Advancing Gravitational-Wave Detection Through Ion Implantation for Low Thermal Noise Coatings

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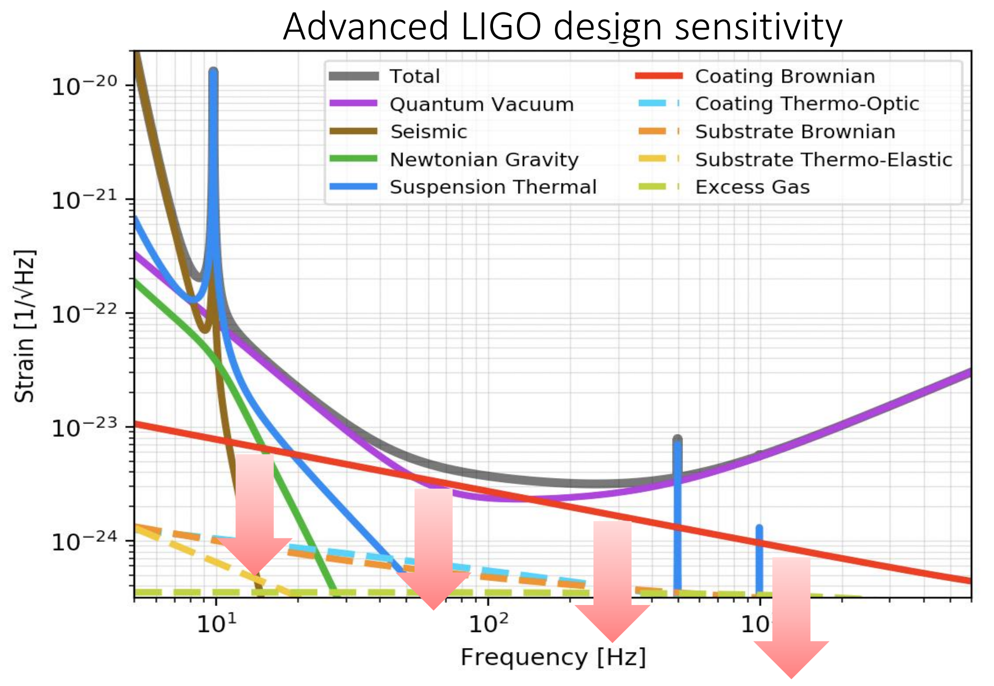
Next-Generation GW Detectors and Coating Thermal Noise

- Aim for a factor 10 improvement at mid and high frequencies
  → ET-HF: room temperature and high laser power

- Low frequencies: improvement of a factor of 100 to 1000
  → ET-LF: low temperature and low laser power



Credit: PyGWINC - https://git.ligo.org/gwinc/pygwinc

mirror temperature

mirror thickness

$$\mathrm{CTN} = \sqrt{\frac{4k_B T}{\pi^2 f w^2 Y_{\mathrm{sub}}}\, d\phi \left[\frac{Y_{\mathrm{coat}}}{Y_{\mathrm{sub}}} + \frac{Y_{\mathrm{sub}}}{Y_{\mathrm{coat}}}\right]}$$

beam radius (on mirror)

coating mechanical loss

Coating thermal noise (CTN)

- ➢ Lower for larger beams
- ➢ Determined by material properties
- ➢ Frequency dependent: more prominent at low frequencies
- ➢ Temperature dependent → motivation for using silicon mirror substrates in ET-LF (+ better coatings)
- ➢ Lower for thinner coatings

New approach for coatings development

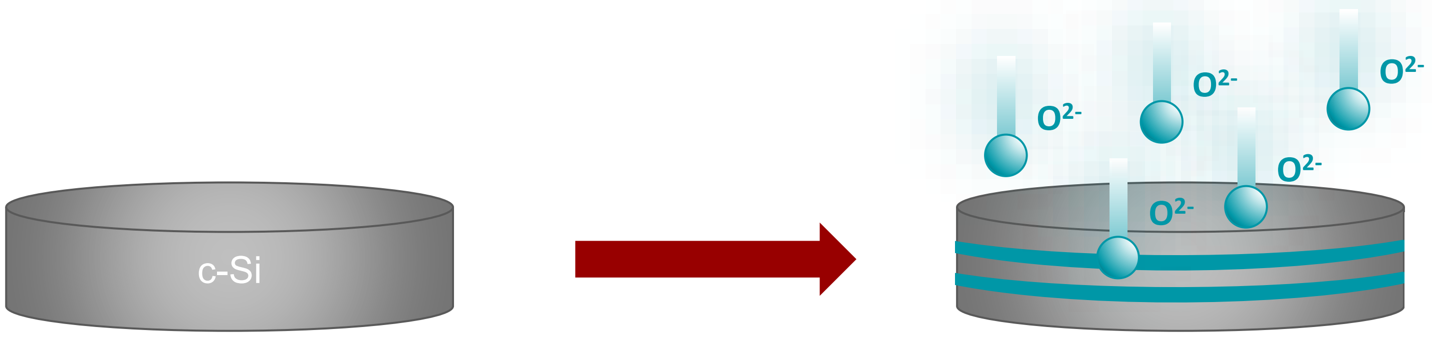
- Use the crystalline silicon mirror substrate to form some of the layers:
  excellent optical and thermal noise properties (high refractive index)

- Implant oxygen or nitrogen ions to form silica (SiO_2) or silicon nitride (SiN) layers:
  SiN is one of the most promising amorphous materials (low refractive index)

