Deep-Well GaAs-InGaAs-AlGaAs Quantum-Cascade-Laser Design for Room-Temperature Operation at 6.8 μm

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Optimized GaAs/AlGaAs quantum cascade lasers (QCLs) have demonstrated room-temperature (RT) pulsed operation [1] at a wavelength of ~9.4 μm. Irrespective of the operating temperature, lasing is precluded for wavelengths < 8 μm because of intervalley scattering when the X-valley in the injection barrier becomes aligned with the upper lasing level [2]. Here, we present a design which allows for a reduction of the wavelength for RT operation from ~9.4 μm to 6.8 μm by using $In_{0.1}Ga_{0.9}As$ quantum wells in the active region.

Fig. 1 shows the band diagram with the relevant wavefunctions and layer thicknesses of the designed structure. The offsets between the upper lasing state and the Γ- and X-band edges are designed to be similar to those for the 9.4 μm structure, thus allowing for relevant comparisons between the two structures. A tensile-strained GaAsP layer is placed in front of the injection barrier to partially compensate for the compressive strain in the active region. Since the strain is not perfectly balanced, it is difficult to grow a device of more than 25 stages. The small number of stages is compensated by designing a waveguide with low-index AlGaAs cladding layers (Fig.2), which provide an active-region confinement factor, Γ, of 33%, similar to the 28% value used in the 36-stage, 9.4 μm device [1].

The 25-stage active region is surrounded on either side by 1.3 μm-thick, low-doped GaAs ($4x10^{16}$ /cm^3) layers followed by 0.3 μm-thick $Al_{0.9}Ga_{0.1}As$ ($1x10^{18}$ /cm^3) and 1 μm-thick GaAs ($4x10^{16}$ /cm^3) layers. The contact layer is a 1 μm-thick, highly doped ($5x10^{18}$ /cm^3) GaAs. The ratio of calculated losses for the 9.4 μm and 6.8 μm devices is found to be 1.33, as expected, given that free-carrier absorption decreases with decreasing wavelength. Considering the experimentally determined value of 20 cm^{-1} for the waveguide losses, α_w, of the 9.4 μm device [1], we estimate an α_w value of 15 cm^{-1} for the 6.8 μm device.

The Monte Carlo simulator [3] incorporating both Γ− and X-valley transport has been employed to simulate the output characteristics of the proposed QCL structure. The applied field vs. current density is shown in Fig. 3a, at the temperatures of 77 K and 300 K. The computed current densities include the leakage current through the next-stage Γ−continuum (Γ_c) states, as well as the leakage through the X-valley states [3]. At 300 K, the large X-valley leakage current at fields above 60 kV/cm is caused by the increased coupling between the injector states and the next-stage Γ_c states, which ultimately leads to pronounced interstage X-to-X leakage due to strong same-stage Γ_c-X coupling [3]. Fig. 3b shows the modal gain vs. current density. At 300 K, without the inclusion of the X-valleys, the modal gain increases linearly with the current density up to high gain values. When the X-valley transport is included, the modal gain saturates at current densities above 17 kA/cm^2, due to the carrier loss to the X-valleys that reduces the population inversion. Taking the mirror loss of α_m=4 cm^{-1} and the above-estimated α_w=15 cm^{-1} value, the threshold-current densities are found to be 5 kA/cm^2 at 77 K and 14 kA/cm^2 at 300 K, values similar to the ones obtained for the 9.4 μm QCL.

In conclusion, we have designed a deep-well (i.e., strained $In_{0.1}Ga_{0.9}As$ active quantum wells) GaAs-based QCL which can achieve room-temperature operation at 6.8 μm, with no penalty in the threshold current density.

[1] H. Page, C. Becker, A. Robertson, G. Glastre, V. Ortiz and C. Sirtori, "300 K operation of a GaAs-based quantum-cascade laser at λ≈9 μm", *Appl. Phys. Lett*. vol. 78, pp. 3529-3531, May 2001.

[2] L. R. Wilson, D. A. Carder, J. W. Cockburn, R. P. Green, D. G. Revin, M. J. Steer, M. Hopkinson, G. Hill, R. Airey, "Intervalley scattering in GaAs-AlAs quantum cascade lasers", *Appl. Phys. Lett*. vol. 81, pp.1378-1380, Aug. 2002.

[3] X. Gao, D. Botez, I. Knezevic, "X-valley leakage in GaAs/AlGaAs quantum cascade lasers", *Appl. Phys. Lett*. vol. 89, Art. No. 191119, Nov.2006.

