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Enhancement of Light Extraction Efficiency of UVC-LED by SiO_2 Antireflective Film

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Abstract: In order to achieve high quantum efficiency of AlGaN-based deep ultraviolet light-emitting diodes (UVC-LED), it is important to improve the light extraction efficiency (LEE). In this paper, theoretical simulation and experiment of SiO_2 anti-reflective film deposited on UVC-LED were investigated. The effect of different SiO_2 thickness on the light extraction efficiency of 275 nm UVC-LED was studied, showing that 140 nm SiO_2 anti-reflective film can effectively improve the light output power of UVC-LED by more than 5.5%, which were also confirmed by the TFCALC simulation. The enhancement of UVC-LED light extraction efficiency by this antireflective film is mainly due to the $\frac{3\lambda}{2}$ light coherent effect at the SiO_2/Al_2O_3 interface. Our work proved the promising application of antireflective coating on UVC-LED.

Keywords: UVC-LED; light extraction efficiency; antireflective film; optical simulation; SiO_2

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1. Introduction

In the past few decades, AlGaN-based ultraviolet light-emitting diode (UV-LED) has been attracting extensive attention due to its applications in water sterilization, surface disinfection, and biological detection, thanks to its compactness, long-term reliability, and being free of contamination [1–6]. With the outbreak of the coronavirus epidemic in 2019 (COVID-19) [7,8], more researchers joined the development of highly efficient UVC-LED, since it is promising for virus disinfection [7–10]. However, until now, UVC-LED still suffered low quantum efficiencies and weak optical output power. Despite many efforts by various teams [11–14], the external quantum efficiency (EQE) is still low, suffering from low light extraction efficiency (LEE). Several factors (such as: absorption of GaN capping layer [15], transverse magnetic (TM) [5] mode issue, reflection loss at sapphire/air interface [16]) have hindered the LEE of UVC-LEDs below 10%. In view of the low LEE of UVC-LEDs, various attempts, such as: highly reflective metals [17,18], photonic crystals [19], distributed Bragg reflector [20] and so on [21–27] were used to improve the light extraction. However, these methods have flaws of poor metal adhesion, complex structures, difficult fabrication processes, and low mass production efficiency and repeatability, and have not been applied in mass production.

In the field of dielectric optics, the reflected (or transmitted) light intensity can be significantly enhanced or weakened by modulating the coherent interference and phase difference of the two reflected light waves by parallel top and down interfaces. For example, film with optical thickness of $\frac{\lambda}{4}$ was often used to reduce reflectivity. Based on above, in this paper, by depositing SiO_2 antireflective films with different thicknesses on the backside of sapphire substrate, the effect of SiO_2 thin films on UVC light transmittance were studied. The light output of UVC-LED was increased by 5.5% with $\frac{3\lambda}{4}$ optical thickness SiO_2 film. The transmittance spectrum and optical filed distribution of SiO_2 coatings on UVC-LEDs were also investigated by TFCALC simulation.

2. Experiments

Firstly, the UVC-LED wafer was grown on c-plane sapphire substrate using metal organic chemical vapor deposition (AIXTRON-Crius) system. The epi structure includes a 3 µm-thick AlN buffer layer, 1.6µm n-type (Si-doped) $Al_{0.55}Ga_{0.45}N$ layer, an active region consisting of 5 pairs of multi-quantum wells, 80 nm p-type (Mg-doped) $Al_{0.75}Ga_{0.25}N$ electron blocking layer and 20 nm p-type GaN contact layer. The wafer was then mesa-etched by inductively coupled plasma etching to expose the n-AlGaN contact layer, where Cr/Al/Ti/Ni/Au as n-contact was electron-beam evaporated and annealed at 850 °C for 40 s. The p-type electrode made of Ni/Au was then e-beam deposited and annealed at 600 °C for 150 s. Au/Sn was used as the P/N pad of the 40 mil × 40 mil flip-chip LED structure, as shown in Figure 1. The SiO_2 anti-reflective films (0–280 nm) was then deposited on the backside of sapphire by NAURA EPEE550 PECVD with H_4Si (100 sccm), N_2O (1800 sccm), N_2 (700 sccm) as gas source, 90 Pa chamber pressure, 150 °C reaction temperature and 90 W RF power. The light output power of UVC-LED was measured by LDM-150-UV system from SIDEA Semiconductor Equipment Co. Ltd. The enhancement of LED output power was further investigated by the transmittance measurement of Al_2O_3/SiO_2 double-layer structure. The 250–300 nm light incident from the Al_2O_3 side and transmitted through SiO_2 surface. The transmittance spectrums were simulated by TFCALC software and also measured by RT-V equipment from Yiguang Technology Co., Ltd., Shenzhen, China.

