High-Power and High-Efficiency True Green Laser Diodes

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The authors demonstrated InGaN green laser diodes (LDs) that were grown on semipolar {20$\bar{2}$1} GaN substrate and achieved output power of over 100 mW in the spectral region beyond 530 nm. In the range of 525-532 nm, these LDs realized wall plug efficiencies as high as 7.0-8.9%, which exceed those reported for *c*-plane LDs. Moreover, the InGaN green LDs are expected to have a long lifetime of over 5,000 hours under auto power control of 50 mW at a case temperature of 55˚C. These results suggest that the InGaN green LDs grown on the {20$\bar{2}$1} plane are ideal as light sources for applications that require wavelengths of over 525 nm.

Keywords: semipolar, GaN, green, semiconductor, laser

1. Introduction

Recently, the development of InGaN-based green laser diodes (LDs) has been the subject of extensive studies since these lasers would find immediate application in red-green-blue (RGB) laser projectors, enabling high color reproducibility, focus-free operation, and power saving at the same time. Although green lasers based on SHG*1 technologies are already available, semiconductor LDs have advantages in size, stability, and efficiency for commercial application.

It is known that two problems exist in achieving longer wavelength on InGaN-based green LDs. One is a decrease in luminescent efficiency due to piezoelectric fields. Blue-violet LDs, which were the first InGaN-based LDs used in Blue-ray players, employ (0001) plane (*c*-plane) GaN substrates. On the *c*-plane, large piezoelectric fields are created in the direction of the *c*-axis due to a spontaneous polarization caused by the asymmetry of the crystal as well as the strain resulting from a lattice mismatch between the InGaN active layer and the GaN substrate. These piezoelectric fields spatially separate an electron wave function and a hole wave function in the quantum wells (QWs) and reduce luminescent efficiency. The second problem is In compositional fluctuations with increasing In contents in the InGaN active layer caused by the immiscibility of InN with GaN. Although these fluctuations improve luminescent efficiency on blue LEDs*2 due to the localized carrier[(1)], they generate non-radiative defects on green LDs. Moreover, these fluctuations increase the luminescence spectrum width and reduce the differential gain, leading to the increase of operating currents[(2),(3)].

In spite of these problems, many groups have succeeded in lasing in the spectral range from the blue-green to the green regions since 2009. Although the wavelength over 500 nm was believed to be difficult to achieve on the *c*-plane, CW*3 operation at 515 nm has been demonstrated at room temperature (RT) by improving the crystalline quality of QWs[(4),(5)]. More recently, a lasing wavelength of 531 nm has also been reported[(6)]. In addition, an approach using a nonpolar or semipolar plane has been carried out with the expectation of lowering the piezoelectric fields. Although lasing wavelengths of 499 nm on a nonpolar m-plane[(7)] and 426 nm on a semipolar (11$\bar{2}$2) plane have been reported[(8)], both planes are subject to the problem of the crystalline quality of InGaN QWs. Under these circumstances, we have been investigating other novel planes, putting priority on the crystalline quality rather than reducing the piezoelectric fields to zero, and have found out the superiority of a {20$\bar{2}$1} plane. By fabricating LDs on this plane, we have successfully demonstrated the world's first true green pulsed operation at 531 nm in 2009[(9)], followed by CW operation at 520 nm[(10)] and lower threshold CW operation at 525 nm with J_{th} = 4.3 kA/cm^2 [(11)].

This time, in a joint development with Sony Corporation, we have succeeded in the CW operation of InGaN green LDs fabricated on semipolar {20$\bar{2}$1} GaN substrates with output power of over 100 mW in the spectral region beyond 530 nm. We have also demonstrated the long-term reliability of these LDs at 55˚C. In this paper, we report on the recent progress on development of the semipolar {20$\bar{2}$1} green LDs.

2. Experiment

First, we focus on the semipolar {20$\bar{2}$1} plane GaN substrates we utilized. As shown in **Fig. 1**, this is a typical low-index plane tilted at 75.1˚ to the *c*-plane towards the *m*-axis, and both Ga and N atoms exist at the surface of this plane. While the piezoelectric fields on a nonpolar *m*-plane and a semipolar (11$\bar{2}$2) plane reduce to zero, those on the {20$\bar{2}$1} plane are one-third of those on the *c*-plane and oriented in opposite direction.

