Lead Chalcogenide Mid-Infrared Vertical External Cavity Surface Emitting Lasers

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Summary

This thesis is a contribution to the effort of providing appropriate laser sources for several applications in the mid-infrared region. The first Vertical External Cavity Surface Emitting Lasers (VECSEL) in the mid infrared range were here demonstrated. To our best knowledge these are the longest wavelengths obtained from VECSELs up to now. They cover a very important gap in the molecular finger print region between 3.5 µm and 6.5 µm.

The VECSELs were realized using narrow gap lead chalcogenide semiconductors. These materials belong to the most suited semiconductors for the fabrication of mid-infrared lasers. They have a direct band gap and they cover the whole mid infrared region from < 3 µm up to > 20 µm wavelength. The active regions have a thickness of multiples of half optical wavelengths (resonant design). They consist either of a homogeneous layer, or Quantum Wells (QW) located at the maxima of the electric field in the layer. Due to the considerable temperature dependence of the band gap values of lead chalcogenides, the design of the VECSELs has to be optimized for a certain temperature range. The VECSELs were optically pumped with a 1.55 µm laser.

Room temperature PbTe VECSELs grown on silicon substrates were demonstrated. They operate in pulsed mode and emit at 3.6 µm wavelength with ~ 1 mWp output power. The maximum
output power was observed at 100 K with 1.2 W<sub>p</sub> in pulsed mode, and 17 mW in continuous wave mode.

In addition, the first single mode and continuously tunable mid-IR VECSELs are reported. The active region is again a one wavelength thick PbTe layer grown on silicon. The emission wavelength is at ∼ 5 µm with a total tuning range as high as 0.4 µm for temperature between 100 and 140 K. Single mode results due to the short cavity (∼ 100 µm), while continuous tuning is achieved by altering the cavity length using piezoelectric drivers.

In order to reach longer wavelengths PbSe as gain medium was also used. Room temperature PbSe VECSELs grown on BaF<sub>2</sub> substrates were fabricated. They operated in pulsed mode and emission was at 4.2 µm wavelength. If optimized for low temperature, 6.5 µm emission wavelength is obtained at T = 100 K.

Quantum well (QW) VECSEL structures offer the lowest threshold powers. In addition, QW blue-shift the emission wavelengths with values depending on the width of the wells. VECSELs using PbSe QW embedded in Pb<sub>0.95</sub>Eu<sub>0.05</sub>Se as barrier layers were fabricated. Threshold power was below 0.2 W at T = 100 K, while laser emission wavelength was at ∼ 4.8 µm.
Zusammenfassung

Diese Arbeit beschäftigt sich mit der Forschung und Entwicklung von IV-VI Halbleiterlasern im mittleren Infrarot. Bleichalkogenide sind eine der am besten geeigneten Halbleitermaterialien für die Herstellung von Lasern in diesem Wellenlängenbereich. Sie besitzen eine direkte Bandlücke und decken den gesamten Bereich des mittleren Infrarot von \( < 3 \, \mu m \) bis zu \( > 20 \, \mu m \) Emissionswellenlänge ab. Die ersten VECSEL (Vertical External Cavity Surface Emitting Laser) im mittleren Infrarot-Bereich wurden im Laufe dieser Arbeit realisiert. Zudem sind dies die VECSEL mit der längsten Emissionswellenlänge.

Die aktiven Schichten bestehen entweder aus einer homogenen Schicht oder aus Quantum wells (QW). Aufgrund der erheblichen Temperaturabhängigkeit der Bandlücke bei Bleichalkogeniden muss das Design der VECSEL jeweils für einen bestimmten Temperaturbereich optimiert werden. Die VECSEL wurden optisch mit einem 1.55 \( \mu m \) Laser gepumpt.

Raumtemperatur PbTe VECSEL auf Silizium-Substrat wurden erfolgreich realisiert. Sie emittieren gepulst betrieben bei 3.6 \( \mu m \) Wellenlänge mit \( \sim 1 \, mW_p \) Ausgangsleistung. Gepulst betrieben wurde eine maximale Ausgangsleistung von 1.2 \( W_p \) bei 100 K erreicht, wohingegen im Dauerbetrieb 17 mW gemessen wurde.
Zusammenfassung

Durch Verkürzung der Kavitätslänge kann der VECSEL mono-mode betrieben werden. Bei Verschiebung des externen Spiegels kann die Wellenlänge der Emissionsmode kontinuierlich abgestimmt werden. Die auf einem Silizium-Substrat gewachsene aktive PbTe Schicht ist optisch eine Wellenlänge dick. Die Emissionswellenlänge liegt bei \( \sim 5 \mu m \) mit einer insgesamt Abstimmung von 0.4 \( \mu m \) für einen Temperaturbereich zwischen 100 und 140 K.

Um längere Wellenlängen zu erreichen wurde auch PbSe als aktives Medium verwendet. Raumtemperatur PbSe VECSEL auf BaF\(_2\) Substraten wurden hergestellt. Sie emittieren im gepulsten Betrieb bei 4.2 \( \mu m \). Mit einer Optimierung für tiefe Temperaturen wurde eine Emissionswellenlänge von 6.5 \( \mu m \) bei T = 100 K erreicht.

Quantum well VECSEL Strukturen zeigten die niedrigsten Schwellwertleistungen. Darüber hinaus kann mit QW eine Blauverschiebung der Emissionswellenlänge erreicht werden, welche abhängig von der Breite der Quantum wells ist. VECSEL mit PbSe QW, eingebettet in Pb\(_{0.95}\)Eu\(_{0.05}\)Se als Barrierschichten, wurden hergestellt. Die Schwellwertleistung lag unter 0.2 W bei T = 100 K, und die Wellenlänge bei \( \sim 4.8 \mu m \).
1 Introduction

1.1 Motivation

The demand for infrared optical sources has been increasing enormously during the last decades. Despite uncountable success in the optoelectronic field, some wavelengths particularly in the mid-infrared range are still especially challenging. Since the strongest absorption lines of many gases lay in this wavelength range (see Fig. 1.1), the mid-infrared (mid-IR) range is also called the molecular fingerprint region.

There are many applications for mid-infrared optical sources for high resolution gas spectroscopy. For instance, in medical analysis, the detection of the existence and the concentration of specific molecules, which are markers for various diseases, is very important. One example is the diagnosis of asthma by detecting traces of NO\textsubscript{x} in the breath analysis [1]. Furthermore environmental and specific pollution monitoring is most sensitive in this wavelength range. This includes hydrocarbons, HCl, CO, SO\textsubscript{2} and many others. However these applications need the appropriate optical sources.

Therefore this work is focused on the fabrication of new mid-infrared optical sources, the so called Vertical External Cavity Surface Emitting Lasers (VECSEL). Our VECSELS are based on
lead chalcogenide material which allow covering the whole mid-IR range.

Lead chalcogenides (PbSe, PbTe, Pb_{1-y}X_{y}Y, x = Eu, Sr, Sn, Y = Se, Te) as gain medium offer the possibility to cover wavelengths ranging from $< 3$ to $> 20 \, \mu m$ as presented in Fig. 1.1. Some important gas absorption lines are included in this figure, too. Note that the $3$ to $5 \, \mu m$ and $8$ to $12 \, \mu m$ atmospheric window lay in this range.

![Wavelength coverage of lead chalcogenides and absorption lines of different gases in the mid-IR](image)

**Figure 1.1:** Wavelength coverage of lead chalcogenides and absorption lines of different gases in the mid-IR [2].

The following chapters of this work describe the principles, the fabrication processes of the VECSEL, and present the achieved results.
1.2 Edge Emitters and V(E)CSELs

The conventional edge emitting diode lasers are characterized by the emittance of their laser beam through the edge parallel to the surface. On the contrary, VCSELs (Vertical Cavity Surface Emitting Lasers) and VECSELs (Vertical External Cavity Surface Emitting Lasers) emit their laser beam perpendicular to the wafer surface. This is achieved by placing a thin (µm thick) gain layer between two high reflecting mirrors. In VCSELs, the structure is monolithic with two plane Bragg mirrors. Contrary, the external cavity of VECSELs allows to use a curved separate second mirror with a radius of curvature R. The ratio R/L (L is the cavity length) determines the mode diameter on the active layer. V(E)CSELs offer several advantages compared to edge emitters.

Unlike the edge emitters VCSELs have a large and circular output aperture, which leads to a circular beam with small divergence angle. This property make them very efficient in coupling into fibers and optical components with minimal losses. Even if the first V(E)CSELs were multi-mode lasers, single longitudinal mode V(E)CSELs have become common devices. Furthermore, it is possible to obtain a transverse single-mode emission with a beam of near circular symmetry. This is in contrast to the highly astigmatic beam of edge emitting diode lasers with large aperture angles in the fast axis.

The V(E)CSELs are also characterized by their relatively low threshold powers compared to edge emitting lasers \[3\]. This is due to the reduced volume of the active region combined with very high reflective Bragg mirrors.
1 Introduction

(a) Edge emitter

(b) VCSEL

(c) VECSEL

Figure 1.2: Semiconductor lasers.

An obvious advantage is the possibility of testing the lasers at different fabrication steps at the wafer level. The geometry of V(E)CSELs allow easy alignment and packaging, which decreases the fabrication costs.

