Strain-compensated InGaAs/InAlAs quantum-cascade lasers

Liu Feng-Qi, Wang Zhanguo, Li Lu, Wang Lijun, and Liu Junqi
Key Laboratory of semiconductor materials science, Institute of semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, China
Phone :+8601-82304026, Fax:+8601-82305052, Emial: fqliu@red.semi.ac.cn, zgwang@red.semi.ac.cn

Abstract- *Molecular beam epitaxy (MBE) growth of strain-compensated InGaAs/InAlAs quantum cascade lasers is reported. Accurate control of material composition, growth rate, doping level and interface quality can be realized by optimizing growth conditions.*

Quantum cascade lasers (QCLs) have significant potential for a wide range of technological applications at mid-infrared wavelengths, such as gas sensing and space communication. Eminent improvements have been obtained in the last few years towards room-temperature continuous-wave, high power and low-threshold operations [1-4]. An effective approach to improve the performance of QCLs is employing strain-compensated $In_xGa_{(1-x)}As/In_yAl_{(1-y)}As$ ($x>53\%$, $y<52\%$) materials in the active region of the QCLs. One distinct merit of the strain-compensated materials system is that the enlarged conduction band discontinuity provides the potential for decreasing threshold current density, while another pronounced merit lies in that this strain-compensated superlattice can prevent and suppress the defects (especially, the threading dislocations) propagation and evolution in the active region. Here we report the issues associated with the epitaxial growth of strain-compensated InGaAs/InAlAs QCLs.

Our MBE system is a solid source MBE equipped with valved crackers for the phosphorus and arsenic sources. High quality QCL materials depend on the accurate control of the InGaAs and InAlAs components. The first step is to determine the optimum growth parameters of lattice-matched single layers of $In_{0532}Ga_{468}As$ and $In_{0.523}Al_{0.477}As$. Fig. 1 gives the double crystal X-ray diffraction (DXRD) results of single layers of nominal $In_{0532}Ga_{468}As$ and $In_{0.523}Al_{0.477}As$ which lattice-matched to InP substrates. The target mismatch about $\sim 10^{-5}$ is proved. The doping concentration is measured by electrochemical capacitance-voltage profiling and Hall method. For strained $In_xGa_{(1-x)}As$ and $In_yAl_{(1-y)}As$ layers, the growth parameters can be deduced from lattice-matched counterparts and experimental verification. Our experience indicates that the doping concentration is Indium mole fraction dependent.

The specific designs presented here of strain-compensated QCL structures for $\lambda \approx 5.7\mu m$ (wafer G359, $In_{0.6}Ga_{0.4}As/In_{0.44}Al_{0.56}As$), 4.8μm (wafer G358, $In_{0.678}Ga_{0.322}As/In_{0.365}Al_{0.635}As$), and 7.4μm (wafer G335, $In_{0.64}Ga_{0.36}As/In_{0.38}Al_{0.62}As$) employ design methods similar to the published previously [5,2,6]. Laser wafers with active region of 30-35 periods were grown on n-doped ($2\text{-}4\times10^{17}$ cm^{-3}) InP substrates. 2-2.5μm-thick n-InP layers with graded doping (6×10^{16} -$5\times10^{18} cm^{-3}$) are used as upper cladding layers. The strain-compensated $In_xGa_{(1-x)}As/In_yAl_{(1-y)}As$ structures were grown at a substrate temperature of 505°C. Typical MBE growth rates, 0.62-0.95μm/h for strained $In_xGa_{(1-x)}As$ and 0.75-1.3μm/h for strained $In_yAl_{(1-y)}As$ were used during wafers growth. The thick InP layers were grown at a substrate temperature of 490°C and growth rate of 0.75μm/h.