The semipolar {20$\bar{2}$1} plane GaN substrates were produced by HVPE*4. The substrates exhibit *n*-type conductivity and threading dislocation densities of less than 1×10^6 cm^{-2} [(12)]. The LD structures were grown by OMVPE*5. An *n*-type GaN layer was grown directly on the GaN substrate, followed by an *n*-type InAlGaN cladding layer, an *n*-type InGaN waveguiding layer, an InGaN multiple QW active region, a p-type AlGaN electron-blocking layer, a *p*-type InGaN waveguiding layer, a *p*-type InAlGaN cladding layer, and a *p*-type GaN

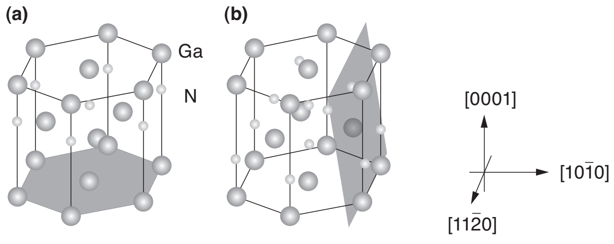

Fig. 1. (a) *c*-plane GaN substrate, (b) $\{20\bar{2}1\}$ plane GaN substrate

contact layer. The quaternary InAlGaN cladding layer lattice-matched to the GaN substrate is a key factor to high crystalline quality. A ridge waveguide of 2-µm width was fabricated by conventional dry etching and photolithography techniques. The 500-µm-long cavities and mirror facets were formed by cleaving. The front facets were coated with dielectric mirrors of approximately 50% in reflectivity.

3. Result

Figure 2 (a) compares the output power of different types of green LDs[(13)-(15)]. The green LDs fabricated on the $\{20\bar{2}1\}$ plane exhibit output power of over 100 mW in the spectral region beyond 530 nm. The output power was 168 mW at 522.0 nm, 167 mW at 525.1 nm, 105 mW at 531.3 nm, 107 mW at 532.1 nm, and 75 mW at 535.7 nm under CW operation at RT. In our previous work, we reported on the exceptionally low threshold current densities of these LDs in comparison with those of the *c*-plane LDs in the green spectral region of 520-530 nm. For practical application, however, the slope efficiencies needed to be improved[(11)]. This time, we optimized the cavity length and mirror reflectivity, and succeeded in improving the slope efficiency fourfold while suppressing the increase of the threshold current. This improvement of the slope efficiency has led to the remarkable progress in the maximum output power.

We now discuss the WPE[*6] of semipolar $\{20\bar{2}1\}$ and *c*-plane green LDs. As shown in **Fig. 2 (b)**, in the green spectral region, our $\{20\bar{2}1\}$ plane LDs clearly exhibit higher WPEs. The difference in the WPE between two crystal orientations increases with increasing wavelength. This difference may be attributed to the higher compositional homogeneity of In-rich InGaN QWs on the $\{20\bar{2}1\}$ plane and the weaker piezoelectric fields. As discussed in the previous works, the narrow electroluminescence line width, uniform microscopic PL image, and abrupt interfaces of QWs indicated the homogeneity of InGaN QWs grown on the $\{20\bar{2}1\}$ plane[(16)]. This is supported by other experimental results obtained by time-resolved photoluminescence measurements[(17)]. The experimental results obtained in this work indicate that the deterioration in the crystalline quality of the InGaN QWs with increasing In composition is inhibited by fabricating the InGaN QWs on the $\{20\bar{2}1\}$ plane. In addition, the improvement of the WPE has enabled CW lasing at 536.6 nm, as shown in **Fig. 3**, which is the longest lasing wavelength by an InGaN LD, to the best of our knowledge.

Next, we focus on the device characteristics of our recent semipolar $\{20\bar{2}1\}$ green LDs. The temperature dependences of light output power vs. current (*L-I*) and voltage vs. current (*V-I*) for a typical green LD under CW operation are shown in **Figs. 4 (a) and (b)**, respectively. The threshold current, threshold current density, and threshold voltage at a case temperature (T_c) of 25°C were 59 mA,

