Influence of the InAs/GaSb superlattice period composition on the electro-optical performances of T2SL infrared photodiode

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Antimonide (Sb)-based materials
GaSb, InAs, AlSb, InSb, (Ga,In,Al,As,Sb)

MWIR Laser diodes
GaSb or InSb substrate
GaSb, InAs, AlSb, InSb, (Ga,In,Al,As,Sb)

MWIR detectors
InSb & InAsSb photodiodes
InAs/GaSb Superlattice (T2SL) photodiodes

SEM image of IR Laser diode
InAs/AlSb QCL
GaInAsSb EELs & VCSELs

SEM image of IR mesa photodiode
InSb & InAsSb photodiodes
InAs/GaSb Superlattice (T2SL) photodiodes

MBE machine RIBER compact 21E
InAs/GaSb heterostructure: Type-III or type-II broken gap band alignment (InAs CB lower than GaSb VB)

InAs/GaSb type-II superlattice (SL)

SL = a periodic stacking of InAs and GaSb layers with a period $d$ of a few nm thick

SL = coupled MQW $\Rightarrow$ energy minibands $\Rightarrow$ Fundamental absorption between V1C1 suitable for Infrared detection (3-30µm)

**Type-II Superlattice (T2SL) photodiode**

$\Rightarrow$ T2SL Photodiode to compete InSb and MCT high performance IR detectors

$\Rightarrow$ T2SL FPA commercially available (2015): [IRNOVA, SCD, IRcamera]

**BUT** works have to be done to improve performances…
Our motivation: study the influence of SL period composition (flexibility) on the performances of MWIR T2SL photodetector.

Influence of SL period composition:
- on material-rich structure
- on dimensionality
- on residual type of doping
- on electrical & electro-optical performances
Choice of SL period for MWIR domain

![Graph showing energy vs period and wavelength vs period for InAs and GaSb monolayers.](image)

**Fundamental C1V1 energy**

- Electron miniband C1
- Hole miniband V1

**Energy (eV)**

- InAs(ML)
- GaSb(ML)

R = \frac{\text{InAs(ML)}}{\text{GaSb(ML)}}

**Period (Å)**

- 3Å=1ML

**Wavelength (µm)**

- T=77K

**Symmetrical period**
Choice of SL period for MWIR domain

MWIR spectral domain addressed by the same SL thickness ratio $R$

Fundamental C1V1 energy

Photoluminescence spectra

$R = \frac{\text{InAs(ML)}}{\text{GaSb(ML)}}$

$T = 77K$

$T = 80K$

$R = 1$

Period (Å)

Wavelength (µm)

Symmetrical period

6 8 10 12 14 16
Choice of SL period for MWIR domain
Choice of SL period for MWIR domain

一批bandgap energy addressed by different SL thickness ratio R

Fundamental C1V1 energy

For a given band gap ➔ different material-rich structures
Choice of SL period for MWIR domain

Same bandgap energy addressed by different SL thickness ratio $R$

For cut-off wavelength around 5µm (@77K)
SL pin photodiodes have been fabricated by MBE with active zone thickness of 1µm.

Same bandgap energy addressed by different SL thickness ratio R

Choice of SL period for MWIR domain

- Choice of SL period for MWIR domain
- Same bandgap energy addressed by different SL thickness ratio R
- SL pin photodiodes have been fabricated by MBE with active zone thickness of 1µm

**10/19 SL**
- GaSb (p) substrate
- \( \text{GaSb} p^+ (\text{Be}) \) doped SL
- \( \text{GaSb} p^- = 1 - 2 \times 10^{18} / \text{cm}^3, e = 0.5 \mu \text{m} \)
- \( \text{InAs} n^+ = 2.1 \times 10^{18} / \text{cm}^3, e = 20 \text{nm} \)
- SL nid active zone \( R = 0.5 \) or 1 or 2

**10/10 SL**
- MBE growth control of InAs/GaSb superlattice on GaSb substrate

**7/4 SL**
- Mesa diodes & photodiodes
Influence of SL period composition on PR spectra

Same cut-off (5µm @ 77K) but photoresponse spectra strongly different!
GaSb-rich

InAs-rich

Symmetric

Photoresponse spectra

\[ R = 0.5 \]

\[ R = 1 \]

\[ R = 2 \]

Wavelength (μm)

Photoresponse intensity (a.u.)

