Silicon Photonics for HEP Applications

Myth or Reality?

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Credit for other illustrations:
EU-FP7 Helios Silicon Photonics course (http://www.helios-project.eu/Download/Silicon-photonics-course)
STM (Group IV Photonics 2014, http://www.photonics21.org/uploads/DQcQ0X4ZRv.pdf)
Université Paris Sud (CERN-EP-ESE seminar https://indico.cern.ch/event/291295/)

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What is Silicon Photonics ?

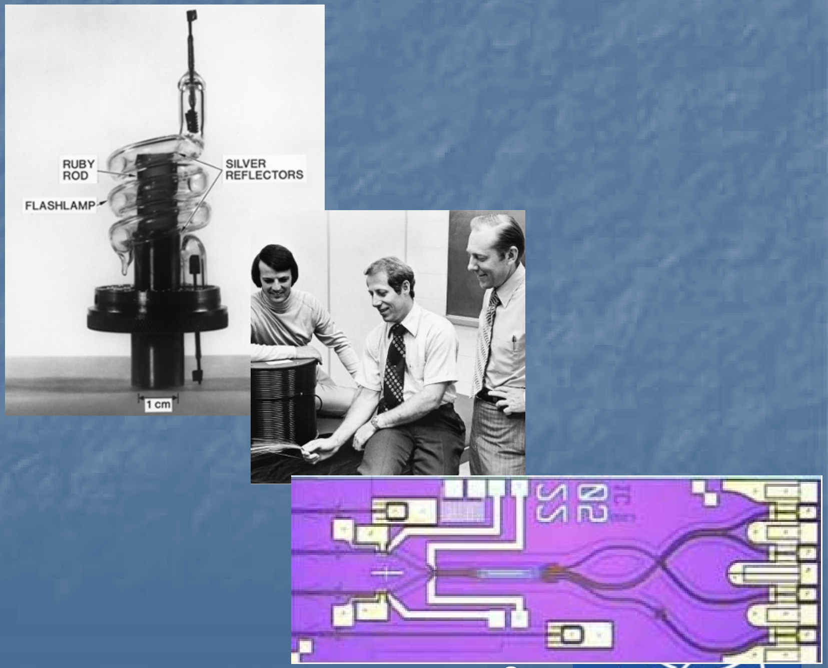
- A photonic system using silicon as an optical medium
- The silicon waveguide lies on top of a silica cladding layer (SOI)
- Silicon is patterned with sub-micron precision into planar microphotonic components

- Expectations:
  - Fuel Moore's law by enabling low-power high-density chip scale optical communication
  - Replicate for photonics the amazing success of CMOS electronics
  - Open the possibility to explore and exploit light-matter interactions at sub-wavelength dimensions

Electronics and Photonics, a historical perspective

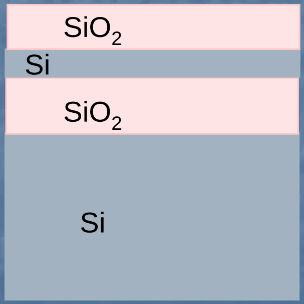
- Electronics
  - 1947: 1st transistor
  - 1959: first planar transistor
  - 1961: first planar IC

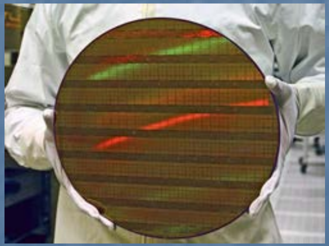
- Photonics
  - 1960 1st Ruby laser
  - 1962 first semiconductor laser
  - 1970: 1st RT CW semiconductor laser
    1st low loss optical fibre
  - 1984: 1st InP opto IC (HBT plus laser)
  - 1985: Reports about Si optical modulators
  - 1988: 1st RT CW VCSEL
  - 1989: 1st Er-doped fibre amplifier



Silicon for optics: Pros

- Transparent in 1.3-1.6 µm region
  - √ Low loss waveguides
- Take advantage of CMOS platform
  - √ Mature technology
  - √ High production volume
- Low cost
- Silicon On Insulator (SOI) wafer
  - √ Natural optical waveguide
- High-index contrast (n_{Si}=3.5 – n_{SiO2}=1.5)
  - √ Strong light confinement
    - ➢ Small footprint (450nm x 220nm)

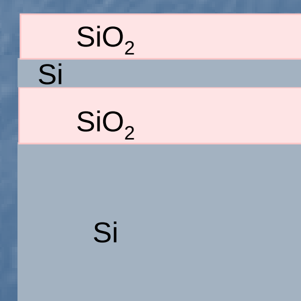


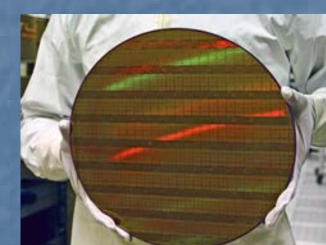


Silicon for optics: Pros and Cons

- Transparent in 1.3-1.6 µm region
  - √ Low loss waveguides
- Take advantage of CMOS platform
  - √ Mature technology
  - √ High production volume
- Low cost
- Silicon On Insulator (SOI) wafer
  - √ Natural optical waveguide
- High-index contrast (n_{Si}=3.5 – n_{SiO2}=1.5)
  - √ Strong light confinement
    - ➢ Small footprint (450nm x 220nm)

- Indirect bandgap material
  - √ No or weak electro-optic effect
  - √ “Lacks” efficient light emission
    - ➢ No Si laser
- No detection in 1.3-1.6 µm region
- Strong light confinement
  - √ Large mode mismatch with fibre





Silicon Photonics for HEP Applications

Outline

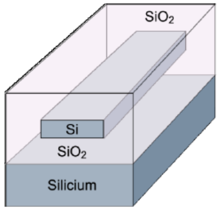
A: Process and Devices 1: Waveguiding

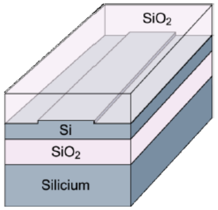
A) Technology
B) Radiation
C) Design
D) Integration
E) System

1. Waveguides and in/out-couplers
2. Modulators
3. Detectors
4. Full circuits

Silicon optical waveguides:

- Silicon on insulator substrate
- Rib or strip waveguide

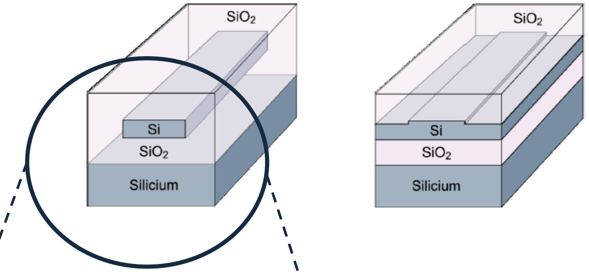


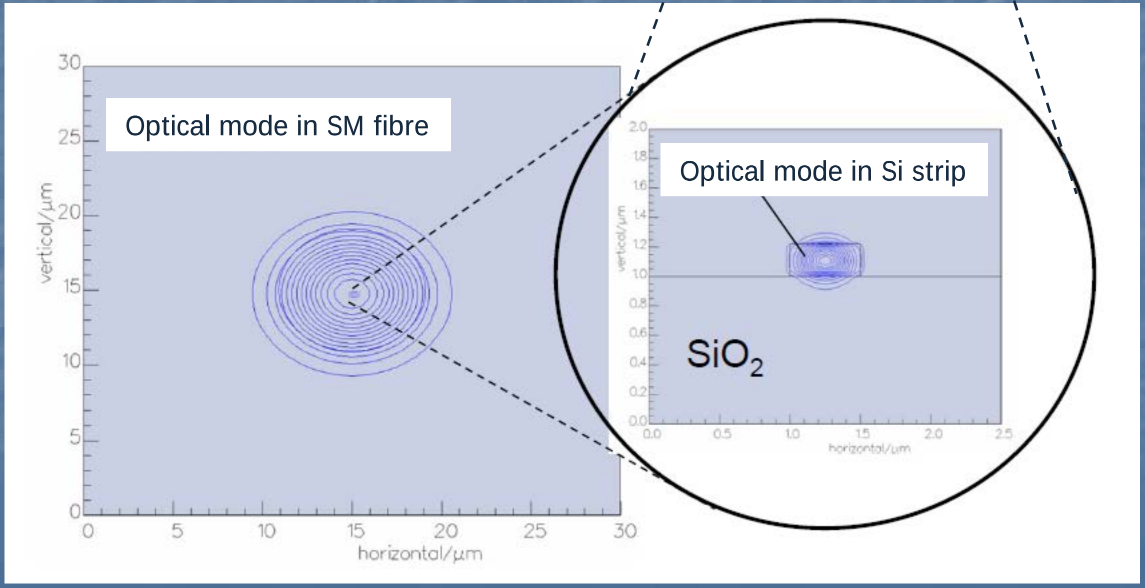


Process and Devices 1: Waveguiding

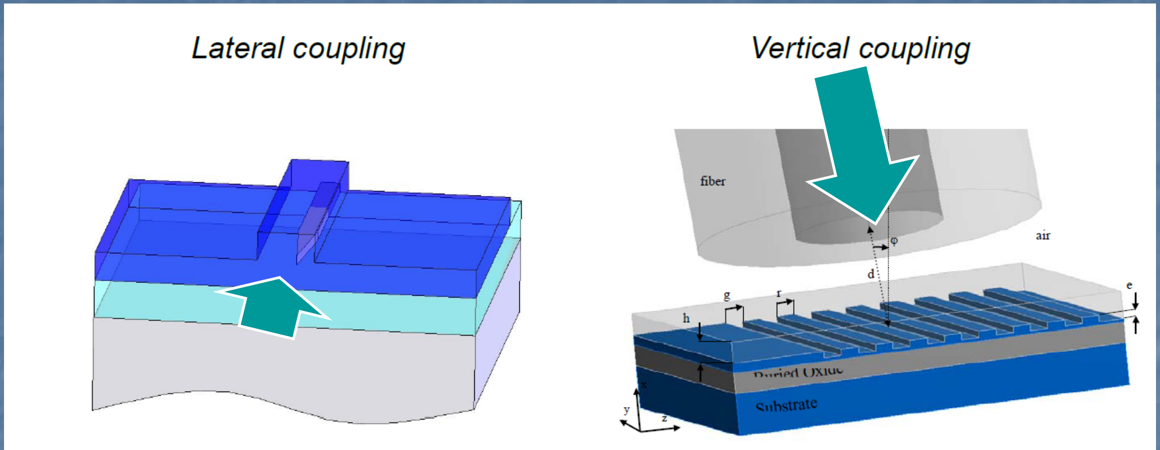
Silicon optical waveguides:

- Silicon on insulator substrate
- Rib or strip waveguide



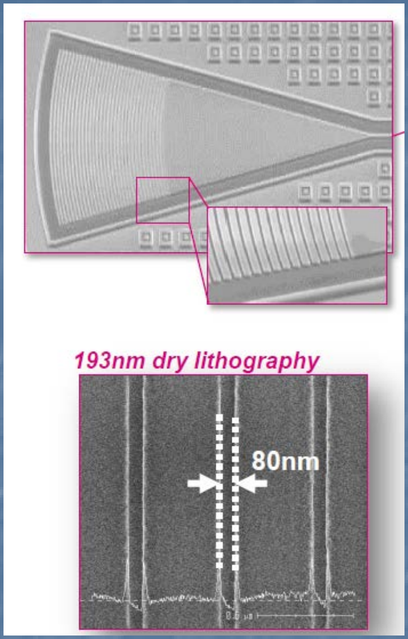


Process and Devices 1: In and Out-coupling

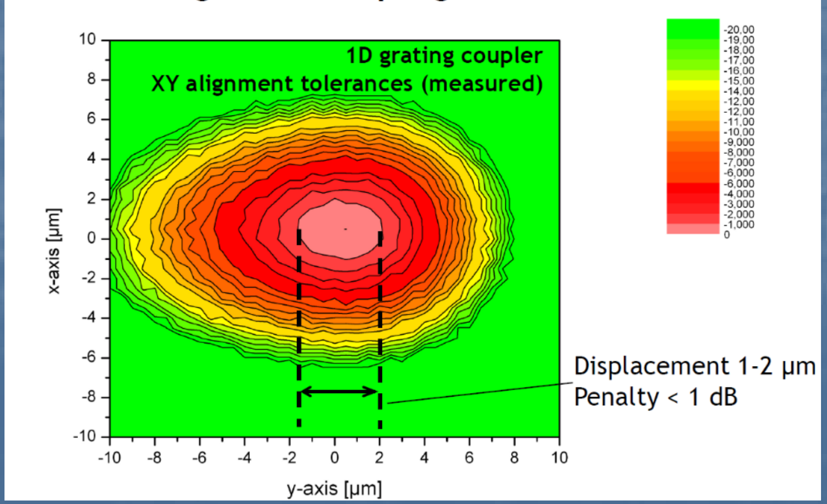


- typically based on inverted tapers
- spotsize: ~3 µm

- typically based on gratings
- spotsize: ~ 10 µm



Vertical - single fiber coupling issues

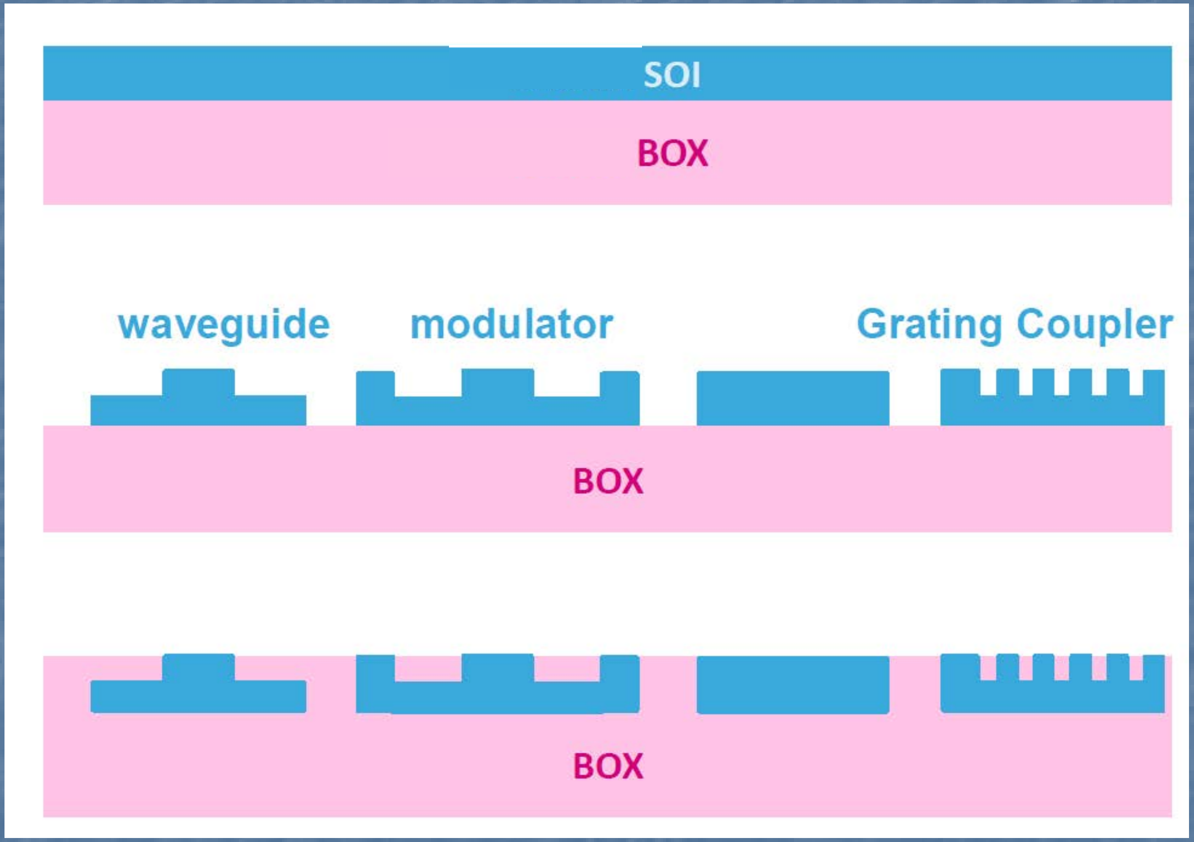


Process and Devices 1: Waveguiding and Coupling

SOI wafer

Pattern/etch

Oxide regrowth

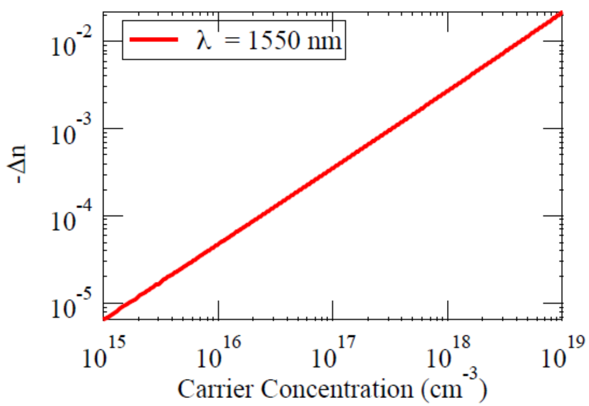


Process and Devices 2: Phase Modulation

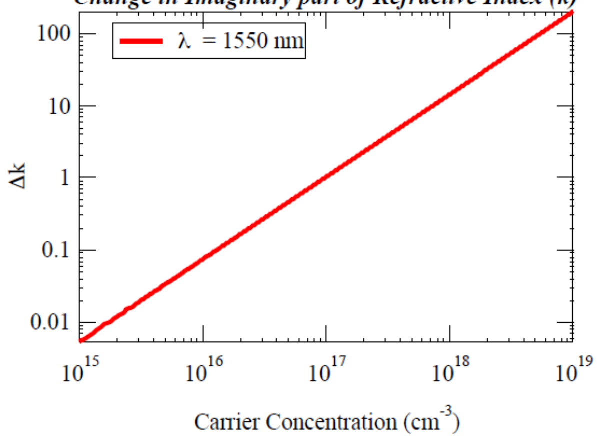
Plasma dispersion effect in silicon.

- Changing the free carrier concentration in the silicon changes the real and imaginary parts of the refractive index :
  1. changes to the real part (n) → change the effective index of the waveguide (n_{eff}).
  2. changes to the imaginary part (k) → change the absorption (α) of the waveguide.

Change in Real part of Refractive Index (n)

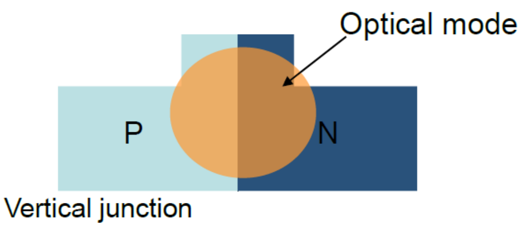


Change in Imaginary part of Refractive Index (k)

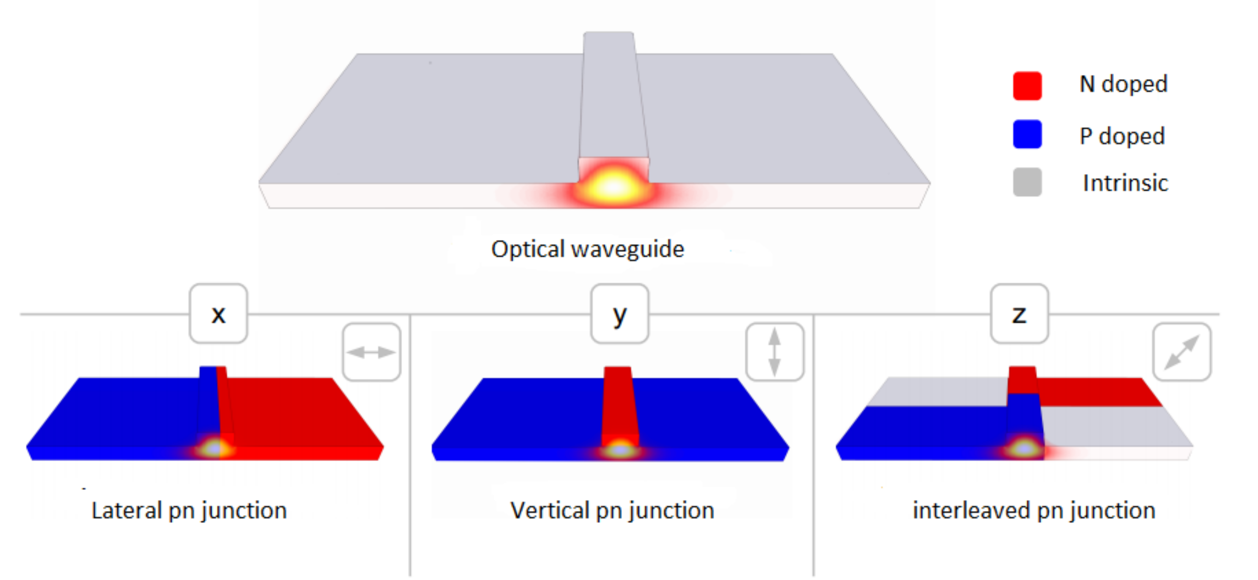


Effect is small - large number of carriers needed to get a 0.1% change in n.

