InAs/AlSb quantum-cascade lasers grown on Silicon

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OUTLINE

- InAs/AlSb quantum cascade lasers: properties
- Integration on Si: motivations
- Molecular-beam epitaxy on Si
- Laser properties
- Summary – Perspectives

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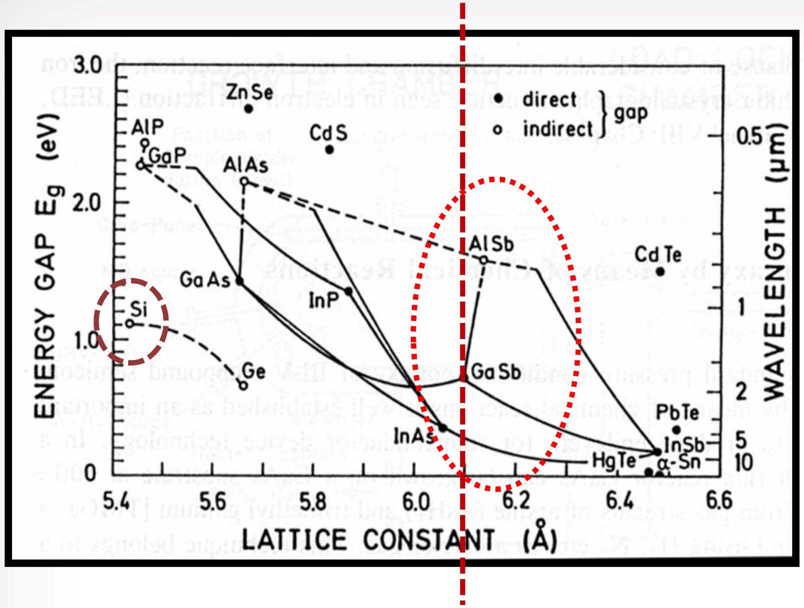
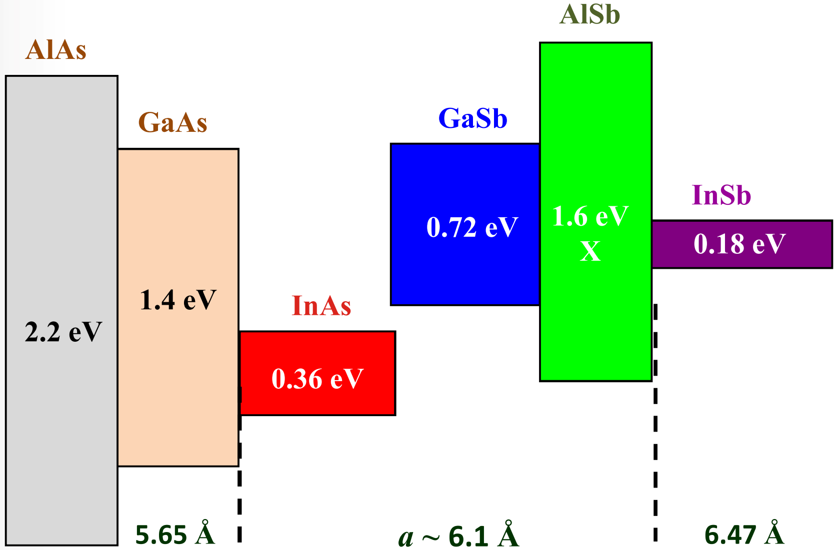




Antimonide compound semiconductors

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

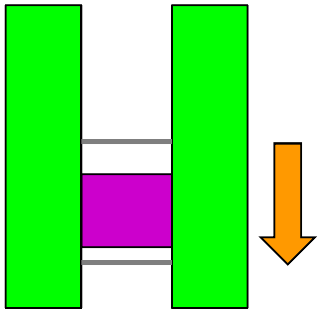
☞ ***Unrivalled band structure engineering***

☞ ***Mismatch with Si ~12%***

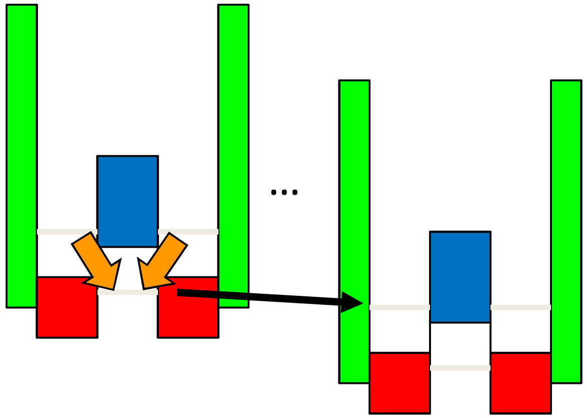
III-Sbs: perfectly suited for the IR wavelength range

