第35卷第6期
2016年12月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 35, No. 6
December, 2016

文章编号: 1001 - 9014(2016)06 - 0672 - 04

DOI: 10.11972/j.issn.1001 - 9014.2016.06.007

High-power, high-efficient GaSb-based quantum well laser diodes emitting at 2 μm

LIAO Yong-Ping[1,2], ZHANG Yu[1,2], YANG Cheng-Ao[1,2], HUANG Shu-Shan[1,2], CHAI Xiao-Li[1,2],
WANG Guo-Wei[1,2], XU Ying-Qiang[1,2], NI Hai-Qiao[1,2], NIU Zhi-Chuan[1,2]*

(1. State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors,
Chinese Academy of Sciences, Beijing 100083, China;
2. Synergetic Innovation Center of Quantum Information and Quantum Physics,
University of Science and Technology of China, Hefei 230026, China)

Abstract: GaSb-based AlGaAsSb/InGaSb type-I quantum-wells (QW) 2 μm laser diodes (LDs) have been grown by MBE system. Stripe-type waveguide LDs with facets uncoated were fabricated and characterized. For single LD device, the maximum output power was 1.058 W under continuous wave (CW) operation at working temperature of 20℃. The maximum wall plug efficiency (WPE) was 20.2% and peak wavelength was 1.977 μm with injection current 0.5 A. The output power under pulse mode of 1000 Hz in 5% duty cycles was 2.278 W.

Key words: high power, laser diodes, infrared, quantum wells
PACS: 42.55.Px, 78.55.Cr, 78.67.De

大功率高效率2μm锑化镓基量子阱激光器

廖永平[1,2], 张 宇[1,2], 杨成奥[1,2], 黄书山[1,2], 柴小力[1,2],
王国伟[1,2], 徐应强[1,2], 倪海桥[1,2], 牛智川[1,2]*
(1. 中国科学院半导体研究所 超晶格与微结构国家重点实验室,北京 100083;
2. 中国科学技术大学 量子信息与量子物理协同创新中心,安徽 合肥 230026)

摘要:通过MBE外延系统生长了2 μm GaSb基AlGaAsSb/InGaSb I型量子阱激光器,并制备了宽面条形波导激光器件,在20℃工作温度下,器件最大连续激射功率达到1.058 W,当注入电流为0.5 A时,峰值波长为1.977μm,最大能量转换效率为20.2%,在脉冲频率为1 000 Hz,占空比为5%的脉冲工作模式下,最大激射功率为2.278 W.

关 键 词:大功率;激光二极管;中红外;量子阱

中图分类号:O43 **文献标识码**:A

Introduction

High power diode lasers emitting between 1900 nm to 4000 nm are important light sources for applications such as tunable diode laser absorption spectroscopy (TDLAS), medical diagnostics, free-space optical communications and missile countermeasures[1-5]. The (AlGaIn)(AsSb) materials system is well suited for the fabrication of quantum well (QW) based semiconductor lasers to cover this specific range[6]. Over the last couple of years, lots of excellent works have been reported either increasing the light power or expanding the wavelength. SUNY at Stony Brook, Fraunhofer institute, and Univer-

---

Received date: 2016-03-25, **revised date**: 2016-09-28 **收稿日期**:2016-03-25, **修回日期**:2016-09-28

Foundation items: Supported by National Basic Research Program of China (2014CB643903, 2013CB932904), National Natural Science Foundation of China (61435012, 61274125, and 61274013), National Special funds for the Development of Major Research Equipment and Instruments, China (2012YQ140005), and Strategic Priority Research Program (B) of Chinese Academy of Sciences (XDB01010200)

Biography: LIAO Yong-Ping (1989-), male, Beijing, China. Ph. D. Research area involves the device epitaxy and fabrication of GaSb-based high power laser diodes operating from 2 to 4 μm. E-mail: liaoyp981@semi.ac.cn

* **Corresponding author**: E-mail: zcniu@semi.ac.cn

sity Montpellier etc. have made a large number of amazing works in this field[7-9]. For example, diode lasers with a type-I QW active region operating at room temperature (RT) has been up to 3.44 μm in CW regime[8] and 3.73 μm in pulsed mode[10]. The maximum output power of a 2 μm diode laser has reached to 1.9 W under CW mode at 18℃[11]. We have also made some progress over the last two years either increasing the 2 μm lasers diodes' light power[12-13] or expanding the lasing spectrum to longer wavelength range[14-15]. Seeking for lower threshold current density, we attempted to decrease directly the number of quantum wells from 2[11] to 1, the detail theoretical analysis can be found in Ref. [16]. And we also increased Al component from 0.3 and 0.5[12] to 0.35 and 0.6 in the waveguide layer and confinement layer, respectively, for higher lasing power and energy efficiency, which would be contributed by a stronger carrier and optical confinement. Consequently, we remarkably decreased the threshold current density, increased the lasing power and energy efficiency of the LD devices compared with Ref. [11] and Ref. [12] which will be introduced in this paper.