Process and Devices 2: Phase Modulation



- Theoretical performances: birefringence free device
  - *Gardes et al Opt. Express 13, 8845 (2005)*
  - $V_\pi L_\pi$=2.5 V cm
  - rise and fall times: 7 ps (drive voltage =-5 volts)
  - excess loss: 2 dB for TE and TM polarizations

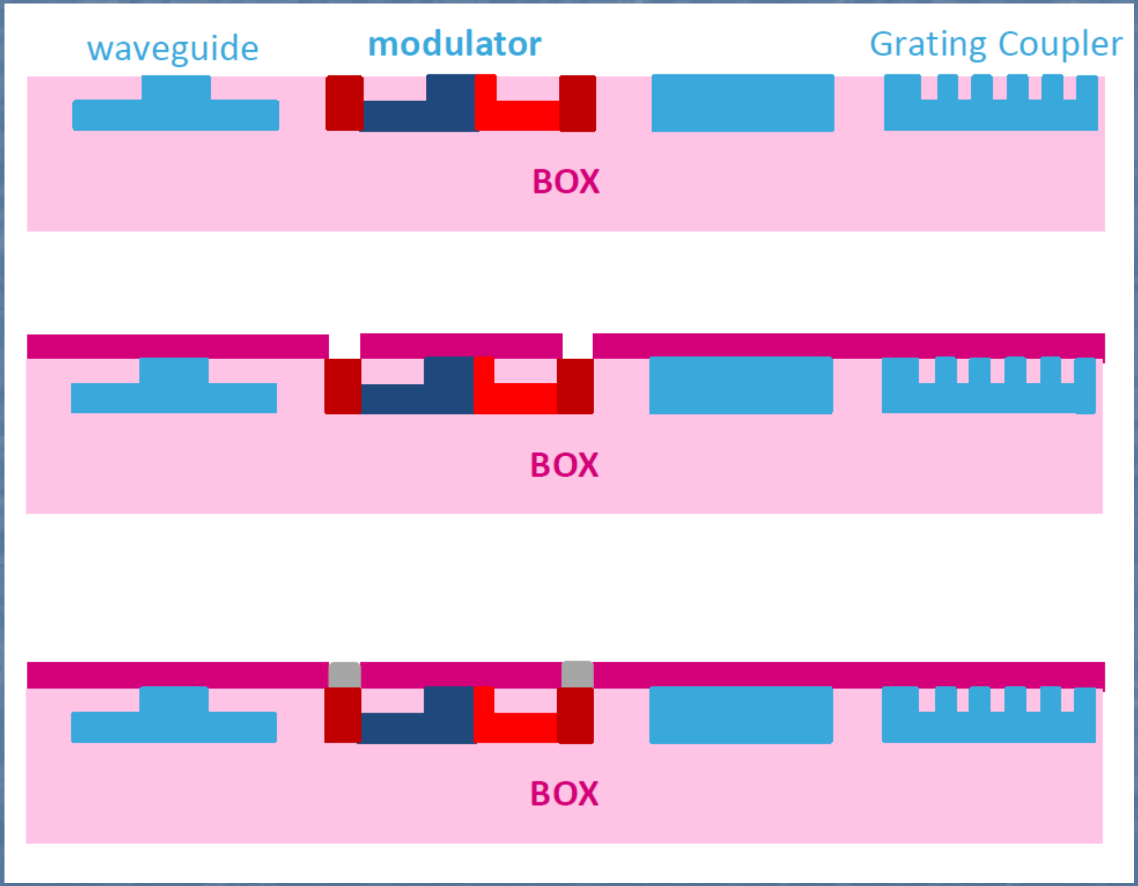


Process and Devices 2: Phase Modulation

Doping

Silicide/etch

Salicide



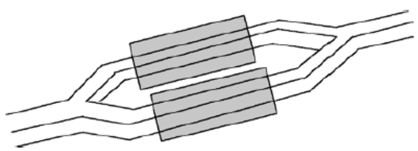
Process and Devices 2: Intensity Modulation

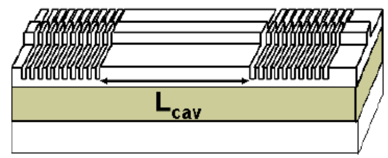
To convert phase modulation into intensity modulation:
<u>waveguide integrated interferometric structure</u>

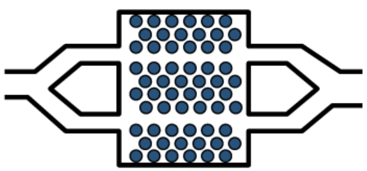
Mach Zehnder

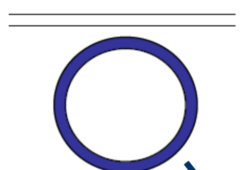
Resonators

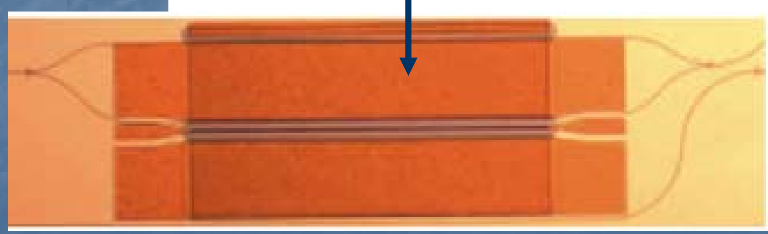
Photonic crystal

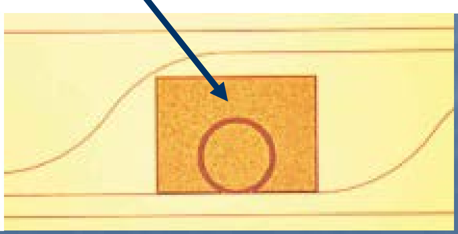






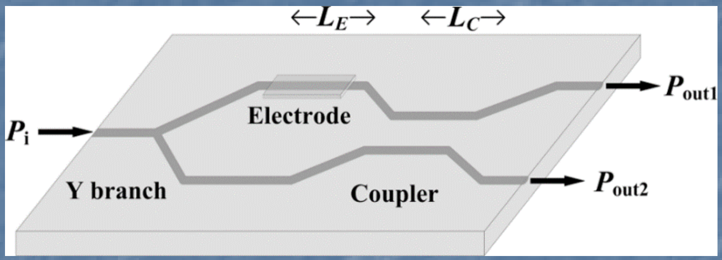


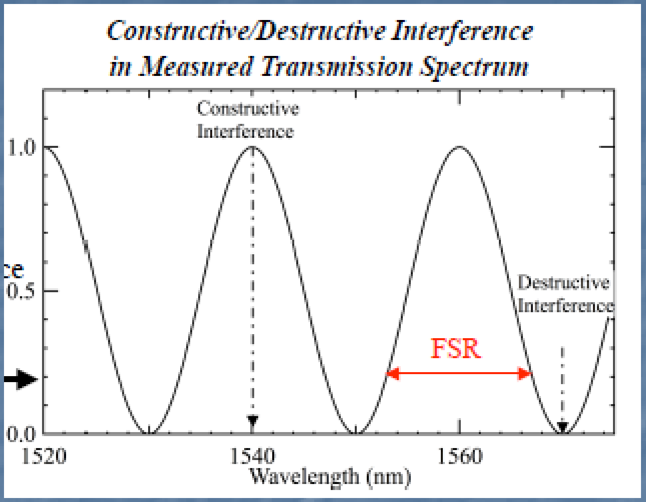


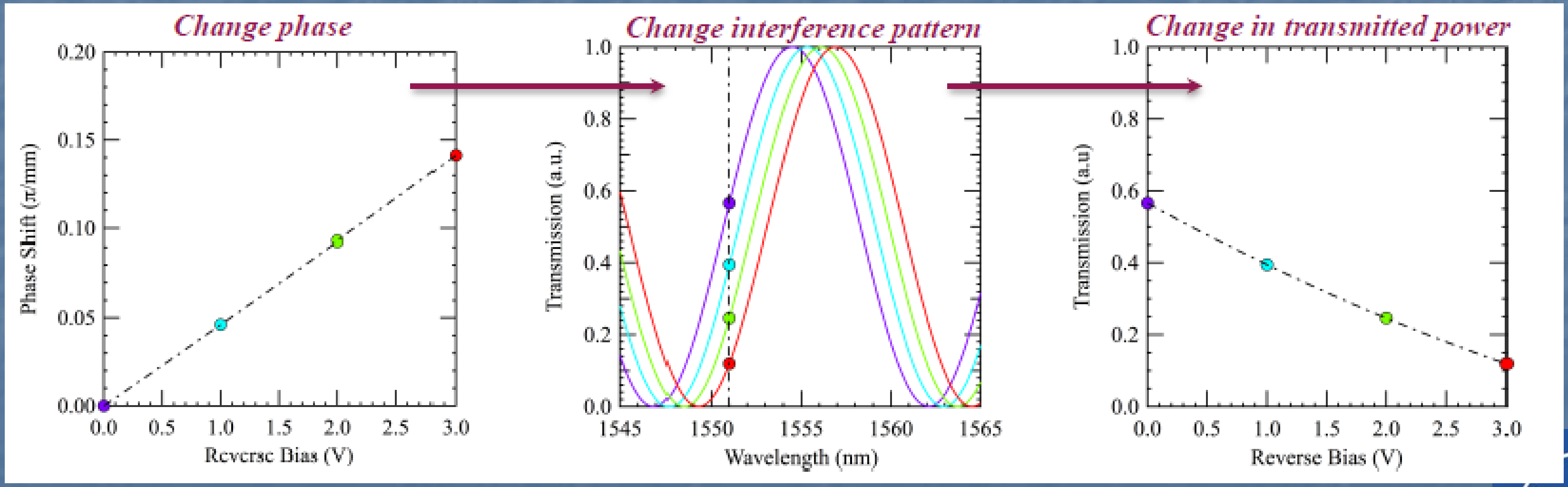


Si modulators performance: a) static

Integrated Mach-Zehnder modulator

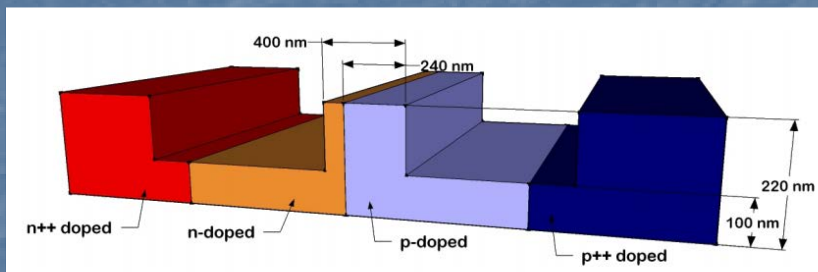


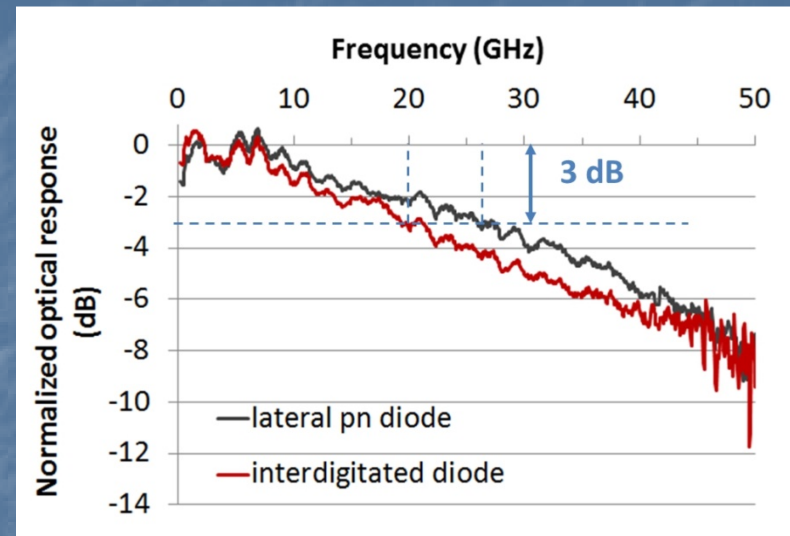


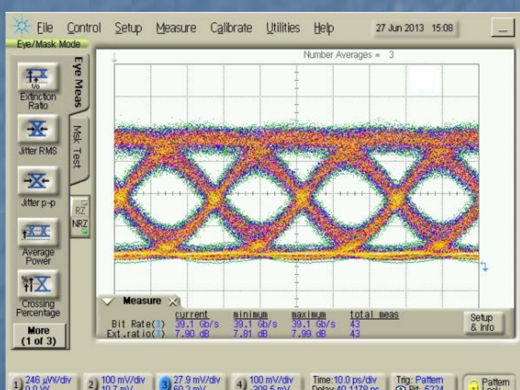


Si modulators performance: b) dynamic

0.95mm long Mach-Zehnder modulator





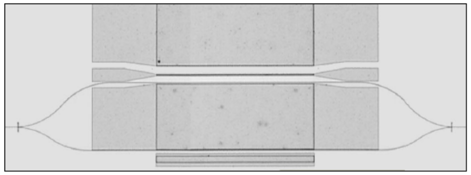


- ✓ $V_\pi L_\pi$ ~2.2 V.cm
- ✓ Extinction ratio: 8 dB
- ✓ Insertion loss: 4 dB
- ✓ Frequency: 26 GHz
- ✓ Data rate: 40 Gbit/s
- ✓ Vmod=7V

D. Marris-Morini et al, Opt. Exp. (2013)

Si modulators performance: c) power

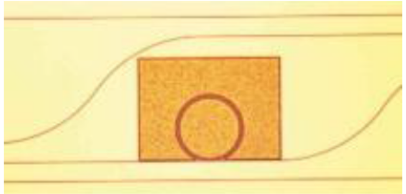
40 Gbit/s Mach Zehnder modulator



L=1.8mm => C ~0.5 pF
V_{pp} = 7 V

Energy/bit ~ 6 pJ/bit

10 Gbit/s ring modulator



Ring radius of 50 µm => C ~0.08 pF

Energy/bit ~ 0.7 pJ/bit

Laser excluded

1pJ/bit = 1mW/Gbps

Optical wavelength-division multiplexed (WDM) links in internet
- ~ 10 nJ/bit (total) (Tucker, 2008)

Reading from DRAM
- ~ 30 pJ/bit (Dally, 2009)

Communicating a bit off chip
- Several to 10's pJ/bit

Floating point operation (FLOP)
- ~ 1pJ/bit (50 pJ for double precision (64b) operation) (Dally, 2009)

Energy stored in DRAM cell
- ~ 10 fJ

Switching one CMOS gate
- < 1 fJ

(1 electron at 1V, or one photon ~ 0.16 aJ)

(one google search ~1kJ)

W. Dally, "Power Efficient Supercomputing," talk at ACS, 2009
R. S. Tucker, "Energy and the Internet," OECC '08, Sydney, Australia, July 2008; also J. Baliga, K. Hinton, and R. S. Tucker, "Energy Consumption of the Internet," Optical Internet, 2007 and the 2007 32nd Australian Conference on Optical Fibre Technology. COIN-ACOFT 2007. Joint International Conference on 24-27 June 2007, Page(s):1 – 3; K. Hinton et al., "Power Consumption and Energy Efficiency in the Internet," IEEE Network 25, 2, SI pp6-12 (Mar. Apr. 2011)

Process and Devices 3: Detection

A) Technology
B) Radiation
C) Design
D) Integration
E) System

Ge in Si

☺ ☹

- Absorption coefficient of pure Ge
  - $\alpha \approx 9000\ cm^{-1}$ at $\lambda = 1.3\mu m$

    $\Rightarrow L_{ABS}^{95\%} \approx 3.3\mu m$ (!)