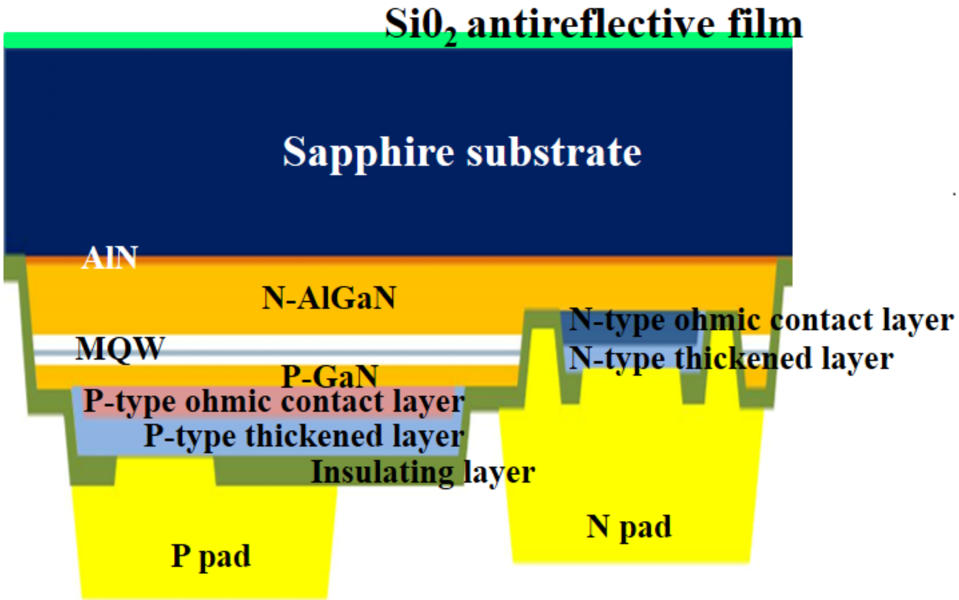

Figure 1. Device structure of UVC-LED with anti-reflective SiO_2.

3. Results and Discussion

Figure 2a presents the electroluminescence (EL) spectra of UVC-LEDs, showing the 275 nm centered luminescence. With deposition of SiO_2 antireflective film with different thicknesses, the light output powers of UVC-LEDs were enhanced. As shown in Figure 2b, under 350 mA, the output powers of UVC-LEDs were improved by 3.04%, 5.28% (from 60.39 mW to 63.58 mW), 4.13% and 3.28% by 70, 140, 210 and 280 nm SiO_2 antireflective films, respecitvely. Figure 2c,e show the output power increasing ratio of anti-reflection UVC-LED from 50 to 500 mA. The increasing ratio was stable around 5.5% under every current injection. Since the current–voltage (I–V) characteristic of all DUV-LEDs were stable, the EQE of UVC-LEDs were also enhanced by same percentage. The EQE of UVC-LEDs consists of internal quantum efficiency (IQE) and LEE. In this work, the active regions and carrier transportation were not modified by depositing SiO_2 on the backside of the sapphire. The enhancement of EQE should be induced by the increasing of LEE. Similar LEE-enhanced percentages were also observed in UVC-LEDs after package.