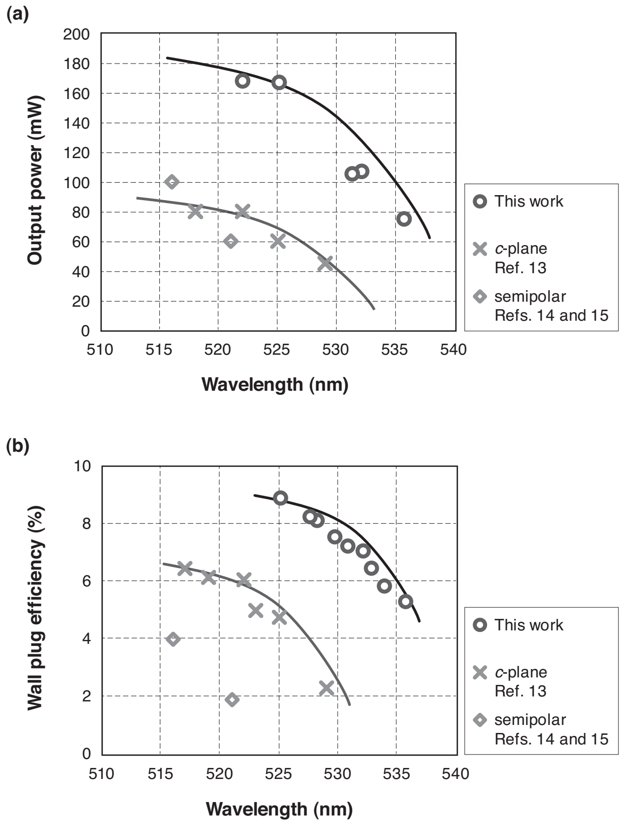

Fig. 2. Dependence of (a) output power and (b) wall plug efficiency on lasing wavelength for three different types of InGaN green LDs

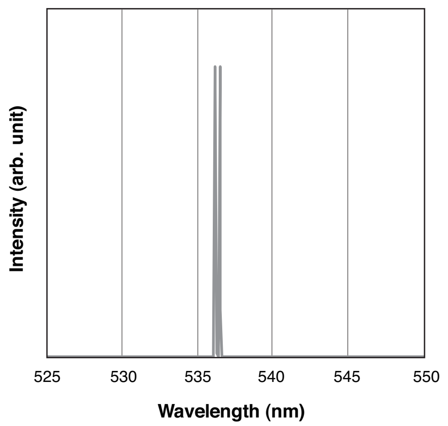

Fig. 3. Lasing spectrum of the $\{20\bar{2}1\}$ plane LD under CW operation at RT

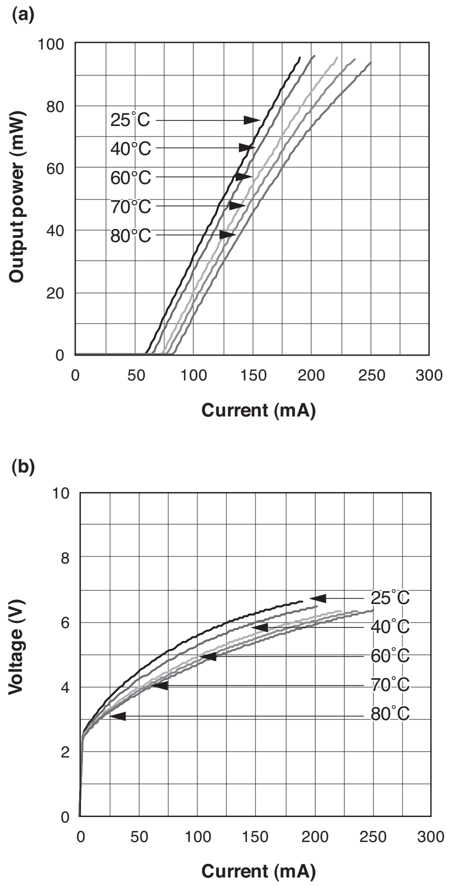

Fig. 4. Temperature dependence of (a) the *L-I* characteristics and (b) the *V-I* characteristics of the semipolar $\{20\bar{2}1\}$ green LD lasing at 528.1 nm under CW operation

