63.4: *Invited Paper:* Development and Application Prospects of InGaN-based Optoelectronic Devices Prepared in Nonpolar Orientations

Hisashi Masui and Shuji Nakamura
Solid-State Lighting and Energy Center, Materials Department, College of Engineering, University of California, Santa Barbara, California 93106-5055, USA

Abstract
High-power light-emitting diodes (LEDs) and laser diodes have been realized on nonpolar planes of bulk-GaN substrates. Spontaneously polarized light emission is obtained from nonpolar LEDs, which is believed to improve the system energy efficiency when nonpolar LEDs are combined with liquid-crystal displays. Preliminary experimental results are reported.

1. Introduction
Solid-state lighting has attracted vast attention in terms of the energy saving, for which light-emitting diodes (LEDs) are the key technology. White LEDs [1] have been used for liquid-crystal display (LCD) backlighting. This way of using white LEDs is not energy efficient since LCDs utilize polarized light, which is obtained by passing light through a polarization film. Polarization films have a typical transmission of 30% (50% by eliminating one of two polarizations and 20% by absorption of the film). In addition, color filters are necessary for color LCDs, thereby lowering efficiency further. Nonpolar-oriented InGaN LEDs emit polarized monochromatic light, which is believed to offer a reduction in optical energy absorption in the LCD unit. The present report demonstrates advantages in energy savings by employing nonpolar LEDs with an LCD unit in addition to recent results in the nonpolar optoelectronics research. Preliminary studies can be found in Ref. 2.

GaN-related materials crystallize in wurtzite structure (two-constituent hexagonal). Figure 1 is an illustration representing a GaN crystal. The basal plane (called the *c* plane) is an electrically polar plane. When GaN films are prepared on nonpolar planes, in-plane crystal symmetry (rectangular symmetry) becomes lower than the films prepared on the *c* plane (hexagonal symmetry). As a result, light emission from these nonpolar films can have polarized characteristics to the surface-normal direction. This mechanism was known for many years [3-5], but it was not until recently that device applications were sought as electroluminescence was demonstrated in 2005 [6].

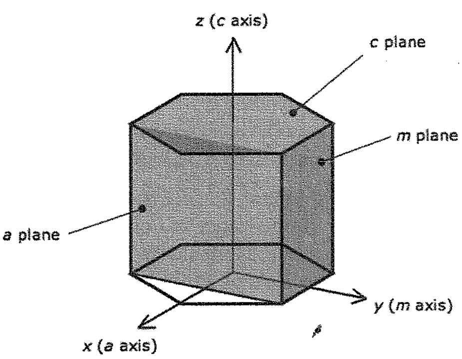

Figure 1. A hexagonal prism representing GaN crystal structure with conventional nomenclature of crystallographic planes and Cartesian coordinate axes. The *a* and *m* planes are two major nonpolar planes. Colors painting crystallographic planes do not indicate any physical significance, but only for graphical clarity.

2. Recent progresses in nonpolar LEDs
Nonpolar-oriented device growths were unsuccessful until bulk-GaN substrates became commercially available in 2006. Since then, high-power LEDs and laser diodes have been realized on the *m*-plane [7,8]. Optical polarization studies have been accelerated: low-temperature characteristics [9], sample preparation effects [10], and crystallographic orientation effects [11]. The *a*-plane, on the other hand, has not been competitive in optoelectronic devices for not-well-understood reasons [12].

3. Experiments and Results
Nonpolar LED samples used in the experiments were fabricated by the metalorganic chemical-vapor deposition (MOCVD) method on *m*-plane oriented GaN substrates. LED structures consisted of a multiple QW stack of InGaN/GaN that was sandwiched by *n*- and *p*-type GaN layers. Conventional mesa structure (an active area ~ 300 × 300 μm^2) was fabricated on the LED wafers. Details of sample LED preparation are described elsewhere [13]. Similar LEDs were prepared in the *c*-plane orientation as a comparison. The nonpolar LEDs emitted blue light in the 450-nm range with a

