第 29 卷　第 12 期
2008 年 12 月

半　导　体　学　报
JOURNAL OF SEMICONDUCTORS

Vol.29　No.12
Dec.,2008

259W QCW Al-Free 808nm Linear Laser Diode Arrays

Liu Suping, Zhong Li[†], Zhang Haiyan, Wang Cuiluan, Feng Xiaoming, and Ma Xiaoyu

(*National Engineering Research Center for Optoelectronic Devices, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*)

Abstract: Through optimizing the tensile-strained single quantum well (SQW) epitaxial structure and introducing double-channel deep isolation groove etching technologies of linear laser diode arrays, GaAsP/GaInP/AlGaInP SQW separate confinement laser emitting structures are grown by low-pressure metal organic chemical vapor deposition and 1cm-wide laser bars with 50% fill factor are fabricated. The cross sections of the channels are analyzed using scanning electron microscope. Mounted on passively cooled copper heat sinks, the laser bars achieve an output power of 259W in quasi-continuous-wave (200μs pulse width and 2% duty cycles) operation at a driving current of 300A, which is the upper limit of power supply in our measurement setup, and no catastrophically optical mirror damage is observed. A peak power conversion efficiency of 52% is obtained at 104A with 100W output power. At a high-power operation of 100W, the spectrum of the bar has a centric wavelength of 807.8nm and full width at half maximum of 2.4nm. The full angles at half maximum power for fast axis and slow axis are 29.3° and 7.5°, respectively.

Key words: laser diode; array; quasi-QW; Al-free
PACC: 4255P; 4260　　**EEACC**: 4320J
CLC number: TN248.4　　**Document code**: A　　**Article ID**: 0253-4177(2008)12-2335-05

1　Introduction

High power diode laser bars are widely used as the pumping sources for solid-state lasers, which can operate in continuous-wave (CW) mode or quasi-continuous wave (QCW) mode. QCW diode laser pumping solid-state lasers are the key assembly parts for laser weapons and optoelectronic countermeasures systems, such as laser distance ranging, laser guidance, laser radar, laser communication, laser weapon simulator, and laser target recognition. Compared with CW mode operation, QCW mode operation can obtain higher optical output power because there is no serious thermal effect[1]. Especially, 808nm laser diode arrays operating at QCW peak powers of at least 100W per bar are required for 1064nm Nd:YAG lasers[2]. There is still a continual drive to increase the output powers of these laser diode bars. The Occident and Japan keep ahead in this field with several large corporations actively engaged in the market. The available 808nm QCW output power of the current commercial products is in the level of 100～200W per bar. Recently, Jenotpik laser diode Gmbh has demonstrated that their 808nm AlGaAs/GaAs laser bars, which were mounted on standard heat sinks, exhibited more than 300W QCW (200μs pulses width, 2% duty cycles (d.c.)) output power with 50%- filling factor (FF, ratio of the active to the whole area of the laser diode bar) and more than 400W QCW (200μs pulses width, 1% d.c.) output power with 75%-FF[3]. The overall-efficiency was in a wide range more than 50% with a maximum of 57%. Output powers of 2.5kW (>300W per bar) were demonstrated from a stack with 8bars. Furthermore, these laser bars sandwiched between microchannel coolers were measured up to 705W QCW (100μs pulses width, 0.1% d.c.) output power with 40%-FF. In the domestic region, however, there are few reports of QCW laser bars on this wavelength range in recent years, and to the best of our knowledge, the reported highest output power of 808nm laser bar was 157W (200μs pulses width, 1% d.c.).[4]

However, these results are all based on compress-strained AlGaAs/GaAs material system, from which the oxidation of aluminum and the spreading of defects during device operation are thought to limit the peak output power, as well as the lifetime of the laser bars. In these aspects, the Al-free active region is believed to be superior concerning the absence of uncoated mirror facet oxidation, the higher catastrophically optical mirror damage (COMD) without special facet preparation, and long-term reliability[5]. But until now, owing to the difficulties in epitaxial layer design and growth, and high FF laser array fabrication etc., the reported peak output power of Al-free laser bars is inferior to that of Al-containing devices[6,7].