1 Device desigh and fabrication

The laser structure, as shown in Fig. 1, was grown on (100)-oriented 2-inch GaSb: GaTe substrates using a solid source Gen-II MBE system. A n-type $Al_{0.60}Ga_{0.40}As_{0.02}Sb_{0.98}$ cladding layer with a thickness of 2 μm was grown after a buffer layer. Then a 10 nm wide InGaSb QW was centrally inserted into a 540 nm non-doped $Al_{0.35}Ga_{0.65}As_{0.02}Sb_{0.98}$ waveguide layer. After that, another p-type $Al_{0.60}Ga_{0.40}As_{0.02}Sb_{0.98}$ cladding layer with a thickness of 2 μm was added symmetrically to form an optical confinement structure. The entire structure ended with a 250 nm thick high p-doped GaSb layer for ohmic contact, as well as for separating Al-rich cladding layer from air[17]. The ternary compound InGaSb in the QWs was about 2% compressive strained with Ga 0.82 and In 0.18 concentrations according to the targeted 2 μm central wavelength[18]. The lattice constants of the quaternary compounds $Al_{0.35}Ga_{0.65}As_{0.02}Sb_{0.98}$ and $Al_{0.60}Ga_{0.40}As_{0.02}Sb_{0.98}$ in the waveguide layer and cladding layer, respectively, were well matched to GaSb substrate.

After the epitaxy, a 2 mm length cavity, 100 μm wide and 2.3 μm deep ridge was fabricated using standard contact optical lithography in combination with inductively coupled plasma (ICP) etching techniques. A 250 nm thick SiO_2 insulation layer was deposited using plasma enhanced chemical vapor deposition (PECVD). After that, a 90 μm wide, 1.9 mm length injection window was opened with dry-etching. We sputtered 500/500/10000 Å Ti/Pt/Au as the contact electrode after that. Backside processing started with substrate mechanical thinning and mechano- chemical polishing followed by the deposition of n-contact metallization and annealing. The wafer was processed into 1-cm-wide bars having a 20% fill-factor. One bar was chipped into single laser emitters. Single devices were mounted junction side down using indium solder on copper heat sinks (C-mount).

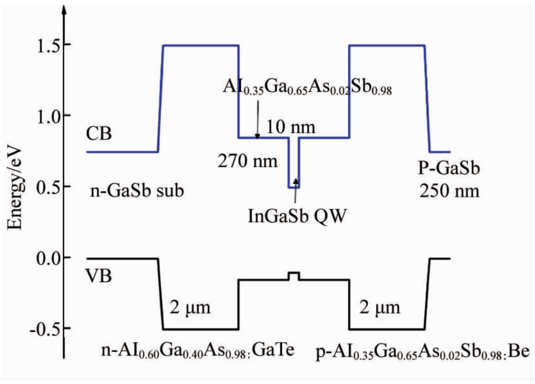

Fig. 1　Epitaxial structure with a single QW, high Al components and non-doped waveguide layer
图 1　单量子阱,高铝组分以及非掺杂波导层的外延结构

2 Laser performances

Figure 2 shows the CW *I-V-P* characteristics of a single laser diode without facets coated. For a single LD (single emitter) device, the maximum output power under CW operation is 1.058 W under working temperature of 20 ℃ with a slope efficiency 311.96 mW/A. The maximum wall plug efficiency (WPE) is 20.9% at 0.7 A injected current. WPE decreases as we increase the injection current, which means the proportion of light power decreases and the thermal increases. The WPE is still more than 7% at the maximum light power. The peak wavelength is 1 977.7 nm when injection current is 0.5 A, as indicated in Fig. 3.

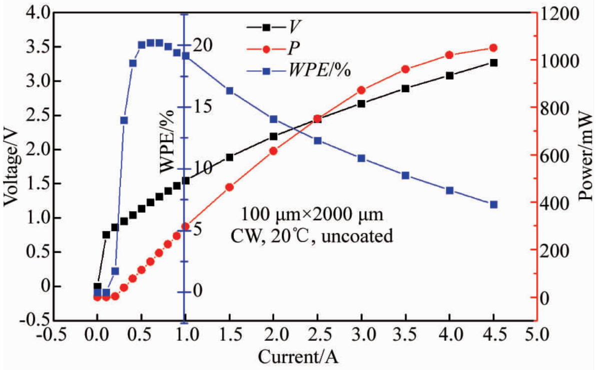

Fig. 2　The CW *I-V-P* and *I-WPE* curve of a single emitter
图 2　单管连续激射时的电流—电压—功率图以及电流—能量效率关系曲线

The threshold current density was decreased remarkably from 150 A/cm² of Ref. [11] and 143 A/cm² of Ref. [12] to 88 A/cm². A large Al component difference between waveguide layer and confinement layer forms a large index difference and bandage offset, which provide a strong optical and carrier confinement, and it is helpful to obtain a low threshold current and large slope efficiency. The quantum well number of one, instead of two, is also contributed to this result. The increasing of Al component from 0.3 to 0.35 in the waveguide layer (or barrier) will not change the lasing wavelength sensitively anyway.

