Co-funded by
the European Union

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

FZU
Institute of Physics of the
Czech Academy of Sciences

Radiation Effects on Surface and Bulk Properties of ATLAS18 Miniature Strip Sensors: Insights from Low-Dose Gamma Irradiation and Annealing Studies

18. 11. 2025

V. Fadeyev, P. Federicova, P. Gallus, J. Kozakova, J. Kroll, M. Kutova,
I. Mandic, M. Mikestikova, J. Kvasnicka, P. Tuma, M. Ullan, Y. Unno, I. Zatocilova

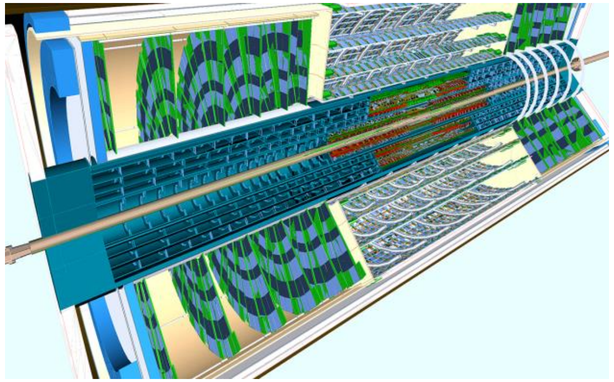
Outline

- Introduction
- Motivation from previous studies
- Samples and gamma irradiation
- IV and CV tests
- Annealing at temperatures of 60°C, 160°C and up to 300°C
- Temperature dependence of total, bulk and surface currents
- Summary

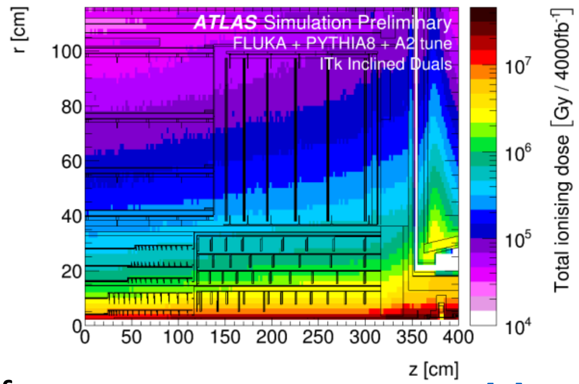
Introduction

- **ATLAS Inner Tracker (ITk) strip sensors ATLAS18**
  - Single-sided n^+-in-p
  - 6-inch wafer processing, thickness ~300 µm
  - AC-coupled readout, strips biased via R_{bias} resistors
  - common p-stop isolation (4e12 ions/cm^2)
  - ITk includes: 2 barrel types and 6 End-Cap types: R0-R5

ATLAS ITk



Radiation environment ATLAS Phase II upgrade (4000fb^{-1})

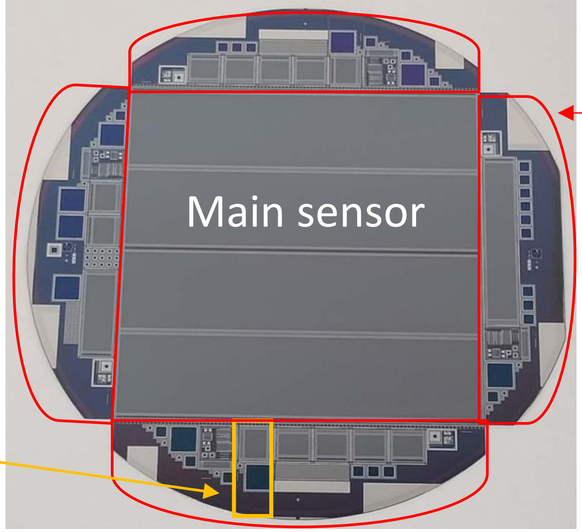


[1]

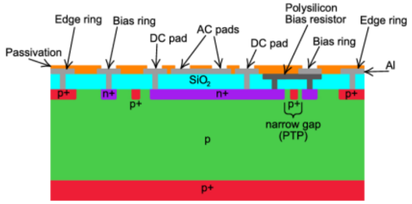
- **maximal nominal radiation fluence (TID) based on 4000 fb^{-1}**
  - 1.6 x 10^{15} n_{eq}/cm^2 (66 Mrad) (testing with safety factor 1.5)
- **radiation tolerance verified** through extensive irradiation studies during development, including exposures to various particle types and energies
- **high radiation fluence and TID impact on sensor properties:**
  - NIEL -> bulk - displacement damage - increase of leakage current, effective doping concentration and CCE change
  - TID -> surface damage: accumulation of positive charge in SiO2 and the Si/SiO2 interface

This talk - characterization of mini sensors and MD8 diodes under low TIDs relevant for early ITk operation

ATLAS ITk strip sensor wafer



Test Structures



More about ATLAS ITk in
- ATLAS ITk Detector in Thomas's talk
- QC of ATLAS Itk strip sensors in Pavla's talk
- QA of ATLAS ITk strip testchips in Bob's talk
- …

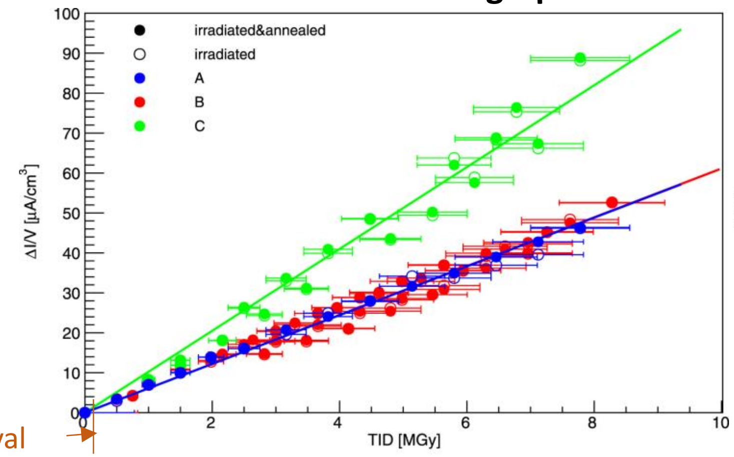
Motivation – previous studies

- Results from previous studies of irradiated gamma **diodes**, **mini** and **main strip** sensors, and **modules** indicate that bulk current increases linearly with TID, while surface current saturates at low TIDs.

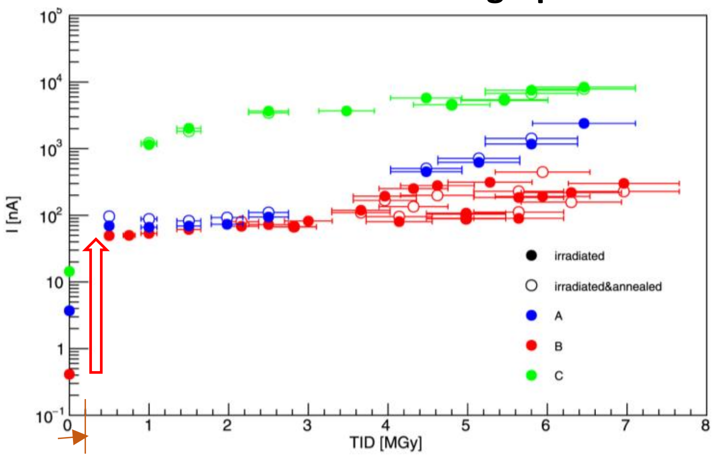
γ-irradiated DIODES (high TIDs up to 840Mrad)

- Bulk current after γ irradiation increases linearly with TID, while **surface current** saturates. Unfortunately, the minimum dose in this previous study [2] was about 66Mrad, making it impossible to determine at what low dose the surface current saturates.

Bulk Current after high γ TID



Surface Current after high γ TID

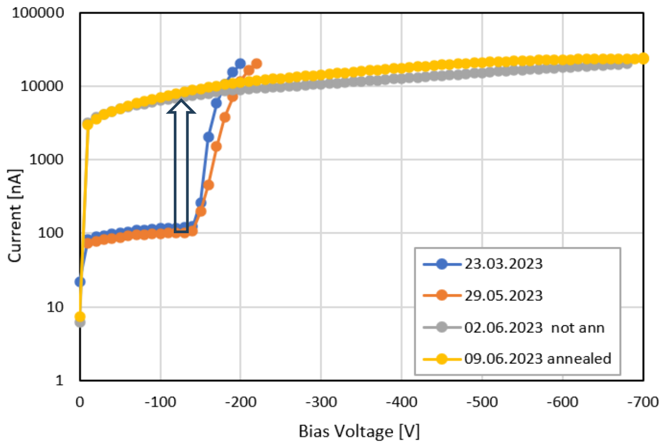


This study covers low TID interval

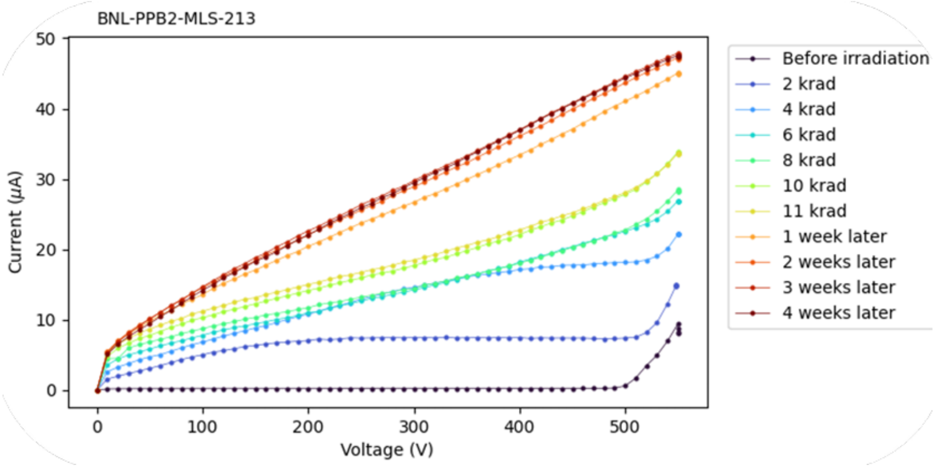
γ-irradiated ITk main strip sensor and module

