Molecular beam epitaxy growth of InGaSb/AlGaAsSb strained quantum well diode lasers*

Zhang Yu(张宇)[1], Wang Guowei(王国伟)[2], Tang Bao(汤宝)[2], Xu Yingqiang(徐应强)[2], Xu Yun(徐云)[1,†], and Song Guofeng(宋国锋)[1]

[1]Nano-Optoelectronics Laboratory, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
[2]National Laboratory for Superlattice and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract: 2 μm InGaSb/AlGaAsSb strained quantum wells and a tellurium-doped GaSb buffer layer were grown by molecular beam epitaxy (MBE). The growth parameters of strained quantum wells were optimized by AFM, XRD and PL at 77 K. The optimal growth temperature of quantum wells is 440 ℃. The PL peak wavelength of quantum wells at 300 K is 1.98 μm, and the FWHM is 115 nm. Tellurium-doped GaSb buffer layers were optimized by Hall measurement. The optimal doping concentration is 1.127×10^{18} cm^{-3} and the resistivity is 5.295×10^{-3} Ω·cm.

Key words: InGaSb; AlGaAsSb; strained quantum wells; Te doped

DOI: 10.1088/1674-4926/32/10/103002 **PACC:** 7360F; 7280E; 6855

1. Introduction

Mid-infrared diode lasers emitting in the spectral region from 2 to 5 μm are in high demand for a variety of applications, such as medical diagnostics and treatment, infrared countermeasures, light detection and ranging, remote trace-gas monitoring, and secure free-space communications. These are being paid more and more attentions by scientists all over the world.

Over the past decade, remarkable progress has been made in the development of laser diodes based on compressively strained quarternary (AlGaAsSb/InGaAsSb)[1−4] and quinary (AlInGaAsSb/InGaAsSb)[5, 6] heterostructures. The fact that type I laser diodes operating within the 2 to 2.5 μm spectra region can provide Watt level optical power in the continuous wave (CW) regime at room temperature has been demonstrated by several groups[1−7]. Devices operating at 2 μm demonstrated 1.5 W in the CW regime at RT by Chen *et al.* in 2010[7], by using compressively strained InGaSb/AlGaAsSb quantum wells. However, the device output power decreases in the spectral region above 3 μm due to an increase in carrier and photon losses with wavelength. The CW output power of 65 mW was demonstrated at 12 ℃ for 3.2 μm laser diodes by Belenky *et al.* of University Stony Brook in 2009[8]. Domestic scientists[9, 10] had researched antimonide-based lasers for many years, and the output power of CW at room temperature is about 6 mW[9] and 42 mW[10], respectively.

As we know, the quality of the active layers and buffer layer plays an important role in antimonide based lasers. In this paper, the InGaSb/AlGaAsSb quantum wells were grown and the quality of the active layer was optimized by carrying atomic force microscopy (AFM), X-ray diffraction (XRD) and photoluminescence (PL) measurements of the material. An important feature of QW design is the use of InGaSb 1.1% compressive strained wells that improve the hole confinement. On the other hand, tellurium-doped GaSb buffer layers were optimized by Hall measurement results.

2. Growth and optimization of quantum wells

InGaSb/AlGaAsSb strained quantum wells were grown using a VG80H MKII molecular beam epitaxy system equipped with As and Sb valved cracker sources. First, components of Ga, In and Al in $In_{0.18}Ga_{0.82}Sb$ and $Al_{0.35}Ga_{0.65}As_{0.02}Sb_{0.98}$ epitaxy layers were accurately controlled by adjusting the Ga/In, Al/Ga and As/Sb beam flux. Then $In_{0.18}Ga_{0.82}Sb/Al_{0.35}Ga_{0.65}As_{0.02}Sb_{0.98}$ active regions,