Fig.2(a) gives DXRD result of the wafer G359. The zero-order superlattice X-ray diffraction peak shows a nearly perfect lattice match to the InP substrate, which indicates that the active region layers, based on $In_{0.6}Ga_{0.4}As/In_{0.44}Al_{0.56}As$, have been properly strain-balanced to give a net zero strain. Excellent periodicity of satellite peaks indicates good quality of the material. Double-channel ridge waveguide lasers of various cavity lengths, with the facets left uncoated, were fabricated by photolithography and wet chemical etching. Ti/Au was used for contacts. Lasers were bonded epilayer-side down on a copper submount with In solder. Fig.2(b) illustrates the typical pulsed lasing spectrum at 60°C, the lasing wavelength is about 5.72 μm. This facet-uncoated laser can operate at 265K in continuous-wave mode. For solid source MBE, the growth of high quality thick InP is somewhat difficult, for the reason of Indium induced oval defects. With the increase of epitaxial InP thickness, the accumulated effect of oval defects will be exaggerated.

Fig.3 gives DXRD result of the wafer G358(λ =4.8 μm). Peak output power up to 2.6 W of an uncoated 22m-wide and 4 mm-long laser is obtained at room temperature. Fig.4 gives the schematic conduction band diagram of 7.4 μm QCL active region, DXRD result of the whole structure, and the typical lasing spectrum at room temperature. By optimizing growth rate and substrate temperature, a typical 4.7μm QCL structure consists of 30 active/injector stages were grown. Excellent material quality and uniformity are evidenced by the narrow (15-25 arcsec) full width at half maximum measurements of the satellite peaks.

This work was supported by the National Science Fund for Distinguished Young Scholars and other Research Projects of China (Grant numbers: 60525406, 60736031, 2006CB604903, 2007AA03Z446).

References

[1] M.Beck, J. Faist et al, **Science 295** (2002)p.301.

[2] A. Evans, M. Razeghi et al, Appl.Phys.Lett. **85**(2005)p. 2166.
[3]Y.Bai, M. Razeghi et al, Appl.Phys.Lett.**93** (2008)p.021103.
[4]A. Lyakh, F.Capasso et al, Appl.Phys.Lett. **92**(2008)p.111110.
[5]S.Blaser, J. Faist et al, Appl.Phys.Lett. 86(2005)p.041109.
[6]J.S.Yu, M.Razeghi et al, Appl.Phys.Lett.**88** (2006)p.091113.

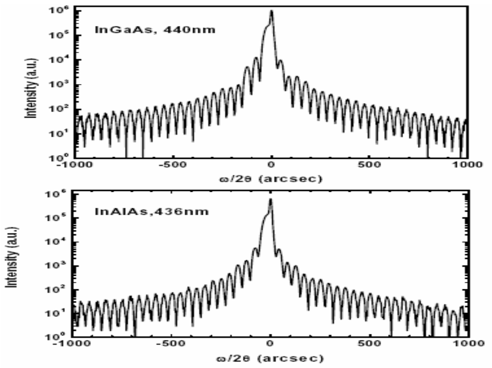


Fig.1 DXRD results of InGaAs and InAlAs layers

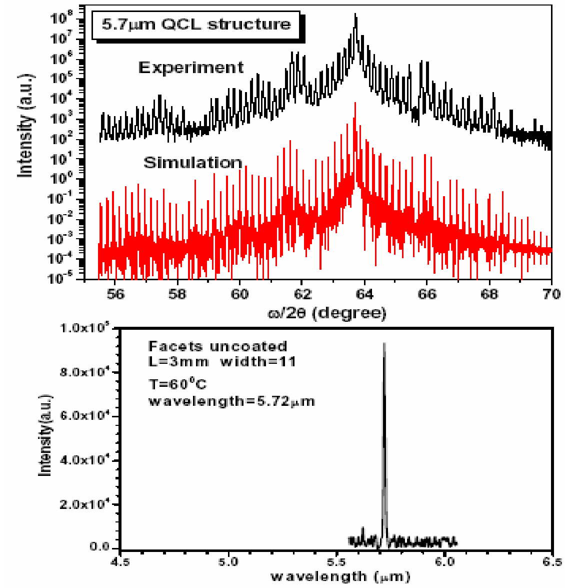


Fig.2 DXRD result and lasing spectrum of G359 (λ~5.7μm)