- ~100× increase in total current after 11krad of TID observed in main sensors and modules [3, 4]

Main strip sensor: Total current (TID – 11 krad)



γ-irradiated module with glue on the guard ring



Samples and gamma irradiation

Samples:

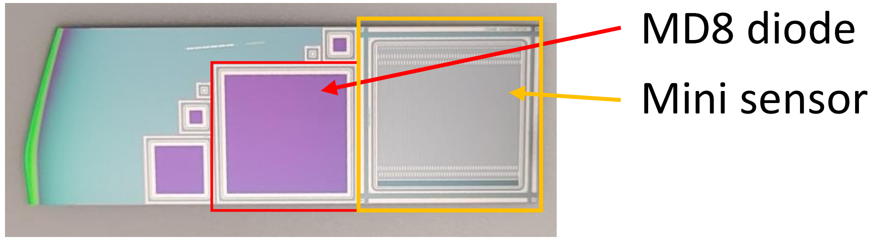
- ATLAS ITk MD8 **diodes** - active thickness 295 μm
  - active area 0.545 cm^2
  - MD8p with p-stop implant between Bias and Guard Ring
  - regular MD8 without p-stop
- ATLAS ITk Mini **strip** sensors - active thickness 295 μm
  - active area 0.64 cm^2
  - Segmented structure

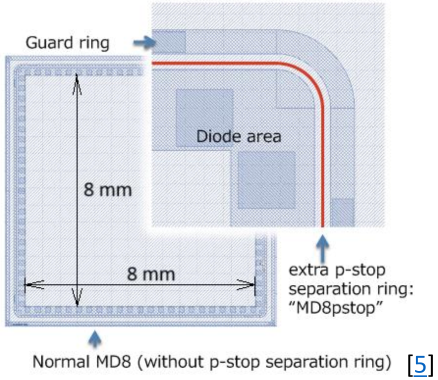
Irradiation:

- ^{60}Co gamma rays
- 14 different TIDs in range 0.5 – 100krad, 2Mrad, 4.1Mrad
- Dose rate: 1.6 - 8.5 krad/min
- Dose rate uncertainty: <5%
- Samples irradiated in **C**harge **P**article **E**quilibrium box (Al+Pb)

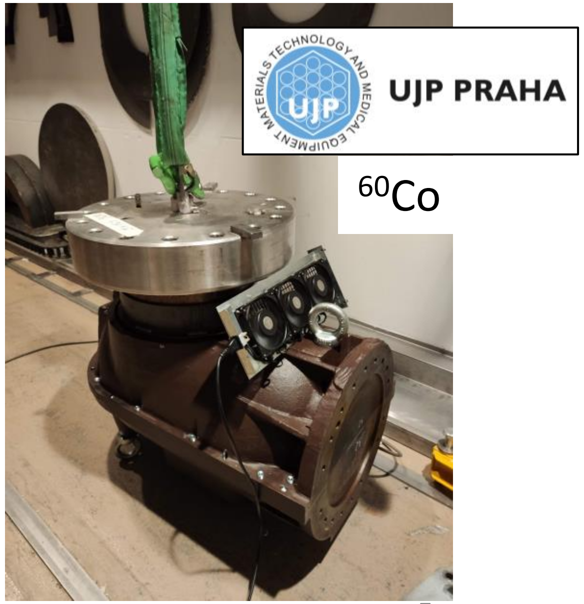
Tests:

- IV, CV characteristics
- Annealing studies
- Temperature dependence
- Transient Current Technique (TCT)





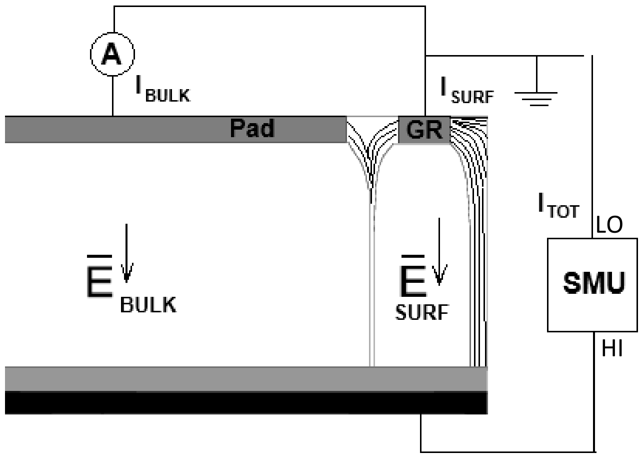
CPE box with samples



Total, Bulk, and Surface currents

- **Bulk leakage current (I_{bulk})** flowing exclusively through active volume of diode/strip sensor bounded by guard ring
- **Surface leakage current (I_{surf})** dominating outside of this guard ring (sum of real surface current and bulk current in the edge volume)
- **Total leakage current (I_{tot})** $I_{\rm tot} = I_{\rm bulk} + I_{\rm surf}$

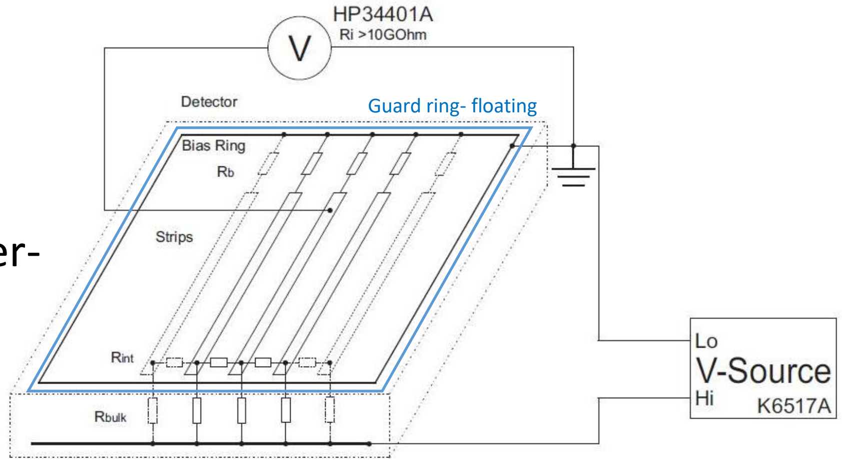
Setup for measurement of I_{tot} and I_{bulk} in diodes with <u>contactable</u> guard ring



Setup for measurement of I_{tot} and I_{bulk} in strip mini sensors with <u>non-contactable</u> guard ring

$I_{\rm bulk} = n \; x \; I_{\rm strip}$
n = 104 … # of strips in mini sensor

Assumption: All bias resistors have the same R_{bias}, there is no compensating inter-strip current flowing between strips (through R_{int}) and voltage drop V at any strip is the same: $V = I_{strip} * R_{bias}(T)$

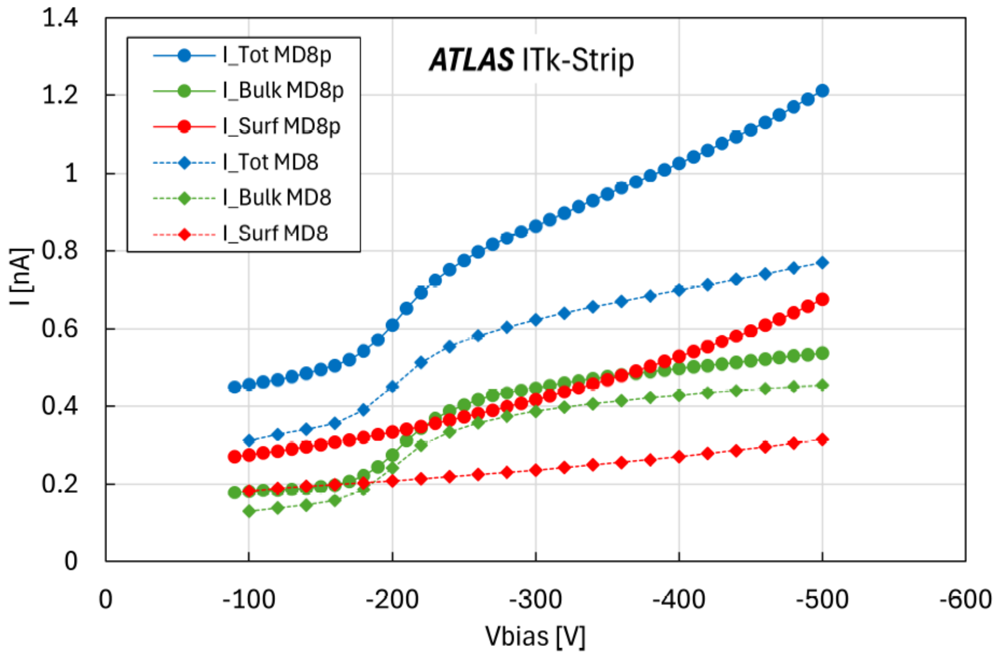


V is measured on few random strips using high-input-resistance voltmeter ($R_{input} > 10G\Omega$), minimizing measurement-induced loading errors (more details in backup).
Since $R_{input} \approx 10\,000 \times R_{bias}$, voltmeter negligibly impacts current distribution in sensor.

