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High power GaSb-based 2.6 μm room-temperature laser diodes with InGaAsSb/AlGaAsSb type I quantum-wells

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Abstract: GaSb-based InGaAsSb/AlGaAsSb type-I quantum-wells (QWs) laser diodes have been successfully fabricated. The wavelength is expanded to 2.6 μm with high output power. The device structures were grown by molecular beam epitaxy. Under the optimized QWs growth temperature of 500℃, the compressive strain of the QWs are defined to 1.3% for better optical quality. With a ridge width of 100μm and cavity length of 1.5 mm, the maximum output power of single facet without coating has reached up to 328 mW under continuous wave (CW) operation at room temperature and 700 mW under pulse condition. The threshold current density is 402 A/cm^2.

Key words: GaSb-based, laser diodes, quantum-wells, mid-infrared
PACS: 42.55.Px, 78.55.Cr, 78.67.De, 68.65.Fg

高功率 GaSb 基 2.6 微米 InGaAsSb/AlGaAsSb I 型量子阱室温工作激光器

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摘要:成功制备出 2.6μm GaSb 基 I 型 InGaAsSb/AlGaAsSb 量子阱高功率半导体激光器. 利用分子束外延设备(MBE)生长出器件的材料结构. 为了得到更好的光学质量,将量子阱的生长温度优化至 500℃,并将量子阱的压应变调节为 1.3%. 制备了脊宽 100 μm 、腔长 1.5 mm 的激光单管器件. 在未镀膜下该激光器实现了最大 328 mW 室温连续工作,阈值电流密度为 402 A/cm^2,在脉冲工作模式下,功率达到 700 mW.

关　键　词:镓锑基;半导体激光器;量子阱;中红外

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Introduction

High power laser diodes emitting in the mid-infrared (MIR) spectral range, which contains strong absorption lines of many important gases[1], are of great demand for a number of applications such as atmospheric pollution monitoring, infrared countermeasures and laser surgery[2]. GaSb-based type-I quantum-wells lasers are competitive in the 2 ~ 3 μm range due to the higher power and working temperature compared with InP-based material system[3]. 2.6 μm lasers with single longitudinal mode selection part such as DFB are desired for H_2S gas sensing in petroleum industry[4-5]. With the potential of low-cost and high-volume production capability, the GaSb material platform offers advantages in the high differential gain and low voltage due to the great material quality of lattice matched growth of

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AlGaAsSb in QWs.

Limitation arises from the increasing indium concentration in the QWs as the wavelength move forwards because of the strong degradation of hole confinement[6-8]. Domestic researches have extended the wavelength to 2.4 μm with 28 mW output power[9]. To extend the wavelength further to 2.6 μm, compressive strain in QWs was introduced in epitaxial growth to suppress hole leakage by the hole confinement, meanwhile the crystal lattice defect should be avoided to ensure the material quality. In this paper, we will present the optimization of both the growth temperature and compressive strain of the InGaAsSb/AlGaAsSb quantum-wells (QWs) and show the fabrication of 2.6 μm single emitter diode laser device with 100 μm-wide and 1.5 mm-long cavity. High optical output power of 328 mW operating at continuous wave (CW) mode and 700 mW at pulse condition at room-temperature (RT) were obtained from the device.

1 Experiments

The laser diodes were grown by solid source Gen-II molecular-beam epitaxy (MBE) on 2-inch Te doped n-GaSb substrates. Figure 1 schematically depicts the epitaxial structure and the energy bands of the diode laser. 500-nm thick heavily Te doped GaSb buffer layer was firstly deposited on the substrate to improve the flatness of the substrate and electroconductivity. The active region consists of three 10-nm thick compressive strained $In_{0.42}Ga_{0.58}As_{0.16}Sb_{0.84}$ QWs spaced by 20-nm thick lattice matched $Al_{0.27}Ga_{0.73}As_{0.02}Sb_{0.98}$ barrier layers. Two 300-nm thick undoped $Al_{0.27}Ga_{0.73}As_{0.02}Sb_{0.98}$ separated confined layers (SCLs), which surround the active region, were chosen to improve the optical confinement of the laser. The 0.7 μm waveguide core that includes the active region and SCLs is sandwiched between two 2 μm wide $Al_{0.55}Ga_{0.45}As_{0.05}Sb_{0.95}$ cladding layers. The n-cladding layer is Te doped to 5×10^{17} cm^{-3}, and the p-cladding layer is Be doped to 2×10^{18} cm^{-3} which is the same as the doping level of p-GaSb cap layer.

