A low-threshold and high-power oxide-confined 850-nm AlInGaAs strained quantum-well vertical-cavity surface-emitting laser*

Guan Bao-Lu(关宝璐), Ren Xiu-Juan(任秀娟), Li Chuan(李 川), Li Shuo(李 硕), Shi Guo-Zhu(史国柱), and Guo Xia(郭 霞)†

Opto-electronic Devices Research Laboratory, Beijing University of Technology, Beijing 100124, *China*

(Received 14 February 2011; revised manuscript received 22 April 2011)

A low-threshold and high-power oxide-confined 850-nm AlInGaAs strained quantum-well (QW) vertical-cavity surface-emitting laser (VCSEL) based on an intra-cavity contacted structure is fabricated. A threshold current of 1.5 mA for a 22 μm oxide aperture device is achieved, which corresponds to a threshold current density of 0.395 kA/cm^2. The peak output optical power reaches 17.5 mW at an injection current of 30 mA at room temperature under pulsed operation. While under continuous-wave (CW) operation, the maximum power attains 10.5 mW. Such a device demonstrates a high characteristic temperature of 327 K within a temperature range from −12 °C to 96 °C and good reliability under a lifetime test. There is almost no decrease of the optical power when the device operates at a current of 5 mA at room temperature under the CW injection current.

Keywords: vertical-cavity surface-emitting laser, strained quantum-well, oxide confinement

PACS: 42.55.Px, 42.60.By, 42.72.Ai **DOI:** 10.1088/1674-1056/20/9/094206

1. Introduction

High-power, high-efficiency and low-threshold vertical-cavity surface-emitting lasers (VCSELs) are becoming desirable candidates for optoelectronic applications in high-speed optical communication and interconnects. VCSELs with an emitting wavelength at 850 nm are widely used in short-distance data links.[1−3] Commercial competition has promoted extensive studies of the basic theory and technology for these devices in order to improve the quantum efficiency and to reduce the threshold current ($I_{\rm th}$) for high-speed modulation.[4,5]

However, there are difficulties with the physical aspects of the device, such as the alignment of the gain peak, the cavity resonant peak and the distributed Bragg reflector (DBR) reflective centre, which are governed by the material growth and the improvement of the single round-trip optical gain, thereby making the VCSEL device difficult to fabricate. In addition, in the case of large active regions, hardly any current can reach the broad central active region and the injection is mostly restricted to a narrow ring area close to the active-region perimeter.[6] It has become more and more difficult to improve device performance, lower the threshold current density ($J_{\rm th}$) and enhance the output power. The reported lowest $I_{\rm th}$ of such a device was about 1.3 mA with a 14 μm oxide aperture under continuous-wave (CW) operation.[7−9] An $I_{\rm th}$ value of 290 μA for a 5 μm-diameter aperture at 840 nm was regarded as the lowest threshold ever obtained for any VCSEL before 1997.[10] The highest slope efficiency was about 0.9 W/A with an $I_{\rm th}$ value of 5 mA for a 25 μm-diameter aperture 850 nm VCSEL.[11]

In the present paper, we utilize the strained AlInGaAs/AlGaAs quantum well (QW) as the active region material instead of the traditionally unstrained InGaAs/GaAs QW, which is the most commonly used active region material in commercially available 850 nm VCSELs. We obtain a VCSEL with a $J_{\rm th}$ value of 0.395 KA/cm^2, which is lower than the previously reported value. Such a VCSEL also shows a high slope efficiency (0.88 W/A) with an output power of 17.5 mW at 30 mA injection current under pulsed operation. While under CW operation, the output power of the VCSEL can reach 10.5 mW at a 20 mA injec-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60908012 and 61076148) and the Foundation of Beijing Municipal Education Commission, China (Grant No. KM201010005030).

†Corresponding author. E-mail: guo@bjut.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

tion current. The characteristic temperature T_0 of the VCSEL is determined to be about 327 K by using the temperature-dependent $J_{\rm th}$ experiment. The output power is almost not reduced after nearly 1000 h lifetime testing, which is performed at room temperature with a 5 mA injection current under CW operation.

