Silicon Photonics for HEP experiments

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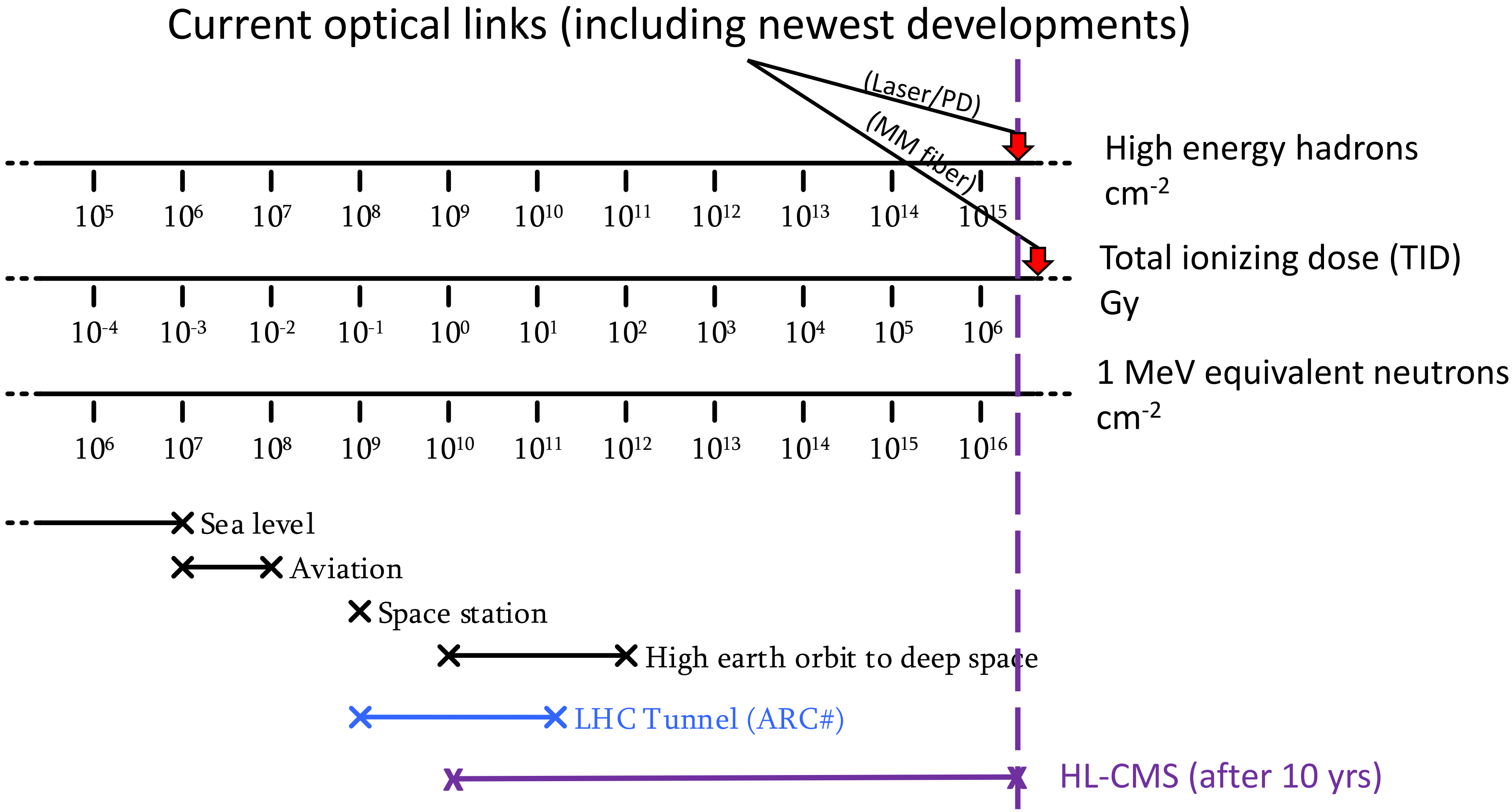
EP-ESE Seminar

09.04.2019

Outline

- Reminder: Why are we investigating Silicon Photonics?
- Reminder: What is Silicon Photonics and how does it work?
- Testing of radiation resistance of Silicon Photonics devices
- Next steps

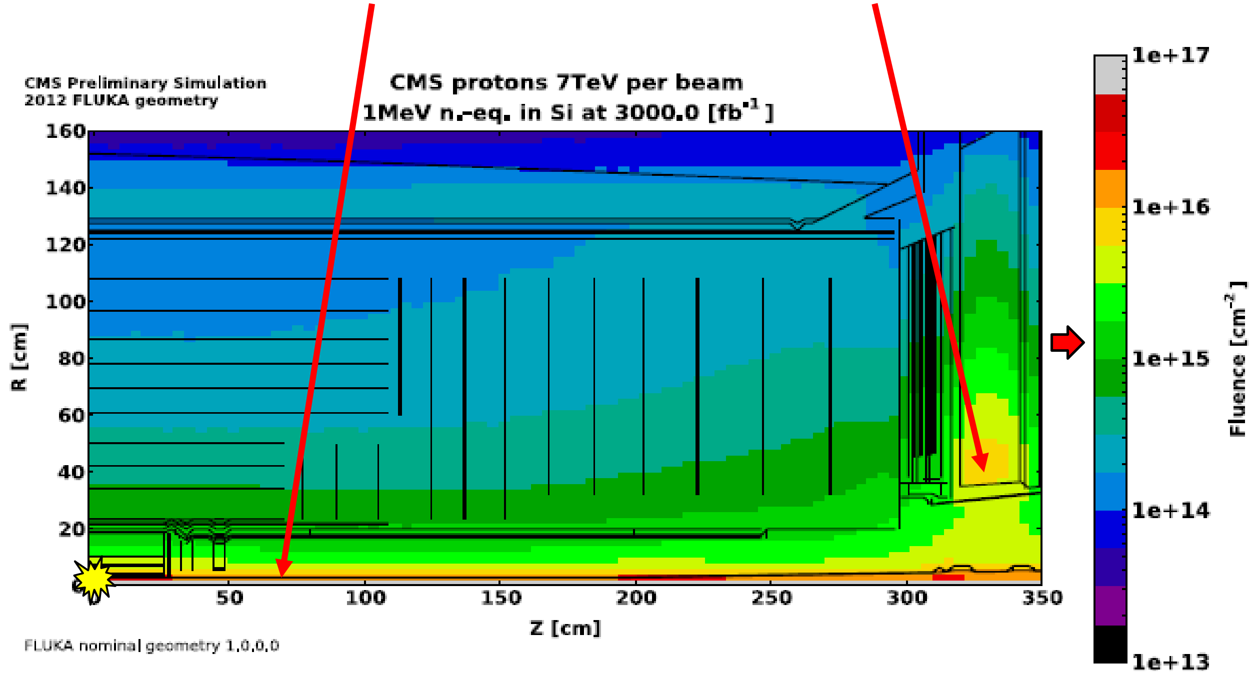
Radiation resistance of optical links



Motivation to investigate Silicon Photonics

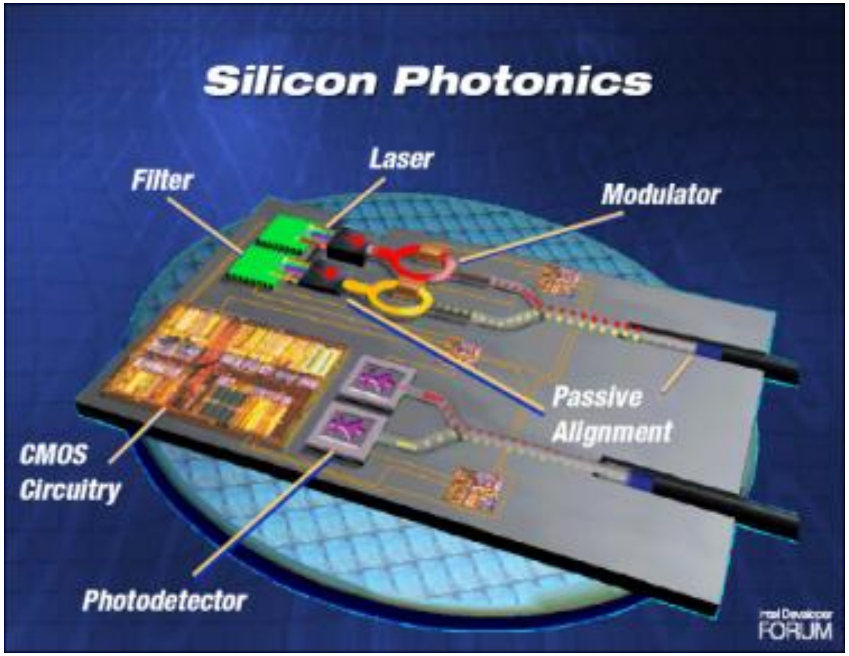
A) VL and VL+ reach their limits with the end of HL-LHC

B) No solution for extreme areas, so far: Cu-links



C) Because of space restraints in the innermost detector region highly integrated links are needed

What is Silicon Photonics?



from: https://ic.tweakimg.net/ext/i.dsp/1109883395.png

- Highly integrated photonics platform:
  - Filters, lasers, photodetectors, modulators and electronics grown or implemented on the same piece of Silicon

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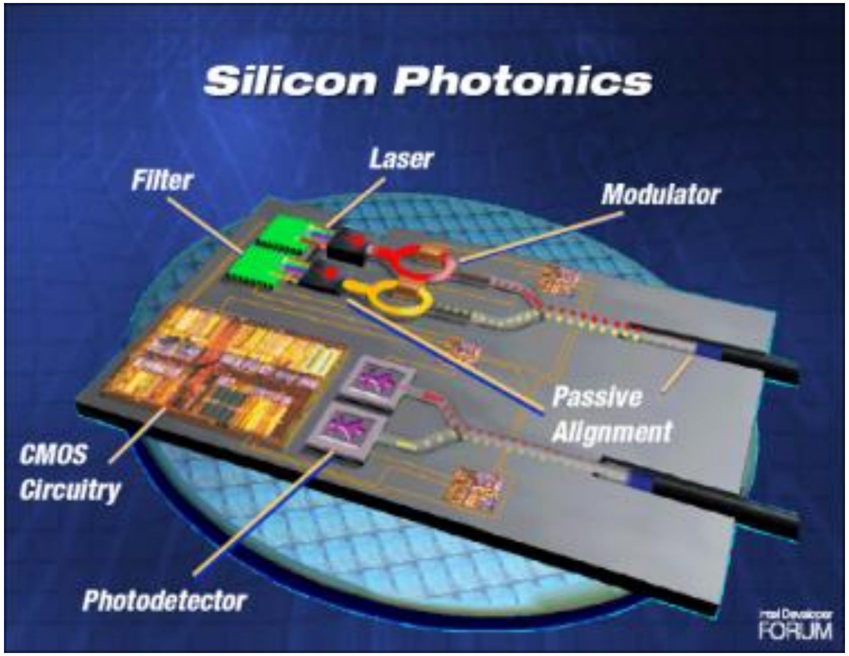

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- Highly integrated photonics platform:
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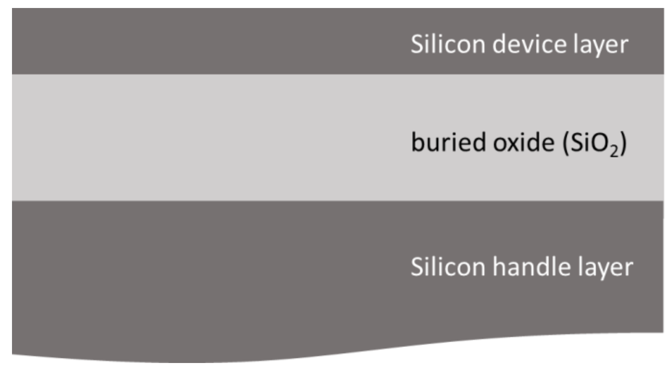
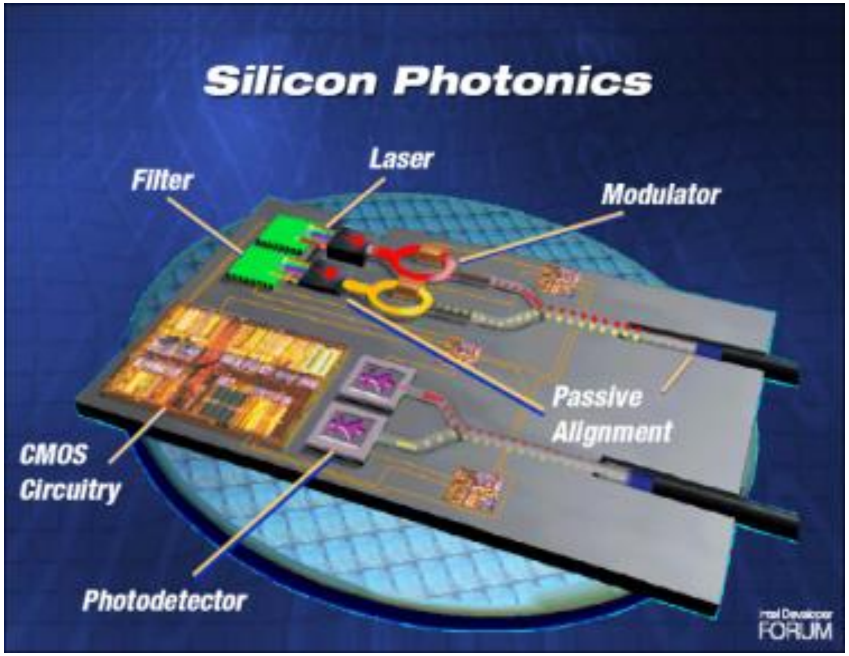
  - Using Silicon On Insulator (SOI) Wafers



What is Silicon Photonics?



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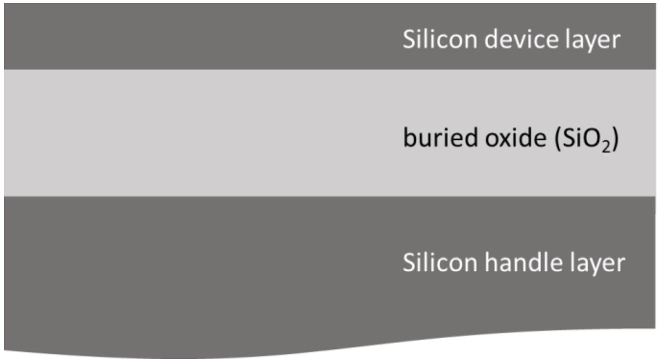
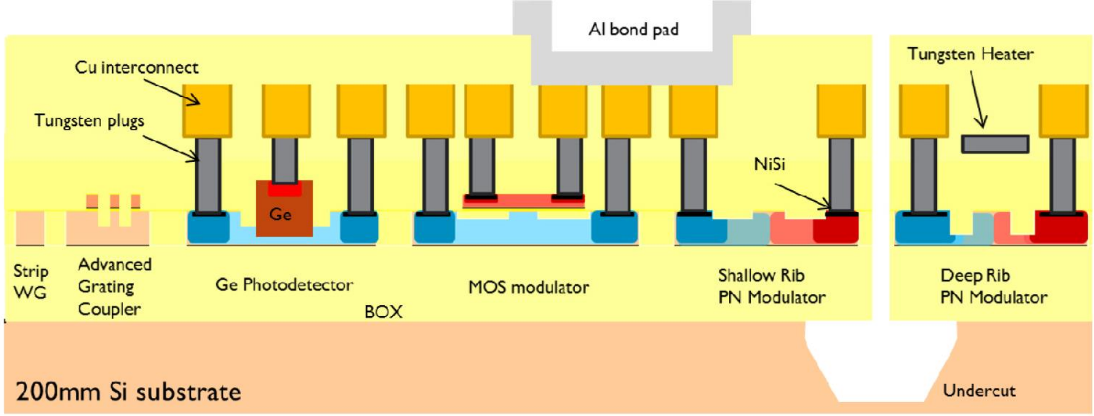


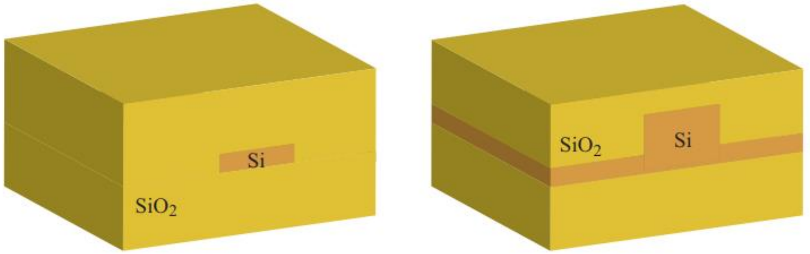


- Well established CMOS processes (patterning and doping of silicon device layer) are used to produce SiPh devices.

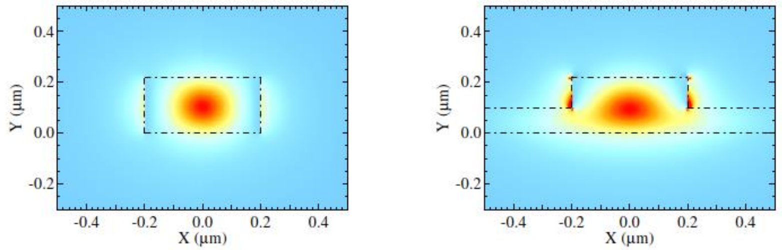
P. P. Absil *et al.*, "Silicon photonics integrated circuits: a manufacturing platform for high density, low power optical I/O's," *Opt. Express*, vol. 23, no. 7, p. 9369, Apr. 2015

Waveguides – How light travels through the chip

- Structure similar to optical fibers: waveguide core and waveguide cladding
- Fundamental principle: total internal reflection
- More accurate description: optical modes



Optical mode

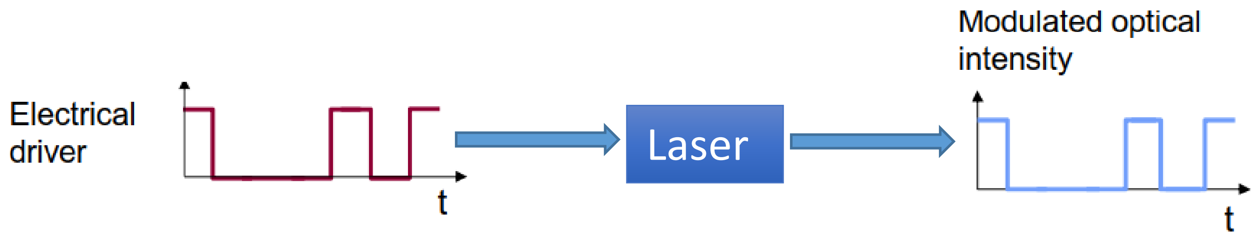


Channel Waveguide   Rib Waveguide

- The deeper the silicon etch the better the confinement
- Depending on the dimensions different optical modes are guided
- Optical communication: preferred to have only the fundamental mode → **single mode**

How is light modulated in Silicon Photonics?