Sb-based IR devices

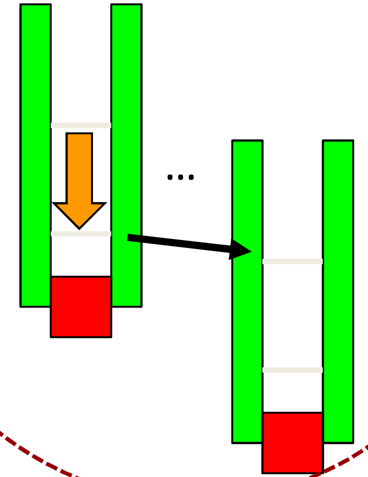
QW Lasers
GaInAsSb/AlAsSb



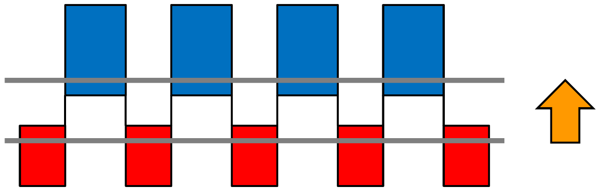
Interband Cascade Lasers
InAs/GaSb/AlSb



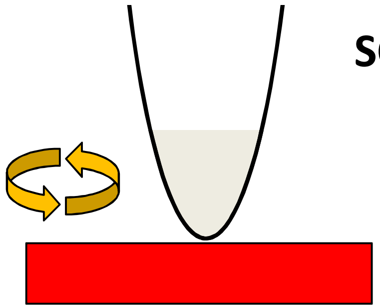
Quantum Cascade Lasers
InAs/AlSb



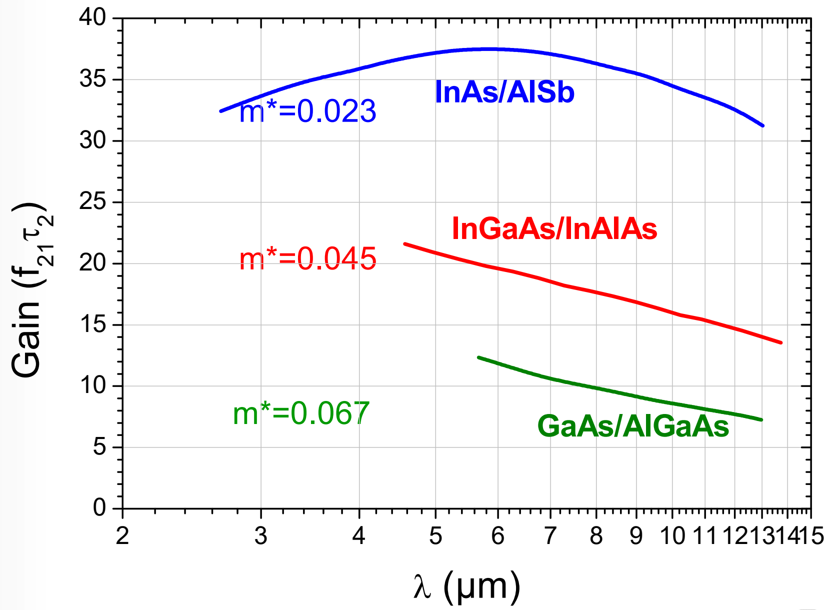
Type II SL Detectors
InAs/GaSb (or InAs/InAsSb)



SC Plasmonics
InAs(Sb)

