Surface-Emitting Single-Mode Quantum Cascade Lasers

M. Austerer, C. Pflügl, W. Schrenk, S. Golka, G. Strasser

Zentrum für Mikro- und Nanostrukturen, Technische Universität Wien, Floragasse 7, A-1040 Wien

We present high power surface-emitting single mode GaAs-based quantum cascade lasers (QCLs) in the mid-infrared. By using an air-AlGaAs waveguide combined with second-order distributed feedback processing, we obtained optical output via the surface above 3W. Surface-normal dual-lobe light emission exceeds the emission from one as-cleaved facet by a factor of six.

Introduction

Significant improvements during the last decade made quantum cascade lasers [1] (QCLs) interesting for many applications, where coherent light emitters in the mid- and far-infrared are required. An important step for the use of these devices was the achievement of single mode emission. This was first demonstrated by processing the lasers as first order distributed feedback (DFB) lasers, where a grating which is imposed on top of the laser selects a single mode within the gain spectrum of the device [2], [3]. Recently, tunable single mode emission was also achieved by grating-coupled external cavity QCLs [4].

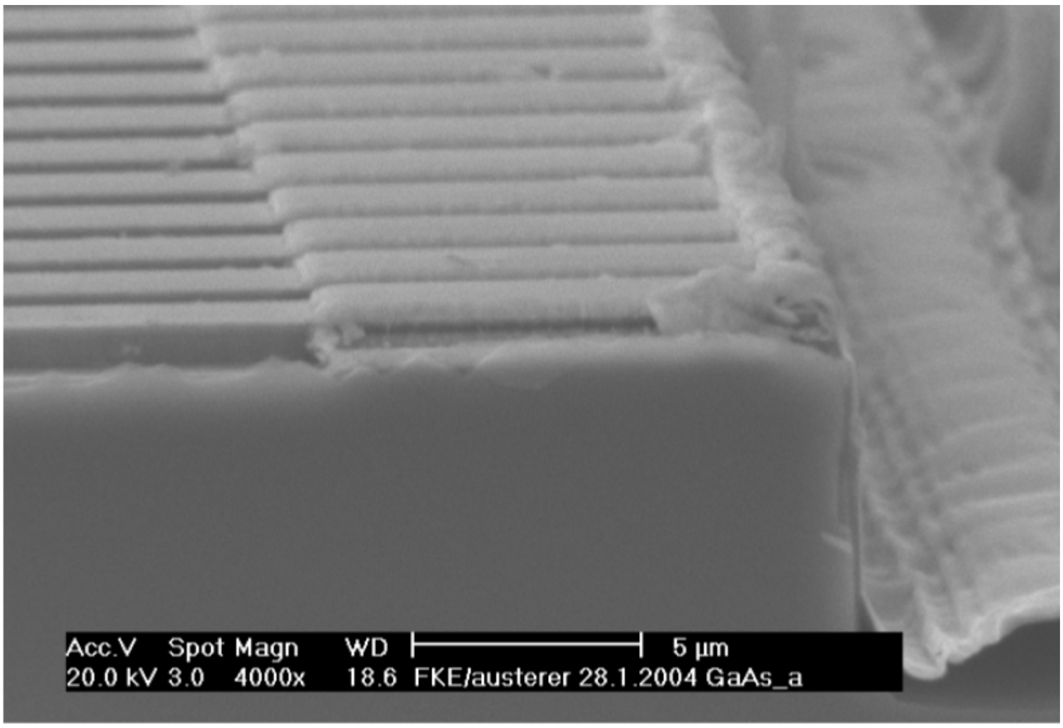

Fig. 1: REM image of the processed DFB laser ridges.

QCLs are based on intersubband transitions. Selection rules for transitions in quantum wells allow gain only for TM polarized electromagnetic waves. Therefore conventional vertical cavity surface emitting laser design is not suitable for QCLs. If one wants to exploit the advantages of surface normal emission another approach must be taken. One successful way to achieve surface emission is to use two-dimensional photonic crystals [5]. We have chosen a distributed feedback design where the feedback is given through a second-order Bragg grating etched into the surface of the laser ridge. Such surface emitting QCLs have been realized both in the InGaAs/InAlAs/InP and also in the GaAs/AlGaAs material system [6], [7]. Appropriate etch depths, a low loss top air cladding and metallization of the grating peaks only, lead to high power surface emission. Surface emitting QCLs have the big advantage that the radiation field could be increased significantly and the beam divergence is reduced.

