531 nm Green Lasing of InGaN Based Laser Diodes on Semi-Polar {20$\bar{2}$1} Free-Standing GaN Substrates

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Lasing in pure green region around 520 nm of InGaN based laser diodes (LDs) on semi-polar {20$\bar{2}$1} free-standing GaN substrates was demonstrated under pulsed operation at room temperature. The longest lasing wavelength reached to 531 nm and typical threshold current density was 8.2 kA/cm^2 for 520 nm LDs. Utilization of a novel {20$\bar{2}$1} plane enabled a fabrication of homogeneous InGaN quantum wells (QWs) even at high In composition, which is exhibited with narrower spectral widths of spontaneous emission from LDs than those on other planes. The high quality InGaN QWs on the {20$\bar{2}$1} plane advanced the realization of the green LDs.

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Demands for compact InGaN based green laser diodes (LDs), which are expected to be used as light sources in mobile full-color laser projectors, are rapidly growing. Although green lasers based on second harmonic generation (SHG) technologies are already available, semiconductor LDs have advantages in size, stability and efficiency in practical uses of these devices. InGaN based LDs on conventional (0001) *c*-plane GaN substrates have been actively developed toward longer wavelengths[1–3] and recently the longest lasing wavelength of 515 nm has been reported.[4] However, lasing at even longer wavelength is believed to be difficult owing to their large electric fields caused by both spontaneous and piezoelectric polarization, which are intrinsic phenomena of the polar *c*-plane. These electric fields give rise to the quantum confined Stark effect (QCSE) and reduce the radiative recombination probability within the quantum wells (QWs) especially at longer wavelength.[5,6] An attractive alternative approach to circumvent these effects is to grow laser structures on non-polar and semi-polar planes such as {10$\bar{1}$0} (*m*-plane), {11$\bar{2}$0} (*a*-plane), {11$\bar{2}$2} planes, and others.[7,8] Recently, *m*-plane LDs lasing at wavelengths of 499.8 nm under cw operation have been reported.[9] Furthermore, in the case of semi-polar {11$\bar{2}$2} plane LDs, stimulated emission at 514 nm by optical pumping has been demonstrated,[10] while the lasing wavelength by current operation remains at 426 nm.[11] However, the other crucial problems still remain for green laser emission. The most influential issue is to fabricate high-quality green InGaN QWs. Increasing In composition of InGaN QWs on *c*-plane induces dark spots and drastically reduces the photoluminescence (PL) intensity, which is attributed to thermally-induced defects by In diffusion in the InGaN QWs.[12,13] Alternatively, high density stacking faults were generated in the InGaN QWs on *m*-plane.[14] Whereas there are few reports on QW quality on {11$\bar{2}$2} plane, broadening of electroluminescence (EL) peak with increasing EL wavelength has been indicated.[15] Thus, we explored novel planes which are desirable for fabricating green LDs.

In this work, we report the growth of high quality InGaN QWs on free-standing GaN substrates with the novel semi-polar {20$\bar{2}$1} plane, resulting in green laser emission of 531 nm under pulsed operation at room temperature (RT).

The semi-polar {20$\bar{2}$1} plane GaN substrates were produced by hydride vapor phase epitaxy (HVPE). Threading dislocation (TD) densities of the substrates are less than 1×10^6 cm^{-2}. The substrates exhibit n-type conductivity and the resistivity is sufficiently low (approximately 0.01 Ω cm) to form ohmic contacts on the back surface of the substrates.[16] The LD structures were grown by metal organic chemical vapor deposition (MOCVD). An n-type GaN layer was grown directly on the GaN substrates, followed by an n-type InAlGaN cladding layer, an n-type InGaN waveguiding layer, a three-period InGaN multiple QW (MQW) active layer, a p-type AlGaN electron-blocking layer, a p-type InGaN waveguiding layer, a p-type InAlGaN cladding layer, and a p-type GaN contact layer. The typical growth temperature for MQW is 750 °C, which is almost same as that on *c*-plane GaN substrates.

