Interstrip Isolation of p-type Strip Sensors

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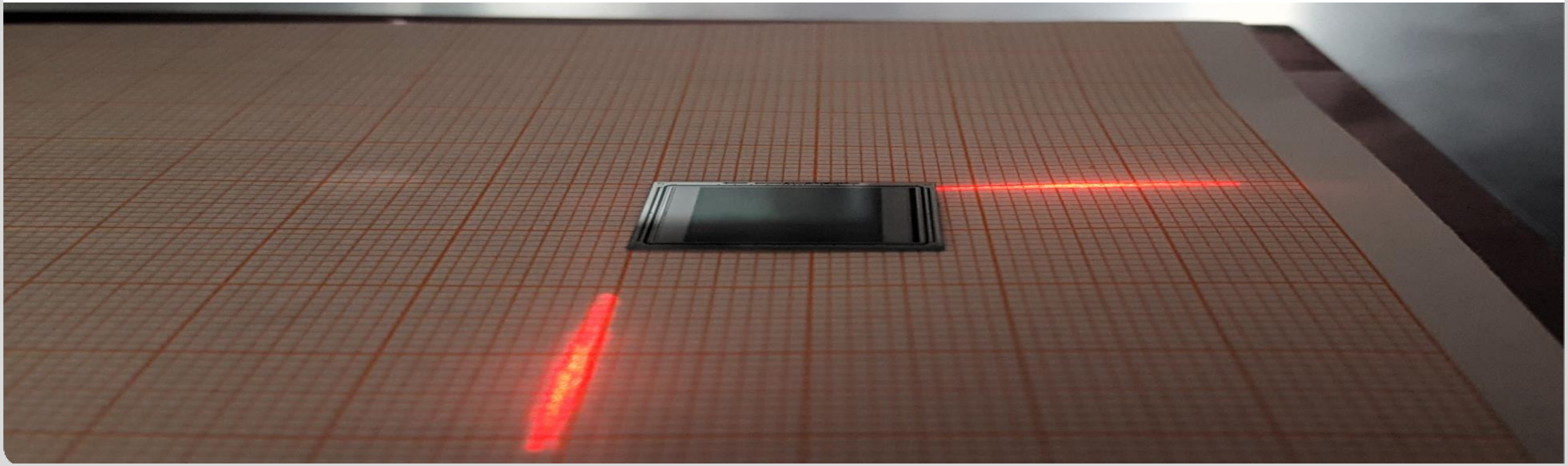
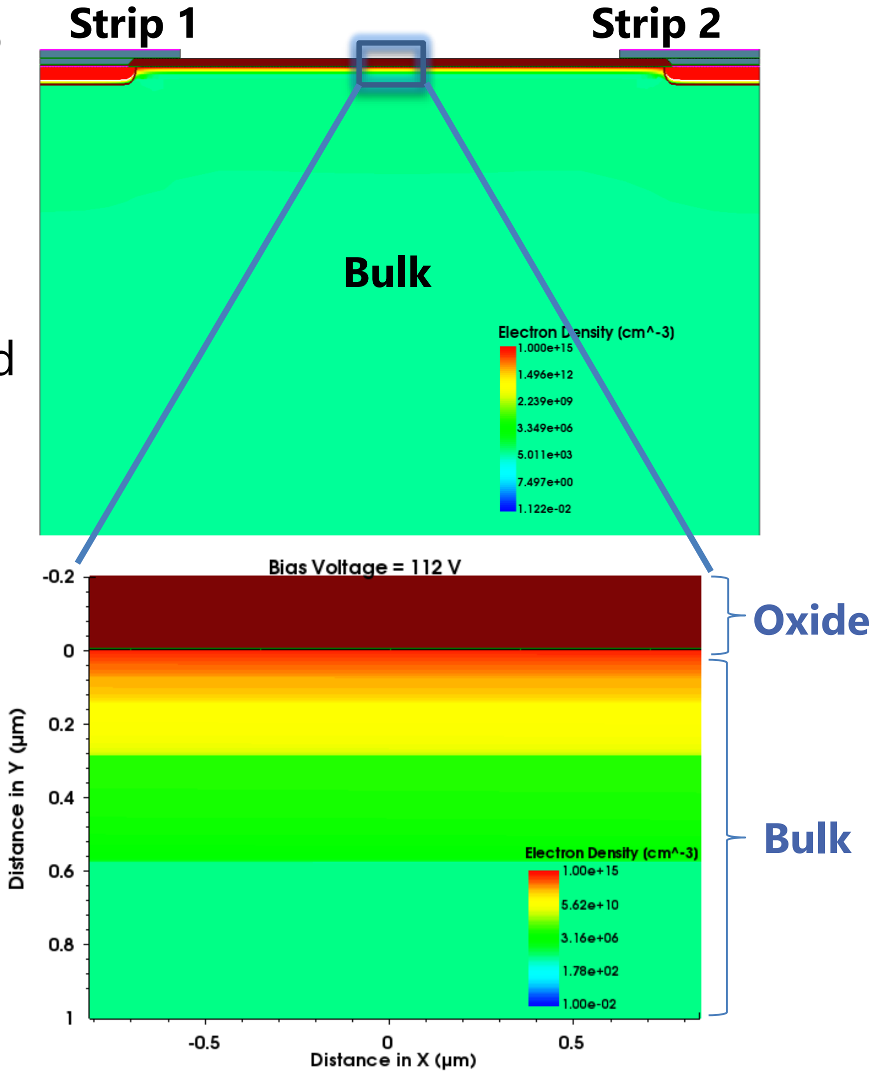
Institute of Experimental Particle Physics (ETP)



Introduction

- General understanding regarding the strip isolation of n-in-p sensors:
  - Positive oxide charge in the **SiO_2 surface (brown layer)**
    → Interstrip isolation implant required (e.g. p-stop/common or p-spray)
  - Without isolation structure
    → Formation of an electron accumulation layer
    → Short-circuited strips (decrease of spatial resolution)



Previous Investigations

- Proven that sensors with p-stop (or p-spray) structure are functional [1]
    - Before and after irradiation
- Sensors **without any specific isolation process**
    - Irradiated with 7 x 10^{14} n_{eq} cm^{-2} protons
    - High interstrip resistance (R_{int}) observed [2]

      → Not explainable with the intuitive understanding
- Attempts to explain and simulate the observation (e.g. [3])
    - Irradiation generates surface-near acceptor states (bulk defects)

    → Build-up of negative charge prevents the electron accumulation
- Further understanding required
    - Interplay of surface and bulk damage → **New irradiation study**

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[1] M. Printz, PhD Thesis, EKP-2016-00009
[2] Y. Unno et al NIMA.2007.05.256
[3] R. Dalal et al. 2014 JINST 9 P04007

Comprehensive Irradiation Study

- Study with **sensors without any isolation implant** (small test-sensor placed on CMS Tracker prototype wafers from HPK)
- Comprehensive irradiations with x-rays, protons and neutrons
  - Emulate pure surface damage with x-rays
  - Interplay of surface and bulk damage with protons and neutrons
  - Interstrip resistance measurements to qualify the isolation
- **Reproduce and understand** the results with the help of simulations!