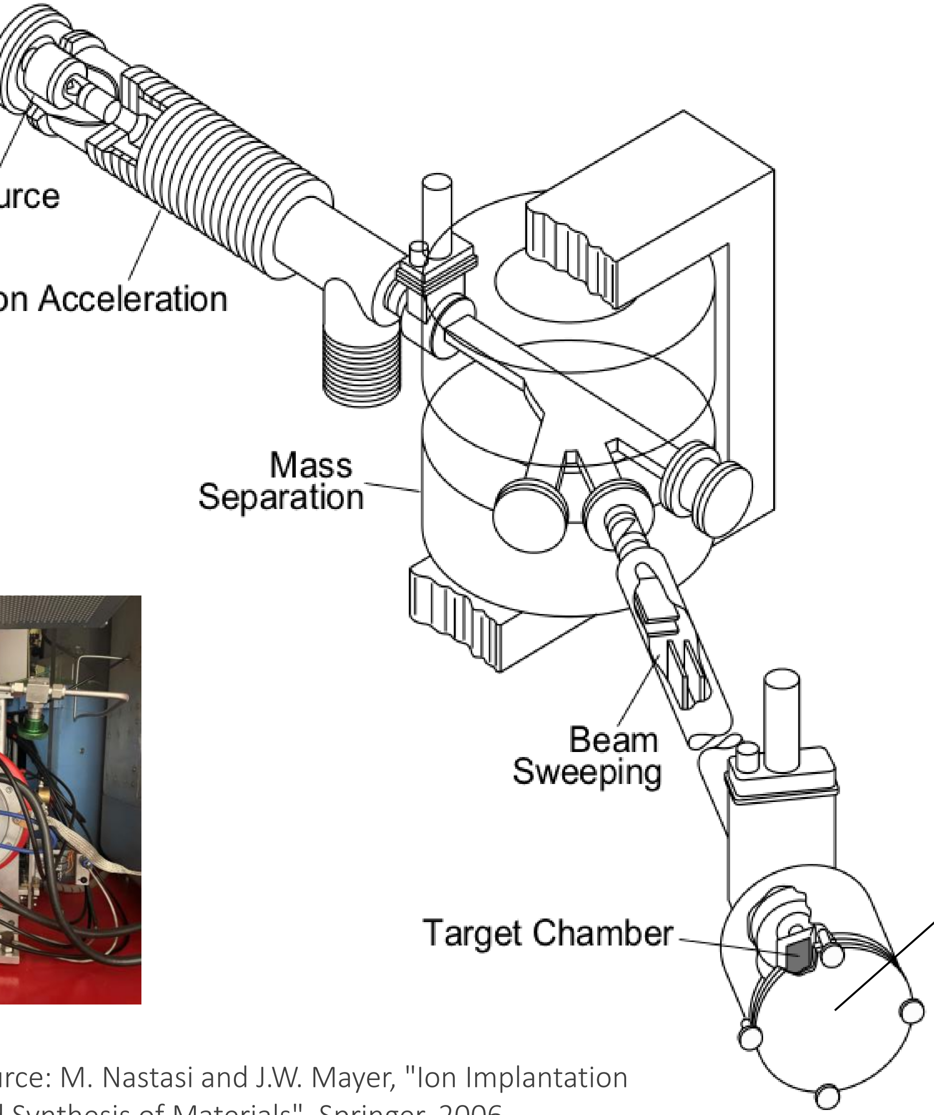
- Preserving the low absorption and mechanical loss of crystalline silicon while creating a reflective stack

- High refractive index contrast ($\Delta n = 3.48 – 2.05 = 1.43$ @ 1550 nm)

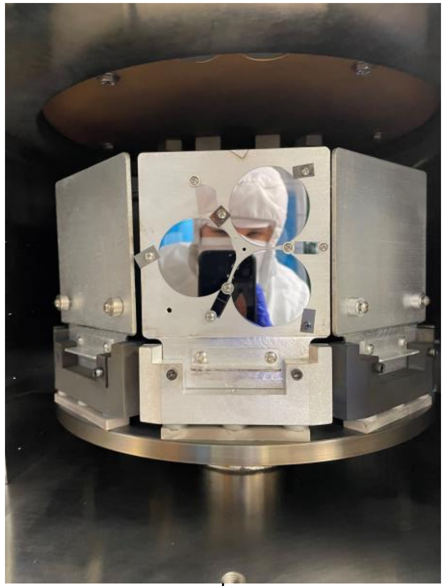
- Solves size issues of ‘externally grown’ single-crystalline coatings



How ion implantation works



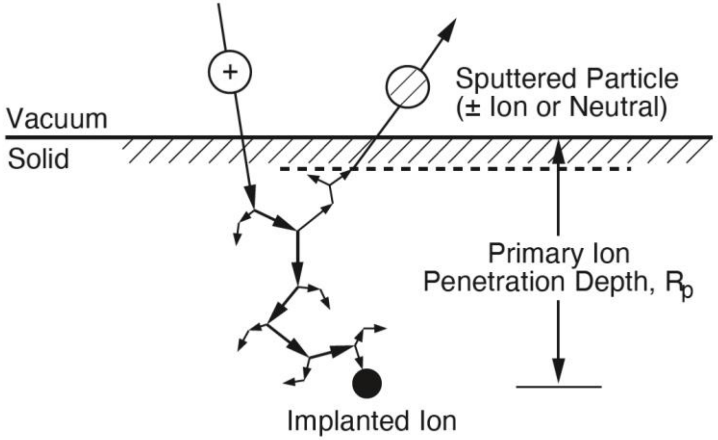
Source: M. Nastasi and J.W. Mayer, "Ion Implantation and Synthesis of Materials", Springer, 2006.



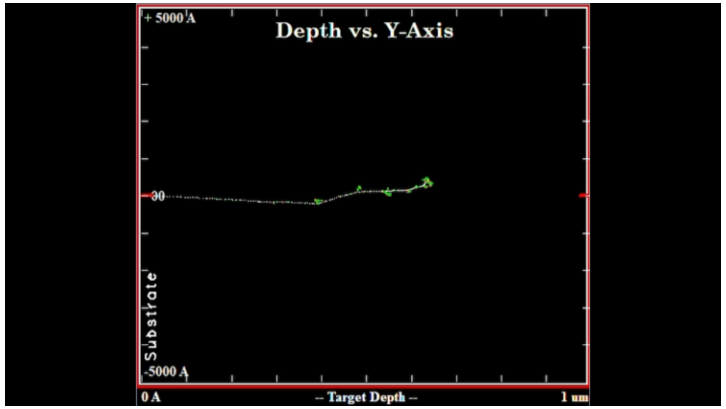
SRIM simulations

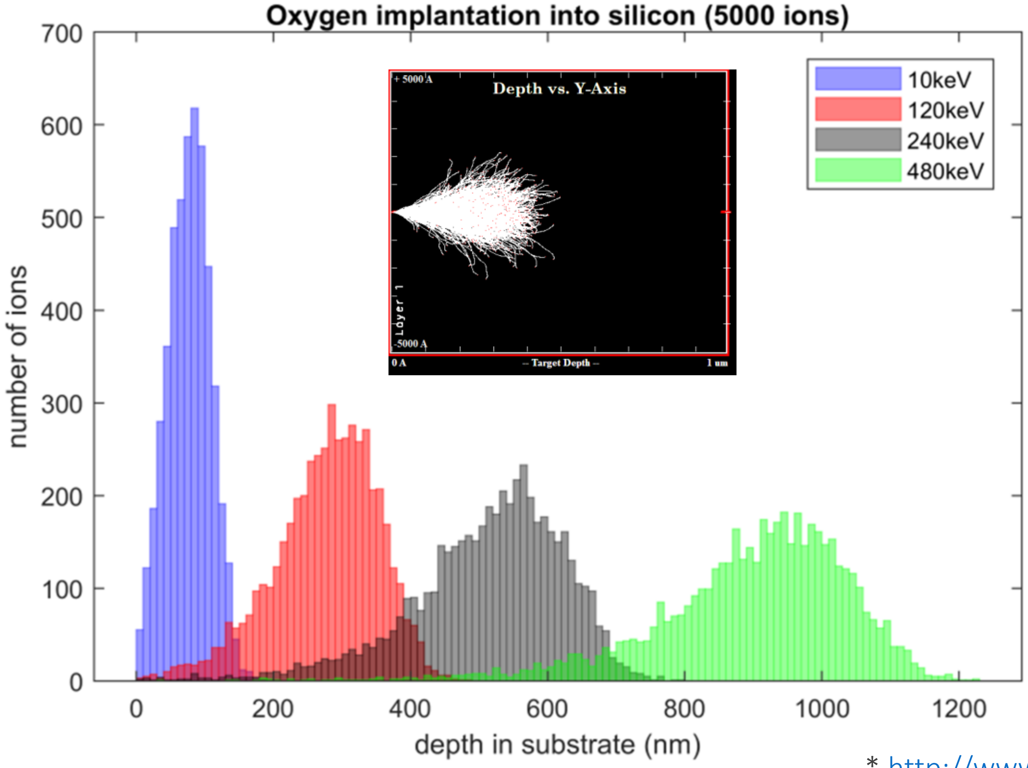
- Simulations are performed using SRIM (Stopping Range of Ions in Matter) software package*

