Silicon Photonics

Prof. Sasan Fathpouri

fathpouri@creol.ucf.edu
http://ipes.creol.ucf.edu

CREOL, The College of Optics and Photonics
University of Central Florida
Orlando, FL, 32816

A Short Course at
CREOL Industrial Affiliates Symposium
March 6, 2014
2:45-3:15 pm, Room 102, CREOL Bldg.
Instructor’s Bio

2005: Ph.D., University of Michigan, Ann Arbor
Dissertation on Lasers and Spintronic Light Sources Based on III-V Quantum Dots
Advisor: Pallab Bhattacharya

2005-2007: Postdoctoral Fellow, UCLA
Mentor: Bahram Jalali
2007: Visiting Assistant Professor, UCLA

2008: Senior Researcher at Ostendo Technologies, Carlsbad, CA

2008-Present: Assistant Professor
CREOL, The College of Optics and Photonics, UCF
Relevant works by the instructor

Silicon Photonics
Bahram Jalali, Fellow, IEEE, and Sasan Fathpour, Member, IEEE

Invited Paper

Silicon Photonics
B. Jalali and S. Fathpour
IEEE Journal of Lightwave Technology
40th Anniversary Special Issue on Optoelectronics
vol. 24, pp. 1400–1415, December 2006

Silicon Photonics for Telecommunications and Biomedicine
Edited by S. Fathpour and B. Jalali, CRC Press, 2012

Interested in a full course:
OSE 6938S: Integrated Photonics
Course Outline

- Part 1: Introduction and passive silicon photonic devices
  - Applications
  - A bit of history
  - Silicon-on-insulator waveguides, MMI, AWG, etc.

- Part 2: Active silicon photonic devices
  - Light modulation, detection, and emission in silicon

- Part 3: Current trends and challenges
  - Will photonics truly merge with VLSI CMOS?
  - Competing technologies for silicon photonics

- Part 4: Nonlinear silicon photonics
  - Physics and devices

Contents focused on:
1. Applications  2. New functionalities  3. Instructor’s expertise
Battle between Optics and Copper

Drive optics to high volumes and low costs
Why Integrated Photonics?

Advantages to discrete photonic components:

- More compact
- Higher bandwidth
- Wavelength multiplexing
- Batch fabrication, i.e., cheaper
- More reliable
- Possibility of integration with electronics
- Immunity to mechanical vibrations

Bye Bye!

Hello!
The Vision for Integrated Photonics or Optoelectronic Integrated Circuits

Amplifier and/or Laser

Filter

Modulator

CMOS Circuitry

Passive Alignment

Photodetector

Courtesy of Intel Inc.

Figure: http://www.tweakers.net/ext/i.dsp/1109883395.png
Si Photonics: An Industry 25 Years in the Making

Dr. Richard Soref (USAF) pioneered Si photonics in the '80s

“...single-crystal Si will be suitable for building directional couplers, filters, star couplers, optical switches, mode converters, polarizers, interferometers, and modulators that operate at \( \lambda = 1.3 \) or 1.6 \( \mu m \) (and beyond)-essentially every integrated-optical component except an optical source. The use of Si for photodetection at 1.3 \( \mu m \) has also been suggested.”


Fundamental work developing silicon waveguides between 1985-1989

Application 1: Low-Cost Optical Transceivers

**160 Gb/s Transceiver - IBM**


**10 Gb/s Transceiver - Luxtera**

Key to success: a high volume market

Luxtera: 4x10 Gb/s Active Optical Cable
Optical Interconnects for Data Centers and Supercomputers

Sun Microsystems’s Data Center Technology

IBM’s Supercomputing Technology
Evolution of Rack-to-Rack Optics in Supercomputers

VCSEL-based Optics has displaced electrical cables today

Future directions for optical cables:
- Lower cost (well below $1 per Gb/s)
- Higher bitrates: 10+ Gb/s per channel
- More optics as bandwidths increase
- Smaller footprint for O/E modules
- Move optics close to logic

Huge market for Active Optical Cable (AOC)
Vision for 2020 – Optically connected 3-D Supercomputer Chip

- 36 “Cell” 3-D chip
- Silicon photonics layer integrated with high performance logic and memory layers
- Layers separately optimized for performance and yield

Photonic layer not only connects the multiple cores, but also routes the traffic

- Logic plane: ~300 cores, ~5TF (36 “superores”)
- Memory plane: ~30GB eDRAM
- Photonic plane: On-Chip Optical Network
  >20 Tbps (bidirectional) optical on-chip (between supercores)
  >20 Tbps optical off-chip

System level study:
IBM, Columbia, Cornell, UCSB

Courtesy of Jeff Kash
Futuristic Application: Optical Interconnects

- D. A. B. Miller, *JSTQE* 2000
- M. Kobrinsky et al., *Intel Technology Journal*, 2004
- Wyatt Gibbs, *Scientific American* 2004
- P. Fauchet et al., *JSTQE* 2006

Microelectronics in the Last Half a Century

Texas Instruments

Intel’s 62- Core Xeon Phi: 5 billion transistors

1958

2014

Smaller
Smaller
Smaller
Smaller
Smaller
Smaller
Smaller

Sasan Fathpour, CREOL
Celebrated Moore's Law

Source: Intel
Will Silicon Have Steel’s Destiny?

