Antimonide-based optoelectronic devices epitaxially grown on Silicon

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  – French national research agency (*ANR*)
  – European Union H2020

OUTLINE

- Antimonide opto devices on Si: motivations
- III-Vs on Si: issues
- GaSb on off-cut Si substrates
  - epitaxial templates
  - GaSb-based laser diodes
  - InAs/AlSb quantum-cascade lasers
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  - MBE templates
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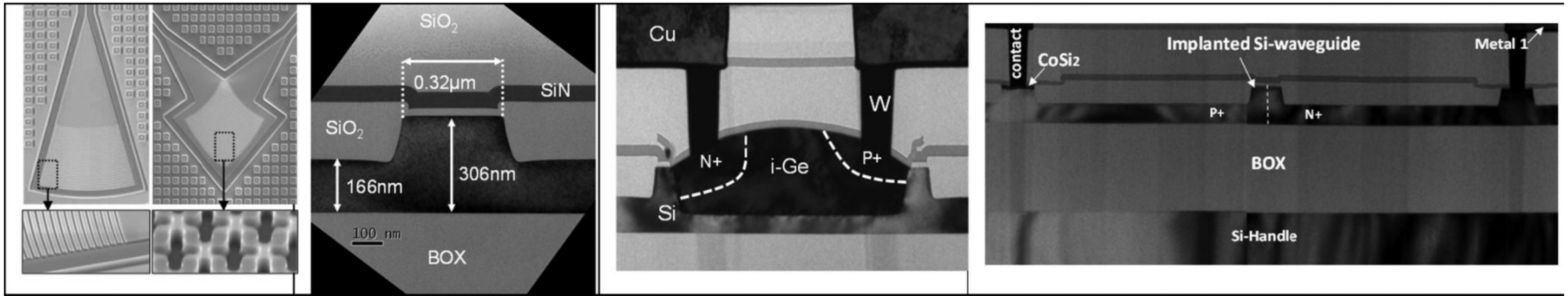
Silicon Photonics R&D and Manufacturing on 300-mm Wafer Platform

Si photonics

F. Boeuf *et al.* (ST Microelectronics)

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 2, JANUARY 15, 2016

A complete toolbox!

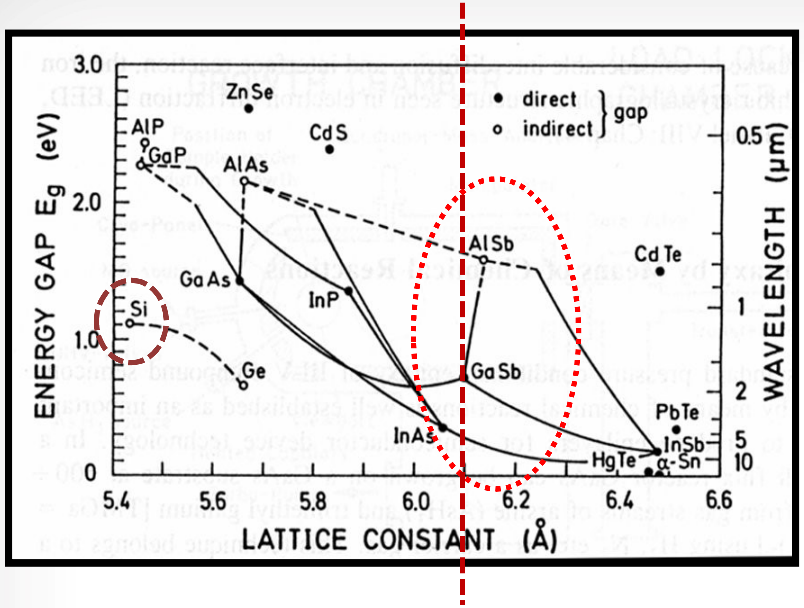


Surface Grating Coupler | TE Rib Waveguide | Integrated waveguide Ge photodiode | Integrated P/N junction depletion mode High Speed Phase Modulator.

Almost complete: the laser is still missing!

Si and Ge are indirect bandgap materials: no light emission

Si-photonics needs III-V semiconductor materials



Antimonide compound semiconductors

GaSb, AlSb, InSb, InAs and their alloys

- **Large bandgap range:**

  0.1 – 1.8 eV

- **Various band alignments:**

  Type I, Type II, Type III

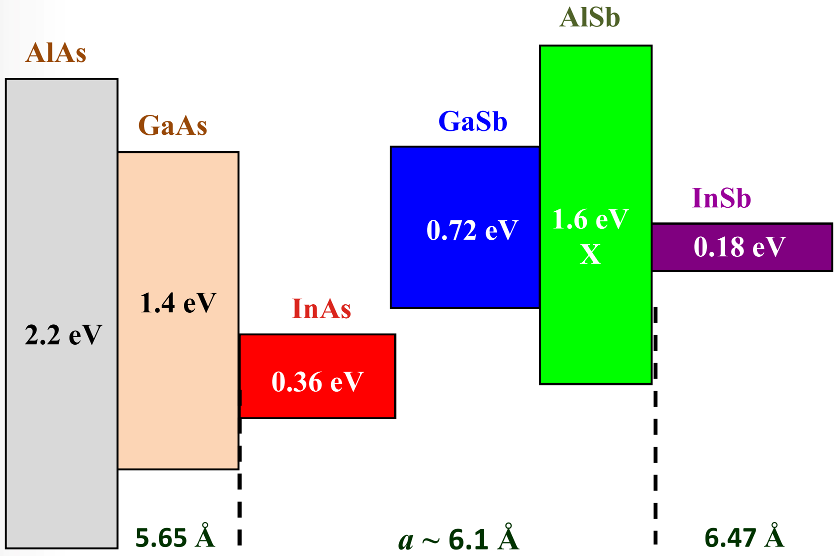
- **Large band offsets:**

  ΔE_c = 0 – 2 eV

  ΔE_v = 0 – 0.5 eV

☞ ***Unrivalled band structure engineering***

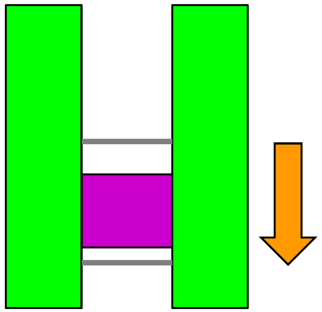
☞ ***Mismatch with Si ~12%***



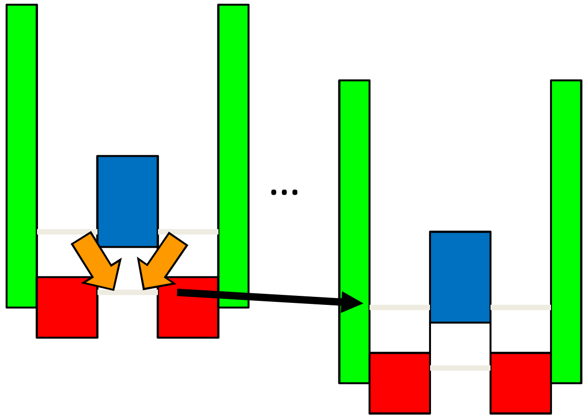
III-Sbs: perfectly suited for the IR wavelength range

