Si-Photonics at CERN

TWEPP 2013 , Perugia, Italy

Opto Working Group ,26th September 2013

Sarah Seif El Nasr-Storey

Outline

- Background
  - Silicon photonics devices at CERN
- *First Radiation Tests of Si-photonics devices*
- *Simulating Effect of radiation on Si-photonics based modulators*
  - *SOI based modulators - a quick introduction*
  - *First results from simulations*
- *Conclusions and future work*

Background : Interest in silicon photonics at CERN

- Silicon photonics :
- photonic functions (light transmission/modulation/detection) can be integrated into silicon technology
- would be faster, smaller, and (potentially) cheaper than currently available optoelectronic components
- all properties which make them interesting to investigate for HEP applications
- Collaboration with academic and industrial partners, providing us with components for which the suitability of silicon-photonics devices for HEP applications can be studied.

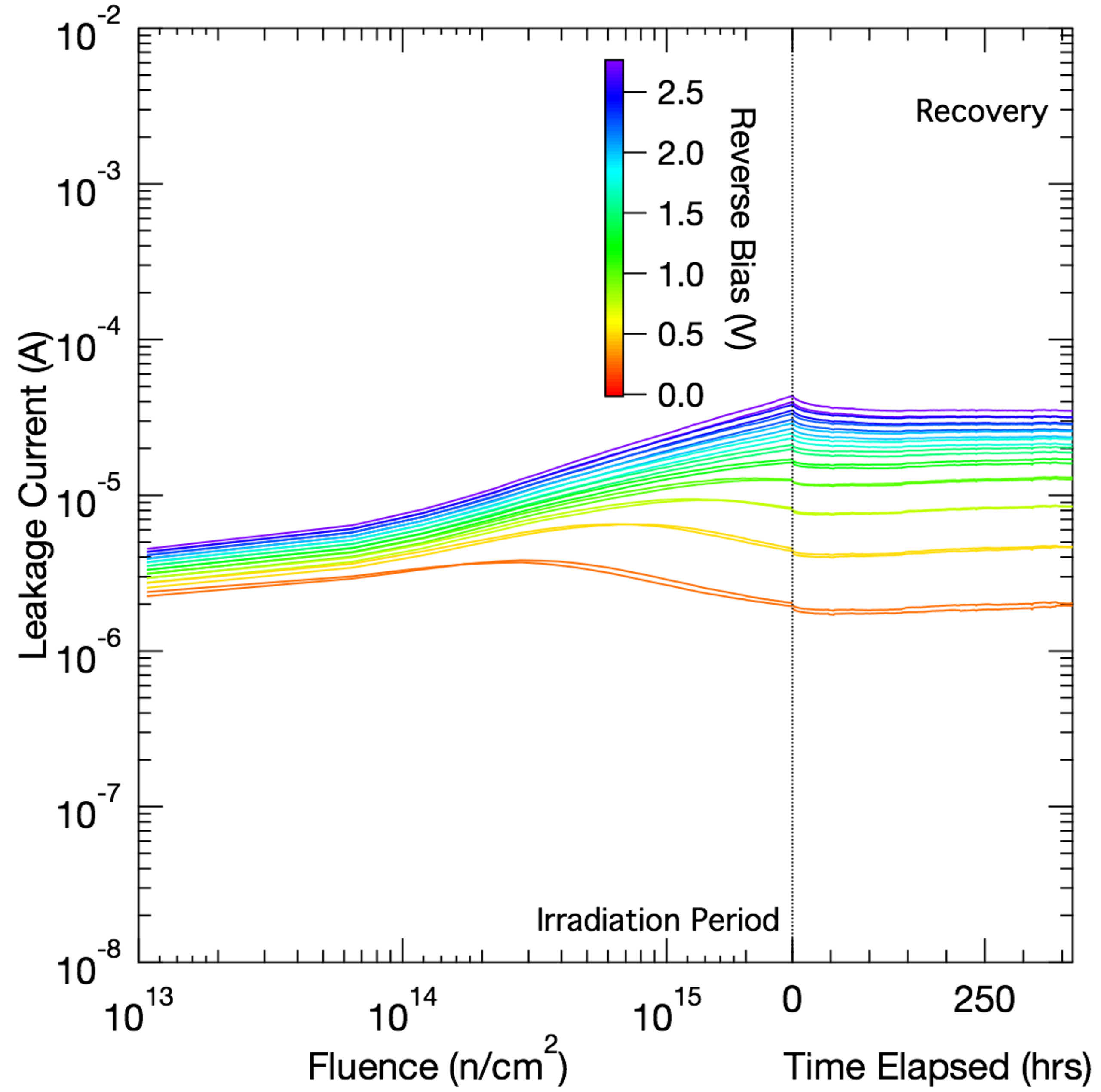
Outline

- *Background*
  - *Silicon photonics devices at CERN*
- First Radiation Tests of Si-photonics devices
- *Simulating Effect of radiation on Si-photonics based modulators*
  - *SOI based modulators - a quick introduction*
  - *First simulation results*
- *Conclusions and future work*

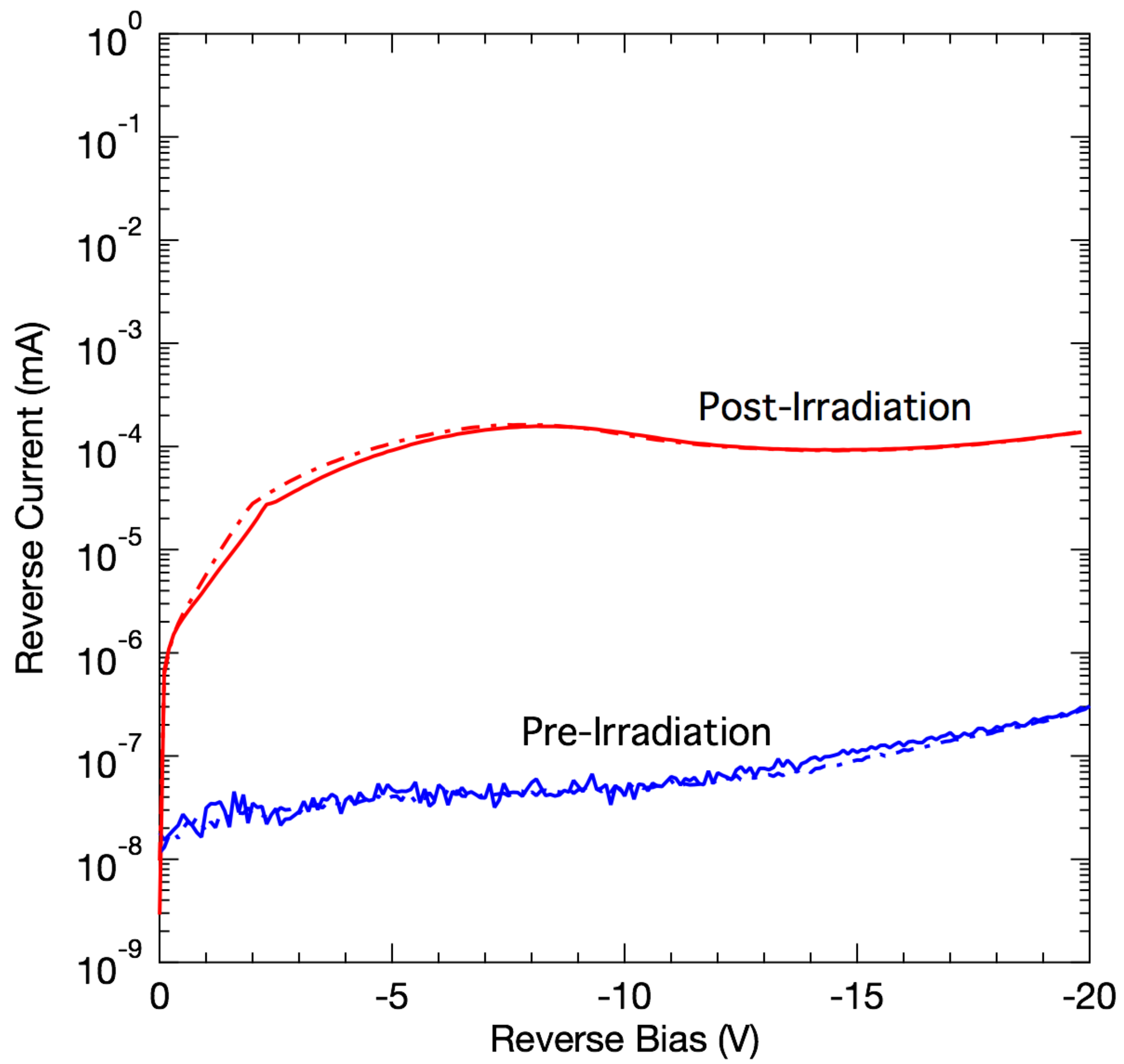
First radiation tests of Si-photonics based devices

- First samples of Si-photonics devices (Ge-on-Si photodiodes, modulators, lasers) received in second half of 2012 for initial tests

- Radiation tests (simple before and after tests using the 24 GeV proton beam at CERN, and on-line measurements of the change in leakage currents of the devices were carried out) (see poster in poster session)



Increase in leakage current of Ge-on-Si photodiodes irradiated with 20 MeV neutrons at Louvain-la-Neuve



