AIP Applied Physics Letters

Linearly polarized light emission from InGaN light emitting diode with subwavelength metallic nanograting

Liang Zhang, Jing Hua Teng, Soo Jin Chua, and Eugene A. Fitzgerald

Citation: Appl. Phys. Lett. **95**, 261110 (2009); doi: 10.1063/1.3276074
View online: http://dx.doi.org/10.1063/1.3276074
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v95/i26
Published by the American Institute of Physics.

Linearly polarized light emission from InGaN light emitting diode with subwavelength metallic nanograting

Liang Zhang,[1,2,a)] Jing Hua Teng,[3,b)] Soo Jin Chua,[1,2,c)] and Eugene A. Fitzgerald[1,4]
[1]*Advanced Materials for Micro- and Nano-systems Programme, Singapore-MIT Alliance, Singapore 117576, Singapore*
[2]*Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, Singapore*
[3]*Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*Star), 3 Research Link, Singapore 117602, Singapore*
[4]*Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 19 October 2009; accepted 25 November 2009; published online 31 December 2009)

Surface emitting linearly polarized InGaN/GaN light emitting diode (LED) is demonstrated using a subwavelength metallic nanograting. The aluminum based grating with a period of 150 nm is fabricated on top of the *p*-contact layer in a conventional InGaN LED structure grown on (0001) oriented sapphire substrate. Polarization ratio can reach 7:1, the highest ever reported polarization ratio directly from a light emitting diode. The polarization characteristics are studied in details both experimentally and theoretically, suggesting an effective way to make polarized light emission devices. © *2009 American Institute of Physics*. [doi:10.1063/1.3276074]

Upon prosperous commercialization of InGaN based semiconductor optoelectronic devices, light emitting diodes (LEDs) have become universal in illumination and signal applications. While the improvement of the basic characteristics like efficiency and power level will benefit the replacement of the conventional light sources to realize solid-state lighting, further improvement in other features can bring about more unique applications. One notable characteristic is the polarized light emission, which would be highly desirable for many applications, e.g., imaging[1] and liquid crystal backlighting.[2,3] Several authors have reported polarized light emission from LED structures grown on nonpolar[4,5] or semipolar GaN substrates.[6]

InGaN/GaN LEDs epitaxially grown on (0001) oriented sapphire substrates are most commonly used in the market due to their high efficiency, power, and long lifetime. It has been reported that light emitted in certain directions shows some degree of polarization.[7] Although valence band intermixing can result a dominant polarization along quantum well plane, it only emits from the edge of unpacked LED chips.[8] Conventional packaged LEDs having surface emission are generally considered to be unpolarized light sources. Different approaches such as using special reflector design[9] and photonic crystals[10] have been investigated recently to get polarized light emission from such widely used LED structures. However, complex design, fabrication, and packing process are involved, and the resulting polarization ratio is still not high enough.

In the present study, we investigate the approach employing sub-wavelength metallic nanograting (SMNG) to realize the polarized light emission in conventional InGaN/GaN LED grown on (0001) oriented sapphire. Figure 1(a) shows the cross-sectional view of the InGaN/GaN green LED with the SMNG structure fabricated on top. Conventional LED structure was grown on (0001) sapphire substrate by metal organic chemical vapor deposition and produced by standard process including photolithography, plasma etching, metal deposition, and alloying. Electron beam lithography (EBL) is used to pattern 150 nm period aluminum (Al) SMNG on top of a thin layer of SiO_2, which was deposited by plasma enhanced chemical vapor deposition on top of the Ni/Au *p*-type 5 nm/5 nm ohmic contact layer. It is noted that this predeposited SiO_2 serves as both a protective layer for *p*-metal contact surface during etching process and as an insulating layer between the metal grating and *p*-contact. Figure 1(b) shows the optical micrograph of the fabricated SMNG LED mesa, where the EBL area appears darker due to the SMNG pattern shown in Fig. 1(c).

Figure 2 shows the room temperature electroluminescence (EL) spectra of SMNG LED at a forward current of 10 mA. The peak wavelength and the full width at half maximum (FWHM) of the emission spectra of the LED are 546 and 80 nm, respectively. Compared with original LED without SMNG fabricated, there was no obvious change for both peak wavelength and FWHM, which is consistent with the fact that our SMNG is designed for giving almost uniform transmission efficiency within this spectrum range. It can be seen from the inset optical micrograph that the emission area is exclusively defined by the region with SMNG pattern. Through SMNG pattern outside active region, light still can be coupled out.