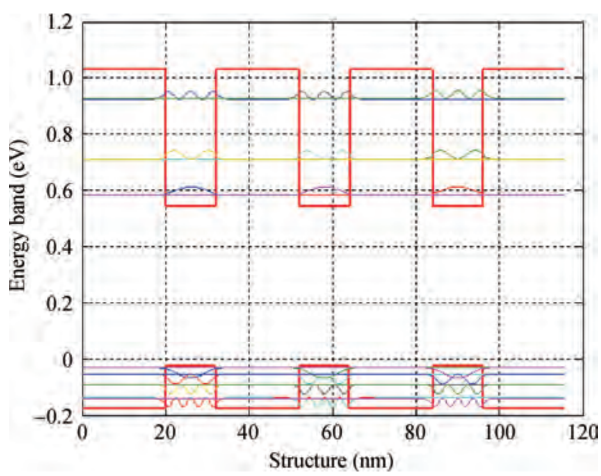

Fig. 1. Band structure and wave function of quantum wells.

* Project supported by the Beijing Natural Science Foundation (No. 4112058) and the Science Foundation of the Chinese Academy of Sciences (No. CXJJ-11-M20).
† Corresponding author. Email: xuyun@semi.ac.cn
Received 18 April 2011, revised manuscript received 9 June 2011

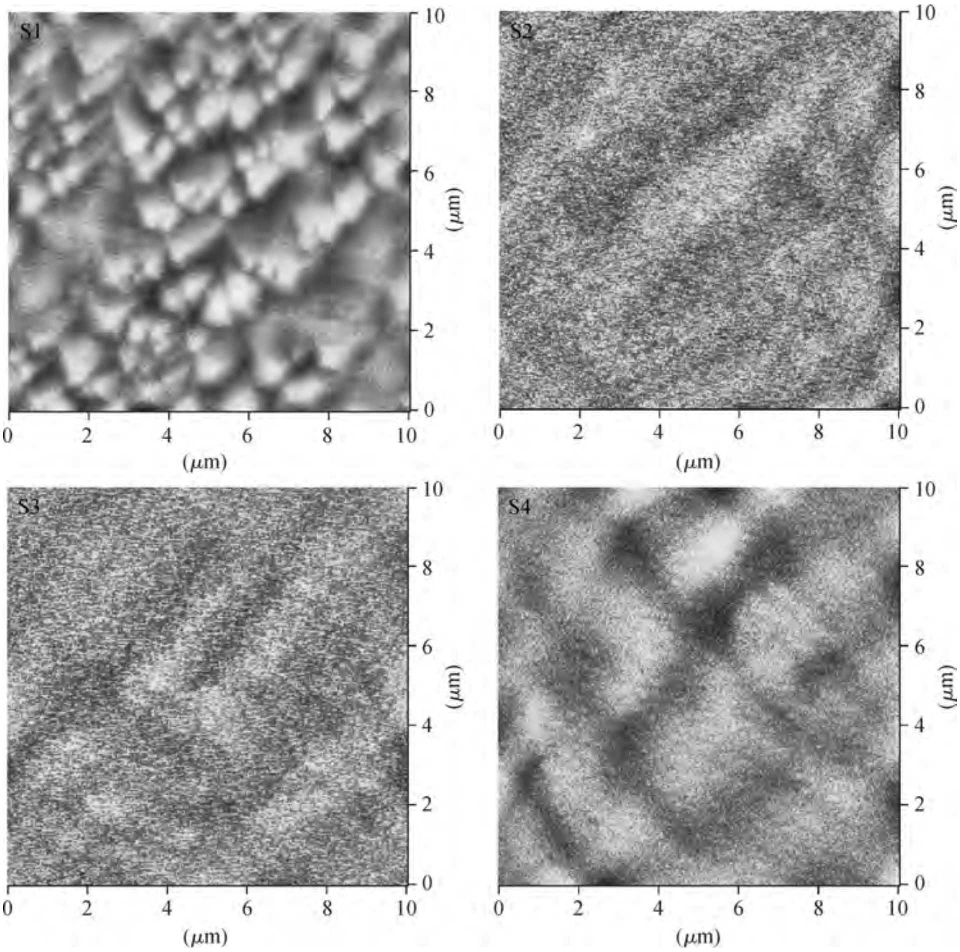

Fig. 2. AFM surface morphology images of samples S1–S4.