More about "Simulation of the Electrical Performance of the ITk ATLAS18 Test Diode and Main Sensors Before and After Irradiation" see Yuzhan's poster
For the "Investigation of the current-generation mechanisms in the edge region of planar silicon sensors using TCAD and TCT" see Peilin's poster

Currents before and after low-γ irradiation – MD8

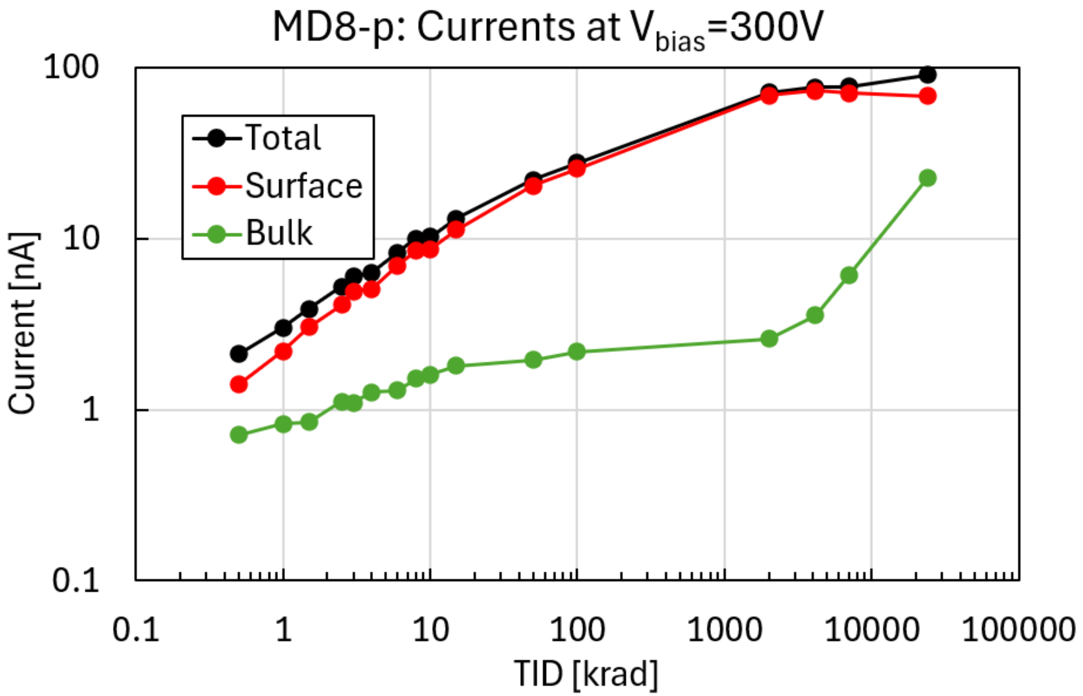
Total, bulk, and surface currents in **MD8 diodes**



- **Before irradiation**, bulk and surface currents are comparable in magnitude
- Surface current is slightly larger in diodes with p-stop between BR and GR than in regular diodes – without p-stop [6].

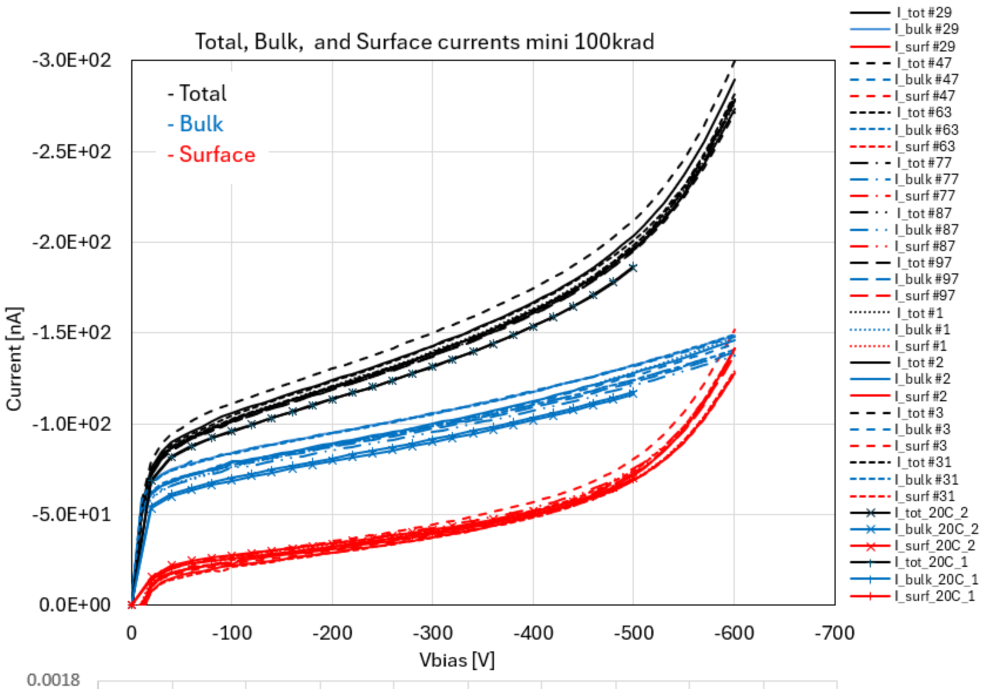
γ-irradiated MD8 diodes (low TIDs)

Total, bulk, and surface currents vs TID



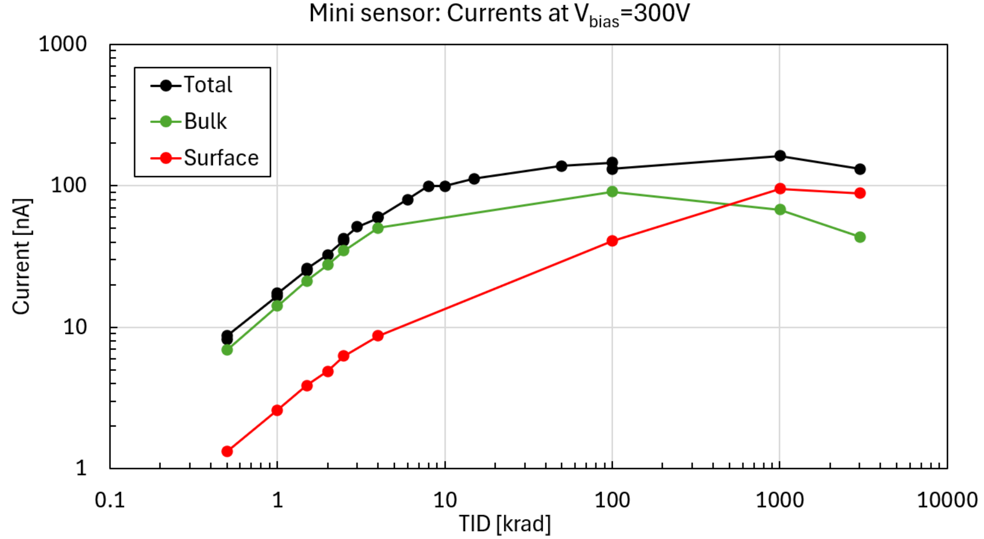
- After γ-irradiation, the surface current (which is a sum of the real surface current and the bulk current in the edge volume) increases even at low TID values and is dominated by the real surface current
- It seems that **surface current reaches saturation at 2Mrad**
- Interesting is increase in bulk current, further investigation needed

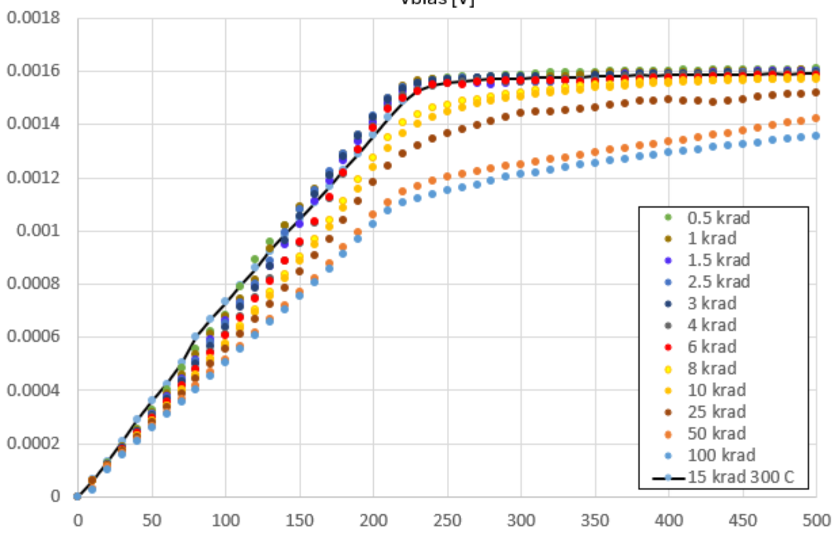
IV and CV vs TID of mini sensors

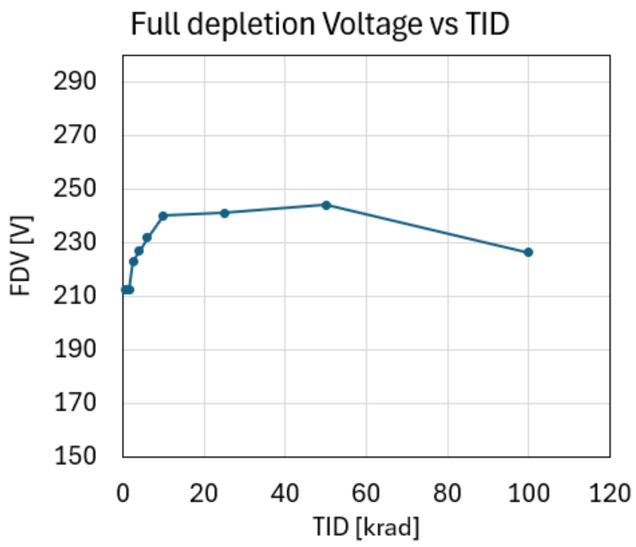


γ-irradiated mini sensors (low TIDs)

Total, bulk, and surface currents vs TID





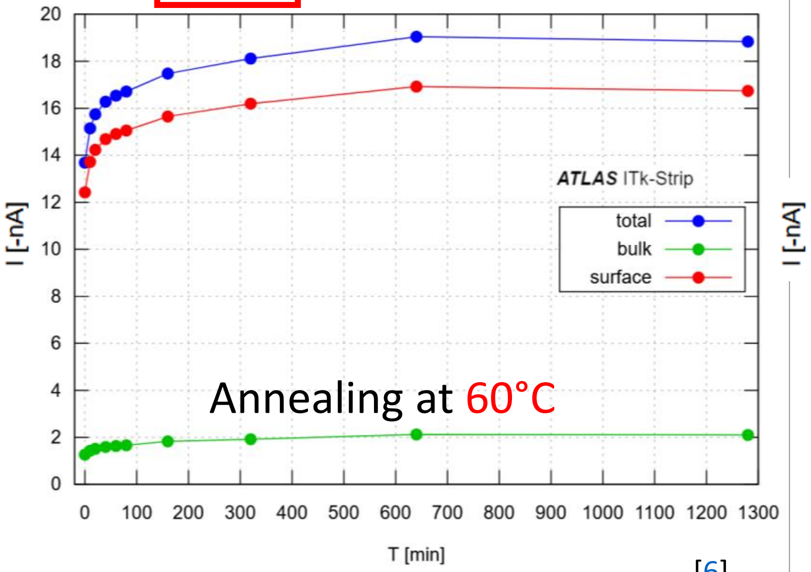


mini sensors

- At low TID values, the **bulk current dominates** the total current.
- **The surface current appears to saturate ~2Mrad**
- CV curves vary with TID, while the FDV remains nearly constant across the measured TID range – indicating that the observed changes are primary **surface-related, as expected**

