

**Lecture Topics**

- Course introduction
- Ray optics & optical beams
- Waveguides / optical fibers
- Optical amplifiers
- Fiber optics and applications
- Lab work
- **Silicon photonics**
- Structural coloration
- Plasmonics
- Poster Presentation & discussion

**Silicon Photonics**  
**First, why silicon?**

- ❖ Si has higher melting point than Ge
- ❖ Cut in Voltage of Si (0.7 eV) is greater than Ge(0.3 eV)
- ❖ Si has a larger band-gap than Ge and because of this, the phenomenon of thermal pair generation is smaller in Si than in Ge. This means that at the same temperature the noise of the Si devices is smaller than the noise of Ge devices
- ❖ Peak Inverse Voltage ratings of Silicon diodes are greater than Germanium diodes.
- ❖ Reverse current for Si device is in nanoAmps whereas it may be upto mA for Ge devices.
- ❖ The good quality and extremely controlled oxide of silicon, SiO<sub>2</sub>
- ❖ *Silicon is the second most abundant material on earth*

**Silicon Electronics & Challenges**

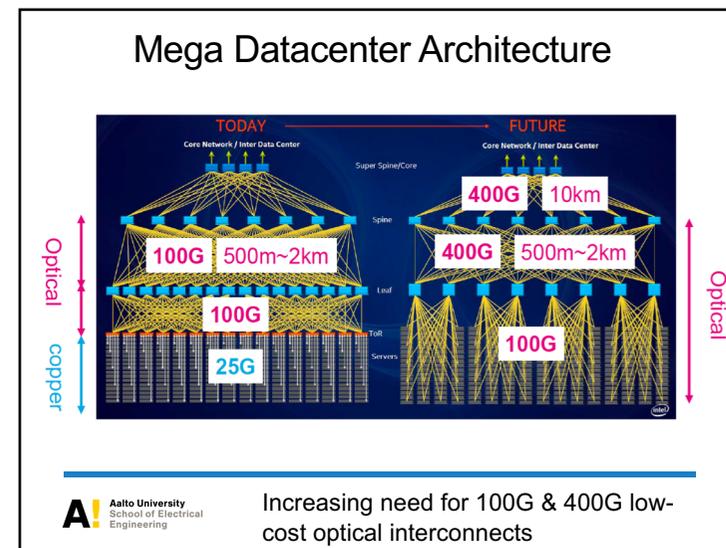
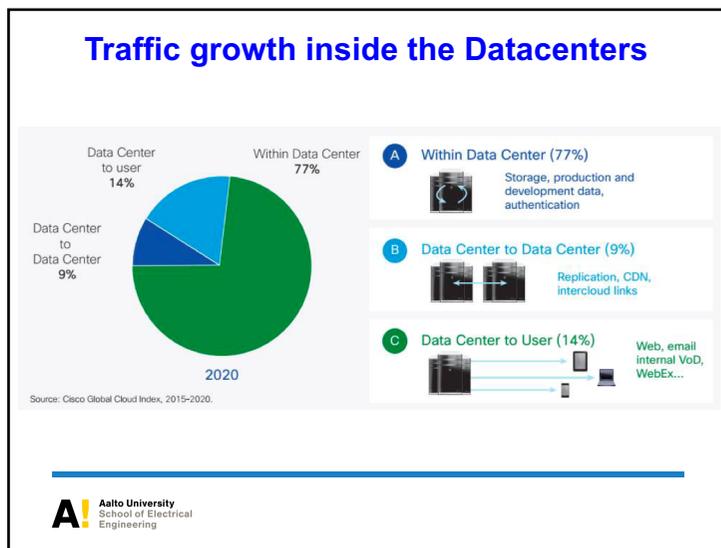
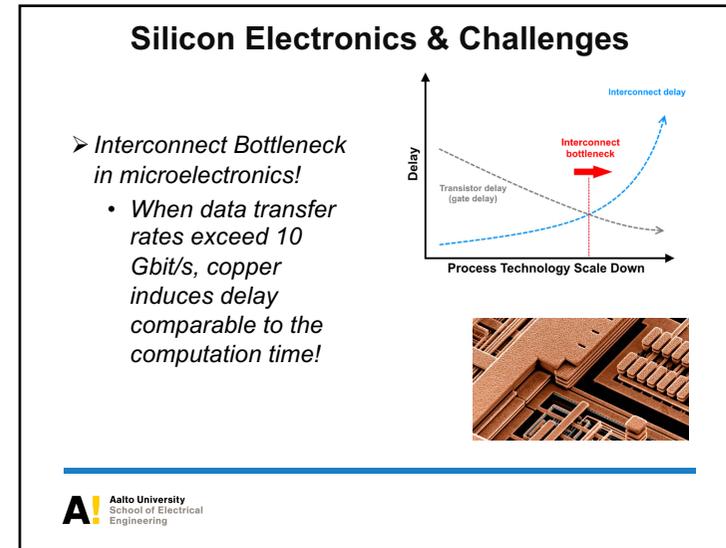
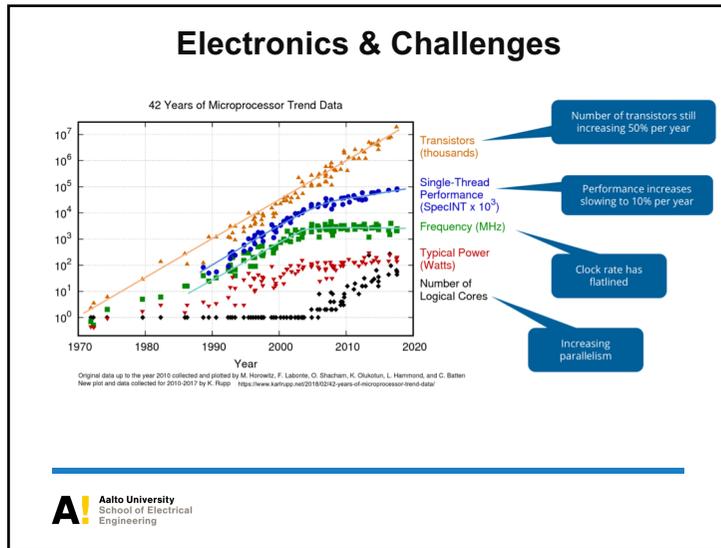
**MOORE'S LAW AND MICROPROCESSOR PERFORMANCE**