- US steel production increased at an exponential rate from 1860 to 1900.
- In 1900-1950, it increased at a more modest rate.
- Steel remains the principal structural material.
Copper Interconnect Limitations

- Problems with chips today:
  1) Latency
  2) Bandwidth
  3) Power Dissipation
  4) Electromagnetic Interference
  5) Signal Integrity

Pentium 4
Problem 1: Latency of Global Interconnects

Latency = Resistance x Capacitance
\sim 1/\kappa^2

Unlike transistors, for which performance improves with scaling, the delay of interconnects increases with scaling.

Jim Brown et al., CICC 2004
Optimal Reverse Scaling

Figure 4: Schematic diagram showing the increase in the effective resistivity of copper as a function of Cu width (i.e., not including the barrier thickness)

Problem 2: Bandwidth

Need for optical chip-to-chip interconnects: SONY CELL™ Processor

9 core main processor
256 GFLOPS @ 4GHz

Memory
XIO
FlexIO
Graphics Processor

FLOPS: floating-point operations per second

Sony CELL Processor (Playstation 3)

26 GB/s
77 GB/s (max)

http://www.scei.co.jp/corporate/release/pdf/050517e.pdf,
It is an irony that the integrated circuits’ (IC) clock stopped increasing the year its inventor, Jack Kilby, died in 2005!

David A. Muller, Nature Materials 5, 645 (2005)
Problem 3: Power Dissipation

The graph shows the relationship between feature size (μm) and chip maximum power density (W/cm²) for different processor generations:

- **Pentium Pro**: 30W
- **Pentium**: 14W
- **I486**: 2W
- **I386**: 1W
- **Pentium II**: 35W
- **Pentium III**: 35W
- **Pentium 4**: 75W
- **Itanium**: 130W

The graph indicates a trend where power dissipation increases with decreasing feature size. The feature size is shown on the x-axis, and the power density is shown on the y-axis. The line on the graph represents the trend, with data points for each processor generation.


http://sss.lanl.gov/presentations/021003-UlUC.pdf
Options for Global Interconnects Beyond the Metal/Dielectric System

- **Use Different Signaling Methods**
  - Signal design
  - Signal coding techniques
- **Use innovative design and package options**
  - Interconnect-centric design
  - Package intermediated interconnect
  - Chip-package co-design
- **Use Geometry**
  - 3D
- **Use Different Physics**
  - Photonics (emitters, detectors, free space, waveguides)
  - RF/microwaves (transmitters, receivers, free space, waveguides)
  - Terahertz photonics
- **Radical Solutions**
  - Nanowires/nanotubes
  - Molecules
  - Spin
  - Quantum wave functions

Ultimate solution:
The most potent antidote would be to discover an interconnect nanotechnology that provided high-temperature, superconductive materials with resistivity → 0

INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS
2005 EDITION
Optical Interconnects

Optical interconnect

Optical clocking source

Inter-chip  Intra-chip

Wavelength Division Multiplexing:

\[ \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \ldots, \lambda_n \]

Optical Receiver
(photodetector/TIA)

Local electrical H-tree distribution

http://photonics.mit.edu/Optical_Clock.html
It is not electrons or other charge carriers that carry the signals in wires, rather it is electromagnetic waves (of one kind or another).

Signals in wires do not propagate at the electron velocity (~ $10^6$ m/s) but at light velocity (or somewhat smaller if the cables are filled with a dielectric).

However, in electrical interconnection, the signals do move at a slower bit rate, i.e., the RC delay limits the bandwidth.
Photonics is good for silicon but is silicon good for photonics?

- Transparent in 1.3-1.6 $\mu$m region
- CMOS compatibility
- Low cost
- High-index contrast - small footprint

- High index contrast - high waveguide loss
- No detection in 1.3-1.6 $\mu$m region (in bulk Si)
- No linear electro-optic effect
- No efficient light emission
- High cost of state-of-the-art CMOS
Why Silicon Photonics?


