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GaN-based violet laser diodes grown on free-standing GaN substrate*

Zhang Li-Qun(张立群)[a)†], Zhang Shu-Ming(张书明)[a)], Jiang De-Sheng(江德生)[a)], Wang Hui(王 辉)[a)], Zhu Jian-Jun(朱建军)[a)], Zhao De-Gang(赵德刚)[a)], Liu Zong-Shun(刘宗顺)[a)], and Yang Hui(杨 辉)[a)b)‡]

[a)] *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*

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

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A violet laser diode (LD) structure is grown on a free-standing c-plane GaN substrate and 4 μm×800 μm ridge waveguide LDs are fabricated. The electrical and the optical characteristics of LDs under different facet-coating and chip-mounting conditions are investigated under pulse mode operation. The active region temperatures of p-side up and p-side down mounted LDs are calculated with different injection currents. The calculated thermal resistances of p-side up and p-side down mounted LDs are 4.6 K/W and 3 K/W, respectively. The threshold current of the p-side down mounted LD is much lower than that of the p-side up mounted LD. The blue shift of the emission wavelength with increasing injection current is observed only for the LD with p-side down mounting configuration, due to the more efficient heat dissipation.

Keywords: GaN laser diode, mounting configuration, active region temperature
PACC: 4255P

1. Introduction

Since the first GaN-based laser diode was demonstrated by Nichia,[1] its investigations have been the focus of III–V nitride semiconductors and devices. GaN-based LDs have light spectra in a wide range from 342 nm to 500 nm.[2,3] UV LDs have important applications in biotechnological, medical and pharmaceutical fields.[4−6] Violet LDs have been commercially used in high-density optical data storage systems. The blue and underdeveloped pure green LDs are promising light sources for RGB (red, green, blue) full colour laser projection displays.[7]

Previously we demonstrated the continuous-wave operation of GaN-based violet LDs grown on c-plane sapphire substrate.[8] However, their final yield was low because of the complexity of the fabrication process and the difficulties in cleaving and p-side down mounting of LDs on sapphire substrate. On the other hand, the low thermal conductivity of sapphire substrate results in a high thermal resistance and a short lifetime of the device. These problems do not happen to the homoepitaxially grown LDs on free-standing (FS) GaN substrate. In fact, nowadays nearly all of the high performance and commercially available GaN-based LDs are grown on FS–GaN substrates.[9−11] Based on the research on epitaxial growth, device design and fabrication techniques, we demonstrate here pulse current injection violet LDs on FS–GaN substrate. The characteristics of LDs on FS–GaN substrate are carefully investigated for the devices under different facet coating and chip mounting conditions.

2. Experiment

A Thomas Swan 3×2" close-coupled showerhead reactor metalorganic chemical vapour deposition (MOCVD) system was used to grow the LD structure. TMGa, TMAl, TMIn, CP_2Mg, SiH_4 and ammonia were used as precursors. The growth process was controlled by an in-situ optical reflectometry monitor.

The epitaxial layer structure is composed of a 1 μm thick AlGaN/GaN:Si superlattice (SL) cladding layer, a 0.1-μm thick unintentionally doped GaN

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†E-mail: lqzhang@semi.ac.cn
‡Corresponding author. E-mail: hyang@red.semi.ac.cn

waveguide layer, an $In_{0.1}Ga_{0.9}N/In_{0.02}Ga_{0.98}N$ MQW structure consisting of five 3-nm thick undoped $In_{0.1}Ga_{0.9}N$ well layers separated by six 8-nm thick Si-doped $In_{0.02}Ga_{0.98}N$ barrier layers, a 20-nm thick p-type $Al_{0.2}Ga_{0.8}N$:Mg electron blocking layer, a 0.1 μm thick unintentionally doped GaN waveguide layer, a 0.4 μm thick AlGaN/GaN:Mg SL cladding layer, and a 20-nm thick p-type GaN:Mg contact layer. The average Al compositions of the n-type and p-type cladding layers determined by x-ray diffraction are 8% and 6.7%, respectively. The light absorption coefficient of unintentionally doped GaN is much lower than those of Si-doped and Mg-doped GaN.[12,13] The results of waveguide simulation show that the internal absorption loss is greatly reduced by undoping of the waveguide layers.[14]