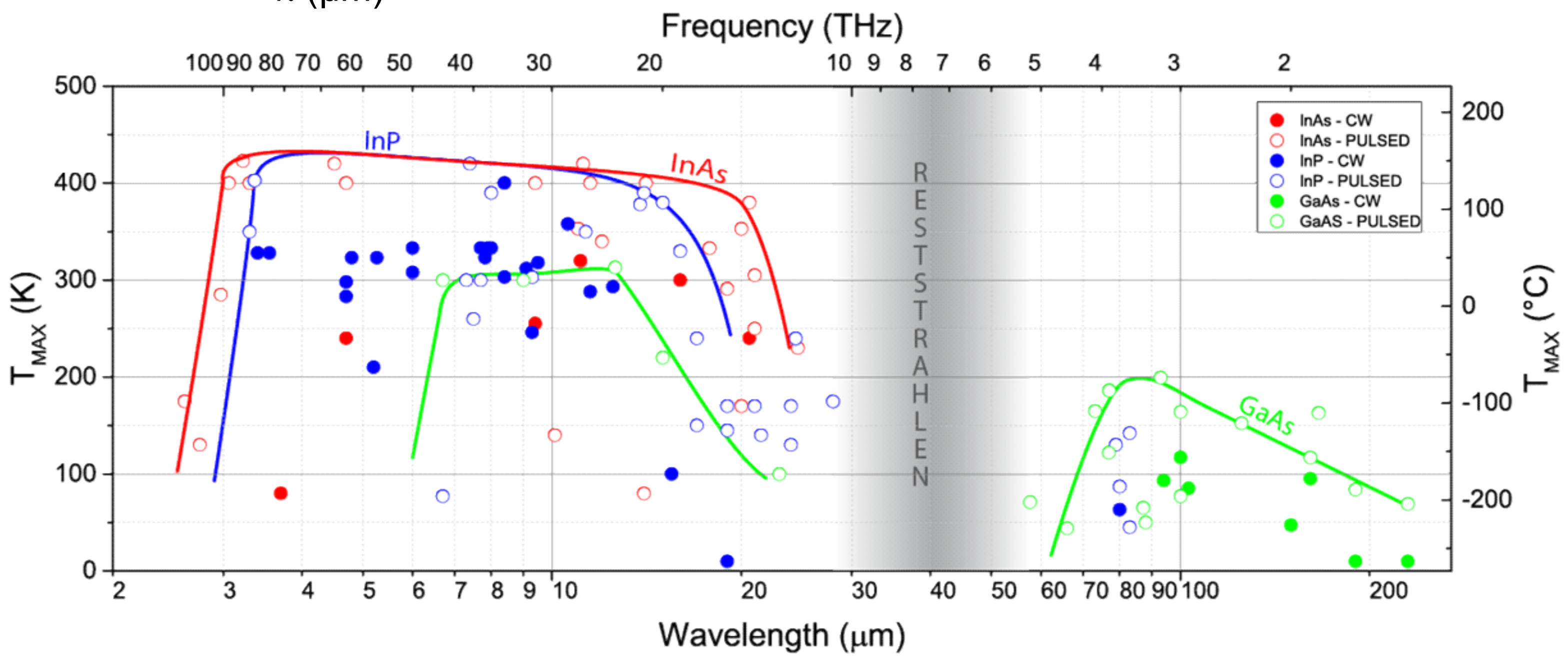


InAs/AlSb: very good intrinsic properties for QCLs

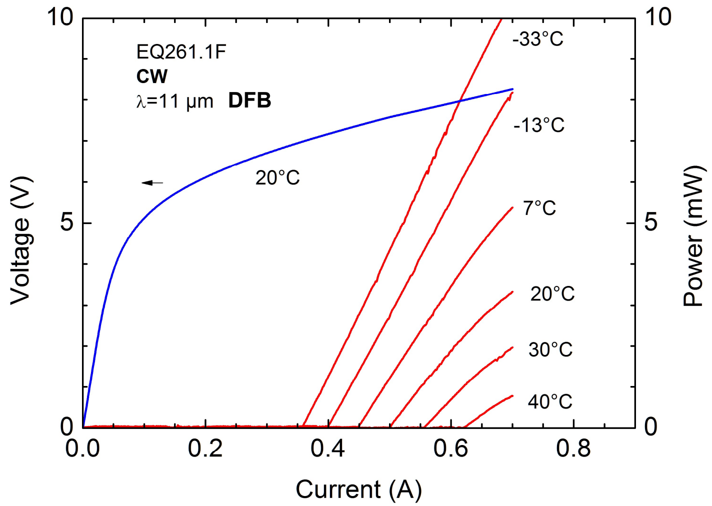


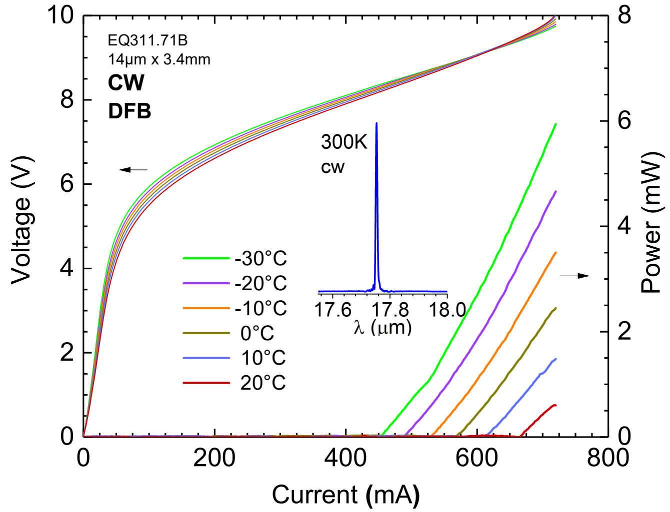
Gain in QCL

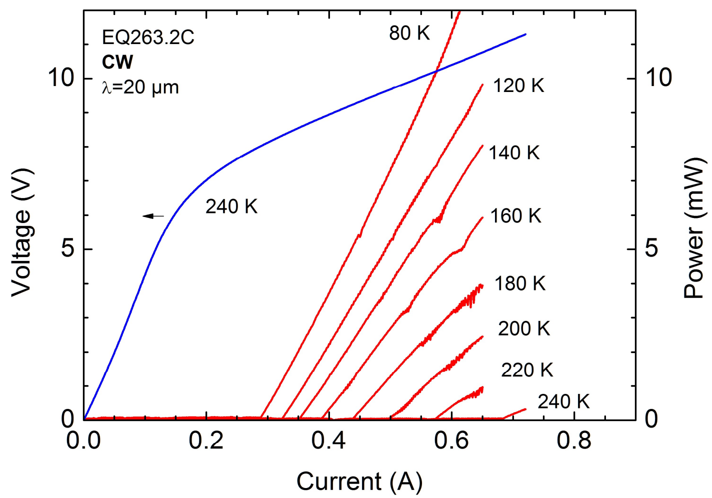
$$g\ \alpha\ \frac{1}{m*^{3/2}}$$



Long wavelength InAs/AlSb QCLs: state of the art







T_{max} continuous wave

40°C at λ = 11 µm

20°C at λ = 15-18 µm

-30°C at λ = 20 µm

J_{th} ~ **1 kA/cm² at RT**

λ_{max} **25.5 µm (pulsed)**

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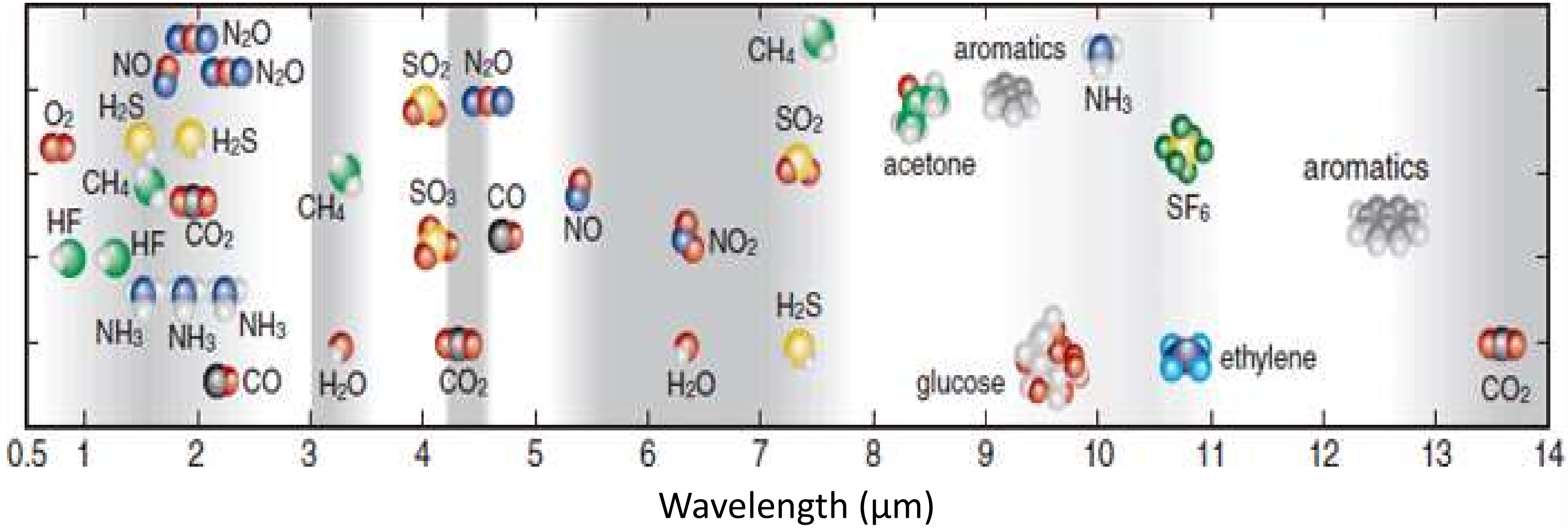
The sensing challenge

www.daylightsolutions.com



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.

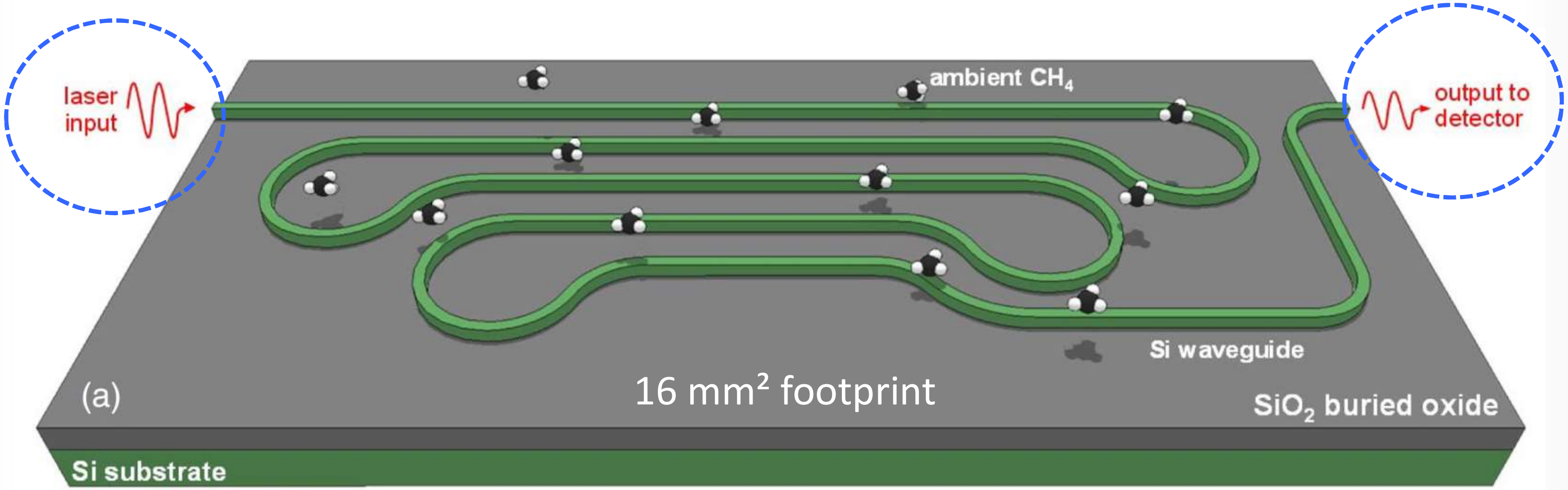
Increasing demand for low-cost, small footprint, smart, photonic sensors.