Figure 3 shows the EL intensity as a function of the orientation angle of the linear polarizer placed between the InGaN/GaN green SMNG LED and the spectrometer. The intensity was determined from measuring the central wavelength peak intensity of each spectrum taken under different polarizer-rotating angle with 5° intervals. The measured intensity varies with the polarizer-rotating angle, revealing polarized light emission from the LED. The maximum and minimum intensities indicate the relative magnitude of the two orthogonal polarizations, respectively. The minimum intensity measured is less than 0.14 when normalized to the

a)Electronic mail: lzhang@mit.edu.
b)Electronic mail: jh-teng@imre.a-star.edu.sg.
c)Electronic mail: elecsj@nus.edu.sg.

0003-6951/2009/95(26)/261110/3/$25.00

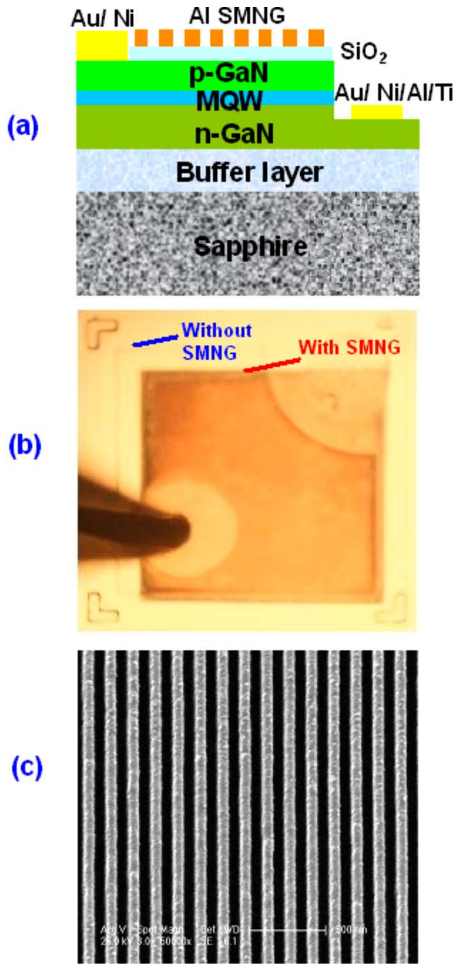

FIG. 1. (Color online) (a) Schematic diagram of the cross section of the InGaN/GaN SMNG LED. (b) Optical micrograph of fabricated SMNG LED mesa, where the SMNG patterning area appears as darker square. (c) Scanning electron microscope image of SMNG with a grating period of 150 nm.

maximum, resulting a measured polarization ratio (defined as I_{max}/I_{min} as in Refs. 8–10) above 7:1, which is much higher than that achieved by other methods.[8–10] Compared with simulated results with perfect SWNG using rigorous coupled-wave analysis (RCWA),[11] as seen by the solid curve in Fig. 3, the measured results exhibit increasing departure when the polarizer rotates toward the extinction position, while the RCWA curve almost reach zero for a perfect linear polarization without any orthogonal component.

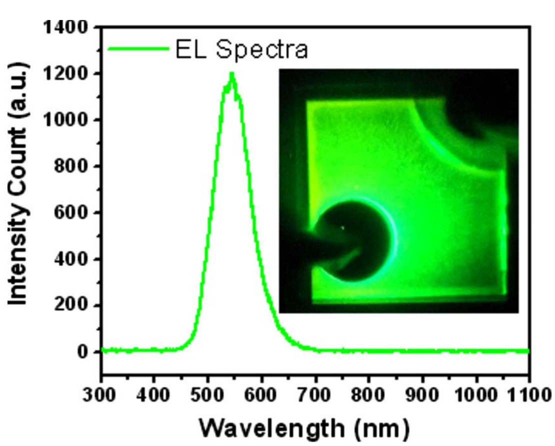

FIG. 2. (Color online) Room temperature EL spectra of the InGaN/GaN SMNG LED at a forward injection current of 10 mA, The inset image is the optical micrograph showing the green light emission across the mesa.