Design and Characterization

The laser material is grown by molecular beam epitaxy on (100) GaAs substrates. The gain media is embedded in the most cases in a double plasmon enhanced waveguide. Such a waveguide consists of ~1 µm thick highly doped cladding layers (~$4x10^{18}$ cm^{-3}), and ~3.5 µm thick low doped spacer layers (~$4x10^{16}$ cm^{-3}). The highly doped layers are used for light confinement and the spacer layers reduce the penetration of the guided mode into the cladding layers as they show huge free carrier absorption. A surface plasmon waveguide is usually used for long wavelength material ($\lambda > 20$ µm) because of the reduced thickness, which is important for MBE growth.

Different cavity types such as Fabry Perot (FP), distributed feedback (DFB), and cylinder lasers were fabricated. Reactive ion etching was used for directional etching to obtain vertical etch profiles (Fig. 1). SiN is used for insulation and the extended contacts are sputtered. The grating for the DFB lasers was etched into the surface of the top cladding layer and covered with metal. The light is confined by total internal reflection in the case of cylinder shaped lasers. The lasers were soldered with In on Cu plates and wire bonded.

Our laser material is grown by solid source molecular beam epitaxy on n-doped GaAs (Si, $2x10^{18}$ cm^{-3}. The active region consists of 40 cascades of a GaAs/$Al_{0.45}Ga_{0.55}As$ three well design [8]. As a waveguide we have chosen an air/AlGaAs cladding in order to reduce absorption losses compared with a typical double-plasmon waveguide. Our calculations yield a waveguide loss coefficient of $\alpha = 3.8$ cm^{-1}, whereas the structure with a double-plasmon waveguide has α-values of 12 cm^{-1}. The significant reduction of the losses was investigated by comparing the threshold current density of this device with a device (both fabricated as Fabry-Perot lasers) with the same active region but a double plasmon waveguide. The threshold was reduced from 4.1 kA/cm^2 to 2.7 kA/cm^2 at 78 K and from 11.8 kA/cm^2 to 7.8 kA/cm^2 at 240 K, whereas we have comparable output powers and emission spectra. A reduction of the threshold current is favorable concerning the strong self-heating due to the applied current of electrically pumped lasers. In the case of 2^{nd} order DFB lasers a low loss top waveguide is particularly important because the light is coupled out via the surface.

Taking the waveguide structure and the desired wavelength of 8.9 microns into account, a suitable grating period ($\Lambda = 2.8$ µm), duty cycle ($\sigma = 0.5$) and grating depth (1.1 µm) were calculated. The grating was exposed on top of the MBE grown material by means of optical lithography and reactive ion etching (RIE) (see Fig.1). The grating peaks were covered with a metal to provide a homogenous lateral current distribution even for wide ridges. Then the ridges (30 to 70 µm) were defined also by RIE (depth 10 µm). The metal on the grating peaks is actually contacted by side contacts with an overlap of about 8 µm on both sides, resulting in a width of the surface emission window w_{wind} between $w_{wind} = 14$ µm (w = 30 µm) and $w_{wind} = 54$ µm (w = 70 µm). The extended contacts are insulated with SiN. The cleaved laser facets are left uncoated and the laser bars are mounted epilayer up on a temperature controlled cold finger in a flow cryostat.