On the other hand, a longer resonant cavity of 2000 μm provided a higher lasing power but would not increase the voltage consuming at all.

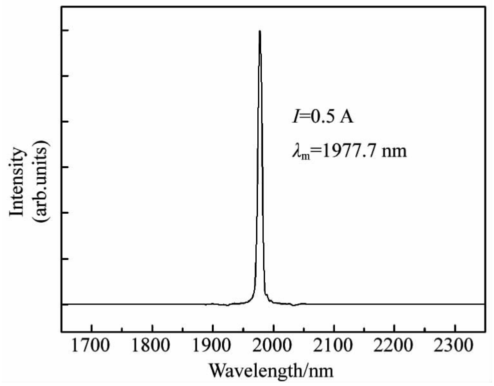

Fig. 3 The laer spectrum at an injection current of 0.5 A
图 3 注入电流为 0.5 A 时器件的激射图谱

The laser peaks at 1 977.7 nm and the full width at half maximum (FWHM) is about 7.9 nm when injected current is 0.5 A, as shown in Fig. 3.

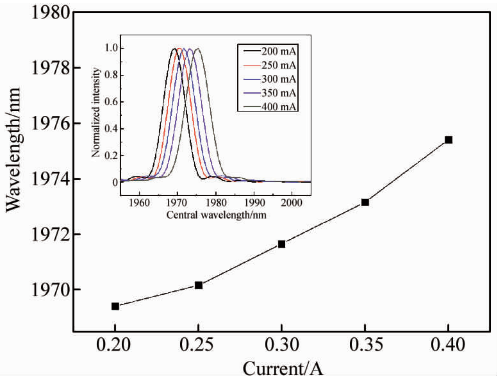

Fig. 4 Red-shifts of the lasing wavelength as injected current varying from 0.2 A to 0.4 A, the inset shows the normalized lasing spectrum with different currents
图 4 当注入电流由 0.2 A 增加到 0.4 A 时器件激射波长出现红移现象,插图表示在不同注入电流时的归一化激射谱

The laser spectrum peaks at 1969.4 nm with 0.2 A and 1975.4 nm with 0.4 A, which is mainly caused by the self-heating effect[19]. In addition, mode hopping induced by increasing the injected current may also contributes to the red-shift of the central wavelength, which is determined by the multi-mode characteristics of the laser diode[20]. The current coefficient of the wavelength, i.e., the dependence of the wavelength on the injection current, as shown in Fig. 4, is about 30 nm/A.

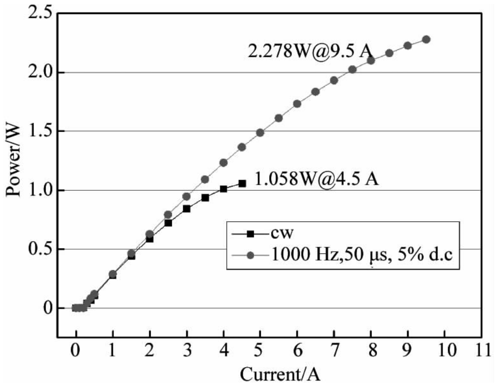

Fig. 5 The *P-I* features in two operating models
图 5 器件在两种工作模式下的电流—功率曲线图

Figure 5 shows that the maximum output power under pulse mode of 1 000 Hz in 5% duty cycles is 2.278 W whit inject current as 9.5 A. The *P-I* curve of the pulsed regime is the same as that in the CW model at low injected current when I <2 A. Then it begins to diverge with the increase of current, which can be explained by the thermal effect of the device.

