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Introduction

Light-emitting diodes (LEDs) have attracted renewed interest in the past decades with the appearance of the worlds first efficient **blue**-emitting GaN LED, for the reason that it could make all-solid-state lighting for large-scale energy saving. Compared with the traditional incandescent and fluorescent light sources, LEDs have longer lifetime, higher overall efficiency, as well as better technical functionality for many new lighting applications. Driven by energy saving and further CO_2 emission reduction, high brightness LEDs, as a GREEN light source, represents a multi-billion market that is predicted to grow to $12 billion by 2013 globally.
Currently, white LEDs are made by mixing yellow color and blue color. Yellow is wavelength converted from blue by phosphors. But phosphors degraded much faster than the LED chips, leading to the white LEDs turning blue over time. Recently, fluorescent SiC has also been approved as an ideal wavelength converter for white LEDs because it has better color rendering ability and long life time [1].

Experiments

The B and N co-doped 6H-SiC epilayers were grown on 6H-SiC (0001) substrates having 1.4 degree off-orientation in the $<11\bar{2}0>$ direction by the fast sublimation growth process [2] at temperature of 1725 ºC. The growth process is driven by a temperature gradient created between the source, in a form of polycrystalline SiC plate, and the substrate. B was introduced into the epilayers by co-doping from the source and N incorporation was controlled by adjusting N_2 gas pressure during the growth.
To enhance the extraction efficiency of the f-SiC, cone-shaped antireflection nanostructures (ARS) are fabricated on the surface of f-SiC epilayers. A positive resist layer was first spin-coated on the 6H-SiC sample and then prebaked. The designed mask pattern was transferred to the resist coating by applying the e-beam lithography. After the development, a hard mask layer was deposited on the patterned resist with a subsequent lift-off process. The dot-shaped pattern was then obtained on the hard mask. The dry etching process using SF_6 and O_2 precursors was carried out in the reactive-ion etching system.
Photoluminescence (PL) measurements were realized by using an Olympus reflected fluorescence system microscope, a 377 nm diode laser as excitation source (focused by a 20X objective), and an Instrument System CAS 140B spectrometer at room temperature.
The surface reflectance of the bare and ARS SiC samples were measured from 390 to 785 nm by a goniometer system at a measured angle of 6 degrees, where 0 degree is the direction normal to the sample surface. The angle-resolved photoluminescence spectra were also acquired by the same goniometer system. The 377 nm diode laser was used as the excitation source which was normal to the sample backside and the detected emission angle varied from 16 to 80 degrees.
The scanning electron microscope (SEM) image was acquired by field-emission SEM Zeiss.

Results and discussions

To investigate the optimized dopant concentrations of N and B, five samples with varied N and B concentrations were studied. The atomic dopant concentrations measured by secondary ion mass spectrometry (SIMS) are listed in Table 1.

Table 1. *Dopant concentrations and normalized PL peak intensities of the samples*

Sample	B concentration [cm^{-3}]	N concentration [cm^{-3}]	PL peak intensity [Normalized to sample d]
a	8.0×10^{18}	4.0×10^{16}	0.0 %
b	6.9×10^{18}	3.2×10^{18}	6.6 %
c	6.9×10^{18}	6.0×10^{18}	8.3 %
d	4.4×10^{18}	9.0×10^{18}	100 %
e	5.2×10^{18}	9.2×10^{18}	77.1 %

Their corresponding PL spectra are shown in Fig. 1. All samples show PL emission peak at 587nm and FWHM of 120nm. As N concentration increases from sample a to sample d, the emission intensity increases as well. Sample d has the strongest PL emission. Then the emission intensity drops as the N concentration increases further.

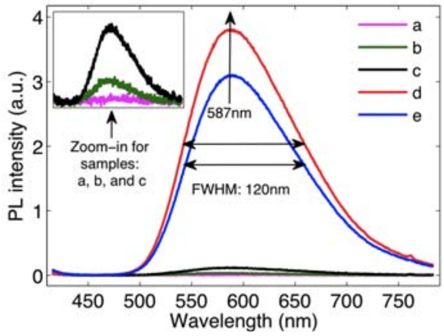

Fig. 1. *Measured PL spectra of B-N doped 6H-SiC samples (inset: zoom-in for sample a, b, and c), same peak wavelength at 587 nm and FWHM of 120 nm were observed in all the spectra.*

Bare and ARS samples are compared in terms of reflectance, spatial emission distribution and angle-resolved PL and the results are shown in Fig. 2. An oblique-view SEM image of the ARS pattern is shown in the inset of Fig. 2(a). The cone-shaped ARS structure has bottom diameter of 250 nm, pitch of 350 nm, and height of 1.4 µm. The reflectance spectra of bare sample and ARS structure are shown in Fig. 2(a). 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 1.0 % and the minimum reflectance close to 0 was observed at around 400 nm for the ARS SiC sample. Fig. 1(b) shows the spatial emission patterns for both samples, one can see that the luminescence intensity increased at all emission angles with a well preserved spatial emission pattern. It is also found that the luminescence intensity was enhanced by more than 91 % in a very large emission angle range (up to 70 degree). From Fig. 1(c), 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 degree, which could be attributed to the Fabry-Pérot microcavity interference effect. In Fig. 1(d), 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.

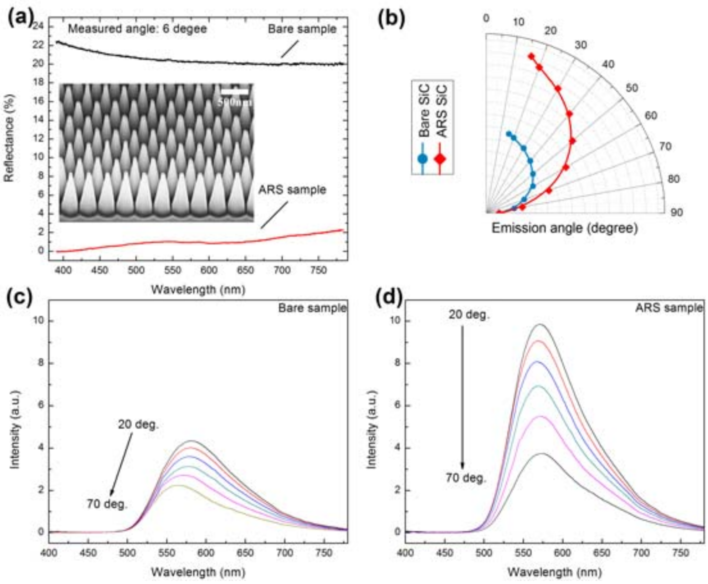

Fig. 2: *(a) Surface reflectance (inset: SEM figure of fabricated ARS on SiC); (b) spatial emission pattern; angle-resolved photoluminescence of (c) bare and (d) ARS SiC samples.*

Conclusion

Optimized N and B concentration of f-SiC has been found. Cone-shaped ARS structures have been fabricated and tested that it is an effective way to suppress the surface reflection for the fluorescent SiC sample in the whole visible spectral range. These promising results pave the way for f-SiC as a wavelength converter for white LEDs.

Ref.

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