Doctoral Thesis

PbSe quantum well based mid-infrared vertical surface emitting lasers on silicon

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PbSe quantum well based mid-infrared vertical surface emitting lasers on silicon

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presented by

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Abstract

This thesis is focusing on the development of Vertical External Cavity Surface Emitting Lasers (VECSEL) in the mid-infrared region. The strongest absorption lines of many gases lie in this spectral region, e.g. fundamental vibration modes of C-H, O-H, N-H bonds. This allows the realisation of countless spectroscopic applications.

The lasers described in this work are based on IV-VI semiconductors. They have many favourable properties, like excellent beam quality, large wavelength tunability and simple structure. The VECSEL is emitting the light vertical to the gain layer and consists of two highly reflective Bragg mirrors with an active layer in between. One mirror is mounted externally. The active layer is grown on Si substrate and consists of a homogeneous PbSe active layer or PbSe quantum wells (QW) with various thicknesses. The laser is optically pumped with a commercial 1.55 µm wavelength laser.

A new modular design has been developed with three separate parts (two mirrors and one active layer on separate substrates) forming the VECSEL. The new design facilitates direct comparison between different structures, since a new active layer can be combined with already existing mirrors. It further allows to optimise
VECSEL based on PbSe QW in PbSrSe and PbEuSe host material are realised. With PbEuSe as host material lasing from 3.6 µm to above 5 µm wavelength is reached. Threshold powers are below 0.2 Wp at low temperatures, but the maximum operation temperature is limited to 245 K. This is explained by a band alignment transition of the heterostructure from type I to type II with increasing temperature.

VECSEL with PbSe QW in PbSrSe host material show lasing up to 330 K. With one single device the emission wavelengths range from 3.6 µm up to 5.1 µm. Emission at 3.2 µm wavelength near room temperature (RT) is realised with 4 nm thick QW. The analysis of experimental results leads to the conclusion that the laser performance is limited by short carrier lifetimes and thermal leakage of generated carriers.

By decreasing the cavity length of the VECSEL to below 100 µm single-mode emission is achieved. In combination with a moveable external mirror a continuously tunable, single-mode VECSEL around 3.3 µm emission wavelength is realised. The VECSEL operates near RT and is based on PbSe QW in PbSrSe host material. This laser may be applied for detection of various hydrocarbons and hydroxides.

With a homogeneous PbSe active layer emission wavelengths are up to 5.6 µm at low temperatures. The laser operates at RT due to a soldering process to effectively remove the heat from the active region.
Zusammenfassung


Die in dieser Arbeit beschriebenen Laser basieren auf IV-VI Halbleitern und haben viele hervorragende Eigenschaften, wie z.B. eine exzellente Strahlqualität, eine grosse spektrale Durchstimmbarkeit und eine einfache Struktur. VECSEL emittieren das Licht senkrecht zur aktiven Schicht, welche sich zwischen zwei Spiegeln mit hoher Reflektivität befindet. Ein Spiegel ist gekrümmt und extern montiert. Die aktive Schicht besteht entweder aus einer homogenen PbSe Schicht oder aus PbSe Quantentöpfen (QW) mit unterschiedlicher Dicke. Der VECSEL wird optisch mit einem 1.55 μm Pumplaser angeregt.

Im Verlauf dieser Arbeit wurde ein neuer VECSEL-Aufbau entwickelt. Der Laser besteht nun aus drei separaten Teilen (aus zwei Spiegeln und einer aktiven Schicht auf verschiedenen Substraten). Da somit die aktive Schicht mit bereits existierenden Spiegeln kom-

VECSEL wurden mit PbSe QW in PbSrSe und PbEuSe als Host- bzw. Barrierenmaterial hergestellt. Mit PbEuSe als Barrierenmaterial werden Wellenlängen zwischen 3.6 \( \mu \text{m} \) und 5 \( \mu \text{m} \) emittiert. Schwellenpumpleistungen unter 0.2 \( W_p \) wurden gemessen, doch eine maximale Temperatur von \( \sim 245 \text{ K} \) konnte nicht überschritten werden. Dies wird darauf zurückgeführt, dass die Heterostruktur mit steigender Temperatur von Typ I auf Typ II wechselt.

VECSEL mit PbSe QW in PbSrSe lasen bis zu 330 K. Mit einem einzigen Laser ist es möglich einen Wellenlängenbereich von 3.6 \( \mu \text{m} \) bis 5.1 \( \mu \text{m} \) abzudecken. Mit 4 nm dicken QW wird eine Wellenlänge von 3.2 \( \mu \text{m} \) nahe Raumtemperatur (RT) erreicht. Durch Analyse gemessener Daten kann darauf geschlossen werden, dass vor allem die kurze Lebenszeit der Ladungsträger und das Entweichen der Ladungsträger aufgrund thermischer Anregung die Schwellenpumpleistung erhöhen.

Wird die Kavitätslänge des VECSEL auf unter 100 \( \mu \text{m} \) verkürzt, wird nur eine Mode emittiert. In Kombination mit einem beweglichen, externen Spiegel wurde ein Laser realisiert, dessen einzige Mode bei 3.3 \( \mu \text{m} \) kontinuierlich spektral verschoben werden kann. Die aktive Schicht besteht aus PbSe QW in PbSrSe als Host-Material. Dieser VECSEL lased nahe RT und kann zur Detektion von Kohlenwasserstoffen und Hydroxiden eingesetzt werden.

Mit einer homogenen PbSe Schicht wurde Laser-Emission bis zu 5.6 \( \mu \text{m} \) Wellenlänge bei tiefen Temperaturen erreicht. Der Laser kann durch eine verbesserte Wärmeabfuhr (Löten) bei RT betrieben werden.
Chapter 1

Introduction

Lasers in the mid-infrared (MIR) are widely used for spectroscopic applications since the vast majority of gases have absorption lines in the wavelength region between 2 - 25 µm. Due to these strong vibrational absorption bands optical techniques allow a non intrusive detection of smallest gas concentrations and can be applied in many fields like environmental monitoring, high speed exhaust gas analysis, chemical reaction examination, industrial process control and many more [1].

Some of the requirements for laser sources for spectroscopic applications are a sufficient output power, a narrow linewidth, an ease of tailoring the emission wavelength and a rapid wavelength tunability [2]. Worldwide a big effort is taken to meet these requirements for MIR laser by applying different material systems and laser designs. Nevertheless, only few laser types are available in the wavelength range between 3 - 5 µm.
Mid-Infrared semiconductor lasers

IV-VI semiconductor laser

The first diode laser based on IV-VI semiconductors was already developed in 1964 using a PbTe active region [3] and up to now lead salt lasers based on various other IV-VI compounds like PbSe, PbS and PbSnSe have been realised [4–7]. Most of edge emitting diode lasers operate at cryogenic temperatures and their output power is \( \sim 1 \text{ mW} \). However, for a PbSe based diode laser a maximum operation temperature of 333 K with 10 ns pulses is reported [5].

In addition other types of IV-IV lasers have been realised, like optically pumped edge emitters [8], vertical cavity surface emitting laser (VCSEL) [9, 10], vertical external cavity surface emitting laser (VECSEL, see description below) [11, 12] and microdisk laser [13, 14] covering a wavelength range from below 3 \( \mu \text{m} \) to above 20 \( \mu \text{m} \) [15]. With wispering-gallery mode microdisk laser - based on PbSe quantum wells (QW) in PbSrSe host material - continuous wave (CW) emission up to 273 K is reached [13]. This clearly demonstrates the potential of the IV-VI semiconductors for laser applications.

Type I Interband III-V Laser

For lasers in the MIR particularly the III-V semiconductors are widely used. Based on type I interband transitions wavelengths up to and above 3 \( \mu \text{m} \) are reached. For GaSb based diode lasers emission wavelengths up to 3.4 \( \mu \text{m} \) are achieved [16]. CW operation at room temperature (RT) with optically pumped VECSEL based on AlGaIn/AsSb (on GaSb substrate) with an emission wavelength of 2.8 \( \mu \text{m} \) was reported by Rösener et al. [17].
Emission wavelengths above 3 µm are difficult to achieve with III-V semiconductors due to the high band gap energy of the lattice matched materials. Therefore more complex laser designs have been developed, which employ different transition mechanisms. The ICL uses a type II interband transition between InGaAsN/GaAsSb QW [18]. For these "W"-structure lasers emission above 4 µm was reported [19] for edge emitters.

A type of laser receiving much interest is the QCL based on intraband (intersubband) transitions in the conduction band of a repeated stack of QW [20]. This type of laser requires a very detailed knowledge of the used materials and a highly developed fabrication process. Therefore, up to now QCL have been realised only with III-V semiconductors. Depending on the materials used and the thicknesses of the QW the emission wavelengths range from 3.1 to 250 µm [21, 22]. Also CW at room temperature is achieved over a broad wavelength range. Due to selection rules, no stimulated emission of photons normal to the confinement direction is allowed. However, by using diffraction gratings output coupling perpendicular to the surface with decreased divergence angles of the output beam has been achieved [23–25].
VECSEL based on IV-VI semiconductors

VECSEL

A VECSEL is a semiconductor disk laser emitting the light vertical to the active layer. The laser consists of two high reflectivity mirrors with the active region in between. One of the mirrors is mounted externally, forming an airgap inside the cavity. Due to optical pumping VECSEL are power scalable and a homogeneous excited carrier density along the active region is achieved. Further, because no doping of the active region is needed, the carrier density is lower compared to diode lasers. This leads to decreased losses caused by Auger recombination and free carrier absorption.

Further advantages of VECSEL are their vertical heat flow, easy tunability and a very good beam quality, i.e. a very narrow circular output cone with a divergence angle $\sim 1^\circ$ [26–28]. In contrast, edge emitting lasers emit a strongly astigmatic beam with a large aperture angle in the fast axis. Additional optics is needed to collimate the beam which increases the complexity and the cost of the laser devices.

For optically pumped IV-VI VECSEL just 10-40 layers are needed, compared to up to 2000 layers needed for quantum cascade lasers (QCL). Furthermore no after-growth etch or photolithographic process is needed. In combination with a simple alignment and packaging process the complexity and fabrication costs are well below those of comparable laser sources.

IV-VI semiconductors

IV-VI materials like PbTe, PbSe and PbS are very well suited for MIR laser applications due to their direct band gap of 270-420 meV (at RT). The band gap energy is highly temperature sensitive and by alloying with Eu, Sr or Sn a wavelength region $< 3 \mu$m and $> 30 \mu$m can be covered - the whole MIR range. Furthermore, due to the nearly symmetric bandstructure and the absence of a heavy
hole band the Auger coefficient is much lower compared to III-V materials with similar band gap energies.

**IV-VI based VECSEL**

Combining the properties of the IV-VI semiconductors and the VECSEL-structure, a very good beam quality over a large wavelength range in the MIR is achieved. IV-VI based VECSEL have so far been realised only by our group. They are based on PbSe, PbSnSe and PbTe active layers on Si and BaF$_2$ substrates [11, 12, 29–33]. An emission wavelength up to 10 $\mu$m is achieved. The maximum operation temperature is 318 K and output powers are up to 1 W$_p$.

In this work Vertical External Cavity Surface Emitting Laser (VECSEL) based on IV-VI semiconductors have been realised operating from 3.2-5.8 $\mu$m. Using QW based structures, maximum operation temperatures of 330 K are reached. A new modular design leads to a more efficient VECSEL fabrication and offers a new versatility in combining mirrors and active layers to operating VCSEL and VECSEL. By decreasing the cavity length monomode emission near RT is achieved, which is continuously tunable around 3.3 $\mu$m. This VECSEL can be used to detect various hydrocarbons and hydroxides, which have absorption lines in this spectral region.
Chapter 2

IV-VI Semiconductors

2.1 Properties

The lasers described in this work are based on the lead chalcogenides like PbTe and PbSe, which belong to the classes of narrowgap semiconductors. These IV-VI materials have a direct narrow band gap of about 300 meV at room temperature (RT) and are therefore very suitable for lasers in the mid-infrared (MIR). They show a couple of extraordinary features, like low Auger coefficients and a very large band gap tunability. The material parameters are listed in table 2.1.

Crystal structure

PbTe and PbSe crystallises in the face centred cubic (rocksalt) structure (figure 2.1). Every Pb atom is surrounded by six Te or Se atoms, the bonds are ionic. Because of the NaCl crystal structure the IV-VI semiconductors are also called lead salts.

The lattice constant of PbTe is 6.46 Å, for PbSe 6.12 Å [34]. By alloying with Y=Eu, Sr or Sn every Y atom replaces one Pb atom, the alloy is therefore described as Pb$_{1-x}$Y$_x$Te(Se). Due to alloying the lattice constant changes slightly, less than 0.2% for x=0.05 [35–38].
The layers are grown by molecular beam epitaxy (MBE) on 3 inch Si wafers. Si has a lattice constant of 5.43 Å, the lattice mismatch to the IV-VI compounds is very large, up to 20%. There is also a large difference in the thermal expansion coefficient (2.6 · 10⁻⁶ K⁻¹ for Si and ∼20 · 10⁻⁶ K⁻¹ for lead salts at RT). These preconditions are at first sight all but ideal to grow high quality epitaxial lead chalcogenide layers on Si substrates.

