Silicon photonics in 3 µm SOI

Timo Aalto

Photonic Integration Conference, October 2, 2018, High Tech Campus Eindhoven, The Netherlands
Many PIC platforms to choose from

- Silicon ICs dominate, but PICs come in many flavors

<table>
<thead>
<tr>
<th>Material</th>
<th>Maturity</th>
<th>Density</th>
<th>Complexity</th>
<th>Chips per wafer</th>
<th>Foundries</th>
<th>MPW</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$ (PLC)</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low/Medium</td>
<td>Few</td>
<td>No</td>
<td>Hybrid</td>
</tr>
<tr>
<td>SiO$_2$N$_y$</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>None</td>
<td>No</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>High</td>
<td>M/H</td>
<td>Medium</td>
<td>Medium/High</td>
<td>Few</td>
<td>Yes</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Silicon</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Several</td>
<td>Yes</td>
<td>Hyb./Heter./Monol.</td>
</tr>
<tr>
<td>InP</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Several</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>GaAs</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium/High</td>
<td>Few</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>LiNbO$_3$</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>None</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Polymers</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High (roll-to-roll)</td>
<td>Few</td>
<td>No</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Chalcogenides</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>N/A</td>
<td>None</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>Germanium</td>
<td>Low</td>
<td>M/L</td>
<td>Low</td>
<td>N/A</td>
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<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>SiC</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>N/A</td>
<td>None</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>Diamond</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>N/A</td>
<td>None</td>
<td>N/A</td>
<td>No</td>
</tr>
</tbody>
</table>
Many open access Si photonics platforms

- **Si310-PH**
  - Passive + heaters
  - 310 nm SOI

- **IHP SG25_PIC**
  - Passives + Heaters
  - 220 nm SOI
  - + Implanted PIN
  - + Flip-chip

- **IHP SG25H4_EPIC**
  - Photonic BiCMOS
  - 3 µm SOI

- **Customized actives & Passives with EBL**
  - 220/340 nm SOI

- **220 nm SOI**
  - 220 nm SOI
  - 220/300 nm SOI
  - 220 nm SOI
What is silicon photonics?

Generating, manipulating, guiding and using light
In Photonic Integrated Circuits (PICs)
fabricated on silicon chips
processed on silicon-on-insulator (SOI) wafers

Primarily single-mode (SM) components and systems
Main application areas for Si photonics

- Health Care
- IoT & Autonomous Systems
- IT & Telecom
- Agri & Food
- Manufacturing & Industry 4.0
- Military & Aerospace
- Consumer Electronics & Lighting
VTT Technical Research Center of Finland

- Leading research and technology company in the Nordic countries
- Micronova clean room: 150 mm wafers, 2 600 m²
- MPW and dedicated runs for Si photonics
Path to small and medium volume manufacturing via VTT Memsfab Ltd.

- Same Micronova fab and same processing tools used
- Scalability to >1000 SOI wafers/year
- Upgrade to 200 mm wafer size in ~2 years
Single-mode rib waveguides in 3 µm SOI

- Wavelength independent SM operation (1.2 µm < λ < 6 µm)
- Propagation loss 0.1 dB/cm
- Small birefringency (Δn_{eff} ~10^{-3} in 3 µm SOI)

Height ratio limit: \( h \geq H/2 \)

Width limit:

\[
\frac{W}{H} < 0.3 + \frac{h/H}{\sqrt{1-(h/H)^2}}
\]

Extreme mode confinement and bandwidth

Large Single-Mode Rib Waveguides in GeSi–Si and Si-on-SiO₂

Richard A. Soref, Joachim Schmidtenchen, and Klaus Petermann

Fig. 7. Beam-propagation evaluation of a rib guide with \( 2a\lambda = 4 \text{ μm} \) and \( a-b = 1 \).

Fig. 1. Cross-section of rib waveguide.

Radiative modes

Fundamental mode

\( \Delta > 40\% \)

\( \Delta < 0.4\% \)
Combination of rib and strip waveguides

- Keeping light in the fundamental mode
- About 0.1 - 0.15 dB/cm for both waveguides
- Zero birefringency and full polarization independency

1. Metal mirror
2. Rib waveguide
3. TIR mirror
4. Rib-strip converter
5. Vertical taper
Polarization independent 1x4 AWG

- 100 GHz ch spacing, 5 nm FSR
- Polarization dependency <10 GHz
- 2-3 dB loss

Footprint 2x3 mm² (MPW run #5)
Euler bends with micron-scale radius

- Adopting Euler bends from civil engineering to waveguide optics

Thick-SOI waveguides allow µm-size bends if mode excitation is well-controlled!

\[
\frac{1}{R} = \frac{d\theta}{ds} \propto s \propto \sqrt{\theta}
\]

\[s = 2R\theta\]

\[x(L) = \int_0^L \cos s^2 ds\]

\[y(L) = \int_0^L \sin s^2 ds\]

\[R_{\text{eff}} = 1.3 \, \mu m\]

\[R_{\text{min}} = 0.9 \, \mu m\]

Loss < 0.1 dB/90°
Euler bends with micron-scale radius

Bending loss with >20 µm radius is negligible and within measurement accuracy (±0.02 dB/90°)
Low-loss 3 µm SOI PICs for mid-IR

- SLED emitting 2.55 µm wavelength
- Waveguide propagation loss is too small for precise measurement
- Bend loss <0.01 dB/bend
Thick SOI waveguides can handle Watt-level power also at NIR

