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Hongjian Li, Haojun Zhang, Panpan Li, Matthew S Wong, Yi Chao Chow, et al.. Development of efficient semipolar InGaN long wavelength light-emitting diodes and blue laser diodes grown on a high quality semipolar GaN/sapphire template. Journal of Physics: Photonics, 2020, 10.1088/2515-7647/ab8cb1 . hal-03022832

HAL Id: hal-03022832

<https://hal.science/hal-03022832>

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PERSPECTIVE • OPEN ACCESS

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To cite this article: Hongjian Li *et al* 2020 *J. Phys. Photonics* **2** 031003

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OPEN ACCESS

RECEIVED
21 November 2019REVISED
22 January 2020ACCEPTED FOR PUBLICATION
23 April 2020PUBLISHED
28 May 2020

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PERSPECTIVE

Development of efficient semipolar InGaN long wavelength light-emitting diodes and blue laser diodes grown on a high quality semipolar GaN/sapphire template

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Abstract

Semipolar/nonpolar GaN-based optoelectronic devices become attractive due to several advantages such as alleviation of quantum-confinement Stark effect, high polarization ratio and optical gain. High performance semipolar/nonpolar InGaN light-emitting diodes (LEDs) and laser diodes (LDs) grown on semipolar/nonpolar bulk GaN substrate have been demonstrated. Owing to the limited size of such costly substrate, hetero-epitaxial growth of semipolar/nonpolar LEDs and LDs on foreign substrate causes lots of attentions. However, it is very challenging to realize efficient semipolar/nonpolar optoelectronic devices on foreign substrate due to the high dislocation density and possibly high basal plane stacking fault density. In this article, we review two growth methods to obtain high crystal quality semipolar (11-22) and (20-21) GaN layers on specially patterned sapphire substrate. The use of these substrates leads to the realization of efficient long wavelength InGaN semipolar LEDs and the first demonstration of semipolar blue LDs grown on foreign substrate shown in our previous reports. These results demonstrate significant progress in exploring the semipolar GaN materials quality and the devices efficiency grown on foreign substrate.

1. Introduction

III-nitride optical devices like light emitting diodes (LEDs) and laser diodes (LDs) have been well developed due the wide application in general illumination, display backlighting, and automotive headlights [1–3]. The commercially available GaN-based LEDs with the wurtzite structure grown along the c-direction, however, suffer from the quantum-confined Stark effect (QCSE) due to the large polarization-related electric fields, leading to a reduction of electron-hole wave-function overlap in the quantum wells (QWs) [4,5]. The QCSE becomes more severe in long wavelength InGaN LEDs such as green and yellow LEDs [6].

To overcome the challenges of the QCSE in the InGaN QWs, semipolar and nonpolar orientations are proposed to grow GaN optical devices, which show reduced or eliminated polarization fields [7–10]. Semipolar and nonpolar GaN optical devices also offer other advantages such as a high polarization ratio and high optical gain [7–10]. The polarized emitting light from semipolar and nonpolar LEDs could be employed as the backlighting source for liquid crystal displays (LCDs). In LCDs, a polarizer is required since the emission light from commercial c-plane LEDs is unpolarized, which results in an energy conversion loss [11,12]. High efficiency semipolar/nonpolar LEDs and LDs can be only demonstrated on semipolar and nonpolar bulk GaN substrates, which are very costly and only available with a small area [13]. This limits the application of semipolar/nonpolar optical devices. Growing semipolar/nonpolar GaN devices on low cost and large size foreign substrate like sapphire and silicon is attractive [9,10]. However, semipolar and

