The study of gamma-radiation induced displacement damage in n^+-in-p silicon diodes

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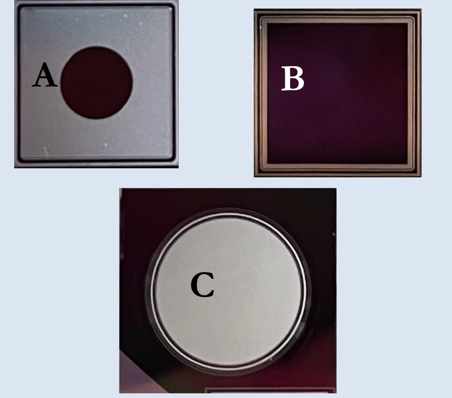
Introduction:

- Currently, there is a lack of studies of gamma irradiated high resistivity p-type silicon.
- Bulk damage of silicon detectors induced by gamma rays was previously studied in detail for n-type bulk.
- The presented study focuses on bulk damage caused by gamma irradiation from ^{60}Co to p-type silicon diodes with various oxygen concentrations and silicon bulk resistivities.
- The main goal of the study was to characterize the gamma-radiation induced displacement damage by measuring current-voltage characteristics (IV), and the evolution of the full depletion voltage (V_{FD}) with total ionizing dose by measuring capacitance-voltage characteristics (CV).
- **This study was performed to quantitatively evaluate the bulk damage in Si n^+-in-p high resistivity sensor when exposed to radiation up to high total ionizing doses (TID) 8.3 MGy**

Samples:

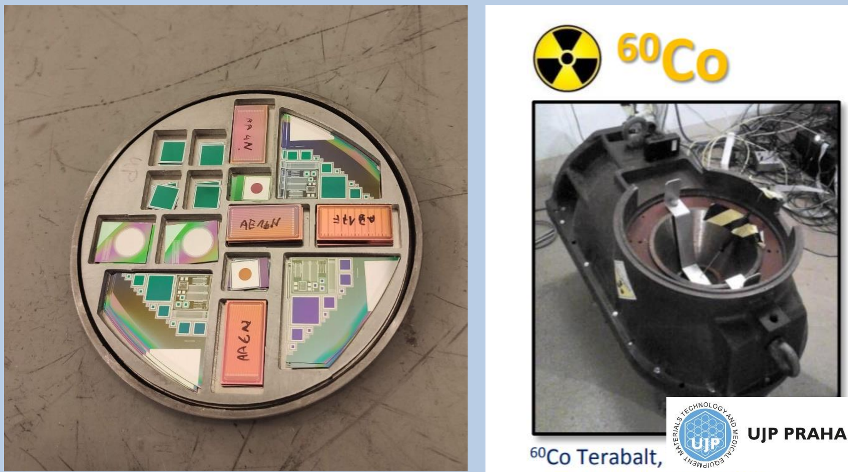
- Study was carried out on three types n^+-in-p standard float zone diodes from three different manufacturers.
- Diodes have comparable active areas and thickness but different silicon bulk resistivity.

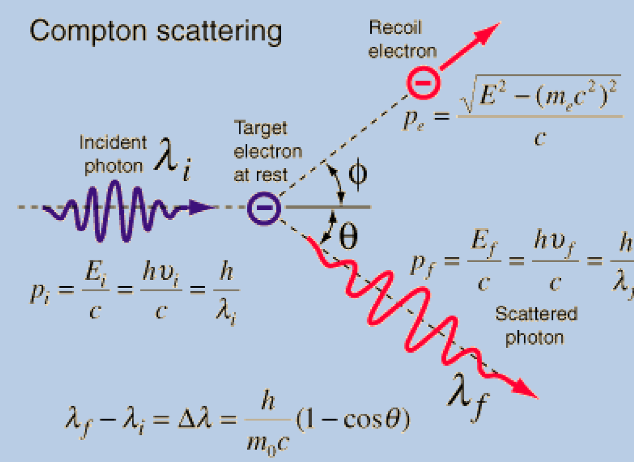
	A	B	C
Active Thickness d [μm]	285	290	285
Active area A [mm²]	49.95	51.55	50.17
Active Volume V [cm³]	0.0142	0.0149	0.0143
Bulk Capacitance C_{bulk} [pF]	18.79	19.48	19.88
Full Depletion Voltage V_{FD} [V]	283.6 ± 12.0	273.4 ± 10.7	36.9 ± 8.3
Bulk Resistivity ρ [kΩ.cm]	3.077 ± 001	3.301 ± 0.001	23.975 ± 4.012