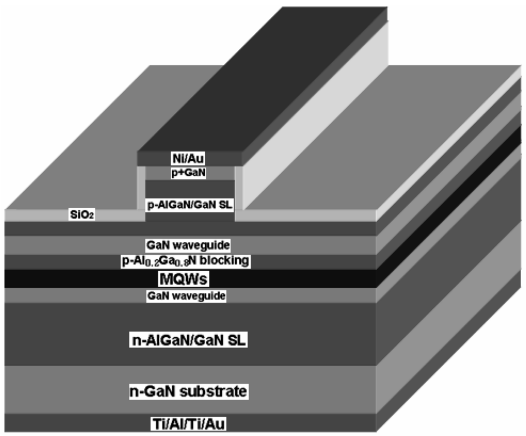


Fig.1. Schematic diagram of ridge-waveguide LDs based on FS–GaN substrates.

A schematic diagram of the LDs based on FS–GaN substrates is shown in Fig.1. The fabrication process of LDs on FS–GaN substrate is rather simple compared with that of LDs on sapphire substrate. Firstly, a 4-μm-wide ridge stripe along the $\langle 11-20\rangle$ direction of the substrate was formed by dry etching to a depth of about 0.4 μm. Secondly, SiO_2 was deposited on the surface and a window for p-type Ohmic contact was formed by wet etching. Thirdly, Ni/Au was evaporated onto the p-type GaN contact layer and annealed as a p-electrode. Fourthly, the substrate was thinned and polished to be less than 150 μm and Ti/Al/Ti/Au were evaporated onto the backside of the substrate as an n-electrode. Finally, the wafer including epitaxial film and substrate was cleaved along the a{11–20} plane. The cavity length was 800 μm. To reduce the threshold current, the front and rear facets of the cavity were coated with quarter-wave TiO_2/SiO_2 dielectric multi-layers with reflectivities of 70% and 90%, respectively.

The epitaxial film and GaN substrate have the same orientations of cleavage plane. With this advantage, nearly all the obtained cleaved facets of LDs based on FS–GaN substrate are mirror-like as shown in Fig.2. As a contrast, in the case of LDs grown on sapphire substrate, most of the cleaved facets are jagged with a lot of striations, and mirror-like facets are very hard to obtain by cleaving.[15,16]

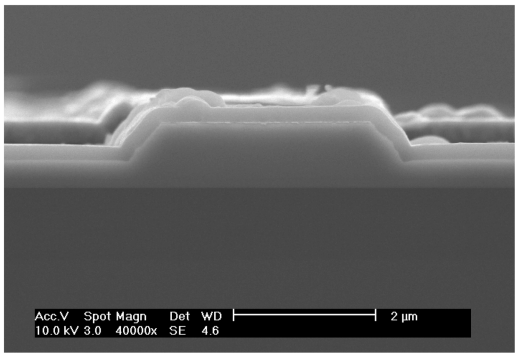


Fig.2. Secondary electron microscopic images of the cleaved laser facets of LDs grown on FS–GaN substrate.

3. Results and discussion

The light output intensity as a function of injection current (L–I) and the voltage–current (V–I) characteristics were tested for three kinds of LDs: (i) two LDs (named LD A and LD B) that were measured by metal probes without packaging; (ii) the above-mentioned LDs whose front and rear facets were coated with dielectric films (named LD A′ and LD B′), which were also measured by metal probes without packaging; (iii) the LDs mentioned in (ii), which were mounted p-side up (for LD A′) or p-side down (for LD B′) on the copper heat sinks (named LD A″ and LD B″). All measurements below were carried out under pulse mode operation with 300 ns width pulse and 0.06% duty cycle.