The lattice mismatch can be overcome by growing a thin CaF₂ layer directly on the Si substrate. CaF₂ has a similar lattice constant as Si (a_{CaF₂} = 5.46 Å) and a layer thickness of 2 nm was found to be optimal for high quality samples [39]. Afterwards the IV-VI materials can be grown.

The thermal expansion mismatch is not severe as long as the IV-VI layers are grown on Si substrates with (111) orientation, because the lead-chalcogenide layers can relax the arising strain due to change of temperature by glide of dislocations [40]. There exist three \{001\}\{110\}-type glide systems and the glide planes are inclined by 54° with respect to the surface. Due to this relaxation mechanism the layers are nearly unstrained [41].
### 2.1 Properties

<table>
<thead>
<tr>
<th>Crystal Structure</th>
<th>PbSe</th>
<th>Pb_{0.99}Eu_{0.01}Se</th>
<th>Pb_{0.99}Sr_{0.01}Se</th>
<th>Pb_{0.99}Sn_{0.01}Se</th>
<th>PbTe</th>
<th>Pb_{0.99}Eu_{0.01}Te</th>
<th>EuTe</th>
<th>Si</th>
<th>BaF_{2}</th>
<th>CaF_{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>lattice constant [Å]</td>
<td>6.12</td>
<td>&gt; 0.30</td>
<td>&gt; 0.31</td>
<td>&lt; 0.26</td>
<td>&gt; 0.37</td>
<td>&gt; 0.37</td>
<td>6.6</td>
<td>5.43</td>
<td>6.2</td>
<td>5.46</td>
</tr>
<tr>
<td>band gap at RT [eV]</td>
<td>0.27</td>
<td>4.68</td>
<td>&lt;</td>
<td>&lt;</td>
<td>5.6</td>
<td>5.6</td>
<td>2.0</td>
<td>1.1</td>
<td>12.1</td>
<td>11.0</td>
</tr>
<tr>
<td>refractive index at RT at 5 µm</td>
<td>5.0</td>
<td>19.4</td>
<td>-</td>
<td>-</td>
<td>19.8</td>
<td>19.8</td>
<td>2.4</td>
<td>3.42</td>
<td>1.45</td>
<td>1.4</td>
</tr>
<tr>
<td>thermal expansion [10^{-6} K^{-1}]</td>
<td>19.4</td>
<td>1.7</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
<td>2.3</td>
<td>13.6</td>
<td>2.7</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>thermal conductivity [Wm^{-1} K^{-1}]</td>
<td>1.7</td>
<td>&gt; 0.30</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&gt; 0.37</td>
<td>&gt; 0.37</td>
<td>11</td>
<td>142</td>
<td>11.7</td>
<td>9.6</td>
</tr>
<tr>
<td>references</td>
<td>35, 42, 43</td>
<td>38, 43</td>
<td>38, 42</td>
<td>35, 42</td>
<td>12, 45</td>
<td>45</td>
<td>47, 49</td>
<td>50, 52</td>
<td>33, 55</td>
<td>33, 55</td>
</tr>
</tbody>
</table>

**Table 2.1:** Properties of the used materials. The sign ‘<’ (‘>’) indicates smaller (larger) values compared to the binary compound.
Band structure

The band structure of the IV-VI semiconductors includes a direct narrow band gap of $\sim 300$ meV at RT for PbTe and PbSe. The band extrema are at the four equivalent L points of the Brillouin zone [57]. In this region of k-space they are nearly mirror images of each other, resulting in similar effective masses of electrons and holes. The constant energy surfaces near the band edges are elongated ellipsoids along the $\langle 111 \rangle$ directions. The anisotropy coefficient $m_l/m_t$, the ratio between longitudinal and transversal effective masses, is $\sim 10$ for PbTe and $\sim 2$ for PbSe [34].

\[ \text{Figure 2.2: Cutoff wavelength of PbYSe as function of temperature for different compositions.} \]

The band gap energy is highly temperature dependent with a value of around $+0.5$ meV/K [34]. Thus, contrary to most other semiconductors it increases with temperature.

The band gap energy changes also by alloying. With the addition
of Sn the band gap energy decreases \[58-60\]. With the addition of Eu \[45, 61\] or Sr \[38, 62\] the band gap energy increases. The dependence of the cut-off wavelength with respect to temperature and composition is shown in figure 2.2. For an alloy concentration below 40% the band gap is direct and may change to an indirect one at higher concentrations \[63, 64\].

Furthermore, to change the transition energy there is the possibility to grow quantum wells (QW). Depending on the the width of the wells and the band offsets between the conduction/valence band extrema of the barrier and well material a desired blueshift can be realised. A more detailed description of the QW behaviour will be given in chapter 5.

With the described possibilities to change the cut-off wavelength of the IV-VI semiconductors it is possible to cover a wavelength range from \(< 3 \, \mu m\) to \(> 30 \, \mu m\).

**Thermal conductivity**

The VECSEL are optically pumped. The pump power ranges from 100 mW\(_P\) up to 25 W\(_P\). In addition a large quantum deficit is present: the laser is pumped with a 1.55 \(\mu m\) wavelength laser and the output wavelength ranges between 3.2 \(\mu m\) and 10 \(\mu m\). Thus, 50% and more of the incoming radiation is converted into heat.

With increasing temperature losses like Shockley-Read-Hall and Auger recombinations increase and therefore an efficient heat removal is essential to improve the lasing performance. Unfortunately the values of the thermal conductivity of IV-VI materials are very low (see table 2.1) and a temperature increase in the active region up to 40\(^\circ\)C is observable during laser operation in pulsed mode. Already minor improvements like Al heatspreader \[11\] or In bonding onto the heatsink \[12\] increase the maximum operation temperature considerably. Hence, a further improved thermal management should result in better laser performances.
Material gain

For a high excited carrier density in a material the absorption may become negative and gain, the amplification of light, occurs. To compute the gain for bulk PbSe, the gain formula of Anderson [65] and the parameters of Lu [66] are taken.

![Material gain of PbSe for different temperatures and carrier concentrations.](image)

**Figure 2.3:** Material gain of PbSe for different temperatures and carrier concentrations.

The gain for different carrier concentrations and temperatures is plotted in figure 2.3. With increasing carrier concentration the gain broadens and the gain maximum increases and shifts to higher energy values. By increasing the temperature, the energy gap increases and a further shift of the gain to higher energies occurs.

Thus, for a high pump power, the laser emission is shifted to shorter wavelengths.
Further properties

Lead salts are very fault tolerant. This is due to the very high dielectric constant $\epsilon$ for all IV-VI semiconductors ($\epsilon > 150$ at RT [67] and up to $10^3 - 10^4$ for low temperatures [34]). This high dielectric constant is shielding carriers from charged defects [68, 69]. The defects are mainly caused by dislocations and even with $10^6$ dislocations per cm$^2$ high carrier mobilities up to $10^6$ cm$^2$/(Vs) are reached [70]. This is of high importance for the fabrication of MIR-devices. Also the strain relaxation mechanism on Si while changing temperature has no considerable influence on the electronic and optical performance [35]. But nevertheless also for the lead salts a decreased material quality leads to reduced carrier lifetimes, although this effect is not as pronounced as in other material systems.

The real part of the dielectric constant is related to the real part $n$ and complex part $k$ of the refractive index via

$$\epsilon = n^2 - k^2.$$  

This leads to high values of $n$ for the lead salts (5.8 for PbTe and 5.0 for PbSe at RT [45]). In combination with materials with low refractive index like EuTe or BaF$_2$ high reflective Bragg mirrors can be realised. The refractive index changes with temperature (it decreases with higher temperature) and with composition. The addition of Eu, Sr or Sn decreases the refractive index, which gives the possibility to tailor it e.g. for an anti-reflection coating.
2.2 Recombination mechanisms

The basic principle of a laser is to excite enough electrons into a higher level to generate population inversion and to achieve stimulated recombination of electrons with holes. But there are other recombination processes, which are unwanted and reduce the laser performance.

Shockley - Read - Hall recombination

The crystalline quality of the material has an important influence on the lifetime of the generated carriers [71, 72]. Due to imperfections like defects or impurities energy levels in the band gap are formed. These energy levels act as recombination centres by capturing injected carriers and are therefore also called trap levels. A steady-state recombination rate is given by [73]

\[
R_{SRH} = \frac{np - n_i^2}{\tau_p n (1 + e^{E_F - E_T} k_B T) + \tau_n p (1 + e^{E_F - E_T} k_B T)}
\]

\(n (p)\) is the electron (hole) density, \(n_i\) is the intrinsic carrier concentration. \(\tau_{n(p)}\) is the electron (hole) lifetime, \(E_F\) the Fermi energy, \(E_T\) the energy level of the trap, \(k_B\) the Boltzmann constant and \(T\) the temperature.

At a high enough carrier concentration the recombination rate by traps is proportional to the carrier concentration.

\[
R_{SRH} = A_{SRH} \cdot n = \frac{n}{\tau_{SRH}}
\]

(2.1)

\(R_{SRH}\) differs from sample to sample since it depends on the structural quality of the crystal. With Hall measurements of single layers and by fitting experimental values of the threshold power carrier lifetimes \(\tau_{SRH}\) from 0.1 to 3 ns are determined.
2.2 Recombination mechanisms

**Spontaneous emission**

An excited electron may after some time without any interaction spontaneously return to its ground state by the emission of a photon. The emitted photon will have a random phase, direction and wavelength and can therefore not contribute to the lasing action. Although every lasing starts by at least one spontaneous recombination, this effect is unwanted and leads to the reduction of the carrier density in the upper level. The spontaneous emission rate $r_{sp}$ depends on the probability $f_c$ to have an electron in the upper level, $f_v$ to have a hole in the ground state, the density of states $\rho_c$ and $\rho_v$ and the transition probability $W_{sp}$ [73]. In equilibrium $r_{sp}$ is given by

$$r_{sp}(\hbar \omega) = \int [f_c(E_c) (1 - f_c(\hbar \omega - E_c))] W_{sp}(E_c) \rho(E_c) \rho(\hbar \omega - E_c) dE_c$$

(2.2)

To get the total spontaneous recombination rate one has to integrate $r_{sp}$ over all possible emission frequencies.

$$R_{sp} = \int_{E_g}^{\infty} r_{sp}(\hbar \omega) d(\hbar \omega)$$

A calculation for PbTe is given by Galeskii et al. [74].

This type of radiative recombination is proportional to the square of the carrier concentration.

$$R_{sp} = B_{sp} \cdot n^2$$

(2.3)

**Auger recombination**

The Auger recombination is a non-radiative process. In a basic Auger-process the released energy of recombination of an electron with a hole is transferred to a third carrier, which gets excited to a higher state. The process can further involve trap states or phonons. PbTe and PbSe have very low Auger coefficients $C_A$ in the order
of $10^{-28}$ cm$^6$s$^{-1}$. This is a factor 10-100 times lower compared to the III-V semiconductors with similar band gap energies [75]. The low Auger coefficient results from mirror-like conduction and valence bands of the lead chalcogenides and the absence of a heavy hole band [76]. According to Emtage [77] the Auger recombination rate for a non-degenerated, n-type IV-VI semiconductor is

$$R_A = \left(2\pi\right)^{\frac{5}{2}} \frac{N' n^3 q^4 (k_B T)^{\frac{1}{2}} \hbar^3}{N^2 e_{\infty}^2 E_g^2 m_l^t m_l^t} \frac{m_l E_g}{e^{2m_l k_B T}}$$

(2.4)

$$= C_A \cdot n^3$$

(2.5)

$N'(N)$ number of valence (conduction) bands

$n$ carrier density

$q$ electron charge

$e_{\infty}$ high frequency dielectric constant

$k_B$ Boltzmann constant

$T$ temperature

$m_l(t)$ longitudinal (transversal) effective mass

$E_g$ band gap energy

The assumptions are

$$\frac{m_l}{m_l} \ll 1 \quad \text{and} \quad \frac{m_l k_B T}{2m_l} \ll E_g.$$  

In calculations in the following chapters the formula 2.4 was used even in cases where the assumptions do not strictly apply, like for PbSe with $m_l/m_l \approx 0.5$.

The recombination through the Auger process increases strongly with carrier density. It is important to mention, that the limit of minimal losses set by the Auger recombination is a fundamental limit, which can not be overcome.
In the two-dimensional case of quantum wells only few published calculations try to evaluate the Auger coefficient for IV-VI materials. Lemke et al. [78] came to the conclusion that for temperatures above 150 K the Auger coefficient for QW is just slightly smaller than in the case of bulk layers. Similar results were published for 2D III-V structures [79, 80].