- Monte Carlo simulations to calculate trajectories, energy loss, and implantation profiles



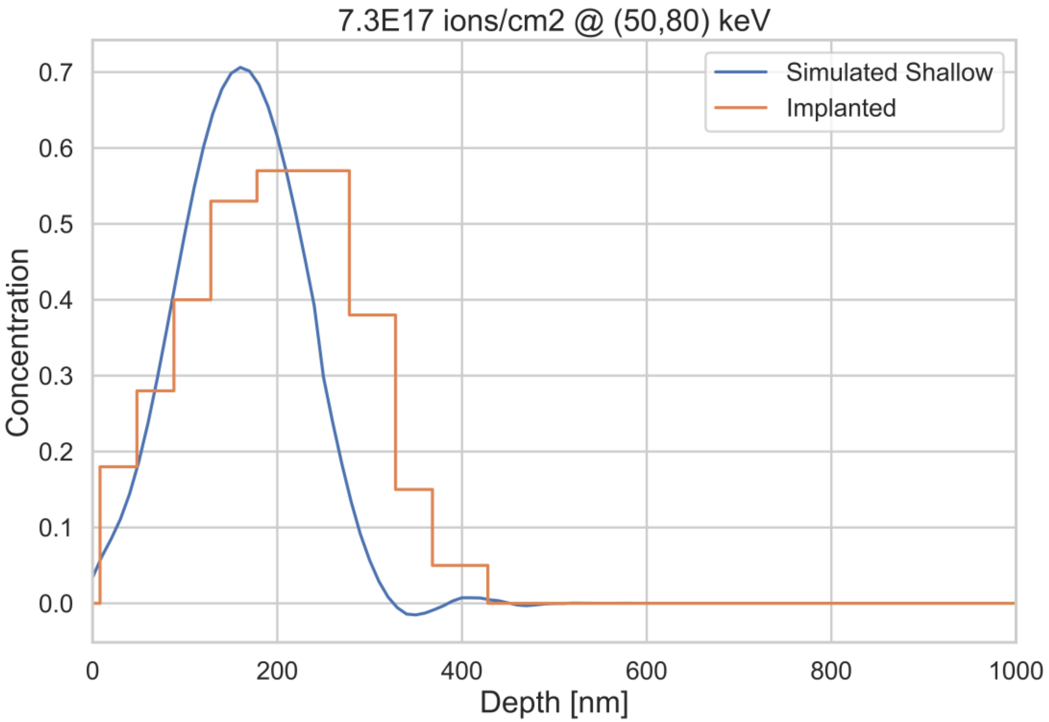
- The ion is colliding with substrate atoms until all the kinetic energy is transferred, stopping it at an energy-dependent depth



