IV-VI Semiconductor Based Microcavities and Vertical Cavity Surface Emitting Lasers for the 4 – 6 µm Wavelength Range

W. Heiss, G. Springholz, T. Schwarzl

Microelectronics Institute, Johannes Kepler University Linz, A-4040 Linz, Austria

We have grown IV-VI semiconductor-based mid-infrared microcavities with very high quality factors by molecular-beam epitaxy. The used PbTe/EuTe Bragg mirrors with three to five periods exhibit reflectivities in excess of 99.7%. In a first order microcavity a very narrow Fabry-Perot resonance is observed with a full width at half maximum of 78 µeV. This corresponds to an ultra high effective finesse of 1700. Furthermore, we have demonstrated for the first time vertical laser emission in the 4 – 6 µm wavelength range from an optically pumped lead-salt microcavity.

1. Introduction

Microcavities consisting of high reflectivity Bragg interference mirrors have attracted tremendous interest during the last few years due to their unique physical properties and high potential for device applications. High quality microcavities with mirror reflectivities above 99 % are a prerequisite for vertical cavity surface emitting diode lasers (VCSELs). Other applications, for which moderate reflectivities are sufficient, include resonant cavity light emitting diodes and Fabry-Perot filters and modulators. Microcavities also exhibit interesting physical properties based on quantum optical effects, like cavity polaritons. Up to now the only semiconductors used for the fabrication of microcavity structures are III-V and II-VI compounds. In our present work we have explored the possibilities for fabrication of micro-cavities from IV-VI semiconductors for optoelectronic device applications in the mid infrared.

Laser devices for the mid infrared (MIR) range (2 – 30 µm) are of high interest due to the various gas absorption lines in this region permitting sensitive gas spectroscopy. The typical semiconductors used for that purpose are the lead salts (IV-VI semiconductors). These IV-VI lasers are all edge emitting devices. Thus, we explored the feasibility of surface emitting lead salt lasers in adopting the concept of microcavity lasers and demonstrated for the first time IV-VI vertical cavity surface emitting lasers (VCSELs) at 4.8 and 6.1 µm with high finesse PbEuTe/EuTe microcavity structures [1,2].

2. Microcavities with ultra high finesse

The IV-VI microcavities were fabricated by molecular beam epitaxy on (111) oriented BaF_2 substrates using PbTe and EuTe for the quarter wavelength layers in the Bragg mirrors, and PbTe as cavity material. The advantage of this combination of materials is the very high refractive index contrast of 90 % between the PbTe and EuTe layers. The design of the microcavity structures was based on theoretical calculations using the transfer matrix method, with the dispersion of the refractive indices of the layer materials determined by FTIR transmission measurements. The optical characterization of the multilayer samples was performed with FTIR transmission measurements.

