High efficient light-emitting diodes with antireflection subwavelength gratings

著者	羽根　一博
journal or publication title	IEEE photonics technology letters
volume	14
number	8
page range	1064-1066
year	2002
URL	http://hdl.handle.net/10097/35130

doi: 10.1109/LPT.2002.1021970

High Efficient Light-Emitting Diodes With Antireflection Subwavelength Gratings

Y. Kanamori, M. Ishimori, and K. Hane

***Abstract*—A two-dimensional subwavelength grating (SWG) has been fabricated on a GaAlAs light-emitting diode (LED). The SWG is patterned by electron beam lithography and etched by fast atom beam with Cl_2 and SF_6 gases. The fabricated grating has 200-nm period and the tapered grating shape with aspect ratio of 1.38 to prevent reflection in the spectral region including 850 nm light emission. The emission is increased by 21.6% at the normal emission angle. The total emittance is increased by 60% with the SWG in comparison with that of the flat surface.**

***Index Terms*—Electron beam lithography, etching, gratings, light-emitting diodes, nanotechnology, periodic structures.**

LIGHT-EMITTING diodes (LEDs) are used in many applications such as optical communication systems and light illuminating components. Most of such applications need the LEDs with high power, high luminance, and high efficiency. It is important to improve external quantum efficiency of the LEDs. The external quantum efficiency of the LEDs is almost limited by internal reflection at the boundary between the material of LED and its surrounding medium. Due to the large difference of the refractive index at the boundary, transmittance of light from the LEDs is very low. To overcome this problem, some new approaches [1]–[3] are proposed as well as the multilayer coating. The LED with a roughened top surface and a back mirror is a promising approach to overcome this problem [1]. Propagation angle of light reflected at the rough surface is changed, and the light escapes from the LED after multiple reflection in the material. However, due to the absorption by the active layer, the emission efficiency is not always high.

A subwavelength grating (SWG) is a very fine surface structure with the period sufficiently smaller than the wavelength of light. The SWG with the tapered grating shape and high aspect ratio, suppresses reflection drastically over a wide spectral bandwidth and a large field of view [4]–[17]. Although the SWG is a grating, it does not generate diffraction beams except zeroth order. The reflected and the transmitted wave fronts are not degraded. In addition, the two-dimensional SWG is independent on the polarization direction. The SWG behaves ideally as a gradient index layer with the effective refractive index determined by the filling factor of the grating and the groove mediums.

In this letter, the two-dimensional SWG has been fabricated on a GaAlAs LED with the peak wavelength of 850 nm. The fabricated grating has 200-nm period and the tapered grating shape with aspect ratio of 1.38 to prevent reflection in the spectral region including 850-nm light emission. To our knowledge, the SWG is fabricated on the LED surface for the first time. The emission is increased by 21.6% at the normal emission angle.

In the fabrication of the SWG, electron beam (EB) lithography and fast atom beam (FAB) [18] etching with Cl_2 and SF_6 gases were used. The LED used is a bare chip. In the FAB etching process, the alternate etching technique using the SF_6 and Cl_2 gases was proposed for fabricating the tapered grating with high aspect ratio. First, the front surface of the LED wafer was coated with an EB positive resist. The EB resist was about 400 nm thick. The SWG pattern consisting of two-dimensional grating lines was drawn on the resist by the EB machine at the acceleration voltage of 30 kV. The resist grating was used as a mask for the FAB etching. In the FAB etching, the SF_6 was first used as the process gas at the flow rate of 6.44 sccm for 10 min at the discharge voltage of 2 kV and the discharge current of 25 mA. Secondly, the Cl_2 gas was used as the process gas at 1.7 sccm for 1 min at the voltage of 3 kV and the current of 20 mA. Thirdly, the SF_6 was used again for the etching under the same condition as used in the first process for 4 min. In the case of SF_6 gas, the GaAlAs was etched mainly by physical sputtering, and it generated tapered shape. In the case of Cl_2 gas, the GaAlAs was etched chemically, and thus the vertical hole with high aspect ratio was produced. By combining the two processes alternately, the tapered profile with high aspect ratio was fabricated, which was essential for suppressing the Fresnel reflection at the boundary. After the FAB etching, the residual EB resist was removed with acetone.

Fig. 1(a) and (b) show the top and oblique views of the fabricated SWG on the surface of the LED wafer, respectively. The grating has 200-nm period and it is approximately 275-nm deep. The grating shape of the SWG was designed by theoretical calculation based on the rigorous coupled-wave analysis (RCWA) proposed by Moharam [19]. In the case of the grating with the triangular sectional shape, the reflectivity calculated on the basis of RCWA became sufficiently low with the shorter grating period than 200 nm and the grating depth from 200 to 400 nm. The SWG is fabricated in the area of 100-μm square. The grating profile of the SWG can be controlled by changing EB expose time, FAB etching time and the process gases. As shown in Fig. 1(b), the SWG consists of the conical profile grating. The reflectivity of the fabricated SWG was also measured from the front side as a function of wavelength. The reflectivity of the SWG was considerably reduced to be less than 1.0% ($\sim$1/50 of the original reflectivity) in the wavelength region from 400 to 780 nm. At the wavelengths of 440 and 780 nm, the reflectivities of the SWG decreased to 0.02% from 45.31% and 38.1% of the original flat surface of the LED wafer, respectively. At

Manuscript received February 20, 2002; revised April 12, 2002.