VECSELs are currently of high interest due to their good beam quality, high power and power scalability as well as wavelength tunability. They are used for different applications including intracavity high sensitivity spectroscopy, frequency doubling or mode locking \[4,5\]. An interesting quality in VECSELs is the possibility of tuning the wavelength by changing the cavity length. This will result into single mode continuously tunable VECSELs. For recent reviews of VECSEls in the visible range see \[6\] and in mid-IR \[5\].
1.3 Mid-infrared Semiconductor Lasers: State-of-the-art

**IV-VI Lasers**

Edge emitting IV-VI laser diodes are known since 1964 and are still widely used for mid-infrared spectroscopy [7]. The highest reported CW operation temperature of such devices is 223 K [8]. They are fabricated with bulk IV-VI substrates like PbTe or PbSe. According to theoretical calculations, room temperature continuous wave (cw) emission of IV-VI lasers is possible [9], but is not demonstrated up to now.

More recently, monolithic VCSELs have been described. They are optically pumped and emit in the 4-7 \(\mu\)m wavelength range, and in pulsed mode, up to above room temperature (RT) [12,13,14,15].

**Interband III-V-based Lasers**

Laser diodes emitting at room temperature in CW regime using interband GaSb based Type I structure have been fabricated with wavelength up to 2.8 \(\mu\)m [66,17,18,19]. The use of quaternary material AlInGaAsSb can extend the wavelength up to 3.36 \(\mu\)m [20].

VECSELs have been described for different wavelengths employing interband GaSb based semiconductors. They are typically optically pumped [5,4]. The longest wavelength reached up to now with a VCSEL is \(\sim\) 2.9 \(\mu\)m [21].
Interband Cascade Lasers (ICL)

Interband edge emitting cascade lasers (ICL) use type-II quantum wells as active region in a so called W arrangement. The electrons after making a radiative transition from the conduction band to the valence band are transferred back to the conduction band due to the semi-metallic band alignment between InAs and GaSb \[22\]. Recently, the first room temperature ICL in CW operation has been demonstrated emitting at 3.6 µm wavelength \[23\].

Difference Frequency Generation (DFG)

DFG uses a non linear optical medium (periodically poled LiNbO\(_3\) crystal: PPLN \) to provoke an interaction between two different near infrared lasers. The result of this interaction is the sum or the difference of the frequency of the two pump beams. In the mid infrared region difference frequency generation between a tunable \(\sim 1570\) nm and a 1064 nm lasers generates a tunable \(\sim 3.3\) µm wavelength. Still longer wavelength are achieved by the DFG of 860 nm and 1064 nm lasers resulting in \(\sim 4.5\) µm wavelength. [24,25].

The Quantum Cascade Laser (QCL)

Unlike most conventional semiconductor lasers, quantum cascade lasers (QCL) are based on intersubband radiative transitions in the conduction band. QCLs are well known for the mid-infrared wavelength range. They were predicted in 1972 and first demonstrated in 1994 \[26\]. Nowadays, QCLs operate at room temperature. QCLs are based on lattice matched superlattices (InGaAs/InAlAs or GaAs/AlGaAs) containing at least \(\sim 40\) periods. They cover a wide wavelength range from slightly below 4 µm up to the THz region around 250 µm \[27\]. In more recent develop-
ments, quantum cascade lasers were fabricated with wavelengths of $\sim 3.1 \ \mu\text{m}$ \cite{28}.

The fact that the polarization selection rules are not satisfied for intersubband transitions in case of a VCSEL structure, QCLs remain up to now edge emitters \cite{29}.
1 Introduction
2 IV-VI Materials and Heterostructures

The key properties of lead chalcogenides and the other materials (BaF$_2$, EuTe ..) used in this work are described in this chapter. Approximative models for the radiative and non-radiative recombination processes are given. These models are used to calculate carrier charge density and the material gain.

2.1 Crystal Structure

Lead chalcogenides like PbSe, PbTe, PbS and also EuTe have the NaCl structure (Fig. 2.1). In this work, lead chalcogenide layers are grown by molecular beam epitaxy (MBE). Several substrate types have been used to grow IV-VI materials in the past. The first option is a IV-VI single crystal substrate. However, this type of substrates are very expensive, soft and difficult to handle during the fabrication process. Other different substrates have proven to be more convenient. Very high quality epitaxial lead chalcogenide layers have been grown on BaF$_2$ and Si(111) substrates [30,31,32].

Some properties of these materials are listed in table 2.1. When grown on BaF$_2$, lattice mismatch is 1-5% and there is nearly no thermal mismatch. In contrast when using Si substrates, a huge lattice as well as thermal expansion mismatch has to be overcome.
In addition, IV-VI, BaF\(_2\) and Si have different crystal structures (Fig. 2.2, 2.1).

![Figure 2.1: Two structures: (a) Lead chalcogenide (b) BaF\(_2\) structure](image)

To obtain high quality epitaxial layers a very thin layer of CaF\(_2\) (thinner than the critical thickness for misfit dislocation generation) is employed for compatibility. Si(111) oriented substrates
<table>
<thead>
<tr>
<th></th>
<th>PbSe</th>
<th>PbTe</th>
<th>BaF2</th>
<th>CaF2</th>
<th>EuTe</th>
<th>EuSe</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice constant</td>
<td>a₀ (Å)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.125</td>
<td>6.461</td>
<td>6.19</td>
<td>5.46</td>
<td>6.2</td>
<td>6.6</td>
<td>5.43</td>
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<tr>
<td>Refractive index,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 K</td>
<td>4.92</td>
<td>5.79</td>
<td>1.45</td>
<td>1.40</td>
<td>2.4</td>
<td>2.31</td>
<td>3.4</td>
</tr>
<tr>
<td>Thermal conductivity,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 K (W/mK)</td>
<td>1.7</td>
<td>2.3</td>
<td>10.9</td>
<td>9.7</td>
<td>11</td>
<td>0.24</td>
<td>124</td>
</tr>
<tr>
<td>Band-gap energy,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300K (eV)</td>
<td>0.27</td>
<td>0.31</td>
<td>11</td>
<td>12.1</td>
<td>2.4</td>
<td>1.8</td>
<td>1.107</td>
</tr>
<tr>
<td>Thermal expansion coeff (10⁻⁶K⁻¹)</td>
<td>19.4</td>
<td>19.8</td>
<td>19.8</td>
<td>19.1</td>
<td>13.6</td>
<td>13.1</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 2.1: Material properties properties of Lead chalcogenide Si, EuTe, EuSe, BaF₂ and CaF₂.

are used in order to obtain (111) oriented CaF₂ and IV-VI layers. This is because the main glide system for fluorides and IV-VIs is \(\{100\}<110>\), the glide planes are inclined with respect to the (111) surface. Therefore dislocations can glide. Due to the easy glide of misfit dislocations in the lead chalcogenide layers, thermal strains can relax. In addition, interactions of the gliding dislocations may lead to annihilation of dislocations and therefore to better quality \([34][35]\).
2.2 Electronic Band Structure

Lead chalcogenides (PbTe, PbSe, PbS) and their ternary compositions containing Eu, Sr or Sn are narrow-gap semiconductors. They have a direct band-gap at the L-point of the Brillouin zone. The almost mirror symmetry of the conduction and the valence band gives the electrons and holes almost identical effective masses and mobilities \cite{44,7}.

The band gaps and their corresponding cut-off wavelengths of the lead chalcogenides are quite sensitive to temperature. In Fig. 2.3 the band-gap and the cut-off wavelengths of PbSe and PbTe are plotted as function of temperature. It is possible to tune the cut-off wavelength over more than 2 µm (≈ 30% of the wavelength) by changing the temperature from 100 K to 300 K.

![Figure 2.3: Band-gap and cut-off wavelength of PbTe and PbSe for different temperatures.](Image)
Alloying lead chalcogenide with Sr, Eu or Sn shifts the cut-off wavelengths of the ternary materials. A blue shift result for Eu and Sr, or red shift in the case of Sn. For example the band gap $E_g$ is calculated for $\text{Pb}_{1-x}\text{Eu}_x\text{Se}$ and $\text{Pb}_{1-x}\text{Eu}_x\text{Te}$ by the following empirical formulas [45]:

(for $x < 5\%$ )

- $\text{Pb}_{1-x}\text{Eu}_x\text{Se}$ :
  \[
  E_g(x, T) = 0.001 \cdot (190 + \frac{0.51T^2}{T-56} (1 - 9.8x) + 5880x)
  \]

- $\text{Pb}_{1-x}\text{Eu}_x\text{Te}$ :
  \[
  E_g(x, T) = 0.001 \cdot (146.3 + \frac{0.475T^2}{T+40.7} (1 - 3x) + 3000x)
  \]

where:
- $T$ is the temperature in K and $E_g$ is the band-gap in eV.

![Figure 2.4](image)

**Figure 2.4:** Cut-off wavelength of $\text{Pb}_{1-x}\text{Eu}_x\text{Te}$ (left) and $\text{Pb}_{1-x}\text{Eu}_x\text{Se}$ (right) as function of Eu concentration at different temperatures.

The corresponding cut-off wavelengths are presented for three different temperature in Fig. 2.4. By changing the concentration of Eu in $\text{Pb}_{1-x}\text{Eu}_x\text{Te}$ by only few percents, the cut-off wavelength is shifted by $\sim 40\%$. 

Another property of IV-VI material is given by their ionic bonds (Pb\(^{+2}\) and Te\(^{-2}\)) and their large homogeneity range. Lead rich PbSe or PbTe is n conducting, while the tellurium rich PbTe is p conducting. The absence of a Te atom is the source of two electrons, while the absence of a Pb atom is the source of two holes \[46\].

### 2.3 Recombination Processes

#### 2.3.1 Non-radiative Recombination Processes

**Auger Recombination**

Auger recombination is non-radiative because the transition energy of the electron (hole) from the conduction band to the valence band is not converted to a photon but transferred to another electron (or hole), this latter will be excited to a higher energy state in the same band. After this process the electron will relax to the ground state without generating any photons. Auger recombination poses is the fundamental limit of recombination processes even in perfect crystal.

