Silicon Photonics : Industrial Reality and Future Evolutions

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STMicroelectronics, Crolles

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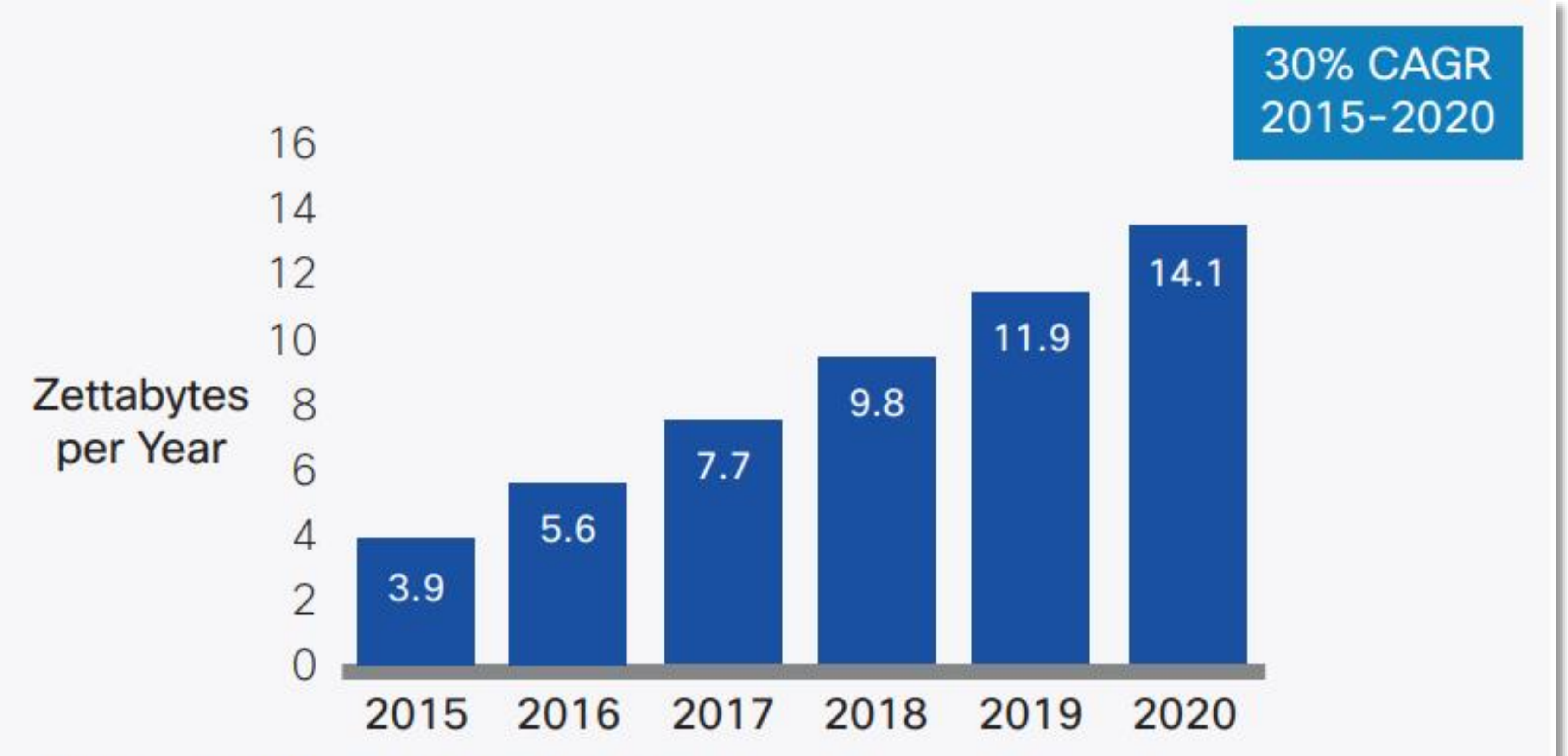
Outline

- I - Introduction
- II - Silicon-Photonics in Datacenters
- III - Technology Platform for 200G & 400G
- IV - Future Evolutions
- V - Conclusion

Traffic in Data Centers : the ZettaByte era



Source: Cisco Global Cloud Index, 2015-2020.

Traffic in datacenters is doubling every 3 years

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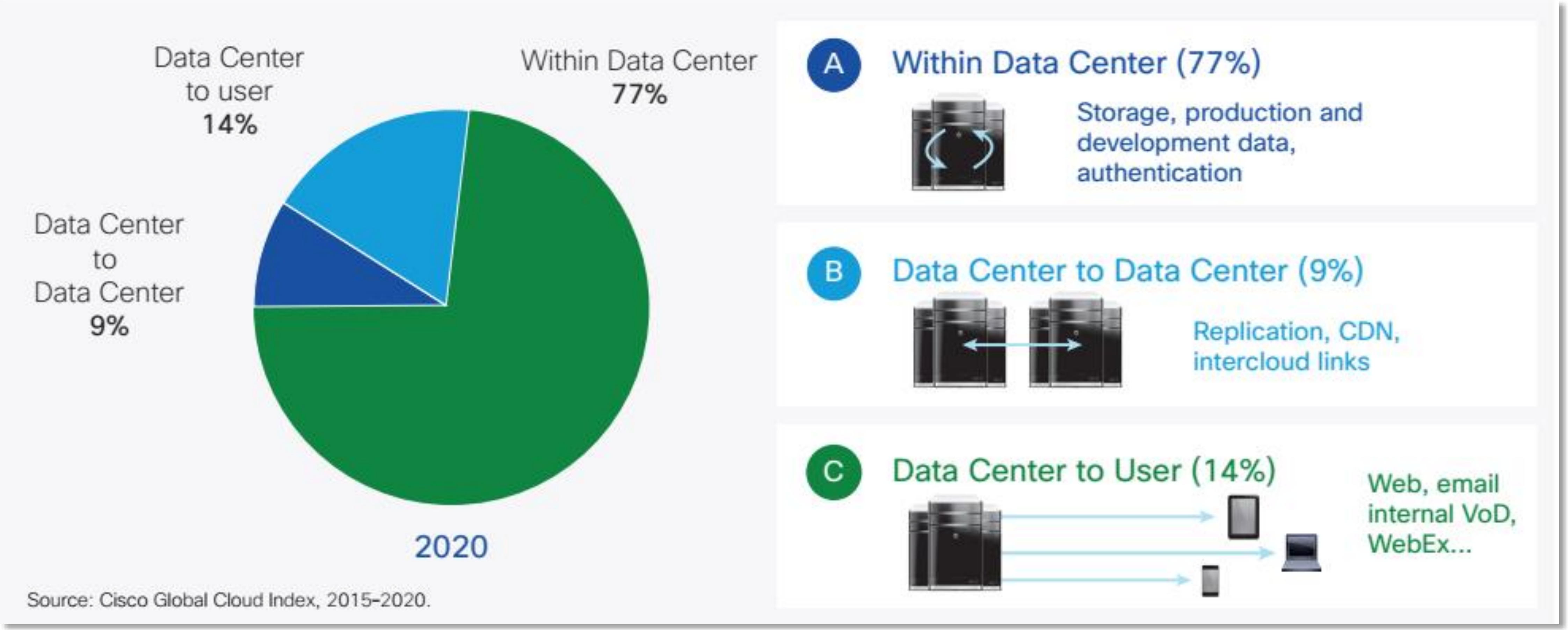
Traffic growth is indise the Datacenters



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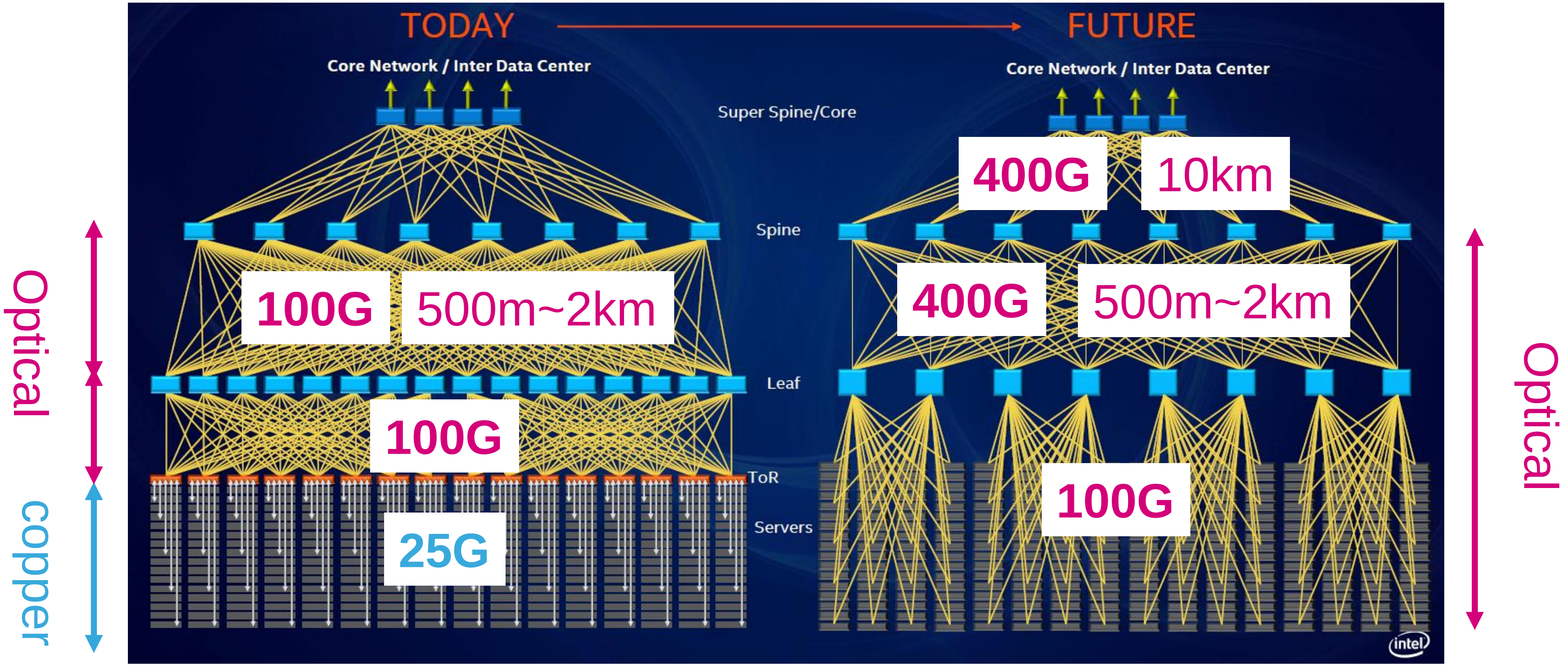
Mega Datacenter Architecture



Increasing need for 100G & 400G low cost optical interconnects

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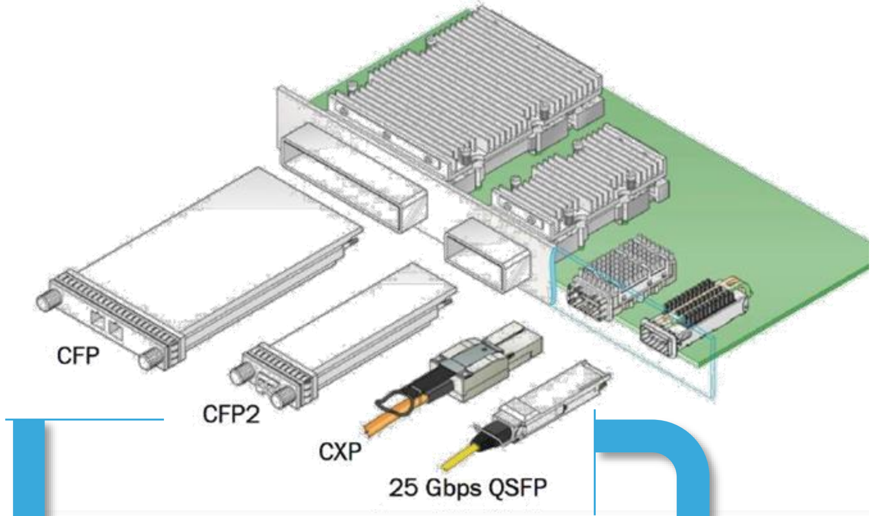
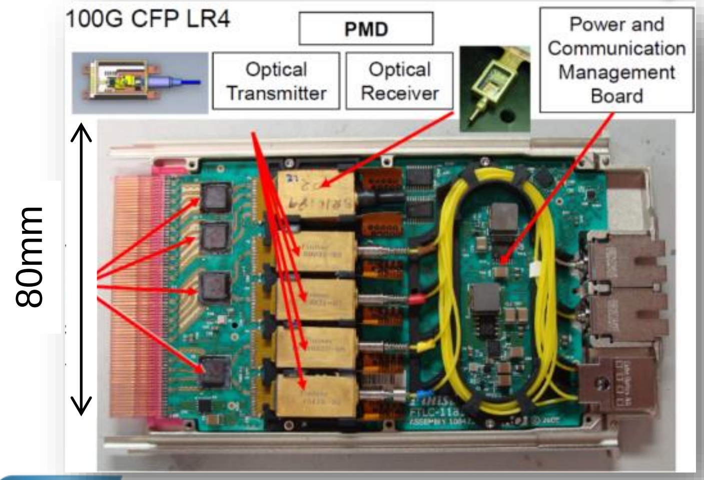
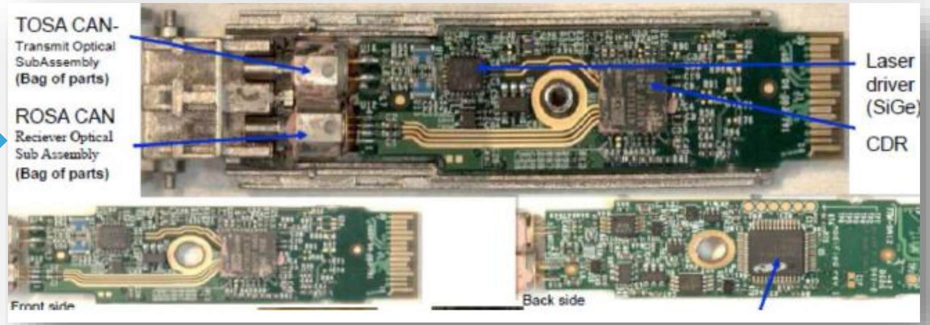
Example of Pluggable Optics