In this paper, we demonstrate the Al-free 808 nm linear laser diode arrays that operate in QCW mode.

---

† Corresponding author. Email: zhongli@semi.ac.cn

Received 25 March 2008, revised manuscript received 2 August 2008

The linear bar arrays under investigation are 50%-FF arrays with GaAsP/GaInP tensile-strained SQW separate confinement structure. The optimum thickness and composition of the SQW are discussed for a minimum threshold current. Double channels deep isolation grooves etching technologies are designed to optically-electrically isolate the emitters from each other effectively.

2 Design and fabrication

2.1 QW structure design and growth

The superiorities of tensile-strained quantum well (QW) lasers are in large part due to modification of 2-dimensional (2D) energy dispersion of the QW band-structure. Since tensile strain and quantum size effect have the opposite effect on hole energy at $k = 0$, the splitting of the valence subbands and the ratio of light-hole/heavy-hole effective mass affect the resulting optical gain spectrum and threshold current density of the quantum-well laser quite significantly[6]. To address this issue, our QW structure design is focused on minimizing threshold current to achieve high efficiency and high output power.

In general, small splitting between the first and higher subbands causes an increased population of the higher subbands and hence arouses the competition between them, which leads to enhanced threshold currents and polarization switching[8]. Therefore, for the purpose of reducing threshold current and increasing output power, the inter-subband splitting, mainly referring to the first light-hole (lh1) band and the first heavy-hole (hh1) band, should be as large as possible. Aiming to the wavelength 808nm, the absolute strain value in the GaAsP QW is typically around 0.5%. The splitting between the light and heavy hole bulk band edges induced by such small strain is possibly not sufficient to overcome the subbands splitting induced by the quantum confinement. The increase of both phosphorus composition (i.e., the increase of the absolute strain value) and QW thickness (i.e., the decrease of the quantum confinement) lead to larger lh1-hh1 energy splitting value $\Delta E_{\mathrm{hh1-lh1}}$[8]. However, higher electron and hole subbands appear for thicker QWs, which cause the additional population of those subbands, such as the second light-hole (lh2) subband in this case. In order to compromise the population of higher subbands of both hh1 and lh2, the GaAsP QW layer in our laser structures are designed by determining the energy splitting between the first and second light hole subbands $\Delta E_{\mathrm{lh2-lh1}}$ to equal with the value of $\Delta E_{\mathrm{hh1-lh1}}$. As shown in Fig. 1, optimized QW structures (composition and thickness) for modifying the desired lasing wavelength of GaAsP/GaInP active layer are theoretically calculated based on square quantum well model and solid model theory, taking into account the spin-orbit splitting energy. The room temperature spontaneous transition wavelengths of electron to light-hole (e-lh) and electron to heavy-hole (e-hh) are shown simultaneously. For each desired wavelength, a unique pair of composition and thickness is optimized correspondingly. Since there is a red shift of lasing emission wavelength for high power operation because of the band shrinkage, the experiential room temperature spontaneous emission wavelength designed for 808nm lasing emission is about 797nm. The optimized composition (from the left axis in Fig. 1) and the QW thickness (from the right axis) can be obtained from the crossing points with each desired wavelength. In Fig. 1, the solid circles (i.e. the crossing points) corresponding to the e-lh transition for 808nm lasing emission wavelength indicates that the threshold current density of the laser is expected to be minimized with the QW thickness of about 14nm and phosphorus composition of about 0.16.

