Double-metal waveguide $\lambda \simeq 19\,\mu m$ quantum cascade lasers grown by metal organic vapour phase epitaxy

J.A. Fan, M.A. Belkin, M. Troccoli, S. Corzine, D. Bour, G. Höfler and F. Capasso

Quantum cascade lasers designed to emit at $\lambda \simeq 19\,\mu m$ grown by metal organic vapour phase epitaxy are demonstrated to operate in pulsed mode up to 170 K. The structures are processed into a double-metal waveguide that enhances mode confinement while minimising waveguide losses. The performance of the material grown at rates of 6 and 1 Å/s is compared. The devices constitute the longest-wavelength quantum cascade lasers grown by metal organic vapour phase epitaxy to date.

Introduction: Since their development in 1994, quantum cascade lasers (QCLs) [1] have undergone improvements in electronic and waveguide structure, which have resulted in enhanced lasing power, temperature performance and wavelength range. Currently, QCLs have been demonstrated to operate in the mid-infrared ($\lambda = 3$–$24\,\mu m$) and terahertz (60–300 μm) spectral ranges. Mid-infrared QCLs are currently used for several applications, particularly in the field of trace gas detection [2]. Historically, QCLs have been grown by molecular beam epitaxy (MBE). Recently, metal organic vapour phase epitaxy (MOVPE) grown mid-infrared QCL structures have been demonstrated [3]. MOVPE is well suited for commercial application, given its ability to support fast growth rates (1–5 μm/h), low defect densities and multi-wafer deposition. Over the past several years, QCLs grown by MOVPE have been shown to produce performance comparable to that of the MBE-grown devices for wavelengths between 5 and 12 μm, providing continuous-wave operation with hundreds of milliwatts of output power at and above room temperature [4, 5]. It is important to demonstrate the applicability of MOVPE growth technique to longer wavelength QCLs. The extension of QCL emission to longer wavelength requires the growth of samples with thinner barriers, which demands better control of layer thickness and high interface abruptness.

In this Letter, we report pulsed operation of $\lambda \simeq 19\,\mu m$ quantum cascade lasers grown by MOVPE, which represent the longest wavelength semiconductor lasers grown by MOVPE to date.

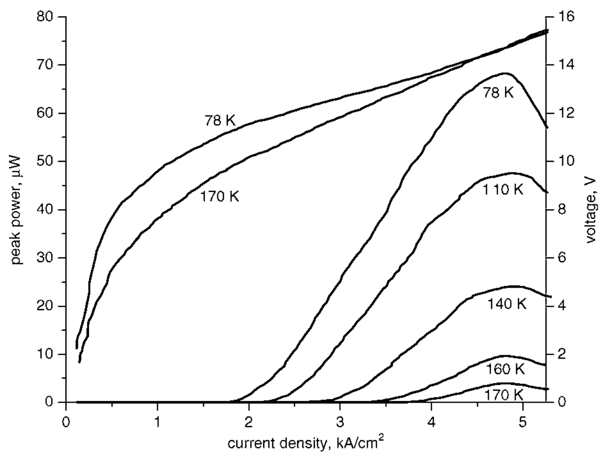

Fig. 1 *Light–current (bottom and left axes) and current–voltage (bottom and right axes) characteristics of device processed from material grown at 1 Å/s obtained at different temperatures*

Light–current data is not corrected for estimated 10% collection efficiency

Experiment: The active region design is based on the layer sequence described in [6]. The injector doping in our device was reduced by a factor of two (to $n_s \sim 1.36 \times 10^{11}\,cm^{-2}$) in comparison with that in [6]. As indicated in [7], this helps to improve the temperature performance of the devices. The growth started on Fe-doped high-resistance InP substrate with 0.3 μm-thick InP layer Si-doped to $10^{17}\,cm^{-3}$, followed by 10 nm-thick layer of InGaAs Se-doped to $3 \times 10^{19}\,cm^{-3}$, 40 nm-thick layer of InGaAs Si-doped to $10^{17}\,cm^{-3}$, 75 repetitions of the active region multilayer, 40 nm-thick layer of InGaAs Si-doped to $10^{17}\,cm^{-3}$, and finally 10 nm-thick layer of InGaAs Se-doped to $3 \times 10^{19}\,cm^{-3}$. Two wafers were grown: a 'fast-grown' sample was grown at the rate of 6 Å/s and a 'slow-grown' sample was grown at the rate of 1 Å/s. The lasers were processed as double metal waveguides following the procedure detailed in [8], then cleaved, indium-soldered on Ni/Au plated copper blocks, and bonded for testing.

A calibrated helium-cooled silicon bolometer was used as a detector. Lasers were mounted in a liquid-nitrogen flow cryostat and tested in pulsed mode with 50 ns long pulses at 100 kHz repetition rate, with an additional modulation at 600 Hz, necessary to accommodate the slow response of the bolometer. Light was collected using two 2-inch parabolic mirrors: one with a 5 cm focal length to collect the light from the lasers and the other with a 10 cm focal length to refocus the light into the detector.

