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Room-temperature continuous-wave operation of GaN-based blue-violet laser diodes with a lifetime longer than 1000 h

Feng Liang[1], Jing Yang[1, †], Degang Zhao[1, 2, †], Zongshun Liu[1], Jianjun Zhu[1, 2], Ping Chen[1], Desheng Jiang[1], Yongsheng Shi[1], Hai Wang[1], Lihong Duan[1], Liqun Zhang[3], and Hui Yang[3]

[1]State Key Laboratory of Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

[2]Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

[3]Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou 215123, China

Abstract: GaN-based continuous-wave operated blue-violet laser diodes (LDs) with long lifetime are demonstrated, which are grown on a *c*-plane GaN substrate by metal organic chemical vapor deposition with a $10 \times 600\ \mu m^2$ ridge waveguide structure. The electrical and optical characteristics of a blue-violet LD are investigated under direct-current injection at room temperature (25 °C). The stimulated emission wavelength and peak optical power of the LD are around 413 nm and over 600 mW, respectively. In addition, the threshold current density and voltage are as small as 1.46 kA/cm^2 and 4.1 V, respectively. Moreover, the lifetime is longer than 1000 hours under room-temperature continuous-wave operation.

Key words: GaN-based blue-violet laser diodes; long lifetime; threshold voltage

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1. Introduction

GaN-based laser diodes (LDs), owing to their broad stimulated wavelength range and small device size, have attracted a great deal of attention to the applications in ultraviolet (UV) Raman spectroscopy[1], optical coherence tomography[2], biomedical science[3], underwater wireless optical communication[4, 5], and laser-based televisions (TVs) and small portable projectors[6–9] since Nakamura and his coworkers demonstrated the first GaN-based blue-violet LDs in the 1990s[10, 11]. Especially, GaN-based blue-violet LDs can be used in high-density optical data storage systems[12–15] and the next generation optical atomic clocks[16–18]. Therefore, GaN-based LDs with a steady output and a long working lifetime are expected. In fact, in 2013 and 2017 our group had successively demonstrated the blue-violet LD array with a maximum optical power of 7.5 W[19] and the blue-violet LD with a peak optical power of 20 W[20], respectively, under a pulsed injection current. Their threshold current density was around 3.5 kA/cm^2. In this paper, we demonstrate the room temperature (RT, 25 °C) continuous-wave (CW) operation of GaN-based blue-violet LD with a lifetime longer than 1000 h.

2. Experiments

In this work, GaN-based blue-violet LDs are grown on *c*-plane GaN substrate by metal organic chemical vapor deposition (MOCVD). The trimethylgallium (TMGa) or triethylgallium (TEGa), trimethylaluminum (TMAl), trimethylindium (TMIn), NH_3, dicyclopentadienyl magnesium (Cp_2Mg), and SiH_4 are used as the Ga, Al, In, N, Mg, and Si sources, respectively. The LDs are grown in proper sequence, and the epitaxial structure is shown in Fig. 1. Firstly, a thick n-GaN layer is grown on GaN substrate, and then an n-AlGaN cladding layer (CL), an n-GaN lower waveguide (LWG) layer, InGaN/GaN multi-quantum wells (MQWs), a p-AlGaN electron-blocking layer (EBL), a p-GaN upper waveguide (UWG) layer, a p-AlGaN cladding layer, a p-GaN layer, and a very thin heavily Mg-doped GaN (p^{++}-GaN) layer are grown subsequently. In addition, a 10-μm-wide ridge stripe is formed by dry etching along the <1-100> direction, and a 600-μm-long cavity is fabricated by cleaving along the {1-100} plane after grounding and polishing the GaN substrate to reduce its thickness. The front and rear cleaved cavity facets are coated, and the reflectivity is 10% and 90%, respectively. Moreover, Ti/Pt/Au and Pd/Pt/Au are used to form Ohmic contacts with n-GaN substrate and p-GaN contact layer, respectively.

3. Results and discussions

The optical spectrum of stimulated emission from the GaN-based LD under CW operation is shown in Fig. 2. It can be seen that the peak wavelength is around 413 nm, and the full width at half maximum (FWHM) of the spectrum is small, i.e. about 0.4 nm. In addition, the inset of Fig. 2 shows the far field pattern of the laser beam when the blue-violet LD illuminates a page of white paper. These results indicate the success in the fabrication of GaN-based blue-violet LD with a lasing wavelength of around 413 nm and CW operated at room temperature.