The authors are with the Department of Mechatronics and Precision Engineering, Tohoku University, 980-8579 Sendai, Japan.

Publisher Item Identifier S 1041-1135(02)06085-8.

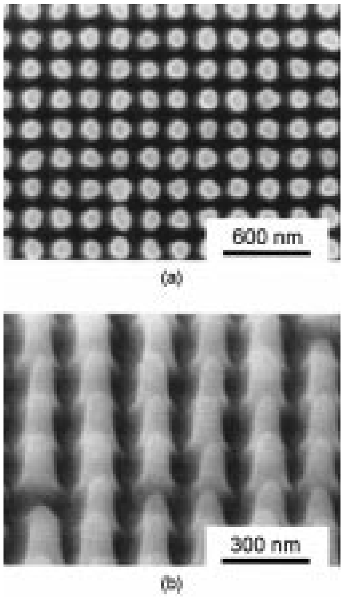

Fig. 1. Scanning electron micrographs of the SWG fabricated on the surface of the LED wafer. (a) Top view. (b) Oblique view.

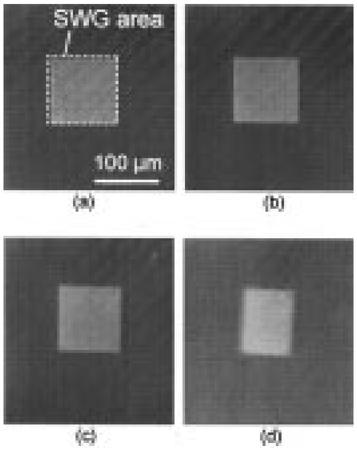

Fig. 2. Optical micrographs of the emission from the SWG observed at angle θ. (a) $\theta = 0°$. (b) $\theta = 10°$. (c) $\theta = 20°$. (d) $\theta = 40°$.

wavelengths longer than 780 nm, because the light was hardly adsorbed by the GaAlAs, the measured reflectivity included direct reflection from the flat surface of the backside. Therefore, the wavelength region effective for suppressing the surface reflection was broad enough to cover the emission spectral from LED.

Fig. 2(a)–(d) show the optical micrographs of the surface of GaAlAs wafer observed at different angles θ ($\theta = 0°$ corresponds the surface normal). The surrounding medium of the SWG is air. The input current to the LED is 20 mA. It is obvious that the 100-μm square SWG area is brighter than the other area even at the large emission angles.

Fig. 3 shows the intensities of the light emitted from the SWG area and the flat surface area measured as a function of θ. The measured intensities are normalized by the maximum intensity for the flat surface. The emission is increased by 21.6% at the normal emission angle. We think this increase is adequate from the calculation result that the transmittance of the SWG increases to 99.6% from 69.9% of the flat surface of the LED wafer. At all the measured angles, the emission from the SWG is increased in comparison with that from the flat surface. Although the flat surface emits little light at the angle higher than 40°, the light is emitted even 60° in the SWG region. The ratio of the emission intensity from the SWG region to that from the flat surface is increased with increasing the emission angle. This fact shows that the SWG works effectively as the antireflection surface even at a large emission angle although the magnitude of the emission is smaller than that at the low angle. Since the transmitted wave front is not degraded by the SWG, smooth emission profile is obtained as shown in Fig. 3. The total emittance is increased by 60% with the SWG in comparison with that of the flat surface.

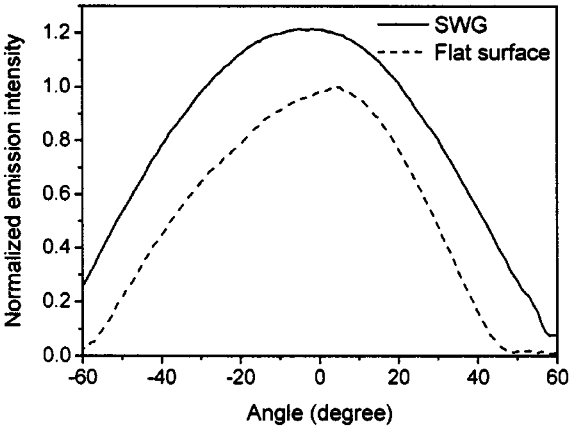

Fig. 3. Normalized emission intensity as a function of emission angle.

We showed the improvement in emission efficiency and emission angle of LED by fabricating the subwavelength grating on LED. The period and depth of the SWG were 200 and 275 nm, respectively. For fabricating the tapered grating, which was essential to suppress the Fresnel reflection at the interface, we introduced three-steps FAB etching process combined with EB patterning. The proposed technique will be powerful for improving the luminance and the emission angle of LEDs used in displays.