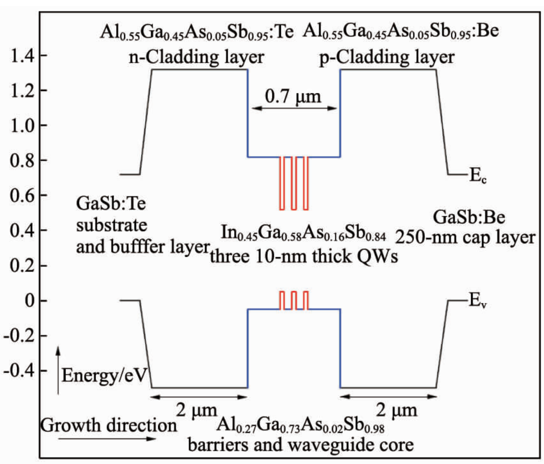

Fig. 1 Epitaxial structure and energy band of the laser devices
图1 I型量子阱激光器材料外延结构和能带示意图

The growth temperature of the QWs is the vital parameter in the MBE epitaxy of the laser[10]. At low growth temperature, the mobility of In and Ga atoms decreases, which causes the formation of islands, thus results in the poor lattice quality[11]. While the atoms would exchange at the interface between QWs and barriers which deteriorates the quality of QWs if the growth temperature is too high[12]. To find the compromised growth temperature of the QWs, photoluminescence (PL) measurements at 77 K were carried out on three QWs samples with the growth temperature at 480℃, 500℃ and 520℃, respectively. All the PL spectra were obtained with a Fourier transform infrared spectrometer (FTIR) by detecting the PL signals excited by a 500 mW 628 nm diode laser. The QWs samples were cooled to 77 K by liquid nitrogen to avoid thermal effects brought by phonon disturbance. Figure 2 presents the PL spectra of the three samples. The peak intensity and full wave at half maximum (FWHM) of the PL spectrum were extracted to indicate the optical quality of QWs. It is obvious that the sample grown at 500℃ has the best optical quality among the three samples so that the growth temperature of QWs was optimized to 500℃.

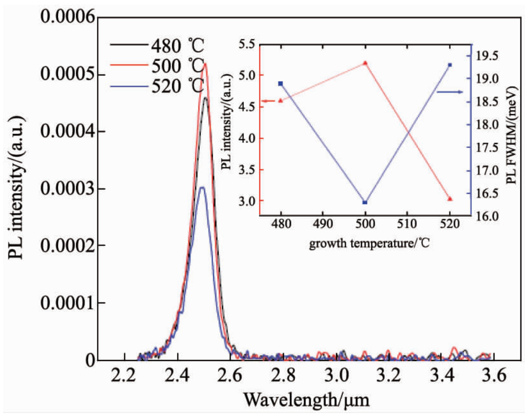

Fig. 2 PL spectra measured at 77 K of three QWs samples with growth temperature at 480℃, 500℃ and 520℃, respectively
图2 量子阱材料在不同生长温度(480℃,500℃,520℃)下的低温(77 K)光致发光谱(PL谱)

Compressive strain was introduced in the QWs to improve the laser differential gain, but the compressive strain of QWs is limited by the deterioration of lattice quality as the strain increases[13-14]. Four QWs samples with compressive strain of 0.7%, 1.0%, 1.3% and 1.5%, respectively, were grown by changing the As contents of the QWs. The PL and high resolution X-ray diffraction (HR-XRD) measurements were performed to assess the optical quality and lattice quality, respectively. Figure 3 shows the PL spectra and XRD profiles of the four samples. As the compressive strain increased from 0.7% to 1.3%, the PL intensity increased sequentially thanks to the improvement of valence band offset. As we can see from the XRD measurement in Fig. 3, the material quality of the sample with 1.5% compressive strain began to deteriorate so that the PL intensity of this sample decreased compared with the sample with 1.3% compressive strain. So the compressive stain of QWs was optimized to 1.3% in comprehensive consideration of both the differential gain and lattice quality.