Irradiation:

- Diodes irradiated by ^{60}Co gamma source in Charge Particle Equilibrium box according to ESA/SCC Basic Spec. No. 22900
  - Dose enhancement from low-energy scattered radiation is minimised by producing electron equilibrium
  - Uniform distribution of energy deposited in samples is ensured
- Temperature up to 35 °C
- Dose rate 160-190 Gy/min in silicon
- Dose rate uncertainty: less than 5% within the box.
- Diameter of irradiation area 6 cm





- Displacement damage caused by ^{60}Co gammas is primarily due to interaction of Compton electrons having a maximum energy of 1.2 MeV.
- Cluster production is not possible - minimum electron energy needed for clusters is ~8 MeV.
- Max. recoil energy for the primary knock-on Si-atom by Compton electron is ≈ 140 eV.
- Damage is exclusively due to point defects.
- Min. electron energy needed for single displacements for V-I (Frenkel pair) is 260 keV

Compton scattering

Incident photon λ_i; Target electron at rest; Recoil electron; Scattered photon λ_f

$p_e = \frac{\sqrt{E^2 - (m_e c^2)^2}}{c}$

$p_i = \frac{E_i}{c} = \frac{h\nu_i}{c} = \frac{h}{\lambda_i}$

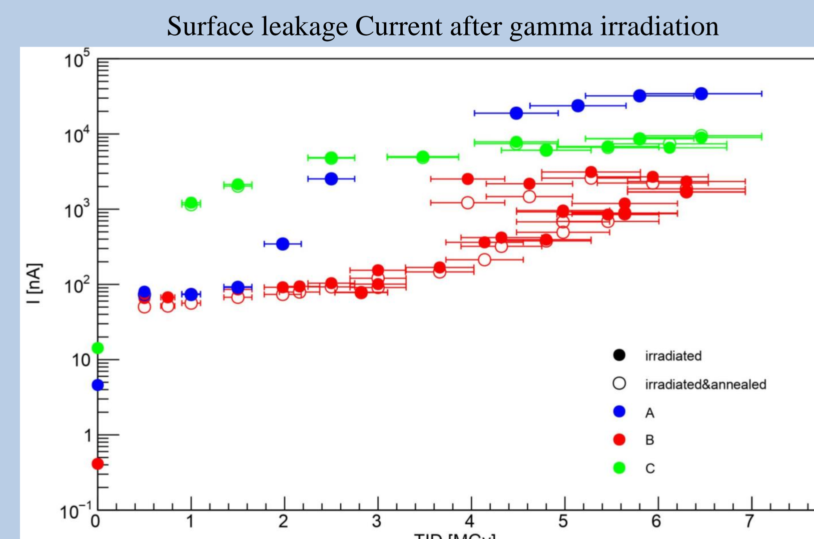
$p_f = \frac{E_f}{c} = \frac{h\nu_f}{c} = \frac{h}{\lambda_f}$