	X-Rays	**Protons**	**Neutrons**
Facility	X-ray tube (KIT)	ZAG (KIT)	Reactor (JSI, Ljubljana)
Energy	U_{tube} = 60kV	≈ 23 MeV Hardness factor ≈ 2	Continuous spectrum [http://www-f9.ijs.si/~mandic/ReacSetup.html]
Radiation Damage	Surface damage	Bulk and surface damage (150 kGy per 1 x 10^{14} n_{eq} cm^{-2})	Bulk and surface damage (1 kGy per 1 x 10^{14} n_{eq} cm^{-2})

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Interstrip Resistance before Irradiation

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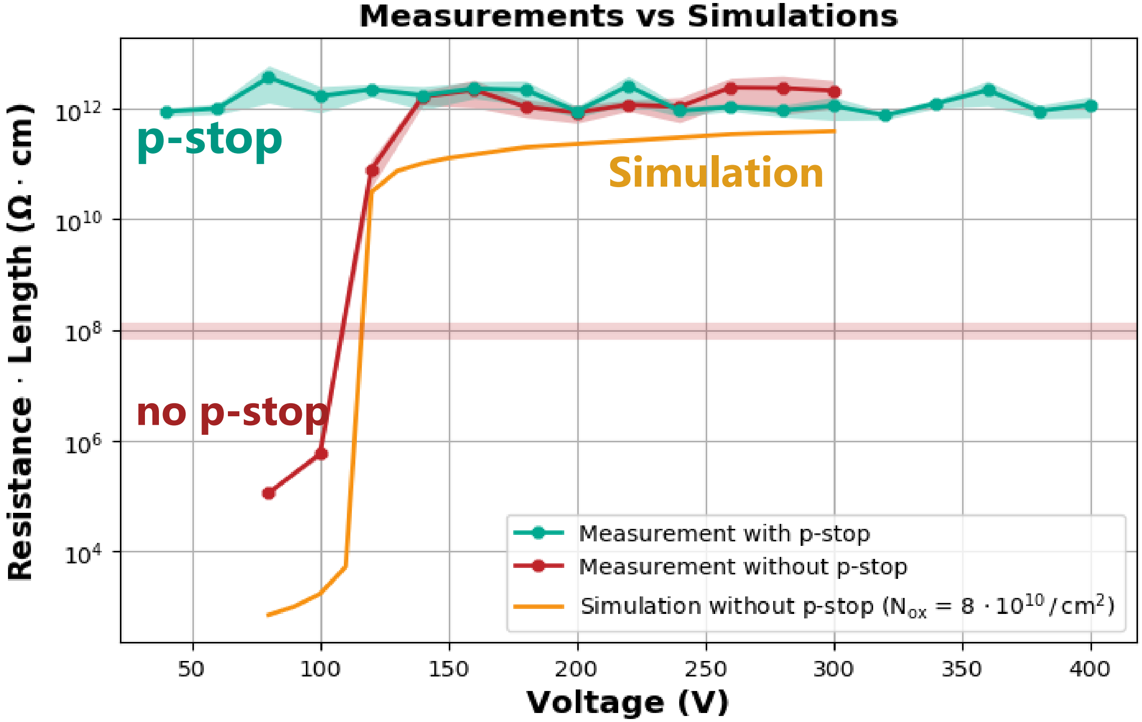
Voltage Dependence of Interstrip Resistance

- Interstrip resistance measured with a small interstrip bias and current measurement
- Sensor **without interstrip implant** shows a rise of six orders of magnitude of the interstrip resistance above roughly 100 V to a **sufficient level** (approximation)
- **Simulated behaviour** fits with fixed oxide charge $N_{ox} = 8 \times 10^{10} cm^{-2}$
- Comparison: **P-stop** ($N_{dop} \approx$ 4-5 $\times 10^{15}/cm^3$) beneficial for low bias voltages ($V_{fd} \approx 300$ V)



← Lower limit for a sufficient strip isolation

Simulations with Synopsys - Sentaurus

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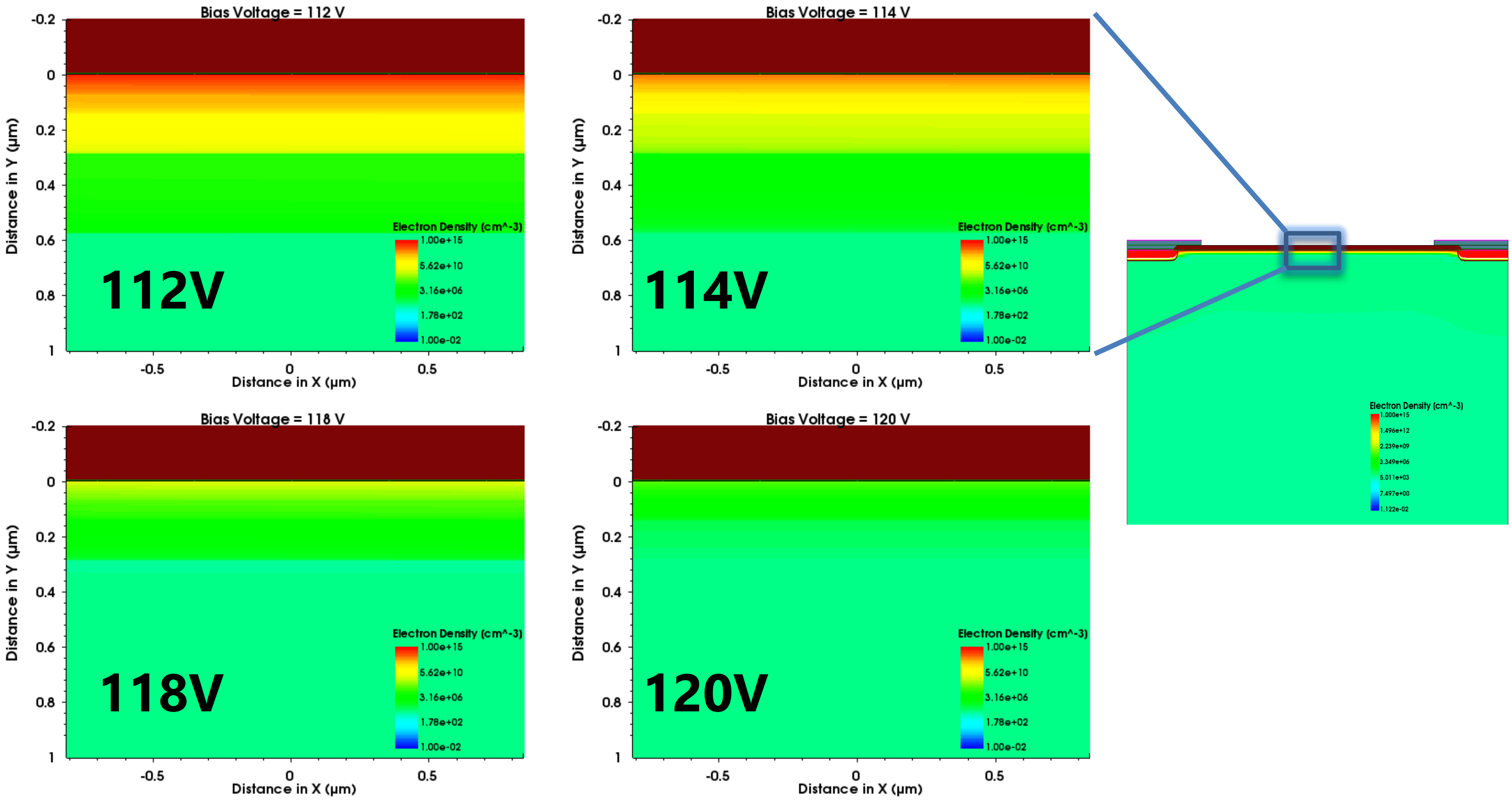
Destruction of Electron Accumulation Layer



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Interstrip Resistance after Irradiation