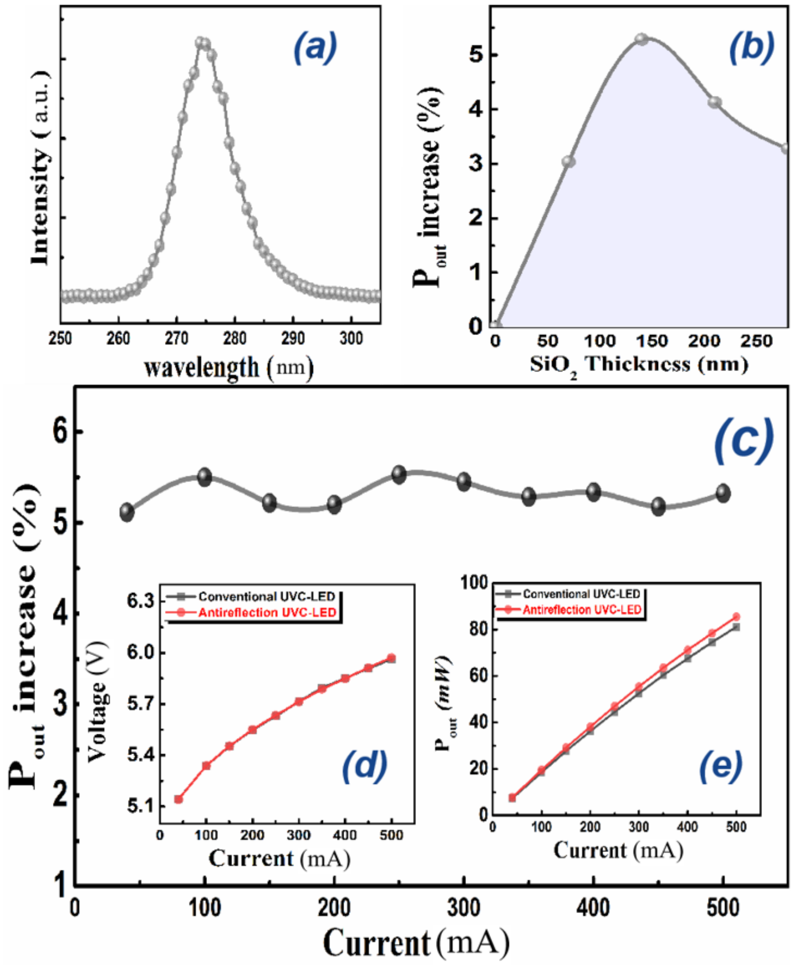

Figure 2. (**a**) EL spectra of the DUV-LEDs; (**b**) the P_{out} increase with different SiO_2 thicknesses; (**c**) the P_{out} increase with current with 140 nm SiO_2; (**d**) I–V characteristic; and (**e**) I–L characteristic.

For specifying the origin of LEE enhancement in UVC-LEDs, 0–280 nm SiO_2 were also deposited onto Al_2O_3 substrate to form SiO_2/Al_2O_3 double layers. Transmitted spectrums of these layers were simulated and experimentally measured. Figure 3 shows a schematic of SiO_2/Al_2O_3 film, which was loaded to simulate the light transmittance at different incident angles θ and wavelengths. Figure 4a shows the transmission spectra with different SiO_2 thicknesses at normal incidence ($\theta = 0°$) by TFCALC. Figure 4b shows the experimental transmittances of bare Al_2O_3 and 140 nm SiO_2/Al_2O_3 at normal incidence, which were consistent with the theoretical simulation in Figure 4a. The transmittance of 275 nm photon increases about 6% (Figure 4b)–6.25% (Figure 4a) by the 140 nm SiO_2 antireflective coating. Combined with the 5.5% elevation of antireflective 275 nm UVC-LED in Figure 2c, it was believed that the enhancement of transmission by 140 nm SiO_2/Al_2O_3 structure should be the dominant factor for higher EQE of antireflective UVC-LED. The mechanism of light-extraction enhancement at 140 nm SiO_2 is mainly due to the coherent suppression of two reflected light waves (R1 and R2 in Figure 3) when the light is incident from the Al_2O_3 side. The first light wave, R1, is directly reflected by the Al_2O_3/SiO_2 interface and the second light wave transmits through the Al_2O_3/SiO_2 interface after being reflected (R2) by the SiO_2/air interface. When R1 and R2 interfere with $\frac{(2n+1)\lambda}{2}$ phase difference, coherent suppression of reflected light occurs, weakening the total reflected light and enhancing transmitted power. In this work, the enhanced transmittance of around 275 nm at a thickness of 140 nm comes from the coherent suppression effect by $\frac{3\lambda}{2}$ phase difference.