Gain-guided lasers with 10 µm stripes were fabricated by conventional deposition and lift-off technique. A p-type electrode was evaporated on the p-type contact layer, and an n-type electrode was evaporated on the backside of the wafer. The 600 µm long cavities and mirror facets were formed by cleaving method. Both facets were coated with dielectric mirrors of 80 and 95% reflectivity.

Figure 1(a) shows the lasing spectrum above threshold for the semi-polar {20$\bar{2}$1} plane LD with the longest lasing wavelength. Laser characteristics were measured under pulsed operation at RT, with a pulse width of 500 ns and a duty ratio of 0.5%. The maximum peak of lasing spectrum was observed at 531 nm. Threshold current (I_{th}) was 924 mA, corresponding to a threshold current density (J_{th}) of 15.4 kA/cm^2. An image of the LD chip under pulsed operation is shown in Fig. 1(b). Green laser emission can be clearly seen from the LD chip.

Figure 2 shows light output power vs current (*L*–*I*) and voltage vs current (*V*–*I*) curves for a typical LD with lasing wavelength of 520 nm in this work. Threshold current (I_{th}) was 491 mA, corresponding to a threshold current density (J_{th}) of 8.2 kA/cm^2. The threshold voltages (V_{th}) were 17.7 V. The maximum output power was 28 mW at a current of 1240 mA. The slope efficiency was 0.04 W/A. The high operating voltage of this semi-polar LD was mainly due to unoptimized p-type ohmic contacts. Low slope efficiency is also needed to be improved by adjustment of the device structure to a green emission region.

EL peak wavelength shift of the 495 nm LD on {20$\bar{2}$1} plane was investigated to compare with those on other

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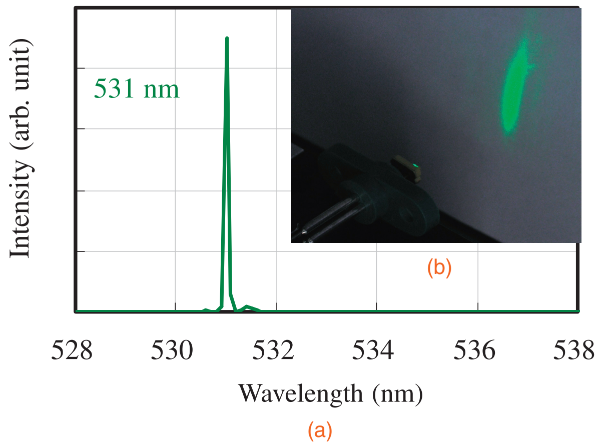

Fig. 1. (a) Laser emission spectrum of semi-polar $\{20\bar{2}1\}$ plane green LD under pulsed operation. (b) Lasing image of the green LD.

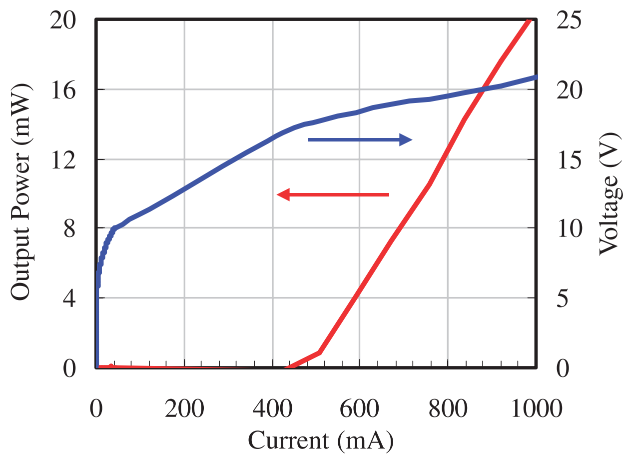

Fig. 2. Typical light output power–current–voltage (*L*–*I*–*V*) characteristics of semi-polar $\{20\bar{2}1\}$ plane LD with lasing wavelength of 520 nm under pulsed operation.

planes. The spontaneous emission wavelength is shifted from 513 to 499 nm with increasing an injection current density from 0.02 to 5 kA/cm^2, which corresponds to the blue-shift of 14 nm. This value is slightly larger than those reported on non-polar *m*-plane LDs[17] and comparable to those on semi-polar $\{11\bar{2}2\}$ plane,[15] whereas this is remarkably smaller than those on polar *c*-plane LDs.[3]