Signal modulation in Laser based Transmitter:



How is light modulated in Silicon Photonics?

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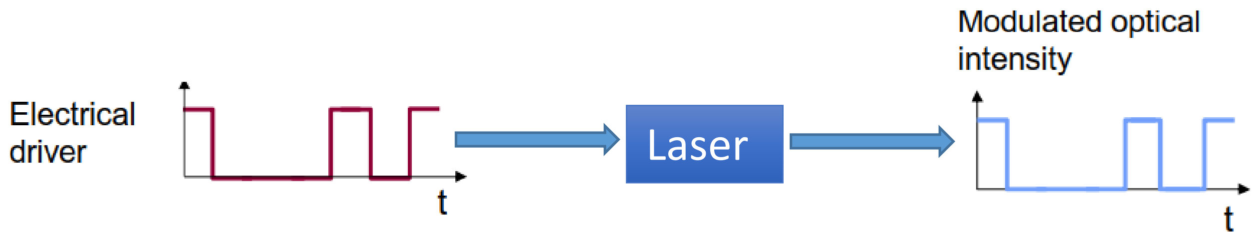
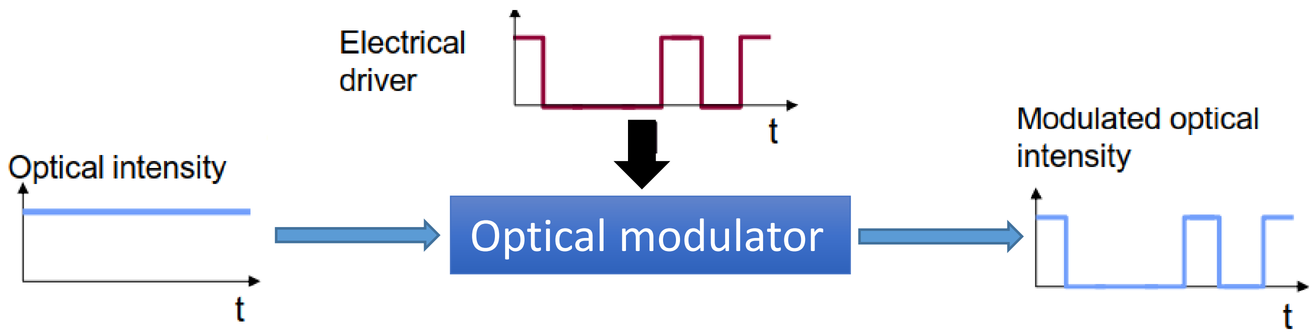


Signal modulation in SiPh based Transmitter:



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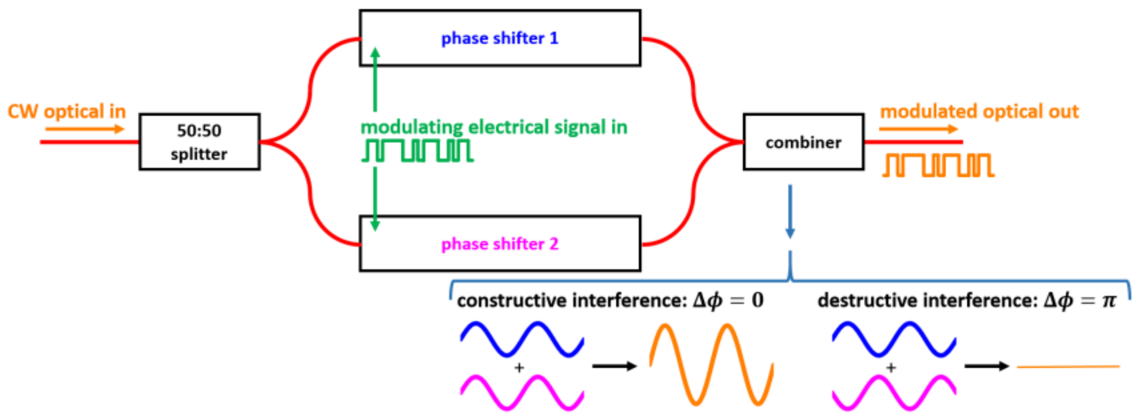
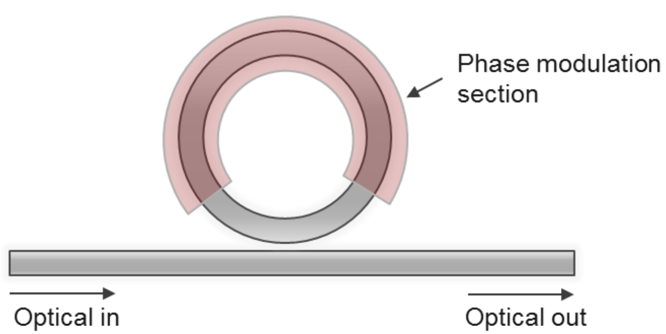
So far we investigated two modulator types

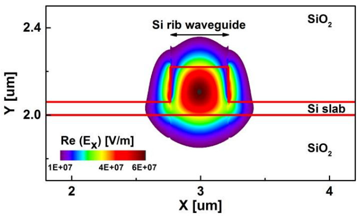
Mach-Zehnder-Modulator (MZM)

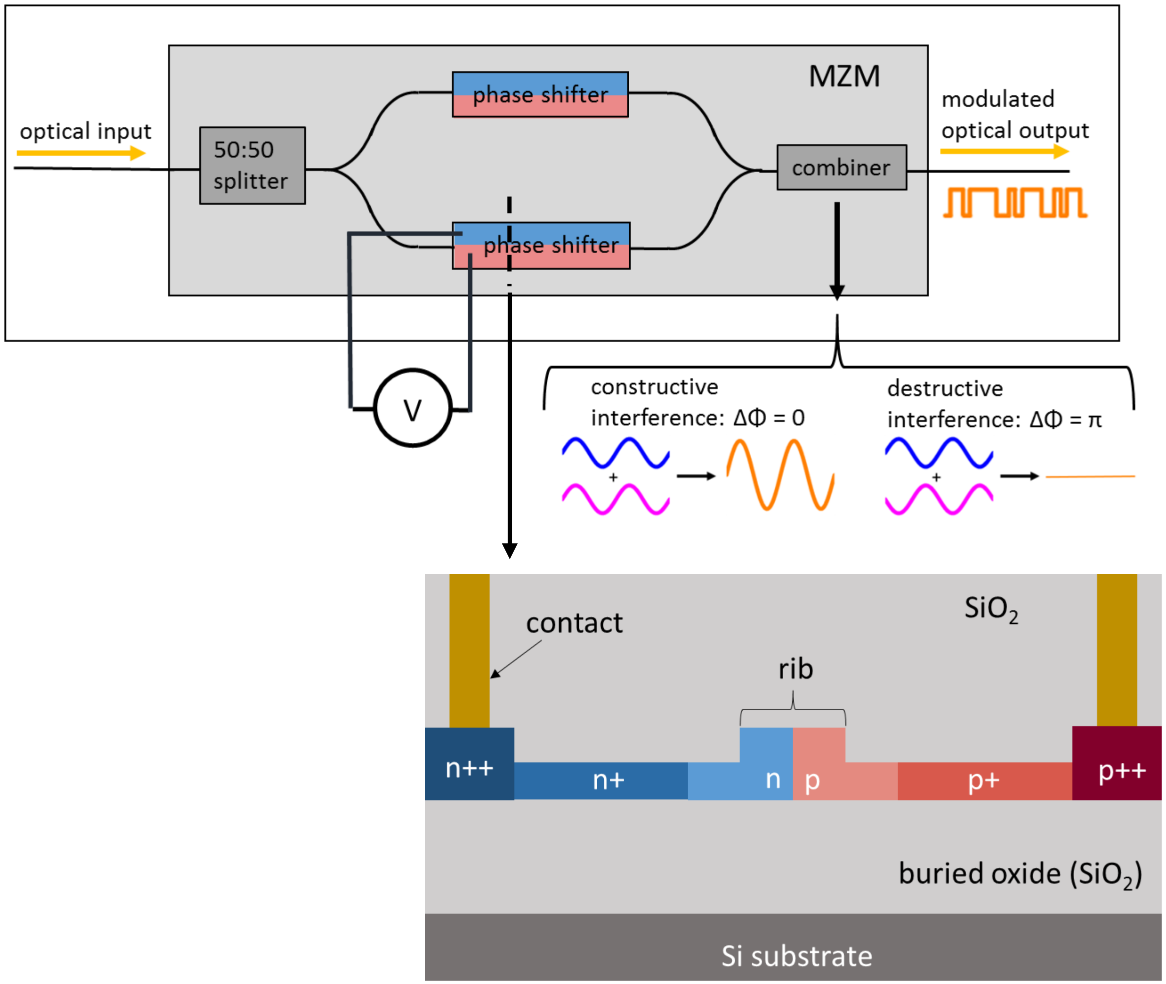


Ring Modulator (RM)



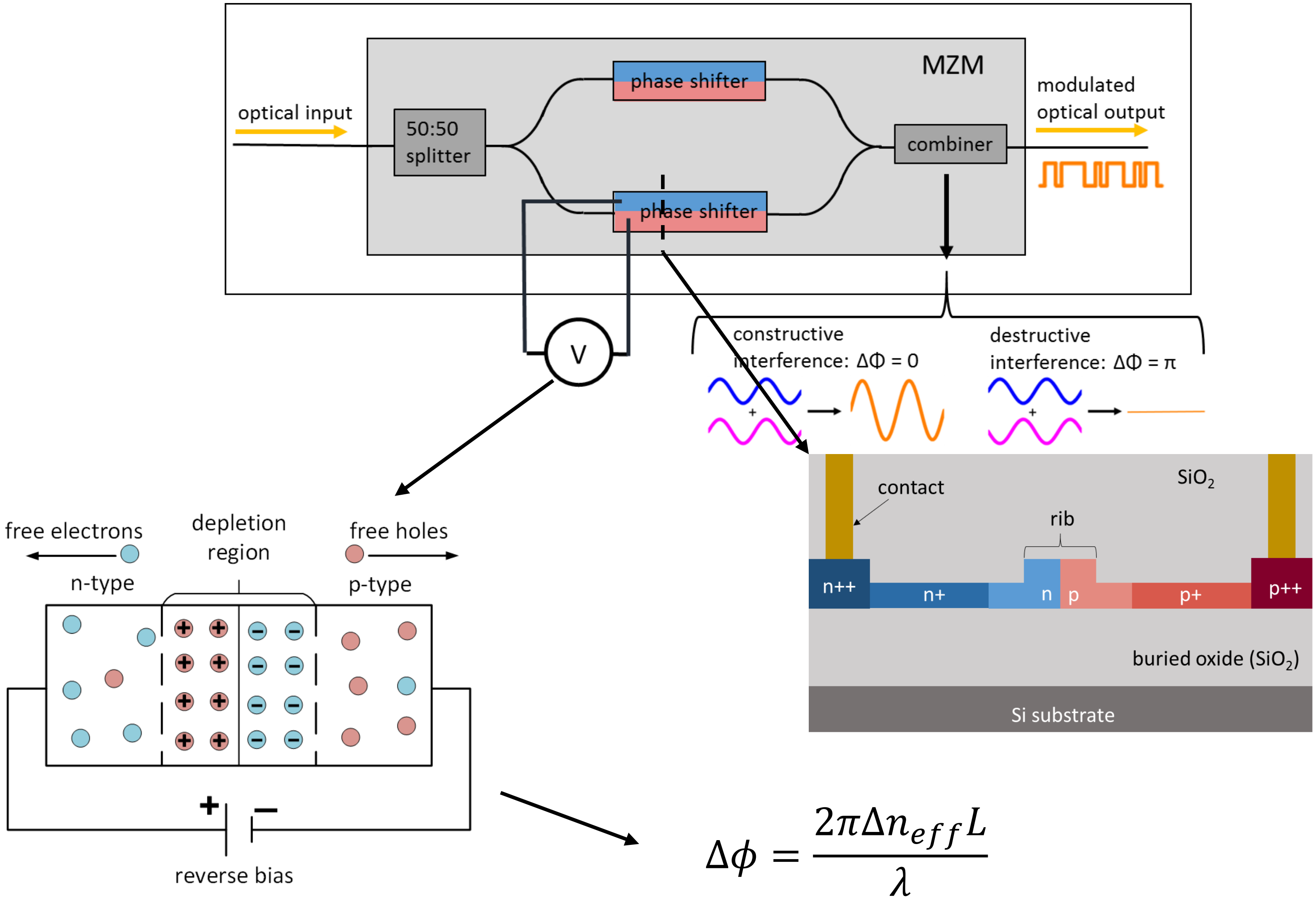
How does a MZM work?





Depletion type Phaseshifter:
Rib waveguide with pn-junction

How does a MZM work?



$$\Delta\phi = \frac{2\pi \Delta n_{eff} L}{\lambda}$$

Silicon photonics a possible alternative for data transmission?

Advantages:

- Compatibility with CMOS electronics (high density integration)
- small footprint
- higher bit rate
- reduced power consumption

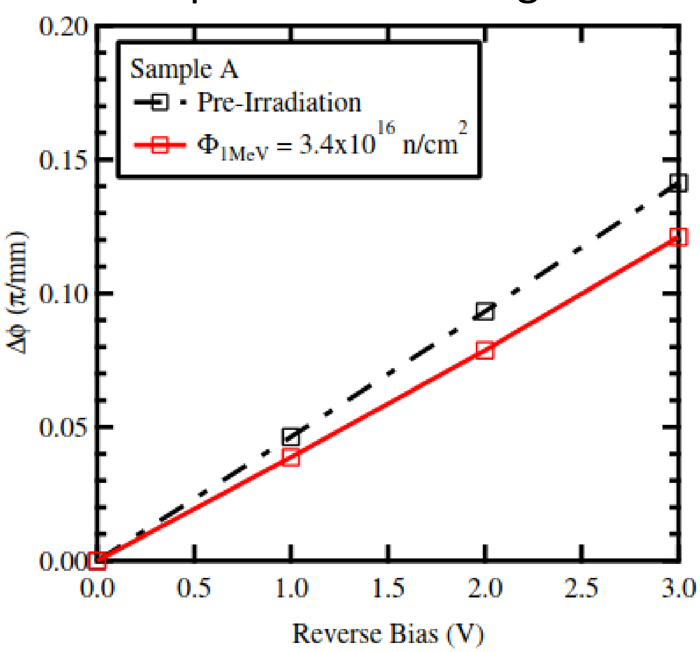
→ This sounds all very good

BUT what about radiation hardness???

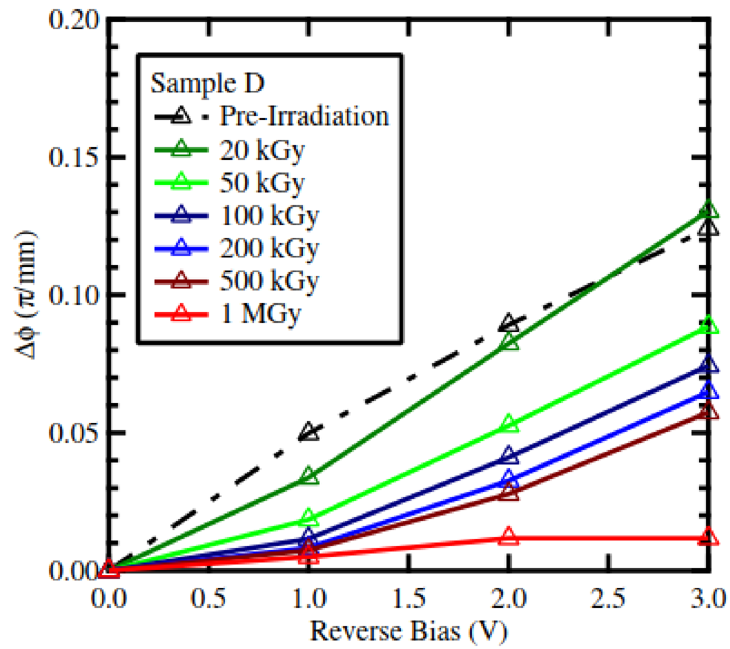
First irradiation tests performed

At the beginning focus on MZMs as those where the more advanced and promising devices at this time

Displacement damage:

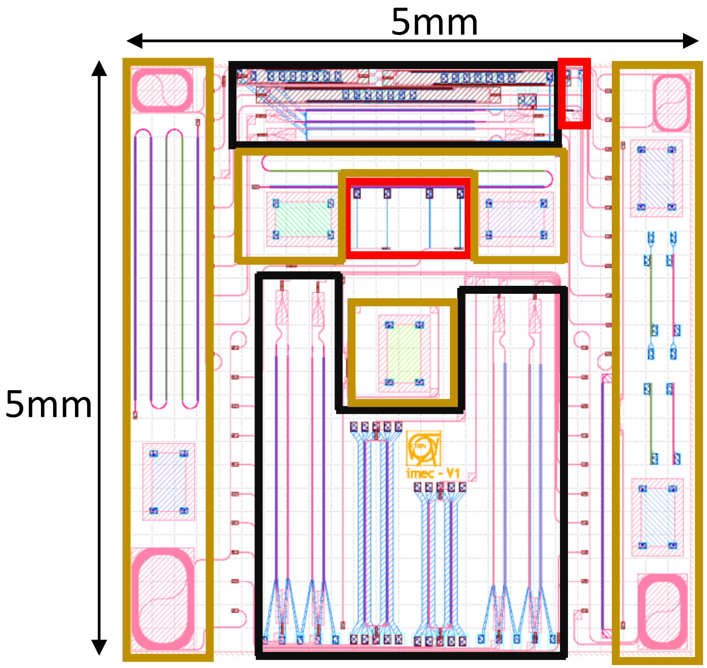


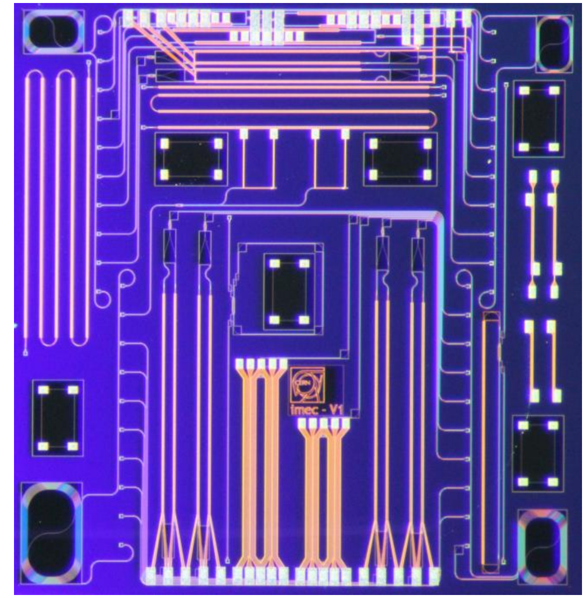
TID:



Very resistant against displacement damage BUT strong degradation due to ionization!!!

