New Developments on Si Photonics at CERN

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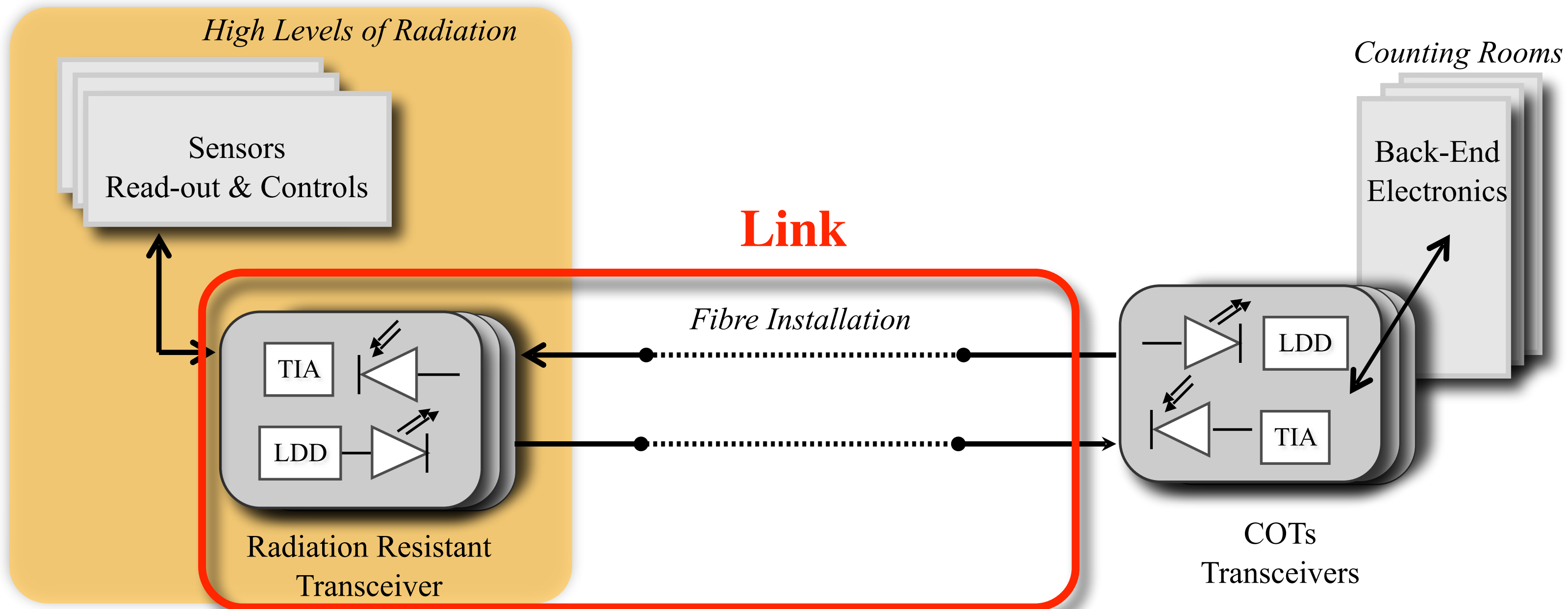
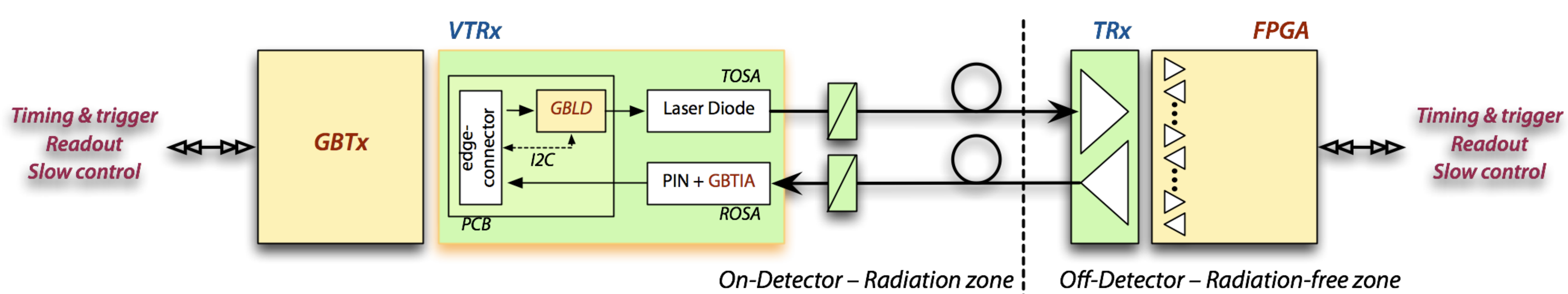
Optical Links for LHC data-transmission.

- Tens of thousands of optical links are currently used by all LHC experiments

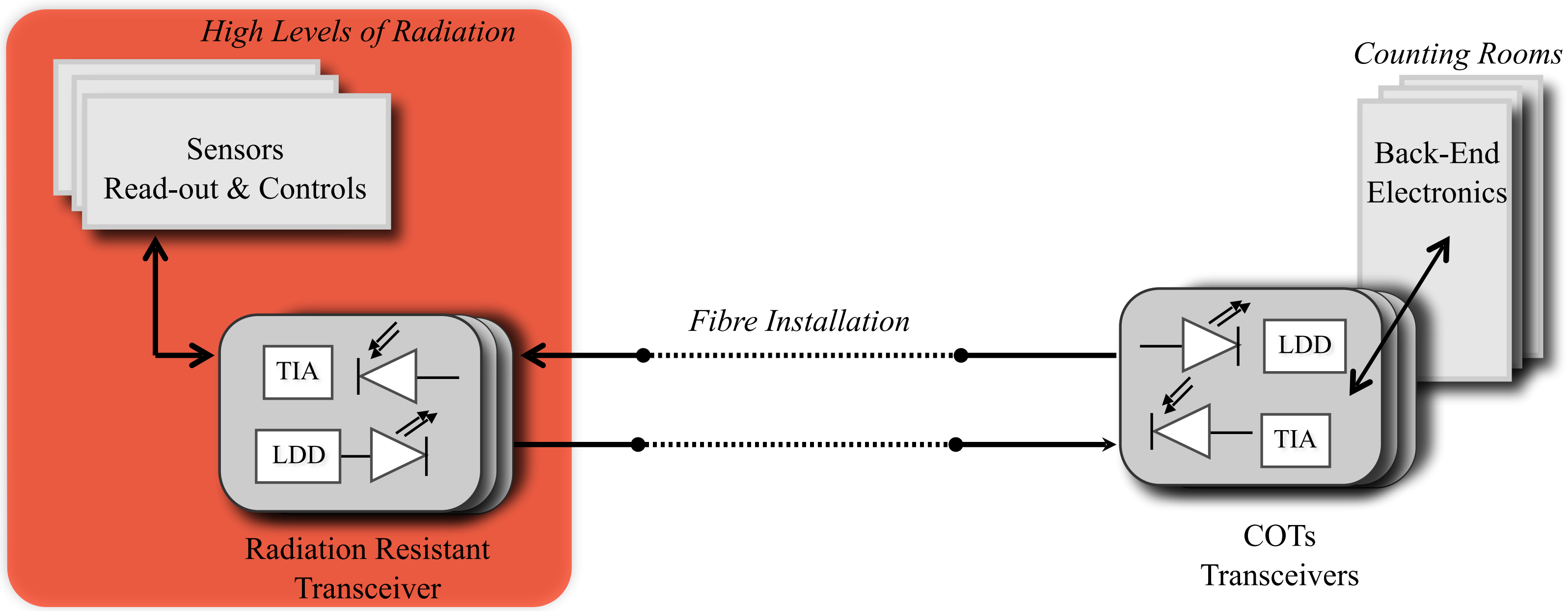


- Links are based on :
  - COTs lasers and photodiodes qualified for use in the LHC environment.
  - Custom radiation hard laser drivers, amplifiers , serializers/deserializers
- Links for Phase I upgrade largely provided by the Versatile Link Project
  - Bi-directional @ 5.0 Gbps , Front-end pluggable module, rad-hard front-end
    - GBT chipset for rad-hard custom ASICs



Electronics for HL-LHC applications.

- Increase in luminosity (~x5) requires upgrades to electronics/detector system
  - increased granularity of detectors → higher number of read-out channels
  - increased data rates for links → 10.0 Gb/s
  - higher levels of radiation for on-detector electronics → ~x5 TID + particles/cm^2



- Directly-modulated VCSEL-based links will continue to be the workhorse of the optical links :
  - improved packaging techniques enable small form-factor/multi-channel devices
  - intrinsic bandwidth of VCSELs still well beyond target data-rates for Phase II
  - radiation-levels are workable for all but pixel environments
- Work has started on identifying design solutions for a high-speed, multi-channel, small form-factor front-end transceiver that meets HL-LHC requirements based on experience from the Versatile Link.