Sb-based IR devices

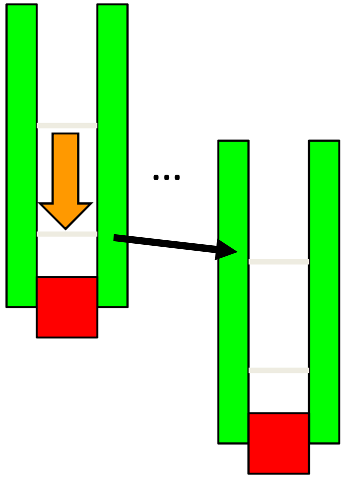
QW Lasers
GaInAsSb/AlAsSb



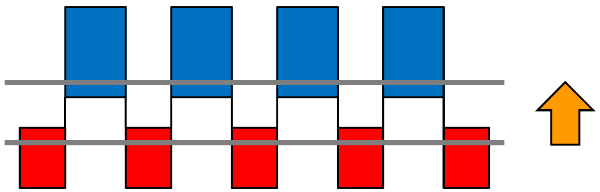
Interband Cascade Lasers
InAs/GaSb/AlSb



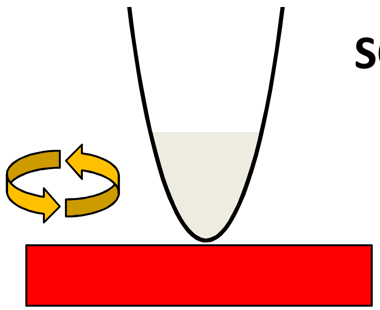
Quantum Cascade Lasers
InAs/AlSb



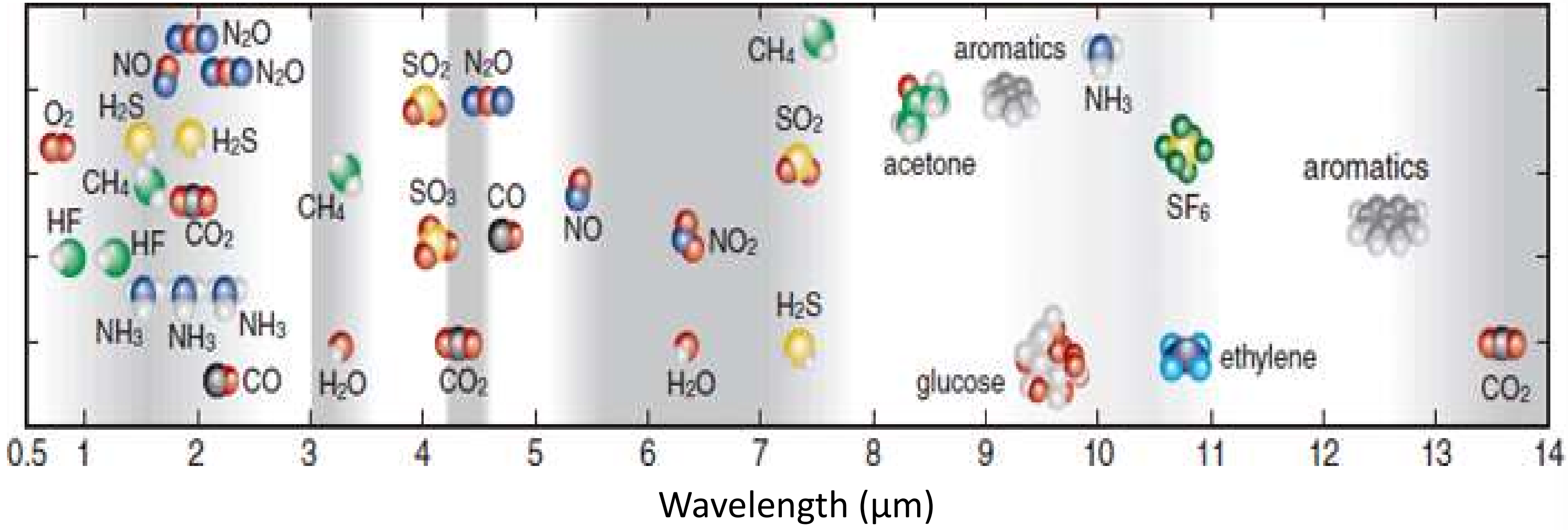
Type II SL Detectors
InAs/GaSb (or InAs/InAsSb)



SC Plasmonics
InAs(Sb)



The sensing challenge



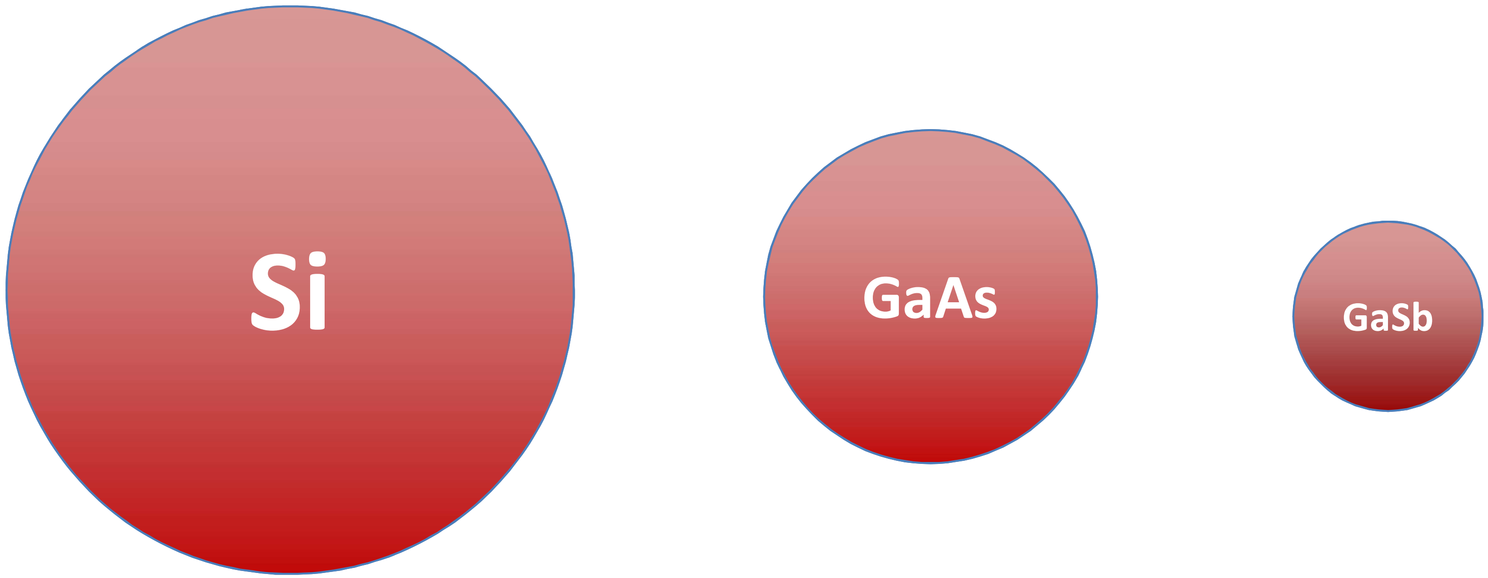
Mid-IR: atmosphere transparence windows + "fingerprint" region

A wealth of applications

Atmospheric pollution monitoring, industrial process control, food industry, health, security, free space optics, etc.

Increasing demand for low-cost, small footprint, smart, photonic sensors.

The substrate challenge



	Si	GaAs	InP	GaSb
Diameter (mm)	300	175	100	100
\$/cm²	0.5	2	6	12

Low cost mid-IR devices → Si platform.

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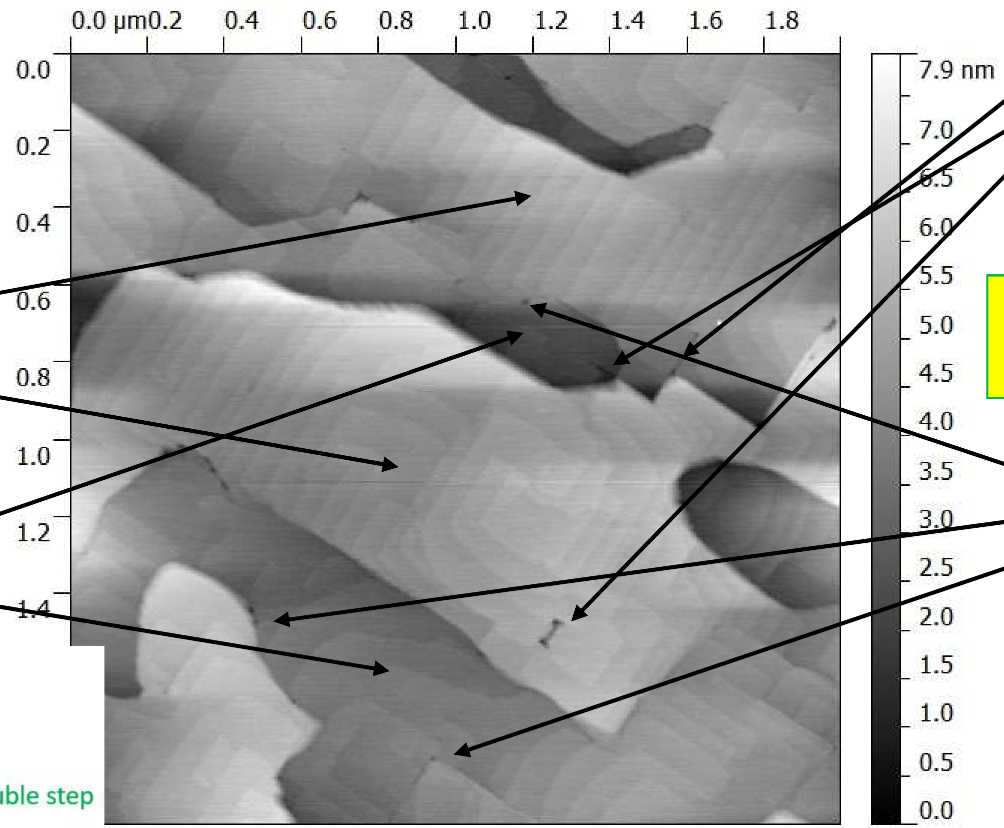
III-V epitaxy on Si: a number of mismatches