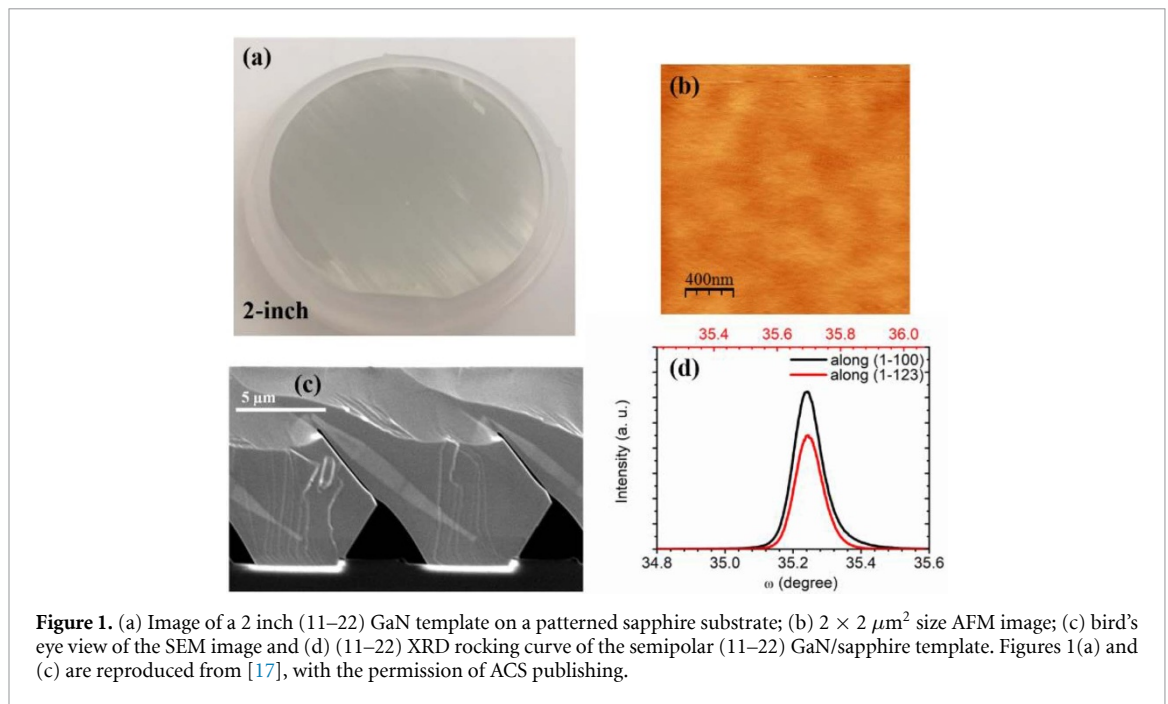


Figure 1. (a) Image of a 2 inch (11–22) GaN template on a patterned sapphire substrate; (b) $2 \times 2 \mu\text{m}^2$ size AFM image; (c) bird's eye view of the SEM image and (d) (11–22) XRD rocking curve of the semipolar (11–22) GaN/sapphire template. Figures 1(a) and (c) are reproduced from [17], with the permission of ACS publishing.

nonpolar GaN layers grown on a foreign substrate suffer from high defect densities like basal stacking faults (BSFs) and threading dislocations (TDs), resulting in a low quantum efficiency and poor device performance [14]. In our recent studies, we presented state-of-the-art efficient semipolar (11–22) and (20–21) GaN LEDs grown on high crystal quality semipolar GaN templates on a patterned sapphire substrate [15–18]. Also, blue semipolar LDs have been firstly demonstrated on a high crystal quality (11–22) GaN/sapphire template [19]. In this paper, we discuss the progress of materials growth for a high crystal quality semipolar GaN template on a sapphire substrate, efficient semipolar GaN long wavelength LEDs, and semipolar blue LDs grown on a foreign substrate. Polarized phosphor-free white semipolar (20–21) LEDs grown on a patterned sapphire template have also been presented [20].

2. Materials growth of the high quality semipolar template

2.1. Growth of high crystal quality (11–22) GaN on a patterned sapphire substrate

A three-step growth method was employed to obtain a planar (11–22) GaN template on a patterned r-plane sapphire using metal-organic chemical vapor deposition (MOCVD). The c-plane (0001) of the r-plane sapphire substrate was initially exposed by wet chemical etching. The GaN layer was grown on the inclined c-axis, and then the adjacent crystals were coalesced, which is referred to as three-step growth [21,22]. Figure 1(a) is an image of a 2 inch (11–22) GaN template on a patterned sapphire substrate after polishing. A smooth surface with a roughness of 0.1 nm in a $2 \times 2 \mu\text{m}^2$ area was observed by atomic force microscope (AFM), as shown in figure 1(b). The cross-sectional image obtained by scanning electron microscopy (SEM) of the semipolar (11–22) GaN on a patterned sapphire substrate is shown in figure 1(c). The nucleation facet is controlled on the open window of the patterned sapphire substrate along (1–100), which can significantly reduce the density of the TDs and the density of the BSFs. Defect-blocking air voids were created by overlapping the adjacent crystals in three consecutive steps through a fine-tuned growth condition, which are helpful for inhibiting the propagation of TDs and BSFs toward the free surface. X-ray diffraction (XRD) rocking curves for the on-axis (11–22) reflection are shown in figure 1(d). A full width at half maximum (FWHM) along the (1–100) and (11–23) were measured to be 321 and 348 arcsec, respectively, which indicate a high crystal quality of a semipolar (11–22) GaN layer grown on a patterned sapphire substrate. The final defect densities of the BSFs and the TDs were 70 cm^{-1} and $5 \times 10^7 \text{ cm}^{-2}$, respectively [15,17,18,21,22]. A more detailed description of the growth process of a semipolar (11–22) template on a sapphire substrate can be found in [21].