photons



electrons

- TX : Modulated laser source or laser+external modulator
- RX : Photodiodes
- Driving electronics and TIA

Increasing Optical Communication Use

III-V → Si

Photonics

\+

Electronics

→ High Low cost

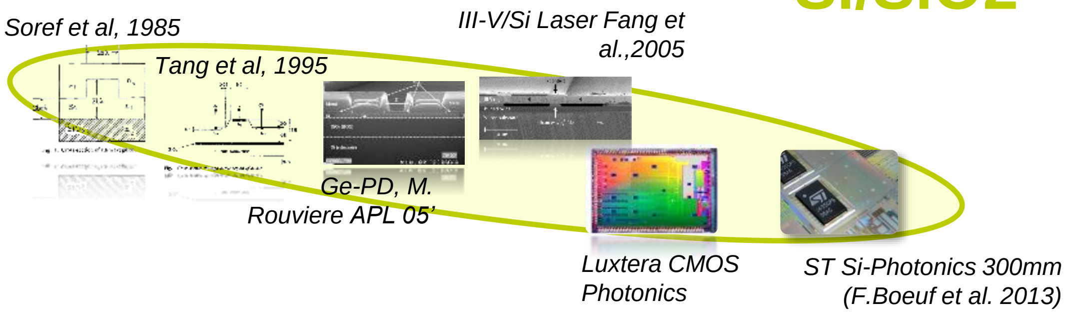
90% CMOS/BiCMOS (Si)

Started in middle of 80s : Si-Photonics

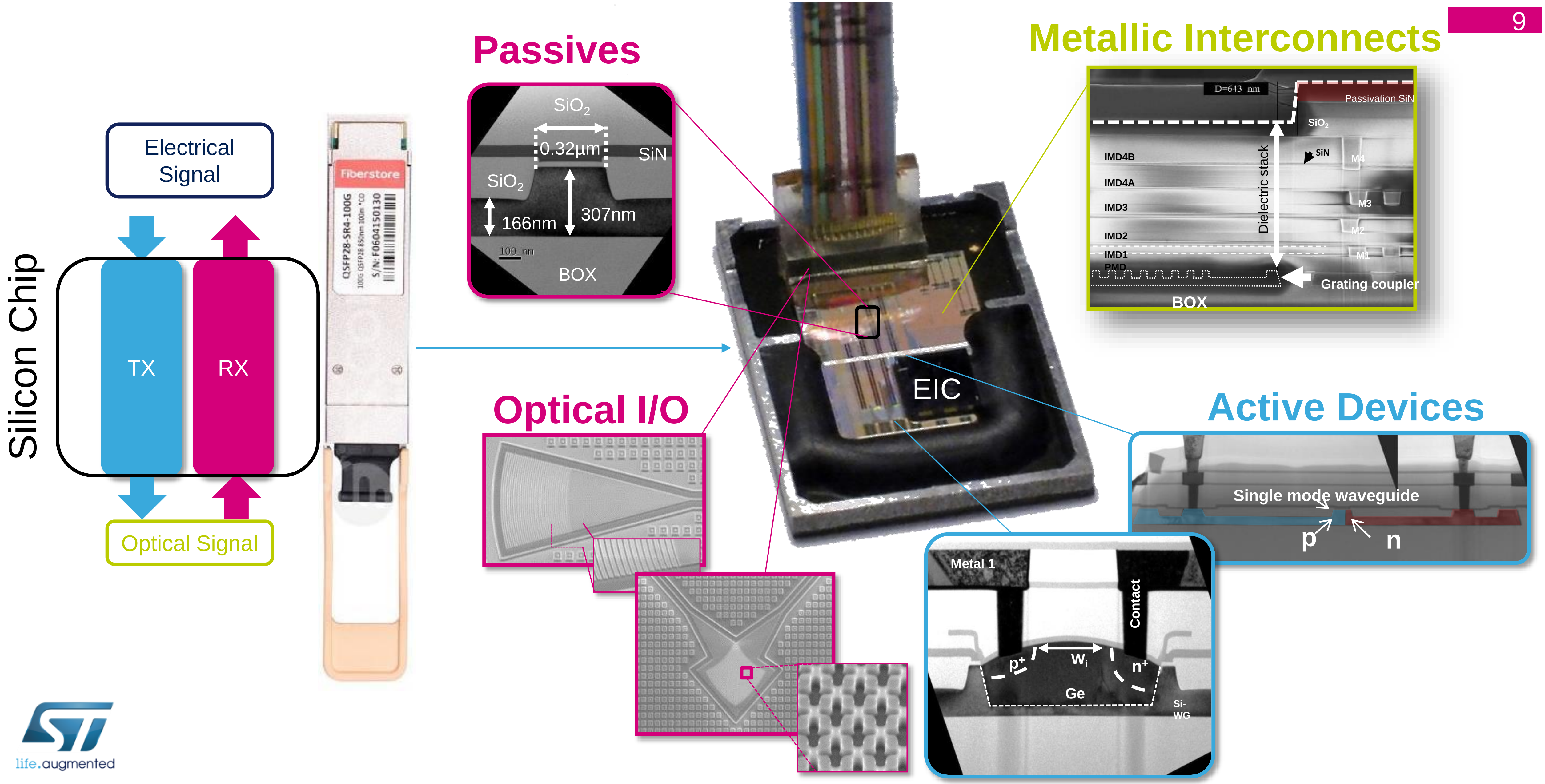
- Transparence of Si in telecom wavelength range
- Silicon On Insulator (SOI) wafer
- High-index contrast (n_{Si}=3.5 – n_{SiO2}=1.5)
    - Strong light confinement

- Indirect bandgap material
    - Lacks efficient light emission

Si/SiO2



ST's 100G PSM4 - PIC25G Technology



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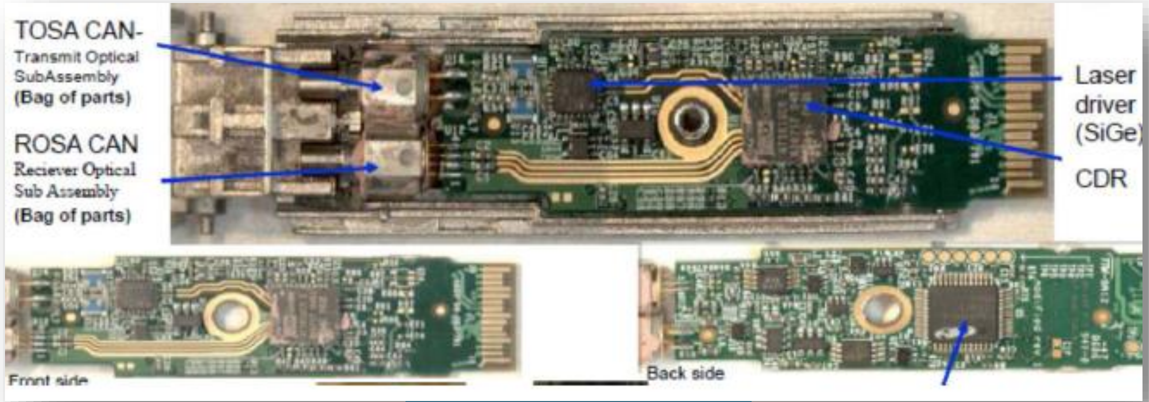
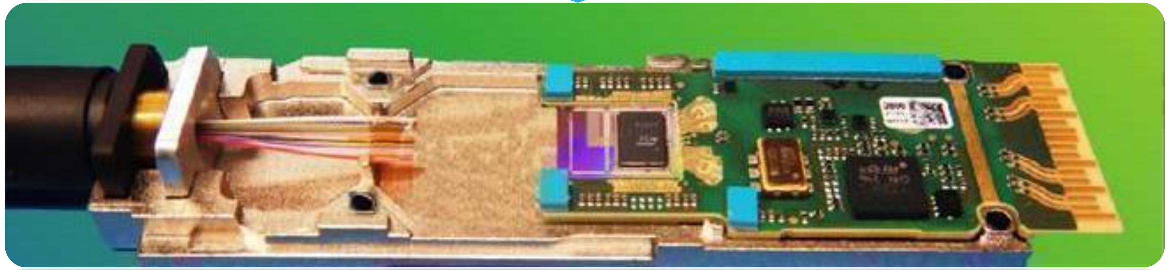
ST 100G PSM-4 Si-Photonics in QSPF28

Optical Module based on discreet components





Si-Photonics Optical Module

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Si-Photonics Market vs ST-Technologies

100G	200G	400G	800G
4x25G PSM	4x50G PSM	4x100G PSM 4x100G WDM 1x100G FR	
PIC25G	PIC25G-P3	PIC50G	DAPHNE R&D
NRZ signal 20GHz HSPD PN Modulator Rib Si-Waveguides Grating coupler	PAM-4 signal 25Gbd/s 50GHz HSPD PN Modulator Gen2 Rib Si-Waveguides Grating coupler Thick-Cu Metallization	PAM-4 signal 50 Gbd/s 50GHz HSPD PN Modulator Gen3 Rib,Deep Rib,Strip Si-Waveguides Grating coupler WideBand Coupling « 3D » SiN Strip & Rib waveguides Thick-Cu Metallization	

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Si-Photonics Market vs ST-Technologies

100G → **200G** → **400G** → **800G**

100G	200G	400G	800G
4x25G PSM	4x50G PSM	4x100G PSM 4x100G WDM 1x100G FR	
PIC25G	PIC25G-P3	PIC50G	DAPHNE R&D

PIC25G
- NRZ signal
- 20GHz HSPD
- PN Modulator
- Rib Si-Waveguides
- Grating coupler

PIC25G-P3
- **PAM-4 signal 25Gbd/s**
- **50GHz HSPD**
- **PN Modulator Gen2**
- Rib Si-Waveguides
- Grating coupler
- **Thick-Cu Metallization**

PIC50G
- PAM-4 signal 50 Gbd/s
- 50GHz HSPD
- PN Modulator Gen3
- Rib,Deep Rib,Strip Si-Waveguides
- Grating coupler
- WideBand Coupling
- « 3D » SiN Strip & Rib waveguides
- Thick-Cu Metallization