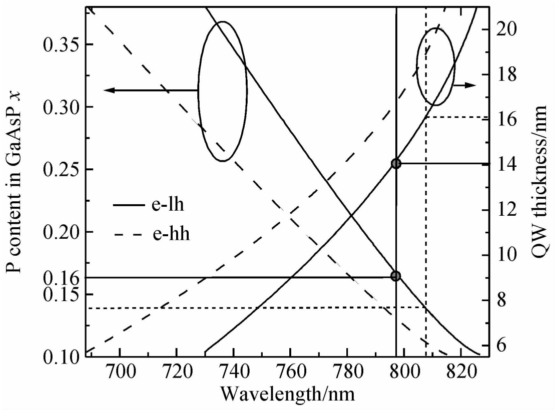


Fig.1 Optimized GaAsP SQW thickness and composition for modifying the lasing wavelength of GaAsP/GaInP active layer

Figure 2 shows the schematic diagram of the laser-emitting unit structure of the Al-free linear laser

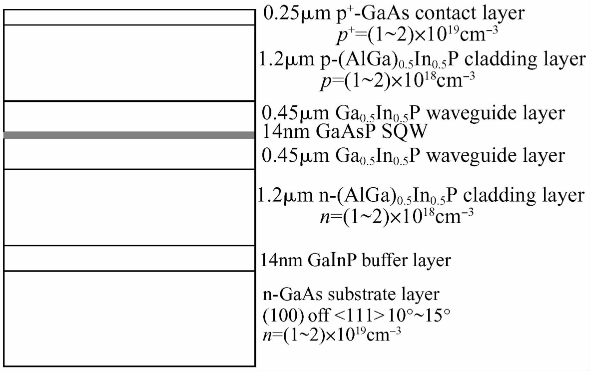
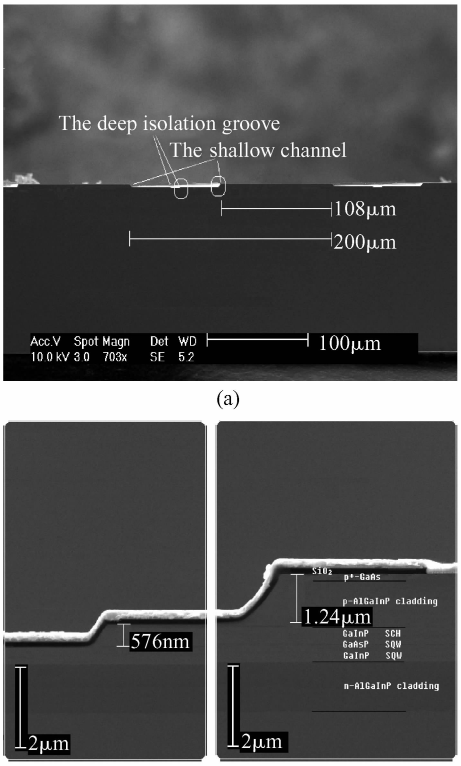


Fig.2 Schematic diagram of the epitaxial structure of the Al-free linear bar arrays with SQW separate confinement heterostructure

diode arrays. Such structure is grown on n-GaAs substrate (100) oriented 10°～15° off towards 〈111〉 A by LP-MOCVD system. On the n-GaAs substrates, a 0.4μm-thick n-GaInP buffer layer, a 1.2μm-thick n-AlGaInP lower cladding layer (Si doped, ～(1～2)$\times 10^{18}$ cm^{-3}), a 0.45μm-thick undoped GaInP lower optical waveguide layer, a 14nm-thick undoped $GaAs_{0.84}P_{0.16}$ SQW, a 0.45μm-thick undoped GaInP upper optical waveguide layer, a 1.2μm-thick p-AlGaInP upper cladding layer (Zn doped, ～(1～2)$\times 10^{18}$ cm^{-3}), and a 0.25μm-thick p^+-GaAs contact layer (Zn doped, ～10^{19} cm^{-3}) are grown consequently. The precursors for Ga, In, Al, As, and P are trimethylgallium (TMGa; held at 0℃), trimethylindium (TMIn; held at 17℃), trimethylaluminum (TMAl; held at 17℃), 100% arsine (AsH_3), and 100% phosphine (PH_3), respectively. The p- and n- type dopants used are DMZn and SiH_4, respectively. Growth is performed at a total pressure of 6～10kPa and substrate temperatures of 700～760℃, except for the p^+-GaAs contact layer. The total gas flow rate is 50L/min. The growth conditions of GaInP, such as growth temperature and V/III ratio, are controlled elaborately for disordered alloys[9]. Photoluminescence measurements provide information of the wavelength, together with the QW width and lh1-hh1 splitting.