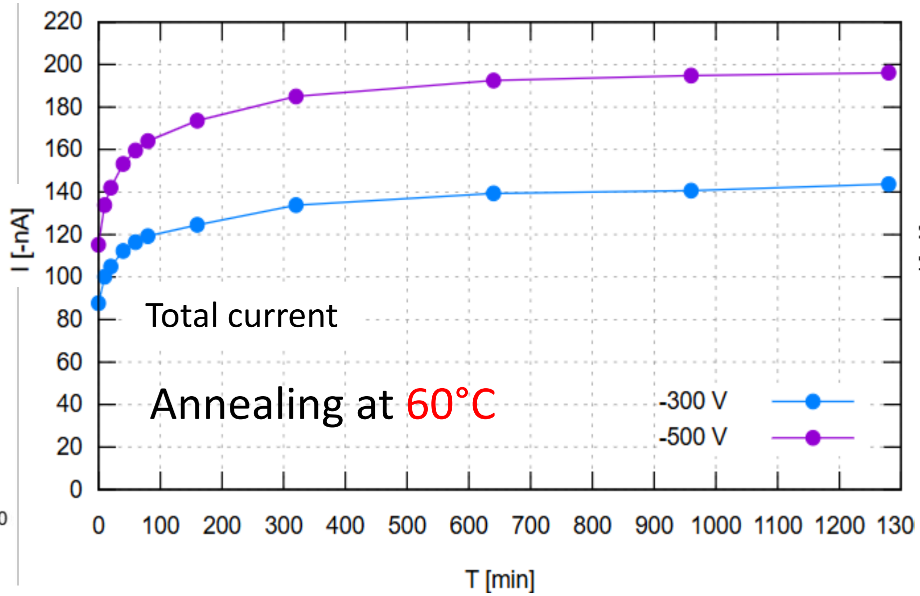
Annealing at 60°C and 160°C
Currents comparison of MD8 diode and mini sensor

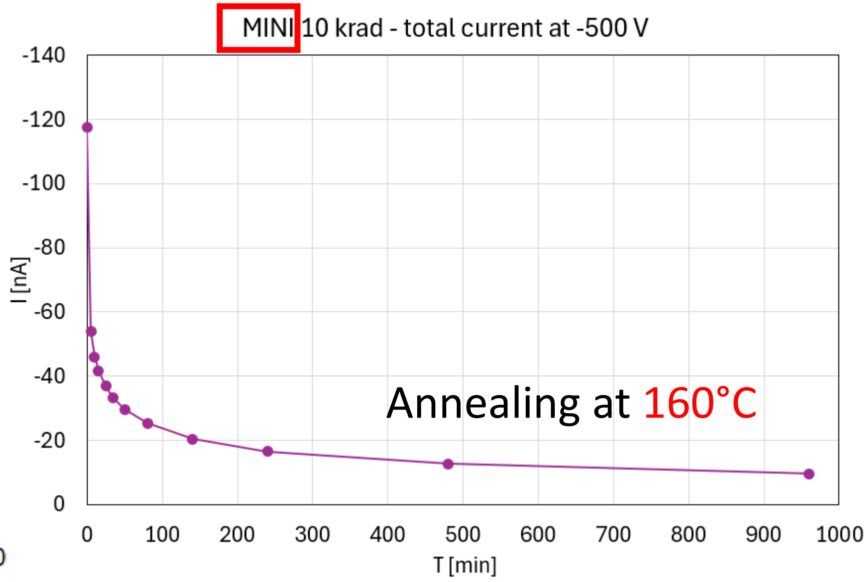
DIODE MD8p 25krad, 300V

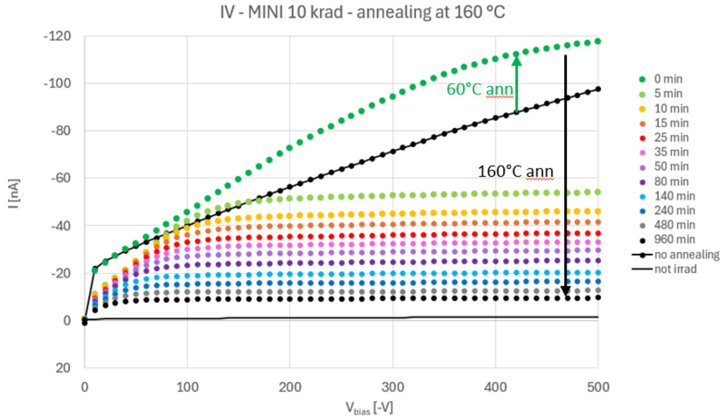


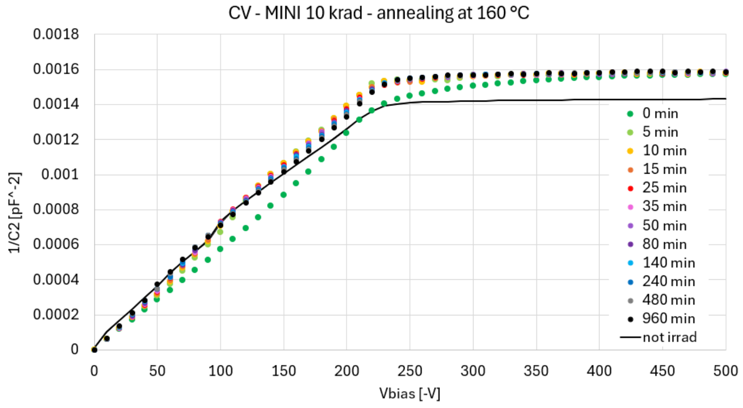
[6]

MINI sensor 25krad, 300V









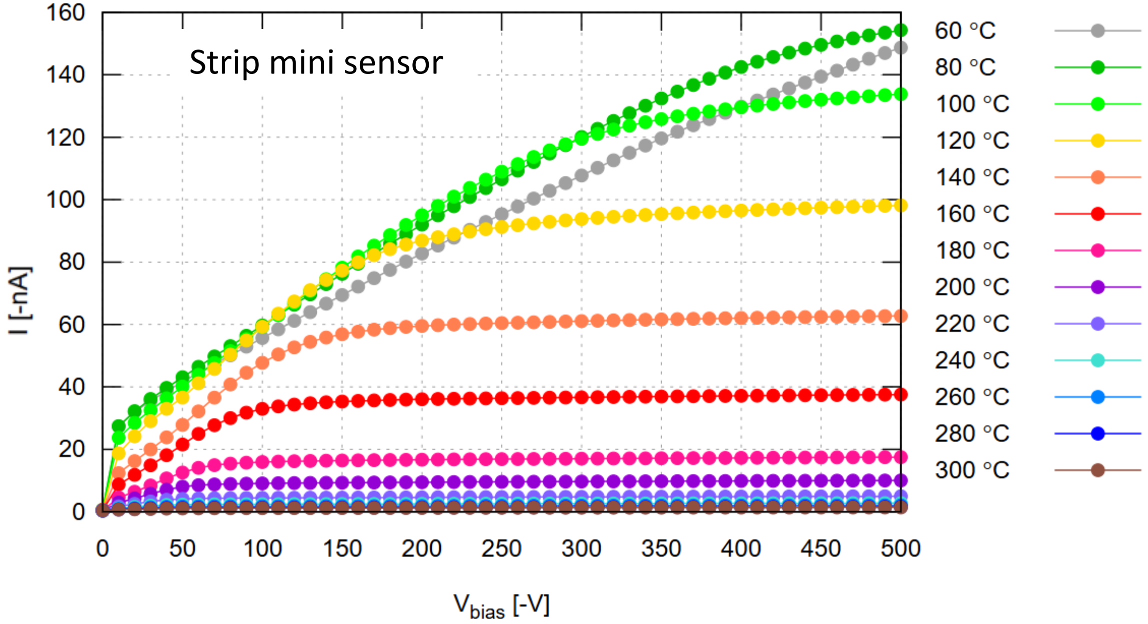
- Currents are increasing with 60°C annealing (saturating at ~640 min.) but decrease significantly at 160°C
- CV did not change

-> low TID-induced changes appear to be surface related, as expected

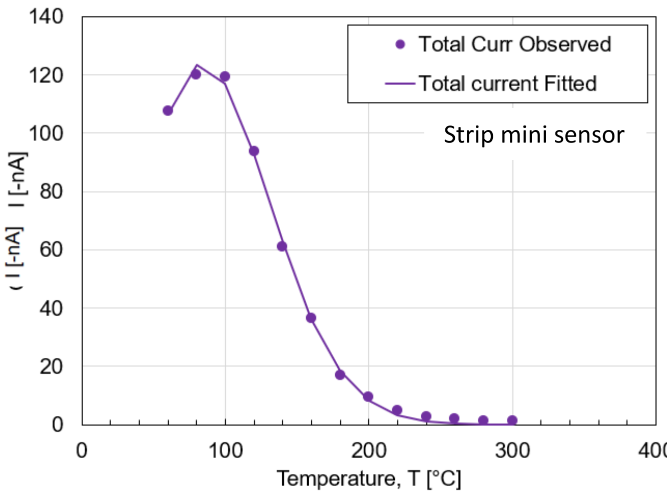
Annealing at increasing temperature 60°C - 300°C:

- Mini sensor and MD8 diode irradiated to low-TID of 15 krad initially underwent annealing for 80 min at 60°C, followed by isochronal annealing with 20-minute steps and temperatures ranging from 80°C to 300°C
- Currents exhibit an increase up to 80 -100 °C. However, at higher annealing temperatures decreases significantly, returning to levels comparable to those before irradiation.