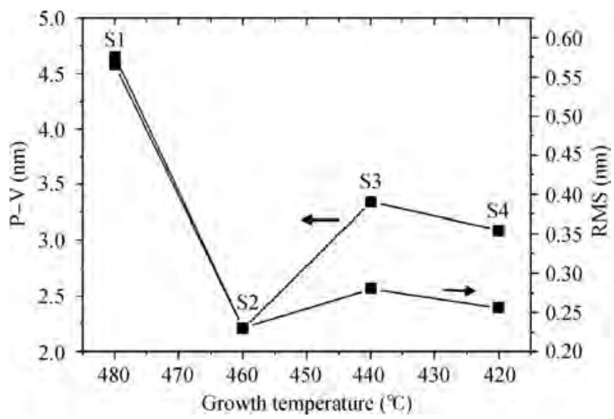

Fig. 3. P–V and RMS of samples S1–S4.

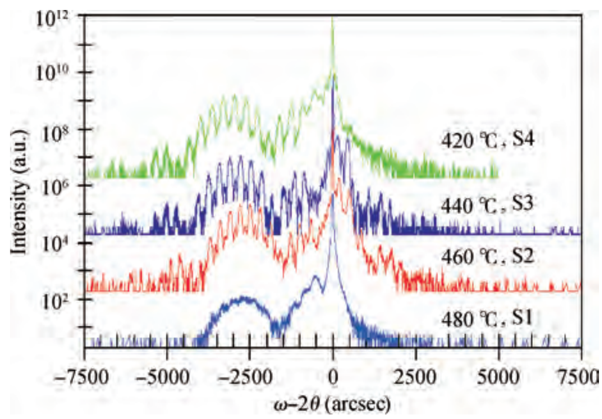

Fig. 4. XRD profiles of samples S1–S4.

consisting of three 12 nm InGaSb wells separated by 20 nm wide lattice-matched AlGaAsSb barriers, were grown on GaSb substrate. Then a 10 nm GaSb cap layer was grown. Four samples S1–S4 were grown at 480, 460, 440 and 420 ℃ respectively. The growth rate of GaSb were 0.5 ML/s.

The band structure and wave function of three 12 nm InGaSb/20 nm AlGaAsSb quantum wells were modelled with one-dimensional finite difference[11], as shown in Fig. 1. The transition energy of quantum wells is 0.615 eV and the transition wavelength is 2.016 μm.

The surface morphology of samples measured by AFM are shown in Figs. 2 and 3. From Fig. 3 we can see that the root mean square (RMS) of S2, S3 and S4 is less than 0.3 nm (only one atom thickness). What's more, the best growth temperature is 460 ℃ deduced from the value of peak–valley (P–V) and RMS of the surface roughness in Fig. 3.

The XRD measurement result is shown in Fig. 4, from which we can see that the diffraction peaks of S1 are indistinguishable, indicating the poor material quality of S1. A growth temperature of 480 ℃ is so high that In atoms may diffuse

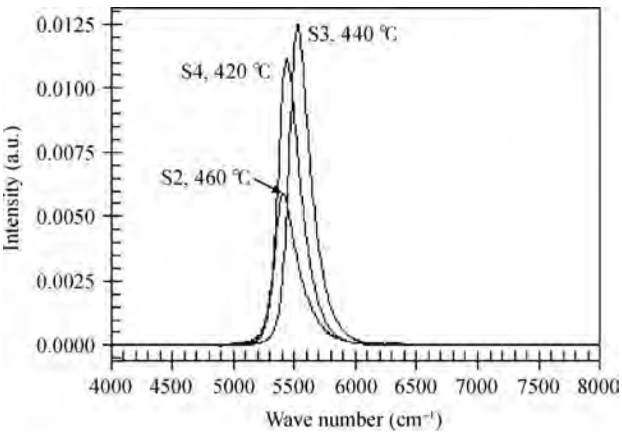

Fig. 5. PL spectra of S2–S4 at 77 K.