Moore's Law Means More Performance

• "The number of transistors in a dense integrated circuit doubles approximately every two years."  
– Gordon Moore 1965.

Source: Ramnath C. Laxton & Jara P. Laxton (2012), Management Information Systems: Managing the Digital Firm, Tenth Edition, Pearson.

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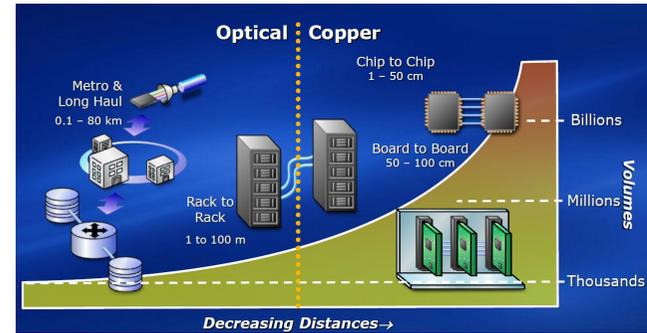


## Why Optical interconnection VS Electronic interconnection ?

- ✓ *Faster speed*
- ✓ *Higher bandwidth*
- ✓ *Energy-efficiency*

Global data centers used roughly 416 terawatts ( $4.16 \times 10^{14}$  watts) (or about 3% of the total electricity) last year, nearly 40% more than the entire United Kingdom. And this consumption will double every 2/3 years.

## Optical VS Electronic interconnection

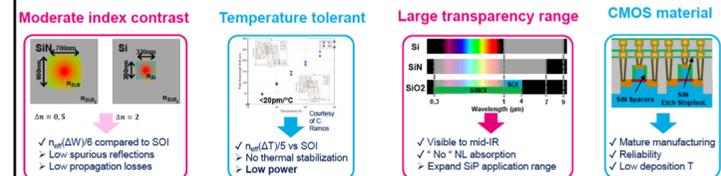


## The dawn of Silicon photonics

- *Silicon is the second most abundant material on earth*
- *Silicon photonics uses the same fabrication techniques as microelectronics*
- *Information is transferred as light, rather than electrical current*
- *The light travels inside patterned silicon/silicon nitride waveguides*

