depth of 300 nm approximately as shown in the SEM picture of figure 2(*b*). The surface morphology of LED II can be evaluated by the corresponding AFM image which possesses a root mean square (RMS) roughness of 118 nm and a surface depth of 280 nm approximately for the p-GaN cap as shown in figure 2(*d*).

All the LED samples are fabricated using the following standard processes with a mesa area of 950 × 950 μm^2. A SiO_2 layer with a thickness of 520 nm is deposited onto the LED sample surface by using plasma enhanced chemical vapor deposition (PECVD). Photo-lithography is used to define the



(*a*) (*b*)

(*c*) (*d*)

Figure 2. SEM and AFM images of (*a*), (*c*) smooth surface and (*b*), (*d*) pit rough surface for p-GaN.

mesa pattern after wet etching of SiO_2 in a BOE solution. The mesa etching is then performed with the Cl_2/Ar etching gas in an inductively coupled plasma reactive ion etching (ICP-RIE) system, which transferred the mesa pattern onto the n-GaN layer. A 300 nm thick ITO layer is subsequently evaporated onto the sample surface. The ITO layer has a high electrical conductivity and a high transparency (>95% at 460 nm). Ti/Al/Ni/Au and Ni/Au contacts are subsequently deposited onto the exposed n- and p-type GaN layers to serve as the n- and p-type electrodes. For comparison, PC LED I and LED II with and without TiO_2/SiO_2 ODR are fabricated from exactly the same chip size and wavelength on the fabricated wafers. The designed ODR is composed of 14 pairs of TiO_2/SiO_2, which are evaporated onto sapphire by an E-beam evaporator. The photonic band of the designed 1D PhC is a complete photonic band gap (CPBG) between 437 nm and 472 nm when the refractive indices of TiO_2 and SiO_2 are given by 2.52 and 1.48, respectively, at wavelength 455 nm [12]. When an ODR is made using the designed 1D PhC and incorporated into a GaN LED with a peak emitting wavelength of 455 nm and a full-width at half-maximum (FWHM) of about 20 nm, it shows very high reflectance for wavelengths falling within the emitting spectrum of the LED. It should be noted that the ODR is well controlled to cover the sapphire surface and can reflect the downward light generated in the QW region onto the top surface of the device.

Figure 3 shows the measurement transmittance results of our fabricated TiO_2/SiO_2 ODR from the designed 1D PhC with 14 pairs. The incidence angle is with respect to the normal direction of the dielectric structure surface. To approach the omnidirectional characteristic, four transmittance curves with different incidence angles (e.g. 0°, 30°, 60°, 85°) for unpolarized light versus wavelength are shown. We observe that high reflectance (>99.5%) can be achieved between the wavelengths 441 nm and 465 nm, with an incidence angle of up to 85° (e.g., the yellow region) which falls in the CPBG region as expected by our designed 1D PhC. As the number of pairs increases, the omindirectional stop band of the ODR

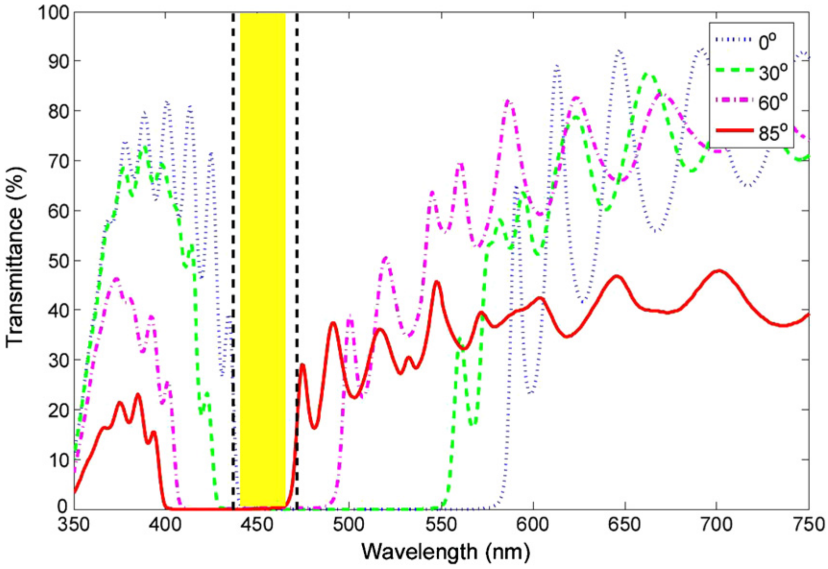


Figure 3. Measured transmittance curves for unpolarized light versus wavelength at different incidence angles.

Table 1. Light intensity and enhanced per cent results of LED I and LED II with/without TiO_2/SiO_2 ODR, respectively.