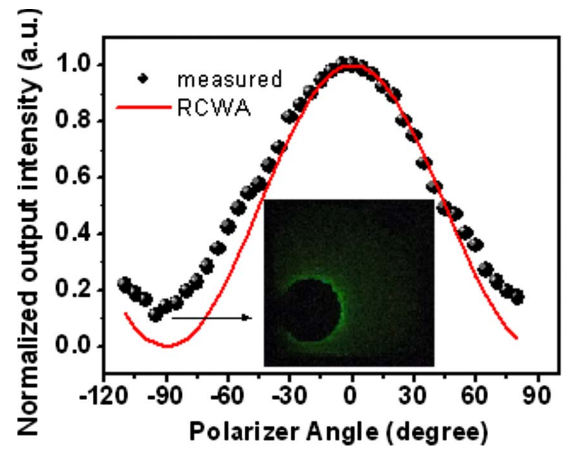

FIG. 3. (Color online) EL intensity of the InGaN/GaN SMNG LED as a function of the polarizer-rotating angle within one period range. Dots are measured with 5-degree intervals while red curve is simulated by RCWA also with 5-degree intervals but connected as a continuous curve. The inset image shows optical micrograph of the eclipselike light emission around the *p*-pad when polarizer angle is placed at extinction position.

To investigate the origin of this nonzero orthogonal component measured, the optical micrograph of light emission from the LED was taken when the polarizer angle placed at the extinction position, as shown in the inset figure of Fig. 3, where an eclipselike distribution of light is observed. This eclipselike emission of light through polarizer placed at the extinction position suggests that light around the edge of the *p*-pad has a lower polarization degree. This is possibly because of the nonconformal deposition of aluminum around the pad from shadowing effect during e-beam evaporation and the uneven resist resulted grating pattern distortion around the pad. Thus such small amount of emission contributes to the nonzero intensity measured at the polarizer's extinction position. It should be possible to reduce by process modification and dose correction to greatly enhance the final polarization ratio. It is also noted that, there is no emission except for above-mentioned eclipselike emission around the edge of the *p*-pad, confirming that both the emission from active region and the coupled-out emission though SMNG outside active region are linearly polarized.

The polarization results described above can be explained by the restricted motion of electrons perpendicular to the SMNG. When the spontaneous emission from quantum wells arrives at the LED surface, for light having polarization along the grating direction, the conduction electrons are coherently driven along SMNG with unrestricted movement. The physical response of SMNG is exactly the same as the case of thin metal sheet. For light having polarization perpendicular to grating direction, since the period of SMNG is much smaller than the incident wavelength, the electron movement is confined similar as in the case of the dielectric, the Ewald–Oseen field generated by electrons is no longer sufficiently strong to cancel the incoming field, resulting in transmission of this single polarization. It is noted that the working principle cannot be explained by excitation of the plasmon resonance surfacewaves,[12] and is distinguished from Ref. 13, which has grating periods close to the wavelength and works in the resonance region of localized surface plasmon. The period of SMNG here is much smaller than the wavelength and closer to the quasistatic limit. Applying effective-medium approximation, the SMNG here could be equivalently modeled as a uniaxial birefringent layer with its ordinary and extraordinary refractive indices n_o and n_e as[14]

$$n_o^2 = n_1^2 \frac{w}{p} + n_2^2 \left(1 - \frac{w}{p}\right), \tag{1}$$

$$\frac{1}{n_e^2} = \frac{1}{n_1^2}\frac{w}{p} + \frac{1}{n_2^2}\left(1 - \frac{w}{p}\right), \tag{2}$$

where n_1 is the refractive index of metal, n_2 is refractive index of the space materials, and w and p are the width and period of the grating, respectively. For the Al based SMNG discussed here, the refractive index of Al at the LED peak wavelength and the two sides of the FWHM of the EL spectrum are[15] $n_1 = 0.963 + i6.7$ ($\lambda = 546$ nm), $0.826 + i6.28$ ($\lambda = 506$ nm), and $1.15 + i7.15$ ($\lambda = 586$ nm), respectively, with $n_2 = 1$ for the air in between. Accordingly, the effective ordinary and extraordinary refractive indices of SWNG are $n_o = 0.6885 + i4.6857$ and $n_e = 1.4292 + i0.0045$ for $\lambda = 546$ nm, $n_o = 0.5915 + i4.3850$ and $n_e = 1.4315 + i0.0047$ for $\lambda = 506$ nm, $n_o = 0.8210 + i5.0074$ and $n_e = 1.4272 + i0.0043$ for $\lambda = 586$ nm, respectively, and n_o is along SMNG. Based on these values, SMNG functions as metallic layer for polarization along n_o axis and as a dielectric for polarization along n_e axis. The transmission leakage polarized along the n_o axis is tiny based on the above values, thus a high transmission contrast ratio is promising to obtained.