Is there room for improvement?

- What more can we ask of the HL-LHC optical links?
  - bring optical links all the way to pixel level - region of detector with highest granularity/channel-density that would benefit the most from going optical
    - need : *extremely radiation-hard devices*.
  - even higher channel density with less power consumption
    - need : *extremely small/compact devices*.
  - increase flexibility in producing custom transceivers for HEP
    - need : *improved access to the design level of the optoelectronics*.
  - complete integration of links with sensors
    - need : *ability to easily hybridize optoelectronics with sensors/ASICs.*

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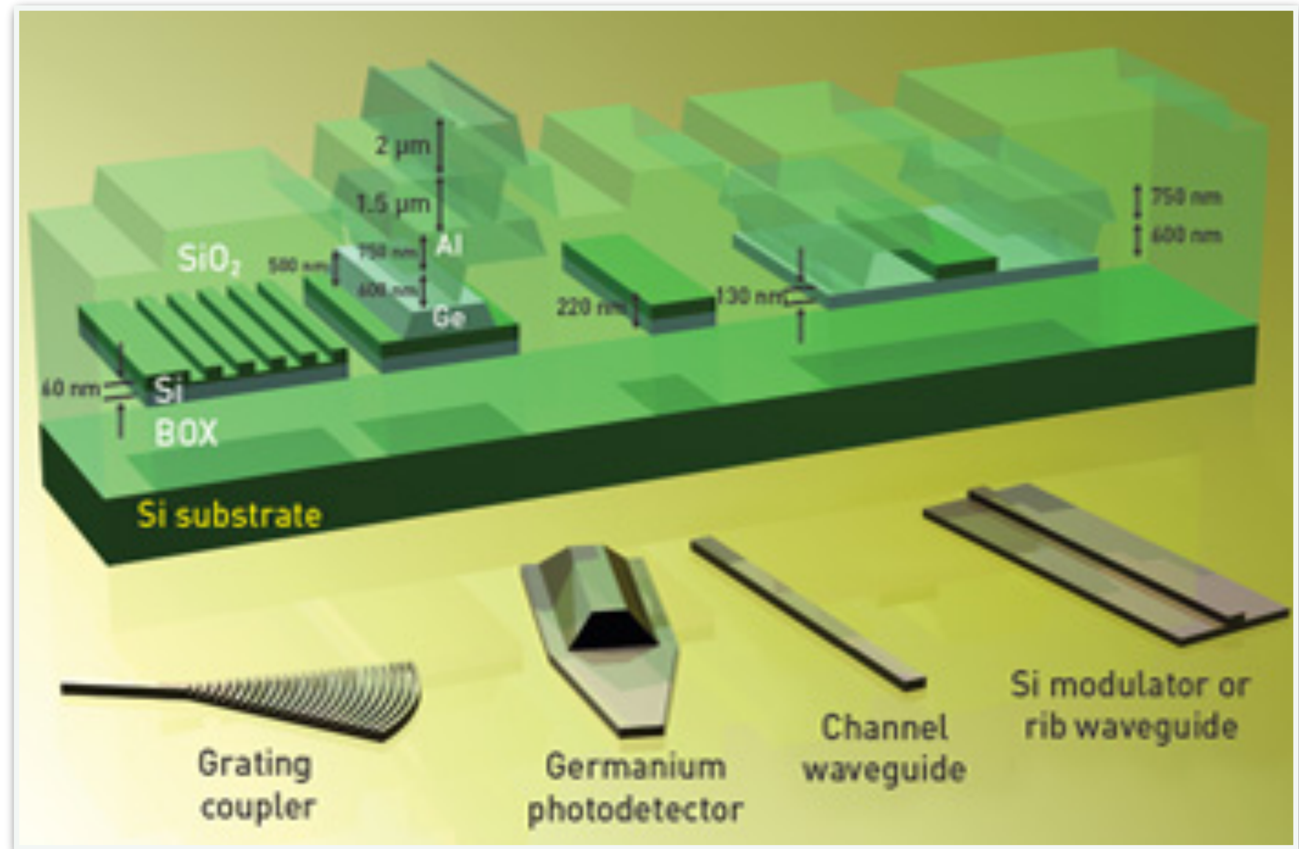
Silicon Photonics?

Outline

- Silicon Photonics
  - What is it?
  - Where do we start looking?
- CERN evaluation of the radiation-resistance of silicon photonics devices
  - first radiation tests on silicon modulators
- Looking ahead

Silicon photonics : a full optical circuit in silicon.

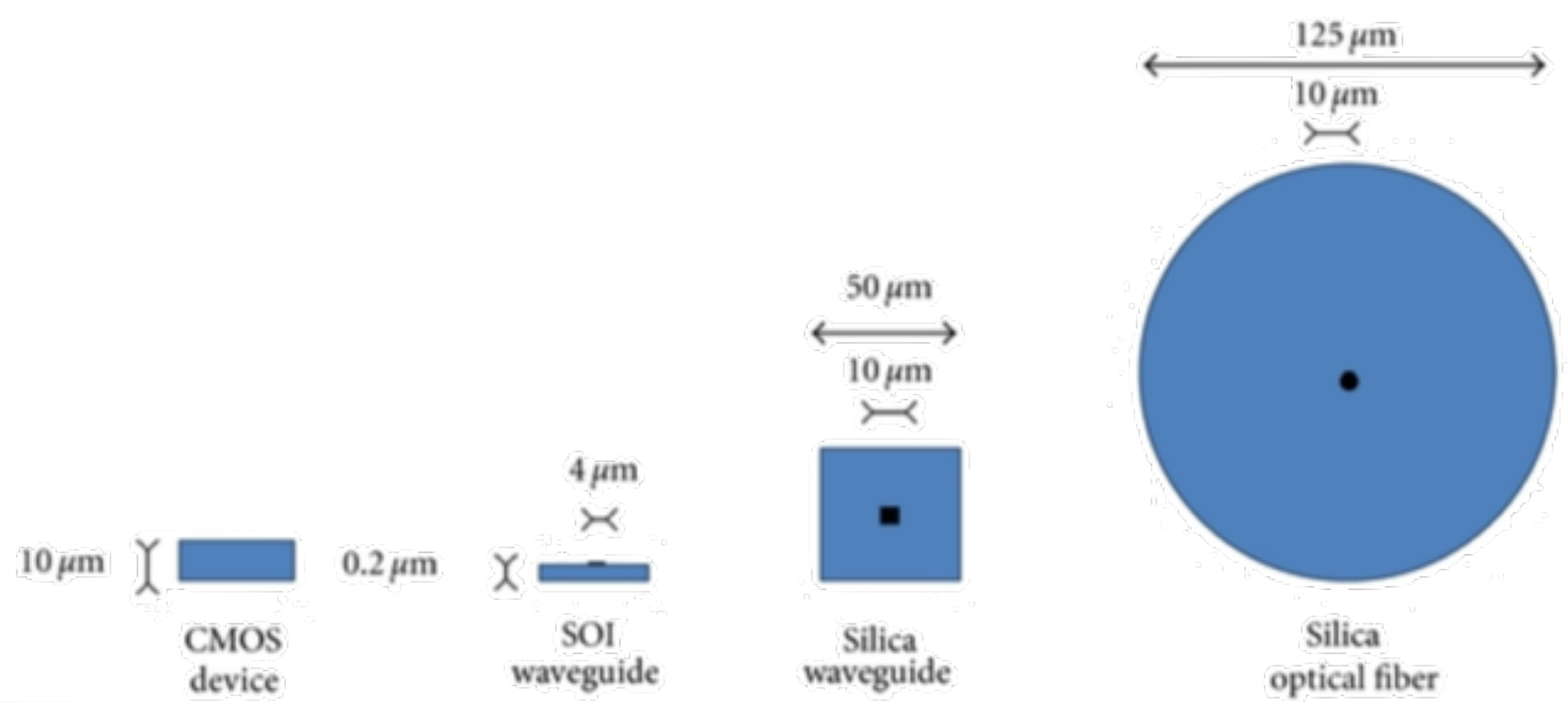
- Silicon photonics :
    - manufacturing of photonics circuits on Silicon using CMOS process technology in a CMOS fab on SOI wafers



- Complete production/integration of the components required to make a full optical circuit in a single piece of silicon :
    - passive components
        - ***low loss waveguides , optical couplers*** , optical splitters
    - active components
        - ***Photodiodes , Lasers, Modulators***

Optical confinement in SOI wafers.