Imec Silicon Photonics test chip



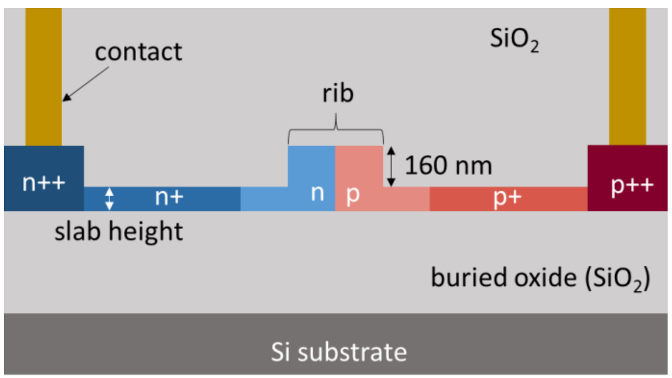


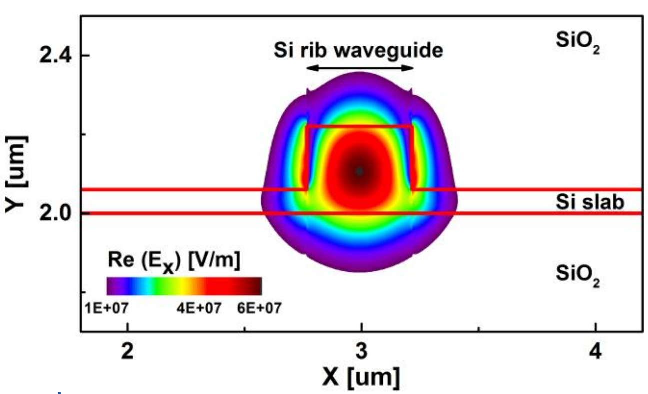
- 12 modulators: MZM building blocks (deep etch with travelling wave electrodes), MZM customized designs (deep and shallow etch without travelling wave electrodes) and a RM building block
- 3 germanium on silicon photo diodes
- Various passive test components
- Produced on 200 mm SOI wafers in the IMEC ISIPP25G technology (ePIXfab MPW)

Improvement of radiation hardness by design

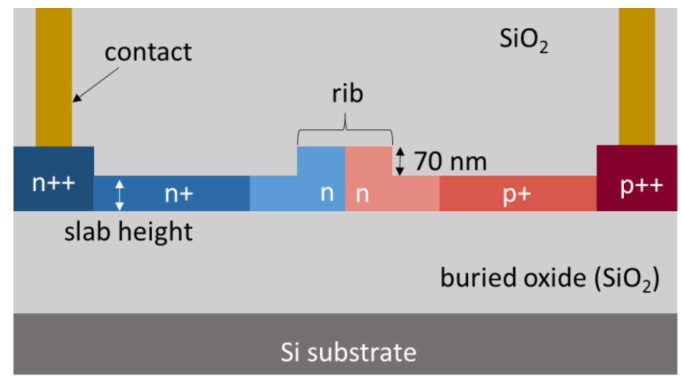
To experimentally test the influence of design variations **2 customized designs** are produced in **2 doping concentration** flavors and are compared

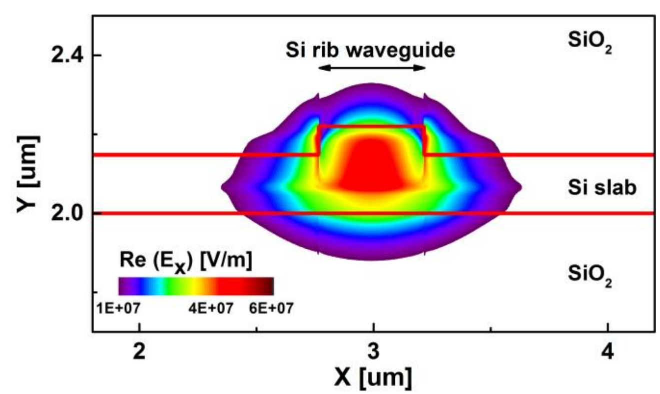
deep etch





shallow etch





X-ray irradiation tests of MZMs

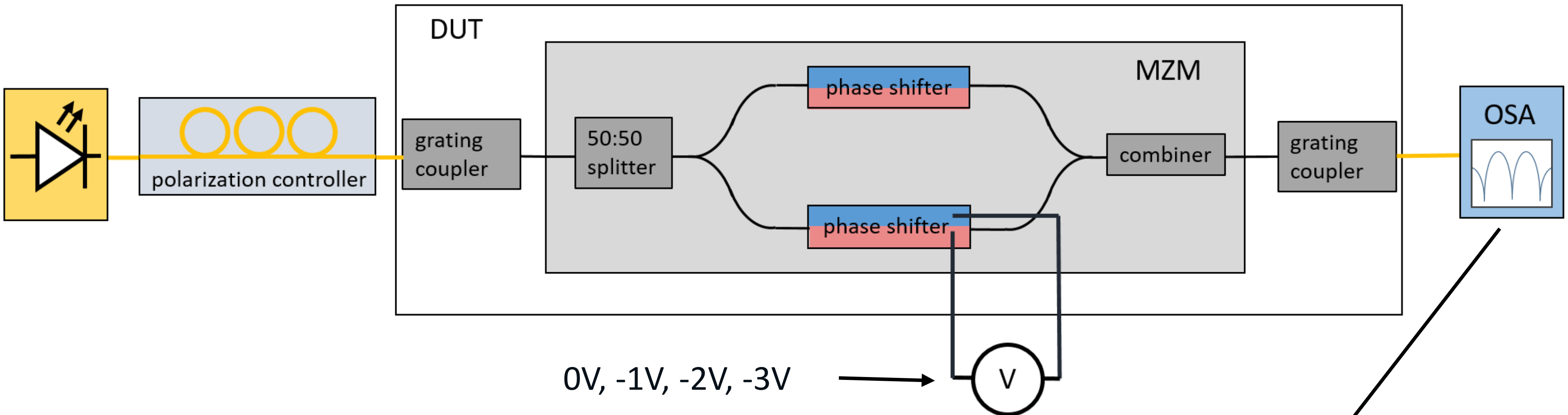
1st Influence of Design:

- Slab height – etch depth
- Doping concentration

2nd Influence of environment and measurement parameters:

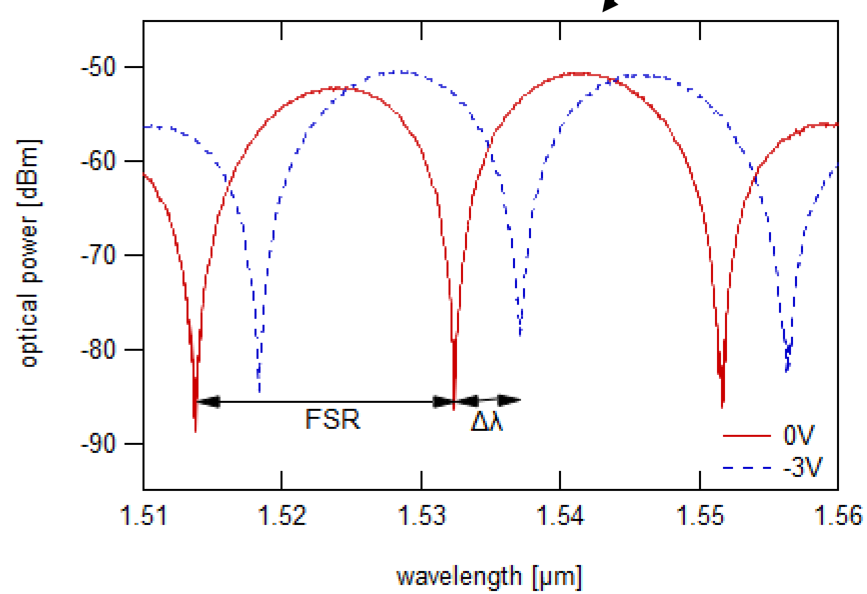
- Temperature dependence
- Bias dependence
- Post-irradiation and annealing

Testing of MZMs – Static phase shift

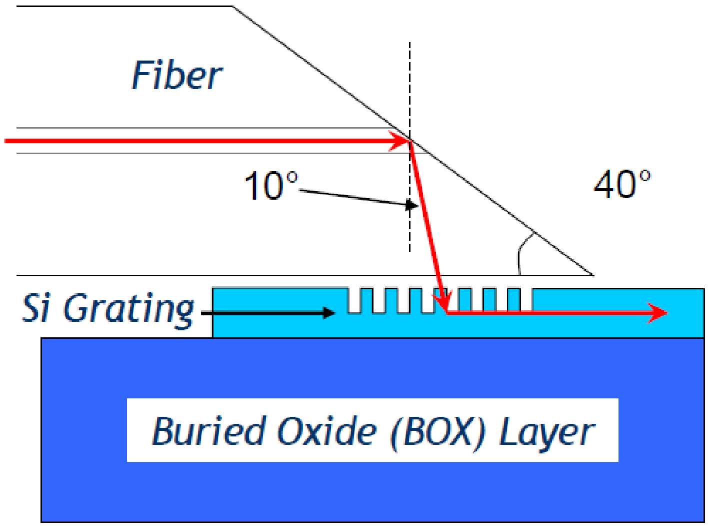


- Fitting spectra and extraction of FSR and Δλ
- Calculating ΔΦ for -1V, -2V and -3V reverse voltage

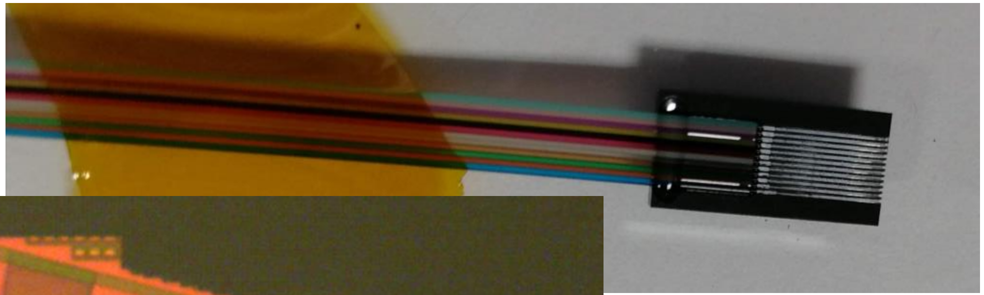
$$\Delta\Phi = \frac{2\Delta\lambda}{FSR \cdot L}$$