Start with pure surface damage – x-ray irradiation

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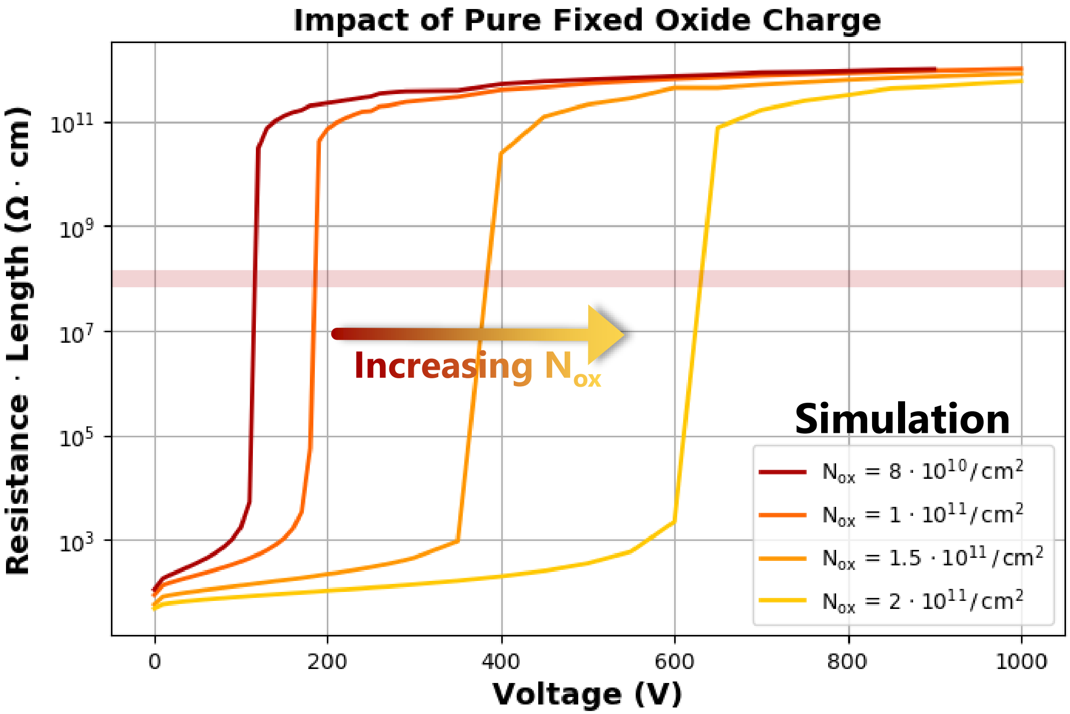
Expectation for X-Ray Irradiation

- Intuitive understanding
  - X-ray irradiation ionises the surface
    → Increased oxide charge concentration
  - Expectation: Interstrip resistance decreases
- Simulations: Shift of the curve to higher bias voltages for **Increasing N_{ox}**



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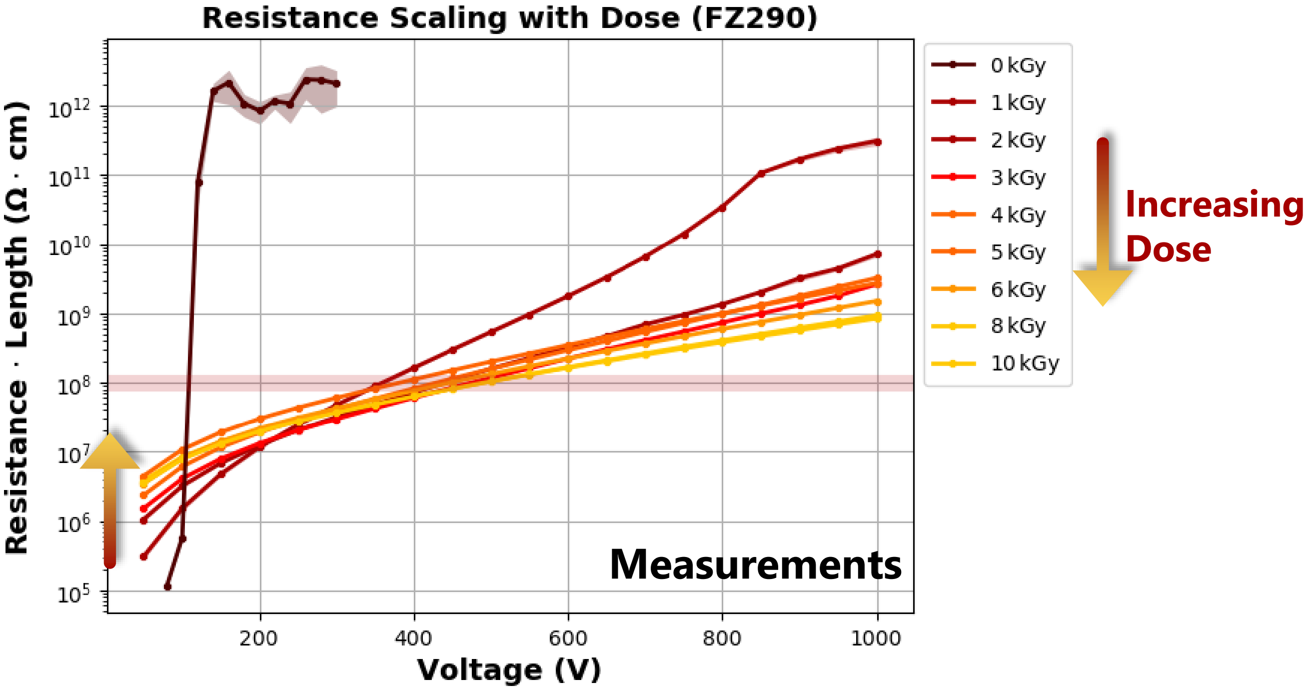
Irradiation with X-Rays

- Sensor **without isolation implant** successively irradiated with X-rays
- Outcome: **Decrease of R_{int}** with **increasing dose** (more surface damage) ✓
  - Shape changed → fixed oxide charge model not sufficient anymore
- But also: **R_{int} increases** with increasing dose for low bias voltages
- Saturation of the effects reached at 10 kGy