GaSb-rich

Symmetric

InAs-rich

Same cut-off but MQW versus SL behavior

**GaSb-rich**

MQW behavior

b) 10/19 SL structure

InAs

GaSb

\( l < f_{e_i}, f_{v_i}> \cdot l^2 < 10\% \)

InAs/GaSb SL

(10MLs/19MLs)

(3nm / 5.7nm)

\( f_{v_i}^2 \)

\( f_{c_i}^2 \)

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Photoresponse spectra

- Photoresponse spectrum is proportional to the excitonic absorption
- Spectral absorption shape is relative to the joined density of states

\[ D_{cv}(E) = \frac{2V_\alpha}{\Gamma(\alpha/2)} \left( \frac{\mu}{2\pi\hbar^2} \right)^{\alpha/2} (E-E_g)^{\alpha/2-1} \]

\( \alpha = 2.75 \) to \( \alpha = 2.25 \) represent the influence on dimensionality.
Electrical measurements

- **J(V) results**

77 K

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Current Density (A/cm²)</th>
<th>$R_0A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaSb-rich</td>
<td>10/19 SL (≈110 periods)</td>
<td>$J(-50mV)=3\mu A/cm^2$</td>
</tr>
<tr>
<td>InAs-rich</td>
<td>10/10 SL (≈170 periods)</td>
<td>$J(-50mV)=0.2\mu A/cm^2$</td>
</tr>
<tr>
<td></td>
<td>7/4 SL (≈300 periods)</td>
<td>$J(-50mV)=0.04\mu A/cm^2$</td>
</tr>
</tbody>
</table>

Same cut-off but electrical performances strongly different!
**Electrical measurements**

- **J(V) results**

  ![Graph showing J(V) results]

Different cut-off but same electrical behavior for each kind of structure

\[ J_{GR} \propto \frac{\eta_l}{\tau_{GR} \sqrt{N_{Res}}} \]
Electrical measurements

- **J(V) results**

![Graph showing J(V) characteristics](image)

**Intrinsic carrier concentration** \( n_i \)

\[ n_i = f(\varepsilon_g, T, m_{\text{eff}}^*) \]

Different cut-off but same electrical behavior for each kind of structure

- **Symmetric**
- **GaSb-rich**
- **InAs-rich**

High coupling

⇒ small masses
⇒ \( n_i \downarrow \)
⇒ \( J_{\text{GR}} \downarrow \)

⇒ Low \( J_{\text{dark}} \) value of InAs-rich SL
Electrical measurements

- **J(V) results**

![Graph showing dark current density vs wavelength for different GaSb contents.](image)

- **Carrier lifetime** $\tau_{GR}$ (Svensson et al., JCG 334 (2011))

![Graph showing carrier lifetime vs GaSb content.](image)

- **Different cut-off but same electrical behavior for each kind of structure**

$J_{GR} \propto \frac{n_t}{\tau_{GR}\sqrt{N_{Res}}}$

- High $J_{dark}$ value of GaSb-rich SL
Electrical measurements

- **J(V) results**

  - **Energy (eV)**
    - 0.22 to 0.30
  - **Wavelength (µm)**
    - 5.8 to 4
  - **Dark current density (A/cm²)**
    - 1E-9 to 1E-4

  - **J(V=-50mV) @ 77 K**
    - R~0.5
    - R=1
    - R~2

- **Carrier lifetime τ_{GR}** (Svensson et al., JCG 334 (2011))

  - **GaSb content (%)**
    - 35 to 65
  - **GaSb-rich**
  - **Symmetric**

  - Different cut-off but same electrical behavior for each kind of structure

  - τ_{GR} ↑ ➔ high J_{dark} value of GaSb-rich SL

- Electrical performances of InAs/GaSb SL diode are strongly dependent on GaSb-content
  - Ga-free InAs/InAsSb SL diode

\[
I_{GR} \propto \frac{n_i}{\tau_{GR} \sqrt{N_{Res}}}
\]
Transport ➔ type of SL material

![Diagram showing electrical measurements and conductivity change]

Change in type of apparent conductivity

$$R_H = \frac{1}{e} \left( \frac{p\mu_P^2 - n\mu_n^2}{p\mu_P + n\mu_n} \right)^2$$

$$\mu_n \gg \mu_P$$

Symmetric SL is p-type!!
Electrical measurements

- **Transport ➔ type of SL material**

![Graph showing ln(n) vs 1/T for InAs/GaSb SL.](image)

- InAs/GaSb SL
  - GaSb-rich (p-type)
  - InAs-rich (n-type)

- Symmetric SL
  - p-Type

- Residual carrier concentration (cm⁻³)
  - GaSb-rich (R=0.5): 3.5x10¹⁵
  - Symmetric (R=1): 2.5x10¹⁵
  - InAs-rich (R=2): 8x10¹⁴

- **Influence on type of doping**

- **Hall resistance**
  - T = 77K

- **Magnetic field [T]**
  - GaSb-rich structure p-type
  - InAs-rich structure n-type
InAs-rich SL
N-type structure
Minority carriers: holes
Very low dark current
3D spectral shape

GaSb-rich SL
P-type structure
Minority carriers: electrons (high QE)
High dark current
2D spectral shape

Influence of SL period composition
- same cut-off for different SL periods with different properties/performances
- same cut-off with n-type or p-type residual SL doping
Conclusion ➔ Combined structure