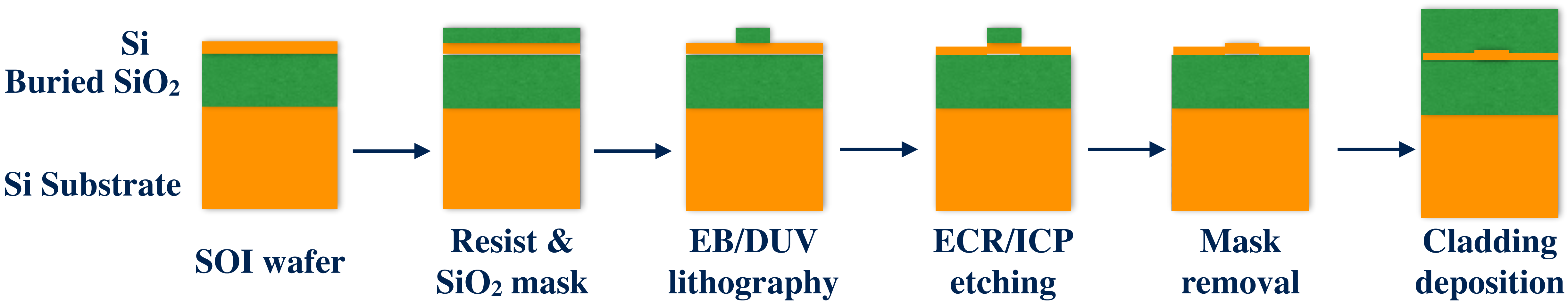
- SOI wafer is a natural optical waveguide due to the difference in refractive index between the Si and SiO_2 layers of the SOI wafer
  - high index contrast between Si and SiO2 for low-loss waveguides
  - core-size ≤ 400 nm for Single-Mode (SM) operation in the 1310-1550 nm telecom-band
    - typical core-size for SM fibre is 9 μm

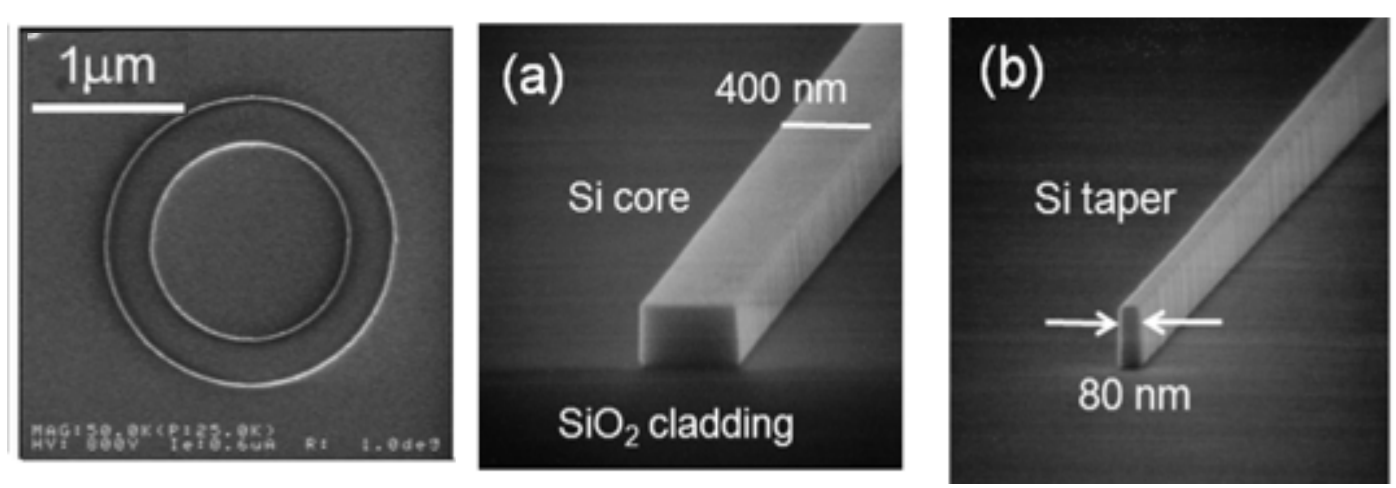


L. Pavesi, “Will silicon be the photonics material of the third millennium?” Journal of Physics: Condensed Matter, vol. 15, pp. 1169–1196, 2005.

Passive components in SiPh : waveguides.

- Waveguides are patterned onto the SOI wafer using standard CMOS fabrication processes
  - electron-beam (EB) lithography/laser deep ultraviolet (DUV) lithography technologies developed for the fabrication of electronic circuits in CMOS are re-used to manufacture the sub μm waveguides
    - capable of forming 100-nm patterns
  - silicon core formed by low-pressure plasma etching with an electron-cyclotron resonance (ECR)/inductive coupled plasma (ECP).
  - cladding layer deposited by a low-temperature process (e.g. PE-CVD)

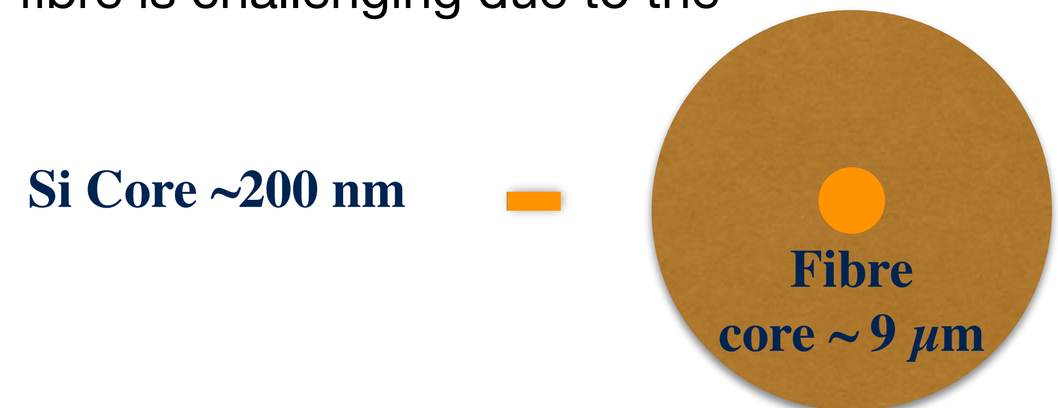




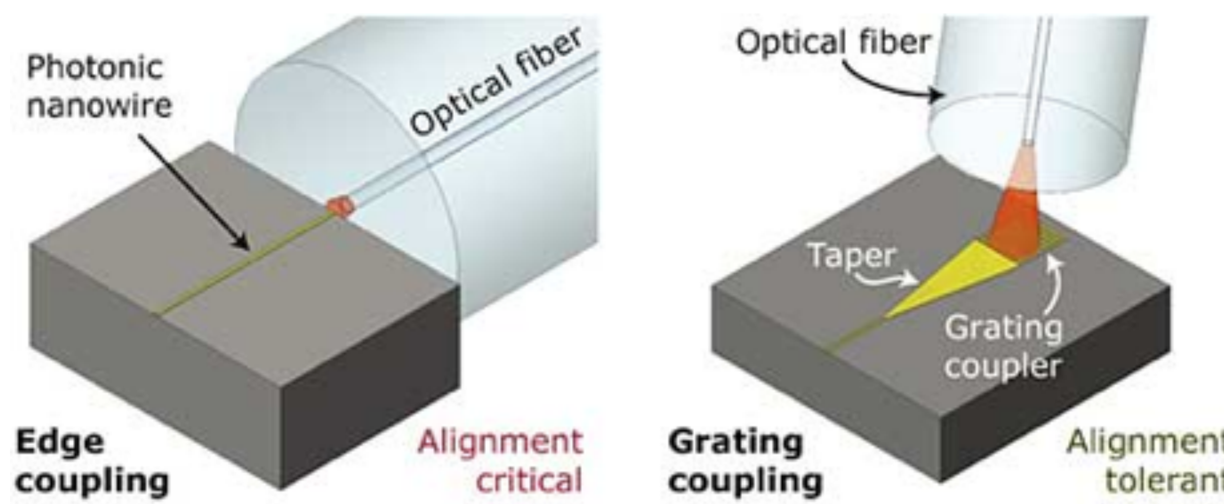
SEM images of SiPh passive structures : K.Yamada et.al *Silicon Photonics Based on Photonic Wire Waveguides*

Passive components in SiPh : couplers.

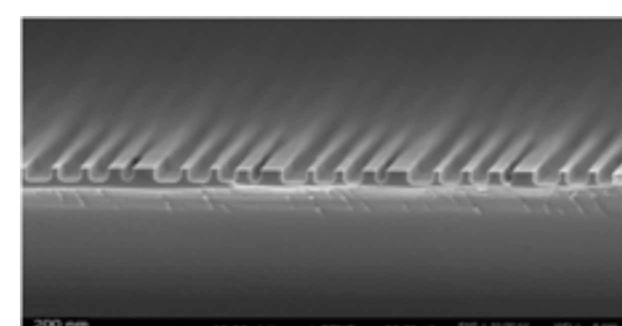
- SM fibre is still used to connect an optical circuit to the “outside world”
  - interface between photonics devices and the optical fibre is challenging due to the differences in the size of the two devices



- Although processes have been developed to allow for horizontal coupling (tapers/spot-size converters) usually vertical coupling techniques are used to relax alignment tolerances for coupling between photonics circuits and SM fibre.



