Short Wavelength and Strain Compensated InGaAs/AlAsSb Quantum Cascade Lasers

D. G. Revin, M. J. Steer, R. J. Airey, A. B. Krysa, M. Hopkinson, L. R. Wilson, S. Menzel and J. W. Cockburn

***Abstract*—We report the first realization of short wavelength (3.05 – 3.6 µm) lattice matched $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$/InP quantum cascade lasers (QCLs). We present the first demonstration of strain compensated InGaAs/AlAsSb/InP QCLs operating at wavelengths near 4 µm. The lasers with indium composition in the InGaAs quantum wells up to 70% display no degradation compared with lattice matched devices. We demonstrate that the performance of InGaAs/AlAsSb QCLs can be improved if AlAsSb barriers in the quantum cascade laser active region are replaced by AlAs layers.**

***Index Terms*—Intersubband transitions, midinfrared emission, short-wavelength operation, strain compensation, quantum cascade lasers**

I. Introduction

RECENTLY, significant progress has been made in the development of "short wavelength" quantum cascade lasers (QCLs) emitting in the λ ≈ 3 - 4 µm range. The InGaAs/AlAsSb on InP system is of particular interest for short wavelength QCL development, since it combines a very high ΔE_c with compatibility with well-established InP device processing and waveguide technology. However until recently QC laser action has been observed in this materials system for wavelengths only above 3.7 µm (λ ≈ 3.9 µm at room temperature) [1,2]. Moreover, it has been suggested [2] that QCL operation may not be possible at wavelengths below about 3.7 µm in devices based on $In_{0.53}Ga_{0.47}As$ quantum wells lattice matched to InP. The basis for this assertion is that for shorter wavelengths, the upper laser level (confined by the Γ-point conduction band profile) is calculated to lie higher in energy than the expected position of the X-point conduction band minima (E(Γ-X) ≈ 520 meV for $In_{0.53}Ga_{0.47}As$ [3]). Such a situation might be expected to lead to a reduction in injection efficiency and/or intersubband population inversion due to intervalley scattering, and hence suppression of laser action. In this report we explore the short wavelength limits for QCLs based on lattice matched $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$/InP, and also report the development of strain compensated devices, in which the indium concentration in the quantum wells is increased. In the latter structures, the Γ-X separation is increased by up to 100 meV and is expected to extend the short wavelength limit for laser transitions to be free from the effects of intervalley scattering. We also verify that strain compensated $In_{0.6}Ga_{0.4}As/AlAs_{0.67}Sb_{0.33}$ QCLs with AlAs barriers in the active region demonstrate much better performance compared with the lasers having identical design but with $AlAs_{0.67}Sb_{0.33}$ throughout the whole core region.

D. G. Revin, L. R. Wilson, S. Menzel and J. W. Cockburn are with Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom (e-mail: d.revin@sheffield.ac.uk)

M. J. Steer, R. J. Airey, M. Hopkinson and A. B. Krysa are with EPSRC National Centre for III- V Technologies, University of Sheffield, Sheffield S1 3JD.

II. Laser Design details

Six QCL structures were studied with core regions each comprising 30 periods of active and injector regions. The overall layer thicknesses starting at the high doped (n × 10^{18} cm^{-3}) InP substrate are as follows: 2 µm low-doped InP/ 0.2 µm low-doped $In_{0.53}Ga_{0.47}As$ spacer/ core region/ 0.2 µm low-doped $In_{0.53}Ga_{0.47}As$ spacer / 2 µm low-doped InP/ 1 µm highly doped InP/ metal contact. The core regions and spacer layers were grown by molecular beam epitaxy and InP cladding layers were deposited by metal organic vapour phase epitaxy. Prior to the growth of QCL structures calibration growth was made on test superlattice structures. The indium fraction in InGaAs layers for strain compensated lasers was regulated by two separate indium sources. During these calibrations appropriate increased fraction of As and reduced fraction of Sb in AlAsSb barriers were found for both lattice matched and strain compensated compositions in order to maintain minimal overall strain. The QCL wafers were processed by wet etching into laser ridge structures with different width and soldered epilayer-up without facet coatings. The samples were driven at 5 kHz with 50 ns pulses.

III. Short wavelength lasers

Two lattice matched $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ QCL structures (M3255 and M3253) were designed for laser emission at λ = 3.5 µm and λ = 3.1 µm respectively. For the M3255 and M3253 lasers the energy positions of the upper laser levels are calculated to be about 20 meV and 120 meV respectively above the position of the X-point ground.