$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$

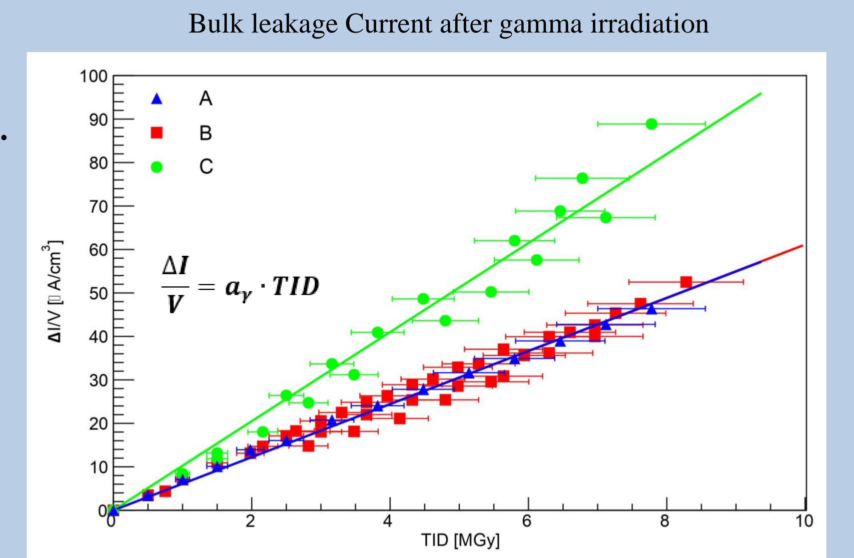
Leakage Current after Irradiation:

- Great care was taken to properly determinate leakage current contributing only to active volume of diode (I_{bulk}) by subtracting parasitic currents contributed by diode surface (I_{sur}).

$I_{tot} = I_{bulk} + I_{sur}$



- Surface current of diode increases significantly even at the initial TID, after which it rises only gradually

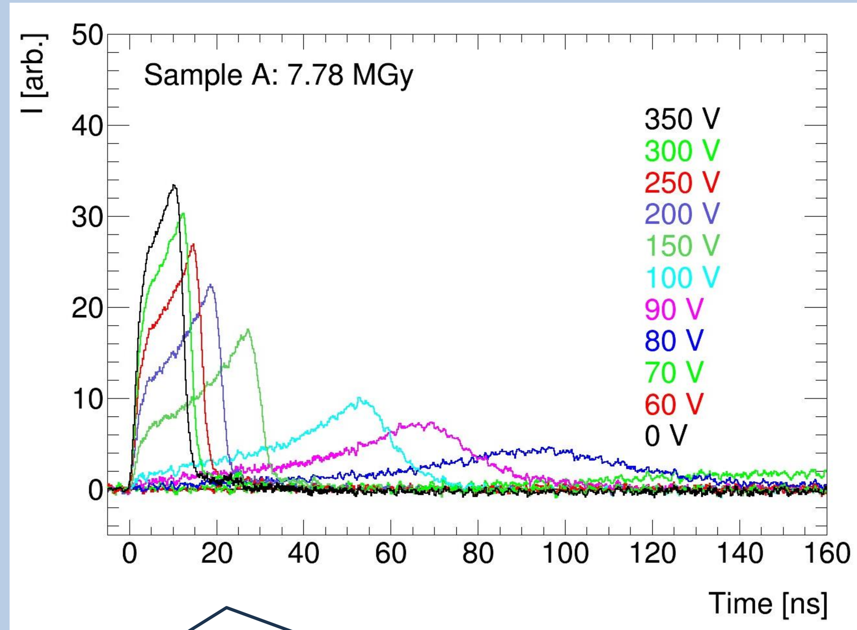


- Bulk leakage current normalised to active volume at V_{FD} vs TID
- Linear increase of bulk current with increasing TID
- Diodes with similar ρ and V_{FD} show same radiation damage.

