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# Development of efficient semipolar InGaN long wavelength light-emitting diodes and blue laser diodes grown on 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 (QCSE), 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

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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 headlight. [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-functions 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 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 substrate, which are very costly and only available in 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 are attractive. [9, 10] However, semipolar and nonpolar GaN layers grown on foreign substrate suffer from high defects 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 patterned sapphire substrate. [15~18] Also, blue semipolar LDs have been firstly demonstrated on high crystal quality (11-22) GaN/sapphire template. [19] In this paper, we discuss the progress of materials growth for high crystal quality semipolar GaN template on sapphire substrate, efficient semipolar GaN long wavelength LEDs and semipolar blue LDs grown on

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foreign substrate. Polarized phosphor-free white semipolar (20-21) LEDs grown on patterned sapphire template were also presented. [20]

## 2 Materials growth of the high quality semipolar template

### 2.1 Growth of high crystal quality (11-22) GaN on patterned sapphire substrate

A three-step growth method was employed to obtain planar (11-22) GaN template on 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. GaN layer was grown on the inclined c-axis, and then the adjacent crystals were coalesced, which is referred as three-step growth. [21, 22] Figure 1(a) is the image of a 2-inch (11-22) GaN template on patterned sapphire substrate after polishing. A smooth surface with a roughness of 0.1 nm in a $2\times2\ \mu m^2$ area can be observed by atomic force microscope (AFM), as shown in figure 1(b). The cross-sectional image by scanning electron microscope (SEM) of the semipolar (11-22) GaN on 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 threading dislocations density and the BSFs density. Defect-blocking air-voids were created by overlapping the adjacent crystals in three consecutive steps through fine-tuned growth condition, which are helpful for inhibiting the TDs and BSFs propagation towards the free surface. The 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 semipolar (11-22) GaN layer grown on patterned sapphire substrate. The final defect densities of BSFs and TDs were 70 $cm^{-1}$ and $5\times10^7$ $cm^{-2}$, respectively. [15, 17, 18, 21, 22] More descriptions in detail about the growth process of semipolar (11-22) template on sapphire substrate can be found in Ref. [21].

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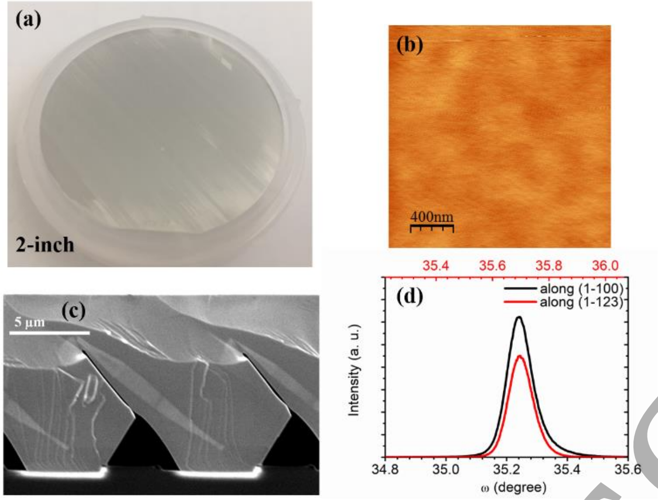


Figure 1(a) Image of a 2-inch (11-22) GaN template on patterned sapphire substrate; (b) 2×2 $\mu m^2$ size AFM image; (c) Bird's eye view SEM image and (d) (11-22) XRD rocking curve of the semipolar (11-22) GaN/sapphire template. Figure 1(a) and 1(c) are reproduced from [17], with the permission of ACS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

### 2.2 Growth of high crystal quality (20-21) GaN on patterned sapphire substrate

Unintentionally doped semipolar (20-21) GaN layer was grown on 4-inch (22-43) patterned sapphire substrate using MOCVD. [16, 23, 24] A schematic diagram of growth process and sapphire orientations are shown in figure 2(a). Patterned trenches with 6-µm period were formed on the sapphire substrate and the inclined c-axis was exposed by dry etching. The semipolar (20-21) GaN layer was achieved by coalescing the adjacent nucleated crystals. Detailed description of the growth process of the semipolar (20-21) GaN template on patterned sapphire substrate can be found in Ref. [23]. Figure 2(b) is the image of a 4-inch polished (20-21) GaN template on pattered sapphire substrate. The roughness of the surface is measured to be 0.5 nm in an area of 10×10 $\mu m^2$ by AFM 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 pattered sapphire substrate. [24] The final TDs density is around $2\times10^8$ $cm^{-2}$ and the BSF density is low.