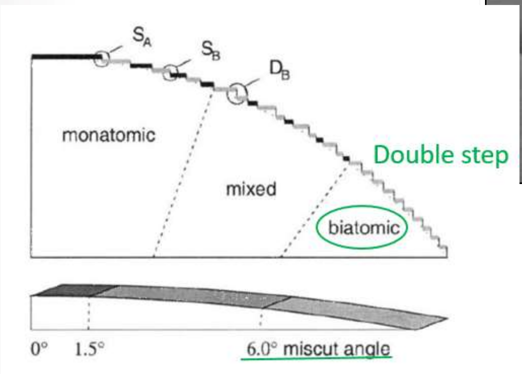
- Surface preparation
- Off-cut substrates

Domain 1

Antiphase boundaries

Domain 2





An AFM view

Twins

- Surface preparation
- Growth conditions

Dislocations

- Nucleation
- Buffer-layer engineering

Dislocations **cannot be avoided**, but their threading density can be reduced

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Si substrates

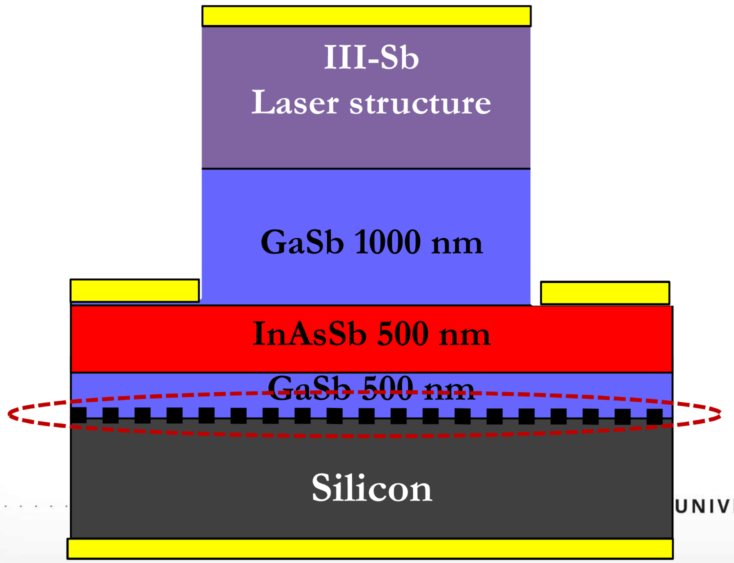
- **4 – 6° offcut (001) 2 inch. Si substrates**

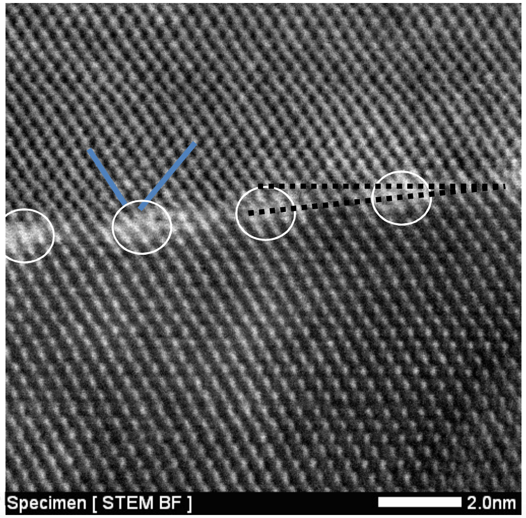
Standard III-V molecular-beam epitaxy (MBE) reactor

- Solid-source MBE with load-lock chamber
- Valved-cracker cells for As and Sb
- Standard group-III effusion cells
- $T_{substrate}$ < 850 °C

- Growth chamber and $T_{substrate}$ not compatible with *in-situ* Silicon de-oxidation
- No Si buffer-layer growth in (most) III-V systems

- 4 – 6° off (001)Si
- *Ex-situ* O_2 Plasma + HF Si preparation cycles
- *In-situ* annealing at 800°C
- 4 MLs AlSb @ 450°C
- 500 nm GaSb buffer layer
- 500 nm InAsSb bottom contact layer
- ~ 1 µm GaSb buffer layer





TEM image: A. Trampert, PDI-Berlin

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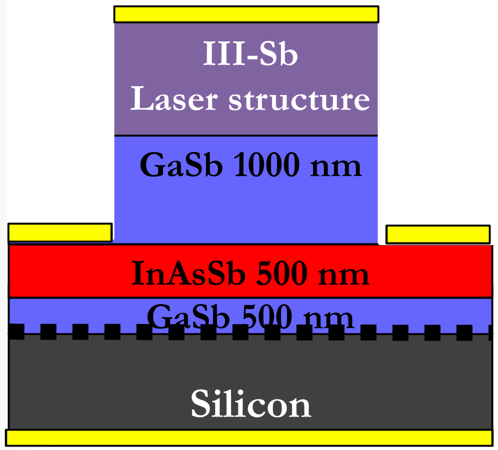
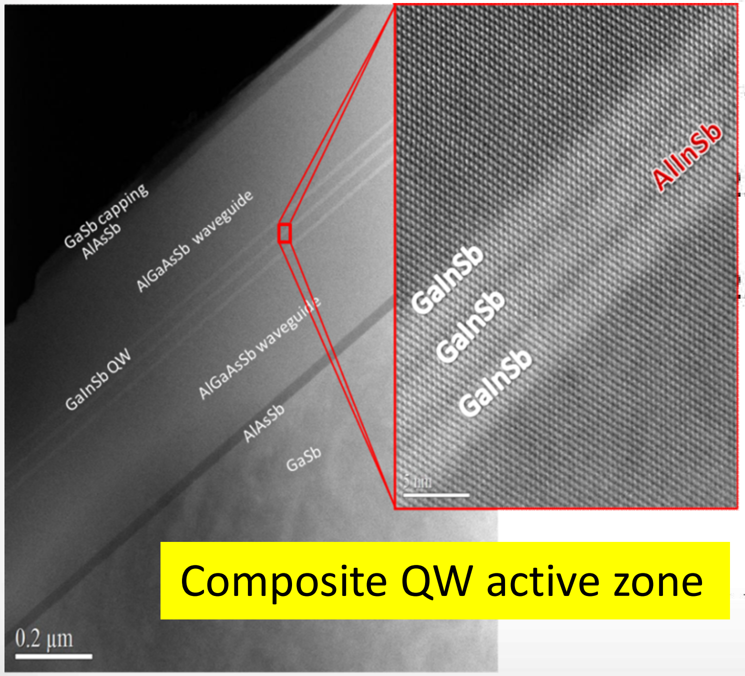
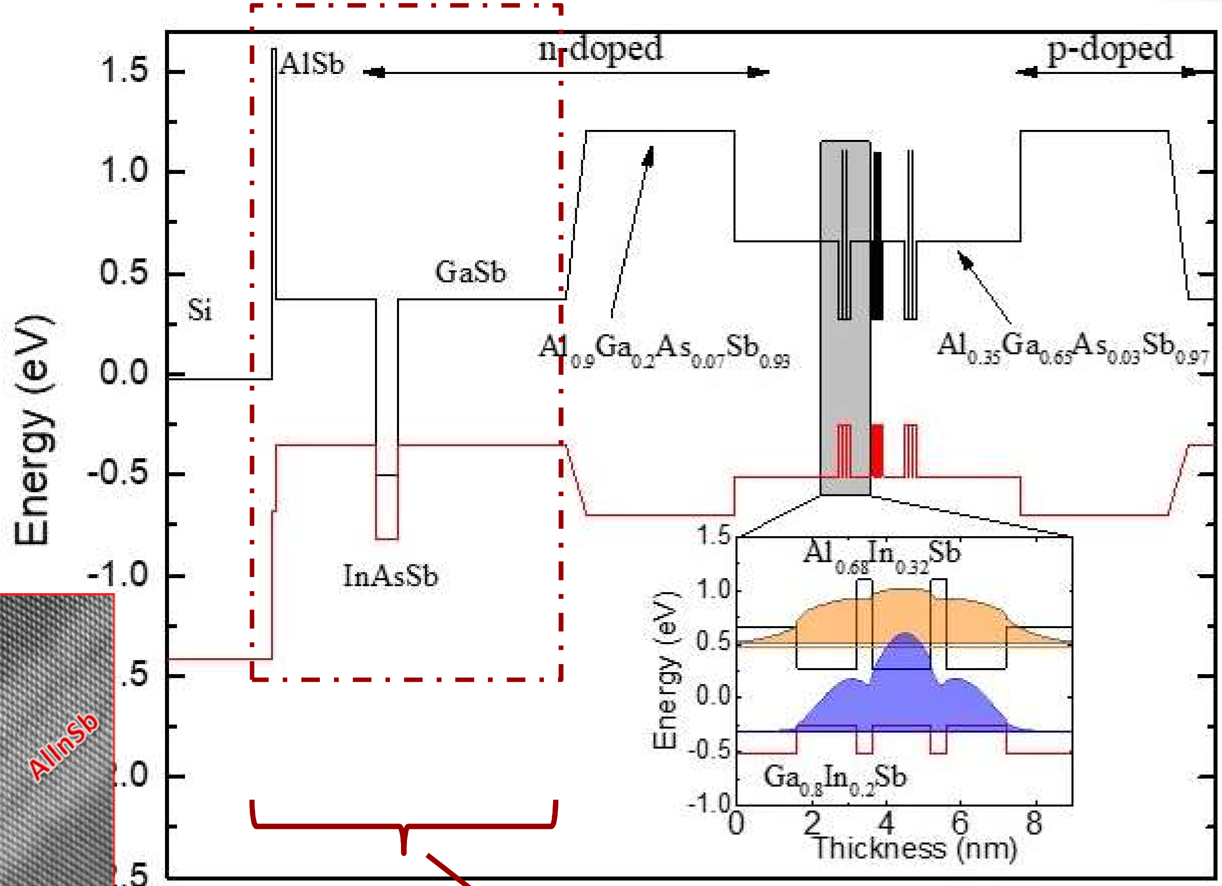
1.55-µm GaSb laser on Si substrate