In conclusion, the total recombination rate \( R_{\text{tot}} \) caused by unwanted recombination processes is written as

\[
R_{\text{tot}} = A_{SRH} \cdot n + B_{sp} \cdot n^2 + C_A \cdot n^3. \tag{2.6}
\]

### 2.3 Growth process

Most of the layers needed for a VECSEL are grown by molecular beam epitaxy (MBE). For the growth process we are equipped with three MBE chambers with solid sources, which are connected via a evacuated tunnel system \((p = 1 \cdot 10^{-8} \text{ mbar})\). In the first chamber a Reflection High Energy Electron Diffraction (RHEED) gun and two sources are installed: CaF\(_2\) and BaF\(_2\). The second MBE chamber is used for PbYTe materials and the third chamber for the PbYSn materials with \(Y = \text{Sr, Eu and Sn}\). An additional Te (Se) source is installed for Te (Se) - rich growth conditions. During the growth process the pressure is between \(10^{-10}\) and \(10^{-7}\) mbar. Fluxes are measured before and after each layer with a quartz crystal monitor.

The active layer and the bottom Bragg mirror are grown on 3 inch silicon (111) substrates. The wafers are cleaned with a modified Shiraki process [81], where a thin and easy removable oxide layer is formed on the surface. This oxide layer is removed in the MBE chamber by heating the substrate above 730°C. To ensure a clean Si surface the wafer is heated up to 1080°C for 5 minutes. The surface of the Si wafer is controlled afterwards by the RHEED method. A 7 × 7 reconstruction is observed for a clean Si (111) surface.

For a good crystalline quality of the lead chalcogenides on Si sub-
strates a 2 nm thick CaF$_2$ buffer layer is needed, which is deposited at a growth-temperature of 750°C.

The substrates are then transferred into a second MBE-chamber for the growth of the mirror or the active layer. The growth temperatures for the IV-VI materials are between 380 and 440°C. The speed of growth is about 1 µm/h.

For the Bragg mirrors on Si substrates alternating layers of EuTe/PbYTe with $Y =$ Eu or Sr with a $Y$ content 2-4% are used. Active layers are grown with PbSe and PbYSe with $Y =$ Eu or Sr. A detailed description of the design of the active layers and mirrors follows later.

The external mirror is a curved Bragg mirror on a BaF$_2$ (111) substrate. The curvature with radius $r_c = 25$ mm is slowly polished into the BaF$_2$ before the growth process. Bragg mirrors with alternating layers of BaF$_2$ and PbEuTe with 2-8% Eu are grown. Unfortunately it is not possible to grow thick BaF$_2$ layers ($d > 700$ nm) on Si substrates. Because of the large thermal expansion mismatch and the hardness of the BaF$_2$ layer cracks form.

Polycrystalline Bragg mirrors on Si substrates with alternating pairs of Si and SiO layers are deposited in a physical vapour deposition chamber. The evaporation materials in graphite crucibles are heated by an electron beam. The silicon substrates are heated up to 100°C during the deposition process by a separate heater to prevent flaking of the deposited layers. The flux is measured continuously with a quartz crystal monitor during the deposition process. The speed of deposition is $\sim 4$ µm/h. The pressure during the growth process is $10^{-6} - 10^{-7}$ mbar.
Chapter 3

VECSEL design

Figure 3.1: Structure of an optically pumped VECSEL consisting of a bottom mirror, active layer and a curved, external mirror.
The **Vertical External Cavity Surface Emitting Laser** is a semiconductor disk laser, which emits the light normal to the gain layer(s). It consists of a flat bottom mirror, an active layer and a curved external mirror, which is mounted in some distance to create the cavity. An air gap is formed inside the cavity (see figure 3.1). VECSEL are power scalable, have a very good beam quality and because they are optically pumped, no photolithographic process is needed after growth.

For a conventional VECSEL-setup the bottom part consists of the semiconductor active layer and the Bragg-mirror. They are grown sequentially on one single substrate. The active layer can be grown on top of the bottom mirror \[31,82,83\] or directly on the substrate with a subsequent mirror \[11,12,31\]. In this case the substrate is inside the cavity and needs to be transparent. The top part is a curved external Bragg mirror.

Unfavourably, the investigation of different active regions involves fabrications of whole bottom parts - especially also the time-consuming deposition of the bottom Bragg mirror. Further, different Bragg mirrors may affect the laser performance.

### 3.1 Modular design

A new modular setup for the VECSEL was developed. Contrary to the standard VECSEL structure described above the setup consists of three separate parts:

1. bottom Bragg mirror on Si substrate
2. active layer on separate Si substrate
3. curved Bragg mirror on BaF\(_2\) substrate for output coupling

For the assembling of the VECSEL the Si-substrate with the active layer is simply placed onto the flat mirror (figure 3.2). Both are held together by a copper sample holder. No bonding process or bonding material is needed. Only the bottom Bragg mirror has a direct
Modular Design: the VECSEL is assembled of three separate parts. No bonding process or bonding material is needed. To create the cavity, the curved mirror is located at some distance. We call this setup modular design.

Using the modular design, only the active layer has to be grown for a new VECSEL, since the active layer can simply be combined with an already existing mirror. This considerably reduces the fabrication time and facilitates direct comparison between different structures.

The reduction of fabrication time is even more important for the development of QW active regions, since many parameters like the barrier material, barrier height and thickness and number of the QW can be varied.

**Figure 3.2:** Modular Design: the VECSEL is assembled of three separate parts. No bonding process or bonding material is needed.
3.2 Distributed Bragg reflectors

Compared to edge emitting lasers the path of light through the active layer per round-trip is much shorter for surface emitting lasers. Thus, the product of the thickness of the active layer $d$ and the gain $g$ is much smaller and the light has to pass the active region several times to achieve lasing. Therefore high reflectivity mirrors, like distributed Bragg reflectors (DBR) are needed.

DBR are dielectric mirrors consisting of pairs of $\lambda_0/4$ thick layers with alternating high and low refractive index ($\lambda_0$ is the design wavelength where the reflection is the highest). The reflection is caused by multiple-interference effects. It is therefore necessary to control the thickness of the layers precisely and to achieve smooth and flat surfaces to minimise scattering effects.

The reflectivity $R$ at the design-wavelength is given by

$$ R = \left( \frac{1 - \frac{n_b}{n_f} \left( \frac{n_1}{n_2} \right)^{2N}}{1 + \frac{n_b}{n_f} \left( \frac{n_1}{n_2} \right)^{2N}} \right)^2. \tag{3.1} $$

$n_1, n_2$ refractive indices of the $\lambda_0/4$ layers

$n_f (n_b)$ refractive indices of the materials in front of (behind) the mirror stack

$N$ number of layer pairs

The width of the photonic stopband is roughly estimated for $n_2 > n_1$ by

$$ \Delta \lambda_0 = \frac{4 \lambda_0}{\pi} \arcsin \left( \frac{n_2 - n_1}{n_2 + n_1} \right). \tag{3.2} $$
Epitaxial DBR

The IV-VI materials have high refractive indices ($n_{\text{PbTe}} = 5.8$, $n_{\text{PbSe}} = 5.0$). In combination with low index materials like EuTe ($n = 2.4$) or BaF$_2$ ($n = 1.45$) highly reflective DBR are grown. Just a few pairs are sufficient to achieve reflectivities above 99.9%.

To eliminate absorption effects in the DBR, alloying with Eu or Sr is often necessary (see figure 2.2). Even for QW active layers, what implicates a shift of the emission wavelength to shorter wavelengths, the addition of 2-4% of Eu or Sr is sufficient to achieve transparent materials.

However, the alloying decreases the refractive index, what deteriorates slightly the reflectivity properties of the DBR (see equ. 3.1 and 3.2).

Simulations of two DBR consisting of 4.5 pairs of Pb$_{1-x}$Eu$_x$Te/EuTe are shown in figure 3.3. The simulation is based on the well known matrix method [85]. With 4.5 pairs and $x = 0.02$ a maximal reflectivity of 99.9% is reached. The stopband width for $R > 99\%$ is 1.7 µm broad.

In comparison, with III-V materials 20 and more of lattice matched layer pairs need to be grown to reach such high reflectivities with a stopband width of 300 cm$^{-1}$ [86].

Polycrystalline Si/SiO DBR

Although the epitaxially grown mirrors are highly reflective over a broad wavelength range, they show constraints for the pump beam. We use a commercial 1.55 µm wavelength laser as pump source and for PbYTe (Y= Eu or Sr) with a Y concentration around 3% the material is absorbing the pump laser. To pump the VECSEL through the mirror (end pumping) the alloy concentrations of PbYTe need to be raised up to 15% for transparency at 1.55 µm. At such high concentrations the refractive index decreases from 5.8 to below 4. More layer pairs need to be grown to reach comparable reflectivi-
Simulation of reflectivity of two DBR with 4.5 Pb$_{1-x}$Eu$_x$Te/EuTe pairs on Si for $x = 0.02$ and $x = 0.15$. With increasing Eu content, the refractive index and thus the reflectivity decreases.

To realise end pumped VECSEL, DBR consisting of Si and SiO were developed [87]. The $\lambda_0/4$ thick polycrystalline layers are evaporated on Si substrates in a physical vapour deposition chamber. The refractive indices of Si ($n_{\text{Si}} = 3.41$) and SiO ($n_{\text{SiO}} = 1.87$) result in a refractive index contrast of $\sim 1.8$. This is considerably less compared to IV-VI based DBR but still sufficient to achieve high reflectivities ($R > 99.5\%$) and a stopband width of more than 1.5 $\mu$m. Five or more layer pairs are needed to reach these specific values.

For end pumping also the transmission of the pump beam through the mirror has to be considered. Figure [3.4] shows the simulation of a DBR with 5 pairs of $\lambda_0/4$ thick Si/SiO layers with
3.2 Distributed Bragg reflectors

Figure 3.4: a) Si/SiO DBR with 5 $\lambda_0/4$ pairs with high reflectivity around 4 $\mu$m. b) By adjusting the layer thicknesses of the last three layers ($d_{8,\text{Si}} = 280$ nm, $d_{9,\text{SiO}} = 668$ nm, $d_{10,\text{Si}} = 235$ nm) from the ideal $\lambda_0/4$ value ($d_{\text{Si}} = 293$ nm, $d_{\text{SiO}} = 535$ nm), the transmission at the wavelength of the pump laser (1.55 $\mu$m) gets enhanced without a significant deterioration of the stopband.

a center wavelength of 4 $\mu$m ($d_{\text{Si}} = 293$ nm, $d_{\text{SiO}} = 535$ nm). The reflectivity of the pump beam is below 20% in a very narrow region only. Thus, with not perfectly controlled growth parameters a high transmission of the pump beam can not be guaranteed. For this reason the thicknesses of the last three layers are changed ($d_{8,\text{Si}} = 280$ nm, $d_{9,\text{SiO}} = 668$ nm, $d_{10,\text{Si}} = 235$ nm). This results in comparable stopbands, but a larger range of high transmission at 1.55 $\mu$m (figure 3.4b)).
3.3 Stability

For VECSEL only the bottom DBR and the active layer may be grown monolithically on one substrate. The top DBR is mounted in some distance, in between is an air gap. With two flat DBR the resonator is only stable if both mirrors are perfectly parallel aligned. In practice such an adjustment is very difficult to achieve.

To realise a stable resonator a flat bottom DBR and an external spherical DBR are used. The resonator type is a hemispherical resonator. The mode beam diameter (TEM\(_{00}\)) on the bottom DBR \(d_1\) of a resonator with length \(L\) and radius of curvature \(r_c\) of the external mirror is [26]

\[
d_1^2 = \frac{4\lambda L}{\pi} \sqrt{(r_c - L)/L}. \tag{3.3}
\]

The mode diameter on the spherical mirror \(d_2\) is

\[
d_2^2 = \frac{4\lambda L}{\pi} \sqrt{L/(r_c - L)}. \tag{3.4}
\]
In our setup we use a curvature radius of 25 mm. The stability condition is now defined by \( d_1 \) and \( r_c \). With \( r_c = 25 \text{ mm} \) and \( d_1 = 100 \mu \text{m} \) there are two possible cavity lengths (see figure 3.5). A cavity length slightly smaller than 25 mm is chosen.