2.2. Growth of high crystal quality (20–21) GaN on a patterned sapphire substrate

An unintentionally doped semipolar (20–21) GaN layer was grown on a 4 inch (22–43) patterned sapphire substrate using MOCVD [16,23,24]. A schematic diagram of the growth process and sapphire orientations are shown in figure 2(a). Patterned trenches with a $6 \mu\text{m}$ period were formed on the sapphire substrate and

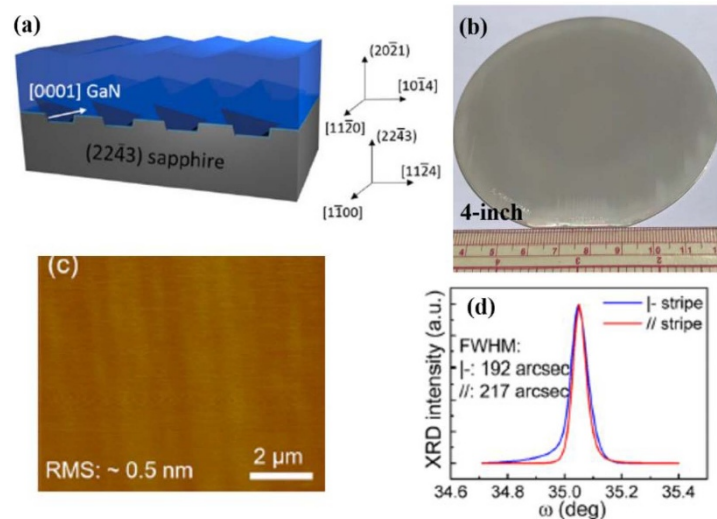


Figure 2. (a) Schematic diagram of the growth process and sapphire orientation in producing the (20–21) GaN. This figure was reproduced from [23] with the permission of AIP publishing. (b) Image of a 4 inch (20–21) GaN layer on a sapphire substrate, (c) $10 \times 10 \mu\text{m}^2$ size AFM image and (d) XRD rocking curve. Figures 2(c) and (d) were reproduced from [24], with the permission of ACS publishing.

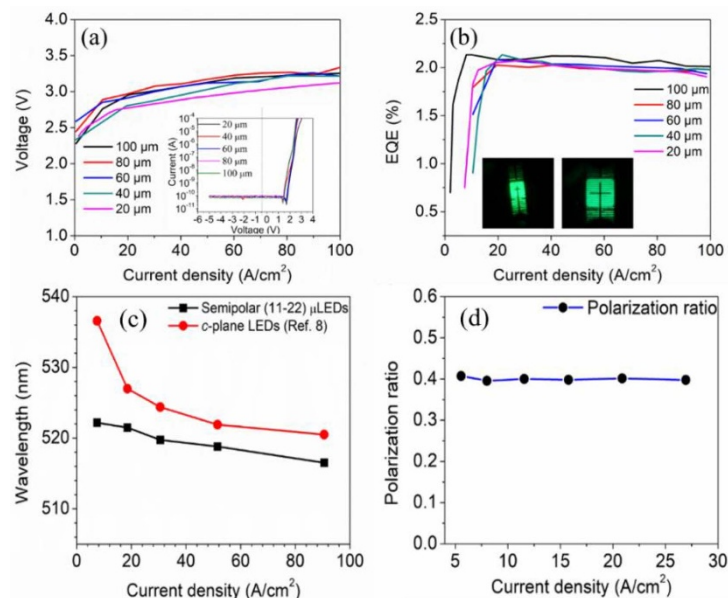


Figure 3. (a) LIV curves of different sizes of μLEDs . The inset is the reverse characteristic; (b) EQE versus current density. The inset show the luminous images of 40×40 and $80 \times 80 \mu\text{m}^2$; (c) wavelength blue-shift of semipolar (11–22) green μLEDs and c-plane polar green LEDs; (d) polarization ratio at various current densities. These figures were reprinted with permission from [18] © The Optical Society.