IV-VI materials are very famous for their low Auger recombination. Their Auger recombinations are about a factor 100 lower compared to III-V compounds of similar band-gap \[47\]. The Auger coefficient of IV-VIs is given by the Emtage expression \[48\]:

\[
C_{pA} = (2\pi)^{5/2} \frac{3}{16} \frac{N'e^4}{N} \frac{(kT)^{1/2}}{E_g^{7/2}} \frac{\hbar^3}{m_l^{1/2}m_t^{3/2}} e^{rE_g/2kT} \tag{2.1}
\]

with \( r = \frac{m_t}{m_l} \)
where:
\( m_t \) is the transversal effective mass.
\( m_l \) is the longitudinal effective mass.
\( e \) the electron charge.
\( N' \) is the number of valley in the conduction band.
\( N \) is the number of valley in the valence band.
\( E_g \) the band-gap.

The formula is valid for the non degenerate case (which is typically not fulfilled for lasers near room temperature). However, even in the degenerate case, the values do not change much \[49\].

**Shockley Read Hall Recombination**

Defects in the semiconductor crystal may trap charges and act as recombination centers. These centers and the recombinations at interfaces are a source of non-radiative recombinations. There is an equal probability of capture at these allowed states in the band-gap for both electrons and holes \[50\]. An exact numerical estimation of the Shockley-Read recombination rates is difficult because it depends strongly on the growth conditions and the epitaxial quality. From the experimental results in section \[5.2\] Shockley-Read lifetimes were estimated between 0.1 ns to 10 ns.

**2.3.2 Radiative Recombination Processes**

**Spontaneous Recombination**

The transition of an electron from the conduction band to the valance band, and its recombination with a hole with the emission of photon is usually described as spontaneous recombination. The probability of that event to happen is strongly dependent of the
density of the electrons in the conduction band and the density of the holes in the valence band. The integral of the transition probability times occupation probability over all possible states gives the recombination rate:

\[ R_{sp}(\hbar \omega) = \int [f_c(E_c)(1 - f_v(\hbar \omega - E_c))] W_{sp}(E_c) \rho_c(E_c) \rho_v(\hbar \omega - E_c) dE_c \]

(2.2)

where:

- \( f_c(E) \): probability to have an electron in the conduction band
- \( [1 - f_v(E)] \): probability to have a hole in the valence band
- \( W_{sp} \): transition probability.
- \( \rho_c(E) \): density of state.

This leads to:

\[ R_{sp} = K^* \frac{N}{e^2 \hbar^3 \pi^2} \frac{E_{1/2}}{kT} \int_{E_g}^{\infty} \frac{\sqrt{E - E_g E^2}}{\left[ 1 + e^{\frac{E - E_g - 2Q_n}{2kT}} \right] \left[ 1 + e^{\frac{E - E_g - 2Q_p}{2kT}} \right]} dE \]

(2.3)

as exemplified by Galeskii [51].

where:

- \( K^* \): is calculated within the Kane-type two-band model from the absorption coefficient.
- \( Q_p \) and \( Q_n \) is the quasi Fermi levels in the valence band and in the conduction band respectively.

### 2.4 Material Gain

The material gain (absorption) of lead chalcogenides depends on various parameters. In this part, we discuss the form, the dependences and the values of the material gain. The calculations use the gain expression given by Anderson [44]:

2.4 Material Gain

\[
g(\omega) = \frac{8\left(\frac{1}{3}P_L^2 + \frac{2}{3}P_T^2\right)}{137n\hbar\omega} - \frac{\hbar\omega - E_g - Q_p - Q_n}{(1 + e^{\frac{\hbar\omega - E_g - 2Q_p}{2kT}})(1 + e^{\frac{\hbar\omega - E_g - 2Q_n}{2kT}})} \left(\frac{\hbar\omega + E_g}{2}\right)^{3/2} \sqrt{\frac{\hbar\omega - E_g}{E_g \frac{h^2}{2m_c} \left(\frac{m_0}{m_c}\right) + 2P_T^2}} \left(\frac{E_g \frac{h^2}{2m_c} \left(\frac{m_0}{m_v}\right) + 2P_L^2}{E_g \frac{h^2}{2m_c} \left(\frac{m_0}{m_c}\right) + 2P_L^2}\right) (2.4)
\]

where:

- \(Q_p\) and \(Q_n\) are the quasi Fermi levels in the valence band and in the conduction band.
- \(P_L\) and \(P_T\) are the intra-band matrix element.
- \(T\) is the temperature and \(E_g\) is the band gap energy.
- \(m_{ct}\) and \(m_{vt}\) are the transversal effective masses in the conduction and valence bands respectively.
- \(m_{cl}\) and \(m_{vl}\) are the longitudinal effective masses in the conduction and valence bands respectively.

In order to calculate the gain (absorption), it is important to determine the quasi Fermi levels in both valence band and conduction band. However, these two parameters are strongly dependent on the charge carrier concentration. Therefore, it is necessary to calculate first all the recombination processes, and then deduce the carrier concentration to calculate the gain.

We used the gain expression of Anderson (eqn.2.4) to calculate the material gain, with different charge carrier concentrations. The gain region becomes wider with increasing carrier density, and the value of the maximum gain higher. Its maximum shifts to higher energies, too (Fig. 2.5). If the temperature is increased, a red shift is observed due to the temperature dependence of the
Figure 2.5: Gain spectra of PbTe for different temperatures and carrier concentrations.

band-gap. And a higher charge carrier concentration is needed to achieve the same amount of gain.
3 Vertical Cavity Surface Emitting Laser

3.1 Introduction

VECSELs are extended versions of VCSELs where one epitaxial Bragg mirror is replaced by an external mirror extending the cavity with an air-gap. In this part some examples and explanations on the fabrication of VECSELs made during the present work are provided.

3.2 Distributed Bragg Reflectors

The gain medium volume in VECSELs is considerably smaller compared to edge emitters. To reach the oscillation condition in the VECSEL cavity a very high reflectivity is required. In this kind of optical devices, DBRs (Distributed Bragg Reflectors) are usually used. A DBR is a sequence of quarter wavelength thick layers with alternating high and low refractive index. The DBR has its maximum reflectivity at the design wavelength $\lambda_0$, this maximum is given by the following equation:

$$R = \left[ \frac{1 - \frac{n_A}{n_B} \left( \frac{n_1}{n_2} \right)^{2N}}{1 + \frac{n_A}{n_B} \left( \frac{n_1}{n_2} \right)^{2N}} \right]^2$$  \hspace{1cm} (3.1)
CHAPTER 3. VECSEL

\( n_A \) and \( n_B \) are the respective refractive indices of the surrounding medium.
\( n_1 \) and \( n_2 \) are the refractive indices of the layers.
\( N \) is the number of pairs.

To increase the maximum reflectivity two methods are possible: Increase the number of pairs or increase the refractive contrast. However, increasing the refractive contrast is more efficient. Because, by doing so, the stop-band width is increased, too.

The stop-band width of a DBR is determined by:

\[
\Delta \lambda_0 = \frac{4\lambda_0}{\pi} \arcsin \left( \frac{n_2 - n_1}{n_2 + n_1} \right),
\]

\( (3.2) \)

it increases with the refractive index contrast.

Combining the high refractive index of the lead chalcogenide materials with low refractive index material like BaF\(_2\) (\( n = 1.45 \)) or EuTe (\( n = 2.4 \)) to fabricate DBRs results to very high reflectivity DBRs with only few pairs.

As example, the DBR reflectivity simulation using Pb\(_{0.93}\)Eu\(_{0.07}\)Te (\( n = 4.55 \)) as high refractive index layer and BaF\(_2\) as low refractive index layer is considered \[52\]. Using the matrix method the reflectivity of these mirrors are calculated. The large index contrast \( n_1/n_2 = 3.13 \) allow a 99.96 % reflectivity with only 3 pairs (Fig. 3.1). To reach such reflectivity with III-V materials, around \( N = 20 \) pairs are needed, mainly due to the much lower index contrast \( n_1/n_2 \approx 1.13 \), and the stop band is \( \sim 0.34 \) \( \mu \)m. The stop-band of lead chalcogenide DBR is very large, it exceeds 3.5 \( \mu \)m.
3.2 Distributed Bragg Reflectors

Figure 3.1: Simulation of a Pb$_{0.93}$Eu$_{0.07}$Te/BaF$_2$ DBRs reflectance, $R = 99.96\%$ with 3 pairs, $R = 99.56\%$ with 2 pairs.

Note that DBRs fabricated with III-V layers are typically lattice matched, while in the IV-VI containing DBRs no exact match is needed. This leads to the favorable properties of the IV-VI system containing DBRs.
3.3 Design and Growth

3.3.1 Growth of Lead Chalcogenide

The growth of the epitaxial layers was performed on cleaved BaF$_2$(111) substrates or on 3” Si(111) wafers by a MBE (Molecular Beam Epitaxy) system with $\sim 10^{-10}$ Torr background pressure. The Si wafers were first cleaned using the Shiraki method \[54\], and then the oxide layer was evaporated by rising the temperature up to $\sim 1100$ °C in the first MBE chamber. Afterwards, a thin CaF$_2$ buffer layer was grown at $\sim 750$ °C. The Si wafer was quickly transferred to a second MBE chamber using a vacuum transfer tunnel. The second MBE chamber was equipped with several effusion cells (Knudsen effusion cells): PbTe, Te, PbSe, Se, Eu, Sr and BaF$_2$. The fluxes were measured using a quartz crystal monitor. PbTe and PbSe are grown using solid sources of binary compounds with an additional Te$_2$ (Se$_2$) flux. The epitaxial layers were grown at temperatures between 380 °C and 440 °C. The growth rate was about 1 µm/hour. For the ternary materials like Pb$_{1-x}$Eu$_x$Te, Pb$_{1-x}$Eu$_x$Se (or Pb$_{1-x}$Sr$_x$Te, Pb$_{1-x}$Sr$_x$Se), the Eu (or Sr) concentration was controlled by the ratio of the PbTe to the Eu (Sr) beam flux. An excess of Te$_2$ flux was always maintained.