2.2　Deep isolation grooves etching technology

After the material growth and quality test, the appropriate stripe geometry designs, such as FF and cavity length are needed to be defined before the next 1cm-bars laser array fabrication. The increase of FF of the laser bar is an efficient means to generate more output power from one diode-laser bar, however, the appearance of so-called spurious modes is a problem for a bar integrated with so many broad-area emitters having the same waveguide layers[10]. These modes have a propagation direction perpendicular to the normal resonator modes, which decrease the overall efficiency and output power of the bar. The mesa structure has been used to suppress the spurious modes[8]. In general, from the point of drastically increasing the losses for such modes, the channels on both sides of the mesa are required to be etched as deep as possible, but it is a challenge for a bar with high FF. Taking the 50%-FF bars in QCW operation for an example, the channel depth should be at least up to the active layer so as to sufficiently suppress of the spurious mode, but it most likely encounters the damage of the crystal quality of the active layer.



(a)

(b)

Fig.3　SEM crossing images of a 50%-FF laser bar with the double channels mesa structures　(a) Partial cross session of a laser bar consisting of two entire mesa structures; (b) Enlargement of a shallow channel and a deep isolation groove

In our experiments, different from the conventional mesa structure with a single channel between the emitters, the deep isolation grooves are secondly etched down to the active layer in the middle of the first shallow channels to optically-electrically isolate the emitters from each other. The shallow channels and deep isolation grooves are accomplished by two processing steps involving lift-off photolithographic technology and certain wet chemical etching treatments with the etchant of the Br/HBr/H_2O mixture after the growth of wafers. The depth of the first channels flanked to the mesa is herein as shallow as only up to the p-cladding layer to protect the active layer of laser emitting units. Figure 3 shows the cross section of such mesa structure by scanning electron microscope (SEM). It can be seen that the depths of the double channels are controlled very strictly. Each laser-emitting unit has an aperture width of about 100μm and a first separation channel distance of about 92μm with a second 10μm-wide deep isolation groove in its middle. Then, the SiO_2 dielectric layer is evaporated and etched to insulate the channels/grooves and protect the laser-emitting units. Ti (15nm)/Pt (35nm)/Au (220nm) metal layers are sputtered on the p^+-doped GaAs layer for metallization of ohmic contact stripes.

After thinning the wafers to about 100μm, ohmic contacts are formed on the n-GaAs substrate by depositing AuGe (70nm)/Ni (35nm)/Au (200nm). In

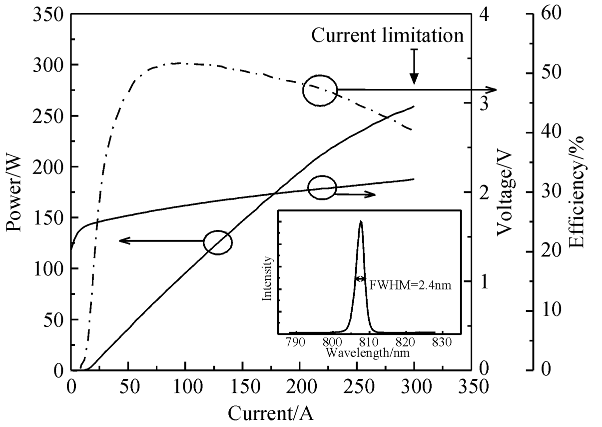


Fig. 4 Typical *L-I-V* characteristics of 1cm diode laser bar with 50% fill factor, 1.2mm cavity operated at 25℃ and 808 nm in QCW mode Peak output power of 259W has been achieved and the characteristics can be rolled over repeatedly.

