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Broadband and omnidirectional light harvesting enhancement of fluorescent SiC

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Abstract: In the present work, antireflective sub-wavelength structures have been fabricated on fluorescent 6H-SiC to enhance the white light extraction efficiency by using the reactive-ion etching method. Broadband and omnidirectional antireflection characteristics show that 6H-SiC with antireflective sub-wavelength structures suppress the average surface reflection significantly from 20.5 % to 1.01 % over a wide spectral range of 390-784 nm. The luminescence intensity of the fluorescent 6H-SiC could be enhanced in the whole emission angle range. It maintains an enhancement larger than 91 % up to the incident angle of 70 degrees, while the largest enhancement of 115.4 % could be obtained at 16 degrees. The antireflective sub-wavelength structures on fluorescent 6H-SiC could also preserve the luminescence spectral profile at a large emission angle by eliminating the Fabry-Pérot microcavity interference effect.

OCIS codes: (220.4241) Nanostructure fabrication; (250.5230) Photoluminescence; (310.6628) Subwavelength structures, nanostructures.

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1. Introduction

White light-emitting diodes (LEDs) consisting of a nitride-based blue LED chip and phosphor are very promising candidates for the general lighting applications as energy-saving and environment friendly light sources [1–5]. Recently, donor-acceptor doped fluorescent SiC has been proven as a highly efficient wavelength converter material much superior to the phosphors in terms of high color rendering index (CRI) value and long lifetime [6, 7]. The donor-acceptor-pair (DAP) band luminescences from the nitrogen (N)-boron (B) doped 6H-SiC present a warm-white color. Combined with the DAP luminescences from the nitrogen-aluminium doped 6H-SiC, pure white light with CRI larger than 90 could be produced [8, 9]. Furthermore, SiC is a well-established substrate material for nitride growth and has an excellent thermal conductivity.

The light extraction efficiency of the SiC-based LED is usually low due to the internal reflection loss arising from the large refractive index difference between the SiC and air interfaces. Antireflective sub-wavelength structures (ARS) have been proved as an ideal approach to enhance the light transmittance over a broad spectral bandwidth [10–13]. Applying the ARS on SiC has been studied on the monochromatic LEDs with undoped SiC as substrate materials [14, 15] and on the 4H-SiC photodiodes [16]. In the present work, the effect of ARS on the fluorescent SiC to enhance the light extraction efficiency over the entire visible spectral range has been studied.

2. Experiments

Homoepitaxial layers of 6H-SiC with N and B dopants were grown by the Fast Sublimation Growth Process [17]. The growth process is driven by a temperature gradient created between

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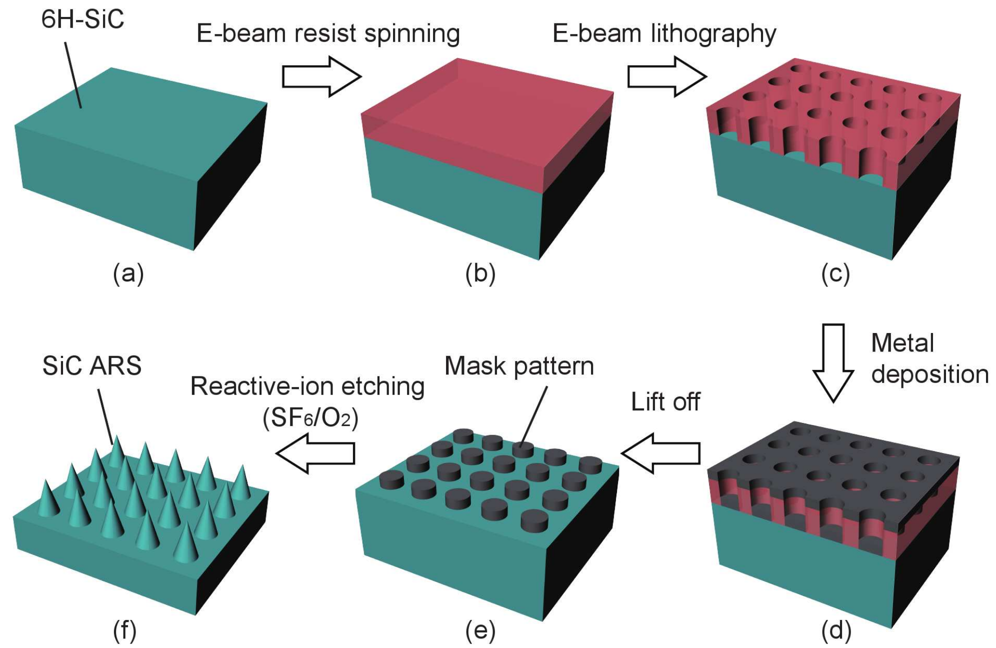

Fig. 1. Schematic illustrations of the SiC ARS fabrication process steps (a)-(f).

the source, in a form of polycrystalline SiC plate, and the substrate. Boron was introduced into the epilayers by doping from the source and nitrogen incorporation was controlled by adjusting the N_2 gas pressure during the growth. The 6H-SiC epilayers were grown on 6H-SiC (0001) substrates with 1.4 degree off-orientation in the $[11\bar{2}0]$ direction at growth temperature of 1725°C.

