Near- and mid- infrared group IV photonics

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Outline

1. Introduction to silicon photonics.

2. Silicon-Germanium-on-Insulator (SGOI) formed by rapid melt growth (RMG).

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Si Technologies Centre of Excellence
School of EEE-NTU

Silicon Photonics: Internet Traffic Predictions

Expanding bandwidth requirements:

• Content delivery:
  ➢ Digital game purchases.
  ➢ Live streaming.
  ➢ Increasing video resolution standards (HDTV, UHDTV...).

• Cloud computing:
  ➢ Microsoft Azure.
  ➢ Amazon EC2.
  ➢ Chrome OS.

1 zetabyte = 10^{12} gigabytes
1 exabyte = 10^9 gigabytes

What Happens in an Internet Minute?

- 1,572,877 GB of global IP data transferred¹
- 10 Million ads displayed²
- 347,222 Tweets²
- 3.3 Million pieces of content shared⁴
- 6.9 Million messages sent⁴
- Netflix + Youtube = more than ½ of all traffic⁶

- $400 Million during Alibaba peak day sales⁵
- 438,801 Wiki page views⁷
- 10 Million WeChat messages at its peak⁸
- 34.7 Million instant messages (MIM) sent⁸
- 194,064 app downloads¹⁰
- $133,436 in sales¹¹
- 38,194 photos uploaded¹³
- 4.1 Million searches¹⁵
- 100 hours of video uploaded¹⁶
- 138,889 hours of video watched¹⁶
- 23,148 hours of video watched¹⁷

And Future Growth is Staggering

- By 2017, mobile traffic will have grown 13X in just 5 years¹
- In 2017, there will be 3X more connected devices than people on Earth¹
- All digital data created reached 4 zettabytes in 2013¹⁸
Silicon Photonics: What about Power?

- In 2010, Google disclosed a typical global power consumption of ~ 260 Megawatts of power\(^1\).
- Google’s data centres account for less than 1% of the power used by data centres in 2010\(^2\).
- In 2010, data centres are thought to have accounted for ~1.5% of the global power consumption.
- If we double bandwidth without increasing power efficiency, we need more power plants!

Source:
\(^1\)New York Times - Google Details, and Defends, Its Use of Electricity.
\(^2\)Jonathon Koomey - Growth in data center electricity use 2005 to 2010.
Silicon Photonics: Requirements for Optical Interconnects

- Optics should ideally use less power than current wire interconnects:
  - <1 pJ/bit for off-chip\textsuperscript{1,2}.
  - <50-220 fJ/bit for global on-chip\textsuperscript{1,2}.

- CMOS compatibility:
  - Control costs by utilising existing CMOS infrastructure and processes.

- Components:
  - Light source.
  - Waveguides.
  - Wavelength Division Multiplexers (WDM).
  - Modulators.
  - Detectors.
  - Switches and Routers.

- Dense spatial connections & WDM (section 2).

Source:
\textsuperscript{1}D. A. B. Miller, Proc. IEEE 97, 1166 - 1185 (2009).
\textsuperscript{2}G T Reed et al, Nature Photonics 8, 518 – 526, (2010).
Silicon Photonics: Why is Silicon Photonics the Answer?

• The prospect of integrating CMOS electronics and photonics on the same substrate:
  ➢ Greater functionality.
  ➢ Improved performance.
  ➢ Cost reductions.

• Mature processing derived from years of development in the electronics industry.

• High refractive index contrast (compact components).

• Lower power interconnects.

• Massive interconnect density (WDM).

• Low cost for mass markets.
Silicon Photonics: Market Predictions

Source: Silicon Photonics Report - Yole Développement.
Silicon Photonics: Applications in Quantum Photonics

- Silicon photonics promises a fully integrated system platform for a range of quantum applications:
  - Quantum Communications.
  - Quantum sensing.
  - Quantum computation and simulation.

- Devices already demonstrated.