The sensing challenge

Methane absorption spectroscopy on a silicon photonic chip

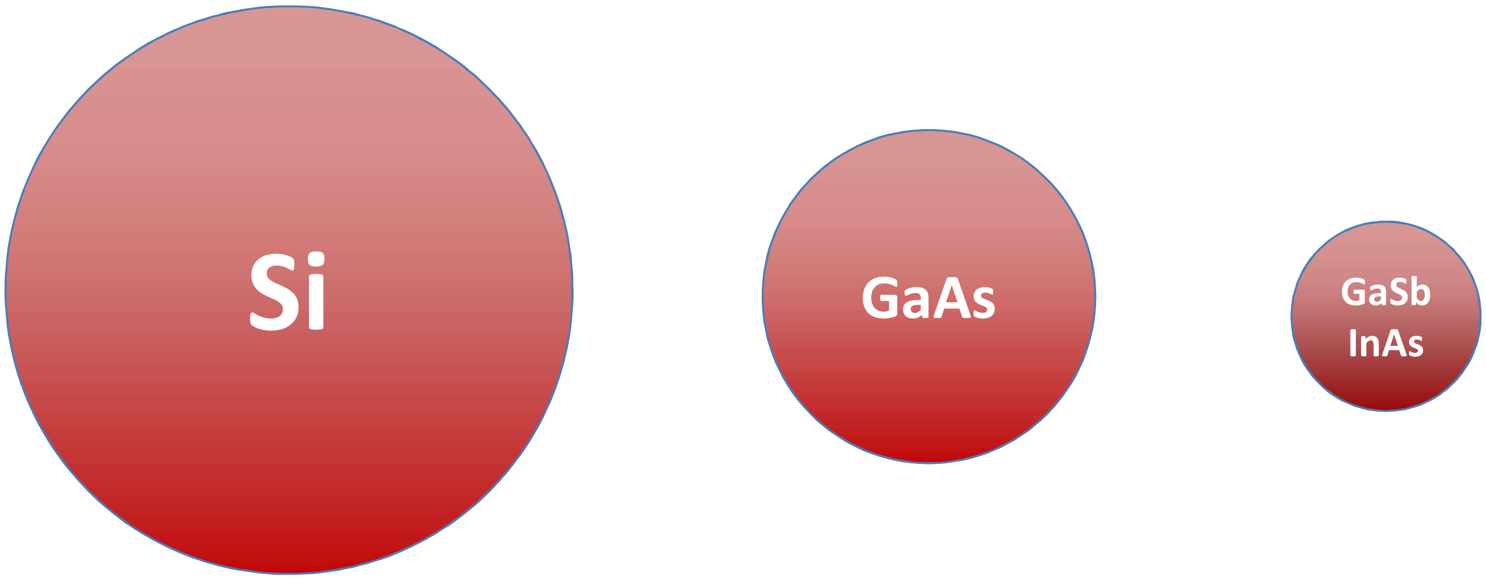
Tombez *et al.*, IBM TJ Watson Res. Center

Vol. 4, No. 11 / November 2017 / *Optica* 1322



Need for integrated opto devices

The substrate challenge



	Si	GaAs	InP	GaSb/InAs
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

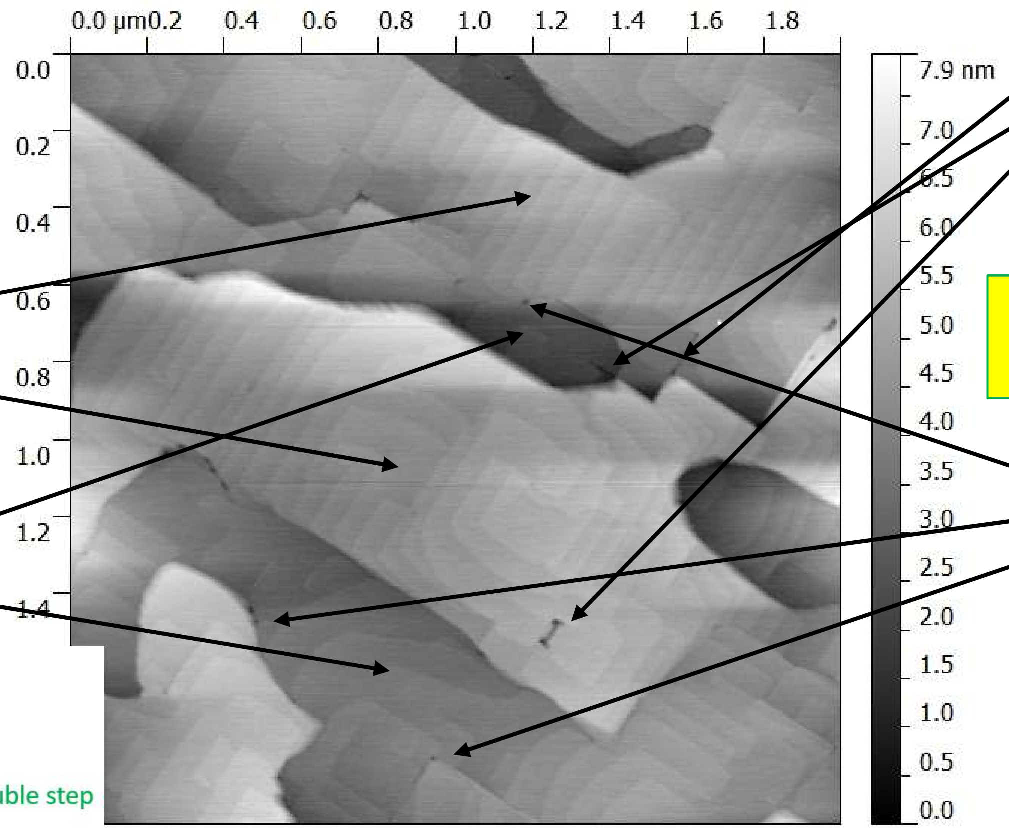
Twins

- Surface preparation
- Growth conditions

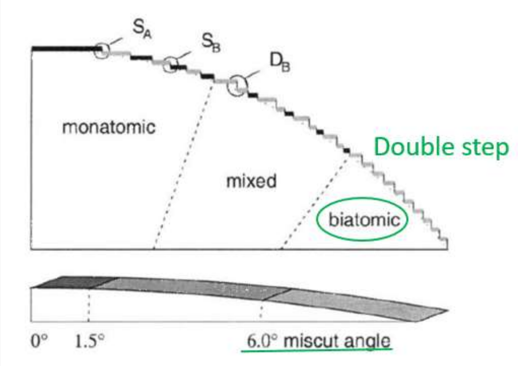
Domain 1

Antiphase boundaries

Domain 2



Dislocations



An AFM view

- Nucleation
- Buffer-layer engineering

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

Si substrates

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

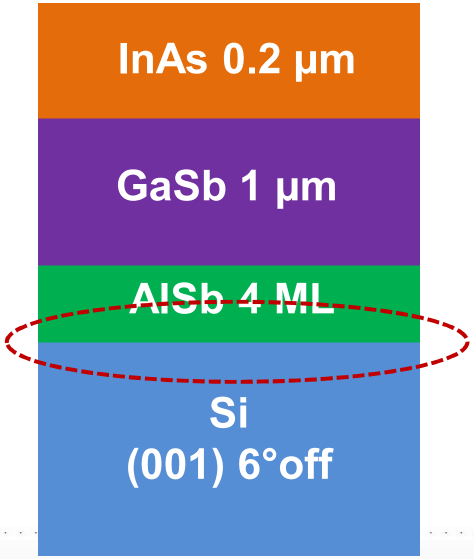
Standard III-V molecular-beam epitaxy (MBE) reactor

