Lead-Salt Microcavities for the Mid-Infrared

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Operation of optically pumped IV-VI vertical-cavity surface emitting lasers is reported. The microcavity structures were grown by molecular beam epitaxy on BaF_2 (111) substrates. High reflectivity $Pb_{1-x}Eu_xTe$/EuTe multilayers are used as Bragg interference mirrors of the cavity. Stimulated emission at wavelengths between 3 and 4.5 µm is generated either in PbTe quantum wells embedded at the antinode positions of the microcavity or in correlated, self-organized PbSe quantum dots.

1. Introduction

Narrow band gap IV-VI semiconductor compounds (lead salts) are important materials for optoelectronic devices for the mid-infrared (MIR) spectral region (3 – 30 µm). As a result of their favorable band structure, lead salt diode lasers were obtained with cw operation temperatures up to 223 K [1] and up to 60 °C in pulsed mode [2]. This represents the highest cw operation temperature for electrically pumped MIR diode lasers. The major application for such lasers is high resolution and high sensitivity chemical gas analysis as well as atmospheric pollution monitoring. This is due to numerous absorption lines of many gaseous molecules in the MIR range.

Apart from the conventional edge emitting lasers, very recently, surface emitting lead-salt mid-infrared microcavity lasers were demonstrated for the first time [3]. These vertical cavity surface emitting lasers (VCSELs) offer several advantages like a circular output beam with small divergence, single mode operation, and the possibility of high monolithic integration. In addition, VCSELs offer the possibility for reducing the threshold currents and increasing operation temperatures.

In this work, lead-salt VCSELs working in the wavelength range between 3 and 4.5 µm are presented. With optical pumping, pulsed laser operation is demonstrated up to a temperature of 65 °C. In addition, stimulated emission from correlated, self organized PbSe quantum dots, embedded between PbEuTe/EuTe Bragg interference mirrors is shown. This is of high interest since quantum dot lasers have been predicted to yield strongly increased material gain and differential gain, lower threshold currents, higher modulation band widths and better temperature stability as compared to quantum well lasers.

2. Sample details

The microcavity structures were grown by molecular beam epitaxy (MBE) on (111) oriented BaF_2 substrates. Sample 1 consists of a $Pb_{0.94}Eu_{0.06}Te$ cavity with a thickness corresponding to two times the optical wavelength (λ) with nine inserted PbTe quantum wells (QWs). The cavity is embedded between two dielectric Bragg mirrors. The bottom mirror consists of three periods of $Pb_{0.95}Eu_{0.05}Te$/EuTe $\lambda/4$ layer pairs. Because of the very high refractive index contrast of the layers of more than 80 %, this yields a mirror reflectivity of more than 99 %. To enable optical pumping, the top mirror has to be transparent at the pump wavelength. Therefore, the Eu content in the ternary layers of the top mirror was increased to 20 %. This leads to a reduced refractive index contrast, so that four layer pairs had to be used to obtain a reflectivity of 98 %. As active laser material, nine 20 nm wide PbTe QWs were inserted in the cavity close to the five antinode positions of the electric field.

Sample 2 contains a superlattice of correlated, self-organized PbSe quantum dots between the two dielectric Bragg mirrors. These are formed during heteroepitaxial growth of PbSe on $Pb_{1-x}Eu_xTe$ (111) due to the 5.4 % lattice mismatch [4]. Due to the strong increase of the $Pb_{1-x}Eu_xTe$ energy band gap with Eu content ($\Delta E_g/\Delta x_{Eu}$ = 4.48 eV at 4 K), a quantum confinement of the free carriers in the PbSe dots is achieved already for Eu concentrations of a few percent. We have chosen x_{Eu} = 5%, the same concentration as used for the growth of the mirrors. To obtain PbSe dots with an areal dot density of about 5 x 10^{10} cm^{-2}, an average dot height of 120 Å, a width of 300 Å, and a size dispersion of typically around ±15 %, 5 monolayers PbSe were deposited at a substrate temperature of 360° C whereas the mirrors were grown at 260 °C. Fig. 1 shows a cross section of the sample 2, by a sketch in (a), a SEM micrograph of the complete VCSEL structure in (b), and the PbSe dot arrangement in the superlattice by the TEM images of a reference sample grown under identical conditions in (c).