Here we present an approach to fabricate the periodic cone-shaped ARS on the N-B doped 6H-SiC by using the reactive-ion etching (RIE), and the fabrication process is illustrated in Fig. 1. Firstly, the positive e-beam resist (ZEP520) was spin-coated on the SiC sample (Fig. 1(a)) and then pre-baked on a hot plate at 160°C for 2 minutes (Fig. 1(b)). By using the e-beam lithography (JEOL JBX9300FS) with a subsequent development process, the designed pattern was transferred to the e-beam resist coating (Fig. 1(c)). A hard mask material (chromium) layer was then deposited on the patterned SiC by the e-beam evaporation (Fig. 1(d)). Followed by a lift-off process, the dot-shaped pattern of chromium was obtained as a hard mask layer (Fig. 1(e)). The dry etching process using SF_6 and O_2 precursors was carried out in the RIE system. During the etch process, the radio frequency power (100 W), process pressure (30 mT), and gas flow rates (20 sccm SF_6, 5 sccm O_2) of the RIE were carefully chosen. After 12 minutes etching, the cone-shaped ARS with designed configuration (bottom diameter of 240 nm, pitch of 340 nm, height of 1.2 μm, and hexagonal arrangement) were finally formed on the SiC surface (Fig. 1(f)). An oblique-view scanning electron microscope (SEM) figure of the SiC sample with ARS array is shown in Fig. 2(a).

3. Characterization and results

The surface reflectance of the bare and ARS SiC samples were measured by a goniometer system at a measured angle of 6 degrees (deg.), where 0 deg. is the direction normal to the

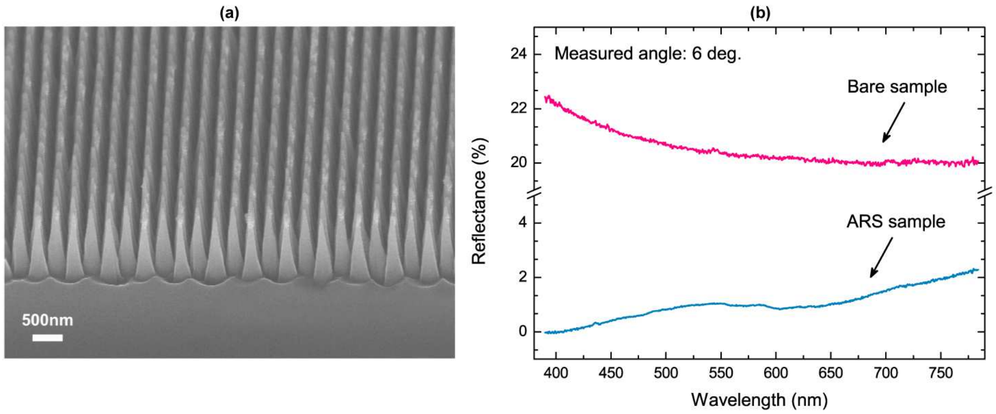

Fig. 2. (a) An oblique-view SEM figure of the SiC sample with ARS, and (b) reflectance spectra of the SiC samples with and without ARS (measured at 6 deg.).

sample surface. The reflectance spectra were measured from 390 to 785 nm which covers the entire visible spectral range (typically from 390 to 750 nm) and the results are shown in Fig. 2(b). It is seen that the surface reflection is effectively suppressed by applying the SiC ARS. The average reflectance over the measured spectral range decreased from 20.5 % to 1.01 % and the minimum reflectance close to 0 was observed at around 400 nm for the ARS SiC sample. Although the reflectance starts to increase at above 680 nm, the reflectance over the entire visible spectral range is below 2 %. This result suggests that the SiC ARS is an effective way to suppress the surface reflection for the fluorescent SiC sample in the whole visible spectral range.

The angle-resolved room temperature photoluminescence spectra of the SiC samples with and without the ARS were also acquired by the same goniometer system. A 377 nm diode laser was used as the excitation source which was normal to the sample surface and the detected emission angle varied from 16 to 80 degrees. The broad DAP band luminescence of the N-B doped fluorescent SiC has a peak wavelength at round 578 nm and a full width at half maximum of 110 nm which is a merit as wavelength converter material. From Fig. 3(a), it is seen that the luminescence intensity of the bare SiC decreases together with a blue shift of the peak wavelength as the emission angle increases from 20 to 70 deg., which could be attributed to the Fabry-Pérot microcavity interference effect explained in the Ref. [7, 18, 19]. In Fig. 3(b), although the luminescence intensity of the ARS SiC also decreases with larger emission angle, the peak wavelength remains the same which is due to the elimination of the Fabry-Pérot microcavity interference effect by introducing the ARS on the SiC surface.