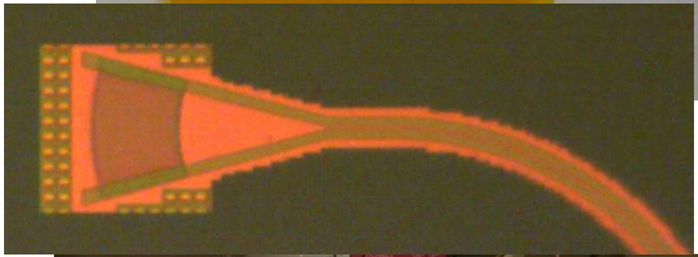


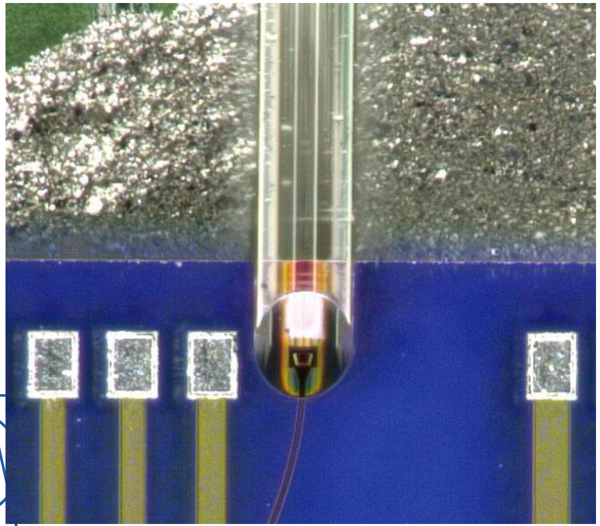
Planar fiber coupling - Pigtailing

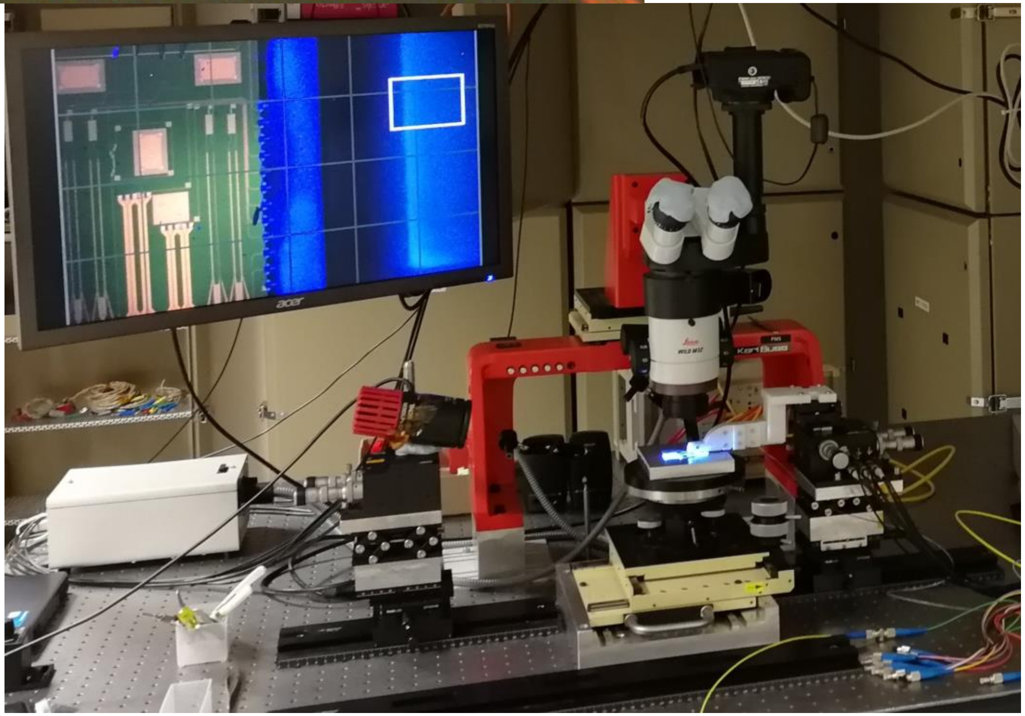


B. Snyder et al, IEEE TRANSACTIONS ON COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY, VOL. 3, NO. 6, JUNE 2013

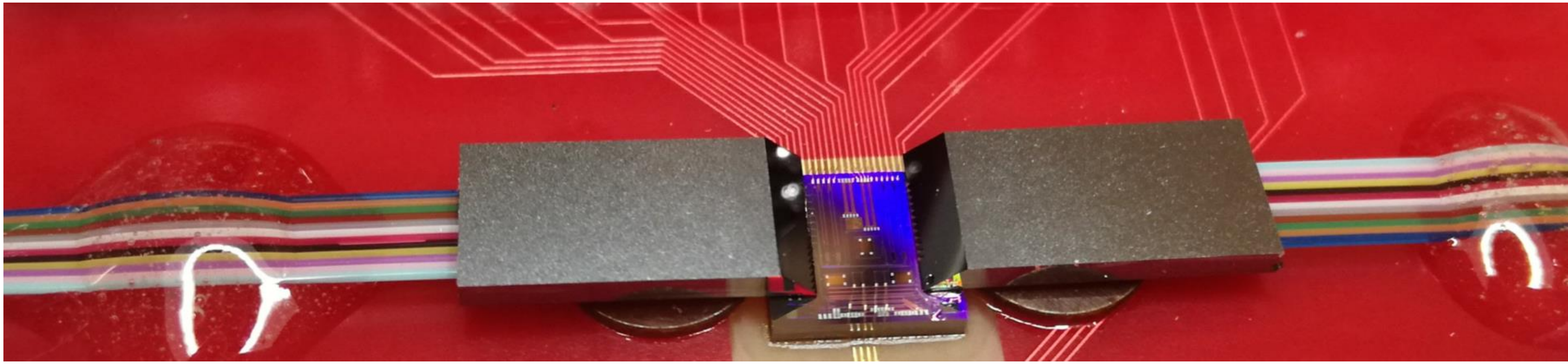


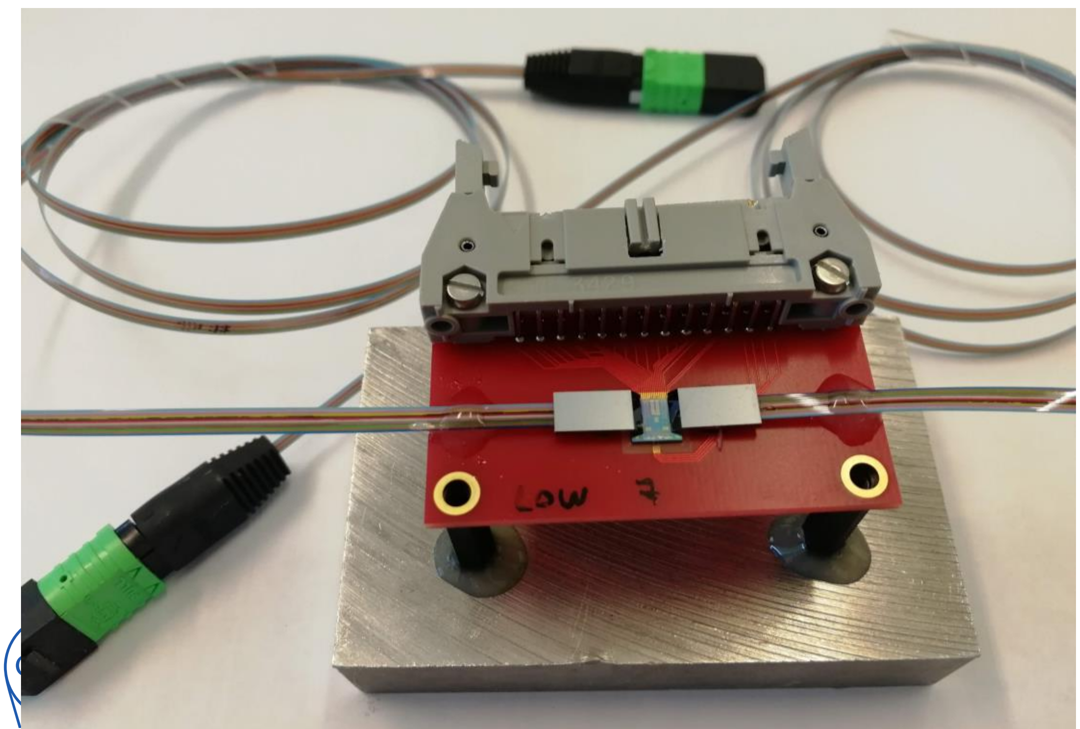


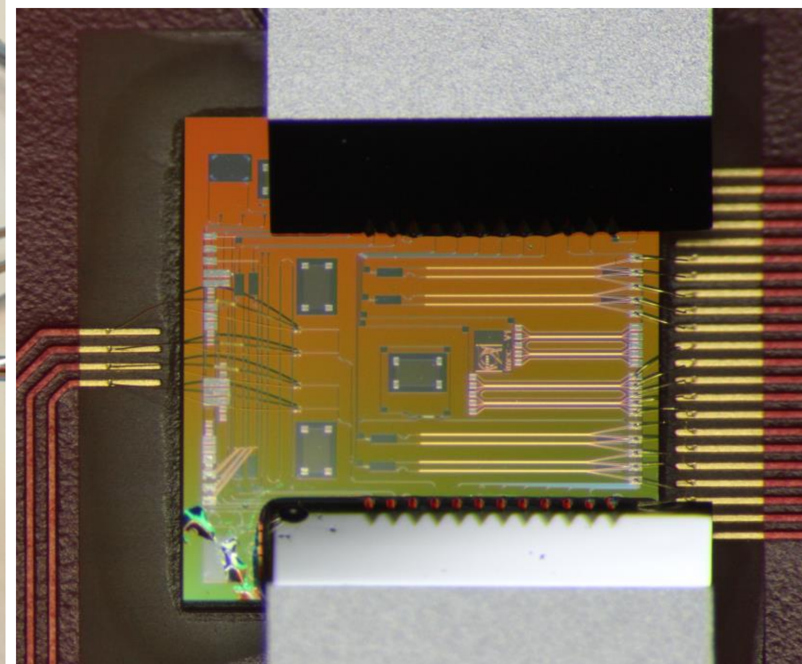




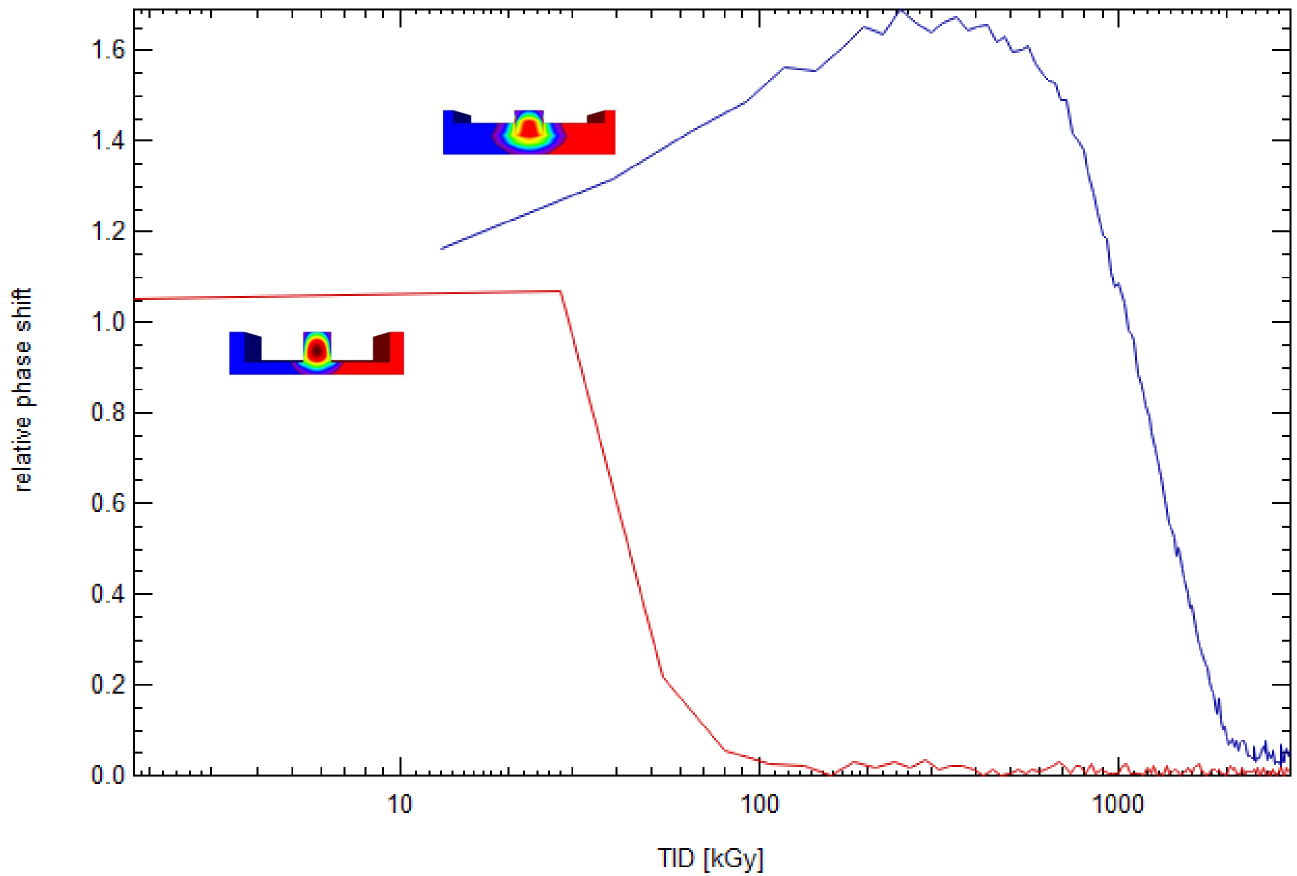
Assembled chip





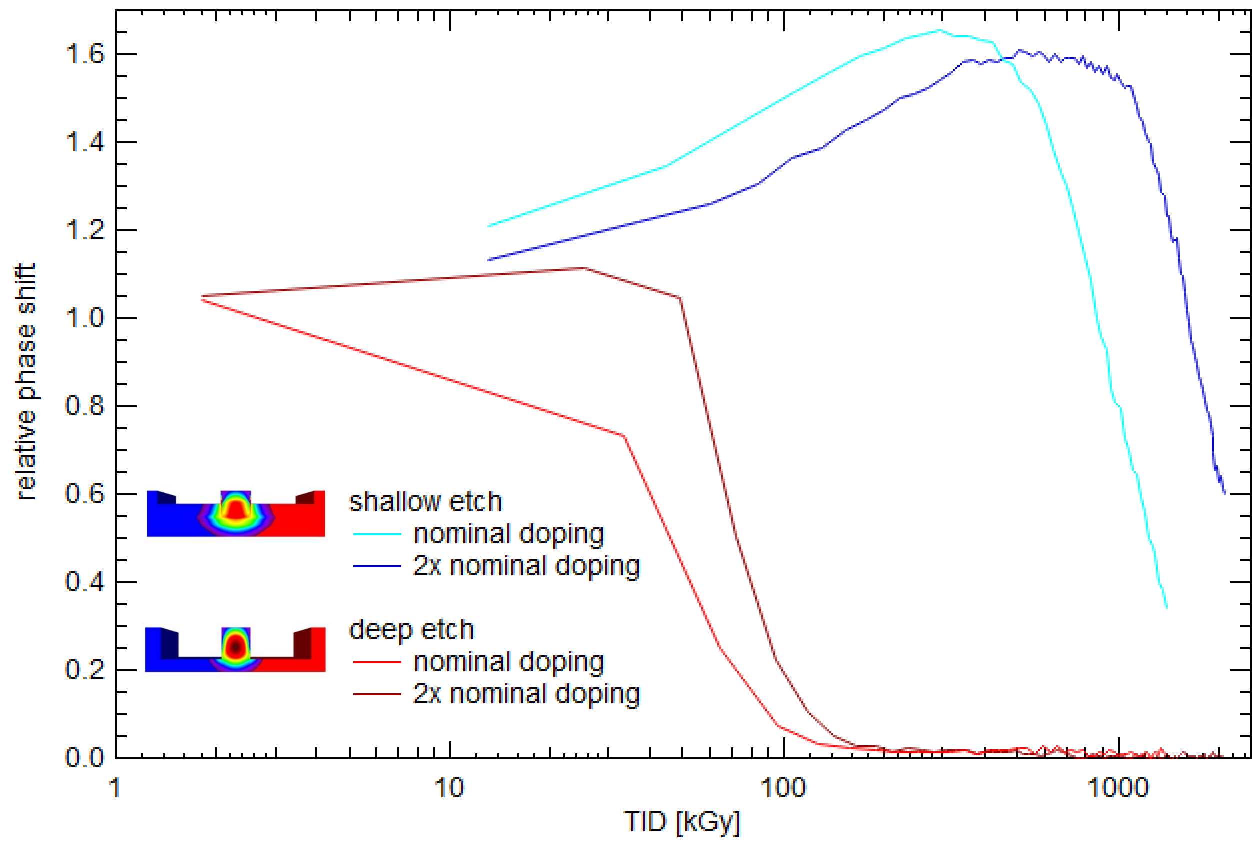


X-ray test - Deep etch vs. shallow etch



- ☺ The shallower the better the radiation resistance
- ☹ The shallower the lower the mode confinement → lower modulation efficiency and higher losses

X-ray test - High doping vs. low doping



- ☺ The higher the better the radiation resistance (slab region)
- ☺ The higher the bigger the phase shift (rib)
- ☹ The higher the bigger the losses in the phase shifter (rib)

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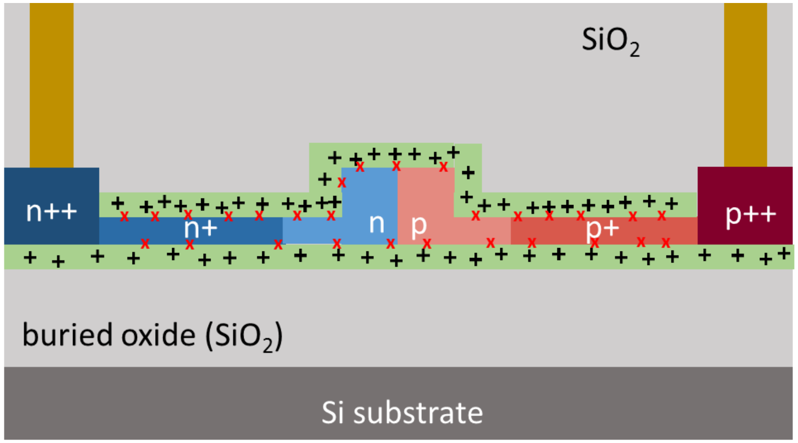
Effect of ionizing radiation on Silicon Photonics

Ionizing radiation creates e-h pairs in the rather thick oxide. This leads to:

A. Hole trapping in deep traps in the oxide close to the Si/SiO2 interface
B. Buildup of acceptor/donor interface traps
C. Hydrogenation – Passivation of dopants



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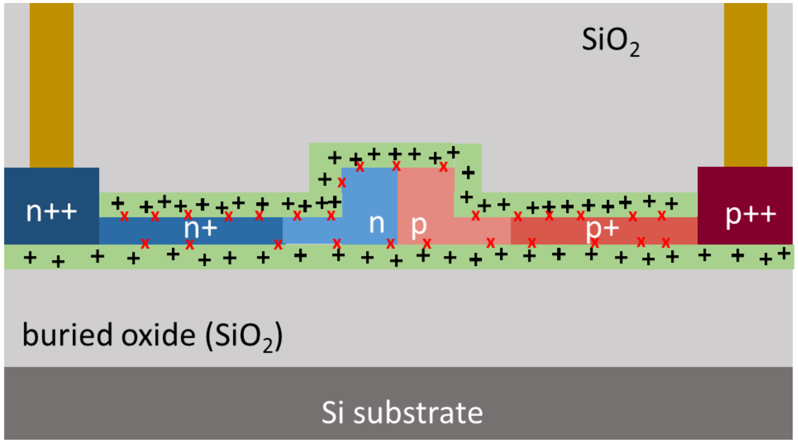
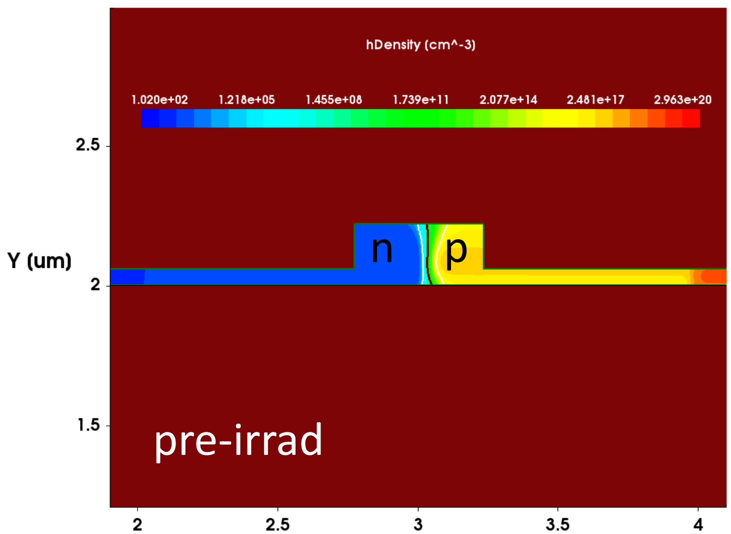
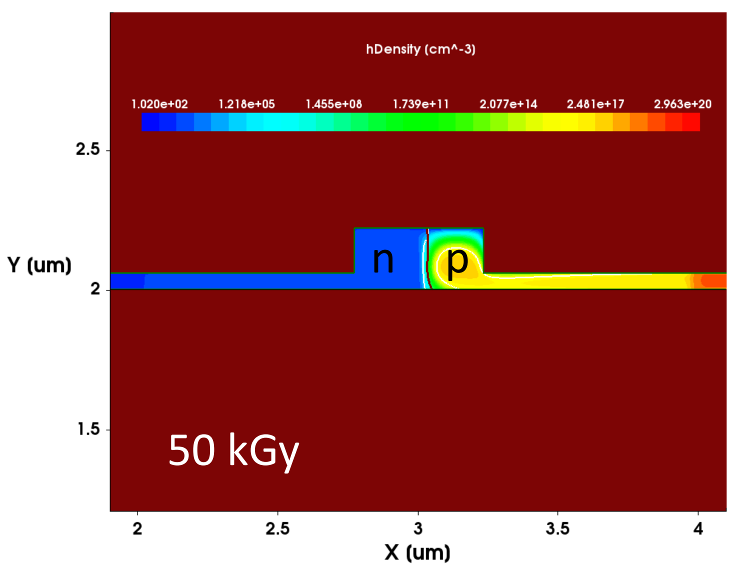
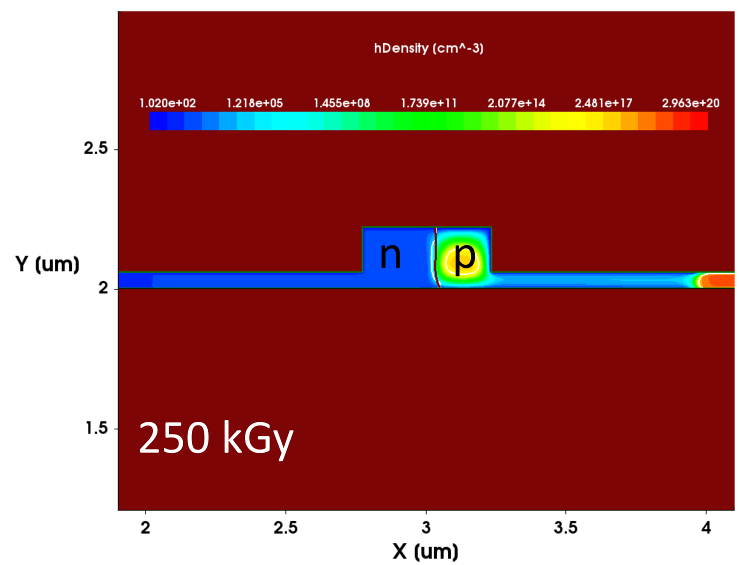