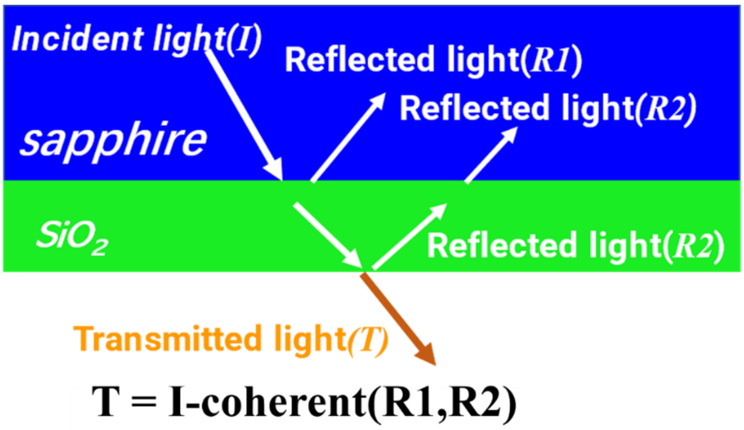

Figure 3. Optical simulation of SiO_2/Al_2O_3 structure.

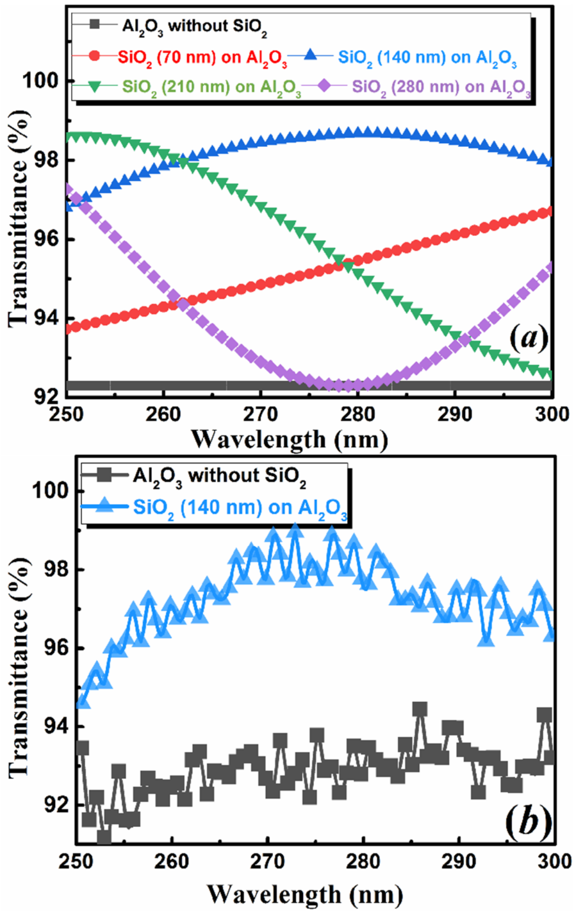

Figure 4. Transmittance of SiO_2 antireflective film: (**a**) simulated transmittance (Angle = 0°) of SiO_2/Al_2O_3 structure with different SiO_2 thicknesses; (**b**) experimental transmittance (Angle = 0°) of SiO_2/Al_2O_3 structure with 140 nm SiO_2.

The increase ratios of UVC-LEDs output power (Figure 2b) were also consistent with the increase ratio of light transmittance of SiO_2/Al_2O_3 at different SiO_2 thickness (0–210 nm). This also confirmed that the increasing of UVC-LED EQE came from the light transmittance.

However, in Figure 4a, 280 nm SiO_2 has no increasing on transmittance, while in Figure 2b, the experimental light output power of 280 nm SiO_2/Al_2O_3 corresponding UVC-LEDs increased by about 3.3%. We attributed this phenomenon to the enhanced transmission of UVC light from other angles. Figure 5 shows the simulated transmittance of anti-reflection SiO_2/Al_2O_3 with different SiO_2 thicknesses from different incident angles. At the 280 nm SiO_2, when the incident angle increases above 15°, the transmittance increases significantly, which is different from other thicknesses. This is because that when the incident direction deviates from normal incidence, the optical phase difference of the two reflections will also deviate, thereby achieving the partial enhancement of the transmittance.