the inclined c-axis was exposed by dry etching. The semipolar (20–21) GaN layer was achieved by coalescing the adjacent nucleated crystals. A detailed description of the growth process of the semipolar (20–21) GaN template on a patterned sapphire substrate can be found in [23]. Figure 2(b) is an image of a 4 inch polished (20–21) GaN template on a patterned sapphire substrate. The roughness of the surface is measured by AFM to be 0.5 nm in an area of $10 \times 10 \mu\text{m}^2$ as shown in figure 2(c). The X-ray rocking curve width of the (20–21) peak in figure 2(d) was 192 and 217 arcsec parallel and perpendicular to the stripes, respectively, which suggests a high crystal quality of the semipolar (20–21) GaN template grown on a patterned sapphire substrate [24]. The density of the final TDs is around $2 \times 10^8 \text{ cm}^{-2}$ and the density of the BSF is low.

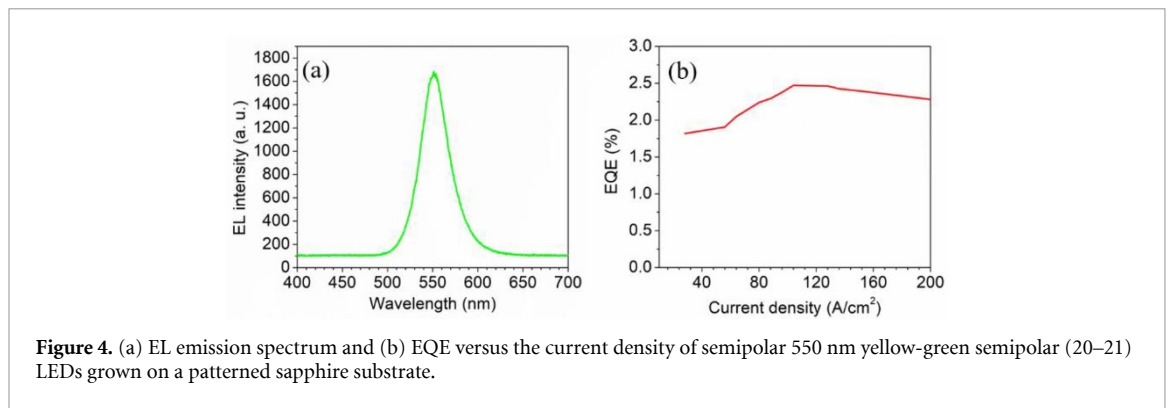


Figure 4. (a) EL emission spectrum and (b) EQE versus the current density of semipolar 550 nm yellow-green semipolar (20–21) LEDs grown on a patterned sapphire substrate.

3. Long wavelength semipolar InGaN LEDs grown on a high quality GaN/sapphire template

3.1. Semipolar (11–22) InGaN green micro-LEDs grown on a high quality (11–22) GaN/sapphire template

Semipolar (11–22) green 520 nm LEDs were grown on a patterned sapphire substrate by MOCVD. Squared micro-size LEDs (μ LEDs) were fabricated. A SiO₂ sidewall passivation layer was deposited by atomic-layer deposition (ALD) [18,25]. The current density-voltage (LIV) curves of the μ LEDs are plotted in figure 3(a), which demonstrate a turn-on voltage of around 2.5 V and forward voltages ranging from 2.8–3.2 V at 60 A cm⁻² for various sizes of μ LEDs. The reverse current is a key parameter related to the density of the BSFs. An extremely low leakage current of 0.1 nA at a reverse voltage of -5 V was found in the semipolar μ LEDs with different sizes, which suggests a low density of BSFs in the semipolar (11–22) GaN layer grown on a patterned sapphire substrate. A uniform electrical luminous image of the devices can be observed in the inset of figure 3(b). Moreover, all packaged μ LEDs show a size-independent peak external quantum efficiency (EQE) of around 2% as can be seen in figure 3(b). Although such EQE remains lower than the value of the green LEDs grown on a semipolar bulk GaN [15] or c-plane substrate [26], this is the first demonstration of efficient semipolar green μ LEDs grown on a foreign substrate. As shown in figure 3(c), the semipolar (11–22) green μ LEDs present a reduced wavelength blue-shift of 5 nm with increasing current density from 5–90 A cm⁻², which is much smaller than the blue-shift of 16 nm in c-plane polar green LEDs. Moreover, the semipolar (11–22) μ LEDs show a current density independent polarization ratio of 40%, as shown in figure 3(d), which has potential application as back lighting sources for LCDs [27].

