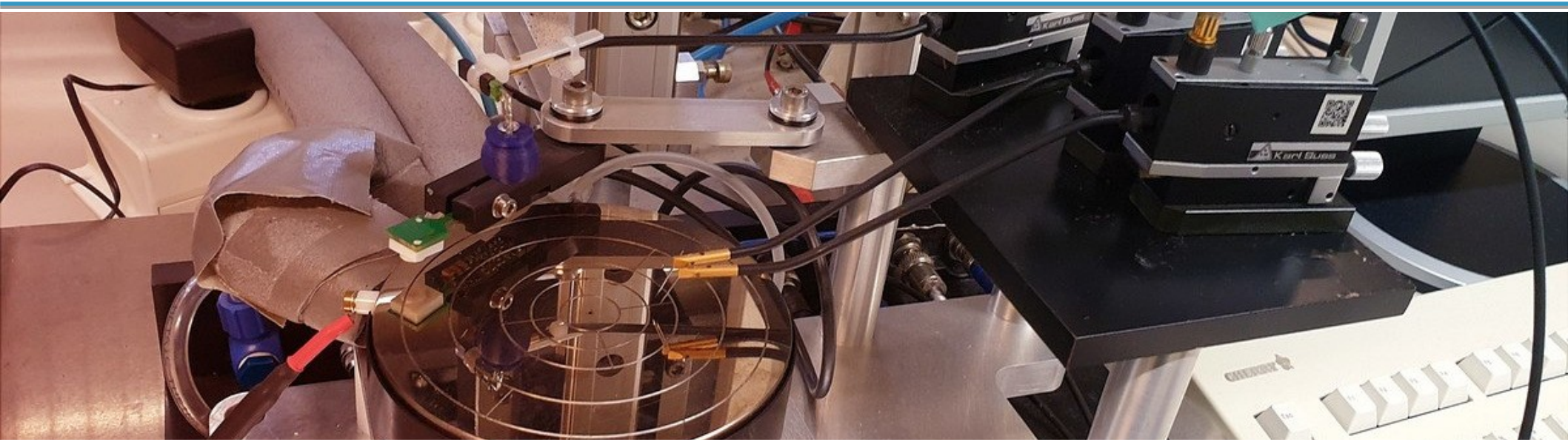
Update on boron removal effect in silicon sensors



Chuan Liao[a], E. Fretwurst[a], E. Garutti[a], J.Schwandt[a], A. Himmerlich[b], M. Moll[b], Y. Gurimskaya[b], I. Pintilie[c], L. Makarenko[d]

[a]Institut für Experimentalphysik, Universität Hamburg

[b]European Organization for Nuclear Research (CERN), Geneva, Switzerland

[c]National Institute of Materials Physics, Bucharest, Romania

[d]Belorussian State University, Minks, Belarus

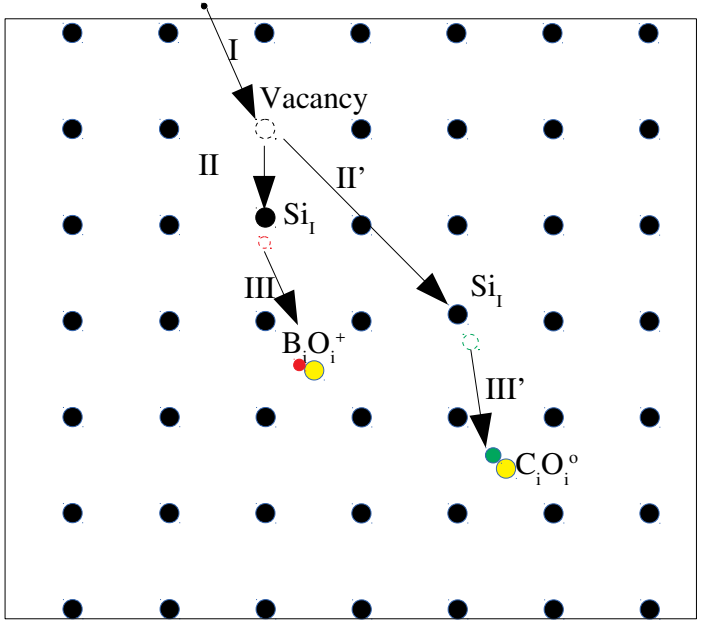
High-D

Sep 5, 2022

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Bulk damage in p-type silicon sensor