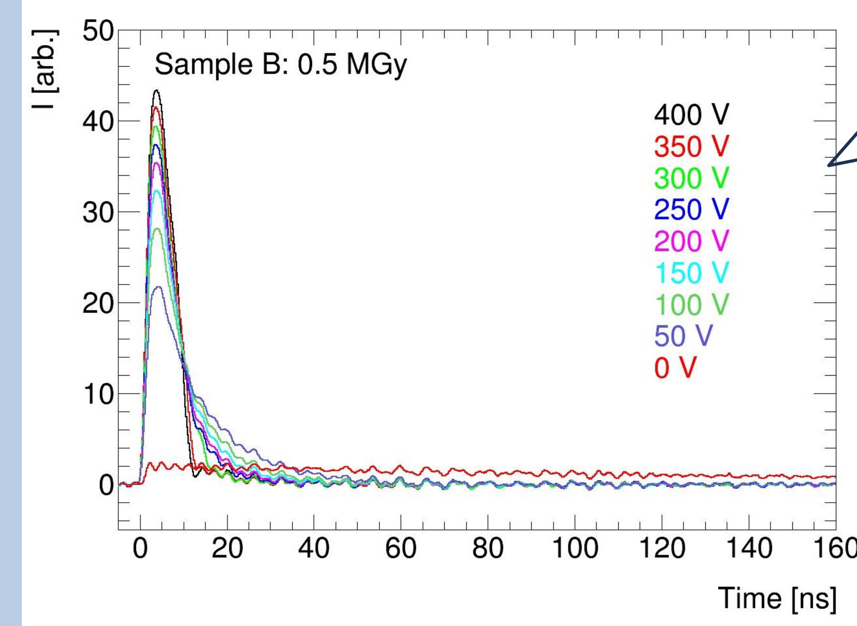
Sample	α_γ [A·cm⁻³·MGy⁻¹]	ρ [kΩ·cm]	V_{FD} [V]
A	(6.33 ± 0.08)·10⁻⁶	3.077 ± 001	283.6 ± 12.0
B	(6.49 ± 0.09)·10⁻⁶	3.301 ± 0.001	273.4 ± 10.7
C	(10.20 ± 0.30)·10⁻⁶	23.975 ± 4.012	36.9 ± 8.3

TCT:

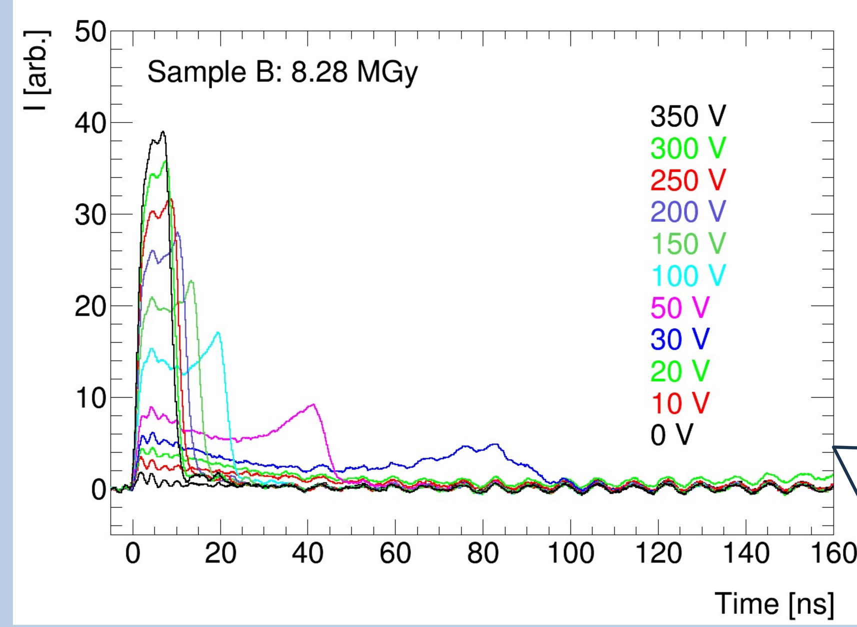
- Transient Current Technique (TCT) was used to verify V_{FD} and to extract electric field distribution and the sign of space charge N_{eff} of silicon diodes irradiated to the lowest and the highest TID
- Diodes were illuminated from n+ side by red laser 660nm