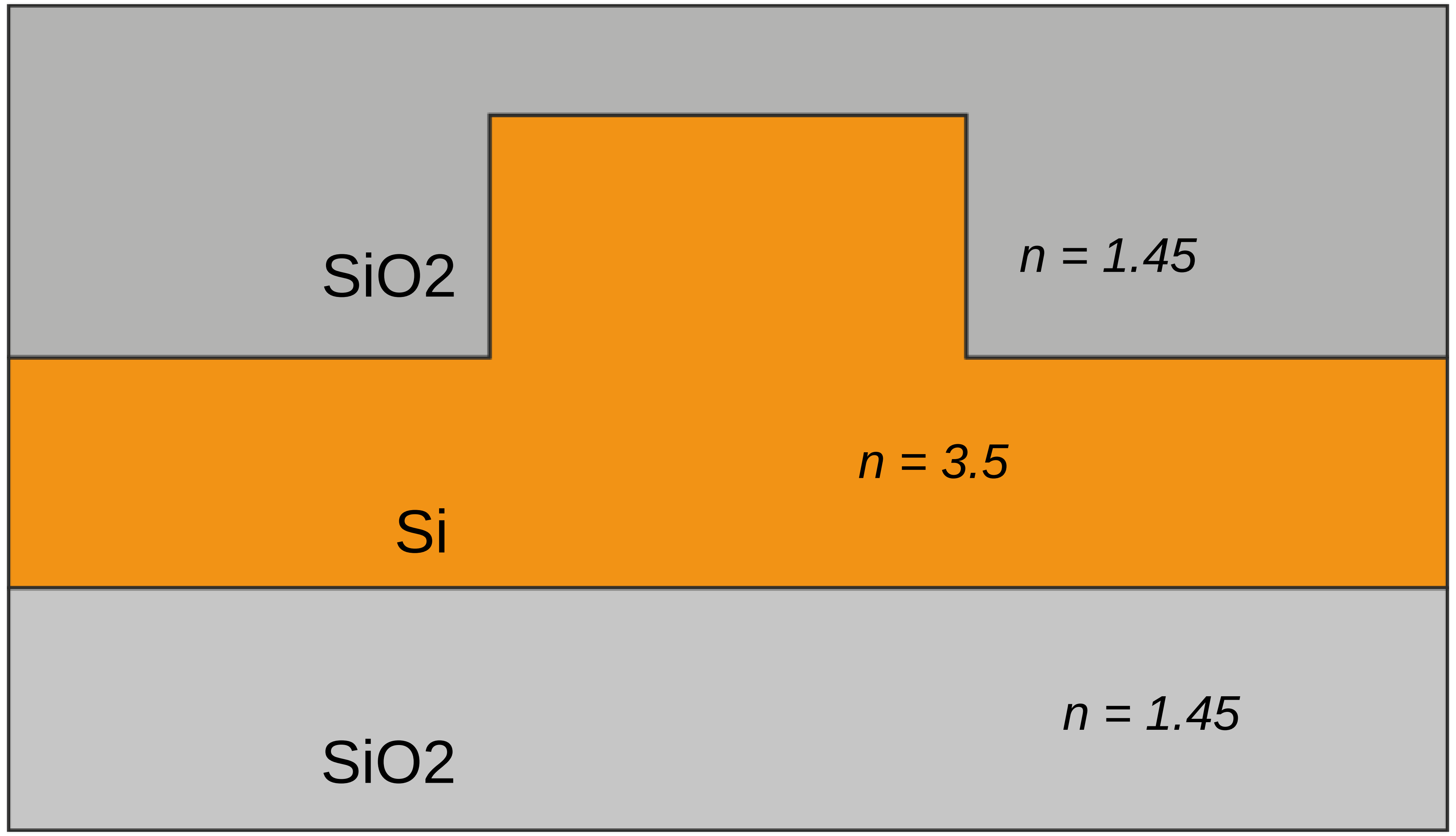
Increase in leakage current of SOI modulators irradiated with 24 GeV protons at CERN

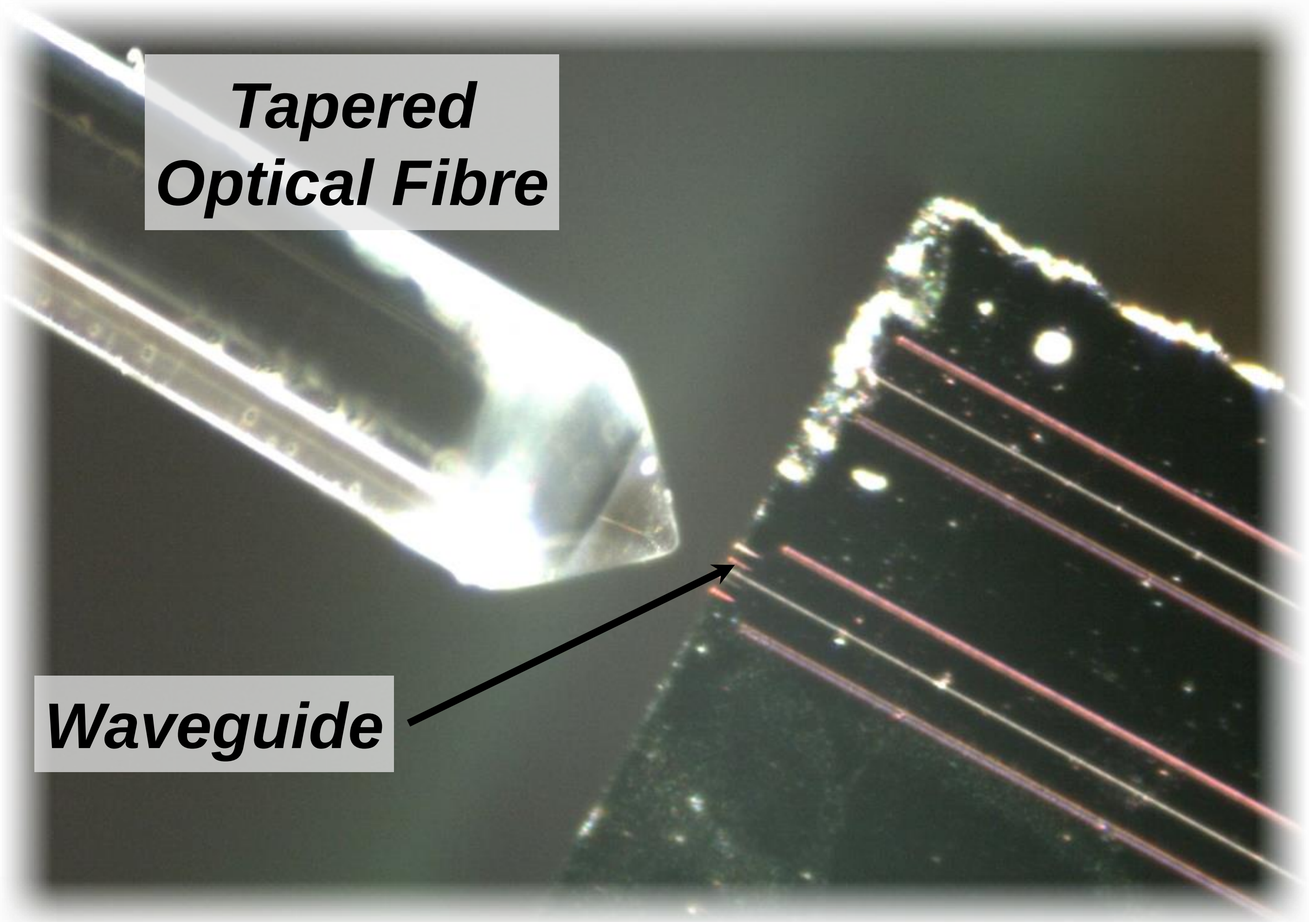
Outline

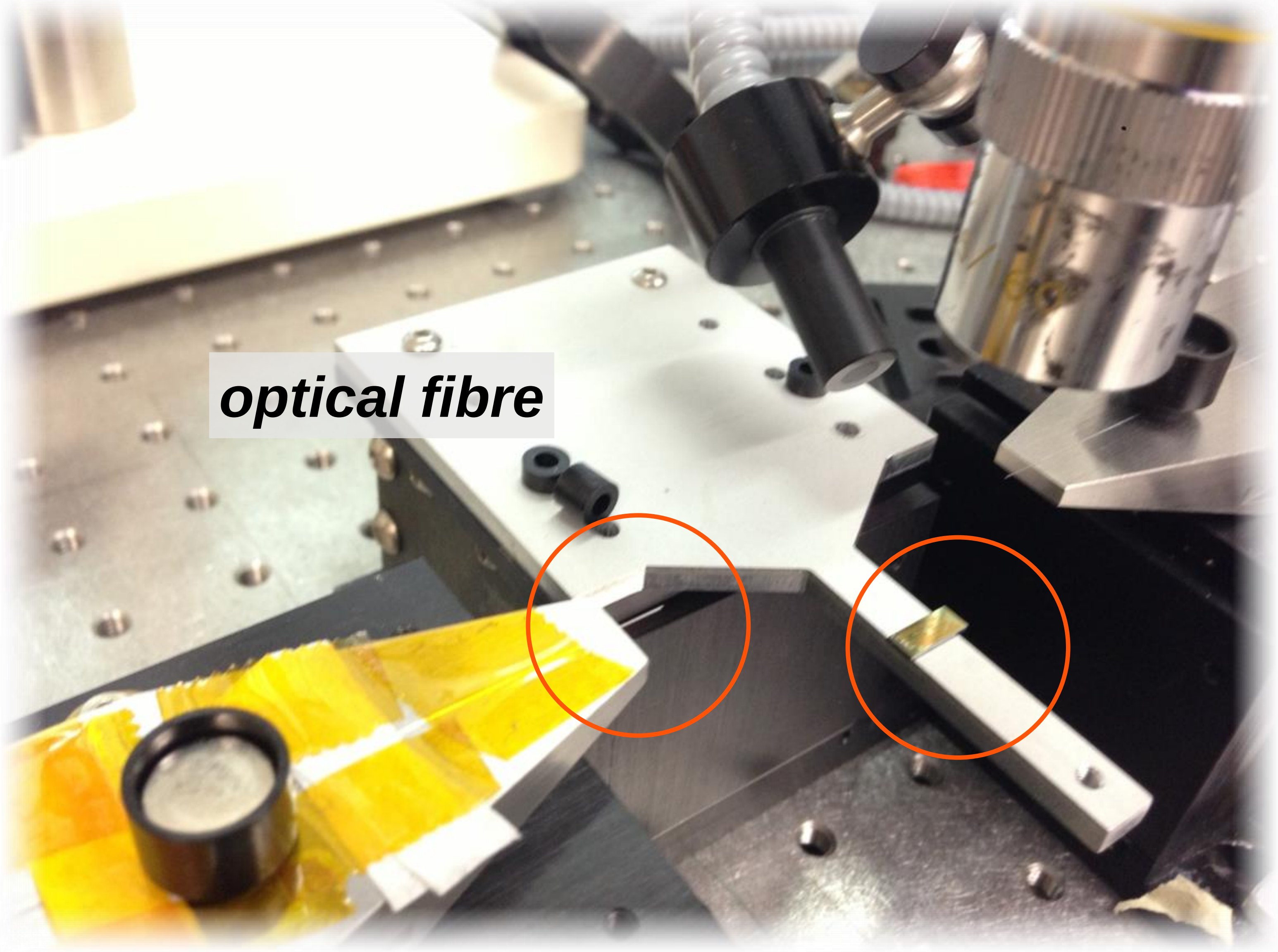
- *Background*
  - *Silicon photonics devices at CERN*
- *First Radiation Tests of Si-photonics devices*
- Understanding the impact of radiation on Si-photonics based modulators
  - SOI based modulators - a quick introduction
  - First simulation first results
- *Conclusions and future work*

Principle of operation of SOI modulators

- First, what is a Silicon-On-Insulator modulator - start with an optical waveguide built in silicon