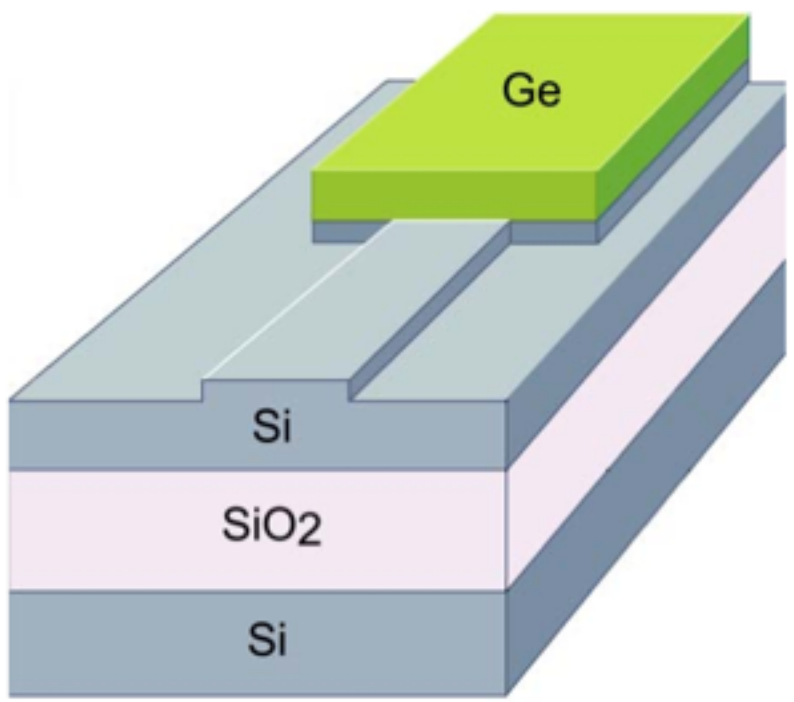
- Grating couplers :
  - the grating period is designed to match a specific wavelength and coupling angle



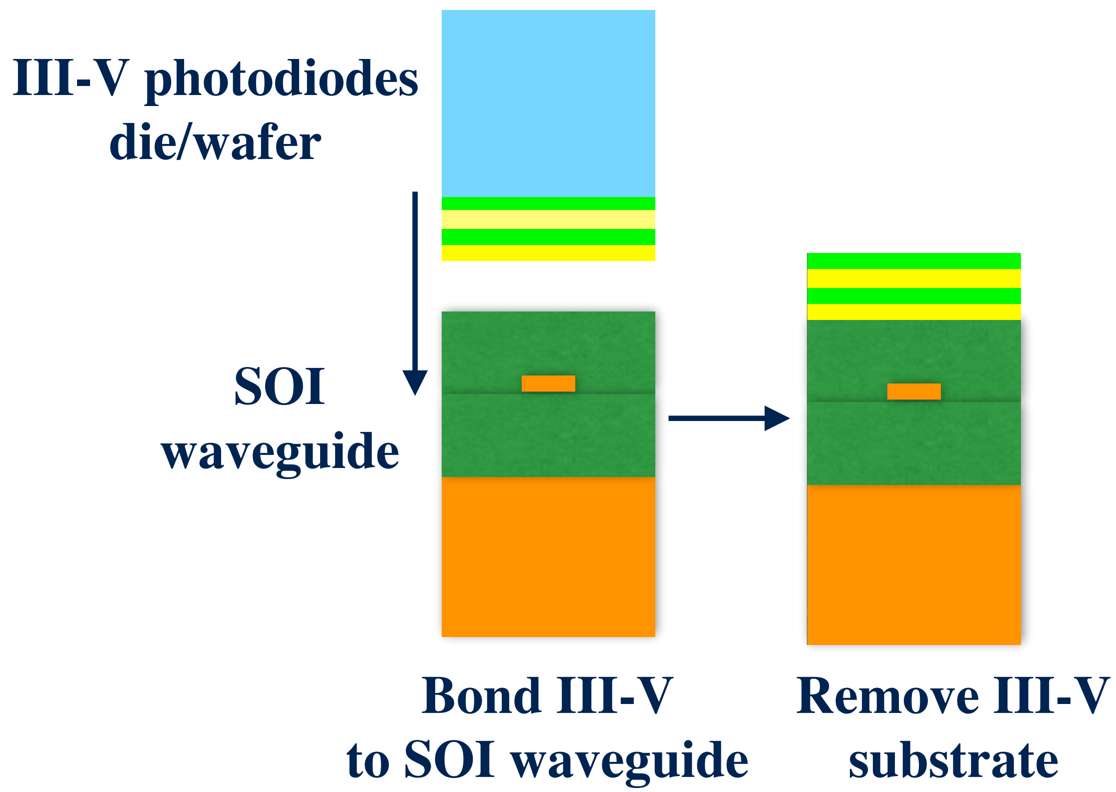
SEM images of SiPh grating coupler.

Active components in SiPh : photodiodes.

- Silicon is transparent in the 1300-1550 nm telecom band , but a photodetector needs to absorb light !
  - active (detection) region is grown directly on the SOI waveguide in a material with good absorption in the IR region (Ge-on-Si).
  - active region in III-V compound is heterogeneously integrated on-to the SOI waveguide (III-V-on-Si) :
    - direct epitaxy of III-V using buffer layer
    - molecular bonding of III-V wafers/dies



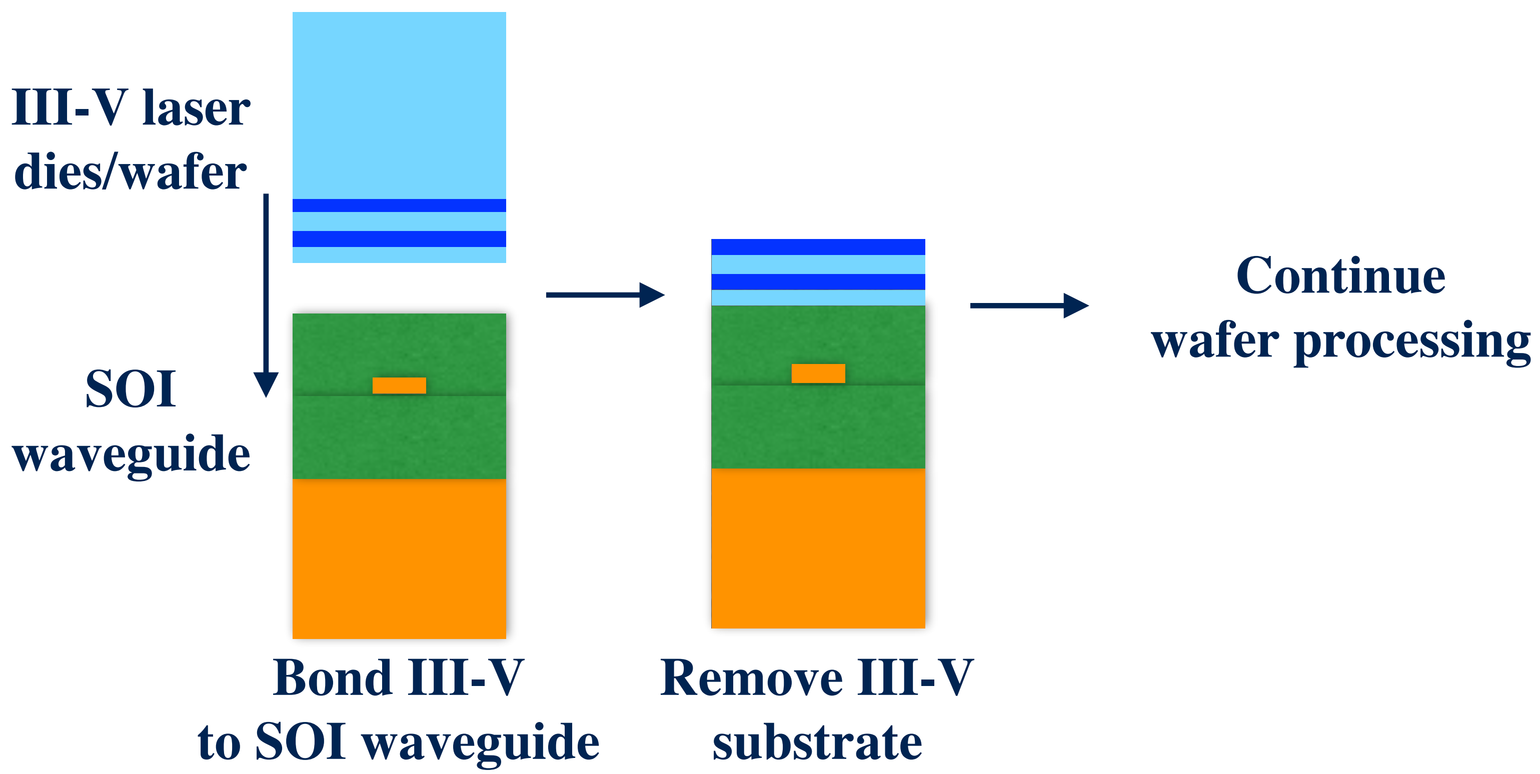
Surface illuminated Ge-Photodiode
Université Paris Sud



III-V photodetector on Silicon
FP-7 Helios course on SiPh

Active components in SiPh : lasers.