3.2. Semipolar (20–21) InGaN yellow-green LEDs on a patterned sapphire substrate

Semipolar (20–21) 550 nm yellow-green LEDs with a single QW were grown on a (20–21) GaN template on a patterned sapphire substrate using MOCVD. The epitaxial wafer was fabricated into micro-size devices [28]. Figure 4(a) shows the electrical luminous (EL) spectrum of the LEDs at 20 A cm⁻², which exhibits an emission peak wavelength of 550 nm and a FWHM of 37 nm. As shown in figure 4(b), the packaged semipolar (20–21) yellow-green LEDs show a state-of-the-art EQE of 2.3%. A detailed study of materials growth and characterizations and the electrical and optical properties of yellow-green LEDs is published elsewhere [28].

3.3. Polarized phosphor-free white semipolar (20–21) LEDs on a patterned sapphire substrate

Polarized monolithic white semipolar LEDs were realized by integrating blue and yellow QWs directly on a 4 inch patterned sapphire substrate, based on the high crystal quality semipolar InGaN QWs described in 3.2 [20]. In this design, the emission spectrum and color temperature can be precisely controlled by tuning the number of QWs and the In content in the QWs. Figure 5(a) shows a side view of the distribution of In atoms in the active region using atom probe tomography (APT). The top blue QW and the bottom yellow QW can be clearly observed. Figure 5(b) presents the LIV characteristic of standard LEDs with a size of 0.1 mm². The output power was measured to be 3.9 mW at 100 mA, which is the highest output power among white semipolar InGaN LEDs on foreign substrates [29,30]. The forward voltage was 3.3 V at 20 mA. The polarization ratio is defined by $\rho = (I_{x'} - I_{y'}) / (I_{x'} + I_{y'})$, where $I_{x'}$ and $I_{y'}$ are the maximum and minimum integrated intensities of the emission spectra that pass through the polarizer when the polarizer is aligned along the x' -direction and y' -direction. In the (20–21) orientation, the x' -direction and y' -direction are along (1–210) and (10–1–4), respectively. Figure 5(c) presents the emission spectra of the semipolar (20–21) LEDs with the polarizer aligned along (1–210) and (10–1–4), respectively. Two emission peaks of 445 and 565 nm can be seen, which originate from the blue and yellow QWs, respectively. The polarization ratio was calculated to be 0.30. The phosphor-free white semipolar LEDs can be employed in visible light

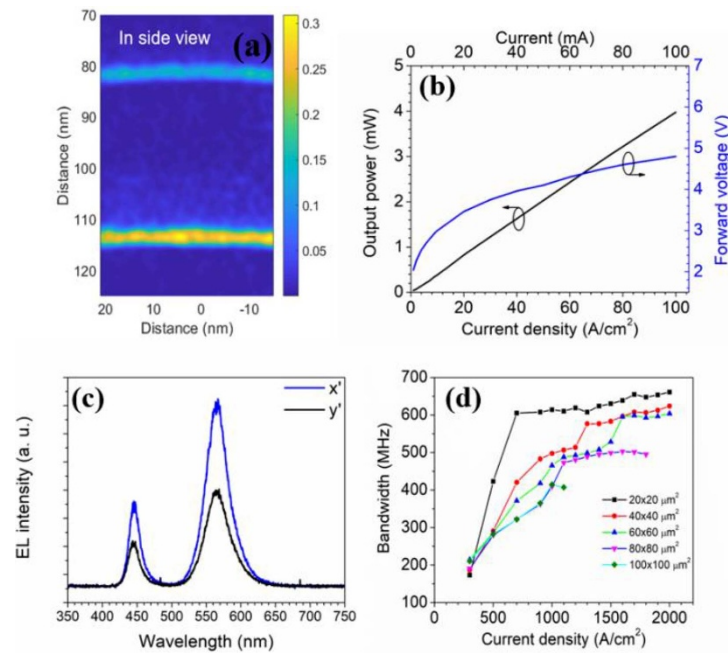


Figure 5. Side view of the distribution of indium in the active region by APT; (b) LIV of regular size LEDs; (c) EL emission spectra with the polarizer; (d) results of 3 dB MBs with various current densities in different sizes of μ LEDs. Reproduced with permission from Elsevier [20].