    $\Rightarrow$ Low capacitance devices

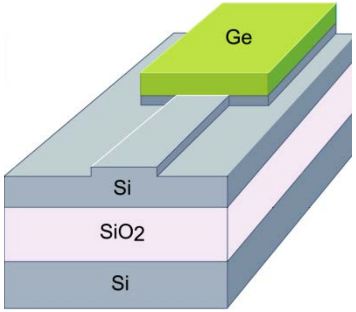
    $\Rightarrow$ High frequency operation
- High carrier mobility

- Lattice misfit with Si of about 4.2%

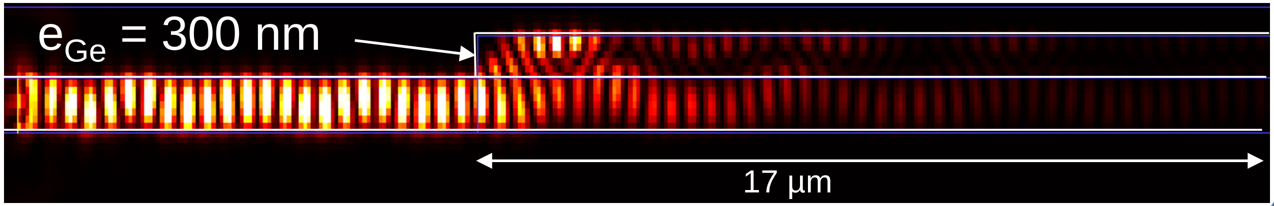
  $\Rightarrow$ specific growth strategies required (wafer-scale and localized)
- Low indirect bandgap: E_G=0.66eV

  $\Rightarrow$ high dark current for MSM devices

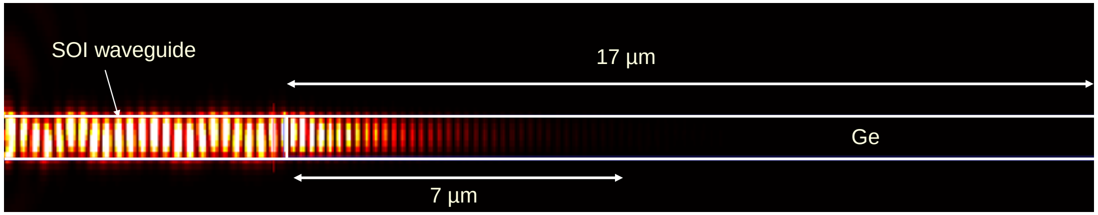
Process and Devices 3: Detection

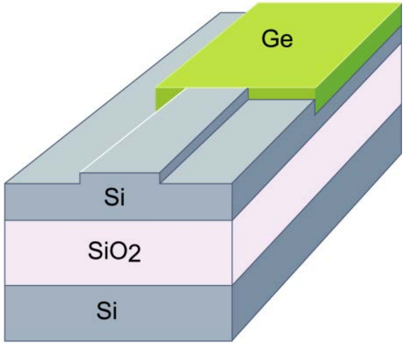


Vertical coupling



Butt coupling





⇨ Short absorption length => Low capacitance
⇨ Light absorption is independent of Ge film thickness

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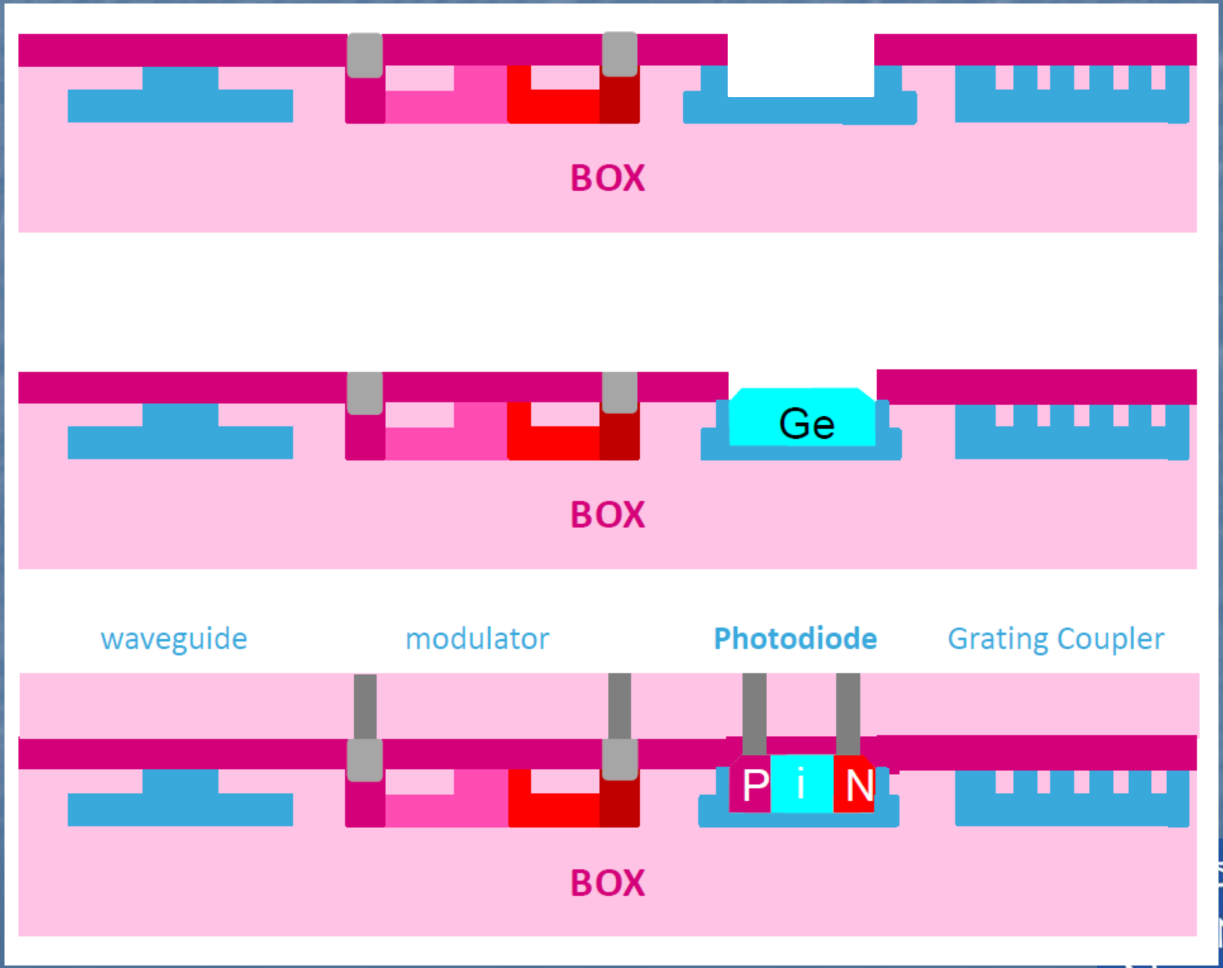
Process and Devices 3: Detection

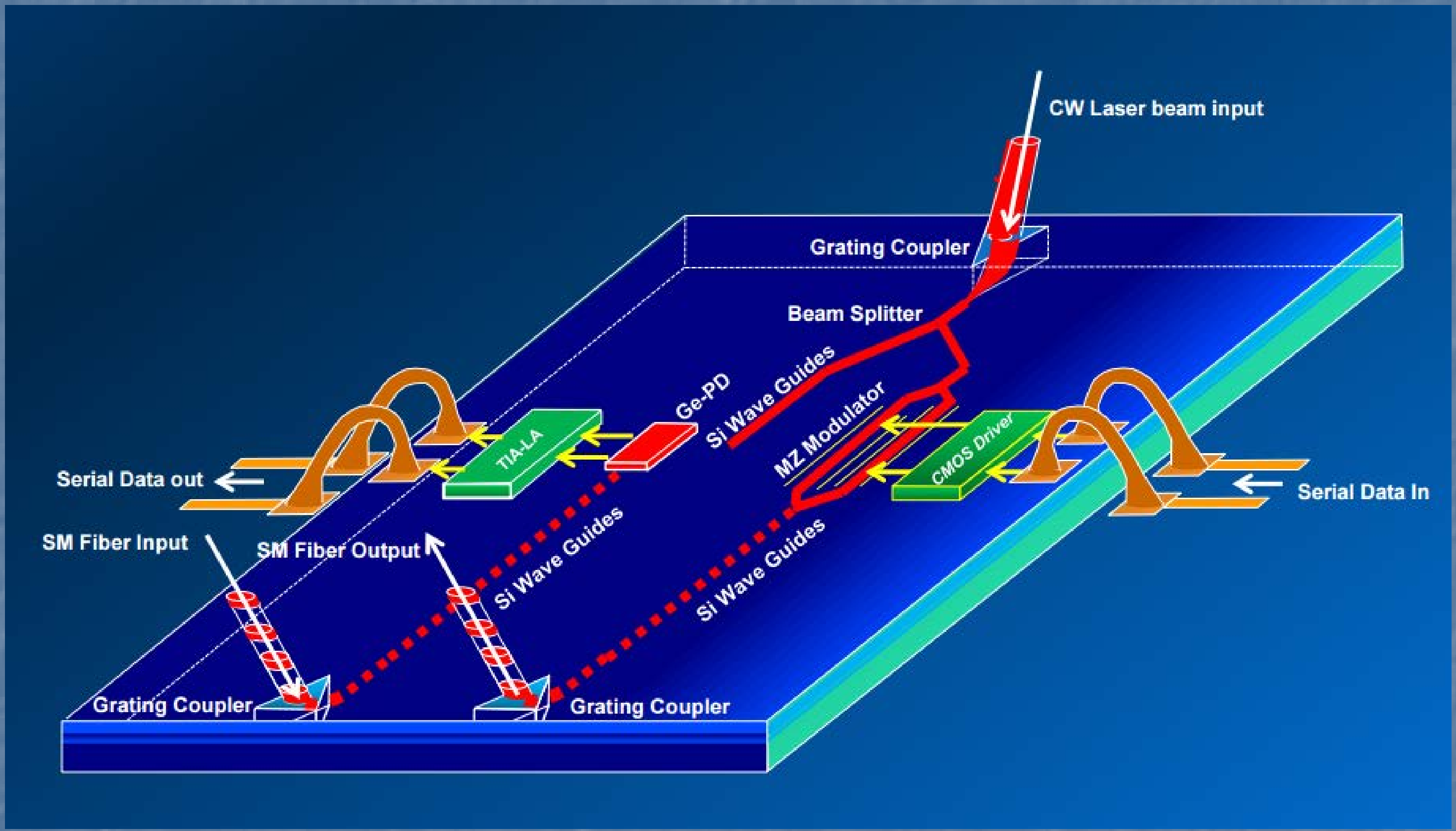
Cavity

Ge deposition

Doping
Contacting
Oxide regrowth



Process and Devices 4: Full Circuit



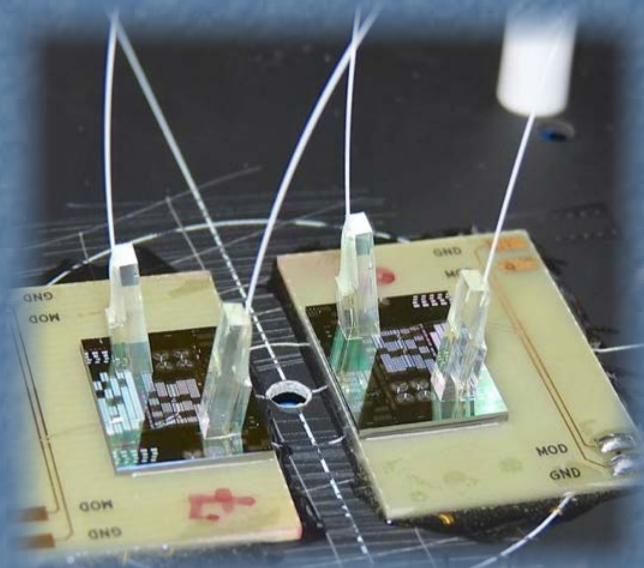
A) Technology
B) Radiation
C) Design
D) Integration
E) System

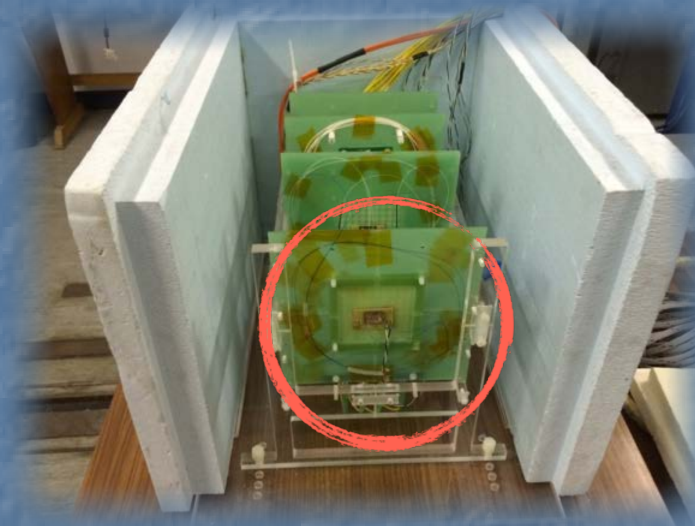
So, why is Si-Photonics of interest to HEP?

A) Technology
B) Radiation
C) Design
D) Integration
E) System

- Radiation resistance potentially as good as Si-sensors and CMOS electronics
- Possibility to design custom circuits in MPW framework
- Possible Co-integration with sensor and electronics

B. Radiation testing MZI Modulators





Devices ready for testing. Devices provided by the Université Paris Sud and fibre coupling done by CEA-LETI.

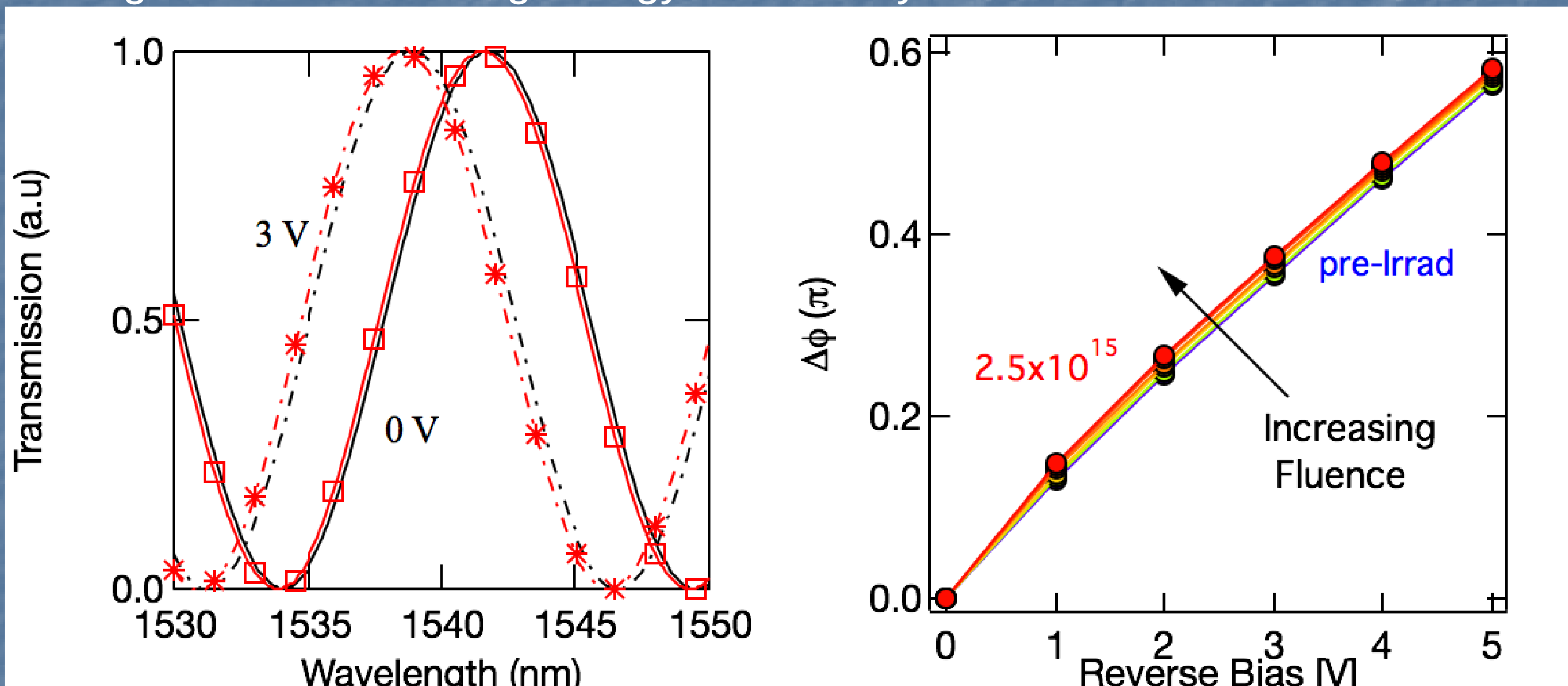
a) High-intensity neutron beam line at the Cyclotron Resource Center in Louvain-la-Neuve used to expose devices to non-ionizing radiation (5×10^{16} 1 Mev $n_{eq}cm^{-2}$)

b) X-ray irradiation facility at CERN used to expose the devices to X-rays (1.3 MGy)

CERN

Radiation testing MZI modulators: a) displacement damage

- Damage from non-ionizing energy loss is very small

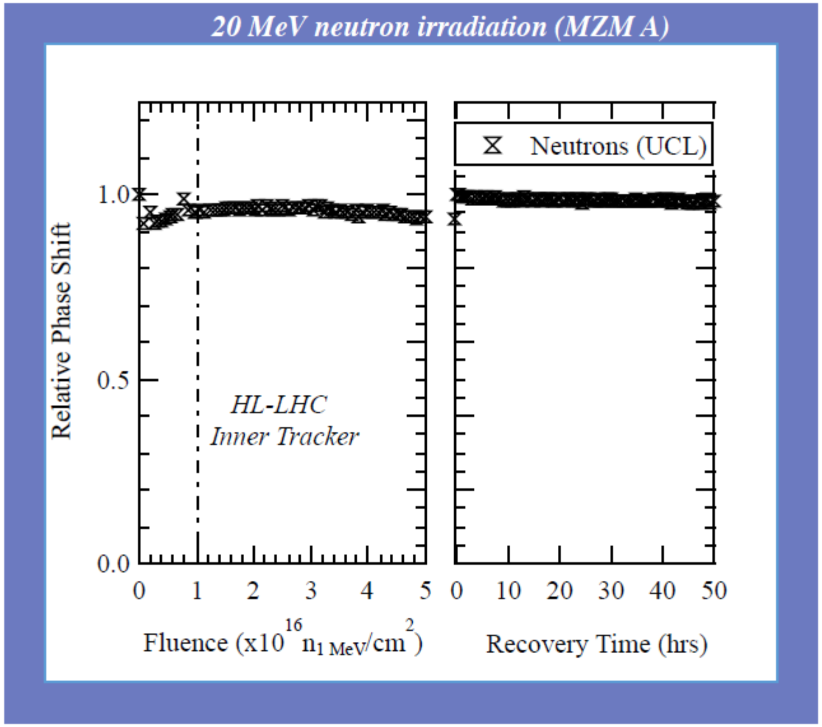


	0 V	3 V	
	□	*	pre-Irrad
	□	*	$2.5x10^{15}$ n_{eq}

Radiation testing MZI modulators: a) displacement damage

A) Technology
B) Radiation
C) Design
D) Integration
E) System

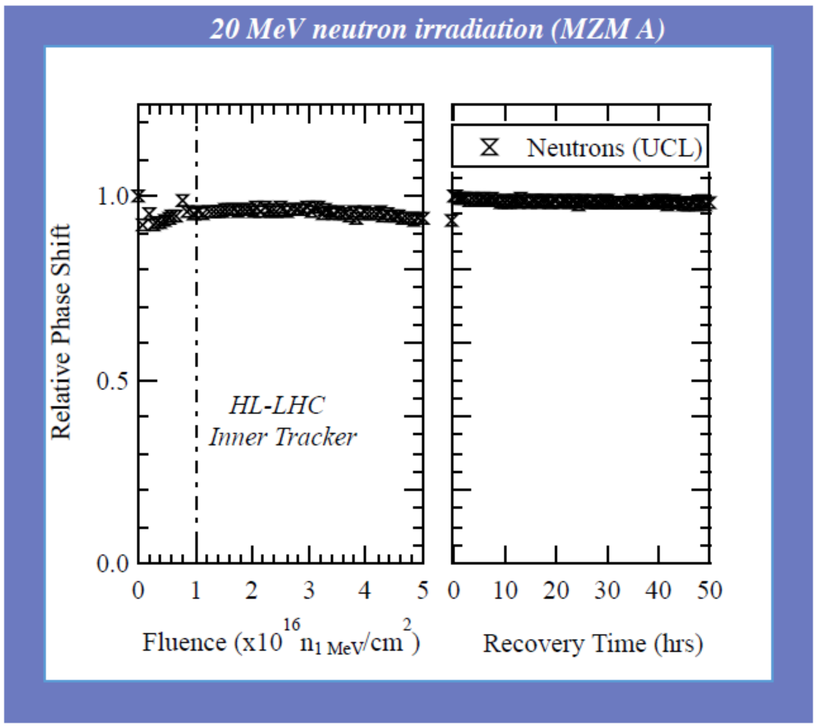
- Track phase-shift (*normalized to its pre-irradiation value*) at -1.0 V during irradiation & recovery periods (*all at room temperature*) :
  - neutron irradiation

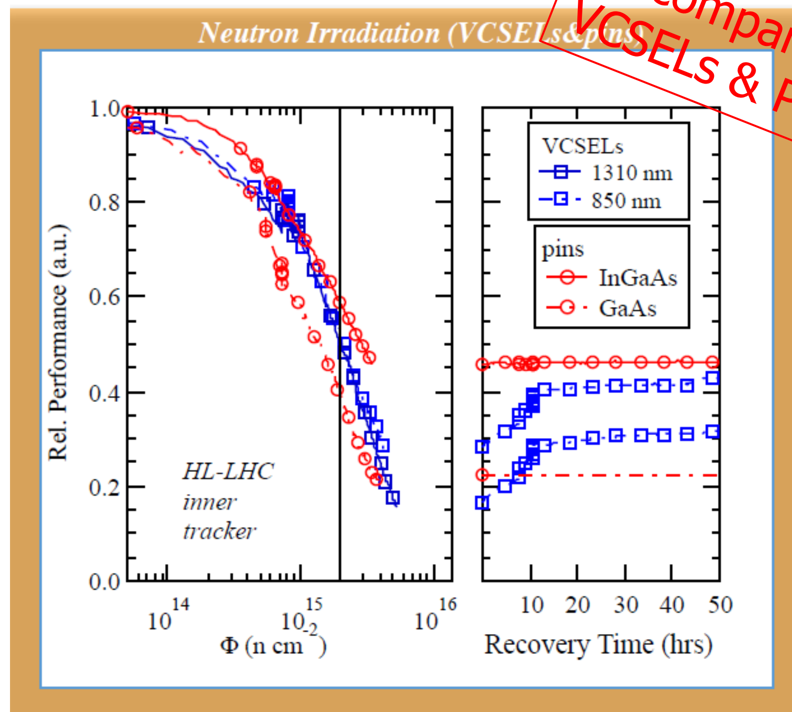


Radiation testing MZI modulators: a) displacement damage

- Track phase-shift (*normalized to its pre-irradiation value*) at -1.0 V during irradiation & recovery periods (*all at room temperature*) :
  - neutron irradiation
  - Modulators vs VCSELs