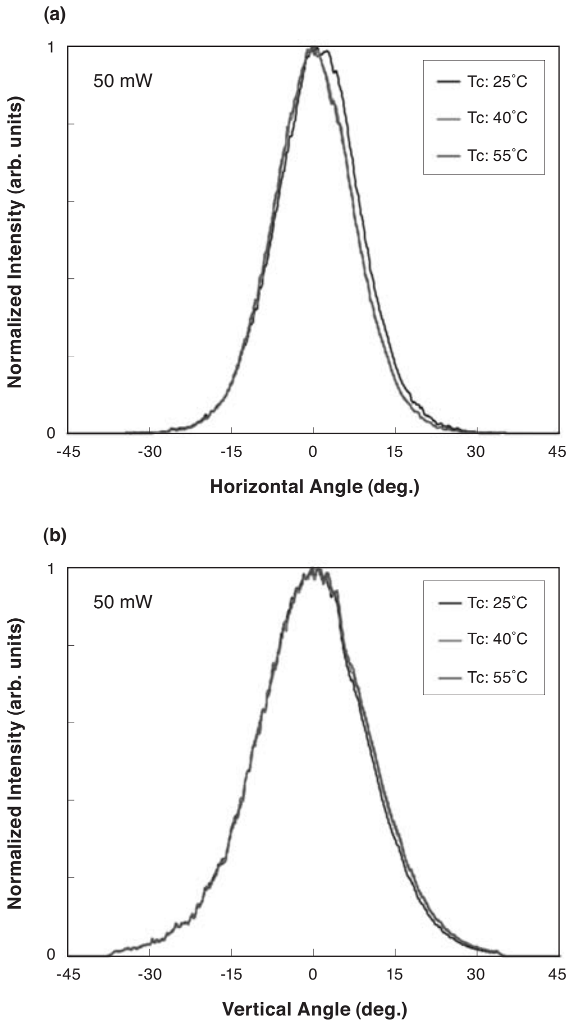

Fig. 5. (a) Lateral FFPs and (b) vertical FFPs for a green LD with output power of 50 mW under CW operation in the T_c range from 25 to 55°C

5.9 kA/cm^2, and 4.7 V, respectively. The lasing wavelength was 528.1 nm under 70 mW at a T_c of 25˚C. The threshold voltage has been reduced from 6.4 V of our previous work to 4.7 V, as a result of the improvement of the contact resistivity and the optimization of the doping profile. Along with the improvement of the slope efficiencies discussed above, the reduction of the threshold voltage contributed largely to the higher WPEs. **Figure 4 (a)** shows that, although there is a slight thermal rollover, our green LDs output more than 90 mW at 80˚C, indicating that they are suitable for use in portable devices with limited heat sink capability. Figure 5 shows typical far-field patterns (FFPs) for an output power of 50 mW at T_c values of 25, 40, and 55˚C. From **Figs. 5 (a) and (b)**, the beam divergence angles were measured to be 16.6˚ parallel to and 23.2˚ perpendicular to the substrate plane. The perpendicular-to-parallel aspect ratio was 1.4, which means that the beam shape of this LD is suitable for practical use.

Finally, we conducted lifetime tests for five different green LDs with lasing wavelengths in the range of 527.5-530.8 nm. The tests were carried out at a T_c of 55˚C for an output power of 50 mW in the automatic power control (APC) mode. The typical threshold current, threshold voltage, and slope efficiency were 73 mA, 4.5 V, and approximately 0.5 W/A, respectively. **Figures 6 (a) and (b)** show the time dependence of the operating current and operating voltage, respectively. As seen in these figures, the operating current and operating voltage remain stable during 1,000 h of testing, with the average rates of increase of 2.44% and 2.96%, respectively. The lifetime was estimated to be more than 5,000 h when it was defined as the point where the operating current increases to 1.3 times its initial value. We also conducted lifetime tests for two LDs with peak output wavelengths of 528.2 and 529.1 nm. The tests were carried out at a T_c of 55˚C for an output power of 70 mW in the APC mode. The results for the operating current and operating voltage are shown in **Figs. 7 (a) and (b)**, respectively. During 500 h of testing, the average rates of increase in the operating current and operating voltage were 4.51% and 3.59%, respectively. The lifetime was estimated to be more than 2,000 h. To ensure lifetime of over 2,000 h, the critical initial power consumption for green LDs needs to be less than 1 W. The lifetime is expected to be prolonged by reducing the operating current and operating voltage.