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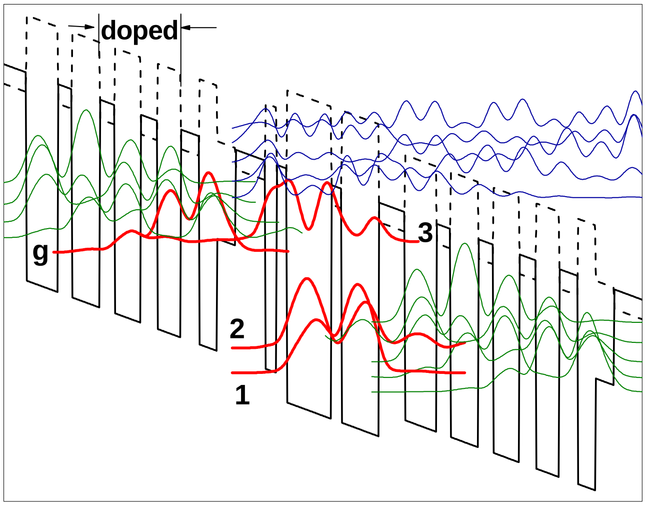

Fig. 1 Conduction band profile and the moduli-squared of the relevant wavefunctions at the above threshold electric field of 60 kV/cm. The layer thicknesses are in Å, starting from the exit barrier, are 28, 34, 15, 30, 16, 28, 18, 25, 20, 19, 20, 32, 12, 11, **48**, 11, **40**. The doped layers are underlined and the sheet doping density is 3.8x10^{11} /cm^2. The bold layers are the $In_{0.1}Ga_{0.9}As$ quantum wells and the $GaAs_{0.6}P_{0.4}$ strain compensation layer is boxed. The dashed line in the figure is the X-valley conduction band edge.

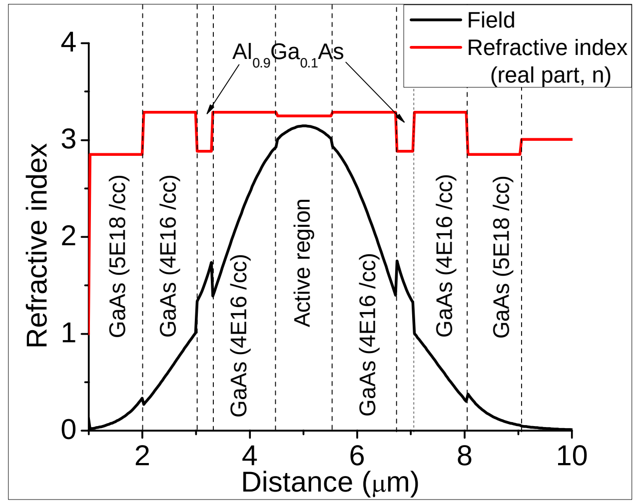

Fig. 2 Intensity profile of the TM mode of the waveguide and schematic representation of the structure of the waveguide.

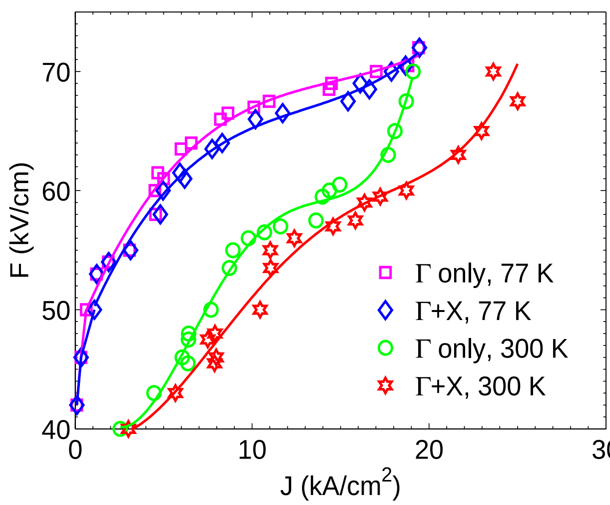

Fig. 3a Applied field vs current density for the proposed QCL at 77 K and 300 K, with and without the X-valley transport included.

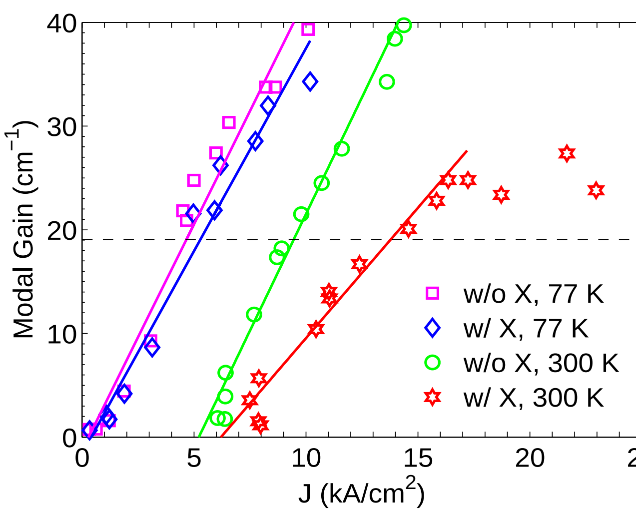

Fig. 3b Modal gain vs current density at 77 K and 300 K, with and without the X-valley transport included. The dash line indicates the total losses $\alpha_w + \alpha_m$.