TEM: G. Patriarche, CNRS

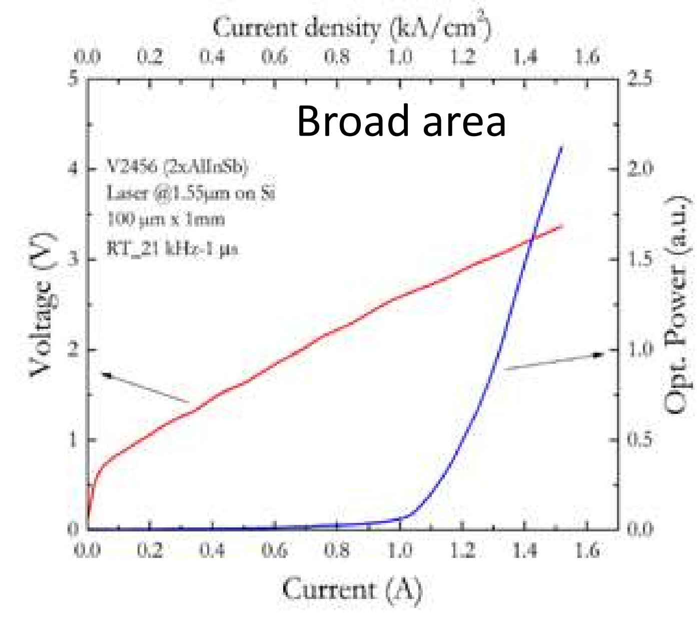


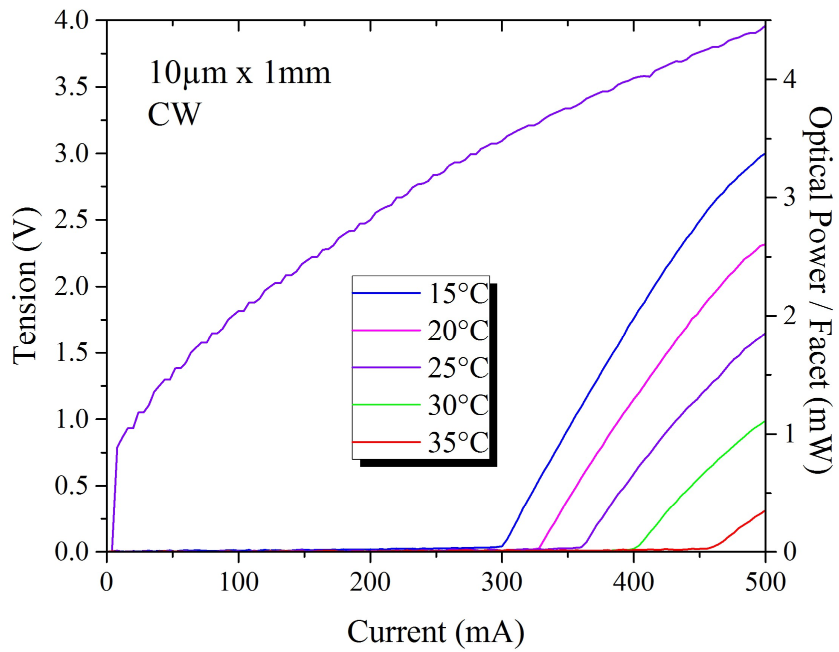
Composite QW active zone

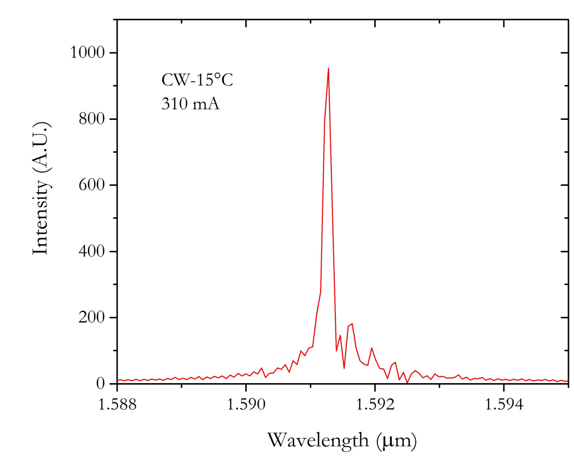


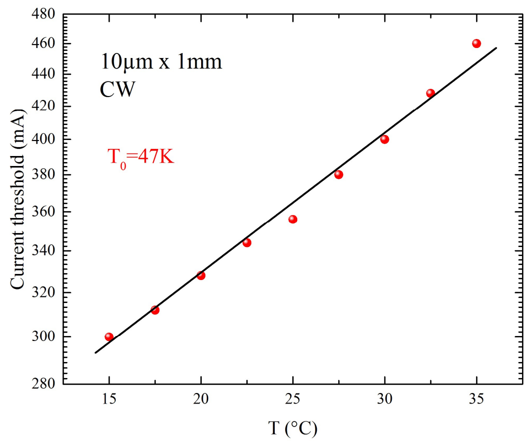
GaSb-based template

1.55-µm GaSb laser diode on Si substrate









- λ ~ 1.59 µm
- CW operation up to 35°C
- P_{out} > 3mW @ 15°C
- $T_0 \sim$ 47 K
- $J_{th}(Si) \sim$ 3-5 x $J_{th}(GaSb)$