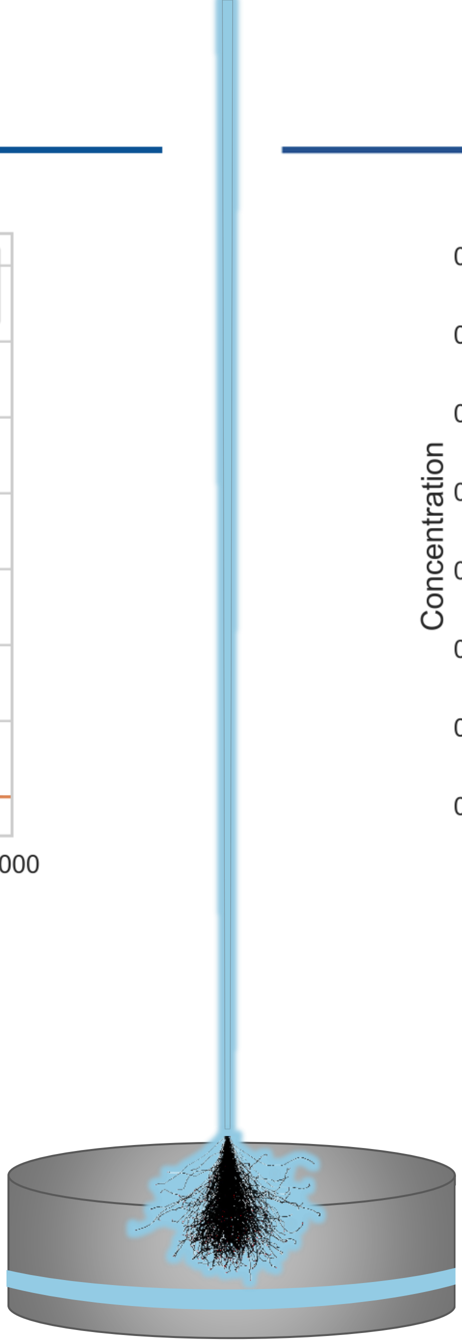


* http://www.srim.org/

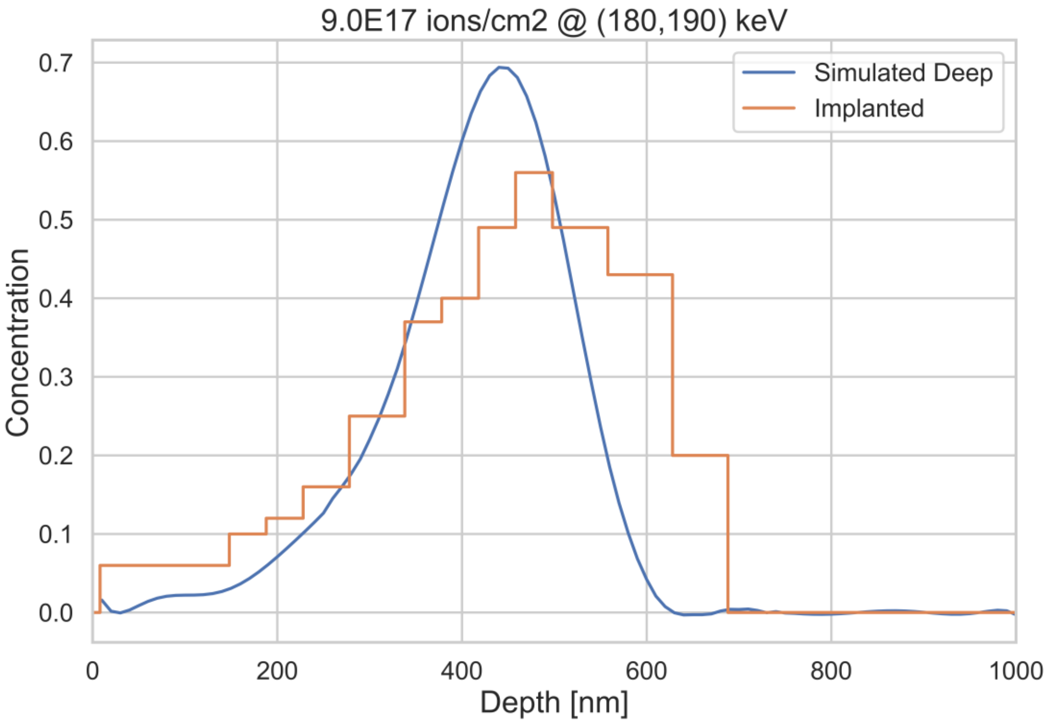
SiO_2 shallow layer



	SRIM	RBS
Depth [nm]	168	199
Thickness [nm]	190	230

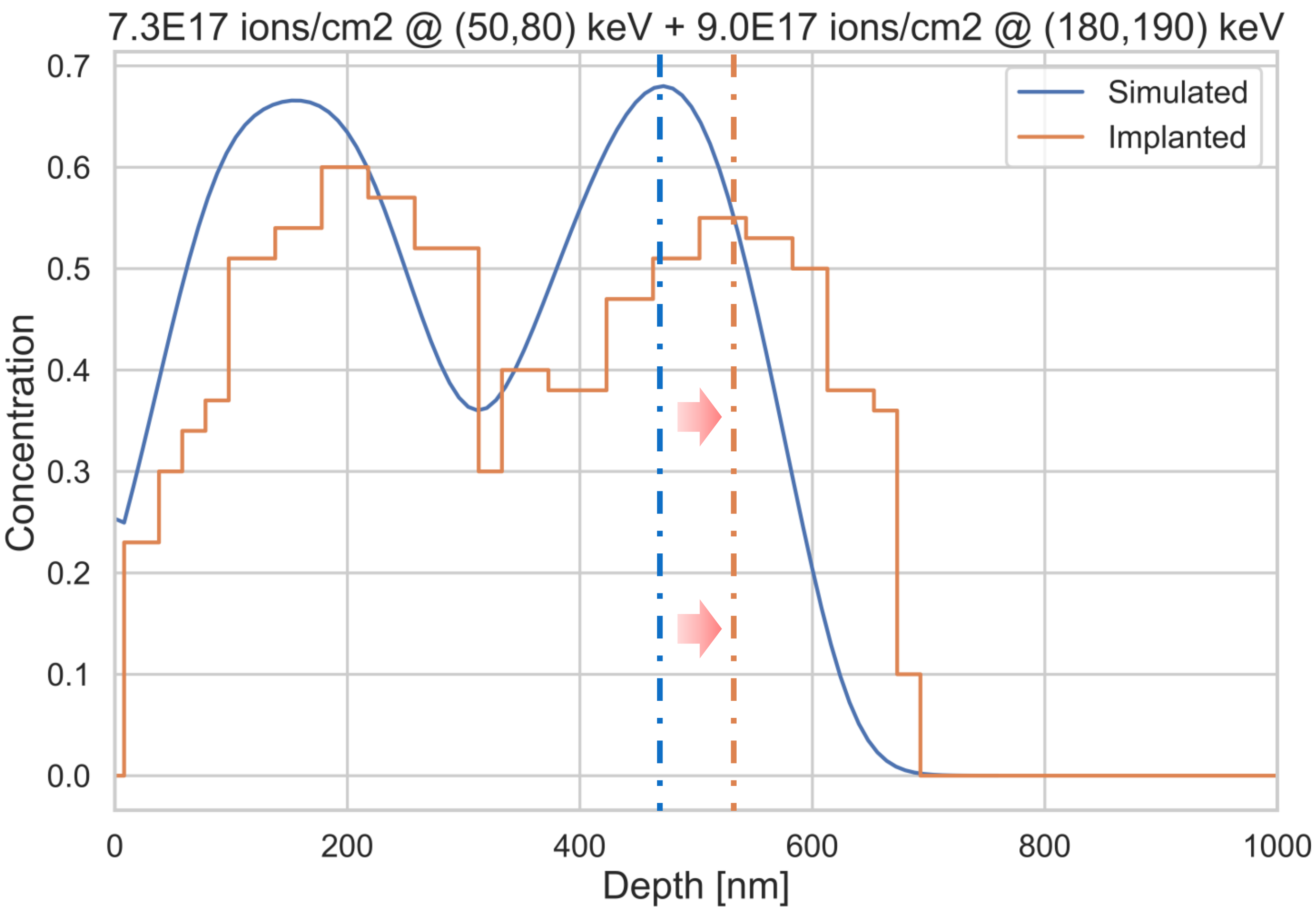


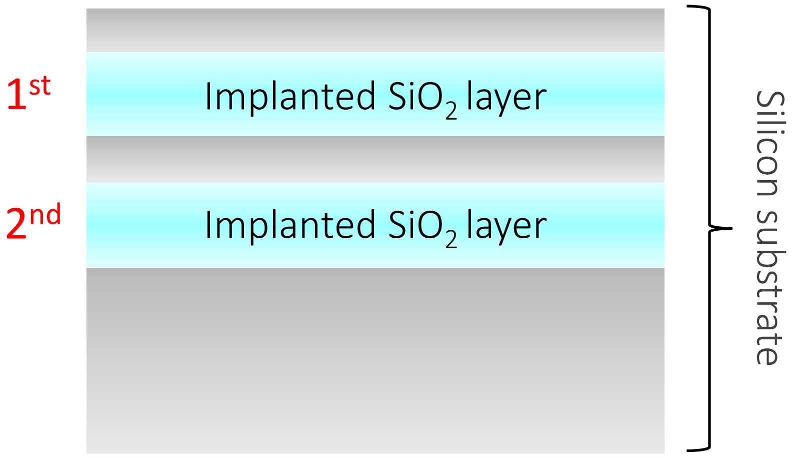
SiO_2 deeper layer



	SRIM	RBS
Depth [nm]	448	475
Thickness [nm]	220	280

Double SiO_2 layer – Shallow layer first