DAPHNE R&D

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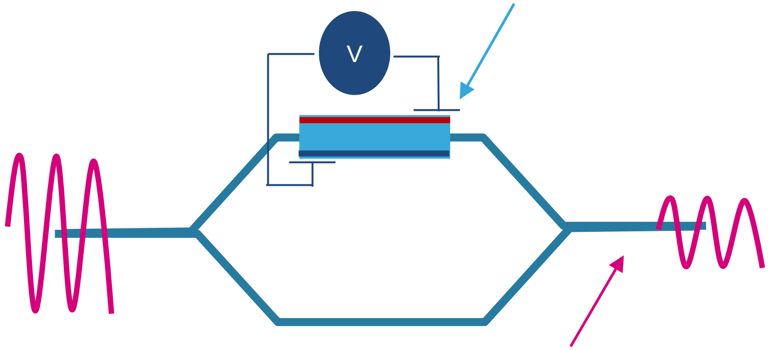
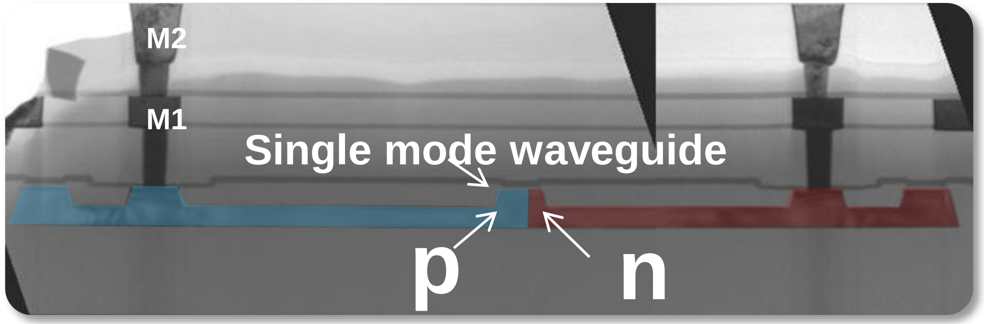
Gen2 Carrier Depletion Based High-Speed Phase Shifter

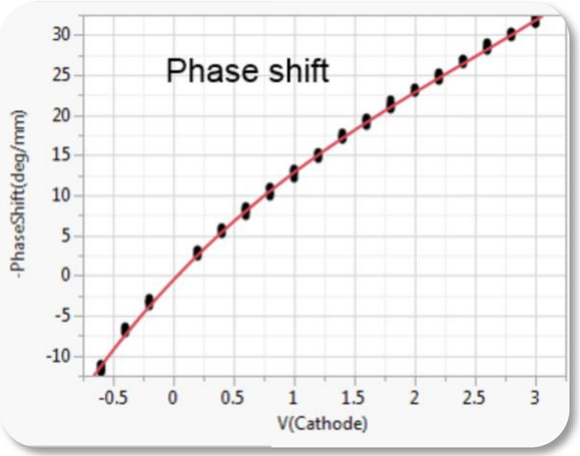
Phase shift = refractive index change



Amplitude modulation using interferometer



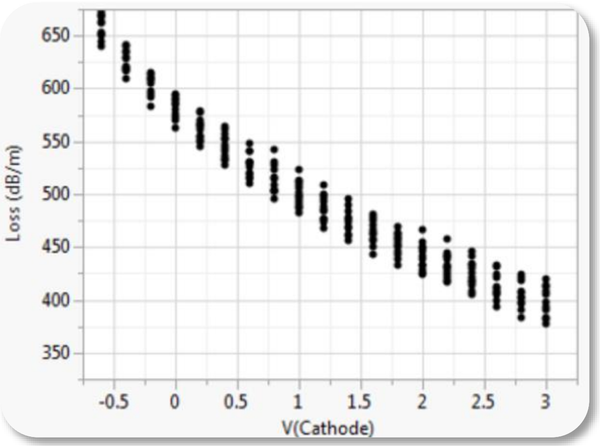
$\Delta\varphi$: Phase Shift



~20°/mm@1.8V

(+ 50 % vs GEN1)

α : Loss



0V~0.57dB/cm@0V

Higher is better

$$\beta = \frac{\Delta\varphi_{/mm}}{\alpha_{/mm}}$$

Lower is better

Improved TX efficiency

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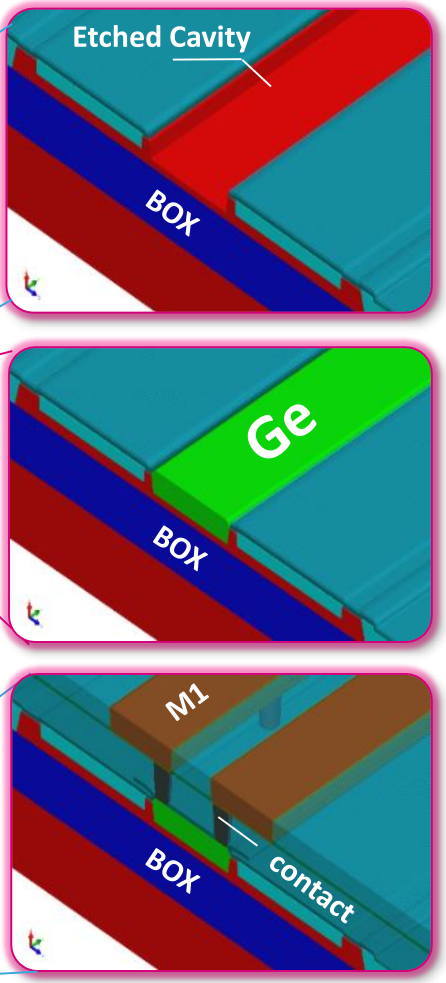
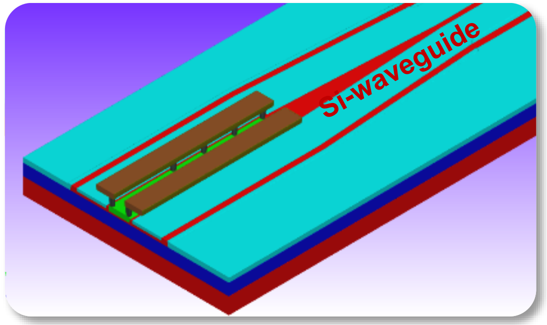
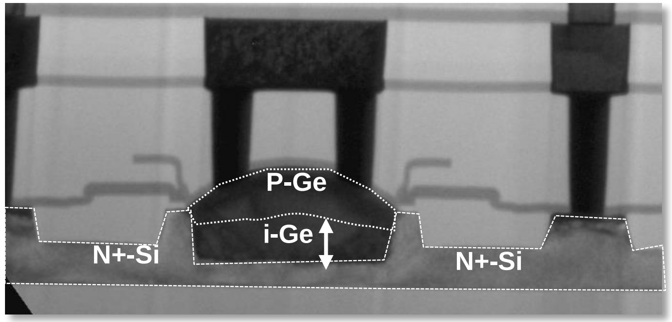
High Speed 60GHz Photodiode

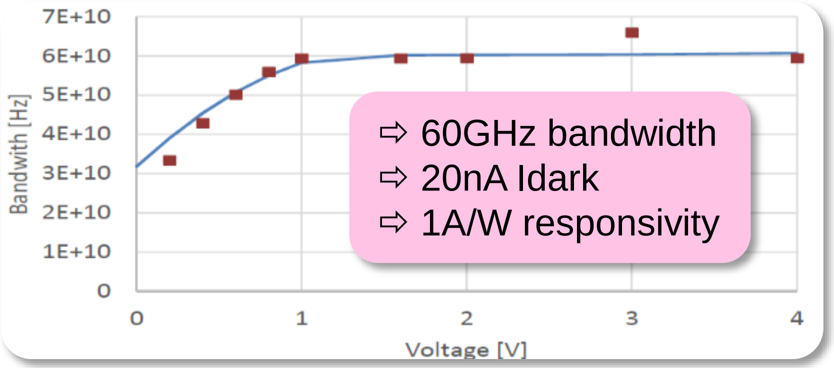
Photodiode

- Oxide Deposition
- Cavity Patterning
- Silicon Etching
- Germanium SEG
- SiN Capping
- N/P Definition
- Contact Patterning
- Metal 1 dep.



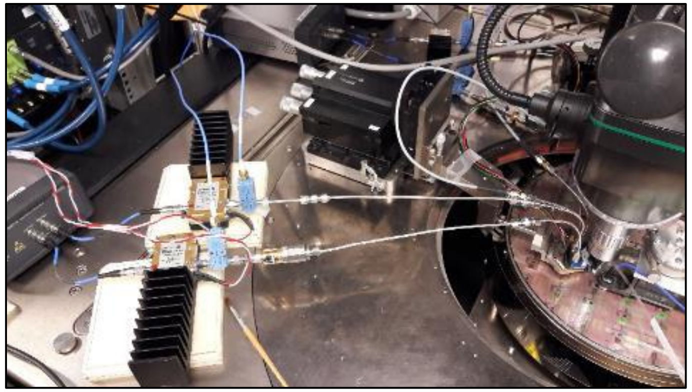






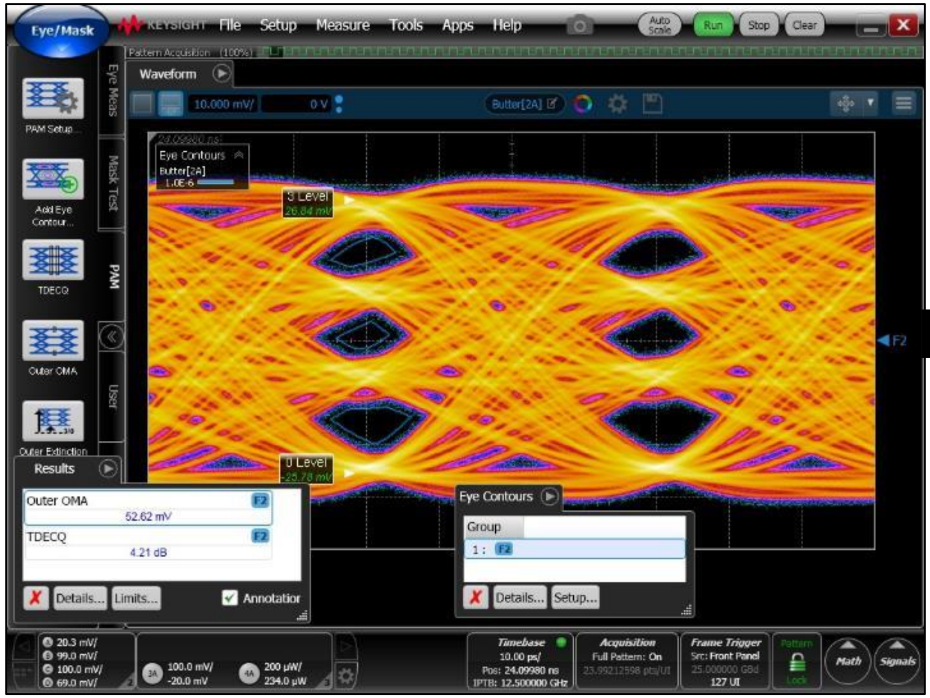
S.Cremer et al. CSISC 2016

On Wafer TX 25Gbaud-PAM-4 (50Gbits/s)

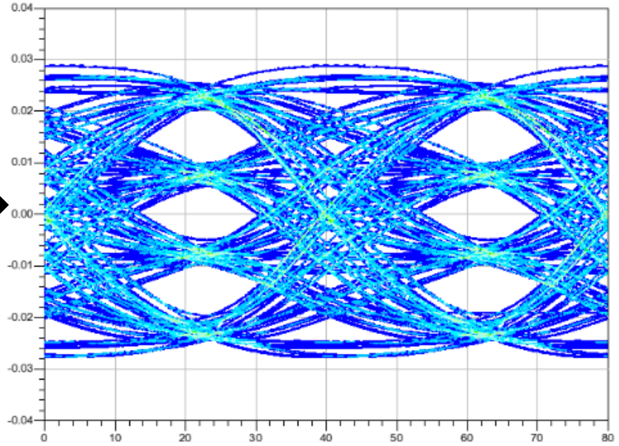


PAM modulation = 4 states = 2 bits/symbol

Eye + BER contour @ HSPD: 25GBaud PAM4



Retro-Simulations



J.F Carpentier & P. Lemaitre

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- PN Modulator
- Rib Si-Waveguides
- Grating coupler

PIC25G-P3
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- 50GHz HSPD
- PN Modulator Gen2
- Rib Si-Waveguides
- Grating coupler
- Thick-Cu Metallization

PIC50G
- **PAM-4 signal 50Gbd/s**
- 50GHz HSPD
- PN Modulator Gen3
- **Rib,Deep Rib,Strip Si-Waveguides**
- Grating coupler
- **WideBand Coupling**
- **« 3D » SiN Strip & Rib waveguides**
- Thick-Cu Metallization

