Vertical-Emitting Microcavity Lasers for the Mid-Infrared based on PbEuSe/BaF$_2$ Broad Band Bragg Mirrors

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We report on molecular beam epitaxially grown mid-infrared surface-emitting microcavity lasers operating in continuous wave (cw) mode. The devices are based on high-reflectivity broad band Bragg mirrors consisting of three periods of PbEuSe and BaF$_2$ λ/4 layers. This material combination exhibits a high ratio between the refractive indices of 2.9, leading to a broad mirror stop band with a relative width of 65%. Optical excitation of the laser structures with a PbSe active region results in cw stimulated emission at various cavity modes between 7.3 µm and 5.9 µm at temperatures between 54 K and 135 K. Laser emission is evidenced by a strong line width narrowing with respect to the line width of the cavity mode and a clear laser threshold at a pump power of 130 mW at 95 K.

Introduction

Mid-infrared lasers are of great importance for high-resolution gas spectroscopy due to the numerous absorption lines of almost all molecular gases in this spectral region. Thus, these lasers have a wide range of applications, including pollution monitoring, trace gas sensing, medical diagnostics, time resolved exhaust gas analysis, as well as free space communication. Lead salt diode lasers have long been used in these applications because they cover the whole 3 to 30 µm wavelength region and feature the highest operation temperatures of conventional infrared band gap lasers. This is due to their favorable electronic band structure as well as the two orders of magnitude lower non-radiative Auger recombination rates as compared to those of III-V or II-VI narrow band gap semiconductors. As a consequence, also the first vertical-cavity surface-emitting lasers (VCSELs) for the mid-infrared were developed using the IV-VI semiconductors [1]. VCSELs offer a variety of advantages such as a small beam divergence, single mode operation and the possibility of monolithic integration. The lead salt mid-infrared VCSELs show optically pumped pulsed operation up to a temperature of 340 K and continuous-wave (cw) operation up to 100 K [2]. Here, we present optically pumped cw PbSe VCSELs with PbEuSe/BaF$_2$ broad band Bragg mirrors exhibiting a high ratio between the refractive indices of 2.9. These cw lasers operate at different microcavity modes at temperatures between 54 K and 135 K.

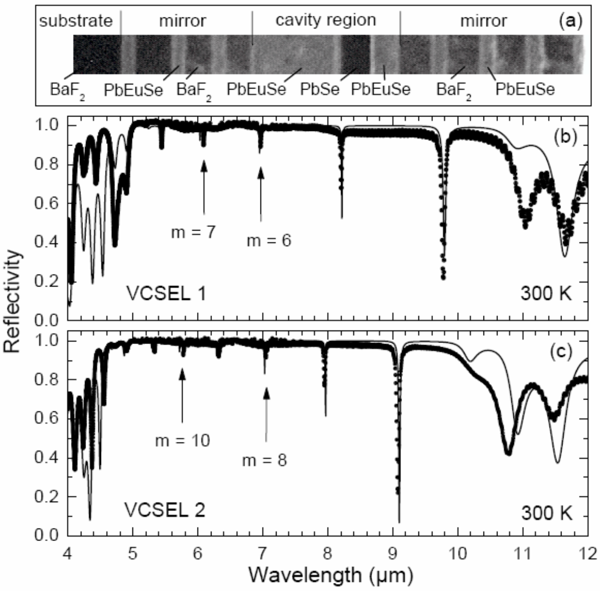

Fig. 1: (a) Cross sectional SEM micrograph of a PbSe VCSEL with PbEuSe/BaF_2 Bragg mirrors. (b), (c) FTIR reflectivity spectra of two PbSe VCSEL structures ((b) VCSEL 1, (c) VCSEL 2) measured at 300 K (dots). The corresponding transfer matrix simulation is depicted as solid line. The resonances intended for lasing are indicated by arrows and their order m is given.

Experimental

Structure, Design and Experimental Set-up

The laser structures were designed by transfer matrix calculations using the exact dispersion of the optical constants of the individual layer materials as determined by Fourier-transform infrared (FTIR) spectroscopy of reference layers. The structures were all grown by MBE onto (111) BaF_2 substrates. The growth temperature was 380 °C and the growth rate was 1.1 µm/h for all layers. The PbEuSe/BaF_2 high reflectivity laser mirrors exhibit a very large refractive index ratio n_1/n_2 of 2.9 and relative stop band widths $\Delta\lambda/\lambda_c$ of 65 %. Both the refractive index ratio and the stop band width are not only among the largest for MBE grown Bragg mirrors, but also for Bragg mirrors fabricated by other methods with less limitation on the material choice [3]. Compared to the most common III-V semiconductor Bragg mirrors, the refractive index ratio and the stop band width is a factor of 3 and 7 larger, respectively. Such a high index contrast leads to a reflectivity in excess of 99 % for only three layer pairs, thus being suitable for a VCSEL mirror. The laser cavity region is comprised of a PbEuSe buffer layer followed by the PbSe active region. The complete laser structure can be seen in the cross-sectional scanning electron microscopy (SEM) image of VCSEL 1 in Fig. 1(a). The individual parts of the multilayer structure and the materials are indicated in the image. Due to the strong temperature dependence of the IV-VI band gap energy, lead salt VCSELs have to be tailored for a certain operation temperature [1] at which the maximum of the gain has to coincide with the cavity resonance. Here, we have chosen for our structures temperatures between 50 K and 140 K. This temperature range corresponds to the spontaneous emission of PbSe between 7.5 µm and 5.8 µm which therefore, is the design wavelength range for the cavity resonances intended as lasing modes. All samples were characterized by room temperature FTIR reflectivity measurements. The laser samples were optically excited by a CO laser operated in cw mode at a wavelength of 5.2 µm. The emitted light was measured by a liquid-nitrogen-cooled HgCdTe photoconductive detector through a grating spectrometer using lock-in technique.