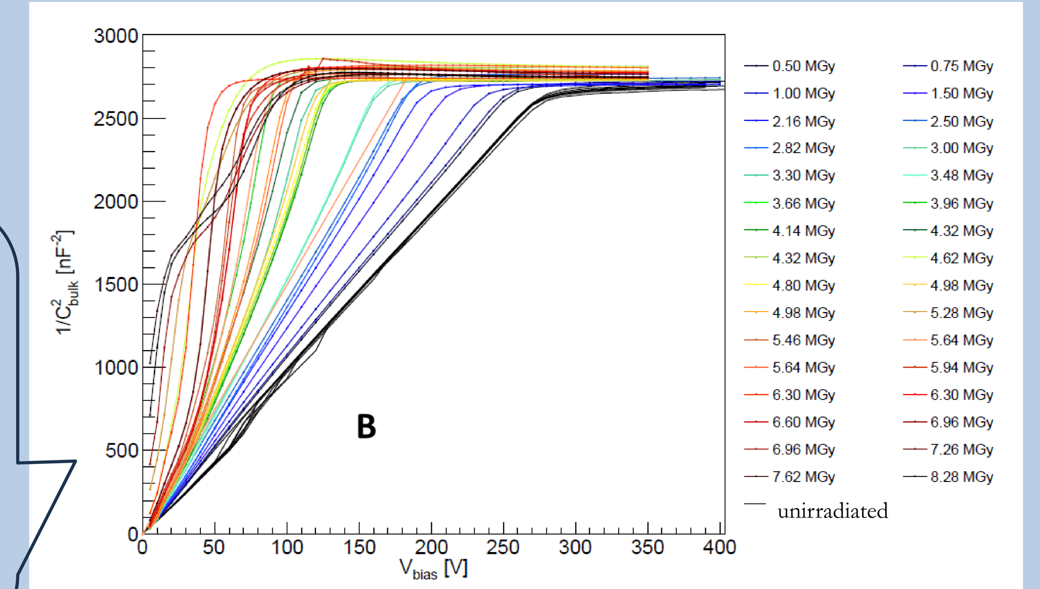
Sample A: 7.78 MGy
- Gamma inverted bulk from p-type bulk to n-type
- p-n junction is on the back side
- No signal to 60V => V_{FD} ~ 70V



Sample B: 0.5 MGy
- high E-field on n+ side, falling towards p+ side ➔ n+-in- p type of device
- V_{FD}: 250V-300V

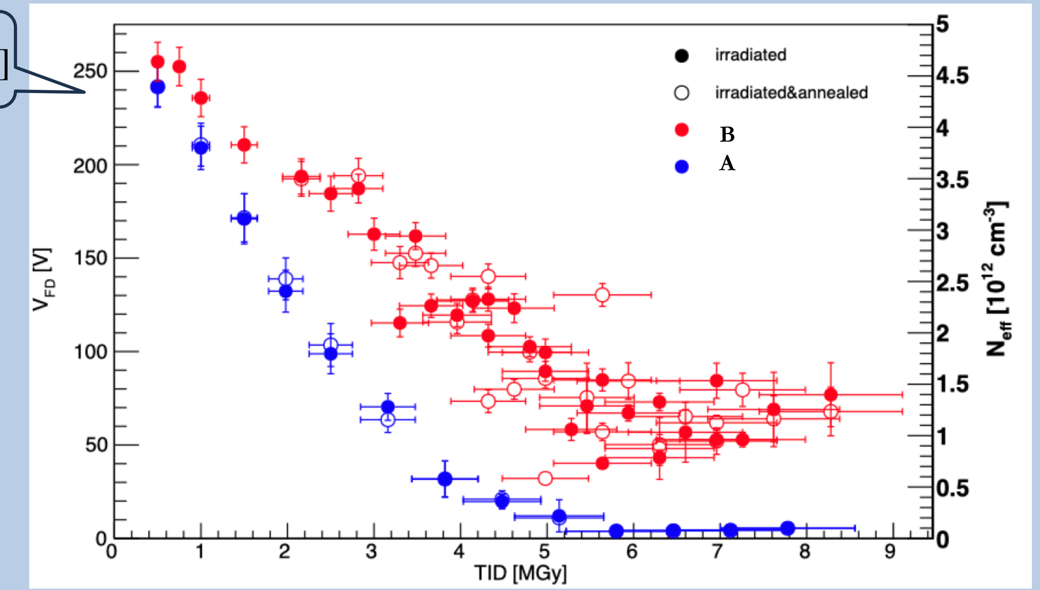


Sample B: 8.28 MGy
- V_{FD} ~ 30 V,
- pulse has two peaks, so bulk is p-type on n+ side and n type on p+ side with neutral bulk in-between, E-field is everywhere
- n-type but space charge concentration low
- V_{FD} between 30V-40V