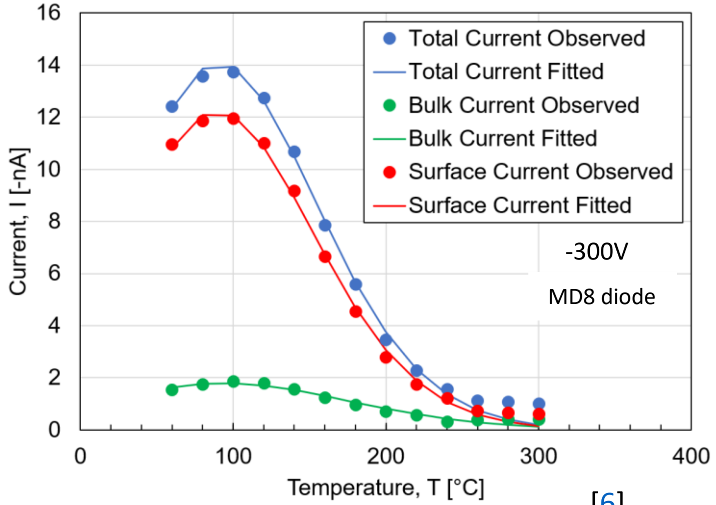
Total current IV



Total current in increasing temperature



Currents in increasing temperature



[6]

- Consistent results obtained in diode as in segmented mini sensor, total currents decreases significantly with high temperature annealing

	MD8 diode			Mini
	Total	Bulk	Surface	Total
E [eV]	0.064	0.041	0.065	0.113

$$I(T_n) = I(T_{n-1}) \exp\left[-\frac{E}{k_B}\left(\frac{1}{T_{\rm ref}} - \frac{1}{T_n}\right)\right]$$

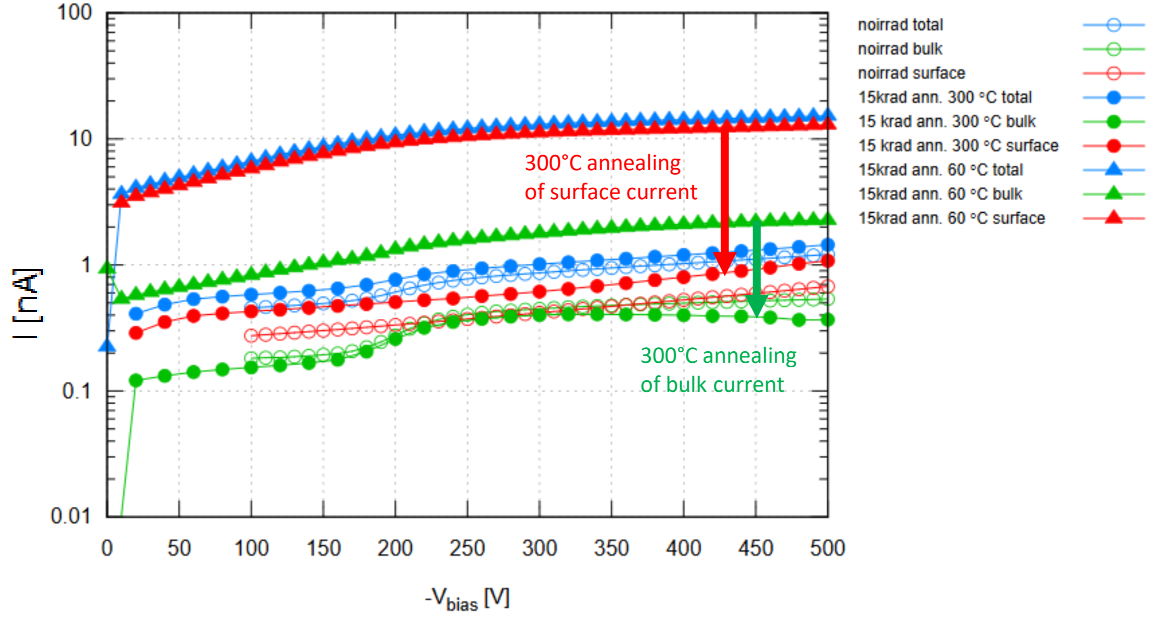
annealing with an activation energy E

- $I(T_{n-1})$: current of the previous temperature T_{n-1}
- T_{ref} : reference temperature at the max

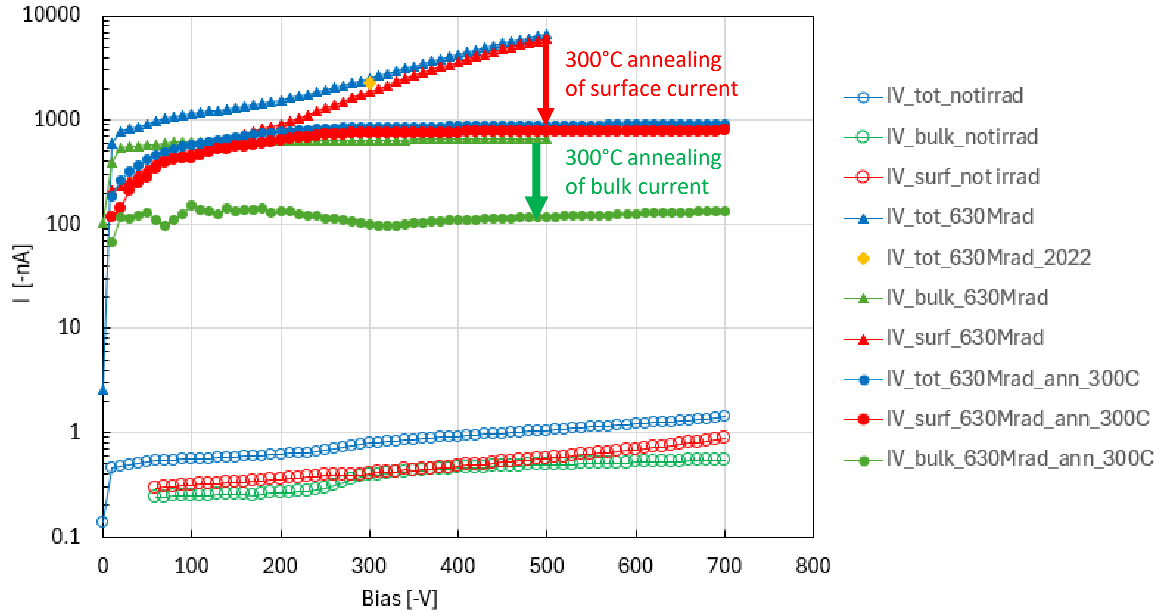
the physics behind the function is under study

Currents of low- and high-TID MD8 diodes after annealing up to 300°C

Currents of low TID (15krad) MD8 diode



Currents of high TID (630Mrad) MD8 diode

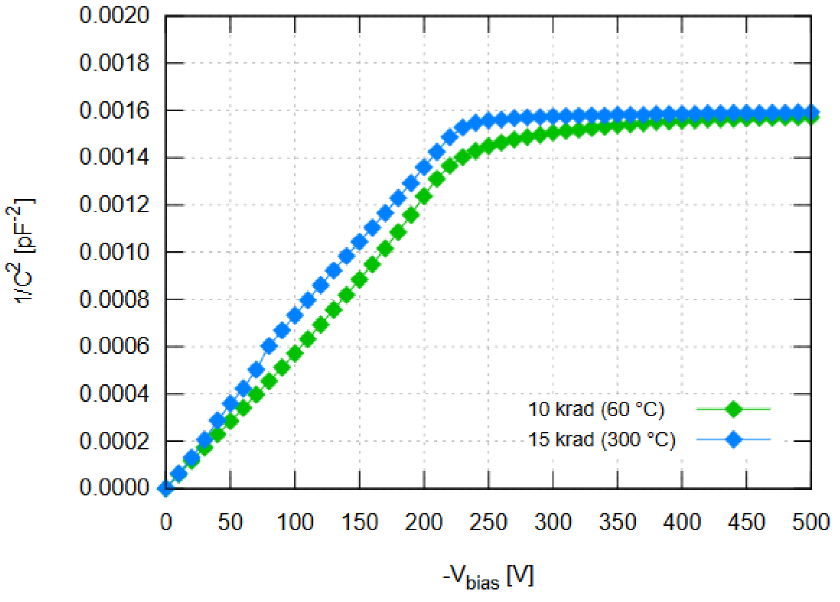


Comparison of total, bulk, and surface currents

- Measurements before and after irradiation, and after 1 h annealing at 300°C (15krad and 630 Mrad)
- In both low- and high-TID diodes, surface current dominates the total current
- Low-TID diodes: bulk and surface currents return to pre-irrad values after 300°C annealing
- High-TID diodes: currents decrease after annealing but remain above pre-irrad levels (need more time of annealing?)