order to form a current-blocking Schottky barrier outside the 100μm stripes, an Au contact layer (100nm) is deposited onto the p^+-contact overall surface. The additional Schottky barrier permits the laser diodes to be bonded p-side down on indium-coated copper heatsinks to sustain high current measurements. The wafer is cleaved to obtain standard 1cm bar with cavity length of 1.2mm consisted of 50 emitters. Low reflection ($R<5\%$) and high reflection ($R>95\%$) coating are formed on the front and rear facets, respectively. After processing, the bars are bonded p-side down on passively-cooled heat sinks using indium solder. Then the laser diode 1cm-bars undergo a preliminary test of the optical power and voltage as a function of drive current (*L-I-V*) using an integrating sphere and power meter. The lasing spectrum and the far-field divergence angles are tested as well.

3 Results

Figure 4 shows a typical *L-I-V* characteristic of such a 50%-FF 1.2mm cavity length laser bar at an ambient temperature of 25℃ in QCW (200μs pulses, 2% d.c.) operation, which is typical for Nd:YAG laser pumping application. A maximum output power of 259W is achieved without occurrence of COMD at 300A, limited by the maximum driving current of power supply in our measurement setup. To the best of our knowledge, this power is higher than any previously reported 808nm individual laser diode bar in Al-free material[7]. Even higher power values can be expected by improving the thermal management, such as using water-cooled production-type copper microchannel coolers instead of passive cooled heat sinks. The *L-I* curve keeps in good linear dependence with the driving current up to 200A. However, because of the heat intensities generated at the laser diode array with a large temperature rise at the device, which cannot be dissipate by the passively cooled heat sinks, thermal rollover is observed. The lasing wavelengths at driving current of 25 and 300A are 799.6 and 812.5nm, respectively. According to the experiential temperature dependent wavelength shift of 0.3nm/℃, the temperature rise is about 43℃ at 259W output power. Therefore, it indicates that the limiting factor under QCW operating conditions is a rollover of the power current characteristic, but not the COMD. It indicates that Al-free active regions without passivation of the cleaved surfaces inherently results in a reduced surface-recombination velocity [11] and high COMD threshold.

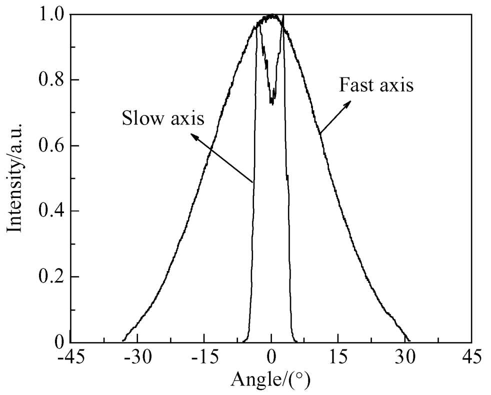


Fig. 5 Far field characteristics of a passively cooled laser bar at 104A (100 W) QCW operation

The bar has a typical threshold current of 15.7A (262A/cm^2) and the maximum slope efficiency of 1.15W/A. The peak power conversion efficiency (PCE) of 52% is obtained at driving current of 104A with 100 W output power. The measured turn-on voltage V_0 and series resistance R_s are as low as 1.59 V and 3.3mΩ, respectively. At high-power operation of 100W, the lasing spectrum of the bar had a centric wavelength of 807.8nm and FWHM of 2.4nm, as shown in the inset of Fig. 4. In Fig. 5, the measured FWHM far-field divergence angles for fast axis and slow axis are 29.3° and 7.5°, respectively.

4 Conclusion

In summary, 50%-FF Al-free 808nm linear laser diode arrays mounted on passive heat sinks with maximal output power of 259W are presented at power-supply limited drive current of 300A in this paper. COMD is not observed in these experiments. The peak PCE of 52% is obtained at driving current of 104A and output power of 100W. At the operation of 100W output power, the spectrum of the bar has a centric wavelength of 807.8nm and FWHM of 2.4nm. These data are evidence of the capability of the optimized QW structure at 808 nm wavelength and two step isolation etching technology for high FF laser bar, as well as the high quality of the epitaxial growth, processing and assembly.