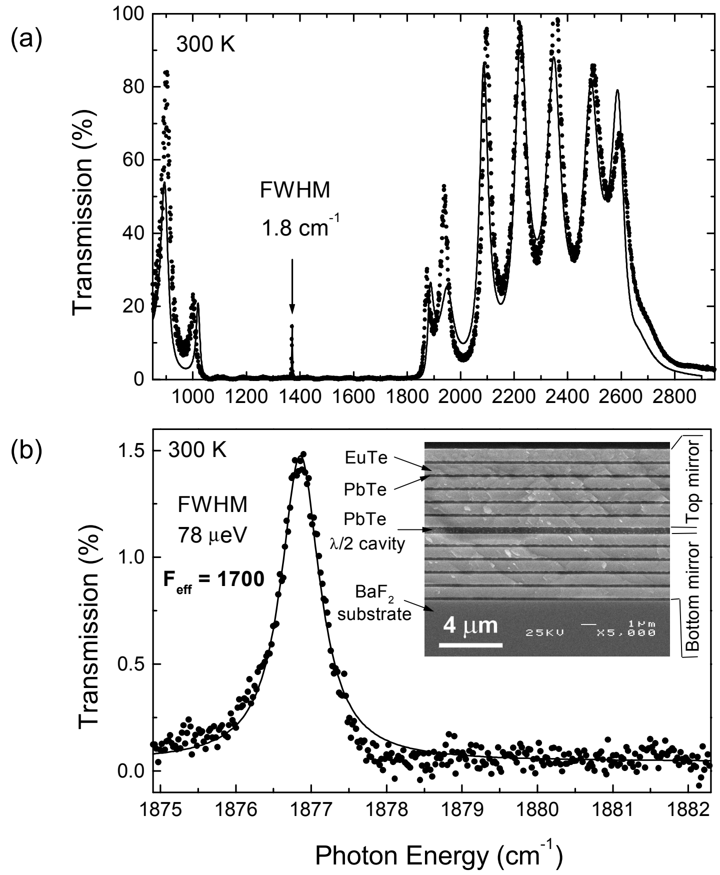

Fig. 1: FTIR transmission spectrum at 300 K of (λ/2) PbTe/EuTe microcavities with (a) a four pair bottom Bragg mirror and a three pair top mirror, and (b) five layer pair bottom and top Bragg mirror. The dots represent the measured data and the solid line the theoretical transmission spectrum calculated by the transfer matrix method. For (b) the peak was fitted with a Lorentzian, which yields a peak width of 0.63 cm^{-1} and an effective finesse of 1700. The inset shows a scanning electron micrograph of the selectively etched cleavage edge of the microcavity structure (b) with an additional (λ/4) EuTe top layer.

Figure 1 (a) shows the FTIR transmission spectrum at room temperature of a microcavity structure designed for an operation wavelength of 7.3 μm. It consists of four PbTe/EuTe Bragg mirror pairs at the bottom and three mirror pairs at the top of the sample, with a half wavelength PbTe cavity in between. The transmission spectrum exhibits a very wide stop centered around the cavity resonance at 1370 cm^{-1} (λ = 7.3 μm). Outside of the stop band Fabry-Perot interference appear with a transmission cut off at 2600 cm^{-1} due to the absorption edge of PbTe. The full width at half maximum (FWHM) of the cavity peak is only 1.8 cm^{-1}, providing evidence for the high quality of the microcavity. The FTIR spectrum around the cavity resonance for a microcavity with *five* PbTe/EuTe quarter wavelength layers as top and bottom mirrors is shown in Fig. 1 (b). The Lorentzian shaped sharp resonance at ν_r =1877 cm^{-1} (λ_r = 5.32 μm) exhibits a

FWHM of only 0.63 cm^{-1}, which corresponds to a cavity quality factor or finesse of 2980. Taking into account the finite penetration of the light into the Bragg mirrors with an effective cavity length of 1.74 for the given refractive index contrast, an *effective* cavity finesse of 1700 can be deduced [3]. This represents by far the highest finesse for any mid-infrared Fabry-Perot cavity reported so far, and even exceeds the best effective finesse value of GaAs/AlAs microcavities.

3. Vertical emitting mid-infrared laser structures

In the following, the fabrication of IV-VI semiconductor vertical cavity surface emitting lasers for the 4 – 6 µm range is demonstrated. The samples were grown by molecular beam epitaxy on (111) oriented BaF_2 substrates and consist of two distributed Bragg reflectors with λ/2 or 2λ microcavities in between. PbTe quantum wells (QWs) are inserted at the antinode positions of the cavity as laser active layers. For one set of samples (A), the Bragg mirrors consisted of PbEuTe layers with alternating Eu concentration [2] and with 18 and 24 periods for the upper and lower mirrors. For the second set of samples (B), the mirrors consisted of $Pb_{0.95}Eu_{0.05}Te$ alternating with EuTe layers. In this case, due to the very high refractive index contrast of over 80 % only three layer pairs are required to obtain ultra-high cavity finesses [1]. The VCSELs were optically pumped with pulsed laser excitation. Strongly forward directed stimulated emission was found at 6.07 µm for samples (A) at 25 K with a line width of 11 nm (370 µeV).