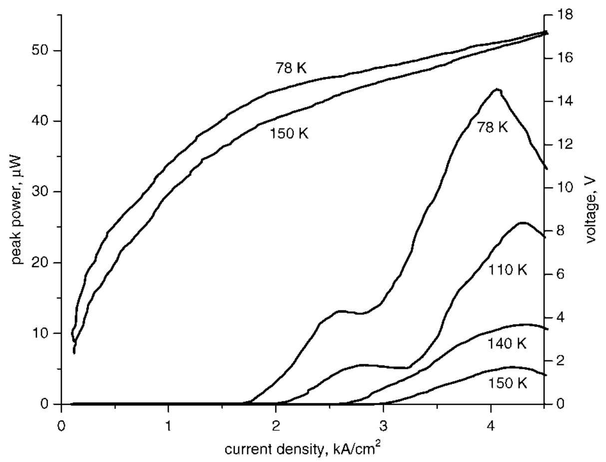

Fig. 2 *Light–current (bottom and left axes) and current–voltage (bottom and right axes) characteristics of device processed from material grown at 6 Å/s obtained at different temperatures*

Light–current data is not corrected for estimated 10% collection efficiency

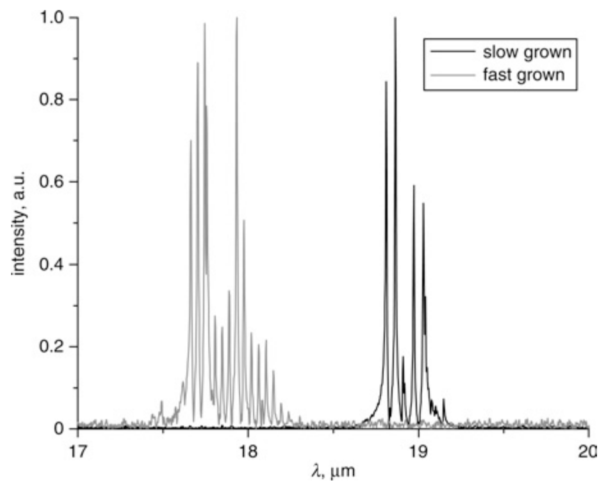

Fig. 3 *Emission spectra of slow- and fast-grown devices obtained at 80 K in pulsed mode*

Devices operated at peak currents of 4.5 and 4 A, respectively

Results: Fig. 1 shows the light–current (L–I) and current–voltage (I–V) characteristics of a slow-grown structure with a 1 mm-long and 50 μm-wide ridge. The device achieved a maximum operating temperature of 170 K with ~70 μW of peak power reaching the bolometer. Fig. 2 shows the L–I and I–V characteristics of a fast grown structure with a 1.5 mm-long 35 μm-wide ridge. The device achieved maximum operating temperature of 160 K with ~45 μW of peak power reaching the bolometer. Upon comparison of the fast and slow grown structures, the threshold currents for both are comparable, with the slow-grown structure threshold at 1.85 kA/cm² and the fast-grown structure threshold at 1.75 kA/cm² at 80 K. However, the slow-grown structure has somewhat better power and temperature performance. Fig. 3 shows the spectra of the fast- and slow-grown structures. The spectra are multimode as expected from Fabry-Perot structures. The emission wavelength of the fast-grown device is shifted to $\lambda \simeq 18\ \mu m$ in comparison to the emission wavelength of the slow-grown device and the MBE-grown devices reported in [6, 7].

The temperature performance of our devices is comparable to that of 10% higher doped MBE-grown structures ($n_s \sim 1.5 \times 10^{11}\ cm^{-2}$) processed as single-metal or double-metal surface plasmon waveguide [7, 8]. In particular, [7] reported a maximum operating temperature of 170 K for the MBE-grown structures processed as single-metal surface plasmon waveguide and [8] a slightly worse (by ~10 K) temperature performance for the devices processed from the same MBE-grown QCL structure into double-metal waveguides. The threshold current density at 80K for our structures is 10% smaller than that reported in [7]. These data demonstrate that the quality of MOVPE-grown long-wavelength QCL material is comparable to that of MBE grown material, even for relatively fast MOVPE growth rates.

Conclusions: We have demonstrated MOVPE-grown QCLs operating at $\lambda \simeq 19\ \mu m$, processed into double-metal waveguides. The lasers processed from a material grown at 1 and 6 Å/s operated in pulsed mode up to 170 and 160 K, respectively. The threshold current density and the temperature performance of the devices were similar to those of similarly doped MBE-grown counterparts. Our devices are the longest-wavelength QCLs grown by MOVPE to date.

Acknowledgment: The structures were processed in the Center for Nanoscale Systems at Harvard University, a member of the National Nanotechnology Infrastructure Network.

23 August 2007
Electronics Letters online no: 20079450
doi: 10.1049/el:20079450

J.A. Fan, M.A. Belkin, M. Troccoli and F. Capasso (*Harvard School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*)

E-mail: mbelkin@seas.harvard.edu

S. Corzine, D. Bour and G. Höfler (*Agilent Labs, 3500 Deer Creek Road, Palo Alto, CA 94304, USA*)

Present address of M. Troccoli and G. Höfler: Argos Tech, 3671 Enochs St, Santa Clara, CA 95051, USA

Present address of S. Corzine: Infinera HQ, 169 Java Dr, Sunnyvale, CA 94089, USA

Present address of D. Bour: Photodigm, Inc., 1155 E. Collins Blvd. #200, Richardson, TX 75081, USA

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