Silicon Photonics

Michal Lipson
Cornell University
Outline

• Motivation for Silicon Photonics
• Ultra Low Loss Waveguides and Ring Resonators
• Electro-Optics Modulation
• Integrating Silicon Photonics with CMOS
Motivation for Silicon Photonics
Photonics Drives Telecom

Relative Information Capacity (bit/s)

Year

1880 1900 1920 1940 1960 1980 2000 2020 2040

~10Mbps.Km

Telephone lines first constructed

10-2 100 102 104 106 108 1010 1012 1014

OPTICAL FIBER SYSTEMS

Single channel (ETDM)

Multi-channel (WDM)

Communication Satellites

Carrier Telephony first used 12 voice channels on one wire pair

Advanced coaxial and microwave systems

Early coaxial cable links

We are experiencing this drive on-chip!

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Luxtera CMOS Photonics Technology

Silicon 10G Modulators
driven with on-chip circuitry
highest quality signal
low loss, low power consumption

Flip-chip bonded lasers
wavelength 1550nm
passive alignment
non-modulated = low cost/reliable

Silicon Optical Filters - DWDM
electrically tunable
integrated with control circuitry
enables >100Gb in single mode fiber

Complete 10G Receive Path
Ge photodetectors
trans-impedance amplifiers
output driver circuitry

Fiber cable plugs here
Ceramic Package

The Toolkit is Complete
✓ 10Gb modulators and receivers
✓ Integration with CMOS electronics
✓ Cost effective, reliable light source
✓ Standard packaging technology
Silicon Photonics For Multi-Core Interconnect

Bergman-Columbia, J. Kash, IBM

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High Confinement Waveguides For Functional Devices

- Intensity in the waveguides can be orders of magnitude higher than the intensity in the core of single mode optical fiber.
- Nonlinear optical effect can be excited with moderate optical power in short distances.

Silicon waveguides:
- High index contrast (very small waveguides: 3 orders of magnitude light enhancement when compared to fibers)
- Compatible with CMOS microelectronics.
- Ability of large-scale integration.
Fabrication

Ebeam Lithography → EBeam Resist

- Si: 250nm
- Si Substrate

Etching using RIE → Width = 450nm

- Si Substrate

Oxide Deposition
Orientation Of The Waveguides

Highly polarization dependent
Silicon waveguide

~3% transmission

Fiber

Silicon waveguide

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Naive Solution

0.5 μm

10 μm

cm
Inverse Taper

NTT, IBM

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A Very Small Waveguide

\[ \cos \theta \sim q \frac{\pi}{n k_o h} \]

If \( q=1 \) and \( h \) small, \( \cos \theta \sim \frac{\pi}{n k_o h} \) is large (small angle)

Small angle means very large evanescent field!
Inverse Taper

- 0.5 μm
- 20 μm
- 10 μm
Simulations

95% efficiency
<1dB losses

Ring Fabrication

Scanning electron micrograph of a ring resonator

Diameter = 12 μm
Width = 450 nm
Gap = 200 nm

Ebeam Lithography
EBeam Resist
Si: 250 nm
Si Substrate

Etching using RIE
Width = 450 nm
Si Substrate

Oxide Deposition
Si Substrate
Strong Light Confining Structures

Device is very sensitive to small perturbations in the Silicon
Ultra Low Loss Waveguides and Ring Resonators
State Of Art

Decreasing Losses In Silicon Waveguides

Etched Channel Waveguide: 1 – 2 dB/cm

Decreasing Losses In Silicon Waveguides

Shallow Etch Rib: 0.3dB/cm

Oxidized Shallow Rib: 0.4dB/cm

Po Dong, Wei Qian, Shirong Liao, Hong Liang, Cheng-Chih Kung, Ning-Ning Feng, Roshanak Shafiiha, Joan Fong, Dazeng Feng, Ashok V. Krishnamoorthy, and Mehdi Asghari, "Low loss shallow-ridge silicon waveguides," Opt. Express 18, 14474-14479 (2010)

Etchless Waveguides

Oxide Etch

Oxidation

Ebeam patterning

Etchless Waveguides

Waveguides dimensions: 315-nm high by 1-μm wide.

Losses < 0.3 dB/cm.
Results

• Etchless waveguide has a loss < 0.3 dB/cm.

• Waveguide is 1-μm wide by 70-nm high with an 8-nm slab.
Electro-Optics Modulation
Overview

Electro-optical modulation in pure-silicon platform relies on free carrier dispersion (FCD)

FCD is a change in refractive index of a material due to change in free carrier density within the material.