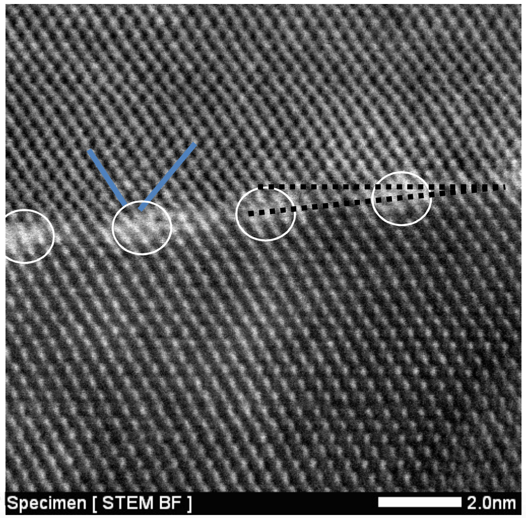
- Solid-source MBE with load-lock chamber
- Valved-cracker cells for As and Sb
- Standard group-III effusion cells
- $T_{substrate}$ < 850 °C

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

InAs/GaSb on Si templates

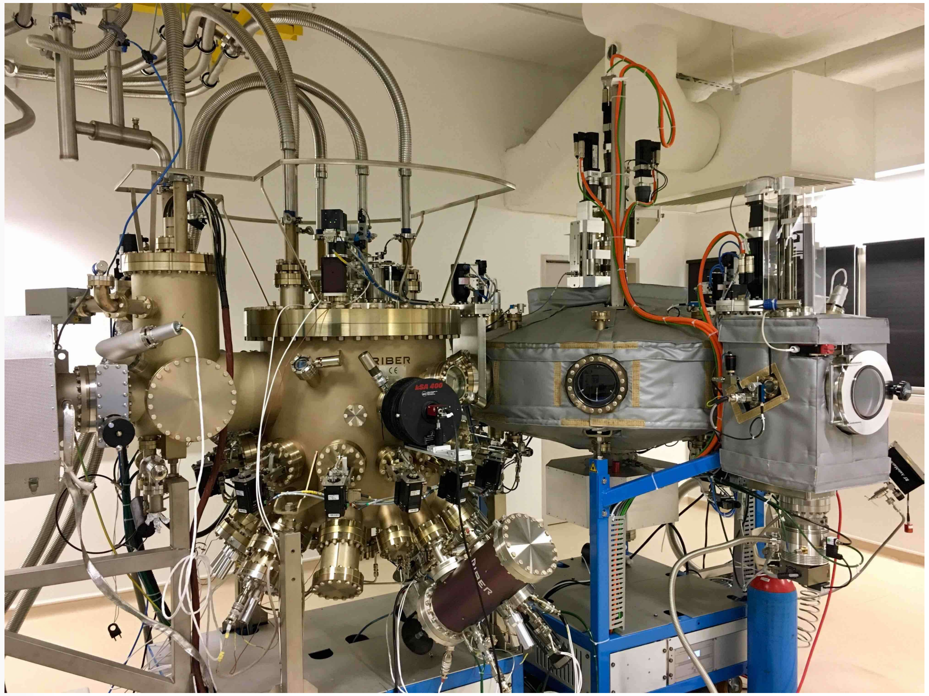
- 4 – 6° off (001)Si
- *Ex-situ* O_2 Plasma + HF Si preparation cycles
- *In-situ* annealing at 800°C
- 4 MLs AlSb @ 450°C
- ~ 1 µm GaSb buffer layer
- 200 nm InAs





TEM image: A. Trampert, PDI-Berlin

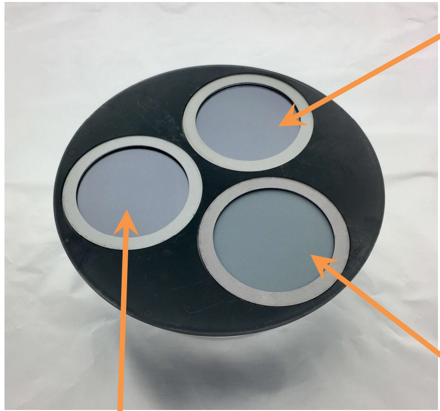
MBE growth



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

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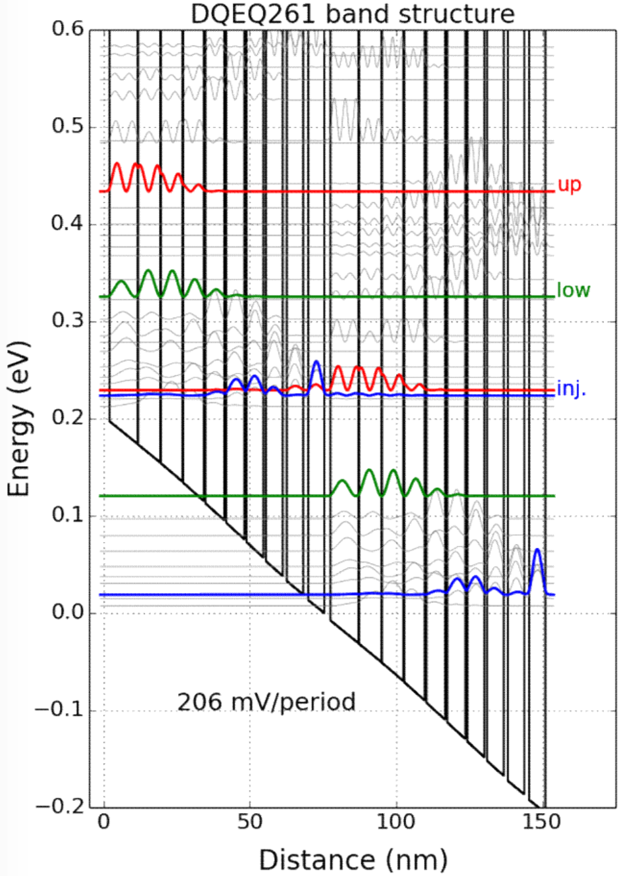
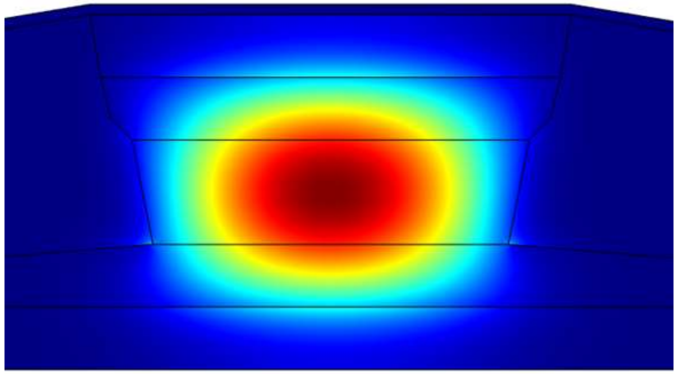
QCL structure

