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Watt-class Operation of GaN-based Blue and Green Laser Diodes

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ABSTRACT

Visible laser diodes have recently attracted a great deal of attention as light sources for various display and lighting applications. In this paper, recent progress in green and blue lasers developed at Sony, which realize watt-class output power, are reported.

1 INTRODUCTION

Laser diodes have found a wide range of applications in recent years, and it is expected that demand will increase further still. Particularly in the field of laser projectors, products such as head-mounted displays, mobile projectors, business and home projectors, and digital cinema projectors are being developed by exploiting the excellent characteristics of lasers.

Projectors using laser light sources have many advantages over conventional lamps and light-emitting diodes (LEDs) in terms of high brightness, high optical reproductivity, small size, quick start-up, and long life. Laser projectors mainly use laser sources that emit visible light. As the projection area increases, so does the demand for high-output-power lasers. In high-brightness projectors, lasers with a watt-class output power or higher are used.

Lasing wavelengths of 467 nm and 532 nm are required to meet the ITU-R Recommendation BT.2020. GaN-based laser diodes can generate light in the blue and green spectral regions, and watt-class output power has been demonstrated [1-4]. If the laser output power could be further increased, the number of installed lasers could be reduced, which would allow downsizing of light source modules and cost reduction. However, high-power lasers generate a large amount of heat, and this necessitates special cooling mechanisms, which is a major technical challenge.

Against this background, we have developed high-efficiency blue and green lasers. In this paper, recent progress on high-power and high-efficiency lasers developed at Sony is presented.

2 Polar and semipolar GaN substrates

Watt-class blue and green LDs reported to date have been fabricated on conventional c-plane GaN substrates [1-3]. Such LDs have a strong piezoelectric field inside InGaN quantum wells with a high indium concentration, which degrades the luminous efficiency by reducing the recombination probability. It has therefore been difficult to fabricate green or longer-wavelength light-emitting devices on c-plane GaN substrates.

In order to overcome this problem and fabricate green lasers, we used semipolar $\{20\bar{2}1\}$ GaN substrates. Figure 1 shows schematic models of the crystal structures of GaN. The $\{20\bar{2}1\}$ plane is tilted by 75° from the *c*-plane toward the *m*-plane. The reduction of piezoelectric effects in the $\{20\bar{2}1\}$ plane has been demonstrated both theoretically [5] and experimentally [6]. Moreover, it has been found that InGaN quantum wells on the $\{20\bar{2}1\}$ plane have higher In-atom homogeneity and thickness uniformity than those on the *c*-plane [7].

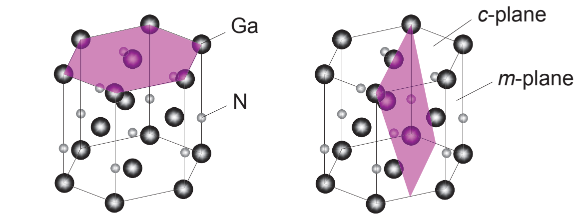


Fig. 1 Schematic models of crystal structures of GaN
Colored areas indicate the (a) c-plane and (b) $\{20\bar{2}1\}$ plane.

3 Green Laser Diodes

For the reasons cited above, we use semipolar $\{20\bar{2}1\}$ GaN substrates to fabricate our green lasers. The first

CW lasing of a green laser on the $\{20\bar{2}1\}$ plane was reported by Sumitomo's group in 2009 [8], and our group reported the first watt-class output power [9].

3.1 Structure

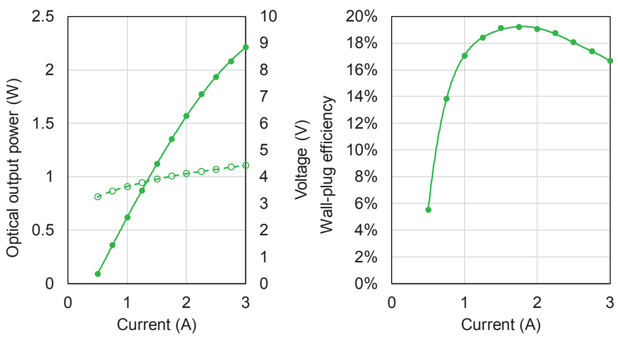
The green lasers were grown on free-standing semipolar $\{20\bar{2}1\}$ GaN substrates by metal organic chemical vapor deposition (MOCVD). The epitaxial structure consisted of an n-type AlInGaN cladding layer, an n-type InGaN optical waveguiding layer, InGaN multiple quantum wells, an InGaN optical waveguiding layer, a p-type AlGaN cladding layer, and a p-type GaN contact layer.