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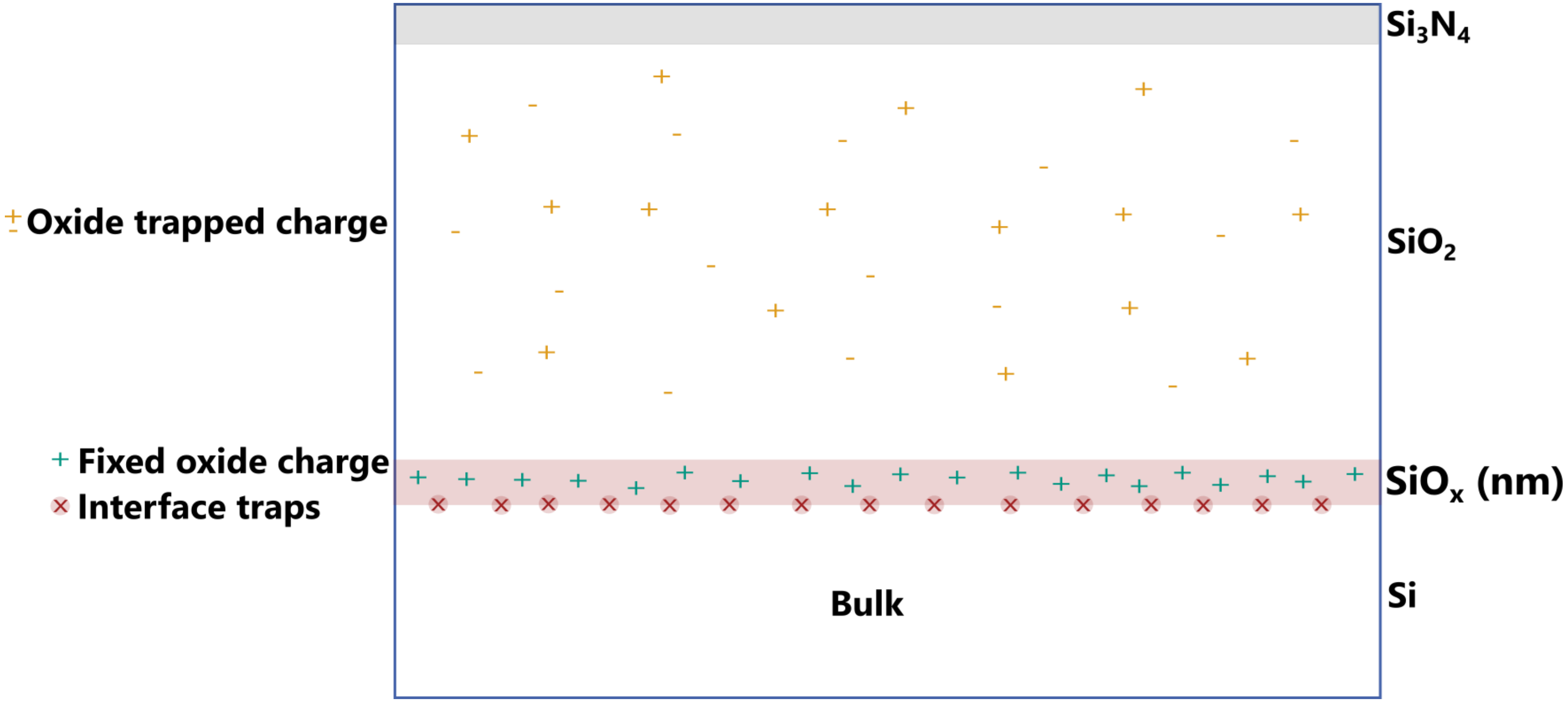
Surface Defect Model

- **Fixed charge** in Si/SiO_2 interface ~ $\mathbf{N_{ox}}$
  - Oxide trapped charge incorporated within N_{ox} for the simulations
- Perugia [4] model: **Interface traps** ~ $\mathbf{N_{it}}$
  - Gaussian distribution of energy levels of donor and acceptor traps



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[4] F. Moscatelli et al., IEEE Transactions on Nuclear Science, 2017, Vol. 64, Issue: 8, 2259 - 2267

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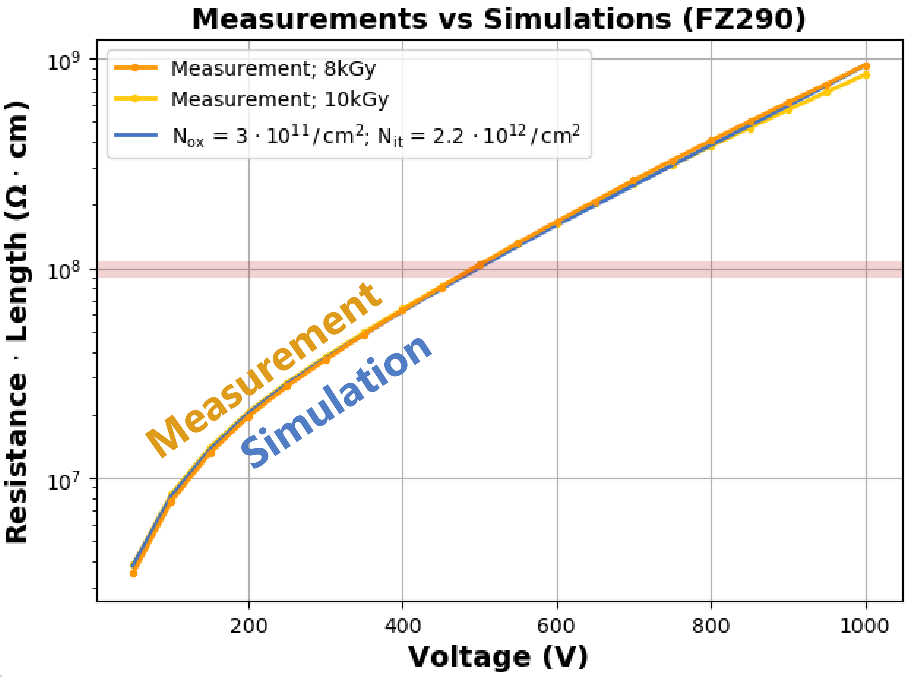
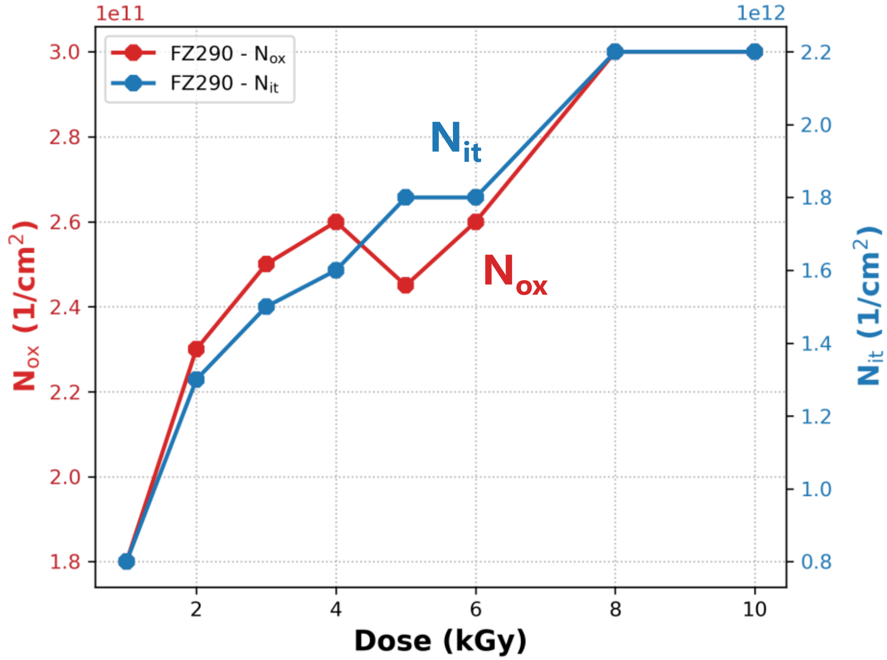
Defect Fitting after X-Ray Irradiation

- Defect concentrations N_{ox} and N_{it} have been adjusted so that the measured behaviour is reproduced (for every irradiation step)
- Example of a decent fit for the saturation dose at 8-10 kGy (left plot)
- Summary of the resulting defect concentrations (right plot)
  - Saturation concentrations: $N_{ox} \approx 3 \times 10^{11}\,\mathrm{cm}^{-2}$ and $N_{it} \approx 2.2 \times 10^{12}\,\mathrm{cm}^{-2}$





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Interstrip Resistance after Irradiation

