Photonic Integrated Circuits
Photonic Integrated Circuits

- Planar lightwave circuits
- Integrated optoelectronic devices
- Wafer-scale technology on substrates (chips)
- Technology limitations
Photonic Integrated Circuits - Technologies

- III-V Integration Platforms
- Silicon Photonics
- Silica-on-Silicon - Silica glass (fused Silica)
- Polymer Integration Platforms
- Lithium niobate (LiNbO₃)
III-V Semiconductor Technology

Advantages
- Solutions for:
  - Lasers
  - Optical amplifiers
  - Modulators
  - Detectors
- Monolithic integration of passive/active components within fully functional chips
- Ultra-high speed EO characteristics
- High reliability

Disadvantages
- Extensive integration approach due to CMOS incompatibility
- Increased propagation losses (>0.5 dB/cm)
- Limitations of mass production due to small wafers (InP)
- Low index contrast (\(\Delta n/n\))
III-V monolithic integration of complex devices for...

- **Telecom (1)-(3)**
- **Datacom (5),(7)**
- **Sensing (4),(6)**
- **Bio-Medical (8)**

Meint Smit et al, “A Generic Foundry Model for InP-based Photonic ICs, presented at OFC, paper OM3E, March 4-8, 2012, Los-Angeles, CA, USA

**Hybrid integration on Si-based platforms**

- GaInNAs(Sb) SOAs flip-chip bonded on SOI
- GaAs -and InP-based hybrid integration on SOI platform:

**ICT-GALACTICO**

**ICT-BOOM**

**ICT-RAMPLAS**
Silicon Photonics: Overview

Future promise

- Photonic components (i.e. modulators, detectors, sources) fully compatible with CMOS technology
- Photonic links may replace copper links for very short distances and co-exist with electronics in functional optoelectronic chips

- Ability to reuse the huge technology base and supply chain from electronics industry
Silicon Photonics: Key characteristics

- **Advantages**
  - Low cost
  - Take advantage of CMOS platform
  - High index contrast -> strong light confinement -> small footprint
  - Transparent in 1.3-1.6 um region
  - Devices with sub-wavelength dimensions feasible

- **Disadvantages**
  - *Indirect* bandgap material
  - *No or weak* electro-optic effect
  - Relatively lossy waveguides
  - Lacks efficient *light emission* - no electrically pumped Si laser
Silicon Photonics: towards silicon laser

- **Approach**
  - hybrid silicon photonic integrated circuit technology
    - bonding of functional III-V active components onto silicon-on-insulator substrates
  - bonding of III-V epitaxial layers
    - wafer or die bonding of III-V films on Si and processing thereof
  - hetero-epitaxial growth of III-V on Si
    - selectively grow III-V crystals on Si substrate
  - selective growth of Germanium on Si
    - growth of Ge layers on silicon oxide trenches

- InP VCSELs on SOI: ICT-MIRAGE
- microdisc laser: ICT-HELIOS
- microdisc laser: UCSB
- Ge laser: MIT
Glass: Overview

Main technology implementations
- silica-on-silicon
- laser inscription on glass
- TriPlex

How it works
- Waveguiding in glass (SiO2)
- Introduce dopants to create index difference (small to medium): similar material & dopants used in optical fibers
- SiO₂ surrounded and encapsulated by high index Si₃N₄ cladding/box section
### Glass: Key characteristics

#### Advantages

- Low propagation loss (<0.01 dB/cm)
- Low polarization dependence
- Broad wavelength coverage (vis. to IR)
- Low-loss coupling to single-mode fiber (less than 1 dB typical, 0.15 dB is feasible)
- Weak thermo-optic effect: low temperature dependence
- Reliable material, tolerance to environmental

#### Disadvantages

- Large modal area and bending radius: low density integration
- Limited active functionalities available, most remain in the lab (e.g. amplification)
- Weak thermo-optic effect: not so efficient for λ-tuning functions
- Fabrication may involve more costlier processes than competitive technologies for passive component integration (e.g. polymers)
Glass: applications