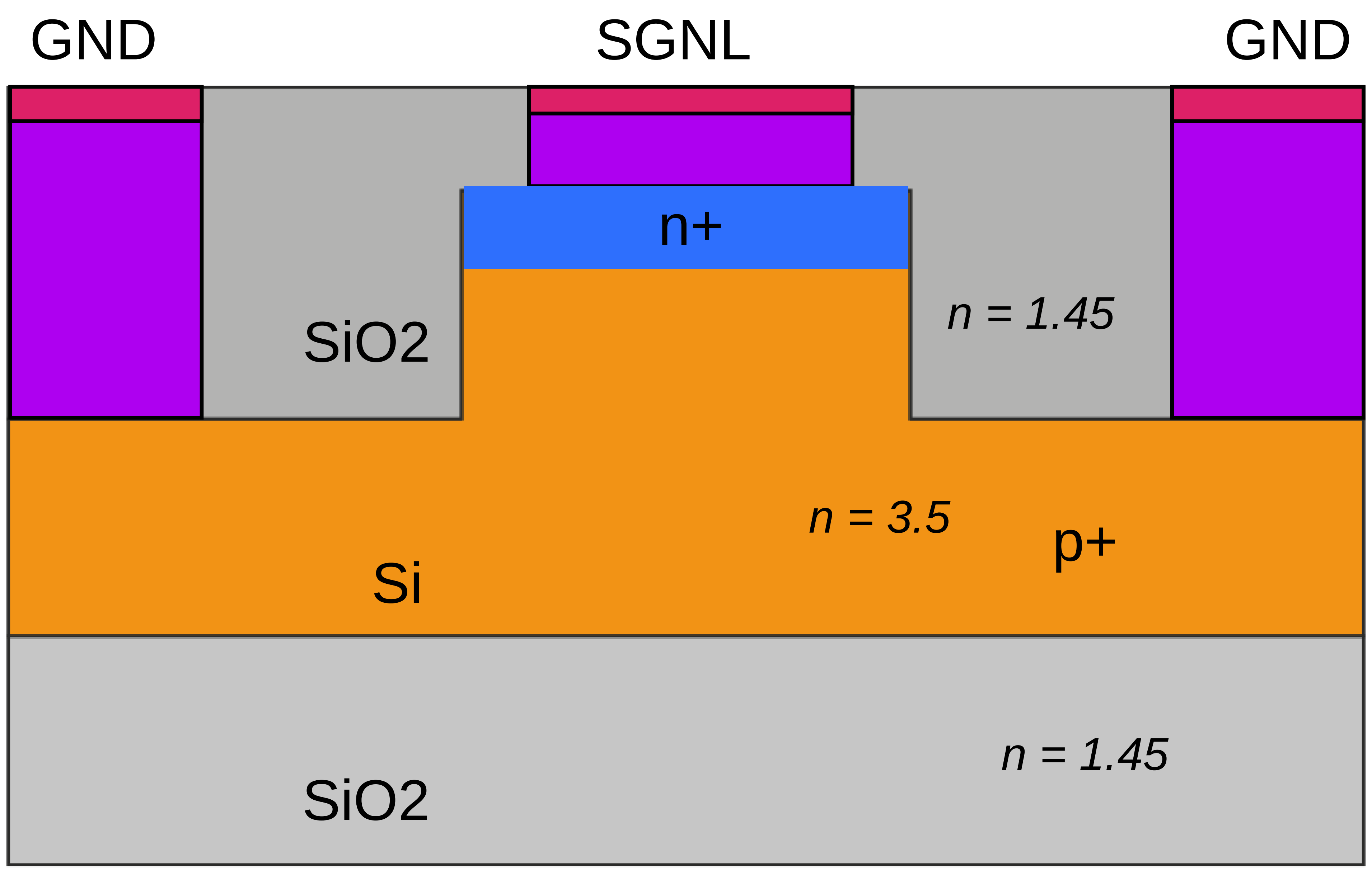


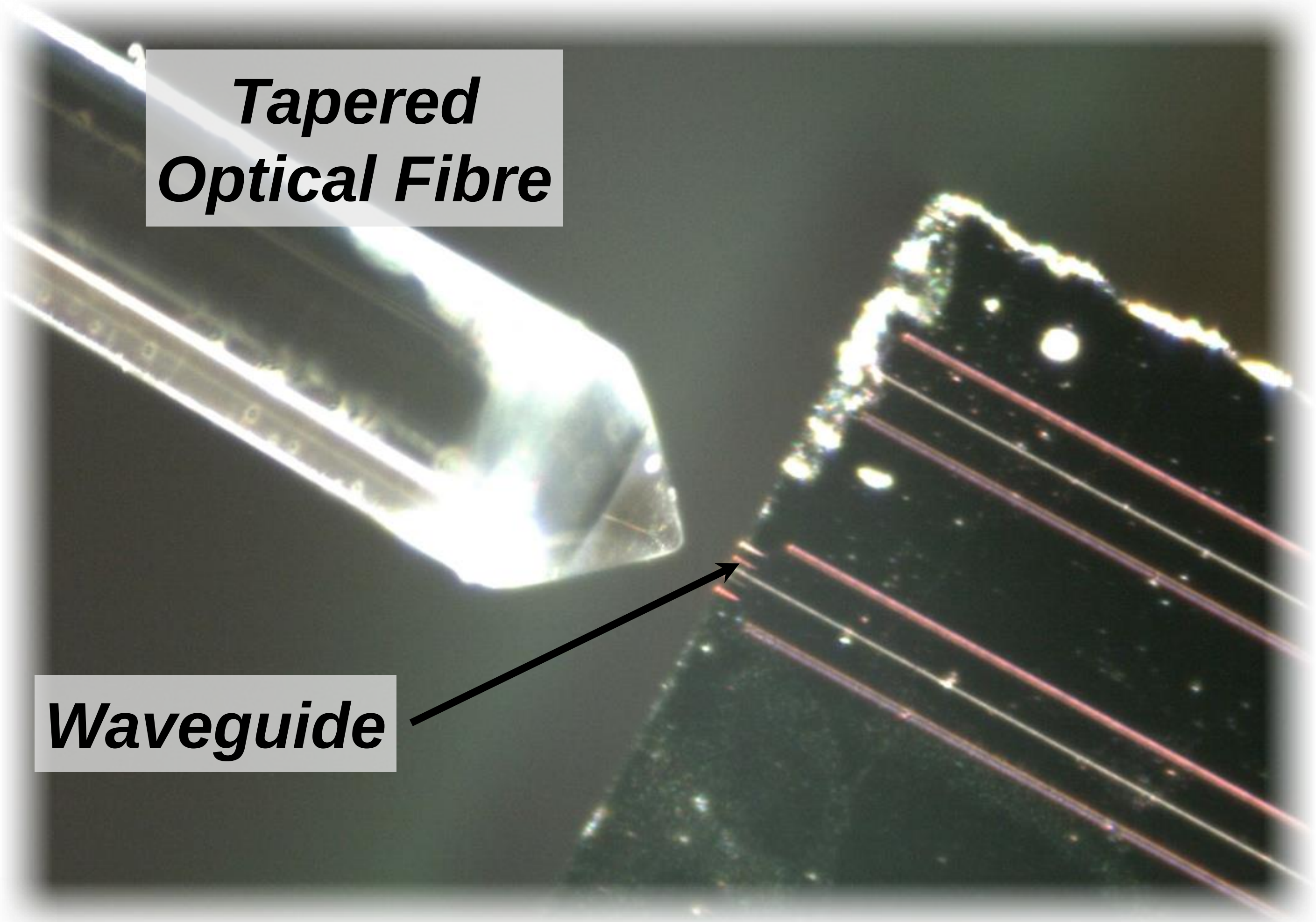


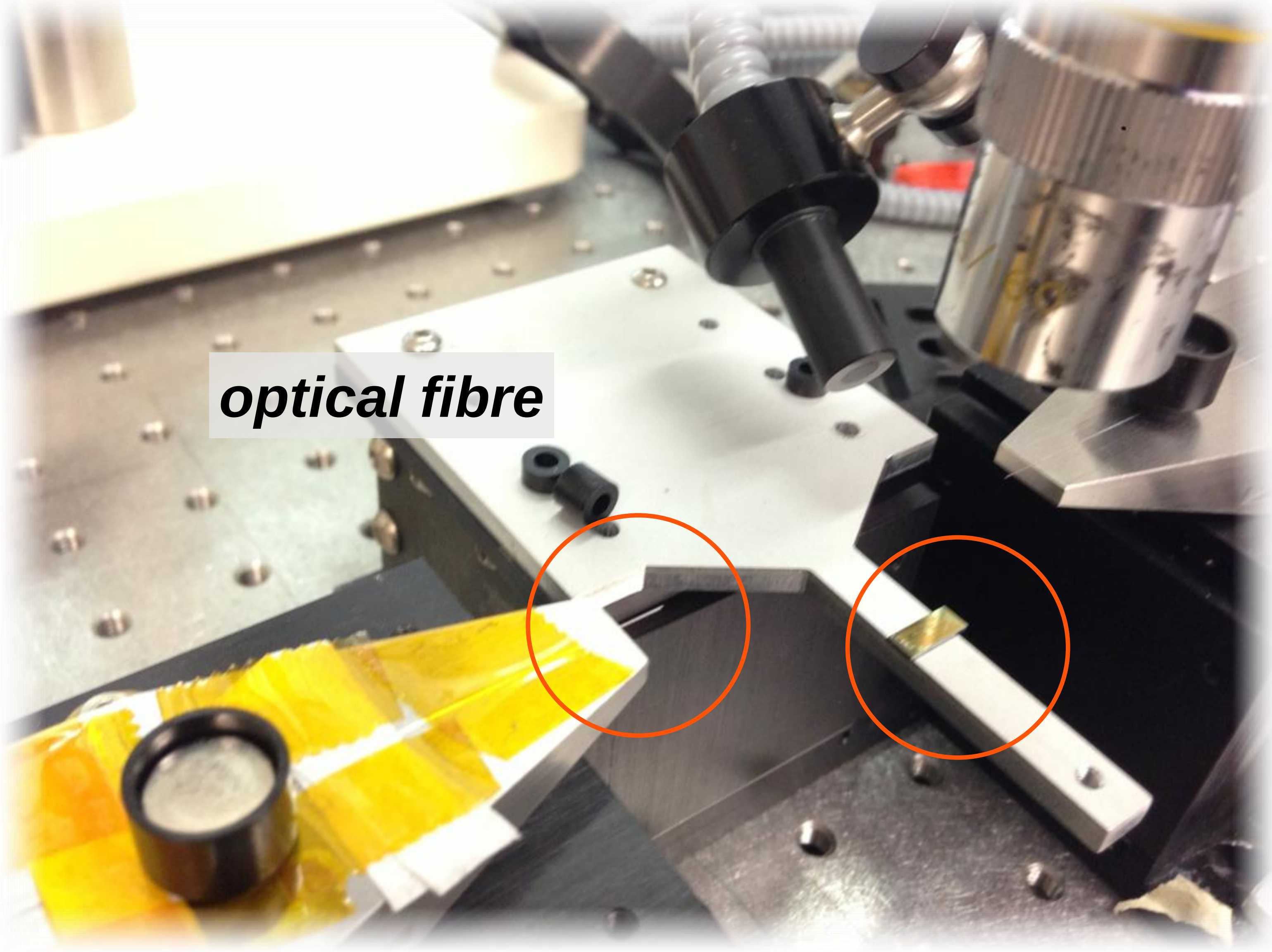
- Light confined in x and y using rib structure shown above (rib width and height carefully selected to allow single-mode operation)

Principle of operation of SOI modulators

- First, what is a Silicon-On-Insulator modulator - start with an optical waveguide built in silicon