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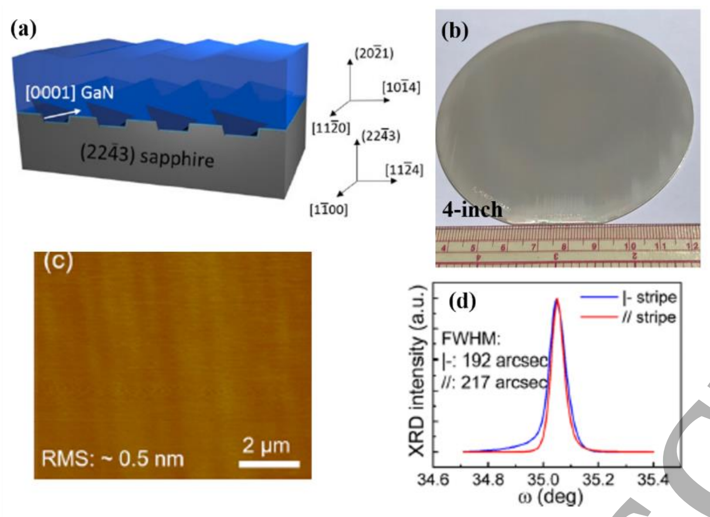


Figure 2(a) Schematic diagram of growth process and sapphire orientation in producing (20-21) GaN. This figure reproduced from [23] with the permission of AIP Publishing. (b) Image of a 4-inch (20-21) GaN layer on sapphire substrate, (c) 10×10 μm$^2$ size AFM image and (d) XRD rocking curve. Figs. 2(c) and (d) were reproduced from [24], with the permission of ACS Publishing.

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

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

Semipolar (11-22) green 520 nm LEDs were grown on patterned sapphire substrate by MOCVD. Squared micro-size LEDs (μLEDs) were fabricated. A $SiO_2$ sidewall passivation layer was deposited by atomic-layer deposition (ALD). [18, 25] The current density-voltage (LIV) curves of μLEDs are plotted in figure 3(a), which demonstrate a turn-on voltage around 2.5 V and forward voltages ranging from 2.8 to 3.2 V at 60 A/cm$^2$ for various sizes μLEDs. The reverse current is a key parameter related to the BSFs density. An extremely low leakage current of 0.1 nA at a reverse voltage of -5 V was found in the semipolar μLEDs with different sizes, which suggests a low BSFs density in the semipolar (11-22) GaN layer grown on patterned sapphire substrate. Uniform electrical luminous image of the devices can be observed from the inset of figure 3(b). Moreover, all packaged μLEDs show a size-independent

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peak external quantum efficiency (EQE) around 2% from figure 3(b). Although such EQE remains lower than the value of green LEDs grown on semipolar bulk GaN [15] or c-plane substrate, [26] this is the first demonstration of efficient semipolar green μLEDs grown on foreign substrate. As shown in figure 3(c), the semipolar (11-22) green μLEDs present a reduced wavelength blue-shift of 5 nm with increasing current density from 5 to 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) μLEDs show a current density independent polarization ratio of 40% from figure 3(d), which has potential application as back lighting sources for LCDs. [27]