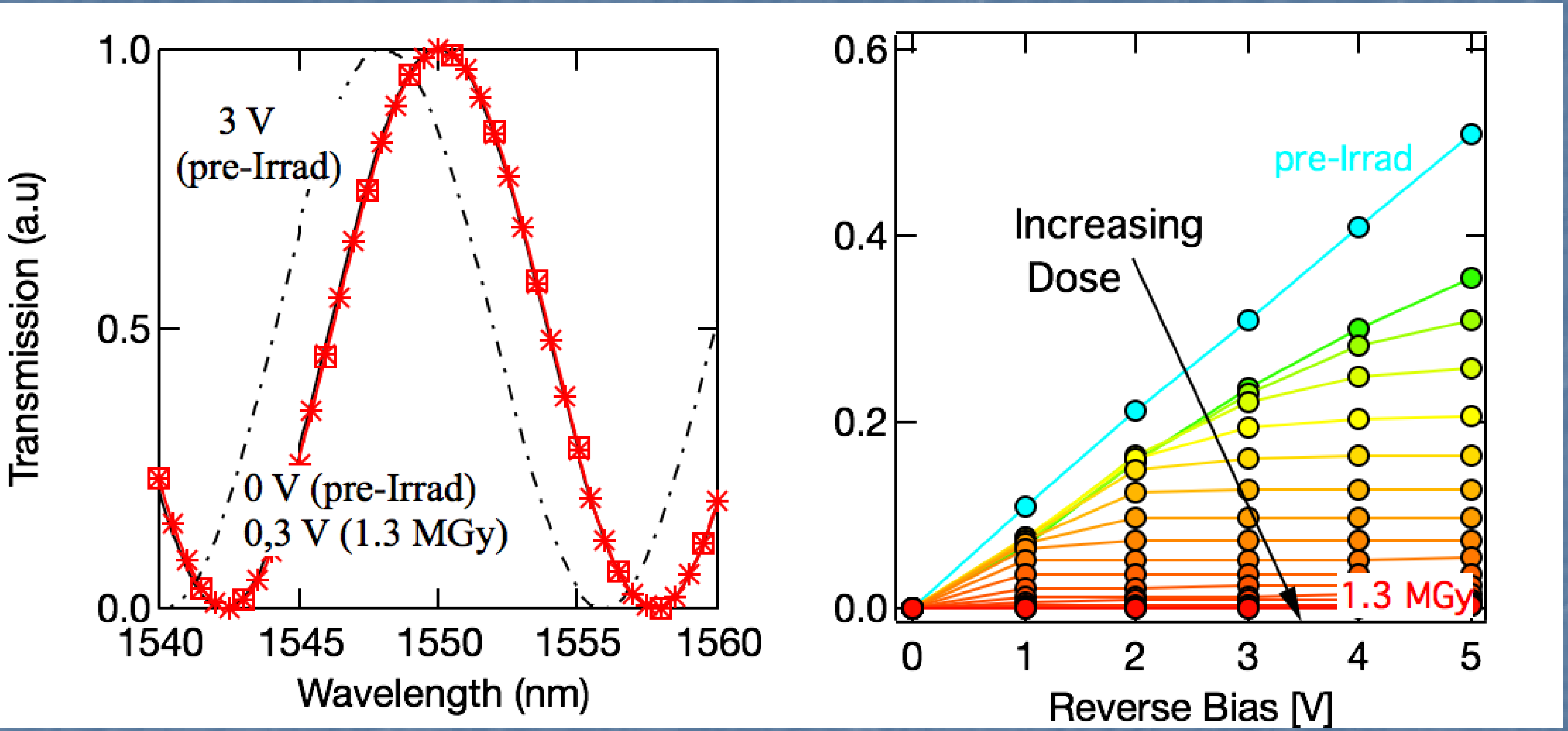
As comparison: VCSELs & Pins





Radiation testing MZI modulators: b) ionizing damage

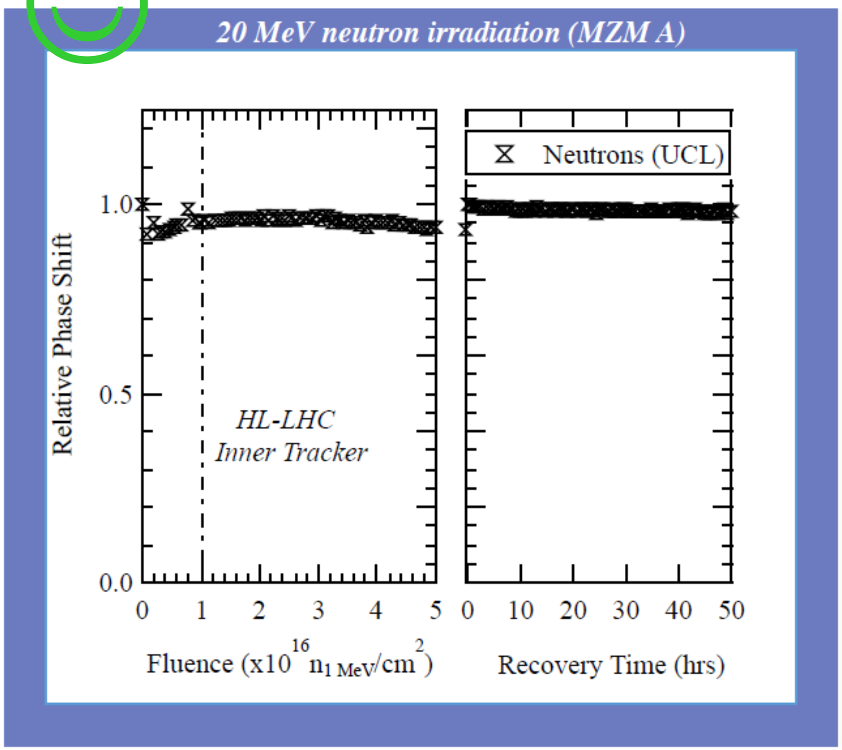
Devices are no longer functional after exposure to 1.3 MGy of ionizing radiation.

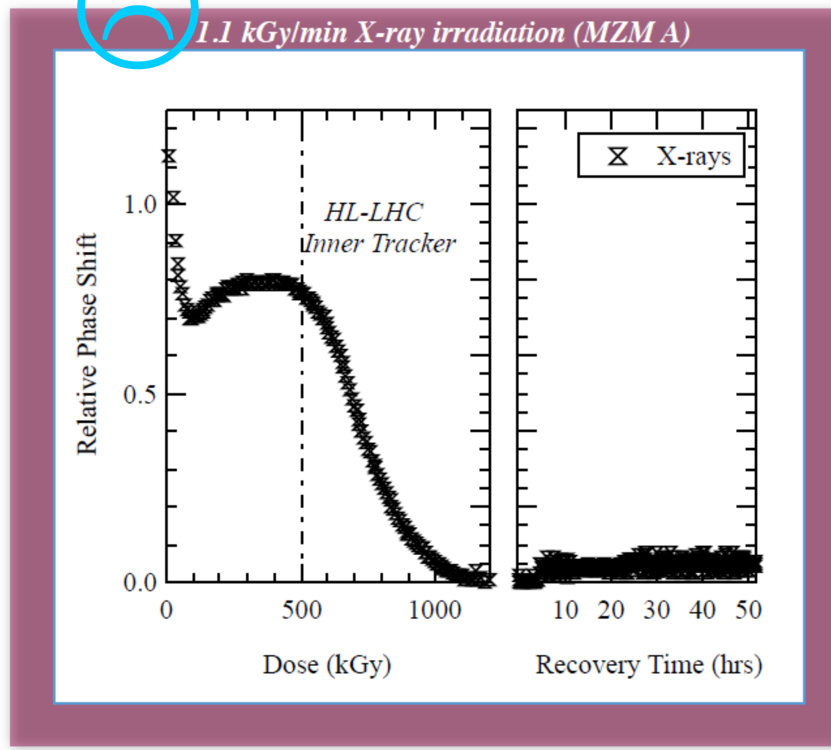


0 V	3 V	
□	*	pre-Irrad
□	*	1.3 MGy

Radiation testing MZI modulators: c) summary

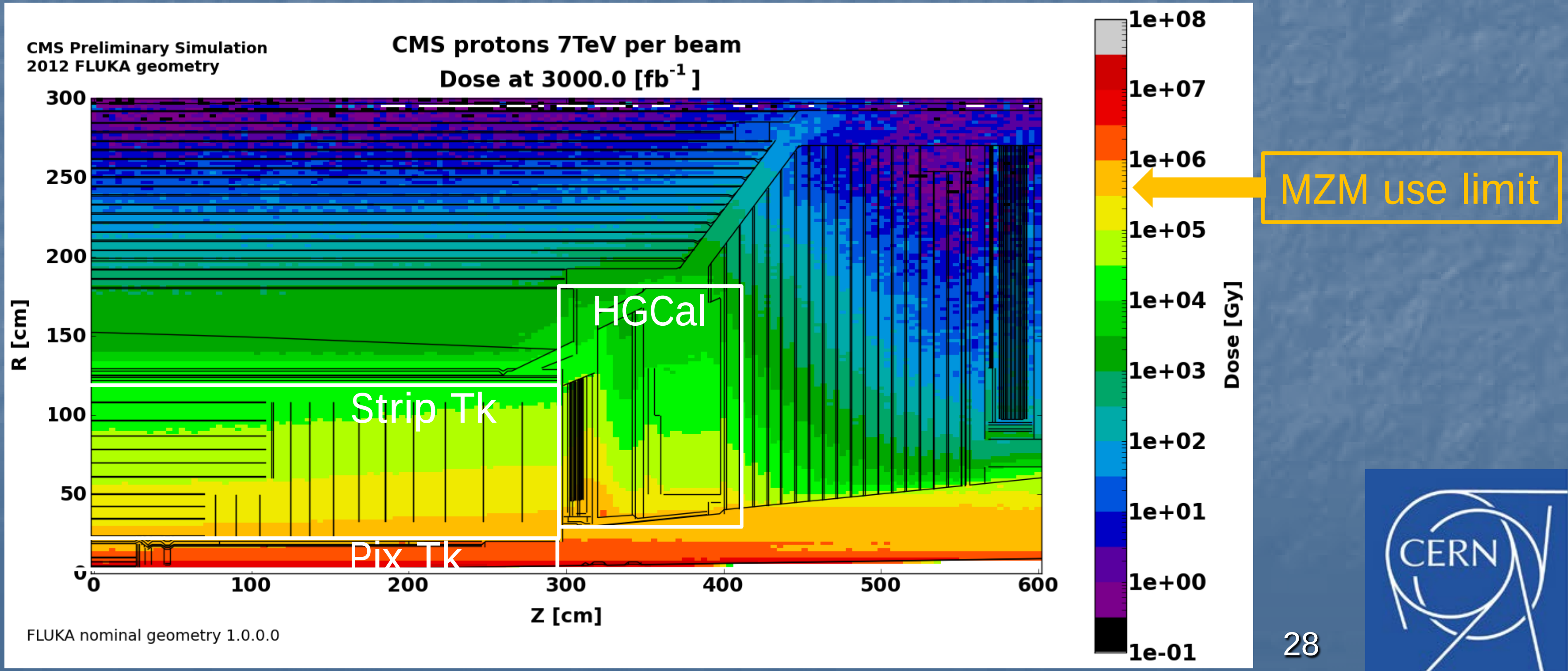
- Track phase-shift (*normalized to its pre-irradiation value*) at -1.0 V during irradiation & recovery periods (*all at room temperature*) :
  - neutron irradiation
  - X-ray irradiation





Si-Photonics MZM Use range in HL-LHC detector

- Before device optimization:
  - Use-range smaller or possibly similar to active (VCSEL-based) optoelectronics
  - Large process dependence
  - Sensitivity to TID but not to displacement



A) Technology
B) Radiation
C) Design
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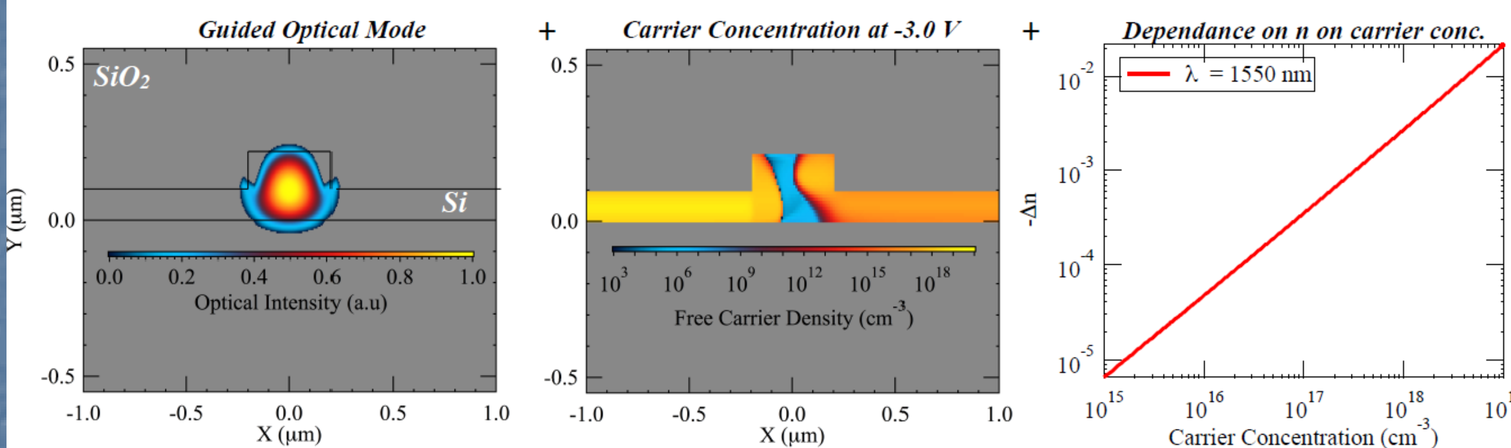
E) System

Modeling Radiation Damage in a MZM

- Change in phase at a given applied bias can be calculated using :
    - the mode profile of the guided optical mode (ψ).
    - the carrier concentration (e,h) in the silicon at a given applied bias.
    - the dependence of (n) on the carrier concentration.

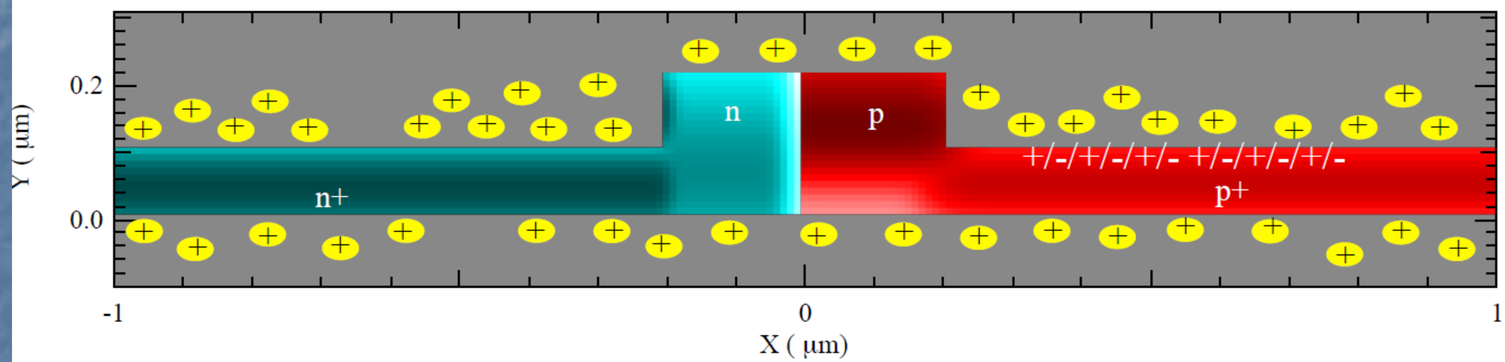
$$\Delta\phi \propto \int\int \Delta n \; |\Psi(x,y)|^2 dx \; dy$$



Modeling Radiation Damage in a MZM

Adding radiation damage to electro-optic simulation.

- Fixed charge (Not) and interface traps are added to the device :
  - N_{ot} → positive fixed charge in the oxide.
  - N_{it} → acceptor/donor traps in the Si/SiO_2 interface.



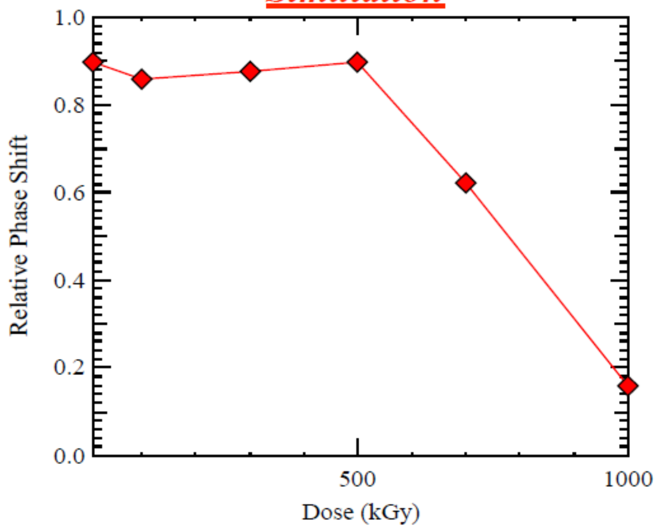
- Both are calculated as a function of dose using :
  - N_{ot} :
    - the electric field in the oxide (to calculate # e-h pairs).
    - *the distribution of hole traps in the oxide.*
  - N_{IT} :
    - *the introduction rate of interface traps.*
    - *the maximum concentration of interface traps.*

Modeling Radiation Damage in a MZM

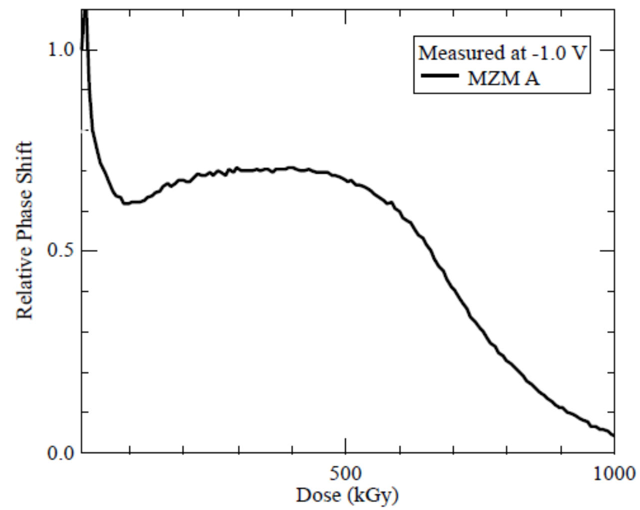
Simulating an irradiated SiPh MZM.

