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A semipolar $(1\ 0\ \bar{1}\ \bar{3})$ InGaN/GaN green light emitting diode

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ABSTRACT

We demonstrate the first green InGaN/GaN light emitting diode (LED) grown on a planar semipolar $(10\bar{1}\bar{3})$ GaN template. The LED structure is grown by metalorganic chemical vapor deposition (MOCVD), and the 20 μm-thick, specular and optically transparent template is grown by hydride vapor phase epitaxy (HVPE). The fabricated devices have a peak emission wavelength of ~525 nm and demonstrate rectifying behavior, with a low operating voltage of 3.25 V at 20 mA. We observe a small ~7 nm blue-shift in the peak emission wavelength during electroluminescence measurements, over the range 20 to 250 mA. We also see an almost linear increase in the output power from 5 mA to 250 mA, with no appreciable decrease in the external quantum efficiency over the same range. Additionally, we observe evidence of polarization anisotropy in the emission from the semipolar green LEDs.

INTRODUCTION

The performance of conventional *c*-plane GaN-based optoelectronic devices suffers from the effects of strong polarization-induced electric fields along the conduction direction, which result in a reduced overlap between electron and hole wavefunctions [1-3]. These devices consequently demonstrate low radiative recombination rates, and a blue-shift in peak emission wavelength with increasing bias. There have been several recent demonstrations of light emitting diodes (LEDs) fabricated on non-polar *a*- and *m*-plane GaN that show greatly reduced to zero blue-shift of peak emission wavelength [4-7], and other recent work on non-polar GaN has yielded hole concentrations that are almost an order of magnitude higher than for *c*-plane GaN [8]. The effects of the strong polarization-induced electric fields may, conceivably, also be mitigated or potentially eliminated by growing films on so-called 'semipolar' planes. A semipolar plane is any plane that may not be classified as a *c*-, *a*- or *m*- plane, and has at least two non-zero *h*, *i*, or *k* Miller indices and a nonzero *l* Miller index ($\{10\bar{1}1\}$, $\{10\bar{1}2\}$ and $\{10\bar{1}3\}$ planes, for example). It is expected that devices grown on these semipolar planes should also demonstrate a reduced blue-shift in peak emission wavelength [9] and higher hole concentrations [10]. Further, preliminary work also suggests that the indium incorporation efficiency for growth on semipolar planes is comparable to that for growth on the *c*-plane.

EXPERIMENTAL DETAILS

A 20 µm-thick, specular and optically transparent semipolar $(10\bar{1}\bar{3})$ GaN template was grown using hydride vapor phase epitaxy (HVPE) on an *m*-sapphire substrate [11], and the LED structure was regrown on this template by metalorganic chemical vapor deposition (MOCVD). Figure 1 shows a detailed schematic of the device structure. Light emitting diodes (LEDs) were then fabricated from the grown structure using conventional methods. A Cl_2-based reactive ion etch was first used to define 300µm × 300µm mesas. This was followed by the deposition of the contact metals by e-beam evaporation - Pd/Au (5/6nm) was used as the transparent *p*-GaN contact, and Ti/Al/Ni/Au (20/50/20/300 nm) was used as the *n*-GaN contact. This was followed by on-wafer testing of the fabricated devices. All measurements were performed at room temperature, and the details of the test setup may be found elsewhere [4].

DISCUSSION

Figure 2 shows representative current-voltage characteristics for the fabricated semipolar $(10\bar{1}\bar{3})$ green LEDs, and for a commercially available *c*-plane LED that shows emission at approximately the same peak wavelength. The semipolar LED shows characteristic rectifying behavior, with an operating voltage of 3.25 V at a forward current of 20 mA, and a dynamic series resistance of 14.3 Ω. By comparison, the commercial *c*-plane LED has an operating voltage of 3.95 V at a forward current of 20 mA, and a dynamic series resistance of 28.9 Ω. The lower operating voltage in the case of the semipolar LED as compared to the commercial *c*-plane LED may be related to reduced polarization-induced electric fields in the former case.

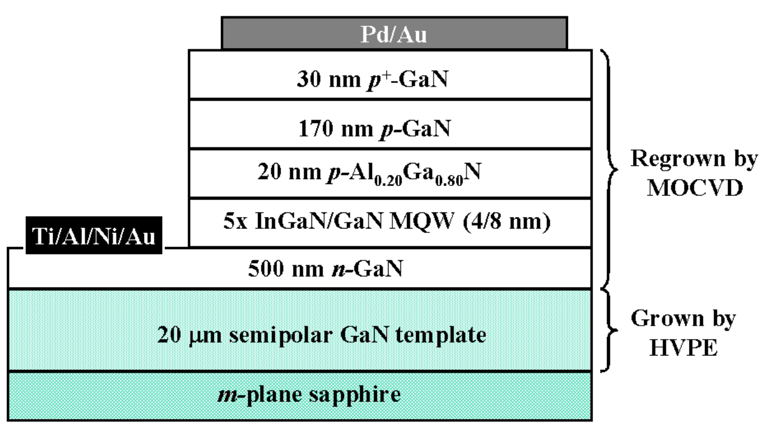


Figure 1. Schematic diagram of the semipolar green LED structure.