Fig. 3 shows the voltage and optical power of GaN-based blue-violet LD as a function of the forward direct-current (*P–I–V*) measured at room temperature. It is observed that the

Correspondence to: J Yang, yangjing333@semi.ac.cn;
D G Zhao, dgzhao@red.semi.ac.cn
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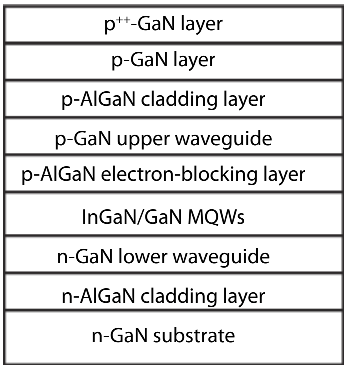

Fig. 1. Schematic diagram of the epitaxial structure for the GaN-based blue-violet LDs.

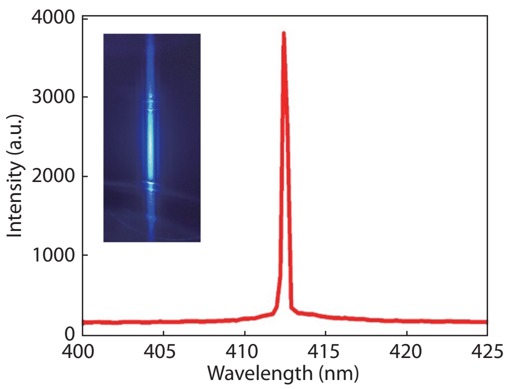

Fig. 2. (Color online) The optical spectrum of stimulated emission for a GaN-based blue-violet LD. The inset shows the far field pattern of laser beam.

optical power increases sharply and lasing starts when the injection current is higher than 87.6 mA. Thus, the threshold current is taken as 87.6 mA, and the corresponding threshold current density is 1.46 kA/cm^2. In addition, the peak optical power is larger than 600 mW under an injection current of 800 mA, and the corresponding current density is around 13.33 kA/cm^2.

It is found that the operating voltage under the threshold current, i.e. threshold voltage, is as low as 4.1 V. Such a low threshold voltage may be mainly attributed to our previous works on the improvement of the p-GaN Ohmic contact. In our previous study, we demonstrated the influence of residual carbon impurities in the heavily Mg-doped GaN (p^{++}-GaN) layer on the performance of p-GaN Ohmic contact. A low specific contact resistivity (ρ_c) of 6.8 × 10^{-5} Ω·cm^2 is obtained by properly controlling the residual carbon impurity incorporation in the p^{++}-GaN layer[21, 22]. Recently, the p-GaN Ohmic contact has been significantly improved further. The specific contact resistivity is characterized by current–voltage (*I–V*) measurements based on the circular transmission line model (CTLM) with a contact inner radius (*r*) of 200 μm and eight different out radius (*R*) ranged from 215 to 260 μm. The details about the CTLM experimental method can be found in Refs. [21, 22]. As shown in Fig. 4, the *I–V* curves are straight and the specific contact resistance is as low as 1.1 × 10^{-6} Ω·cm^2. It implies that an excellent Ohmic contact is obtained, and it is beneficial to achieving a small threshold voltage for GaN-based LD.

We have taken the aging experiment to check the lifetime of blue-violet LDs, which is performed at room temperature under a fixed current injection. Fig. 5 shows the optical out-

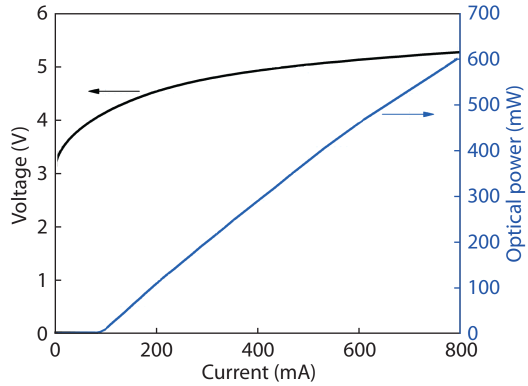

Fig. 3. (Color online) Power–current–voltage (*P–I–V*) curves of a GaN-based blue-violet LD at room temperature.

