Low threshold THz QC lasers with thin core regions

Y. Chassagneux, J. Palomo, R. Colombelli, S. Barbieri, S. Dhillon, C. Sirtori, H. Beere, J. Alton and D. Ritchie

It is demonstrated that the active region thickness of THz quantum cascade lasers can be reduced by a factor of 2 without effects on the threshold current density and maximum operating temperature of the laser. Pulsed and continuous-wave operation, with a low threshold $J_{th}=$ 71 A/cm^2, are obtained for a 5.86 µm-thick THz QC laser. The emission is peaked at $\lambda \simeq 115$ µm and the waveguide resonator is based on a metal-metal geometry.

Introduction: THz quantum cascade (QC) lasers are semiconductor-based pulsed- and continuous-wave (CW) sources of coherent radiation covering the frequency range between 1.9 and 5 THz ($\lambda \simeq$ 60–160 µm) [1, 2]. Currently, the best temperature performance has been obtained using resonators where the mode confinement is provided by a double-sided metal waveguide [3–5], mostly because of their improved thermal properties. The main drawbacks of this waveguide geometry are the low power extraction and poor beam quality [6], both a consequence of the sub-wavelength radiation confinement [7]. However, contrary to standard dielectric or even one-sided surface plasmon waveguides, extensively used for mid-infrared (mid-IR) and THz QCLs, metal-metal waveguides offer the opportunity of reducing to a minimum the active-region (AR) thickness without sacrificing the confinement factor, which remains always close to unity [8]. The propagation losses increase when the AR is thinner due to a stronger mode penetration into the metal layers, but if thin contact layers are employed ($\simeq$ 100/200 nm) the losses can be kept reasonably low, as is shown in Fig. 1. From the Figure we can predict an increase of the total losses ($\alpha_{mirror}+\alpha_{waveguide}$) of approximately 40/50% when the active region is reduced from $\simeq$12 to $\simeq$6 µm. The mirror losses are $\simeq$0.93 and $\simeq$1.85 cm^{-1}, for AR thicknesses of 6 and 12 µm, respectively, as deduced from [6].

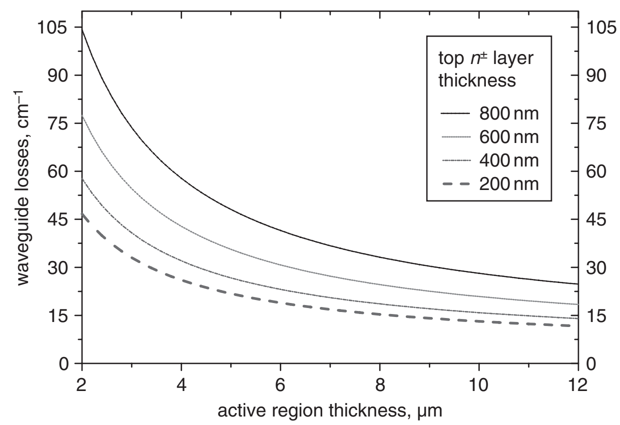

Fig. 1 *Waveguide losses (α_w) against active region thickness for typical metal-metal waveguide and for several different thicknesses of top n^+-GaAs contact layer*

Thickness and doping of bottom contact layer are 80 nm and 5×10^{18} cm^{-3}, respectively. The simulation is one-dimensional and has been performed for $\lambda=115$ µm. The complex indexes of refraction used for simulation are: $n_{Au}=262+i\times411$; $n_{AR}=3.59+i\times3.58E\text{-}3$; $n_{GaAs\text{-}2E18}=4.81+i\times16.36$; $n_{GaAs\text{-}5E18}=7.51+i\times26.23$.