- Parameters describing radiation damage were varied to produce a degradation in the simulated phase-shift which best matches the measured data :

Simulation



Measurement



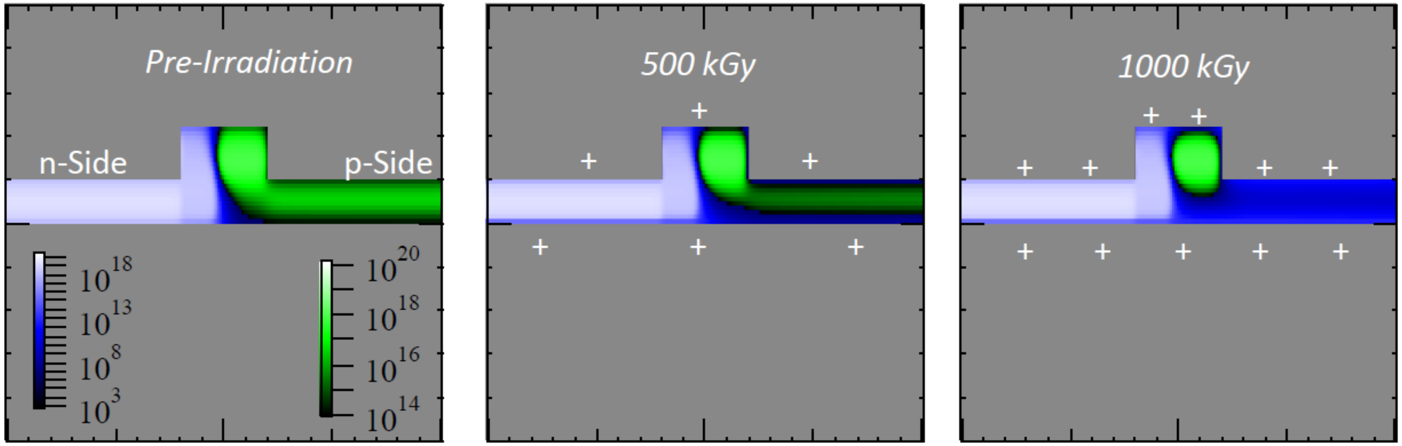
Looking for reasonable qualitative agreement!!

A) Technology
B) Radiation
C) Design
D) Integration
E) System

Modeling Radiation Damage in a MZM

Using the simulation to understand why devices fail.

Free-Carrier Concentration in SiPhMZM at different doses



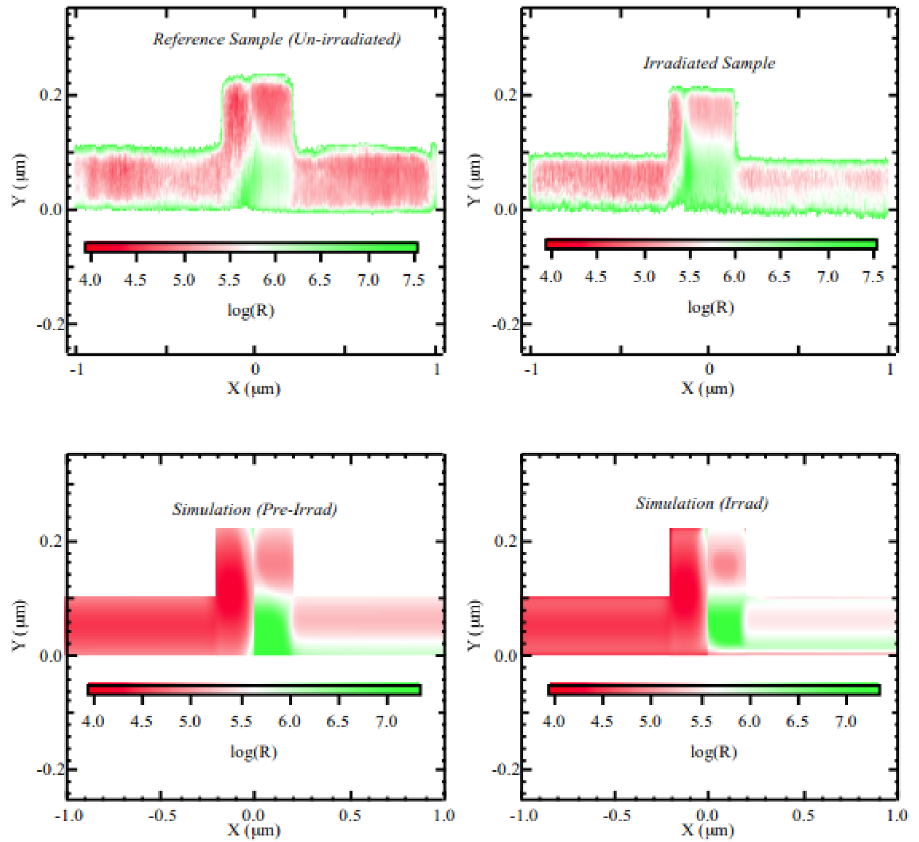
- What happens to a SiPh MZM as its exposed to ionizing radiation?
  - Positive charge build-up at the Si-SiO2 interface leads to this "pinch-off" effect :
    - decrease in hole concentration on the p-side of the slab.
      - increased resistance on the p-side of the slab.
        - can no longer deplete the p-n junction.
          - no phase-shift.

Tuning simulation to fit characterization

Simulation vs. SSRM (Scanning Spreading Resistance Microscopy)

Measurement

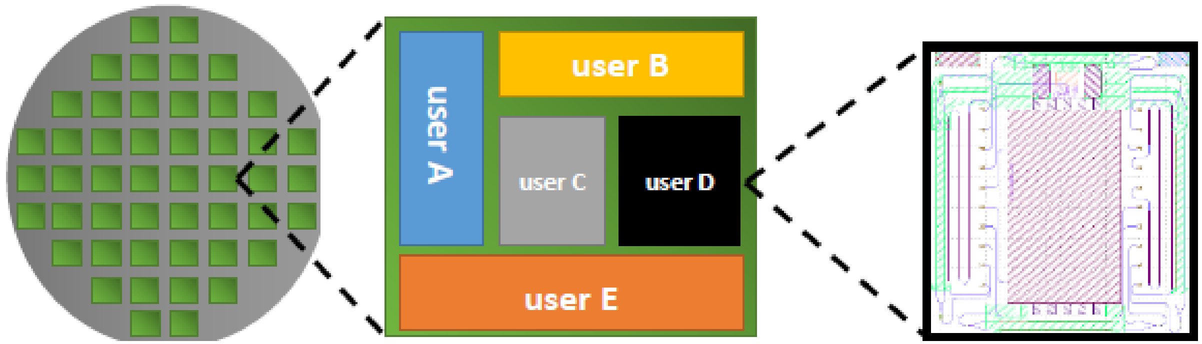
Simulation



Radiation Resistance: Wrap Up

- Radiation resistance of MZMs potentially as good as Si-sensors and CMOS electronics
  - But thick oxide layers (on top and bottom) make devices sensitive to ionizing damage
- Possibility to design custom circuits in MPW framework
- Co-integration with sensor and electronics

C. Designing a custom MZM for HEP



SOI wafer
200 mm
130nm node

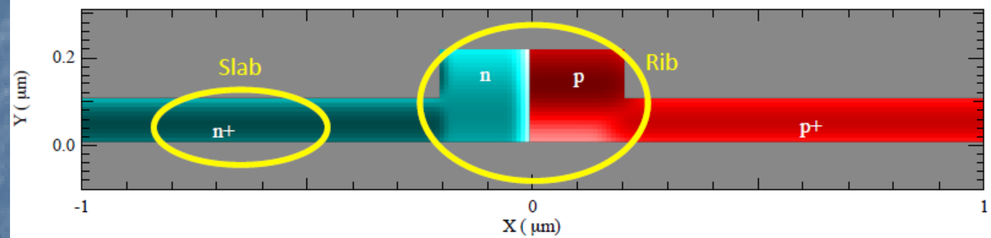
shared mask layout

CERN reticle
5x5 mm^2 (imec)
3.4x3.7 mm^2 (CEA-Leti)

- Multi Project Wafer (MPW) run chosen to fabricate:
  - offered through **ePIXfab**
  - administered through **Europractice**
- 2 different designs submitted to two foundries:

Improving MZM radiation hardness

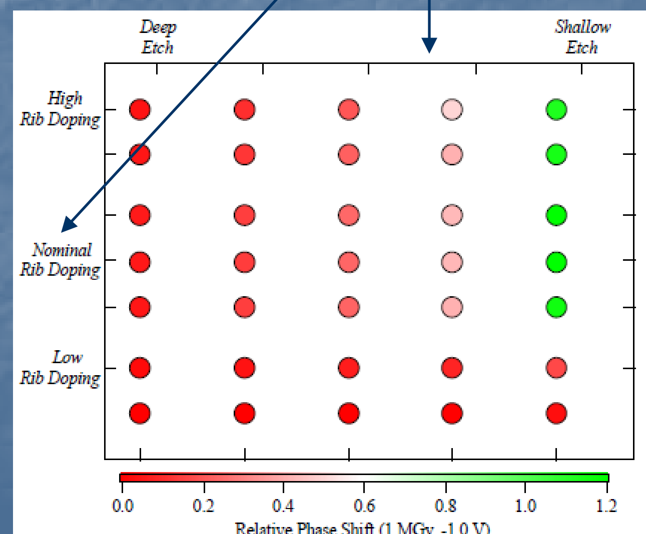
- Simulation can be used to optimize performance of MZM before and after considering the effects of ionizing radiation.



Scan process parameters available to MPW user

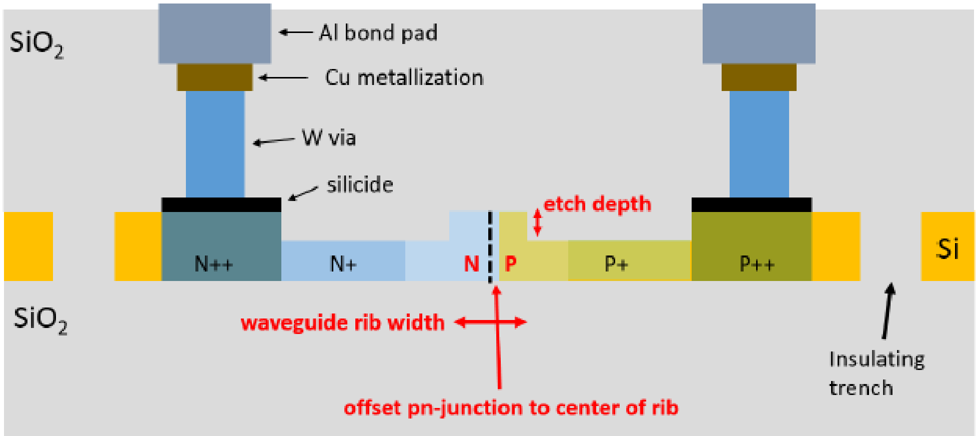
	Parameter	Range
Doping Concentration in the Rib	*D*	*0.1-10x*
Slab Thickness (/ etch depth)	*h*	*Shallow-Deep*

Model MZM efficiency change after 1MGy

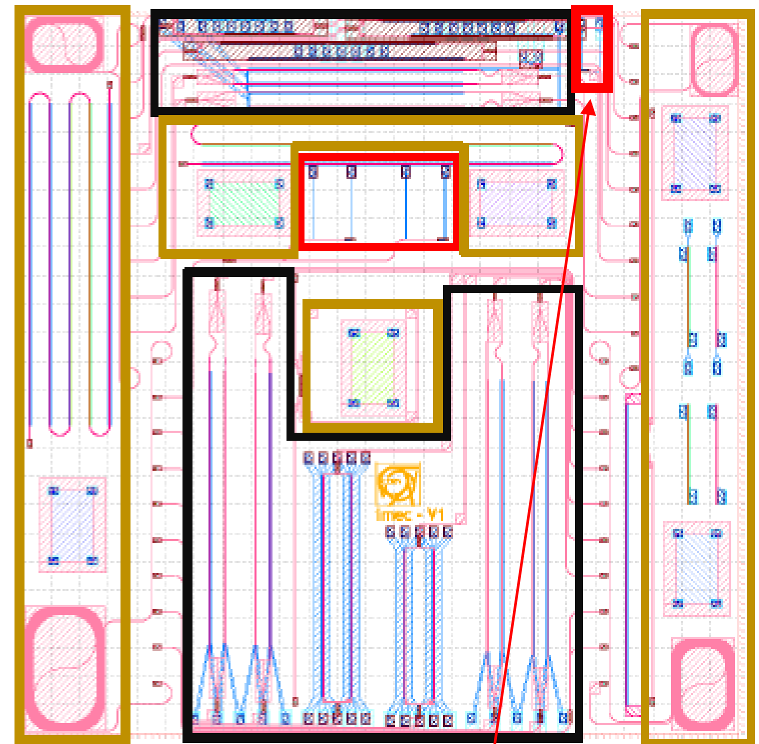


First full custom Si-Photonics chip from CERN

Cross-section through a typical MZM phase shifter with lateral pn-junction



Free Design Parameters	Range
waveguide doping (P/N)	discrete: nominal, 2x nominal
etch depth	discrete: shallow, deep
waveguide rib width	continuous: >150nm
pn-junction offset	continuous within rib width



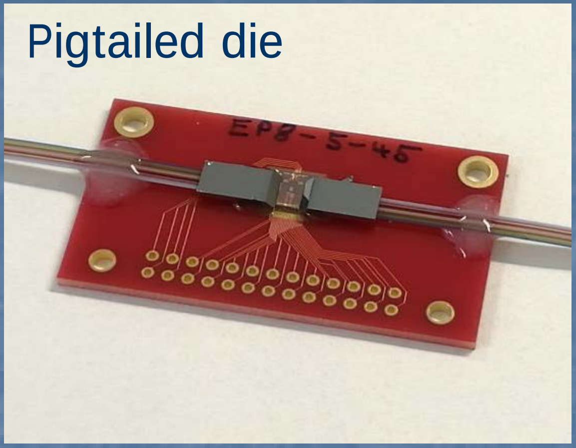
Chip contains

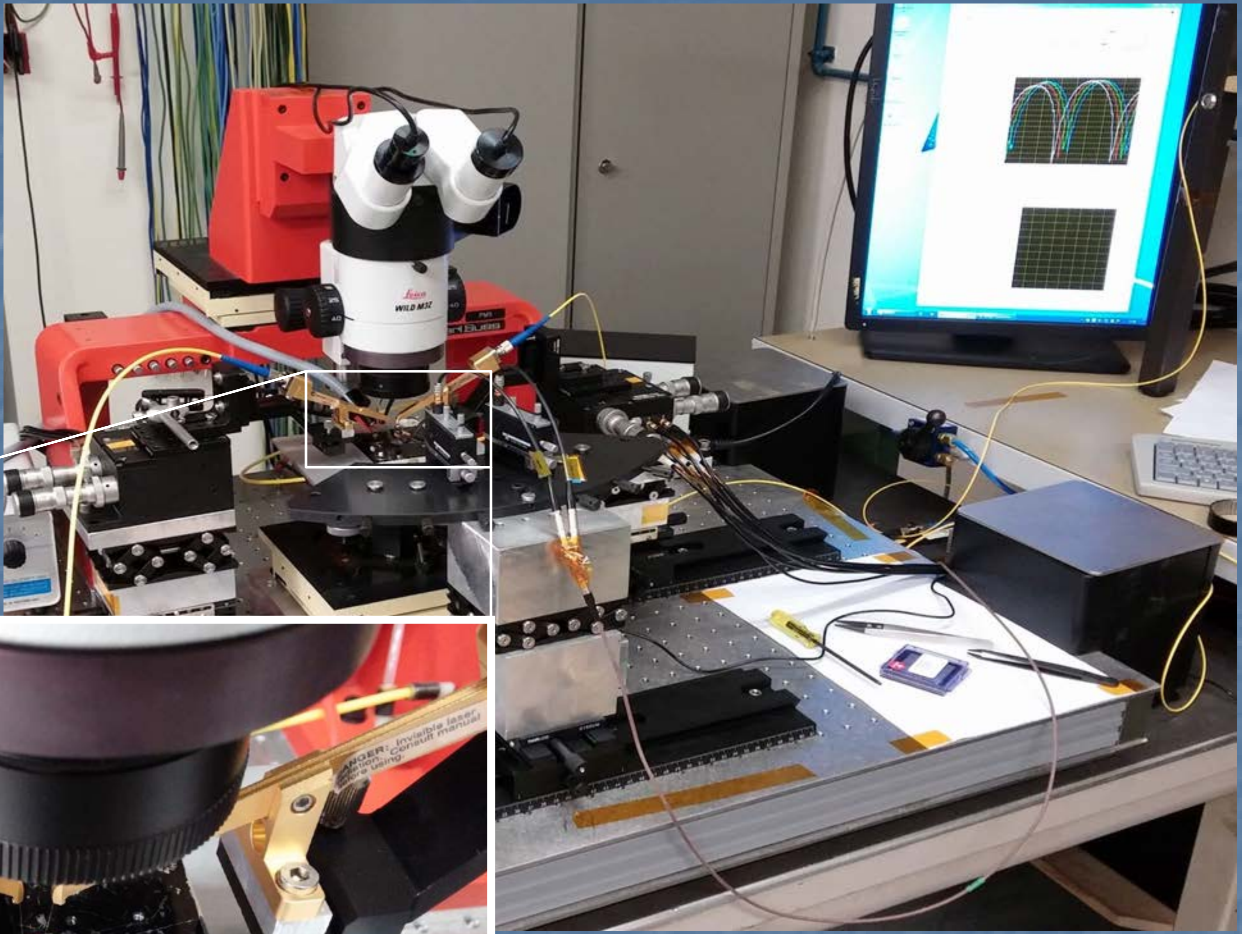
- 12 modulators
- 3 photo diodes (germanium on silicon)
- Various passive test components (e.g. sheet resistance, waveguide loss)

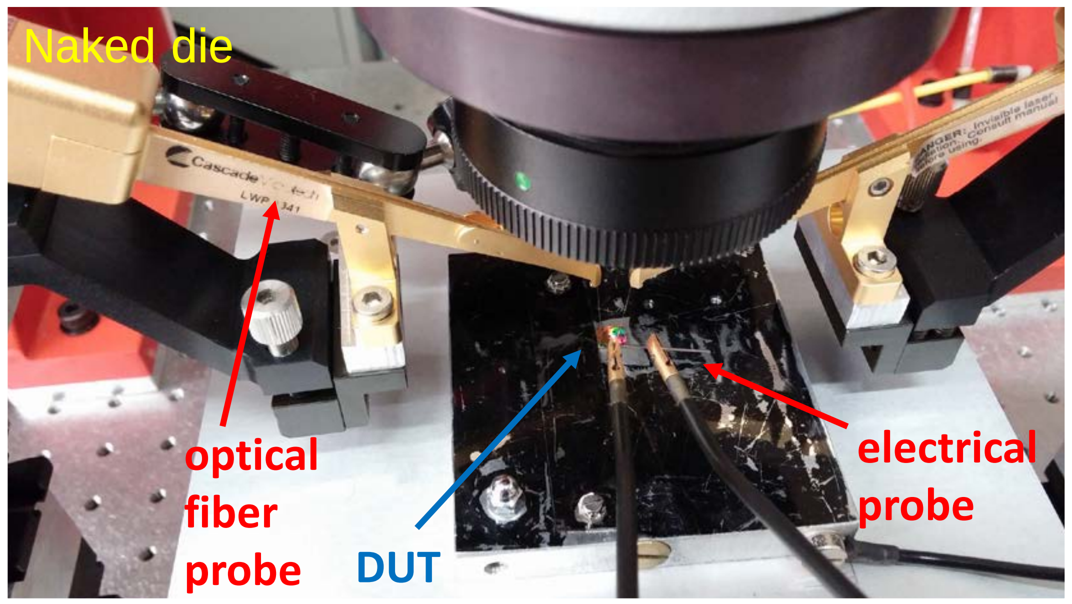
- IMEC 130nm CMOS (65nm-grade litho)
- 5x5mm die, 40 pcs x 2 doping steps
- 9 months turnaround time
- Heterogeneous design flow