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Crystalline SiGe-on-Insulator: Motivation

1. Tuneable bandgap (modulators etc.).
2. Tuneable lattice constant (epitaxial growth etc.).
3. Higher carrier mobilities than Si (BiCMOS drivers etc.).
4. Ability to fabricate low power electro-absorption (EA) modulators.


Crystalline SiGe-on-Insulator: RMG Fabrication Process

Step 1 - Deposit SiO₂

Step 2 - Etch Seed Windows

Step 3 - Deposit Ge

Step 4 - Etch Ge

Step 5 - Deposit SiO₂

Step 6 - RTA

Silicon

Silicon Dioxide

Germanium
Crystalline SiGe-on-Insulator: RMG Growth Mechanism

- Si diffuses from seed into Ge strip whilst in liquid phase forming SiGe.
- Growth initiates at the Si seed area.
- Epitaxial growth front propagates along SiGe strip.
- Defects confined to seed area.

$\text{SiO}_2$
Crystalline SiGe-on-Insulator: RMG Layer Characterisation

SiGe composition along straight strips

SiGe phase diagram

Crystalline SiGe-on-Insulator: Composition Profile Engineering

- Must increase regrowth front propagation speed:
  - Therefore, must increase the cooling rate.

- Branches, or ‘radiating elements’, increase the cooling rate of the central strip
Crystalline SiGe-on-Insulator: Uniform Composition

- Uniform composition profile is achieved by narrowing the central strip to 3 µm:
  - Branches provide sufficient cooling for steady-state solidification to occur.

Higher anneal temperature means that solidification does not begin until more Si has diffused into the SiGe layer.
Crystalline SiGe-on-Insulator: Composition Tuning by Structural Design

• Combine straight strip properties with tree-structure properties.

• Enables, multiple uniform composition SiGe compositions to be simultaneously formed.

• Only requires one initial deposition step and one anneal step.

Crystalline SiGe-on-Insulator: Quantum Based Applications

- Seed layer for InGaAs quantum dot lasers.
- SiGe quantum well based optical interconnects.

Rapid melt growth removes the need for thick (8 µm) SiGe buffer layers meaning integration with SOI is much simpler.

Liu et al., Nature Photonics, 2011.

Chaisakul et al., Nature Photonics, 2014.
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Mid-IR Silicon Photonics: Motivation

Telecomms/datacomms
Optical fiber communication

Homeland security
Laser detection of explosive devices, or dangerous substances. Most of explosive chemicals show specific absorption footprints in mid-IR region.

Healthcare
Lab on a chip: Infrared spectroscopy aids decease diagnosis

Environmental Monitoring
CO₂, N₂O, CO, butane & methane etc. have strong absorptions in mid-IR (2 to 5 µm) region.
Mid-IR Silicon Photonics: Passive Devices

- Example device - multimode interferometer (MMI):
  - Design optimised using Lumerical Mode Solutions.
  - $\lambda = 2 \, \mu m$, 400 nm Si / 2 $\mu m$ BOX SOI wafer.
  - Written by e-beam lithography (EBL).
  - Etched by reactive ion etching (RIE):
    - Slab height = 100 nm.

<table>
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<tr>
<td>S</td>
<td>1.7</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
</tr>
</tbody>
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Simulated MMI transmission.
Mid-IR Silicon Photonics: Passive Device Measurements

- Data normalised using a straight waveguide.
- The propagation losses for a rib waveguide are around 3~4 dB/cm.
- MMI’s are cascaded to calculate insertion loss:
  - Insertion loss: $0.9 \pm 0.1$ dB/MMI.
  - Measured MMI length is 25.2 µm:
    - Device optimised for 26 µm length.

Loss = $0.9 \pm 0.1$ dB/MMI
Conclusions

• Silicon photonics promises to play a significant role in future technology:
  ➢ For this to become a reality mass production is necessary.

• Rapid melt growth of SGOI enables multiple compositions to be simultaneously grown:
  ➢ High quality material is suitable for state-of-the-art devices, at a low cost.

• Mid-IR silicon photonics could lead new technologies in sensing:
  ➢ Ge-on-Si platform promises more efficient active devices for mid-IR wavelengths.
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