High-power long-wavelength room-temperature MOVPE-grown quantum cascade lasers with air-semiconductor waveguide

Q.J. Wang, C. Pflügl, L. Diehl, F. Capasso, S. Furuta and H. Kan

Quantum cascade lasers grown by metal organic vapour phase epitaxy (MOVPE) with high peak output power of 1.3 W at 300 K emitting a wavelength of 9.8 µm are reported. The devices are processed in wide ridge waveguide structures with an air-semiconductor interface to confine the laser optical mode. This design increases the optical overlap factor and reduces waveguide losses.

Introduction: Quantum cascade (QC) lasers are very important optical sources that can cover the whole mid-infrared range (3–15 µm) for gas sensing, industrial process monitoring, and military applications [1]. They have become even more interesting for commercial applications in recent years because of their successful growth by metal organic vapour phase epitaxy (MOVPE) [2–6] technology, which has a fast growth rate and is compatible with industrial mass production. QC lasers grown by this method have already achieved performance comparable to their molecule beam epitaxy (MBE) counterparts. As continuous-wave (CW) operation for those devices is often desirable for many applications, much attention has been focused on achieving CW operated QC lasers at room temperature [2–7]. For some applications such as remote sensing, however, QC lasers operated in pulsed-mode with high peak output power [8–10] at high temperature are required.

The design requirements for achieving high-power pulsed-operated QC lasers are different from the ones for CW operated QC lasers. In particular, heat dissipation is not as critical in this case as in that of CW operation. Therefore, to achieve high peak output power of QC lasers in pulsed operation, we can increase the number of stages, the waveguide width and the doping level in the active region. A suitable increase of the latter enables high current densities while a large number of stages increases the slope efficiency and the overlap factor of the optical mode with the active region. In addition, broad ridges allow the use of air as a top cladding layer, which helps to reduce the losses compared to structures with top and bottom plasmon confinement layers because of the reduction of free-carrier absorption losses. This is important particularly at longer wavelengths, where the free-carrier absorption in the waveguide layers limits the performance of the devices.

Air-semiconductor waveguide concepts were demonstrated for distributed feedback QC lasers [9, 11] and for devices designed for surface-sensing applications [12]. In the scheme demonstrated here, however, we optimised the structure to obtain a high optical mode confinement (81%) in the active region while keeping an optical waveguide loss (5 cm^{-1}) comparable to a standard waveguide structure with a top plasmon confinement layer [5]. The relevant figure of merit, defined as the optical mode confinement factor over the waveguide loss, is increased by ~17% for the proposed structure compared with the normal waveguide structure. Furthermore, we have chosen a bound-to-continuum design [13,14] for the active region, which has demonstrated high performance at high current densities since fast extraction of the electrons from the lower laser state is achieved.

Device structure and processing: The structure consists of a bottom waveguide cladding of a 1 µm *n*-type doped ($1 \times 10^{18}\ \mathrm{cm}^{-3}$) InP layer and a 2.6 µm *n*-type doped ($5 \times 10^{16}\ \mathrm{cm}^{-3}$) InP layer, followed by a 200 nm-thick *n*-type doped ($3 \times 10^{16}\ \mathrm{cm}^{-3}$) InGaAs layer, a lattice-matched active region, a 200 nm-thick *n*-type doped ($3 \times 10^{17}\ \mathrm{cm}^{-3}$) InGaAs layer, and a top waveguide cladding consisting of a 1.5 µm-thick *n*-type doped ($5 \times 10^{16}\ \mathrm{cm}^{-3}$) InP layer and a thin 10 nm highly doped ($1 \times 10^{19}\ \mathrm{cm}^{-3}$) InP contact layer. The active region consists of 50 stages emitting around 10 µm [13]. The samples were processed into ridge waveguides with standard micro-fabrication techniques. The cross-section of the processed device is shown schematically in the inset of Fig. 1. The ridges were etched around 6 µm deep with $HBr/BCl_3/Ar/CH_4$ plasma in a plasma reactive ion etching machine. A 300 nm-thick Si_3N_4 layer was then deposited and opened on top of the laser ridge. After that, Ti/Au (10 nm/300 nm) electrical contacts were evaporated onto the top of the laser ridge with a 2 µm lateral coverage on each side, with a large central top region not covered by the metal contact layers. This ensures low absorption losses from the Ti/Au contacts. Our calculations show that the lateral current distribution is homogeneous across the entire active region because of the relatively heavily doped *n*-type InGaAs layer grown above the active region. After the substrate was mechanically thinned down to around 260 µm, a back contact of Ti/Au (10 nm/200 nm) was deposited by e-beam evaporation. Lasers with different lengths (0.6, 1, 1.5 and 2 mm) were then cleaved, soldered epilayer up on copper sub-mounts with indium, and wire bonded. Some of the devices were high-reflection (HR) coated on the back facet using Al_2O_3/Ti/Au (200 nm/10 nm/150 nm) via e-beam evaporation.