The integral luminescence intensities of the two samples at different emission angle are compared in Fig. 3(c). In both samples, the luminescence intensity at a large emission angle of 60 deg. is still higher than 52 % of the one at 16 deg., which is quite promising among the most commercial LEDs (less than 30 %). The angle-resolved luminescence enhancement of the ARS SiC is also shown in Fig. 3(d). It is seen that the luminescence intensity is enhanced by larger than 91 % from 16 to 70 deg., and the highest enhancement of 115.4 % is obtained at 16 deg. of the emission angle. Although the enhancement starts to decrease dramatically from 70 deg., the luminescence intensity of the SiC is significantly enhanced in a very large emission angle range.

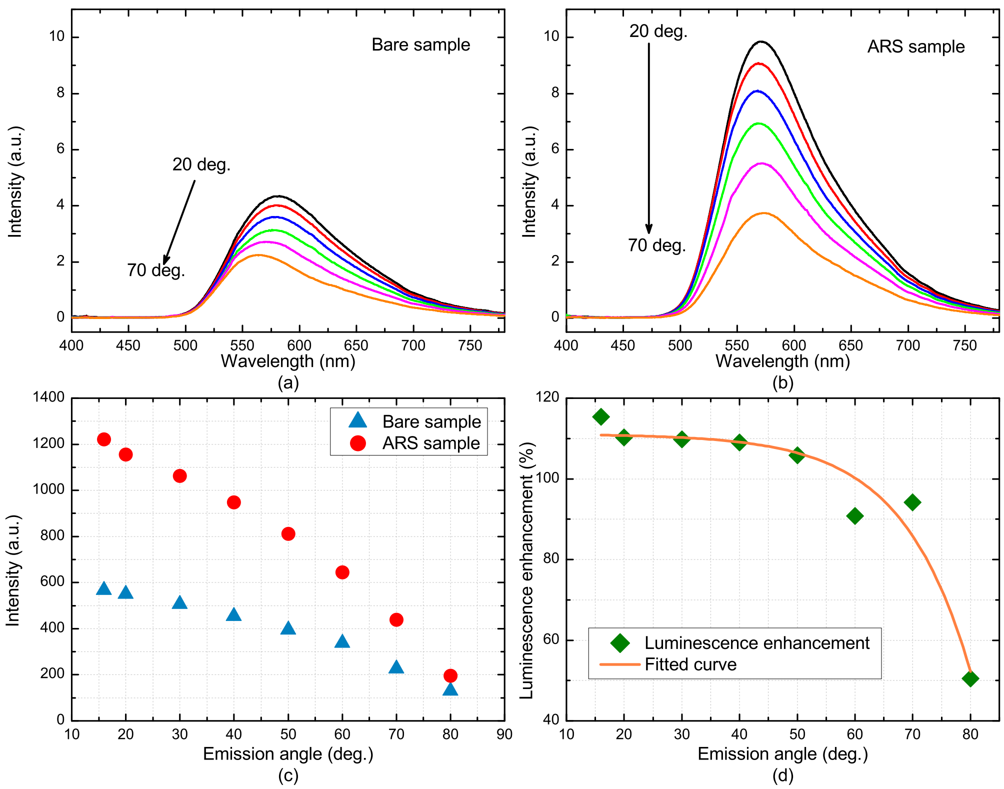

Fig. 3. Angle-resolved photoluminescence spectra from 20, 30, 40, 50, 60, to 70 deg. for the SiC samples (a) without and (b) with ARS; (c) integrated luminescence intensities and the (d) luminescence enhancement of the two SiC samples.

4. Conclusion

A method by using reactive-ion etching is demonstrated to fabricate the ARS array on fluorescent SiC. The surface reflectance over the whole visible spectral range is dramatically suppressed from 20.5 % to 1.01 % by applying the ARS on the SiC sample. From the angle-resolved photoluminescence measurements, it is also found that the luminescence intensity could be enhanced by more than 91 % in a very large emission angle range (up to 70 degrees). In addition, the Fabry-P*é*rot microcavity interference effect could be eliminated to preserve the luminescence spectral profile by introducing the ARS on fluorescent SiC. As a result, broadband and omnidirectional ARS could effectively enhance the light extraction efficiency of the fluorescent SiC, and further improve the external quantum efficiency of the SiC-based white LEDs.

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