<table>
<thead>
<tr>
<th>Waveguide core height x width:</th>
<th>Waveguide core area</th>
<th>Estimated maximum optical power at $\lambda = 1.55$ µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22 x 0.45 µm (nanowire)</td>
<td>0.2 µm$^2$</td>
<td>0.02 W</td>
</tr>
<tr>
<td>3 x 1 µm (narrow strip)</td>
<td>3 µm$^2$</td>
<td>0.3 W</td>
</tr>
<tr>
<td>3 x 3 µm (strip/rib)</td>
<td>9 µm$^2$</td>
<td>0.9 W</td>
</tr>
<tr>
<td>3 x 10 µm (wide strip/rib)</td>
<td>30 µm$^2$</td>
<td>3 W</td>
</tr>
<tr>
<td>12 x 10 µm (strip/rib)</td>
<td>120 µm$^2$</td>
<td>12 W</td>
</tr>
<tr>
<td>12 x 20 µm (wide strip/rib)</td>
<td>240 µm$^2$</td>
<td>24 W</td>
</tr>
</tbody>
</table>
Microwave photonics on 3 µm SOI

- Instantaneous frequency measurement using Kerr nonlinearity in a 35 cm long spiral
- Design and testing at University of Sydney (M. Pagani et al.)

Low-error and broadband microwave frequency measurement in a silicon chip

Mattia Pagani,1 Blair Morrison,1 Yanbing Zhang,1 Alvaro Casas-Bedoya,1 Timo Aalto,2 Mikko Harjanne,2 Markku Kapulainen,2 Benjamin J. Eggleston,4 and David Marpaung1,4

1Center for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS), The Institute of Photonics and Optical Sciences (IPOS), School of Physics, University of Sydney, NSW 2006, Australia
2VTT Technical Research Center of Finland, Espoo 02040, Finland

Received 26 May 2015; revised 29 July 2015; accepted 29 July 2015 (Doc. ID 241693); published 18 August 2015

Instantaneous frequency measurement (IFM) of microwave signals is a fundamental functionality for applications ranging from electronic warfare to biomedical technology. Photonic techniques, and nonlinear optical interactions in particular, have the potential to broaden the frequency measurement range beyond the limits of electronic IFM systems. The key lies in efficiently harnessing optical mixing in an integrated nonlinear platform, with low losses. In this work, we exploit the low loss of a 35 cm long, thick silicon waveguide to efficiently harness Kerr nonlinearity and demonstrate, to the best of our knowledge, the first on-chip four-wave mixing-based IFM system. We achieve a large...
Passive components from MPW runs

- Variety of filters, (de)multiplexers, delay lines etc. demonstrated
Ultra-dense spirals with Euler bends


"DPSK-Demodulation based on Ultra-Compact micron-scale SOI platform," Proc. OFC’15, paper W2A.14
Faraday rotation in 3 µm SOI waveguide

- Polarization rotation cancels out in a conventional layout
- ...but can accumulate if birefringent bends reflect polarization

Spiral footprint ~0.5 mm²

6 cm long
Faraday rotation in 3 µm SOI waveguide

- Polarization rotation averages to zero in a conventional spiral
Faraday rotation in 3 µm SOI waveguide

- Polarization rotation averages to zero in a conventional spiral
- Polarization reflection in the corners allows to produce net rotation
Thermo-optic and electro-optic switches and modulators

- Implanted heaters and contacts in a Si slab
- Heaters for >10 kHZ operation
- PIN modulation >1 MHz

24 mW/π 12 dB ER

5 mW/π 7 dB ER
Ge photodiodes on 3 µm SOI

- Horizontal PIN structure with end-fire coupling from a 3 µm SOI waveguide
- Slow (MHz) operation suitable for a monitor PD
- ~2 µm wide Ge PDs have 0.9 A/W responsivity and <10 µA dark current (at both polarizations)

(Includes ~3 dB fiber coupling loss)
Hybrid integration of active components

- Lasers, amplifiers, modulators and photodetectors have been flip-chip bonded on 3 µm SOI using Au-Au thermo compression bonding.
Hybrid integration of active components

- Some challenges (and solutions)

Spot-size mismatch (converter)

III-V chip length variation (single-sided coupling)
Hybrid VCSEL integration on 3 µm SOI

- New EU-funded project to integrate VCSELs on 3 µm SOI
- Up/down reflecting on SOI mirrors to support flip-chip integration
- Targeting up to 100 Tb/s links
Automated wafer-level testing (WLT)

- Ramping up volume manufacturing requires automated WLT with simultaneous O/E testing
- Fully automated cassette-to-cassette tool
- I/O coupling with up-reflecting mirrors and lensed fibers
Next R&D steps

- Low-loss, low-cost coupling to SSMF arrays

Vertical taper 12 → 2 μm (+ IR output)

IR output of a 3x3 μm down-tapered waveguide

Pigtailed prototype With 3+12 μm SOI
Next R&D steps

- Adiabatic spot-size conversions between SSMF, 3 µm SOI and submicron waveguides
- Combining low-loss, low cost and high bandwidth
CONCLUSIONS

- Many PIC platforms to choose from
- 3 µm SOI technology offers SM PICs with
  - Low loss
  - Small footprint
  - Polarization independent operation
  - Scalability from R&D to production
- Future opportunities:
  - On-chip isolator
  - High-speed modulators and photodetectors
Acknowledgments

- We thank EU, Tekes, Business Finland and industrial partners for funding, and all R&D partners for fruitful collaboration
- RAPIDO-project (EU FP7, grant agreement 619806)
- MIREGAS project (EU H2020, grant agreement 644192)
- PASSION project (EU H2020, grant agreement 780326)
- OPEC-project (TEKES, grant agreement 2814/31/2015)
- RAPSI project (BF, 2018-2020)

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