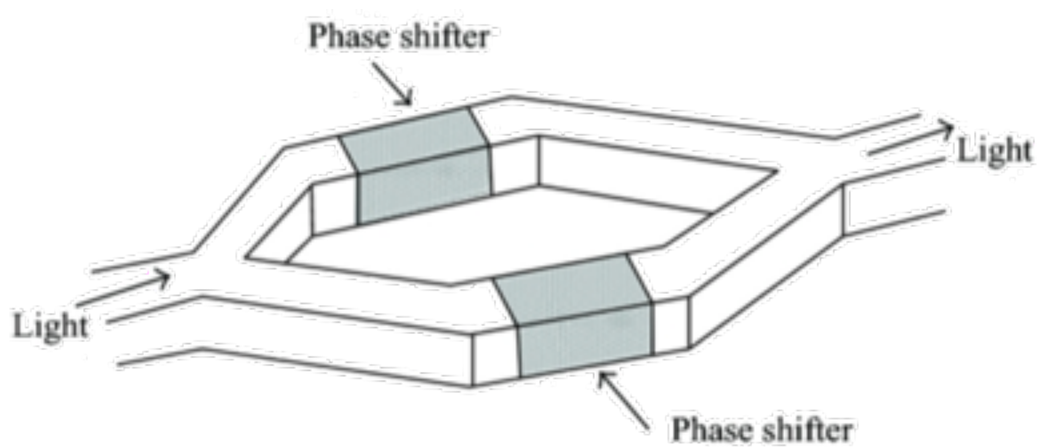
- Silicon is an indirect band gap material (i.e. not by default a lasing medium)
    - have to work pretty hard to make an efficient silicon laser
        - instead the SiPh community seems to have chosen to focus on heterogeneous integration :
            - optical gain (i.e. laser) in standard III-V material
            - coupling to silicon photonics circuits done via SOI waveguides

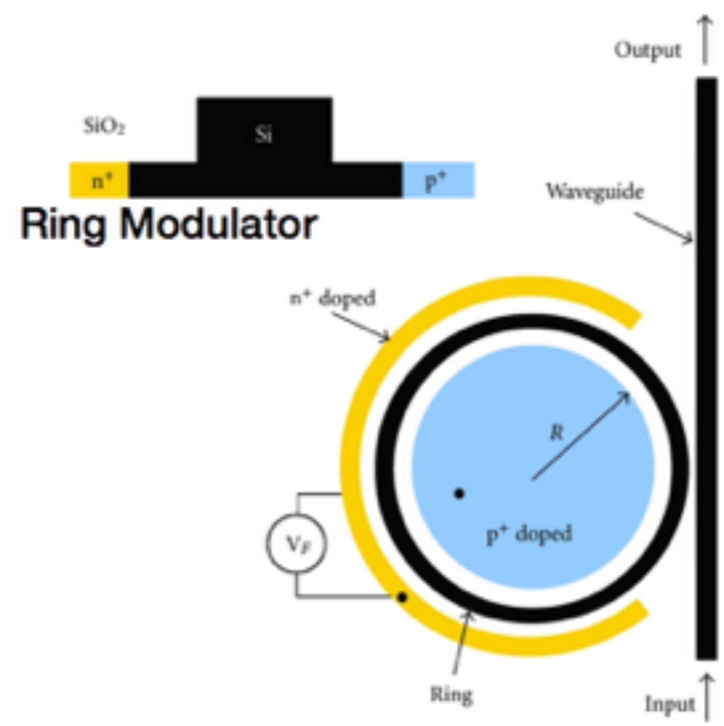


Active components in SiPh : modulators.

- Modulators can also be used for data transmission in photonic circuits.
- Optical intensity modulators are the most common
  - The intensity of light at the output port of the modulator can be changed by varying the applied voltage.
  - two common approaches : interferometers and resonant cavities
    - in both cases modulation depends on changing the refractive index of the active medium

Mach-Zehnder interferometer





Investigating viability of SiPh for HEP.

- For silicon photonics to be considered for future HEP application it must at least meet the requirements set for HL-LHC

Requirements for HEP data transmission (HL-LHC)

high speed - 👍👍

low power - 👍👍

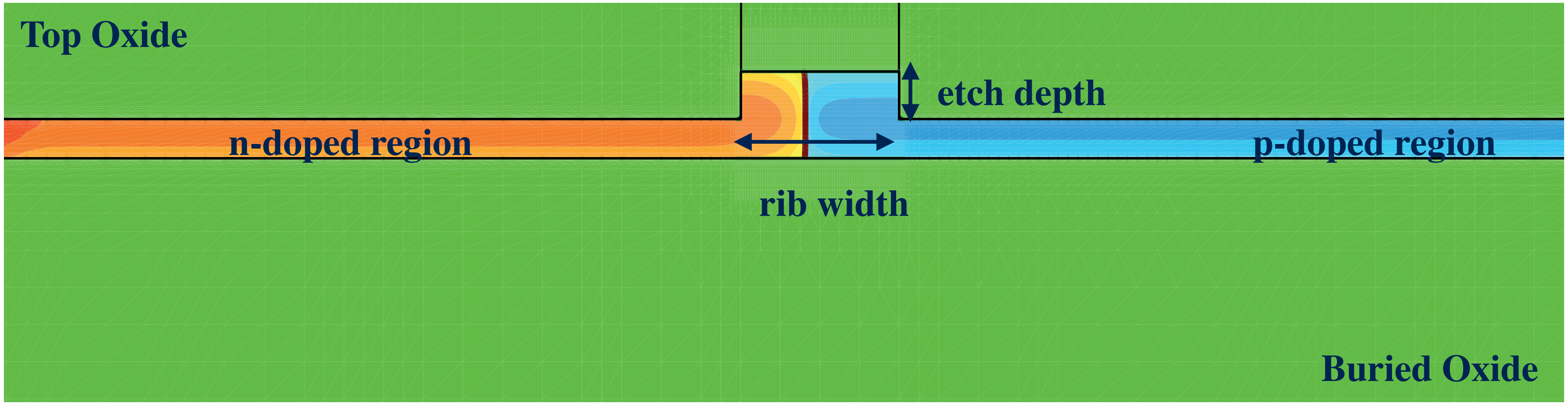
high-channel density - 👍👍

radiation hardness ??

- Radiation hardness to be compared to existing technologies used in state of the art optical links for HEP; i.e. VCSELs and p-i-n photodiodes.
- Start by looking at the basic building blocks of a SiPh circuit, and investigate :
  - Effect of damage from non-ionizing energy loss on the blocks
  - Effect of damage from ionizing energy loss on the building blocks
  - Compare results to VCSELs/p-i-n photodiodes
- Work in the CERN PH-ESE-BE has focused on evaluating the effect of radiation on silicon Mach-Zehnder interferometers provided by the photonics group at the Université Paris Sud.

Silicon Mach-Zehnder Modulators.