3.3.2 Lead Chalcogenide VECSEL

Like all lasers a VECSEL is composed of two mirrors surrounding a gain medium. In our case the second mirror is curved and it has a radius of about 2.5 cm (Fig. 3.2). A spherical mirror interferometer in the confocal configuration has many advantages over plano-plano interferometers, such as easier alignment \[55\].
3.3 Design and Growth

Figure 3.2: Schematic representation of an optically pumped VECSEL

The beam diameter of the TEM$_{00}$ mode on both mirrors are calculated with the following formula $[59]$:

$$w_1^2 = \frac{4\lambda L}{\pi} \sqrt{\frac{R - L}{L}}$$  \quad (3.3)$$

$$w_2^2 = \frac{4\lambda L}{\pi} \sqrt{\frac{R^2}{L(R - L)}}$$  \quad (3.4)$$

where:

$R$ is the radius of curvature of the external mirror.

$w_1$ and $w_2$ are the diameters of the beam at the plane and curved Bragg mirror, respectively.
Figure 3.3: Beam radius: (a) TEM$_{00}$ radius on the half VECSEL, (b) TEM$_{00}$ radius on the curved mirror

In Fig. 3.3 the radius of the beam in mode TEM$_{00}$ is presented as function of the cavity length for a radius of the curved mirror of 25 mm and 50 mm. In Fig. 3.3 (a) the radius of the same mode on the plane mirror (half VECSEL) is presented. In order to achieve small mode diameter (i.e. low thresholds) the cavity length is adjusted to either slightly shorter than the radius of curvature or very short (≈ 100 µm).
3.4 Threshold Power

In this part, an example of the calculations and estimations of the threshold powers and the gain is presented. This is done for homogeneous “bulk” material and quantum wells (QW).

3.4.1 Resonant and Anti-resonant Design

One of the most important property in the characteristics of a laser is the threshold power. To obtain the lowest threshold, a resonant design is used. This design allows to obtain the maximum value of the electric field $E$ in the active region. The maximum value of $|E|^2$ that can be reached corresponds to the highest confinement and therefore, the lowest threshold.

The confinement factor is expressed as [53],

$$\Gamma = \frac{\int_{\text{active}} |E|^2 \, dz}{\int_{L} |E|^2 \, dz} \quad (3.5)$$

where:

- active is the thickness of the active region.
- $L$ is the total cavity length.

In the case of QW structures, the normalized maximum value $|E|^2$ has to occur at the QW positions [56]. For a homogeneous active layer, the optical thickness of the active layer has to be chosen as multiple of $\lambda_0/2$, where $\lambda_0$ the design wavelength.

In Fig. 3.4(a), the schematic plot of resonant designs is presented, the PbSe active layer has an optical thickness of a full wavelength of the design wavelength $\lambda_0 = 4.3 \, \mu m$. The electric
field distribution is plotted at the design wavelength. The incident electric field value is normalized to unity. The normalized maximum value of $|E|^2 = 4$ is reached.

![Figure 3.4: The distributions of calculated electric fields $|E|^2$ for the resonance condition (a) and with an AR-coating (b). The active layer is PbSe ($\lambda_0 = 4.3$ µm), the Bragg mirror consist of 3 pair of BaF$_2$/Pb$_{0.94}$Eu$_{0.06}$Te ($n = 1.45$ and 4.55, respectively)](image-url)
3.4 Threshold Power

An anti-reflection (AR) coating with optical thickness $\lambda_0/4$ can be added, this leads to the field distribution presented in Fig. 3.4(b): The maximum $|E|^2$ is lower by $1/n$ ($n$ the refractive index of the active layer) at $\lambda_0$.

![Graph](image.png)

**Figure 3.5**: Calculated behavior of maximum of $|E|^2$ in the active layer as a function of wavelengths. The active layer is in both cases PbSe with one $\lambda_0$ optical thickness at a design wavelength $\lambda_0 = 4.3$ $\mu$m

In Fig. 3.5 the behaviour of the maximum of $|E|^2$ is presented as a function of the wavelength. First, for the resonant design, by changing the wavelength from $\lambda_0$, one moves out of the exact resonance condition leading to a lower maximal $|E|^2$ value namely lower confinement. For the AR coating design, changing the wavelength from $\lambda_0$ leads to a higher maximal $|E|^2$ value or for higher confinement. Because at some other wavelength $\lambda$ the subcavity becomes a multiple of $\lambda/2$ (resonance condition), and the electric field in the active layer reaches a new maximum values [56]. The advantage of the anti-resonant design is the possibility to obtain
lasing behaviour over a very wide wavelength range, however with relatively high threshold powers compared to the resonant design near resonance.
3.4.2 Homogeneous Active Layer

To calculate the threshold gain, we calculate the necessary gain to satisfy the oscillation condition. This latter is defined as follow:

\[(R_1 R_2)^{1/2} \exp(-\alpha L) = 1\] (3.6)

\[\sin \left(2N \frac{2\pi}{\lambda} L \right) = 0\] (3.7)

where:

- \(R_1\) and \(R_2\) are the reflectivities of the two DBRs.
- \(L\) is the cavity length.
- \(\alpha\) is the net absorption coefficient.

This conditions imply that the optical field will reproduce itself after a round trip in the whole cavity. For this condition to be fulfilled, the threshold gain \(g_{\text{thr}}\) can be obtained by calculating the optical losses:

\[\Gamma g_{\text{thr}} = \alpha_{\text{mir}} + \alpha_{\text{int}}\] (3.8)

where

\[\alpha_{\text{mir}} = \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right)\] (3.9)

\(\alpha_{\text{mir}}\) are the mirrors losses and \(\alpha_{\text{int}}\) is the internal losses.

Fig. 3.6 shows the calculated threshold gain behaviour as a function of the wavelength for the VECSEL presented schematically in Fig. 3.2. As described before, the resonance design allows low threshold at the design wavelength \(\lambda_0 = 4.3\) µm. The calculations
were made for the case of a VECSEL without substrate in the cavity, and secondly for a VECSEL with a BaF\(_2\) substrate in the cavity. This latter works as an etalon and its thickness determines the spacing between the maxima.

**Figure 3.6:** The gain characteristic calculated for a PbSe active region at 300 K for a VECSEL as presented in Fig. 3.2 (resonant design) without substrate in the cavity (red) and with the substrate (blue). Design wavelength 4.3 µm, \(d_{\text{PbSe}} = 840\) nm, 2.5 pair Bragg mirror.

Taking into account the recombination processes defined in the preceding chapter, we can calculate the carrier density (and thereby the gain) near threshold by solving the following equation:

\[
\frac{\partial n}{\partial t} = F(P) - \left[ \frac{n}{\tau_{\text{SHR}}} + R_{sp}(n) + C_A n^3 + R_{st} N_{\text{Ph}} \right] \tag{3.10}
\]
where:
$\tau_{SHR}$ is the Shockley-Read-Hall recombination lifetime.
$R_{sp}$ is the spontaneous radiative recombination.
$C_A$ is the Auger coefficient.
$R_{st}$ is the stimulated recombination.
$F(P)$ is the generated charge carrier rate by the optical pumping power $P$.
$N_{Ph}$ is the intra-cavity photon density.

This equation is solved for the near threshold condition where the last term of the stimulated recombination can be neglected.

\textbf{Figure 3.7:} Gain calculation of PbSe bulk in resonant design at $T = 300$ K, 10 W pump power with a 1.55 µm pump laser.

Under these assumptions the net gain was calculated for the VEC-SEL presented in Fig. 3.2, and the net gain dependence on the wavelength is plotted in Fig. 3.7.
The parameter used are
\( \tau_{SHR} = 0.5 \text{ ns.} \)
\( P_{in} = 10 \text{ W (1.55 } \mu \text{m pump laser).} \)
\( r = 100 \mu \text{m radius of the pump area.} \)

After solving eqn. 3.10 near threshold, the corresponding carrier charge density is \( n = 1.065 \times 10^{18} \text{ cm}^{-3} \).

By comparing the threshold gain values (Fig. 3.6) to the net gain characteristics (Fig. 3.7), we can estimate the wavelength range where lasing of the VECSEL will occur.
3.4.3 Quantum Well as Active Layer

Quantum well lasers have usually demonstrated lower threshold than the bulk laser [57]. Furthermore, in order to reach shorter wavelengths, the blue shift effect of quantum wells have been used. Employing QWs offers more freedom in selecting the design wavelength. The wavelength of the quantum well is determined by the width of the well and the band-gaps of the gain medium and the barrier layers.

Fig. 3.8 displays the cut-off wavelength of PbSe bulk and PbSe quantum well with different thickness as function of the temperature. The PbSe quantum well is embedded in Pb$_{0.95}$Eu$_{0.05}$Te. In this calculation we used a symmetric quantum wells.