FCD always comes with free carrier absorption (FCA), due to Kramers-Kronig relation.
Forward PIN

Based on injection of carriers in a forward bias diode operation.

Can achieve very high index change per applied voltage due to exponential I-V characteristic of a diode.

Limited in speed due to carrier dynamics

Ring Resonator Based Electro-optic Modulator On Silicon-On-Insulator-Microns In Size


Fabrication

Scanning electron micrograph of a ring resonator

Width = 450nm

Diameter = 12μm

Gap = 200nm

Microscope image of fabricated optical modulator with electrical contacts

Ebeam Lithography

Etching using RIE

Oxide Deposition

Via Hole Etching and Ion Implantation

Contact Metallization

Si Substrate
Modulation Results (DC)
Dynamic Response

0.4 Gbit/s generated with 3.3 Vpp in micron-size device!


Lifetime under junction: 0.2 nsec
Micrometer Scale Silicon Electrooptic Modulator At 20 Gbps

PRBS $2^{10}-1$

>9dB modulation depth!

Q. Xu, M. Lipson, Optics Express Feb 2007
Integrating Silicon Photonics with CMOS Microelectronics
Silicon Photonics

Chip-scale optical data communication

Crystalline Silicon (n = 3.5)

Silicon Dioxide (n = 1.5)

Want electro-optic devices that are fast, small, and closely integrated with silicon microelectronics
Requirements Of Photonics

No Real-Estate Available in the Front-End!
Overview

There are three distinct approaches to combining photonics and electronics

– ‘Traditional’ SOI photonics by IBM, Luxtera, etc
– ‘Photonic Bridge Chip’ (e.g. by Oracle)
– ‘Localized Substrate Removal (LSR)’ bulk CMOS photonics (e.g. by MIT)
– ‘Deposited optics multi-chip module (MCM)’ (e.g. by Cornell)

Pros and Cons of each approach is discussed.
Deposited Silicon
Deposited Silicon

Crystalline grains: vertical, ~300 nm

Grain Boundaries: amorphous Si, ~1 nm thick

Silicon dioxide

Side view

Cross-section TEM of crystallized LPCVD film

Polysilicon

Silicon dioxide

100 nm

Grain size ≈ Device size
Backend Photonics

Increased Density in 3D

Silicon nitride

Silicon dioxide

Poly

Metal

Silicon

n
p

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Poly Rings

\[ Q = 20,000 \]
\[ \alpha \approx 15 \text{ dB/cm} \]

\( \Delta \lambda = 0.079 \text{ nm} \)


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Fabrication

Cross-section (not to scale)

Silicon substrate

Thermal oxide

Polysilicon

n-

p+

n+
Fabrication

Cross-section (not to scale)

Top view (microscope)

Schematic
Polysilicon Electro-Optic Modulator

10 micron device:

2.5 Gb/s NRZ $2^7-1$ PRBS electrical signal applied, ±4 V swing, 4 V DC bias

- 10 dB modulation depth
- No reverse bias (fast recombination)
- Power consumption ~ 2 mW (<1 pJ/bit)

LCD Industry: Laser Annealing

Deposit low-temperature amorphous-Si
Melt and crystallize Si with fast laser pulse
Currently used in mass production for high quality TFT-LCD displays
Passive SiN Waveguides

Increased Density in 3D
Silicon Nitride, Si$_3$N$_4$

- $n=2$
- $\lambda > 400\text{nm}$
- Propagation Losses $< 0.1 \text{ dB/cm}$
- Low nonlinear absorption

Riedel, 2004
Experimental Setup Layout

4 dB total insertion loss (Fiber to Detector)
Qs up to 3,000,000
Waveguide losses ~0.1 dB/cm
Vertically Coupled Rings
Low-Temp 3D Results

- WG loss < 1.5 dB/cm in L-Band
- Crossing loss 0.04±0.002 dB/cross
- 25 GHz / 24 dB extinction drop port

\[ Q_{\text{load}} = 7,500 \quad Q_{\text{int}} = 170,000 \]
Integration Of Photonics On CMOS
Summary

• Silicon photonics can provide high bandwidth, high speed for current microelectronics.
• High index contrast accounts for highly optical confining structures enabling sub-micron size GHz optical elements, such as optical waveguides, splitters, modulators, emitters, detectors, etc.
• Main challenges that remain: light emission and amplification, thermal sensitivity, integration with CMOS.