3.4 Cavity losses

Cavity losses are optical losses caused by the cavity. In order to overcome these optical losses the condition

\[
\Gamma \cdot g_{\text{thr}} = \alpha_{\text{mir}} + \alpha_{\text{int}}
\]

has to be fulfilled. \( \alpha_{\text{mir}} \) are the mirror losses, \( \alpha_{\text{int}} \) are the internal losses mainly caused by free carrier absorption. \( \Gamma \) is the confinement factor, which takes into account that only a small part of the optical field inside the cavity is confined in the active region.

\[
\Gamma = \frac{\int_{\text{active}} |E|^2 dz}{\int_{\text{cavity}} |E|^2 dz}
\]

The two mirrors with reflectivities \( R_1 \) and \( R_2 \) define the cavity with length \( L \). Each mirror is characterised by

\[
\begin{align*}
I^+(L) &= R_1 I^-(L) \\
I^-(0) &= R_2 I^+(0).
\end{align*}
\]

where \( I^-(\cdot) \) is the light intensity propagating in the negative direction, and \( I^+(\cdot) \) is propagating in the positive direction. With the mirror losses \( \alpha_{\text{mir}} \)

\[
\frac{dI^+(-)}{dz} = -(+\alpha_{\text{mir}}I^+(-)
\]
the solution to this equation is

\[
I^+(z) = I^+(0) e^{-\alpha_{\text{mir}} z} \\
I^-(z) = I^-(L) e^{-\alpha_{\text{mir}} (L-z)}.
\]

At steady state the intensity is not changing after one round-trip,

\[
R_1 R_2 e^{-2\alpha_{\text{mir}} L} = 1.
\]

This leads to

\[
|\alpha_{\text{mir}}| = \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right). \tag{3.6}
\]

Thus, to minimise \( g_{\text{thr}} \) highly reflective DBR are needed, since \( L \) is very short for VECSEL.

**Resonant and anti-resonant design**

The threshold gain \( g_{\text{thr}} \) can further be increased by optimising the active layer design. All the following results are achieved using the resonant design \cite{88}, where the active layer has an optical thickness of a multiple of \( \lambda_0/2 \) (\( \lambda_0 \) is the design-wavelength) and no anti-reflection (AR) coating is employed.

In figure 3.6 \( |\vec{E}|^2 \) of the optical field in the active region is plotted as function of wavelength for two different VECSEL structures. Both structures consist of a 4 pair DBR grown on Si with a \( \lambda_0 = 4 \mu\text{m} \) optically thick active layer with 5 QW at the centre of the PbEuSe host material. For one structure the active region is additionally covered with an AR coating (anti-resonant design).

The resonant design leads at \( \lambda_0 \) to the highest electric fields in the active layer and therefore lowest threshold pump power. When moving away from the design-wavelength \( \lambda_0 \), \( |\vec{E}|^2 \) decreases strongly and thus the threshold increases. Lasing is therefore limited to a narrow wavelength range. Since the band-gap of the IV-VI materi-
als depends strongly on temperature, the emission wavelengths fit to the resonance maximum only over a restricted temperature region, thus limiting the range of operation temperatures.

For the anti-resonant design at $\lambda_0$, $|\vec{E}|^2$ is lower compared to the resonant design but changes only slightly with wavelength. Therefore lasing is possible over a broader wavelength range, which corresponds to a broader region of the operation-temperature [11, 88], at the cost of an increased threshold power.

**Influence of the modular design**

With the modular design at least one Si substrate is located inside the cavity causing subcavity effects and thus influencing $g_{\text{thr}}$. Figure 3.7 shows $g_{\text{thr}}^*$ (ignoring $\alpha_{\text{int}}$) as function of wavelength for
Threshold gain for 3 different VECSEL structures, but with identical mirror and active layer design of figure 3.6. For the resonant design with Si substrate inside the cavity (III.) only the closely spaced minima are plotted.

three different VECSEL structures:

I. resonant design without Si substrate inside the cavity

II. anti-resonant design without Si substrate inside the cavity

III. resonant design with Si substrate inside the cavity (monolithic structure (figure 4.1) or modular design (figure 3.2))

For the anti-resonant design $g_{\text{thr}}^*$ is high over a broad wavelength range. For the resonant design a pronounced, sharp resonance gain minimum occurs. Contrary, for the modular design with a Si substrate (with high refractive index) located inside the cavity, the minimum gets much broader. This curve oscillates with a short period ($\sim 4 \, \text{cm}^{-1}$) caused by interference in the 380 $\mu$m thick Si-wafer. Only the minima, which are closely spaced in this scale, are drawn. This means that the lasing wavelengths jump from one minimum
to the next when slightly changing the temperature. Because the minima are so closely spaced, several of these modes lase simultaneously, resulting in a multimode spectrum.

Thus, with the Si substrate inside the cavity low thresholds and a broad operation temperature range are achieved.
Chapter 4

VECSEL with homogeneous PbSe active layer

VECSEL with a bulk PbSe active layer on BaF$_2$ substrates were already realised in our group. They lase up to above RT [11]. Here a PbSe VECSEL on Si substrate is described.

4.1 VECSEL structure

The structure of the VECSEL is shown in figure 4.1. The active region consists of a homogeneous, 900 nm thick PbSe active layer corresponding to an optical thickness of $\lambda_0$ at 273 K. The active layer is grown on a Si substrate with a 2 nm thick CaF$_2$ buffer layer in between. Subsequently an epitaxial DBR consisting of three PbTe/EuTe pairs is deposited. Due to the higher band gap energy of PbTe compared to PbSe no alloying of PbTe is needed, resulting in a high index contrast of 2.4. Already three layer pairs show a reflectivity of 99.7%.

The external mirror is grown on a curved BaF$_2$ substrate and consists of 2.5 pairs of Pb$_{0.93}$Eu$_{0.07}$Te/BaF$_2$ with a reflectivity above 99%. The curved DBR is mounted externally in a distance of $\sim$ 25 mm.
To achieve a more efficient heat removal from the lasing region, the DBR and a copper plate are covered with a few nm of Cr and $\sim 5 \mu m$ of In and are soldered together at $T = 450 K$. This soldering process increased the maximum operation temperature by more than 50 K.

4.2 Results

The emission spectra of this VECSEL are shown in figure 4.2. Lasing occurs from 130 K to 283 K in pulsed mode (repetition rate 10 kHz, duty cycle 0.1%). The emission wavelength ranges from 5.7 $\mu m$ to 4.4 $\mu m$. This temperature range is larger compared to the PbSe VECSEL on BaF$_2$ operating over a temperature from 213 to 318 K. This is mainly caused by the Si substrate inside the ca-
4.2 Results

![Figure 4.2](image_url)

**Figure 4.2:** Normalised emission spectra of a VECSEL with PbSe active layer on Si. Lasing is achieved from 130 K to 283 K in pulsed mode (repetition rate 10 kHz, duty cycle 0.1%).

vity. Due to the larger refractive index of Si compared to BaF\(_2\), the threshold gain minimum is much broader. However, the maximum operation temperature is 35 K lower compared to earlier results on BaF\(_2\) [11].

The absorbed threshold power is measured at different temperatures in pulsed mode (repetition rate 10 kHz, duty cycle 0.1%). This is shown in figure 4.3. Because the structure is designed for operation at 273 K, the absorbed threshold power \(P_{\text{thr}}\) is clearly above 1 W\(_p\) at low temperatures. At 213 K \(P_{\text{thr}}\) is 11 W\(_p\) and increases further to 21 W\(_p\) at 273 K. These values are comparable to similar PbSe VECSEL grown on BaF\(_2\) substrates, although it is easier to grow high quality IV-VI layer on BaF\(_2\) - due to similar lattice constants - than on Si substrates.
Figure 4.3: Measured absorbed threshold power $P_{\text{thr}}$ at different temperatures. The slope is approximated with a characteristic temperature $T_0=100$ K. For 150 K there is a large uncertainty of the threshold power.

To decrease the threshold values and to increase the operation temperature, VECSEL based on PbSe QW have been developed. The theory and the results of these lasers are presented in the following chapters.
Chapter 5

Quantum wells

5.1 Density of states

The wave-vector $\vec{k}$ of a free electron in a crystal with volume $V = L^3$ has the form

$$k_i = n_i \frac{\pi}{L_i} \quad \text{with} \quad i = x, y, z \quad \text{and} \quad n_i = 1, 2, 3, ... \quad (5.1)$$

The $n_i$ are the quantum numbers of the system. The $k_i$ are inverse proportional to the size of the crystal in the direction $i$. With a uniform crystal, the states are uniformly distributed in k-space. This is shown in figure 5.1(a). By reducing e.g. the dimension $z$ of the crystal down to the quantum regime ($< 50$ nm), like it is the case when forming a QW, the component $k_z$ of the reciprocal vector gets extended. The possible states of the electrons are equally distributed in the $x-y$ plane only. The individual planes then correspond to a certain quantum number $n_z$ (figure 5.1(b)). Because the planes are widely separated ($k_z \gg k_x, k_y$), it is convenient to derive a two-dimensional density of state function [89].

With the area of allowed states $A = k^2 \pi$ and the area for a single state $\pi/(L_xL_y)$, the number of states $N$ can be calculated. When
In an uniform crystal, the states are uniformly distributed in \( x, y \) and \( z \) direction. By reducing the \( z \)-direction of the crystal, \( k_z \) gets elongated and two-dimensional states result.

Considering also higher subbands \( (n_z = 1, 2, 3, \ldots) \) the density of states (DOS) is

\[
\rho_{2D}(E) = \sum_{n_z} \frac{1}{A} \frac{dN}{dE} = \sum_{n_z} \frac{m}{\pi \hbar^2} H(E - E_n) \tag{5.2}
\]

\( H \) is the Heavyside step function and for each additional subband the DOS increases by \( m/(\pi \hbar^2) \). Therefore, the DOS is a step function with discontinuities at each \( E_n \). These discontinuities are also the reason that even at the lowest energy of the subband the gain is still finite, while it is zero for bulk material.

### 5.2 Gain

A general expression for gain of a QW has the form

\[
g(\omega) = \frac{\pi e^2 \hbar \rho_{\text{red}}}{e_0 n_w c m_0^2 \omega} \frac{|M_{\text{QW}}|^2_{\text{avg}}}{\hbar \omega} [f_c(\omega) - f_v(\omega)] \sum_{n_z} H(\omega - \omega_n) \tag{5.3}
\]
With no carriers injected the gain will be negative, absorption occurs. By increasing the density of excited carriers, \( f_c = f_v \) at a specific carrier density \( n_0 \). This is the transparency condition at which the absorption coefficient is zero. For a further increasing carrier density, \( f_c \) exceeds \( f_v \) and gain of radiation occurs.

Looking at the form of the Fermi function

\[
f_{c(v)}(E_{a(b)}) = \frac{1}{1 + e^{\frac{E_{a(b)} - F_{c(v)}}{k_B T}}} \tag{5.4}
\]

with the quasi Fermi levels \( F_c \) and \( F_v \) and the transition energy \( \hbar \omega = E_a - E_b \), one can observe that \( f_c \) has its maximum and \( f_v \) its minimum at the edge of each subband [91]. Thus also the gain is maximal for \( \hbar \omega = E_{n_z} \).

To get an expression for the gain of IV-VI QW, the anisotropic and non-parabolic band structure has to be considered. For non-parabolic bands in the growth direction the energy levels shift towards the band edge. This effect is stronger for higher energy levels \( (n_z = 2, 3, ...) \). A lower carrier concentration is needed to place the Fermi-levels above the energy levels. Thus, for non-parabolic bands in growth direction, gain occurs at lower carrier concentrations compared to parabolic bands [90].

In figure 5.2 the gain for one PbSe QW with 9.5 nm thickness is
Chapter 5: Quantum wells

Figure 5.2: Gain of a 9.5 nm thick PbSe QW in Pb$_{0.93}$Sr$_{0.07}$Se for different carrier concentrations at 100 K. At higher carrier concentrations the energy states of $n_z = 2$ get populated and a second, higher gain peak arises.

shown for different carrier concentrations. Gain is achieved at energies higher than the lowest transition energy. By increasing the carrier concentration the gain increases, but the gain maximum $g_{max}$ remains pinned at the lowest energy of the state $n_z = 1$. By a further increased carrier concentration the second excited state is populated too, resulting in a sudden gain increase at the energy of the state $n_z = 2$. The gain increases with increasing $n_z$.

The equation 5.3 for $n_z = 1$ can be approximated by

$$g_{max} = g_0 \ln \left( \frac{n}{n_0} \right)$$

(5.5)

showing a logarithmic increase of the gain maximum. But this is only true for low carrier concentrations. For higher carrier concentrations the gain provided by one subband (fixed $n_z$) saturates
Saturation of the gain maximum for the level $n_z = 1$ with increasing carrier concentration at 100 K. (figure 5.3). The reason behind the gain saturation is the limited number of states for electron and holes in this subband.

The logarithmic trend of the curve can be characterised by the slope $g_0$ and the carrier concentration $n_0$, the carrier concentration to reach transparency. This carrier concentration is considerably lower compared to bulk materials resulting in lower threshold powers.

### 5.3 Blueshift

The energy of a free electron in a 3D crystal with the volume $V = L^3$ is

$$E = \frac{\hbar^2}{2m} \cdot (k_x^2 + k_y^2 + k_z^2)$$

Because the $\vec{k}$ is inversely proportional to $L$, the energy $E$ can have any positive value.