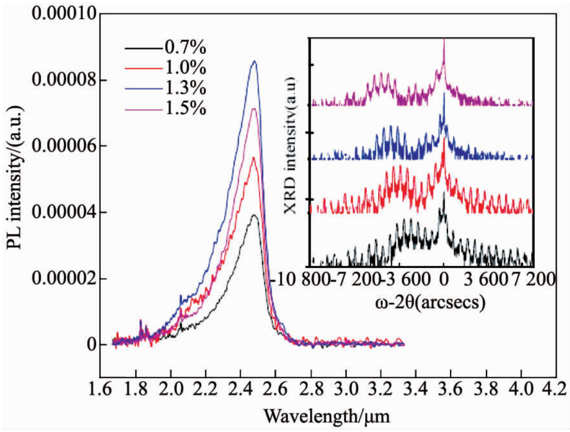

Fig. 3 PL spectra at 77 K and XRD profiles of four QWs samples with compressive strain of 0.7%, 1.0%, 1.3%, 1.5%, respectively

图 3 不同压应变(0.7%,1.0%,1.3%,1.5%)的量子阱材料样品的 X 射线衍射谱和低温(77 K)光致发光谱

The grown epitaxial wafers were processed into diode lasers with a ridge waveguide of 100 μm wide, 1.5 mm long and 2.2 μm deep using contact optical lithography followed by inductively coupled plasma (ICP) dry etching. Then 90 μm wide, 1.4 mm-long electrode aperture was opened using ICP etching on the 200 nm SiO_2 insulation layer deposited by PECVD. After that the p-side Ti/Pt/Au electrode was formed by magnetism sputter system. Figure 4 shows the scanning electron microscope (SEM) cross-section image of the laser. The n-side Ohm contacts were realized by fast-annealing the evaporated AuGeNi/Au film after the wafers were thinned to 180 μm. Finally the wafers were cleaved into single emitters, and all the laser devices were mounted p-side down on copper heat sinks with indium solder.

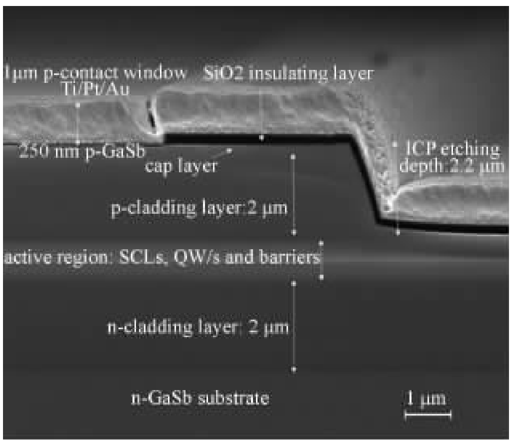

Fig. 4 SEM image of the cross-section of the laser diode

图 4 激光器剖面的扫描电子显微镜(SEM)照片

2 Results and discussion

All the laser performance was measured without facet coating at room temperature (20℃). The measurements of lasers output power were done by a pyroelectric detector and the emission spectra were scanned using a Fourier transform infrared spectroscopy (FTIR) system. Figure 5 shows the laser optical power-current-voltage (*P-I-V*) curve, wall plug efficiency (*WPE*) and corresponding emission spectrum (at 2 A injection current) in CW regime. The central wavelength was up to 2.6 μm with a low threshold current density of J_{th} = 402 A/cm^2 and a slope efficiency of 0.137 W/A. Output power reached up to 328 mW at the injection current of 3.8 A, then as the current increased further the output power was limited for the reason of heat accumulation. The maximum value of *WPE* is 7.24% at 1.5 A, and there is still room for improvement through the reduction of series resistances (R_s) which was 0.28 Ω by now. By reducing Al composition of the cladding layers and extra procession after the polishing of n-side substrate, the Rs will be reduced further to improve the WPE[15]. Figure 6 shows the output power characteristic of the device operating in pulse condition (100 μs current pulses at a 1 kHz repetition rate). The laser emitted as high as 700 mW optical power occurred at 7.5 A from both facets in pulse mode which is high enough for gas sensing application.

