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PHOTONICS RESEARCH GROUP

Near/Mid-Infrared Heterogeneous Si Photonics

Zhechao Wang, PhD

Photonics Research Group – Ghent University / imec , Belgium

ICSI-9, Montreal

Outline

- Ge-on-Si platform
  - Passive components for Mid-Infrared applications
  - Active components
- InP-on-Si platform
  - Nanowire laser configuration
  - Classic laser configuration
- Conclusion

Acknowledgement

Ge on silicon

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Dr. Aditya Malik

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Muhammad Muneeb

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InP on silicon

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Dr. Clement Merckling

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Dr. Marianna Pantouvaki

Dr. Weiming Guo

Bin Tian

European Research Council

Established by the European Commission

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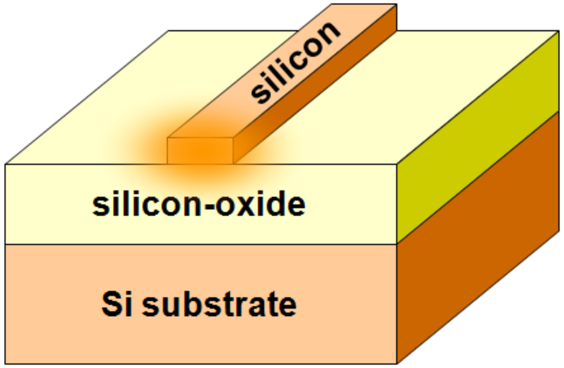
Established by the European Commissic

FWO VLAANDEREN

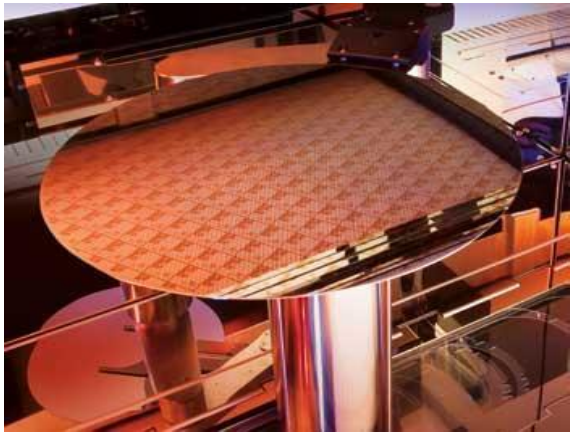
Optical I/O, imec

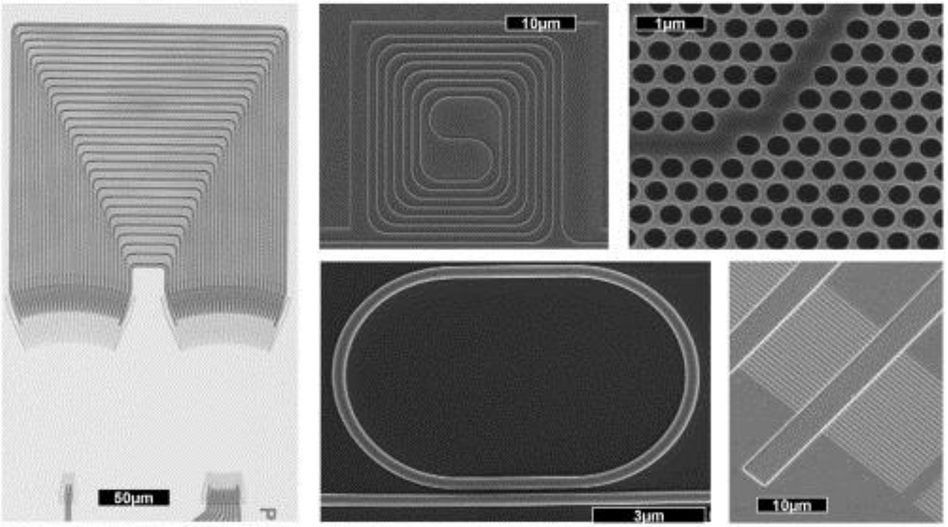
Silicon photonics

- CMOS fabrication technology (200mm/300mm)
- Cost and size reduction of photonic integrated circuits
- High performance passive devices



- Limited transparent wavelength window
- Lack of light sources
- Relatively poor active device performance





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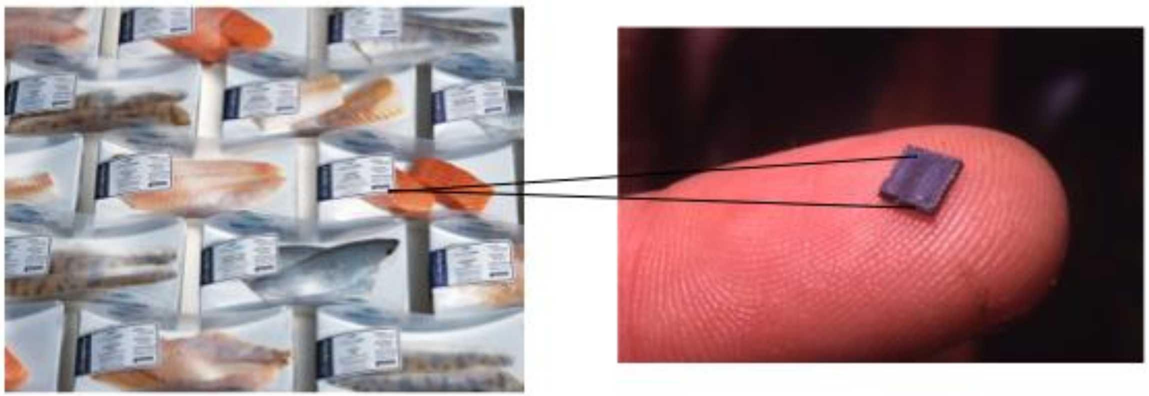
Si Photonics Applications

Mainstream applications: optical interconnect / telecom / biosensors @1.3um,1.55um wavelength

Spectroscopic systems could benefit from PICs at longer wavelength

- Most molecules have strong absorption lines in the SWIR/MWIR
- Make systems cheaper, smaller, more light weight, more robust
- Target liquid and gas SWIR/MWIR spectroscopic sensors

Continuous Glucose Monitoring

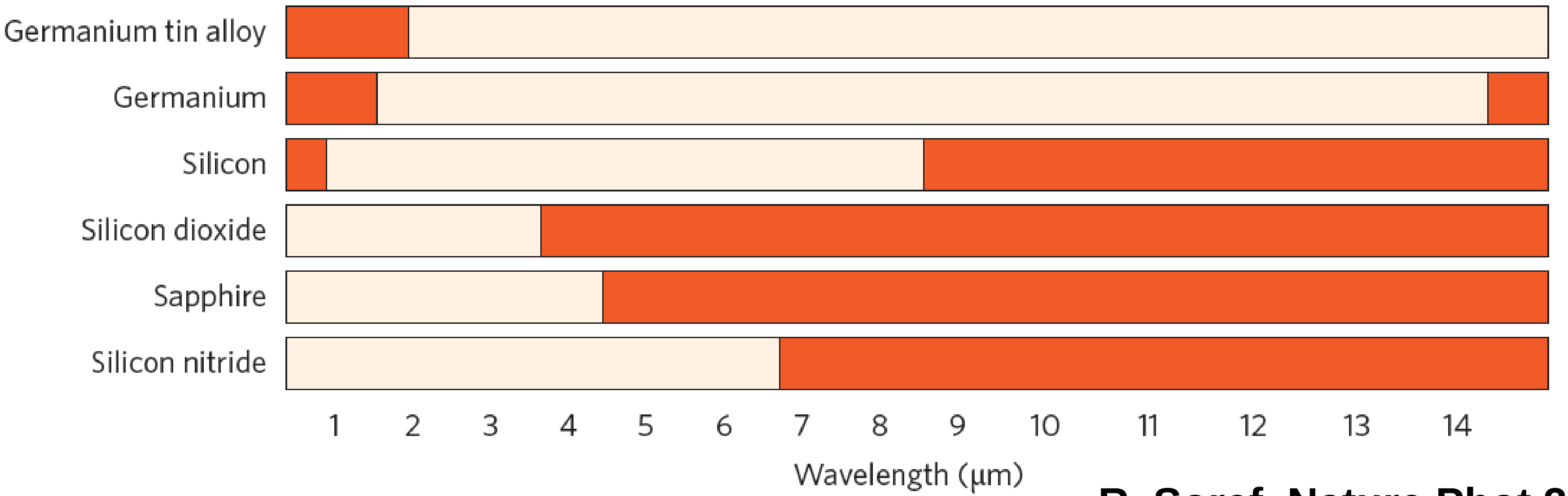


Food spoilage indication

Silicon-based photonic integrated circuits

Transparency windows of materials

- Silicon-on-Insulator can be used up to 4µm (above: absorption of SiO_2)
- For longer wavelengths: use
  - Ge on Silicon
  - Silicon-on-Sapphire
  - Free-standing silicon