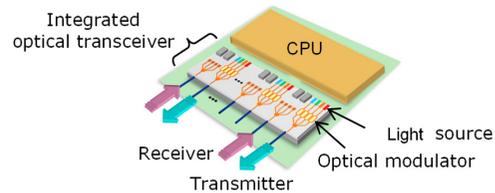


## The dawn of Silicon photonics



## The dawn of Silicon photonics

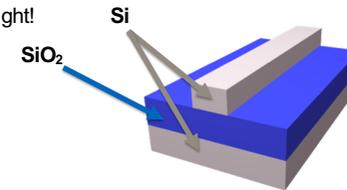
- Silicon photonics combines passive and active components to manipulate light in order to transfer and compute information
- The devices and structures are patterned with nanotechnology on a Silicon-on-insulator (SOI) substrate



## Silicon Photonic Devices

### Waveguides

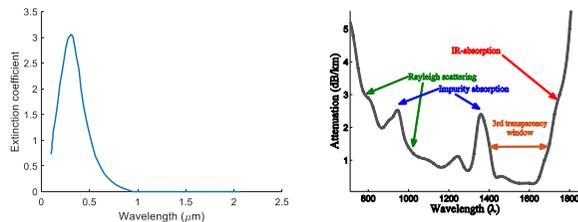
- The light in silicon waveguides is guided via total internal reflection – like in optical fibers
- When the waveguide dimensions are chosen properly, the mode couples into the waveguide
- Silicon benefits from very high refractive index  $n_{Si} \sim 3.5$ .
  - Very high index contrast with  $SiO_2 \rightarrow \Delta n \approx 2$ .
  - Tight confinement of light!



## Silicon Photonic Devices

### Waveguides

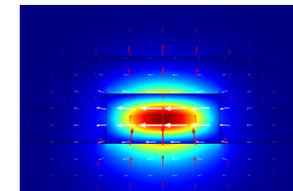
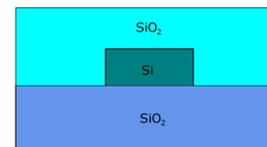
- Silicon is almost transparent at wavelengths > 1100 nm
- Optical fibers have minimum losses at ~1550 nm
  - 1550 nm is often used as the transmission wavelength in silicon waveguides



## Silicon Photonic Devices

### Waveguides

- Examples of waveguide structures
  - Strip waveguide



- Wave-equation:
 
$$\nabla \times \nabla \times E - k_0^2 \epsilon_r E = 0,$$

$$E = E(x, y) e^{-ik_z z}$$

### Silicon Photonic Devices

## Couplers

### Silicon Photonic Devices

## Resonators

➤ Very useful in many applications

- Especially in lasers and sensors

### Silicon Photonic Devices

## Resonators

➤ When light is coupled into a ring resonator, resonance occurs if

$$2\pi R n_{\text{eff}} = m\lambda$$

➤ This is seen as a sharp dip in the transmission spectrum

- Lorentzian lineshape:

$$|E(\omega)|^2 = E_0^2 \frac{\left(\frac{\omega_0}{2Q}\right)^2}{(\omega - \omega_0)^2 + \left(\frac{\omega_0}{2Q}\right)^2}, Q = \frac{\omega_0}{\Delta\omega}$$

### Silicon Photonic Devices

## Resonators

## Silicon Photonic Devices

### Resonators

➤ Small change in the refractive index (i.e. particles) causes the resonance wavelength to shift

$$Ln_{\text{eff}} = m\lambda$$

$$\Delta\lambda = \frac{L\Delta n_{\text{eff}}}{m}$$

Resonant wavelength shift caused by aptamer-protein interaction

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## Silicon Photonic Devices

### Coupling

➤ Edge (“butt”) coupling

- Coupling with tapered fibers

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## Silicon Photonic Devices

### Coupling

➤ Edge (“butt”) coupling

- Coupling with adiabatic tapers

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## Silicon Photonic Devices

### Coupling

➤ Grating coupling:

- Periodic refractive index change in or close to the waveguide core
- Diffraction causes wavefront to distort
- With proper angle, diffraction period and refractive index coupling occurs

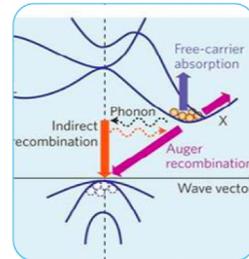
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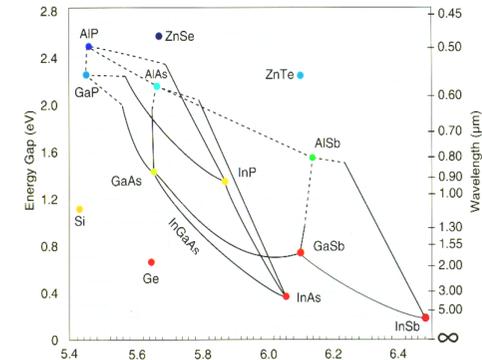
## Silicon Photonic Challenges