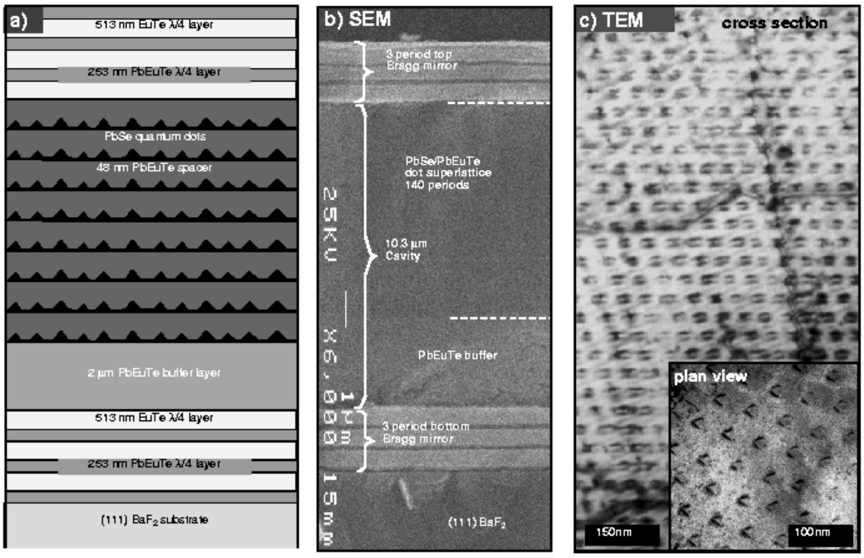

Fig. 1: Schematic representation (a) and cross sectional SEM micrograph (b) of the PbSe quantum dot VCSEL structure. (c) Cross sectional and plan-view TEM micrographs of a PbSe/$Pb_{1-x}Eu_xTe$ dot superlattice reference sample with 5 ML PbSe and 480 Å $Pb_{1-x}Eu_xTe$.

3. Experimental results

For optical pumping of sample 1, we used 100 fs long pulses at a wavelength of 1.97 µm with a repetition rate of 1 kHz. For sample 1 MIR emission can be observed at room temperature. Below laser threshold, the emission spectrum shows a Lorentzian shaped line centered at 3200 cm^{-1} with a width of 160 cm^{-1}. Increasing the excitation density to 1 mJ/cm^{2} results in a considerable narrowing of the emission spectrum and a drastic rise of the luminescence intensity. Both effects indicate the onset of stimulated emission. For excitation powers above 1 mJ/cm^{2} the line width becomes larger again and the integrated emission intensity of the sample linearly increases with rising pump power. Such a linear dependence is expected for laser emission, and it is shown in detail in Fig. 2(a) giving a laser threshold energy density of 0.83 mJ/cm^{2}.

The temperature dependence of the emission spectra of sample S1 excited with an energy density of 8 mJ/cm^{-2} is demonstrated in Fig. 2(b). With increasing sample temperature the laser output intensity at first only slowly decreases until about 55°C above which the intensity rapidly decreases and completely quenches at 70°C. As shown in Fig. 2 (a), with rising temperature also the laser threshold increases slightly from 0.83 mJ/cm^{2} at room temperature to 1 mJ/cm^{2} at 50°C.

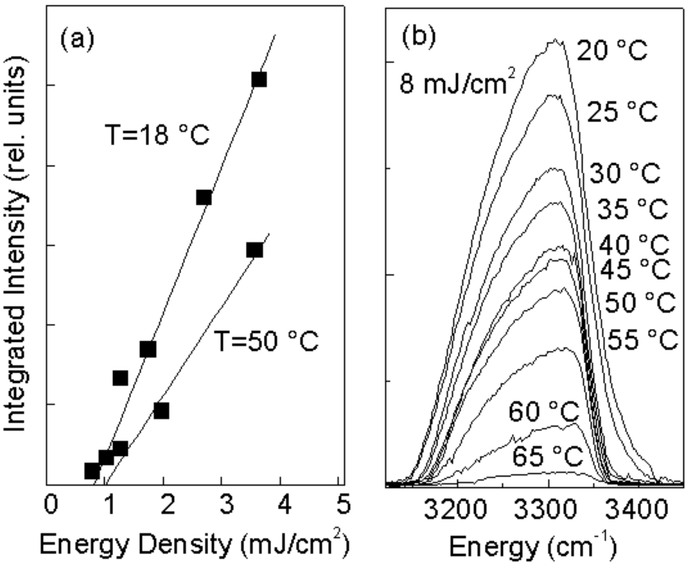

Fig. 2: Dependence of the stimulated emission of sample 1 on excitation intensity (a) and on sample temperature (b). Laser operation is obtained up to 65 °C.