communication (VLC) owing to a larger electron-hole wave-function overlap and a shorter carrier lifetime on semipolar orientation [31]. The conventional yellow phosphor converted white LEDs show a limited 3 dB modulation bandwidth (MB) of only 30 MHz due to the low frequency response of yellow phosphor [32]. The measurement results of 3 dB MBs of the monolithic white semipolar μ LEDs are plotted in figure 5(d). It is found that the highest MB reaches 660 MHz in the $20 \times 20 \mu\text{m}^2$ size μ LEDs, which shows a large potential application in VLC.

4. First demonstration of blue semipolar LDs grown on a high crystal quality (11–22)/sapphire template

The first semipolar blue LDs grown on a foreign sapphire substrate were recently successfully demonstrated by our group by optimizing the structure and growth condition on high crystal quality semipolar (11–22) GaN layers on a patterned sapphire substrate described in 2.1 [19]. The far field pattern of the semipolar LDs grown on a sapphire template is shown in figure 6(a), followed by a lasing peak wavelength of 439 nm as shown in figure 6(b). The LIV characteristic of a semipolar LD with a length of $1800 \mu\text{m}$ and width of $2.5 \mu\text{m}$ is presented in figure 6(c). The semipolar blue LD shows a threshold current density of $\sim 20 \text{ kA cm}^{-2}$ and an output power of 38 mW at 800 mA under a pulse condition. These results represent significant progress in semipolar optical devices grown on sapphire substrates, which could overcome the limitation of costly and small size semipolar bulk GaN substrates. We believe the performance of the devices could be dramatically improved by reducing the BSFs and TDs in the semipolar GaN layers on sapphire substrates and the misfit dislocations in the devices [33].

5. Conclusion

In conclusion, we reviewed two growth methods to achieve high crystal quality semipolar GaN layers on a patterned sapphire substrate. Efficient semipolar green/yellow-green LEDs were obtained on those templates with an EQE of around 2% after packaging. Polarized phosphor-free white semipolar (20–21) LEDs were realized on semipolar (20–21) GaN layers on a 4 inch patterned sapphire substrate, which exhibit a polarization ratio of 0.3 and a 3 dB MB as high as 660 MHz in the small size μ LEDs. Moreover, the demonstration of semipolar (11–22) blue LDs grown on a patterned sapphire substrate were presented.

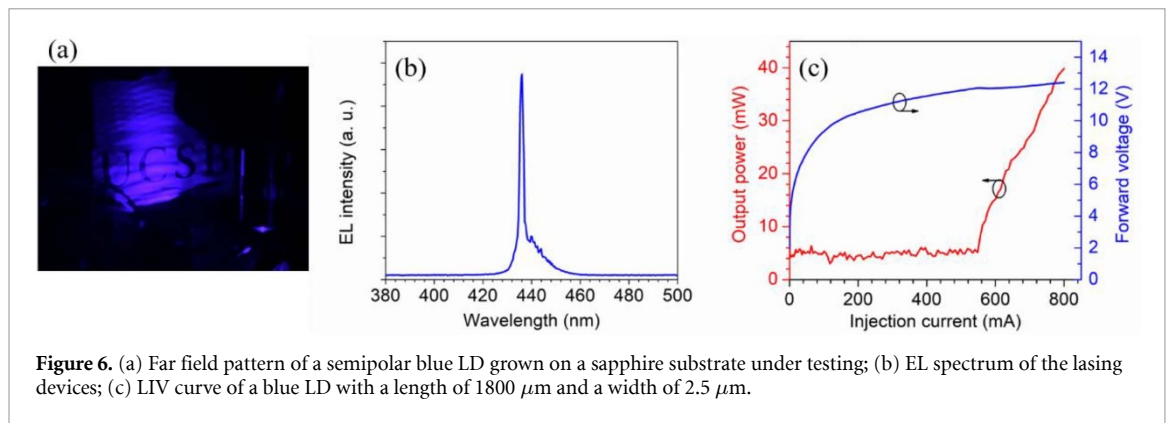


Figure 6. (a) Far field pattern of a semipolar blue LD grown on a sapphire substrate under testing; (b) EL spectrum of the lasing devices; (c) LIV curve of a blue LD with a length of 1800 μm and a width of 2.5 μm .