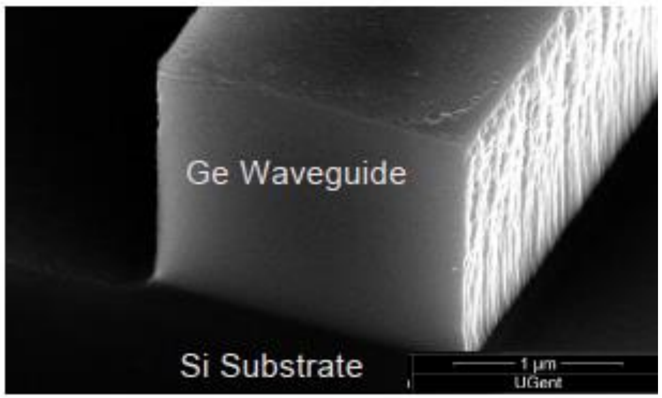


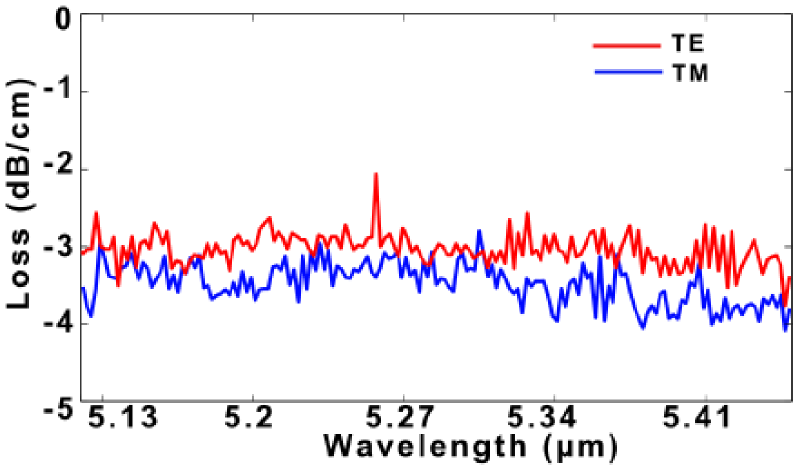
R. Soref, Nature Phot 2013

Silicon-based waveguide structures beyond 4um

Germanium-on-silicon waveguide structures

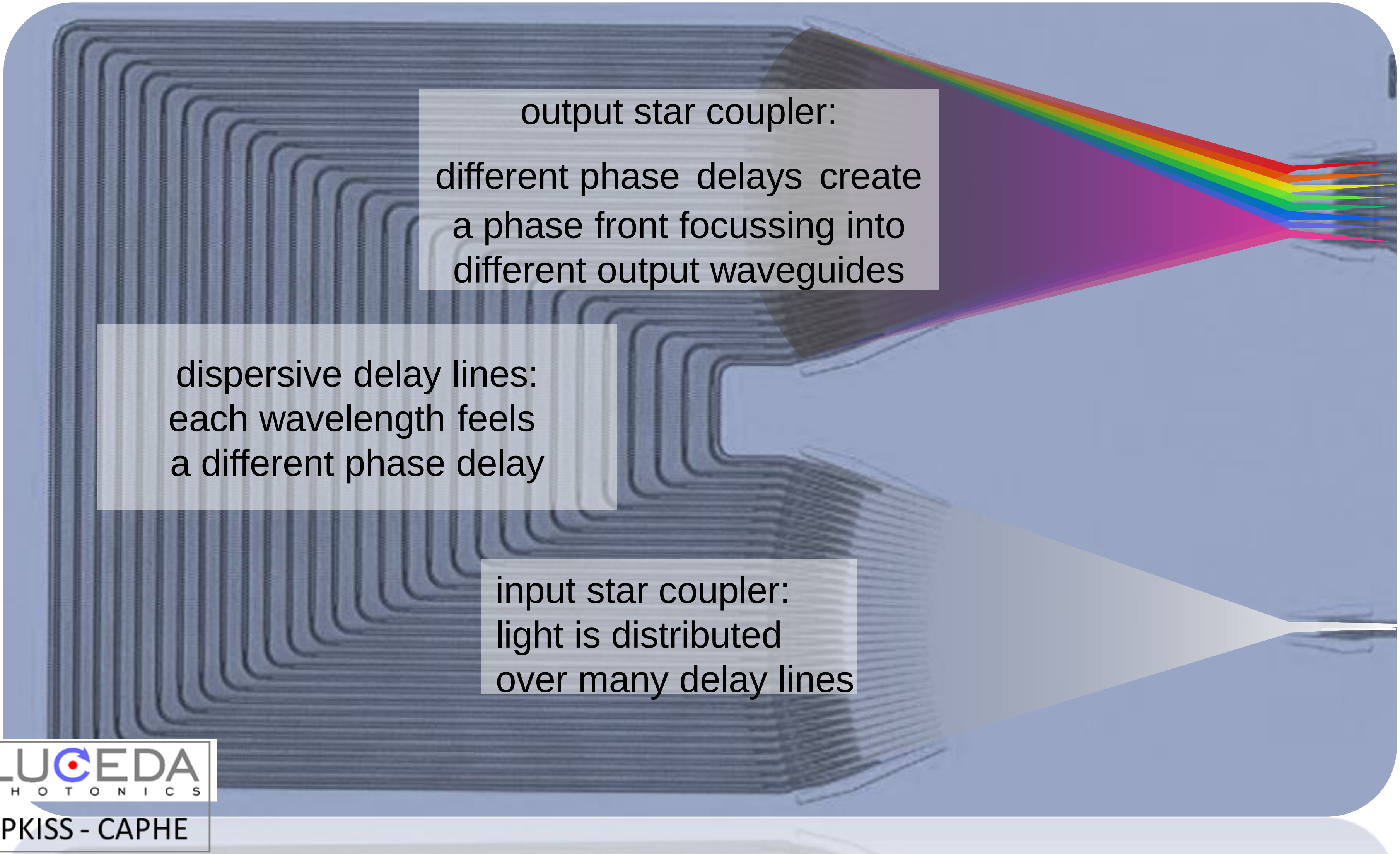
- Epitaxial growth of 2um thick Ge (n=4) on Si (n=3.5)
- Annealing required to reduce the threading dislocation density
- Germanium is transparent up to 14um
- Low waveguide losses in the 5-5.5um wavelength range demonstrated
- Basic components such as arrayed waveguide gratings and planar concave gratings demonstrated