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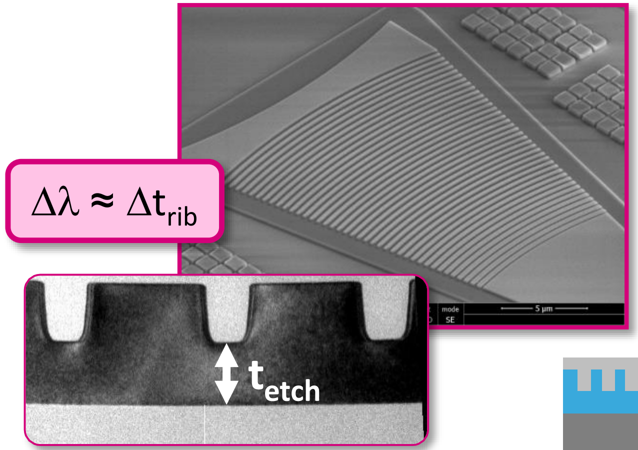
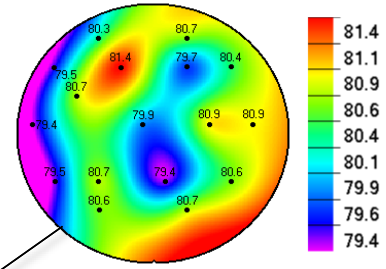
Challenge : Silicon Patterning Uniformity

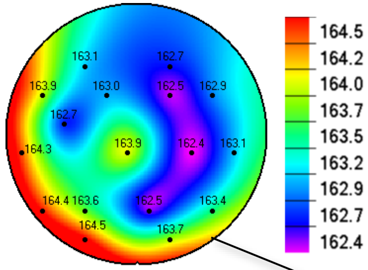
Trench Width Uniformity



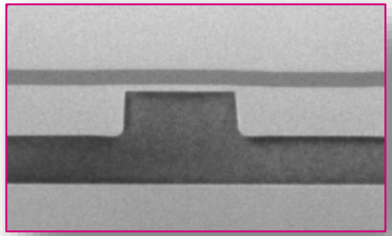


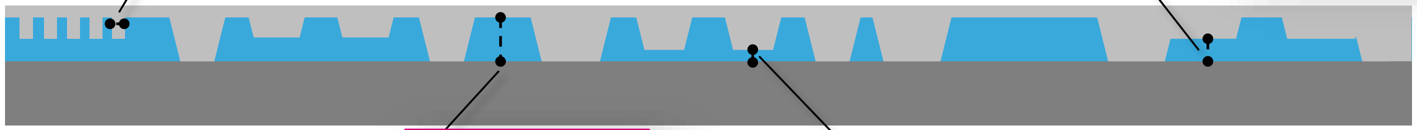
Mean : 80.3 nm
3-sigma: 1.8 nm (2.3 %)
Range : 2.0 nm (2.5 %)

Partial Etch Depth Uniformity

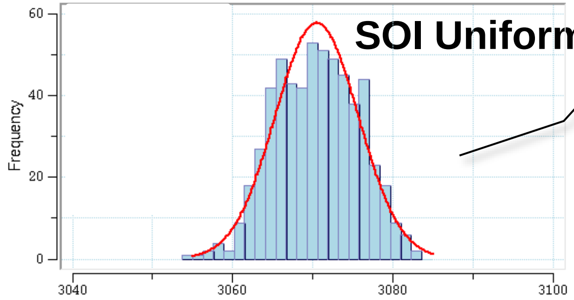


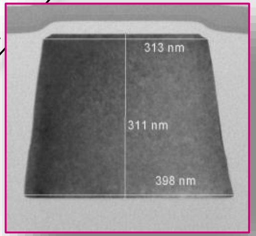
Mean : 163.3 nm
3-sigma: 2.1 nm (1.3 %)
Range : 2.1 nm (1.3 %)



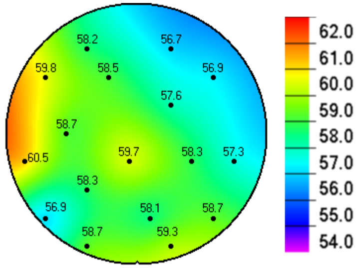


SOI Uniformity

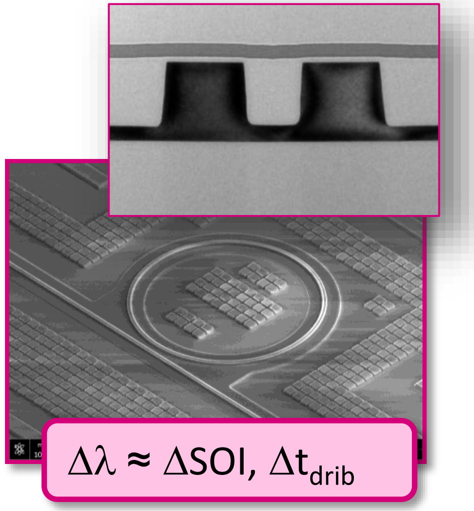




Deep Etch Depth Uniformity



Mean : 58.4 nm
3-sigma: 3.2 nm (5.5 %)
Range : 3.8 nm (6.4 %)



High accuracy in silicon patterning leads to:
- **Lower optical losses**
- **Lesser need for active signal control (power consumption reduction)**

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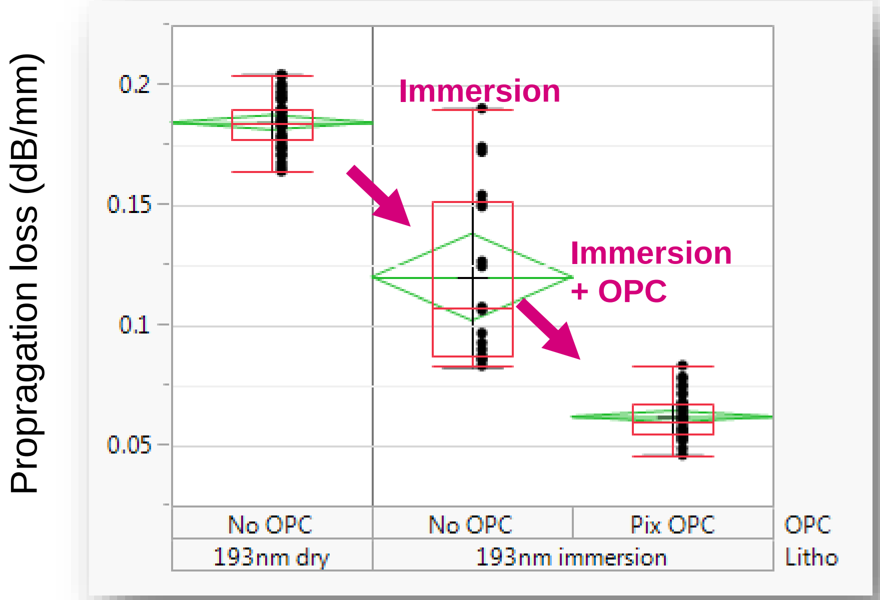
Using 193nm Immersion Lithography in Si-Photonics

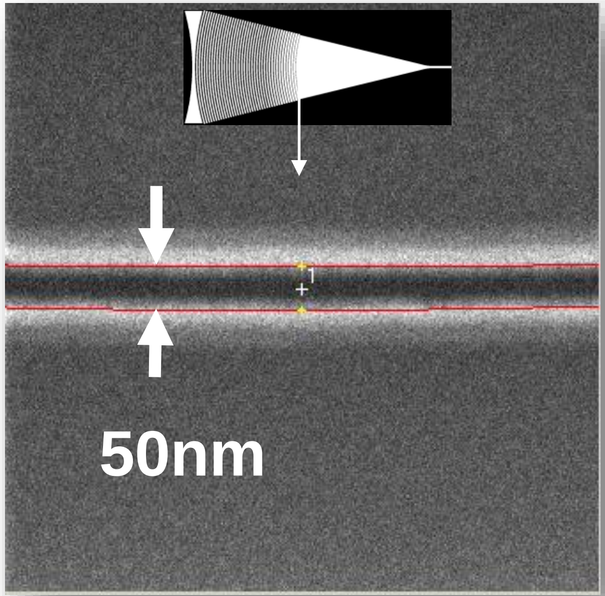
Reduced propagation losses

SMW : 1.8dB/cm → 0.6 dB/cm



Better I/O resolution

Improved performance



Using 193i lithography for Si-Photonics is useful even for BIG devices!

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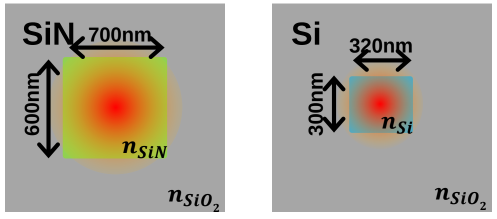
SiN as a Photonic Material

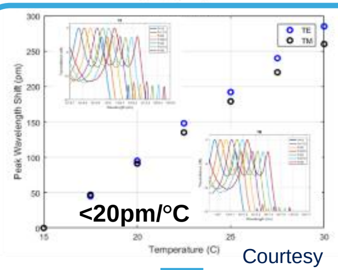
Moderate index contrast



$\Delta n = 0,5$ $\Delta n = 2$

- ✓ $n_{eff}(\Delta W)/6$ compared to SOI
- ➢ Low spurious reflections
- ➢ Low propagation losses

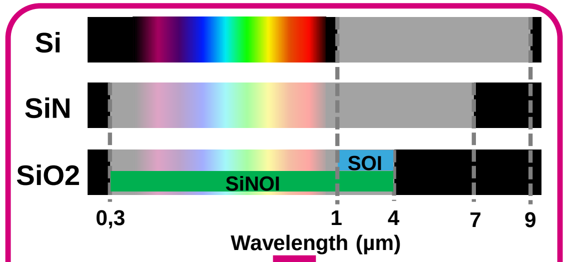
Temperature tolerant



Courtesy of C. Ramos

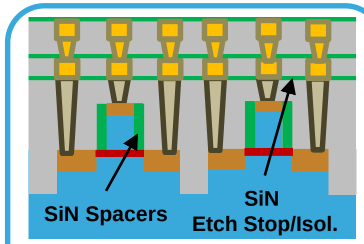
- ✓ $n_{eff}(\Delta T)/5$ vs SOI
- ➢ No thermal stabilization
- ➢ **Low power**