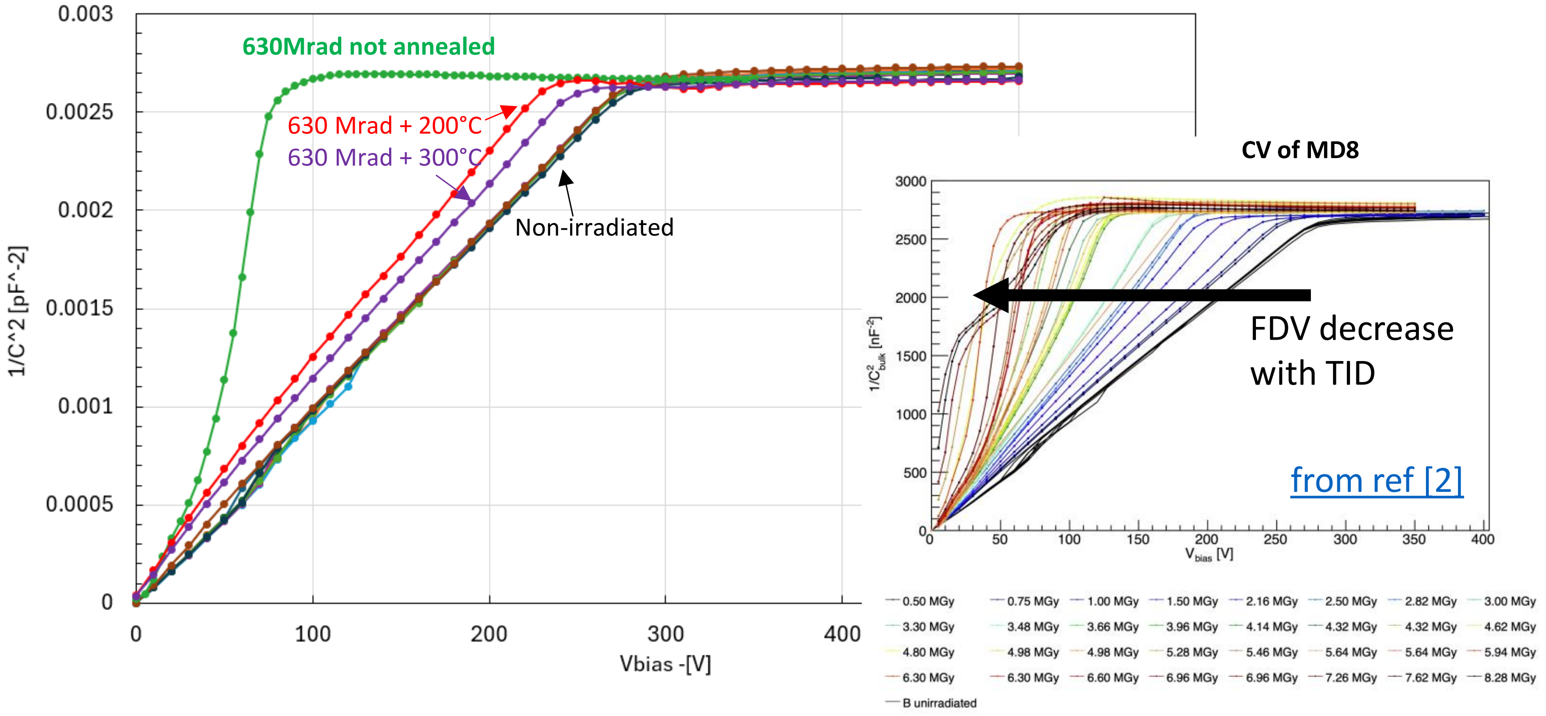
CV characteristics of high- and low-TID MD8 diode and mini sensor after annealing up to 300°C

CV comparison of low-TID mini sensors



- Measured after 80 min at 60°C and 1 h at **300 °C** annealing
- Low-TID irradiation and high-T annealing leave V_{FD} unchanged
  → no bulk damage at low TID.

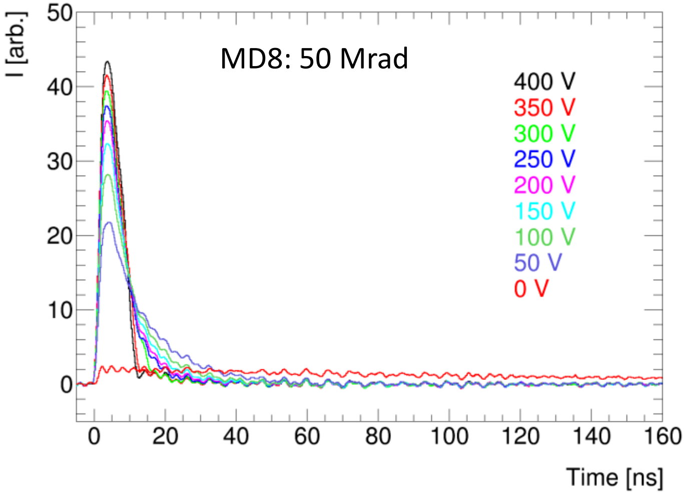
CV comparison of high-TID (630 Mrad) MD8 diode



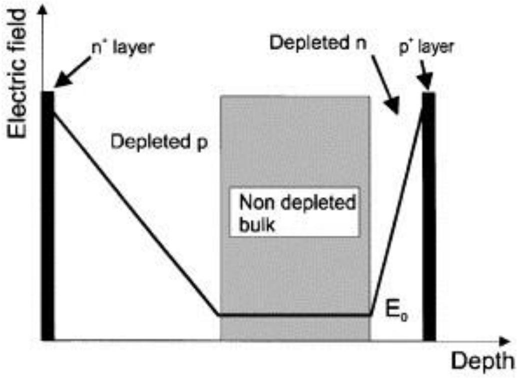
- Measured before and after 1 h annealing at **200°C** and **300 °C**
- Reference: non-irradiated diodes (V_{FD} =275V)
- High-TID reduces V_{FD} from 275 V to ~70 V
- High-Temp annealing increases V_{FD} to 250V (almost back to pre-irrad value)
- Indicates bulk damage induced in high-TID

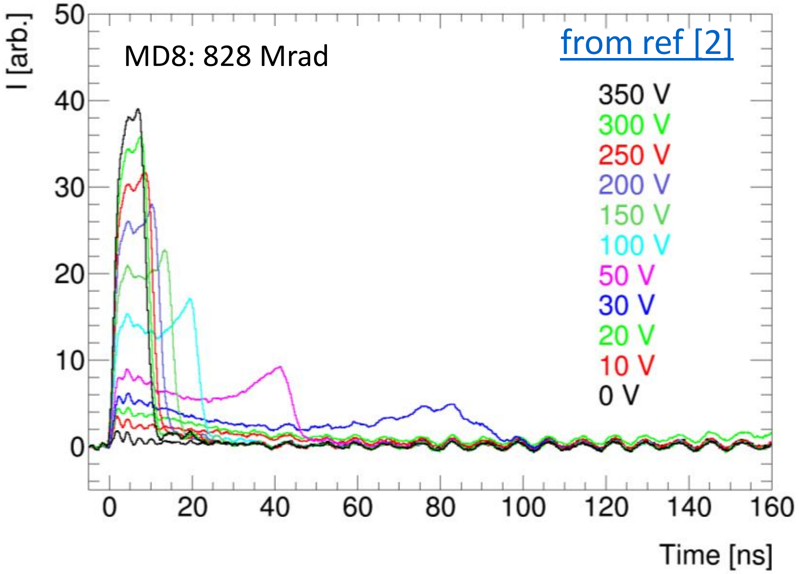
Top-TCT voltage scan

- TCT used to verify V_{FD} and to extract electric field distribution and the sign of space charge N_{eff} of silicon diodes irradiated to
  - low TID of 50 Mrad (previous study [2])
  - the highest TID of 828 Mrad (previous study [2])
  - TID of 630 Mrad and annealed to high temperature of 300°C
- Diodes were illuminated from top - n^+ side by red laser 660 nm



from ref [2]





Diode 50 Mrad

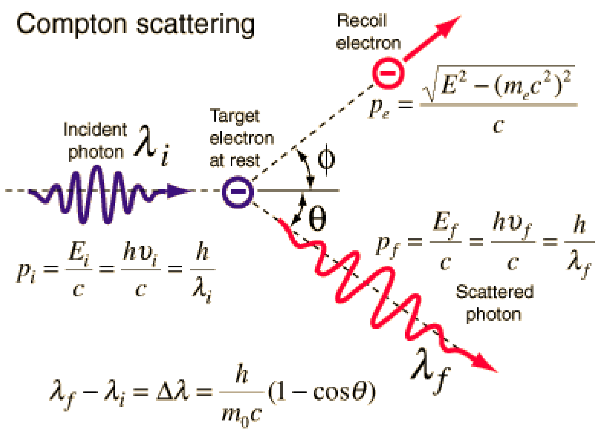
- high E-field on n^+ side, falling towards p^+ side ➔ n^+-in-p type of device
- V_{FD} : 250V-300V

Diode 8.28 MGy

- pulse has two peaks, so bulk is p-type on n^+ side and n-type on p^+ side with neutral bulk in-between, E-field is everywhere with low space charge concentration
- shape of the pulses indicates the double junction with high field regions on both diode sides.
- V_{FD} ~ 30 – 40 V

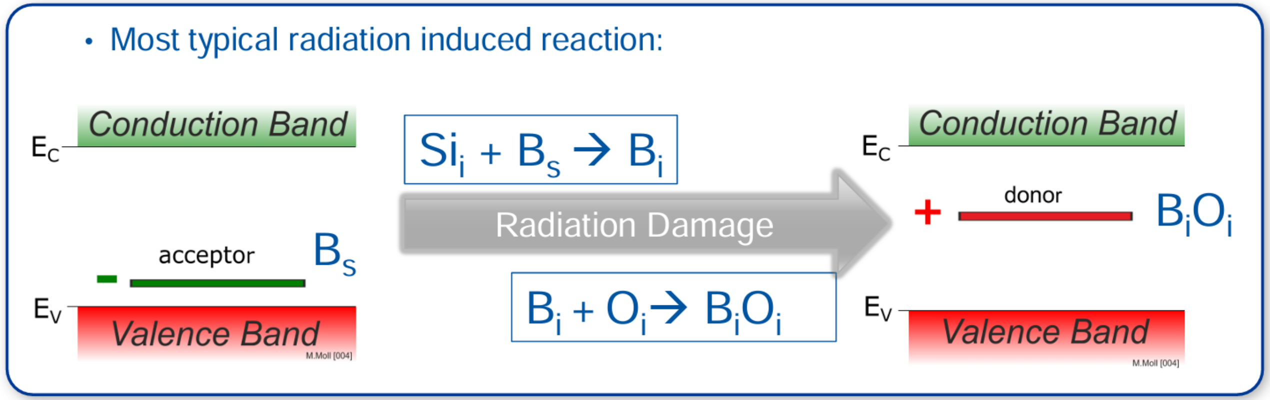
Bulk damage in γ-irradiated B-doped Si

- Displacement damage caused by ^{60}Co gammas is primarily due to interaction of Compton electrons having a maximum energy of 1.2 MeV.
- **Damage is exclusively due to point defects** (min. electron energy needed for cluster production is ~8 MeV)
- Max. recoil energy for the primary knock-on Si-atom by Compton electron is ≈ 140 eV
- Min. electron energy needed for single displacements for V-I (Frenkel pair) is 260 keV