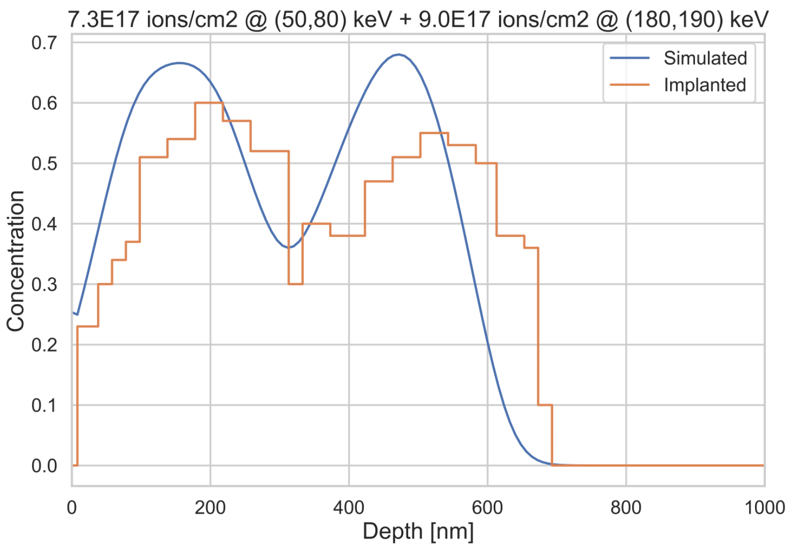


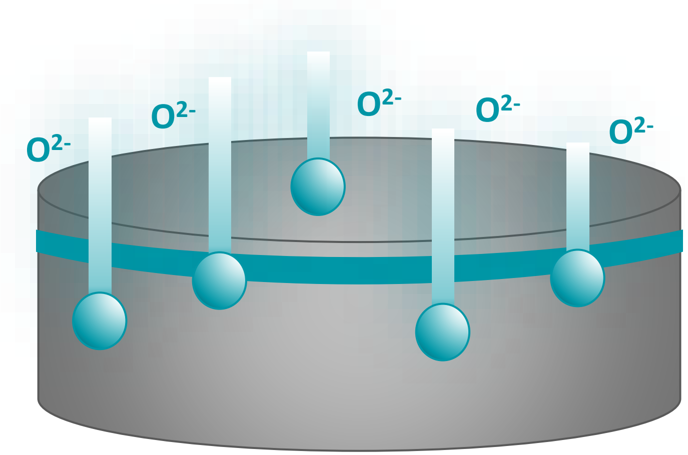


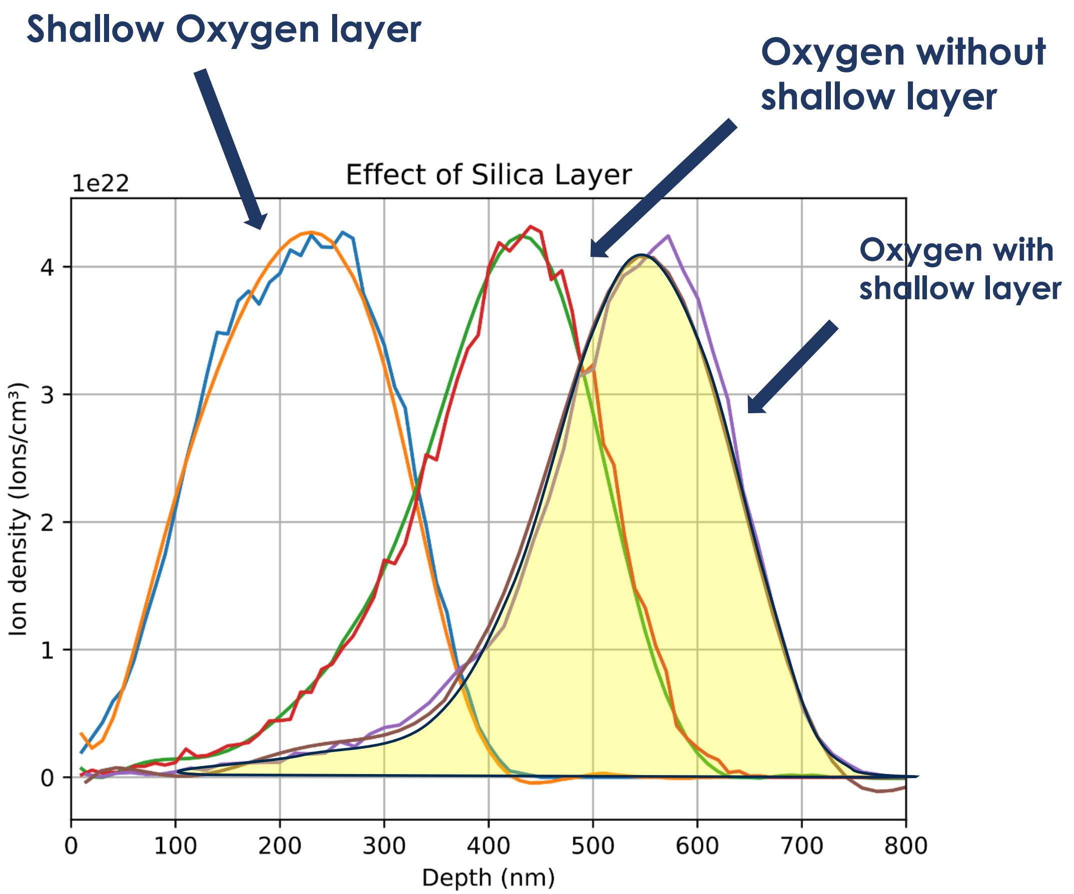
[nm]	SRIM	RBS
$Depth_{shallow}$	160	194
$Thickness_{shallow}$	220	260
$Depth_{deeper}$	450	531
$Thickness_{deeper}$	240	350

N.B. With different parameters (e.g. higher energies) it's possible to achieve a better profile separation.