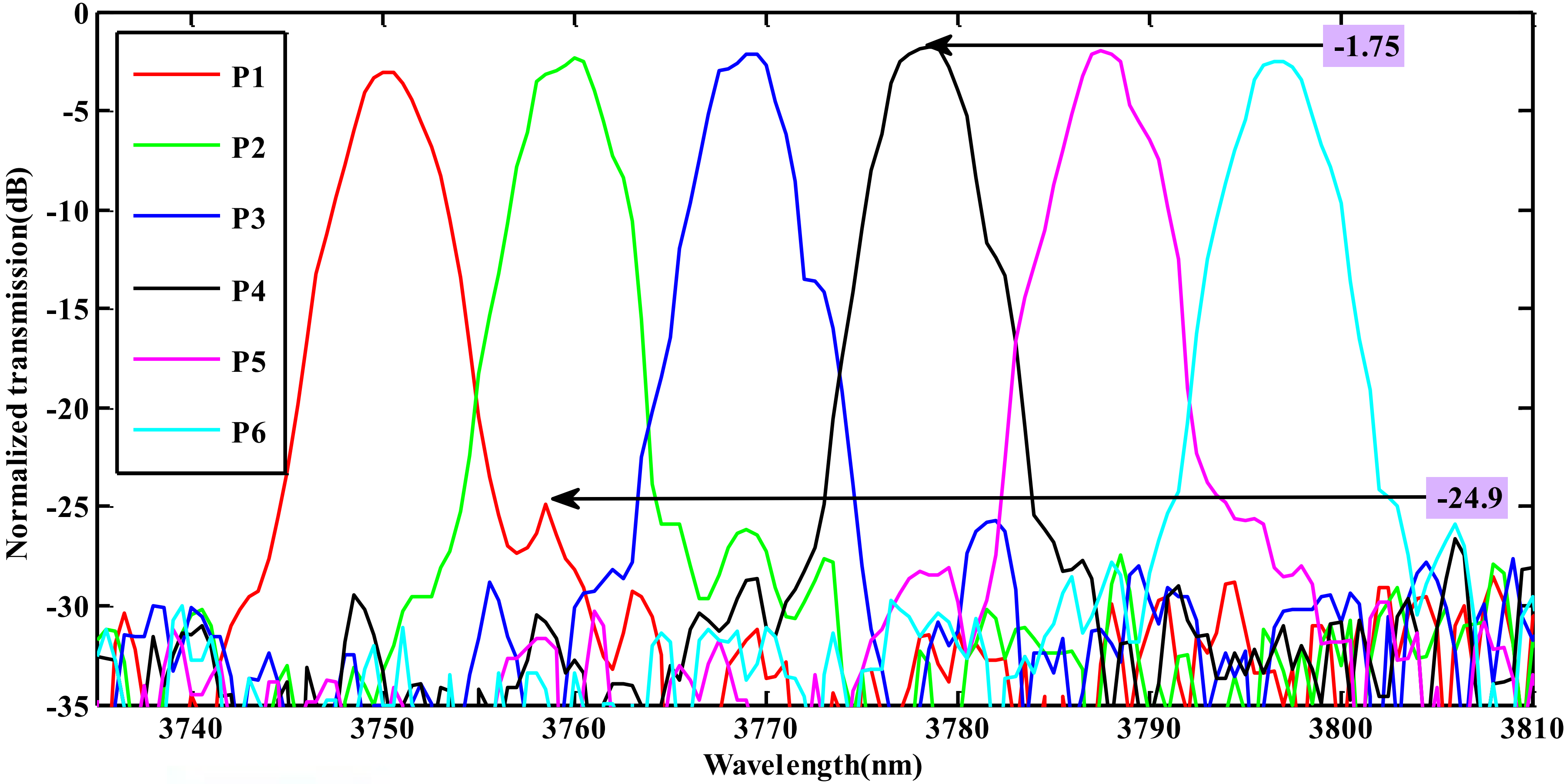


A. Malik et al., PTL 2013

Arrayed waveguide grating spectrometers



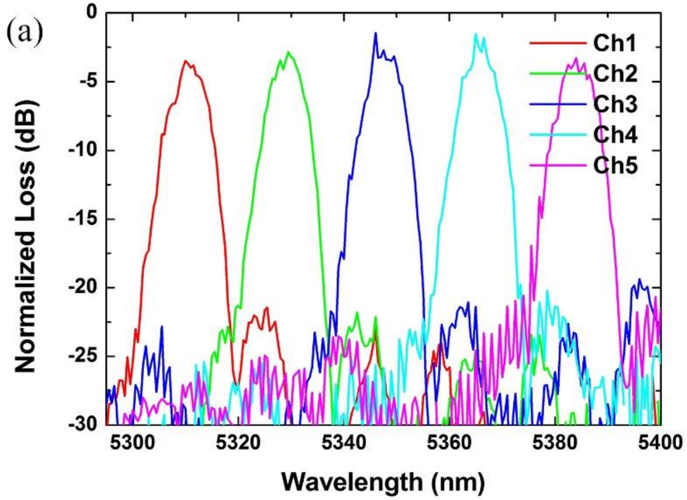
MWIR SOI spectrometers

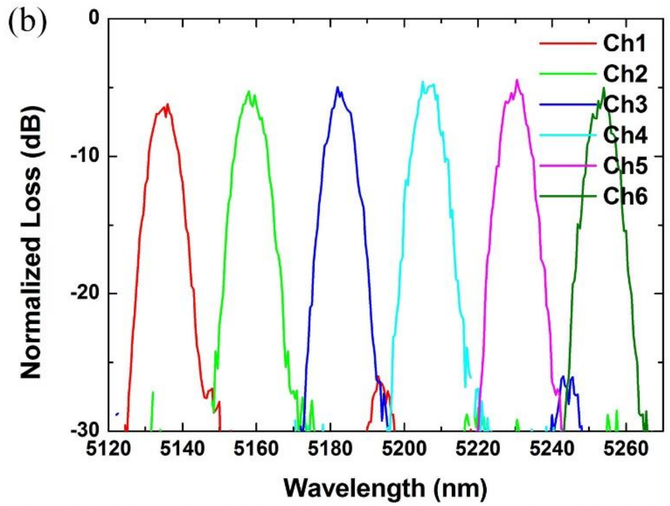


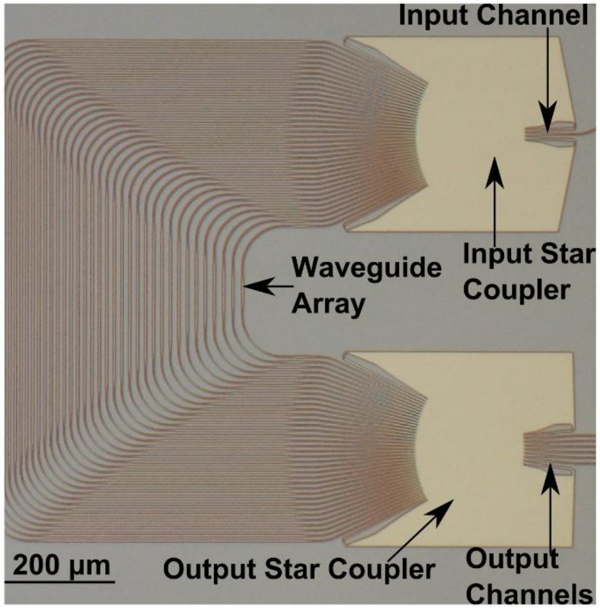
UNIVERSITY OF Southampton

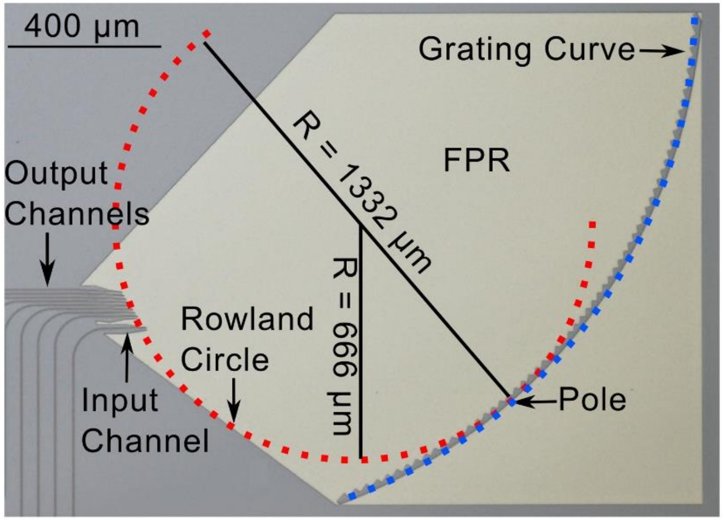
M. Muneeb, Optics Express 2013

5.x um Germanium-on-Silicon spectrometer









A. Malik, Applied Physics Letters 2013

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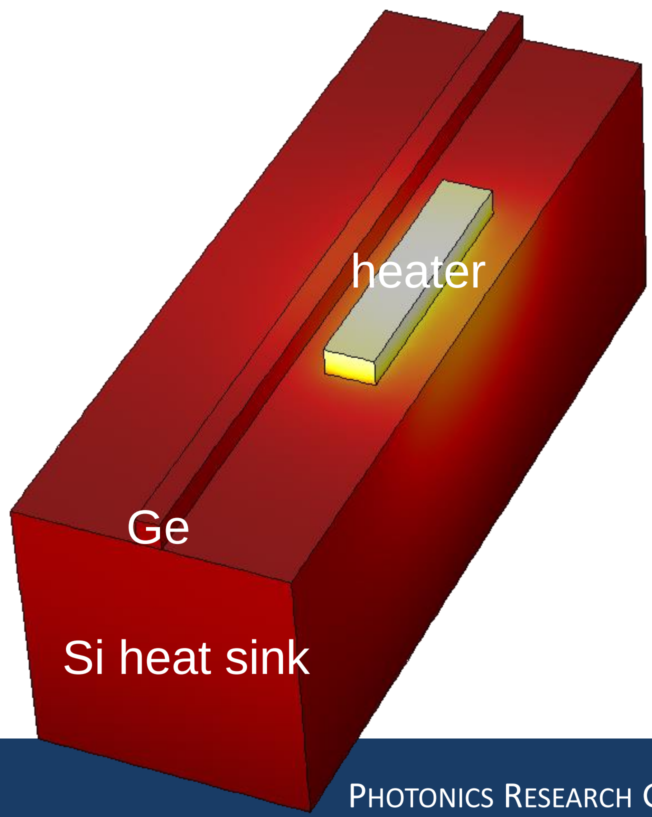
Tuning of mid-infrared waveguide circuits

Thermo-optic tuning:

- well developed on SOI waveguide circuits
- low power consumption (few mW for π phase shift)
- Efficiency on Germanium on Silicon waveguide circuits?



350mW power consumption for π phase shift

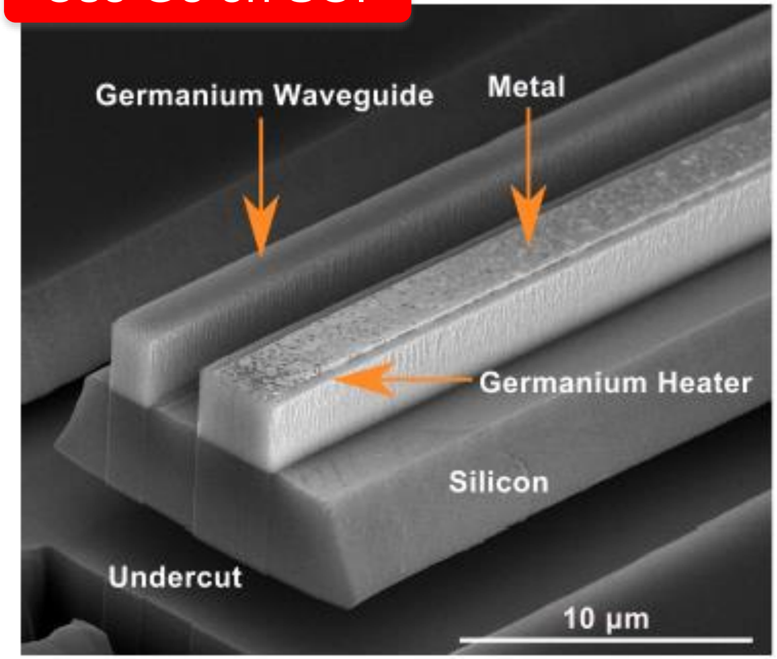
Tuning of mid-infrared waveguide circuits

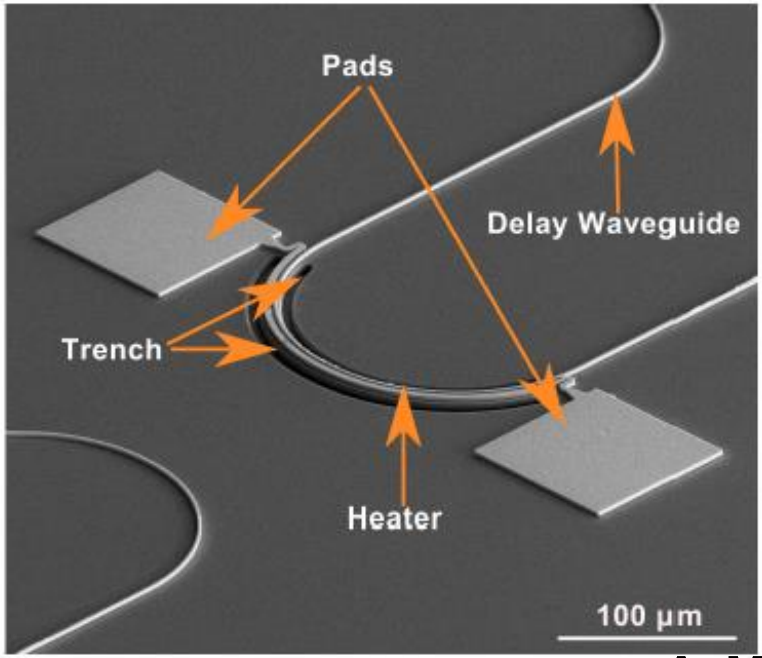
Thermo-optic tuning:

- well developed on SOI waveguide circuits
- low power consumption (few mW for π phase shift)
- Efficiency on Germanium on Silicon waveguide circuits?