LED structure	LED I without ODR	LED I with ODR	LED II without ODR	LED II with ODR
Output power (mW)	113	142	155	189
Enhanced per cent (%)	–	26	37	67

will approach the designed CPBG. Readers who are interested in the detailed band structure calculation and geometry design can further refer to [12].

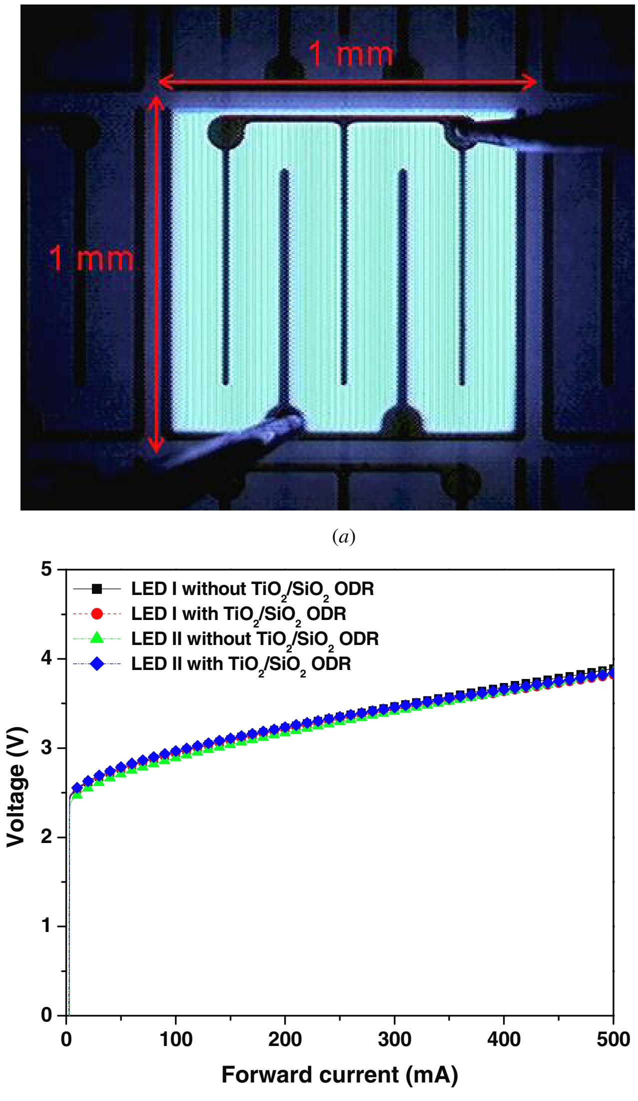
3. Results and discussion

Figure 4(*a*) shows a plane photomicrograph view of our power chip LED to address our electrode pad layout at a driving current of 350 mA. Figure 4(*b*) shows the typical current–voltage (*I*–*V*) characteristics. It is found that the measured forward voltages under an injection current of 350 mA at room temperature for LED I and LED II with and without a TiO_2/SiO_2 ODR are approximately 3.5 V. In addition, the dynamic resistances ($R = dV/dI$) of LED I without/with ODR and LED II without/with ODR are about 2.91, 2.93, 2.78 and 2.81 Ω, respectively. Therefore, in terms of dynamic resistance, there is very little influence on either type of device by incorporating ODR.

The light output is detected by calibrating an integrating sphere with the Si photodiode on the package device, so that light emitted in all directions from the LED can be collected. The intensity–current (*L*–*I*) characteristics of the four kinds of LEDs are shown in figure 5. Table 1 portrays the normalized light output intensity and enhancement percentage of four kinds of LEDs. At an injection current of 350 mA and a peak wavelength of 455 nm for the TO-can package, the light output powers of LED I without TiO_2/SiO_2 ODR, LED I with TiO_2/SiO_2 ODR, LED II without TiO_2/SiO_2 ODR, and LED II with TiO_2/SiO_2 ODR on TO-can are given by 113 mW, 142 mW, 155 mW and 189 mW, respectively. Hence, the enhancement percentages of LED I with TiO_2/SiO_2 ODR, LED II without TiO_2/SiO_2 ODR, and LED II with TiO_2/SiO_2 ODR are 26%, 37% and 67%, respectively, compared to that of LED I without TiO_2/SiO_2 ODR. The comparison results are summarized in table 1. Apparently, the LED II with TiO_2/SiO_2 ODR increases the output power by the highest factor of 1.67, which is close to the multiple of factors 1.26 and 1.37 (1.73), indicating that the effects of ODR and rough surface in our proposed device contribute to the light output power almost independently. Furthermore, at an injection current of 350 mA, the wall-plug efficiency is increased from 9.2% of LED I without TiO_2/SiO_2 ODR to 15.4% of LED II with TiO_2/SiO_2 ODR.