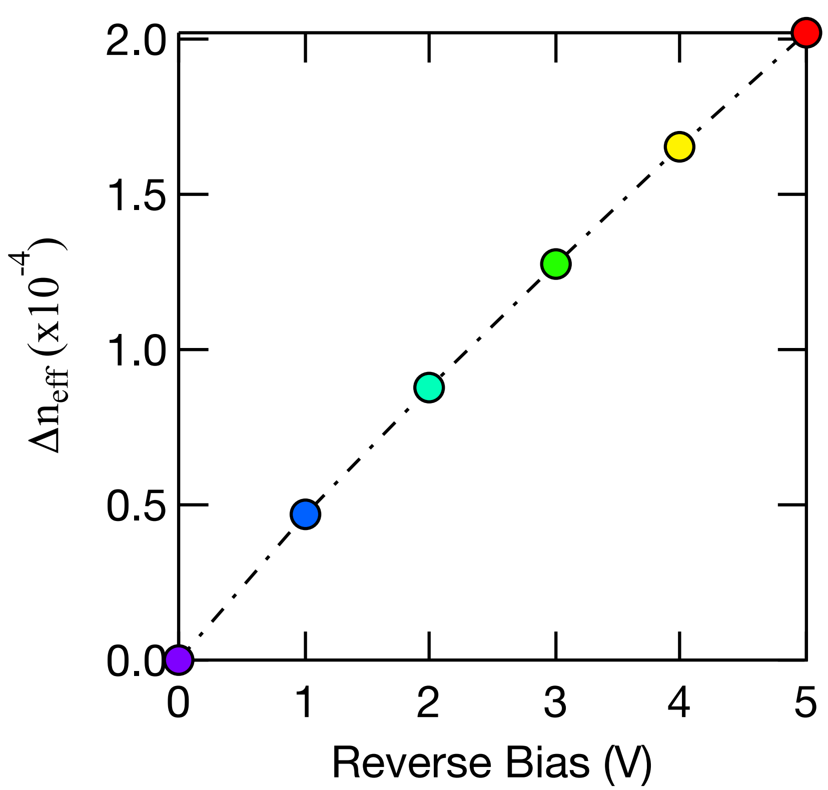
- What does each arm of the Mach-Zehnder interferometer look like?
  - rib width and etch depth chosen to create a single-mode waveguide
  - p-n diode is created by selectively doping regions of the waveguide
  - reverse-biasing the diode changes the carrier densities in the silicon waveguide
  - refractive index of silicon depends on the free-carrier density of the material
  - changing the refractive index of the waveguide changes the effective index (n_{eff}) of the structure
    - think of n_{eff} as, on-average, the refractive index seen by light propagating in the waveguide

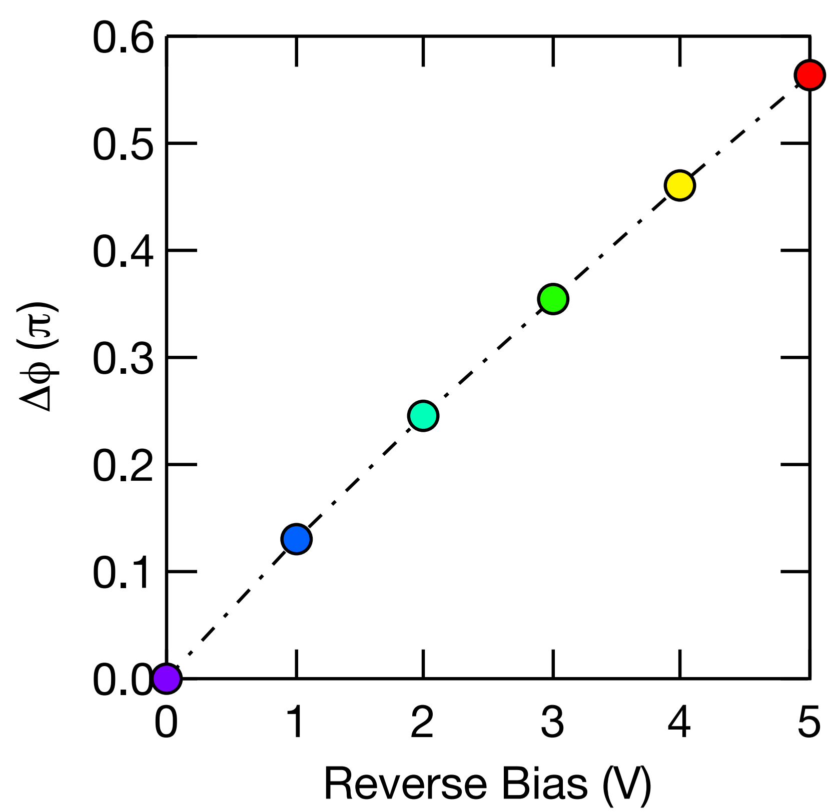


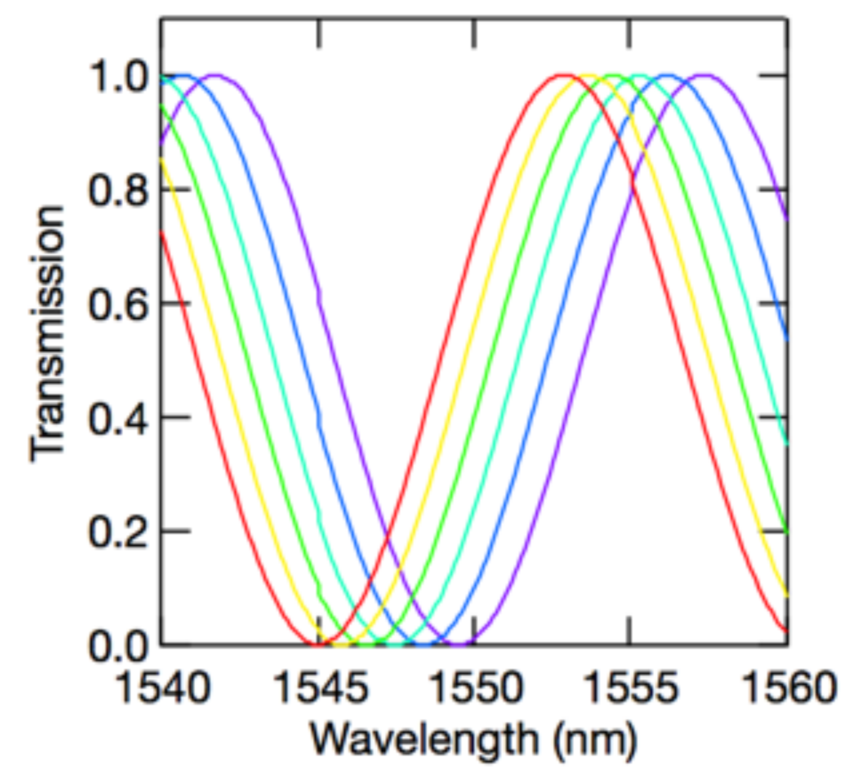
Change carrier density → Changes n_{eff} → Changes phase → Changes transmitted amplitude

Silicon Mach-Zehnder Modulators.

- Changing the reverse-bias applied to the device will induce a phase-shift in the transmission of the interferometer



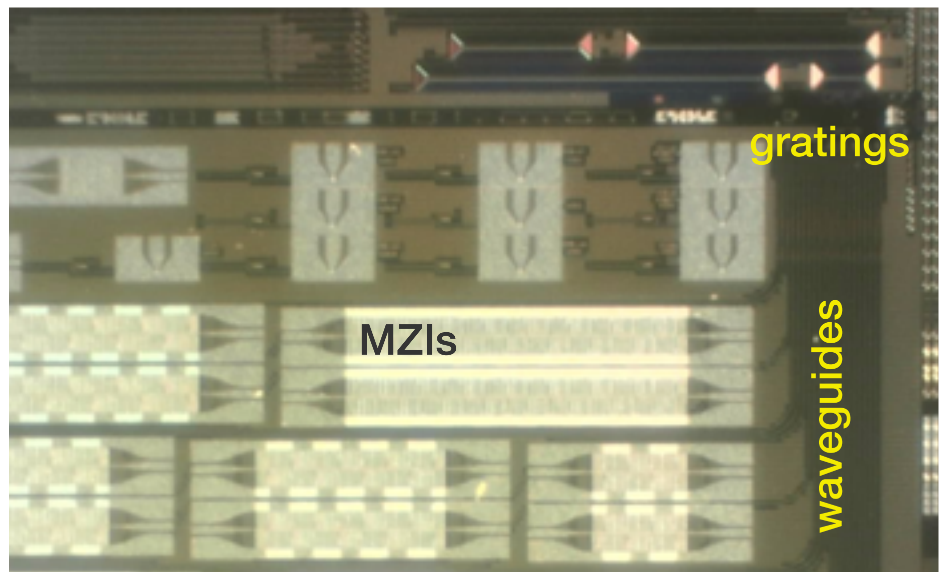




Change carrier density → Changes n_{eff} → Changes phase → Changes transmission

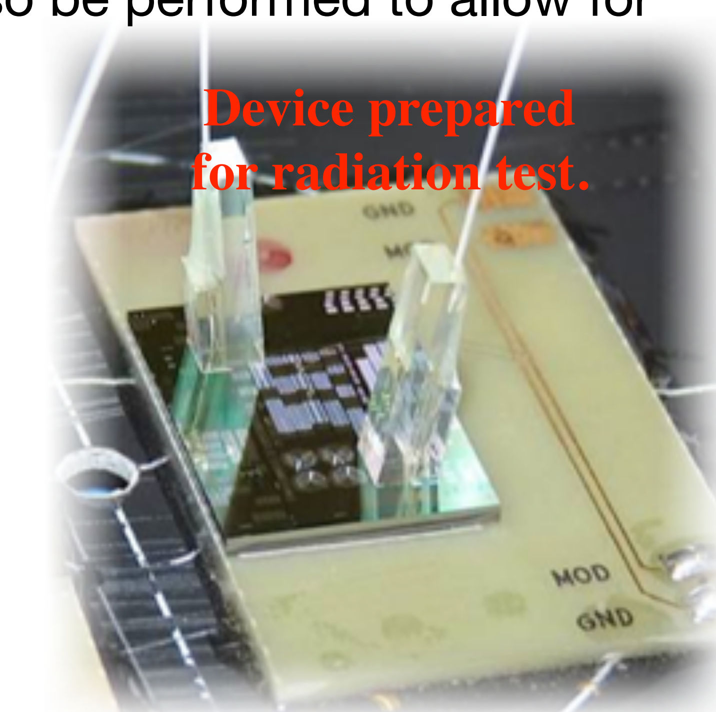
Characterization of Silicon Mach-Zehnder Modulators.