Figures 3(a) and 3(b) show the L–I curves of LD A and LD B and those after facet coating and chip mounting, respectively. The threshold currents of LD A and LD B are reduced from 328 mA and 320 mA to 270 mA (LD A′) and 275 mA (LD B′) after facet coating, respectively. The threshold currents of LD A″ and LD B″ were 252 mA and 234 mA, respectively. A reduction in threshold current was realized by both p-side up and p-side down mounting because the heat generated during operation was transferred to the heat sinks. The threshold voltages of LD A″ and LD B″ are 17.1 V and 17 V, respectively. The relatively high voltage operation of these LDs may originate from the un-optimized growth conduction of the p-type layers.

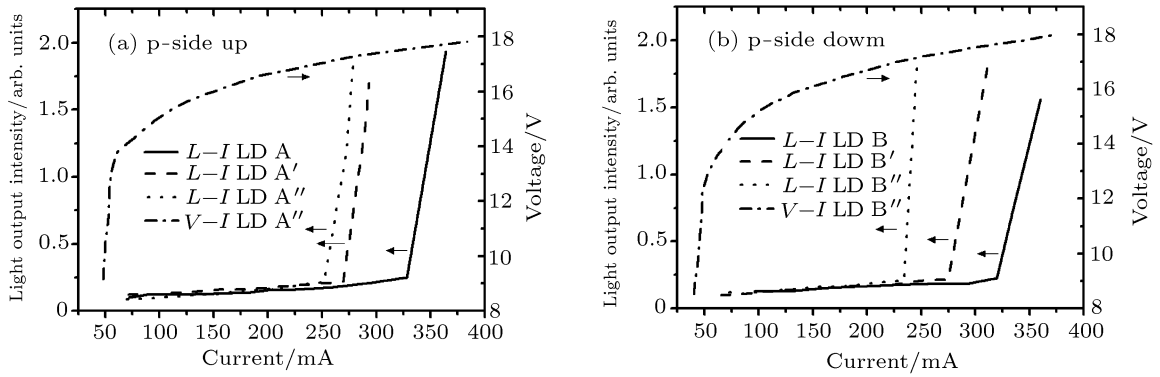


Fig.3. *L–I* and *V–I* characteristics of (a) LD A, LD A′, LD A″ and (b) LD B, LD B′, LD B″ under pulse mode operation.

The self-heating effect of GaN-based LDs will cause an increase of threshold current, which is especially serious when the operation voltage is relatively high. The active region temperatures of LD A″ and LD B″ were calculated by the finite element method with a two-dimensional model. The calculations were made with a pulse duration time of 300 ns. Figure 4 shows the active region temperatures of LD A″ and LD B″ when the injection current ranges from 230 mA to 290 mA. The active region temperature of LD A″ is higher than that of LD B″. At the current of 252 mA the active region temperature of LD A″ is 319.9 K, while that of LD B″ is 313.3 K. The slope of the temperature versus current curve of LD B″ is smaller than that of LD A″. This indicates that the thermal resistance of LD B″ is smaller than that of LD A″. The calculated thermal resistances of LD A″ and LD B″ are 4.6 K/W and 3 K/W, respectively. The p-side down chip mounting results in a more efficient heat dissipation because of the much shorter distance between the active region and the heat sink. Therefore, the threshold current of LD B″ is much lower than that of LD A″.

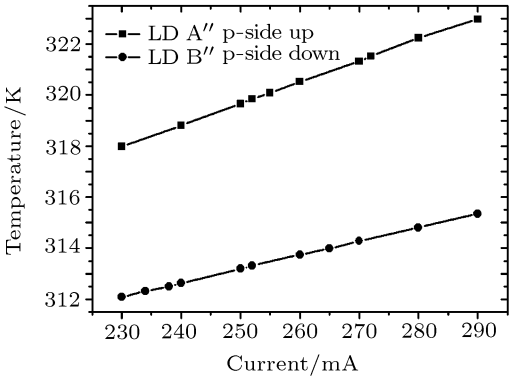


Fig.4. The active region temperatures of LD A″ and LD B″ when the injection current ranges from 230 mA to 290 mA.

