Whispering-Gallery Quantum-Cascade Lasers in the Terahertz Frequency Regime

Gernot Fasching*, Vincas Tamošiūnas†, Alexander Benz*, Aaron Maxwell Andrews*, Karl Unterrainer*,
Reinhard Zobl‡, Werner Schrenk‡ and Gottfried Strasser‡
*Photonics Institute and Centre for Micro- and Nanostructures
Vienna University of Technology, Florag. 7, 1040 Wien, Austria
Email: gernot.fasching@tuwien.ac.at
†Semiconductor Physics Institute
A. Gostauto 11, 01108 Vilnius, Lithuania and
Vilnius Gediminas Technical University
Sauletekio 11, 10223 Vilnius, Lithuania
‡Institute of Solid-State Electronics and Centre for Micro- and Nanostructures
Vienna University of Technology, Florag. 7, 1040 Wien, Austria

***Abstract*—We discuss the characteristics of microcavity quantum-cascade lasers based on microdisk resonators emitting in the terahertz frequency range. Strong mode confinement in the growth and in-plane directions are achieved by a double-plasmon waveguide and due to the strong refractive index mismatch between the gain material and air. This allows laser emission from devices with extremely small mode volumes. Hence, for the smallest microdisks we achieved a threshold current as low as 4.8 mA. Furthermore, the strong mode confinement allows lasing from ultrasmall devices which have increased temperature performance due to better heat management. We have observed dynamical frequency pulling of the resonator mode on the GHz scale. Thus, we were able to estimate the peak gain of the material to 27 cm^{-1}. We have lifted the natural two-fold degeneracy of whispering-gallery modes leading to a splitting of the resonance frequency. Finite-difference time-domain simulations were performed in order to identify the experimentally observed modes, which confirms that most of observed spectral features can be attributed to the lasing emission of whispering-gallery modes.**

***Index Terms*—terahertz, laser, quantum-cascade, microcavity, sub-wavelength.**

I. INTRODUCTION

Optical microcavities allow to confine light to extremely small mode volumes by resonant recirculation. Critical for the realization of a cavity are a high quality factor Q and small volume V. Deviations from the ideal light confinement is described by the Q factor, which is proportional to the confinement time in units of the optical period. The ratio Q/V determines the strength of the various cavity interactions. The control of the spontaneous emission through the Purcell effect [1] is an important application of microcavities, where spontaneous emission can be accelerated, inhibited or made reversible (strong coupling regime). When the emitting dipole is spatially and spectrally on resonance with the single cavity mode, the emission is enhanced by the Purcell factor proportional to Q/V. The development of fabrication techniques allows to fabricate optical semiconductor microcavities of very high quality which enables to observe cavity effects in these solid-state systems. Semiconductor microcavities can be realized as micropillars, microdisks (both shown in Fig. 1), microrings, microtoroids, and photonic crystals. Especially microcavities based on photonic crystals can provide extremely small mode volumes, but is has been shown that Q values in fabricated structures suffer from vertical leakage, which especially indicates for the terahertz (THz) region that double-metal waveguides might be indispensable. The THz frequency range is very attractive to study cavity effects, as standard fabrication processes allow to realize chip based cavities on the micrometer scale with a surface roughness well below $(\lambda/30)$. Significant progress in device performance and emission frequency range has been achieved for THz quantum-cascade lasers (QCLs) since the first intersubband designs were published [2]–[4]. Beside the proper design of the intersubband states waveguiding plays an important role to achieve lasing in the THz frequency range. A different way to obtain feedback for the stimulated emission of THz light than in Fabry-Pérot cavities is the use of circular shaped microresonators. We have recently demonstrated the first double-metal microdisk and microring QCLs operating in the THz frequency region [5] and also very recently the first single-mode emitting microdisk lasers [6].

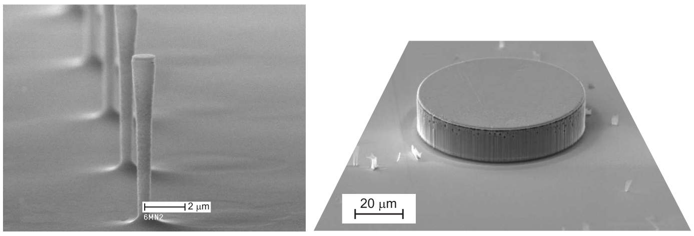

Figure 1. Scanning electron micrograph images of typical semiconductor microcavities where (left) depicts a micropillar with an embedded quantum dot (QD) layer used for single QD spectroscopy in the near-infrared regime and (right) shows a microdisk cavity used for the whispering-gallery QCLs emitting in the terahertz frequency region [7].

In this contribution we present the results of our investigations on ultra-small mode volume THz QCLs based on whispering-gallery modes (WGMs). The reduction of the cavity volume V towards $(\lambda/n_e)^3$, where λ and n_e are the emission wavelength and the effective refractive index has several implications on the emission characteristics and performance of the THz QCLs. Hence, we observed degenerated single-mode and nondegenerated double-mode operation, threshold currents below 5 mA, increased temperature performance, and strong dynamical frequency pulling of the hot resonator mode.