Results

The reflectivity spectra of the two VCSEL samples measured at room temperature are shown in Fig. 1(b) and (c) (dots). A very broad mirror stop band with almost 100 % reflectivity and pronounced interference fringes outside the stop band are found. Due to the several micron thick cavity region, many cavity resonances appear inside the mirror stop bands. The cavity modes near the center of the stop bands are the intended laser modes because they benefit from the highest mirror reflectivities. These resonances are indicated by arrows in Fig. 1(b) and (c). The line widths of the central cavity modes are very narrow with values of about 7 nm demonstrating the high quality of the laser structures.

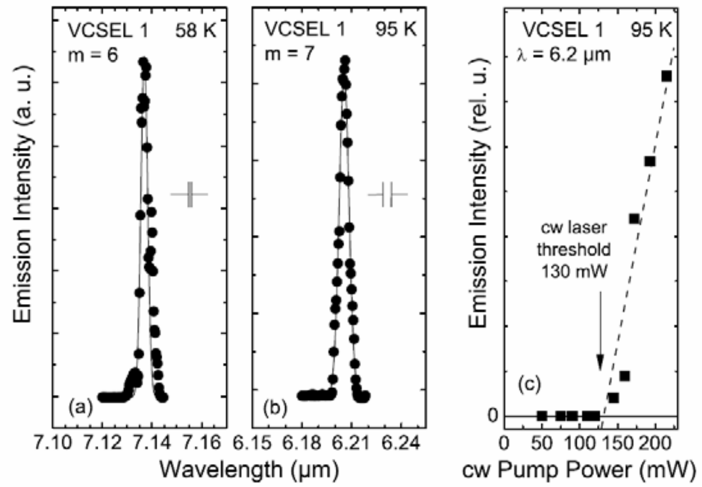

Fig. 2: Laser emission spectra of sample VCSEL 1: (a) mode m = 6 at 58 K, (b) mode m = 7 at 95 K. The lines are Gaussian fits. The spectrometer resolution for each spectrum is denoted by -||-. (c) Emission intensity as a function of the cw pump power for the m = 7 mode at 6.2 µm at 95 K (squares). The laser threshold is indicated. The dashed line is a linear fit to the measured data above threshold.

The optically pumped cw laser emission spectra of VCSEL 1 are shown in Fig. 2(a) and (b). Each of the two central cavity modes gives rise to laser emission at the given design temperatures at which the PbSe spontaneous emission overlaps with the cavity mode [1]. The resonance m = 6 yields its strongest emission at a temperature of 58 K and a wavelength of 7.14 µm, whereas the m = 7 mode emits best at 95 K with a wavelength of 6.2 µm. Both emission lines are fitted with a Gaussian line (solid line), yielding a laser line width of only 2.3 nm and 2.6 nm for the lower and higher temperature mode, respectively. Compared to the line width of the cavity resonances of around 7 nm deduced from the reflectivity spectra, a significant line width narrowing is observed. This is the first strong indication for stimulated emission from the VCSEL structure. One can estimate the expected laser line width by the Schawlow-Townes and Henry formula [4]. Using the measured cavity mode line width of 7 nm, this results in an emission line width (m = 6 mode) of only 0.14 nm at an output power of 0.1 mW [4]. This is a factor of about 20 lower than the measured one, and therefore an indication for additional line width broadening mechanisms present in our VCSEL. However, the Schawlow-Townes formula underestimates the actual laser line width of VCSELs by about one order of magnitude [4]. One such additional broadening effect in our VCSEL could be the interface roughness in the multilayer mirrors, which also broadened the cavity line width. Figure 2(c) depicts the pump power dependence of the emission of the m = 7 mode at 95 K. Obviously, a clear laser threshold at about 130 mW cw excitation power is found with an almost linear intensity increase above threshold and almost no emission below threshold. Therefore, we conclude that the observed spectra represent stimulated laser emission and not just spontaneous emission filtered out of the cavity at the resonance wavelength, which would be not only very weak emission but would display the same line width as the cavity mode and would not show a threshold behavior. The second laser sample VCSEL 2 is similar to the one already described, but is designed for having a laser resonance at a shorter wavelength, thus leading to emission at higher temperatures up to 135 K [4]. The line width of the two measured laser modes are 2 nm and 3 nm, thus showing again the strong line width narrowing as compared to the cavity resonance line width of 7 nm. Furthermore, to our knowledge, 135 K is the highest operation temperature for cw-emission for long wavelength VCSELs with $\lambda >$ 3 µm, which in turn indicates the high quality of our PbEuSe/BaF_2 high-reflectivity broad band Bragg mirrors.

Conclusion

We demonstrated molecular beam epitaxially grown mid-infrared mirocavity lasers operating in continuous wave (cw) mode. The devices are based on high-reflectivity broad band Bragg mirrors consisting of three periods of PbEuSe/BaF_2 layers. Optical excitation of laser structures with a PbSe active region results in cw stimulated emission at various cavity modes between 7.3 µm and 5.9 µm at temperatures between 54 K and 135 K. We evidenced the laser emission by a strong line width narrowing with respect to the line width of the cold cavity mode and a clear laser threshold at a pump power of 130 mW at 95 K.

Acknowledgements

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References

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