Near/Mid-Infrared Heterogeneous Si Photonics

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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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InP on silicon

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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

![Graph showing transparency windows of materials](image)
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

- **Input star coupler**: Light is distributed over many delay lines.
- **Dispersive delay lines**: Each wavelength feels a different phase delay.
- **Output star coupler**: Different phase delays create a phase front focusing into different output waveguides.
MWIR SOI spectrometers

M. Muneeb, Optics Express 2013
5.0 μm 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:
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• Efficiency on Germanium on Silicon waveguide circuits?

8mW power consumption for π phase shift

Use Ge on SOI

A. Malik, submitted
Monolithically integrated GeSn detectors

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

**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

H.T. Chen, Optics Express 2015

S. Gupta, OFC 2015
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Silicon photonics – on-chip laser sources


2005 Raman Si laser


2006 Hybrid laser


2010 Ge laser

Optics Express 14, 9203–9210 (2006)

III-Vs on Si Epitaxy?

2015 GeSn laser

III-Vs epitaxial growth on silicon

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

Mismatch

Lattice constant
Interface polarity
Thermal expansion
InP growth on pre-patterned Si substrate

(001)Si Substrate

Interface engineering
- Rounded Ge
- Suppression of anti-phase boundaries (polarity mismatch)

Defect trapping
- Si V-groove
- Trap threshold dislocations gliding on the {111} (lattice mismatch)

High quality InP island

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

Open up the nanowire

Mix of two crystal phases

Schematics of a type II heterostructure:

Indirect transition?

Delocalized wave-function

Direct carrier transition

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!

A suspended InP waveguide

Robust Si undercut etching process

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

**T = 300K**
- Threshold ~ 22 mW
- $Q \sim 1000$
- $\beta \sim 0.006$
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)

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

DFB cavity
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
  \( \Delta \lambda = 1 \text{ nm} \)

- Period = 165 nm
  \( \Delta \lambda = 1.5 \text{ nm} \)

http://arxiv.org/abs/1501.03025
The next step

Electrical injection
Wavelength @ communication band

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!

1. Virtual lattice matched substrate for III-V regrowth