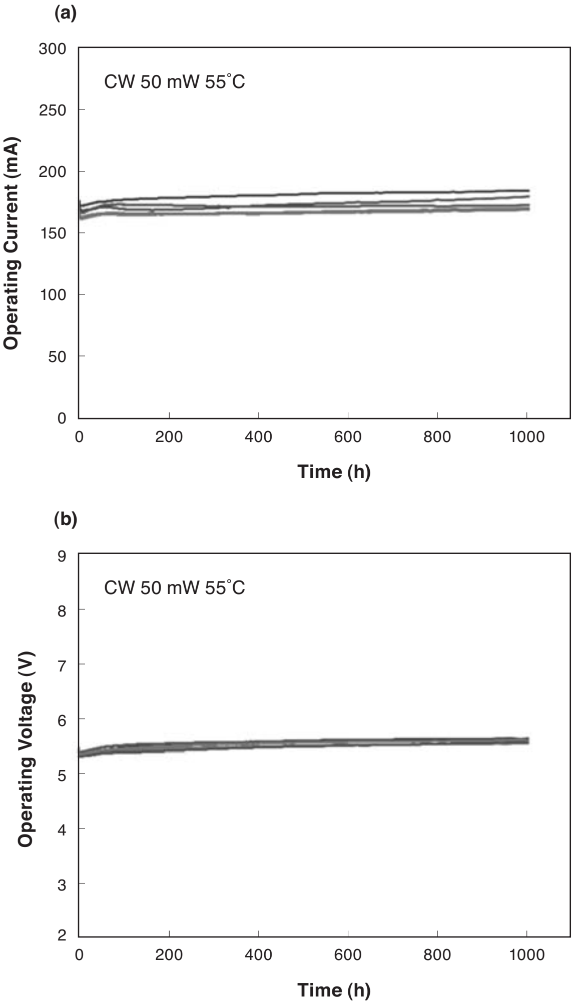

Fig. 6. Change in (a) operating current and (b) operating voltage with time for five green LDs (527.5-530.8 nm). The output power was 50 mW under CW operation in the APC mode at a T_c of 55˚C

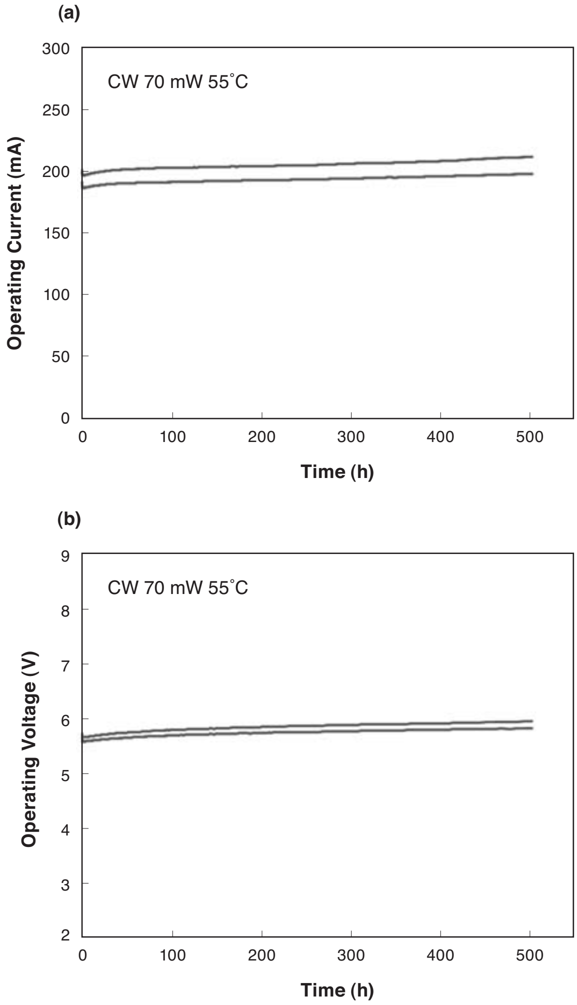

Fig. 7. Change in (a) operating current and (b) operating voltage with time for two green LDs (528.2 and 529.1 nm). The output power was 70 mW under CW operation in the APC mode at a T_c of 55˚C

4. Conclusion

We demonstrated CW operation using InGaN green LDs fabricated on semipolar $\{20\bar{2}1\}$ GaN substrates. These LDs exhibited output power of over 100 mW in the green spectral region beyond 530 nm and WPEs of 7.0-8.9%, which are quite high as compared with those of the *c*-plane LDs, in the wavelength range of 525-532 nm. Moreover, high-power operation of 90 mW was confirmed at 80˚C, indicating the possibility of use in portable devices. The lifetime of these LDs at 55˚C was estimated to be over 5,000 h when operated at 50 mW, and over 2,000 h at 70 mW.

Technical Terms

∗1 SHG (Second Harmonic Generation): A process in which an interaction between photons and a non-linear material generates new photons with half the wavelength of the initial photon.

∗2 LED (Light Emitting Diode): A semiconductor device that transforms energy of electrons into light by current injection.

∗3 CW (Continuous Wave): Optical wave continuing in terms of time.

∗4 HVPE (Hydride Vapor Phase Epitaxy): A production method of semiconductors using a hydride gas as a precursor.

∗5 OMVPE (Organometallic Vapor Phase Epitaxy): A production method of semiconductors using an organometallic as a precursor.

∗6 WPE (Wall Plug Efficiency): A ratio of optical output power to power consumption.

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