A. Castellano *et al.,* APL Phot. 2 (2017) 061301.

More details in: 10.1016/B978-0-12-812136-8.00029-3

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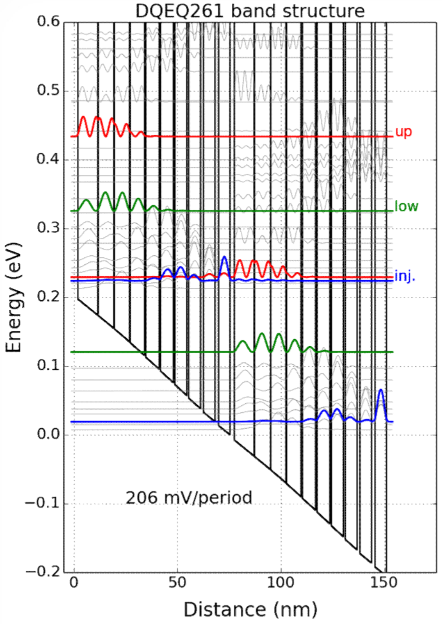
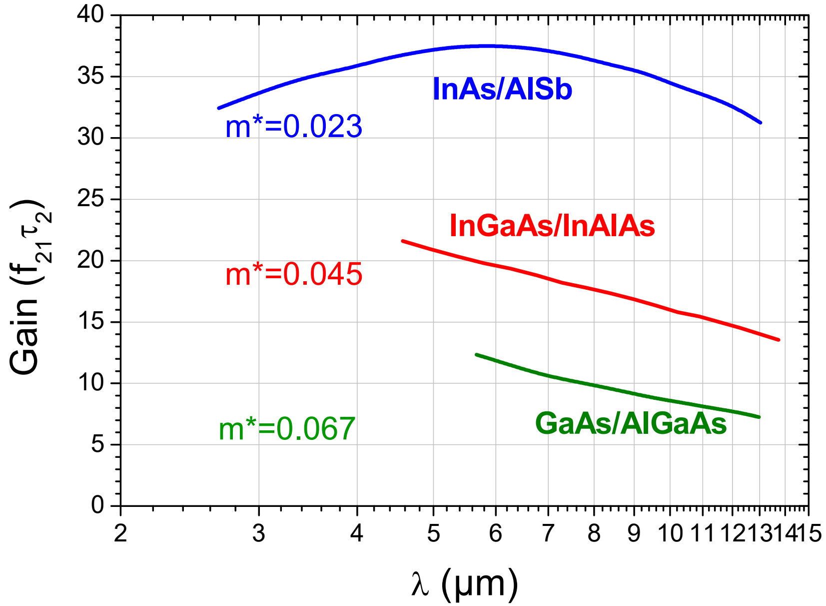
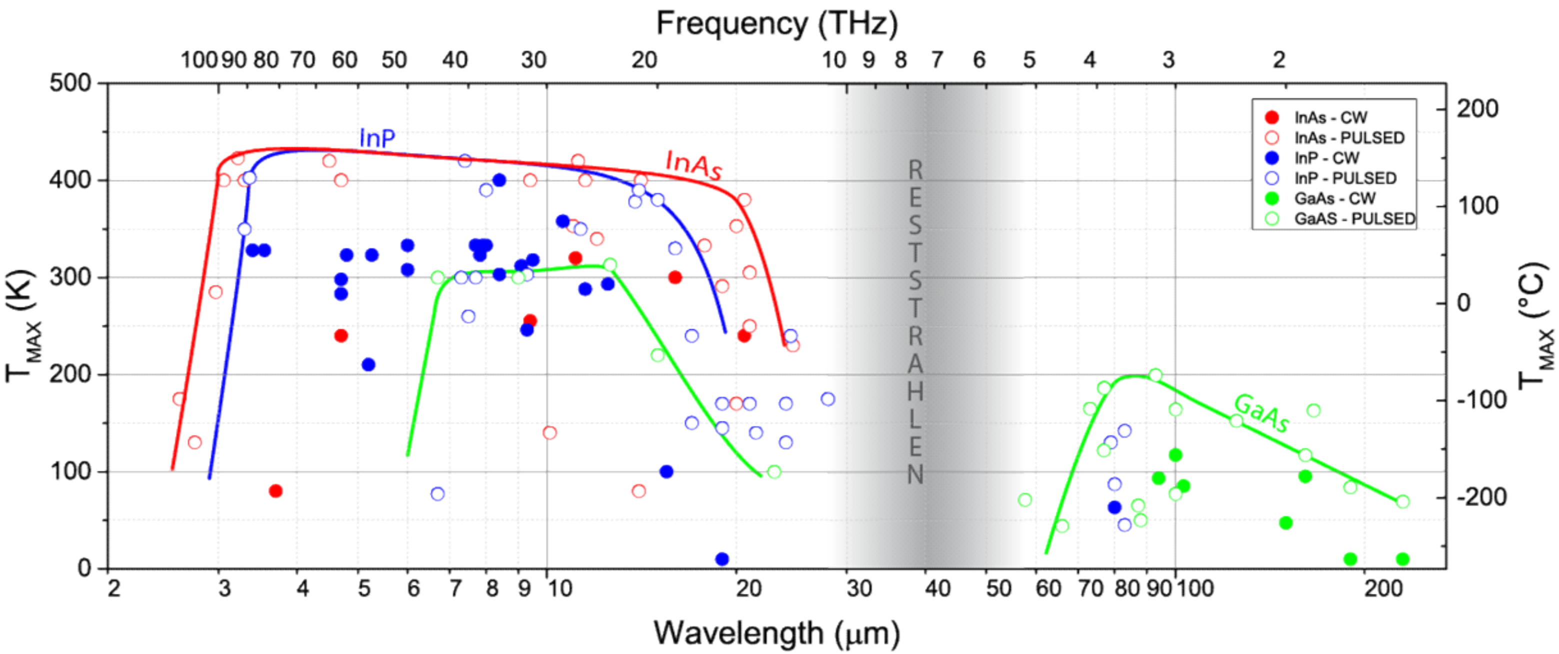
InAs/AlSb: very good intrinsic properties for QCLs



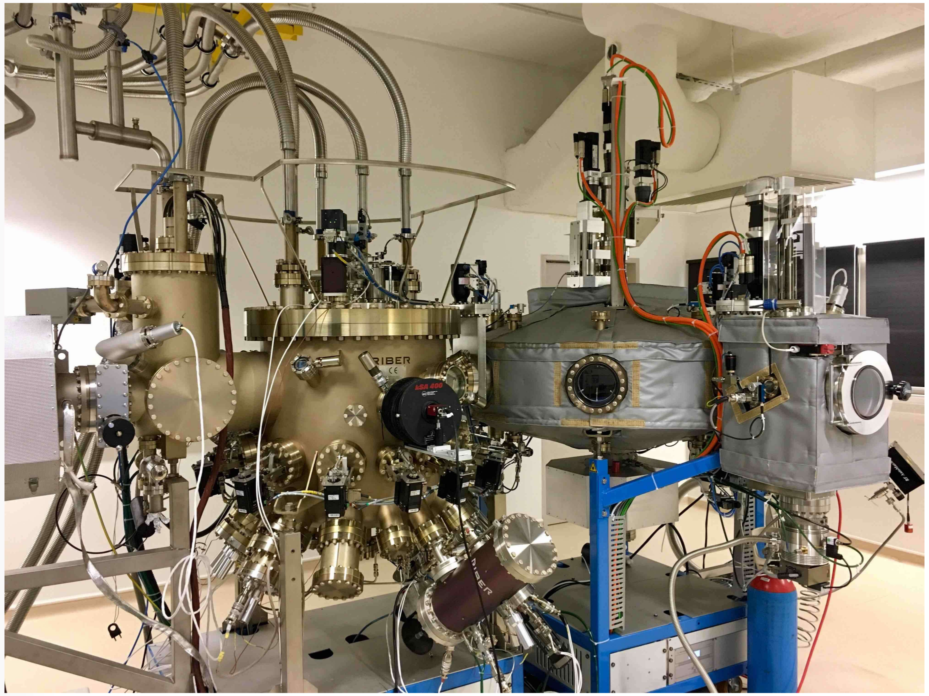
Gain in QCL

$$g \; \alpha \; \frac{1}{m^{*3/2}}$$





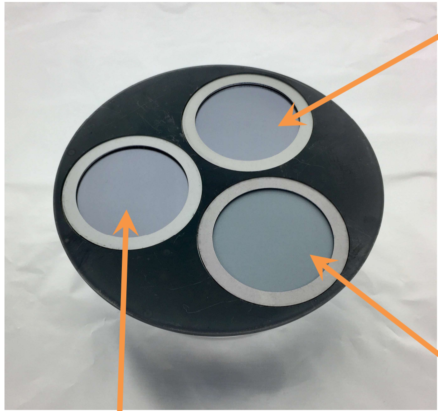
MBE growth



RIBER 412 MBE system

Substrate 2”n-InAs (100)