Both M3255 and M3253 devices display laser emission very close to the calculated wavelengths. The longer wavelength laser M3255 shows much better performance with threshold current density J_{th} equal to 2.6 kA/cm^2 at 80 K and

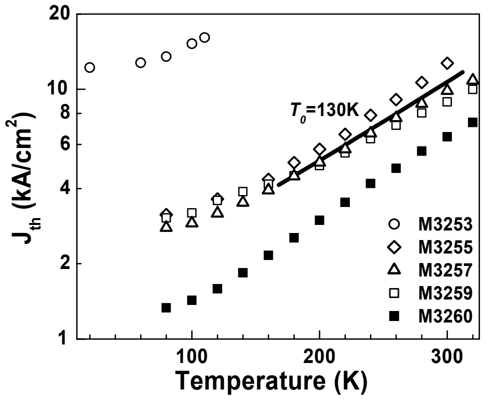

Fig. 1. Threshold current density as a function of the heat sink temperature. The line results from the fit $I_{th}=I_0 \exp(T/T_0)$ for T_0=130K.

10.5 kA/cm^2 at 300 K and pulsed optical power about 30 mW at 300K (Figure 1). The characteristic temperature T_0 is estimated to be about 130 K The emission wavelength shifts from 3.42 µm at 80 K to 3.57 µm at 300 K. A steady increase of emission power is observed with increasing current, with no saturation or "roll-over" of the light-current curves.

The performance characteristics of the λ ~ 3.05 µm QCL are clearly inferior to those of the λ ~ 3.4 µm device. The laser M3253 emits only at temperatures below 110 K with J_{th} ~ 12 kA/cm^2 at 20 K and maximum optical peak power of about 20 mW. The device displays laser action over a relatively limited range of current with pronounced roll-over behaviour in the light-current characteristics.

These results show that the predicted onset of Γ-X intervalley scattering at QCL emission wavelengths of around 3.7 µm does not cause shut-down of laser action at shorter wavelengths in $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ structures.

IV. Strain Compensated Lasers

Three QCL structures (M3254, M3257 and M3259) designed for laser emission at λ ~ 4.1 µm were studied The QCLs are based on an identical design but with different composition of In in the InGaAs quantum wells: 53% (M3254 lattice matched device as a reference), 60% (M3259) and 70% (M3257). The last two lasers are strain compensated. The compressive strain induced by the InGaAs quantum wells was compensated by the tensile strain in the AlAsSb barriers.

As the indium fraction in the InGaAs quantum wells increases, the energy separation between Γ-valley and the minima of X- and L-valleys also rises. Thus for the strain compensated $In_{0.7}Ga_{0.3}As$/AlAsSb system the energy separation between upper laser level and the minimum of the lowest satellite valley is estimated to increase by up to 80 meV relative to the lattice matched composition.

All three devices M3254, M3259 and M3257 display laser emission up to at least 320 K and at wavelengths λ ~ 4 - 4.2 µm. These values, together with the effect of slightly decreased emission wavelength for the strained compensated lasers, are very close to those expected from the calculations. The lasers from all wafers show very similar performance with no degradation for the strain compensated devices. Average J_{th} is equal to 3.4 kA/cm^2 at 80 K and 10.5 kA/cm^2 at 300 K (Figure 1). The pulsed optical peak power recorded for all three wafers is about 1 W at 80 K and 150 mW at 300 K. A steady increase of emission power is observed with increasing current.

QCLs based on the strain compensated InGaAs/AlAsSb material system potentially should be able to achieve emission wavelength as low as about 3.1 µm and the laser transitions in such devices are anticipated to be still free from the effects of intervalley scattering.

However, despite the encouraging results InGaAs/AlAsSb QCLs still show inferior performance at high temperatures compared to other Sb-free InGaAs/AlInAs lasers. One of the obstacles in the way of improving the performance of InGaAs/AlAsSb lasers is higher nonradiative scattering due to compositional fluctuations at quantum well/barrier interfaces in such material system [4]. It was shown previously [5] that introduction of AlAs even one monolayer thick on the InGaAs/AlAsSb interfaces in multi quantum well structures results in significant reduction in such nonradiative scattering and much stronger and narrower intersubband absorption peaks were observed.

In order to verify the influence of AlAs layers on QCL performance AlAs barriers were introduced in the active region (where the intersubband laser transitions occur) of strain compensated $In_{0.6}Ga_{0.4}As/AlAs_{0.67}Sb_{0.33}$ QCL. The $AlAs_{0.67}Sb_{0.33}$ barriers in the injector were left unmodified. The QCL structure (M3260) with the same design as for M3259 but with AlAs barriers in the active region was studied. The observed operating characteristics of the M3260 lasers are significantly different. These lasers demonstrate much better performance with average pulsed J_{th} equal to 1.4 kA/cm^2 at 80 K and 6.7 kA/cm^2 at 300 K (Figure 1). The lasers emit at slightly lower λ ~ 4.05 µm. The maximum pulsed optical peak power recorded at 13 kA/cm^2 is about 500 mW at 300 K. The performance of the lasers with AlAs barriers is also noticeably better compared with lattice matched M3254 and strain compensated M3259 lasers.

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