We now focus on the quality of InGaN QWs on semi-polar $\{20\bar{2}1\}$ planes. Figure 3 summarizes the full width at half maximum (FWHM) of EL peaks for QWs grown on several planes as a function of EL wavelength from this and other works.[15,18,19] Operation current density was selected to be around 150 A/cm^2. FWHMs of QWs on $\{20\bar{2}1\}$ planes are the narrowest among that of QWs on various planes, and the difference between those on $\{11\bar{2}2\}$ plane[15] and $\{20\bar{2}1\}$ planes is enhanced with increasing the EL wavelength as shown in Fig. 3. FWHM values were also unchanged with increasing the QW thickness, while blue-shifts of LDs on $\{20\bar{2}1\}$ planes increased with increasing the QW thickness (not shown here). This result indicates that InGaN QWs on $\{20\bar{2}1\}$ planes exhibit high homogeneity of In concentration even at green region, which give rise to small and stable band tail states even though the QW thickness increases. The

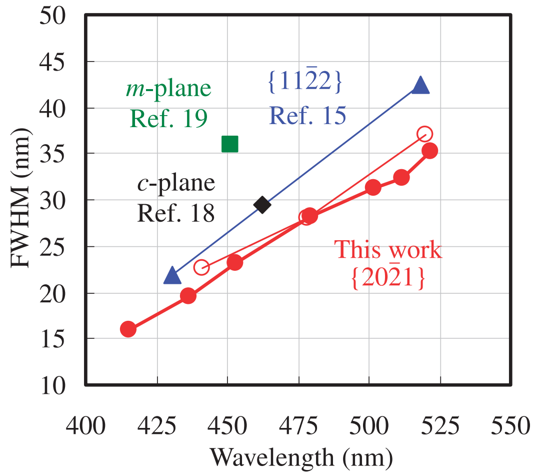

Fig. 3. Dependence of spontaneous emission FWHM on EL peak wavelength under dc operation around 150 A/cm^2. Data for $\{20\bar{2}1\}$ plane QWs in this work with 3 and 4 nm well thickness are indicated as closed and open circles, respectively. Data for $\{11\bar{2}2\}$ plane QWs with 3 nm well thickness,[15] *m*-plane QWs with 4 nm well thickness,[18] and *c*-plane QWs with 2.5 nm well thickness[19] are indicated as closed triangles, closed square, and closed diamond, respectively, for comparison.

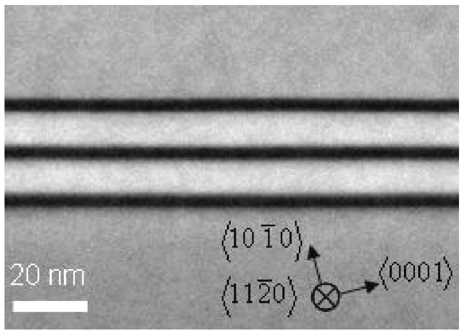

Fig. 4. BF-STEM image from *a*-plane cross section of QWs region on semi-polar $\{20\bar{2}1\}$ plane with lasing wavelength of 520 nm.

reason of high homogeneity of InGaN QWs on $\{20\bar{2}1\}$ planes has not been revealed and still under investigation.

Cross sectional images of InGaN QWs on $\{20\bar{2}1\}$ planes were observed by bright-field scanning transmission electron microscopy (BF-STEM) for the LD with lasing wavelength of 520 nm as shown in Fig. 4. Abrupt interfaces are successfully formed and no defects are observed in the QW region. This is in agreement with the result of narrow FWHMs. Thus InGaN QWs on $\{20\bar{2}1\}$ planes exhibit huge advantage to realize these green LDs.

In summary, we have demonstrated 531 nm green lasing of InGaN based LDs on semi-polar $\{20\bar{2}1\}$ free-standing GaN substrates with low dislocation density under pulsed operation at RT. The typical threshold current density is 8.2 kA/cm^2 for 520 nm LDs. FWHMs of EL spectrum for InGaN QWs on $\{20\bar{2}1\}$ plane were narrower than those on other planes. This indicates that highly homogeneous In composition and QW thickness are obtained in InGaN QWs on $\{20\bar{2}1\}$ plane. The high homogeneity of InGaN QWs was also confirmed by STEM observation. These results proved that semi-polar $\{20\bar{2}1\}$ plane is desirable plane for fabricating green LDs.