SOI: silicon on insulator

- Compatibility with CMOS electronics on SOI wafers
- High-refractive index contrast
  - sharp bends
  - small waveguide cross-sections

**CMOS**

**Silica Waveguide**

**SOI Waveguide**

**Silicon (n~3.5)**

**Buried Silicon Oxide (n~1.5)**

**Silicon Substrate**

- air
  - $n = 1$
Wafer splitting (SmartCut™ Process to produce Unibond® wafers)

A seed wafer, from which a layer of Si will be removed, is oxidized to a desired thickness followed by hydrogen implantation (The oxide will become the BOX after bonding).

After implantation, the seed wafer and the handle wafer are carefully cleaned before bonding in order to eliminate any particle and surface contaminants and to make both surfaces hydrophilic.

A batch of bonded wafer pairs is loaded into a furnace and heated to a temperature of 400–600°C, at which point the wafers split along the hydrogen implanted plane.

The as-split wafer surface has a mean roughness of a few nanometers.

Implant Dose = $5 \times 10^{16}$ cm$^{-2}$

Developed at LETI, France in mid 90’s


Affiliates Day Short Course  
Sasan Fathpour, CREOL
1990's work on Passive Si Optics

Bahram Jalali, UCLA

Directional Coupler, 1996

SOI Arrayed Waveguide Grating WDM, OFC 1997

Multimode Interference Coupler, 1996

Gratings 1998

30

Affiliates Day Short Course

Sasan Fathpour, CREOL
Channel vs. Rib SOI waveguides

- IBM’s Si wire waveguides with 445 nm x 220 nm cross-section:
  - Minimal propagation losses of 3.6 dB/cm for the TE polarization at 1.5 μm
  - Losses per 90° bend are measured to be 0.086 dB for a bending radius of 1 μm and as low as 0.013 dB for a bend radius of 2 μm.

- 1-μm wide rib waveguides
  - Losses are 0.4 dB/cm and 0.5 dB/cm for 380-nm and 200-nm Si film, respectively


Coupling to Si wire waveguides

- The cross-sectional area of a Si wire waveguide is about 1,000 times less than that of an optical fiber.
- Moreover, strong reflective behavior at unmatched connections will degrade dependence of the coupling efficiency on wavelength because of Fabry-Perot resonances, i.e., Fresnel loss.
Coupling light into waveguides

- Conceptually trivial but challenging in practice
- A true example of an engineering problem
- Problem: the small size (at most a few micron) cross-sectional dimensions of WGs
- Solutions:
  - End-fire coupling
  - Prism coupling
  - End-butt coupling
  - Grating coupling
Tapered mode size converters

Coupling light from an optical fiber into a silicon waveguide is like pouring water from a fire hose into a straw
Kotura Inc.: Laterally tapered mode converter

<1 dB coupling loss measured

Transmission %

Adiabatic limit

Taper length
Luxtera Corporation: a 2-D grating design or holographic lens

- The so-called holographic lens is a diffractive-optic structure that mode-matches the fiber with a $0.1 \mu m^2$ waveguide with less than 2.5 dB of loss across the C-band (1532-1562 nm)
- The lens is constructed at the gate polysilicon step, already present in the process, depositing and etching it over the transistor silicon

NTT and IBM approach: polymer tapers

Polymer: 3 μm × 3 μm
Silicon: 0.3 μm × 0.3 μm

- The tip of the taper has to be extremely thin. How thin?

- A 200-μm long taper with a 60-nm wide tip is needed to attain an acceptable conversion loss of 1 dB.


Fig. 4 Transmission spectrum of Si wire waveguide with two mode size converters

Fig. 2 Calculated conversion loss
a Dependence on tip width (taper length = 200 μm)
b Dependence on taper length (tip width = 40 nm)
**Grating couplers**

Different diffraction orders can be satisfied.

Diffracted beams are generated by output coupling of the guided mode field due to scattering by the beam.

Design to minimize diffracted modes!

Image from:
The total coupling loss from a fiber to silicon waveguide comprises the fiber to SiON waveguide loss (\(\sim 0.7\) dB) plus SiON to silicon waveguide loss (2.6 dB).

- A coupling efficiency of 55\% measured.