Including bulk defects

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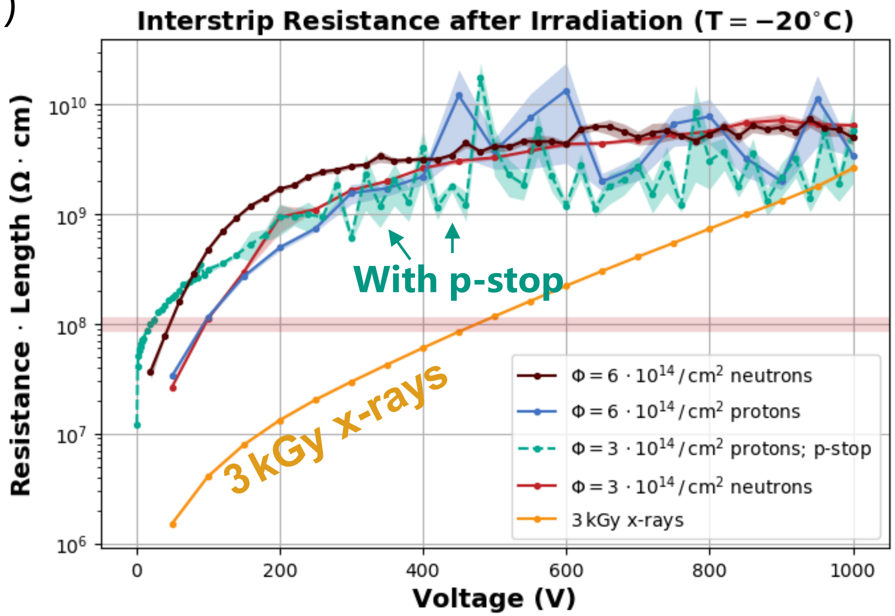
Irradiation with Protons and Neutrons

- Three samples **without isolation implant** and one sample with p-stop
- Similar R_{int} after proton and neutron irradiation (dose in different orders of magnitudes!)
- Comparable R_{int} of sensors with and without p-stop implant! (Fluctuations due to insufficient interstrip low voltage ramp)
- Higher R_{int} than for 3 kGy x-rays!

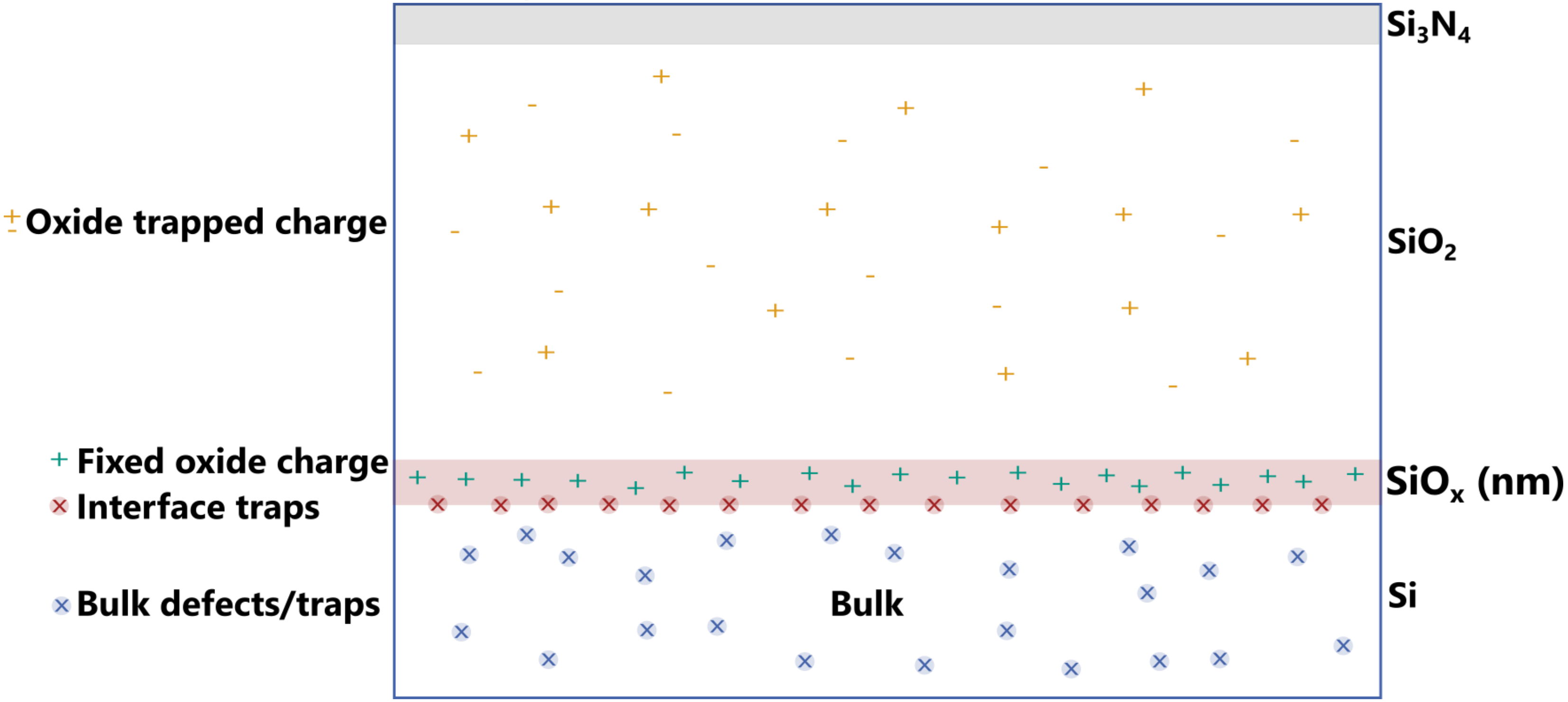
  → Bulk defects keep R_{int} high



Isolation Type	**None**	**None**	**None**	**P-stop**
Fluence	6 x $10^{14} n_{eq} cm^{-2}$	6 x $10^{14} n_{eq} cm^{-2}$	3 x $10^{14} n_{eq} cm^{-2}$	3 x $10^{14} n_{eq} cm^{-2}$
Particle Type	protons	neutrons	neutrons	protons
Dose in Surface	900 kGy	6 kGy	3 kGy	450 kGy

Bulk Defect Model

- Eber model (KIT) for protons and neutrons [5]:
  - Donor level at 0.48 eV
  - Acceptor level at 0.525 eV
- Main difference between proton and neutron model: Introduction rate of defects



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[5] R. Eber, PhD Thesis, IEKP-KA/2013-27