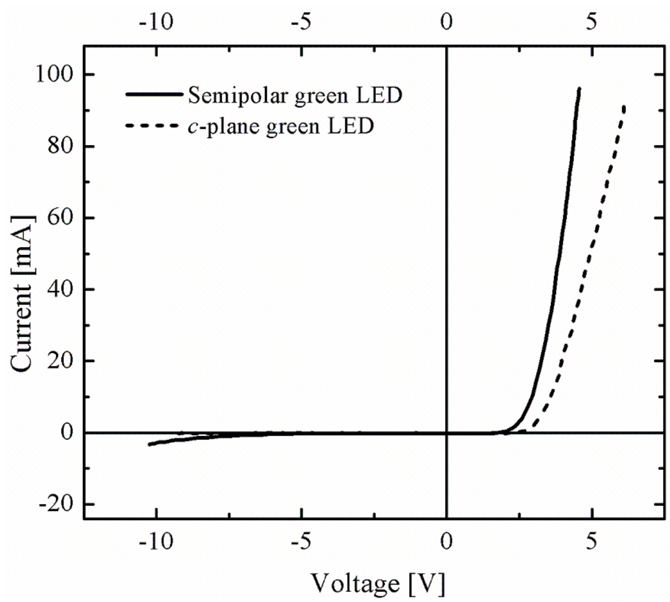
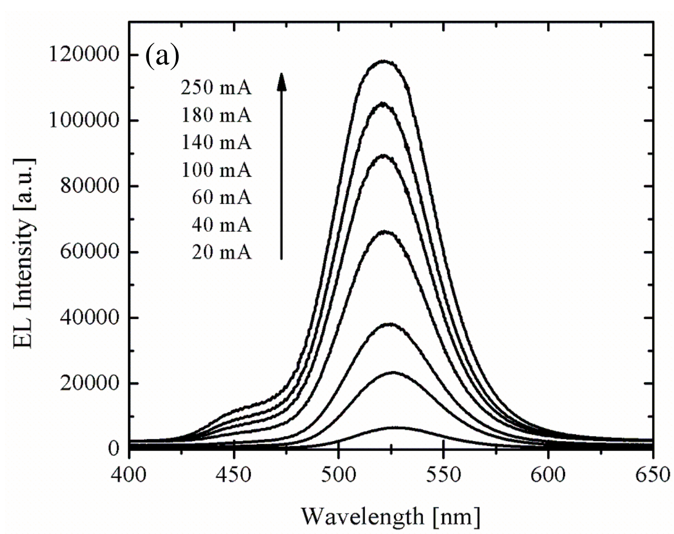


Figure 2. I-V characteristics for the semipolar green LED and the *c*-plane green LED.

The direct current (dc) electroluminescence spectra for the semipolar green LED are shown in Fig. 3(a), over a wide range of drive currents. The device demonstrates a net shift of 6.7 nm in the peak emission wavelength over a 230 mA range, with peak emission wavelengths of 527.1 nm and 520.4 nm at 20 mA and 250 mA, respectively. As shown in Fig. 3(b), the corresponding measurement on the commercial c-plane green LED yielded a significantly higher shift of 12.4 nm in the peak emission wavelength over an 80 mA range. The reduced shift in the peak emission wavelength in the case of the semipolar device may be attributed to reduced polarization-induced electric fields in the vicinity of the quantum wells, as compared to the *c*-plane device.



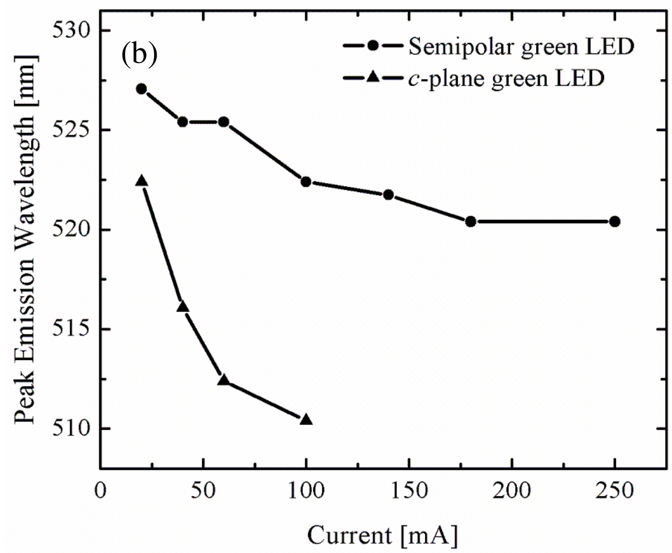


Figure 3. (a) Electroluminescence spectra for the semipolar green LED (b) Peak emission wavelength vs. current for the semipolar green LED and the *c*-plane green LED.