![Figure 3.8: Cut-off wavelength as function of temperature for PbSe bulk and quantum well Pb$_{0.95}$Eu$_{0.05}$Se/PbSe structures with 20 nm, 15 nm, 10 nm and 5 nm thick QW.](image-url)
The gain of a quantum well is given by [58]:

\[
g(\omega) = \frac{\pi e^2 \hbar \rho_{\text{red}}}{\epsilon_0 n_r c m_0^2 W} \frac{|M_{QW,n}|^2}{\hbar \omega_0} \left[ F_c(\omega) - F_v(\omega) \right] \sum_{n=1}^{\infty} H(\omega_0 - \omega_n)
\]

where:

- \(|M_{QW,n}|^2\) is the momentum matrix element of 3-D conventional lasers.
- \(\rho_{\text{red}}\) is the reduced density of states.
- \(n_r\) is the refractive index.
- \(H(\omega_0 - \omega_n)\) is the Heaviside function.
- \(W\) is the quantum well width.
- \(n\) is the nth subband, \(\omega_0\) is the lasing frequency.

**Figure 3.9:** Gain as a function of photon energy for 10 nm thick PbSe QW at \(T = 100\) K.

Fig. 3.9 shows the gain of 10 nm thick PbSe QW as function of
3.4 Threshold Power

A photon energy at $T = 100$ K and two different charge carrier densities ($n = 1 \cdot 10^{17}$ cm$^{-3}$, $n = 4 \cdot 10^{17}$ cm$^{-3}$).

The maximum gain is at the cut-off of the QW. In Fig. 3.10, the maximum gain as function of the carrier charge density $n$ is plotted. We notice that the gain is negative up to a certain carrier density $n_0$ called transparency carrier charge density. This latter is higher for higher operation temperature. This plot shows that the maximum gain changes approximately logarithmically with charge carrier density up to a certain saturation value.

![Figure 3.10: Maximum gain as function of carrier concentration for 10 nm thick PbSe quantum wells](image)

If we consider only the logarithmic part of the gain, the maximum gain can be written as the empirical expression:

$$G(n) = g_0 ln(n/n_0)$$  \hspace{1cm} (3.11)
where:

- $n_0$ is the transparency carrier density.
- $g_0$ is the material gain coefficient.

By combining eqn. 3.11 with the oscillation condition, Kuznetsov [59] demonstrate the following relations for the threshold charge carrier density and threshold power for a VECSEL:

\[
n_{th} = n_0 \left( \frac{1}{R_1 R_2 T_{loss}} \right)^{(2\Gamma g_0 N_w L_w)^{-1}}
\]

(3.12)

where:

- $T_{loss}$ is the round-trip loss transmission factor.
- $R_1$ and $R_2$ are the mirrors reflectivities.
- $\Gamma$ is the longitudinal confinement.
- $L_w$ and $N_w$ are the width and the number of QWs.

The threshold power is:

\[
P_{th} = n_{th} \frac{h \nu N_w L_w A_p}{\eta_{abs} \tau(n_{th})}
\]

(3.13)

where:

- $\tau(n_{th})$ is the carrier lifetime at threshold.
- $\eta_{abs}$ is the pump absorption efficiency.
- $A_p$ is the optically pumped area.

Using eqn. 3.13 the threshold power and its dependence on the number of QWs is calculated and presented in Fig. 3.11. The choice of the required quantum well number for low threshold power depends strongly on the material gain coefficient $g_0$ and on the product $R_1 R_2 T_{loss}$. 

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3.4 Threshold Power

Figure 3.11: Threshold power as a function of the QWs number for different mirror reflectivity

The output power of the VECSEL can be calculated by using the following expression:

\[
P_{\text{out}} = (P_{\text{pump}} - P_{\text{th}}) \eta_{\text{dif}}
\]

\[
\eta_{\text{dif}} = \eta_{\text{out}} \eta_{\text{quant}} \eta_{\text{abs}}
\]

where:

- \( P_{\text{pump}} \) is the pumped power.
- \( \eta_{\text{dif}} \) is the differential efficiency.
- \( \eta_{\text{quant}} \) is the quantum-defect efficiency.
- \( \eta_{\text{out}} \) is the output efficiency.
In Fig. 3.12 the calculated output powers of the above described VECSEL as function of the pump power for different mirror reflectivities are plotted. By changing the reflectivity of the output mirror the threshold power and the output power are changed. To achieve a small threshold power the reflectivity is increased as presented in the example with 99% where the threshold is \( \sim 1 \) W. However, the maximum output power is obtained with \( R \approx 97\% \) but with an higher threshold power (2 W).

**Figure 3.12:** Output power versus pump power. For parameters see text.


3.5 Intra-cavity Tunable VECSELs

In order to achieve continuously tunable VECSELs, a free spectral range broader than the net gain wavelength region is needed to obtain a single longitudinal mode.

Free Spectral Range of Fabry-Perot Optical Cavity

The free spectral range is the frequency spacing between two successive resonance maximums or minimums of the transmittance. The transmittance of a Fabry-Perot optical cavity is given by the following formula [60]:

\[
T = \frac{(1 - R)^2}{(1 - R)^2 + 4R \sin^2(\delta/2)}
\]

\[
\delta = \frac{4\pi nL \cos \theta}{\lambda} = 2m_w \pi
\]

\( \delta \) is the phase difference between two travelling wave of one round trip.

The free spectral range is given by:

\[
\Delta \nu = \frac{c}{2L}
\]

where:

- \( L \) is the total optical thickness.
- \( c \) is the light velocity.

If we presume that the net gain region is \( \sim 200 \) nm wide, in order to obtain one single mode, the FSR must be > 200 nm.
**Figure 3.13:** Calculated transmission of Fabry-Perot cavity

\[ \text{cm}^{-1} \text{ for } 5 \, \mu\text{m wavelength}. \text{ consequently the total optical cavity length should be shorter than } L < 62.5 \, \mu\text{m}. \]

In Fig. 3.13 the calculated transmission of a Fabry-Perot cavity versus wavelength is plotted for a total cavity length \( L = 50 \, \mu\text{m}, 50.5 \, \mu\text{m} \) and \( 51 \, \mu\text{m} \). The total possible tuning range is given by:

\[
\frac{\Delta \nu}{\nu} = \frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L} = 4%. \quad (3.17)
\]

The width of the the transmitted peaks depend highly on the reflectivity of the two mirror and the free spectral range. The width at half maximum of each peak is given by:
3.5 Intra-cavity Tunable VECSELs

\[
FWHM = FSR \frac{1 - \sqrt{R_1 R_2} e^{-\alpha d}}{\pi (R_1 R_2)^{\frac{1}{4}} e^{-\alpha d/2}} \quad (3.18)
\]

The FWHM of the cavity mode decrease with increasing reflectivity, in Fig. 3.13 the transmitted peaks are plotted for \( L = 50 \mu m \) and \( R = 80\%, 90\%, 99\% \). However, note that the width of the laser line is much smaller than the FWHM of the cavity.
CHAPTER 3 VECSER
4 Thermal Management

Every semiconductor laser needs rather high excitation power leading to substantial temperature increase in the active region. In addition, due to the difference between the pump laser wavelength (1.55 µm, corresponding to 0.8 eV) and the output wavelength (5 µm; corresponding to 0.248 eV), around 70 % of the pumped power is converted to heat. The accumulation of this heat causes an additional huge increase of the temperature.

In consequence, the performances of the VECSEL diminish. As the gain decreases with increasing temperature, the threshold power increases and the wavelength shifts (in case of IV-VI material, the band gap increases with temperature). A good thermal design is needed for the removal of this heat. Unfortunately the BaF$_2$ substrate has a low thermal conductivity, and IV-VI materials are even worse. The thermal conductivities of selected semiconductors and other materials are listed in Table 4.1.

Unlike the edge emitters, it is mainly the vertical heat flow which determines the temperature rise of the active region since the excitation diameter is much larger than the thicknesses of the active and mirror layers involved.

The simplest approach is a uniform heat input over a circular disc on a slab of thickness $d$. Even here, there is no analytical solu-
### 4 Thermal Management

#### Table 4.1: Thermal properties properties of Lead chalcogenide, Si, Diamond, SiC, Al, EuTe, EuSe, BaF₂ and CaF₂.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal expand coeff (10⁻⁶/K)</th>
<th>Thermal conductivity (W m⁻¹K⁻¹) at 300 K</th>
<th>heat capacity (J/Kg.K) at 300 K</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbTe</td>
<td>19.81</td>
<td>1.9</td>
<td>156</td>
<td>[63]</td>
</tr>
<tr>
<td>PbSe</td>
<td>19.4</td>
<td>1.45</td>
<td>174</td>
<td>[63]</td>
</tr>
<tr>
<td>EuTe</td>
<td>13.6</td>
<td>~10</td>
<td>-</td>
<td>[?]</td>
</tr>
<tr>
<td>BaF₂</td>
<td>19.8</td>
<td>50 (100K)-11.2(300K)</td>
<td>456</td>
<td>[62]</td>
</tr>
<tr>
<td>CaF₂</td>
<td>19.1</td>
<td>120 (100K)-12 (300 K)</td>
<td>-</td>
<td>[62]</td>
</tr>
<tr>
<td>Si</td>
<td>2.6</td>
<td>~160</td>
<td>703</td>
<td>[36]</td>
</tr>
<tr>
<td>Al</td>
<td>23.1</td>
<td>~270</td>
<td>900</td>
<td>[67,36]</td>
</tr>
<tr>
<td>Cu</td>
<td>16.5</td>
<td>~390</td>
<td>384</td>
<td>[67,36]</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.18</td>
<td>~1600</td>
<td>520</td>
<td>[67,36]</td>
</tr>
<tr>
<td>In</td>
<td>32.1</td>
<td>~81</td>
<td>233</td>
<td>[67,36]</td>
</tr>
<tr>
<td>SiC</td>
<td>4.3</td>
<td>~490</td>
<td>690</td>
<td>[67,36]</td>
</tr>
</tbody>
</table>

For the distribution of temperature in space, but an expression for the stationary temperature excursion at the hottest point at the center of the pumped disc is obtained using the method of images [64].

\[
\Delta T(r) = \frac{P}{k \pi \omega_0^2} \left[ \omega_0 + 2d - \sqrt{\omega_0^2 + 4d^2} \right]
\]

where:
- \( \omega_0 \) is the radius of the pumped area.
- \( d \) is the thickness of the slab.
- \( P \) is the pump power.
- \( k \) is the thermal conductivity.
In our case there are three possible solutions to minimize the rise of temperature. First, the deposition of a material with very high thermal conductivity directly on the epitaxial layers. Second, to use a substrate with a better thermal conductivity. The third solution is to remove the substrate (epi-lift-off) and capillary bonding with a high thermal conductivity material (SiC or diamond) [65,66].