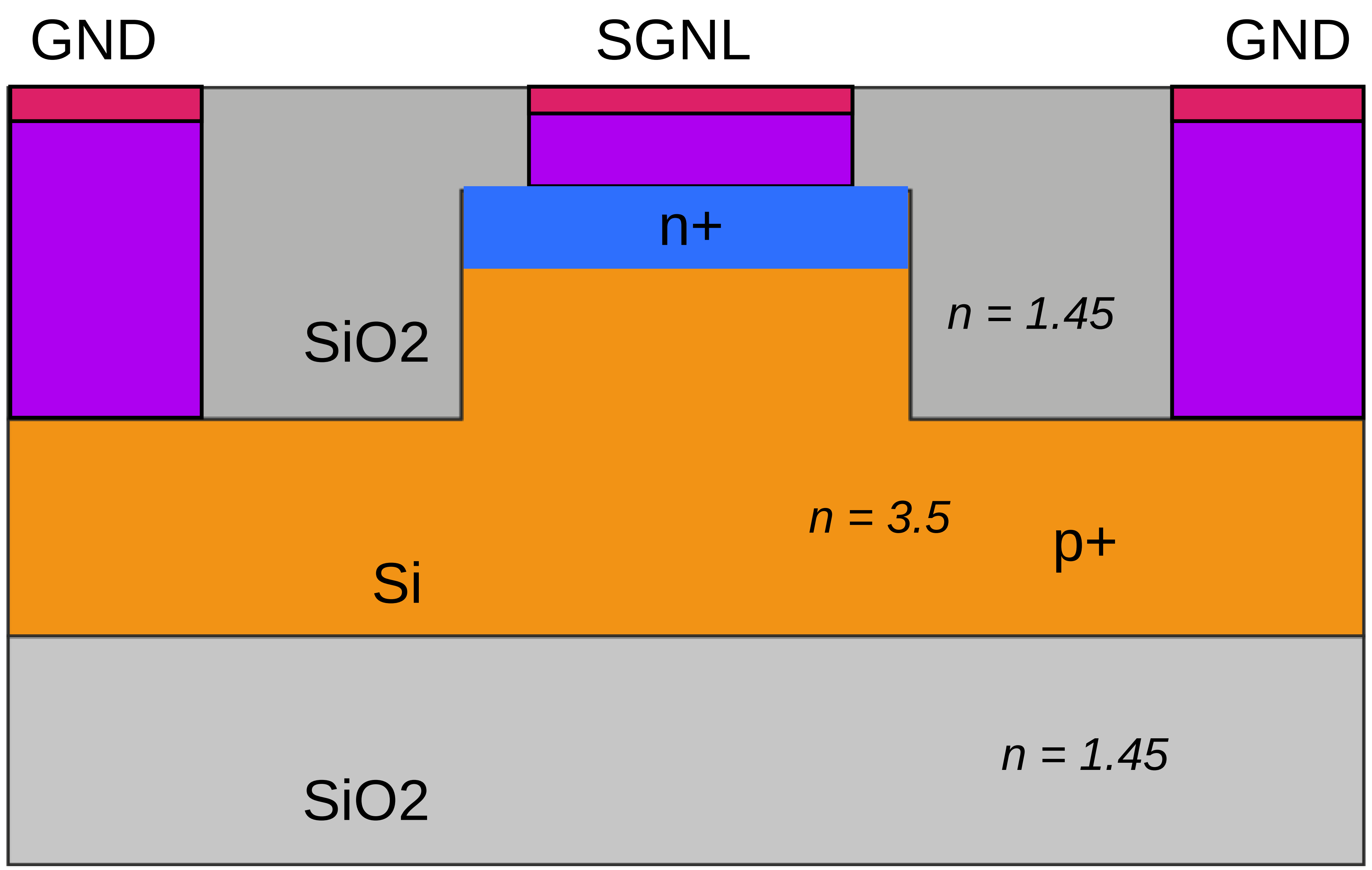


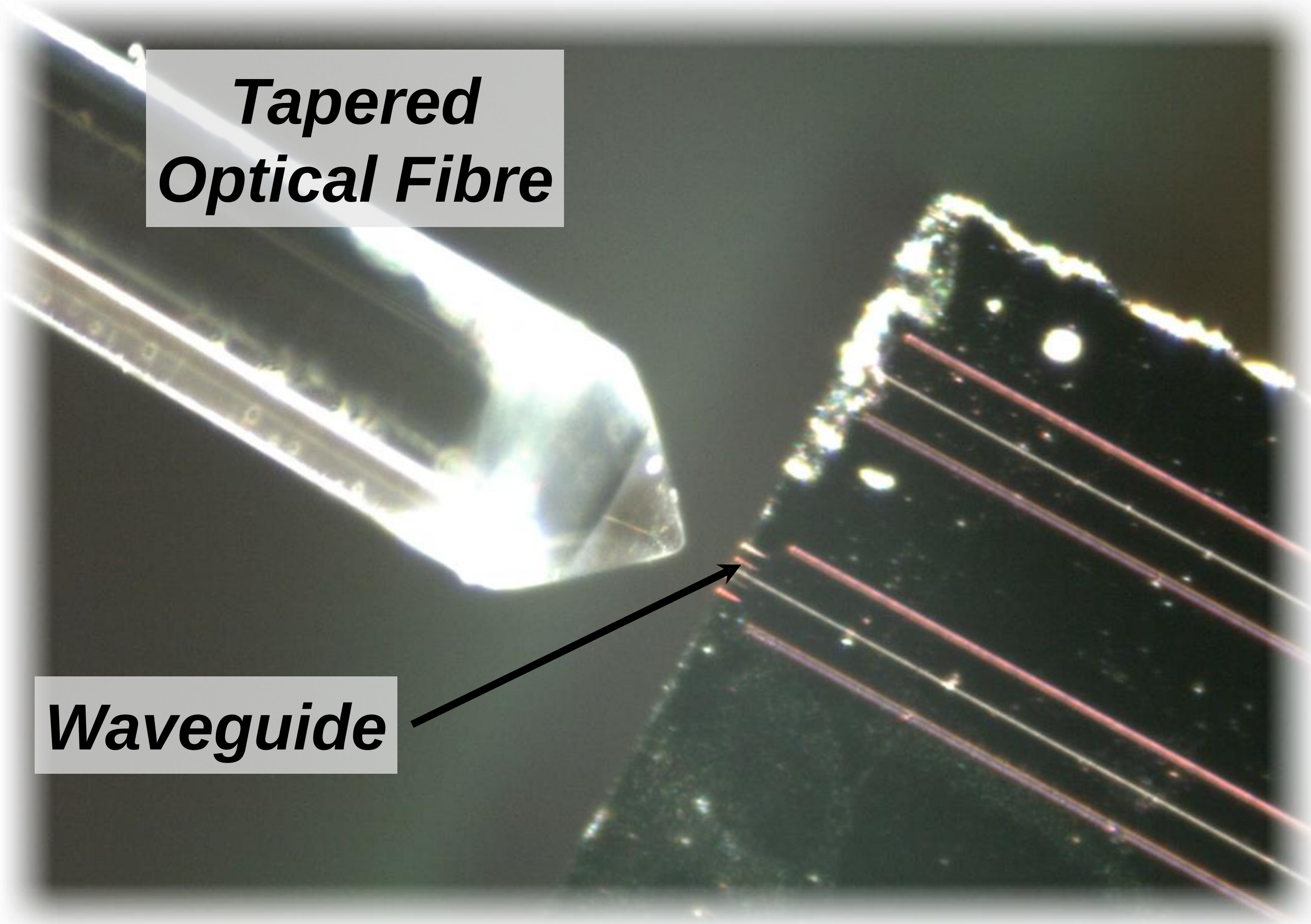
- Light confined in x and y using rib structure shown above (rib width and height carefully selected to allow single-mode operation)

- junction is formed in the rib waveguide region and the light is phase modulated by applying a reverse bias to the junction

Principle of operation of SOI modulators

- First, what is a Silicon-On-Insulator modulator - start with an optical waveguide built in silicon