When reducing the $z$ dimension of the crystal, $k_z$ can just have
well defined values (see equation 5.1). The energy of the electron is now defined as

\[ E = \frac{\hbar}{2m} \cdot \left( k_x^2 + k_y^2 + \frac{n_z \pi}{L} \right) \quad \text{with} \quad n_z = 1, 2, 3, ... \quad (5.6) \]

The energy in \( x \) and \( y \) direction can have any value, but in \( z \) direction the energy value is quantised. Thus the lowest possible value for \( E \) is greater than zero. This energy shift of the lowest state is called \textit{blueshift}.

To calculate the energy levels in a quantum well with a finite barrier height \( V \), the equation

\[ \frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial z^2} \psi(z) = (V - E) \psi(z) \]

with the effective mass \( m^* \) needs to be solved [92]. Two solutions
arise: one for even states and one for odd states

\[ k_z \tan \left( \frac{k_z L_z}{2} \right) = K_z \]

\[ -\frac{1}{k_z} \cot \left( \frac{k_z L_z}{2} \right) = -\frac{1}{K_z} \]

with the wavevector in the QW \( k \) and the wavevector in the barrier material \( K \). Using equation [5.6], the blueshift is calculated. In figure [5.4] the total blueshift (energy shift of both ground states) of a single PbSe QW is plotted for different values of \( V \) as a function of the well width. A symmetric type I band alignment is assumed \((V = 0.5 \cdot (E_{g,\text{barrier}} - E_{g,\text{PbSe}}))\) with identical hole and electron masses.

### 5.4 Design of the active layer

The active layer consists of PbSe QW embedded in a host material. The resonant design is used, i.e. active layer thicknesses of a multiple \( \lambda_0 / 2 \) and no AR layer.

Contrary to a bulk layer, the generated electrons in the host material have to diffuse to the QW, where they are captured and provide gain. To achieve low threshold powers and high temperature operation, the effective gain, the product of the gain \( g \) and the light intensity \(|E|^2\), has to be considered [88].

Inside the cavity the amplified light is a standing wave. To maximise the effective gain, the QW are placed where the standing electric field is high. For a \( \lambda_0 \) thick active layer these regions are in the centre and at the edges of the layer. If the thickness is reduced to a \( \lambda_0 / 2 \) thick layer, the regions with a high standing electric field are only near the edges of the active layer (see figure [5.5]).

A lead chalcogenide layer with thickness of one \( \lambda_0 \) absorbs already \( \sim 90\% \) of the incoming pump radiation of 1.55 \( \mu \text{m} \) wavelength). This restricts the thickness of the active region and thus the number of QW.
Figure 5.5: QW active layer with $\lambda_0$ and $\lambda_0/2$ thickness.

The number of QW is further restricted when considering the threshold power $P_{\text{thr}}$. In a simplified model [26] with the approximated gain formula 5.5, the threshold carrier density $n_{\text{thr}}$ and $P_{\text{thr}}$ are calculated

$$n_{\text{thr}} = n_0 \left( \frac{1}{R_1 R_2 T_{\text{loss}}} \right)^{(2\Gamma g_0 N_w d_w)^{-1}}$$

$$P_{\text{thr}} = n_{\text{thr}} \frac{\hbar \omega N_w d_w A_p}{\eta_{\text{abs}} \tau(n_{\text{thr}})}$$ (5.7)

$R_1, R_2$ reflectivities of the mirrors
$T_{\text{loss}}$ additional losses for one round-trip
$\Gamma$ confinement factor
$N_w$ number of QW
$d_w$ thickness of QW
$A_p$ pump spot area
$\eta_{\text{abs}}$ pump absorption efficiency
$\tau(n_{\text{thr}})$ carrier lifetime at threshold condition.

$P_{\text{thr}}$ is shown in figure 5.6 for different mirror reflectivities $R = R_1 \cdot R_2$ as a function of QW number. The higher the mirror losses are, the higher the gain needs to be to reach the lasing condition.
The gain can be increased by more QW or a higher carrier density. By increasing the carrier density, spontaneous emission and Auger recombination increase and thus the carrier density needs to be increased even further. This is shown by the drastic $P_{\text{thr}}$ increase for a low number of QW. By increasing the QW number, more pump power is needed to create population inversion in every QW. Therefore $P_{\text{thr}}$ increases also for a too high number of QW. A trade-off needs to be done to minimise $P_{\text{thr}}$.

Figure 5.6: Threshold power as function of the number of QW with 10 nm thickness each. For increasing losses more QW are needed to minimise the threshold power.
Chapter 6

VECSEL with PbSe QW in PbEuSe host material

The following results were all obtained using the modular design. The general modular design structure was already described in section 3.1. In the following a detailed description of the VECSEL structure is given (section 6.1). Experimental results are described (sections 6.2) and conclusions regarding the band alignment are drawn (section 6.3). At the end of the chapter the versatility of the modular design is shown (6.4).

6.1 VECSEL structure

The structure of a VECSEL with a $\lambda_0$ thick active region based on PbSe QW in PbEuSe is shown in figure 6.1. The bottom Bragg mirror consists of 4.5 pairs of $\lambda_0/4$ thick Pb$_{0.97}$Eu$_{0.03}$Te/EuTe layers grown on a Si (111) substrate. The top layer of the DBR is a high index PbEuTe film, because Eu oxidises quickly in normal atmospheric conditions and a surface deterioration of EuTe is observed. The mirror ($\lambda_0 = 3.7$ $\mu$m) shows a maximum reflectivity of more than 99.8% and a stopband width of 1.7 $\mu$m for $R > 99\%$.
Figure 6.1: Structure of the modular VECSEL with PbSe QW in PbEuSe host material.

Figure 6.2: Measured reflectivity spectra of the mirrors employed in figure 6.1. The dip in the spectra at around 2350 cm$^{-1}$ is caused by CO$_2$ absorption.
The top curved Bragg mirror is grown on a BaF$_2$ substrate and consists of 2.5 pairs of Pb$_{0.97}$Eu$_{0.03}$Te/BaF$_2$ layers ($\lambda_0 = 3.7 \, \mu m$). Due to the high refractive index contrast ($n_{PbEuTe} / n_{BaF_2} = 3.6$) the maximum reflectivity is above 99% and the stop-band is more than 2 $\mu m$ broad. The cavity length is slightly shorter than the radius of curvature ($r_c = 25$ mm) of the top mirror to define a lasing region in the active layer with a diameter of $\sim 200 \, \mu m$.

The active region consists of PbSe QW in PbEuSe host material with a thickness of $\lambda_0$ or $\lambda_0 / 2$. It is grown on a Si (111) substrate. The Eu content in the host material is between 5% and 8% and the QW are placed at the centre or at the edges of the active layer, depending on the active layer thickness.

**Properties of PbEuSe as host material**

The right choice of the host material is essential for the laser performance and needs to meet certain requirements. Its band gap energy $E_g$ must be higher than the transition energy of the QW. To confine the electrons and the holes in the QW, a type I band alignment is required. Further, to reduce strain effects and to achieve a good crystalline quality, the lattice constants of the materials should be similar. Finally, the generated electrons in the host material need to diffuse to the QW, thus a high carrier mobility is favourable to reduce recombinations at defects.

**Strain and optical deformation potential**

The lattice constant of EuSe is 1-2% larger compared to PbSe [57, 93-96]. Thus, applying Vegard’s law, with 5% Eu a lattice mismatch of 0.05-0.1% is present, the QW are grown approximately lattice matched.

To calculate the influence of the strain caused by a thick, unstrained PbEuSe on the transition energies in PbSe, the band struc-
ture needs to be considered. In the [111] growth direction the four valleys at the L-point of the Brillouin zone are divided into one longitudinal and three oblique valleys. The strain induced shift of $E_g$ can be calculated for the normal valley in [111] direction

$$\delta E_g^N = D_d (2\epsilon_\parallel + \epsilon_\perp) + D_u \epsilon_\perp$$  \hspace{1cm} (6.1)

with the in-plane ($\epsilon_\parallel$) and perpendicular ($\epsilon_\perp$) uniaxial strain parameters. $D_d = D_d^c - D_d^\gamma$ and $D_u = D_u^c - D_u^\gamma$ are the dilatation and uniaxial acoustic deformation potentials, respectively \[97\].

The strain parameters are connected via a constant factor

$$\epsilon_\perp = -A \epsilon_\parallel$$

$$A = 2 \frac{C_{11} + 2C_{12} - 2C_{44}}{C_{11} + 2C_{12} + 4C_{44}}$$ \hspace{1cm} (6.2)

The values for the stiffness tensor $C_{ij}$ for PbSe are reported by Lippmann et al. \[98\]. $A = 1.15$ is obtained at RT. $C_{ij}$ is weakly temperature dependent and thus the value of $A$ changes slightly to 1.17 at 77 K. With the values at RT equation (6.1) can be written as

$$\delta E_g^N = \epsilon_\parallel (0.85 D_d - 1.15 D_u).$$

The data for $D_d$ and $D_u$ are taken from references \[97, 99, 100\] and vary between 3.53 eV and 6.5 eV for $D_d$ and and between −0.5 eV and −3.7 eV for $D_u$. Thus, for not exactly known lattice parameters and deformation potentials, the possible values $\delta E_g^N$ vary considerably between 1.8 meV and 9.8 meV.

For oblique valleys the strain induced energy shift is given by

$$\delta E_g^O = D_d (2\epsilon_\parallel + \epsilon_\perp) + D_u (8\epsilon_\parallel + \epsilon_\perp)/9.$$ \hspace{1cm} (6.3)

Using the same values for $A$ and $C_{ij}$ as before, this equation can
be simplified to

\[ \delta E_g^O = \epsilon_\parallel (0.85 D_d + \frac{6.85}{9} D_u) \]

which leads to a strain induced energy shift between 1.1 meV and 4.2 meV. Hence, there is a strain induced splitting of the energy states, which is only caused by the uniaxial deformation potential. This can be seen by comparing equation 6.1 and 6.3

\[ \delta E_g^N - \delta E_g^O = \frac{8}{9} D_u (\epsilon_\perp - \epsilon_\parallel) \]

The strain induced energy shifts change the transition energy by 1-2% only. Furthermore, no reasonable change of the valence or conduction band offset is expected, which should influence the laser performance.

This assumption is in agreement with results of Tacke et al. [94] reporting no deterioration of the laser characteristics of the PbSe/PbEuSe heterostructures compared to lattice matched PbSe/PbEuSeTe structures. Furthermore, changes in the band alignment were reported for IV-VI [101] and III-V semiconductors [17]. Both exhibit tensile strains clearly above 1%.

**Band alignment**

The addition of Eu to PbSe increases \( E_g \) very rapidly. With only 5% Eu the cutoff wavelength shifts from \( \sim 4.6 \, \mu m \) to \( \sim 3.0 \, \mu m \) at RT (see figure 2.2 at page 10).

About the band alignment of the PbSe/PbEuSe heterostructure only few and often contradicting results were published. PbSe/PbEuSe heterostructures with low Eu content were reported to exhibit a type I band alignment at RT, which turns into type II at lower temperatures [103]. Others [93, 100] deduce a type I band alignment from optical measurements from 100 K to RT. Shi et al. [102] determined the valence band offset \( \Delta E_v \) at low temperatures. The result is shown in figure 6.3. \( \Delta E_v \) increases linearly with temperature and
by extrapolating the linear trends a transition from type I to type II is expected at $\sim 220$ K.

Unfortunately, with such varying band offset data, band engineering can not be done. Only rough estimates can be made, which hinders the optimisation of the active layer structure.

**Interdiffusion between PbSe and PbEuSe**

An important aspect for the PbSe/$\text{Pb}_{1-x}\text{Eu}_x\text{Se}$ heterostructure is the abruptness of the Eu content at the interface. Inter-diffusion of Eu into the QW would lead to an inhomogeneous energy profile along the QW with varying energy states. This would diminish the material gain and prevent lasing operation at high temperatures. With annealing experiments at $420$ °C a upper inter-diffusion limit of

![Figure 6.3: Measured valence band offset $\Delta E_v$ and band gap difference $\Delta E_g$ between Pb$_{0.935}$Eu$_{0.065}$Se and PbSe by Shi et al. [102]. The lines are a linear fit. The crossing at 220 K indicates a vanishing conduction band offset.](image-url)
Eu of \( D = 8 \cdot 10^{-18} \, \text{cm}^2/\text{s} \) was estimated resulting in very abrupt heterointerfaces \[104\]. This low diffusion coefficient \( D \) allows the growth at temperatures above 400 \(^\circ\text{C}\), ensuring a good crystalline quality. The authors assume that the low diffusion coefficient is valid also for other selenide material systems like PbSrSe.

### Carrier mobility

![Graph of carrier mobility vs temperature for PbSe and PbEuSe](image)

**Figure 6.4:** Experimentaly obtained carrier mobility of a 1.2 \( \mu \text{m} \) thick PbSe layer and a 1.0 \( \mu \text{m} \) thick \( \text{Pb}_{0.945}\text{Eu}_{0.055}\text{Se} \) layer containing 5 PbSe QW.