2. Design and fabrication of the device

The epitaxial layers were grown on a (100) misoriented n-type GaAs substrate by metal-organic chemical vapor deposition (MOCVD). The fabrication started with a 30-pair quarter-wavelength Si-doped $Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As$ layer distributed Bragg reflector at the bottom. Then, the three-quantum-well active region of the three strained AlInGaAs/AlGaAs QWs separated by $Al_{0.5}Ga_{0.5}As$ barriers was grown, which was symmetrically embedded in a 1.5 wavelength optical cavity. The current confinement was achieved by a 60 nm $Al_{0.98}Ga_{0.02}As$ layer to determine the current aperture. Then a C-doped $Al_{0.1}Ga_{0.9}As$ layer was grown as the ohmic contact layer. Finally, 20 pairs of undoped top $Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As$ DBR were grown, which were used to reduce the free carrier absorption during the light emission out of the top DBR. The resonance wavelength was pinned at 852 nm obtained by the reflection spectrum measurement, while the calculated value for the designed structure was about 853 nm through the matrix transition method.[12]

Conventional photolithography and the wet etching technology were used to fabricate the VCSEL. In the fabrication of the VCSEL device, there were three axes that needed to be aligned exactly. Figure 1 shows the schematic diagram of the co-axis intracavity-contacted VCSEL structure. After the $Al_{0.98}Ga_{0.02}As$ layer was exposed by the wet etching, the current confinement was achieved by laterally oxidizing the 60-nm-thick $Al_{0.98}Ga_{0.02}As$ layer at 430 °C under N_2 gas bubbling through deionized water at 80 °C for approximately 30 min. An $Al_{0.98}Ga_{0.02}As$ layer was used instead of an AlAs layer, because $Al_{0.98}Ga_{0.02}As$ has a better mechanical stability during the thermal process.[13–16] The oxide-aperture size of the VCSELs was 22 μm. The Ti-Au and AuGeNi-Au were deposited as p-type and n-type ohmic contacts, respectively. After annealing, the single chip was cleaved and packaged without a heat sink for measurements at room temperature.

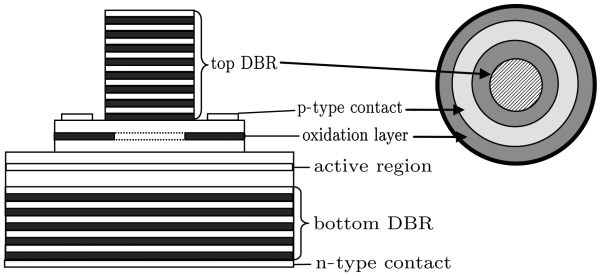


Fig. 1. Schematic of the cross section of the oxide-confined intra-cavity VCSEL structure used in this work.

3. Experiment and performance

The typical light–current–voltage (L–I–V) characteristics of the VCSEL investigated in this paper with a circular oxide aperture of 22 μm and under the pulsed and the CW operation are shown in Fig. 2. The pulse width and the repeat rate are 30 μs and 100 Hz, respectively. The peak output optical power is 17.5 mW at 30 mA injection current and the differential resistance at 50% of the maximum output optical power is about 150 Ω. The threshold voltage $V_{\rm th}$ is about 1.7 V with an about 0.3 V increase over the voltage dropping on the emission laser due to the large series resistance that mostly originates from the thin and long $Al_{0.1}Ga_{0.9}As$ layer. The $I_{\rm th}$ is 1.5 mA, confirmed by the differential method, and the corresponding $J_{\rm th}$ is 0.395 KA/cm^2. The peak slope efficiency is about 0.88 W/A at 6.5 mA, which corresponds to an external differential quantum efficiency of about 61%. When the operation is in CW mode, the optical power and the voltage drop

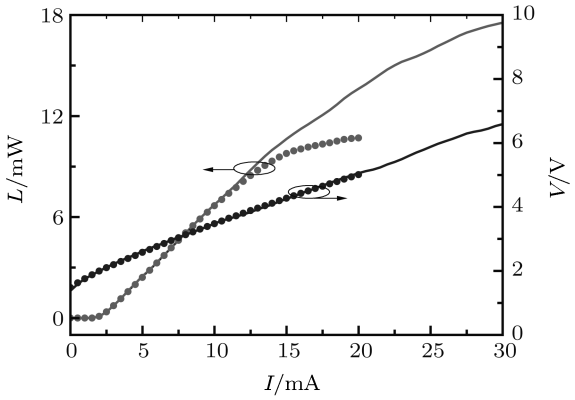


Fig. 2. Typical light–current–voltage (L–I–V) characteristics of the VCSEL under pulsed and CW operation with a circular oxide aperture of 22 μm in diameter. The lines and the dots denote results under the pulsed and the CW operations, respectively. The $I_{\rm th}$ values are equal to 1.5 mA. The peak output powers reach 17.5 mW and 10.5 mW under the pulsed and the CW operations, respectively. The threshold voltage is about 1.7 V.