Shallow layer effect

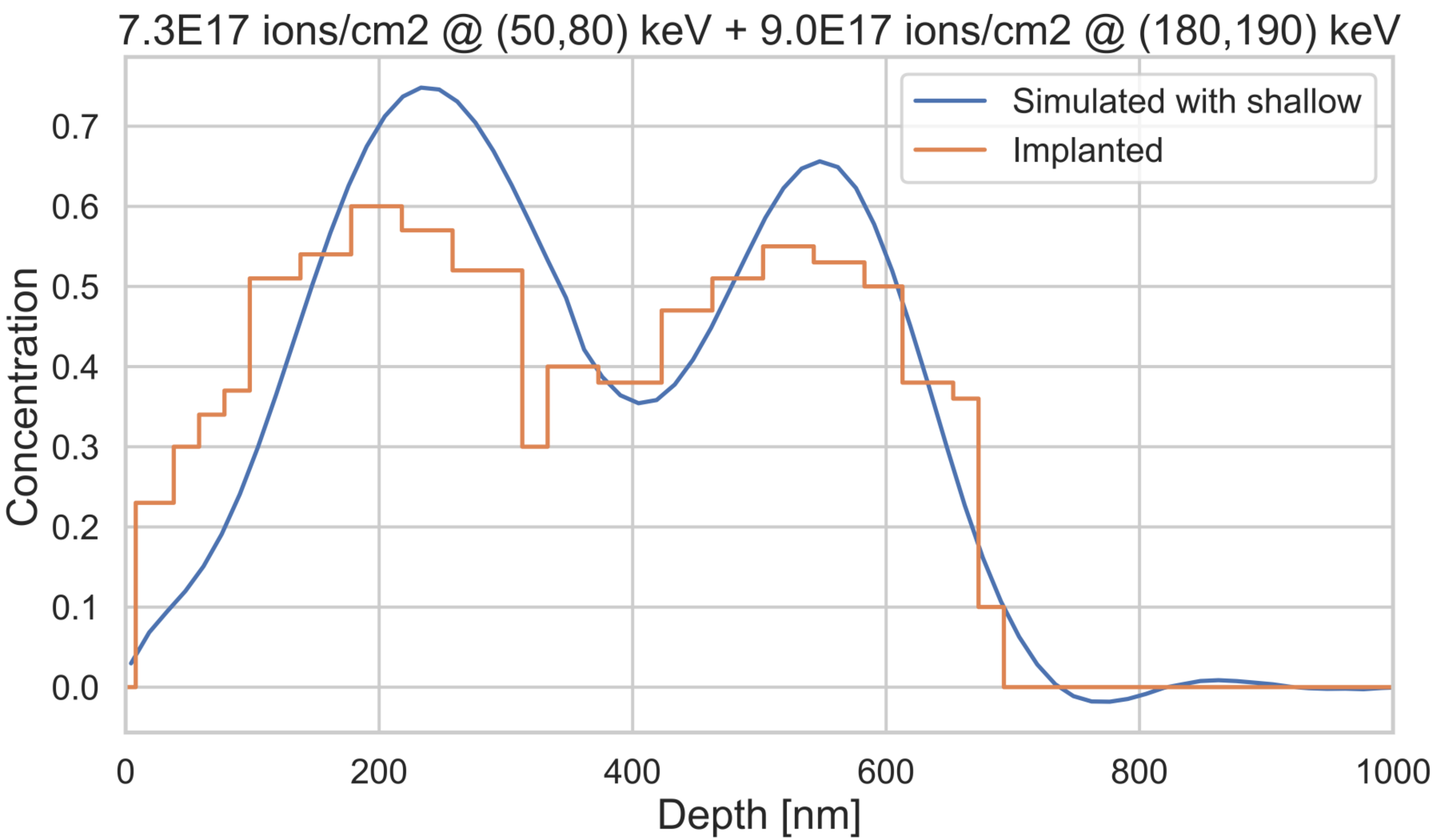






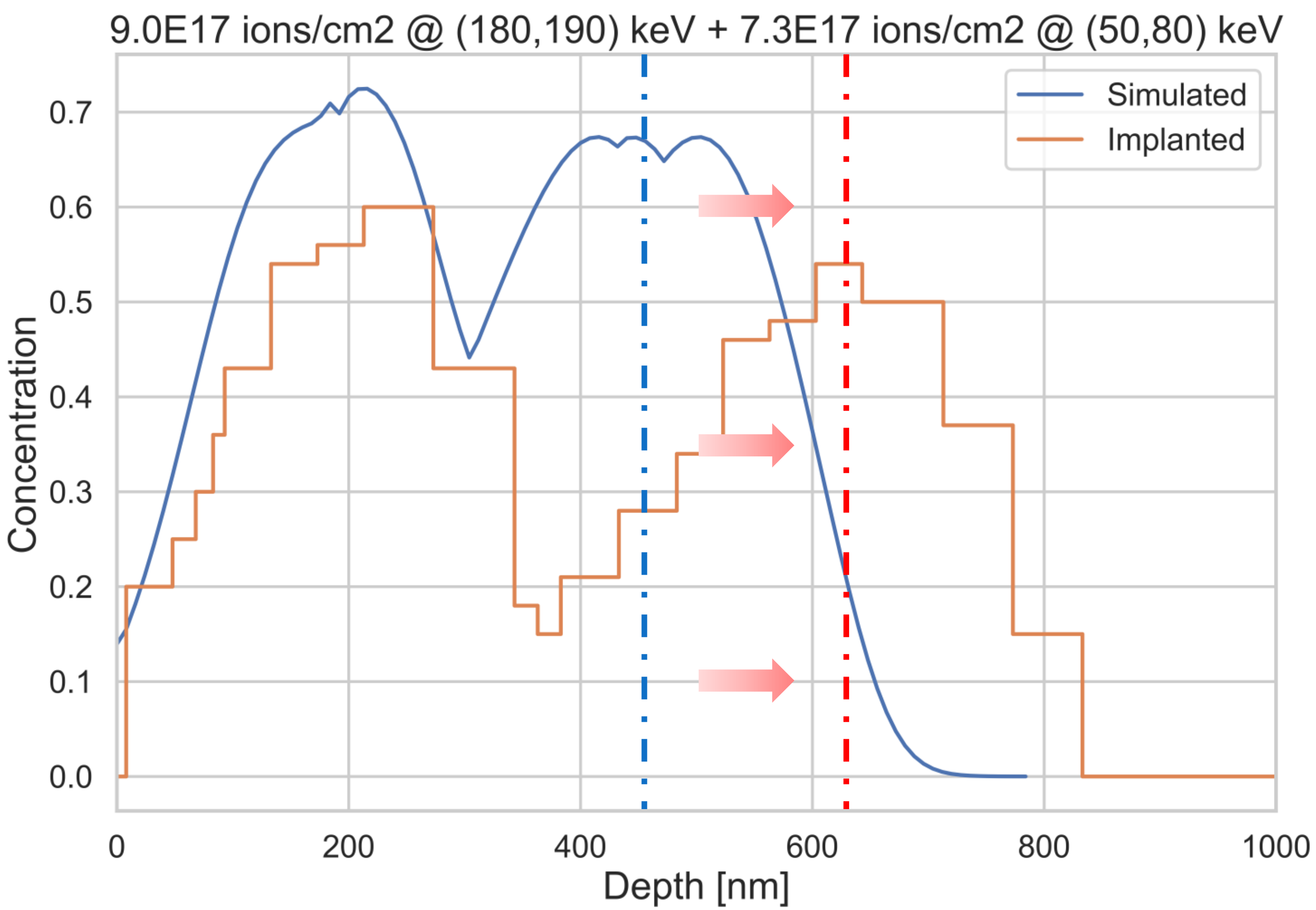
When implanting a shallow oxygen layer into silicon, a deeper layer requires less energy because the implanted material has less resistance for implantation.