Design



Four quantum wells
Vertical transitions

Waveguide



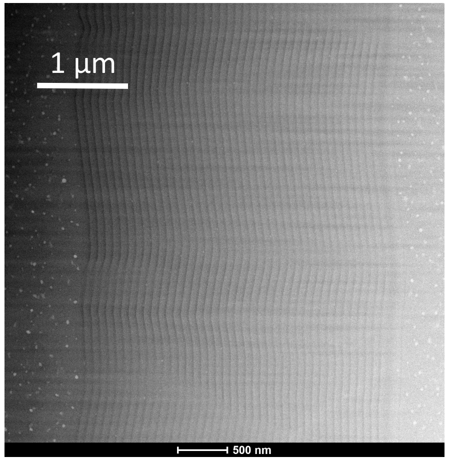
Cladding n^+InAs	**2 µm**
Spacer n-InAs	**2.5 µm**
QCL active region	**3 µm**
Spacer n-InAs	**2.5 µm**
Cladding n^+InAs	**2 µm**

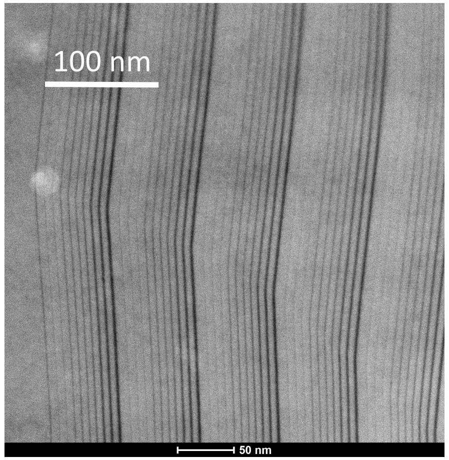
Substrate n-InAs OR InAs/GaSb/Si template

