Optically pumped lead-chalcogenide infrared-emitters on Si-substrates

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low-cost mid-IR emitters:
pump optically with low cost 0.8 - 1.5 µm laser-diodes!

a) 3-6 µm edge-emitting laser:
- EuSe (0.9 µm)
- Pb$_{0.95}$Eu$_{0.05}$Se (1 µm) & n x PbSe QW (10nm)
- Pb$_{0.91}$Eu$_{0.09}$Se (1.3 µm)
- BaF$_2$ (200nm)
- CaF$_2$ (10nm)

b) 3-6 µm “wavelength transformer”:
- (VCSEL in sub-threshold)

TDLS E16, p.144
a) QW laser structure on Si

Si (100) or Si (111)

- CaF$_2$ (10nm)
- EuSe (0.9 µm)
- Pb$_{0.91}$Eu$_{0.09}$Se (1.3 µm)
- Pb$_{0.95}$Eu$_{0.05}$Se (1 µm) + PbSe (10nm QWs)
- Pb$_{0.91}$Eu$_{0.09}$Se (1.3 µm)
- BaF$_2$ (200nm)
- CaF$_2$ (10nm)

λ$_{pump}$

λ$_{out}$

epi lift-off and cleave

Wet or dry etch

(100)

(111)

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a) on Si(100): Epi lift-off and cleave

- Heat-sink
- Active layer
- Glass
- Glue

$L = 80-500 \, \mu m$

Length of resonator

$\lambda_{pump}$

$\lambda_{out}$

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a) laser results on Si(100), cleaved mirrors

Pb$_{91}$Eu$_{09}$Se/Pb$_{95}$Eu$_{05}$Se & 3 x PbSe QW/EuSe) lift off from Si(100)

$L = 255 \text{ mm}$
$d_{\text{tot}} = 2.6 \text{ mm}$

QW: $d_{\text{PbSe}} = 10\text{nm}$

$\text{diff. QE} \sim 20\%$

$T = 105K$
$T = 145K$
$T = 175K$
$T = 185K$
$T = 195K$

$T_o \sim 30K$

limited power of pump-diode: lasing up to 250 K
a) on Si(111): no cleaved mirrors

dry-etched mirrors for PbSe-based DH & QW laser structures on Si(111)

3 lasers with different cavity lengths etched in one substrate
detail of a back Bragg mirror with two λ/4 grooves for very high reflectivity

front mirrors \( R_1 = 45\% \)
back mirrors \( R_2 = 78\% \)
a) laser results on Si(111), etched mirrors

\[ \text{Pb}_{0.90}\text{Eu}_{0.10}\text{Se}/\text{PbSe/EuSe}; \quad \text{DH} \quad d=200 \text{ nm} \]

on Si(111)

\[ \text{L}=270 \mu\text{m} \]

\[ \text{d}_{\text{tot}} = 2.7 \mu\text{m} \]

\[ 105 - 195 \text{ K} \]

\[ 205 \text{ K} \]

\[ 215 \text{ K} \]
Pb$_{90}$Eu$_{10}$Se/PbSe/EuSe DH

I$_{th} \propto e^{T/T_0}$

$L=268\mu m$
$d=2.7\mu m$

PULSER
I (AMPL.) 10 A
PRF  8 kHz
PW  150 nsec

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a) Specifications: optically pumped IV-VI mid-IR lasers (preliminary):

Material: PbX/PbEuX (X = Se, Te), grown by MBE on Si-substrate

Structure: Edge emitter, length of resonator e.g. 300 µm (matched to width of pump-source)
Width of resonator: given by pump source (no lateral delineation needed)

Crystallographic orientation, Resonant mirrors and mount:
grown on Si(100): (100)-orientation, epitaxial lift-off, cleaved mirrors, mount on heat-sink
grown on Si(111): (111)-orientation, etched mirrors, heat-sink=Si-substrate

Wavelength range: with PbSe QWs: ca. 3 - 6 µm
given by design (width of the QWs) and temperature.
longer wavelengths up to 30 µm: with PbSnSe QWs (in preparation)

wavelength tuning:
- by temperature
  ca. 2 x 10^-3 /K (change of band-gap with T), ca. 3 x 10^-4/K (for fixed mode, mainly T-dependence of refractive index)

- by mechanical movement:
  move laser bar with slightly varying thickness of QWs with respect to pump laser

Excitation: low cost laser-diode with e.g. 870 nm wavelength
(focusing: Use a lens, or just place the IV-VI laser structure near (within e.g. 30 µm) the pump laser exit face.