Simulation of ionizing radiation effects – hole density

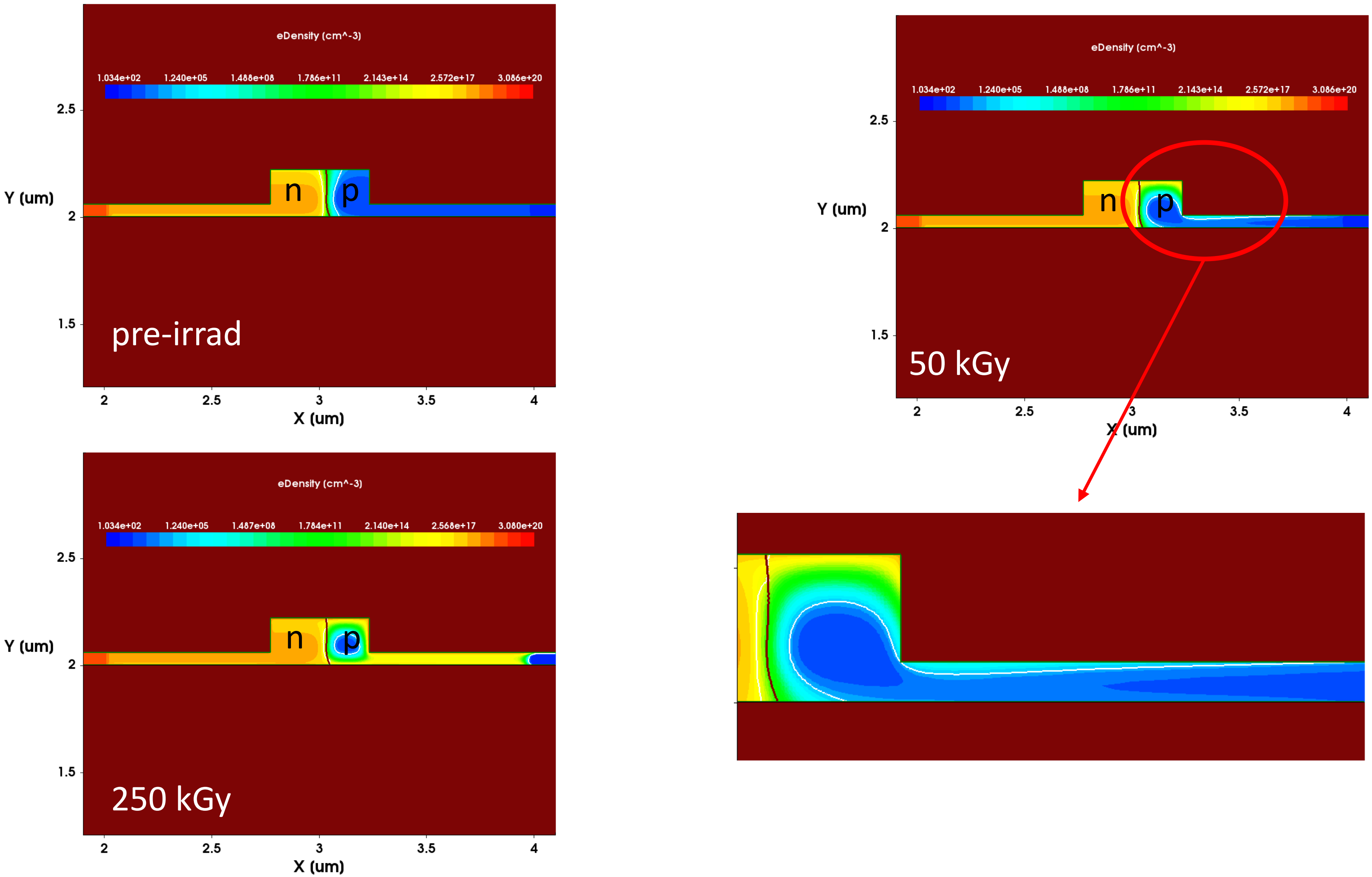


With increasing irradiation the concentration of positive charge close to the interface increases





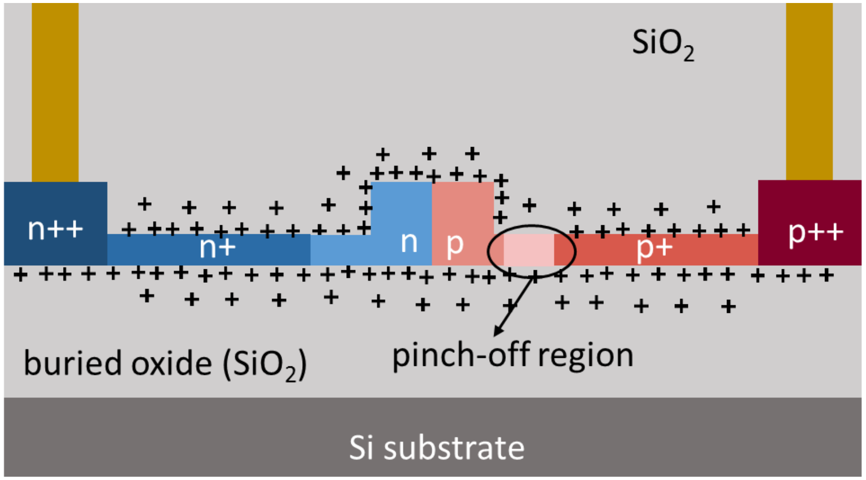
Simulation of radiation effects – electron density



What did we learn from the simulation?

- The positive charges trapped close to the interface lead to an accumulation of electrons and removal of holes on the p-side

→Pinch-off in slab region → no modulation possible anymore



→Both; increasing the doping and the slab height leads to a delay of the pinch-off effect

X-ray irradiation tests of MZMs

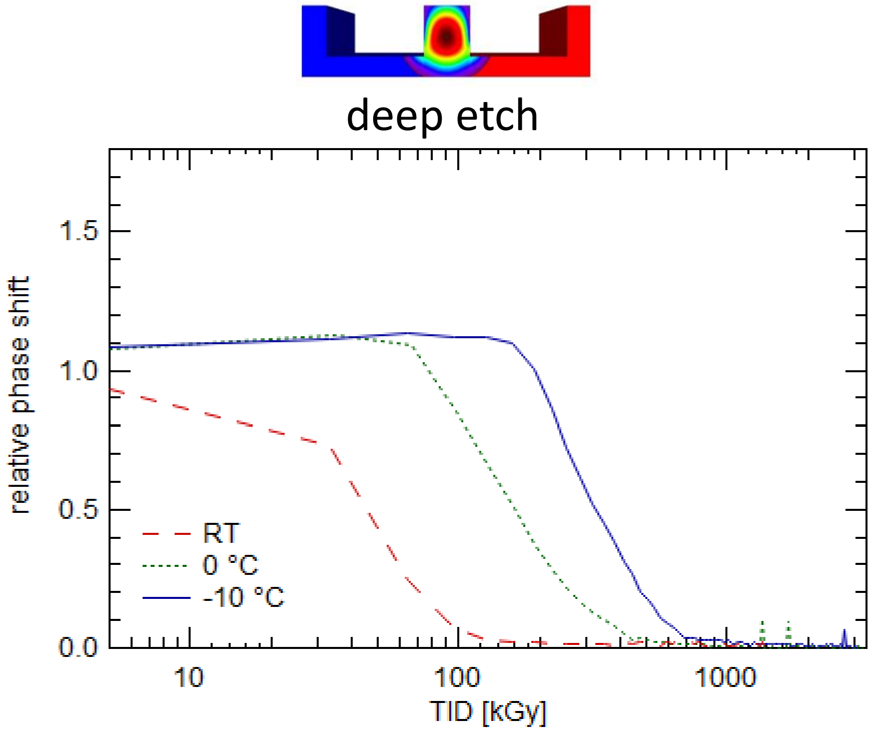
1st Influence of Design:

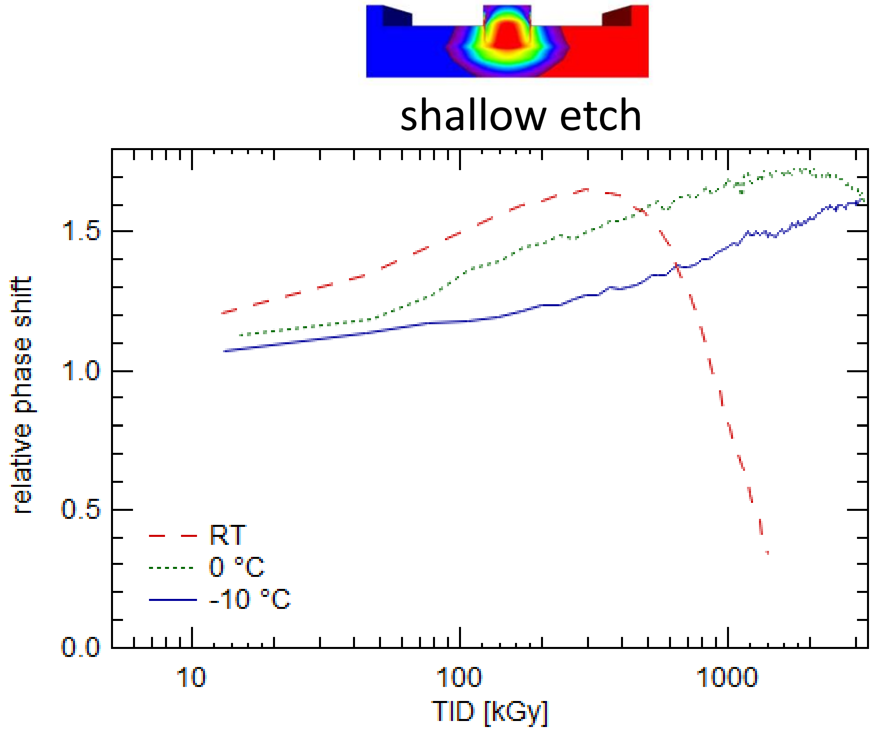
- Slab height – etch depth
- Doping concentration

2nd Influence of environment and measurement parameters:

- Temperature dependence
- Bias dependence
- Post-irradiation and annealing

X-ray test - Temperature dependence





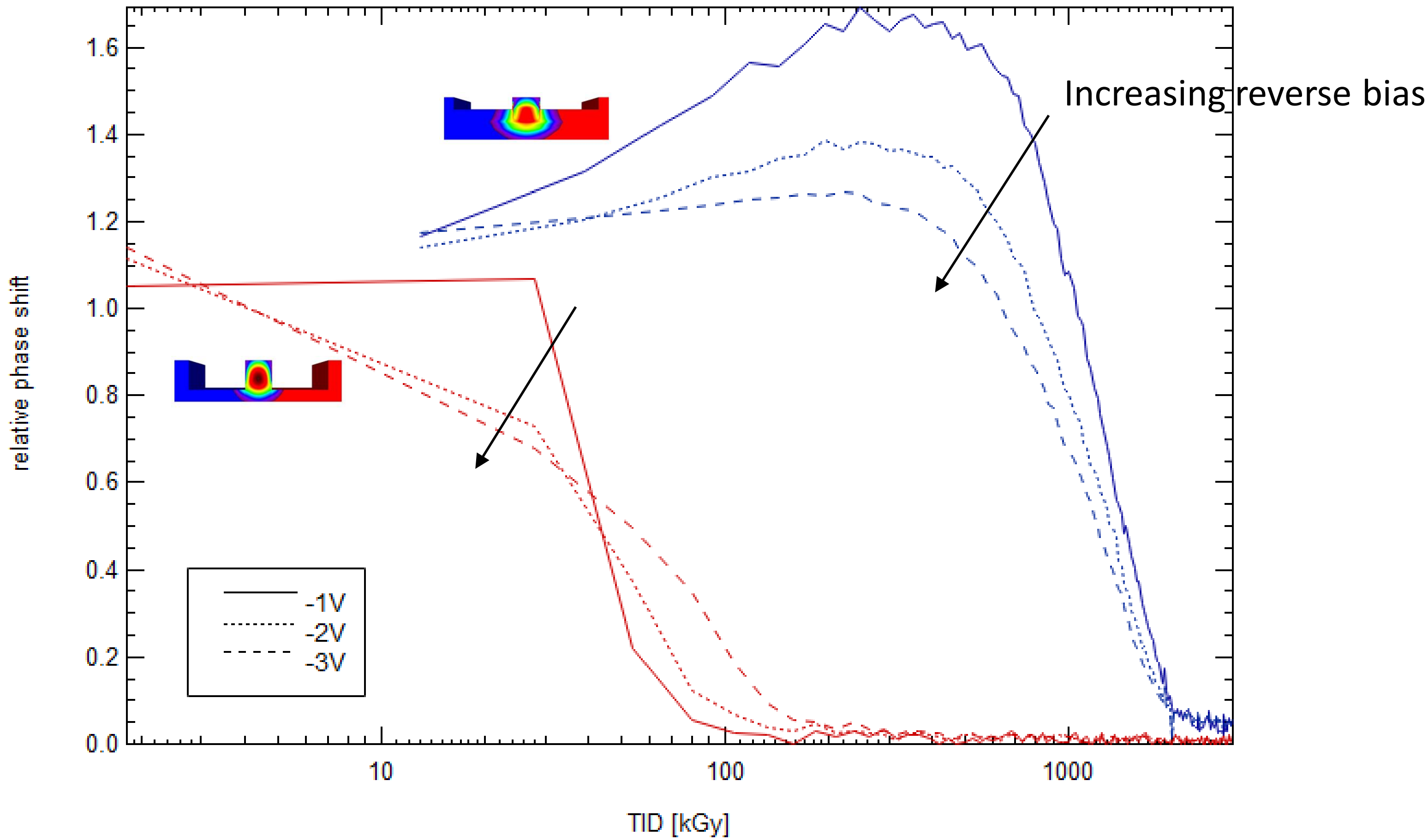
☺ The lower the temperature the higher the radiation tolerance for shallow and deep etch devices

Reason: Reduction of hole mobility → lower rate at which deep traps are filled and interface traps are built up

Effect of biasing during irradiation

- Reverse bias applied during irradiation → decreased radiation resistance
- Forward bias applied after irradiation → device recovery (annealing)

X-ray test - Bias dependence



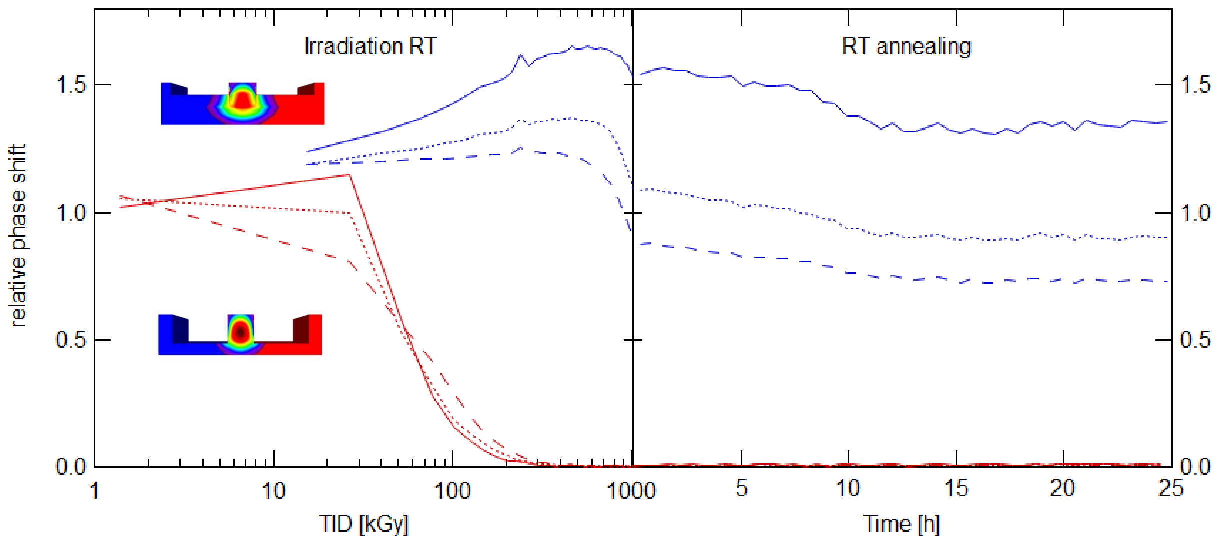
The higher the bias the higher the electric field → holes move faster through the oxide towards the interface

Effect of biasing during irradiation

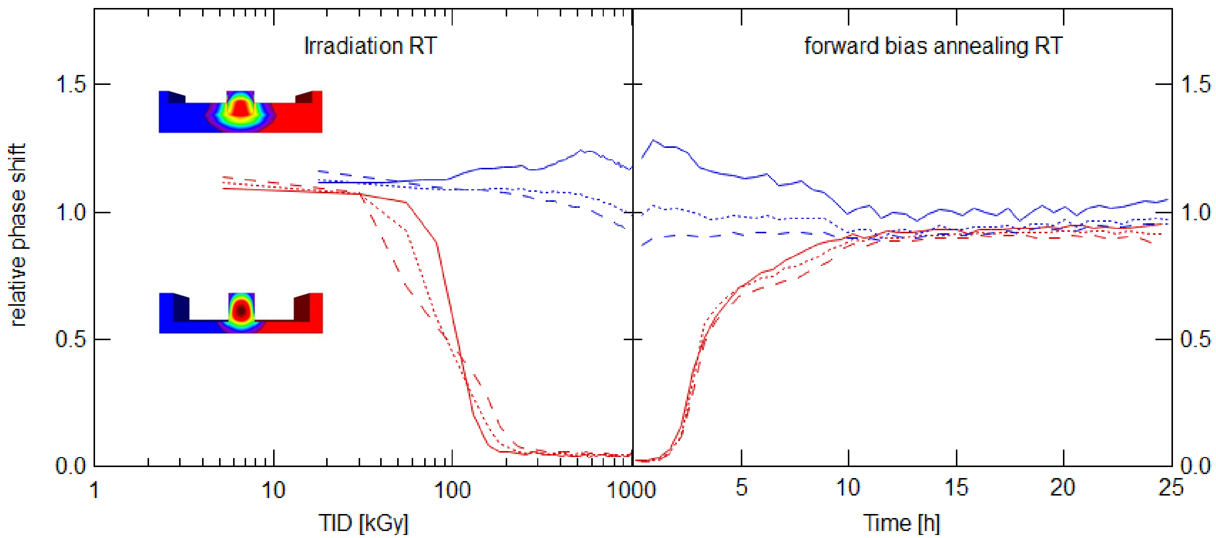
- Reverse bias applied during irradiation → decreased radiation resistance

- Forward bias applied after irradiation → device recovery (annealing)

Annealing due to forward biasing



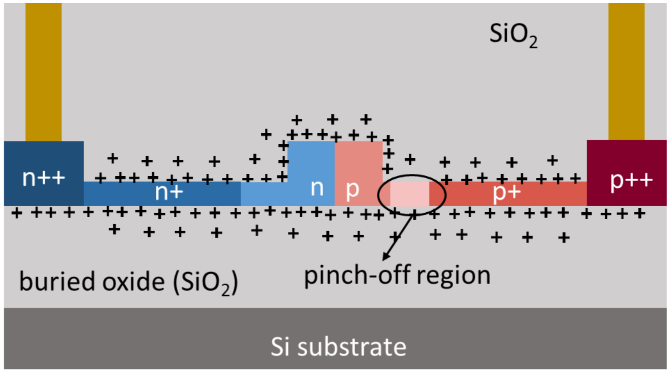
no forward bias at all (no IV)



2 mA forward current for 1 min every cycle

Annealing due to forward biasing

What’s the reason for the forward bias annealing???