Acknowledgments

Funding of this work was provided by the UCSB Collaborative Research in Engineering, Science and Technology (CREST) Malaysia project. Part of this work was done in the UCSB nanofabrication facility.

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References

- [1] Nakamura S 1998 The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes *Science* **281** 956
- [2] Schubert E F and Kim J K 2005 Solid-state light sources getting smart *Science* **308** 1274
- [3] Narukawa Y, Ichikawa M, Sanga D, Sano M and Mukai T 2010 White light emitting diodes with super-high luminous efficacy *J. Phys. D: Appl. Phys.* **43** 354002
- [4] Lee Y J, Chiu C H, Ke C C, Lin P C, Lu T C, Kuo H C and Wang S C 2009 Study of the excitation power dependent internal quantum efficiency in InGaN/GaN LEDs grown on patterned sapphire substrate *IEEE J. Sel. Top. Quantum Electron.* **15** 1137
- [5] Li H, Li P, Kang J, Li Z, Zhang Y, Li Z, Li J, Yi X, Li J and Wang G 2013 Quantum efficiency enhancement of 530 nm InGaN green light-emitting diodes with shallow quantum well *Appl. Phys. Express* **6** 052102
- [6] Yamamoto S, Zhao Y, Pan -C-C, Chung R B, Fujito K, Sonoda J, DenBaars S P and Nakamura S 2010 High-efficiency single-quantum-well green and yellow-green light-emitting diodes on semipolar (20–21) GaN substrates *Appl. Phys. Express* **3** 122102
- [7] Feezell D F, Speck J S, DenBaars S P and Nakamura S 2013 Semipolar (20–2–1) InGaN/GaN light-emitting diodes for high-efficiency solid-state lighting *J. Display Technol.* **9** 190
- [8] Zhao Y, Sonoda J, Pan -C-C, Brinkley S, Koslow I, Fujito K, Ohta H, DenBaars S P and Nakamura S 2010 30-mW-class high-power and high-efficiency blue semipolar (1011) InGaN/GaN light-emitting diodes obtained by backside roughening technique *Appl. Phys. Express* **3** 102101
- [9] Wang T 2016 Development of overgrown semi-polar GaN for high efficiency green/yellow emission *Semicond. Sci. Technol.* **31** 093003
- [10] Scholz F 2012 Semipolar GaN grown on foreign substrates: a review *Semicond. Sci. Technol.* **27** 024002
- [11] Kowsz S J, Young E C, Yonkee B P, Pynn C D, Farrell R M, Speck J S, DenBaars S P and Nakamura S 2017 *Opt. Express* **25** 3841
- [12] Kowsz S J, Pynn C D, Oh S H, Farrell R M, Speck J S, DenBaars S P and Nakamura S 2015 Demonstration of phosphor-free polarized white light emission from monolithically integrated semipolar InGaN quantum wells *Appl. Phys. Lett.* **107** 101104
- [13] Zhao Y, Fu H, Wang G T and Nakamura S 2018 Toward ultimate efficiency: progress and prospects on planar and 3D nanostructured nonpolar and semipolar InGaN light-emitting diodes *Adv. Opt. Photon.* **10** 246
- [14] Sharma R, Pattison P M, Masui H, Farrell R M, Baker T J, Haskell B A, Wu F, DenBaars S P, Speck J S and Nakamura S 2005 Demonstration of a semipolar (10–1–3) green light emitting diode *Appl. Phys. Lett.* **87** 231110
- [15] Khoury M, Li H, Kuritzky L Y, Mughal A J, DeMierry P, Nakamura S, Speck J S and DenBaars S P 2017 444 nm InGaN light emitting diodes on low-defect-density GaN templates on patterned sapphire *Appl. Phys. Express* **10** 106501
- [16] Khoury M, Li H, Bonef B, Kuritzky L Y, Mughal A J, Nakamura S, Speck J S and DenBaars S P 2018 Semipolar GaN templates on sapphire: 432 nm InGaN light-emitting diodes and light extraction simulations *Appl. Phys. Express* **11** 036501
- [17] Li H et al 2017 Efficient semipolar (11–22) 550 nm yellow/green ingan light-emitting diodes on low defect density (11–22) GaN/sapphire templates *ACS Appl. Mater. Interfaces* **9** 36417
- [18] Li H et al 2019 Study of efficient semipolar (11–22) InGaN green micro-light-emitting diodes on high-quality (11–22) GaN/sapphire template *Opt. Express* **27** 24154
- [19] Khoury M et al 2019 Demonstration of electrically injected semipolar laser diode grown on low cost and scalable sapphire substrates *ACS Appl. Mater. Interfaces* **11** 47106
- [20] Khoury M et al 2019 Polarized monolithic white semipolar (20–21) InGaN light-emitting diodes grown on high quality (20–21) GaN/sapphire templates and its application to visible light communication *Nano Energy* **67** 104236
- [21] Tendille F, De Mierry P, Vennéguès P, Chenot S and Teisseire M 2014 Defect reduction method in (11–22) semipolar GaN grown on patterned sapphire substrate by MOCVD: toward heteroepitaxial semipolar GaN free of basal stacking faults *J. Cryst. Growth* **404** 177