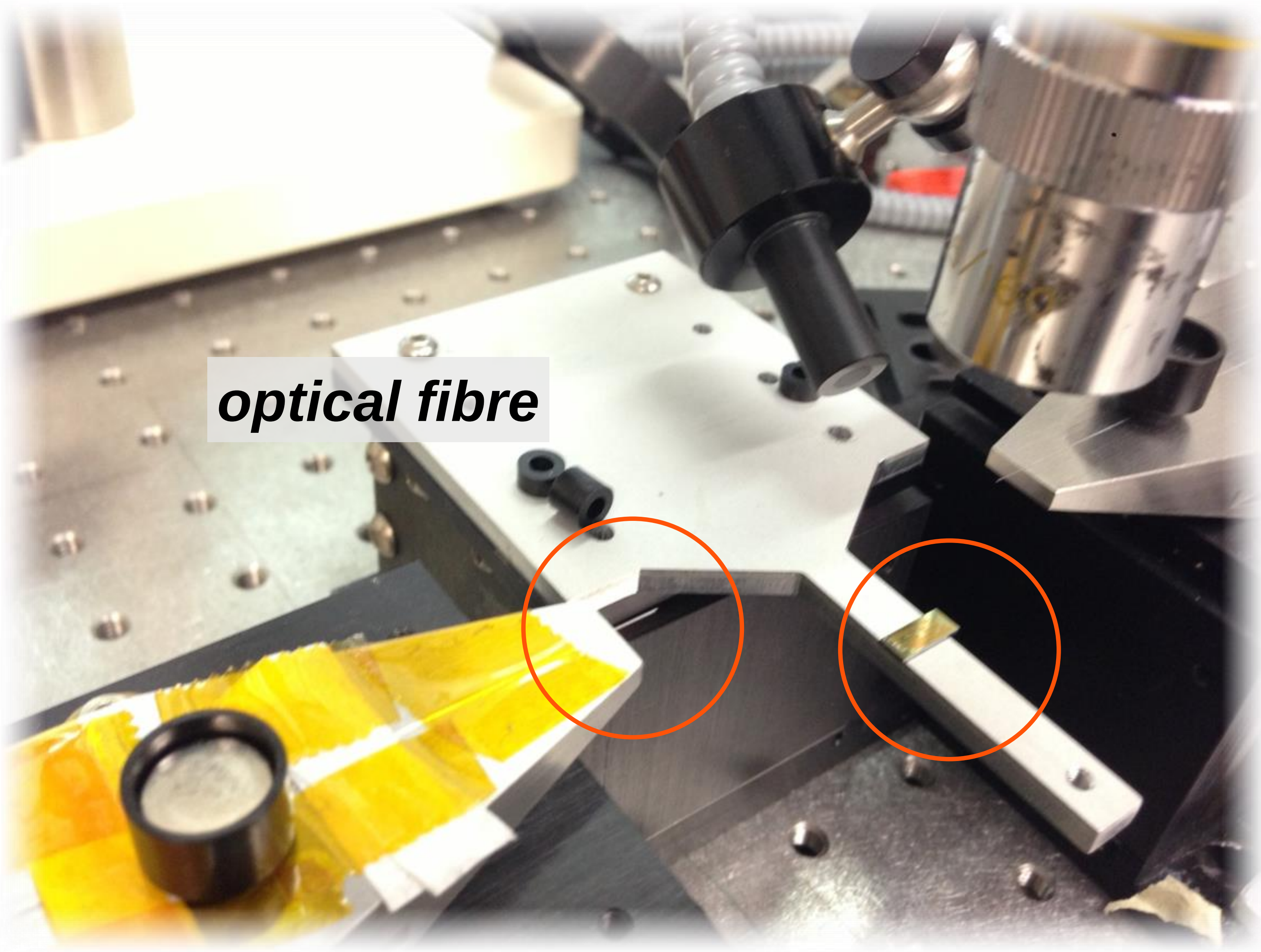


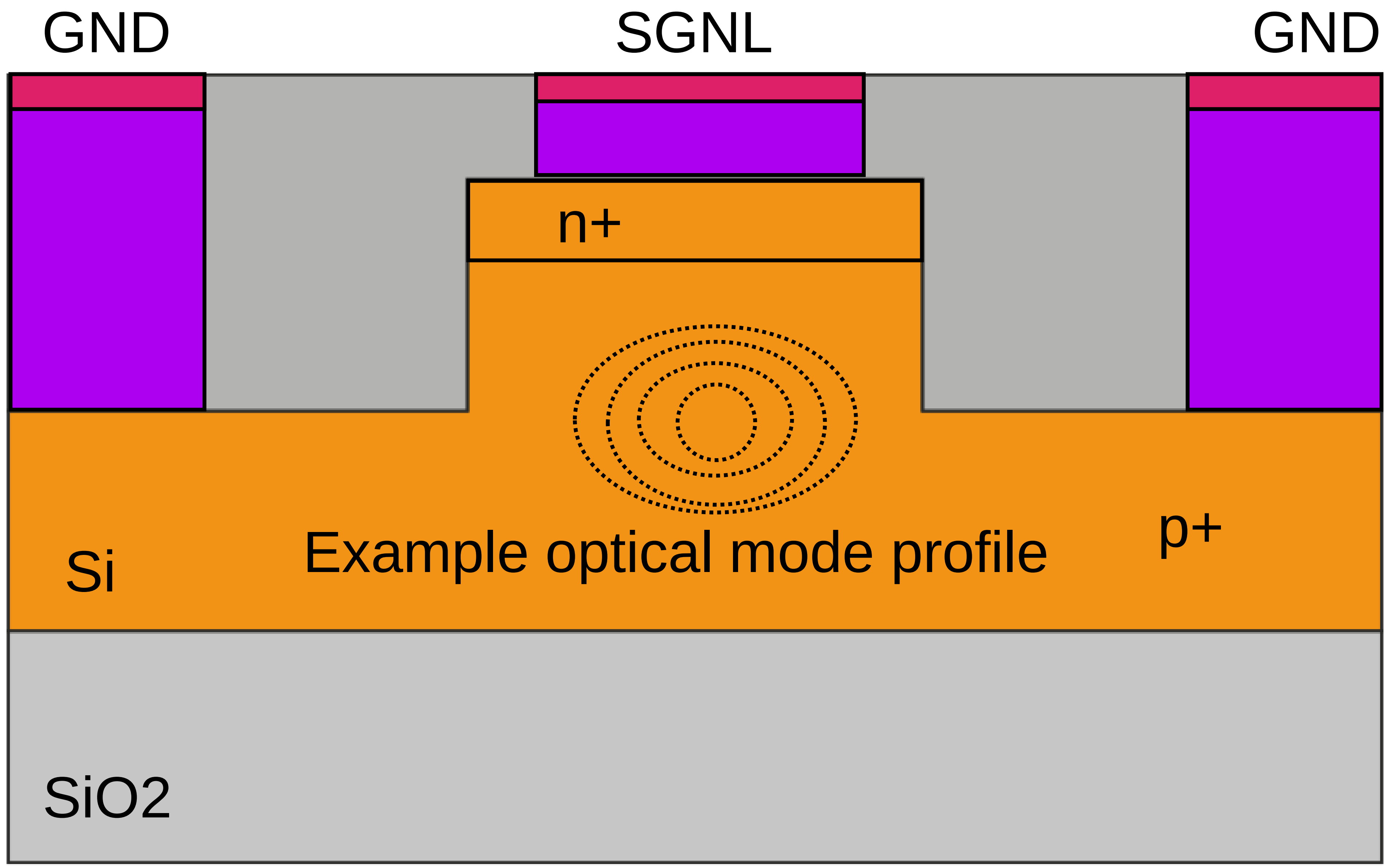


- Light confined in x and y using rib structure shown above (rib width and height carefully selected to allow single-mode operation)

- junction is formed in the rib waveguide region and the light is phase modulated by applying a reverse bias to the junction

- amplitude modulation is obtained by integrating structure into the arms of an interferometer





$$\Delta n = \Delta n_e + \Delta n_h = -(a_e \Delta N_e + a_h (\Delta N_h)^{0.8})$$

$$\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = (b_e \Delta N_e + b_h \Delta N_h)$$

ƛ [um]	a_e	a_h	b_e	b_h
1.3	6.2×10^{-22}	6.0×10^{-18}	6.0×10^{-18}	4.0×10^{-18}
1.5	8.8×10^{-22}	8.5×10^{-18}	8.5×10^{-18}	6.0×10^{-18}

[1] Kramers-Krong Analysis of Electro-Optical Switching in Silicon
[2] Electrooptical Effects in Silicon

The change in the effective refractive index of the waveguide material is then defined as :

$$\Delta n_{eff}(z) = \frac{\int\int \Delta n(x,y,z)|E(x,y,z)|^2 dx\, dy}{\int\int |E(x,y,z)|^2 dx\, dy}$$

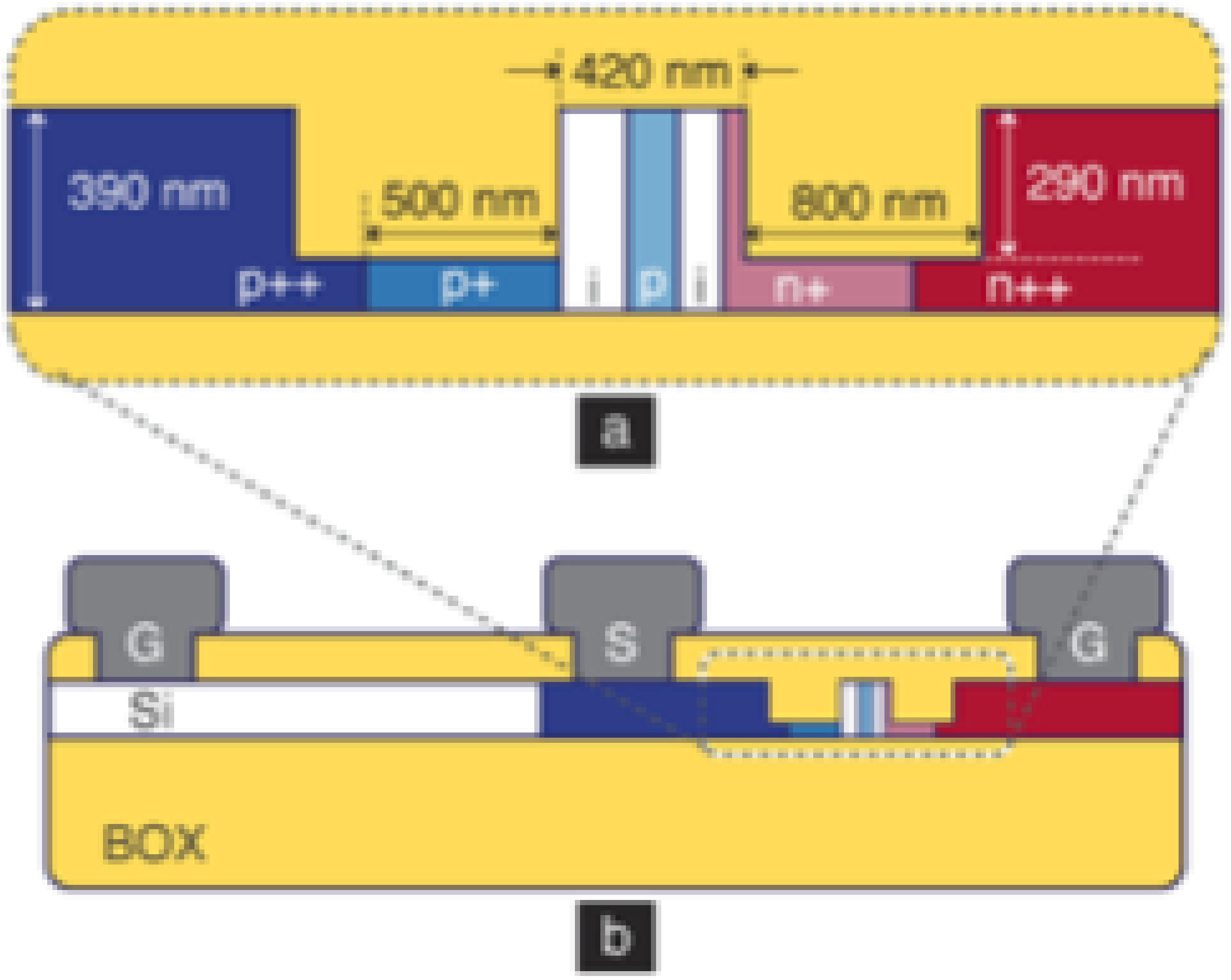
, where E(x,y,z) is the optical mode profile of the traveling ligh

and the change in effective refractive index required to obtain a full π phase shift is