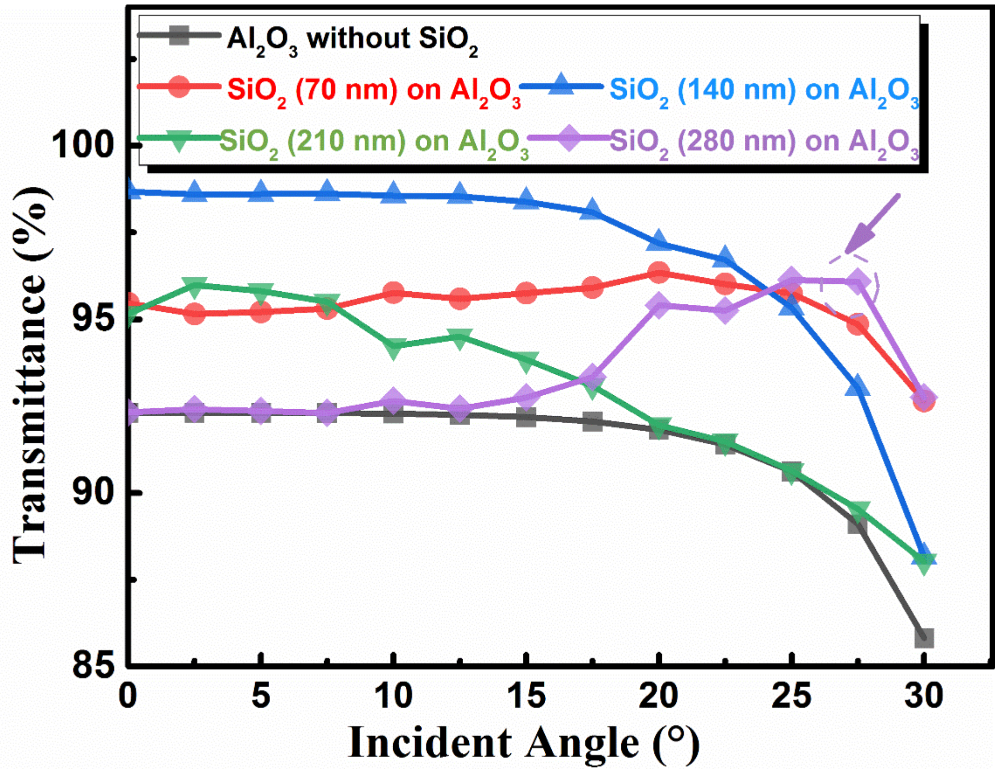

Figure 5. Simulation results of transmittance in 275 nm at different angles.

The surface morphology of sapphire backside and SiO_2 anti-reflection coating were characterized by AFM, which are shown in Figure 6. The results showed that after the deposition of SiO_2, the RMS roughness reduced from 1.01 nm of sapphire to 0.45 nm of SiO_2. It means that the improvement of LEE comes from the effect of the coherent intervene of anti-reflection coating rather than surface roughness.

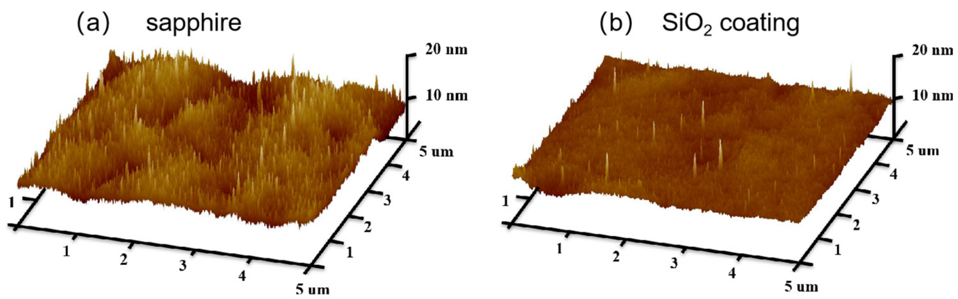

Figure 6. Surface morphology of (**a**) sapphire backside and (**b**) SiO_2 anti-reflection coating.

4. Conclusions

In this paper, the optical power of UVC-LED was increased by 5.5% by introducing a 140 nm SiO_2 antireflective coating on the backside of sapphire. The simulated transmittance spectra presents that the enhancement of the light power of the LED was attributed to the optical intervene suppression of $\frac{3\lambda}{4}$ coherent reflected light. Our work shows that the antireflective coating is promising to improve light output efficiency of UVC-LED. It is worth noting that the SiO_2 anti-reflection film could only partially improve the Fresnel reflection loss issue in UVC LED. Other concerning problems of UVC-LEDs' LEE (such as: TM mode, GaN capping layer's absorption etc.) could be overcome by further research.

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