The output power and external quantum efficiency (EQE) of the semipolar green LED were also measured as a function of drive current. The results of these on-wafer measurements are shown in Fig. 4. We observed an approximately linear increase in the output power from the semipolar green LED within the range 5-250 mA, with a peak measured dc output power of 264 µW at 250 mA. The EQE peaked at a value of 0.052%, at a drive current of 120 mA, and decreased slightly at higher drive currents. The relatively low output power and EQE values are believed to be a result of non-optimized device growth conditions, and are expected to increase significantly with further optimization of MOCVD growth conditions, as well as improvements in the HVPE-grown semipolar GaN template quality. Additionally, since these measurements were performed on-wafer, we expect a significant (~fivefold) increase in output power after packaging.

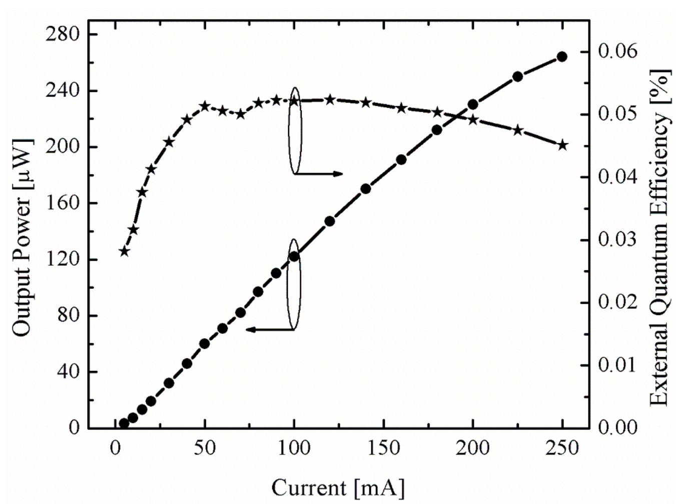


Figure 4. On-wafer output power vs. current and EQE vs. current for the semipolar green LED.

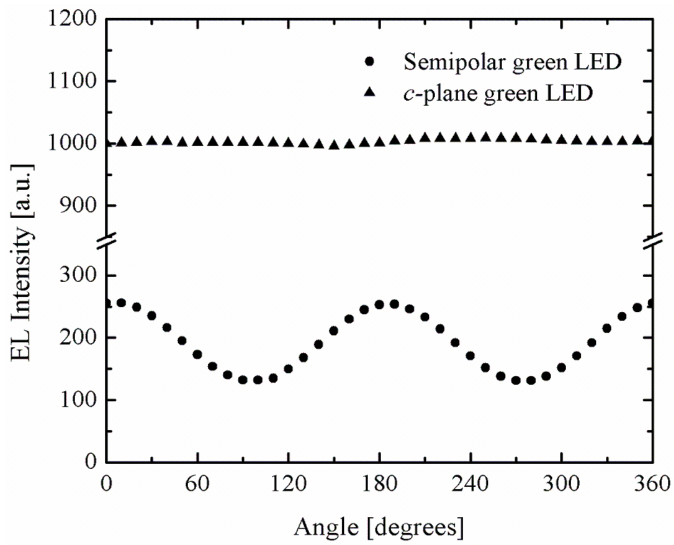


Figure 5. Electroluminescence intensity as a function of the orientation of the polarizing filter for the semipolar green LED and the *c*-plane green LED.

The fabricated semipolar LEDs also showed evidence of polarization anisotropy in their EL emission, when tested on-wafer. When the EL intensity for the semipolar LED was plotted as a function of the orientation of a polarizing filter placed between the LED and a Si photodiode, a periodic variation in the EL intensity with angle was observed, indicating that the emission from the LED is partially polarized. This is shown in Fig. 5. A simple calculation of the polarization ratio yielded a value of 0.32 at a drive current of 20 mA. A corresponding *c*-plane LED that was also tested on-wafer did not show any evidence of polarization anisotropy of emission, under the same measurement conditions. While polarization anisotropy of emission has already been reported in the case of non-polar devices [7], we believe this to be the first such demonstration in the case of a semipolar device.

CONCLUSIONS

In summary, we have demonstrated the first green LED grown by MOCVD on a semipolar $(10\bar{1}\bar{3})$ GaN template. The device demonstrated typical diode-like behavior with a low operating voltage of 3.25 V at 20 mA, and a series resistance of 14.3 Ω. EL spectra collected over a range of drive currents showed a small ~7 nm blueshift in the peak emission wavelength from 20 mA to 250 mA. The output power for the device increased almost linearly with the drive current from 5 mA to 250 mA. A peak EQE of 0.052% was observed at a drive current of 120 mA, and the EQE did not decrease appreciably at higher drive currents. We expect an improvement in device performance with further optimization of both the template quality as well as device growth conditions. We also observed evidence of polarization anisotropy in the electroluminescence from the fabricated devices, and a polarization factor of 0.32 was measured. We believe that these results are indicative of reduced electric fields along the conduction direction, as is predicted for semipolar planes.

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