In conclusion, we have experimentally demonstrated polarized light from surface emitting InGaN/GaN green LED by using SMNG. The device is based on the most widely used InGaN/GaN LED structures grown on (0001) oriented sapphire substrates. A polarization ratio of 7:1 or ~88% polarization light has been observed, which is the highest reported polarization ratio ever achieved in a single LED. Rigorous coupled wave analysis was used to design and simulate the SMNG structure. The polarized emission is attributed to the restricted movement of electrons perpendicular to the grating direction which has dimension much smaller than the wavelength. The technique introduced here can easily be extended to other LEDs in different wavelength by adjusting the SMNG dimensions.

This work was supported by the Singapore-MIT Alliance fund and IMRE A*STAR project fund. L.Z. would like to thank the Singapore-MIT Alliance for the provision of Ph.D fellowship.

[1]S.-S. Lin, K. M. Yemelyanov, E. N. Pugh, Jr., and N. Engheta, Opt. Express **14**, 7099 (2006).
[2]S. H. B. J. Jagt, H. J. Cornelissen, D. J. Broer, and C. W. M. Bastiaansen, J. Soc. Inf. Disp. **10**, 107 (2002).
[3]S. M. P. Blom, H. P. M. Huck, H. J. Cornelissen, and H. Greiner, J. Soc. Inf. Disp. **10**, 209 (2002).
[4]N. F. Gardner, J. C. Kim, J. J. Wierer, Y. C. Shen, and M. R. Krames, Appl. Phys. Lett. **86**, 111101 (2005).
[5]T. Koyama, T. Onuma, H. Masui, A. Chakraborty, B. A. Haskell, S. Keller, U. K. Mishra, J. S. Speck, S. Nakamura, S. P. DenBaars, T. Sota, and S. F. Chichibu, Appl. Phys. Lett. **89**, 091906 (2006).
[6]R. Sharma, M. Pattison, H. Masui, R. M. Farrell, T. J. Baker, B. A. Haskell, F. Wu, S. P. DenBaars, J. S. Speck, and S. Nakamura, Appl. Phys. Lett. **87**, 231110 (2005).
[7]J. Shakya, K. Knabe, K. H. kim, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **86**, 091107 (2005).
[8]M. F. Schubert, S. Chhajed, J. K. Kim, and E. F. Schubert, Appl. Phys. Lett. **91**, 051117 (2007).
[9]M. F. Schubert, S. Chhajed, J. K. Kim, E. F. Schubert, and J. Cho, Opt. Express **15**, 11213 (2007).
[10]C.-F. Lai, J.-Y. Chi, H.-H. Yen, H.-C. Kuo, C.-H. Chao, H.-T. Hsueh, J.-F. T. Wang, C.-Y. Huang, and W.-Y. Yeh, Appl. Phys. Lett. **92**, 243118 (2008).
[11]M. G. Moharam and T. K. Gaylord, J. Opt. Soc. Am. A **3**, 1780 (1986).
[12]M. Xu, H. Urbach, D. deBoer, and H. Cornelissen, Opt. Express **13**, 2303 (2005).
[13]K.-C. Shen, C.-Y. Chen, H.-L. Chen, C.-F. Huang, Y.-W. Kiang, C. C. Yang, and Y.-J. Yang, Appl. Phys. Lett. **93**, 231111 (2008).
[14]Z. Ge and S.-T. Wu, Appl. Phys. Lett. **93**, 121104 (2008).
[15]D. Y. Smith, E. Shiles, and M. Inokuti, in *Handbook of Optical Constants of Solids*, edited by E. D. Palik (Academic, Orlando, 1985), pp. 369–406.