Comparison of IV–VI Semiconductor Microcavity Lasers for the Mid-Infrared with Active Regions of Different Dimensionality

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A comparison between IV-VI vertical-cavity surface-emitting mid-infrared lasers containing active regions of different dimensionality is presented. Optically pumped laser emission is observed at wavelengths between 3.5 and 4.4 µm. The microcavities consist of high-reflectivity EuTe/PbEuTe Bragg mirrors, with active regions consisting of either a self-organized PbSe/PbEuTe quantum-dot superlattice, PbTe/PbEuTe multi-quantum wells or bulk-like PbTe. For the 0D active medium, laser emission is obtained at temperatures up to 150 K. The results for the lasers with 2D active region are similar to those with the 3D bulk-like active region, for which lasing is observed up to 317 K. The threshold pump intensity is only 4 kW/cm^2 at 195 K, and 15 W/cm^2 at room temperature.

Introduction

Coherent emitters for the mid-infrared range are of high interest due to various gas absorption lines in this region allowing high-resolution gas spectroscopy. For these applications, typically edge-emitting semiconductor lasers made from lead salt (IV-VI) compounds are used permitting to access emission wavelengths as long as 30 micron at cw operation temperatures as high as 223 K. Apart from the conventional edge-emitting lasers also surface-emitting lead salt microcavity lasers were recently demonstrated. The surface-emitting microcavity lasers offer several advantages over edge emitters, like small beam divergence, single mode operation, and simplified monolithic integration.

Up to now, different types of IV–VI microcavity lasers have been realized based on bulk material, quantum wells, as well as quantum dots as active regions, and with optically stimulated laser emission observed up to temperatures of 290, 340 [1], and 90 K [2], respectively. However, a direct comparison of the performance of the different types of lasers has been hindered by the fact that different cavity structures as well as different excitation sources have been used in these studies. We have done a comparison between IV–VI vertical-cavity surface-emitting lasers (VCSELs) containing active regions of different dimensionality but with a nearly identical optical design of the cavity [3]. In addition, the same optical set-up as well as pump source was used for laser excitation and characterization. This allows studying the influence of the dimensionality of the active material on the laser properties.

Design and Materials Issues

The multilayer VCSEL samples were grown by molecular beam epitaxy on (111) oriented BaF_2 substrates. The microcavity is formed by a high-reflectivity $Pb_{0.94}Eu_{0.06}Te$/ EuTe Bragg mirror with only three layer pairs (bottom mirror) exhibiting a reflectivity above 99 %. This is possible due to the exceptionally high refractive index contrast of up to 80 % between the mirror materials. In order to make the top mirror transparent for the pump wavelength of 1.907 µm, the Eu-content in the $Pb_{1-x}Eu_xTe$ layers of the top mirrors was increased to 30 %. Thus, four layer pairs have to be used to obtain a reflectivity of about 98 %.

The laser active regions consist either of highly-ordered PbSe/PbEuTe self-organized zero dimensional (0D) quantum dot superlattices [2] with 236 periods of 5 monolayers PbSe and 48 nm $Pb_{1-x}Eu_xTe$ (x = 0.05), two dimensional (2D) PbTe/PbEuTe multiquantum wells [1] with nine 20 nm wide PbTe quantum wells (QWs) embedded in $Pb_{0.94}Eu_{0.06}Te$ barrier layers, or three dimensional (3D) bulk-like PbTe with a thickness of 1115 nm grown on top of a 960 nm $Pb_{0.94}Eu_{0.06}Te$ buffer. The cavities are optimized for a wavelength of 3.7 µm, 3.5 µm or 3.3 µm, which are the spontaneous emission wavelengths of the respective active regions at room temperature.

Results

All samples were characterized by high-resolution Fourier-transform infrared transmission measurements clearly showing narrow cavity resonances with line widths between 1 and 3 meV. The VCSELs were optically pumped with 10 ns pulsed laser excitation at a wavelength of about 1.9 micron. The stimulated type of emission from the cavities is evidenced by a clear threshold behavior [3], a considerably line width narrowing with respect to the resonance line width in the transmission spectra [3] and a strongly forward directed emission profile with a divergence smaller than 1° as shown in Fig. 1.