Advanced Passive Devices: WDM Components

- Need for various integrated devices to perform many functions that can be categorized as:
  - 1) **Amplitude/intensity components:**
     - couplers, splitters, amplifiers, attenuators, reflectors, modulators
  - 2) **Phase components:**
     - Phase shifters, phase modulators
  - 3) **Polarization components:**
     - Polarizes, polarization splitters, polarization controllers
  - 4) **Wavelength components:**
     - Wavelength filters, multiplexers, demultiplexers
  - 5) **Frequency components:**
     - Frequency shifters, filters
  - 6) **Active components:**
     - Lasers, amplifiers
  - 7) **Circulators:**
     - Optical isolators, optical circulators

A lot of these components are available based on fibers for in-line fiber optics operation. Is silicon photonics ready to compete?
Waveguide directional couplers

- Coupling ratio \( R[\%] = \frac{P_c}{(P_t+P_c)} \times 100; \ R \ [\text{dB}] = -10 \times \log(R[\%]) \)
- Excess loss \( L_i[\text{dB}] = 10 \times \log\left[\frac{P_i}{(P_t+P_c)}\right] \)
- Insertion loss = \( 10 \times \log\left(\frac{P_i}{P_c}\right) = R \ [\text{dB}] + L_i \)
- Directivity = \( 10 \times \log\left(\frac{P_r}{P_i}\right) \)
- Good directional couplers should have
  - Low insertion loss and high directivity
- Commercially available in fibers:
  - \( R \sim 50/50 \) to \( 1/99 \)
  - Excess loss < 0.1 dB \( \rightarrow \) insertion loss < 3.4 dB
  - Directivity better than -55 dB
- Can integrated devices beat fiber-based devices?
Multiplexers/Demultiplexers

- Directional couplers are wavelength-sensitive (look at the theory)
- Consider a coupler with $\kappa_1, \kappa_2$ at $\lambda_1$ and $\lambda_2$, respectively, so that $\kappa_1L = m\pi$ and $\kappa_2L = (m-1/2)\pi$
  - $P_2(\lambda_1,L) = P_i \times \sin^2(\kappa_1L) = 0$
  - $P_2(\lambda_2,L) = P_i \times \sin^2(\kappa_2L) = P_i$
- That is a 2x2 demultiplexer
- The same device can be used as a multiplexer (how?)

incident $P_i$  $\lambda_1$ only

$\lambda_2$ only
Multimode Interference (MMI) splitters

- The MMI coupler consists of single-mode input and output waveguides separated by a slab region.
- The slab region supports a large number of modes that propagate with different phase velocities leading to periodic self-imaging.
- The output waveguides are placed at the positions of the intensity peaks.
- The length of the multimode section scales as \( L \sim W^2/m \), where \( m \) is the number of maxima in the image (or the fanout) and \( W \) is the effective WG width.

**MxN Star Couplers**

- A star coupler combines the optical signals entering from its multiple input ports and divide them equally among the output ports.

- In contrast to demultiplexers, star couplers do not contain wavelength-selective elements, as they do not attempt to separate individual channels.

- The number of input and output channels may not be the same.

  - For example, for video distribution, a relatively small (e.g., 100) channels may be sent to thousands of subscribers.

An 8x8 star coupler formed by using twelve 2x2 single-mode fiber couplers.

Integrated M x N Star Coupler

Arrayed Waveguide Grating (AWG) or phased-array (PHASER) Devices

- The WDM signals experience different phase shifts due to different waveguide lengths
- Moreover, the phase shifts are wavelength-dependent because of the frequency dependence of the mode-propagation constant
- Different channels focus to different output waveguides

A. Kaneko et al., J. Select. Topics Quant. Electr. 5, 1227 (1999)
Silicon Photonics-Based AWG

\[ \lambda_1 \lambda_2 \lambda_3 \lambda_4 \]

Fabry-Perot filters

- FSR: \( \Delta \lambda = \frac{\lambda_R^2}{2n_gL} \); 
  \( n_g = n_{\text{eff}} - \lambda \frac{d n_{\text{eff}}}{d \lambda} \) group index of refraction
- FWHM: \( \delta \lambda = \lambda_R^2 \times \frac{(1-R)}{(2\pi L n_g)} \times \frac{(1-R)}{\sqrt{R}} \),
- Finesse: \( F = \frac{\text{FSR}}{\text{FWHM}} = \frac{\Delta \lambda}{\delta \lambda} = \frac{\pi \sqrt{R}}{(1-R)} \)
- Quality Factor: \( Q = \frac{\lambda_R}{\delta \lambda} = n_g \lambda \omega_R \sqrt{R}/c(1-R) \)
- Large FSR (\( \Delta \lambda \)) and small FWHM (\( \delta \lambda \)) are demanded (why?) \( \rightarrow \) large \( F \)
- For today’s DWDM systems, optical filter bandwidths of < 0.8 nm are desirable, which can be met by integrated FP resonators
  - However, their FSR is < 10 nm, i.e., multiple channels are passed at the same time
  - To achieve 40 nm FSR, < 9 nm cavity lengths are required!!
Ring resonators