80 chips delivered Oct 2015

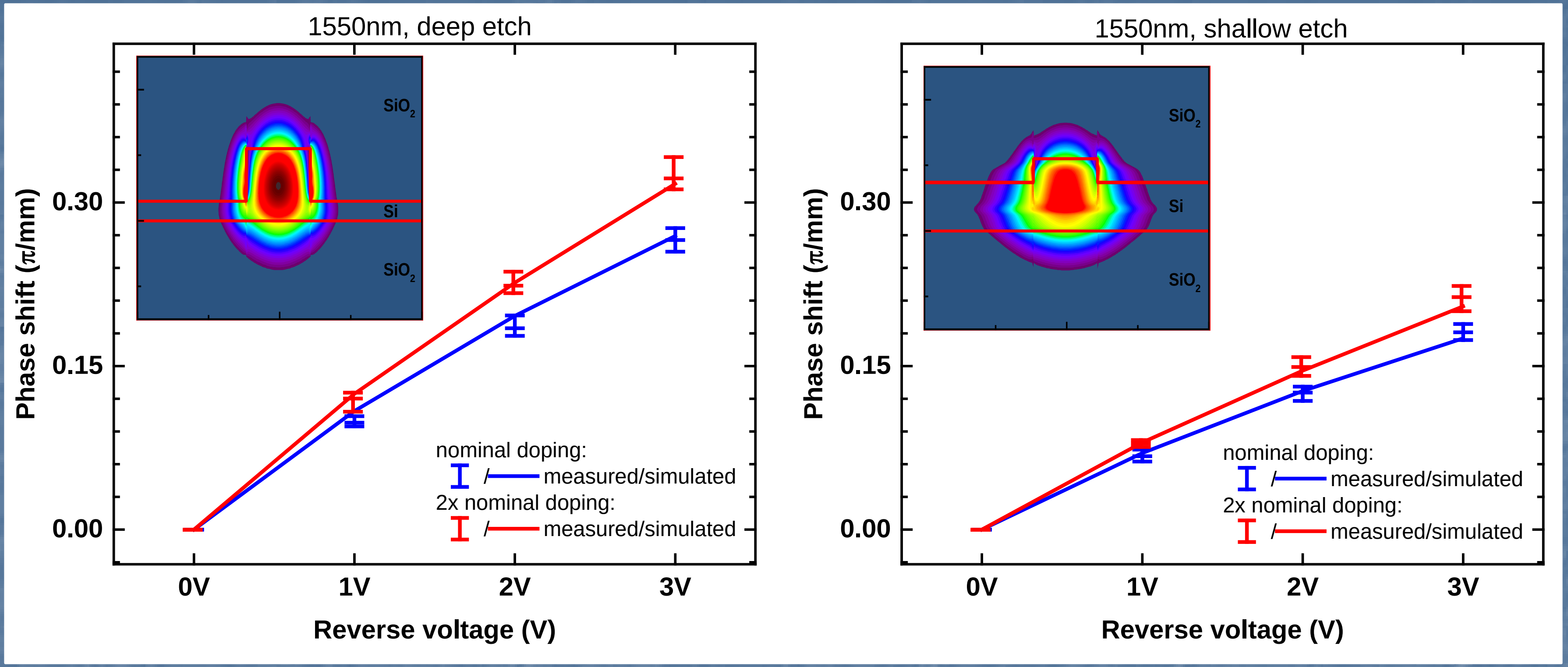
Characterization







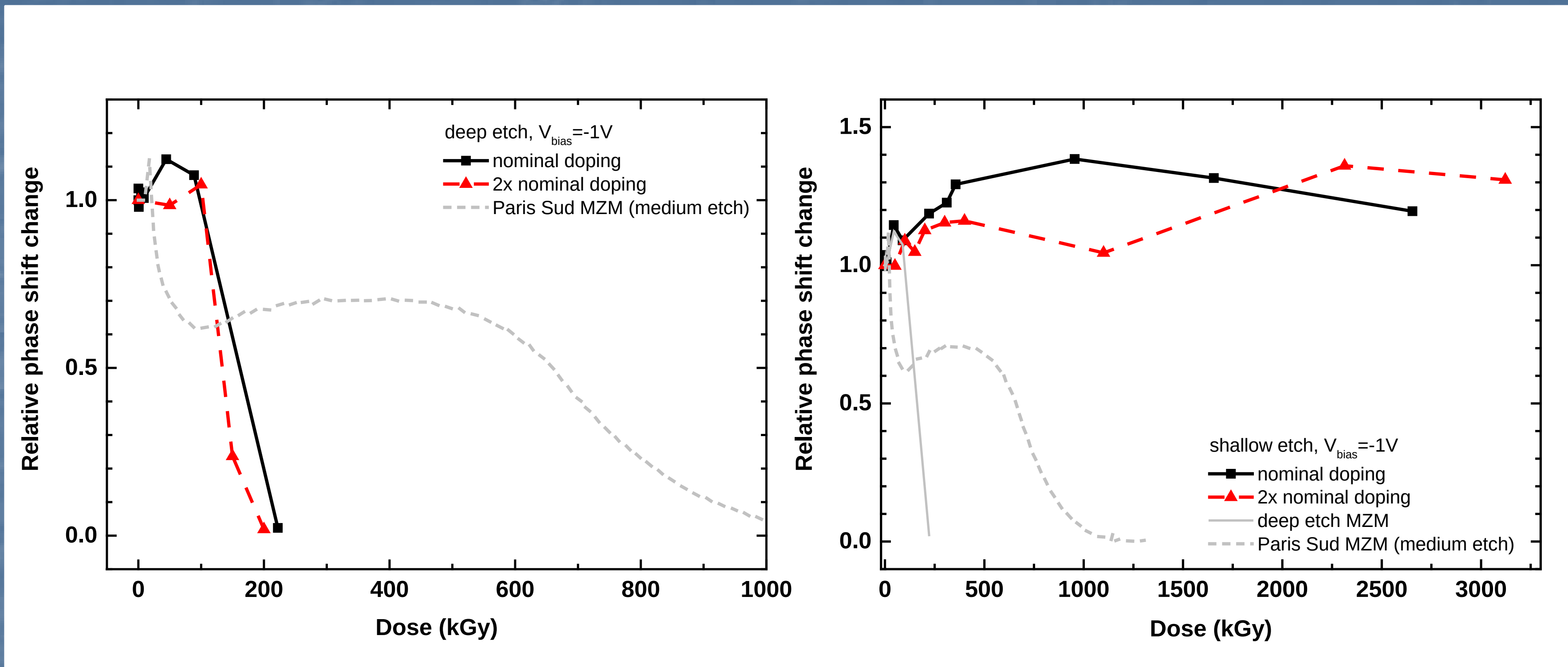
Pre-Irradiation Characterization



- Good agreement between pre-irradiation measurements and simulations for CERN designed SiPh MZMs
- deep etch MZMs show larger phase shift because optical mode is more strongly confined in waveguide

➔ larger overlap with depletion zone of pn-junction

During-irradiation Characterization



- measurements confirm qualitative predictions: resistance to dose can be improved
- etch depth, doping concentrations, energies and profiles are not precisely known

  ➔ quantitative agreement between model and devices cannot be expected
- Irradiation conditions are not representative of final operational situation
  - Room temperature, No bias during irradiation
- More results to be published this fall (Radecs, TWEPP, NSS)

Custom MZM Design: Wrap Up

- A) Technology
- B) Radiation
- C) Design
- D) Integration
- E) System

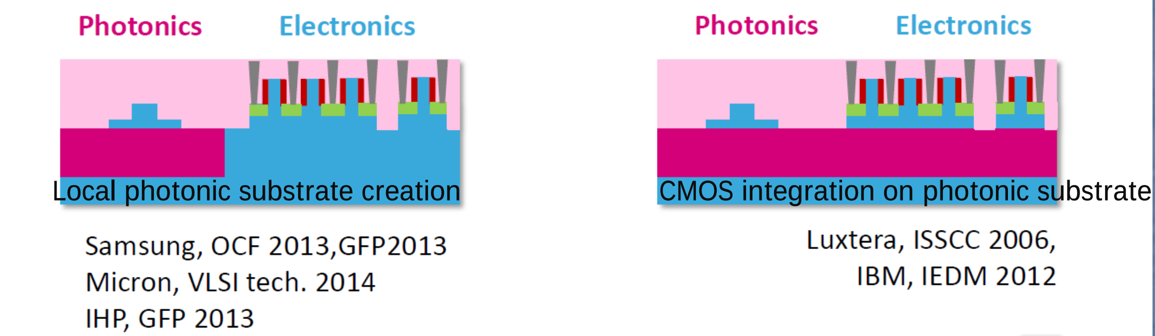
- Possibility to design custom circuits in MPW framework
  - Successful first submission
  - Preliminary simulation, design and characterization results indicate good prospect of developing extremely radiation hard modulators
    - But full control of doping conditions likely to be needed (i.e. dedicated engineering run and process customization)
  - Modelling effort must continue to the point where a simulation can be trusted to validate a design before submission

- Co-integration with sensor and electronics

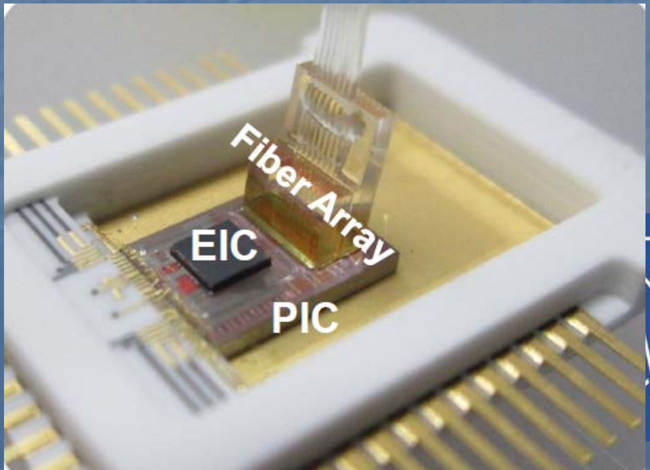
D. Co-Integration a) with electronics

A) Technology
B) Radiation
C) Design
D) Integration
E) System

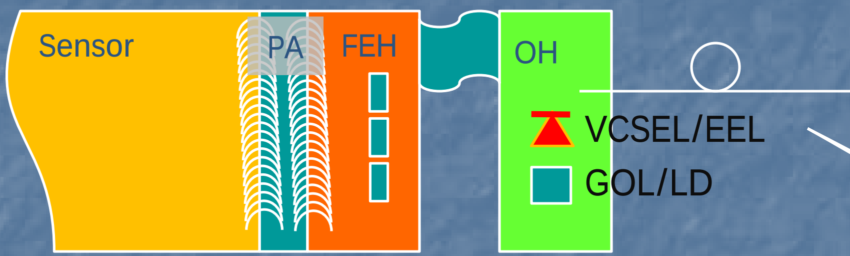
- Co-Integration of electronics and photonics can be achieved in a hybrid or monolithic fashion
- Si-Photonics requires thick oxide (~1um compared to 10-100nm for current SOI processes)
- Monolithic approaches have been successfully demonstrated, also commercially



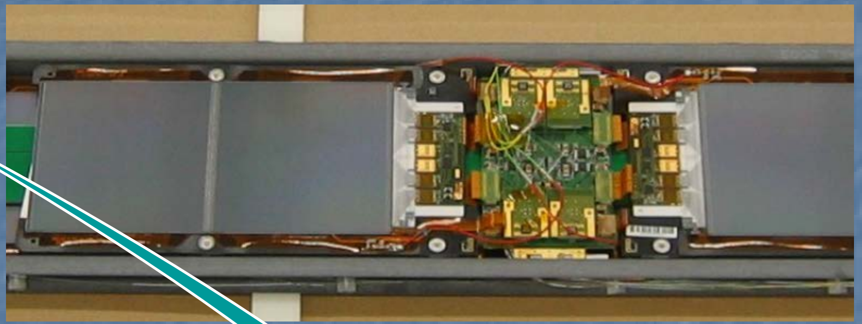
- But hybrid integration allows more flexibility at least in our specific context
  - Electronics and photonics can be optimized separately
  - Photonic circuit becomes interposer

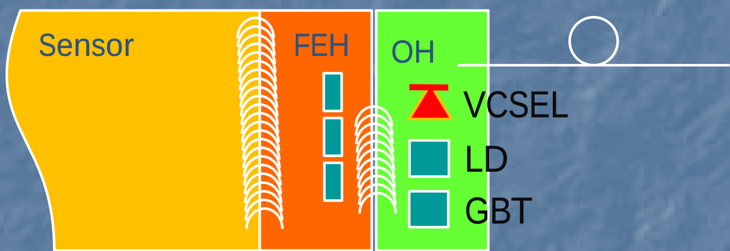


D. Co-Integration b) with sensors

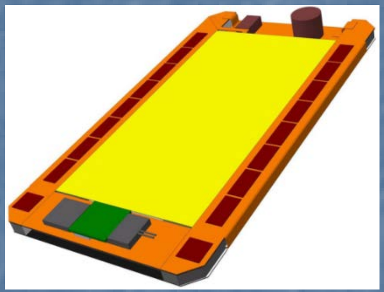


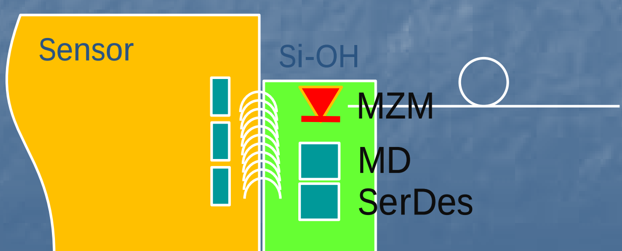
- LHC Tracker (2005)



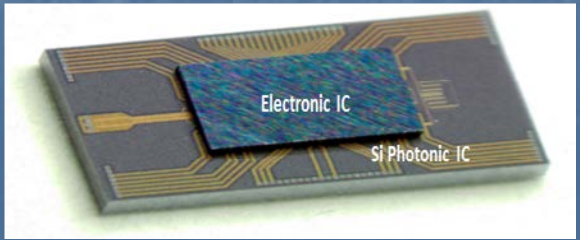


- HL-LHC Tracker (2020)





- R&D, full Si module (2025?)



E. System

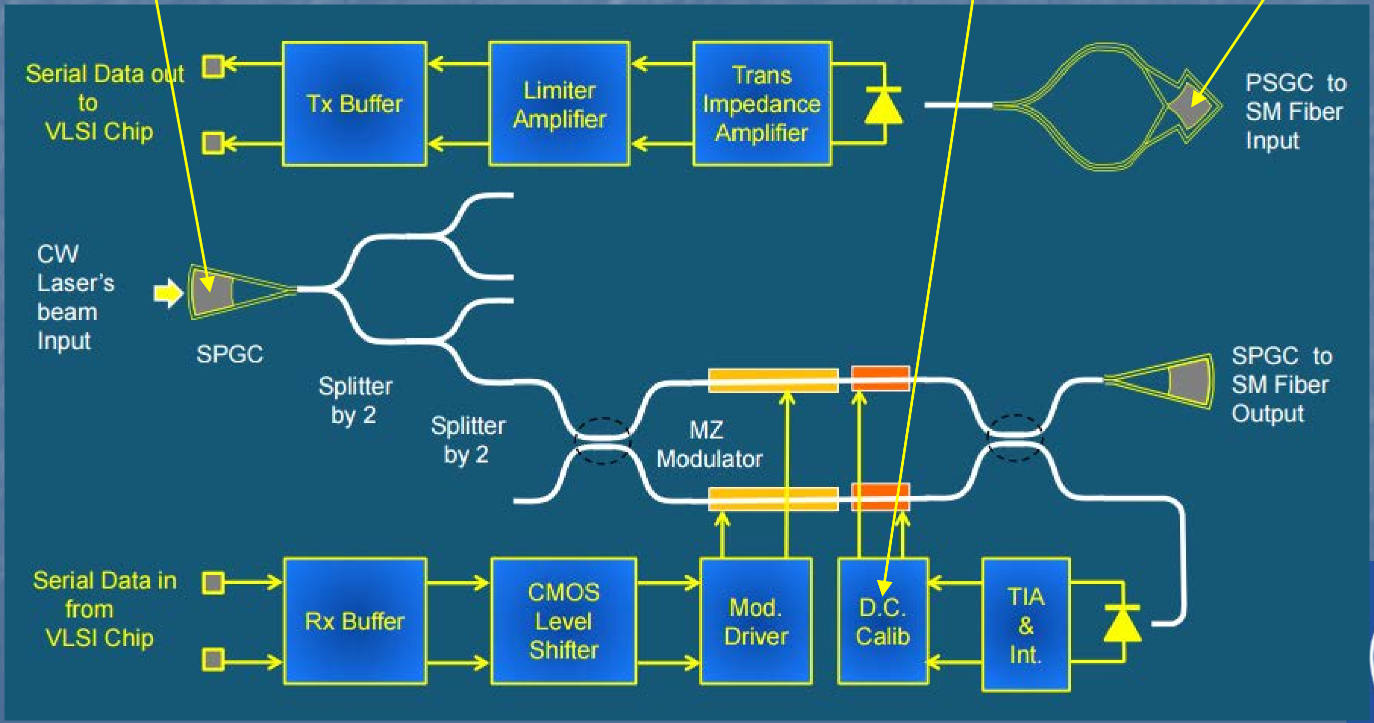
- The system-level challenges of Si-Photonics:
  - MZM System-on-a-chip
    - Maintain stable operating point
    - Manage polarization diversity
    - Reduce insertion loss
    - Reduce power dissipation
  - System-in-a-detector
    - Feed CW optical power
    - Maintain laser polarization
    - Manage power budget
      - Optical
      - Electrical