Impact of Bulk Defects on the Surface Properties

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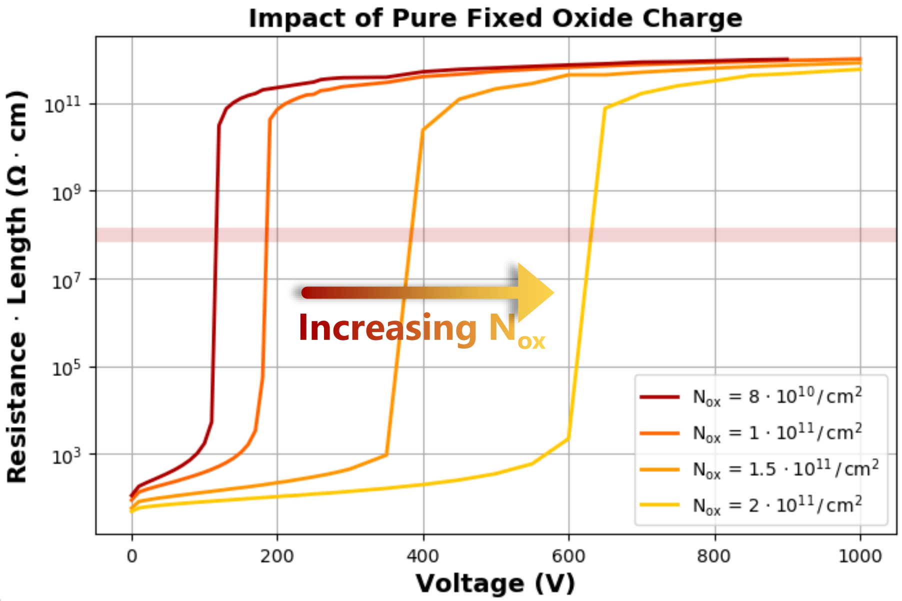
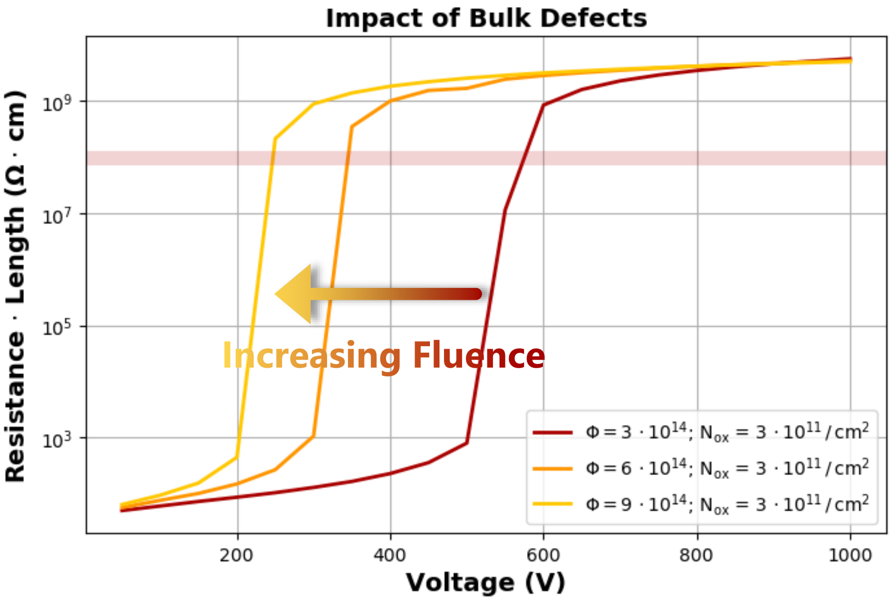
- Acceptor and donor states induced into the bulk
- Acceptor trap occupation is higher in the surface region than donor occupation
- Acceptor states are negatively charged when occupied
- Visualisation of the compensation effect due to bulk defects

  → A higher bulk defect concentration shifts the R(V) curve to lower voltages



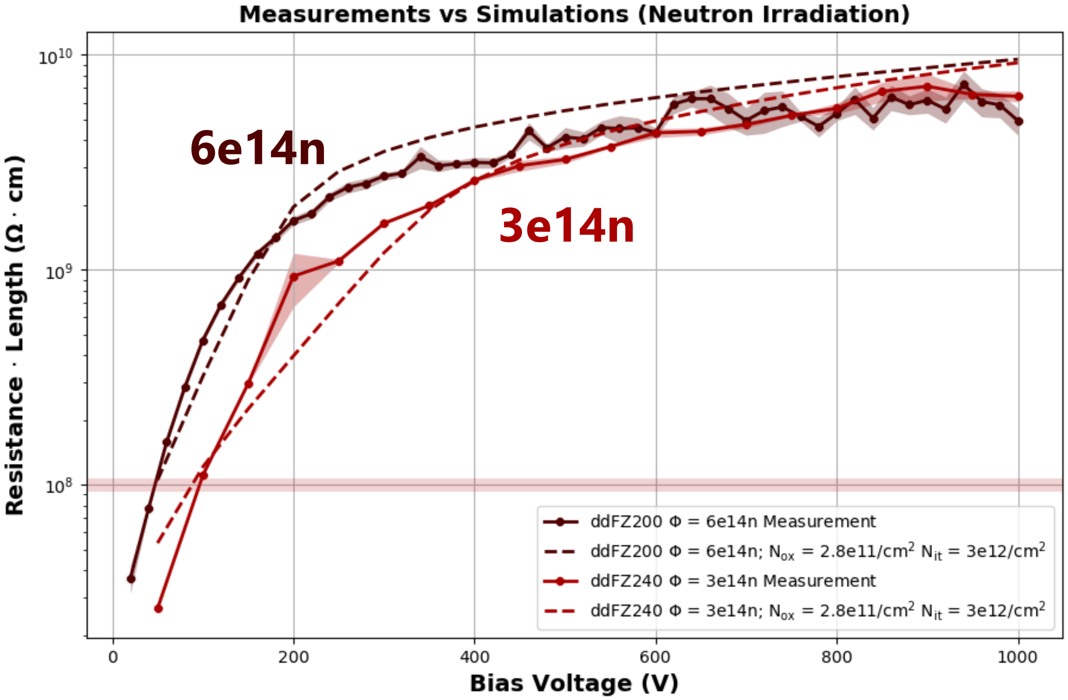
Impact of Pure Fixed Oxide Charge



Impact of Bulk Defects

Defect Fitting – Neutrons

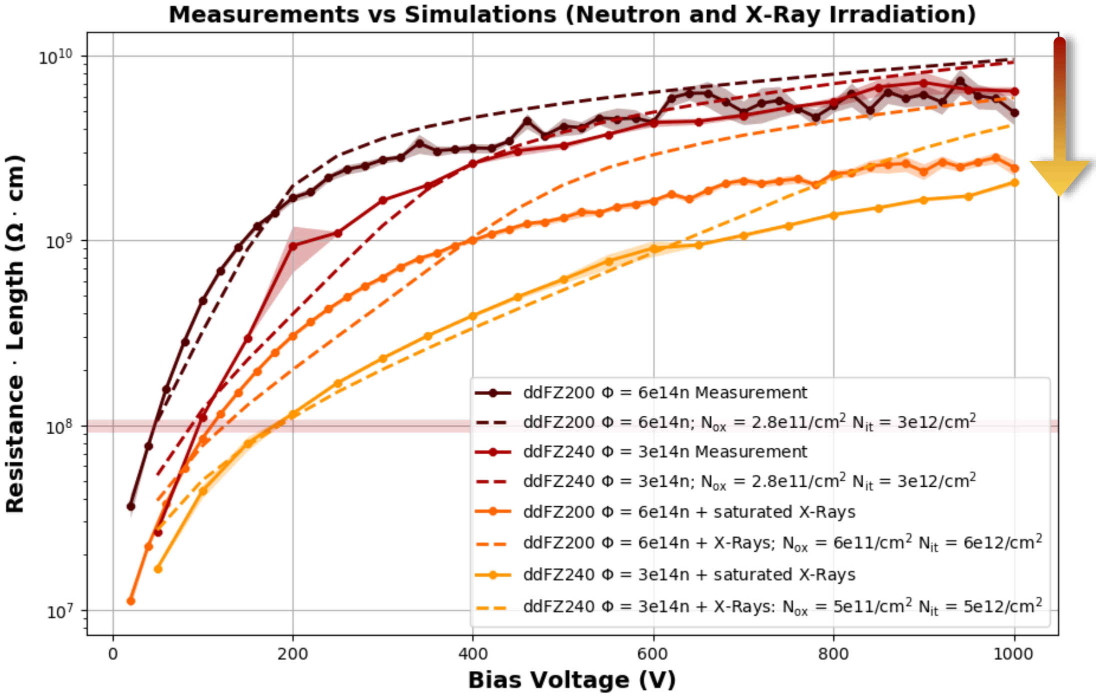
- Irradiation with **6e14** and **3e14 neutrons** (6 kGy and 3 kGy)
- Adjusted N_{ox} and N_{it} to fit the measurements → Outcome consistent with x-ray irradiation
- **Measurements reproducible with the combination of Eber and Perugia model!**
- Further irradiation with x-rays → Higher surface/bulk defect ratio



Defect Fitting – Neutrons

- Irradiation with **6e14n**, **3e14n**, **6e14n + x-rays** and **3e14n + x-rays**

- **Measurements reproducible with the combination of Eber and Perugia model!**
  - N_{ox} and N_{it} had to be adjusted to higher values (x2) for the combination of neutrons and x-rays → Influence of neutron irradiation on the saturation concentration?