- Light is coupled into the ring via evanescent field of the input WG (also known as input bus)
- The ring is at resonance when the full trip around the ring is \( m \times 2\pi \), where \( m \) is an integer
- Resonance wavelength:
  \[ \lambda_R = 2\pi R \frac{n_{\text{eff}}}{m}, \]
where \( R \) is the ring radius
- FSR:
  \[ \Delta\lambda = \frac{\lambda_R^2}{2\pi R n_g} \]
- Assuming weak coupling between the ring and the two waveguides (both represented by \( \kappa \)):
  - FWHM:
    \[ \delta\lambda \approx \frac{\kappa^2 \lambda_R^2}{4\pi^2 R n_g} \]
  - \( F \approx \frac{2\pi}{\kappa^2}, Q = \frac{\lambda_R}{\delta\lambda} \approx \frac{4\pi^2 R n_g}{\kappa^2 \lambda_R} \)

- At resonance, light coupled into the ring constructively interferes with the input light
- As a result, optical intensity in the ring can build up and be significantly higher than the waveguide
- But of course, light will also experience loss
Ring resonator filters: MUX/DEMUX


• Finesse, $F$, defined as $\Delta \lambda / \delta \lambda$, while quality factor, $Q$, defined as $\lambda_R / \delta \lambda$

• Alternative way of looking at $Q$:
  • If $N$ is the number of round trips required to reduce optical intensity to $1/e$ of the initial value, the finesse is $F = 2\pi \times N$
  • $Q = \omega_R T N = 2\pi N c T / \lambda_R$ ($T$: time for trip around the ring)
Bragg Gratings as filters

- At phase-matching condition: \( \lambda_{\text{reflected}} = \lambda_B = 2n_{\text{eff}}\Lambda/m \)
- FSR = \( \lambda_B (m = 1) - \lambda_B (m = 2) = n_{\text{eff}}\Lambda \)
  - As low as 0.12-nm channel spacing, i.e., FSR demonstrated
- Linewidth: \( \Delta \omega = 2\kappa_Gc/2n_{\text{eff}} \rightarrow \Delta \lambda = \Lambda^2\kappa_G/(2\pi n_{\text{eff}}) \)
- Maximum reflectivity: \( R_{\text{max}} = \tanh^2(\kappa_GL) \)
- For a narrowband filter: small \( \kappa_G \)
- For a high-efficiency filter: \( \kappa_GL \gg 1 \)
Integrated silicon photonic filters

$F = 375, Q = 39,350$
$FSR = 0.083 \text{ nm} = 1.8 \text{ THz}$

$F = 591, Q = 280,000$
$FSR = 3.25 \text{ nm} = 428 \text{ GHz}$

Q. Xu et al., Nature 435, 325 (2005)
M.W. Pruessner et al., LEOS 2006, 46 (2006)

$F = 196, Q = 10,774, FSR = 81.7 \text{ nm} = 8.9 \text{ THz}, FWHM = 0.15 \text{ nm}$
Cascaded apodized grating waveguides for delay lines

S. Khan and S. Fathpour:
Optics Letters 38, 3914 (2013)
Optics Express 21, 19538 (2013)
Optics Express 20, 19859 (2012)
Optics Express 19, 11780 (2011)

Demonstration of tunable optical delay lines based on apodized grating waveguides

Funded by the National Science Foundation (NSF)
Part II: Active silicon photonics

Silicon optical modulators
Optical modulation in Si Photonic Circuits

• Which effect will work?
  • Pockels (linear electro-optic) effect
  • Kerr (second-order electro-optic) effect
  • Franz-Keldysh effect
  • Thermo-optic effect
  • Plasma dispersion effect
Pockels (linear electro-optic) effect

- In a linear electrooptic material, like LiNbO$_3$, the index ellipsoid is changed in the presence of an applied electric field, $E_{dc}$, i.e., $\Delta n \propto E_{dc}$, via the electrooptic coefficients $r_{ijk}$.
- The key for having Pockels effect is using an anisotropic medium.
- Silicon has a centrosymmetric lattice structure:
  - All $r_{ijk}$ vanish.
  - Si lacks second-order nonlinear effect.
  - Pockels effect is virtually nonexistent in silicon 😞.
Kerr (second-order electro-optic) effect

- Kerr effect is related to third-order optical nonlinearity (P \( \propto X^{(3)}E^3 \))
- In Kerr effect, \( \Delta n \propto E_{dc}^2 \)
  - \( \Delta n = s_{33} n_0 E_{dc}^2/2 \)
  - \( s_{33} \) is the Kerr coefficient
  - \( n_0 \) is the unperturbed refractive index
- In Si, \( \Delta n \sim 10^{-4} \) achieved for \( E_{dc} \sim 10^6 \text{ V/cm} \)
- The effect is relatively small compared to plasma dispersion effect

Franz-Keldysh effect:
Electroabsorption due to presence of a strong electric field
Franz Keldysh effect also induces electrorefraction
However, the effect diminishes significantly at telecom wavelengths

Fig. 3. Field dependence of electrorefraction at two wavelengths, as determined from Fig. 2. The dashed lines are extrapolations.