InAs



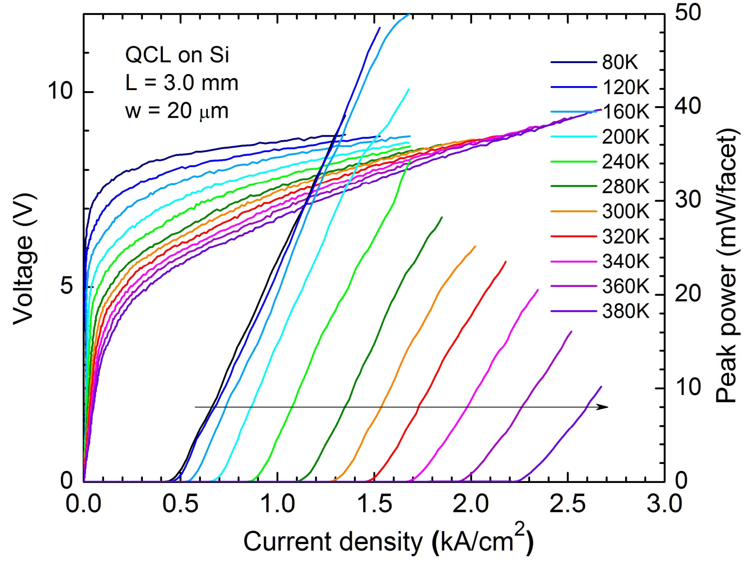
Dummy

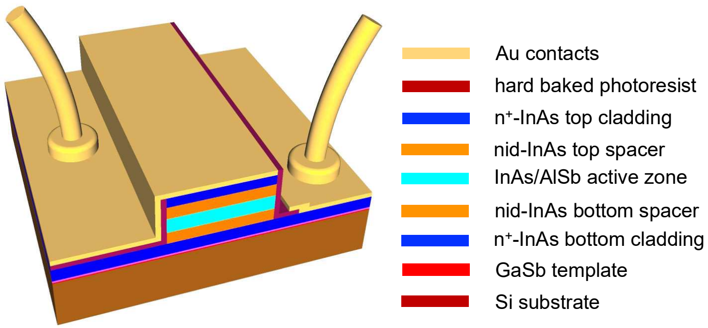
Template on 2” Si (100) 6°off

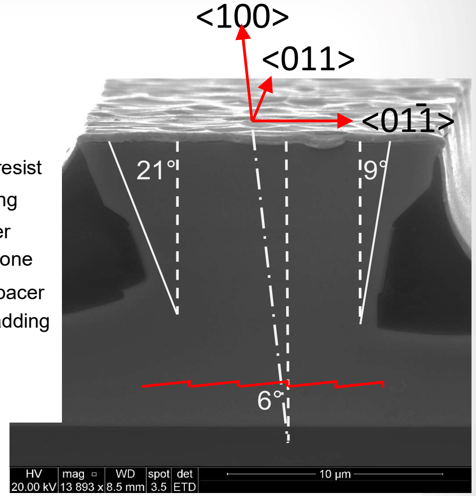
InAs 0.2 µm
GaSb 1 µm
AlSb 4 ML
Si (100) 6°off

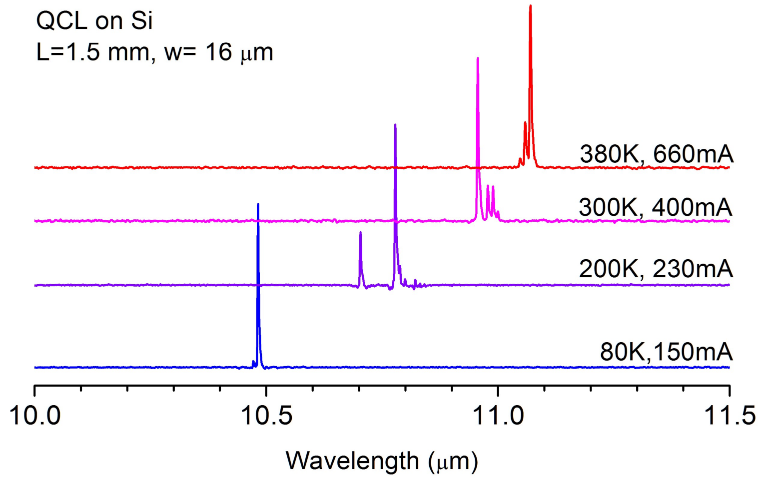
Side-by-side growth on 2 substrates

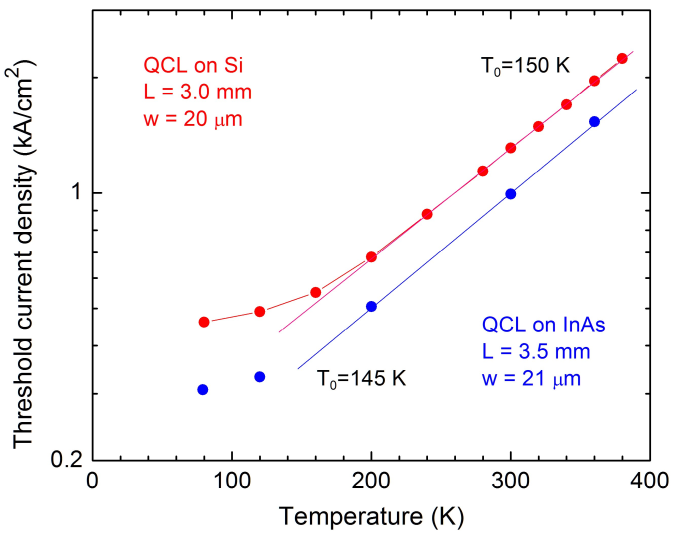
InAs/AlSb QCL on Si











First-ever report of a QCL grown on Si
Similar performances on Si and on InAs substrates

H. Nguyen-Van *et al.*, Sci. Rep. 8 (2018) 7206.

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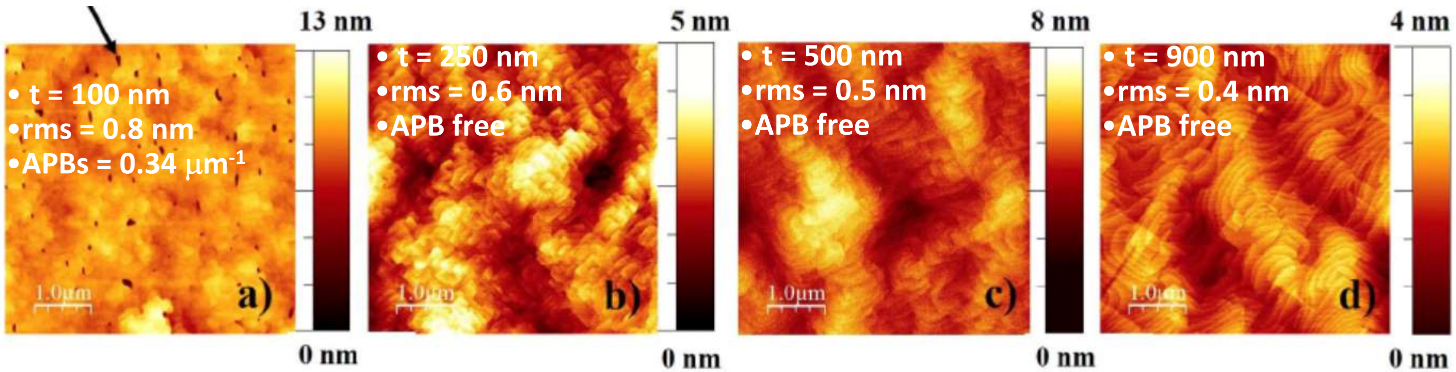
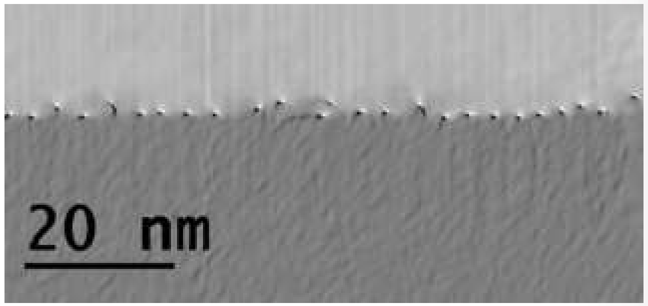
GaSb template grown on on-axis Si by MOVPE

Remote plasma de-oxydation + high temperature annealing under H_2 flow in a Si cluster-tool

→ ***Growth of smooth GaSb epilayers on 300 mm on-axis (001)-Si substrate***



- 0.11° miscut (001)-Si 300 mm substrate
- Low temperature nucleation layer (450 C)
- High temperature GaSb epilayer