Large transparency range



- ✓ Visible to mid-IR
- ✓ " No " NL absorption
- ➢ Expand SiP application range

CMOS material



- ✓ Mature manufacturing
- ✓ Reliability
- ✓ Low deposition T

SOI

- ✓ Active devices
- ✓ Footprint
- ✗ Env./Fab. Sensitivity
- ✗ Power Limitation

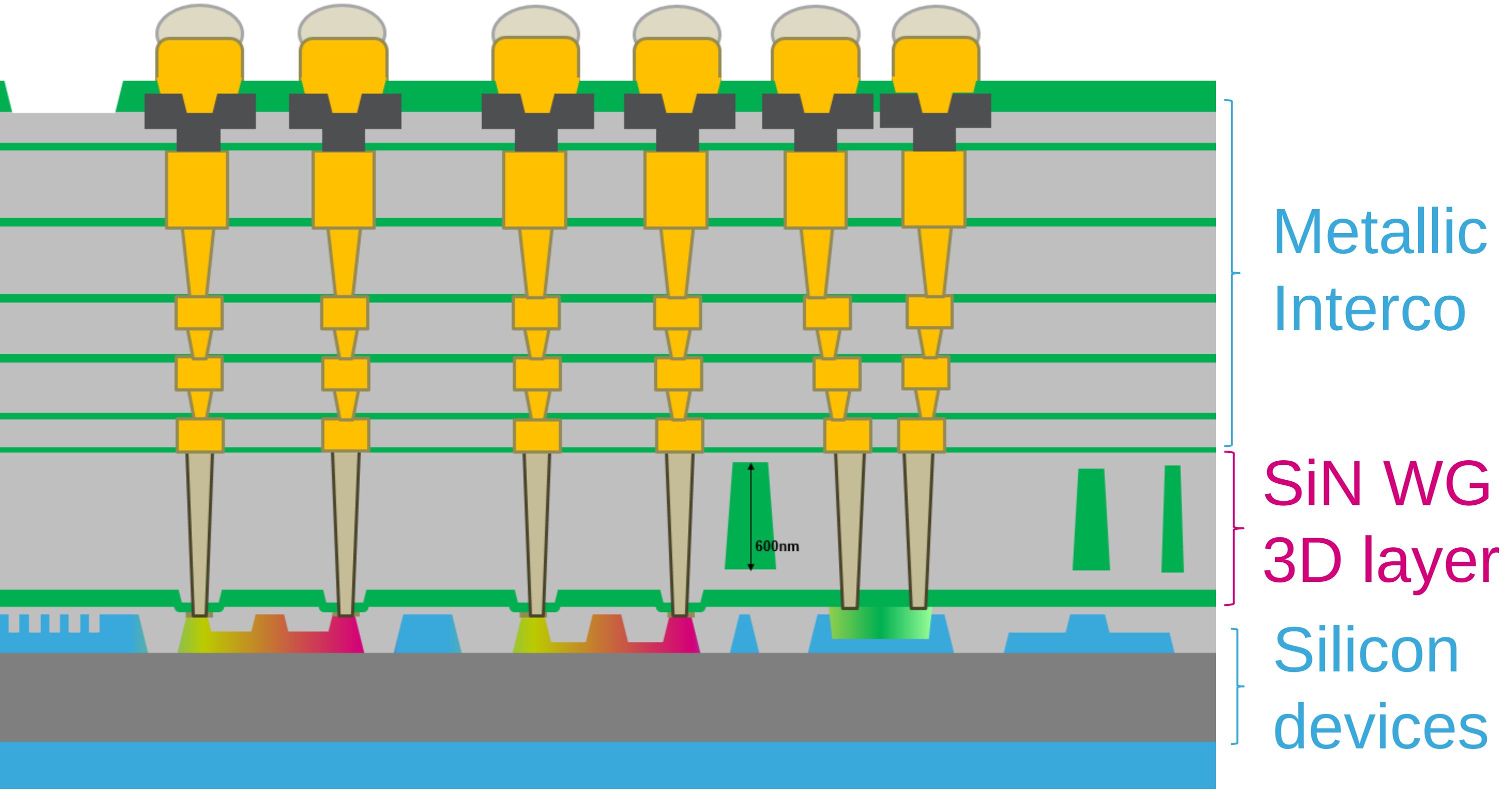
SiN

- ✓ Env./Fab. tolerance
- ✓ Application range
- ✗ Footprint
- ✗ Passive only

Complementary Platforms

Co-integration

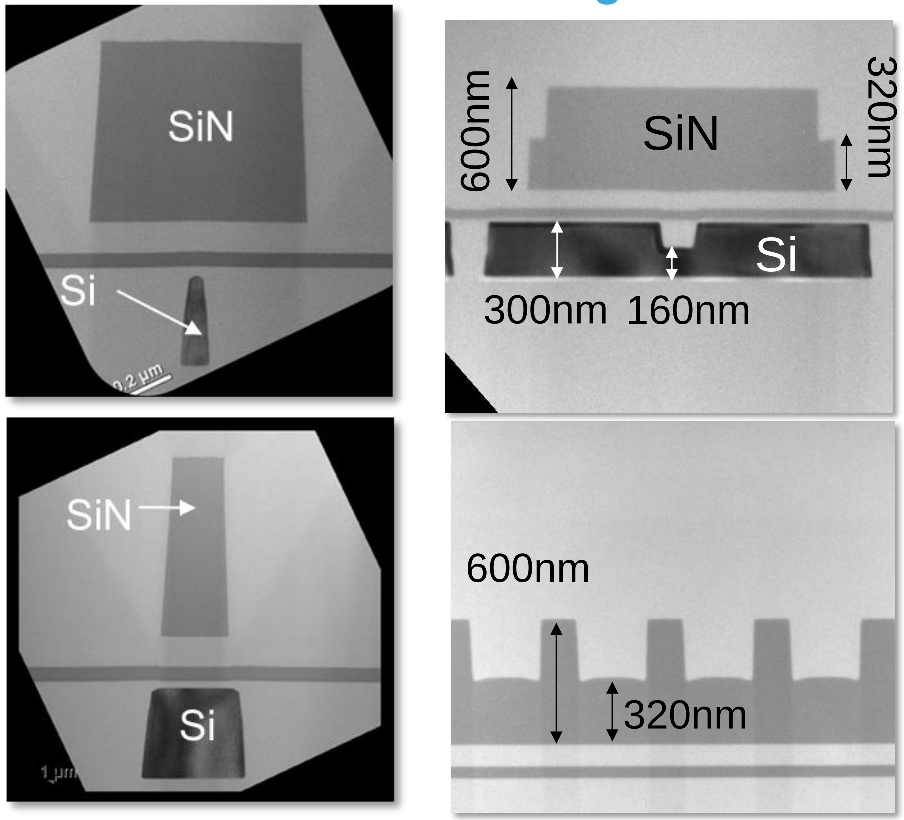
Integrated Silicon Nitride Layer



Silicon nitride layer deposited and patterned within the contacts for the fabrication of additional passive devices.

Si ⇔ SiN transition

Strip & Rib SiN waveguides



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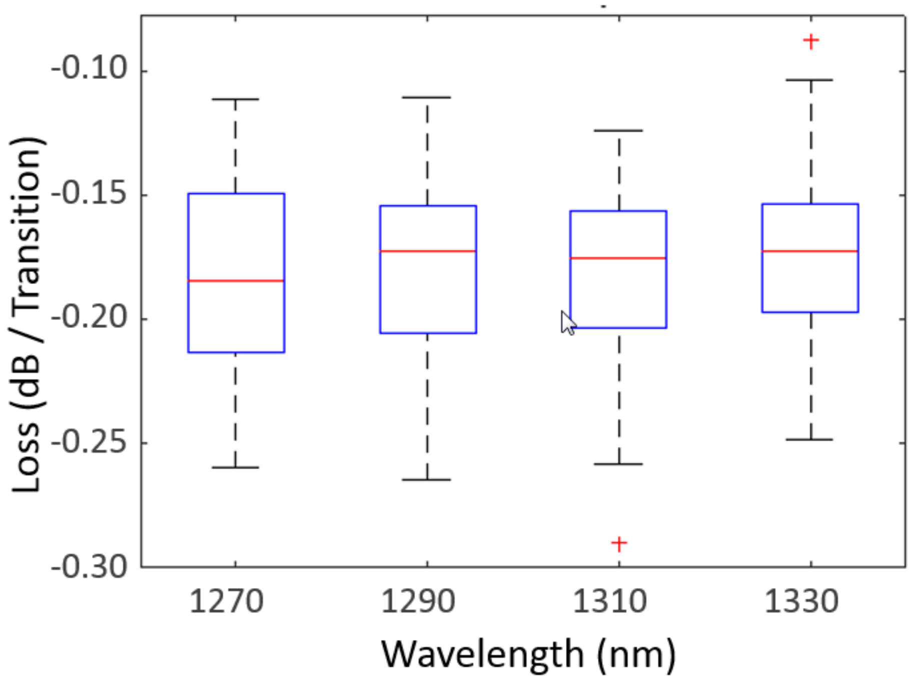
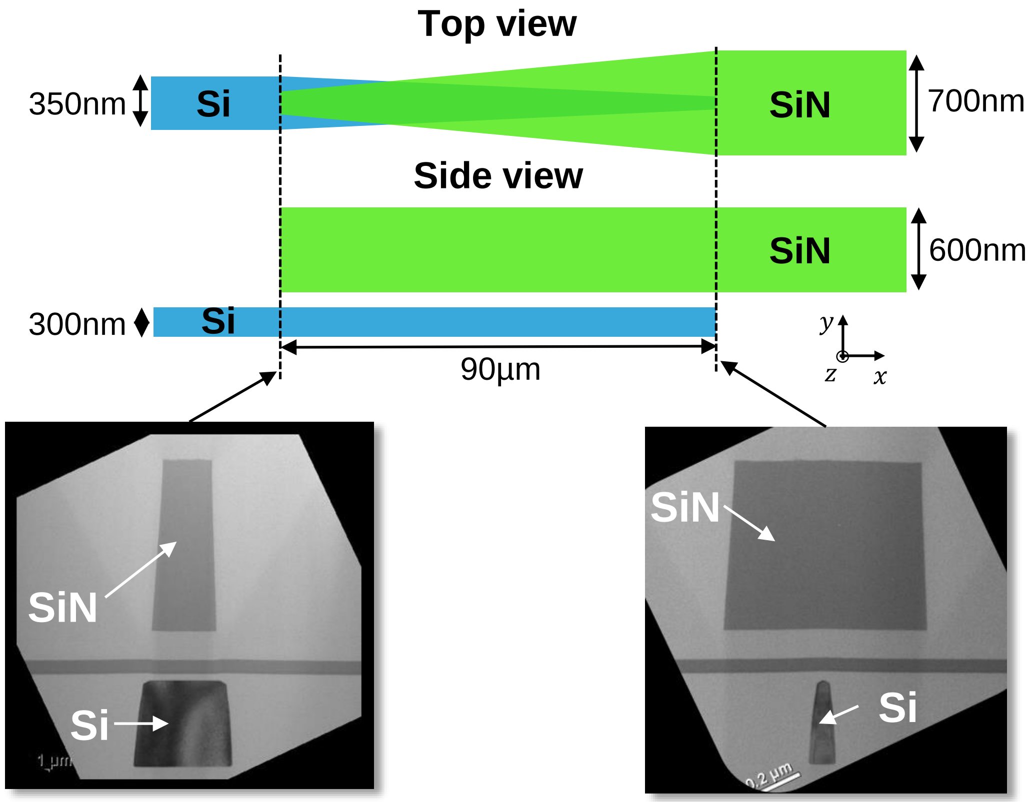
Signal Propagation in SiN at λ = 1310nm

- Strip Waveguide Linear Transmission Losses = **0.6**dB/cm
- Rib Waveguide Linear Transmission Losses < **0.1**dB/cm
- 90° Strip Bend losses (Radius ≥ 40µm) = **0.01**dB/Bend
- Si <-> SiN adiabatic coupling < **0.25**dB/Transition:





Published: GUERBER et al. (ST) SPIE Photonics EU (2018)

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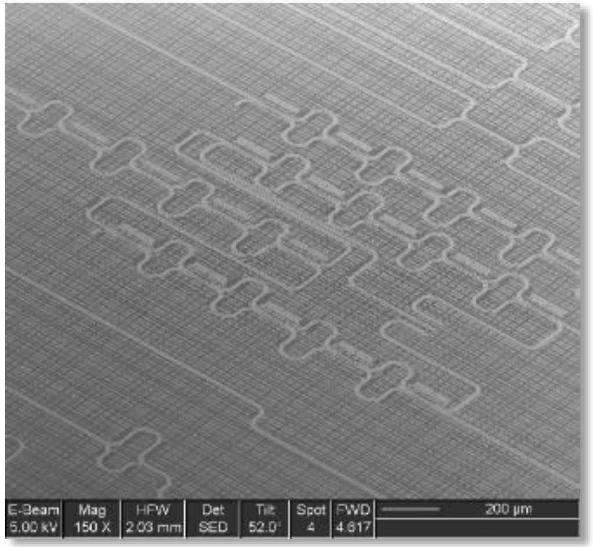
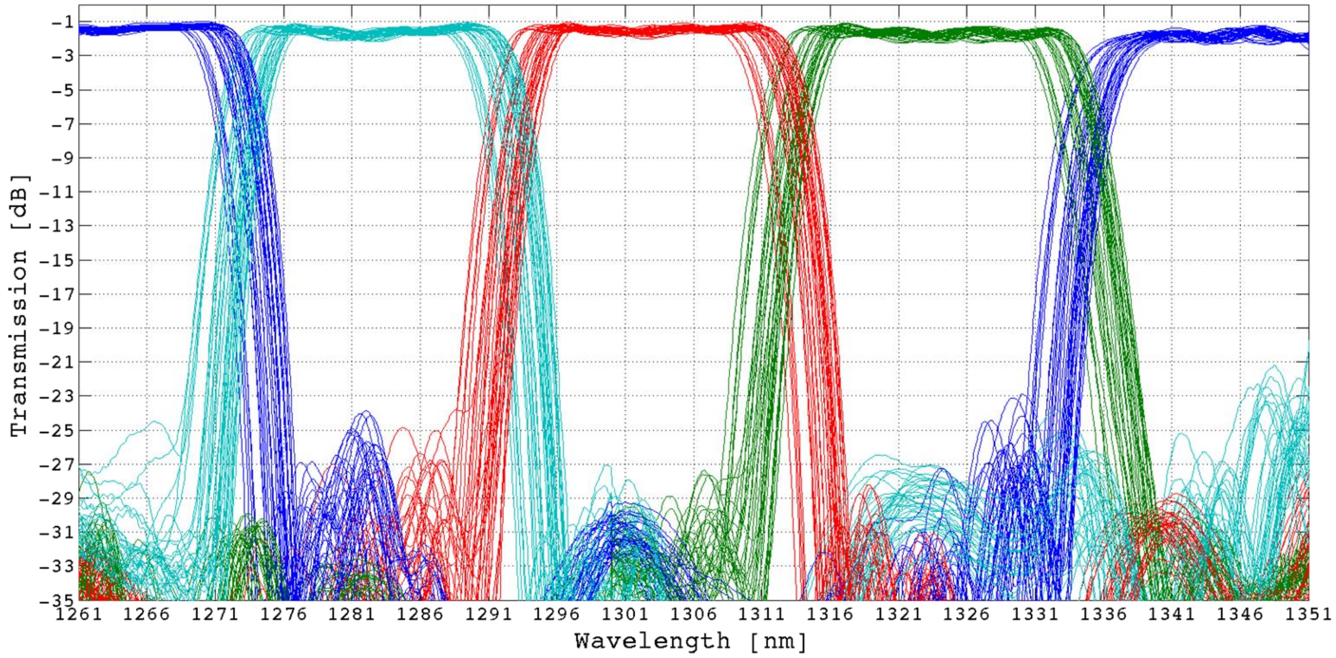
- Transition from Si to SiN devices is feasible within the same circuit