Use Ge on SOI

8mW power consumption for π phase shift





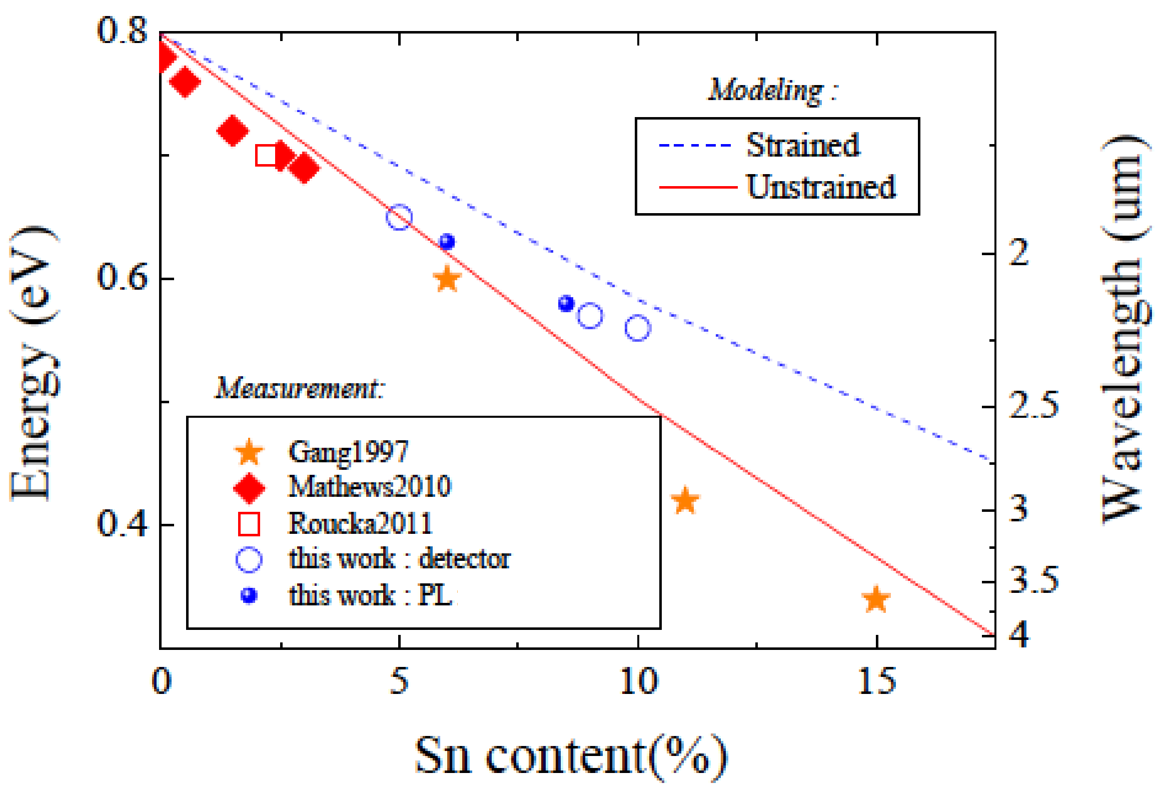
A. Malik, submitted

Monolithically integrated GeSn detectors

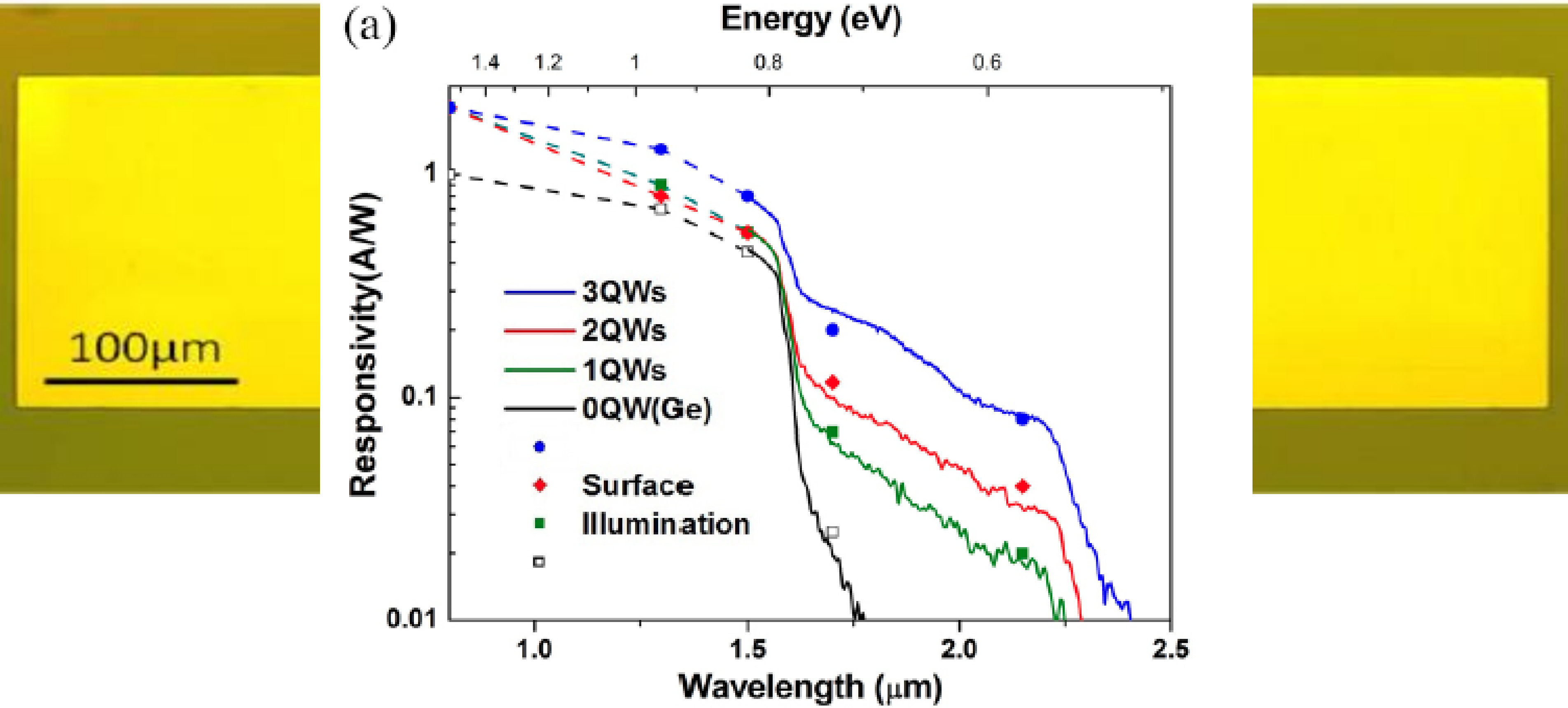
Ge limited to 1.6um

Ge detectors on SOI currently well developed for telecom / datacom

Decrease the bandgap by adding Sn to the Germanium matrix



Monolithically integrated GeSn detectors

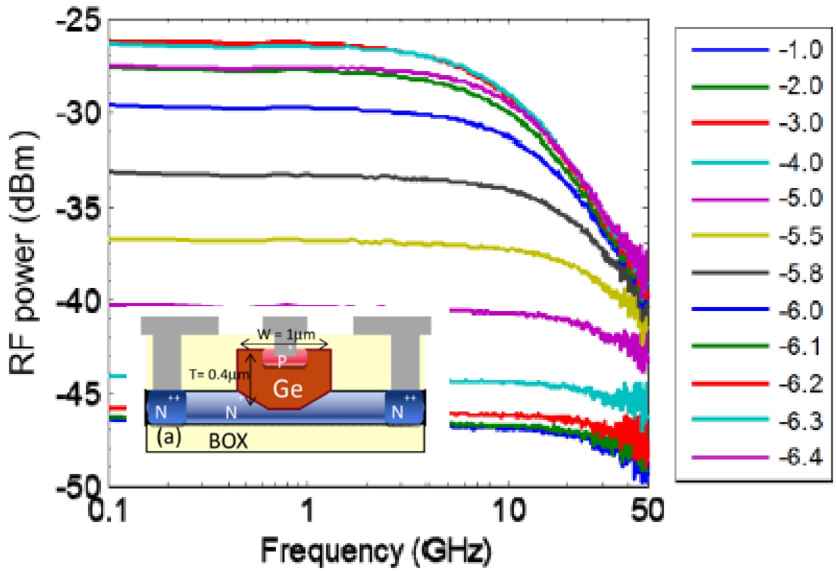


GeSn/Ge multi-quantum well structure
8% Sn content
20nm thick quantum wells – Germanium barriers

A. Gassenq, Optics Express 2012

Recent Ge based devices

Integrated Ge avalanche photodetector

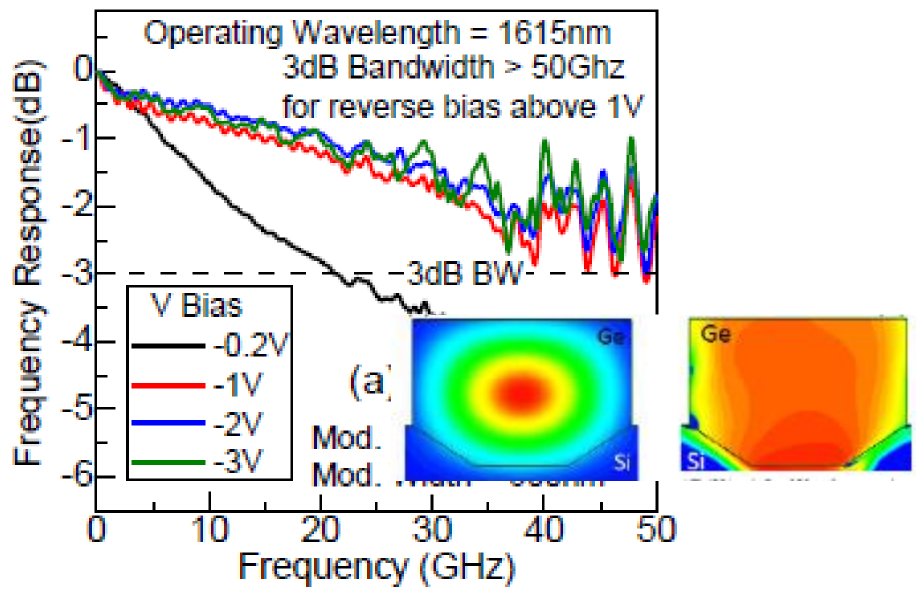


S21 parameter increases substantially as the bias go beyond -2 V.

gain × bandwidth product > 100GHz
5.8dB sensitivity improvement

H.T. Chen, Optics Express 2015

Ge Waveguide Electro-Absorption Modulator



strong confinement of optical and electrical field enabled by submicron Ge/Si waveguide platform

bandwidth greater than 50GHz
capacitance of 10fF
link power penalty of 8.2dB
2Vpp drive swing

S. Gupta, OFC 2015

Outline

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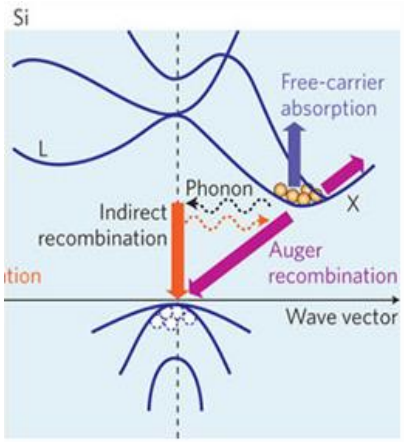
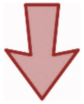
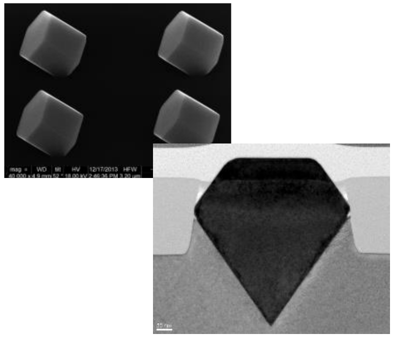
Silicon photonics – on-chip laser sources



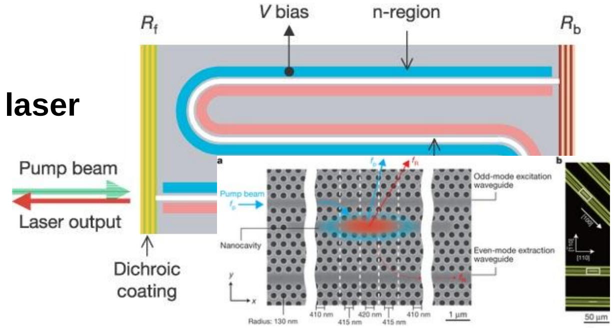
Nature Photonics **4**, 511 - 517 (2010)



III-Vs on Si Epitaxy ?

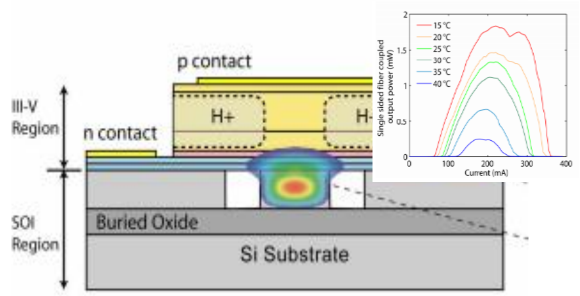


2005 Raman Si laser



Nature 498, 470–474 (2013)

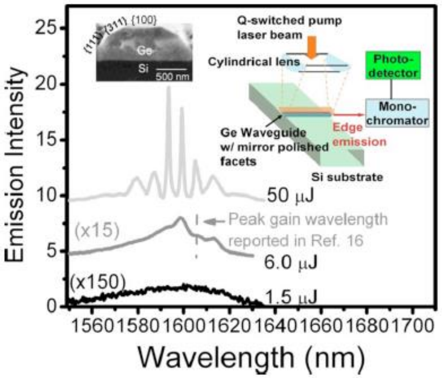
2006 Hybrid laser



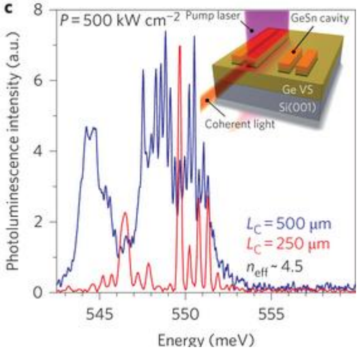
Optics Express **14**, 9203 - 9210 (2006)

2010 Ge laser

Optics Letters **35**, 679 - 681 (2010)



2015 GeSn laser



Nature Photonics **9**, 88–92 (2015)

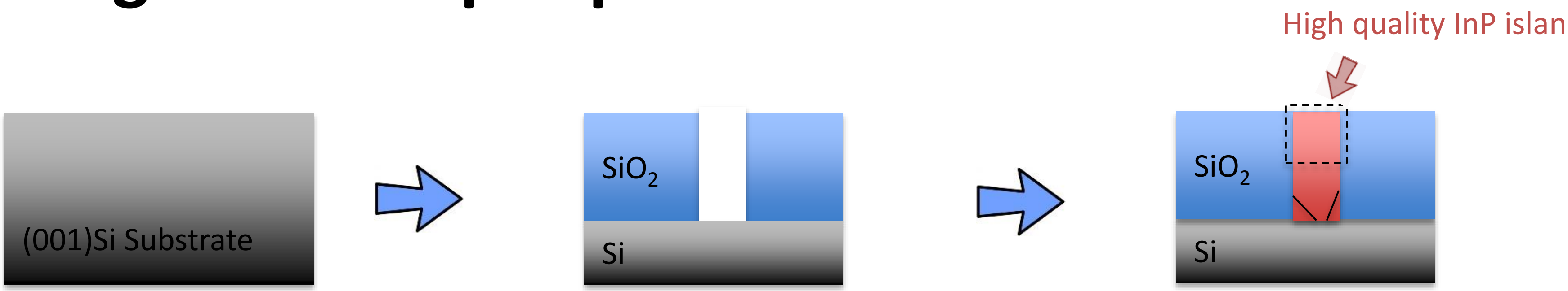
III-Vs epitaxial growth on silicon

Mismatch →
- Lattice constant
- Interface polarity
- Thermal expansion

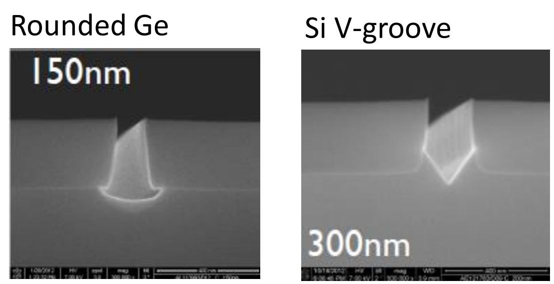
Large area III-Vs growth on silicon:

1. Strain relaxed buffer layers.
2. Lattice matched material system (GaP)
3. GaSb based system
4. Quantum dots (QDs) growth on silicon (with buffer)
5. Nanowire growth on silicon

InP growth on pre-patterned Si substrate

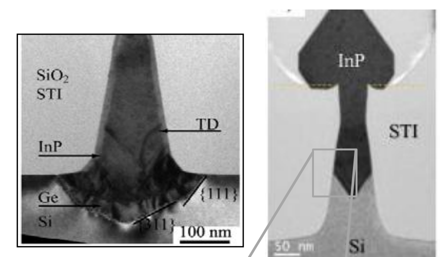


Interface engineering



Suppress anti-phase boundaries (polarity mismatch)

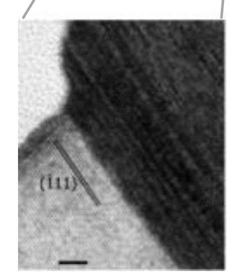
Defect trapping



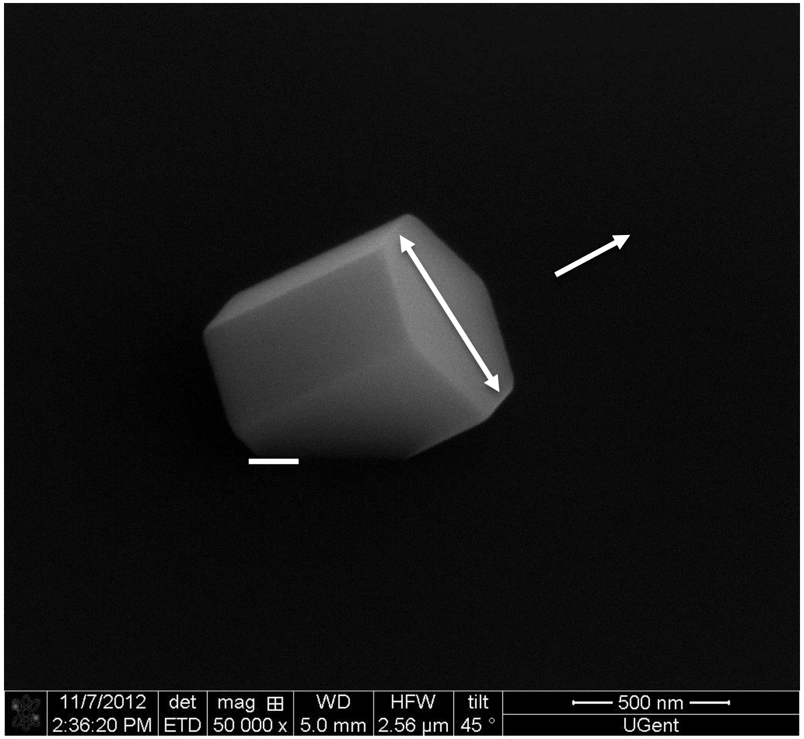
Trap threshold dislocations gliding on the {111} (lattice mismatch)

Crystal Growth & Design, **12,** 4696-4702 (2012)
Journal of Applied Physics, **115**, 023710 (2014)

Complex defect system presents at the InP/Si interface



Titled InP nanowire grown on silicon

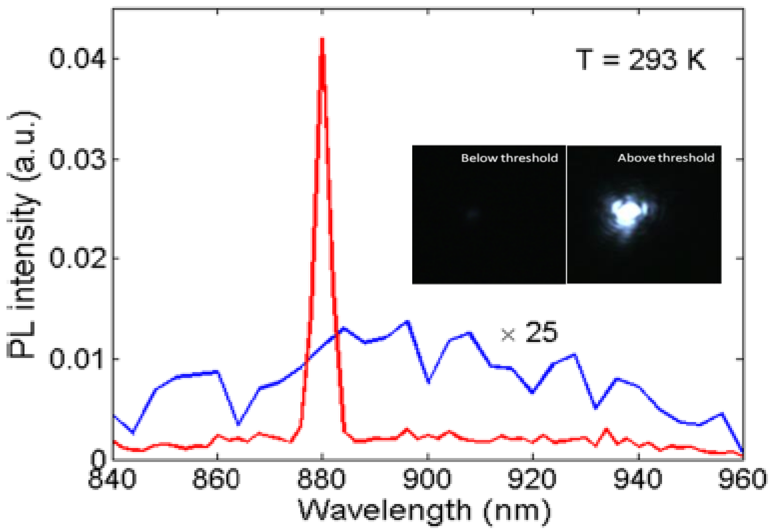


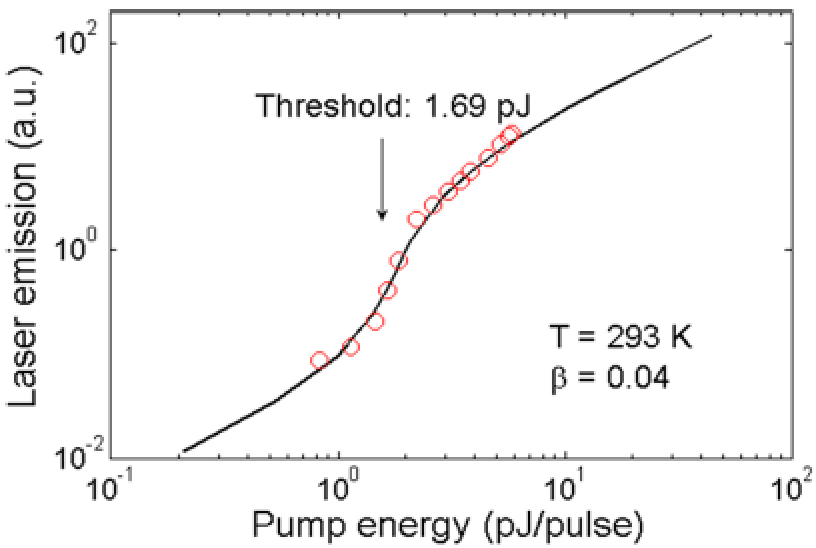
1. Nanowires of more than 500 nm diameter grown on top of InP island of below 100 nm diameter. The length is about 1 µm.
   (Nanowire dimension constraint lifted)

2. Nanowire oriented along <111>
   Hexagonal shaped cross-section
   (Typical for InP nanowire)

Room temperature laser operation

Pumping source: 9 ns pulse train @ 532 nm
Pump area limited to a single nanowire

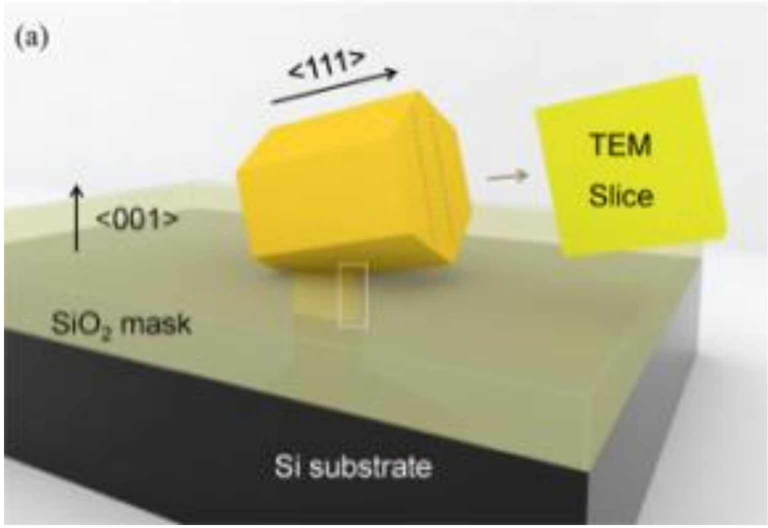


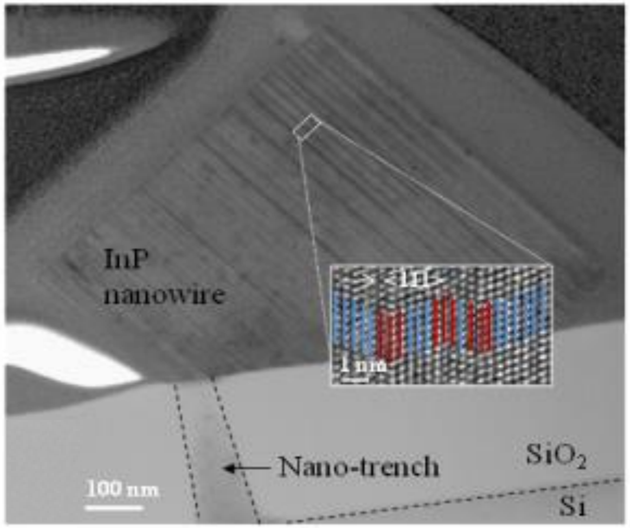


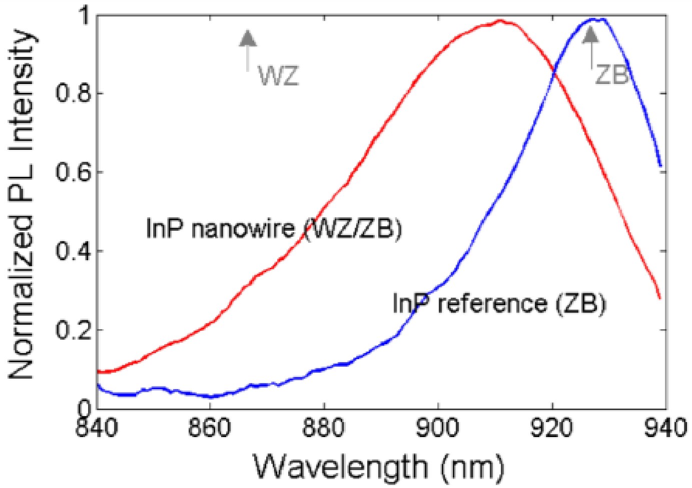
***Nano Lett*., 13, 5063–5069 (2013)**

Open up the nanowire

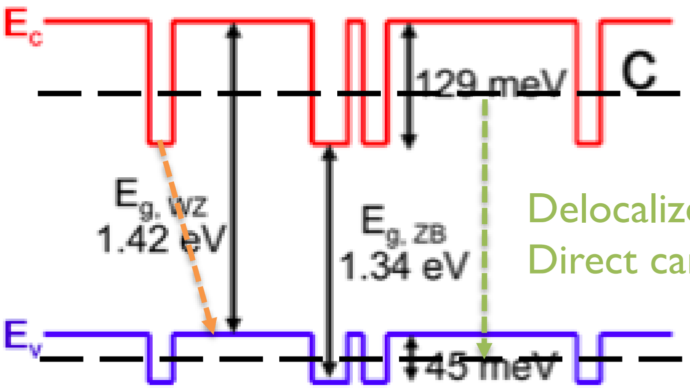
Micro-twins
Mix of two crystal phases







Schematics of a type II heterostructure:

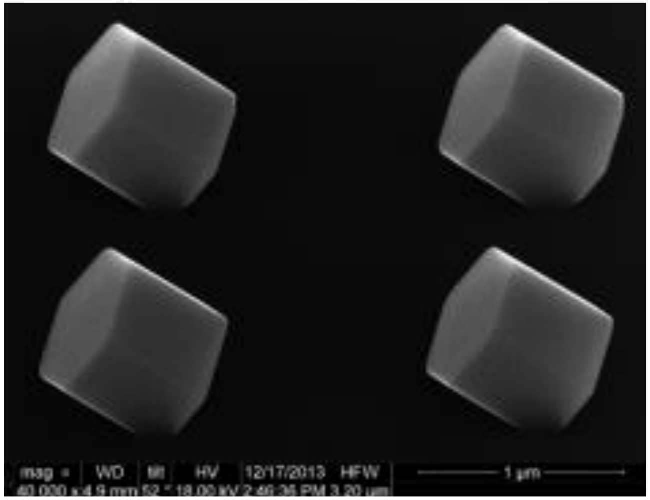


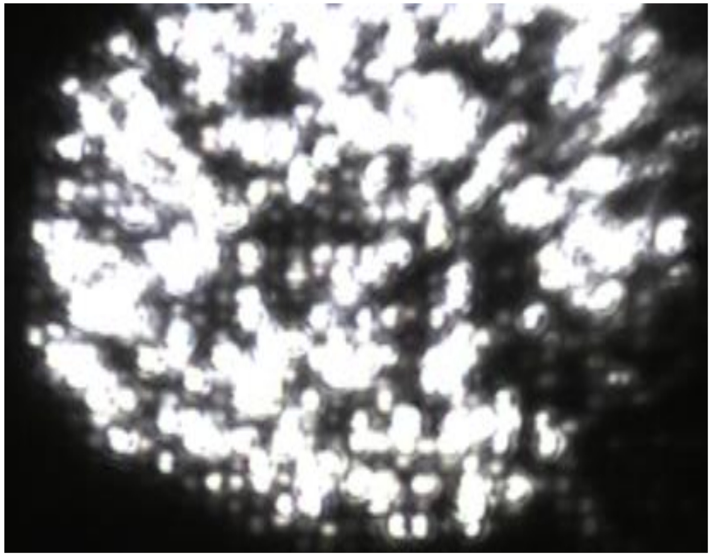
Delocalized wave-function
Direct carrier transition

indirect transition?

***Nano Lett.*, 13, 5063–5069 (2013)**

Yield



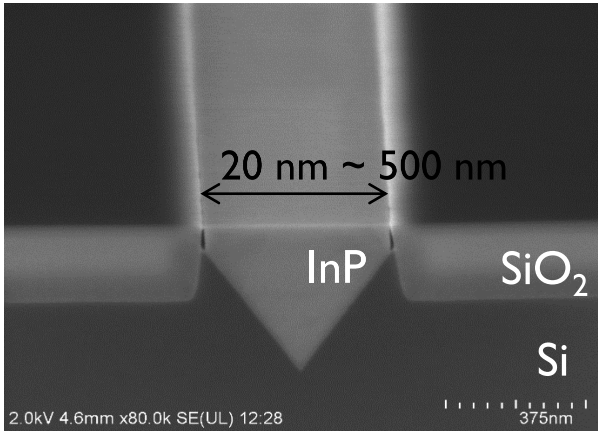


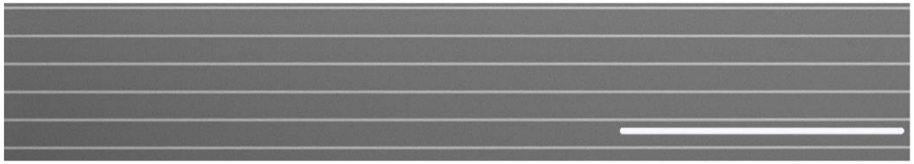
35 nano-lasers are successfully fabricated out of 80 sites.

What industry partners want…

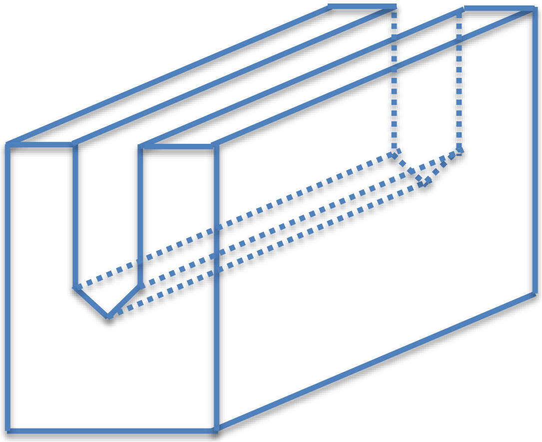
Integration:

- output light coupling
- electrical injection
- wavelength control
- mass production
- ……

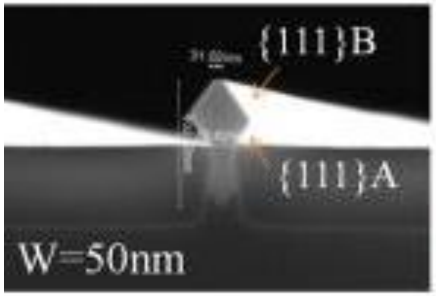




Starting from a longitudinally extended trench



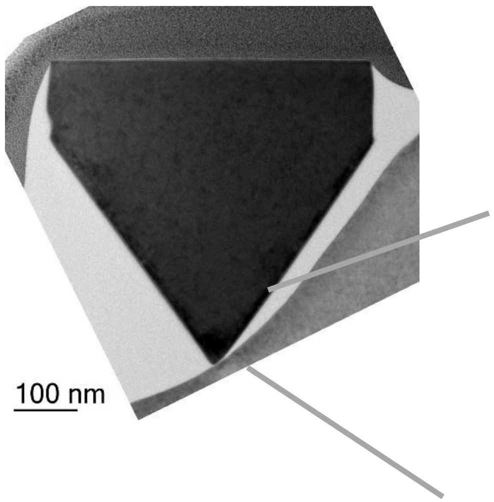
Two step growth of InP

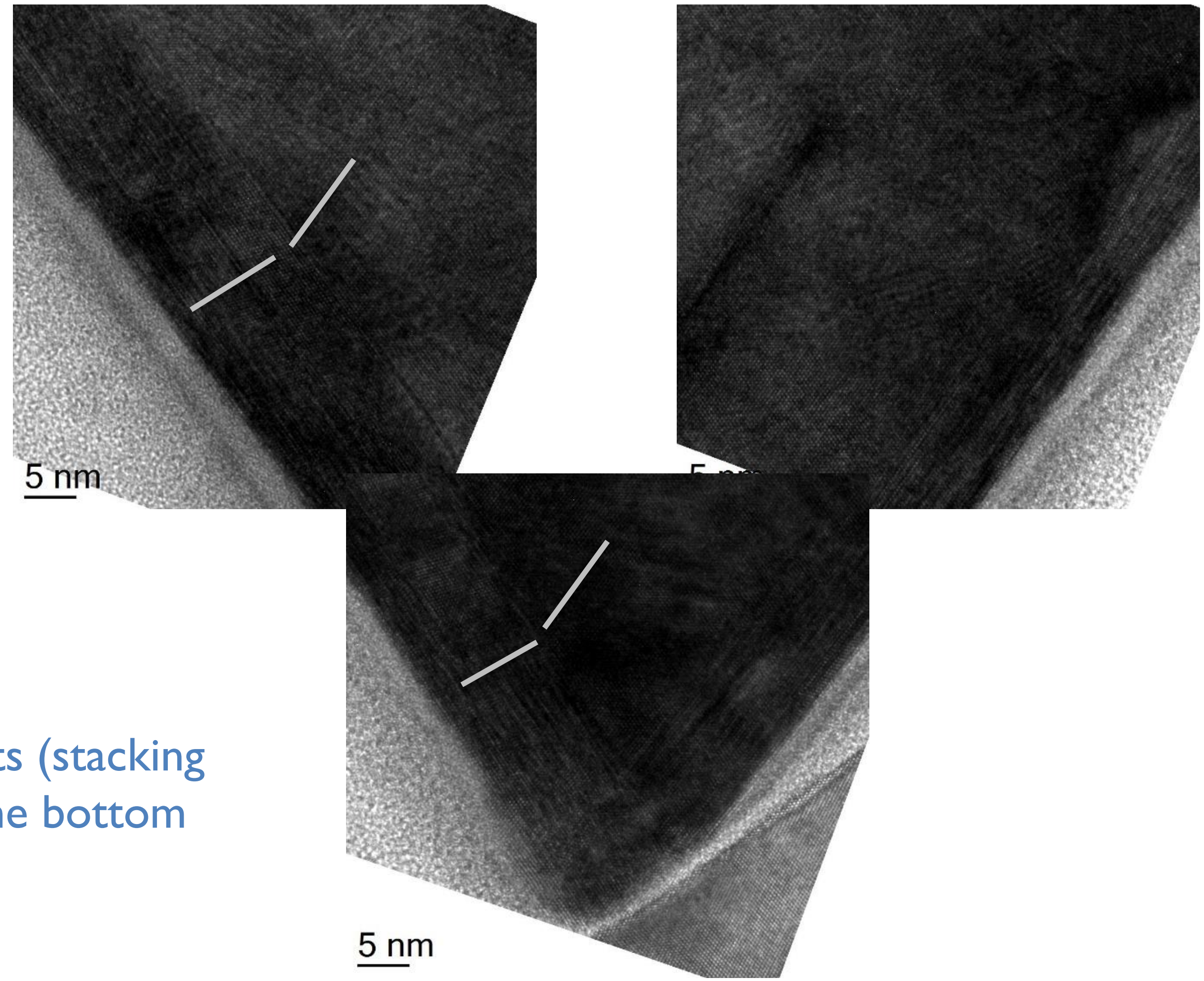


Chemical mechanical polishing (CMP)

Open up the nanowire again…

Cross-section view



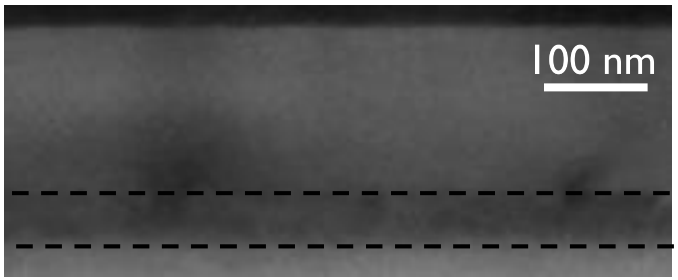


- high density of {111} defects (stacking faults, twins, nanotwins) at the bottom of the {111} InP sidewalls

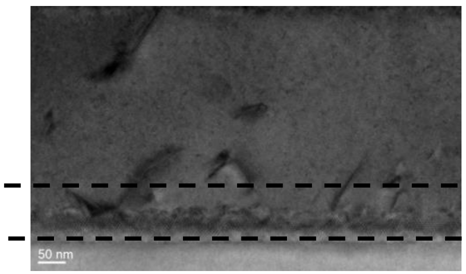
Open up the nanowire again…

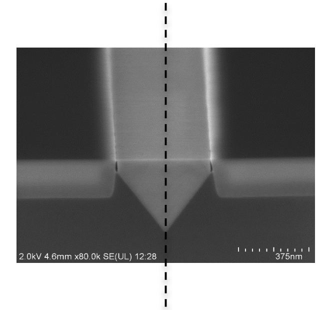
Transmission electron microscope (TEM) inspections