It is well known, that the carrier mobility in IV-VI semiconductors decreases strongly for all IV-VI based ternary compounds \[102, 105, 106\]. An exponential decrease of the electron mobility at low temperatures with alloy composition \( x \) is observed. The main reasons are a very strong alloy scattering of the carriers and the in-
crease of the effective mass by the change of the energy gap for PbEuSe.

In figure 6.4 the measured carrier mobility vs. temperature is plotted for a bulk PbSe layer and an active layer with PbSe QW in Pb$_{0.945}$Eu$_{0.055}$Se host. Around RT the main limiting factor for the carrier mobility is phonon scattering. With decreasing temperature more and more phonons vanish and the carrier mobility increases. At low temperatures the mobility saturates at a certain value determined by the structural quality of the layer.

For the QW active layer the carrier mobility in the host material is measured, which is by a factor 20 lower compared to the PbSe bulk layer at 12 K. This rapid deterioration of the carrier mobility with increasing Eu content is a main limiting factor for the laser performance of QW VECSEL (see section 7.3).
6.2 Results

6.2.1 $\lambda_0$ thick active layer

A $\lambda_0$ thick active layer containing 5 PbSe QW with a thickness of 10 nm was grown on Si substrate. The 5 QW are placed at the centre of the active region, where the electric field is highest to maximise the stimulated emission. They are separated by 20 nm thick barriers. The host and barrier material is Pb$_{1-x}$Eu$_x$Se with $x = 0.055$, the addition of Eu increases $E_g$ from 270 meV to above 400 meV at RT.

![Diagram showing intensity of electric field](image)

**Figure 6.5:** The intensity of the electric field across the structure. The QW are placed at the centre of the active layer, where the electric field is high to maximise the stimulated emission. For convenience the Si substrate is drawn thinner.

In figure 6.5 $|E|^2$ is plotted across the structure for the design wavelength $\lambda_0 = 4 \mu$m. For convenience the Si substrate is drawn thinner.

The laser operates in pulsed mode from 100 K to 245 K. The normalised spectra at different heat sink temperatures are shown in figure 6.6. The emission is multimode and the mode spacing is...
caused by the optical thickness of the Si substrate inside the cavity.

The emission wavelength depends on the thickness of the QW. With 10 nm thick QW a blueshift of $\sim 50$ meV occurs. At 200 K this corresponds to a change of the emission wavelength from 5.5 $\mu$m to 4.5 $\mu$m. Due to the temperature sensitive band gap energy a wavelength range between 4 $\mu$m and 5 $\mu$m is covered.

The light-in/light-out characteristic was measured for different heat sink temperatures with 200 ns pulses and a repetition rate of 10 kHz. Even though the VECSEL was designed for 273 K, the lowest threshold and highest output power were measured at low temperatures. In figure 6.7 the absorbed threshold power $P_{\text{thr}}$ at dif-
Absorbed threshold power over temperature for the VECSEL of figure 6.6. Above 210 K a strong increase of the threshold power is observed. The threshold increase at 100 K is caused by the decreasing stopband of the bottom DBR.

![Diagram of absorbed threshold power over temperature](image)

**Figure 6.7:** Absorbed threshold power over temperature for the VECSEL of figure 6.6. Above 210 K a strong increase of the threshold power is observed. The threshold increase at 100 K is caused by the decreasing stopband of the bottom DBR.

Different temperatures is drawn in a logarithmic scale (the absorbed threshold power is plotted, because nearly half of the pump power is not penetrating into the active region). The lowest value of $P_{\text{thr}}$ is below 0.5 $W_p$ at 120 K. For lower temperatures, the reflectivity of the bottom DBR decreases, thus increasing $P_{\text{thr}}$. With increasing temperature $P_{\text{thr}}$ increases linearly in this logarithmic plot up to 210 K. The slope is approximated with a characteristic temperature $T_0 = 50$ K. Above 210 K a strong increase of $P_{\text{thr}}$ is observed with $T_0 = 17$ K.

By reducing the QW thickness, the blueshift increases and shorter emission wavelengths can be reached. VECSEL were realised with 5 nm thick QW placed at the centre of a $\lambda_0$ thick active layer. The setup is identical with the one shown in figure 6.5. The PbEuSe host material contains 6% Eu and the barriers are 15 nm thick. The
Figure 6.8: Normalised emission spectra of 7 PbSe QW with 5 nm thickness in PbEuSe (λ₀ thick active layer). At higher temperatures lasing up to 3.5 µm occurs.

Normalised emission spectra at different heat sink temperatures are shown in figure 6.8. The emission wavelengths range from 4.25 µm at 100 K and low pump power up to 3.5 µm at 235 K.
6.2 Results

6.2.2 \( \lambda_0/2 \) thick active layer

The carrier mobility decreases strongly, when alloying PbSe with Eu (see figure 6.4). With a carrier mobility \( \mu = 200 \text{ cm}^2/\text{V}s \) at \( T = 300 \text{ K} \) and an assumed carrier lifetime \( \tau = 0.1 \text{ ns} \) the diffusion coefficient \( D \) equals

\[
D = \mu k_B T = 5.2 \text{ cm}^2/\text{s} \tag{6.4}
\]

The diffusion length \( L \) is related to \( D \) by

\[
L_{\text{Diff}} = \sqrt{D \cdot \tau} = 230 \text{ nm} \tag{6.5}
\]

Due to the optical pumping, the carrier generation rate is the highest near the surface of the active layer. The excited carriers must diffuse to the QW located at the centre to contribute to the gain generation. For \( \lambda_0 \) thick active layers described before, the top host layer is \( \sim 400 \text{ nm} \) thick and - based on the assumptions 6.4 and 6.5 - many of the carriers are lost at RT without reaching the QW.

In order to reduce the length the excited electrons have to diffuse to reach a QW, the active layer thickness is reduced to \( \lambda_0/2 \). The regions with a high standing electric field are only near the edges of the active layer (see figure 6.9). Therefore 4 QW are placed near the surface of the active layer and 1 QW near the Si substrate. The maximum distance the generated carriers have to diffuse to reach a QW is more than halved and below \( L_{\text{Diff}} \) of equation 6.5. Further, the QW near the surface are located in the region where most of the carriers are generated. This should lead to a easier population of the QW resulting in lower threshold powers and higher operation temperatures.

In figure 6.10 the threshold power at different heat sink temperatures is plotted for a VECSEL consisting of 5 QW, each 7.5 nm thick, embedded in a \( \lambda_0/2 \) thick active layer. The values of \( P_{\text{thr}} \) are a factor 2 lower compared to \( \lambda_0 \) thick active layers. Due to the
measurement inaccuracy of the pump power, $P_{\text{thr}}$ can only be estimated to be below 0.2 W. The increase of the threshold power with temperature can be characterised with $T_0 = 32$ K. The highest operation temperature is 240 K. The emitted wavelengths range between 4.8 µm at 100 K and 3.9 µm at 240 K (not shown).

Such low threshold values were also obtained for $\lambda_0/2$ thick active layers with 5 nm thick QW, but also for this structure the highest operation temperature was in the range of 225 - 235 K.

Figure 6.9: Intensity of the electric field across the structure $\lambda_0/2$ thick active region. The 5 QW are placed at the edges of the active layer.
Absorbed threshold power over temperature for VECSEL with $\lambda_0/2$ thick active region (5 QW with 7.5nm thickness in PbEuSe). Lower thresholds compared to $\lambda_0$ thick active regions are achieved.

For PbSe QW in PbEuSe host material lasing is achieved over a broad wavelength range from 3.5 $\mu$m to 5 $\mu$m. With thicker QW the emission region can be further expanded to 6.5 $\mu$m at 100 K. With an optimised design of the active layer the influence of the low carrier mobility in PbEuSe can be overcome and $P_{\text{thr}}$ values below 1 W are realised up to 180 K.

Despite all the improvements, the maximum operation temperature of 245 K could not be raised. Independent of the thickness of the active layer, the location, number and thickness of the QW, this temperature marks a limit for our VECSEL. To our best knowledge, also in literature no PbSe/PbEuSe based laser operating at temperatures of 210 K or above was reported so far.

The reason for this limitation could arise from a band alignment

Figure 6.10: Absorbed threshold power over temperature for VECSEL with $\lambda_0/2$ thick active region (5 QW with 7.5nm thickness in PbEuSe). Lower thresholds compared to $\lambda_0$ thick active regions are achieved.
transition from type I at low temperatures to type II at RT. For a type II heterostructure electrons and holes are locally separated (figure 6.11)). Hence, the overlap of the electron and hole wavefunction is decreased resulting in a lower transition probability, which decreases the gain.

As already mentioned, Shi et al. [102] reported a raising valence band offset ($\Delta E_v$) with increasing temperature. For PbSe/Pb$_{1-x}$Eu$_x$Se structures with $x \approx 0.065$ a transition from type I to type II is estimated at 220 K (see figure 6.3). For our structures similar Eu concentrations are used, hence similar transition-temperatures may be expected. This estimate agrees well with the maximum operation temperatures achieved with our VECSEL.

In conclusion, the different designs and structures of PbSe QW VECSEL with PbEuSe as host material should result in different laser characteristics. This is the case for the emission wavelength and $P_{\text{thr}}$. On the other side, the maximum operation temperature never exceeded 245 K. This behaviour may be explained by a type I/type II band alignment transition in this temperature range, which impedes operation near RT.
6.4 Versatility of the modular design

**Figure 6.12:** Two different VCSEL structures. a) Two Si/SiO DBR are employed, enabling pumping and detection of the output at opposite sides. b) To lower the threshold and raise the output power a DBR consisting of PbEuTe/EuTe pairs can be used. Pumping and output coupling is done through the Si/SiO mirror.

In the analysis of the results so far, the influence of using the modular design was neglectable. It indeed shortens the development time and facilitates the comparison of different laser results due to the identical cavity properties. However, for one single laser there is no difference in using a "standard" setup consisting of two parts, or the modular design with three separate parts. But the assembling of a laser out of three separate parts offers the possibility to realise new laser setups.
Our VECSEL are optically pumped with a 1.55 µm wavelength laser. The mirrors grown with MBE consist of PbEuTe/EuTe or PbSrTe/EuTe quarter wavelength pairs. To enable end pumping (pumping through the mirror) the Eu (Sr) content of the mirrors has to be raised up to 15%. But with increasing Eu (Sr) content the refractive index decreases and more layer pairs are needed to ensure a sufficient reflectivity (figure 3.3).

![Figure 6.13: Normalised emission spectra of a VCSEL consisting of 5 PbSe QW with 8 nm thickness in PbEuSe on Si substrate. The active layer is embedded between two Si/SiO DBR on Si substrate. Because of the multiple Si substrates inside the cavity only few modes can develop.](image)

We have developed Si/SiO DBR evaporated on Si substrates, which show a high reflectivity at the desired wavelength with only 5 pairs. They are transparent for the pump beam (page 23). With these mirrors and an active layer on a separate Si substrate, a VCSEL can easily be built by putting the parts together. The struc-
ture of such a VCSEL is shown in figure 6.12a. The laser is pumped through the bottom mirror, the emission output through the top mirror is detected. As an example the emission spectra of a VCSEL with 5 nm thick QW in PbSrSe are shown in figure 6.13. Due to the Si substrates inside the cavity several subcavities are formed and only few resonant modes can develop.

Further, to improve output and the threshold power a DBR grown by MBE consisting of PbXTe/EuTe (X=Eu, Sr) has been used as bottom DBR, since it shows a higher reflectivity. Because this mirror is absorbing the beam of the pump laser, pumping is realised through the the top Si/SiO DBR (figure 6.12b).
Chapter 7

VECSEL with PbSe QW in PbSrSe host material

The following results are achieved with VECSEL based on PbSe QW in PbSrSe host material. After a short description of the VECSEL design (section 7.1) laser results for different active layer structures are reported (section 7.2). They are fitted and analysed (section 7.3). Most of the results have been published [107].

7.1 VECSEL structure

For all of the VECSEL described in this chapter the modular design is used. The DBR are identical with the mirrors for PbSe/PbEuSe based VECSEL (see page 47). The bottom Bragg mirror consists of 4.5 pairs of \( \lambda_0/4 \) thick \( \text{Pb}_{0.97}\text{Eu}_{0.03}\text{Te}/\text{EuTe} \) layers grown on a Si (111) substrate. The top curved Bragg mirror is grown on a BaF\(_2\) substrate and consists of 2.5 pairs of \( \text{Pb}_{0.97}\text{Eu}_{0.03}\text{Te}/\text{BaF}_2 \) layers. The laser setup is shown in figure 7.1.
PbSrSe as host material

PbSrSe has similar properties as PbEuSe. The alloying of PbSe with Sr increases the band gap energy \( E_g \) can be calculated using Sr-content \( x \) and temperature \( T \)

\[
E_g(x, T) = 0.150 + 3.608x - 1.314x^2 + (0.430 - 3.093x + 6.495x^2) \cdot 10^{-3} \cdot T \quad (7.1)
\]

With 5% Sr the cutoff wavelength shifts from \( \sim 4.6 \) \( \mu \)m to \( \sim 3.0 \) \( \mu \)m at RT. Also the refractive index decreases with the addition of Sr [44, 63].