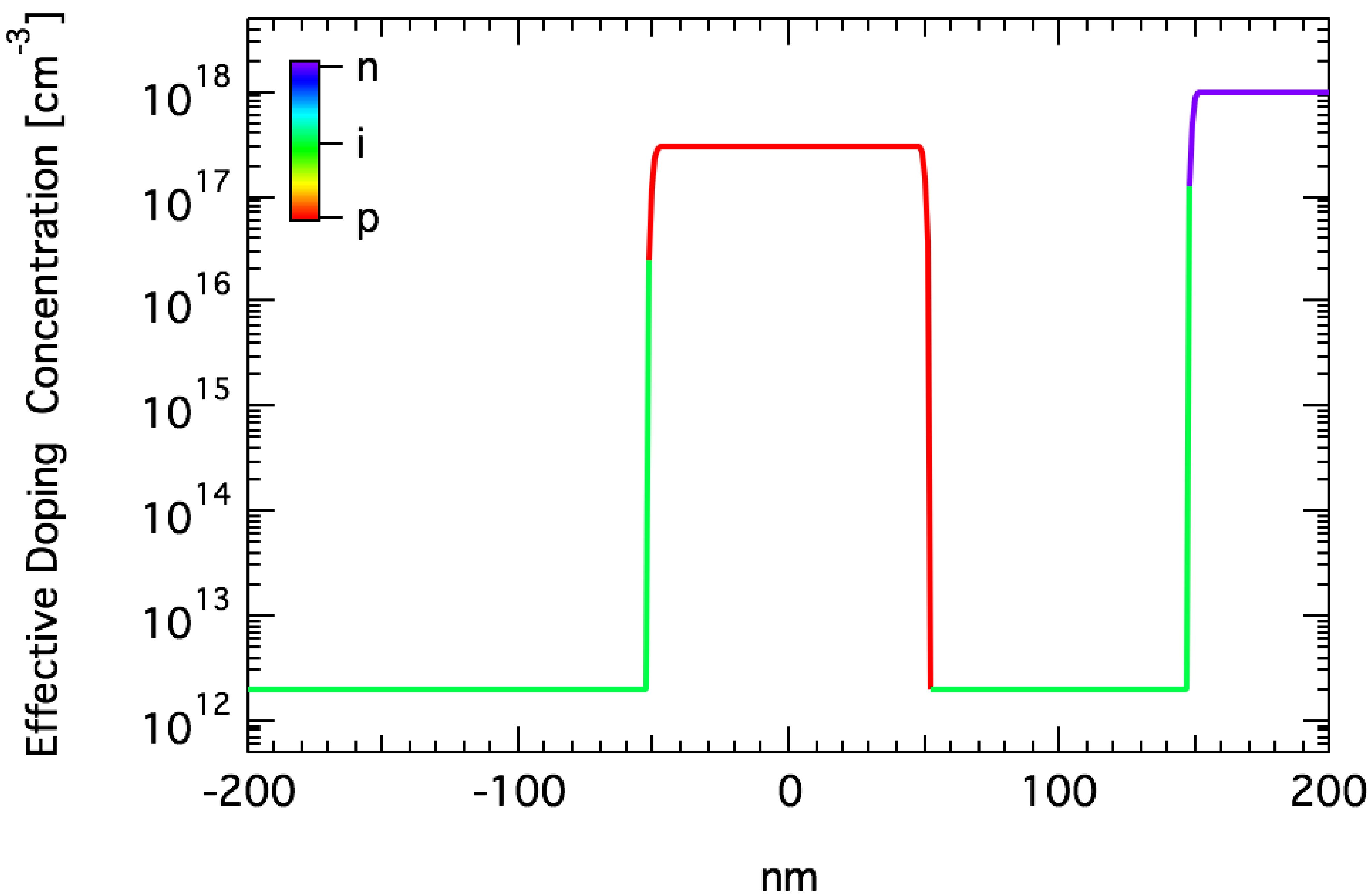
$$\Delta n_{eff} = \frac{\lambda}{2L}$$

, where L is the length of the modulator and ƛ is the wavelength of the traveling light

TCAD Simulation of Phase-Shifting Diode Structure



[40 Gb/s Low-Loss Silicon Optical Modulator Based on pipin Diode]



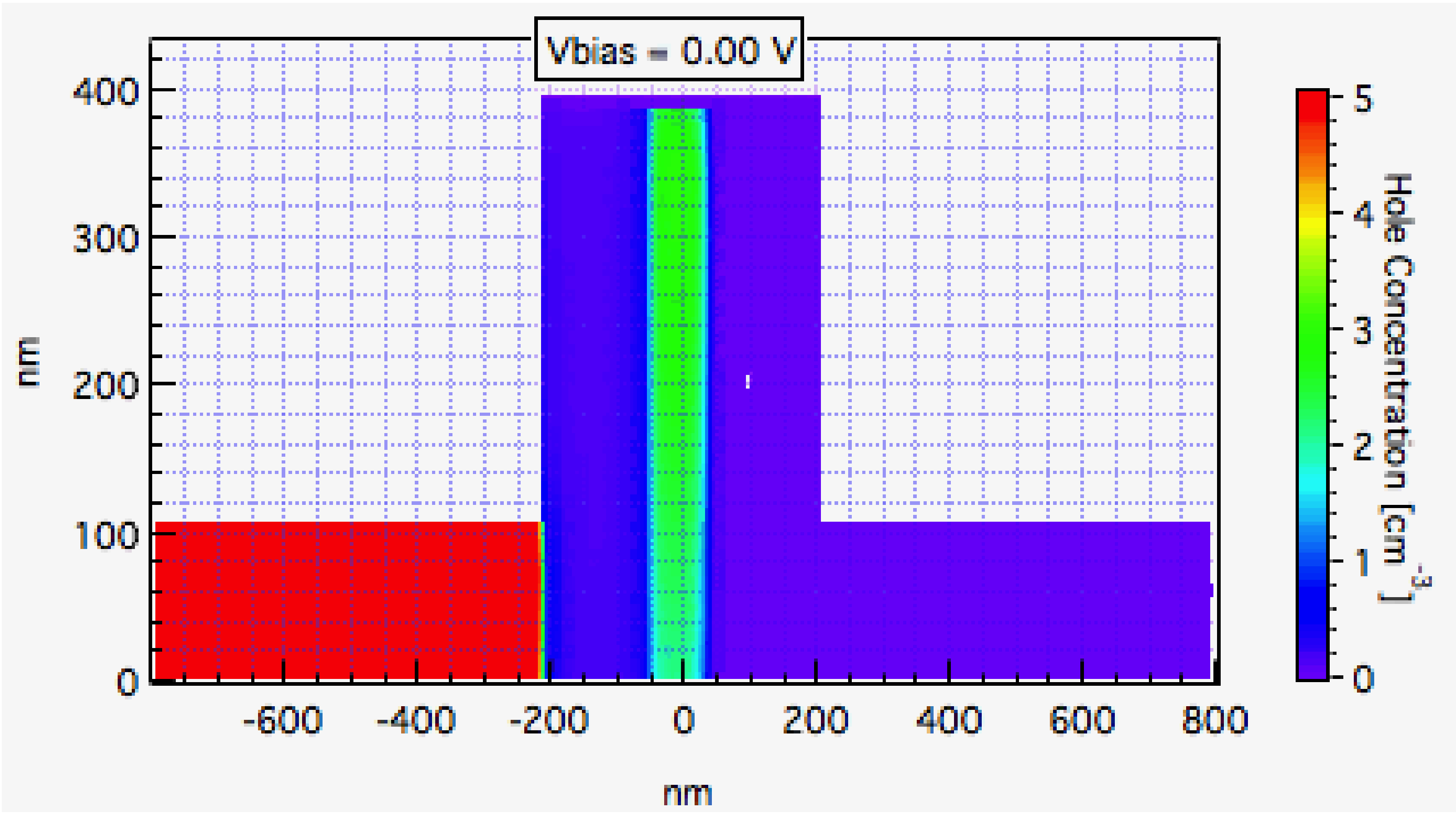
TCAD output of effective doping concentration in rib

Sentaurus TCAD Tools : Sentaurus device - simulates the electrical/thermal/optical characteristics of 2D/3D silicon/semiconductor structures. Sentaurus TCAD Simulation of Paris Sud pipin structures shown in above reference, simulated at reverse biases = 0 - 2.5 V (simulation results recorded every 0.2 V steps.

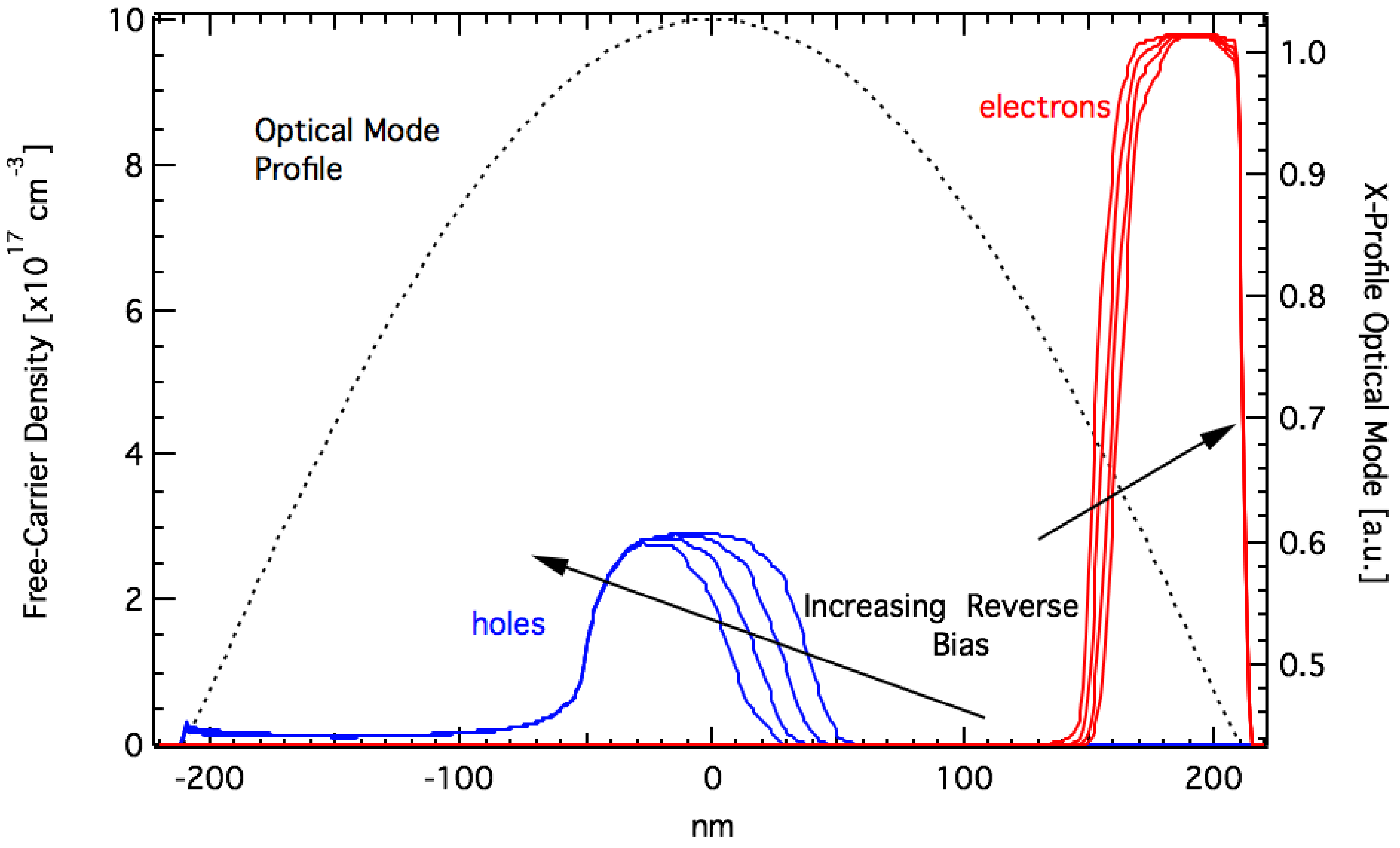
Output of simulation can be used to examine Ne(x,y) and Nh(x,y) , I-V/C-V as a function of applied reverse bias

