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Higher luminance LEDs with nano-structured surface fabricated by self-assembled block-copolymer

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Introduction

The total efficiency of LEDs is determined by the product of the internal quantum efficiency and the extraction efficiency. The internal quantum efficiency of LEDs has improved, but the extraction efficiency remains as low as a few % due to the high refractive index of semiconductors (n=3-3.5). In order to extract more light, we proposed a nano-patterned structure on the LED surface. This structure has two functions: as an antireflective layer completely transmitting incident light below the critical angle to the LED surface, and as gratings that diffract the light larger than the critical angle to extract -1st order light.

Optimized period sizes

The optimized period sizes were obtained from the diffraction equation. The diffraction equation is given as follows:

$$\sin\theta_m - n\sin\theta_i = m\frac{d}{\lambda} \qquad (1)$$

$$(m=0, \pm1, \pm2, \ldots)$$

θ_m and θ_i are the diffracted angle and the incident angle, respectively. n, d, and λ are the refractive index of the substrate, the period length, and the wavelength, respectively. m equals -1 because of the improvement for the extraction by -1st order light extraction. The angle of the incident light that could be diffracted by the equation (1) is shown in Table 1. The period of 600 nm was improper because the incident light within the critical angle was diffracted. The diffraction in the period of 100 nm did not appear. The grating before and behind 200 nm diffracted the incident light more than the critical angle. In order to withdraw two functions, it is necessary to fabricate a structure having a period of about 200 nm.

Fabrication

To fabricate the patterned structure on the semiconductor (GaP) surface by dry etching, we employed the periodic dots pattern with the self-assembled diblock-copolymer process [1]. The diblock copolymer of polystyrene (PS) - polymethyl methacrylate (PMMA) was used in this study. As it was spin-coated on a substrate, the PS forms spherical domain in the polymer thin film by self-assembling phase separation process. For reactive-ion etching (RIE), the PMMA is etched much faster than the PS so that the PS remained. If RIE is continued, the substrate was etched using the remaining PS as a mask. The AFM phase image of the self-assembled polymer pattern is shown in Fig. 1. The average diameter and the period length of the PS dots of 100 nm and 150 nm, respectively, were used.

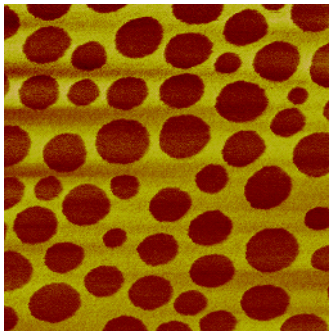


Fig. 1 Self-assembled polymer pattern
AFM image phase image (1μm×1μm)
Darker colors: PS, Lighter colors: PMMA

Table 1 Incident angles that can be diffracted

Period d (nm)	100	150	200	300	600
Incident angles that can be diffracted θ_i, n=3.2, λ= 600 nm	-	69～90°	39～90°	18～69°	0～38°

The GaP was dry-etched by Cl-based inductively coupled plasma using the remaining PS dots as a mask. The patterned structure with a diameter of 100 nm, a period of 150-200 nm, and a height of 400 nm could be fabricated as shown in Fig. 2.

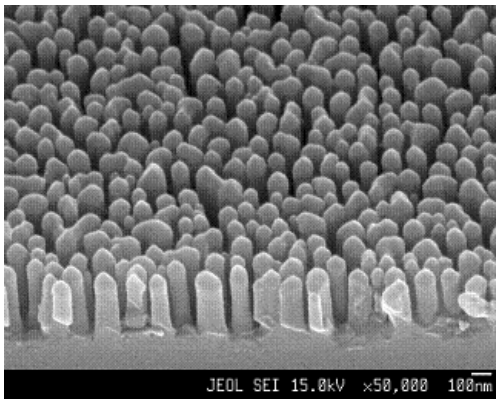
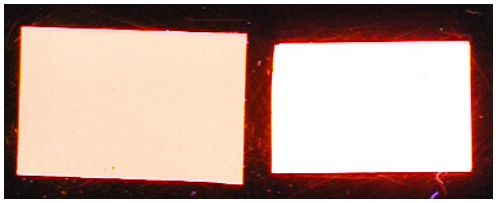


Fig. 2 GaP etching pattern
The diameter is 100 nm, the period is 150-200 nm, and the height is 400 nm.

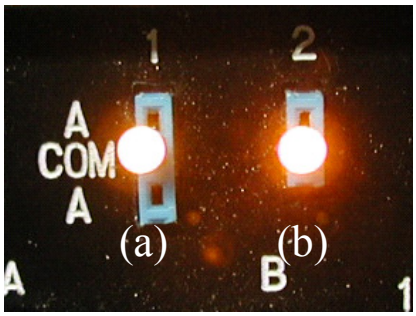
Evaluation

The extraction efficiency was evaluated by a simple method. The red phosphor formed on the back side of the substrate is excited by UV light, and the red light is pumped into the substrate. The light extracted from the surface is picked up on an integrating sphere, and the luminance is measured. Photographs of the UV excitation of the flat surface and the patterned structure, respectively, are shown in Fig. 3. We improved the extraction efficiency of the fabricated surface 160% compared with the flat surface.



(a) Flat surface (b) Patterned structure
Fig. 3 Photograph of the UV excitation
The extraction efficiency of (b) is 2.6 times more than that of (a).

The nano-patterned structure was fabricated on a GaAs/AlGaAs-LED by the same process and the luminance of LEDs was evaluated. A photograph of the emitted LED tips is shown in Fig. 4. The luminance of the LED tip (b) having the patterned structure increased 1.5 times compared with that of the conventional LED tip (a). Higher luminance LED has been achieved by the nano-patterned structured surface.



(a) Flat surface (b) Patterned structure
Fig. 4 Photograph of emitted LED tips

Conclusion

In order to improve the extraction efficiency, we proposed a nano-patterned structure with an antireflection and a diffraction structure. Nano-patterned surfaces were fabricated by self-assembled block copolymers. The extraction efficiency of the fabricated surface on the GaP was improved 160 % compared with that of the flat surface. The luminance of AlGaAs-LED having the patterned structure increased 1.5 times compared with that of the conventional LED.

References

[1] Koji Asakawa and Toshiro Hiraoka: Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 6112-6118