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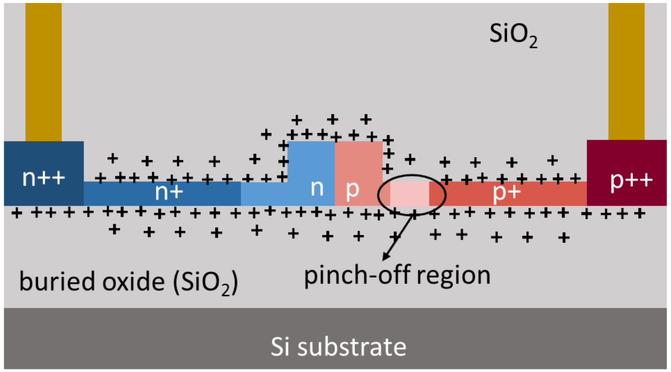
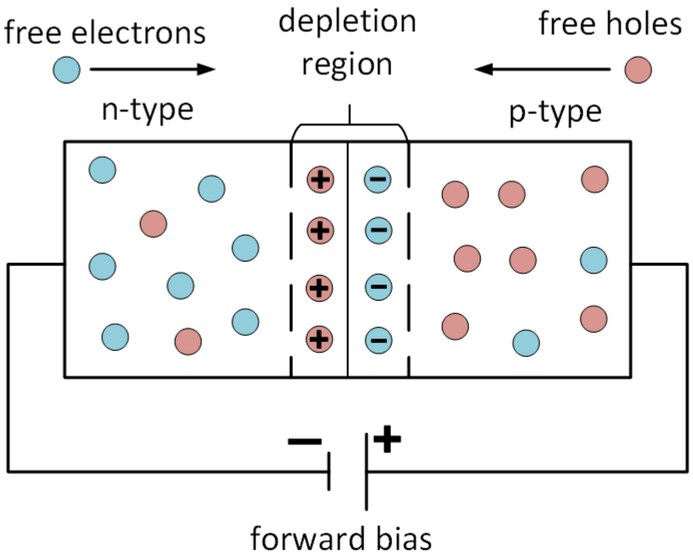


In forward bias electrons are pushed towards the p-side → they can tunnel into the oxide and eliminate trapped holes



Effectiveness of annealing

To evaluate the effectiveness of the annealing re-irradiation tests were performed

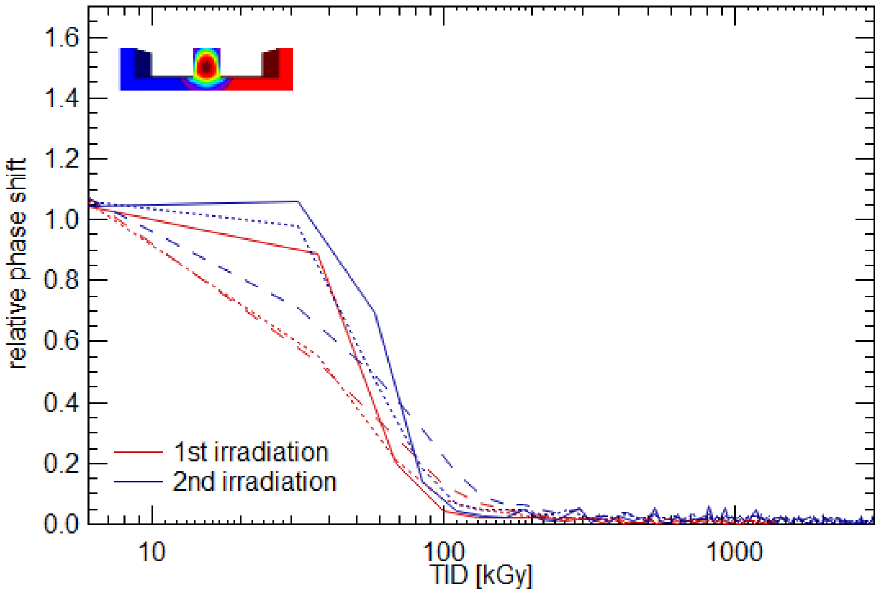
A. 1st irradiation up to device failure

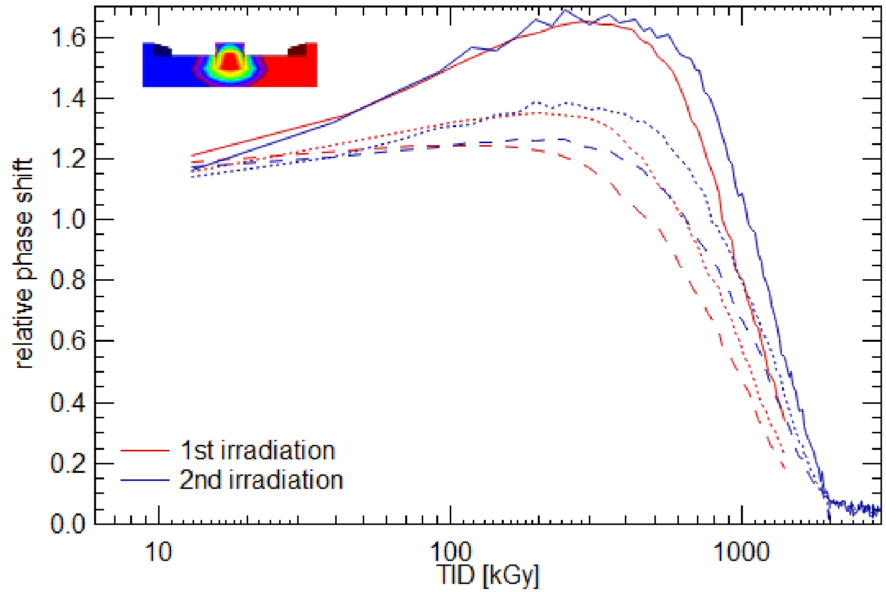
B. Annealing: 10 mA forward current for 24 hrs followed by -3 V reverse bias for 24 hrs

C. 2nd irradiation at the same conditions as 1st irradiation

Annealing and Re-irradiation

After 1st irradiation annealing with 10 mA forward for 24 hrs followed by 2nd irradiation → same irradiation resistance in both irradiation runs → **full recovery of the device!!!**





Forward bias annealing

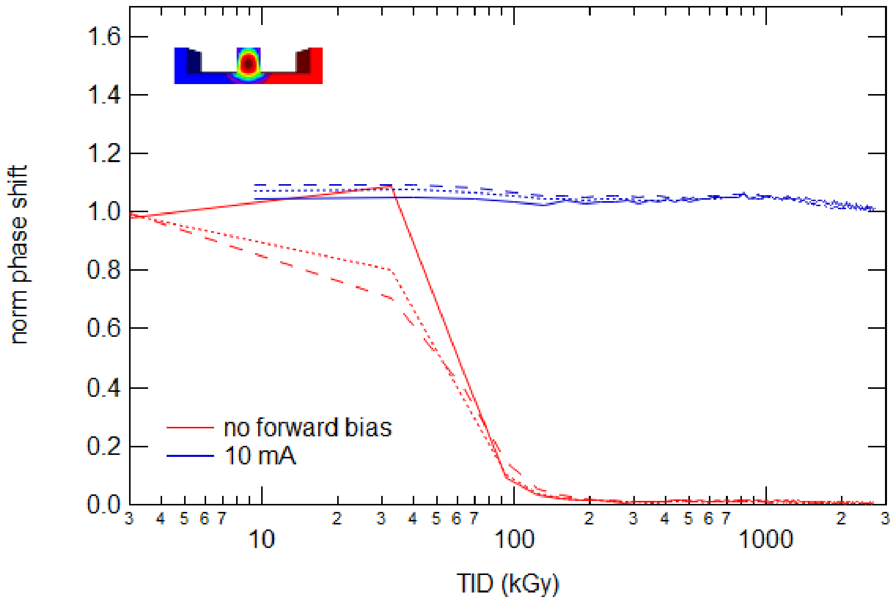
- The next question is; is it possible to compensate the irradiation effects already during irradiation with a high enough forward bias???

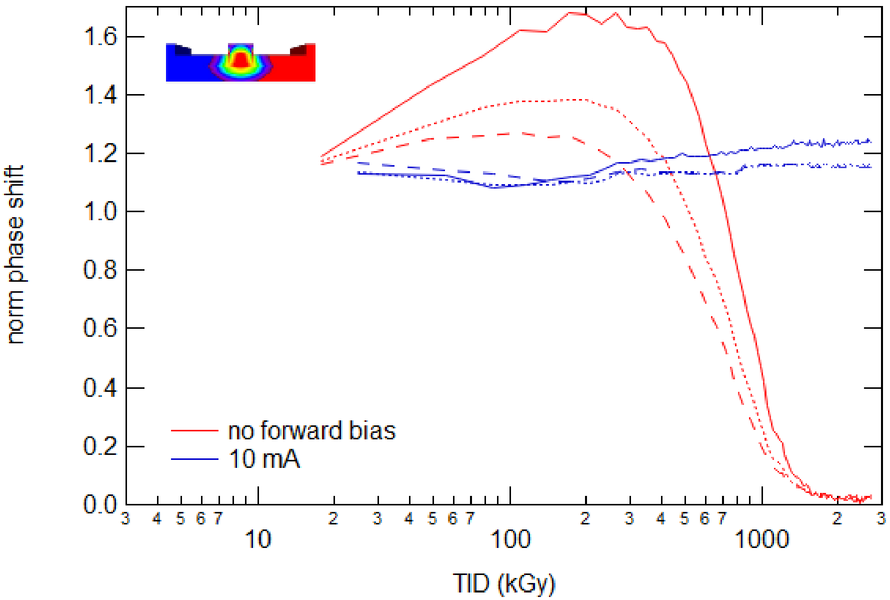
- 2 mA for 1 min every measurement cycle only showed little influence during irradiation

- New test with 10 mA for 1 min every measurement cycle

Forward bias annealing

10 mA forward for 1 minute in every measurement





No degradation up to 3 MGy → compensation of irradiation effect during irradiation

Conclusion of these results

- Forward bias could be applied in phases where operation of HEP experiments are paused eg. shutdowns, technical stops, interfills

- With the possibility of recovery or even compensation of the radiation effect the necessity of designing customized devices together with their drawbacks in functionality is eliminated

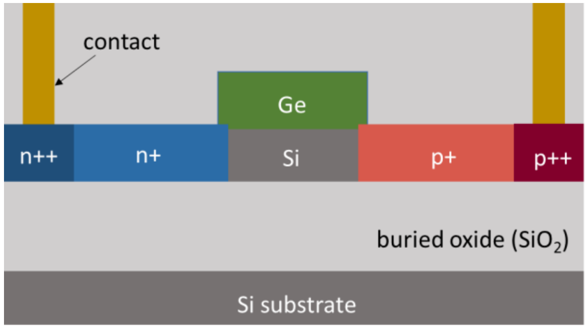
- Standard, performance optimized devices offered by foundries could be used

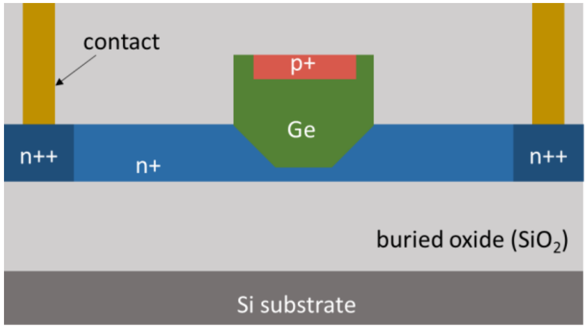
Irradiation tests of SiGe Photodiodes

- To ensure radiation resistance of a system photodiodes have to be tested as well
- We don't have a lot of information about the SiGe photodiodes on our test chip

→Testing of a "black box"

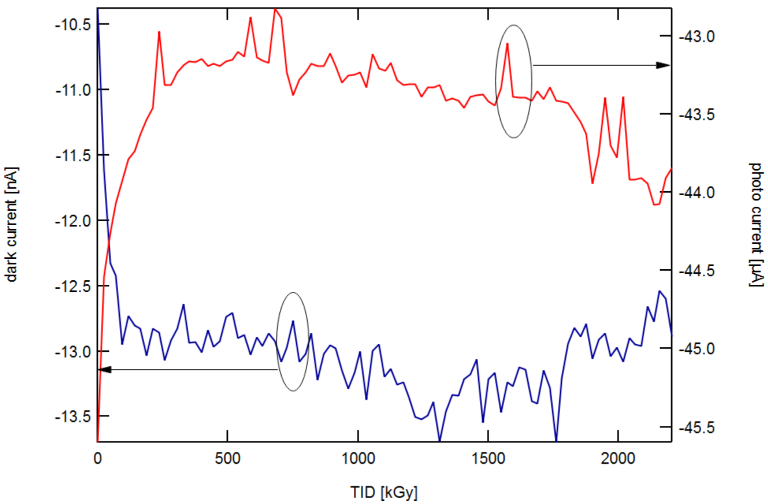
→As it is most likely a PIN diode we were worried about the intrinsic region in the Germanium



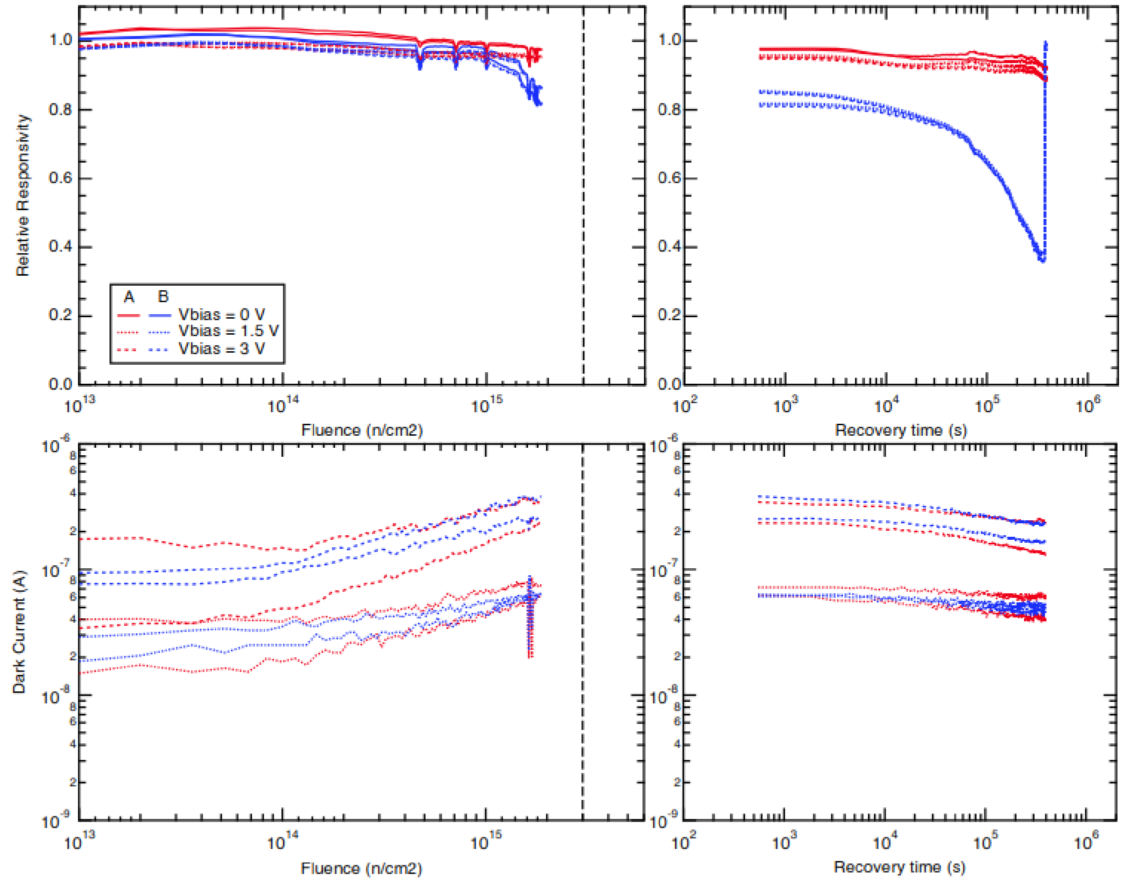


Irradiation tests of SiGe Photodiodes

Ionizing Radiation:



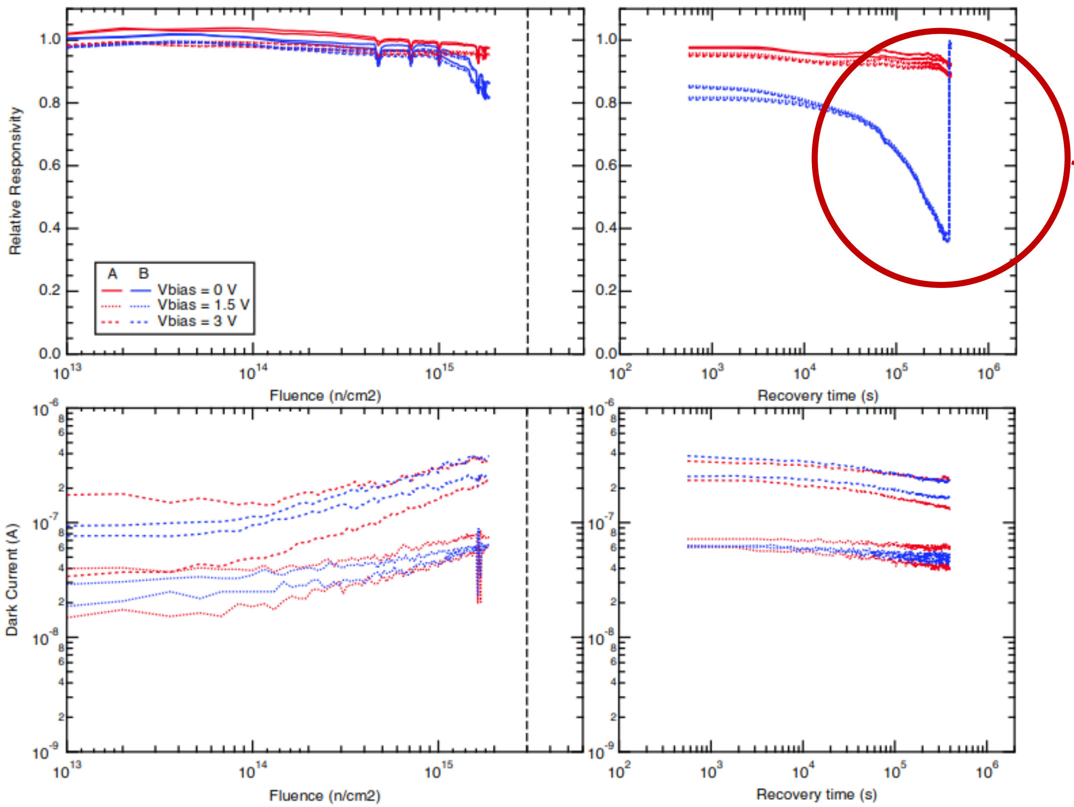
Displacement damage:



High resistance against TID and displacement damage

CERN

Irradiation tests of SiGe Photodiodes



Change in polarization due to movement and release of sticky tape fixing the optical fiber

What knowledge have we gained from these tests?