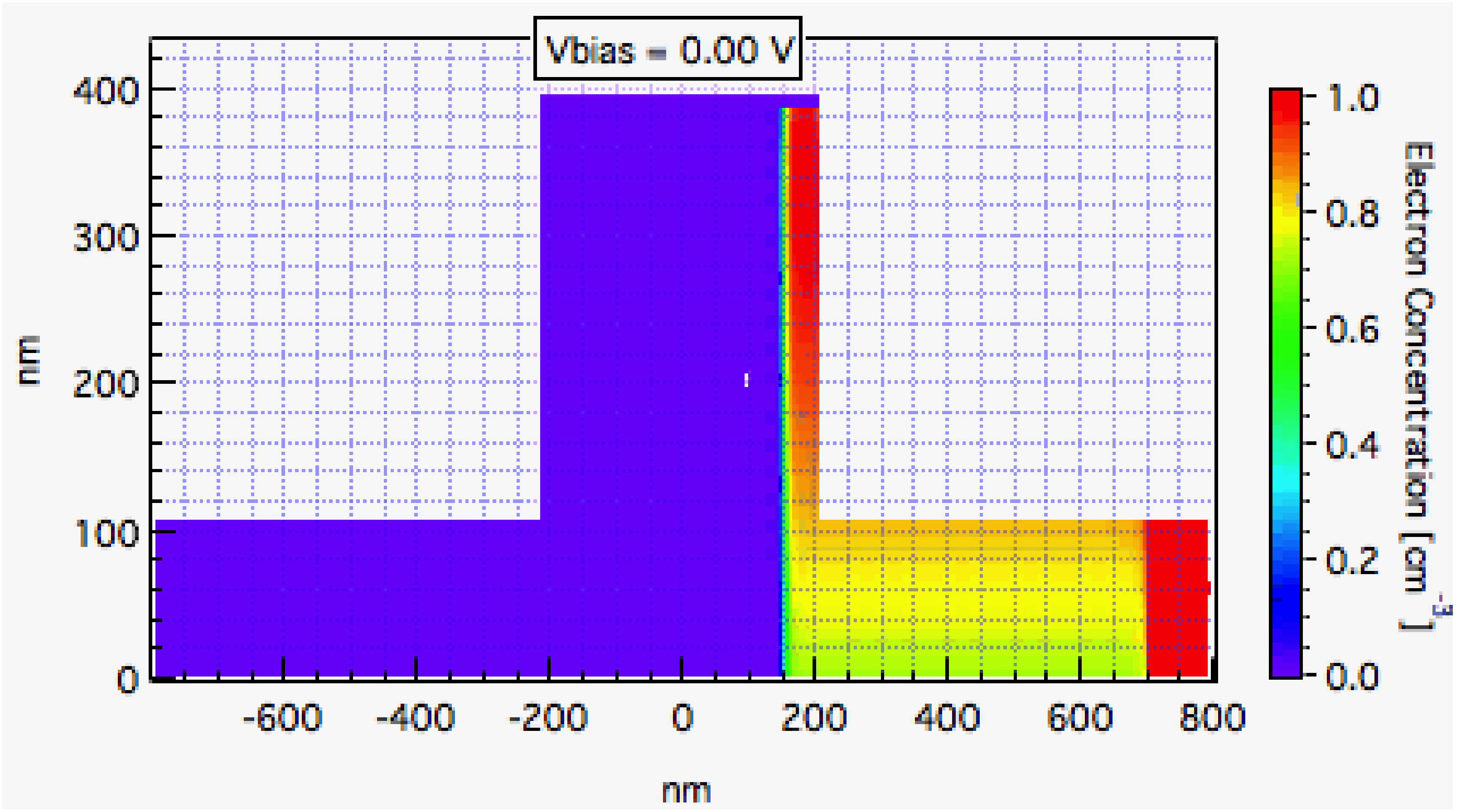
Demonstrate Phase-Shifting Operation in TCAD

- Simulation is capable of producing a map of ΔNe , ΔNh , Δn as a function of (x,y) in the waveguide structure



Free hole density as reverse bias is increased





Free electron density as reverse bias is increased

- As reverse bias of diode increases, can see that concentration of free carriers decreases (active region is depleted)
- Shows you that the device is designed in such a way as to maximize the overlap between the optical mode and the hole concentrations - more important contribution to the change in refractive index.
- Can calculate Δneff at different values of reverse bias : allows you to calculate Vπ for a given diode structure.

Proof of principle : Evaluating how radiation affects the performance of these devices?

- Irradiation of silicon leads to the introduction of deep defects (donors and acceptors) that change the effective doping concentration (Neff = Na - Nd) as a function of fluence :

$$N_{eff} = N_D e^{-c_D \phi} - N_A e^{-c_A \phi} + (b_D - b_A)\phi$$

- where Cd and Ca represent the contribution of shallow donors and acceptors, Bd and Ba are the mean introduction rates of stable defects (donors and acceptors)

- TCAD allows you to define additional traps in the material and will adjust the doping dependent parameters accordingly and solve the poisson and continuity equations

$$\nabla \cdot [\epsilon \nabla V] = -\frac{\rho}{\epsilon_o} = \frac{q(n - p + N_A - N_D)}{\epsilon_o}$$

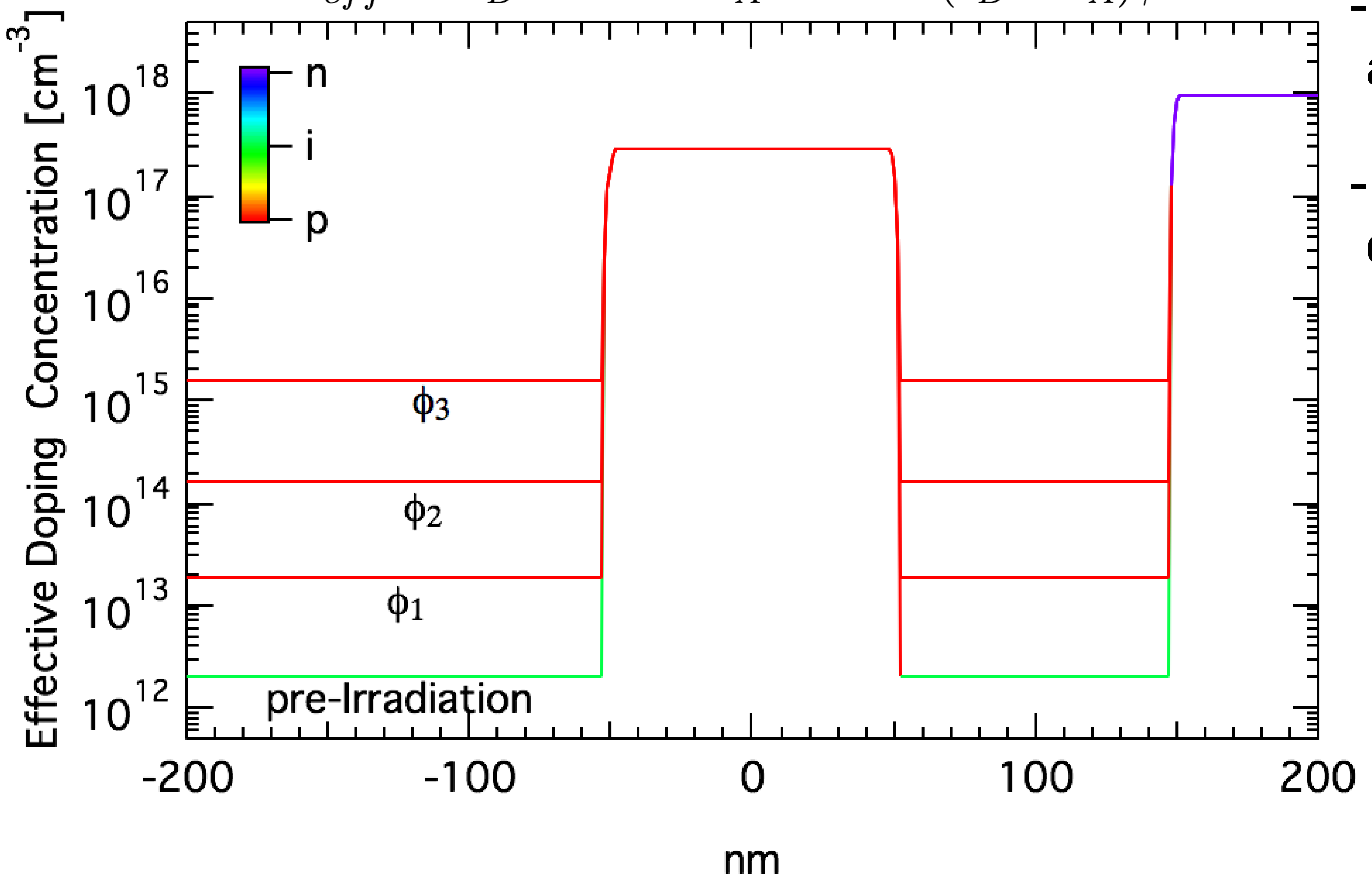
$$\frac{dn}{dt} = (G_n - R_n) + \nabla \cdot J_n = (G_n - R_n) + \nabla \cdot (\mu_n n E + q D_n \nabla n)$$

$$\frac{dp}{dt} = (G_p - R_p) + \nabla \cdot J_p = (G_p - R_p) + \nabla \cdot (\mu_p p E + q D_p \nabla p)$$

- First attempt at modeling the affect of radiation on the material is to include these defect levels and see what happens to the free carrier concentrations

Proof of priniciple : Evaluating how radiation affects the performance of these devices?