DEMUX: Cascaded Mach Zehnder Interferometer

Coarse Wavelength Division Multiplexing applications (CWDM) : 4λ separated by 20nm

- Spec over 14 nm bandwidth
  - Loss typical: 3 dB
  - Loss worst: 4 dB
  - X-Talk worst: 20 dB





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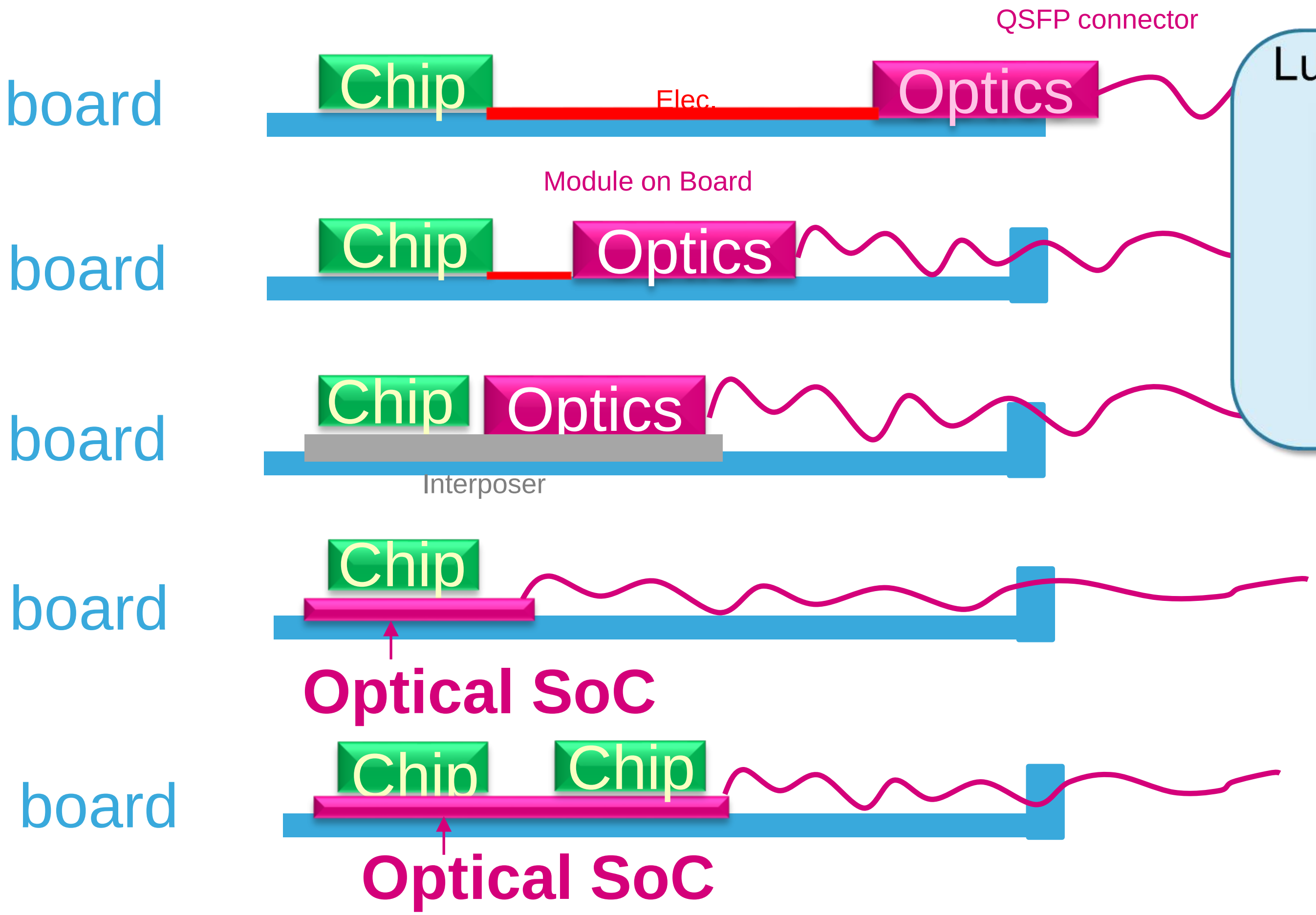
Outline

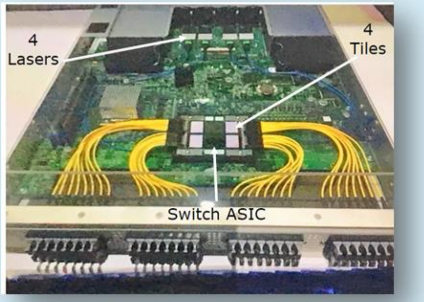
And later ? What should Emerge ?

IEEE Standard : today 100G, 200G,400G, tomorrow 800G,….,3.2TB

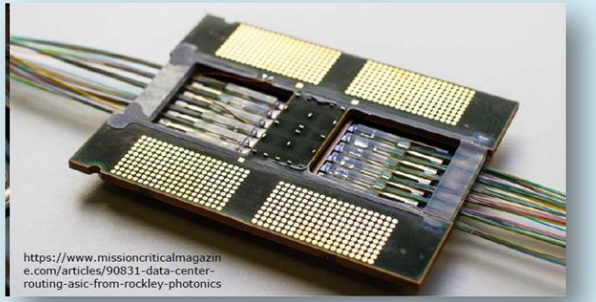
Switch applications and HPC needs : 3.2 TB, 6.4 TB, 12TB/s… 25.6 TB/s



Luxtera : 128x400Gbits



Rockley Switch+ASIC



Ultimately, optics becomes an **active interposer**

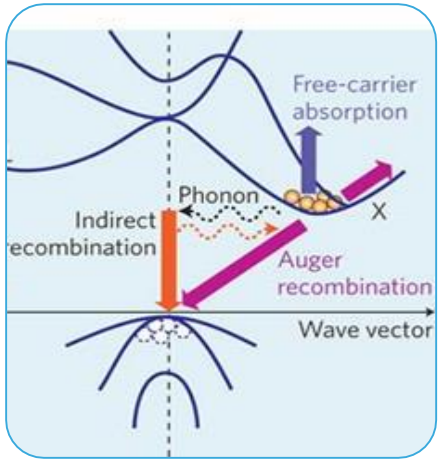
~25 to 50Tb/s
~256 channels

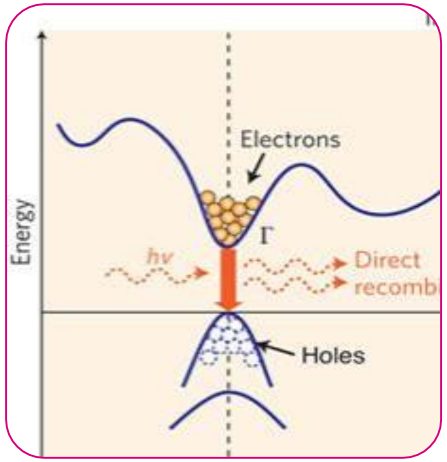
Small footprint TX
Low power
Integrated ligthsource ?

Silicon Limitation

Light Source

Si : indirect bandgap — **InP : direct bandgap**





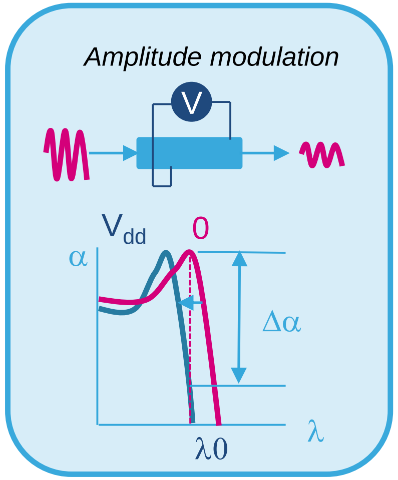
Di Liang et al., Nat. Phot. Feb. 2010

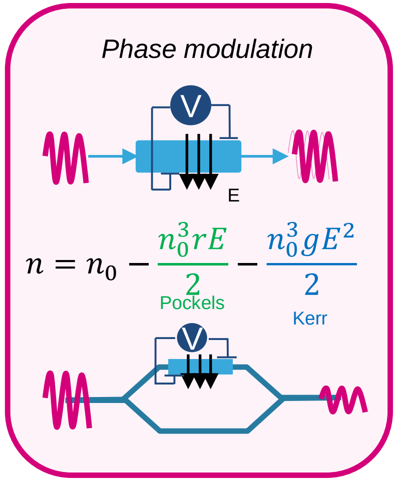
Si laser : low efficiency
GeSn Laser : low maturity, λ > 1.6µm

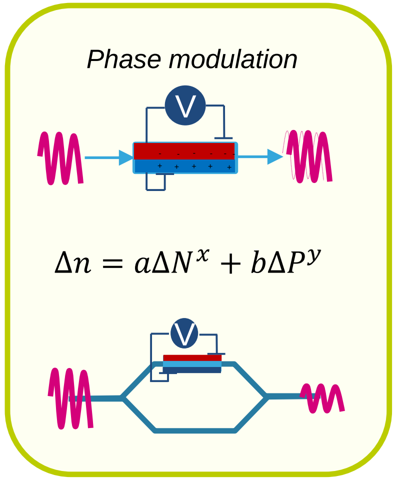
Need to rely on III-V

Modulator Footprint

Electro Absorption — **Electro Refraction** — **Plasma Dispersion**





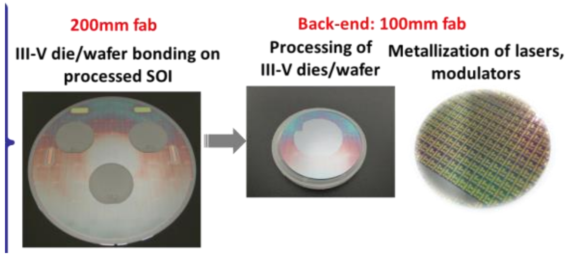


	Electro Absorption	Electro Refraction	Plasma Dispersion
Si	✗	✗	✓
III-V	✓		✓
Ge/SiGe	✓		✓