InAs-rich SL

**N-type structure**
- Minority carriers: holes
- Very low dark current
- 3D spectral shape

GaSb-rich SL

**P-type structure**
- Minority carriers: electrons (high QE)
- High dark current
- 2D spectral shape

**Combine** the advantages of each structure

- N+ contact
- InAs-rich Residual N-type
  - N-side of the junction
- GaSb-rich Residual P-type
  - Active zone
  - P-side of the junction

⇒ pn junction without doping the junction!
**MWIR T2SL photodiode combining SL properties**

- **Cap InAs** $n^* = 5 \times 10^{17} \text{cm}^{-3}$, 20nm
- **SL 7ML InAs/4ML GaSb** $n^* = 5 \times 10^{17} \text{cm}^{-3}$, 100nm
- **SL 7ML InAs/4ML GaSb** N.i.D, 200nm
- **SL 9ML InAs/8ML GaSb** N.i.D, 50nm
- **SL 10ML InAs/12ML GaSb** N.i.D, 50nm
- **SL 11ML InAs/16ML GaSb** N.i.D, 50nm
- **SL 11ML InAs/20ML GaSb** N.i.D, 1.5μm
- **SL 11ML InAs/20ML GaSb** $p^* = 5 \times 10^{17} \text{cm}^{-3}$, 130nm
- **GaSb (P) Substrate**

**Conclusion**

- **Combined structure**

**N-side**
- N+ contact
- InAs-rich Residual N-type
- GaSb-rich Residual P-type
- P+ contact

**Active zone P-side**

**Gradual periods (%GaSb ↓)**

- Combined Structure

---

**MWIR T2SL photodiode combining SL properties**

**Conclusion**

- **Combined structure**

**N-side**
- N+ contact
- InAs-rich Residual N-type
- GaSb-rich Residual P-type
- P+ contact

**Active zone P-side**

**Gradual periods (%GaSb ↓)**

- Combined Structure
### Conclusion ➔ Combined structure

**MWIR T2SL photodiode combining SL properties**

<table>
<thead>
<tr>
<th>Layer Structure</th>
<th>Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap InAs</td>
<td>$n^+ = 5 \times 10^{17} \text{cm}^{-3}$</td>
<td>20 nm</td>
</tr>
<tr>
<td>SL 7 ML InAs/4 ML GaSb</td>
<td>$n^+ = 5 \times 10^{17} \text{cm}^{-3}$</td>
<td>100 nm</td>
</tr>
<tr>
<td>SL 7 ML InAs/4 ML GaSb</td>
<td>N.i.D</td>
<td>200 nm</td>
</tr>
<tr>
<td>SL 9 ML InAs/8 ML GaSb</td>
<td>N.i.D</td>
<td>50 nm</td>
</tr>
<tr>
<td>SL 10 ML InAs/12 ML GaSb</td>
<td>N.i.D</td>
<td>50 nm</td>
</tr>
<tr>
<td>SL 11 ML InAs/16 ML GaSb</td>
<td>N.i.D</td>
<td>50 nm</td>
</tr>
<tr>
<td>SL 11 ML InAs/20 ML GaSb</td>
<td>N.i.D</td>
<td>1.5 μm</td>
</tr>
<tr>
<td>SL 11 ML InAs/20 ML GaSb</td>
<td>$p^+ = 5 \times 10^{17} \text{cm}^{-3}$</td>
<td>130 nm</td>
</tr>
</tbody>
</table>

**HR-XRD spectrum**

11 ML InAs/20 ML GaSb
11 ML InAs/16 ML GaSb
10 ML InAs/12 ML GaSb
9 ML InAs/8 ML GaSb
7 ML InAs/4 ML GaSb

11 ML InAs/20 ML GaSb
11 ML InAs/16 ML GaSb
10 ML InAs/12 ML GaSb
9 ML InAs/8 ML GaSb
7 ML InAs/4 ML GaSb
Conclusion ➔ Combined structure

**MWIR T2SL photodiode combining SL properties**

- 2D spectral shape (as GaSb-rich SL)
- Dark current is lower than the GaSb-rich period but slightly higher than the InAs-rich period

...in progress
Thank you for your attention

Our recent publications on T2SL photodiodes

- **M. Delmas et al** “Midwave infrared InAs/GaSb superlattice photodiode with a dopant-free p-n junction”
  Infrared Physics & Technology, **70**, 76 (2015)

- **E. Giard, et al** “Influence of the p-type doping on the radiometric performances of MWIR T2SL photodiodes”
  Infrared Physics & Technology, **70**, 103 (2015)

- **M. Delmas et al** “Electrical modeling of InAs/GaSb superlattice mid-wavelength infrared pin photodiode to analyze experimental dark current characteristics”

- **E. Giard, et al** “Quantum efficiency investigations of type-II InAs/GaSb MWIR superlattice photodetectors”

- **R. Taalat et al** “Influence of the period thickness and composition on the electro-optical properties of type-II InAs/GaSb midwave infrared superlattice photodetector”