According to different sources the lattice constant of SrSe is 1.7-2.0% larger than the lattice constant of PbSe [110-112]. For a Sr-
content of 5% a lattice mismatch of 0.085-0.1% arises. To calculate
the effect of strain in a thin PbSe layer on the transition energy, the
calculation of page 50 can be adopted. The energy shift for the
normal valley amounts to 3.1 - 9.8 meV. For oblique valleys the
strain induced energy shift can be estimated between 2.2 meV and
4.2 meV. Thus no significant change of the band alignment due to
strain is expected.

Like for PbEuSe, the carrier mobility decreases with increasing
Sr content in PbSrSe. The mobility decreases exponentially with
the absorption edge compared to values of PbSe layers (the addi-
tion of Sr increases the band gap energy) [38]. This is caused by a
decreased crystal quality, resulting in shorter carrier lifetime \( \tau_{SRH} \).

For the material properties no significant difference between
PbEuSe and PbSrSe is reported so far. The band gap shift, the lat-
tice mismatch and thus the induced strain, and the deterioration
of the carrier mobility with increasing Eu (Sr) content are nearly
identical. Nevertheless, the operation temperatures obtained for
PbSe/PbSrSe based lasers are much higher compared to PbSe/
PbEuSe structures. Laser operation around and above RT is ob-
tained with edge emitters [5, 112], VCSEL [9, 113] and even mi-
crodisk lasers [13]. The reasons why QW laser fabricated with
PbSrSe barriers show improved behaviour have not been addressed
in these works.

Even though much progress was made in developing PbSe/
PbSrSe based lasers operating at RT, no reliable data about the band
alignment of the heterostructure are reported. Based on transm-
sion and photo-luminescence measurements, a type I band align-
ment is assumed [4, 109, 111]. However, the valence band offset
\( \Delta E_v \) and the conduction band offset \( \Delta E_c \) are not determined and
therefore band engineering is not possible.
Active layer design

A series of samples with 9.5 nm thick QW was prepared to investigate the impact of the number and position of the QW. The QW are spaced by 20 nm thick PbSrSe barrier layers. Four structures containing 5, 7, 9 and 11 QW were prepared. For the samples with 5 and 7 QW, the QW are placed in the middle of the PbSrSe layer. Due to the limited width of these regions where the electric field is highest, the 2 or 4 additional QW for the 9 and 11 QW samples are placed near the top surface (Fig. 7.2). To prevent unwanted surface effects, a 30 nm thick cap-layer is grown. Near the surface the pump beam intensity and therefore the carrier generation rate is the highest. A high population of the QW with excited carriers near the surface is therefore easier to obtain compared to QW grown near the bottom of the active layer.
7.2 Results

7.2.1 Emission-spectra

![Normalized laser spectra of a VECSEL with 9.5 nm thick PbSe QW in PbSrSe host material at different heat sink temperatures. The active layer contains 9 QW. The spacing between the individual modes (∼4 cm⁻¹) is due to the Si-substrate inside the cavity.](image)

**Figure 7.3:** Normalised laser spectra of a VECSEL with 9.5 nm thick PbSe QW in PbSrSe host material at different heat sink temperatures. The active layer contains 9 QW. The spacing between the individual modes (∼4 cm⁻¹) is due to the Si-substrate inside the cavity.

With all four structures with 9.5 nm thick QW described before, lasing near RT or above is achieved. As an example multimode laser spectra at different heat sink temperatures for the device containing 9 QW are shown in figure 7.3. The maximum output power is ∼250 mW. The separation of the individual modes corresponds to the optical thickness of the Si substrate. Lasing is observed from 100 K up to 330 K heat sink temperature. Because the band gap en-
Energy of the IV-VI semiconductors is highly temperature-sensitive, the emission wavelength ranges from 5.1 µm to 3.65 µm. In terms of wavenumbers this corresponds to a width of 800 cm$^{-1}$. To our best knowledge, this is the broadest emission range a single laser device has ever covered. When exciting the VECSEL with the highest available pump power (25 W$_p$) at the highest heat sink temperature, estimates show that the temperature in the active layer is as high as $\sim$ 350 K.

![Normalised laser spectra of a VECSEL with 11 PbSe QW in Pb-SrSe host material at different heat sink temperatures. Each QW is 4 nm thick. Lasing at a wavelength of 3.3 µm is achieved at the highest operation temperature.](image)

**Figure 7.4:** Normalised laser spectra of a VECSEL with 11 PbSe QW in Pb-SrSe host material at different heat sink temperatures. Each QW is 4 nm thick. Lasing at a wavelength of 3.3 µm is achieved at the highest operation temperature.

One of the advantages of QW is the possibility to tailor the emission wavelength by the QW thickness. In order to reach shorter emission wavelengths, the thickness of the QW was reduced to 4 nm. Normalised emission spectra are shown in figure 7.4. The ac-
tive region is $\lambda_0 = 3.3 \, \mu m$ thick and contains 11 QW in $\text{Pb}_{0.91}\text{Sr}_{0.09}\text{Se}$. 7 QW are placed at the centre of the active layer, 4 underneath the surface (like in figure 7.2 b). The barriers have a thickness of 15 nm.

The emission wavelengths range from 3.7 $\mu m$ at 100 K to 3.35 $\mu m$ at 243 K. The blueshift amounts to $\sim 130$ meV at 243 K compared to bulk PbSe.

### 7.2.2 Operation temperature

![Graph showing maximum operation temperature vs. quantum well thickness](image)

**Figure 7.5:** Maximum operation temperature of PbSe QW in PbSrSe host material as function of the QW thickness. Increasing the thickness of the QW from 4 to 9.5 nm increases the highest operation temperature, which saturates or falls slightly for 14 nm QW. The line is a guide to the eye.

The maximum operation temperature of the PbSe QW VECSEL for the different QW thicknesses is shown in figure 7.5. It is limited
by the maximum pump power available (∼ 25 W absorbed pump power). By increasing the QW thickness, the highest operation temperature rises up to > 320 K and then saturates or falls slightly. The better performance of thicker QW and the saturation of the maximum operation temperature with increasing QW thickness is in accordance with other results [13, 114].

7.2.3 Threshold power

![Graph](image)

**Figure 7.6:** Experimental absorbed threshold power \( P_{\text{thr}} \) vs. temperature for different numbers of PbSe QW with 9.5 nm thickness in Pb-SrSe host material.

For the VECSEL with 9.5 nm thick QW the measured absorbed threshold power \( P_{\text{thr}} \) vs. temperature \( T \) in pulsed mode is plotted in figure 7.6 for the four different structures with 5, 7, 9 and 11 QW. No drastic differences are observed within the measurement
accuracies. Typical characteristic temperatures $T_0$ are $\sim 200$ K at lower temperatures and $\sim 40$ K towards RT. Output power is up to 250 mW$_p$ at 100 K. Lowest $P_{\text{th}}$ are $< 1$ W$_p$ at low $T$, while they increase to $\sim 10$ W$_p$ at RT. Compared to the VECSEL we fabricated with bulk active layers ($d \sim 1$ µm) [12], $P_{\text{th}}$ for the present QW samples is at best 3 times lower. Although this is favourable for development towards CW RT emission, it is much less than expected for QW structures (see below) and cannot be explained to be caused by the modular design.

### 7.3 Discussion

To explain this behaviour, we compared $P_{\text{th}}$ with theoretical values. We first calculated the gain $g^*_\text{thr}(\lambda)$ needed in the QW to obtain threshold (see figure 3.7).

Threshold powers $P_{\text{th}}$ are calculated adapting existing procedures and formulas [65, 90, 115]. The excess carrier density $n_{\text{th}}$ needed in order to overcome the losses,

$$\Gamma g^*_\text{thr}(n_{\text{th}}, \lambda) \geq \Gamma g^*_\text{thr}(\lambda) + \alpha_{\text{int}}(n_{\text{th}}, \lambda)$$

determines $P_{\text{th}}$. The internal losses $\alpha_{\text{int}}$ are mainly due to free carrier absorption $\alpha_{\text{fca}}$. $\alpha_{\text{fca}}$ is proportional to $\lambda^2 n$ and amounts to $< 100$ cm$^{-1}$ for PbSe and a carrier density $n = 10^{18}$ cm$^{-3}$ at 300 K [65]. $P_{\text{th}}$ has to compensate the electronic losses

$$\frac{P_{\text{th}}}{A \cdot d \cdot h\nu} = \frac{n_{\text{th}}}{\tau_{\text{SRH}}} + B_{\text{sp}} n_{\text{th}}^2 + C_A n_{\text{th}}^3$$

where $C_A$ is the Auger recombination coefficient, $B_{\text{sp}}$ spontaneous emission and $\tau_{\text{SRH}}$ Shockley-Read-Hall lifetime. $A$ is the area illuminated, $d$ is the thickness of the active layer, and $h\nu = 0.8$ eV the energy of a 1.55 µm wavelength pump photon. The large quantum defect between this pump wavelength and output wavelength
(3.3 – 5.1 \mu m) considerably increases \( P_{\text{thr}} \).

In III-V semiconductors, \( C_A \) is quite high at long wavelengths, while it is much smaller in narrow gap IV-VI materials. This is due to the symmetric band structure of IV-VIs with no heavy hole band. For PbSe around RT, \( C_A \sim 10^{-28} \text{ cm}^6 \text{ sec}^{-3} \) was obtained experimentally [116], consistent with Emtage’s calculations [77]. No Auger values for QW are available. We assume that the same values apply.

The calculated \( n_{\text{thr}} \) vary from \(~1 \cdot 10^{17} \) to \(~6 \cdot 10^{17} \text{ cm}^{-3} \) between 100 K and RT. The gain \( g \) above threshold increases very steeply with \( n \), e.g. at RT it is already \( >1000 \text{ cm}^{-1} \) at 20\% higher carrier densities than threshold. Therefore, there is no need to know exact values of \( \Gamma_{g^*_{\text{thr}}} + a_{\text{int}}(n) \) and possible other slight losses since they are much lower than the high gain achievable in direct gap semiconductors.

A reasonable fit at lower \( T \) is obtained with \( \tau_{\text{SRH}} = 0.1 \text{ ns} \), while the Auger and spontaneous term are not important even at RT (figure 7.7). For the non QW structures with bulk active PbTe and PbSe layers much higher \( n_{\text{thr}} \) are needed, similar calculations show that \( C_A \cdot n_{\text{thr}}^3 \) is not negligible at the higher temperatures. For these structures, \( \tau_{\text{SRH}} \) of order 1 ns and above were obtained [12, 117].

The origin of the rather low \( \tau_{\text{SRH}} \) may be due to the limited material quality; \( \tau_{\text{SRH}} \) is inversely proportional to the number of defects. Although the IV-VI semiconductors are fault tolerant, a high defect density decreases the carrier lifetime. The defects are mainly caused by the lattice and thermal expansion mismatched growth of the IV-VI layers on Si. However, the significantly lower \( \tau_{\text{SRH}} \) in QW compared to \( \tau_{\text{SRH}} \) in bulk active layers remains unexplained.

A good confinement of the carriers in the QW is crucial for a good laser performance. \( \text{Pb}_{0.93}\text{Sr}_{0.07}\text{Se} \) has a band gap energy of \( \sim 470 \text{ meV} \) at RT. This is \( \sim 200 \text{ meV} \) higher than for PbSe. The con-
Figure 7.7: Experimental $P_{\text{thr}}$ values for 7 PbSe QW with 9.5 nm thickness in PbSrSe host material from figure 7.6. The dashed lines are the calculated $P_{\text{thr}}$ values with $\tau_{\text{SRH}} = 0.1 \text{ ns}$ and 1 ns. Auger and spontaneous recombination as well as free carrier absorption are negligible.

The confinement energy $E_{\text{conf}}$ for QW with 5 nm thickness, which corresponds to a blueshift of $\sim 100 \text{ meV}$, is only $\sim 50 \text{ meV}$ assuming a symmetric type I band alignment (figure 7.8(a)). For a poor carrier confinement thermal leakage as an additional loss mechanism becomes more important towards RT, because $k_B T$ is 26 meV at 300 K.

For 14 nm thick QW (total blueshift $\sim 30 \text{ meV}$) and a symmetric band alignment the confinement energy of $\sim 90 \text{ meV}$ is notably larger (figure 7.8(b)). The larger energy difference should lower the thermal leakage effect. This can also explain the higher maximal operation temperatures for the laser devices with thicker QW.