In addition, it is worthy of note that the enhancement of 26% in LED I with TiO_2/SiO_2 ODR is lower than our result of 31% in [12] for the flip-chip type of LEDs. The higher enhancement on the flip-chip type addresses the effect of the ODR on the sidewall surface, which allows the sidewall to reflect light onto the top direction to increase more light output power.

We also measured the light output radiation patterns of the LED I and LED II with/ and without TiO_2/SiO_2 ODR at a driving current of 350 mA, as shown in figure 6. It is observed that the LED II with TiO_2/SiO_2 ODR shows a higher light extraction efficiency with a view angle of about 150° compared to 144° of LED II without TiO_2/SiO_2, 140° of LED I without TiO_2/SiO_2, and 144° of LED I with TiO_2/SiO_2. The radiation pattern of LED II with TiO_2/SiO_2 ODR also shows a stronger enhancement around the vertical direction, indicating a better white light output power for phosphor-conversion white light applications.



(*a*)

(*b*)

Figure 4. (*a*) Plane view photomicrograph of the power chip LED in operation. (*b*) Measurement current–voltage (*I*–*V*) characteristics of LED I and LED II with/without TiO_2/SiO_2 ODR, respectively.

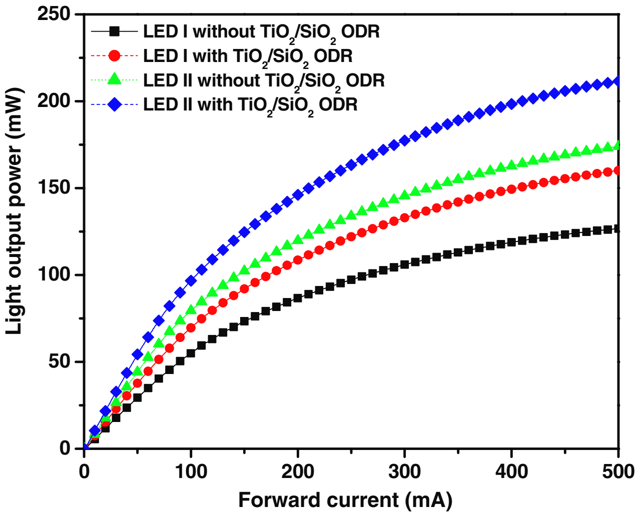


Figure 5. Intensity–current (*L*–*I*) characteristics of LED I and LED II with/without TiO_2/SiO_2 ODR, respectively.

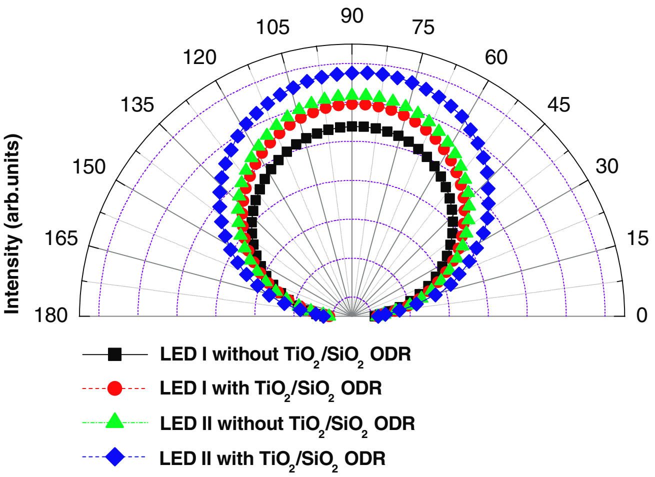


Figure 6. Radiation patterns of LED I and LED II with/without TiO_2/SiO_2 ODR, respectively.

4. Conclusions

In conclusion, GaN-based power chip (PC) LEDs with and without rough surface on p-GaN and TiO_2/SiO_2 omnidirectional reflector (ODR) on the bottom are designed and fabricated. At a driving current of 350 mA and a chip size of 1 mm × 1 mm on the TO-can package, the light output power of PC LEDs with a TiO_2/SiO_2 ODR and pit type of rough surface is enhanced by a factor of 1.67. The higher output power of the PC LED with ODR and rough surface is attributed to higher reflectance of ODR and better light extraction efficiency of rough surface. Furthermore, stronger enhancement around the vertical direction and wider view angle as shown in the radiation pattern for the PC LEDs with ODR and rough surface can be attributed to the same mechanism as well. Our work offers promising potential to increase output powers of commercial light emitting devices, especially, for white light applications.

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