4.1 BaF$_2$ Substrate with Al Heat-Spreader

Using the commercial software comsol, the following thermal simulations in this chapter have been made. Fig. 4.2 shows the temperature profile in the half VECSEL grown on 1 mm thick BaF$_2$ substrate as shown on Fig. 4.1. The 10 µm thick Al layer is employed as heat spreader. The gain medium is 850 nm bulk layer and the DBR consist of 5 layers PbEuTe and BaF$_2$. The maximum increase of temperature reach a $\sim 30$ °C at the center of the pumped area for 1 W pump power.

Figure 4.1: The half VECSEL grown on 1 mm BaF$_2$ substrate and with 10 µm aluminum heat spreader
The dynamic temperature change in the center of the pumped area is plotted in Fig. 4.3. The estimated temperature change is drawn for pulsed mode (for pulse widths $\tau = 100$ ns, 1 $\mu$s, 10 $\mu$s, 0.1 ms, 1 ms, 0.1 s (CW))

Figure 4.2: Temperature distribution in the half VECSEL grown on 1 mm BaF$_2$ substrate, 1 W pumping power over a surface with $r = 100$ $\mu$m.

We notice the saturation of temperature happens at $\sim 1$ ms with temperature rise of $\Delta T = 31$ $^\circ$C. After the pulse the time needed for the removal of the heat depends on the temperature rise (for example for $\tau = 1$ $\mu$s, $\sim 100$ $\mu$s are needed Fig. 4.3).
Figure 4.3: Temperature rise vs time for VCSEL structure as in Fig. 4.1 with a BaF$_2$ substrate and an Al heat spreader, and 1 W pumping power.

4.2 Capillary Bonding

To estimate the improvement and the efficiency of thermal management the lateral and vertical temperature distribution has been calculated for 5 different heat spreader and substrate combinations. In the Fig. 4.4 the temperature rise in the different layers is plotted. The simulations are for a half VECSEL structure pumped with 10 W in CW operation (200 μm diameter).

The two highest temperature rise correspond to VECSELs grown on Si substrate, one is indium soldered on copper and the other one is soldered on diamond. A $\sim 15 \, ^\circ$C temperature difference
The next three curves correspond to half-VECSELs which are transferred on a diamond substrate using the epi-lift-off method and a capillary bonding. Compared to the VECSEL structure on Si substrate, the temperature decreases by \( \sim 70 \, ^\circ C \). Even if the structure soldered on diamond have the lowest temperature in the active layer, it is not significantly lower compared to the one soldered on copper.
5 Results

The results of different fabricated VECSELs are presented in this chapter. Parts and graphics of this chapter have already been published in several articles [A,D,E,F,H].

5.1 PbTe VECSELs on BaF$_2$ Substrates

The first VECSEL emitting above 3 $\mu$m wavelength have been fabricated employing lead telluride as active medium [H].

Two different structures have been realized, their schematic cross sections are shown in Fig. 5.1. The resonant cavity is formed between the bottom Bragg mirror and the top curved mirror. As a transparent substrate, BaF$_2$(111) is used and placed inside the cavity.

For device (a), the gain region consists of a 2 $\mu$m thick PbTe layer grown on an anti-reflection (AR) Pb$_{0.8}$Eu$_{0.2}$Te layer. This AR layer is transparent at the pump wavelength, the wide band-gap which does not absorb the incoming pump wavelength (1.5 $\mu$m) is easily realized by alloying PbTe with Eu. For device (b), two 150 nm thin PbTe gain layers are separated by Pb$_{1-x}$Eu$_x$Te barrier layers.
Figure 5.1: Schematic representation of the IV-VI VECSEL. The two different gain structures (a) and (b) are shown separately together with the optical intensity distribution at 5.3 µm wavelength.

For both device types, the gain structures are followed by a two pair Bragg mirror. As quarter wavelength layers for the Bragg mirror, Pb$_{1-x}$Eu$_x$Te ($y = 0.07$) is used as high refractive index material, while the low index material is BaF$_2$. This leads to a high reflectivity $R \geq 99\%$ over a broad spectral band ranging from 4 µm to 7 µm due to the high index contrast $n_h/n_l$. Its reflectance is $R > 99.5\%$ at the design wavelength of 5.3 µm (corresponding to operation at about 95 K). All layers are grown by solid state molecular beam epitaxy.

An epitaxial curved Bragg mirror completes the resonant cavity. The substrate of this curved mirror is a polished BaF$_2$ sin-
gle crystal which is overgrown by MBE with a similar 2.5 pair Pb$_{1-x}$Eu$_x$Te/BaF$_2$ Bragg mirror.

The Cavity length is slightly shorter than the radius of curvature of the top mirror (25 mm) in order to get a stable resonator with suitable mode diameter. The exciting 1.5 µm laser beam is focused and adjusted to pump through the substrate and to match the pumped area with the VECSEL mode size (200 µm diameter).

The calculated distribution of the electric field (intensity) in the different layers at 5.3 µm wavelength are plotted in Fig. 5.1. The two PbTe gain layers of structure (b) are located at the waists of the standing wave pattern. Here, the composition of the first barrier Pb$_{1-x}$Eu$_x$Te is $x = 0.2$ with a wide band gap transparent to the pump beam. For the composition of the second barrier, Pb$_{1-x}$Eu$_x$Te $x = 0.07$ was chosen. This composition leads to higher refractive index and facilitates to obtain better structural quality of the next layers finally resulting in a better reflectivity of the Bragg mirror.

A crucial item for VECSELs is efficient heat removal. Unfortunately, IV-VI materials as well as BaF$_2$ have rather low thermal conductivities. They depend remarkably on temperature and on the structural quality.

In the next two sections we will present the result obtained without heat spreader, and the improvement obtained after employing an aluminum heat spreader near the active layers.
5 Results

PbTe VECSELs without Heat Spreader

The characteristics of the PbTe VECSEL grown on BaF$_2$ without any heat spreader will be presented here. The 1.55 µm laser employed to pump the VECSEL is pulsed, with 3 µs width and $\sim$ 3% duty cycle for the first measurement. In the second measurement, the pump laser is chopped with 50% duty cycle at 1.2 kHz repetition frequency, or CW.

![Graph showing light-in/light-out characteristics](image)

**Figure 5.2:** Light-in/light-out characteristics at 100 K for pulsed and quasi-CW excitation of structures (a) and (b).

Fig. 5.2 (left panel) shows the light-in light-out characteristics of the two structures in pulsed excitation. For the structure (a) with 2 µm PbTe gain layer, output powers up to $\sim$ 45 mWp are observed. Differential quantum efficiency is about 1.2%. The structure (b) with the two thin gain layers shows higher output...
power at lower excitation and higher differential efficiency. A thermal rollover limits the output power to somewhat above 50 mWp at these rather long pulse widths.

Continuous wave operation has been obtained with the two gain layer structure (b). Maximum emission power was 1-2 mW at 95 K operation temperature, depending sensitively on the precise alignment of the cavity mirrors and pump beam. Fig. 5.2 (right panel) shows light-in/light-out characteristics for quasi-CW excitation with 800 µs pulse widths and 50% duty cycle. The threshold pump power is as low as \( \sim 300 \) mW, while thermal rollover occurs already at 800 mW pump power. Differential quantum efficiency is \( \sim 2\% \). Lasing is observed up to \( \sim 140 \) K with characteristic temperature \( T_0 = 18 \) K.

**PbTe VECSELs with Al Heat Spreader**

Here, we describe a significantly improved version of this device leading to a \( \sim 5 \) fold higher output power and increased operation temperature [E].

As a 1.55 µm laser is used for excitation while the output wavelength is 5 µm, \( \sim 70 \% \) of the pumped power is converted to heat already due to this wavelength difference. A good thermal management is mandatory to obtain large output power. To this end, a thick layer of aluminum (5 µm) is evaporated onto the bottom Bragg mirror after deposition of a BaF \(_2\) intermediate layer, and the structure is attached via this Al-layer to a Cu-heatsink. As already mentioned, the main improvement to the former results is due to this heat spreader.
5 Results

Figure 5.3: Light-in/light-out characteristics at 100 K for pulsed (a) and cw (b) excitation.

A maximum output power of 270 mWp is reached in pulsed mode as plotted in Fig. 5.3 for structure (a) with 2 µm active layer. This power is limited by the pump laser, where the maximum absorbed power is 8.5 W. The Quantum efficiency is up to 14 %.

For the second structure (b) with two 150 nm PbTe layers, we obtained ~ 180 mWp. This is somewhat lower than the results of structure (b), and seems to saturate towards the highest pump power due to beginning of thermal rollover. Both designs have threshold powers < 1 Wp in pulsed mode. In continuous wave operation, the VECSEL has a maximum output power of 2.7 mW and threshold power < 300 mW for both structures.

Typical emission spectra are shown in Fig. 5.4. Multimode emission is observed for high pump power in pulsed mode (Fig.
5.1 PbTe VECSELs on BaF$_2$ Substrates

Figure 5.4: Laser spectra: multimode at higher pumping power (a), monomode for pulsed low power excitation or cw (b) at 100 K, monomode at 165K (c).