Thermo-optic effect

- The refractive index changes by applying heat to the material
- In silicon $dn/dT = 1.86 \times 10^{-4} \text{ /K}$
- $\pi$-shift demonstrated in a 500 μm waveguide with 10 mW of applied heat
  - corresponding to $\Delta T = 7 \degree C \rightarrow \Delta n = 1.3 \times 10^{-3}$

Issues:

- Controlling the temperature rise to the locality of the waveguide
- Efficiency of the mechanism used to deliver heat

Warning:

- Thermooptic effect: $dn/dT > 0$
- Carrier-plasma effect (next slide): $dn/dN < 0$
- The effects could compete in a poorly designed modulator
Plasma dispersion effect (carrier injection/depletion)

- Modulate free-carrier density to modulate optical loss:

\[ \alpha_{FCA} = \Delta \alpha_e + \Delta \alpha_h = (8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P) \]

and/or refractive index:

\[ \Delta n = \Delta n_e + \Delta n_h = -(8.8 \times 10^{-22} \cdot \Delta N + 8.5 \times 10^{-18} \cdot (\Delta P)^{0.8}) \]
The first Si switch (modulator)

- Silicon-based 2 x 2 optical switches fabricated based on refractive index change induced by injected minority carriers
- Carrier injection into the mid-section layer (directional coupler) by forward-biasing the p⁺-n junction diode
- The phase shift by carrier injection allows switching into port 3 or 4

\[ \Delta n \left( \frac{N}{N^+} \right) = 0.015 \]

\[ L = 0.4-2.0 \text{ mm} \]

Intel’s carrier-depletion 40 Gb/s MZI modulator

Travelling-wave design allow co-propagation of electrical and optical signals along the length of the device

In the accumulation operation, the n-type silicon in the phase shifter is grounded and a positive drive voltage, $V_D$, is applied to the p-type polysilicon.

When a positive $V_D$ is applied to the device, a thin charge layer is accumulated on both sides of the gate oxide.

Ring-resonator modulators

- Carrier injection via a p-n junction n into a ring resonator shifts its resonance, leading to a modulation effect
- Used:
  - BOX thickness: 3 μm
  - Waveguide: 450 nm x 250 nm

Q. Xu et al., Nature 435, 325 (2005)
Part II: Active silicon photonics

Photodetectors
Absorption coefficient

\[ \alpha(\omega) = \left( \hbar \omega - E_{g,\text{Si}} \right)^2 \]

\[ \alpha(\omega) = \left( \hbar \omega - E_{g,\text{GaAs}} \right)^{1/2} \]

Direct vs. indirect bandgap materials
Si Photodetectors

- Photodetectors are perhaps the oldest and best understood silicon photonic devices.
- Commercial products operate at wavelengths below 1000 nm, where band-to-band absorption occurs.
- Additionally, used in conjunction with scintillators, they are widely used as X-ray detectors that are used in medical computed tomography equipment and airport luggage scanners.
- For application in fiber-optic communication, silicon is not the right material since it is transparent in the 1300- and 1550-nm operating wavelengths of these networks.
SiGe Photodetectors

- Strain limits the thickness of Ge layers that can be epitaxially grown on silicon.
- A thin Ge layer is preferred from the bandwidth point of view as it minimizes the carrier transit time, but it comes at the expense of reduced absorption and diminished responsivity.
- A waveguide p-i-n geometry is preferred over a normal-incidence design since it allows independent optimization of absorption volume and transit time.
Ge-on-Si Vertical Incidence Photodiodes with 39-GHz Bandwidth (Univ. of Stuttgart)

- The detector comprises a 300-nm-thick intrinsic region, and exhibits zero bias external quantum efficiencies of 23%, 16%, and 2.8% at 850, 1298, and 1552 nm, respectively.

A 15-Gb/s 2.4-V Optical Receiver Using a Ge-on-SOI Photodiode and a CMOS IC

Intel’s 40 Gb/s waveguide photodetectors

T. Yin et al., Optics Express 15, 13965 (2007)
Part II: Active silicon photonics

Light emission in silicon
Silicon Lasers: If only Silicon Were a Direct Band-Gap Material!