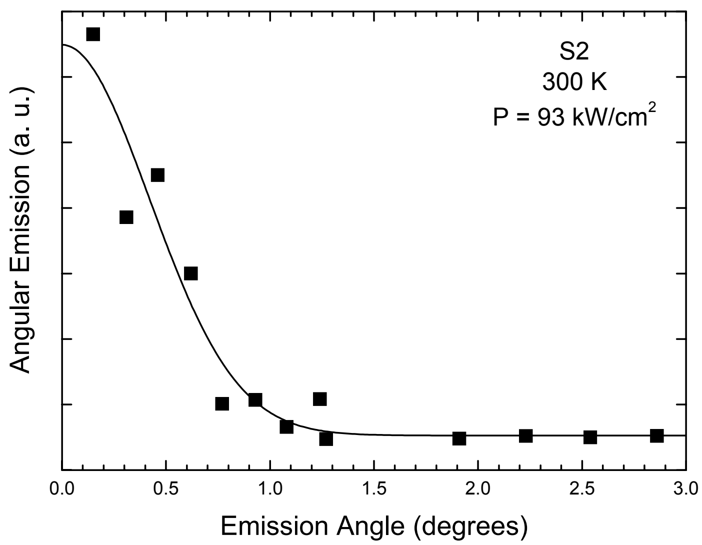

Fig. 1: Laser emission of a QW VCSEL plotted as a function of emission angle at T = 300 K evidencing the strongly forward directed emission with a divergence below 1°.

For the 0D quantum dot active medium, laser emission is obtained between 3.5 and 4 microns at several cavity resonances (due to the large cavity length) at temperatures up to 150 K [3]. The results for the lasers with 2D active regions, as shown in Fig. 2 by the temperature dependence of the laser emission, are similar to those with the 3D bulk-like active regions, for which lasing at 4.4, 3.8 and 3.6 microns is observed up to temperatures as high as 317 K (44 °C) for the 3D active zone and 307 K (34 °C) for the 2D active region. At 307 K the lower edge of the QW gain spectrum shifts out of the cavity resonance frequency and thus the laser operation is quenched as is explained in detail in [1]. It is noted that a similar QW VCSEL with a central cavity mode at higher energy (400 meV) showed laser emission with fs-pulses up to 338 K (65 °C) [1]. The maximum emission intensity of the 3D VCSEL is of the same order of magnitude as that of the 2D VCSEL. Because the gain width in 2D systems is smaller than in 3D systems, the temperature range in which laser emission is observed is smaller for the 2D VCSEL.

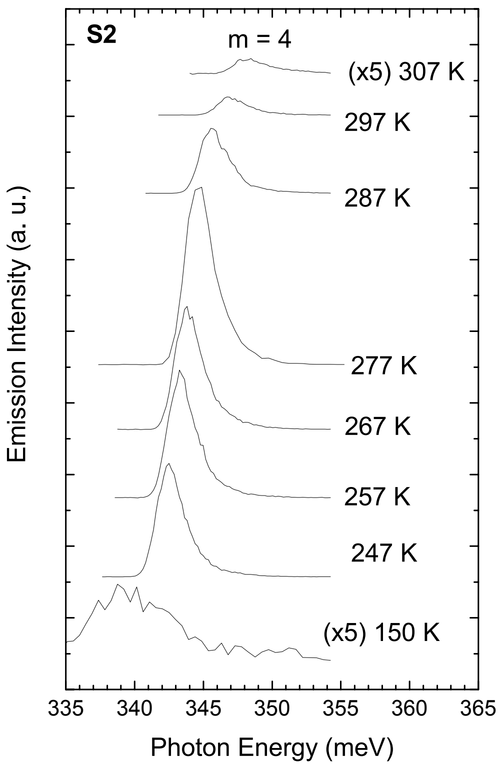

Fig. 2: Emission spectra of the QW VCSEL at various temperatures with constant pump power. The broad emission line at 150 K is due to spontaneous emission.

The threshold pump intensity is only 4 kW/cm^2 at 195 K, and 15.6 kW/cm^2 at room temperature. These values are much smaller than those reported for III-V mid-infrared VCSELs of 235 kW/cm^2 at 260 K, as well as those reported for a bulk-like PbSe VCSEL of about 70 kW/cm^2 at T = 239 K.

Conclusion

In conclusion, above-room-temperature lasing of mid-infrared IV-VI VCSELs with bulk-like PbTe as well as PbTe QWs in the active region was demonstrated up to a temperature of 320 K. The comparison of 0D, 2D and 3D systems in the active region shows that up to now the reduction of the dimensionality does not yield a laser improvement as expected from the squeezing of the wavefunctions. Bulk-like and QW VCSELs show comparable performance. This indicates that the nonradiative recombination losses due to defects are still limiting the laser process. This is obviously more important than the increase of the density of states and localization of carriers in low dimensions.

Acknowledgements

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