- Good news first:
  - The photodiodes are very resistant against displacement damage and TID
  - Modulators are very resistant against displacement damage
  - With increasing the doping concentration and decreasing the etch depth the radiation resistance can be increased → a compromise between radiation resistance and performance has to be found
  - Lower temperatures also increase the radiation resistance
  - Damage produced through TID in modulators can be annealed by forward biasing

What knowledge have we gained from these tests?

- Bad news:
  - Strong degradation of modulators due to TID

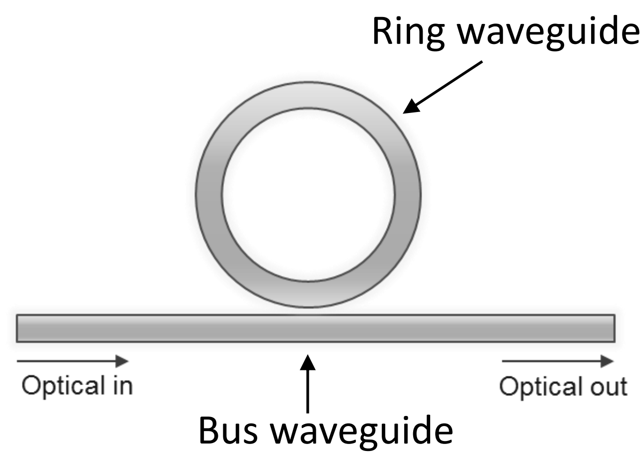
  But even if radiation hardness issue could be solved:

  - Long MZM arms and high biases are necessary to achieve good enough phase shift → long MZM arms lead to high losses and with high doping even more → high input power is necessary
  - To operate the MZM in the quadrature point an additional control circuit is necessary including heaters

  → all these points lead to a high power consumption

Could Ring modulators be an alternative???

Ring resonator

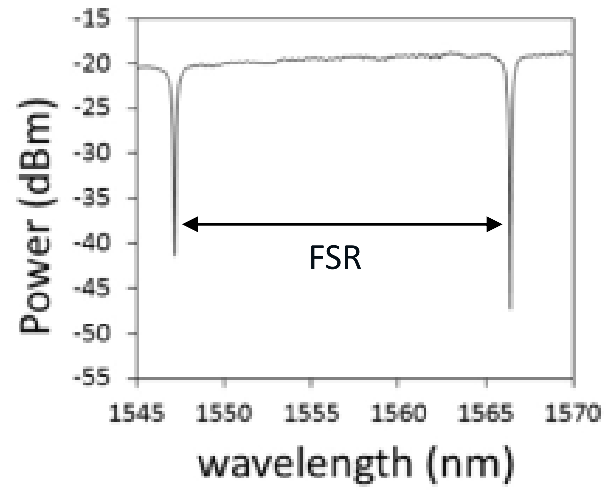


- Optical transmission spectrum of the bus waveguide has notches at the ring resonances → light coupled into ring

- Multiple resonances → FSR depends on the resonator length (ring diameter) → the smaller the ring the bigger the FSR

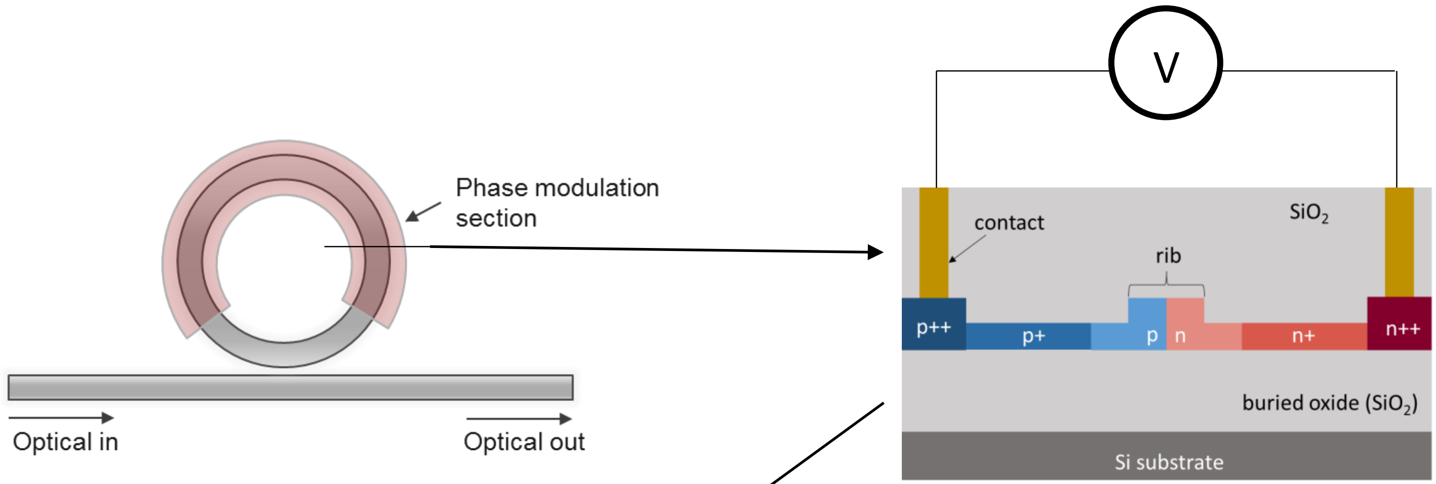
- Resonance occurs when the optical path length is a whole number of wavelengths:
  $$\lambda_{res} = \frac{n_{eff}L}{m}, \quad m = 1,2,3 \ldots$$

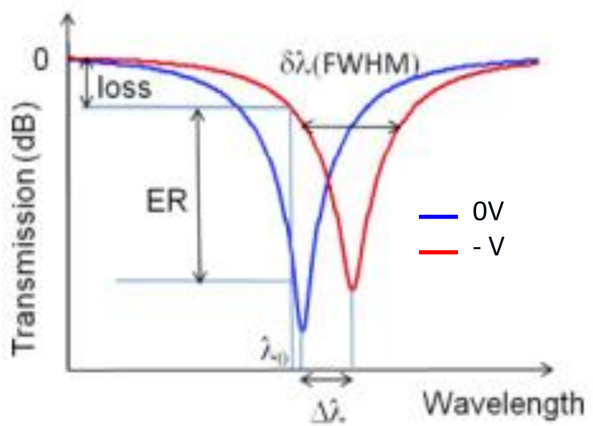
- Resonance wavelength is strongly dependent on temperature



Ring Modulator (RM)

- Ring resonator structure including a phase shifter



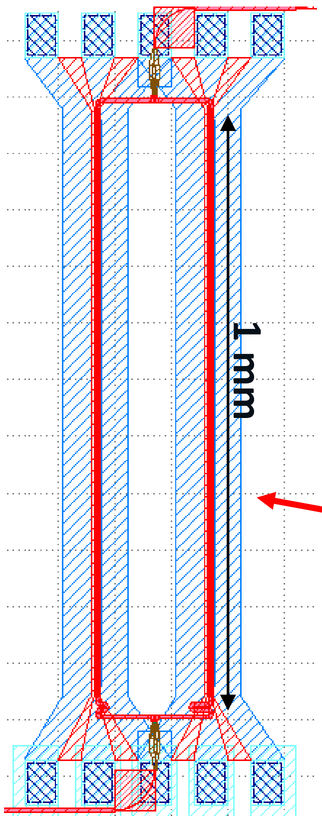


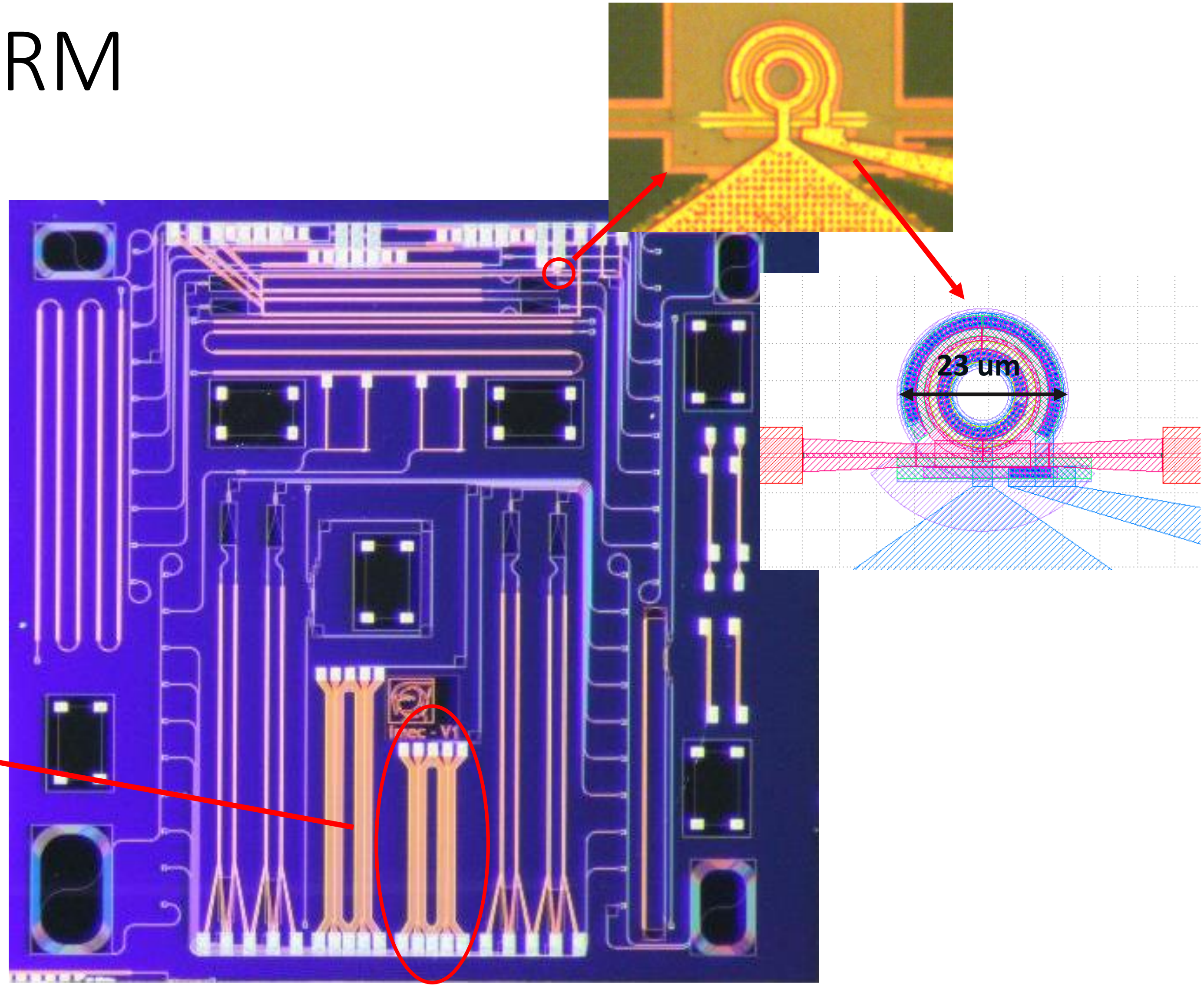
Resonance wavelengths are shifted by applying a reverse voltage to the phase shifter due to change in refractive index → same effect as in MZM

Advantages of Ring Modulator?

- ☺Same phase shifter mechanism as MZM→ should have similar radiation behavior
- ☺More efficient → lower driving voltages needed
- ☺Much smaller structure → negligible optical loss and smaller systems
- ☺Can be used very efficiently in WDM systems → multi channel integration
- ☺Also from foundry site there are a lot of new publications in this direction → general interest increased
- ☹Disadvantages: resonance wavelength strongly dependent on temperature and process variations → for compensation a heater is necessary
- So far we only have one RM without heater

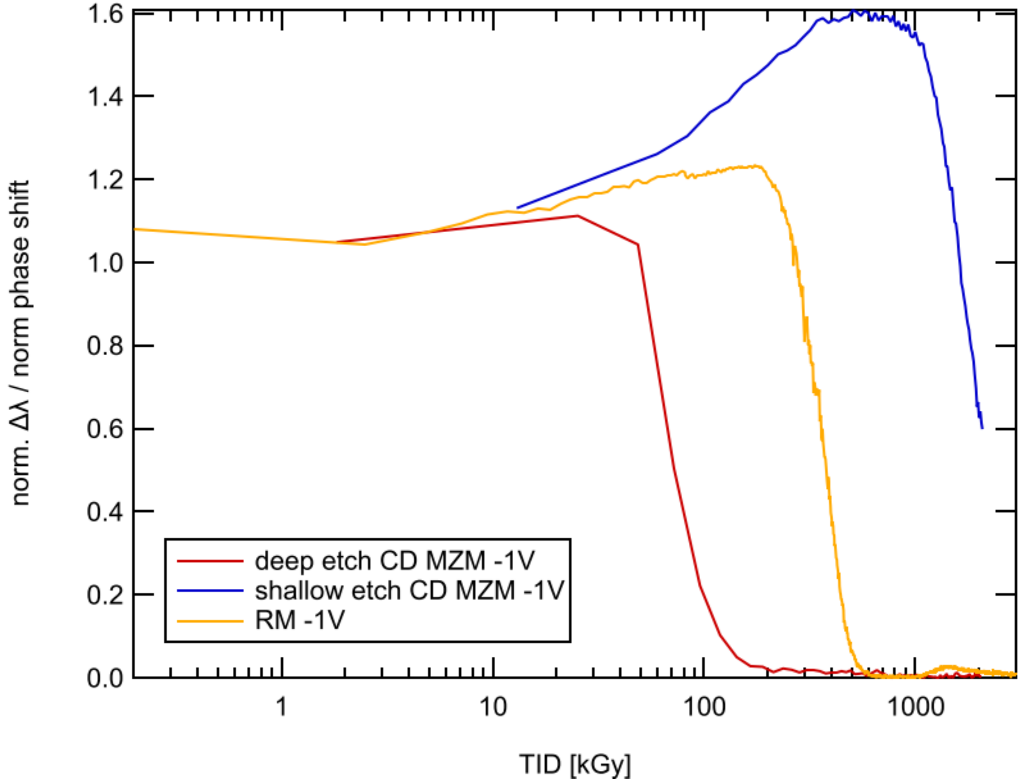
MZM vs RM



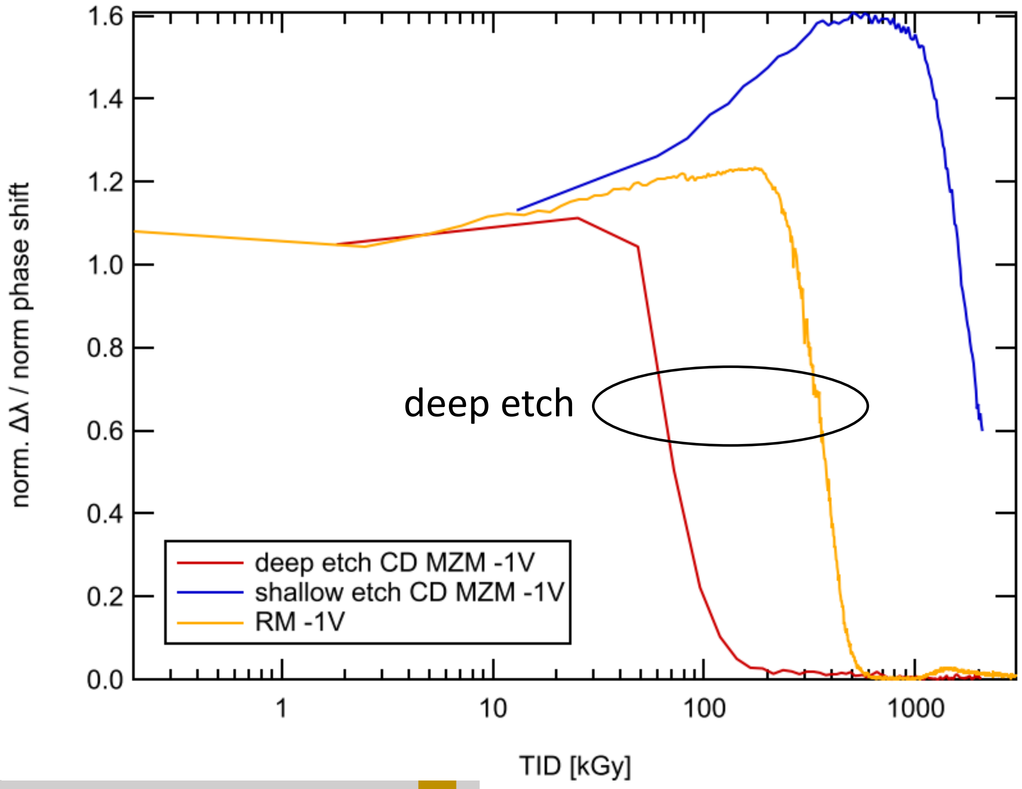


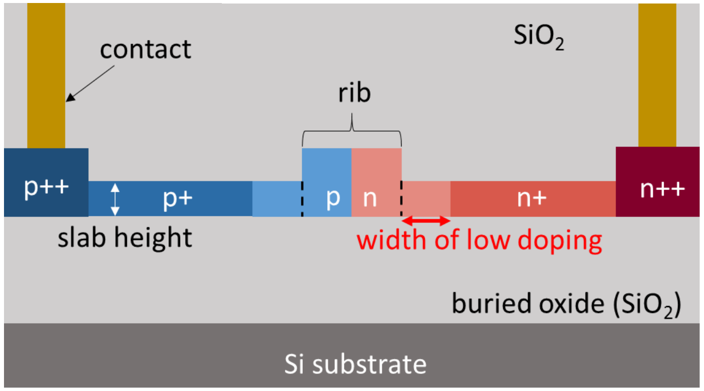
X-ray test - Ring Modulator

Even without heater we were able to keep the temperature stable enough to do a online irradiation measurement