1) T. Miyoshi, T. Yanamoto, T. Kozaki, S. Nagahama, Y. Narukawa, M. Sano, T. Yamada, and T. Mukai: Proc. SPIE **6894** (2008) 689414.
2) K. S. Kim, J. K. Son, S. N. Lee, Y. J. Sung, H. S. Paek, H. K. Kim, M. Y. Kim, K. H. Ha, H. Y. Ryu, O. H. Nam, T. Jang, and Y. J. Park: Appl. Phys. Lett. **92** (2008) 101103.
3) D. Queren, A. Avramescu, G. Brüderl, A. Breidenassel, M. Schillgalies, S. Lutgen, and U. Strauß: Appl. Phys. Lett. **94** (2009) 081119.
4) T. Miyoshi, S. Masui, T. Okada, T. Yanamoto, T. Kozaki, S. Nagahama, and T. Mukai: Appl. Phys. Express **2** (2009) 062201.
5) S. Chichibu, T. Azuhata, T. Sota, and S. Nakamura: Appl. Phys. Lett. **69** (1996) 4188.
6) T. Takeuchi, S. Sota, M. Katsuragawa, M. Komori, H. Takeuchi, H. Amano, and I. Akasaki: Jpn. J. Appl. Phys. **36** (1997) L382.
7) T. Takeuchi, H. Amano, and I. Akasaki: Jpn. J. Appl. Phys. **39** (2000) 413.
8) S.-H. Park: J. Appl. Phys. **91** (2002) 9904.
9) K. Okamoto, J. Kashiwagi, T. Tanaka, and M. Kubota: Appl. Phys. Lett. **94** (2009) 071105.
10) A. Tyagi, Y.-D. Lin, D. A. Cohen, M. Saito, K. Fujito, J. S. Speck, S. P. DenBaars, and S. Nakamura: Appl. Phys. Express **1** (2008) 091103.
11) H. Asamizu, M. Saito, K. Fujito, J. S. Speck, S. P. DenBaars, and S. Nakamura: Appl. Phys. Express **1** (2008) 091102.
12) S. Nagahama, T. Yanamoto, M. Sano, and T. Mukai: Jpn. J. Appl. Phys. **40** (2001) 3075.
13) D. Queren, M. Schillgalies, A. Avramescu, G. Brüderl, A. Laubsch, S. Lutgen, and U. Strauß: to be published in J. Cryst. Growth.
14) A. M. Fischer, Z. Wu, K. Sun, Q. Wei, Y. Huang, R. Senda, D. Iida, M. Iwaya, H. Amano, and F. A. Ponce: Appl. Phys. Express **2** (2009) 041002.
15) M. Funato, M. Ueda, Y. Kawakami, Y. Narukawa, T. Kosugi, M. Takahashi, and T. Mukai: Jpn. J. Appl. Phys. **45** (2006) L659.
16) K. Motoki, T. Okahisa, N. Matsumoto, M. Matsushima, H. Kimura, H. Kasai, K. Takemoto, K. Uematsu, T. Hirano, M. Nakayama, S. Nakahata, M. Ueno, D. Hara, Y. Kumagai, A. Koukitu, and H. Seki: Jpn. J. Appl. Phys. **40** (2001) L140.
17) K. Okamoto, T. Tanaka, and M. Kubota: Appl. Phys. Express **1** (2008) 072201.
18) K. Iso, H. Yamada, H. Hirasawa, N. Fellows, M. Saito, K. Fujito, S. P. DenBaars, J. S. Speck, and S. Nakamura: Jpn. J. Appl. Phys. **46** (2007) L960.
19) A. Chakraborty, B. A. Haskell, H. Masui, S. Keller, J. S. Speck, S. P. DenBaars, S. Nakamura, and U. K. Mishra: Jpn. J. Appl. Phys. **44** (2005) L173.