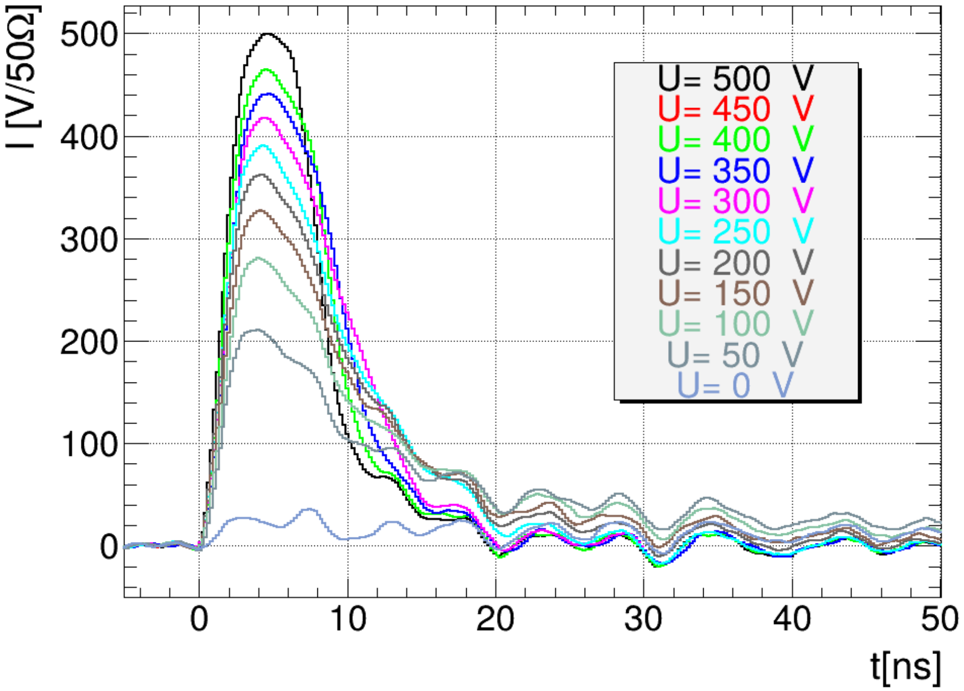
Acceptor removal

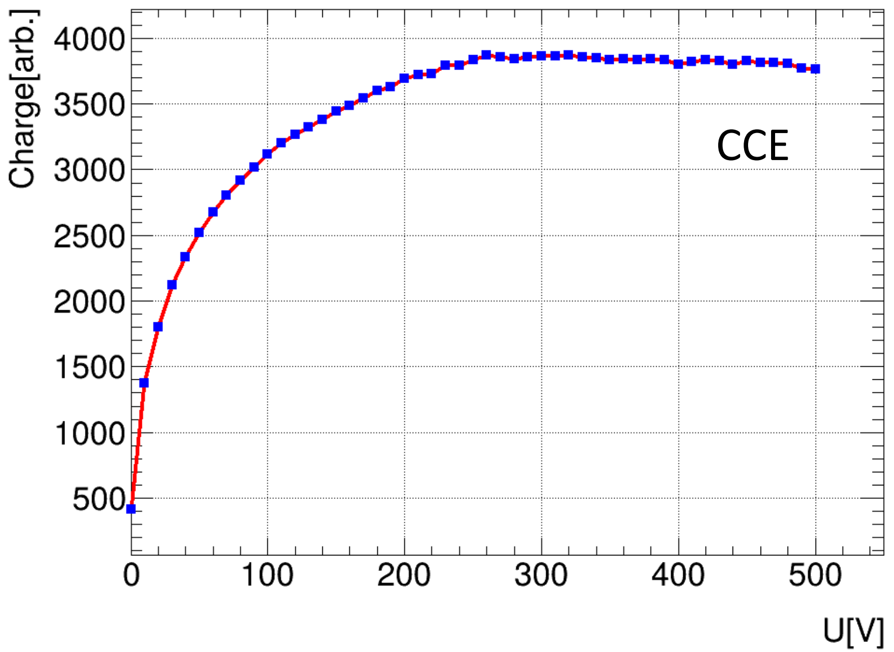
Decrease of Full depletion voltage (i.e. effective dopant concentration N_{eff}) in p-type detectors when irradiated with high-γ TID can be explained by **Acceptor removal effect** - formation of B_iO_i defects that induce a donor-type defect level in upper part of the Si band cap



M. Moll

Top TCT: MD8 diode 630 Mrad annealed to 300°C



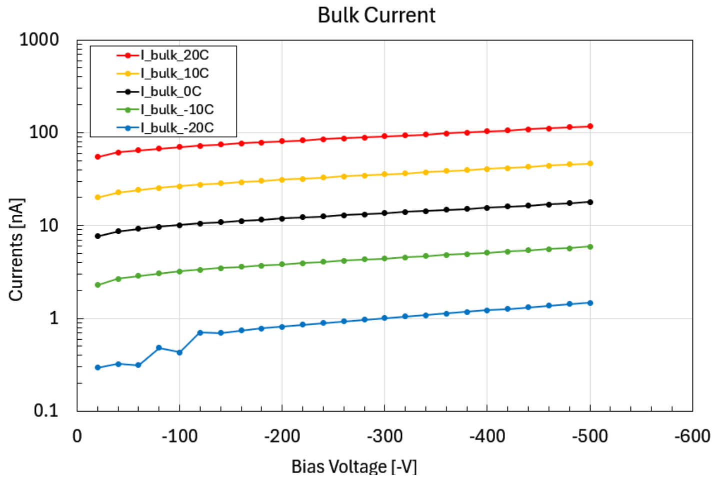


CCE - integral of the pulse from 0 to 25 ns

- V_{FD} ~ 260 V agrees with CV measurements
- bulk is p-type - high pulses already at low voltages ➔ p-n junction is back on the top side, to which red laser light was directed
- V_{FD} has returned to pre-irradiation values, and the p-type is back in the whole volume
- **High temperature annealed the bulk defects (B_iO_i) ->** in agreement with proton irradiated diodes in [8]

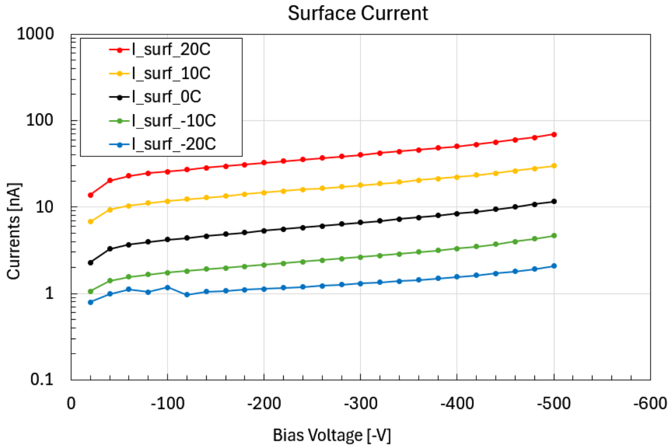
Temperature dependence of Total, Surface and Bulk currents in γ-irradiated samples

- Temperature dependence of bulk current measured in proton- and neutron- irradiated silicon samples is summarized in [7].
- In this study temp. dep. of surface, bulk, and total currents are measured in γ-irradiated mini to 100krad - in range -20°C - +20°C .
- Measured currents fitted by $I(T) = AT^2 \exp\left(-\frac{E_A}{2kT}\right)$, *k is* Boltzmann constant (k = 8.617 × 10^{-5} eV/K)
- free parameters *A* and activation energy E_A for total, surface, and bulk currents.



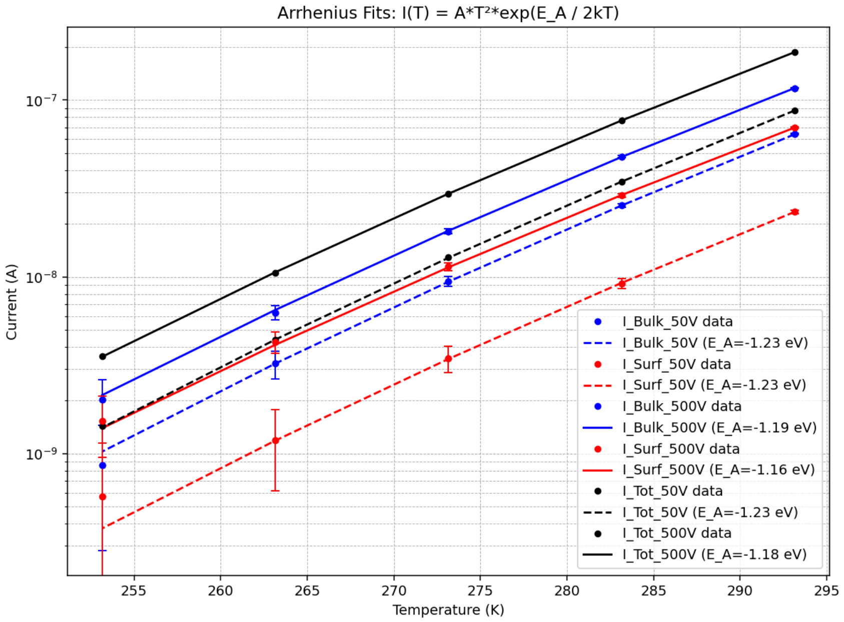
Expected Behavior:

- **Bulk current** flows in **depleted bulk**
- **Surface current** flows in **depleted "inversion layer"** at surface
- In both cases, dominant carriers are electrons, giving similar temperature dependence
- Possible additional effects may arise from **interface traps** influencing surface current - E_A may differ for I_{BULK}, and I_{SURF}
- However, no significant change in radiation formed defects in bulk is expected after low gamma doses.