Si-Ph Transceiver System on a chip

CW optical power

Operating point adjust

Polarization diversity

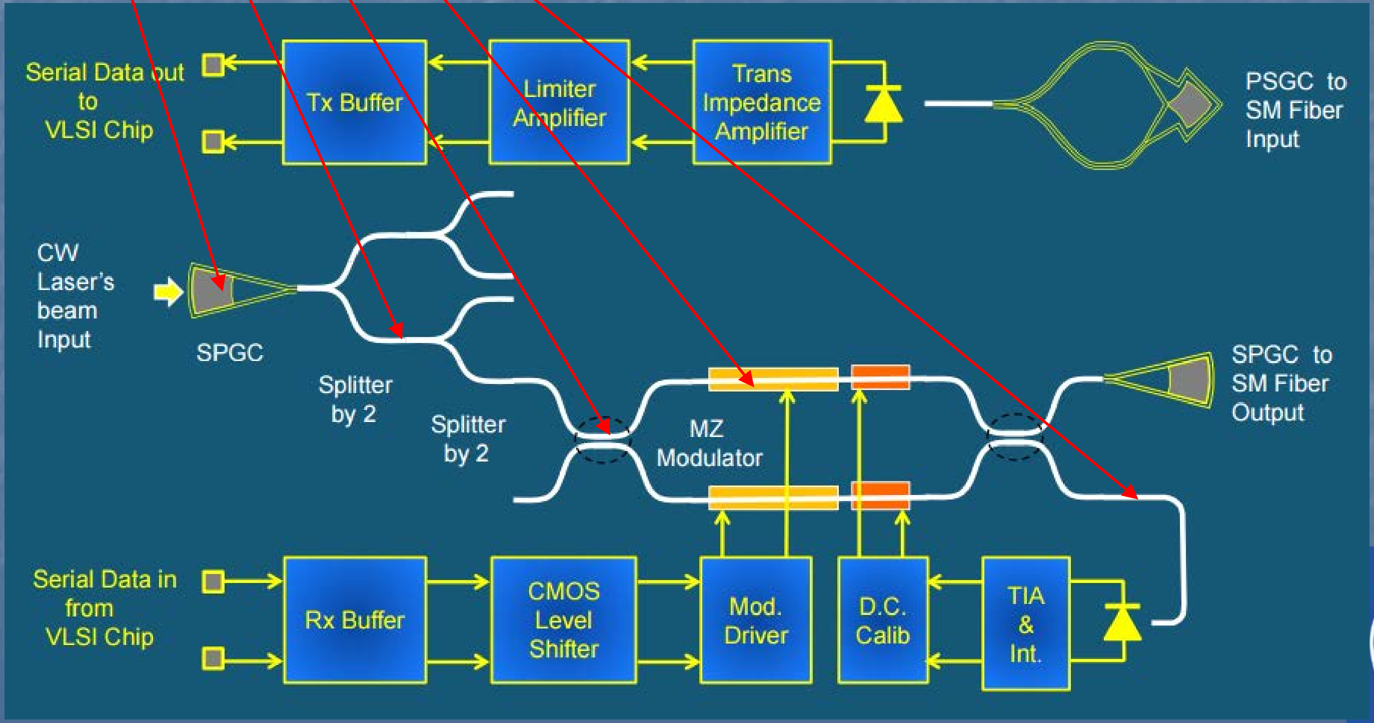


Si-Ph Transceiver System on a chip

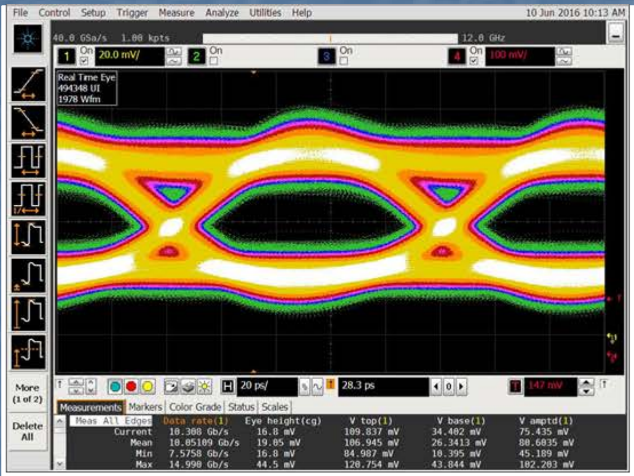
The Insertion Loss challenge (typical loss values shown):

- Grating coupler: 2dB
  - Waveguide loss: 2dB/cm
    - Quadrature point: 3dB
      - Modulator loss: 4dB/mm
        - Taps and misc.: 2dB

Excess loss: typ 15dB

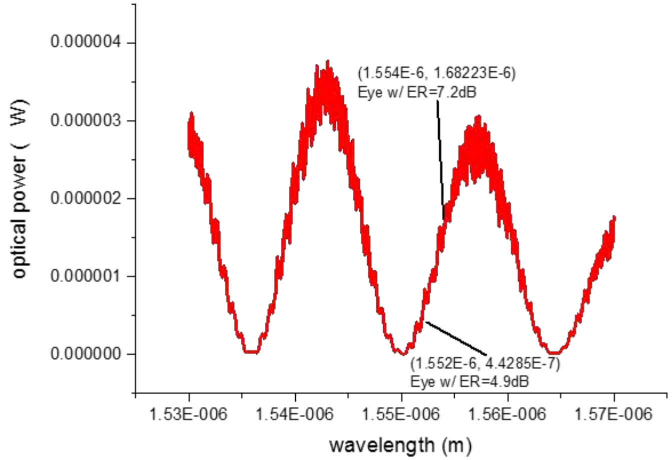


Dynamic MZM transmitter performance



measured for 1.0 mm long travelling wave MZM

- 10Gb/s, Λ=1.554 μm
- Vbias=-3V
- Vpp=6V
- **ER=7.2dB**
- **OMA=-7.6dBm**
- 50Ohm external termination
- 2^31-1 pattern

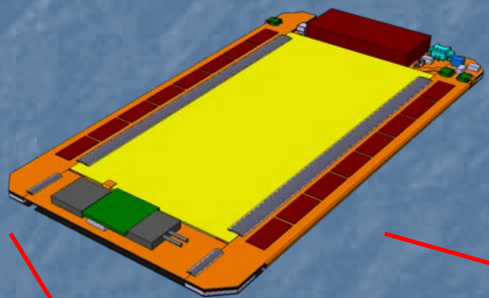


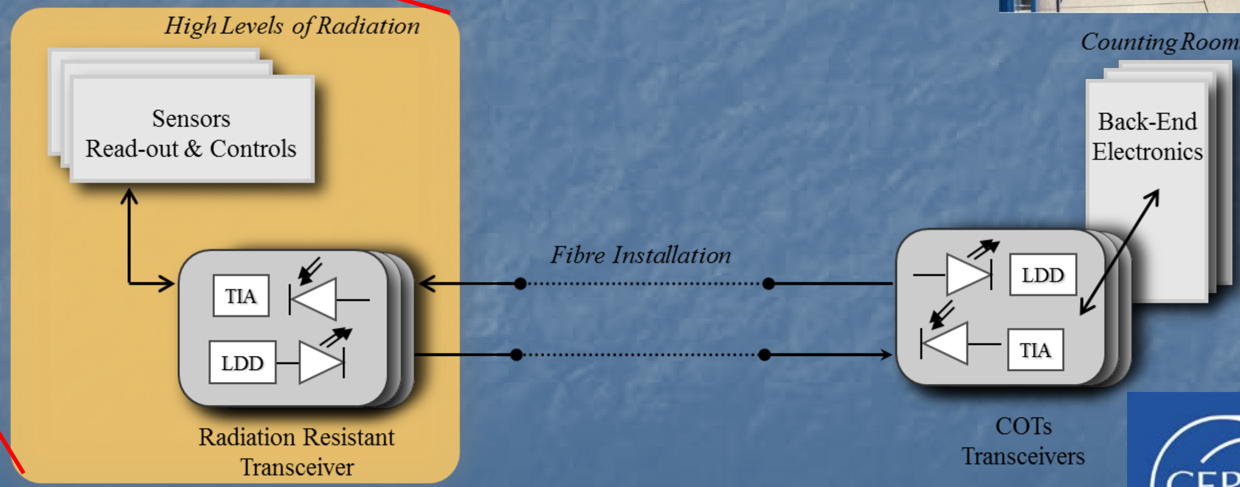
measured for 1.0 mm long travelling wave MZM

- 10Gb/s, Λ=1.552 μm
- Vbias=-3V
- Vpp=6V
- **ER=4.9dB**
- **OMA=-8.7dBm**
- 50Ohm external termination
- 2^31-1 pattern

System in a detector

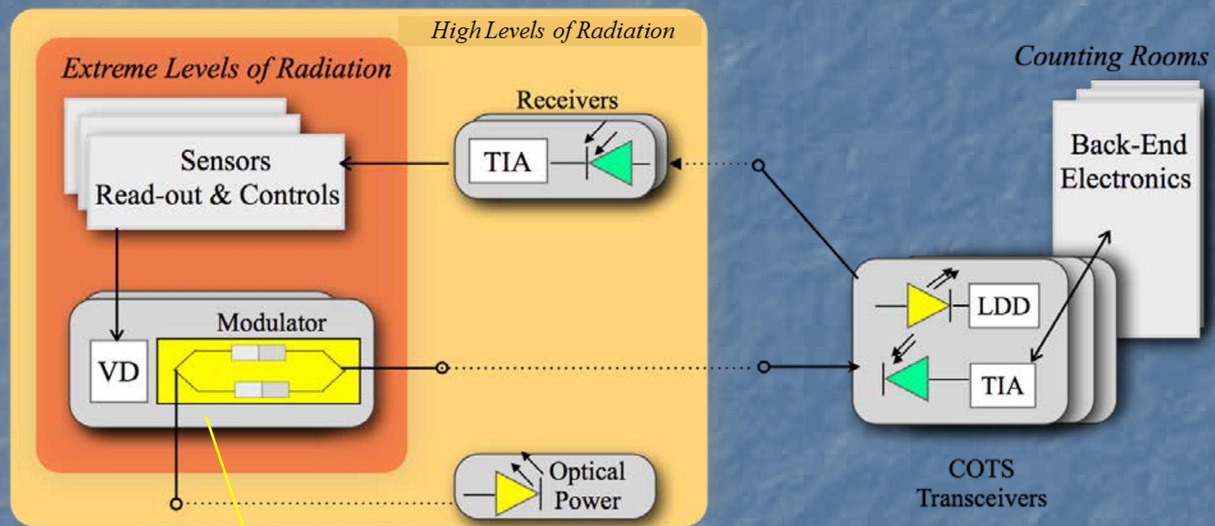
- Current VCSEL-based architecture

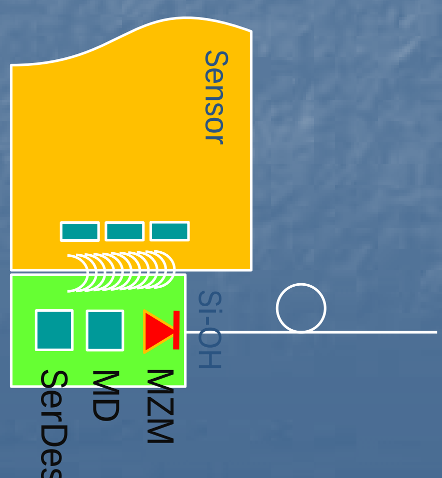




System in a detector

- Modulator-based architecture





- Radiation-resistant modulator
- Radiation-resistant modulator driver
- Packaging solution

E. System: Wrap up

- The system-level challenges of Si-Photonics:
  - Feed CW optical power
  - Maintain stable operating point
  - Manage polarization
  - Reduce insertion loss
  - Co-integrate with electronics and package
- Tough competition with incumbent technology (III-V based)
  - Only few commercial successes so far despite considerable hype
  - Multiple acquisitions of Si-Photonics spin-offs by major actors in networking
- Si-Photonics advantage can be harnessed by:
  - moving to complex systems and architectures (multi-channel, advanced modulation schemes, wavelength multiplexing, etc...)
  - Moving to longer distances and higher bitrates (Single Mode, 400GbE, 2km)
  - Moving to large volume chipscale interconnection, as optical interposer
    - But must reach << pJ/bit efficiency
    - Must develop fJ/b receivers

A) Technology

B) Radiation

C) Design

D) Integration

E) System

Conclusions

- Si-Photonics opens access to custom designed, radiation hard optical circuits for HEP
- Simulation and design flow is available (but still heterogeneous)
- Access to MPW foundry services is possible (but long turnaround time)
- First attempts at modelling, designing and fabricating simple circuits are successful
- Characterization and simulation results are promising
- Co-integration with sensor and electronics is attractive
  - Packaging and system aspects remain very challenging
  - Prepare to invest even more in advanced packaging than in design and process optimization

So: myth or reality ?

- 16 June 2016, CERN EP Detector Seminar by Erik Heijne: Si Detectors: 60 years of innovations

So: myth or reality ?

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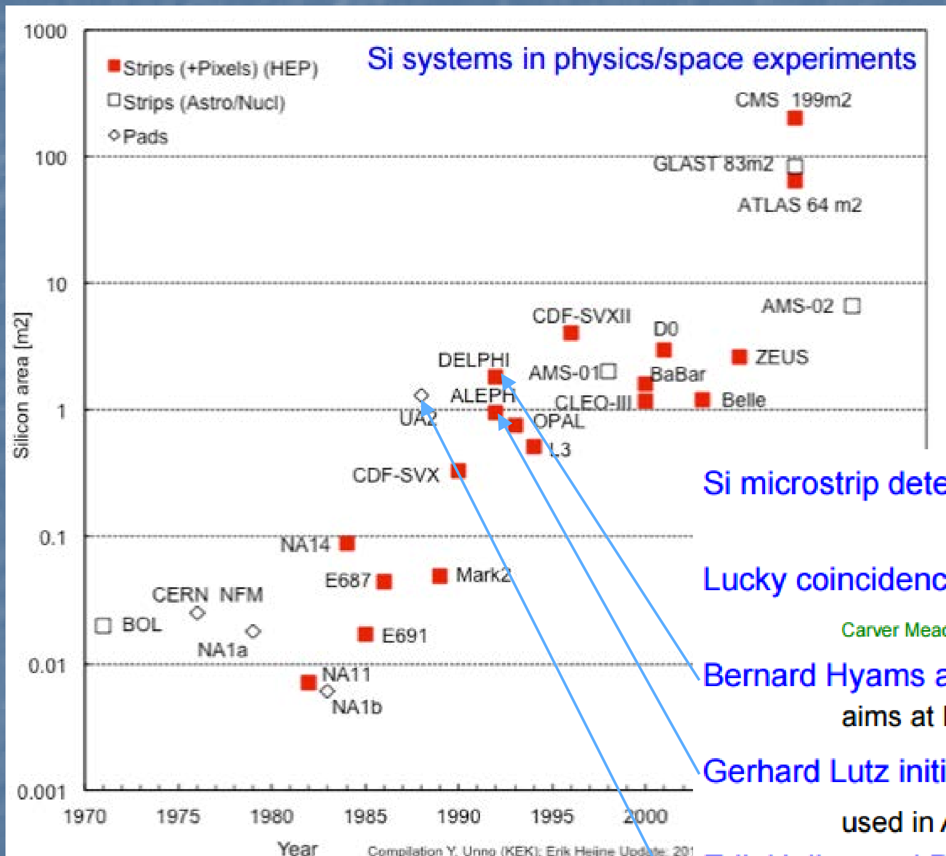
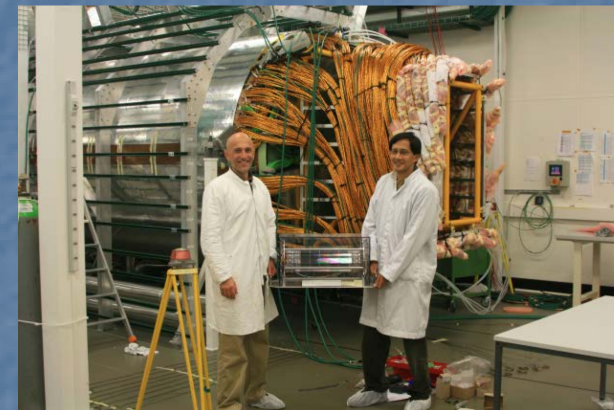




Si microstrip detectors obviously need ICs, but how to do this?

Lucky coincidence: 1979 Mead & Conway design, using multi-project

Carver Mead and Lynn Conway, Introduction to VLSI systems,Addison-Wesley New York 1980

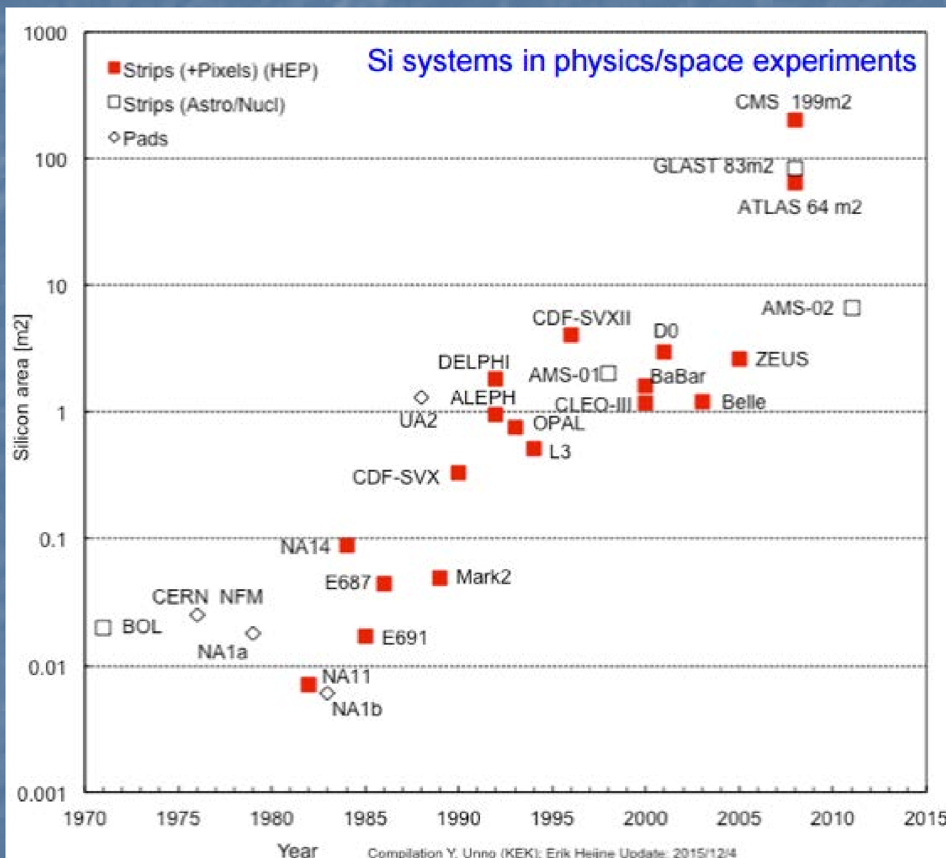
Bernard Hyams asks SLAC, begins Microplex with Sherwood Parker
aims at DELPHI tracker 128 channels NIM A226 (1984)

Gerhard Lutz initiates CAMEX64 with in Dortmund/Duisburg
used in ALEPH and elsewhere 64 channels IEEE TNS 36 (1989)

Erik Heijne and Pierre Jarron begin CCD-based readout with Philips Heijne
first try to include pipeline memory, no good result
begins collaboration ESAT/IMEC (Leuven) resulting in AMPLEX Stuart
used in UA2 Beuville et al. NIM A288 (1990)

Kleinfelder and David Nygren at LBL: Microplex 2 for CDF

So: myth or reality ?