- *90° dislocations array at the interface*

T. Cerba *et al.*, Thin Solid Films 645 (2018) 5 **(LTM, CNRS, CEA, University Grenoble Alpes)**

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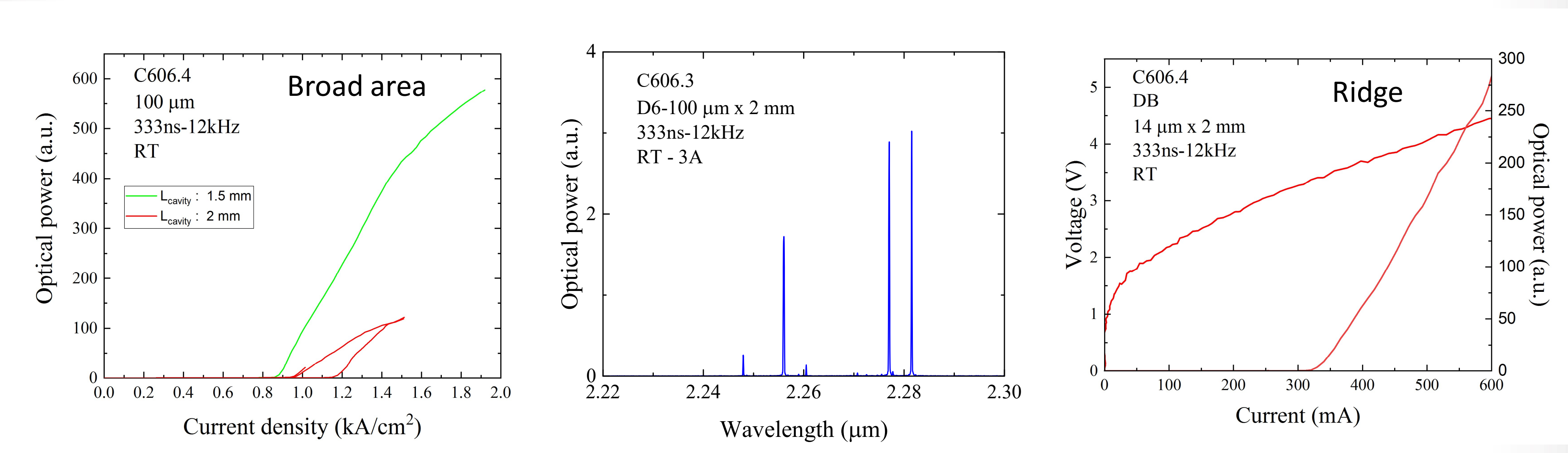
2.3-µm GaSb laser on MOVPE-GaSb/Si template



- Broad Area laser: J_{th} = 0.9 A/cm² (1.5 mm) – 1.2 kA/cm² (2 mm)
- Ridge (14 µm) laser: I_{th} = 325 mA under **pulsed operation**

No cw operation (yet)
Lower performances than on 6°off MBE templates
Under investigation!

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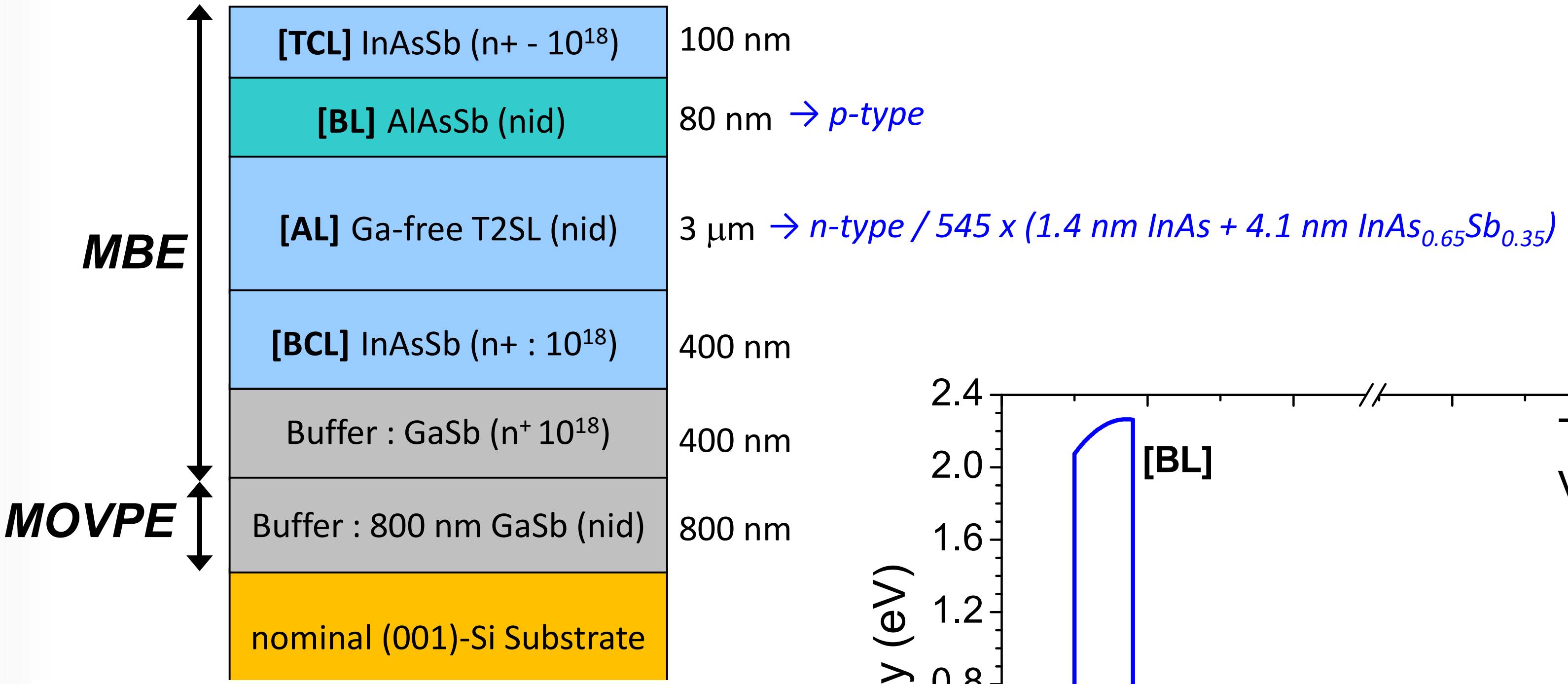
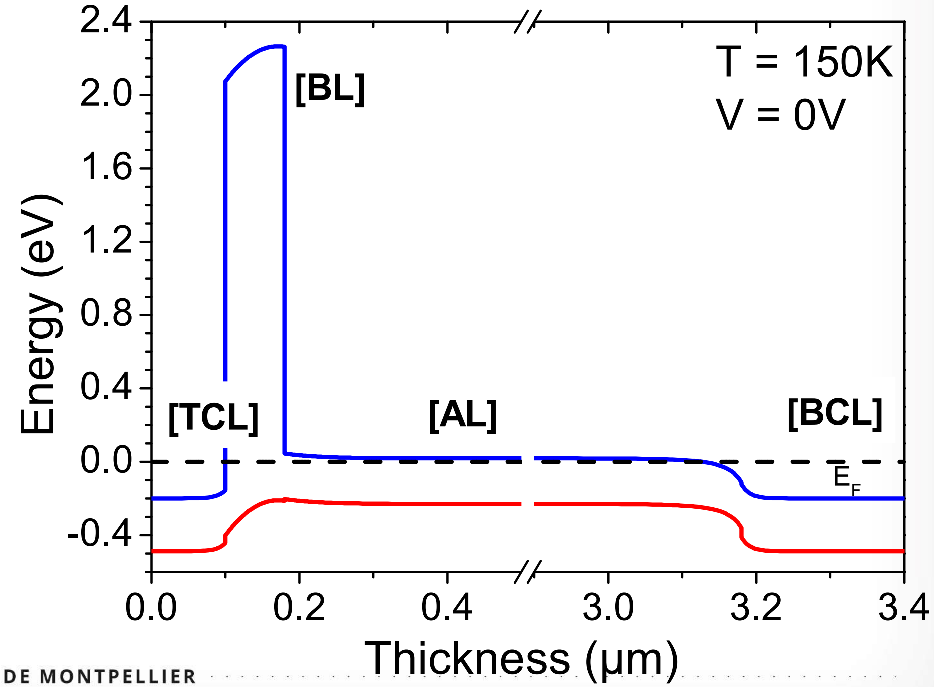
InAs/InAsSb type-II superlattice photodetector on MOVPE GaSb template