II. SAMPLE DESIGN AND FABRICATION

The band structure design of the $Al_{0.15}Ga_{0.85}As/GaAs$ laser structure is based on the four-quantum well THz QCl scheme introduced by Williams [4] which combines resonant tunneling and fast depopulation of the lower laser level by the use of resonant longitudinal-optical (LO) phonons. In comparison to [5] we reduced the doping down to $n_d = 3.5 \times 10^{15}$ cm^{-3} and slightly increased the thicknesses of GaAs and AlGaAs where the vertical lasing transition takes place to decrease the anticrossing of the upper and lower lasing transitions. Hence, we have strongly decreased the threshold and peak current density of the microdisk THz QCl. The heterostructure was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate with 271 cascaded modules resulting in a thickness of the grown laser structure of 15 μm. The QCL devices were processed into a double-metal configuration, which causes a high modal confinement in vertical direction as well as a high lateral confinement due to the semiconductor-air impedance mismatch and drastically reduces the free carrier losses compared to single-plasmon THz QCLs.

III. RESULTS

As we have achieved lasing from microcavities where the cavity volume $V < 2(\lambda/n_e)^3$, it is especially important to properly design the resonator to allow stable single quasi-resonant modes within the gain bandwidth. We have performed full 3D finite-difference time-domain (FDTD) simulations to find the possible modes in such strong confining microdisk cavities. Fig. 2 shows (a) a calculated spectrum and (b,c) two measured spectra of a microdisk cavity. The calculated mode spectrum exhibits a cavity mode at 2.767 THz which is very close to the experimentally observed single-mode emission at 2.806 THz. In addition we have observed a closely spaced double-mode emission with a spacing below 4 GHz as shown in Fig. 2(c) from other microcavities with the same cavity dimensions under the same measurement conditions. For these cavities we broke the rotational symmetry of the resonator leading to a lifting of the natural two-fold degeneracy of the WGMs causing this double-mode emission. In general, the ability to controllably change the field distribution inside the microcavity would lead to a controllable change of the emission frequency as well as the cavity Q. For these degenerated and nondegenerated lasing emissions we have observed nonlinear shifts of the hot resonator mode as a function of the applied electric field. This can be attributed to frequency pulling of the cold resonator mode towards the gain maximum.

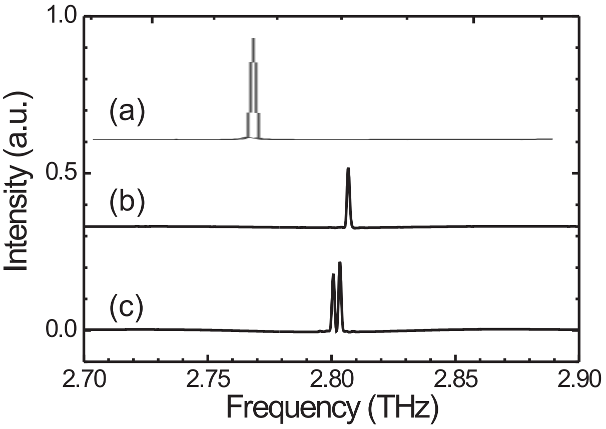

Figure 2. (a) Calculated and (b,c) measured lasing spectra of a microdisk with an outer radius R_{out}=35 μm and a hight $h = 15$ μm. The spectra are shifted vertically for clarity.

As the peak gain shifts with the applied electric field due to the quantum-confined stark-effect (QCSE), the emission depends on the applied electric field. Using a simple two-level model with an Lorentzian shaped gain we were able to fit the experimentally observed lineshifts and approximate the peak gain to 26.6 cm^{-1} [7].

ACKNOWLEDGMENT

The authors acknowledge financial support by the Austrian Science Fund (SFB-ADLIS), the EC Programs “TERANOVA” (IST) and “POISE” (TRM), and the Society for Microelectronics (GME, Austria).

REFERENCES

[1] E. M. Purcell, “Spontaneous Emission Probabilities at Radio Frequencies,” *Phys. Rev.*, vol. 69, p. 681, 1946.

[2] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davis, D. A. Ritchie, R. C. Jotti, and F. Rossi, “Terahertz semiconductor-heterostructure laser,” *Nature (London)*, vol. 417, pp. 156-159, 2002.

[3] G. Scalari, L. Ajili, J. Faist, H. Beere, E. Linfield, D. Ritchie, and G. Davies, “Far-infrared ($\lambda \simeq 87$ μm) bound-to-continuum quantum-cascade lasers operating up to 90 K,” *Appl. Phys. Lett.*, vol. 82, pp. 3165-3167, 2003.

[4] B. S. Williams, H. Callebaut, S. Kumar, Q. Hu, and J. L. Reno, “3.4-THz quantum cascade laser based on scattering for depopulation,” *Appl. Phys. Lett.*, vol. 82, pp. 1015-1017, 2003.

[5] G. Fasching, A. Benz, K. Unterrainer, R. Zobl, A. M. Andrews, T. Roch, W. Schrenk, and G. Strasser, “Terahertz microcavity quantum-cascade lasers,” *Appl. Phys. Lett.*, vol. 87, p. 211112, 2005.

[6] G. Fasching, A. Benz, A. M. Andrews, R. Zobl, T. Roch, W. Schrenk, G. Strasser, K. Unterrainer, and V. Tamošiūnas, “Sub-Wavelength Terahertz Quantum-Cascade Laser Resonators (Presented Conference Paper Style),” presented at CLEO06, Los Angeles, CA, May 21-26, 2006, Paper CTuT3.

[7] G. Fasching, V. Tamošiūnas, A. Benz, A. M. Andrews, K. Unterrainer, R. Zobl, T. Roch, W. Schrenk, and G. Strasser, “Sub-Wavelength Microdisk and Microring Terahertz Quantum-Cascade Lasers,” *IEEE J. Quantum Electron.*, submitted.