Particle or Gamma-ray (Compton effect 1MeV electron)



Schematic of radiation damage in p-type silicon sensor

I: Lattice Silicon atom (Si_s) was knocked out by incident particle and Si_s got recoil energy and turns to interstitial silicon (Si_i)

II: Si_i diffusion in the bulk and impact on Lattice Boron atom (B_s)

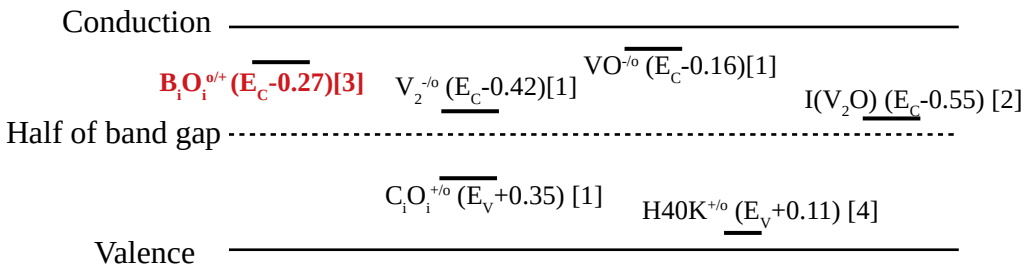
III: B_s was knocked out Si_i and turns to interstitial Boron (B_i) and finally captured by interstitial Oxygen (O_i)

Previous work (presented on RD50 workshop):

Type of Radiation

- 23 GeV Protons (4.3 × 10^{13} n_{eq}/cm^2, N_{eff} = 10^{12}~10^{15} cm^{-3} – **Doping dependent**):
  Comparing the decreases of N_{eff} with defect formation;
  Current related damage parameter α (Hamburg model, cluster related defect);
  Annealing behavior
- 6 MeV electrons (10^{13}~10^{14} n_{eq}/cm^2 – **Fluence dependent**, N_{eff} = 10^{15} cm^{-3}):
  N_{eff}, α and annealing behavior comparing with proton irradiation;
  Comparing the Cz ([C] ≈ 2 × 10^{15} cm^{-3}) and EPI ([C] ≈ 3 × 10^{16} cm^{-3}) diodes
- **^{60}Co – γ ?**

The observed results from both literature and our works(depend on initial doping, type of radiation and fluence):



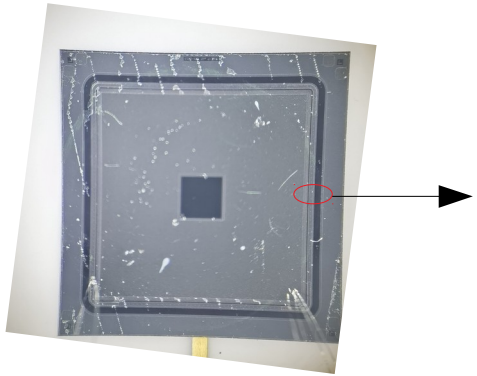
"The radiation damage induced defect in p-type silicon, B_iO_i is investigated"