- Silicon itself is a poor emitter due to its indirect bandgap
  - Emission very inefficient
- Silicon does not absorb light at > 1100 nm
- Modulation/detection are difficult in silicon as well...
- Integration of other materials necessary

Si : indirect bandgap

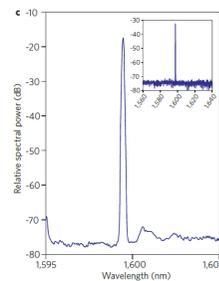
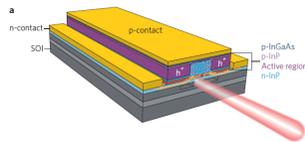


## Laser Sources & Amplifiers



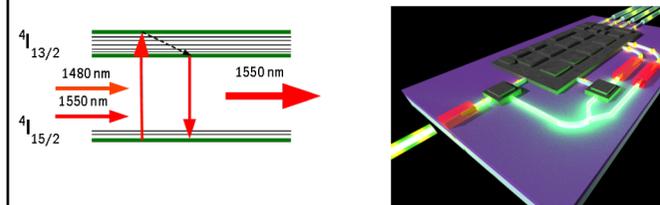
## Laser Sources & Amplifiers

- Hybrid InP-InGaAs laser on Si



## Laser Sources & Amplifiers

- Erbium doped gain



## Silicon Photonic Challenges Modulators

**Electro Absorption**

Amplitude modulation

**Electro Refraction**

Phase modulation

$$n = n_0 - \frac{n_0^3 r E}{2} - \frac{n_0^3 g E^2}{2}$$

Pockels Kerr

**Plasma Dispersion**

Phase modulation

$$\Delta n = a\Delta N^x + b\Delta P^y$$

## Hybrid integration

III-V integration by wafer/patch bonding

III-V-OI

Y. Iku et al. U. of Tokyo, Optics Express, 20, B337, 2012

Hybrid III-V/Si Laser

B. Ben Bakir, et al. " Opt. Express 19(11),(2011), LETI, J. Durel et al (ST/LETI), IEDM 2016

Hybrid III-V/Si Electro-Absorption Modulator

Y.H. Kuo et al. (UCSB),2008

Hybrid III-V/Si MOS-Modulator

J.H. Han et al. IEDM 2016, U-Tokyo

## Silicon Photonic Challenges Integrated Transmitter : Hybrid Laser + Modulator

Light output 900 nm, Heater, InP, MQW, SOI, Si substrate, p-contact, n-contact, R=30%, R=100%

Silicon modulator region, Fiber-coupled modulated signal, Optical signal, Signal ground, Modulator phase control

• Demonstration of a 25 Gb/s transmission using the transmitter, with 2.5 Vpp on each MZM arm.

T. Ferrotti et al., SSSM 2016, Optics Express 2017, CEA-LETI/ST

## Silicon Photonic Applications

Secured Communication

Sensing

**Datacom**

More than DATACOM: Photonic sensors & detectors connecting objects

Bandwidth

Insertion Loss

Power Management

Automotive

## Intel 400G Interconnection in 2019

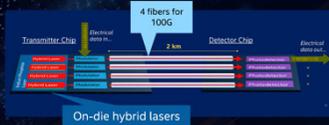
### SILICON PHOTONICS TRANSCEIVERS IN HIGH VOLUME

OVER 1M UNITS SHIPPED, APPROACHING 2M UNIT RUN RATE

#### 100G PSM4 QSFP

- Up to 2 km reach on parallel single mode fiber
- Fully MSA compliant

In volume production



#### 100G CWDM4 QSFP

- 500m, 2 km and 10km reach on duplex single mode fiber
- Fully MSA compliant
- Extended temp -40 to 85°C