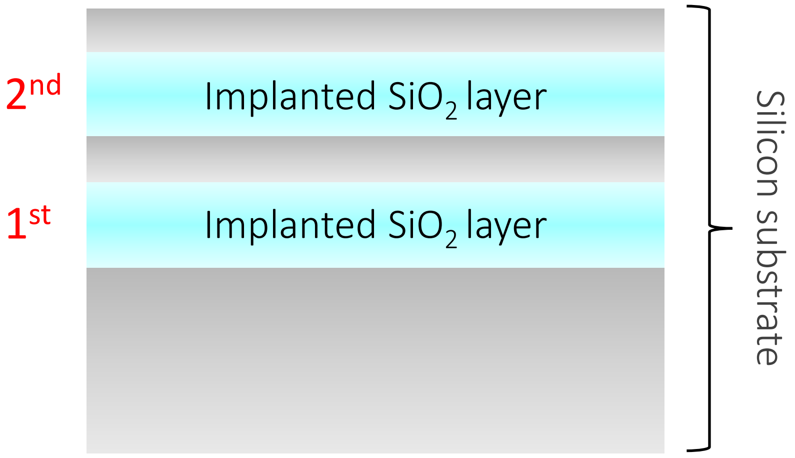
Double SiO_2 layer – Shallow layer first



- ✓ SRIM model considering a shallow layer already implanted gives matching depth for the high energy layer.

Double SiO_2 layer – Deeper layer first





[nm]	SRIM	RBS
$Depth_{shallow}$	190	198
$Thickness_{shallow}$	250	270
$Depth_{deeper}$	460	621
$Thickness_{deeper}$	300	330

High energy layer is deeper than predictions even without interaction with the shallow layer.

Sample expansion

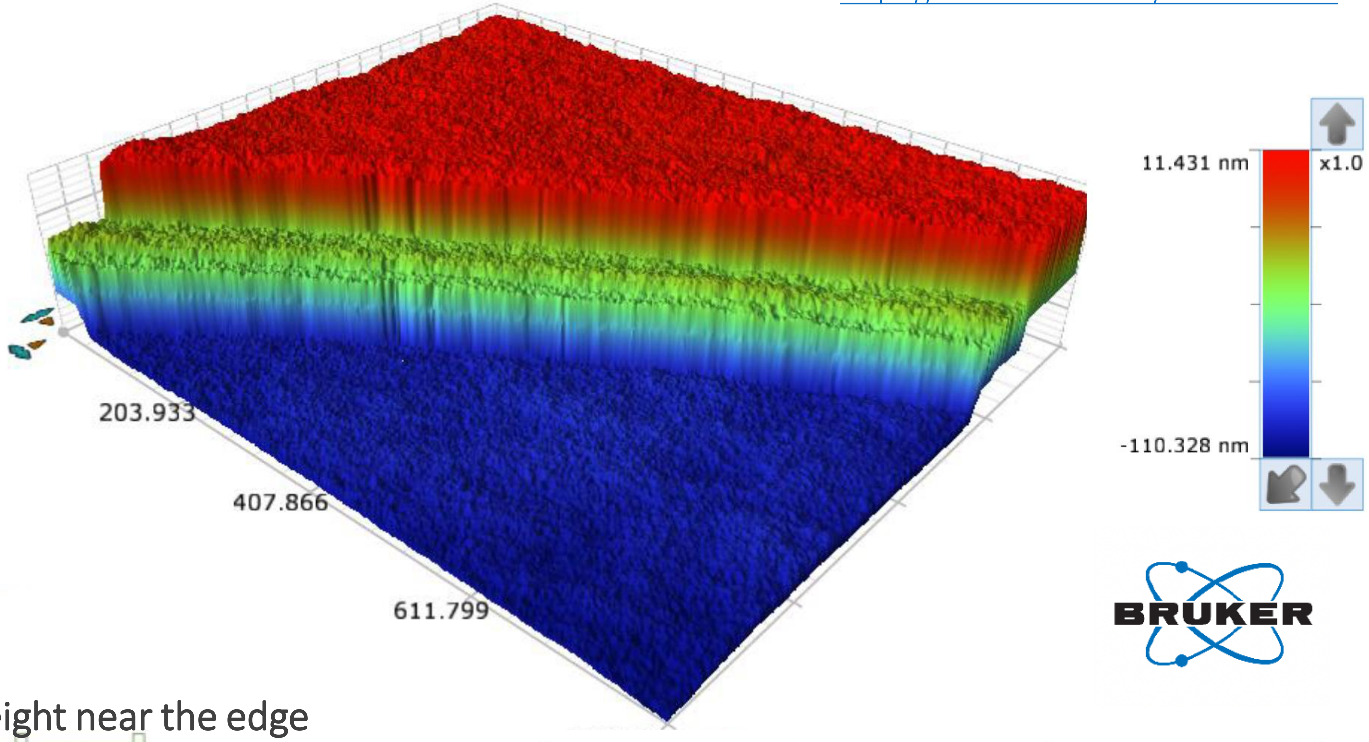
* https://www.bruker.com/contourx-200

➢ Bruker surface metrology tool Contour X-200*

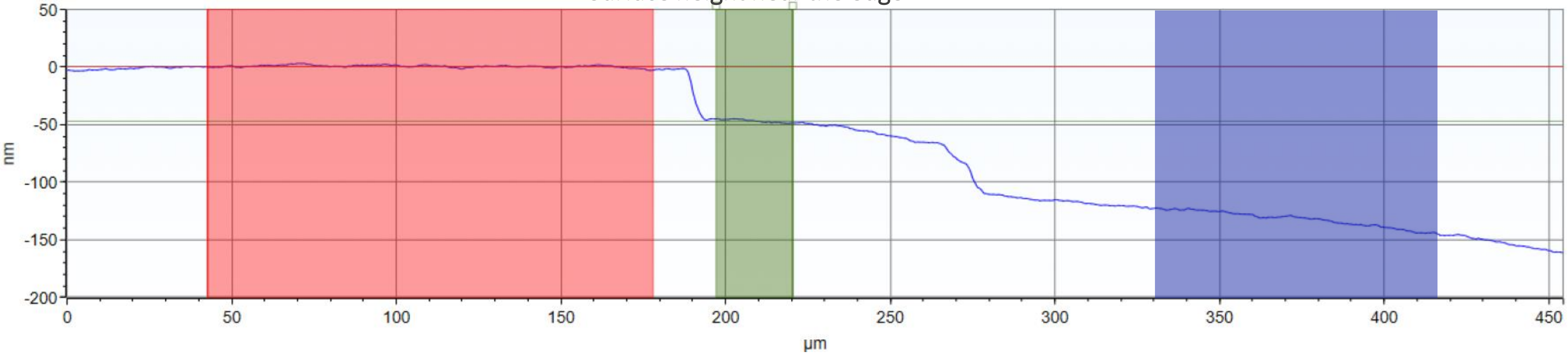
➢ High doses of ions implanted results in a sample expansion

$$|\Delta Z_{shallow}| \cong 48\ \mathrm{nm} \ - \ 7.3\mathrm{E}17\ \mathrm{ions/cm^2}$$