put power as the function of aging time. It can be seen that the optical power decreases slightly along with the increasing aging time, and the optical power keeps larger than 100 mW as the aging time reaches up to around 1067 h. It demonstrates that the lifetime of GaN-based blue-violet LD is longer than 1000 h under a room-temperature continuous-wave operation. It is noted that output power has declined after the LD operates for the right time, which is supposed to be caused by two reasons. First, the increasing temperature due to the accumulation of the heat process can decrease the slope efficiency and reduce the output power. Second, it may be that there are a few dislocations in GaN-based materials, which can reduce the output power along with increasing aging time. Actually, some necessary technological procedures have been taken in the device fabrication process in order to avoid any failure happening in the early stage of the device operation. We think the long lifetime obtained for the blue-violet LDs is due to our previous work for the improvement of Ohmic contact and material growth, and due to the new LD structure design. In details, first, as mentioned above, an excellent Ohmic contact with a very low specific contact resistance is obtained, which is good for reducing operation voltage and contact resistance. Second, the good p-AlGaN materials are grown by reducing the carbon and hydrogen concentration through controlling the growth conditions[23–25]. Third, the emission efficiency of InGaN/GaN MQWs is enhanced by reducing the carbon concentration in MQWs[26]. Fourth, a new LD structure to reduce optical loss and leakage current is proposed and which is beneficial to decreasing the threshold current[27]. Therefore, low threshold current density and voltage can be obtained for the GaN-based blue-violet LD in this study.

4. Conclusion

In summary, the continuous-wave GaN-based blue-violet LDs with a lifetime longer than 1000 h operated at room temperature are demonstrated. The blue-violet LDs are grown on *c*-plane GaN substrate by MOCVD, and a 10 × 600 μm^2 ridge waveguide structure device is fabricated. The stimulated emission wavelength of LD is about 413 nm, and the peak optical power is larger than 600 mW. Moreover, the threshold current density and voltage are as low as 1.46 kA/cm^2 and 4.1 V, respectively. The fabricated GaN-based blue-violet LDs successfully show a long cw working lifetime.

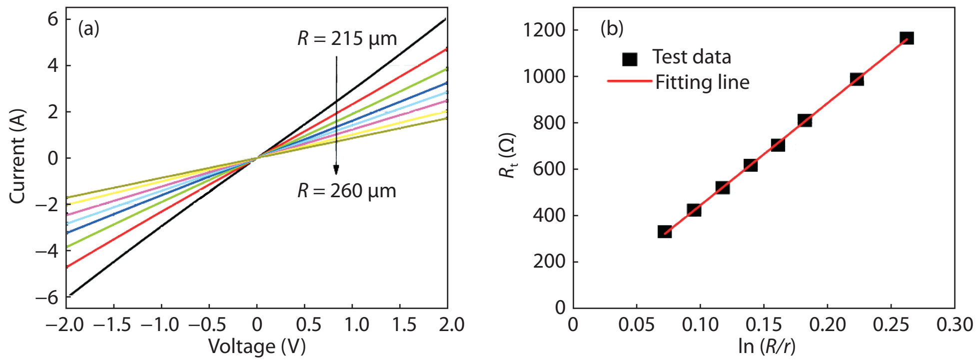

Fig. 4. (Color online) (a) Current–voltage characteristics obtained for different values of *R* between 215 and 260 μm, and (b) the measured data of total resistance (R_t, black squares) as a function of ln(*R*/*r*) and the fitting line (red), by using the circular transmission line model for p-GaN Ohmic contact in the GaN-based blue-violet laser diode. The specific contact resistance is as low as 1.1 × 10^{-6} Ω·cm^2.

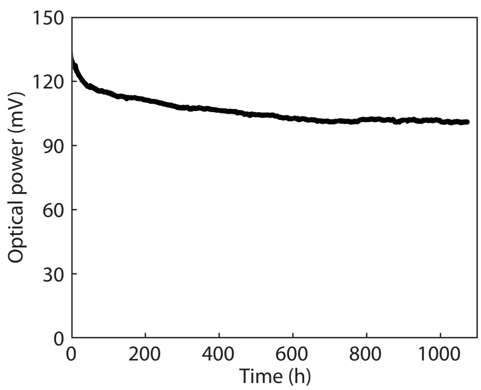

Fig. 5. Optical power of blue-violet LD as a function of the aging time with a fixed injection current at room temperature.

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References

[1] Ruhnke N, Müller A, Eppich B, et al. Compact deep UV system at 222.5 nm based on frequency doubling of GaN laser diode emission. IEEE Photonic Tech Lett, 2018, 30(3), 289

[2] Goldberg G R, Ivanov P, Ozaki N, et al. Gallium nitride light sources for optical coherence tomography. Gallium Nitride Materials and Devices XII, 2017, 101041X

[3] Wunderer T, Northrup J E, Yang Z, et al. Nitride VECSELs as light sources for biomedical applications. CLEO: Applications and Technology, 2013, JM3O.1

[4] Xue B, Liu Z, Yang J, et al. Characteristics of III-nitride based laser diode employed for short range underwater wireless optical communications. Opt Commun, 2018, 410, 525