Emission power: up to 200 mW_p (tested at 4-5 µm wavelength)

Operation temperature:
Presently up to 250K (with pump power of 5 W_p), larger T with larger pump powers
In preparation: Optimising laser structure for lowest threshold near or at RT

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b) on Si(111): Resonant cavity mid-IR-source (at RT)

= VCSEL operated in sub-threshold

pump-laser  (970nm, 50% duty cycle)

Top mirror
R \approx 90\%

Bottom mirror

Substrate

Si(111) or BaF\textsubscript{2}

\begin{align*}
\text{h} & \quad \text{h} \\
\text{L} & \quad \text{L} \\
2\text{H} & \quad \text{QW: PbSe (10nm)}
\end{align*}

\begin{align*}
\text{Pb}_0.95\text{Eu}_{0.05}\text{Se (n=5)} \\
\text{BaF}_2 \\
\text{PbSe (10nm)} \\
\text{BaF}_2 \text{ or } \text{SiO}_2 \\
\text{EuSe or TiO}_2
\end{align*}

\begin{align*}
\text{EuSe or TiO}_2 (n=2.4) \\
\text{BaF}_2 \text{ or } \text{SiO}_2 (n=1.43) \\
\text{EuSe or TiO}_2 \\
\text{BaF}_2 \text{ or } \text{SiO}_2
\end{align*}

\begin{align*}
\text{efficiency: } >10^{-4}
\end{align*}

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b) narrow band IR-source: VCSEL-structure, (I < I_{th}, at RT)

4.2 µm (2381 cm⁻¹) cavity

Refl.

Wavenumber cm⁻¹

calc: cavity mode at λ=4.2 µm
b) Specifications: “Wavelength-transformer” (preliminary):

**Material:** PbX/PbEuX (X = Se, Te), grown by MBE on Si(111)-substrate

**Structure:** 8/2 cavity, Bragg mirror pairs  n x (HL) bottom (exit side),  m x (hL) top (entrance side)

**Excitation:** low cost laser-diode with wavelength at e.g. 870 nm

**Wavelength range:** with PbSe QWs: ca. 3 - 6 µm
determined by design (widths of the QW)
longer wavelengths up to 30 µm: with PbSnSe QW (in preparation)

**Operating temperature:** RT

**Temperature coefficient:** ca. 3 x 10^{-4}/K

**Linewidth:** 0.2% to 7 %, depending on design (finesse of cavity)

**Efficiency:** ca. 10^{-4} (for HL 2H LhLh structure), exp.
higher values probable (by optimizing materials quality)

**Linewidths & efficiencies for differently designed Bragg mirrors** (with still higher reflections):

<table>
<thead>
<tr>
<th>Excit mirror number of HL-pairs</th>
<th>entrance mirror number of Lh-pairs</th>
<th>line-width</th>
<th>increase of efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5.5%</td>
<td>x 1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1.0%</td>
<td>x 7</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.2%</td>
<td>x 40</td>
</tr>
</tbody>
</table>

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b) Application: Resonant cavity mid-IR-source (at RT)

“wavelength transformer” 870 nm --> 3 - 5 µm

\[ \Delta \lambda / \lambda \sim 1 - 5 \% \]

for gas sensing: low cost mass production

- CO: 4.6 µm
- CO₂: 4.2 µm
- CH₄: 3.4 µm
- H₂O: 2.96 µm

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