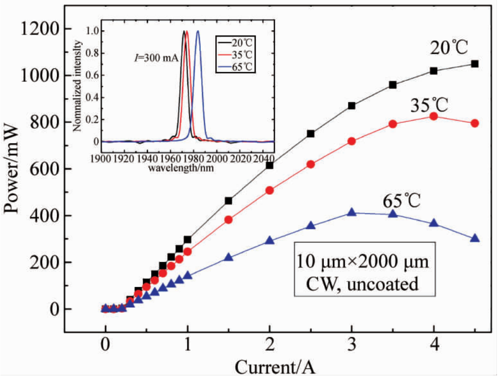

Fig. 6 The variation of light power with the current. The inset show the lasing spectra at different work temperatures
图 6 器件在不同工作温度下的电流-功率特性,插图表示在不同工作温度下器件的激射图谱

We measured the light power under different working temperatures, as shown in Fig. 6. The maximum lasing power descended with the increase of the operating temperature from 20℃ to 35℃, and 65℃ at last. Light power began to decrease around 4 A and 3 A under 35℃ and 65℃, respectively. That was mainly caused by the thermal effect in the active area and lasing facet, which induced the device degradation[21], and finally reduced the lasing power and energy efficiency. On the other hand, the lasing spectrums, as shown in the inset, had an obvious red-shift as temperature changing from 20℃ to 65℃, and the FWHM had also increased, that can be explained by self-heating effect and multi-mode characteristics[19]. We can improve the thermal stability of the diodes by facets coating and improving the bonding condition using a sub-heat sink and so on. These will be our next works.

3 Conclusion

In conclusion, we got 1.058 W CW output power from a single device emitting around 2000 nm under 20℃ operating temperature with facets uncoated and the maximum WPE was 20.2%. The threshold current density was 88.1 A/cm^2 and slope efficiency was 311.96 mW/A. The output power was 2.278 W under pulse mode of 1 000 Hz in 5% duty cycles. At last, we discussed the thermal stability of the devices. Self-heating effect can cause diodes degradation and reduce energy efficiency. We can improve this situation by facets coating and improve the heat dissipation condition and so on.

References

[1] Jean B, Bende T. *Solid-state mid-infrared laser sources* [M]. Germany: Springer, 2003:511 - 546.

[2] Rouillard Y, Genty F, Perona A, *et al.* [J]. *Phil. Trans. R. Soc. Lond.* 2001, A **359**: 581 - 597.

[3] Hodgkinson J, van Well B, Padgett M, *et al.* [J]. *Spectrochimica Acta.* 2006, A **63**: 929 - 939.

[4] Mattiello M, Nikles M, Schilt S, *et al.* [J]. *Spectrochimica Acta.* 2006, A **63**: 952 - 958.

[5] Garbuzov D Z, Martinelli R U, Lee H, Menna R, *et al.* [J]. *IEEE Xplore*, 1997, **70**: 2931 - 2933.

[6] Mermelstein C, Rattunde M, Schmitz J, *et al.* [J]. *Proc SPIE*, 2002, 4651.

[7] Belenky G, Shterengas L, Donetsky D, *et al.* [J]. *Jpn. J. Appl. Phys.* 2008, **47**:8236 - 8238.

[8] Kelemen M T, Gilly J, Rattunde M, *et al.* 2008 [J]. *Proc. of SPIE.* **7583**:75830.

[9] Rouillard Y, Angellier J, Salhi A, *et al.* [J]. *Proc. of SPIE.* 2005, **5738**:120 - 129.

[10] Liang R, Kipshidze G, Hosoda T, *et al.* [J]. *IEEE Photonics Technology Letters.* 2014, **26**:664 - 666.

[11] Donetsky D, Kipshidze G, Shterengas L, *et al.* [J]. Electronic Letters, 2007, **43**:15.

[12] Liao Y P, Zhang Y, Xing J L, *et al.* [J]. *Journal of Semiconductors.* 2015, **36**: 054007.

[13] Liao Y P, Zhang Y, Xing J L, *et al.* [J]. *Chinese Journal of Lasers*, **42**: s102006.

[14] Xing J L, Zhang Y, Liao Y P, *et al.* [J]. *Journal of Applied Physics*, 2014, **116**:123107.

[15] Xing J L, Zhang Y, Liao Y P, *et al.* [J]. *Chin. Phys. Lett.*, **31**: 054204.

[16] Du B X. [J] *Chinese Journal of Luminescence*, 2000, **21**:279.

[17] Xing J L, Zhang Y, Xu Y Q, *et al.* [J] *Chin. Phys.*, 2014, B **23**: 017805.

[18] Eichhorn M, Rattunde M, Schmitz J, *et al.* [J] *Journal of Applied Physics.* 2006, **99**:053105.

[19] Aleahmad P, Bakhshi S, Christodoulides D, *et al.* [J] *Mater. Res. Express.* 2015, **2**:086302.

[20] Yilmazlar I, Sabuncu M. [J] *Optics & Laser Technology*, 2015, **73**: 19 - 22.

[21] Hu J Z, Yang L Q, Shin M W. [J] *Journal of Physics D: Applied Physics*, 2008, **41**:035107.