In the following, emission measurements on a superlattice of self-assembled PbSe Stranski-Krastanow islands embedded in a vertical cavity are presented. Because of the large total cavity length of sample 2 a large number of cavity resonance modes are observed within the stop band region. The central m = 28th cavity mode is located at 290 meV (λ = 4.27 µm), corresponding to the low temperature onset of quantum dot absorption measured on $PbSe/Pb_{1-x}Eu_xTe$ reference samples. The stimulated emission spectra of the VCSEL structure induced by optical pumping with a pulsed Nd:YAG laser is shown in Fig. 3. At 1.5 K, simultaneous emission at the m = 28 and 29th order cavity modes at λ = 4.24 and 4.09 µm occurs, with a line width of only 700 µeV. This two-mode laser operation is a result of the inhomogeneous broadening of the quantum dot gain spectrum to dot size fluctuations. Measurements of the integrated output intensity as a function of pump power indicates an external threshold of P_{th} = 510 kW/cm^2. As shown in Fig. 3, with increasing temperature, the intensity of the 29th mode increases whereas that of the central 28th mode decreases and eventually disappears at a temperature of 40 K. As the temperature is further increased, the 29th emission in turn decreases and at 60K the next higher laser mode turns on. At 70 K, the 29th mode completely disappears, whereas the 30th mode emission persists up to 90 K. This successive switching of the laser emission is explained by the increase of the PbSe band gap with increasing temperature. The envelope of the emission lines is given by the inhomogenously broadened dot gain spectrum with a width of about 18 meV. Similar as in PbTe quantum well VCSELs, the upper limit of operation temperature is caused by the detuning between the gain spectrum and the central cavity modes at higher temperatures. This indicates that much higher operation temperatures can be achieved for the dot lasers by appropriate tuning of the optical cavity modes to the dot emission at higher temperatures.

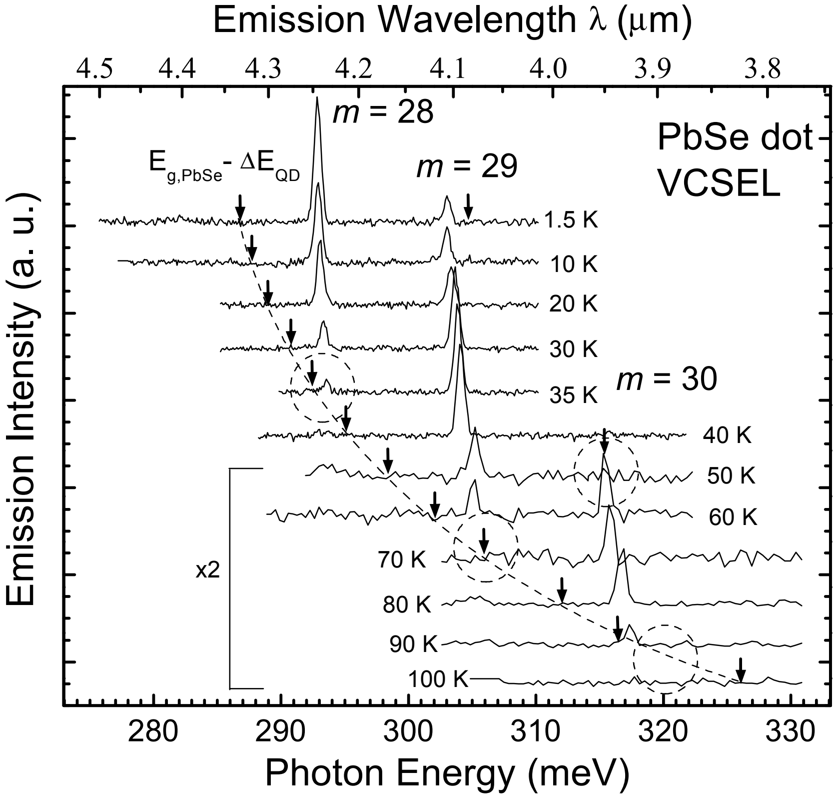

Fig. 3: VCSEL emission spectra at temperatures between 1.5 and 100 K showing the switching of the laser emission to higher cavity modes as the temperature increases. The arrows and dashed line indicate the low energy edge of the quantum dot gain spectrum.

Acknowledgements

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