on the device can follow the corresponding curves measured in the pulsed mode until about 12 mA. Above that, the optical power is a little lower than the pulsed one due to the thermal effect.[17,18] A peak output optical power of 10.5 mW at 20 mA is obtained. The $I_{\rm th}$ is still 1.5 mA with a peak slope efficiency of about 0.90 W/A at 6.5 mA. Due to the large thermal effect on the relatively small active region, the slope efficiency of the VCSEL decreases quickly when the device reaches the peak value.

Figure 3 shows the dependence of $I_{\rm th}$ on the injection current of the VCSEL measured from 261 K to 369 K. The pulse mode is used to reduce the thermal effect on $I_{\rm th}$. The $I_{\rm th}$ decreases as the temperature increases from 261 K to 333 K, which is because the offset between the gain peak and the resonance wavelength dominated by the material dispersion relationship of the VCSEL structure becomes smaller, although the gain spectrum becomes wider with the increasing temperature.[19,20] When the gain peak catches the resonance wavelength, $I_{\rm th}$ drops down to a minimum value of 1.3 mA at 321 K and 333 K. The average temperature is 327 K, which is regarded as the characteristic temperature T_0 in this paper. As the resonance wavelength cannot follow the gain peak and the gain spectrum turns wider and lower as the temperature increases, the $I_{\rm th}$ must increase to overcome the loss for lasing. The T_0 above room temperature is conducive to obtaining a stable threshold current and output power. The emission spectrum at an injection current of $I = 13I_{\rm th}$ is shown in the inset of Fig. 3. The emission wavelength is about 855.4 nm, which can match the resonance wavelength. The full wave at half maximum (FWHM)is about 1 nm. For all applied currents, the emission wavelengths are in a range between 850 nm and 860 nm.

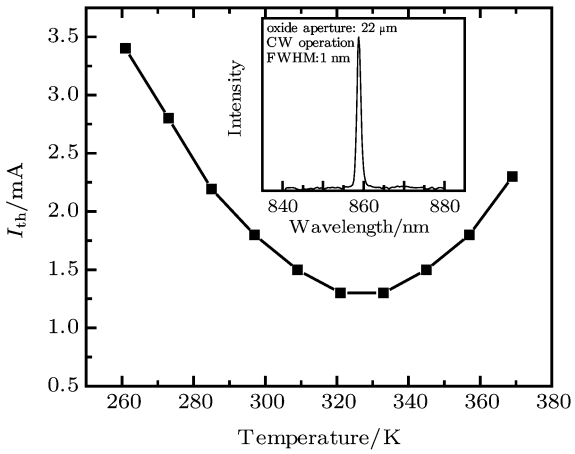


Fig. 3. Dependence of threshold current on temperature. The characteristic temperature T_0 is about 327 K with a minimum $I_{\rm th}$ value of 1.3 mA. The insert shows the emission spectrum at an injection current of $I = 13I_{\rm th}$.

Figure 4 shows the room temperature lifetime test of the two VCSEL devices each with the strained AlInGaAs/AlGaAs QW serving as the active region. The testing current is 5 mA in the CW mode, which trebles the $I_{\rm th}$ value. At the beginning, the optical power data are measured every 23 h till 460 h. After that, the data are measured and recorded every 46 h. After the 935 h total lifetime testing, the optical powers decrease down to 97% and 86% for the two samples, respectively. The data in Fig. 4 are not stable, perhaps due to inconsistency in the manual measurement during the whole testing. However, this result confirms that the strained AlGaInAs/AlGaAs QWs still have a long lifetime.