References

[1] Schröder D, Meusel J, Hennig P, et al. Increased power of broad area lasers (808nm / 980nm) and applicability to 10mm-bars with up to 1000Watt QCW. Proc SPIE, 2007, 6456: 64560N

[2] Stephen M, Vasilyev A. Characterization of 808nm quasi-continuous wave laser diode arrays. Earth Science Technology Conference, 2003: 1

[3] Deichsel E, Schrödera D, Meusela J, et al. High reliable QCW laser bars and stacks. Proc SPIE, 2008, 6876: 68760K-1

[4] Fang Gaozhan, Xiao Jianwei, Ma Xiaoyu, et al. 157W Q-CW AlGaAs/GaAs linear laser diode arrays. Chinese Journal of Semiconductors, 2000, 21(1): 102(inChinese)[方高瞻，肖建伟，马骁宇，等. 157 W 准连续 AlGaAs/GaAs 激光二极管线列阵. 半导体学报，2000, 21(1): 102]

[5] Razeghi M. High-power laser diodes based on InGaAsP alloys. Nature, 1994, 369(6482): 631

[6] Eliashevich I, Diaz J, Yi H, et al. Reliability of aluminum-free 808nm high-power laser diodes with uncoated mirrors. Appl Phys Lett, 1995, 66(23): 3087

[7] Jurgen S, Gert B, Frank B, et al. High-power 810nm GaAsP-AlGaAs diode lasers with narrow beam divergence. IEEE J Sel Top Quantum Electron, 2001, 7(2): 334

[8] Knauer A, Bugge F, Erbert G, et al. Optimization of GaAsP/AlGaAs-based QW laser structures for high power 800nm operation. J Electron Mater, 2000, 29(1): 53

[9] Murata H, Ho I H, Stringfellow G B. Effects of growth temperature and V/III ratio on surface structure and ordering in $Ga_{0.5}In_{0.5}P$. J Cryst Growth, 1997, 170: 219

[10] Diehl R. High-power diode lasers fundamentals, technology, applications. Berlin: Springer, 2000

[11] Unger P. Introduction to power diode lasers. In: High Power Diode Lasers Fundamentals, Technology, Applications. Berlin: Springer, 2000

259W 准连续无铝 808nm 激光二极管线列阵

刘素平　仲　莉[†]　张海燕　王翠鸾　冯小明　马骁宇

（中国科学院半导体研究所 光电子器件国家工程研究中心，北京　100083）

摘要：通过优化张应变量子阱外延结构和设计线列阵双沟道深隔离槽腐蚀工艺，采用低压金属有机化学气相沉积法（LP-MOCVD）生长了 GaAsP/GaInP/AlGaInP 单量子阱分别限制异质结激光器材料，并利用该材料制备了填充因子为 50% 的 1cm 宽线列阵激光巴条，用扫描电子显微镜（SEM）分析了隔离槽的形貌. 在准连续工作条件（200μs 脉宽，2% 占空比）下，封装在被动制冷标准铜热沉上的器件在测试设备允许的最大驱动电流 300A 时可获得 259W 的输出功率，未观察到腔面光学灾变性损伤的发生. 最高功率转换效率在工作电流为 104A 时达 52%，此时输出功率为 100W，激射光谱的中心波长为 807.8nm，半高宽为 2.4nm，快慢轴远场发散角分别为 29.3°和 7.5°.

关键词：激光二极管；列阵；准连续；无铝

PACC：4255P；4260　　**EEACC：**4320J

中图分类号：TN248.4　　**文献标识码：**A　　**文章编号：**0253-4177(2008)12-2335-05

[†] 通信作者. Email: zhongli@semi.ac.cn

2008-03-25 收到，2008-08-02 定稿