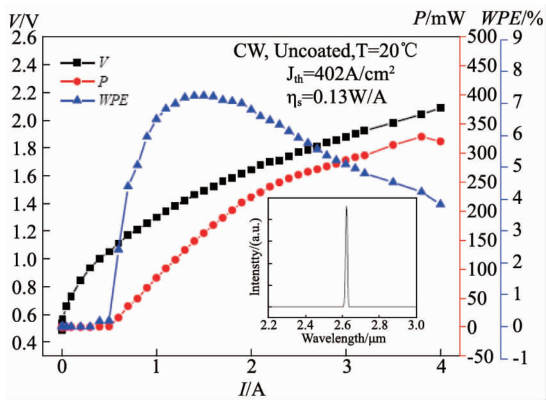

Fig. 5 *P-I-V* and *WPE* characteristics of the laser emitting at *I* = 2 A in the CW mode at RT with uncoated facets

图 5 激光器室温连续工作模式下的光功率-电流-电压关系和不同电流下的插头效率以及在注入电流 *I* = 2 A 时激光器的激射谱

The emission spectra and central wavelength against current (λ-*I*) characteristics are depicted in Fig. 7. From the λ-*I* curve we can clearly figure out that the wavelength shifted linearly towards the longer wavelength as the driving current increased. The slope of the curve was fitted to be 22 nm/A. The central wavelength red-shifted from 2.613 6 μm to 2.626 8 μm when the injection current raised from 1.7 A to 2.3 A mainly due to the thermal effect which brought about the elongating cavity and decreasing bandgap[16].

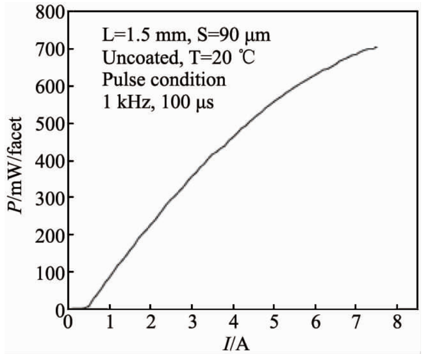

Fig. 6 Output power of laser diode operation in the pulse mode
图6 激光器在脉冲工作模式下的光功率-电流曲线

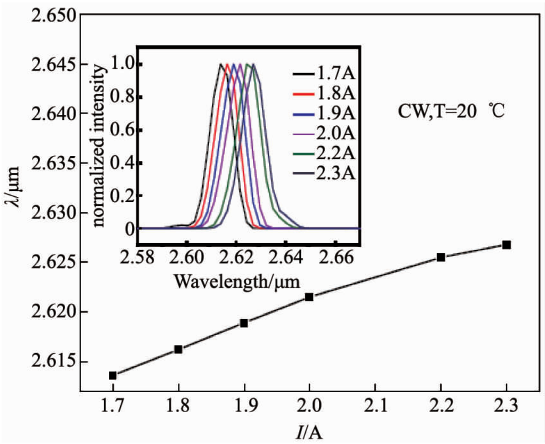

Fig. 7 Emission spectra of laser device with increasing injection current
图7 激光器激射的中心波长与电流的关系曲线以及对应的光谱图

3 Conclusions

In conclusion, we have achieved the 2.6 μm GaSb-based type-I quantum-well laser operating at RT through the optimization of the growth temperature and compressive strain of QWs. The uncoated facet single-emitter laser devices which had 100μm-wide and 1.5 mm-long cavity with threshold current density of 402 A/cm^2 and series resistances of 0.28 Ω were fabricated. The central emission wavelength was 2.627 μm at 2.3 A driving current. High output power of 328 mW in CW and 700 mW in the pulse condition (100μs pulses at 1kHz) were obtained.

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