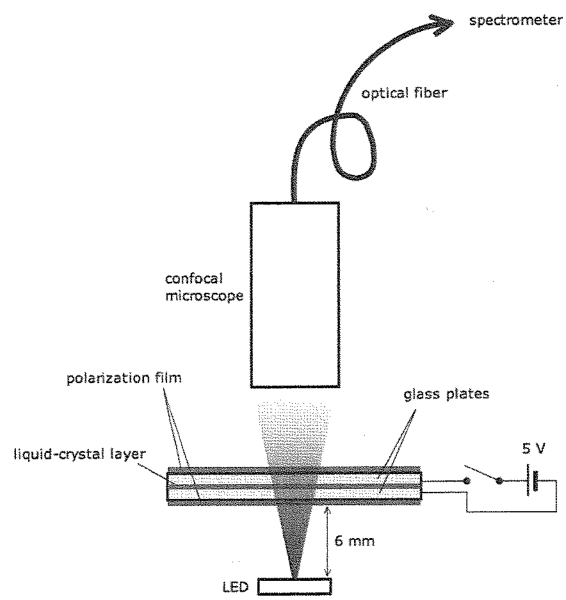

Figure 2. Experimental setup. Light emission from an LED was observed through an LCD unit while the bias voltage (5 V) was turned on and off. The confocal microscope had a collection angle of approximately 10°.

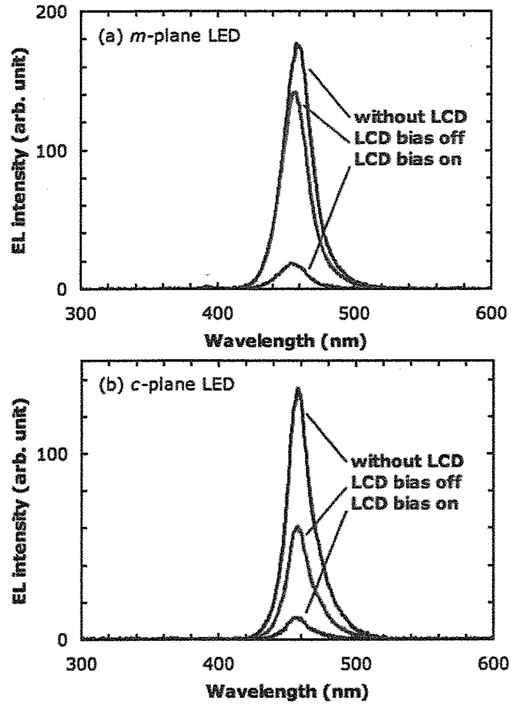

Figure 3. Emission spectra of the two LEDs: (a) the *m*-plane LED and (b) the *c*-plane LED.

typical polarization ratio ρ of 0.9 (surface-normal detection via a confocal microscope), whereas light emission from the *c*-plane LEDs was unpolarized.

These LEDs were placed under an LCD unit in such a way that the polarizations of the entrance polarization film and nonpolar-LED emission were parallel (within the eye accuracy). Light emission was observed via a confocal microscope [14] under three different conditions: the LCD bias (5V) was on, the bias was off, and the LCD unit was removed. The objective lens was 5× with a numerical aperture 0.15. The experimental setup is schematically shown in Fig. 2. Recorded spectra are shown in Fig. 3 for the two types of LEDs. Optical absorption of LED emission by the LCD (bias off) was less in the *m*-plane LED case than the *c*-plane LED case. This result is explained by polarized light emission of the *m*-plane LEDs and promises the improved energy efficiency. Weak light emission was detected when the LCD bias was on, where complete extinction was expected. The reasons for the incomplete extinction are presumably imperfect functioning of liquid-crystal cells, guided and scattered light within the LCD, and misalignment of the experimental setup [2].

4. Summary

GaN-based optoelectronic devices prepared in nonpolar orientations were discussed with an emphasis on polarized light emission from the *m*-plane LEDs and their potential application for LCD backlighting. Nonpolar-oriented devices were fabricated on bulk-GaN substrates via the MOCVD method. Those devices have exhibited high optical output power, polarized light emission, and continuous lasing actions. Nonpolar LEDs have a potential to contribute to energy savings in LCD backlighting applications. Preliminary experiments were performed, where *m*-plane InGaN LEDs were combined with an LCD unit. Advantages in the system energy efficiency over the *c*-plane LEDs were confirmed.

5. Acknowledgements

The authors acknowledge the support of The Solid State Lighting and Energy Center at UCSB.

6. References

[1] K. Bando, K. Sakano, Y. Noguchi, and Y. Shimizu, " Development of High-Bright and Pure-White LED Lamps," J. Light & Visual Environ. Vol. **22**, pp. 2-5, 1998.

[2] H. Masui, H. Yamada, K. Iso, J. S. Speck, S. Nakamura, and S. P. DenBaars, "Non-Polar-Oriented InGaN Light-Emitting Diodes for Liquid-Crystal Display Backlighting," J. SID Vol. **16**, pp. 571-578, 2008.