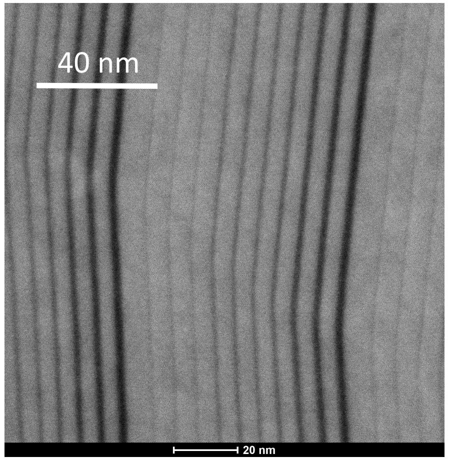
Γ = 0.56

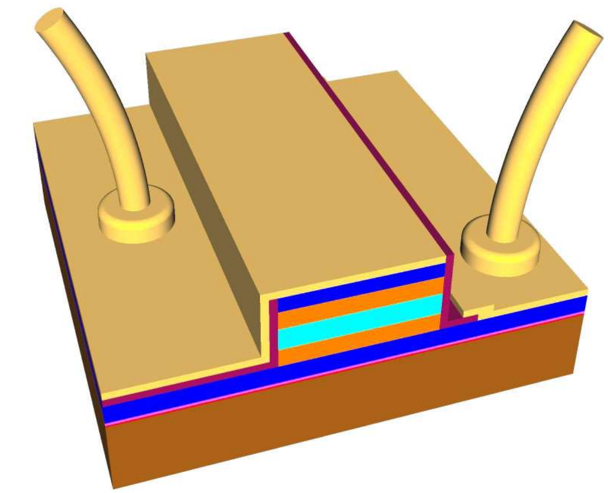
Designed to emit at 11 µm

InAs/AlSb QCL on Si

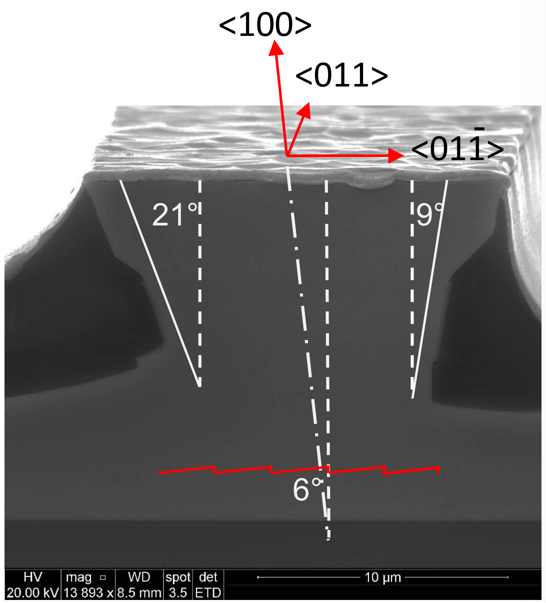




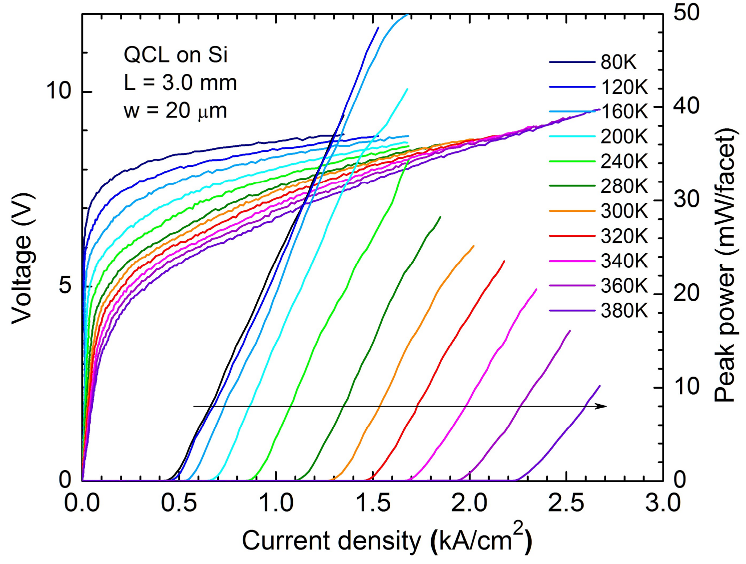


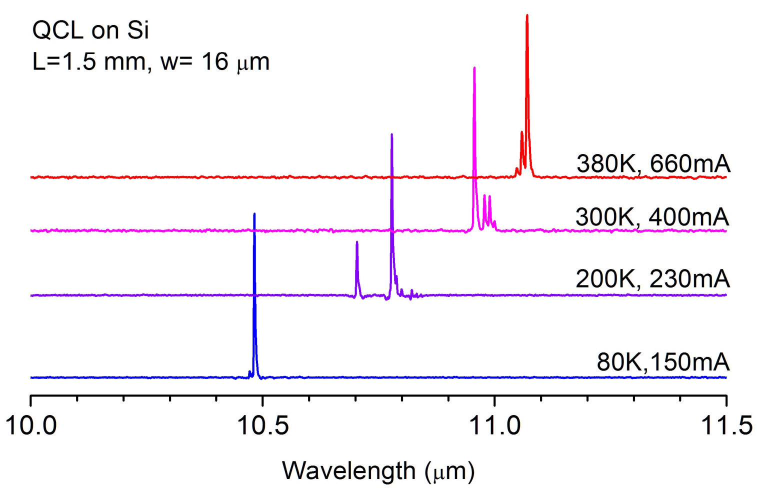


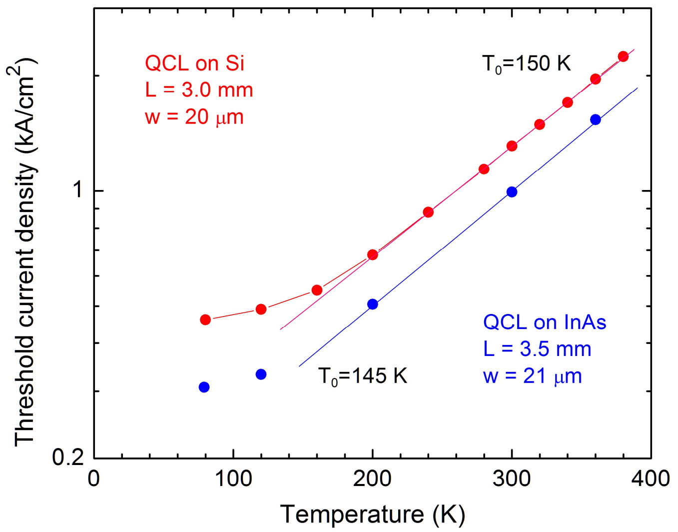
- Au contacts
- hard baked photoresist
- n^+-InAs top cladding
- nid-InAs top spacer
- InAs/AlSb active zone
- nid-InAs bottom spacer
- n^+-InAs bottom cladding
- GaSb template
- Si substrate



InAs/AlSb QCL on Si



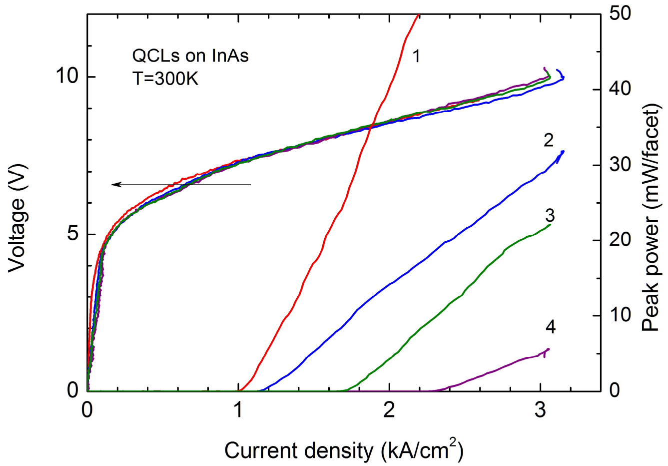


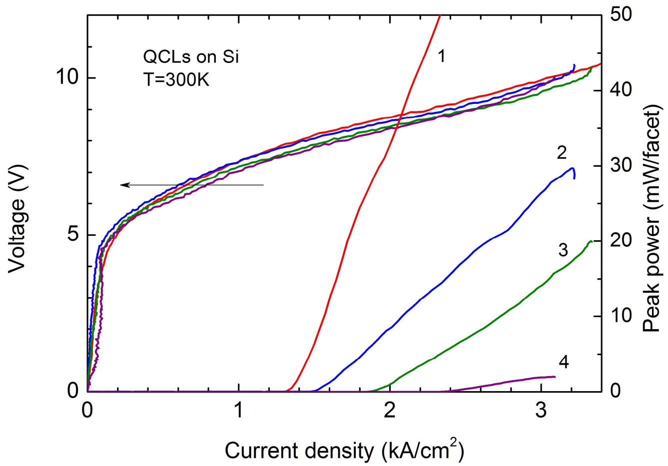


First-ever report of a QCL grown on Si

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

InAs/AlSb QCL on Si





InAs substrate:

1. L = 3.5 mm, w = 21 µm
2. L = 2.3 mm, w = 14 µm
3. L = 1.2 mm, w = 17 µm
4. L = 0.7 mm, w = 17 µm

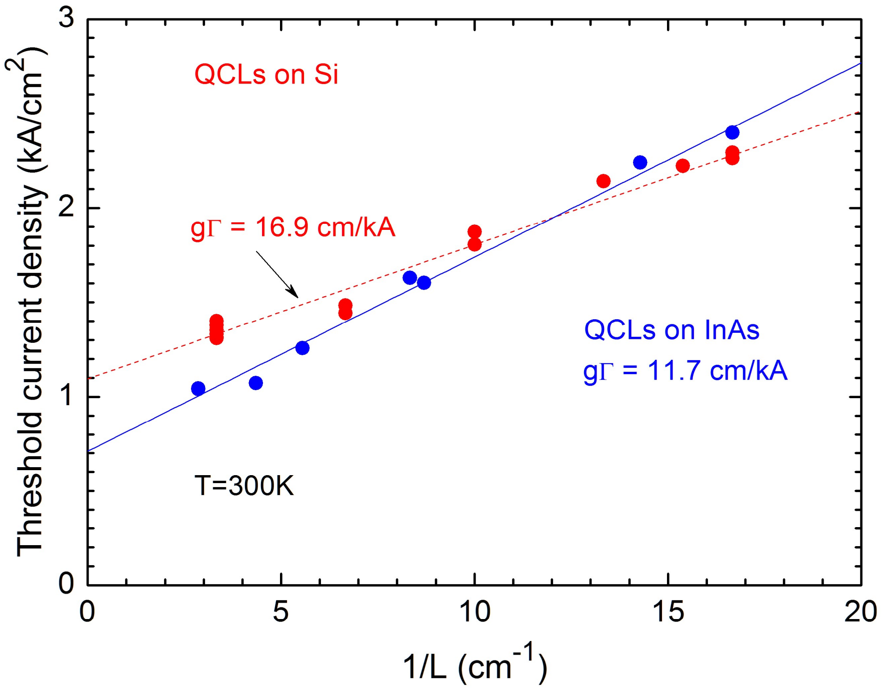
Si substrate:

1. L = 3.0 mm, w = 20 µm
2. L = 1.5 mm, w = 16 µm
3. L = 1.15 mm, w = 15 µm
4. L = 0.6 mm, w = 14 µm

Performances are similar on InAs and on Si substrates!!!