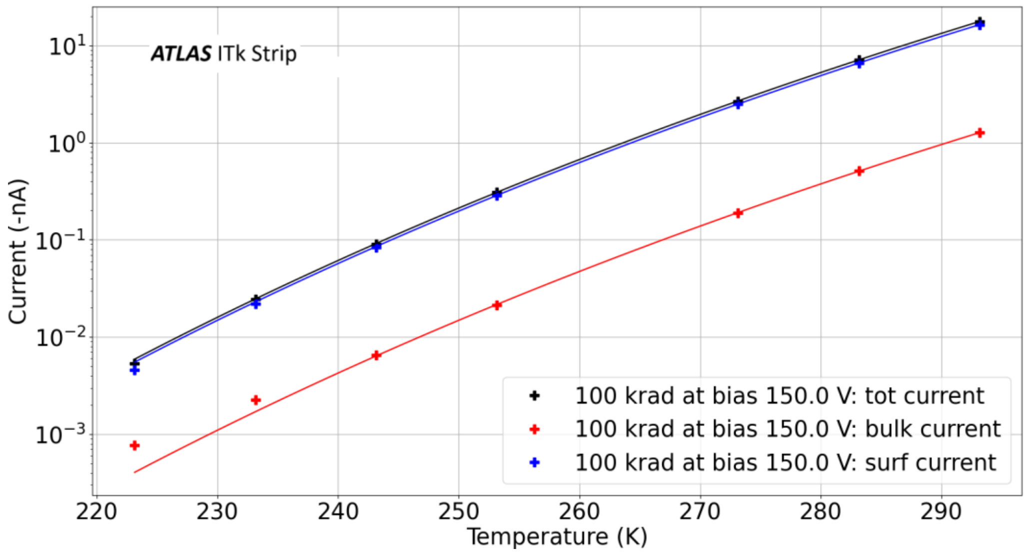


Temperature dependence of I_{tot}, I_{bulk}, and I_{surf}

Mini sensor – 100krad



MD8 diode – 100krad



TID = 100krad

V_bias [V]	E_A (TOT) [eV]	E_A (BULK) [eV]	E_A (SURF) [eV]
50V	1.23	1.23	1.23
500V	1.18	1.19	1.16

TID [krad]	$E_{A(TOT)}$ [eV]	$E_{A(BULK)}$ [eV]	$E_{A(SURF)}$ [eV]
10	1.209	1.192	1.211
50	1.184	1.172	1.185
100	1.201	1.208	1.200

From ref [6]

- No differences were observed between the activation energies E_A derived from temperature dependence for bulk, surface, and total currents.
- Values are consistent with Chilingarov's result (1.209 ±0.007)eV from [7] for neutron and proton irradiation

Summary

- Mini sensors and MD8 diodes from ATLAS18 production wafers irradiated with ^{60}Co γ to a few Mrad - (relevant for early ITk operation).
- **Pre-Irradiation:** Bulk and surface currents are comparable in magnitude.
- **Post-Irradiation**: Total, bulk, and surface currents increases with increasing TID.
  - **Low-dose γ-irradiation** (≤ 2Mrad):
    - Total current increases with TID, driven mainly by surface component, **saturation at ~2 Mrad**
    - High-T annealing (> ~250°C) restores bulk and surface currents to pre-irradiation levels
    - V_{FD} unchanged **→ γ-induced defects are surface-related and fully annealable**
    - Temperature dependence of **surface and bulk currents are same** with agreement of Chilingarov's result E_a =(1.209 ±0.007)eV for protons and neutrons from [7]

  Compare to

  - **High-dose γ-irradiation** (≥ 100s Mrad):
    - Bulk current increases linearly with TID
    - V_{FD} drops significantly (275 V → ~20 V), Si-type change from p- to n-type → probably **initial acceptor removal with charged deep donor B_iO_i formation**
    - High-T annealing (300 °C) restored V_{FD} to pre-irrad value, but only partial currents recovery -> effects under study - Annealing of B_iO_i
- **during the early phase of ITk operation**, gamma-induced effects in strip sensors will remain **small and sensors will be stable**

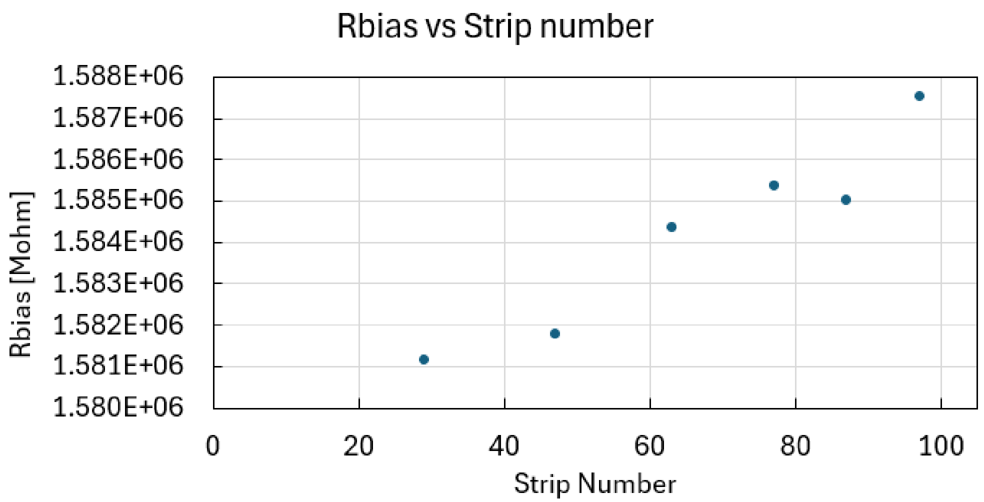
References and Acknowledgement

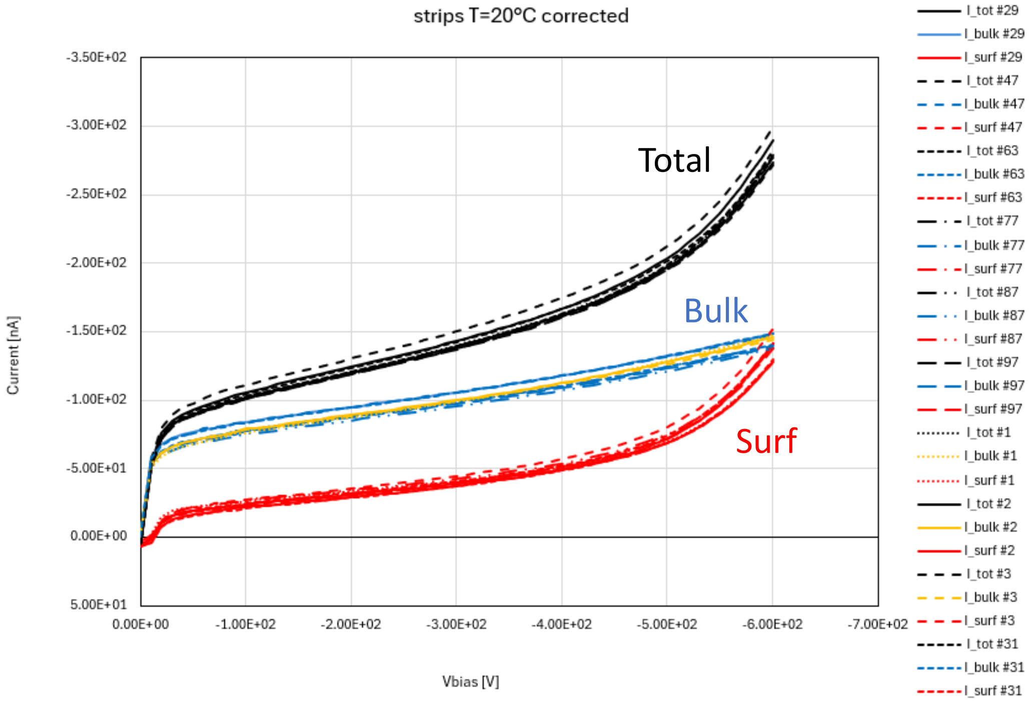
- [1] Experiment ATLAS Public results https://twiki.cern.ch/twiki/bin/view/AtlasPublic/RadiationSimulationPublicResults#Phase_II_Upgrade_Mar_2018_AN1
- [2] M. Mikestikova et al., The study of gamma-radiation induced displacement damage in n-in-p silicon diodes https://doi.org/10.1016/j.nima.2024.169432
- [3] M. Mikestikova et al., Gamma irradiation of ATLAS18 ITk strip sensors affected by static charge https://doi.org/10.22323/1.448.0026
- [4] E. Duden et al., Gamma irradiation of ITk silicon strip modules with early breakdown https://doi.org/10.22323/1.478.0232
- [5] Y. Unno et al., Specifications and pre-production of n+-in-p large format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider, 2023 JINST **18** T03008 https://iopscience.iop.org/article/10.1088/1748-0221/18/03/T03008/pdf
- [6] M. Mikestikova et al., Low dose gamma irradiation study of ATLAS ITk MD8 diodes **DOI** 10.1088/1748-0221/20/08/C08012
- [7] A Chilingarov, Temperature dependence of the current generated in Si bulk, (2013) JINST 8 P10003
- [8] C. Liao *et al.*, "The Boron–Oxygen (B_iO_i) Defect Complex Induced by Irradiation With 23 GeV Protons in p-Type Epitaxial Silicon Diodes," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 3, pp. 576-586, March 2022, doi: 10.1109/TNS.2022.3148030. https://ieeexplore.ieee.org/document/9698047

This work was supported by the European Structural and Investment Funds and the Ministry of Education, Youth and Sports of the Czech Republic via projects LM2023040 CERN-CZ, and FORTE - CZ.02.01.01/00/22_008/0004632, by the US Department of Energy, grant DE-SC0010107, of the Spanish R&D grant PID2021-126327OB-C22, funded by MICIU/ AEI/10.13039/501100011033 and by ERDF/EU, by the Slovenian Research and Innovation Agency (research core funding No. P1-0135).

Backup

Measurement of Bulk current in mini sensors with non- contactable GR
Rbias measurements on 6 bias resistors





MD8 diode – 100krad

- R_{bias} and Voltage drop V were measured on 6 randomly selected strips.
- R_{bias} = 1.584 ± 0.002
- Bias resistors have very consistent bias resistance R_{bias} => there is no need to compensate inter-strip current flowing between strips (through R_{int}) and we assume that the voltage drop at any strip is the same
- The average values of R_{bias} and V are used for analysis.

$$I_{strip} = V / R_{bias}$$

$$I_{surf} = I_{total} - I_{bulk} = I_{total} - n \times I_{strip}$$

n = 104 … number of the strips in mini sensor

- I_{bulk} was also tested on the first three strips to check whether the current at the sensor edge is comparable to that in the middle
- **I_{bulk} current of strip #1, 2, 3 is comparable with the middle ones**

Measurement of Bulk current in mini sensors with non- contactable GR
Temperature dependence of R_{bias}

- R_{bias} is temperature dependent, R_{bias} was tested at +20°, +10°, 0°,-10°, -20°C, -30°C, -40°C, -50°C, and -55°C
- $I_{strip}(T) = V(T) / R_{bias}(T)$

MD8 diode – 100krad