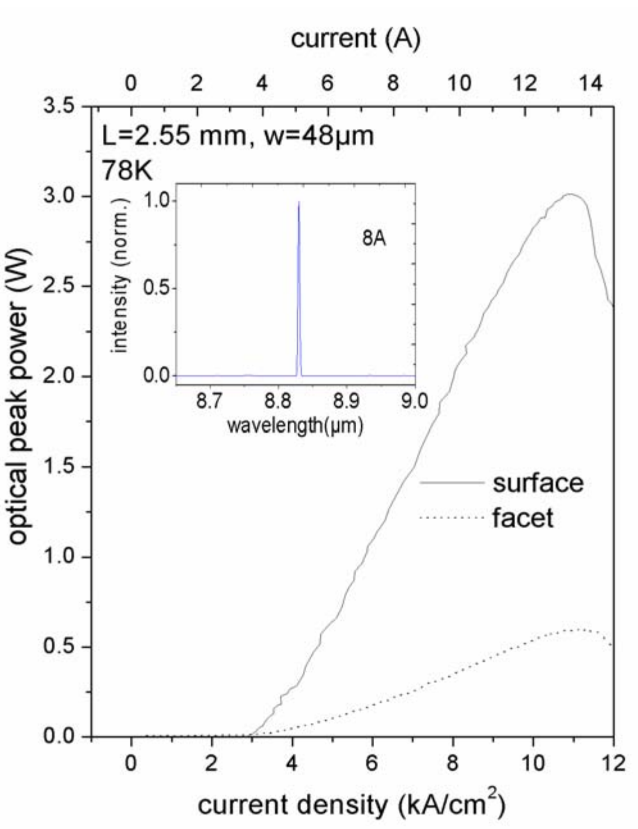

Fig. 2: Absolute light output power versus bias current density for a 2.55 mm long laser at 78 K. The inset shows the spectrum for an applied current of 8 A.

The laser ridges were cleaved to different lengths in order to investigate the critical DFB coupling length. Lasers that are shorter than 1.4 mm, thus having a product of DFB coupling coefficient $\kappa = 7\ cm^{-1}$ and length (cm) smaller than one, do not experience sufficient feedback from the surface grating and are showing typical Fabry-Perot modes. The samples were mounted substrate-down on a turnable cold finger and operated under pulsed bias (100 ns, 5 kHz) at 78 K. By turning the cold finger we could observe both edge and surface emission.

The far field of such lasers exhibits an asymmetric dual lobe pattern, because the near field close to the emitting surface also includes interference terms. An in-detail investigation shows that the relative position of the grating and the end mirrors determines the ratio of the two lobe intensities [9]. The single mode emission wavelength is continuously tunable by the heat sink temperature.

In Fig. 2 absolute light output power versus bias current density for a 2.55 mm long laser is plotted. Single mode emission is observed for all bias currents above threshold (inset of Fig. 2). Light power was measured using a calibrated thermopile detector. We obtained peak output power at 78 K above 3 W via the surface. In the case of edge emission an f/1 AR-coated ZnSe lens was used to collect the light from the highly divergent beam. In both cases the light power was focused onto the thermopile detector by means of a gold coated off-axis parabola. The ratio between surface emission and single-facet emission is determined to be six for this device.

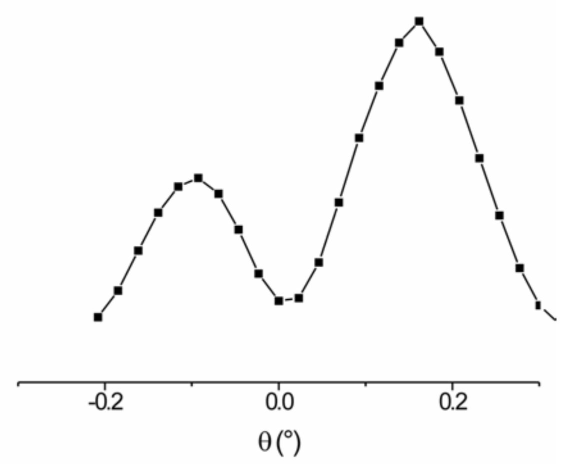

Fig. 3: Far field distribution of the laser emission.

The far field distribution (Fig. 3) of the laser emission was measured using a 1 mm x 1 mm sensitive area liquid-nitrogen cooled HgCdTe detector at a distance of 124 cm away from the laser chip. Lateral resolution of 1 mm results in an angular resolution of 0.046°. The two beam lobes are separated by 0.25° and have an FWHM beam divergence of 0.2° in laser ridge parallel direction. Beam divergence in ridge normal direction is determined by the ridge width, here FWHM beam divergences are in the range of 10° to 20°.

Conclusions

We have shown the high-power capabilities of surface emitting DFB quantum cascade lasers. Single lobe emission surface emission of second order DFB QCLs is proposed by introducing a phase shift into the surface grating. Such low divergence emission pattern would further improve practical usability. In contrary to facet emitters, for many applications no collimating lens would be necessary.

Acknowledgements

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