In this Letter we demonstrate THz QC lasers with an AR thickness of 5.86 µm, i.e. approximately a factor of 2 lower than the typical thickness used so far [4–6]. Despite this considerable reduction in thickness, the performance in terms of threshold current density (J_{th}) and maximum operating temperature (T_{max}) does not degrade. Devices that feature reduced-thickness active regions are interesting for several reasons. First, a thickness reduction eases the semiconductor growth, as 10 µm (or more) -thick epitaxial layers already push MBE technology to its limit, and, in the long term, could represent an obstacle to device commercialisation. Secondly, the operating bias scales linearly with the active region thickness and allows one to limit the *total injected electrical power* in the structure. Finally, the stronger mode penetration into the metal layers could ease the implementation of strongly-coupled first- and second-order gratings by the sole patterning of the top metallic contacts.

Sample structure and growth: The sample was grown by molecular beam epitaxy, with active region thickness of 5.86 µm (45 active region/injector stages, sample V298). The active region, designed for emission at 2.9 THz (12 meV) is described in [9], and is sandwiched between 700 nm, 2×10^{18} cm^{-3}, and 80 nm, 5×10^{18} cm^{-3} doped layers forming the lower and upper contacts. Two quantum wells in the injector superlattice were n-doped at levels of 1.3×10^{16} cm^{-3}, while in [9] the doping level was 1.6×10^{16} cm^{-3}. This doping reduction does not have a dramatic effect, but helps to reduce losses by a few cm^{-1}. Finally, a 300 nm-thick $Al_{0.50}Ga_{0.50}As$ etch stop layer was grown between the substrate and the lower contact layer.

Sample processing: The sample was processed in both standard and metal-metal waveguide configurations. In the former case, the lasers were wet etched into ridge cavities 100/160/220/320 µm wide, and 6 µm deep. Ni/Ge/Au/Ni/Au contacts were used as top and bottom metallisation. In the latter case (metal-metal waveguide), the active region was first thermo-compressively bonded (Au-Au bonding) on top of an n^+GaAs host substrate, and the original semi-insulating substrate removed by wet etching. Subsequently the n^+-GaAs top contact was thinned from 700 to 200 nm to reduce the losses (see Fig. 1) and laser ridges were fabricated by wet etching with the same procedure as above. The devices were cleaved into laser bars ($\simeq$2 mm long), indium soldered to copper blocks, wire bonded, and mounted in a continuous flow liquid helium cryostat for device characterisation.

Measurements and results: The experimental results for wafer V298 (5.86 µm-thick AR) are shown in Figs. 2 and 3. Devices from this *same* wafer were fabricated using the metal-metal (Fig. 2) and also the single-surface-plasmon waveguide geometry (Fig. 3). In the former case the J_{th} at 6 K in CW mode is 71 A/cm^2, and the T_{max} is 60 K. In pulsed mode (data not shown) the T_{max} increases to 75 K, while the J_{th} at 6 K remains unchanged. These values represent low threshold current densities and reasonably high T_{max} for this type of active region with metal-metal waveguides [10], demonstrating that it is indeed possible to reduce the epitaxial thickness of THz QC lasers without compromising performance. The results also suggest that further thickness reductions should be possible.

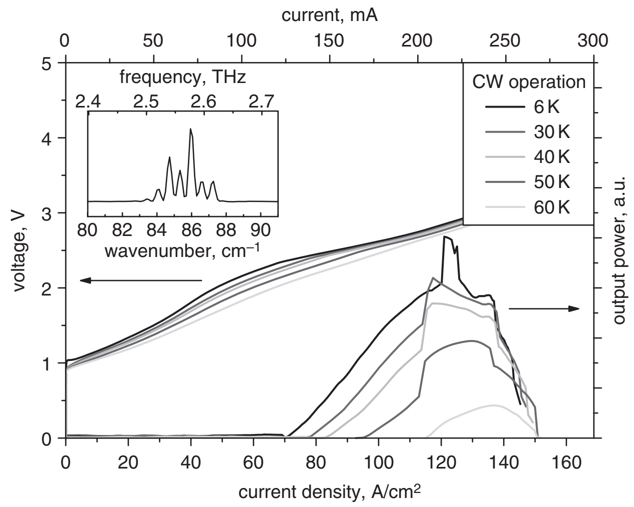

Fig. 2 *L-I-V characteristic (CW) for typical 6 µm-thick (V298) THz QC laser with metal-metal waveguide*