Growth in 50 nm trenches



Growth in 500 nm trenches



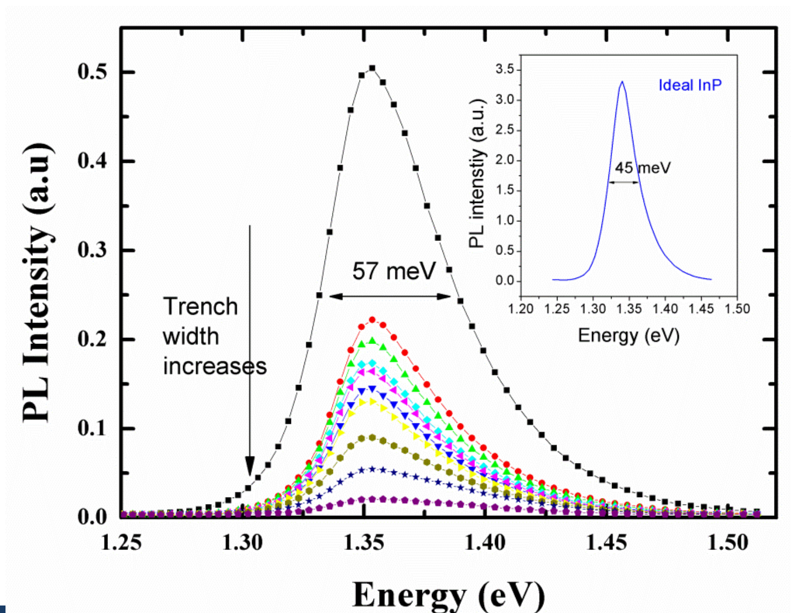


High quality

Defective (30 nm)

Si

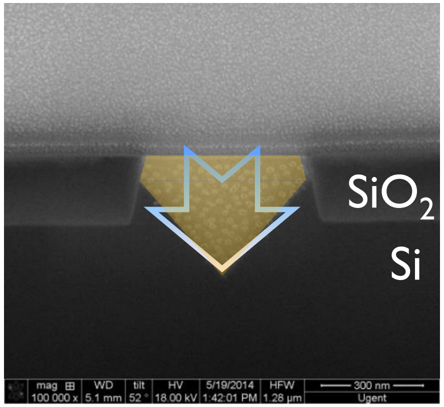
Photo-luminescence inspection (room temperature)



- **Material quality is comparable to the ideal InP epi-layer**
- **Narrow trenches have a better material quality**

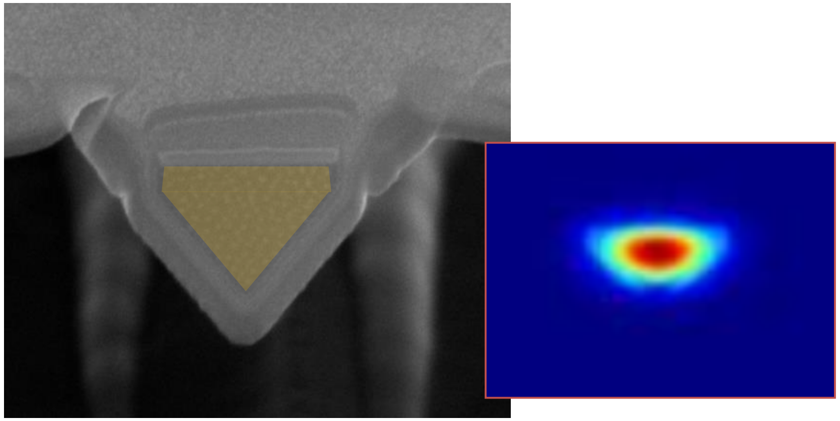
Adaption for photonics!

2. Removal of substrate leakage loss



Huge substrate leakage loss !

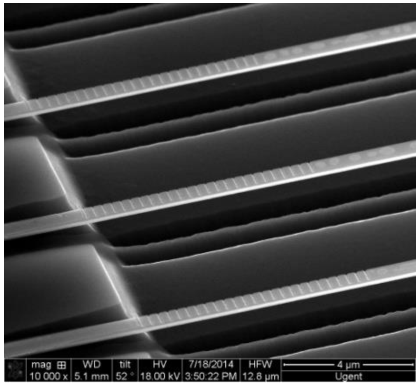
Si undercut



A suspended InP waveguide

Robust Si undercut etching process

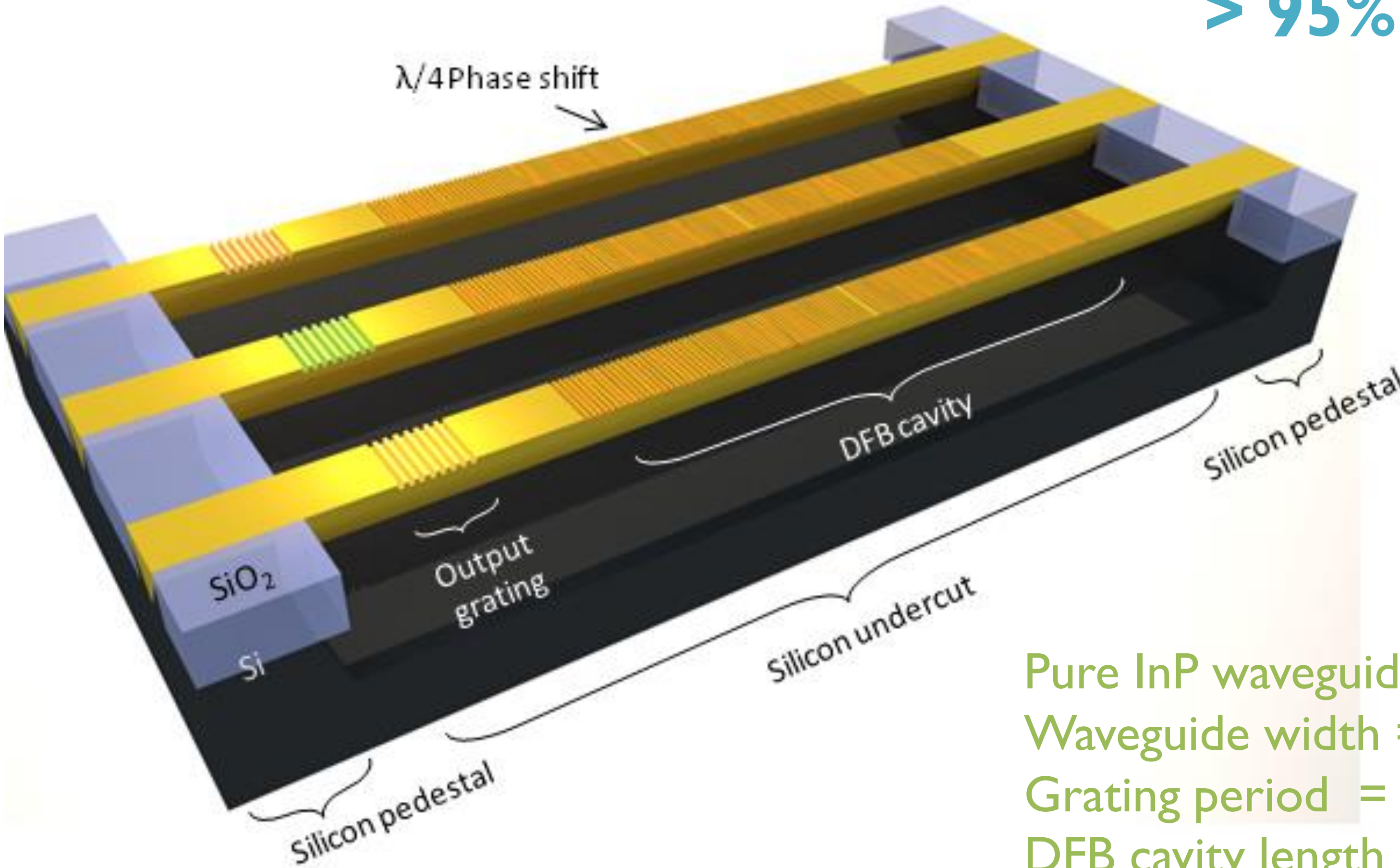
- **High yield**
- **Limited damage on the InP material (verified by PL measurement)**



Cavity definition

Schematic plot of the monolithic InP lasers on silicon

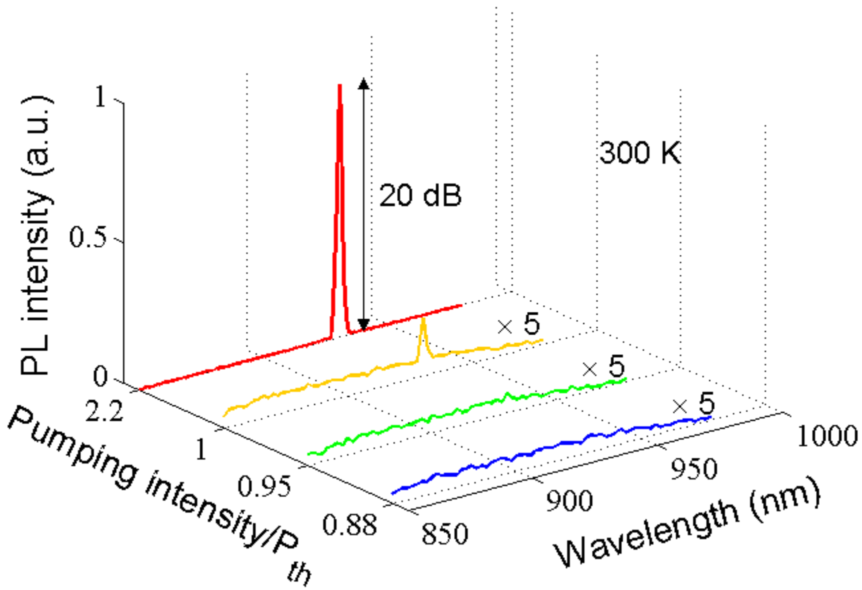
> 95% yield

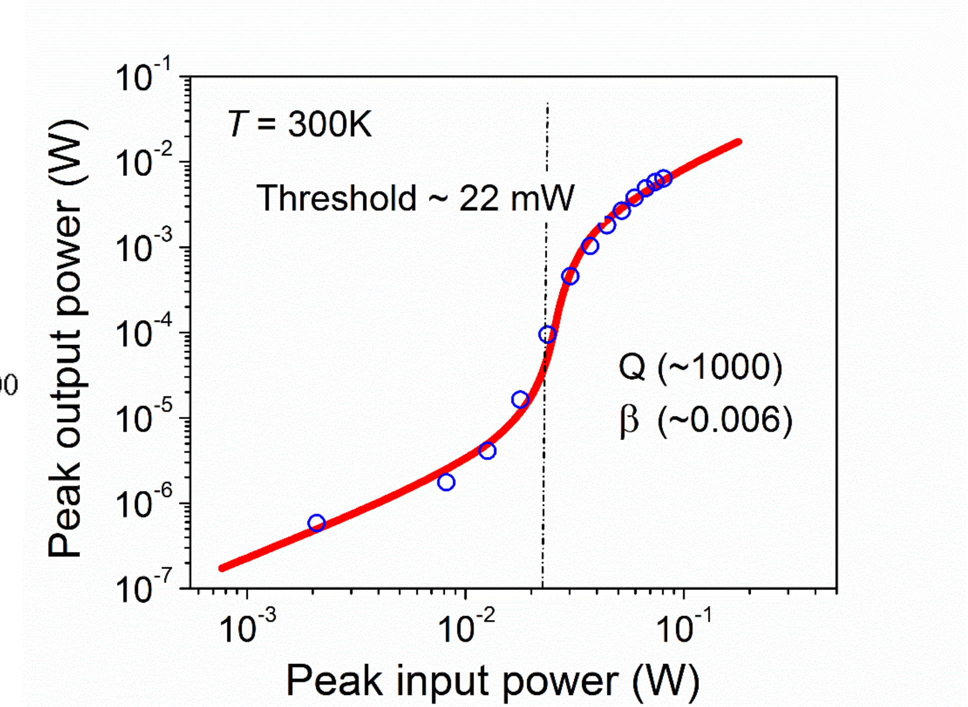


Pure InP waveguide
Waveguide width = 500 nm
Grating period = 163 nm
DFB cavity length = 45 µm