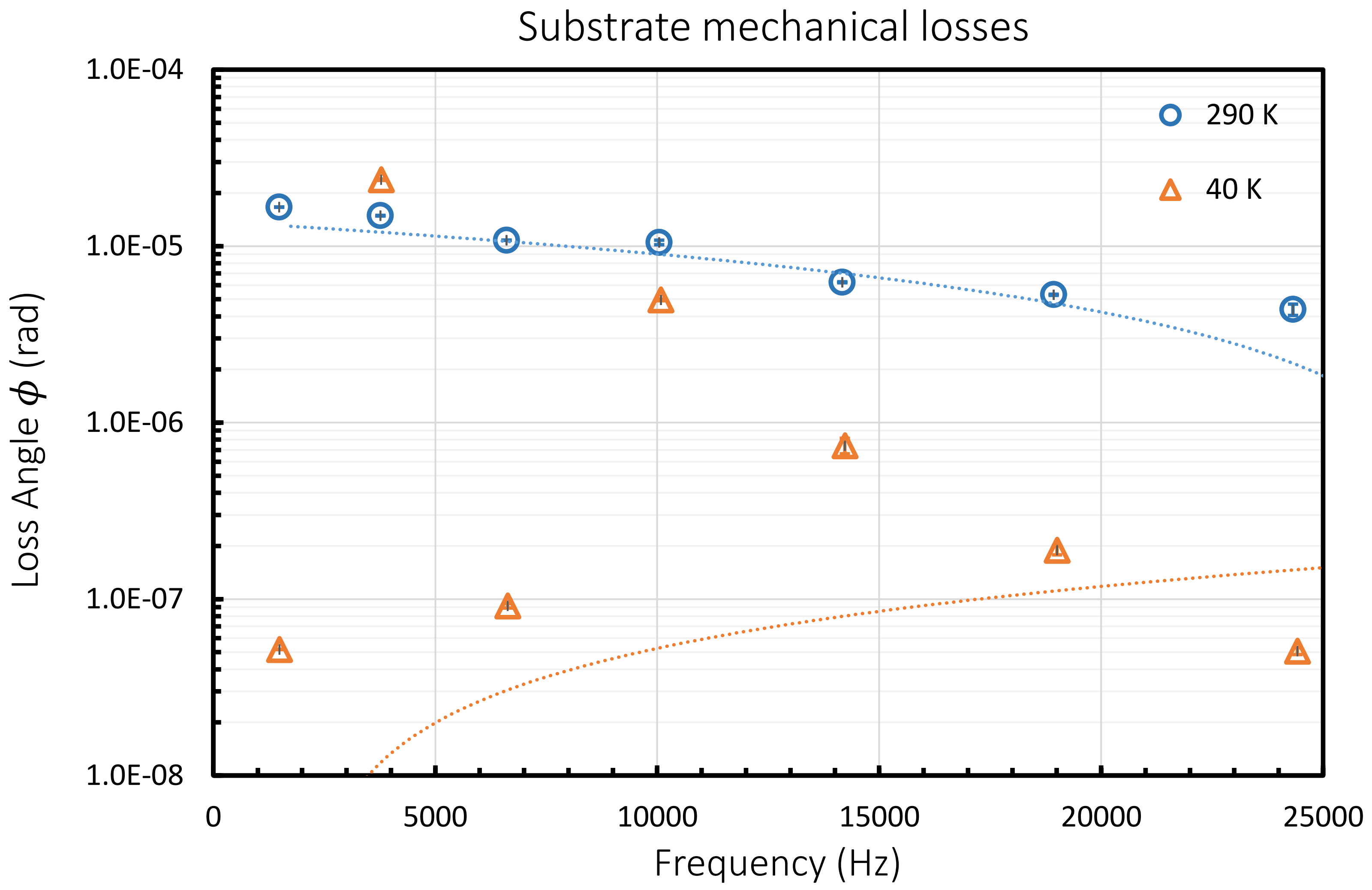
$$|\Delta Z_{deeper}| \cong 87\ \mathrm{nm} \ - \ 9.0\mathrm{E}17\ \mathrm{ions/cm^2}$$

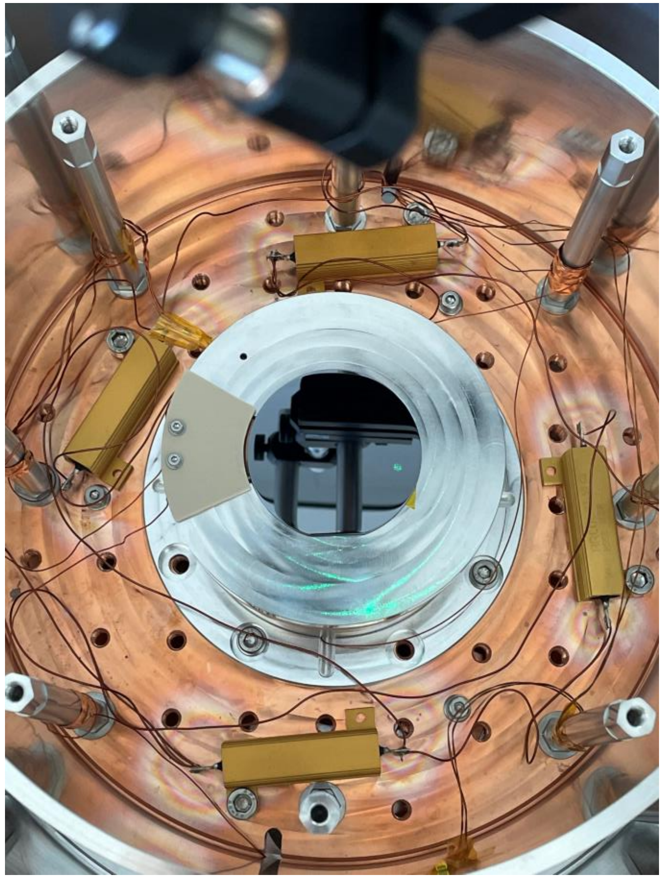


Surface height near the edge



Mechanical losses





Summary

- Successfully implanted several samples to form SiO_2 and SiN layers
- Single and double implanted layers agree with simulations (shall layer effect and sample expansion)
- Three layers design in progress
- Mechanical loss measurements at cryogenic temperatures
- Development of a heat treatment procedure and optical characterization (see Ismail's talk)

Questions?