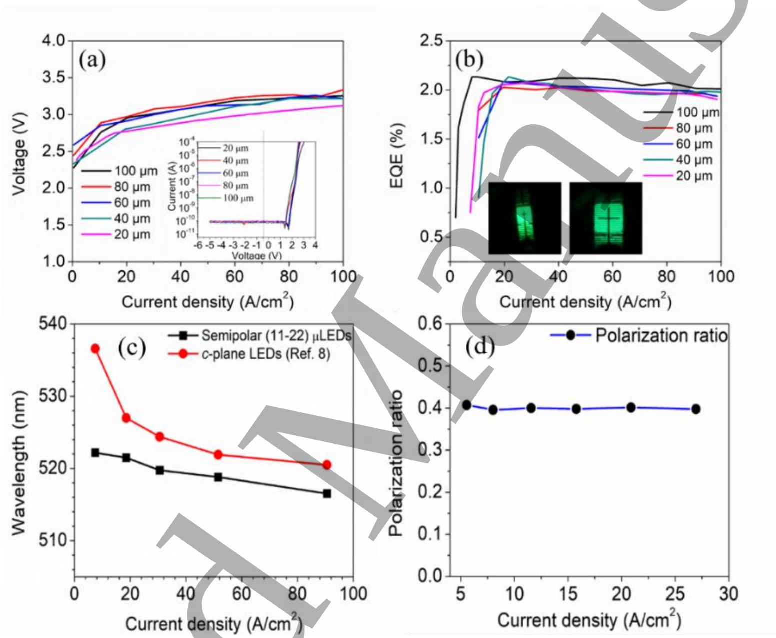


Figure 3(a) LIV curves of different sizes μLEDs. The inset is the reverse characteristic; (b) EQE versus current density. The inset show the luminous images of 40×40 and 80×80 μm$^2$; (c) Wavelength blue-shift of semipolar (11-22) green μLEDs and c-plane polar green LEDs; (d) Polarization ratio at various current densities. These figures are reprinted with permission from Ref. [18] © The Optical Society.

### 3.2 Semipolar (20-21) InGaN yellow-green LEDs on patterned sapphire substrate

Semipolar (20-21) 550 nm yellow-green LEDs with single QW were grown on the (20-21) GaN template on patterned sapphire substrate using MOCVD. The epitaxial

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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-art EQE of 2.3%. Detailed study about materials growth and characterizations and electrical and optical properties of the yellow-green LEDs will be published elsewhere. [28]

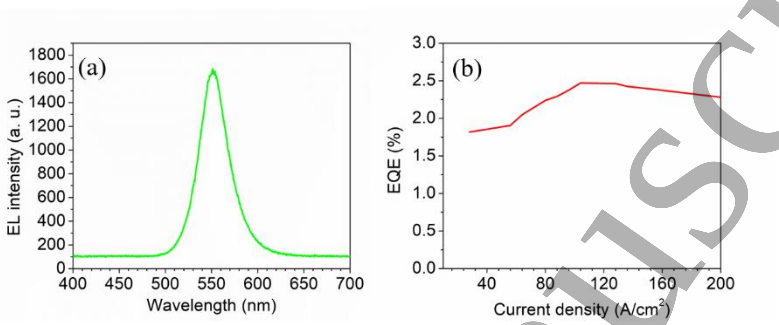


Figure 4(a) EL emission spectrum and (b) EQE versus current density of semipolar 550 nm yellow-green semipolar (20-21) LEDs grown on patterned sapphire substrate.

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

The polarized monolithic white semipolar LEDs were realized by integrating blue and yellow QWs directly on 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 QWs numbers and the In content in the QWs. Figure 5(a) shows a side view distribution of In atoms in the active region using atom probe tomography (APT). It is clear to observe the top blue QW and the bottom yellow QW. Figure 5(b) presents the output power-current-voltage (LIV) characteristic of standard LEDs with a size of 0.1 mm$^2$. 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 substrate [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

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aligned along $x'$-direction and $y'$-direction. In (20-21) orientation, the $x'$-direction and $y'$-direction is 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 the [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 communication (VLC) owing to a larger electron-hole wave-functions 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 3dB MBs in the monolithic white semipolar μLEDs were plotted in figure 5(d). It is found that the highest MB reaches 660 MHz in the 20×20 μm$^2$ size μLEDs, which shows a large potential application in the VLC.