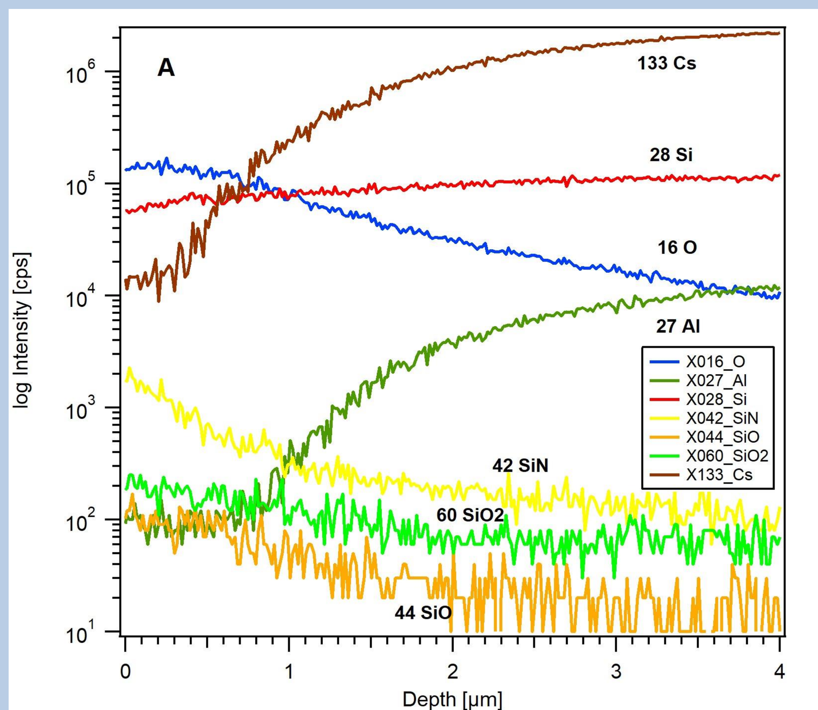
- **Sample B**: CV at different TIDs (unirradiated in black) [1]
- V_{FD} decreases significantly with increasing TID
- V_{FD} (@ 0.5MGy) = 255V (in agreement with TCT results)
- V_{FD} (@ 8.28MGy) = 25V?, 70V? (definition of V_{FD} is difficult at high TID from CV - due to two bumps)

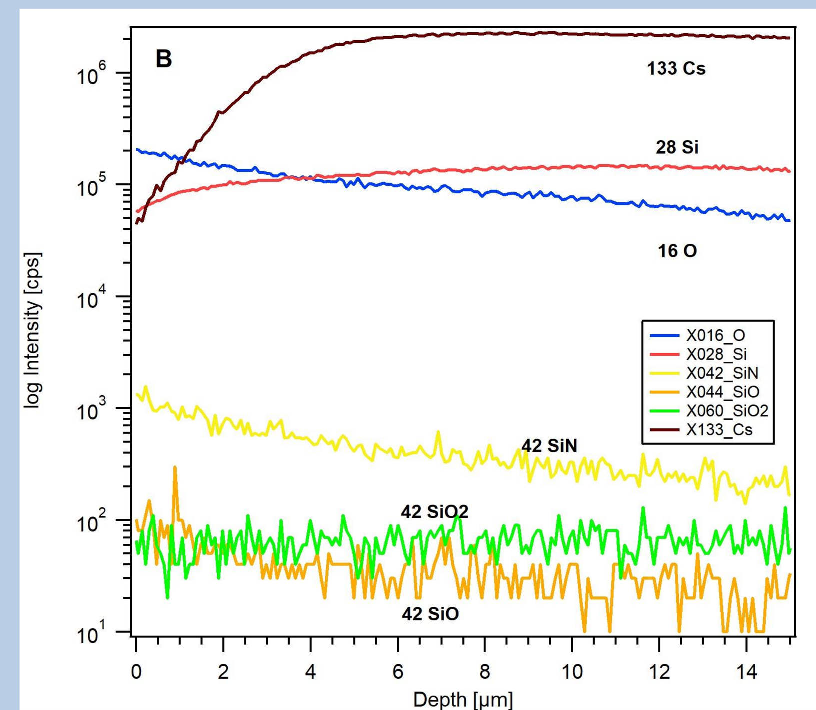
V_{FD} estimated from CV characteristics [1]