- The optical transmission of the MZI is measured using a broadband source and an optical spectrum analyzer :
  - DC measurement of phase-shift achievable for an applied reverse bias.



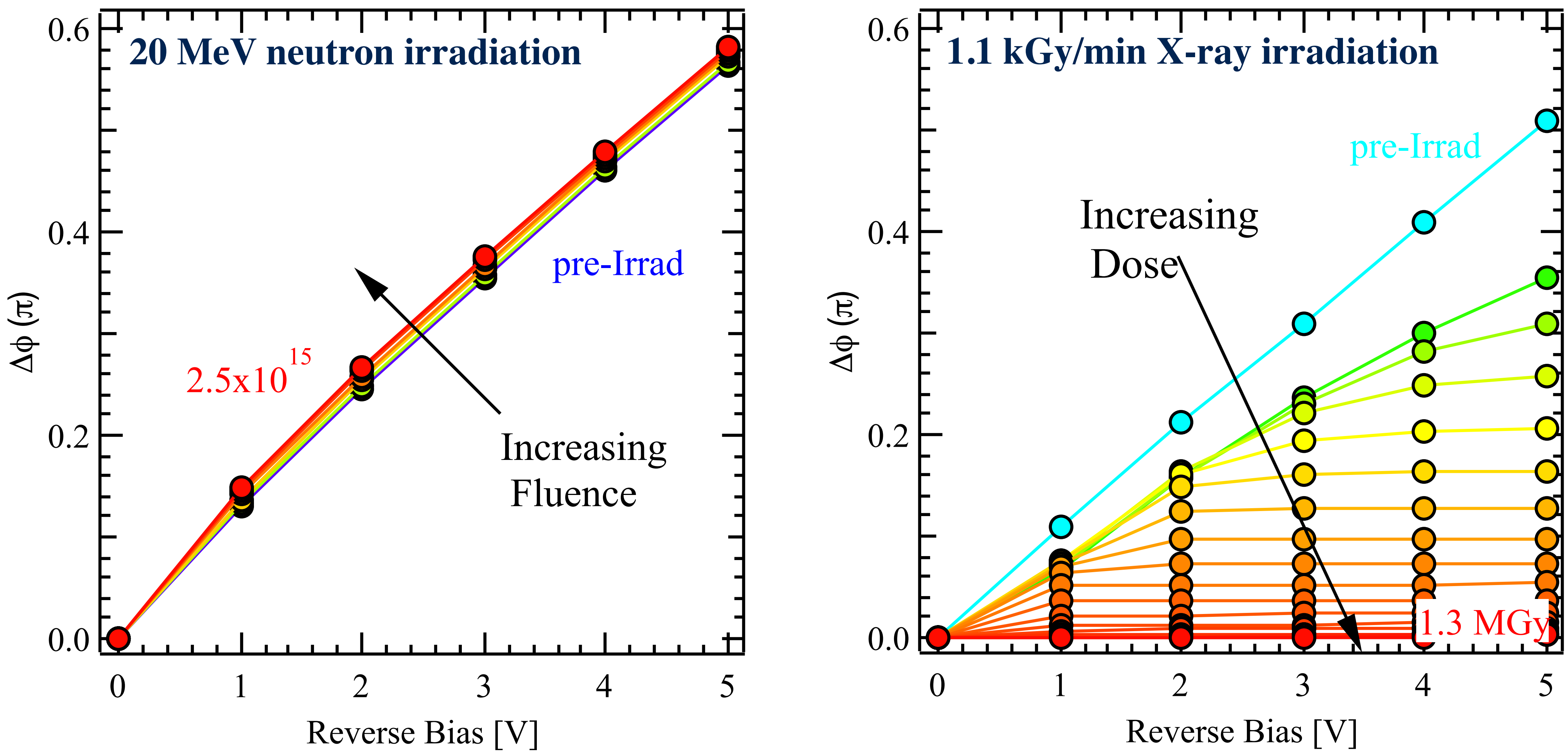
Test-chip from Université Paris Sud

  - Optical bench set-up at CERN to measure test chips
  - Pig-tailing (external to CERN) and bonding (internal) can also be performed to allow for continuous monitoring of devices during radiation tests.



Results from first radiation tests in 2014.

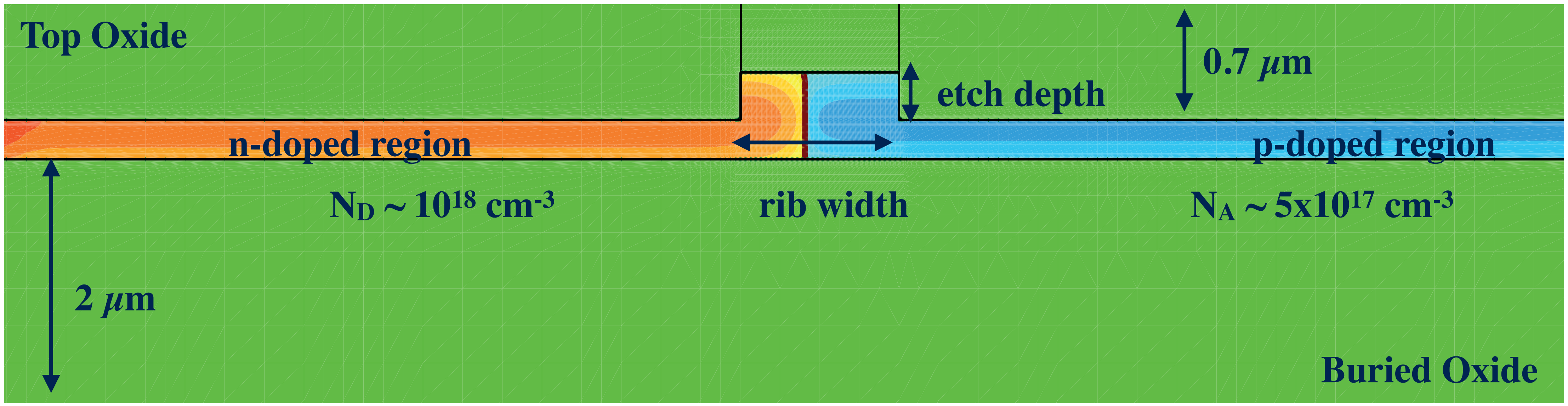
- First tests on radiation tolerance of silicon modulators carried out in 2014



- Neutron irradiation, 20 MeV neutron facility, up-to fluences of 10^{16} n/cm^2 without any significant degradation in performance.
- X-ray irradiation up-to doses of a few MGy shows that the devices are sensitive to damage from ionizing radiation.

Results from first radiation tests in 2014.