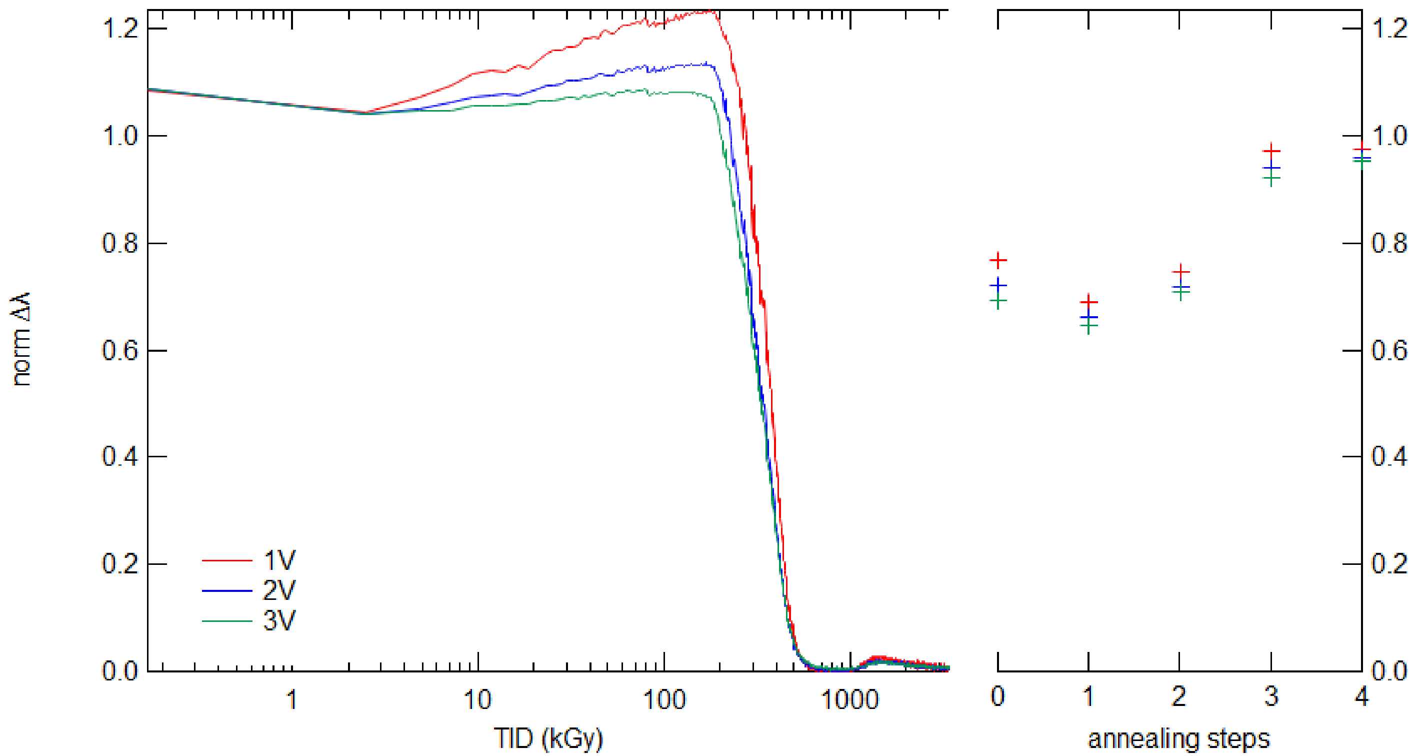
X-ray test - Ring Modulator





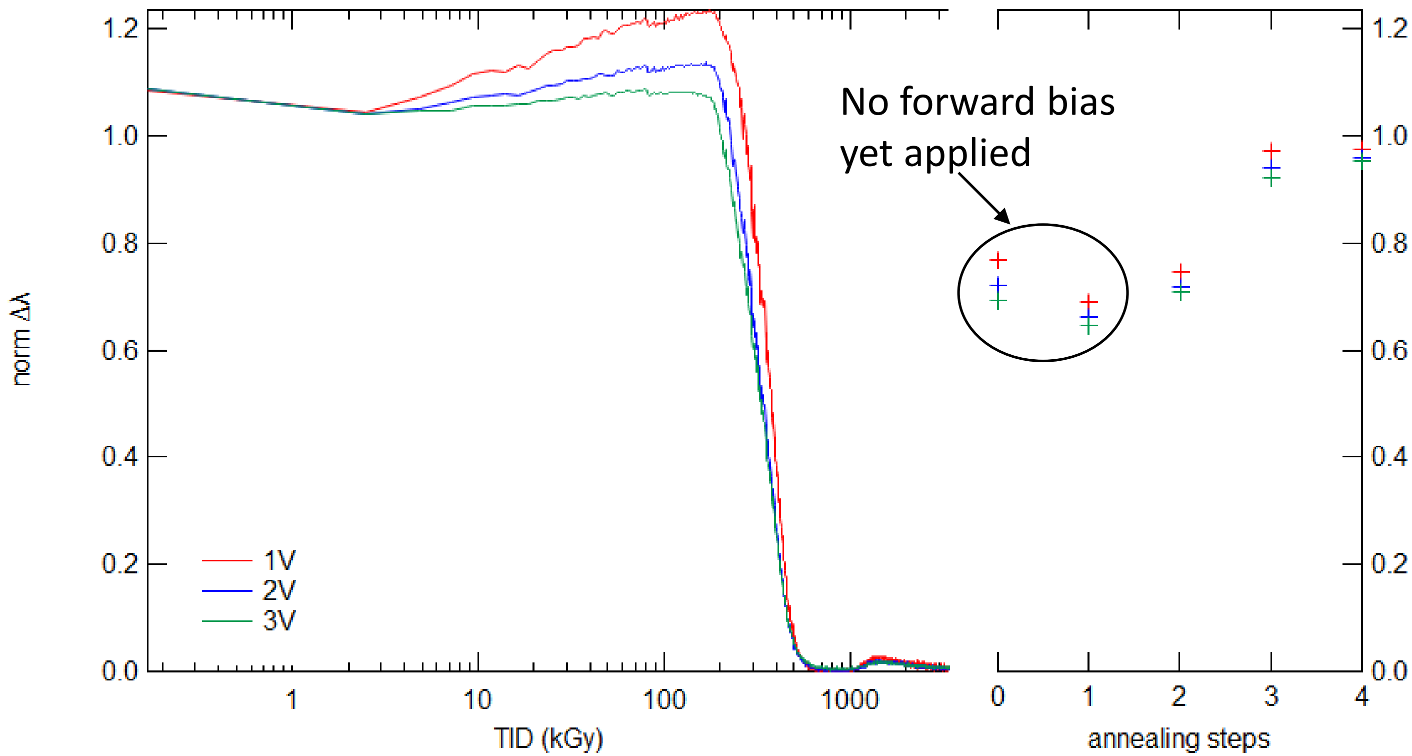
Device	Width of low doping
Deep etch MZM	**500 nm**
Ring modulator	**100 nm**

Annealing Ring Modulator



- No forward bias during irradiation
- Annealing step 0: measurement after 2 month of unbiased storage @ RT
- Annealing setp 1: after two days of measurement (no forward bias)
- Annealing step 2: 1 min 50 uA forward current
- Annealing step 3: 1 min 200 uA forward current
- Annealing step 4: 10 min 200 uA forward current

Annealing Ring Modulator



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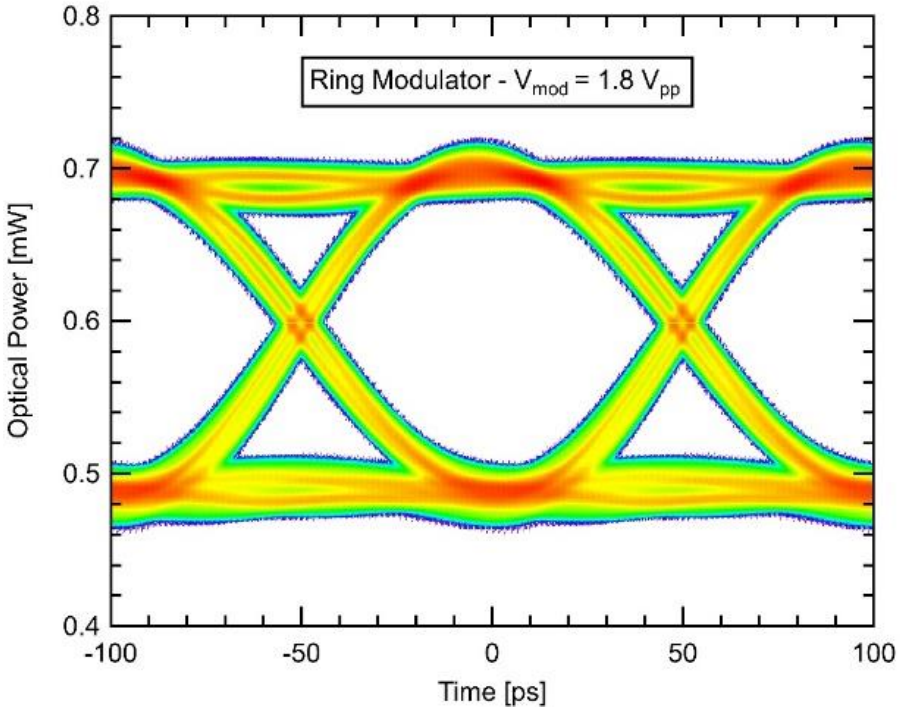
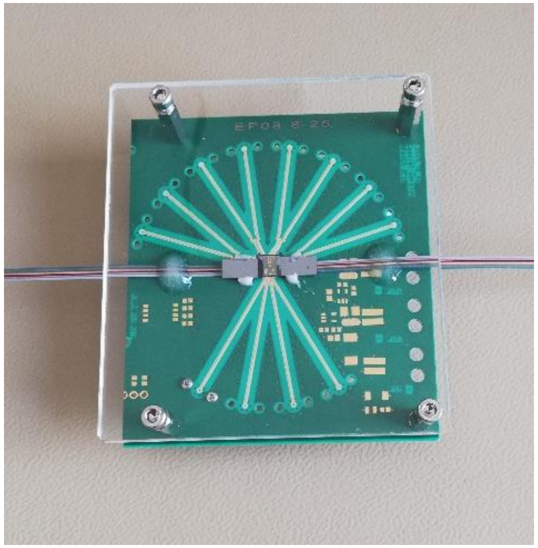
High speed response Ring Modulator

10 Gbps



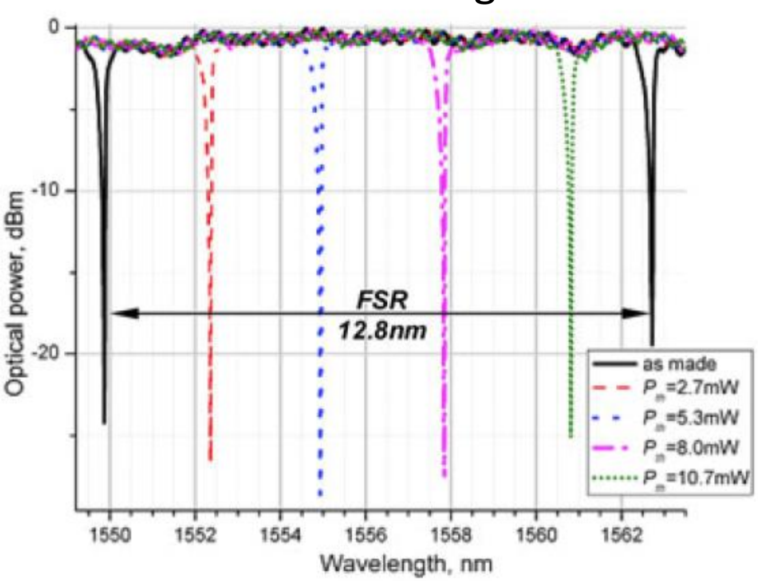


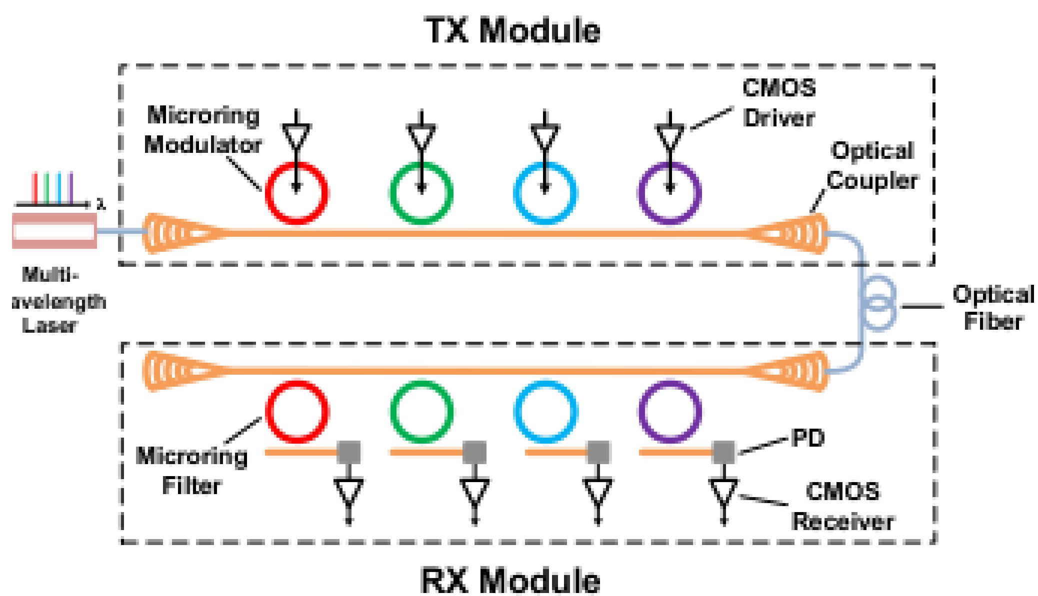
RM in Wavelength Division Multiplexing (WDM) systems

- Due to the big FSR, the possibility of tuning the resonant frequency and the small size, RM are very attractive for WDM systems

- RM of varying radii and/or tuned by heater can be cascaded along a waveguide bus to generate WDM optical modulation

Using of a heater to shift the resonance wavelength





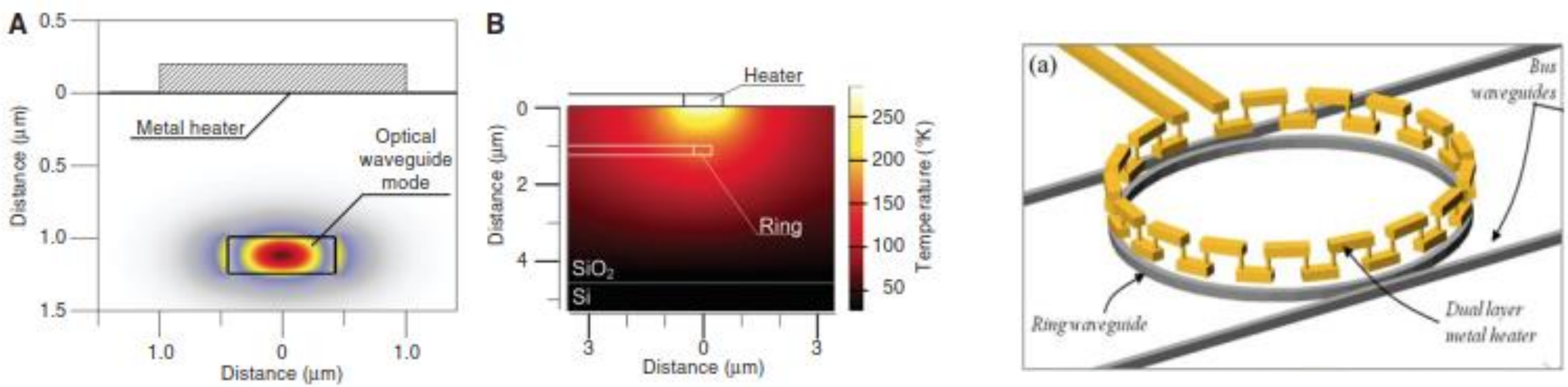
Next steps

- Only a fraction of measurements are done so far
- Right now we are working on a new test chip
  - Stronger focus on ring modulators
  - Structures on system level
  - WDM test structure
- In order to understand the radiation effects better more intensive focus on the radiation model and the device simulations is needed

Back up slides

Tuning of ring modulators - heaters

- Use of resistive structures → nichrome, titanium or doped silicon → running current through these structures creates heat
- Most common configuration → heater on top of ring



- Separation between heater and ring to protect optical mode → not optimal tuning efficiency