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

Q. J. Wang, C. Pfiffl, 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 layer of a 1.5 mm-wide, 1.5 mm-long device operated in pulsed mode with a peak output power of 1.3 W at 300 K at a temperature of 300 K.

Device structure and processing: The structure consists of a bottom waveguide cladding of a 1 μm n-type doped (1 × 10^{18} cm^{-2}) InP layer and a 2.6 μm n-type doped (5 × 10^{16} cm^{-2}) InP layer, followed by a 200 nm-thick n-type doped (3 × 10^{16} cm^{-2}) InGaAs layer, a lattice-matched active region, a 200 nm-thick n-type doped (3 × 10^{17} cm^{-2}) InGaAs layer, and a top waveguide cladding consisting of a 1.5 μm-thick n-type doped (5 × 10^{16} cm^{-2}) InP layer and a thin 10 nm highly doped (1 × 10^{19} cm^{-2}) InP contact layer. The active region consists of 50 stages emitting around 10 μm.

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.

Characterisation: Fig. 1 shows the light-current (I-L) 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 peak output power of 900 mW 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 1.5 mW at a temperature of 300 K.

The luminescence spectrum has a peak around 9.5 μm with a Fourier transform infrared spectrometer in a step-scan mode at 300 K. The FWHM 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.

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; Tc is 231 K in pulsed-mode operation.

Inset: Electroluminescence spectrum of mesa structure and laser spectrum of peaked at λ ~ 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 37.5 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].
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/cm² at 300 K, with an emission wavelength around 9.8 μm.

The characteristic temperature (T₀) 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 T₀ of about 230 K in pulsed-mode operation. We attribute this high T₀ 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.

Acknowledgments: The authors acknowledge financial support and wafer growth from Hamamatsu Photonics K.K., Japan. The devices were processed in the Center for Nanoscale Systems at Harvard University, a member of the National Nanotechnology Infrastructure Network.

© The Institution of Engineering and Technology 2008

26 February 2008

Electronics Letters online no: 20080543
doi: 10.1049/el:20080543

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

E-mail: qijiiewang@gmail.com

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

References


