Pulsed operation of long-wavelength ($\lambda \simeq 11.3\,\mu m$) MOVPE-grown quantum cascade lasers up to 350 K

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Pulsed laser action above room temperature at $\lambda \simeq 11.3\,\mu m$ has been achieved in quantum cascade devices grown by metal organic vapour phase epitaxy (MOVPE). The emission wavelength ($\lambda \simeq 11.3\,\mu m$) is the longest reported for QC lasers grown with this technique. The peak output power at 77 K is approximately 315 mW, decreasing to $\simeq$100 mW at room temperature. The devices display laser operation up to at least 350 K.

Introduction: Recent advances in the field of quantum cascade (QC) lasers have led to dramatic extensions of the operating frequencies and of the material systems available for this technology [1–3]. In addition, the recent emergence of metal organic vapour phase epitaxy (MOVPE) as a viable technique for the growth of QC lasers [4–6], promises to significantly enhance prospects for widespread commercial exploitation of these devices. MOVPE is widely regarded as the industry standard for production-scale epitaxial growth, offering considerable advantages compared with molecular beam epitaxy (MBE), the most commonly-used technique for QCL growth. These include higher growth rates and consequently reduced growth times, long-term stability of growth rates, and better suitability for high-quality InP growth.

Although InP-based, MOVPE-grown QC lasers are a relatively recent development, they have already been shown to challenge the state-of-art MBE-grown device performance at the short wavelength end of the 8–13 µm atmospheric window, in terms of threshold current density, maximum operating temperature and peak power. However, for future applications it is also necessary to demonstrate comparable wavelength agility over the mid-infrared wavelength range. In particular, extension of QCL emission to longer wavelengths requires the growth of samples with thinner barriers, placing higher demands on the control of interface abruptness during the growth process. In the present Letter we report pulsed operation up to $T = 350$ K of MOVPE-grown QC lasers operating towards the far end of the 8–13 µm atmospheric window.

The samples were grown by low pressure (150 torr) MOVPE in a horizontal reactor with a zero-dead-space vent/run valve design. Further details of the growth process can be found in [7]. The sample contains 35 repeats of the following four-well active region + injector structure (beginning with the injection barrier, layer thicknesses in nanometres): **3.4**/2.6/**0.8**/7/**0.8**/6.7/0.**8**/6.3/**1.9**/4.5/**1.1**/4.4/**1.1**/4.4/**1.2**/<u>4.3</u>/**<u>1.6</u>**/<u>4.3</u>/**<u>2.0</u>**/4.0/**2.1**/3.7, where bold numbers refer to $Al_{0.52}In_{0.48}As$ barriers, roman type to $In_{0.53}Ga_{0.47}As$ wells, and the underlined layers are n-doped to $1 \times 10^{17}\,cm^{-3}$. The stack of active regions + injectors is sandwiched between doped InP layers that constitute the waveguide claddings [7].

Fabrication: The samples were processed as standard Fabry-Perot ridge resonators with cleaved facets. The ridges were defined by contact optical lithography, and the semiconductor material was then etched with an HBr-based wet etch. A SiN layer (300 nm thick) was used to provide electrical insulation. After opening of the insulating layer on top of the laser ridges through reactive ion etching, Ti/Au contacts were deposited by Ar-assisted sputtering. Following polishing and back contact deposition, the devices were cleaved, mounted on copper blocks, bonded and loaded into a cryostat for the measurements. Fig. 1 (inset) shows a typical scanning electron microscope image of the facet of a device. The ridge top widths were 10, 14, 18 and 22 µm, with widths at the active region typically 2 µm larger.

Characterisation: The lasers were tested in pulsed mode (100 ns pulse width, 84 kHz repetition rate for laser spectral measurements, and 50 ns at 5 kHz for light-current characterisations). A mercury cadmium telluride (MCT) detector was used for spectral analysis, while a calibrated thermopile was employed to determine the output power. A current-voltage characteristic at 78 K of a typical device is shown in Fig. 1, with a threshold voltage of $\simeq$8 V. For the largest ridges ($\simeq$24 µm) the onset of lasing occurs at a current of $\simeq$0.35 A – corresponding to a threshold current density $J_{th} = 1.05\,kA/cm^2$ – and at a wavelength $\lambda = 10.75\,\mu m$ (Fig. 2*a*). The spectra are always multimode, and they exhibit clear Fabry-Perot fringes. The effective index obtained from the Fabry-Perot fringes spacing is $n_{eff} = 3.4$, close to the waveguide calculation which yields a slightly lower value $n_{eff} \simeq 3.2$. With increasing temperature the emission spectra shift to longer wavelengths (Figs 2*b* and *c*) up to $\lambda \simeq 11.3\,\mu m$, still exhibiting many clear Fabry-Perot fringes. The lasers operated up to temperatures of at least 350 K (Fig. 2*c*), the maximum achievable temperature being limited by the sample holder heater and not by the devices.