In volume production

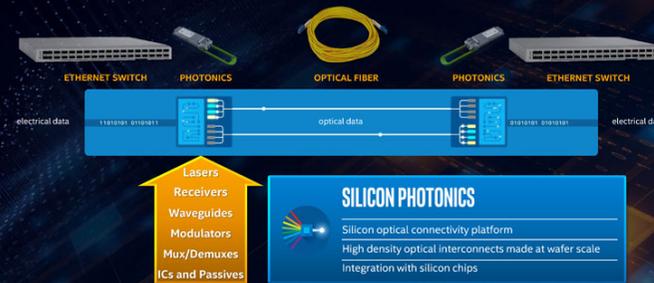


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## Intel 400G Interconnection in 2019

### WHAT IS AN OPTICAL TRANSCEIVER?



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## Intel 400G Interconnection in 2019

### DELIVERING OPTICS AT SILICON SCALE

#### LASER FABRICATION

Silicon (device) wafer, Indium phosphide die. Plasma activation and bonding: InP die are bonded & transferred in parallel to device wafer. InP substrate removal: only active epi layers remain on device wafer. Hybrid laser >90% coupling efficiency.

#### SILICON INTEGRATION

Advanced CMOS manufacturing at Intel fabs on 300mm wafers. Capable of multiple optical wavelengths and integration of multiple optical components.

#### SILICON SCALE

Optical, Electrical, RF. Comprehensive, automated on-wafer optical, electrical, and high-speed test capabilities.

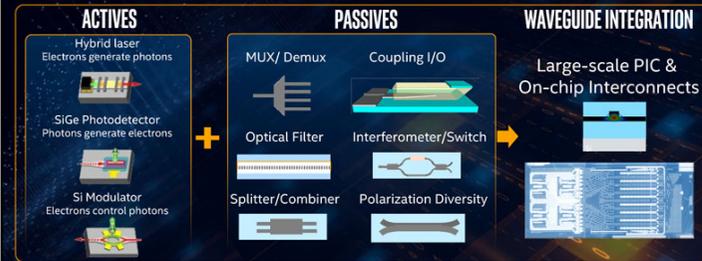
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### SILICON PHOTONIC INTEGRATION

SILICON PHOTONICS INTEGRATED CIRCUITS



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## Intel 400G Interconnection in 2019

### 400G DR4 SILICON PHOTONICS OPTICAL TRANSCEIVER

- 400G Ethernet connectivity for next-generation cloud data centers based on 12.8T Ethernet switches
- Standards-compliant optical interface with extended 2km reach for 400G or 4x100G breakout

**400G QSPF-DD DR4**  
Ramping production end of 2019

QSPF-DD and OSFP form factors

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## Intel 400G Interconnection in 2019

### SILICON PHOTONICS ENABLES OPTICAL CONNECTIVITY AT SCALE

**High Performance**

- Hyperscale data rates (25G, 50G, 100G, 400G+)
- Reliable performance
- Ultra-compact Tx/Rx chips
- High density interconnects

**Low Power Consumption**

- Low power and signal integrity optoelectronic transceiver
- Low power ASIC+SiPh PIC copackage
- Remove electrical I/O constraints
- Low system power

**SILICON PHOTONICS**

**Mature Silicon Technology**

- High volume & proven CMOS process
- Can Integrate with III-V thru bonding
- High yield & low cost at high volume
- Fast time to volume

**Easier & Cheaper Module Assembly**

- Fewer piece parts to assemble
- High consistency and reliability

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## Intel 400G Interconnection in 2019

### 400G DEPLOYMENT WILL ACCELERATE BEYOND 2020

**LESS THAN 3 YEARS TO REACH 1M UNITS IN CLOUD ERA**

4 years  
40 GbE

2.5 years  
100 GbE

2.5 years  
400 GbE

Source: Lightcounting and public market estimates

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## Intel 400G Interconnection in 2019

### HIGHLY INTEGRATED PHOTONICS LIGHTS UP INTEL SILICON

**INTEGRATION DRIVES FORM FACTOR AND BANDWIDTH EVOLUTION**

**SHIPPING: 100G**  
100G PSM4 & CWDM4 MSA Pluggable

First generation 100G Silicon Photonics

**NEW: 400G**  
400G DR4 MSA Pluggable

Next generation 400G Silicon Photonics

**FUTURE: OPTICAL INTEGRATION**  
High density integrated

25.6 Tb Switch

Silicon Photonics integrated for improved power, cost and bandwidth density

Technology development for miniaturization, high-temp operation, low power process

Source: Based on measurements of Intel Silicon Photonics vs traditional optics 'gold box' products

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