The distance between the modes corresponds to the optical thickness of the BaF$_2$ substrate. For low power pulsed or cw excitation emission is single mode (Fig. 5.4(b)). Even though the VECSELs designs were optimized for a temperature of 100 K, they were lasing up to 175 K. At this temperature, the wavelength shifts to 4.2 $\mu$m (Fig. 5.4(c)). The linewidths of the modes are limited by the resolution of the Fourier transform infrared spectrometer used.

The improved version of the optically pumped VECSEL emitting at $> 5$ $\mu$m wavelength has a factor 5 higher output power near 300 mW in pulsed mode and $\sim 3$ mW cw at 100 K by adding an Al layer for heat removal.
5 Results

5.2 PbSe VECSELs on BaF$_2$ Substrates

Several measurement showed that PbSe exhibits a still lower Auger coefficient compared to PbTe which should lead to lower threshold power. For this reason and with the intention to extend the wavelength range to longer wavelengths, PbSe as gain medium is used. We employed a resonant design optimized for room temperature operation. In the resonant design, the active layer has again a thickness of a multiple $\lambda_0/2$ of the design wavelength. This avoids the decrease of the maximum $|E|^2$ values in the active layer. The penalty is less tolerance to deviation from the design wavelength $\lambda_0$. However, this is not a serious issue if a laser is intended to operate in a restricted temperature range only.

In a similar structure to the VECSEL presented in Chapter 3, the cavity is formed between the bottom flat Bragg mirror and the top curved mirror. The active PbSe layer is grown by MBE on a cleaved BaF2(111) substrate located inside the cavity. The thickness of the PbSe is one optical wavelength for emission at about 20 °C, ($\lambda_0 = 4.3 \mu$m). It is overgrown with a 2.5 pair Bragg mirror where Pb$_{0.93}$Eu$_{0.07}$Te (n=4.55) is used for the high index quarter wavelength layer and BaF$_2$ (n=1.46) for the low index layer. A thick Al-layer is added as a heat spreader. The top mirror uses the same Bragg layers, but is grown epitaxially on a curved BaF$_2$ substrate with 25 mm radius of curvature.

Fig. 5.5 shows light-in/light-out characteristics at three different temperatures. Output power is up to 18 mW, limited by the maximum power of the exciting beam. No thermal rollover occurs at -22 °C and 0 °C heat sink temperature, while at 27 °C heat sink temperature rollover limits the maximum output power to ~
6 mW$_p$.

![Figure 5.5: Light-in/light-out characteristics at three different temperatures](image)

Note that from the exciting beam, we estimate that $\sim 30\%$ is lost by reflections before the beam enters the active layer. Most of the remaining beam is absorbed in the 0.85 $\mu$m thick active layer. The exact amount is difficult to estimate since absorption coefficients are not reliably known and depend on structural quality. Finally, due to the large difference between pump (1.55 $\mu$m) and output (4.5 $\mu$m) wavelength, $\sim 65\%$ of the pump power is waisted heat. Therefore, only $\sim 20\%$ of the pump photon power is responsible for the excitation.
Fig. 5.6 shows normalized spectra at different heat sink temperatures. The spectra are multimode with mode spacing given by the thickness of the BaF$_2$ substrate. Lasing is observed between -60 °C up to 45 °C heat sink temperatures. Note that the absolute emission intensities differ considerably between the spectra. The shift in wavelength at the different temperatures is due to the temperature dependence of the band gap of PbSe (0.5 meV/K). From comparing the spectral shift of a spectrum at different excitation level, but otherwise unchanged conditions, we estimate a 20 °C temperature rise when exciting with the highest pump power available. Therefore, lasing occurs at temperatures in the active layer up to $\sim$ 65 °C.

![Figure 5.6: Normalised lasing spectra at different heat sink temperatures](image)

In Fig. 5.7 (left), threshold intensities are plotted as a function of heat sink temperature. The threshold is high at -60 °C, de-
increases and reaches lowest values in the -40 °C to 0 °C temperature range, and increases again at higher temperatures. From the optical simulation with 4.3 µm design wavelength (Fig. 5.7 (right)), the spectral half width of the calculated resonance of $|E|^2$ is $\Delta \lambda \sim 0.3$ µm. With the temperature dependence of 0.5 meV/K of the band-gap of PbSe, this corresponds to $\Delta T \sim 40$ °C for the temperature range of the active layer. This is in qualitative agreement with the measured curve. The shape of the threshold vs temperature curve is asymmetric, the values increase steeper towards the high temperature side than towards the low side. This is due to the general increase in threshold with temperature since higher carrier densities for inversion are needed at higher temperatures.

The lasing of the VECSEL is limited to a certain temperature domain. The simulation of the VECSEL threshold powers as function of the temperature are presented in the Fig. 5.8. The effect of resonance design is nearly negligible if the the product $R_1 R_2 T_i > 99\%$, where $T_i$ is the internal transmission coefficient. However, if
we decrease that product to 90% (increase of the internal and the mirror losses), the resonant design effect is more present and notice that the threshold power has a minimum at the temperature corresponding to the design wave length $\lambda_0$.

In Fig. 5.8 the threshold powers are calculated as function of the temperature for a Shockley-Read-Hall recombination lifetimes $\tau_{SR} = 10$ ns and 0.6 ns. The change of simulated threshold powers as
function of temperature approximately fit the experimental results only if the the product $R_1 R_2 T_i \simeq 90\%$ and the Shockley-Read-Hall recombination lifetime $\tau_{SR} = 0.6$ ns. This rather low $\tau_{SR}$ is due to the limited quality of the PbSe active layer grown lattice mismatched on the BaF$_2$ substrate. The low $R$ may be due to diffuse reflection at the many cleavage steps of the BaF$_2$ substrate.
5.3 PbTe VECSELs on Silicon Substrates

After the successful fabrication of PbTe VECSEL devices grown by MBE on BaF$_2$ substrates [H], we demonstrate a new IV-VI VECSEL where the whole structure is grown on a Si substrate. There are many advantages to use Si substrates [A]. The thermal conductivity is much higher compared to BaF$_2$, and Si wafers are commercially available with large diameters. However, due to the lattice mismatch and high thermal expansion mismatch between IV-VIs and Si, monolithic structures are more difficult to realize. The structure was grown on a Si-substrate with the transparent Si-substrate located inside the cavity. We employed a resonant design, where the active layer has an optical thickness of $\lambda_0$ (the design wavelength).

Fig. 5.9 shows a schematic cross section of the VECSEL. First the Si (111) substrate is overgrown by a 2 nm thick CaF$_2$ buffer layer, then the active layer is grown and followed by a Bragg mirror. All layers were grown by solid source molecular beam epitaxy (MBE). The Bragg mirror is a 3.5 pair of $\lambda_0/4$ wavelength layers with alternating Pb$_{1-y}$Sr$_y$Te material with high refractive index ($n_H = 5.8$ for $x = 0.03$) and EuTe ($n_L = 2.4$) layers with low refractive index. Due to the large index contrast the calculated reflectivity is $> 99.9\%$ over a broad wavelength range.

The samples were In-soldered onto a Cu heat sink. The external top mirror which serves as output coupler is curved with 25 mm radius. High reflection ($> 99\%$) is obtained with 2 1/2 pairs Pb$_{1-x}$Eu$_x$Te ($n_H = 4.55$)/BaF$_2$ ($n_L = 1.45$) layers epitaxially grown onto the polished curved BaF$_2$ surface. The resonant cavity operates in the stable regime and small mode diameter with
5.3 PbTe VECSELs on Silicon Substrates

Figure 5.9: Schematic representation of the PbTe VECSEL on a Si-substrate and Cu heat spreader.

The cavity length is slightly shorter than the radius of the external curved Bragg mirror.

We present mainly results of a sample optimized for low temperature \(-145^\circ\)C operation with a 830 nm thick PbTe active layer. A second similar sample but with a 600 nm thick active layer is optimized for room temperature operation.

The light-in / light-out characteristics of the first sample (830 nm PbTe) at different operating temperatures are presented in Fig. 5.10 for pulsed mode with 100 ns pulse width and 10 kHz repetition frequency. A maximum output power of > 1.1 W (corrected for optical losses in the power measurement set-up) is reached at -172 \(^\circ\)C operation temperature. Threshold power was less than 300 mW. At \(T = -172^\circ\)C with low excitation, for example 3 W input power, we measured an output power of 0.8 W. If we consider the
quantum deficit at this temperature is $\sim 70\%$ (5.2 $\mu$m output vs 1.55 $\mu$m pump wavelength) and the losses of the measurement set-up, the quantum efficiency is $> 75\%$. The output power saturates but there is thermal rollover. This effect could be explained by the fact that even a 100 ns pulse is long enough to cause a considerable temperature increase, and thereby a decrease in the output power. Simulation shows that 100 ns pulse causes a temperature increase of 40% of the steady state value.

Even if this sample was optimized for -145 °C, lasing was observed up to 0 °C temperature in pulsed mode. It still emits a considerable output power $\sim 90$ mWp at -60 °C. With increasing temperatures the threshold increases to $\sim 5$ W at -60 °C. A thermal saturation is observed at $\sim 10$ W input power for all characteristics at the different temperatures.
The CW light-in/light-out characteristic is plotted in Fig. 5.10(b) at $T = -168 \, ^\circ C$ . The maximum output power is $\sim 17 \, mW$. The threshold power was $< 300 \, mW$. Lasing in CW mode was observed up to -140 °C temperature.