Device 89 µm wide, 2 mm long
Inset: Typical spectrum at 4 K for current $I=209$ mA

When the same wafer is processed as a single-surface-plasmon (Fig. 3), the calculated confinement factor drops from 99 to 17.5%, and the computed waveguide losses drop too from $\simeq$20 to $\simeq$5 cm^{-1}. If the mirror losses for a 2 mm-long ridge are taken into account ($\alpha_{mirror}\simeq5.6$ cm^{-1}), a decrease of the theoretical figure of merit of almost 2.9 times (from 49 to 17) is expected for the single-surface-plasmon device. The experimental results agree only qualitatively with the simulations. Indeed, from Fig. 3 we report a J_{th} of 104 A/cm^2 in pulsed operation at 6 K, which represents an increase of only 40% with respect to the metal-metal waveguide. However the T_{max} is only 50 K in pulsed mode. As explained in [11], it is possible that the predicted J_{th} does not match the experimental value because a parasitic current is present between consecutive active regions at low bias, as suggested by the soft turn-on of the IVs. As a consequence, J_{th} is offset compared to its 'loss controlled' value. This is a common problem for THz QC lasers [4, 11], and it makes the direct comparison of the threshold current densities quite difficult. To support this conclusion we note that typical J_{th} measured at 4 K for a 12 µm-thick AR processed in a single plasmon (see [9]) or metal-metal geometry (unpublished data) are of the order of 80/100 A/cm^2, i.e. comparable to those found here, when, according to the computed figure of merit we would expect a decrease in J_{th} by at least 40/50% compared to a 6 µm-thick AR. Although in the present structure the doping level in the active region is slightly lower (1.3×10^{16} cm^{-3} compared to 1.6×10^{16} cm^{-3}), thus reducing the propagation losses (see Fig. 1), the doping reduction alone cannot explain the low J_{th} values that we observe in the thin-AR devices.

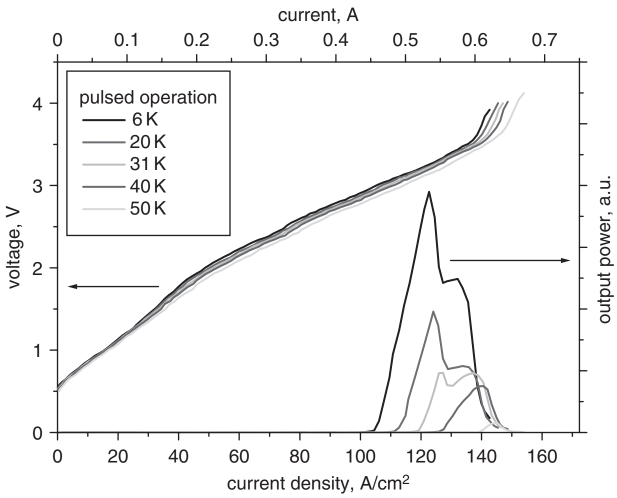

Fig. 3 *L-I-V characteristic (pulsed mode) for typical 6-µm-thick (V298) THz QC laser processed in single-plasmon ridge waveguide configuration*
Device 216 µm wide, 2 mm long

Discussion and conclusions: We have demonstrated THz QC lasers with thin ARs and metal-metal waveguides, yielding low threshold current densities in both pulsed and CW mode. The lack of performance deterioration compared to thicker structures suggests that further reduction of the AR thickness should be possible. Ultra-thin ARs can be advantageous for the implementation of surface-emitting devices, which in principle exploit the laser surface area, and not its thickness, to achieve high power emission. Most importantly, the power consumption is reduced since the operating bias scales linearly with the active region thickness.

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