Room temperature operation

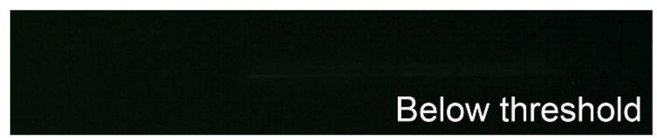
Pumping condition:
532 nm wavelength
9 ns pulse duration

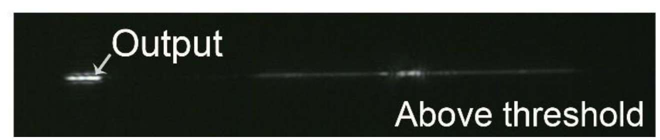




Room for improvement:

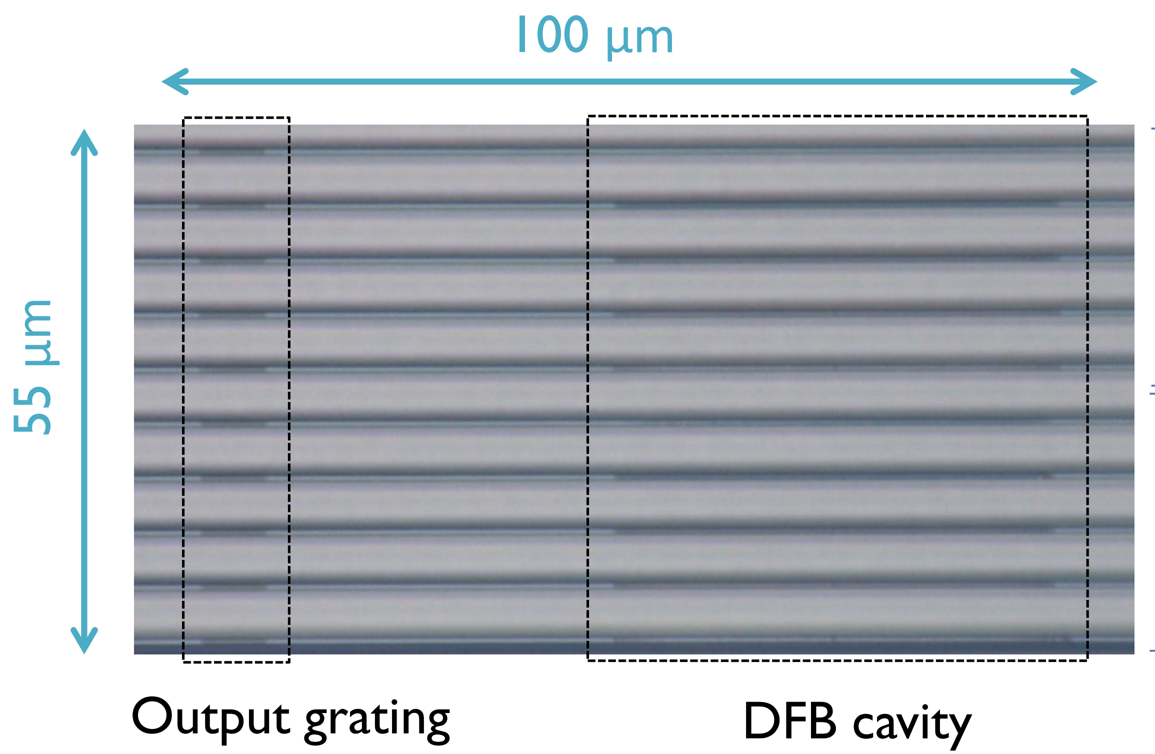
Use narrow waveguide
– better material
Heterostructure
– reduced carrier loss





Laser array

Microscope image of a **10 DFB laser array**



Wavelength tuning
by varying the cavity design

Group 1
Grating period = **163 nm**
Phase shift length:
224 nm ~ 264 nm (10 nm step)

Group 2
Grating period = **165 nm**
Phase shift length:
228 nm ~ 268 nm (10 nm step)

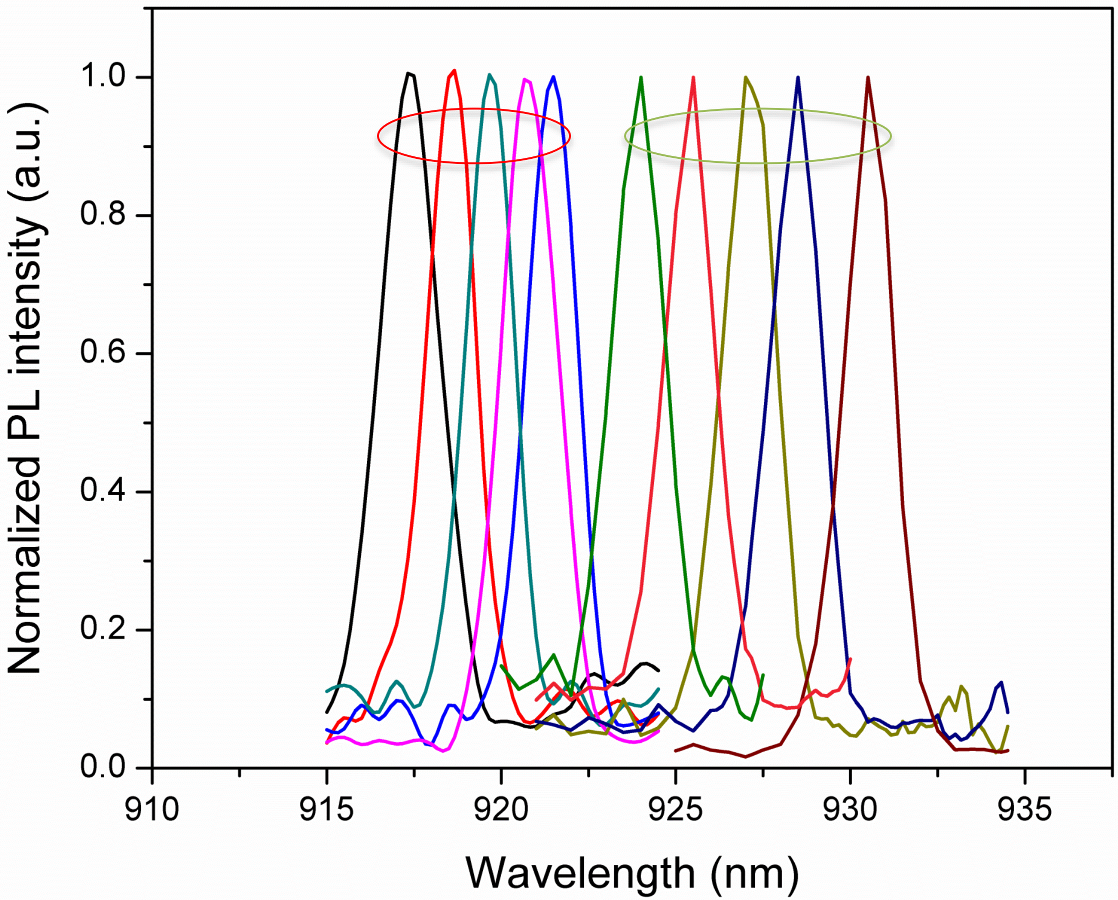
Pure InP waveguide
Waveguide width = 500 nm
Grating etch depth = 60 nm

DFB cavity length = 45 µm
Output grating length = 10 µm

Laser array

- **High yield**
- **Precise wavelength control**

Measured laser spectra from the 10 DFB laser array



Period = 163 nm
Δλ = 1 nm

Period = 165 nm
Δλ = 1.5 nm

http://arxiv.org/abs/1501.03025

The next step

Electrical injection
Wavelength @ communication band → Hetero-structure

Use InP/Si islands as a lattice-matched platform for subsequent ternary or quaternary growth

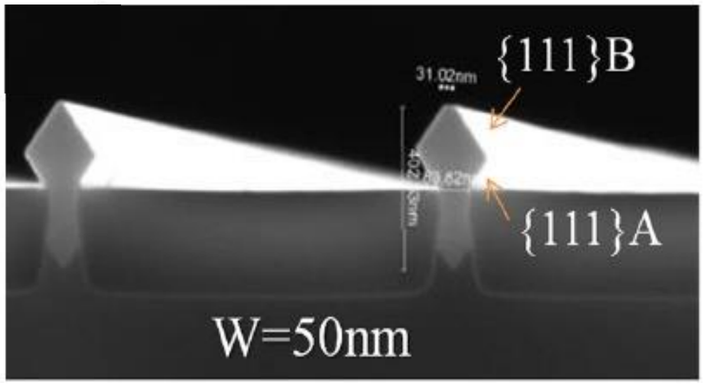
Under investigation

Conclusions

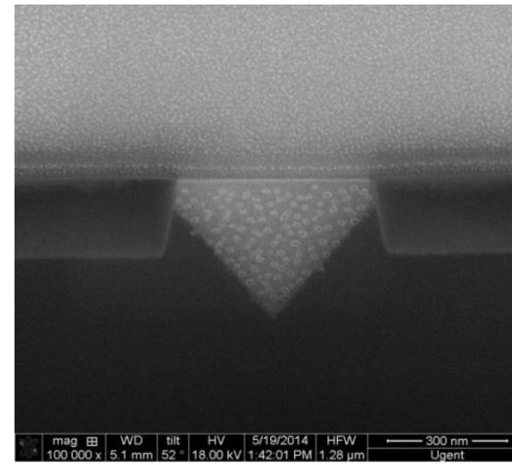
- High performance SWIR/MWIR passive waveguide circuits demonstrated using CMOS fabrication technology
- Ge/GeSn based active devices (photodetectors and modulators) with superior performance demonstrated in the NIR wavelength region.
- Well controlled DFB laser array demonstrated by epitaxial growth of InP on silicon

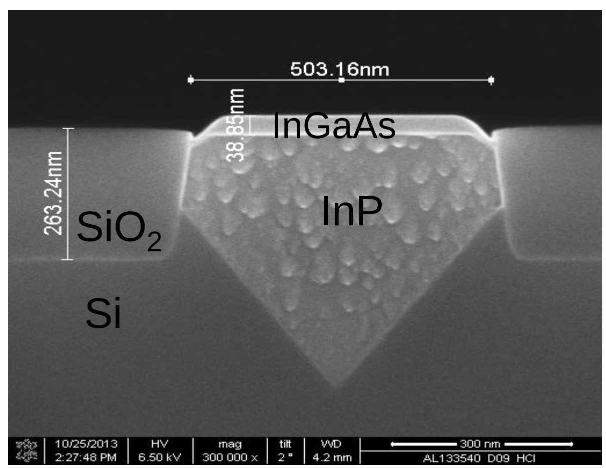
Adaption for photonics!

I. Virtual lattice matched substrate for III-V regrowth



Chemical mechanical Polishing (**CMP**)





III-Vs regrowth