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

QCLs on Si *vs* QCLs on InAs



$$J_{th} = J_{tr} + \frac{(\alpha_w + \alpha_m)}{\Gamma g}$$

$$J_{th} = J_{tr} + \frac{\alpha_w}{\Gamma g} - \frac{\ln(R)}{\Gamma g}\frac{1}{L}$$

QCL on InAs

$g\Gamma$ = 12 cm/kA

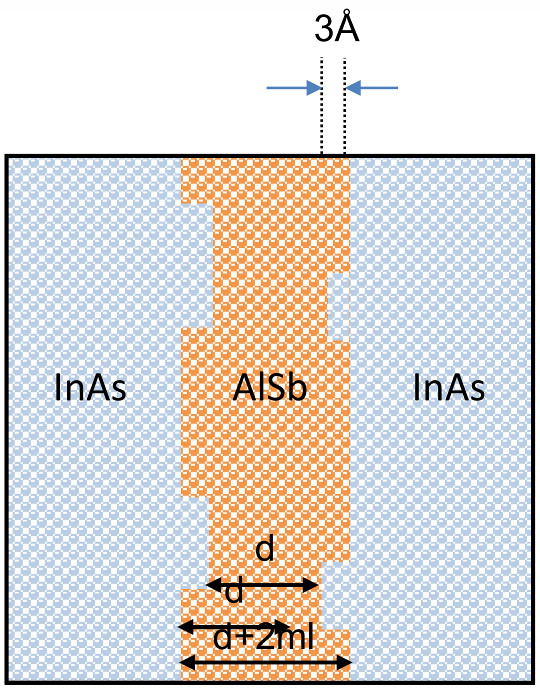
QCL on Si

$g\Gamma$ = 17 cm/kA

Γ = 0.56 optical confinement

Higher gain in QCLs grown on Si

QCLs on Si – why so good?



On-axis perfect interfaces: 1 ML (3Å) roughness

Step flow growth on 6°-off substrate

$$g = \frac{e\hbar}{\varepsilon_0 c m_0} \frac{1}{2\boldsymbol{\gamma_{32}} n L_p} f_{32} \boldsymbol{\tau_3} \left(1 - \frac{\tau_2}{\tau_{32}}\right)$$

$\boldsymbol{\tau_3}$ upper level lifetime

$\boldsymbol{\tau}_3$ = 0.42 ps (LO-phonon emission)

$$\frac{1}{\boldsymbol{\tau_3}} = \frac{1}{\tau_{32}} + \frac{1}{\tau_{31}} + \frac{1}{\boldsymbol{\tau_i}}$$

high barriers ➔ strong interface recombination

$$\frac{1}{\tau_i} \sim (\Delta E_c)^2$$

$\boldsymbol{\tau}_3$ = 0.3 ps with interface scattering

Low interface scattering due to misoriented substrate

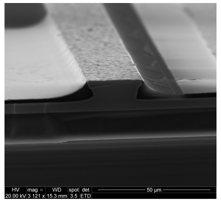
OUTLINE

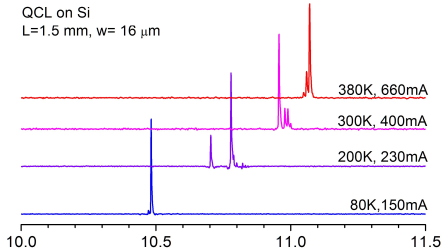
Summary

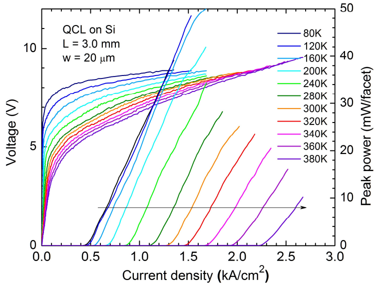
Quantum cascade laser is a very robust technology

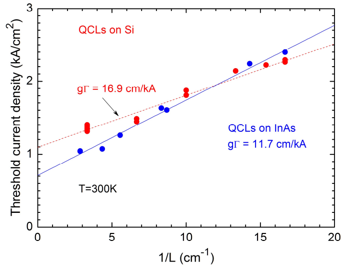
First quantum cascade lasers grown on silicon

- **λ = 11 µm**
- **Low threshold : 1.3 kA/cm^2**
- **High temperature operation: 400K**
- **No significant performance degradation**
- **InAs/AlSb QCLs: from 3 to 25 µm**









Perspectives

- Further work on templates, toward on-axis substrates
- 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**

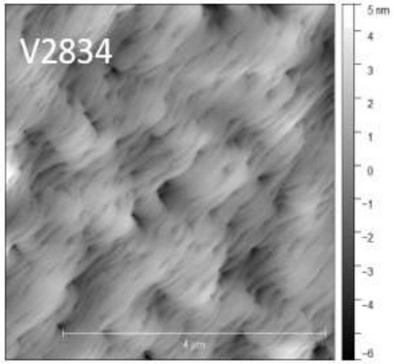
Development of a variety of Mid-IR integrated sensors

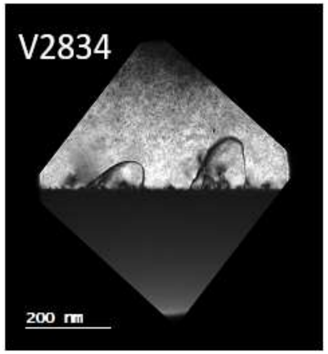
Toward on-axis Si: an AFM view

500 nm GaSb on 0.5° offcut (001) Si

5 x 5 µm² AFM images + TEM

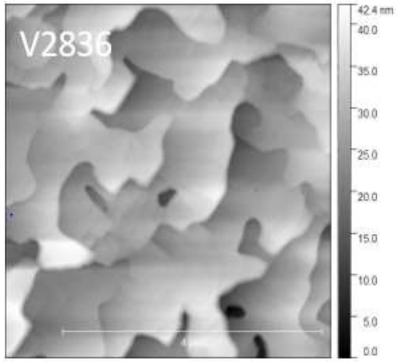
Improved template

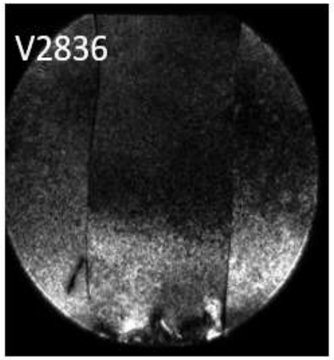




APD free

Original template





60%/40% domain distribution

APD free down to 0.5° miscut

Aknowledgments

Equipex EXTRA

ANR-11-EQPX-0016

FEDER – *grants 47851 & 49793*

Thank you for your attention!