The 15-μm-wide laser stripe was formed by dry etching along the $[\bar{1}014]$ direction, which has been reported to be an advantageous orientation for semipolar $\{20\bar{2}1\}$ GaN [10]. A p-side electrode of indium tin oxide (ITO) was deposited on top of the ridge, and annealed to impart favorable contact characteristics to the p-type contact layer. The ITO layer, which had a much lower refractive index (~2.1) than the active layer, also served as part of the optical cladding layer, enabling good vertical optical confinement.

The facets at both ends were formed by cleaving so that the LD functioned as a 1200-μm-long resonator, and were coated with multilayer dielectric films to adjust the reflectivity.

3.2 Lasing characteristics

Figure 2 shows the optical and electrical characteristics of a green laser with a lasing wavelength of 525 nm, which was assembled on a ⌀9.0 mm TO-CAN with a junction-down configuration. An output power of approximately 1.56 W was obtained at an operating current of 2.0 A, and a maximum output power of 2 W was reached under CW operation at a case temperature of 25°C. The wall-plug efficiency was calculated to be 19.1% at 2.0 A.



(a) (b)

Fig. 2 Lasing characteristics of green laser diodes

(a) I-L and I-V characteristics and (b) wall-plug efficiency for 525-nm green laser measured under CW operation at case temperature of 25°C.

3.3 Reliability

Figure 3 shows the reliability test results for the green LDs. The test was performed under an operating current of 2.0 A at a case temperature of 60°C. The output-power reduction rate was very low and none of the devices broke down due to the common failure mode of catastrophic optical damage (COD) at the mirror throughout the 1,000-h-long test. The lifetime, defined as the time it took the power to degrade to 50% of its initial value, was estimated to be over 20,000 h, which is typically the minimum required value for laser display applications.

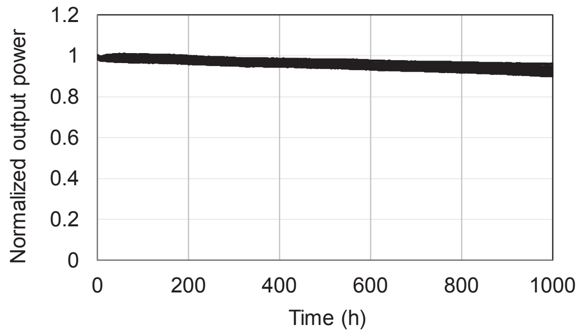


Fig. 3 Reliability tests of green lasers at operating current of 2.0 A and case temperature of 60°C

4 Blue Laser Diodes

In general, blue lasers have two uses: as pure blue light sources and for phosphor excitation. The former enables R/G/B laser-based projectors and the latter, which can yield white light when used with phosphors such as YAG:Ce, realizes not only projector applications but also lighting. We have developed blue laser diodes having a lasing wavelength of 455 nm for white lighting with phosphors and 465 nm for a R/G/B laser-based projector [4].

4.1 Structure

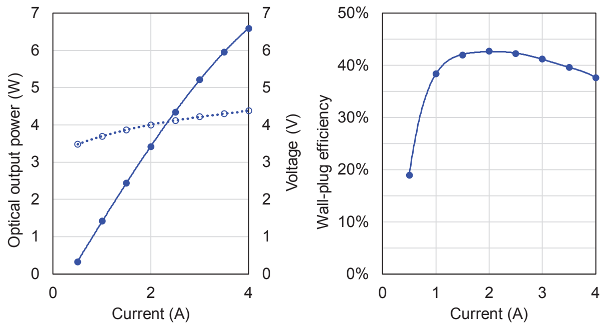
For our blue lasers, we used conventional c-plane GaN substrates because of the low wafer cost and convenient fabrication process. The epitaxial structure consisted of an n-type AlGaN cladding layer, an n-type InGaN optical waveguiding layer, InGaN multiple quantum wells, an InGaN optical waveguiding layer, an electron blocking layer, a p-type AlGaN cladding layer, and a p-type GaN contact layer.