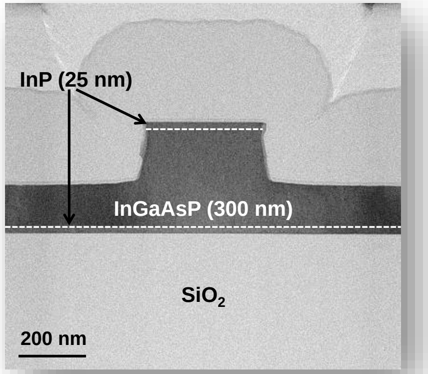
Limited efficiency→ long devices

Improved Devices using III-V Integration

III-V integration by wafer/patch bonding

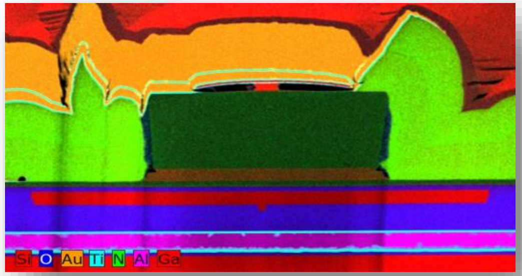


III-V-OI



Y. Ikku et al. U. of Tokyo, Optics Express, 20, B357, 2012

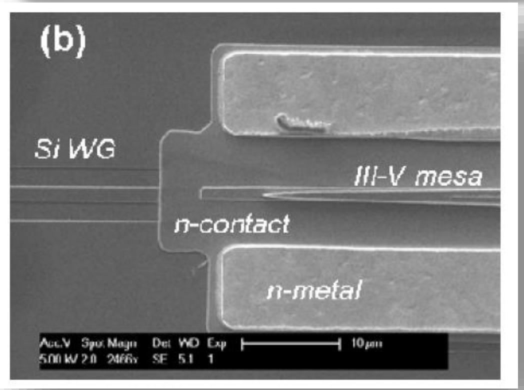
Hybrid III-V/Si Laser



B. Ben Bakir, et al. " Opt. Express 19(11),(2011), LETI.

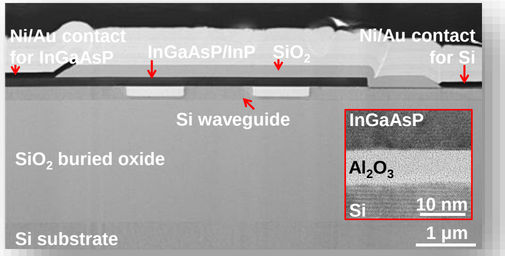
J. Durel et al (ST/LETI), IEDM 2016

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

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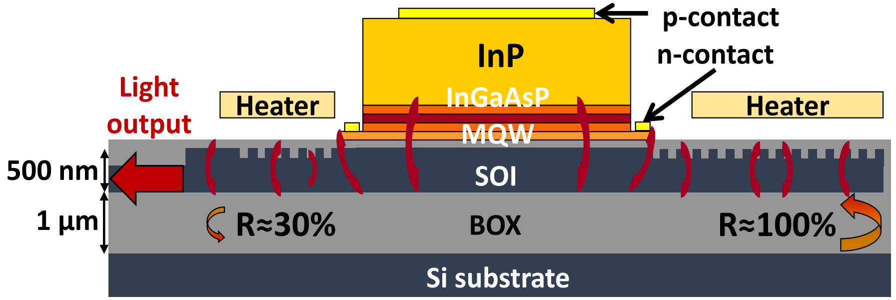
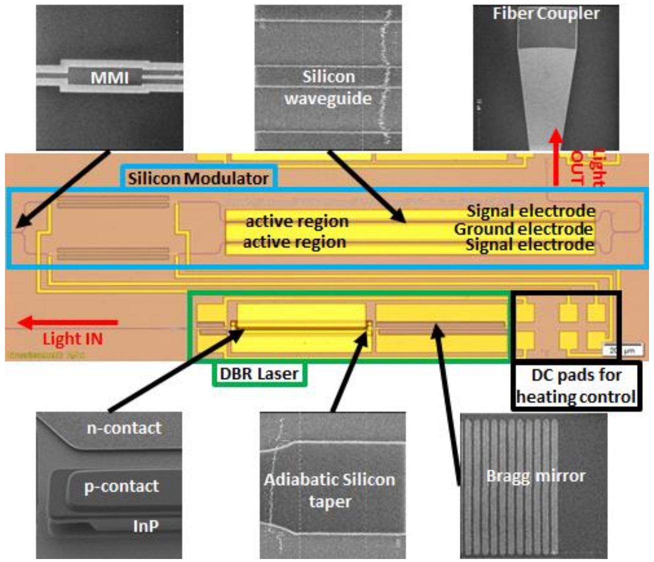
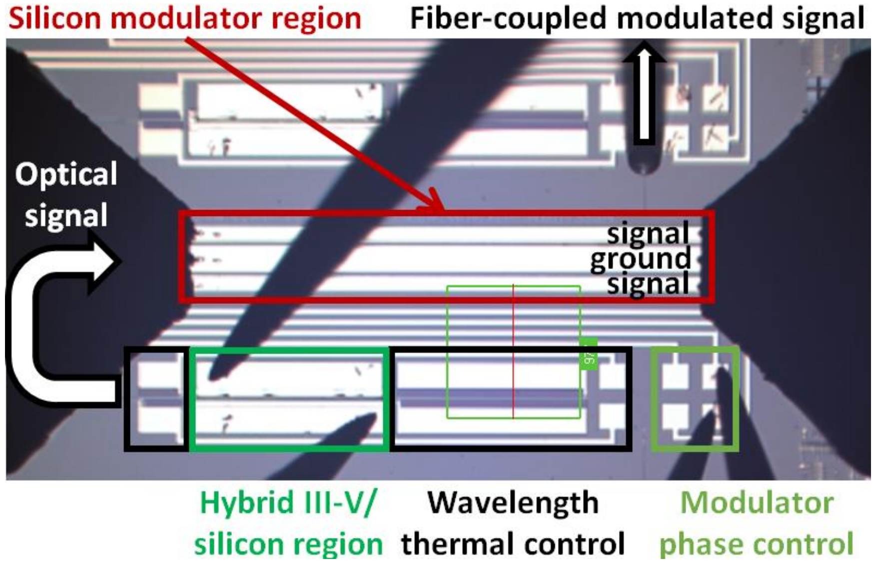
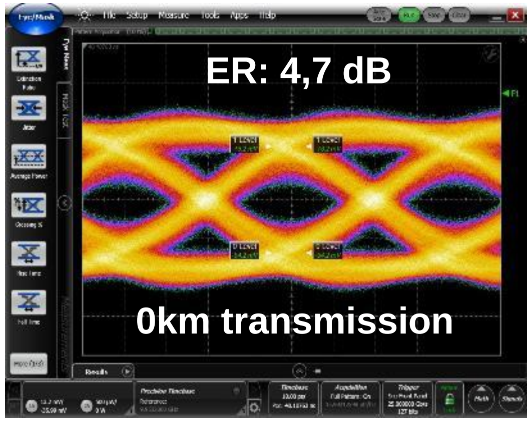
Integrated Transmitter : Hybrid Laser + Modulator

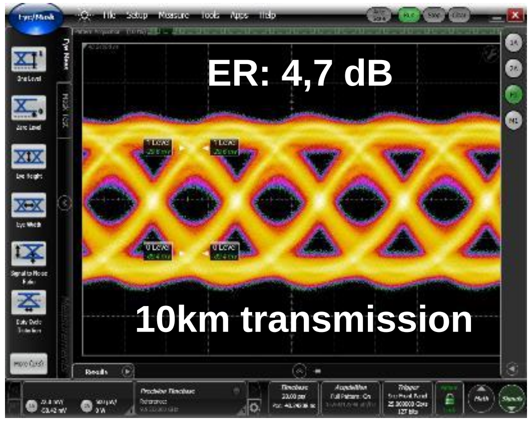






- Demonstration of a **25 Gb/s** transmission using the transmitter, with 2.5 Vpp on each MZM arm.

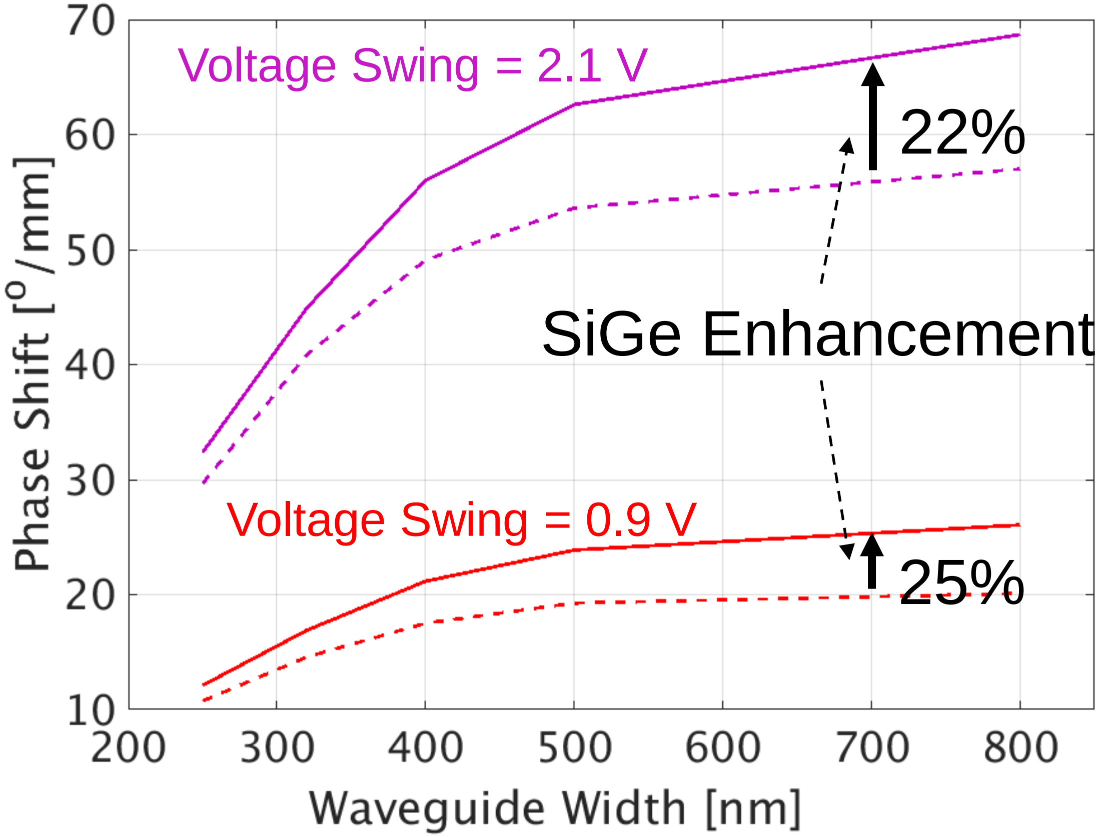


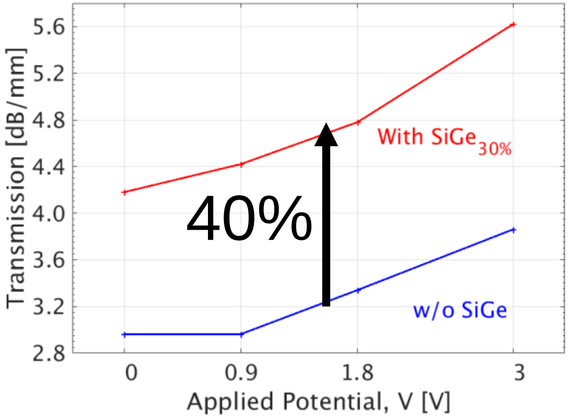


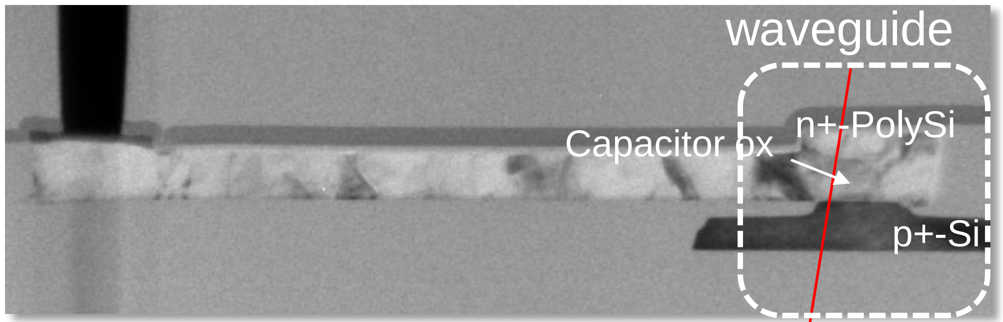
T.Ferrotti et al., SSDM 2016, Optics Express 2017 , CEA-LETI/ST

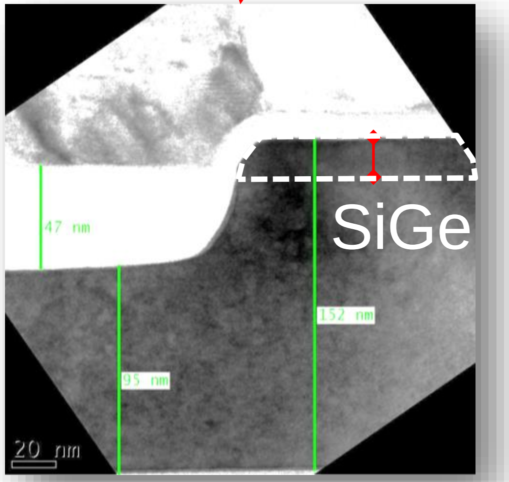
MOS Modulator using SiGe at interface

- 15 nm of $SiGe_{0.3}$ is grown on the silicon waveguide before interface oxide deposition (T_{ox} = 13nm)