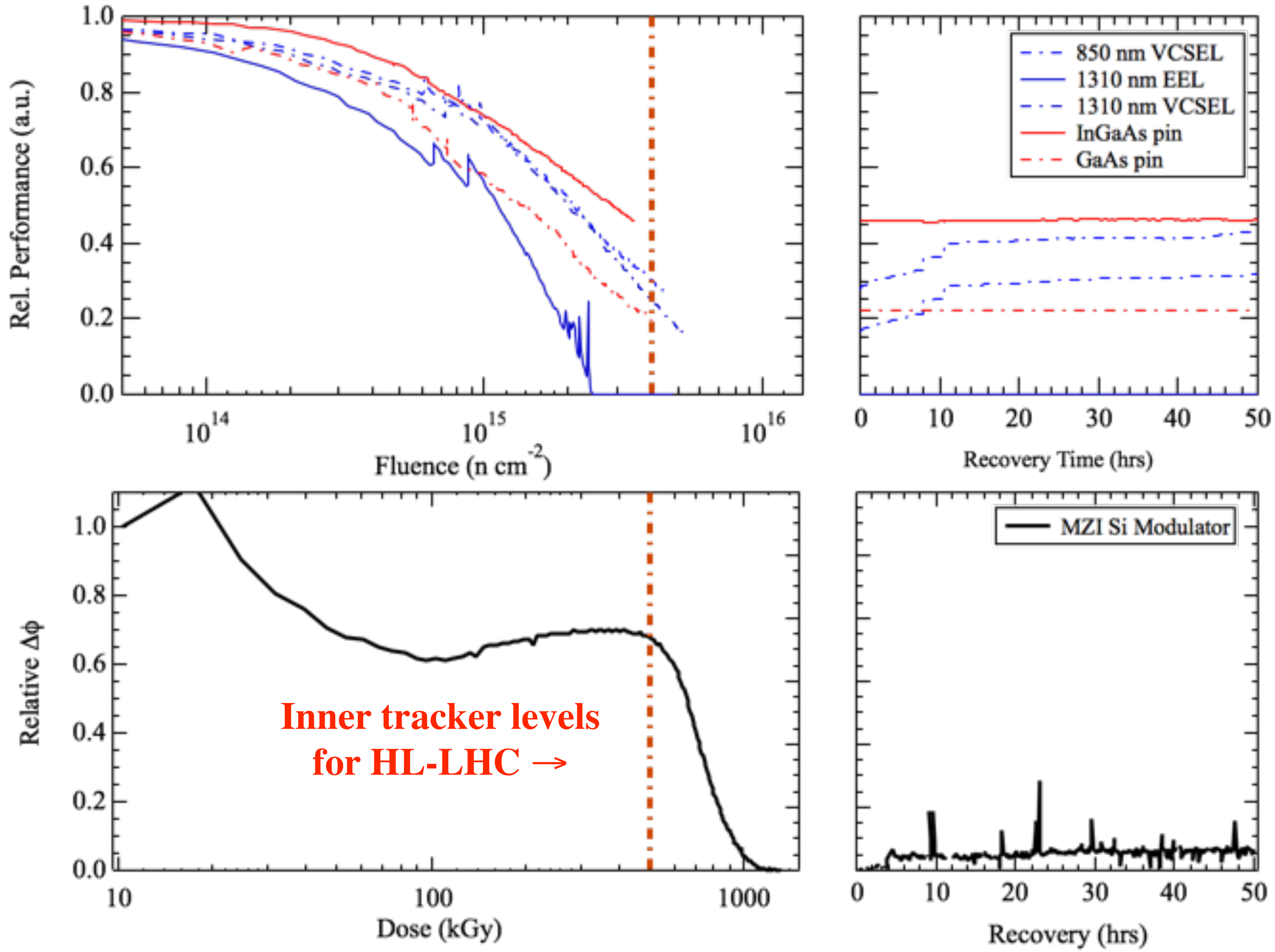
- Look to the structure to try and understand what was measured during the radiation tests



- Highly doped p-n diodes :
  - damage from non-ionizing energy loss typically causes changes in effective doping concentration of silicon (n → p)
    - no intrinsic region in irradiated structures
    - high doping levels (both p and n) compared to typical sensors
- SOI waveguides :
  - thick, not necessarily radiation-hard oxide surrounding the active regions of the phase-shifting diodes
    - damage from ionizing energy loss is known to cause :
      - positive charge build-up in SiO_2 layers
      - additional traps in the Si/SiO_2 interface

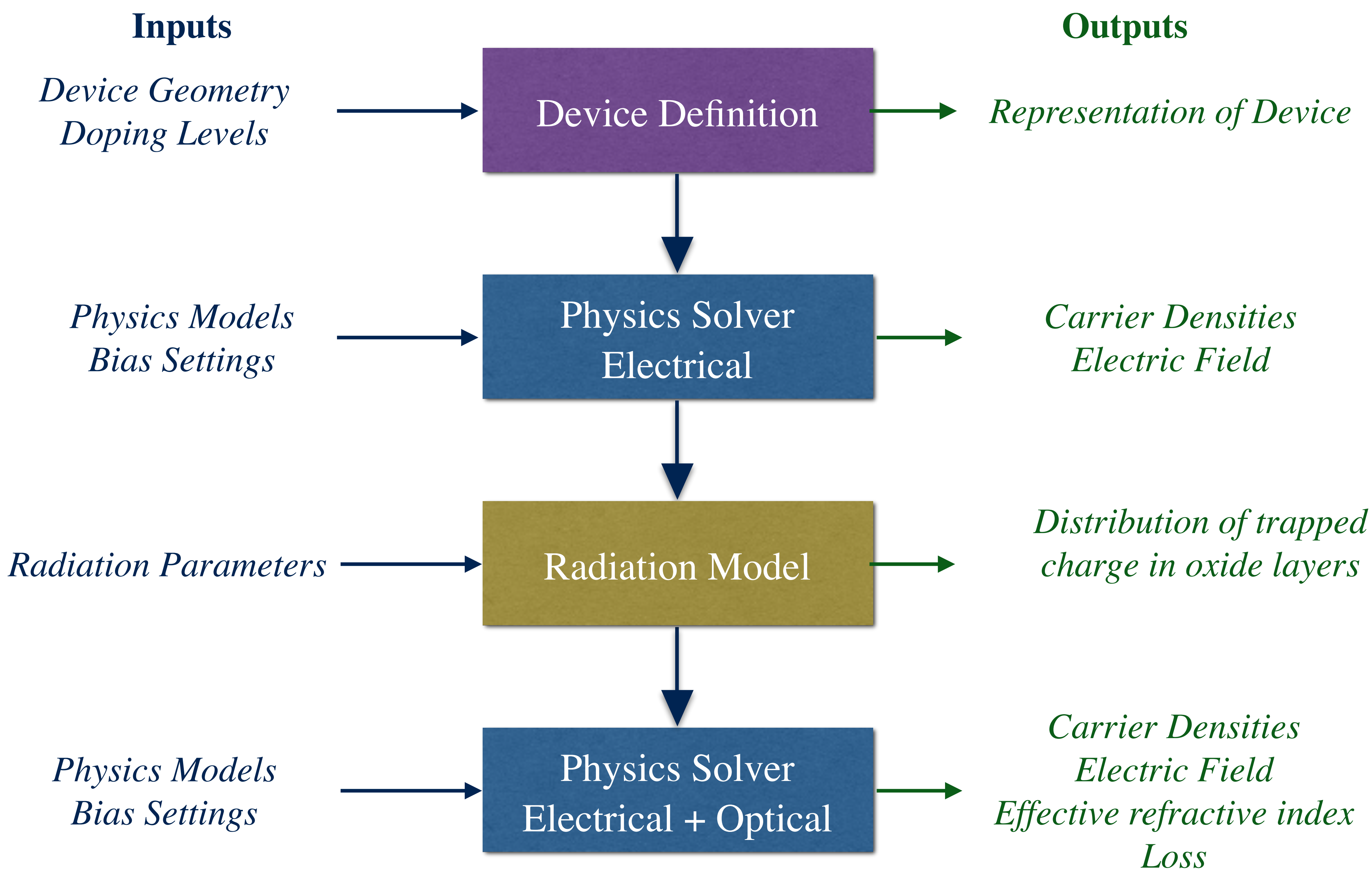
Comparison between standard link components and SiPh modulators.

- While VCSELs and p-i-n photodiodes behave differently, so far we cannot say that the p-n phase shifting modulators are any worse :
    - neither devices are suitable for anything beyond the inner trackers.



Beyond the first radiation tests : a model for TID in silicon photonics Mach-Zehnder modulators.

- Models/simulation tools that are already in use to study the effects of radiation on CMOS transistors and silicon sensors applied to the Mach-Zehnder modulators :
  - predict how design changes to modulators can affect radiation resistance.



Beyond the first radiation tests : ICE-DIP.

- The Intel-CERN European Doctorate Industrial program (ICE-DIP) launched in the fall of 2013 with a work package dedicated to developing a power-efficient, low-cost silicon-photonics data-link for harsh environments
    - Doctoral student in PH-ESE-BE (Marcel Zeiler)

http://openlab.web.cern.ch/ice-dip

- Chips designed to investigate the effect of design parameters on the radiation resistance of silicon photonics chip have been designed and submitted for fabrication :
    - active + passive devices
    - different foundries
- Characterization + Radiation tests planned for later in the year.

Conclusions

- Work has started on evaluating silicon photonics for future data transmission applications at the LHC
- First set of radiation tests completed on silicon-based modulators, so far all results indicate that structures can be as rad-hard as VCSELs/p-i-n photodiodes
  - devices are not affected by non-ionizing radiation (highly doped p-n structures)
  - sensitivity to ionizing radiation attributed to thick oxide layers used in the devices
  - low-dose rate testing and high temperature annealing show that a small amount of recovery can be expected, but not enough to push the devices to the most extreme radiation environments expected at the HL-LHC
- Future Prospects
  - Investigating different models to simulate the pre-and-post irradiation behaviour of silicon modulators and predict favourable design changes
  - New structures (different foundries/doping levels/etch-depths) have been designed and chips in hand expected later in the year