Stacking of the MWIR Ga-free T2SL barrier detector

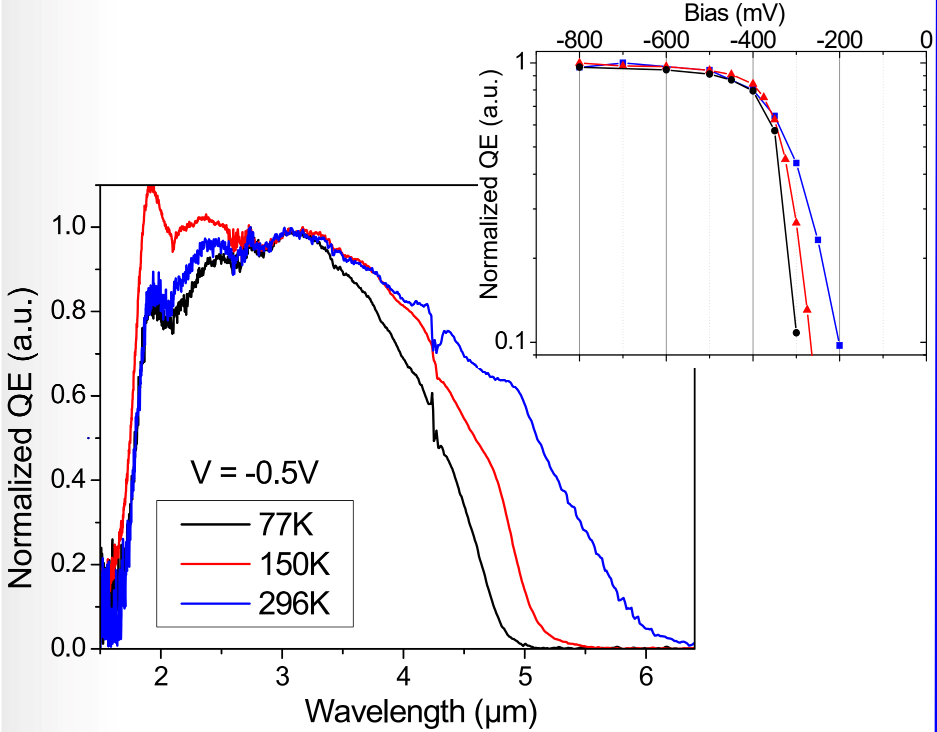


Band diagram @ 150 K and 0 V using ATLAS SILVACO

- *VBO ~ 10 meV between AL and BL*
- *thin depletion layer in the AL (AL: n-type, BL: p-type)*

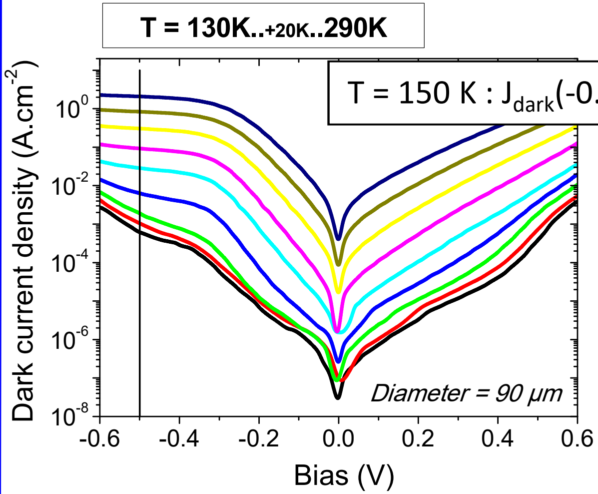
Results

Spectral responses :
(normalized @ 3 µm)



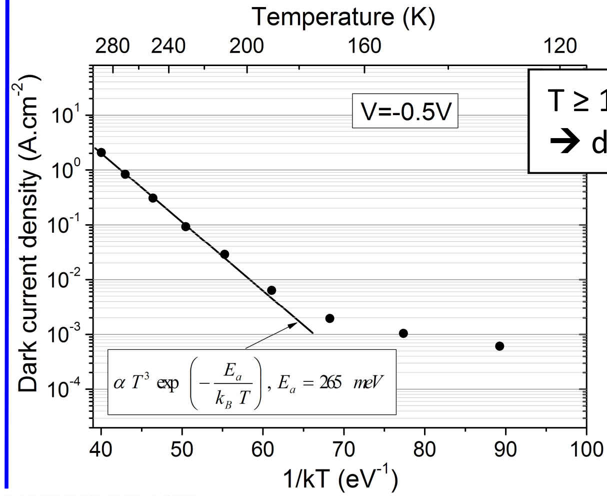
- QE saturates at V_{bias} = -0.5V
- λ_{co} = 4.7 µm @ 150 K
- calibrated QE to be measured

Dark current density :



T = 150 K : J_{dark}(-0.5V) = 1 x 10^{-3} A/cm^2

Arrhenius graph @ V_{bias} = -0.5V



T ≥ 190K : E_a = 265 meV
→ diffusion regime

Durlin *et al.*, IR Phys. Technol. 96 (2019) 29

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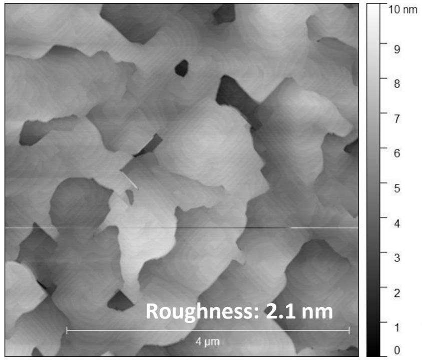
Toward on-axis Si: an AFM view

Improved Si-surface preparation and growth start

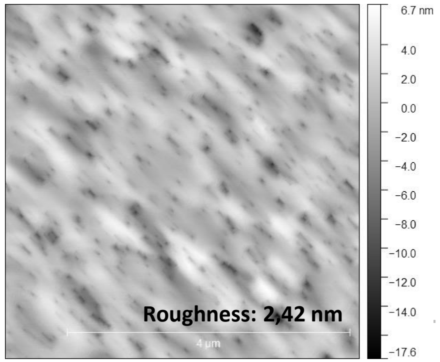
500 nm GaSb on Si

5 μm x 5 μm AFM pictures

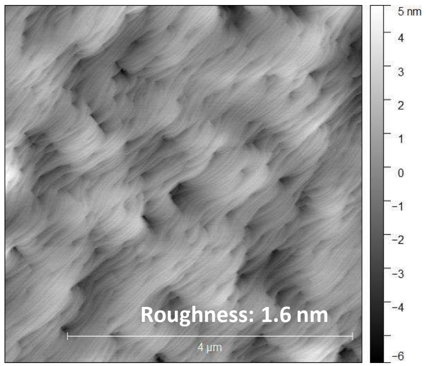
60% / 40 %



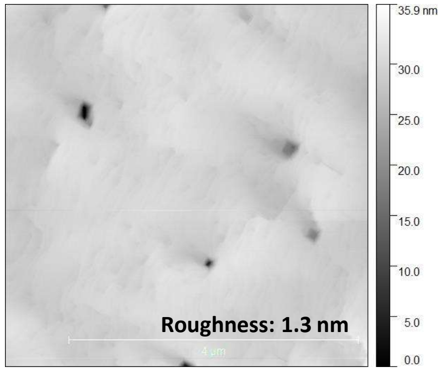
Silicon (001) tilted **6°**



Silicon (001) tilted **1°**



Silicon (001) tilted **0.5°**



APD free down to 0.5° miscut

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GaSb-based lasers on Si: summary

- Laser diodes grown on *off-cut* Si substrates
  - ➡ CW laser operation between 1.5 and 2.X µm
  - ➡ T_{max} > 35 °C, T_0 ~ 50 K, P_{max} = 3 – 10 mW/uncoated facet
  - ➡ J_{th}(Si) ~ 3 – 5 x J_{th}(GaSb)
- First-ever demonstration of QCL grown on *off-cut* Si substrates
  - ➡ InAs/AlSb QCL design (vertical transition) for λ ~ 11 µm
  - ➡ Similar performances on Si and InAs substrates
- Preliminary results on *on-axis* Si substrates (MOVPE template)
  - ➡ Pulsed operation of lasers diodes
  - ➡ InAs/InAsSb type-II superlattice photodetectors
- Anti-phase-domain free GaSb MBE-templates

GaSb-based lasers on Si: what's next?

- Devices on on-axis MBE templates
- Dislocation filtering
- Optimized device design and technology

Future

A complete IR optoelectronics toolbox integrated on Silicon

GaSb ⇨

- **1.5 – 3 µm laser diodes**
- **3 – 5 µm ICLs**
- **3 – 25 µm QCLs**
- **photodetectors**

Development of a variety of Mid-IR integrated sensors

Thank you for your attention!