[3] R. Dingle, D. D. Sell, S. E. Stokowski, and M. Ilegems, "Absorption, Reflectance, and Luminescence of GaN Epitaxial Layers," Phys. Rev. B, Vol. **4**, pp. 1211-1218, 1971.

[4] K. Horino, A. Kuramata, K. Domen, R. Soejima, and T. Tanahashi, "Growth of $(1\bar{1}00)$ Oriented GaN on $(1\bar{1}00)$ 6H-SiC by Metalorganic Vapor Phase Epitaxy," Proc. International Symposium on Blue Laser and Light Emitting Diodes (Ohmsha, Tokyo, 1996), pp. 530-533.

[5] Y. J. Sun, O. Brandt, M. Ramsteiner, H. T. Grahn, and K. H. Ploog, "Polarization Anisotropy of the Photoluminescence of *M*-plane (In,Ga)N/GaN Multiple Quantum Wells," Appl. Phys. Lett. Vol. **82**, pp. 3850-3852, 2003.

[6] N. F. Gardner, J. C. Kim, J. J. Wierer, Y. C. Shen, and M. R. Krames, "Polarization Anisotropy in the Electroluminescence of *m*-plane InGaN-GaN Multiple-Quantum-Well Light-Emitting Diodes," Appl. Phys. Lett. Vol. **86**, 11101, 2005.

[7] K.-C. Kim M. C. Schmidt, H. Sato, F. Wu, N. Fellows, Z. Jia, M. Saito, S. Nakamura, S. P. DenBaars, and J. S. Speck, "Study of Nonpolar *m*-Plane InGaN/GaN Multiquantum Well Light Emitting Diodes Grown by Homoepitaxial Metal-Organic Chemical Vapor Deposition," Appl. Phys. Lett. Vol. **91**, 181120, 2007.

[8] R. M. Farrell, D. F. Feezell, M. C. Schmidt, D. A. Haeger, K. M. Kelchner, K. Iso, H. Yamada, M. Saito, K. Fujito, D. A. Cohen, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Continuous-Wave Operation of AlGaN-Cladding-Free Nonpolar *m*-Plane InGaN/GaN Laser Diodes," Jpn. J. Appl. Phys. Part 2 Vol. **46**, pp. L761-L763, 2007.

[9] S. Nakagawa, H. Tsujimura, K. Okamoto, M. Kubota, and H. Ohta, "Temperature Dependence of Polarized Electroluminescence from Nonpolar *m*-plane InGaN-Based Light Emitting Diodes," Appl. Phys. Lett. Vol. **91**, 171110, 2007.

[10] H. Tsujimura S. Nakagawa, K. Okamoto, and H. Ohta, "Characteristics of Polarized Electroluminescence from *m*-Plane InGaN-Based Light Emitting Diodes," Jpn. J. Appl. Phys. Part 2 Vol. **46**, pp. L1010-L1012, 2007.

[11] H. Masui, H. Yamada, K. Iso, S. Nakamura, and S. P. DenBaars, "Optical Polarization Characteristics of InGaN/GaN Light-Emitting Diodes fabricated on GaN substrates oriented

between $(10\bar{1}0)$ and $(10\bar{1}\bar{1})$ planes," Appl. Phys. Lett. Vol. **92**, 091105, 2008.

[12] H. Yamada, K. Iso, M. Saito, H. Hirasawa, N. Fellows, H. Masui, K. Fujito, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Comparison of InGaN/GaN Light Emitting Diodes Grown on *m*-Plane and *a*-Plane bulk GaN substrates," Phys. Status Solidi RRL Vol. **2**, pp. 89-91, 2008.

[13] H. Yamada, K. Iso, M. Saito, K. Fujito, S. P. DenBaars, J. S. Speck, and S. Nakamura, "Impact of Substrate Miscut on the Characteristic of *m*-Plane InGaN/GaN Light Emitting Diodes," Jpn. J. Appl. Phys. Part 2 Vol. **46**, pp. L1117-L1120, 2007.

[14] H. Masui, H. Yamada, K. Iso, H. Hirasawa, N. N. Fellows, J. S. Speck, S. Nakamura, and S. P. DenBaars, "Optical Polarization of *m*-Plane InGaN/GaN Light-Emitting Diodes Characterized via Confocal Microscope," Phys. Status Solidi A, to be published.