Characterisation: Fig. 1 shows the light-current (*L-I*) characteristics of an HR coated 30 µm-wide, 1.5 mm-long device operated in pulsed mode (pulse width 100 ns and 20 kHz) at heatsink temperatures ranging from 250 to 350 K. At 300 K, the laser emits up to 1.3 W with a threshold current density of 3.1 kA/cm^2. The device still has a 900 mW peak output power at a temperature of 350 K. The slope efficiency of this device is measured to be 820 mW/A at 300 K. The same device before HR coating has a peak output power about 800 mW per facet with a threshold current density of 3.7 kA/cm^2 at 300 K.

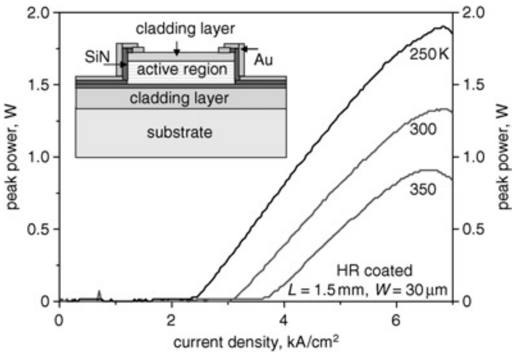

Fig. 1 *LI characteristics of one laser with high-reflection coating at different temperatures*

300 K data measured with power meter directly in front of device. (Data at 250 and 350 K were taken with same device mounted in a cryostat, and corrected for estimated 55% collection efficiency of our cryostat setup
Inset: Schematic structure of processed device, where narrow Ti/Au top contact covers along top of laser ridge with small area on each side

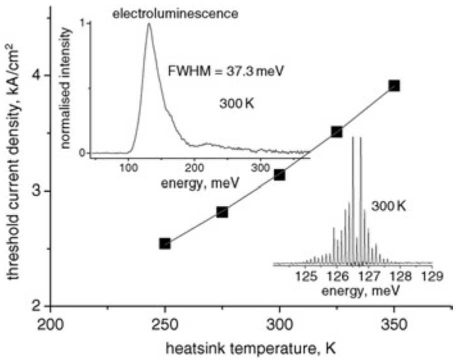

Fig. 2 *Threshold current density of HR coated device against heatsink temperature in pulsed operation*

Solid line is an exponential fit; T_0 is 231 K in pulsed-mode operation
Inset: Electroluminescence spectrum of mesa structure and laser spectrum of peaked at $\lambda \simeq 9.8$ µm device at current density of 3.5 kA/cm^2 at 300 K

The upper inset of Fig. 2 shows the luminescence spectrum of a mesa structure processed from the same wafer. The spectrum is measured with a Fourier transform infrared spectrometer in a step-scan mode at 300 K. The luminescence spectrum has a peak around 9.5 µm at 300 K with a full wave half maximum (FWHM) of about 37.3 meV. This value is relatively large because the active regions [13,14] include many transitions from the upper laser level to the lower energy states. The luminescence spectrum and the FWHM agree well with those obtained from devices with the same bandstructure grown by MBE [14]. This shows that the material grown by MOVPE has a quality comparable to the one grown by MBE. The spectrum of the laser device is also shown in the lower inset of Fig. 2 measured at a current density of 3.5 kA/cm^2 at 300 K, with an emission wavelength around 9.8 μm.

The characteristic temperature (T_0) can be deduced from the increase of the threshold current density with the laser heatsink temperature. As shown in Fig. 2, the solid line is the result of a fit from an empirical exponential function. The data is interpolated in the temperature range from 250 to 350 K. This fit gives a T_0 of about 230 K in pulsed-mode operation. We attribute this high T_0 to the fast electron extraction of the bound-to-continuum design, the high energy difference between the lower laser level and the ground state of the injector, and a good electron confinement in the upper laser level.

Conclusion: We have demonstrated high output power above 1.3 W QC lasers at room-temperature lasing at 9.8 μm grown by MOVPE using an air-semiconductor cladding region above the active region. The same laser has a peak output power above 900 mW at 350 K. The maximum working temperature of the laser exceeds 350 K.

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Q.J. Wang, C. Pflügl, L. Diehl and F. Capasso (*School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*)

E-mail: qijiewang@gmail.com

S. Furuta and H. Kan (*Central Research Laboratories, Hamamatsu Photonics K.K., Shizuoka 434-8601, Japan*)

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