Increase of surface/bulk defect ratio

Summary and Current Work

- Irradiation study on sensors **without interstrip isolation structures** to evaluate the interplay of surface damage and bulk defects
- Before irradiation
  - Electron accumulation layer removed for a certain minimum bias voltage
  - Described correctly with pure fixed oxide charge in the Si/SiO$_2$ interface
- **Replication of the R$_{int}$ measurements after irradiation with**
  - fixed oxide charge
  - **interface traps (Perugia) representing pure surface damage**
  - **bulk defects/traps (Eber - KIT)**
- Current investigations
  - Further evaluation of the fluence scaling of R$_{int}$ for proton irradiation
  - Biased irradiation (so far R$_{int}$ decreased due to biasing as expected)

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Backup

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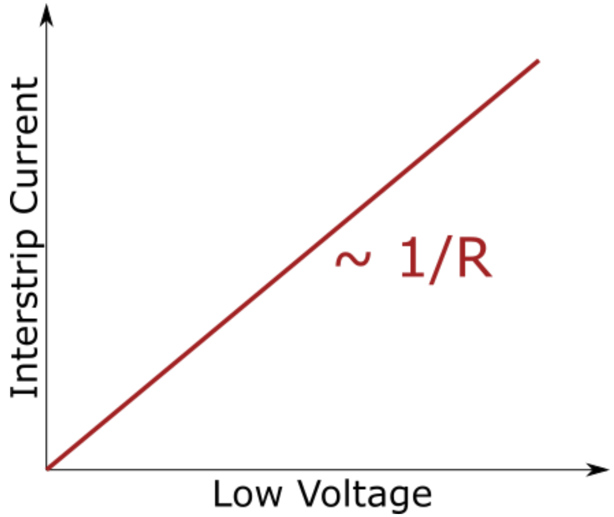
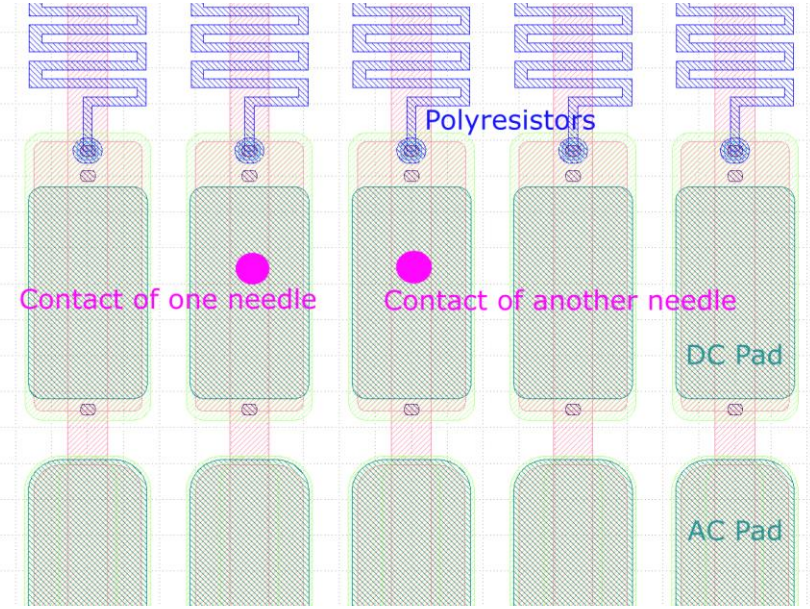
Measurement Procedure

- Measurement procedure for the interstrip resistance (R_{int}) between two strips:
  - Contact two neighbouring strips and apply a low voltage (ramp) on one
  - Measure the current flow on the other strip
  - Plot current over the applied low voltage
    - Inverse slope equals the interstrip resistance
  - Take R_{int} of several strips (5-10)

→ Mean value and standard deviation





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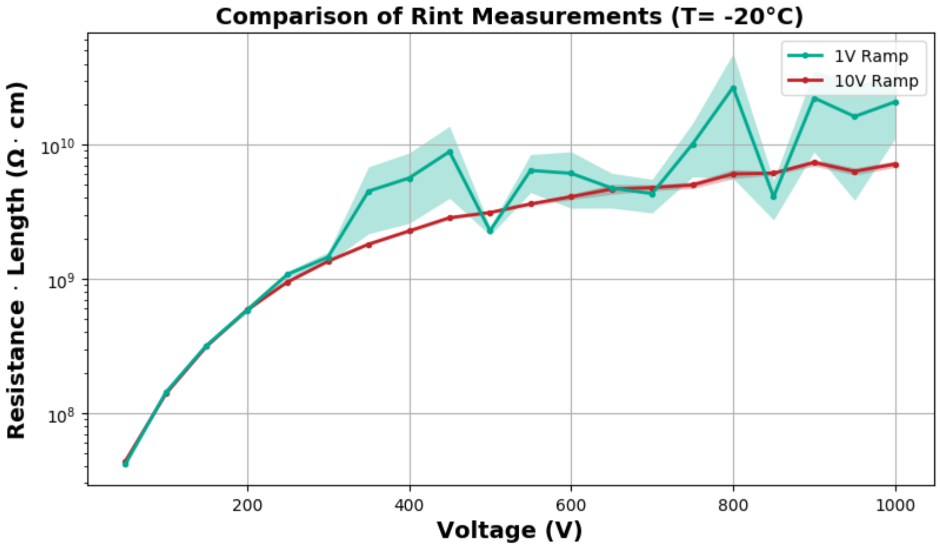
Measurement Procedure II

- Voltage ramp between two strips usually to 1 V max
- High leakage current after proton or neutron irradiation
  → Measured current between two strips dominated by strip leakage current
  → High fluctuations
- Illustration of R_{int} scaling with the voltage for a proton irradiated sample
  → Fluctuations are significantly lower with a 10 V ramp – similar shape ✓