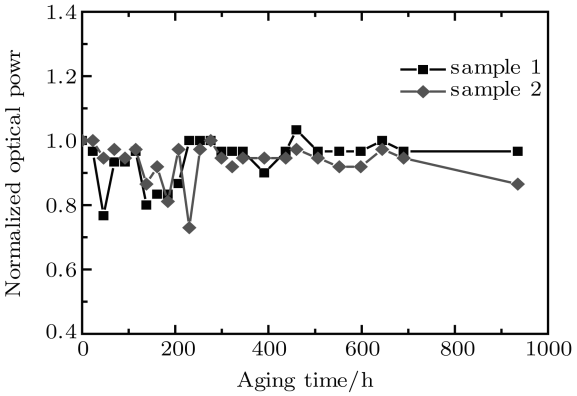


Fig. 4. Lifetime test result of the VCSEL under 5 mA CW operation at room temperature. After 935 h, there is almost no change in the optical power.

4. Conclusion

A high-performance 850 nm AlInGaAs-AlGaAs strained QW VCSEL with an intra-cavity contact and a lateral oxide-confined structure is successfully fabricated, which shows a low threshold current, a high output optical power and a high slope efficiency. We also investigate the dependence of the threshold current on the temperature to obtain a T_0 value of 327 K. The lifetime testing result indicates almost no change in the optical power after the 935 h testing. We believe that the improvement in processing and material growth will further enhance the performance of the VCSEL devices.

References

[1] Westbergh P, Gustavsson S J, Haglund A, Mats S, Andrew J and Larsson A 2009 *IEEE J. Sel. Top. Quantum Electron* **15** 694

[2] Shi J W, Weng W C, Kuo F M, Yang Y J, Pinches S, Geen M and Joel A 2010 *IEEE Photon. J.* **2** 960

[3] Ding Y, Fan W J, Xu D W, Tong C Z, Liu Y and Zhao L J 2010 *Appl. Phys.* B **98** 773

[4] Yang H, Guo X, Guan B L, Wang T X and Shen G D 2008 *Acta Phys. Sin.* **57** 2959 (in Chinese)

[5] Chen M, Guo X, Guan B L, Deng J, Dong L M and Shen G D 2006 *Acta Phys. Sin.* **55** 5842 (in Chinese)

[6] Sarzala R P 2007 *Semicond. Sci. Tech.* **22** 113

[7] Lin C K and MacDoiuga M H 1997 *IEEE Digest of the IEEE/LEOS Summer Topical Meetings* August 11–15, 1997, Montreal, Canada, pp. 11–15

[8] Vez D, Hunziker S G, Kohler R, Royo P and Moser M 2004 *Electro. Lett.* **40** 1210

[9] Dang G T, Mehandru R, Luo B, Ren F, Hobson W S, Lopata J, Tayahi M, Chu S N G, Pearton S J, Chang W and Shen H 2003 *J. Lightw. Technol.* **21** 1020

[10] Coldren L A, Hegblom E, Strzelecka E, Ko J, Akulova Y and Thibeault B 1997 *Proc. SPIE* **3003** 2

[11] Grabherr M, Miller M, Jager R, Wiedenmann D and King R 2004 *Proc. SPIE* **5364** 174

[12] Su S T, Tang S F, Chen T C, Chiang C D, Yang S T and Su W K 2006 *Proc. SPIE* **6132** 61320L-1

[13] Huffaker D L, Graham L A, Deng H and Deppe D G 1996 *IEEE Photon. Technol. Lett.* **8** 974

[14] Osin'ski M, Svimonishvili T, Smolyakov G A, Smagley V A, Mac'kowiak P and Nakwaski W 2001 *IEEE Photon. Technol. Lett.* **13** 687

[15] Hvisc S, Harris Jr J and Solomon G 1998 *National Nanofabrication Users Network* pp. 60–61

[16] Ochiai M, Giudice G E, Temkin H, Scott J W and Cockerill T M 1996 *Appl. Phys. Lett.* **68** 1898

[17] Lai F I, Hsueh T H, Chang Ya-hsien, Shu W C, Lai L H, Kuo H C and Wang S C 2003 *Solid-State Electron.* **47** 1805

[18] Mutig A, Lott J A, Blokhin S A, Wolf P, Moser P, Hofmann W, Nadtochiy A W, Payusov A and Bimberg D 2010 *Appl. Phys. Lett.* **97** 151101

[19] Sadofev C J, Blumstengel S, Puls S and Henneberger J F 2006 *Appl. Phys. Lett.* **89** 051108

[20] Soibel, Mansour A, Qiu K, Hill Y, Yang C J and Rui Q 2009 *J. Appl. Phys.* **101** 093104