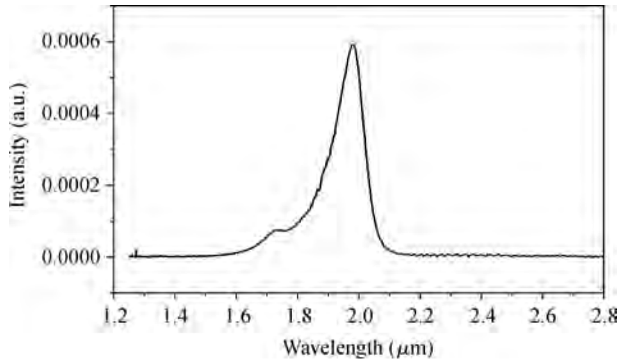

Fig. 7. PL spectra of S3 at RT.

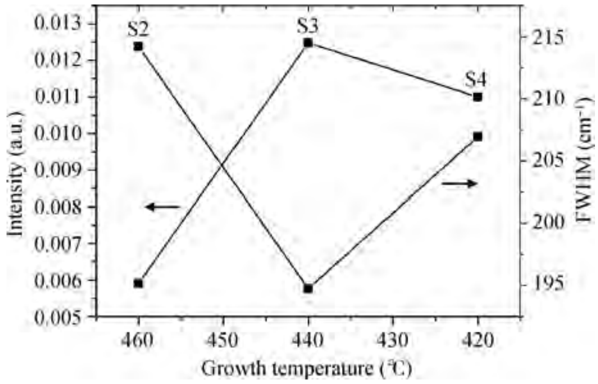

Fig. 6. Intensity and FWHM of PL.

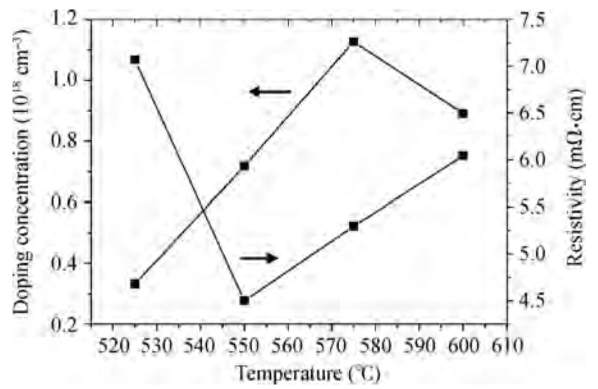

Fig. 8. Doping concentration and resistivity of Te-doped GaSb.

into AlGaAsSb barriers and As and Sb atoms may exchange at the interface, which deteriorates the periodicity and interfaces of the quantum wells. Meanwhile, the third order diffraction peaks of S2, S3 and S4 can even be seen clearly, meaning the relatively high material quality of S2, S3 and S4.

PL measurement of samples S1–S4 was carried out at 77 K and the result is presented in Figs. 5 and 6. We can see that the samples S2, S3 and S4 all present a luminescence peak at 1.8 μm except for S1. Sample S3 even demonstrates a strong PL peak at room temperature, as shown in Fig. 7. The PL peak wavelength of S3 is 1.98 μm, and the full wave at half maximum (FWHM) is 115 nm. The difference in transition wavelength is 1.8% between experiment and modelling.

When the growth temperature is too low, the formation of islands deteriorates the quality of the surface because the mobility of In and Ga atoms decreases. In view of interface and surface quality, the growth temperature must be compromised. So considering the PL intensity and the FWHM of the samples, the growth temperature of quantum wells was optimized at 440 ℃.

3. Growth and optimization of buffer layer

A 0.5 μm tellurium-doped GaSb layer was grown on GaAs substrate by MBE. The temperature of the tellurium source was 525, 550, 575, 600 ℃ respectively. The growth rate of GaSb was 0.5 ML/s.