- [22] Vennéguès P, Tendille F and De Mierry P 2015 Study of defect management in the growth of semipolar (11–22) GaN on patterned sapphire *J. Phys. D: Appl. Phys.* **48** 325103
- [23] Leung B, Wang D, Kuo Y-S, Xiong K, Song J, Chen D, Park S H, Hong S Y, Choi J W and Han J 2014 Semipolar (201) GaN and InGa_N quantum wells on sapphire substrates *Appl. Phys. Lett.* **104** 262105
- [24] Song J, Choi J, Zhang C, Deng Z, Xie Y and Han J 2019 Elimination of stacking faults in semipolar GaN and light-emitting diodes grown on sapphire *ACS Appl. Mater. Interfaces* **11** 33140
- [25] Wong M S, Hwang D, Alhassan A I, Lee C, Ley R, Nakamura S and DenBaars S P 2018 High efficiency of III-nitride micro-light-emitting diodes by sidewall passivation using atomic layer deposition *Opt. Express* **26** 21324
- [26] Abdullah A I, Farrell R M, Saifaddin B, Mughal A, Wu F, DenBaars S P, Nakamura S and Speck J S 2016 High luminous efficacy green light-emitting diodes with AlGa_N cap layer *Opt. Express* **24** 17868
- [27] Zhao Y et al 2011 High optical polarization ratio from semipolar (20–2–1) blue-green InGa_N/Ga_N light-emitting diodes *Appl. Phys. Lett.* **99** 051109
- [28] Khoury M et al 560 nm InGa_N micro-LEDs on low-defect density (20–21) semipolar GaN on patterned sapphire substrates *ACS Appl. Mater. Interfaces* (under review)
- [29] Poyiatzis N, Athanasiou M, Bai J, Gong Y and Wang T 2019 Monolithically integrated white light LEDs on (11–22) semi-polar GaN templates *Sci. Rep.* **9** 1383
- [30] Song J, Choi J, Xiong K, Xie Y, Cha J J and Han J 2017 Semipolar (20–2–1) GaN and InGa_N light-emitting diodes grown on sapphire *ACS Appl. Mater. Interfaces* **9** 14088
- [31] Rashidi A, Monavarian M, Aragon A, Rishinaramangalam A and Feezell D 2018 Nonpolar m-Plane InGa_N/Ga_N micro-scale light-emitting diode with 1.5 GHz modulation bandwidth *IEEE Electron Device Lett.* **39** 520
- [32] Le Minh H, O'Brien D, Faulkner G, Zeng L, Lee K, Jung D, Oh Y and Won E T 2009 100-Mb/s NRZ visible light communications using a post equalized white LED *IEEE Photon. Tech. Lett.* **21** 1063
- [33] Wu F, Tyagi A, Young E C, Romanov A E, Fujito K, DenBaars S P, Nakamura S and Speck J S 2011 Misfit dislocation formation at heterointerfaces in (Al, In) Ga_N heteroepitaxial layers grown on semipolar free-standing Ga_N substrates *J. Phys. D: Appl. Phys.* **109** 033505