First order transition: very efficient

2nd order transition: ~ 1000x less efficient
Why Silicon Cannot Amplify Light

- Gain in silicon is lower because of indirect bandgap
- Free-Carrier Absorption prevents silicon from achieving gain
- Auger recombination becomes significant at $N > 10^{19}$ cm$^{-3}$
- Ge is better: less indirect and lower free carrier absorption rate

Light Generation/Amplification Techniques in Si: Series 1

- Erbium-doped Si
- Si rich oxide or Si nanocrystals (NCs)
  - Er-doped Si NCs
- Deposition of boron dopant with \( \text{SiO}_2 \) nanoparticles mix on Si
- Dislocation loops
  (W. L. Ng et al., Nature 410, 192, 2001)
- Surface texturing
  (M. A. Green et al., Nature 412, 805, 2001)
- Band-engineered Ge-on-Si
  using tensile strain and n-type doping
  (J. Liu et al., Optics Letters 35, 679, 2010)
Light Generation/Amplification Techniques in Si: Series 2

- Bonded III-V on Silicon - UCSB/Intel
- Monolithic III-V on Silicon - Univ. of Michigan
- Using nonlinear interactions, i.e., Raman laser (Part IV)

Review articles:

Hybrid AlGaInAs-silicon platform

Bowers et al. UCSB
Paniccia et al. Intel

Startup company: Aurrion LLC (aurrion.com)
Santa Barbara, CA

Use silicon waveguide to guide light, evanescently coupled MQW to provide gain

Two important design parameters
• QW confinement factor: Gain
• Silicon confinement factor: Coupling efficiency to passive photonic devices

Silicon waveguide dimensions determine the confinement factors
Monolithic III-V on Silicon: Univ. of Michigan

Pallab Bhattacharya et al.
Part III:
State of the Industry and Challenges
Kotura 100GbE Integrated Solution

- Integrated WDM platform to offer high aggregate data rates (>100Gb/s) on a single fiber.
- Directly modulated lasers or EMLs
- Silicon acts as a platform for integration as well as an assembly platform
- Eliminates significant number of parts and simplifies assembly

Work funded under NIST ATP Funding

References [1,2]

PD / Surface mount technology

Acquired by Mellanox
Luxtera’s 4 x 10 Gb/s Si Transceivers

- **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 w/ control circuitry
  - Enables >100Gb in single mode fiber

- **Complete 10G Receive Path**
  - Ge photodetectors
  - Trans-impedance amplifiers
  - Output driver circuitry

The Toolkit is Complete
- 10Gb modulators and receivers
- Integration with CMOS electronics
- Cost effective, reliable light source
- Standard packaging technology

Top view of a flip-chipped laser on top of a CMOS die. The laser die is outlined by the dashed white lines.

Germanium photodetector integrated into CMOS, shown with 10-Gbps eye

A. Huang *et al.*, 2006 ISSCC
Intel’s 4 x 12.5 Gb/s Silicon Photonics Link

InP laser evanescently coupled into a Si WG

White Paper, Intel Labs, July 2010
Constituents of CMOS Compatibility

- **Material Compatibility** 😊
- **Process Compatibility** 😊
- **Economic Compatibility** 😞
- **Heat Compatibility** 😞

Is silicon photonic truly CMOS compatible?

(IEEE Spectrum, 2002)
Optical vs. Copper Interconnects

Figure of merit: Bandwidth density/latency

\[ \sim \lambda/3 \sim 200 \text{ nm} \]


WDM signaling is necessary for optical interconnects to be competitive
Side Note: SIMOX 3-D Sculpting in Si

Oxygen Implant

Silicon

SiO2

Two-Photon and Free-Carrier Absorptions


\[
\frac{dI}{dz} = -\alpha I - \beta I^2 - \alpha_{FCA} I, \quad \alpha_{FCA} \propto \Delta N \propto I^2
\]
Two-photon vs. Conventional Photovoltaic Effect

\[ V > 0 \quad \text{and} \quad I < 0 \]

- \( \hbar \omega_p \)
- \( \hbar \omega_p \)

S. Fathpour et al., IEEE J. Quant. Electron. 43 1211 (2007)
Substrate materials used for optical integrated circuits (OIC)

- **PASSIVE (incapable of light generation)**
  - Quartz
  - Lithium niobate
  - Lithium tantalate
  - Tantalum pentoxide
  - Niobium pentoxide
  - Silicon
  - Polymers

- **ACTIVE (capable of light generation)**
  - Gallium Arsenide
    - AlGaAs, InGaAs,…
  - Indium Phosphate
  - InGaP, AlGaP, InGaAsP,…
  - Other III-V and also II-VI semiconductors
III-V optoelectronic integrated circuits

- Pursued since 1980s to monolithically integrate lasers, photodetectors and the driver/detection electronic circuits on the same GaAs or InP chip:
  - OEIC = few channels × (one LD or PD + few transistors)
- Nowadays, more and more optical functions are integrated
- Generally, integration of LDs with drivers is more complicated than photoreceivers:
  - More stringent materials and processing requirements
Two early integrated photoreceivers

Early monolithically integrated photoreceivers used one-transistor amplifiers and dealt mostly with the challenge of differences between PD vs. transistor heterostructures.