Figures 5(a) and 5(b) show the stimulated emission spectra of LD A″ and LD B″ at different injection current values under pulse mode operation, respectively. As shown in Fig.5(a), one fundamental transverse mode emission peak of LD A″ is observed at a current of 255 mA with a peak wavelength of 415 nm and full width at half maximum (FWHM) of 0.5 nm, while two emission peaks appear at the currents 272 mA and 290 mA. The difference in energy between the two peaks is 18.4 meV. The multiple emission peaks may originate from the higher order mode operation together with the fundamental mode at higher injection current.[8]

The emission spectra of LD B″ in Fig.5(b) are different from those of LD A″. At a current of 238 mA, single transverse mode emission is observed with a peak wavelength of 414.5 nm and FWHM of 0.5 nm. Unlike LD A″, a clear blue shift of the peak emission wavelength of LD B″ is observed with increasing injection current. At the currents of 252 mA and 265 mA, the peak emission wavelengths are 413.3 nm and 412.3 nm, respectively. The blue shift is stopped when the injection current is larger than 265 mA. Normally, the blue shift of LDs grown on c-plane substrate with the increase of injection current is assumed to be generated by the energy band filling effect and the screening of the piezoelectric effect.[17] This is just the case for LD B″. However, in the emission spectra of LD A″ such a blue shift was not observed, which may be due to the fact that LD A″ operates at a relatively high active region temperature and it increases with current faster than the LD B″, which can be seen in Fig.4. The thermally induced red shift cancels the blue shift induced by increasing current injection.

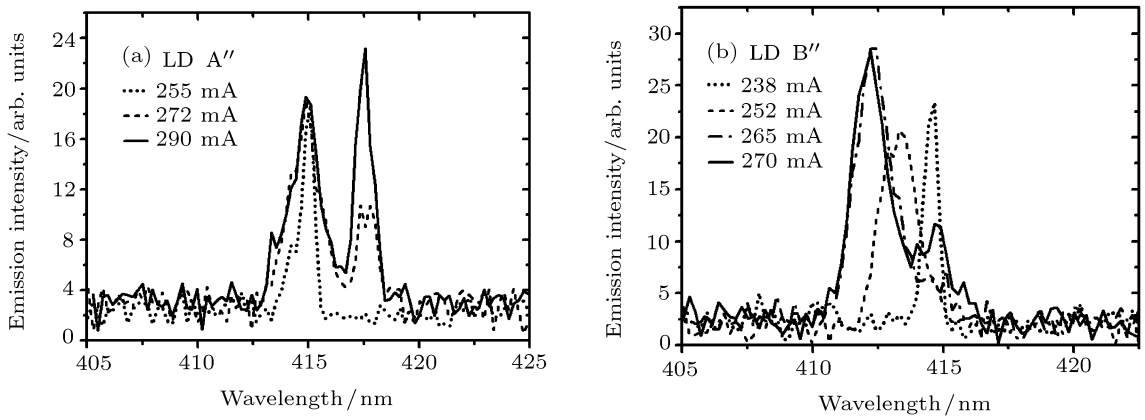


Fig.5. Stimulated emission spectra of LD A″ (a) and LD B″ (b) at different injection current values under pulse mode operation.

4. Conclusion

A violet LD structure is designed and grown on a c-plane FS–GaN substrate. The 4 μm×800 μm ridge waveguide LDs are fabricated with cleaved mirror-like facets. The p-side down mounting makes heat dissipation more efficient, thereby reducing the operation temperature of the active region, the thermal resistance and the threshold current. The blue shift of the emission wavelength with increasing injection current, which is observed only for the p-side down mounted LD, indicates that its active region temperature is lower and its increase with the increasing current is slow compared to that in the p-side up mounted LD.

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