They had a 40-μm-wide ridge-shaped stripe and a 1200-μm-long cavity. A p-side ITO electrode was deposited on top of the ridge and cleaved facets were coated with dielectric multilayer films, as in the case of the green lasers.

4.2 Lasing characteristics

Figure 4 shows the optical and electrical characteristics of a blue laser with a lasing wavelength of

455 nm, which was assembled on a ⌀9.0 mm TO-CAN with a junction-down configuration. The output power and wall-plug efficiency were 5.2 W and 41.2% at an operating current of 3.0 A, and 6.2 W and 39.0% at an operating current of 3.7 A, respectively, under CW operation at a case temperature of 25°C.

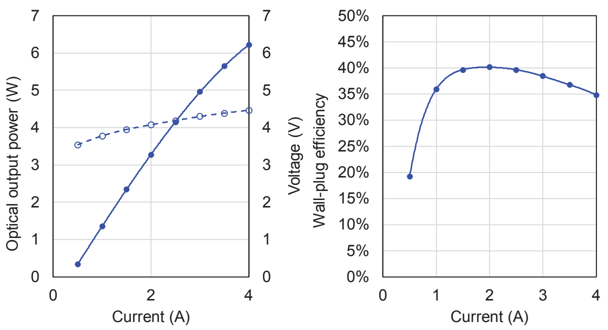


(a) (b)

Fig. 4 Lasing characteristics of blue laser diodes

(a) I-L and I-V characteristics and (b) wall-plug efficiency for 455-nm blue laser measured under CW operation at case temperature of 25°C.

Figure 5 shows the optical and electrical characteristics of a blue laser with a wavelength of 465 nm. The output power and wall-plug efficiency were approximately 5.0 W and 38.4%, respectively, at an operating current of 3.0 A under CW operation at a case temperature of 25°C.



(a) (b)

Fig. 5 Lasing characteristics of blue laser diodes

(a) I-L and I-V characteristics and (b) wall-plug efficiency for 465-nm blue laser measured under CW operation at case temperature of 25°C.

4.3 Reliability

In a previous study, reliability testing was performed at an operating current of 3.0 A and a case temperature of 65°C [4]. However, in the present study, it was found to be possible to operate at a higher current and increase the output power from 5 to 6 watt-class by improving the lasing characteristics and expanding the waveguide width.

Figure 6 shows the reliability test results for the 455-nm blue LDs. The test was performed under an operating current of 3.7 A at a case temperature of 65°C. The output-power reduction rate was very low and none of the devices broke down due to COD throughout the 4,000-h-long test. In this case also, the estimated lifetime was over 20,000 h.

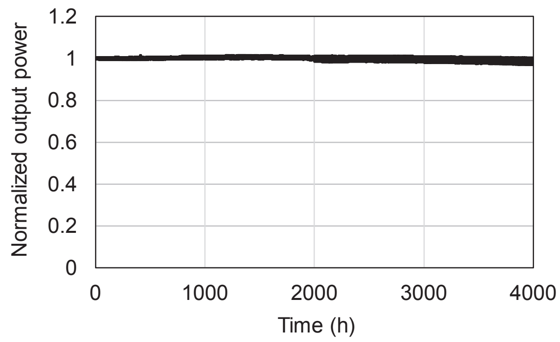


Fig. 6 Reliability tests of 455-nm blue lasers at operating current of 3.7 A and case temperature of 65°C

5 CONCLUSIONS

We achieved high-power output for green and blue laser diodes fabricated on semipolar $\{20\bar{2}1\}$ and *c*-plane GaN substrates, respectively. Under continuous-wave operation, the 525-nm green lasers exhibited an output power of 1.56 W and a wall-plug efficiency of 19.1% at a current of 2.0 A. The 455-nm and 465-nm blue lasers exhibited output powers of 5.2 and 5.0 W and wall-plug efficiencies of 41.2% and 38.4%, respectively, at a current of 3.0 A. These improvements of 455 nm blue laser enabled to demonstrate high reliability even at higher operating current and temperature of 3.7 A and 65 °C, respectively.

Such advances in watt-class green and blue lasers are expected to further advance the widespread use of laser displays and lighting.

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