An early integrated transmitter circuit by Fujitsu

Q2 and Q3: differential amplifier to modulate the laser
Q1: laser bias current controller
Q4: current limiter

FIG. 1. Equivalent circuit of monolithic laser/driver.

Exposed flip-chip bonding pads on the CMOS chip were first metallized with Ti–Ni–Au metals to improve adhesion to the top-level Al on the chip.

PbSn (lead-tin) solder was then deposited on the CMOS chip.

Next, the bottom-emitting VCSEL array on the GaAs chip was flip-chip bonded directly over the CMOS circuits using two coplanar Au contacts per laser.

Epoxy was wicked in-between the chips to act as an adhesive.

The simple two-transistor VCSEL driver was based on a current-shunting principle:

- A PMOS transistor was used to source an adjustable amount of current through the laser.
- An NMOS transistor was used to quickly shunt the current into and out of the VCSEL.

IBM's CMOS-Based Parallel Optical Transceiver Capable of 240-Gb/s Bidirectional Data Rates

- The “Optochip”, which is comprised of VCSEL and photodiode (PD) arrays that are flip-chip bonded to a CMOS IC, is directly soldered to a high-density organic chip carrier to form an optical module, or “Optomodule”.
- The “Optomodule” is then soldered to an underlying circuit board, or “Optocard”, that contains dense arrays of polymer optical waveguides, 45° turning mirrors, and lenses for efficient optical coupling.

C. L. Schow et al., J. Lightwave Tech. 27, 915 (2009)

SLC: surface laminar circuit carrier
InP-based Photonic Integrated Circuits (PIC)

DML: Directly modulated lasers
SOA: Semiconductor optical amplifier
EML: Electroabsorption modulated lasers


Fig. 22. Progression of scaling of the number of functions/chip for InP-based transmitter chips utilized in commercial telecommunications networks. The 100 Gb/s DWDM transmitter PIC’s described in this work represent an order of magnitude increase in scale compared to existing commercial devices.

Fig. 23. Scaling of the data capacity/chip for InP-based transmitter chips utilized in commercial telecommunications networks. Over the last 25 years, the data capacity per chip has doubled an average of every 2.2 years. The 100 Gb/s DWDM transmitter PIC’s described in this work represent an order of magnitude increase in data capacity per chip compared to existing commercial devices.
OneChip Photonics Inc.’s transceiver for fiber-to-the-home (FTTH) applications

OneChip Diplexer PIC integrates a number of photonic devices. Images courtesy of OneChip Photonics Inc.

Monolithic PIC device mounted on the silicon optical bench (SiOB) provides the heart of the bidirectional optical subarray (BOSA), which is then integrated with the transceiver printed circuit board and housing to form the complete transceiver configuration.

http://www.onechipphotonics.com/
Infinera Corporation’s Large-Scale Photonic Integrated Circuit (LS PIC)

- The first commercially deployed monolithic large-scale PICs providing transmit and receive functions
- The transmitter (TX) PIC includes over 50 discrete functions integrated monolithically on a single chip, spread over ten channels with an aggregate data capacity of 100 Gb/s.
- A similar monolithic receiver (RX) PIC (not shown here) supports a similar aggregate data rate of 100 Gb/s.

VOA: Variable optical attenuator
EAM: electroabsorption modulator
OPM: optical power monitoring
AWG: Arrayed waveguide grating
Final Remark on Heterogeneous Optoelectronics

- It appears that for the foreseeable future, hybrid technologies, that combine group IV and III-V semiconductor materials, and perhaps LiNbO$_3$ will most likely dominate integrated optoelectronics:

  - Electronics will most likely be on Si
  - Lasers will most likely be on III-Vs
  - Detectors will more likely be on Ge, but perhaps on III-Vs
  - Modulators could be on either Si, III-Vs or LiNbO$_3$
  - Passive devices (waveguides, filters, etc.) will more likely be on Si but maybe on III-Vs or LiNbO$_3$
Tomorrow’s Talk: Silicon photonics beyond SOI

Near-IR silicon photonics
(~1 to ~3 µm)

Mid-IR silicon photonics
(~3 to ~8 µm)