- Much R&D effort was required in the 80's to develop the microelectronics of the LHC era (see for instance the LAA project)
- A large effort is required now to incubate the optoelectronics of the next decades (if experiments are serious about their aim to massively extract data from their front-ends)
- Only so, will we be able to extract the reality from the myth

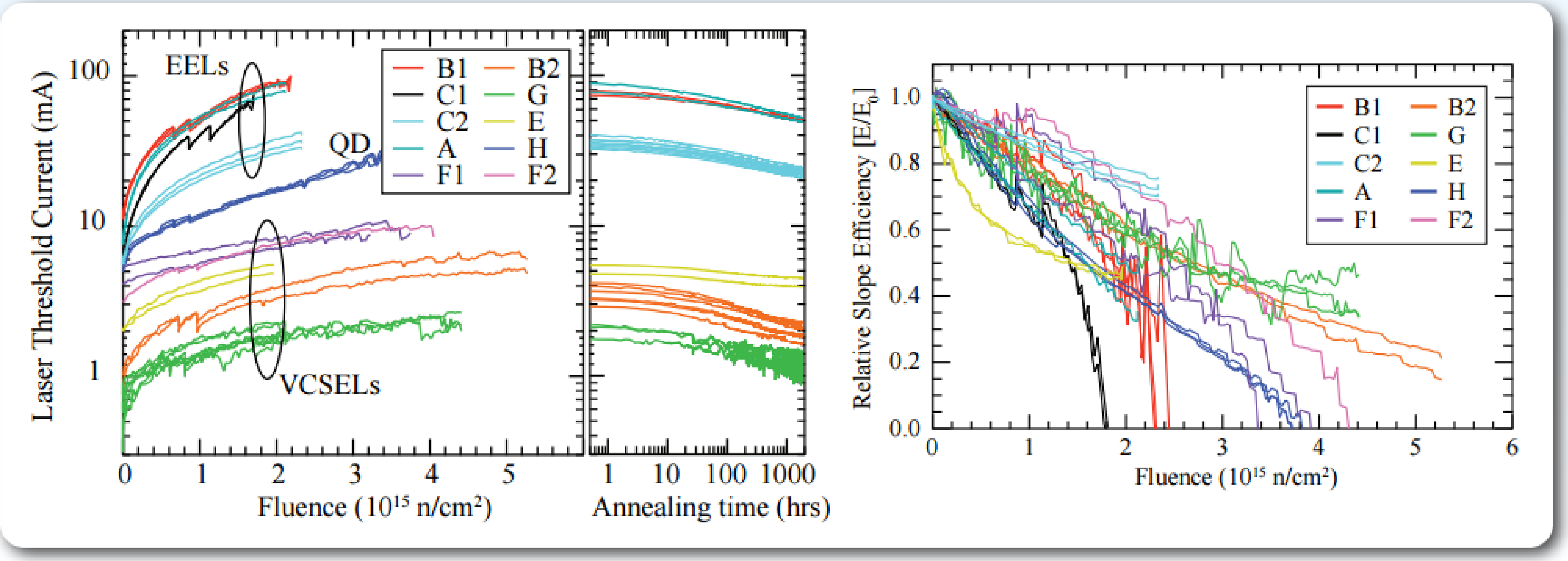
References

- S. Seif El Nasr-Storey, S. Detraz, L. Olantera, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "**Irradiation of new optoelectronic components for HL-LHC data transmission links**," *Journal of Instrumentation*, vol. 8, no. 12, Dec. 2013.
- S. Seif El Nasr-Storey, S. Detraz, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, and M. Zeiler, "**Neutron and X-ray Irradiation of Silicon Based Mach-Zehnder Modulators**," *Journal of Instrumentation*, vol. 10, 2015.
- S. Seif El Nasr-Storey, F. Boeuf, C. Baudot, S. Detraz, J. M. Fedeli, D. Marris-Morini, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, L. Vivien, M. Zeiler, and M. Ziebell, "**Effect of Radiation on a Mach-Zehnder Interferometer Silicon Modulator for HL-LHC Data Transmission Applications**," *IEEE Transactions on Nuclear Science*, vol. 62, no. 1, pp. 329–335, 2015.
- S. Seif El Nasr-Storey, F. Boeuf, C. Baudot, S. Detraz, J. M. Fedeli, D. Marris-Morini, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, L. Vivien, M. Zeiler, and M. Ziebell, "**Modeling TID Effects in Mach-Zehnder Interferometer Silicon Modulator for HL-LHC data Transmission Applications**," *IEEE Transactions on Nuclear Science*, vol. 62, no. 6, pp. 2971 – 2978, 2015.
- M. Zeiler, S. Detraz, L. Olantera, G. Pezzullo, S. Seif El Nasr-Storey, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "**Design of Si-Photonic structures to evaluate their radiation hardness dependence on design parameters**," *Journal of Instrumentation*, vol. 11, 2016.

- M. Zeiler, S. Detraz, L. Olantera, S. Seif El Nasr-Storey, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "**Radiation hardness evaluation and phase shift enhancement through ionizing radiation in silicon Mach-Zehnder modulators**," *in Radiation Effects on Components and Systems (RADECS)* (accepted for publication), 2016-17.
- M. Zeiler, S. Detraz, L. Olantera, C. Sigaud, J. Troska, and F. Vasey, "**A system-level model for high-speed, radiation-hard optical links in HEP experiments based on silicon Mach-Zehnder modulators**," *in Topical Workshop On Electronics For Particle Physics (TWEPP)* (accepted for publication), 2016-17.
- M. Zeiler, S. Detraz, L. Olantera, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "**Comparison of the Radiation Hardness of Silicon Mach-Zehnder Modulators for Different DC Bias Voltages**," *in IEEE Nuclear Science Symposium/Medical Imaging Conference (NSS/MIC)* (accepted for publication), 2016-17.

Backups

Radiation Resistance of Lasers of different types



Versatile Link Specification

Radiation penalties in Link Budget

Versatile Link

Tracker Grade

	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-1.6 dBm	-5.2 dBm	-3.6 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	11.5 dB	7.4 dB	11.8 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	5.4 dB	-	5.4 dB
Fiber radiation penalty	1.0 dB	1.0 dB	1.0 dB	1.0 dB
Margin	**1.8 dB**	**2.0 dB**	**2.8 dB**	**1.8 dB**

A) Technology
B) Radiation
C) Design
D) Integration
E) System

Increasing front panel density of GbE modules

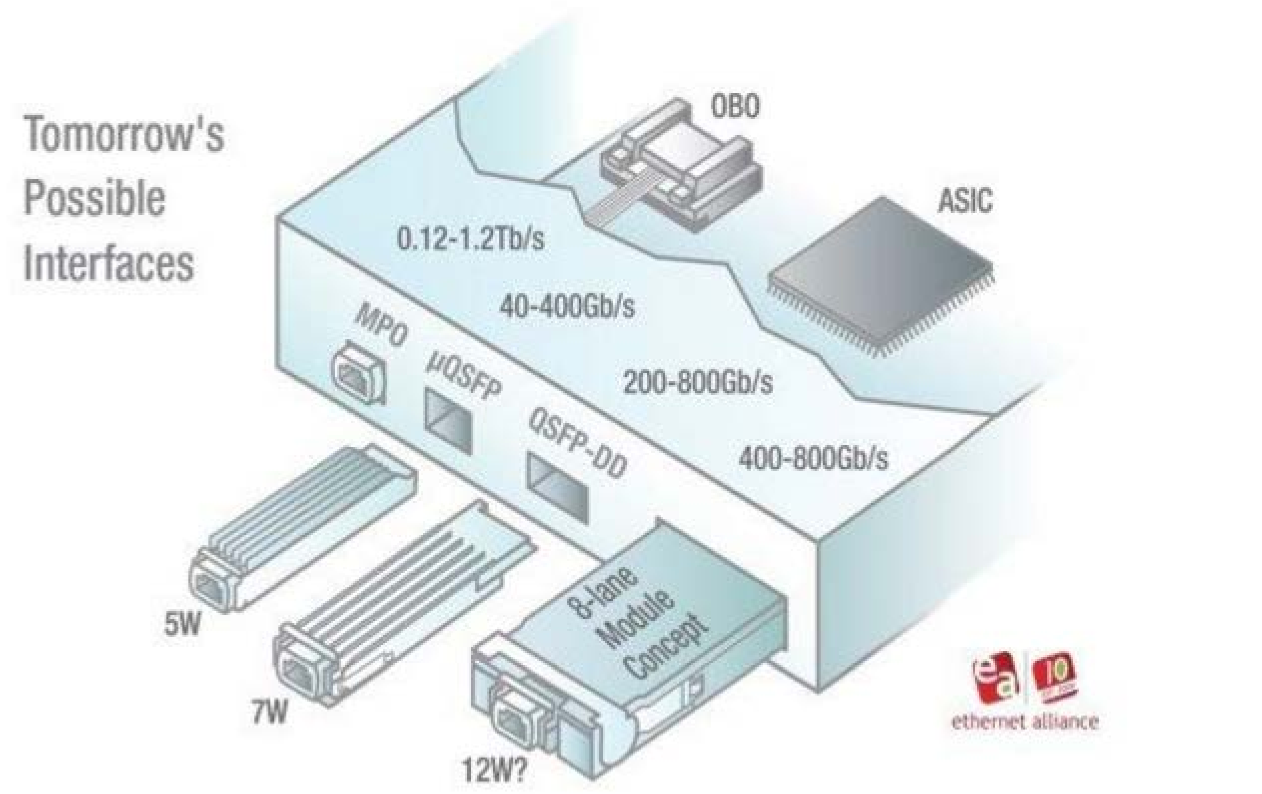


Figure 1. Possible form factors for 400GbE (source: ethernetalliance.org/roadmap)

Telecom vs Datacom evolution towards 400GbE

A) Technology
B) Radiation
C) Design
D) Integration
E) System

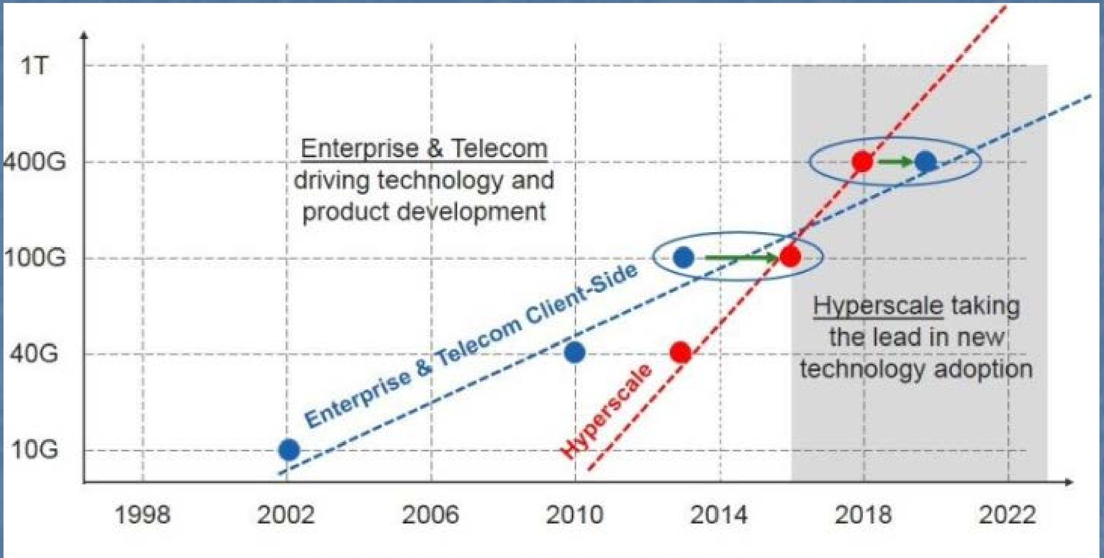


Figure 1. Telecom and datacom adoption timelines.

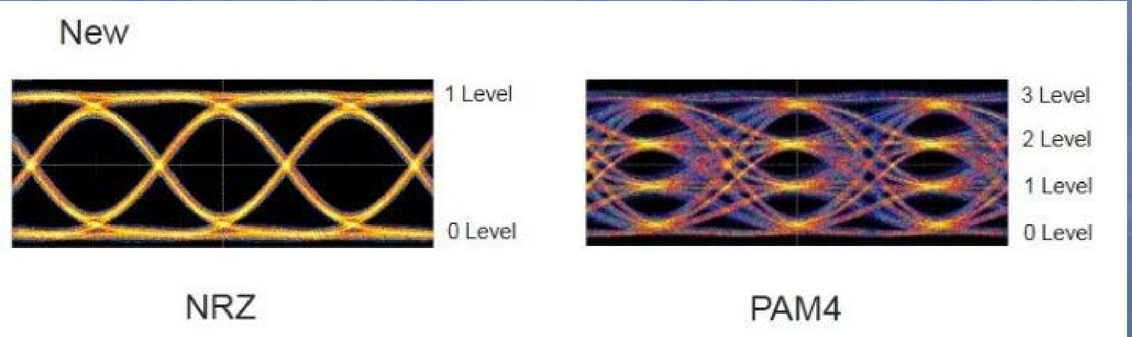


Figure 2. NRZ and PAM4 modulation. (Source: http://globaltek.us.com/awg6010/)

Si (IV) vs III-V

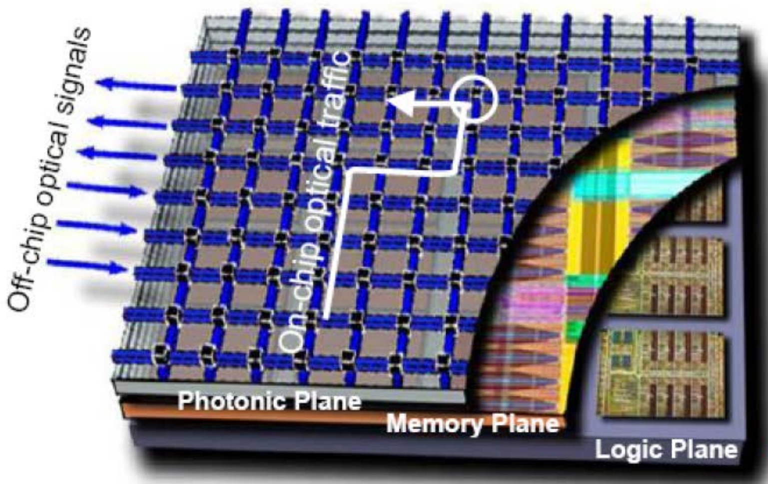
	λ (μm)	Band gap	$\Delta n/n$ (%)	Tx	Rx	waveguides	Optical component
Si	1.1	I	70	No	Yes	Yes	Yes
GaAs	0.8	D	0-14	Yes	Yes	Yes	Yes
InP/InGaAs	1.55	D	0-3	Yes	Yes	Yes	Yes

	Wafer size (R&D)	Wafer size (commercial)	Wafer cost (€)	mm² substrate cost (€)
Si	450 mm	300 mm	100	0.001
SOI	?	300 mm	800	0.008
InP	150 mm	100 mm	300	0.03
GaAs	200 mm	150 mm	300	0.013

A) Technology
B) Radiation
C) Design
D) Integration
E) System

A 2008 Si-Photonics vision for 2018

Vision for 2018 – 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

Logic plane	~300 cores
Memory plane	~30GB eDRAM
Photonic plane	On-Chip Optical Network
	>70Tbps optical on-chip
	>70Tbps optical off-chip
	70Tbps @ 1pJ/b = 70W !!!

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

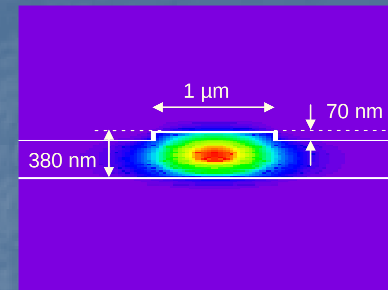
System level study:
IBM, Columbia, Cornell, UCSB
Co-PIs:
Jeff Kash (IBM)
Keren Bergman (Columbia)
Yurii Vlasov (IBM)

Intensity Modulation

Electro-refraction effect:

- carrier density variation: accumulation, depletion, injection

$$\Delta n = -8.8\times10^{-22}\,\Delta N - 8.5\times10^{-18}\,(\Delta P)^{0.8}$$



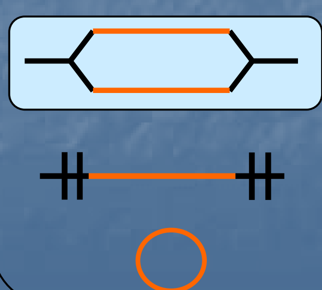
Refractive index variation

Effective index variation of the guided optical mode

Phase variation

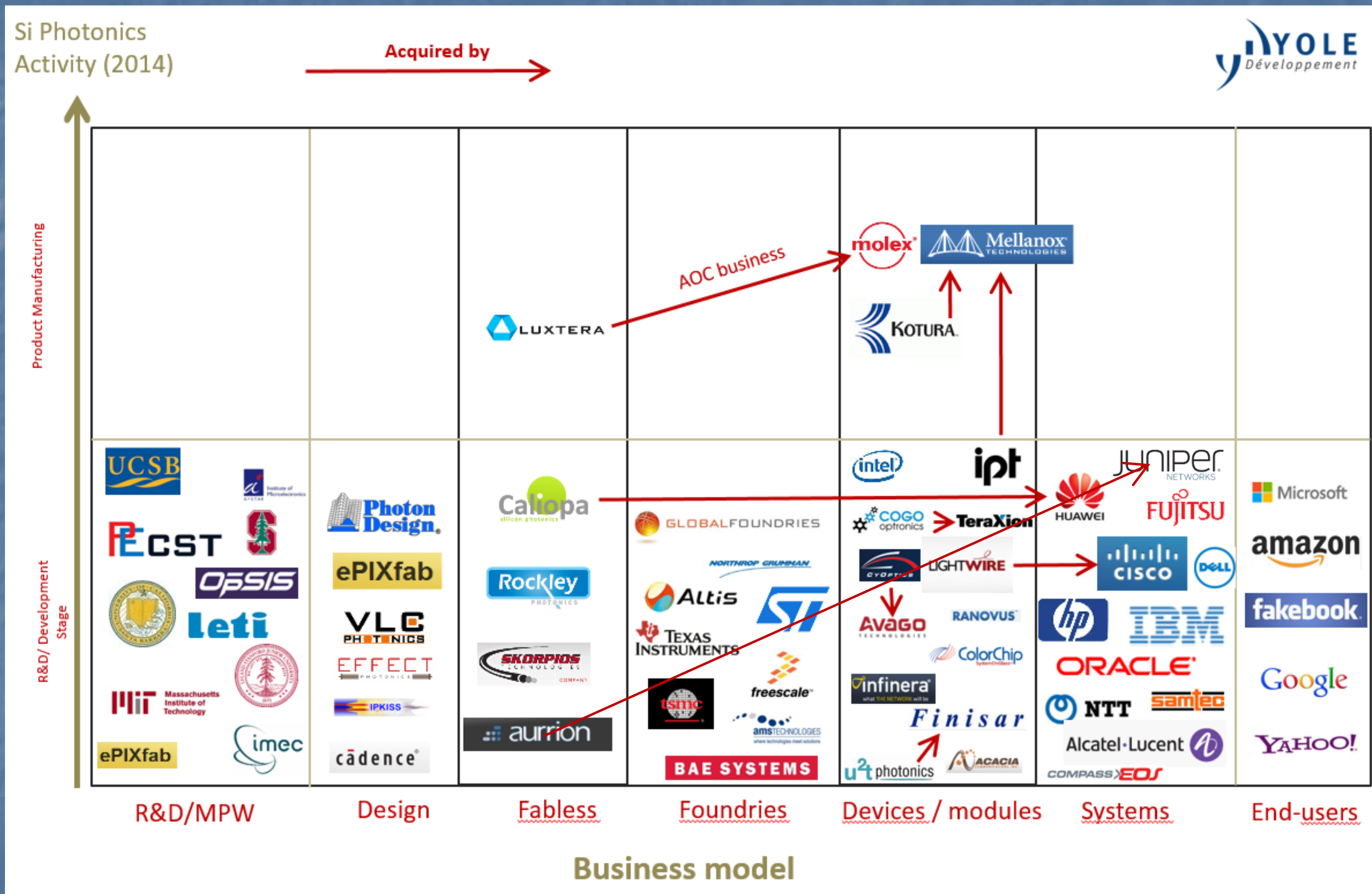
Optical intensity variation

Interferometers



Si-Photonics Supply chain

A) Technology
B) Radiation
C) Design
D) Integration
E) System



Hybrid laser integration

Flip-chip bonded on the chip (example Luxtera)

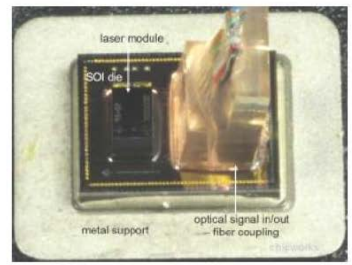


Figure 4: Si CMOS photonics die module – tilt view

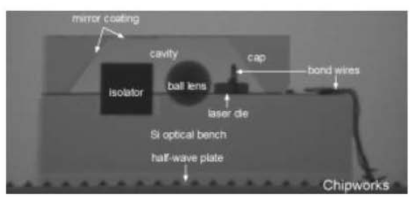


Figure 8: Laser module – side-view X-ray

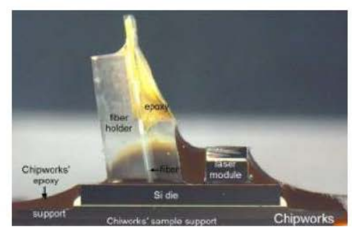


Figure 5: Si CMOS photonics die module – optical cross section