$$N_{eff} = N_D e^{-c_D \phi} - N_A e^{-c_A \phi} + (b_D - b_A)\phi$$

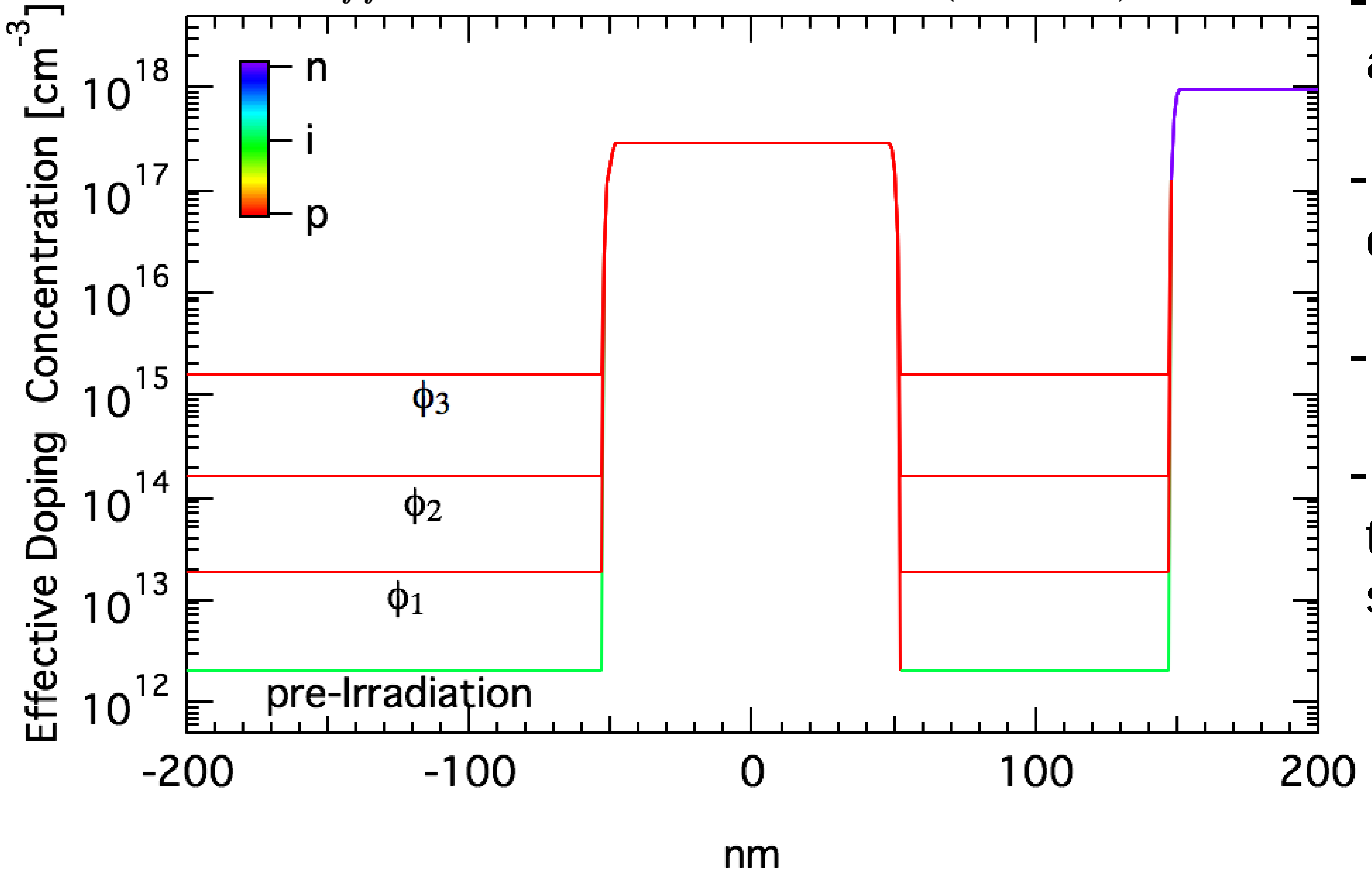


- So simulation models the change in effective doping concentration as the level of defects increases

- Can we see an effect in the leakage current/hole and electron densities?

Proof of priniciple : Evaluating how radiation affects the performance of these devices?

$$N_{eff} = N_D e^{-c_D \phi} - N_A e^{-c_A \phi} + (b_D - b_A)\phi$$

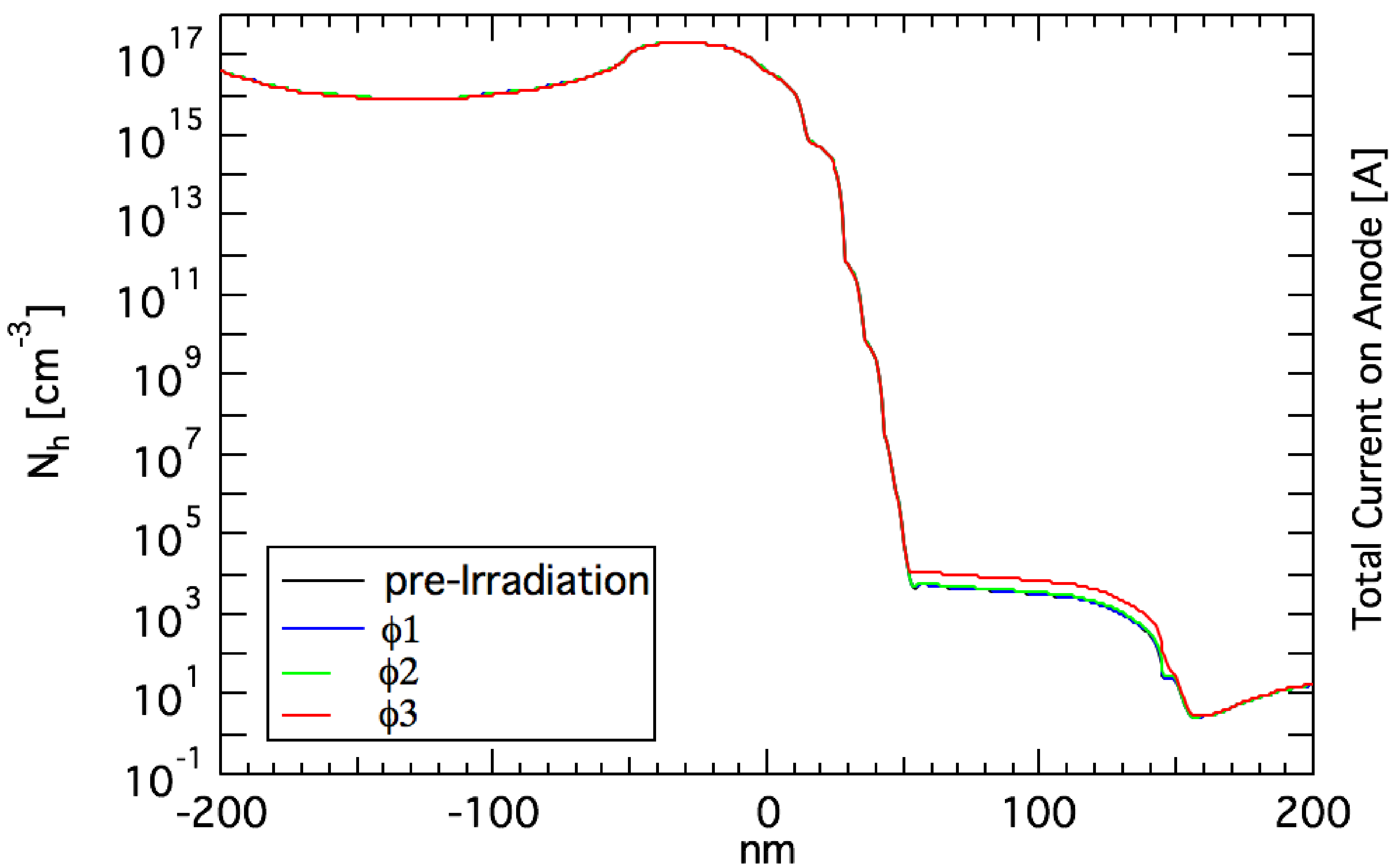


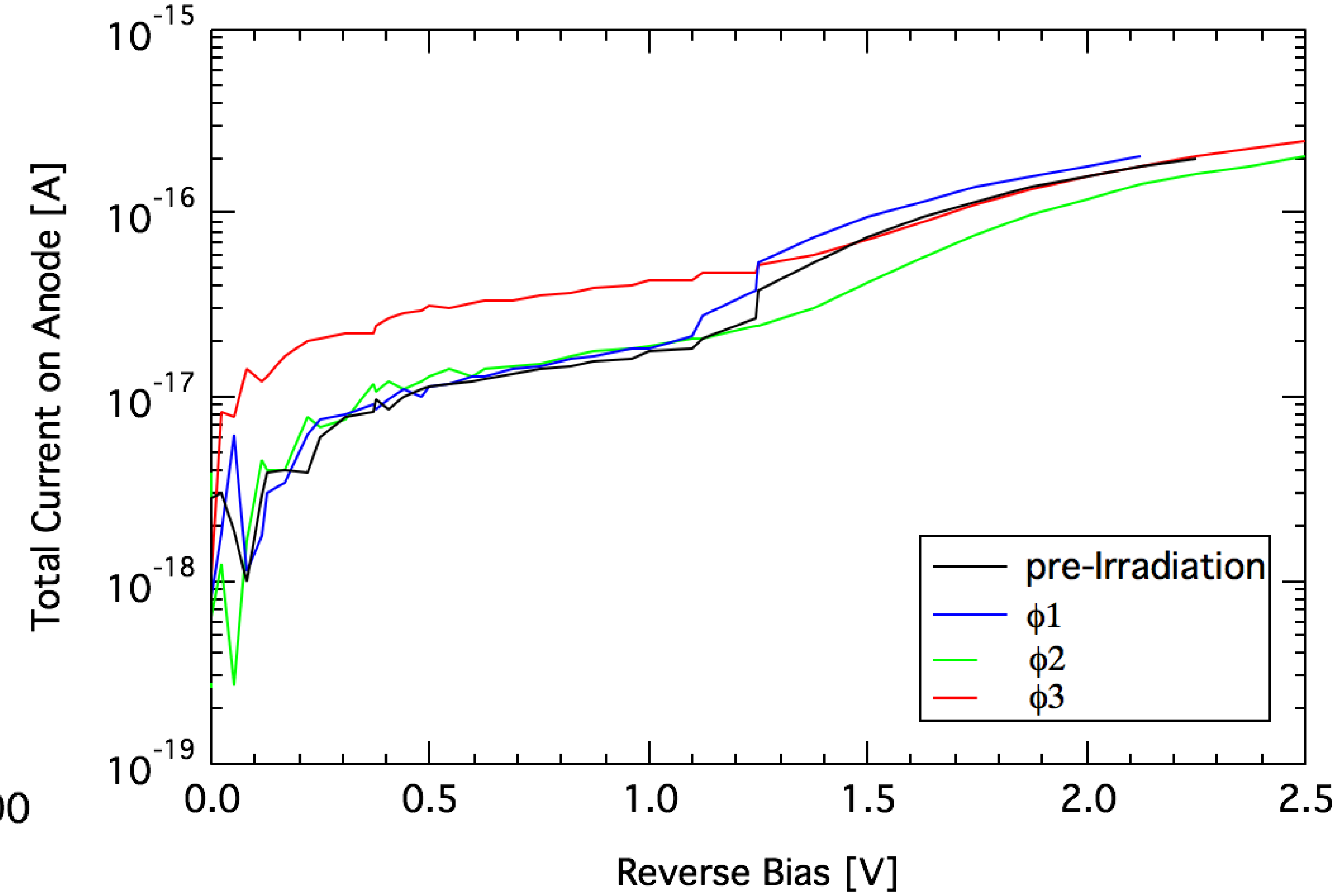
- So simulation models the change in effective doping concentration as the level of defects increases

- Can we see an effect in the leakage current/hole and electron densities?

- Yes... eventually but not in the expected way - and its very small.

- Still working on this - but in principle the simulation tool can be used to predict the behavior of the devices after irradiation in the manner shown here.





Conclusions & Future Work

- Starting to investigate the potential of using silicon-based optoelectronic devices in HEP like environments, starting with the impact of radiation on the DC characteristics of some si-based optoelectronic components :
  - ICE-DIP *http://openlab.web.cern.ch/ice-dip* , an Intel-CERN Doctoral Student Industrial Program (within the FP7 framework) :
    - project dedicated to the use of silicon photonics technology in data transfer systems.
    - Early Stage Researcher starting next week, spending time between CERN , Dublin City University, and Intel
    - ESR will work with Intel on designing the building blocks of a si-photonics link, where the effect of the harsh radiation environment at the HL-LHC will be investigated and used to modify the design
- Difficulties in pig-tailing the devices has meant that only DC tests have been possible so far. Should receive some pig-tailed samples of SOI-based modulators to irradiate at a total fluence test at the end of this year.
- Simulation tools are available which allow us to predict the effect of radiation on these types of devices, make use of the wide knowledge base available for radiation damage in silicon