A band offset ratio of $Q_c = 0.82$ for PbSrSe/PbSe heterostructu-
res at RT was reported by Shen et al. [111]. $Q_c$ is the ratio between $\Delta E_c$ and the difference between the band gap energies of the materials forming the heterostructure.

$$Q_c = \frac{\Delta E_c}{E_{g,PbSrSe} - E_{g,PbSe}}$$

For $Q_c = 0.82$ the heterostructure is still of type I, but the band alignment is highly asymmetric with poorly confined hole states (figure 7.9). $Q_c$ was derived from photoluminescence measurements in that work. A Sr content of 7% leads to a $\Delta E_c$ of 163 meV and a $\Delta E_v$ of 36 meV. Thus, for 14 nm thick QW, the calculated $E_{\text{conf},h}$ is only $\sim 25$ meV, which is nearly equal to $k_B T$ at RT. For 5 nm thick QW $E_{\text{conf},h}$ decreases further to $\sim 9$ meV - the same as $k_B T$ at 105 K. Therefore, assuming $Q_c = 0.82$ for our structures, for thin QW the thermal leakage effect is highly significant over the whole operation temperature range, while for thicker QW it is a major loss mechanism at higher temperatures.
Asymmetric band alignment with band offset ratio $Q_c = 0.82$. This leads to a reduced confinement energy for holes $E_{\text{conf},h}$. For thicker QW the carriers are better confined, but due to the low $\Delta E_v$ thermal leakage of holes is a major loss mechanism for thin as well as for thicker QW.

Similar effects were e.g. found for InGaAsSb QW in 2.7 $\mu$m wavelength laser diodes [118]. Improving the band alignments by optimising the compositions resulted in increased laser performance with these technically well known structures.

From this point of view, increasing the confinement energy by using a higher Sr content for the PbSrSe barrier layers should lead to less carrier leakage. However, it was observed that the laser performance decreases with Sr contents above 7%. This may be caused by the deteriorated crystal quality of the PbSrSe layers with increased Sr content. Therefore a trade off between carrier confinement and crystal quality needs to be done. With $\sim$ 7% Sr the best results are achieved.
Spectroscopic applications often require wavelength tuning of a single laser mode. In section 8.1 a continuously tunable VECSEL at 3.3 µm wavelength operating near RT is presented. In addition a VECSEL with DBR on a micro-electromechanical system (MEMS) has been developed (section 8.2). With MEMS it is possible to realise a more stable and compact setup of a continuously tunable, single-mode VECSEL.

8.1 Continuously tunable VECSEL near RT

In order to achieve a single mode emitting VECSEL, the spacing between the longitudinal modes has to exceed the spectral width of the net gain. The free spectral range $\Delta \nu_{\text{FSR}}$ is calculated by

$$
\Delta \nu_{\text{FSR}} = \frac{c}{2 \sum_{i} n_i d_i}
$$
with the speed of light \( c \), and the refractive index \( n \) of the material \( i \) with the thickness \( d \). Hence, with a decreasing cavity length, the mode spacing increases.

A single mode tunable VECSEL based on a PbTe active region has already been realised in our group. It lases from 90 K to 170 K \cite{33}. The wavelength range covered is between 5.6 \( \mu \)m and 4.7 \( \mu \)m. Single mode emission is achieved with a cavity length of \( \sim100 \) \( \mu \)m. Continuous tuning of the emission wavelength is realised by changing the cavity length. Because the Si substrate is 1.3 mm optically thick, it must be placed outside the cavity. Thus a modular design can not be applied.

Using a homogeneous active layer laser operation near RT could not be achieved with this setup. On the other hand, VECSEL based on PbSe QW in PbSrSe host material have shown lasing above RT
even without any effort of removing the heat from the active region (chapter 7). Therefore a VECSEL with a short cavity was realised based on a PbSe QW active layer.

The structure of a continuously tunable QW VECSEL is shown in figure 8.1. On a Si substrate a 5 pair Pb$_{0.96}$Eu$_{0.04}$Te/ EuTe DBR is grown. The reflectivity is near 99.9% over a broad wavelength range. To reach RT operation and to expand the laser emission to shorter wavelengths, a $\lambda_0=$3.3 $\mu$m thick active layer with QW of 4.5 nm thickness is directly grown on the DBR. The active layer contains 11 QW (7 QW are placed at the centre of the active layer, 4 QW near the surface) in PbSrSe host material with $\sim$8.5 % Sr. The top mirror is a curved Si/SiO DBR with 5 pairs evaporated on Si. It is mounted on a piezoelectric crystal and placed in a short distance to form the cavity. By applying a voltage, the mirror is moved and thus the cavity length is changed. The VECSEL is pumped through the Si/SiO DBR by a 1.55 $\mu$m pump laser.

With increasing temperature, the Fermi distribution of the carriers smears out (equation 5.4). Higher states are therefore more likely populated. This results in a broader gain at higher temperatures. Thus, several longitudinal modes can develop within a cavity length of $\sim$100 $\mu$m. In order to reach monomode emission, the cavity length has to be decreased further to 50 $\mu$m and below.

The normalised emission spectrum at 255 K with a cavity length of $\sim$50 $\mu$m is shown in figure 8.2. The emission wavelength is continuously tunable around 3.2 $\mu$m in a wavelength range of 100 nm just by changing the cavity length. The voltage applied on the piezo-driver ranges from 1 V to 20 V corresponding to a change of the cavity length of $\sim$0.9 $\mu$m. The output power is in the mW$_p$ range with a threshold $< 10$ W$_p$. By decreasing the operation temperature, emission at 3.3 $\mu$m is reached.

Despite the reduced cavity length two longitudinal modes arise at one specific piezo-voltage. This is caused by the broad spectral range of the gain. To achieve emission of just one longitudinal
Figure 8.2: Superimposed and normalised emission spectra at 255 K for different piezo voltages (voltage steps of 1 V). At one cavity length two longitudinal modes are emitted.

mode at every piezo-voltage, the cavity length has to be decreased further or the pump power needs to be reduced.

Because of the characteristics of this laser like

- single mode emission at 3.3 µm
- continuously tunable
- near RT operation
- excellent beam quality

it can be utilised to detect various hydroxides and hydrocarbons.
Mirrors combined with micro-electromechanical systems (MEMS) offer a new way in realising tunable VECSEL with a short cavity ($L < 100 \, \mu m$), leading to a very compact VECSEL setup. The membrane of a MEMS can be moved by applying a voltage.

**Figure 8.3:** The VECSEL consists of a MEMS-DBR placed on top of a PbSe QW active layer and spaced by a 100 $\mu m$ thick foil. The bottom mirror is a PbEuTe/EuTe DBR.

On the thin Si membrane ($d = 20 \, \mu m$) of a MEMS a 5 pair Si/SiO DBR is deposited. Because of strains in the deposited layers, bending of the Si membrane was observed. However, the exact bending parameters were not determined. The reflectivity of the Si/SiO layer stack is above 99%. As active layer 5.5 nm thick QW in PbSrSe are used. The bottom mirror is a 4.5 pair DBR consisting of PbEuTe and EuTe layers on Si. The setup is shown in figure 8.3. Between the active layer and the MEMS-DBR a $\sim 100 \, \mu m$ thick foil defines the air gap. The VECSEL is pumped though the MEMS-DBR.

Laser operation over a temperature range of 150 K with a maxi-
Normalised emission spectra at different heat sink temperatures for a VECSEL with MEMS-DBR. Tuning is achieved due to temperature change. Inset: the longitudinal modes selected by the $\sim 100 \mu m$ airgap are spaced by $A \approx 45 \text{ cm}^{-1}$. $B \approx 4 \text{ cm}^{-1}$ is the mode separation caused by the $380 \mu m$ thick Si substrate inside the cavity. The form of the spectra is the result of the overlap of the two subcavities.

Figure 8.4: Normalised emission spectra at different heat sink temperatures for a VECSEL with MEMS-DBR. Tuning is achieved due to temperature change. Inset: the longitudinal modes selected by the $\sim 100 \mu m$ airgap are spaced by $A \approx 45 \text{ cm}^{-1}$. $B \approx 4 \text{ cm}^{-1}$ is the mode separation caused by the $380 \mu m$ thick Si substrate inside the cavity. The form of the spectra is the result of the overlap of the two subcavities.

The normalised laser spectra are shown in figure 8.4. Since the band gap energy is highly temperature-sensitive, a wavelength range from 4.0 to 3.45 $\mu m$ is covered. This also demonstrates the broad reflection stopband of the MEMS-DBR.

The small airgap and the Si substrate form two subcavities selec-
ting longitudinal modes. Due to

\[
\frac{\Delta \nu}{\nu} = \frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L}
\]  

(8.1)

the air gap separates the modes by \(\sim 45 \text{ cm}^{-1}\) (figure 8.4 inset distance A) and the 380 \(\mu\text{m}\) thick Si substrate causes a mode spacing of \(\sim 4 \text{ cm}^{-1}\) (figure 8.4 inset distance B). The form of the emission spectrum is the result of the overlap of both selection effects.

The wavelength shift is only caused by temperature change. No tuning by the movement of the MEMS-DBR is done. These first attempts are promising in developing a mechanically tunable MEMS-based VECSEL.
Chapter 9

Conclusion

Vertical External Cavity Surface Emitting Lasers (VECSEL) based on PbSe active layers on Si substrates have been realised. The combination of the VECSEL structure and IV-VI semiconductors allows to achieve a very good beam quality over a large wavelength range in the MIR. The laser realised in this work emit in a wavelength region from 3.2 µm to 5.8 µm and operate up to 330 K. The VECSEL are optically pumped by a commercial 1.55 µm pump laser.

A single VECSEL with a homogeneous PbSe active layer on Si substrate covers a wavelength range from 5.8 µm to 4.4 µm with a maximum operation temperature of 283 K. The soldering process for an improved heat removal from the active region is essential to reach operation near RT and the broad operation temperature range of 150 K.

To shorten the development time a new VECSEL setup consisting of three separate parts has been developed, which is called modular design. In addition to the decreased fabrication time it facilitates direct comparison between different structures. Furthermore, it al-
allows the combination of different mirrors and active layers to form new types of VCSEL and VECSEL. Most of the results reported in this work have been achieved with this modular design.

To decrease the emission wavelength and to achieve lower threshold values PbSe based QW structures have been realised employing PbEuSe and PbSrSe as barrier material.

With PbEuSe as barrier material wavelengths from 5.0 μm to 3.6 μm are emitted with threshold powers below 0.2 W at low temperatures. Despite different VECSEL structures with varying active layer designs, a maximum operation temperature of 245 K could not be overcome. This can be explained by a band alignment transition from type I to type II with increasing temperature.

In addition, VECSEL with PbSe QW in PbSrSe host material have been developed. The maximum operation temperature is 330 K and with a single device lasing operation from 5.1 μm to 3.6 μm is achieved. With 4 nm thick QW lasing at wavelengths as short as 3.2 μm has been realised. By analysing the $P_{\text{thr}}$ values and the carrier confinement it was found that the short carrier lifetimes and thermal leakage limit the laser operation. Thermal leakage is probably enhanced due to a not symmetric band alignment of PbSe and PbSrSe.

The emission output so far is multimode. To reach emission of only one single longitudinal mode the cavity length is reduced to 50 μm. The emission wavelength of a VECSEL with 4.5 nm thick PbSe QW is continuously tunable around 3.3 μm by moving the external mirror. The VECSEL operates at 260 K and is suited for spectroscopic applications to detect various hydrocarbons and hydroxides. For such a short cavity length end pumping is required. Thus Si/SiO DBR have been developed, which are transparent for the pump beam at 1.55 μm wavelength.
VECSEL based on IV-VI materials operate from 3 µm to 10 µm wavelength. In combination with a short cavity tunable monomode emission near RT is possible. Therefore they offer the possibility to be employed in many spectroscopic applications in the MIR. By improved thermal management - e.g. with the use of diamond heat-spreaders - CW operation at RT is feasible.
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Own Publications

Articles


Own Publications


Conference Presentations

**Invited Talks**


2. H. Zogg, M. Rahim, A. Khiar, M. Fill and F. Felder. Lead chalcogenide mid-IR VECSEL operating up to above room temperature. *MIOMD-X, 10th Intl. Conf. on Mid-Infrared Optoelectronics: Materials and Devices, Shanghai, China*, Sep. 5-9, 2010


**Contributed Talks**


7. M. Fill, M. Rahim, A. Khiar, F. Felder, H. Zogg, A. Ishida, S. Kobayashi, T. Yokoyama and D. Cao. Modular PbSrSe/PbSe and PbSrS/PbS VECSEL on Si-Substrate. 40th Freiburg Infrared Colloquium, Freiburg, Germany, Feb. 16-17, 2011


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Poster presentations


2. A. Khiar, M. Rahim, M. Fill, F. Felder and H. Zogg. Optically pumped 6 – 10 µm IV-VI VECSELs. MIOMD-X, 10th Intl. Conf. on Mid-Infrared Optoelectronics: Materials and Devices, Shanghai, China, Sep. 5-9, 2010

3. M. Fill, M. Rahim, A. Khiar, F. Felder and H. Zogg. Modular IV-VI VECSELs on Si. MIOMD-X, 10th Intl. Conf. on Mid-Infrared Optoelectronics: Materials and Devices, Shanghai, China, Sep. 5-9, 2010


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Curriculum Vitae

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