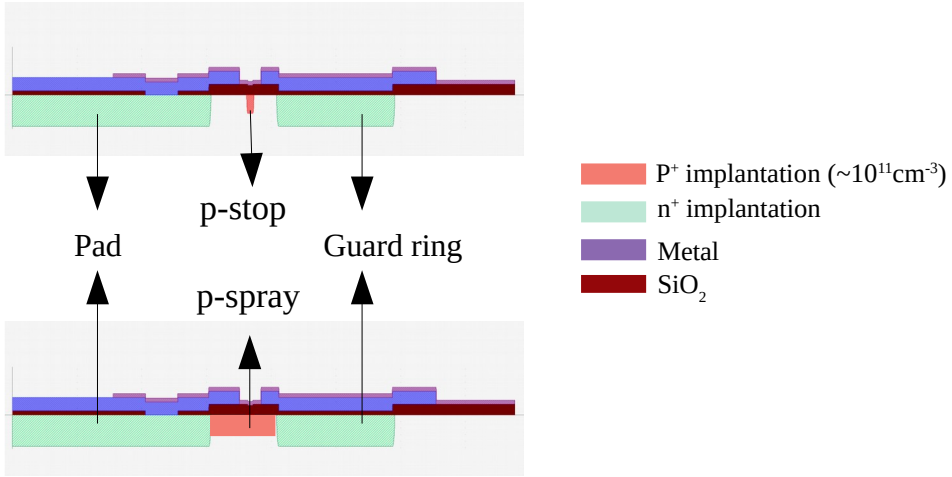
Sample information

Details of samples investigated (high resistivity ~3 kΩcm p-type FZ material from Hamamatsu)

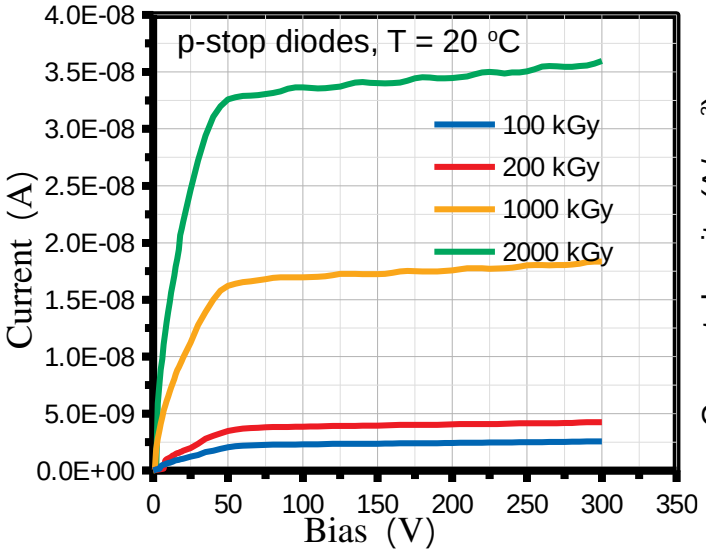
Initial doping, bulk (cm^{-3})	~3.5 × 10^{12}			
^{60}Co-γ irradiation (kGy)	100(94±0.96)	200(189±3.9)	1000(924±27)	2000(1860±56)
Area (cm^2)	0.25			
Thickness (μm)	150			