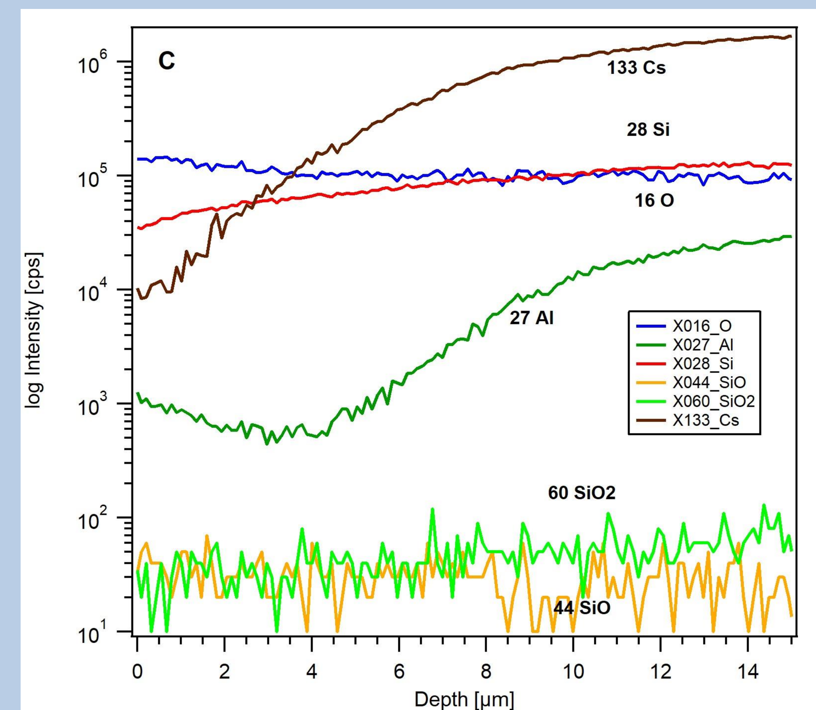


SIMS:

- Secondary-ion mass spectrometry (SIMS) technique used to determine the relative concentration of oxygen in individual samples
- Primary source Cs ions with energy of 7keV







- The SIMS method used does not allow for the determination of absolute concentrations of oxygen; rather, it only provides relative concentrations in comparison to individual samples.
- Concentration of oxygen decreases with increasing depth of diode.
- Decrease in oxygen concentration is least pronounced in sample C and most significant in sample A.
- Sample B, unlike the other two samples, does not contain a measurable concentration of aluminium.

Conclusions:

- Bulk leakage current of gamma irradiated high resistivity p-type silicon increases linearly with total ionizing dose, and damage coefficient depends on initial resistivity and/or oxygen concentration of silicon diode
- Effective doping concentration, and therefore also V_{FD}, significantly decreases with increasing total ionizing dose, before starting to increase again at specific dose. This indicated to silicon bulk type inversion.
- We assume that initial decrease of effective doping concentration is caused by effect of acceptor removal.
- The Transient Current Technique (TCT) measurements confirmed type inversion in both measured diodes irradiated to high TIDs.
- IV and CV measurements of the gamma irradiated diodes did not reveal any annealing effect.

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References:

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