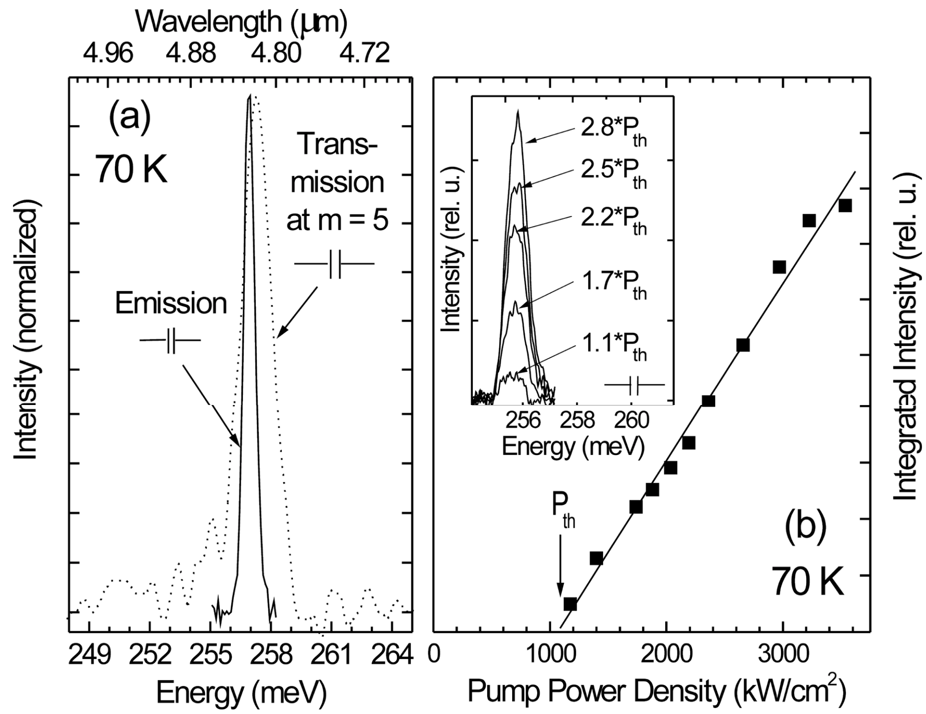

Fig. 2: (a) VCSEL emission spectrum (solid line) and corresponding cavity resonance peak (dashed line) from FTIR measurements at 70 K. The stimulated emission was induced by optical pumping with a $Nd:YV0_4$ laser.
(b) Integrated emission intensity at 4.82 µm versus pump power. The insert shows the emission spectra at various pump powers. The spectral resolution of the measurements is marked by –| |– .

The other VCSEL structure (B) emitted at 4.82 µm at temperatures between 35 K and 85 K (see Fig. 2) with an estimated threshold power density of about 5 kW/cm^2 and an emission line width of only 4 nm (210 µeV). The line widths linearly decrease with increasing pump power, as expected for laser emission. Both emission wavelengths agree with the microcavity resonances, and a pronounced spectral narrowing with respect to the cavity mode is observed. From a detailed analysis of the emission behavior, we find clear evidence that the maximum operation temperature is not due to intrinsic effects but is related to the detuning between the cavity mode and the spontaneous emission of the active material arising from the strong temperature dependence of the PbTe band gap. Therefore, much higher operation temperatures are expected for cavities with resonances matching the spontaneous emission at higher temperatures.

4. Summary

We have demonstrated the fabrication of ultra-high-finesse IV-VI microcavities for the mid-infrared spectral region using high-reflectivity PbTe/EuTe Bragg mirrors. Due to the high refractive index contrast between the materials, only three to five layer pairs are required for reflectivities over 99.7 %. Transmission measurements show one sharp resonance in the center of the mirror stop-band. From the full width at half maximum of the resonance peak, an effective finesse of 1700 was found.

In addition, we demonstrated an optically pumped mid-infrared vertical cavity surface emitting quantum well laser based on IV-VI compounds. Because no cleavage is required for facet formation, these devices can be grown on readily available BaF_2 substrates, which provide major advantages over conventional lasers on lead salt substrates. As a consequence, vertical emitting lasers could lead to higher operation temperatures and lower threshold currents for mid-infrared IV-VI lasers, which opens promising perspectives for device applications.

References

[1] G. Springholz, T. Schwarzl, M. Aigle, H. Pascher, and W. Heiß, 4.8 µm vertical emitting PbTe quantum well lasers based on high finesse EuTe/PbEuTe microcavities, *Appl. Phys. Lett*. **76**, 1807 (2000)

[2] T. Schwarzl, W. Heiß, G. Springholz, M. Aigle, H. Pascher, 6 µm vertical cavity surface emitting laser based on IV-VI semiconductor compounds, *Electronics Letters* **36***,* 323 (2000)

[3] T. Schwarzl, W. Heiß and G. Springholz, Ultra-high-finesse IV-VI microcavities for the mid infrared, *Appl. Phys. Lett.*, **75**, 1246, (1999)