Aims:
- Investigate B_iO_i defect
- Other induced defects

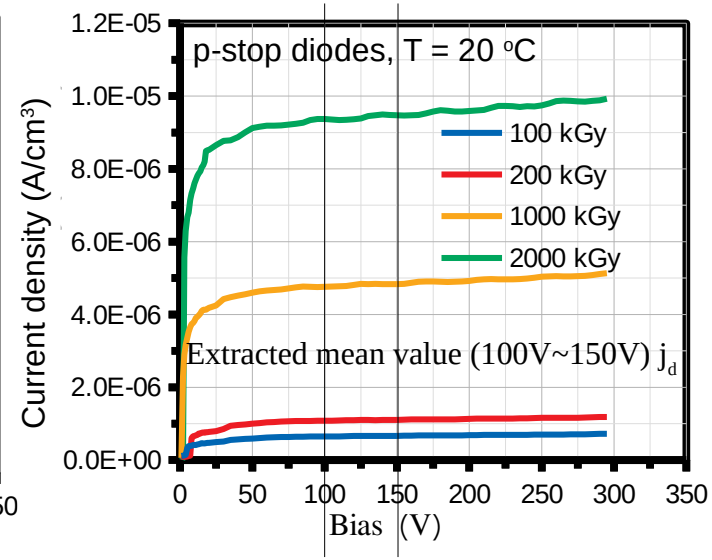




I-V measurements

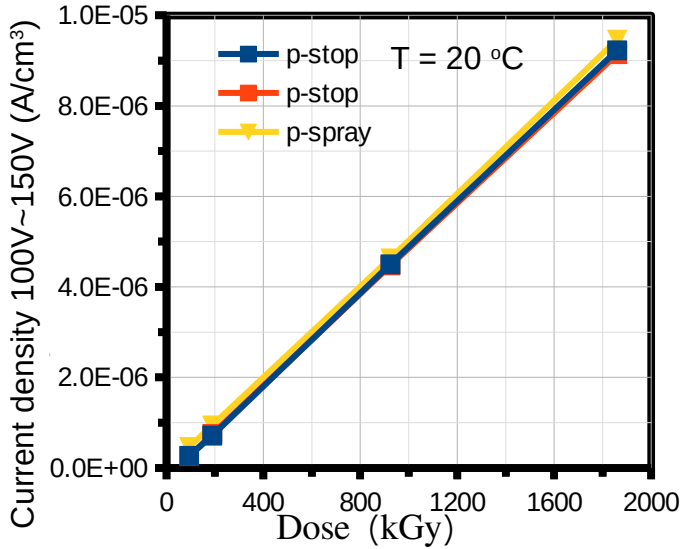


I-V measurements

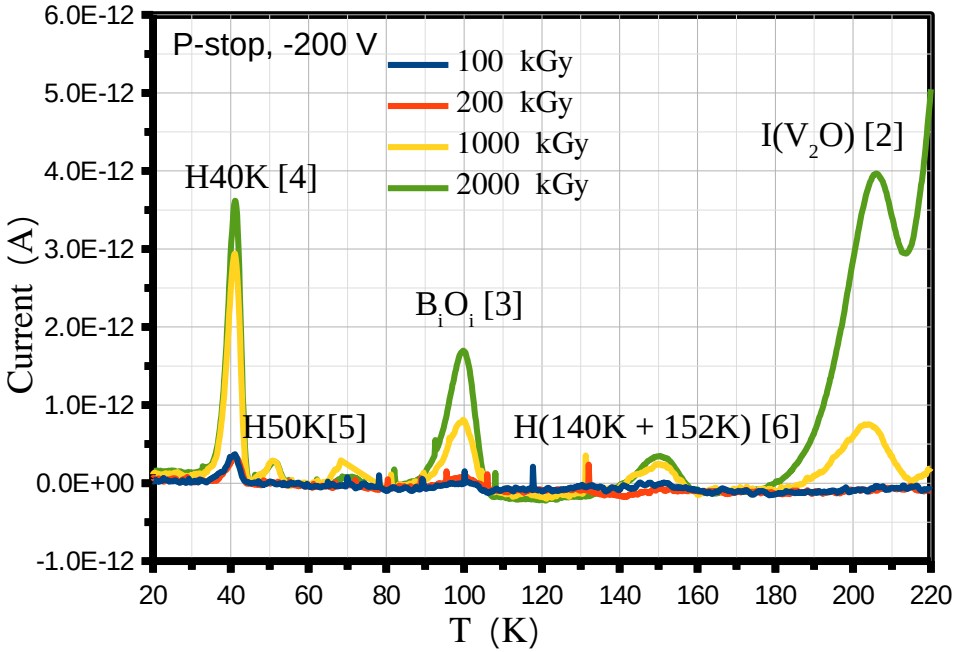