Passive components
*(commercial)*

- WDM multiplexers
- FTTH splitters
- thermo-optic switches

Hybrid integration of complex devices

- III-Vs
- LiNbO₃
- polymers

III-V integration on silica-on-silicon platform:
ICT-APACHE
Polymers: Overview

- Main material systems
  - SU-8, PMMA, ZPU-12, etc
  - Blending polymer solutions to achieve precise control of material optical properties

- Main types of polymer platforms
  - Passive
  - Electro-optic
  - Active
Polymers: Key characteristics

• **Strengths**
  - Low propagation loss (<0.5 dB/cm)
  - Low birefringence
  - Precise and continuous engineering of material properties
  - Unique properties (large TO, EO, non-linear)
  - Good and easy ability to process
  - Ease of hybrid integration via butt coupling

• **Weaknesses**
  - Low index contrast, bulky device
  - Not suitable for high temperature process
  - Some materials raise reliability issues
  - No full suite of active functionalities available out of the lab
Polymers: Applications

- Hybrid Optical/Electrical datacom PCBs
  - Waveguide PCB integration
  - Cards for optical backplane

- 40G and 100G communication applications
  - High speed Mach-Zehnder modulators
  - Variable optical attenuator arrays
Disruptive Technologies Overview: Plasmonics

- **How it works**
  - **Surface plasmons**: coherent electron oscillations at a metal–dielectric interface
  - **Surface plasmon polaritons**: plasmons excited by visible or infrared electromagnetic waves
  - **Localized surface plasmon resonance**: collective oscillation of electrons in nanometer-sized structures

- **Potential applications**
  - **Chip-scale communications**: Interconnects
  - **Sensing**: Biosensors, lab-on-a-chip
Disruptive Technologies Overview: Photonic Crystals

- **How it works**
  - **Photonic Crystals (PhC):** material with periodic dielectric constant in some particular dimensions (1D, 2D, 3D)
  - **Principle of operation:** if periodicity lattice is in the order of wavelength of light, it will reflect the light in the particular wavelength
    - Create range of forbidden wavelengths, called photonic bandgap, that cannot propagate through the PhC medium
    - Introduce defects in lattice to trap light and create a non-TIR based waveguide

- **Main technology implementations**

<table>
<thead>
<tr>
<th>Waveguide Components</th>
<th>Photonic Crystal Fibers</th>
<th>Slow light Modulators</th>
<th>Evanescent Fiber Coupling</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Waveguide Components Diagram" /></td>
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</table>
Disruptive Technologies Overview: Carbon-based materials

- How it works
  - Graphene:
    - 2-dimensional, crystalline allotrope of carbon / 1-atom thick layer of graphite
    - Absence of bandgap – absorbs light over wide spectral range (ultraviolet to terahertz)
    - Material optical properties can be modified by externally tuning the bandgap of graphene layers and bi-layers
  - Carbon nanotubes (CNT):
    - Allotropes of carbon with cylindrical nanostructure based on honeycomb carbon lattice
    - Depending on lattice orientation, CNT acts as metal or semiconductor
    - Semiconductor CNTs are direct bandgap materials and can be used to generate and detect light
    - Single- or multi-walled nanotube configurations are possible
Silicon Photonics

Photonic Integrated Circuits Example
Silicon Photonics Wafer Fabrication

https://www.youtube.com/watch?v=AMgQ1-HdElM
Silicon Photonics: Design

- **Crossection**
  - The transverse impression of the integration platform
  - Depends on the integration technology
  - Varies according to the process flow
  - Can be directly imported in the crossection simulation tools (mode solvers)
Silicon Photonics: Design

- **Waveguide mode**
  - Electric field distribution in spatially inhomogeneous structures (waveguides)
  - Self-consistent during propagation
  - The shape of the complex amplitude profile in the transverse dimensions must remain exactly constant

- **Effective index**
  - In homogeneous transparent media, the refractive index $n$ can be used to quantify the increase in the wavenumber (phase change per unit length) caused by the medium
  - The *effective refractive index* $n_{\text{eff}}$ has the analogous meaning for light propagation in a waveguide
  - Depends not only on the wavelength but also (for multimode waveguides) on the mode in which the light propagates