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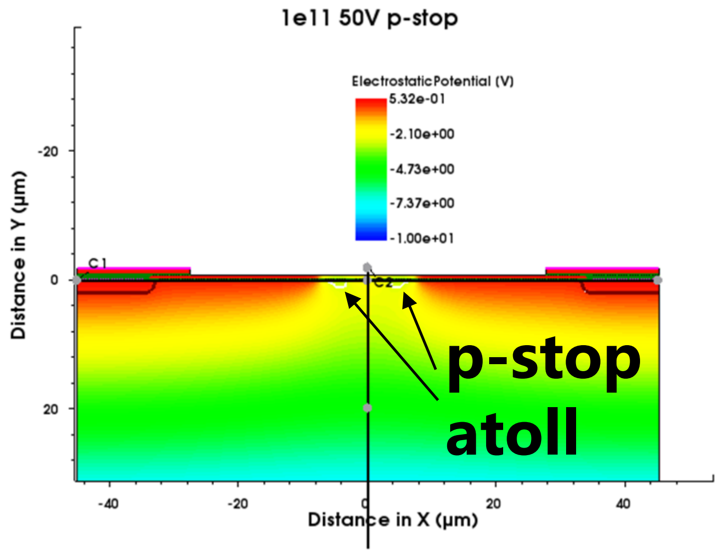
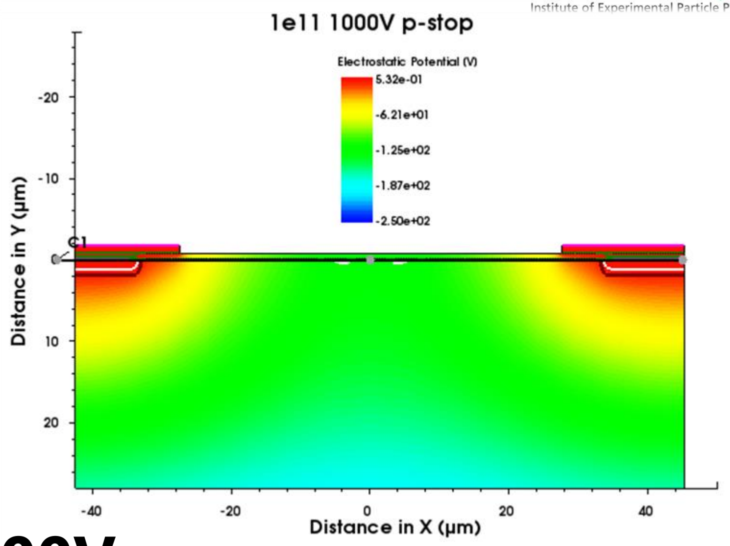
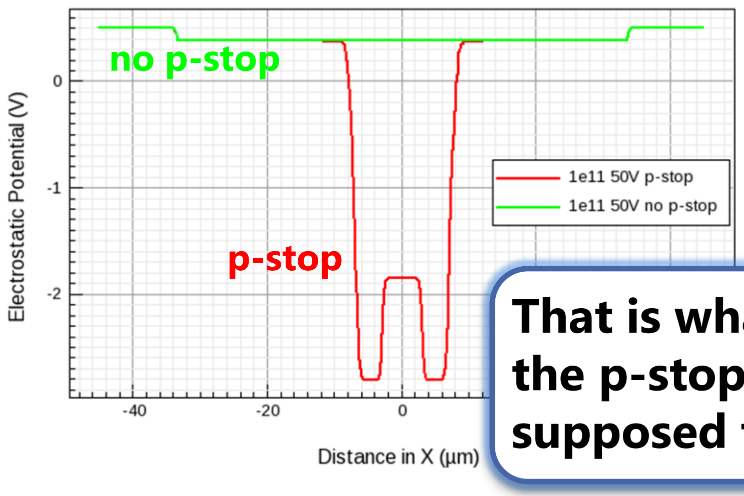
Electrostatic Potential



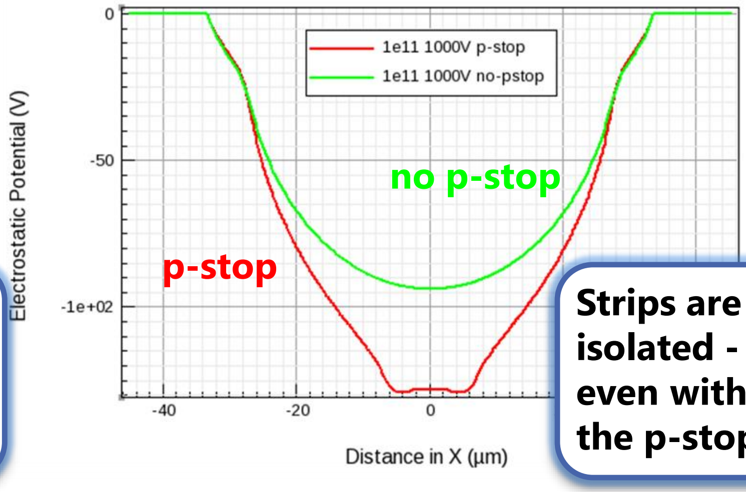


50V Electrostatic Potential Cut through Y = 30 nm



That is what the p-stop is supposed to do!

1000V Electrostatic Potential Cut through Y = 30 nm



Strips are isolated - even without the p-stop!

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Defect Models

- **Fixed charge** in Si/SiO$_2$ interface ~ N$_{ox}$
- Gaussian (Perugia [4]) **interface traps** ~ N$_{it}$
  - Gaussian donor: (0.7 ± 0.07) eV – eX/hX section 1e-15 (100%)
  - Gaussian acceptor 1: (0.4 ± 0.07) eV – eX/hX section 1e-15 (40%)
  - Gaussian acceptor 2: (0.6 ± 0.07) eV – eX/hX section 1e-15 (60%)

- **Proton defects/traps** (Eber [5])
  - Deep donor: 0.48 eV – eX/hX section 1e-14 (N$_d$ = fluence * 5.598 - 3.949e14)
  - Deep acceptor: 0.525 eV – eX/hX section 1e-14 (N$_a$ = fluence * 1.189 + 6.454e13)
- **Neutron defects/traps** (Eber [5])
  - Deep donor: 0.48 eV – eX/hX section 1.2e-14 (N$_d$ = fluence * 1.395)
  - Deep acceptor: 0.525 eV – eX/hX section 1.2e-14 (N$_a$ = fluence * 1.395)

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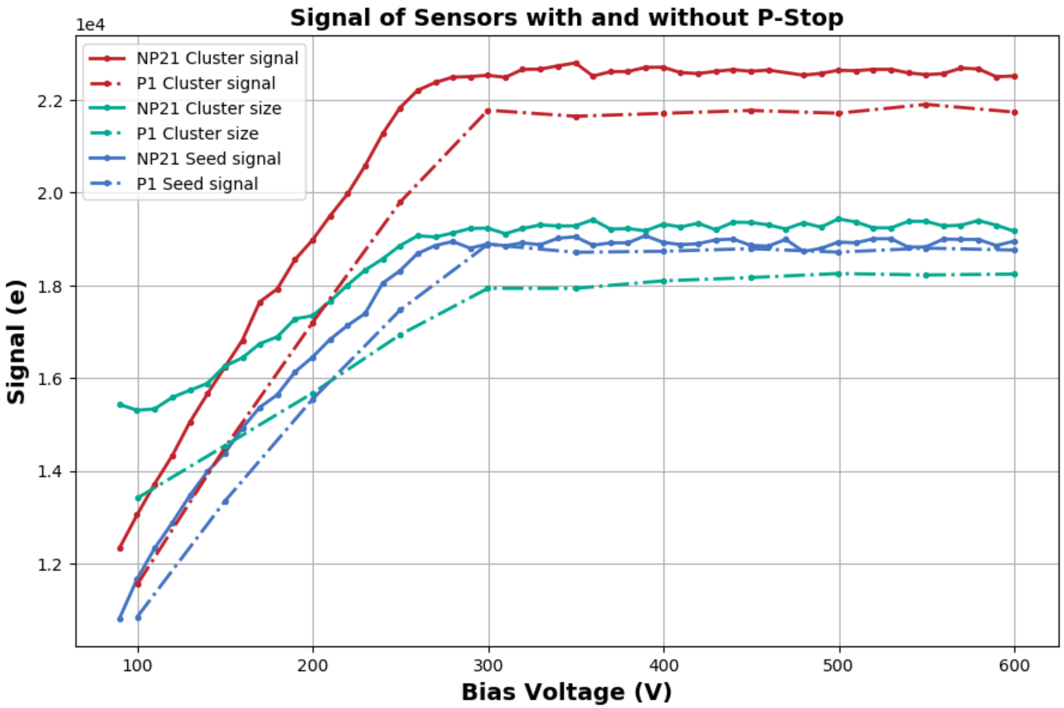
[4] F. Moscatelli et al., IEEE Transactions on Nuclear Science, 2017, Vol. 64, Issue: 8, 2259 - 2267

[5] R. Eber, PhD Thesis, IEKP-KA/2013-27

Signal Comparison without Irradiation

- Comparison of the signal properties of a sensor with p-stop (dot-dashed line) and without any isolation structure (continuous line)
- Cluster size multiplied by 10 000 for visibility
- Outcome: No significant difference → both useable!



Seed signal

Cluster signal