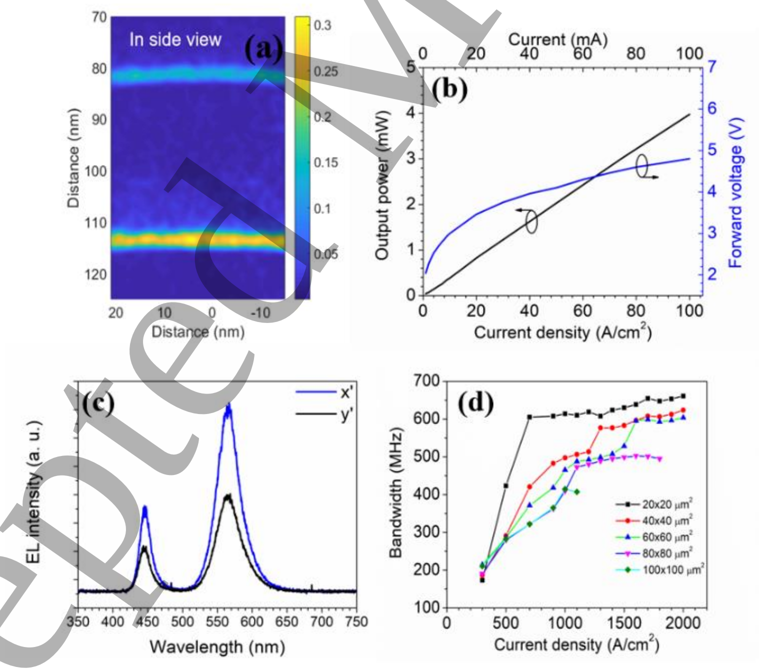


Figure 5(a) The side view distribution of indium in the active region by APT; (b) LIV of regular size LEDs; (c) EL emission spectra with the polarizer; (d) Results of 3dB MBs with various current densities in different sizes μLEDs. Reproduced with permission from Elsevier [20].

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

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

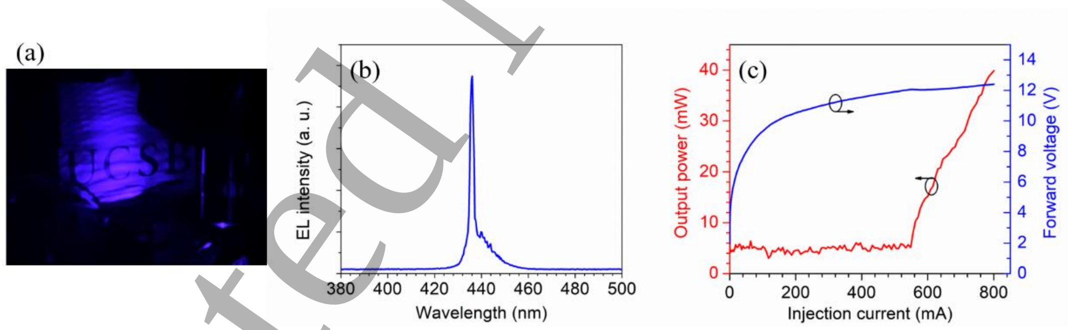


Figure 6(a) Far field pattern of a semipolar blue LD grown on sapphire substrate under testing; (b) EL spectrum of the lasing devices; (c) LIV curve of a blue LD with 1800 μm length and 2.5 μm width.

## 5. Conclusion

In conclusion, we review two growth methods to achieve high crystal quality semipolar GaN layers on patterned sapphire substrate. Efficient semipolar green/yellow-green LEDs were obtained on those templates with an EQE around 2%

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after packaging. Polarized phosphor-free white semipolar (20-21) LEDs were realized on semipolar (20-21) GaN layers on 4-inch patterned sapphire substrate, which exhibit a polarization ratio of 0.3 and a 3dB MB as high as 660 MHz in the small size µLEDs. Moreover, the demonstration of semipolar (11-22) blue LDs grown on patterned sapphire substrate were presented.

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