[5] Huang Y F, Tsai C T, Chi Y C, et al. Filtered multicarrier OFDM encoding on blue laser diode for 14.8-gbps seawater transmission. J Lightwave Technol, 2018, 36(9), 1739

[6] Strauβ U, Brüninghoff S, Schillgalies M, et al. True-blue InGaN laser for pico size projectors. Gallium Nitride Materials and Devices III, 2008, 689417

[7] Buckley E. Laser wavelength choices for pico-projector applications. J Display Technol, 2011, 7(7), 402

[8] Essaian S and Khaydarov J. State of the art of compact green lasers for mobile projectors. Opt Rev, 2012, 19(6), 400

[9] Gan Y, Lu Y, Xu Q Y et al. Compact integrated green laser module for Watt-level display applications. IEEE Photonic Tech Lett, 2013, 25(1), 75

[10] Nakamura S, Senoh M, Nagahama S I, et al. Violet InGaN/GaN/AlGaN-based laser diodes with an output power of 420 mW. Jpn J Appl Phys, 1998, 37(6A), L627

[11] Nakamura S, Senoh M, Nagahama S I, et al. InGaN-based multi-quantum-well-structure laser diodes. Jpn J Appl Phys, 1996, 35(1B), L74

[12] Hardy M T, Feezell D F, DenBaars S P, et al. Group III-nitride lasers: a materials perspective. Mater Today, 2011, 14(9), 408

[13] Moustakas T D, Paiella R. Optoelectronic device physics and technology of nitride semiconductors from the UV to the terahertz. Rep Prog Phys, 2017, 80(10), 106501

[14] Kim J, Kim H, Lee S N. Thermal degradation in InGaN quantum wells in violet and blue GaN-based laser diodes. Curr Appl Phys, 2011, 11(4), S167

[15] Masui S, Nakatsu Y, Kasahara D, et al. Recent improvement in nitride lasers. Gallium Nitride Materials and Devices XII, 2017, 101041H

[16] Najda S P, Perlin P, Suski T, et al. AlGaInN laser-diode technology for optical clocks and atom interferometry. Gallium Nitride Materials and Devices XII, 2017, 101041L

[17] Najda S P, Stanczyk S, Kafar A, et al. Tapered waveguide high power AlGaInN laser diodes and amplifiers for optical integration and quantum technologies. Quantum Technologies & Quantum Information Science, 2017, 104420O

[18] Najda S P, Perlin P, Suski T, et al. GaN laser diodes for high-power optical integration and quantum technologies. Gallium Nitride Materials and Devices XIII, 2018, 1053217

[19] Chen P, Zhao D G, Feng M X, et al. A high power InGaN-based blue-violet laser diode array with a broad-area stripe. Chin Phys Lett, 2013, 30(10), 104205

[20] Zhao D G, Jiang D S, Le L C, et al. Performance improvement of GaN-based violet laser diodes. Chin Phys Lett, 2017, 34(1), 017101

[21] Liang F, Zhao D G, Jiang D S, et al. Improvement of Ohmic contact to p-GaN by controlling the residual carbon concentration in p^{++}-GaN layer. J Cryst Growth, 2017, 467, 1

[22] Liang F, Zhao D G, Jiang D S, et al. Influence of residual carbon impurities in a heavily Mg-doped GaN contact layer on an Ohmic contact. Appl Opt, 2017, 56(14), 4197

[23] Yang J, Zhao D G, Jiang D S, et al. Investigation on the compensation effect of residual carbon impurities in low temperature grown Mg doped GaN films. J Appl Phys, 2014, 115(16), 163704

[24] Yang J, Zhao D G, Jiang D S, et al. Influence of hydrogen impurities on p-type resistivity in Mg-doped GaN films. J Vac Sci Technol A, 2015, 33(2), 021505
[25] Liang F, Yang J, Zhao D G, et al. Influence of hydrogen impurity on the resistivity of low temperature grown p-$Al_xGa_{1-x}N$ layer ($0.08 \le x \le 0.104$). Superlattice Microstruct, 2018, 113, 720
[26] Yang J, Zhao D G, Jiang D S, et al. Emission efficiency enhanced by reducing the concentration of residual carbon impurities in InGaN/GaN multiple quantum well light emitting diodes. Opt Express, 2016, 24(13), 13824
[27] Liang F, Zhao D G, Jiang D S, et al. Performance enhancement of the GaN-based laser diode by using an unintentionally doped GaN upper waveguide. Jpn J Appl Phys, 2018, 57, 070307