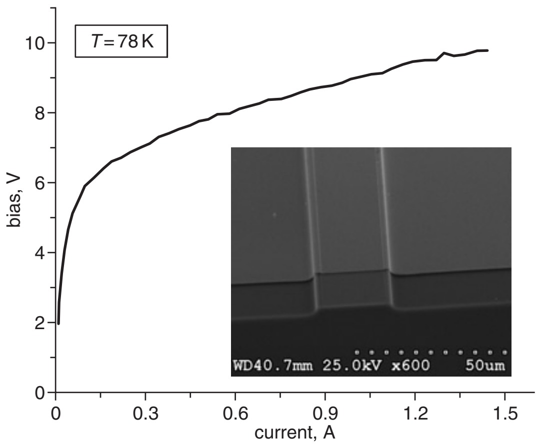

Fig. 1 *Current-voltage characteristic at 78 K of ridge laser device (width = 24 µm, length = 1.5 mm)*
Differential resistance, when structure aligned, $\simeq 2.8\,\Omega$
Inset: Scanning electron microscope image of cavity facet of typical device

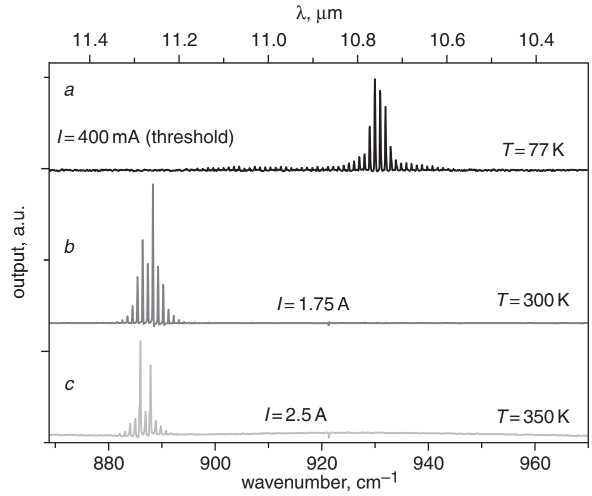

Fig. 2 *Spectra of selected devices at 77, 300, 350 K*
a 77 K
b 300 K
c 350 K
Spectra acquired in rapid-scan using Fourier transform infrared spectrometer equipped with external nitrogen cooled MCT detector. Devices operated in pulsed mode (pulsed width = 100 ns, repetition rate = 84 kHz). Effective index of refraction deduced from Fabry-Perot fringes is $n_{eff} = 3.4$

The peak power light-current curves at 78 and 300 K are plotted in Fig. 3. The power is reported without any correction due to the collection efficiency, which we estimate to be $\simeq$50%. A peak power of more than 300 mW is obtained at 78 K, while at room temperature we measured almost 100 mW. At 350 K the devices still emit few mW output power. The slope efficiencies at 78 and 300 K are 130 and 60 mW/A, respectively.

Finally, for narrower ridges we observed an increase of the threshold current density (a factor of 2.5 for 12 µm-wide ridges). The increased losses in these narrower devices result from the deeper penetration of the optical mode into the lossy SiN insulating layer and metallic contacts on the ridge sidewalls.

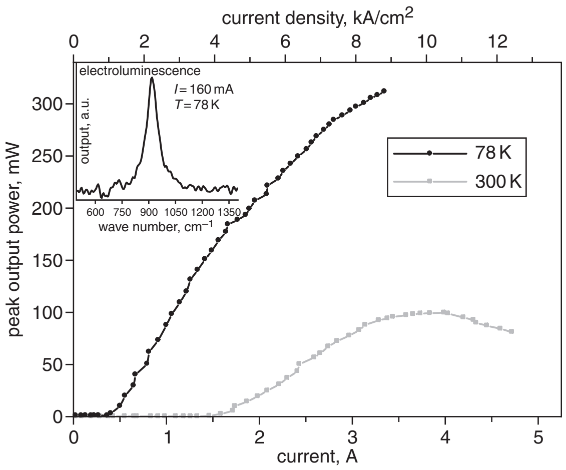

Fig. 3 *Light-current characteristic of typical device (ridge width = 24 μm, cavity length = 1.5 mm) at 77 and 300 K*

Measurements performed in pulsed mode (50 ns pulses, 5 kHz repetition rate). Power measured using calibrated thermopile detector
Inset: Electroluminescence spectrum below threshold
FWHM $\simeq 80\ \mathrm{cm}^{-1}$ (10 meV), indicating good uniformity between active regions. Measurement performed in step-scan using Fourier transform infrared spectrometer equipped with external MCT detector. Resolution set to 8 cm^{-1}

Conclusion: We report pulsed, above room-temperature operation of $\lambda \simeq 11.3$ μm QC lasers grown by MOVPE. The devices display laser action up to at least 350 K, with peak optical powers of a few hundred mW at 77 K, and $\simeq 100$ mW at room temperature. The maximum achievable temperature is limited by the sample holder heater and not by the devices. Further improvements are expected by using SiO_2 instead of SiN as insulating material owing to lower absorption losses at these long wavelengths. In turn this will allow very narrow ridges continuous-wave operation.

Acknowledgments: We thank S. David and J. Palomo for technical support. R. Colombelli and V. Moreau acknowledge support from the European Science Foundation, through the EURYI 'Young Investigator Award' programme. This work is supported by the UK Engineering and Physical Sciences Research Council (EPSRC).

 5 September 2005
Electronics Letters online no: 20053190
doi: 10.1049/el:20053190

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