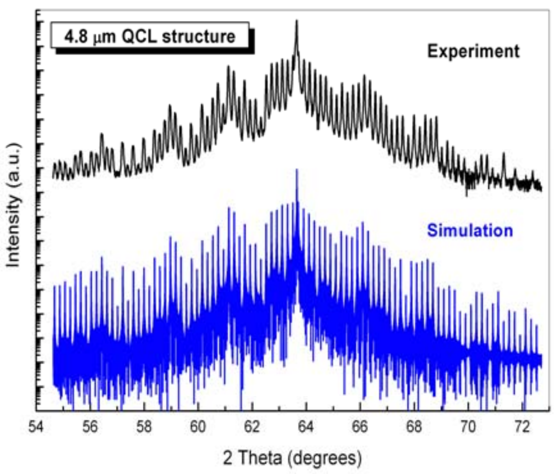
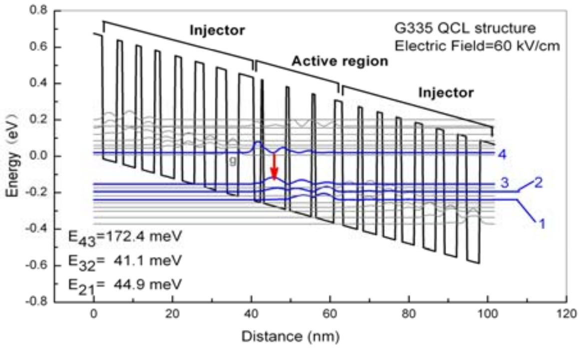


Fig.3 DXRD result of G358 (λ~4.8μm)



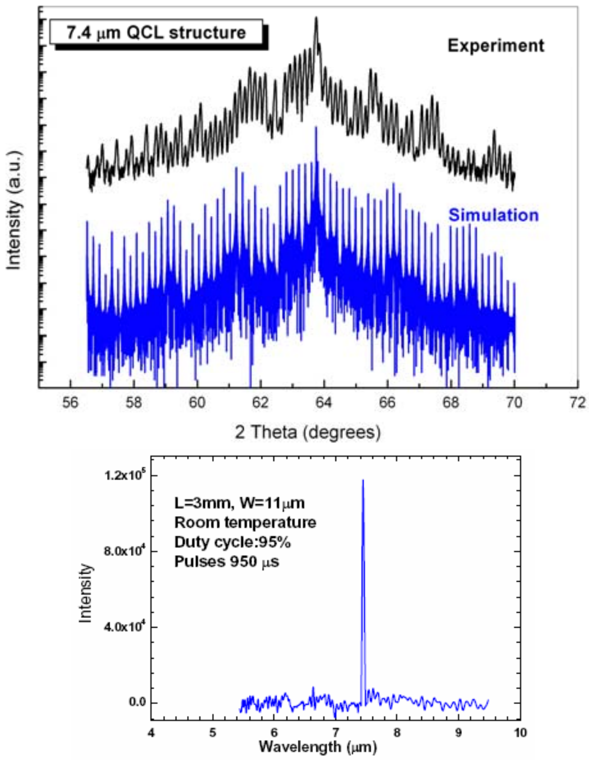


Fig.4 DXRD result and lasing spectrum of G335 (λ~7.4μm)

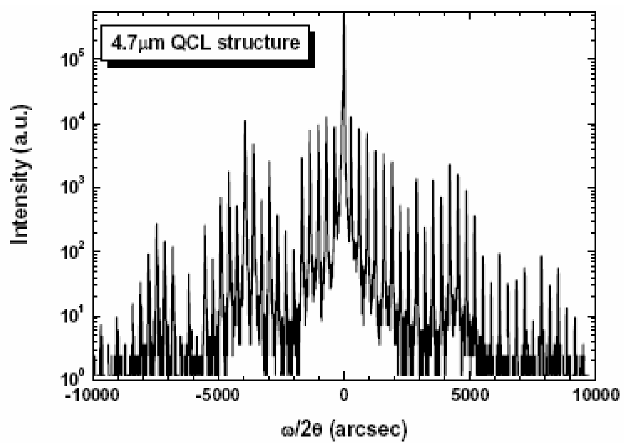


Fig.5 DXRD result of λ~4.7μm QCL structure