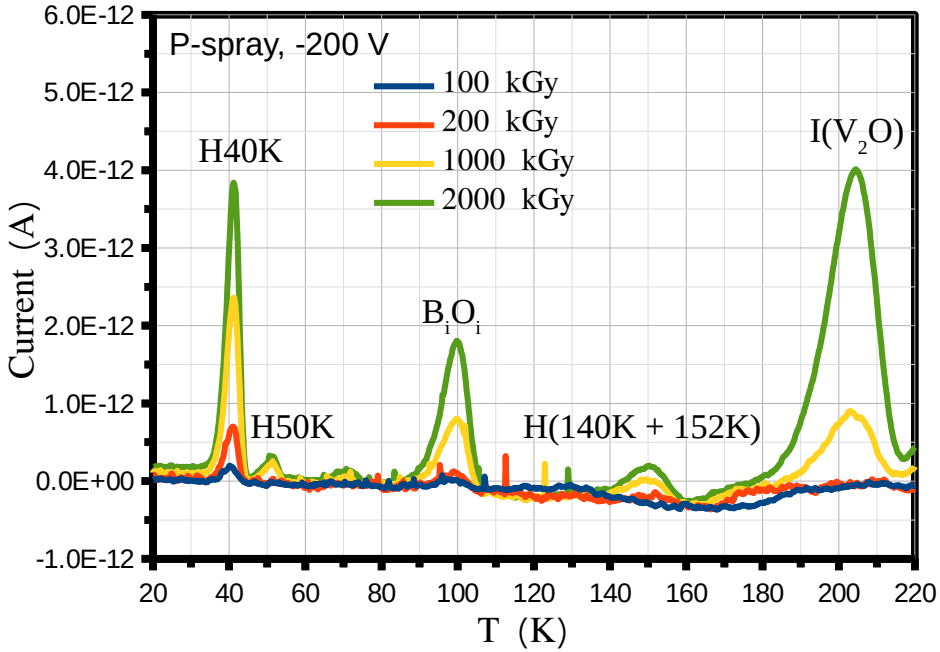
100 V 150 V

Current density given by I-V and C-V (100 kHz for p-stop diodes)



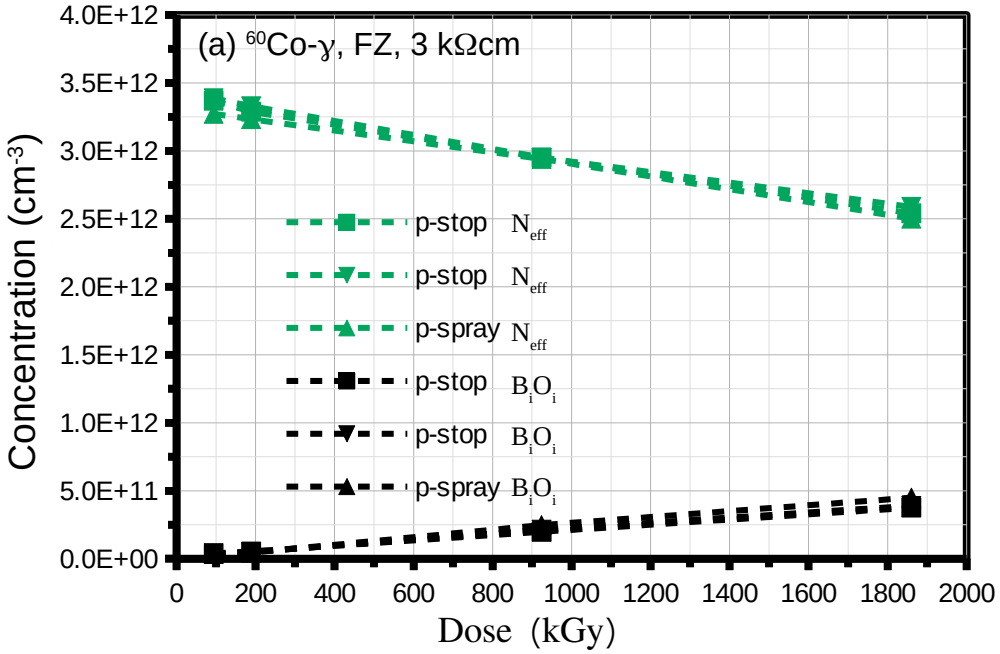
Thermally Stimulated Current (TSC) measurement