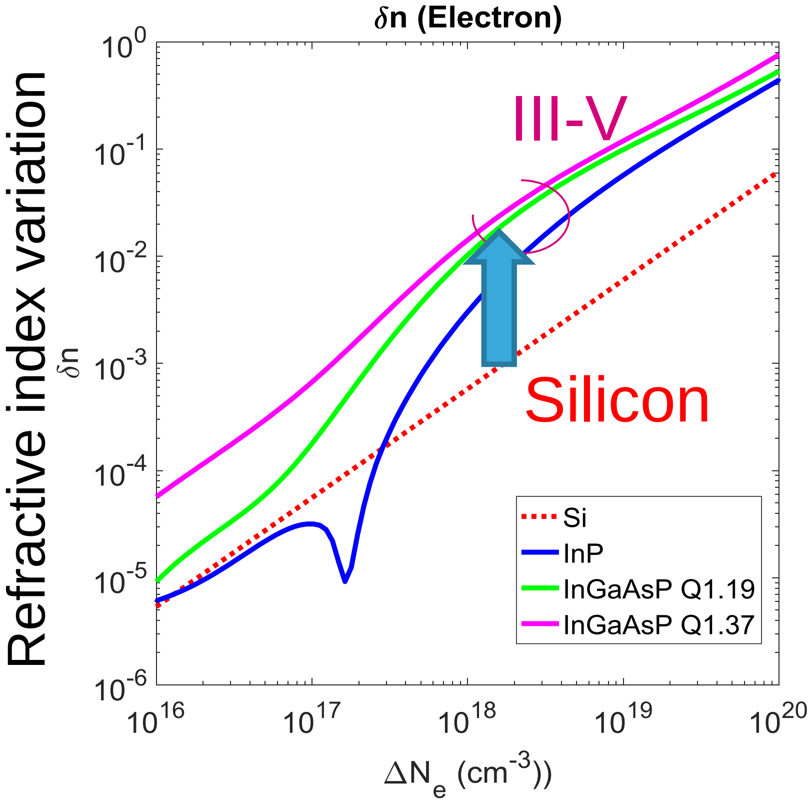




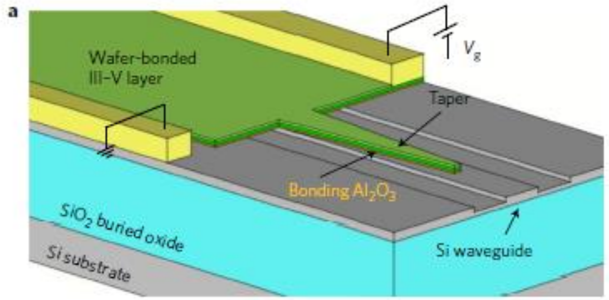
- 25% improvement in efficiency measured when using SiGe in capacitive structure

[3] HAN et al. (U. of Tokyo) IEEE GFP 2012
[4] TAKENAKA et al. (U. of Tokyo) IEDM 2016

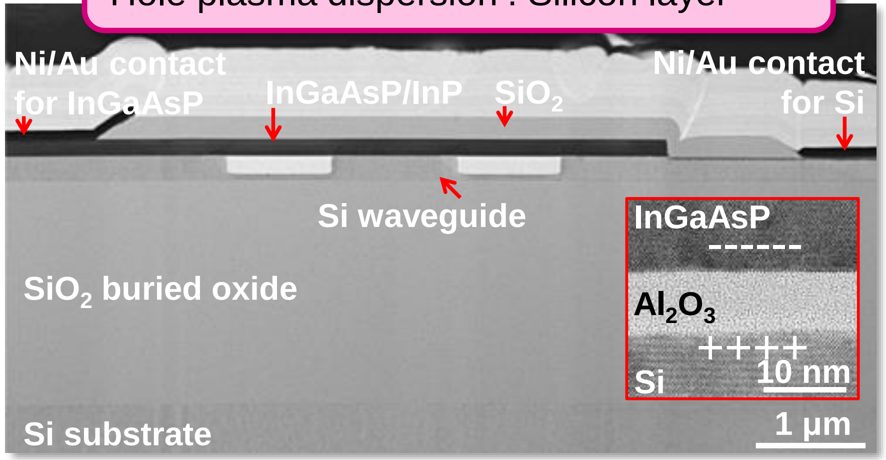
Heterogeneous Integration on SOI : Efficient Modulation



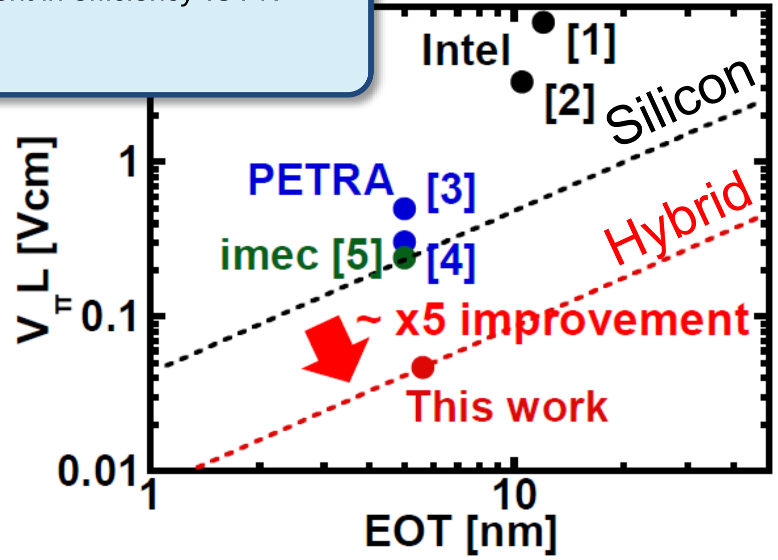
Carrier Density Variation



Electron plasma dispersion : III-V layer
Hole plasma dispersion : Silicon layer



50X improvement in efficiency vs PN junction
5X versus Si

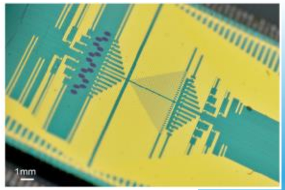


J.H. Han et al., IEDM 2016 J.H. Han, F.Boeuf et al., Nat. Photonics 2017

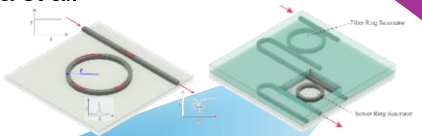
Secured Communication

Sensing

Quantum Computing
Ji Wang et al., Science



Silicon-Based Optical Biosensors
Laura Lechuga et al.

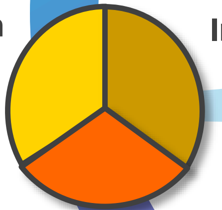


More than DATACOM
Photonic sensors & detectors connecting objects

Datacom

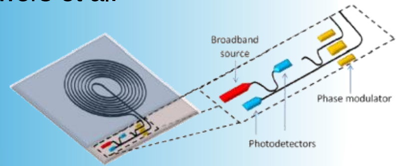
Bandwidth

Insertion Loss

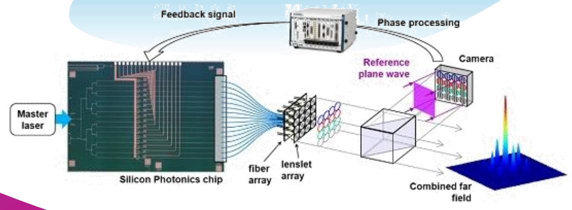


Power Management

Hybrid silicon waveguide optical gyroscope
John Bowers et al.

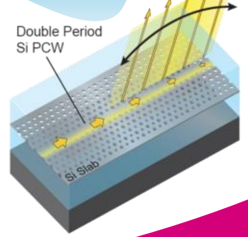


Atmospheric LiDAR anemometer
Jérome Bourderionnet et al.



Photonic Crystal based Lidar
T. Baba et al.

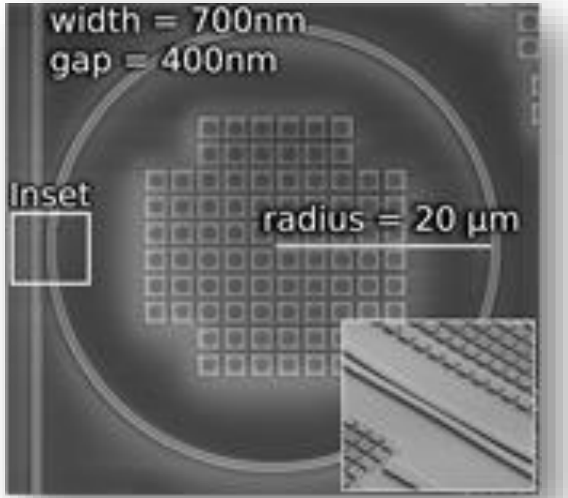
(Takeuchi et al., ICO-24, Tu2K-03 (2017))



Automotive

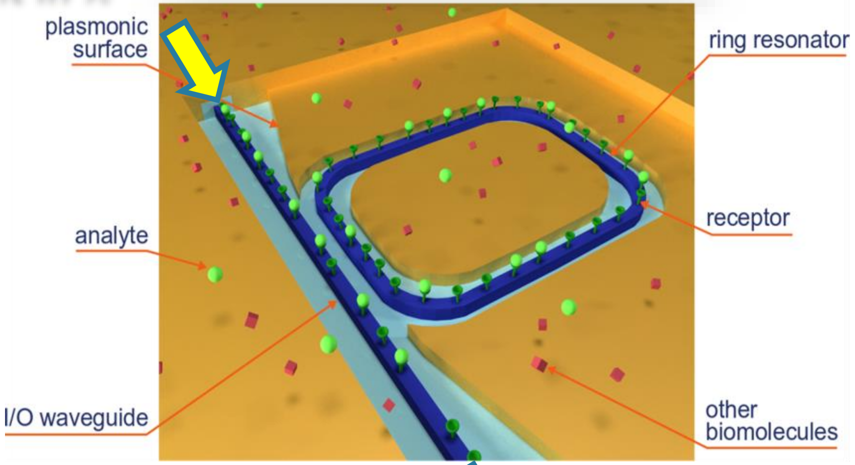
Optical Sensor using DAPHNE

SiN ring resonator



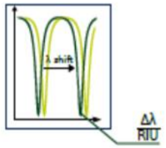
Molecules adsorption modifies effective optical index on the ring resonator surface Resonant peak shift with this effective index

Light in λ



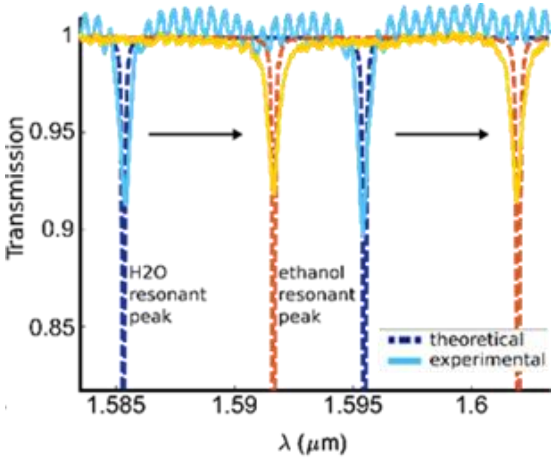
Output measure

λ shift



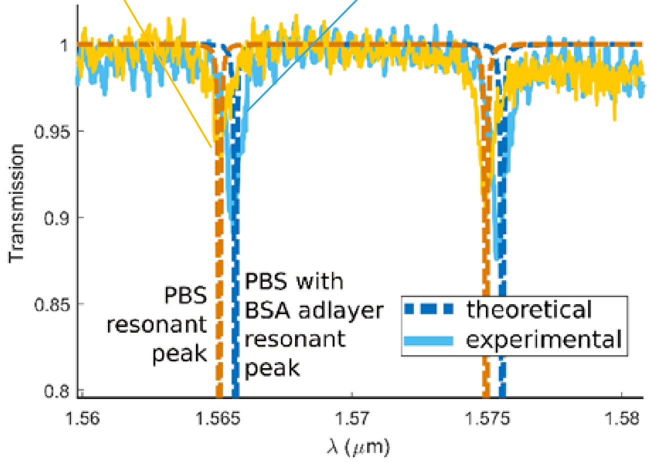
Light out

M. Calvo et al., SSDM 2018



phosphate-buffered saline solution (PBS)

surface functionalization layer (bovine serum albumen, BSA)



0.5 nm resonant peak shift per nm thickness change in biological add layer

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Conclusion

- After 20 years of research and development , Silicon Photonics became an industrial reality thanks to the increase of Datacenter-Applications
- Despite relatively large feature size compared to advanced CMOS, Si-Photonic requires advanced processing tools to guarantee high-yield
- Basic building blocks have a high maturity level, but performance improvement are still mandatory to adress the IEEE ethernet roadmap and ultimately the chip-to-chip communication market
- Heterogeneous Integration of materials with Silicon, such as Ge or III-V, and TSV is a promising path to demonstrate complex optical SoC to adress several 10s of Tb/s communications
- Research on Si-Photonics for « More Than Datacom » is very active at the international level

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- Collaborations : R. Orobtchouk, P. Charrette, M. Takenaka, S. Takagi

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