Figure 5.11: Laser spectra: First sample with 830 nm thick PbTe active layer, multimode at high CW pumping power (a), and pulsed excitation (b) at low temperature (-172 °C); second sample (600nm thick PbTe) pulsed excitation at room temperature (c) 

In Fig. 5.11 we present typical spectra of the VECSELs emissions. Fig. 5.11(a) shows the spectrum of CW mode emission at -168 °C and high power excitation. The spectrum is multimode at $\sim 4.85 \, \mu m$ wavelength. The distance between two consecutive modes is determined by the optical thickness of the Si substrate inside the cavity. At low emission power, the spectrum is monomode (not shown). The spectrum in Fig. 5.11(b) corresponds to the same sample in pulsed mode operation at -172 °C. The spectrum is multimode at $\sim 5.3 \, \mu m$ wavelength. Due to less heating in pulsed operation, emission is at longer wavelength compared to (a) due to the positive temperature dependence of the band gap. The spectrum of Fig. 5.11(c) corresponds to pulsed excitation of...
the second sample (600 nm thick active layer) at $+23^\circ$C, lasing is multimode and centred at $\sim 3.6 \mu m$. The large shift compared to Fig. 5.11(a) and (b) is again due to the temperature dependence of the bandgap of PbTe.

**Figure 5.12:** Simulated and experimental threshold powers Of the PbTe VECSEL grown on Si substrate as function of temperature.

Fig. 5.12 shows the simulated and the experimental thresholds at different temperatures. For the Auger coefficient near room temperature, the experimental values of Klann et al were used [68]. Reasonable agreement is obtained with $R = 99\%$ reflectance and $\tau$ as high as 3 ns. The latter corresponds to a remarkably high structural quality of the lattice and thermal expansion mismatched
PbTe layer on Si. Despite the threshold gain shows a strong resonance minimum, this minimum is hardly visible in the threshold power. This is caused by the strong temperature dependence of the threshold carrier density.

5.4 PbSe QW VECSELs on BaF$_2$ Substrates

After realizing the first room temperature IV-VI VECSEL, the next target is decreasing the threshold power of the VECSEL. Employing quantum well as gain structure could be an option. In this part we used exactly the same design as described before in section 5.2 with the exception of using QW as gain medium (Fig. 5.13).

![Schematic representation of a PbSe QW VECSEL.](image)

**Figure 5.13:** Schematic representation of a PbSe QW VECSEL.

Five PbSe QWs ($\sim$ 8 nm wide) are embedded in a Pb$_{0.95}$Eu$_{0.05}$Se host of one $\lambda_0$ optical thickness (resonant design). The structure
is grown on a BaF$_2$ substrate. The QW blue shifts the emission wavelengths with values depending on the width of the wells. Fig. 5.14 shows an example of normalized spectra. Laser emission is at $\sim 4.8 \mu\text{m}$ wavelength at this temperature $T = 100$ K.

**Figure 5.14:** Normalised lasing spectra at same heat sink temperatures. The blue-shift of this QW sample is $\sim 1.7 \mu\text{m}$ compared to a bulk active PbSe layer.

The emission corresponding to a "bulk" PbSe VECSEL at the same temperature is $\sim 6.5 \mu\text{m}$. The blue-shift is estimated to be more than $\sim 1.7 \mu\text{m}$ for the QW sample. Lasing occurs up to 170 K heat sink temperature. However, by changing the design wavelength $\lambda_0$ for higher temperature, the PbSe QW VECSEL demonstrated lasing emission up to $\sim 240$ K.

A high output power was measured up to 400 mW$_p$ with 200 ns pulses at $T = 100$ K (Fig. 5.15). The lowest threshold powers are obtained with the quantum well (QW) structures, decreasing...
5.4 PbSe QW VECSELs on BaF$_2$ Substrates

**Figure 5.15:** Light in/light out characteristics for a QW PbSe mid-IR VECSEL when illuminated with a 1.55 µm wavelength laser at $T = 100$ K.

to below $\sim 0.2$ W at $T = 100$ K. In addition, with the emission wavelengths depending on the width of the wells, the wavelength can be easily chosen. As before in section 5.3, the output power saturates with no clear thermal rollover. This can be the result of the temperature increase during the 100 ns pulse. However, the gain saturation in the quantum wells could also be the reason (see Fig. 3.10).
5 Results

5.5 Continuously Tunable VECSEL

We describe here the first single mode and continuously tunable mid-IR VECSEL. A homogeneous PbTe layer serves as gain medium. Because the Si substrate is too thick to allow the intended free spectral range, the Si substrate is located outside the cavity.

![Diagram of a VECSEL](image)

**Figure 5.16:** Schematic representation of the end-pumped VECSEL with piezo-actuator; total cavity length $\sim 100 \, \mu m$.

Two Bragg mirrors form the cavity. The bottom one is a 4 pair epitaxial Bragg mirror consisting of Pb$_{0.98}$Sr$_{0.02}$Te with high refractive index ($n_H = 5.9$) and EuTe with low index ($n_L = 2.4$) grown on a Si(111) substrate. It is overgrown by the active (gain) layer, 1.2 $\mu m$ PbTe. To achieve an optical end-pumping, the external curved mirror has to be transparent for the 1.55 $\mu m$ laser.
This mirror consists of 5 pair SiO/Si stack, forming a Bragg mirror with 5.2 µm design wavelength.

Emission wavelength is \( \sim 5 \) µm with a total tuning range as high as 0.4 µm. The VECSEL is optically end-pumped with a 1.55 µm laser. In this case we use a much shorter cavity, \( \sim 100 \) µm long, in order that the free spectral range allows only one longitudinal mode to develop (Fig. 5.16).

![Figure 5.17: Superimposed normalized spectra with different actuation voltages. Single mode is observed for piezo driver voltage from 10 V to 80 V.](image)

The cavity length can be altered with a piezo-driver. Fig. 5.17 shows spectra obtained at different drive voltages (a voltage difference of \( \sim 80 \) V corresponds to a displacement of \( \sim 2.6 \) µm).
5 Results

0 V and 5 V drive voltages, two modes appear at a distance of 51 cm\(^{-1}\). This corresponds to the free spectral range. At all higher drive voltages, the range where gain occurs overlaps with only one cavity mode. Consequently, only one mode develops at all voltages between \(\sim 8\) V and 80 V. Its wavelength changes linearly with the cavity length, i.e. actuation voltage.

Figure 5.18: Superimposed and normalized laser spectra at different temperatures. Tuning range is \(\sim 400\) nm.

Spectra at different temperatures, but at fixed cavity lengths, are shown in Fig. 5.18. The wavelength is tunable from 5.28 \(\mu\)m down to 4.87 \(\mu\)m by increasing the temperature from 100 K to 137 K, respectively. This is due to the temperature dependence of the band gap energy. Combining the temperature tuning with the mechanical cavity-length tuning, we are able to continuously tune over 400 nm (8% of the wavelength). The output power of the
5.5 Continuously Tunable VECSEL

single mode VECSEL is $> 10$ mW peak, while threshold powers incident on the active layers are $< 3$ W (100 ns pulse width and 10 kHz repetition frequency).
5 Results
6 Conclusions

The main target of this work was to provide a new optical source in the mid-infrared region. The first lead chalcogenide VECSELs were developed. They cover a wide and important region of the mid-infrared. The realized optically pumped VECSELs emit between 3.5 and 6.5 µm wavelength. The excitation is performed optically with a 1.55 µm pump laser. High reflectivity Bragg mirrors based on lead chalcogenide combined with EuTe and BaF$_2$ were fabricated.

The first lead chalcogenide VECSELs were grown on BaF$_2$. The structures are grown with homogeneous PbTe layers on lattice mismatched BaF$_2$ substrates, emitting at > 5 µm wavelength. The improved version of the VECSEL includes an Al layer for better heat removal, it has 300 mW output power in pulsed mode and 3 mW cw at 100 K.

Above room temperature mid-infrared VECSEL have been realized, too. The gain layer is one wavelength thick PbSe grown on lattice mismatched BaF$_2$ substrates followed by a 2 1/2 pair Bragg mirror. The devices are very simple, Emission wavelength was between 4.2 - 4.8 µm at + 40 and - 60 °C respectively. The output powers were between 5 and 18 mW peak with 100 ns wide pulses.
6 Conclusions

Lead chalcogenide VECSEL were also grown on Si-substrates. These VECSELs demonstrate a high output power exceeding 1 W\textsubscript{p} in pulsed mode and 17 mW cw at \sim 100 K. Lasing is observed up to above room temperature. The optical gain medium consists of a one wavelength thick PbTe layer.

Quantum well (QW) structures have been employed for shorter wavelengths. In addition, due to carrier statistics in 2-dimensional structures, lower threshold powers were obtained. The PbSe QWs embedded in Pb\textsubscript{0.95}Eu\textsubscript{0.05}Se host layers were employed. The lowest threshold powers, P\textsubscript{th} < 0.2 W were obtained at T = 100 K. The QW VECSEL demonstrated lasing emission up to 240 K.

Furthermore, we were proud to present a ready to use single mode continuously tunable VECSEL. Such laser is the perfect optical source for sensitive gas spectroscopy. The mechanical cavity length alteration allow 138 nm wavelength tuning. If additionally combined with temperature tuning, the wavelength is tunable over 400 nm (8% of the wavelength). The VECSL is optically end-pumped, and the output power of the single mode VECSEL is > 10 mW\textsubscript{p} peak.

The important advantage of these devices over other mid-infrared lasers is their simplicity, good beam quality and their low costs. Higher output powers and operating temperatures are expected if designs with more efficient heat removal properties are employed. For instance, if diamond with its extremely high thermal conductivity is used as heat spreader, much higher output powers and operating temperatures, even room temperature CW mode is expected.
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