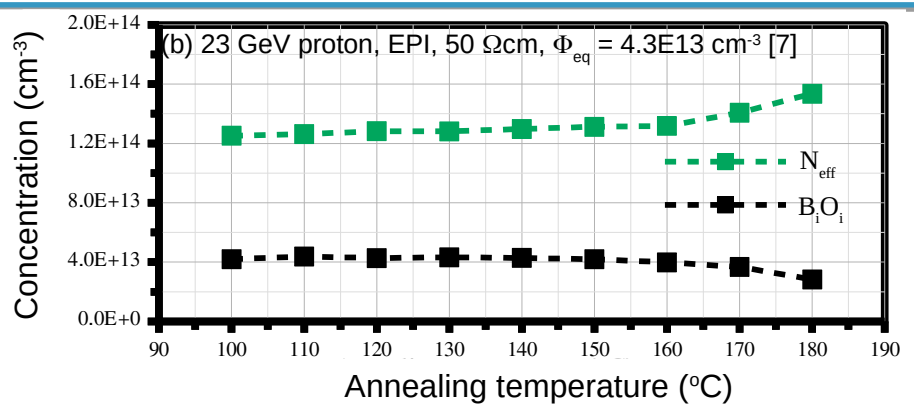


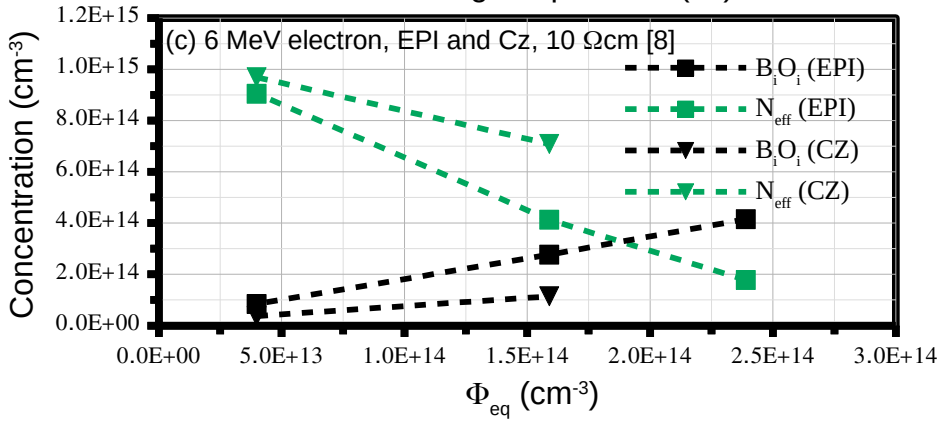


- Forward bias filling, filling current I_{fill} = 0.8 mA, filling temperature at T_{fill} = 10 K for 30 s, heating rate β = 0.183 K/s and $V_{heat\ up}$ = -200 V

$[B_iO_i]$ and N_{eff} (comparison to previous work)