Hall measurement was carried out at room temperature and the result is shown in Fig. 8. The growth temperature with the highest doping concentration and the lowest resistivity was 575 ℃ and 550 ℃, respectively. We can see that it is difficult to improve the doping concentration and reduce the resistivity at the same time. The doping saturation was observed previously[12]. According to Sagar[13], the L-valleys of GaSb, which have a high density of states and a low mobility, lie very close in energy to the central Γ minimum. Therefore, the Hall measurement will underestimate the total carrier concentration due to more carriers transferring to the upper band.

Then considering both the doping concentration and the resistivity, the growth temperature was decided at 575 ℃, at which the doping concentration is 1.127×10^{18} cm^{-3} and the resistivity is 5.295×10^{-3} Ω·cm.

4. Conclusion

The material quality of the strained quantum wells was optimized with the help of AFM, XRD and PL measurement. The optimal growth temperature of the quantum wells is 440 ℃. The PL peak wavelength of the quantum wells at 300 K is 1.98 μm and the FWHM is 115 nm.

Tellurium-doped GaSb buffer layer was optimized by Hall measurement. The doping concentration is 1.127×10^{18} cm^{-3} and the resistivity is 5.295×10^{-3} Ω·cm.

References

[1] Garbuzov D Z, Lee H, Khalfin V, et al. 2.3–2.7 μm room temperature CW operation of InGaAsSb–AlGaAsSb broad waveguide SCH-QW diode lasers. IEEE Photonics Technol Lett, 1999, 11: 794

[2] Rattunde M, Schmitz J, Kiefer R, et al. Comprehensive analysis of the internal losses in 2.0 μm (AlGaIn)(AsSb) quantum-well diode lasers. Appl Phys Lett, 2004, 84: 4750

[3] Turner G W, Choi H K, Manfra M J. Ultralow-threshold (50 A/cm^2) strained single-quantum-well GaInAsSb/AlGaAsSb lasers emitting at 2.05 μm. Appl Phys Lett, 1998, 72: 876

[4] Garcia M, Salhi A, Perona A, et al. Low threshold high-power room-temperature continuous-wave operation diode laser emitting at 2.26 μm. IEEE Photonics Technol Lett, 2004, 16: 1253

[5] Hosoda T, Belenky G, Shterengas L, et al. Continuous-wave room temperature operated 3.0 μm type I GaSb-based lasers with quinternary AlInGaAsSb barriers. Appl Phys Lett, 2008, 92: 091106

[6] Shterengas L, Belenky G, Hosoda T, et al. Continuous wave operation of diode lasers at 3.36 μm at 12 ℃. Appl Phys Lett, 2008, 93: 011103

[7] Chen J F, Kipshidze G, Shterengas L. High-power 2 μm diode lasers with asymmetric waveguide. IEEE J Quantum Electron, 2010, 46(10): 1464

[8] Belenky G, Shterengas L, Wang D, et al. Continuous wave operated 3.2 μm type-I quantum-well diode lasers with the quinary waveguide layer. Semicond Sci Technol, 2009, 24: 115013

[9] Lin C, Zheng Y L, Zhang Y G, et al. Temperature and injection current dependencies of 2 μm InGaAsSb multiple quantum-well ridge-waveguide lasers. J Cryst Growth, 2001, 225: 591

[10] Li Z G, Liu G J, You M H, et al. 2.0 μm room temperature CW operation of InGaAsSb/AlGaAsSb laser with asymmetric waveguide structure. Semicond Lasers, 2009, 19(6): 1230

[11] Tan I H, Snider G L, Chang L D, et al. A self-consistent solution of Schrodinger-Poisson equations using a nonuniform mesh. J Appl Phys, 1990, 68(8): 4071

[12] Chen J F, Cho A Y. Characterization of Te-doped GaSb grown by molecular beam epitaxy using SnTe. J Appl Phys, 1991, 70(1): 277

[13] Sagar A. Experimental investigation of conduction band of GaSb. Phys Rev, 1960, 117(1): 93