REFERENCES

[1] I. Schnitzer, E. Yablonovitch, C. Caneau, T. J. Gmitter, and A. Scherer, “30% external quantum efficiency from surface textured, thin-film light-emitting diodes,” *Appl. Phys. Lett.*, vol. 63, pp. 2174–2176, Oct. 1993.
[2] R. Windisch, P. Heremans, A. Knobloch, P. Kiesel, G. H. Döhler, B. Dutta, and G. Borghs, “Light-emitting diodes with 31% external quantum efficiency by outcoupling of lateral waveguide modes,” *Appl. Phys. Lett.*, vol. 74, pp. 2256–2258, Apr. 1999.
[3] M. Boroditsky, T. F. Krauss, R. Coccioli, R. Vrijen, R. Bhat, and E. Yablonovitch, “Light extraction from optically pumped light-emitting diode by thin-slab photonic crystals,” *Appl. Phys. Lett.*, vol. 75, pp. 1036–1038, Aug. 1999.
[4] S. J. Wilson and M. C. Hutley, “The optical properties of ‘moth eye’ antireflection surfaces,” *Opt. Acta*, vol. 29, pp. 993–1009, 1982.
[5] R. C. Enger and S. K. Case, “Optical elements with ultrahigh spatial-frequency surface corrugations,” *Appl. Opt.*, vol. 22, pp. 3220–3228, Oct. 1983.
[6] Y. Ono, Y. Kimura, Y. Ohta, and N. Nishida, “Antireflection effect in ultrahigh spatial-frequency holographic relief gratings,” *Appl. Opt.*, vol. 26, pp. 1142–1146, Mar. 1987.
[7] S. T. Han, Y.-L. Tsao, R. M. Walser, and M. F. Becker, “Electromagnetic scattering of two-dimensional surface-relief dielectric gratings,” *Appl. Opt.*, vol. 31, pp. 2343–2352, May 1992.

[8] P. Lalanne and G. M. Morris, “Design, fabrication and characterization of subwavelength periodic structures for semiconductor anti-reflection coating in the visible domain,” *Proc. SPIE*, vol. 2776, pp. 300–309, 1996.

[9] S. H. Zaidi, A.-S. Chu, and S. R. J. Brueck, “Optical properties of nanoscale, one-dimensional silicon grating structures,” *J. Appl. Phys.*, vol. 80, pp. 6997–7008, Dec. 1996.

[10] P. Lalanne and G. M. Morris, “Antireflection behavior of silicon subwavelength periodic structures for visible light,” *Nanotechnol.*, vol. 8, pp. 53–56, 1997.

[11] A. Gombert, W. Glaubitt, K. Rose, J. Dreibholz, C. Zanke, B. Bläsi, A. Heinzel, W. Horbelt, D. Sporn, W. Döll, V. Wittwer, and J. Luther, “Glazing with very high solar transmittance,” *Sol. Energy*, vol. 62, pp. 177–188, 1998.

[12] D. L. Brundrett, T. K. Gaylord, and E. N. Glytsis, “Polarizing mirror/absorber for visible wavelengths based on a silicon subwavelength grating: Design and fabrication,” *Appl. Opt.*, vol. 37, pp. 2534–2541, May 1998.

[13] A. Gombert, W. Glaubitt, K. Rose, J. Dreibholz, B. Bläsi, A. Heinzel, D. Sporn, W. Döll, and V. Wittwer, “Subwavelength-structured antireflective surfaces on glass,” *Thin Solid Films*, vol. 351, pp. 73–78, 1999.

[14] K. Hadobás, S. Kirsch, A. Carl, M. Acet, and E. F. Wassermann, “Reflection properties of nanostructure-arrayed silicon surfaces,” *Nanotechnol.*, vol. 11, pp. 161–164, 2000.

[15] Y. Kanamori, M. Sasaki, and K. Hane, “Broadband antireflection gratings fabricated upon silicon substrates,” *Opt. Lett.*, vol. 24, pp. 1422–1424, Oct. 1999.

[16] Y. Kanamori, H. Kikuta, and K. Hane, “Broadband antireflection gratings for glass substrates fabricated by fast atom beam etching,” *Jpn. J. Appl. Phys.*, vol. 39, pp. L735–L737, July 2000.

[17] Y. Kanamori, K. Hane, H. Sai, and H. Yugami, “100 nm period silicon antireflection structures fabricated using a porous alumina membrane mask,” *Appl. Phys. Lett.*, vol. 78, pp. 142–143, Jan. 2001.

[18] Y. Toma, M. Hatakeyama, K. Ichiki, H. Huang, K. Yamauchi, K. Watanabe, and T. Kato, “Fast atom beam etching of glass materials with contact and non-contact masks,” *Jpn. J. Appl. Phys.*, vol. 36, pp. 7655–7659, Dec. 1997.

[19] M. G. Moharam, “Coupled-wave analysis of two-dimensional dielectric gratings,” *Proc. SPIE*, vol. 883, pp. 8–11, 1988.