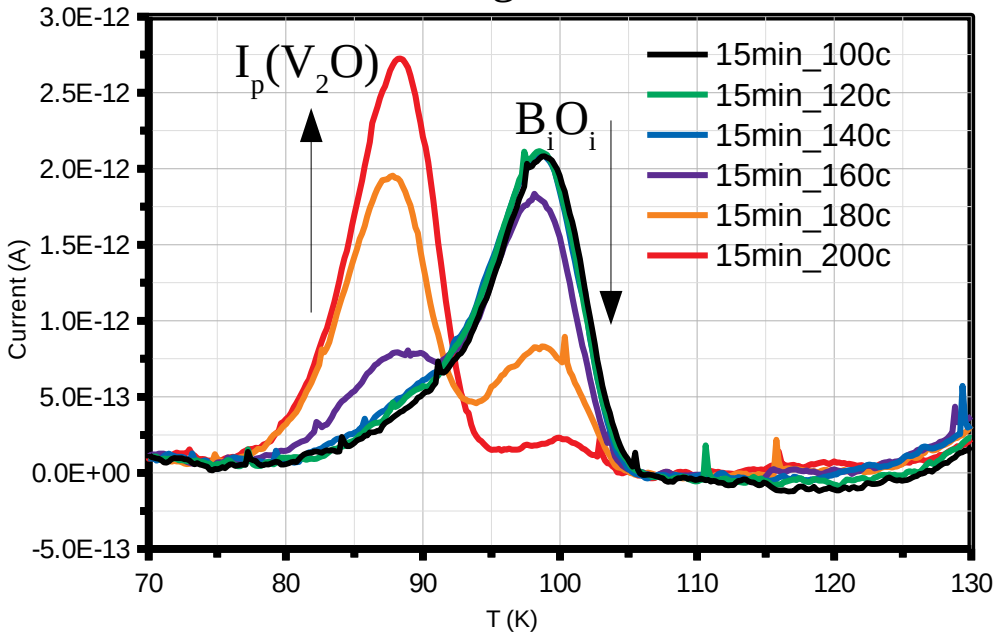




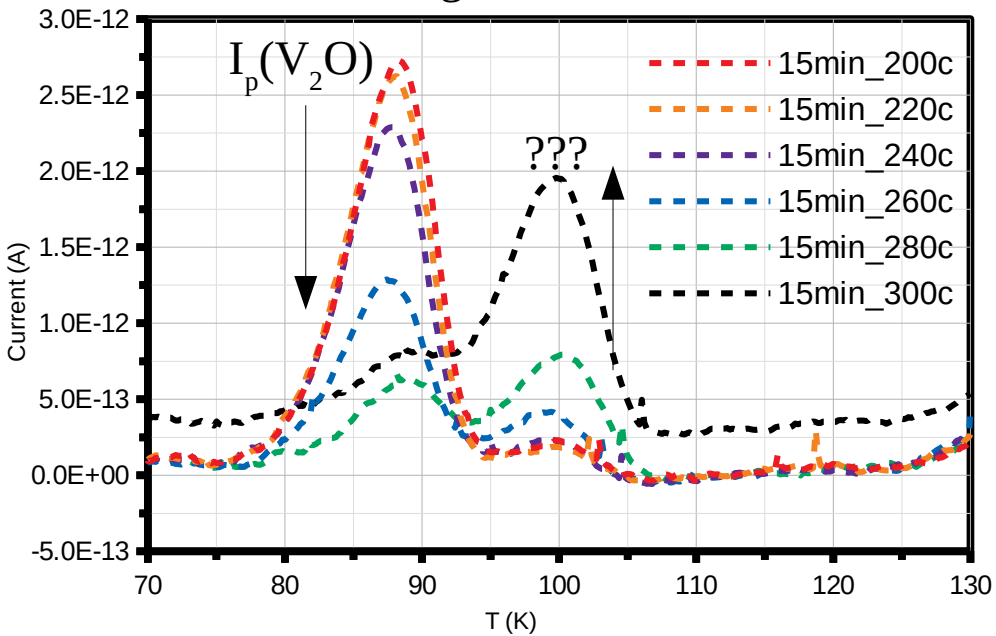
- Development of B_iO_i concentration and N_{eff} with dose value (a), annealing temperature (b) and NIEL fluence transferred by 6 MeV electron (c)
- The decrease of N_{eff} given by CV measurement
- $\Delta Neff \approx 2\times\Delta[B_iO_i]$ (for all figure presented in this slide)

TSC (annealing behavior)
(p-stop, 2000 kGy, Isochronal annealing)

Annealing 100 - 200°C



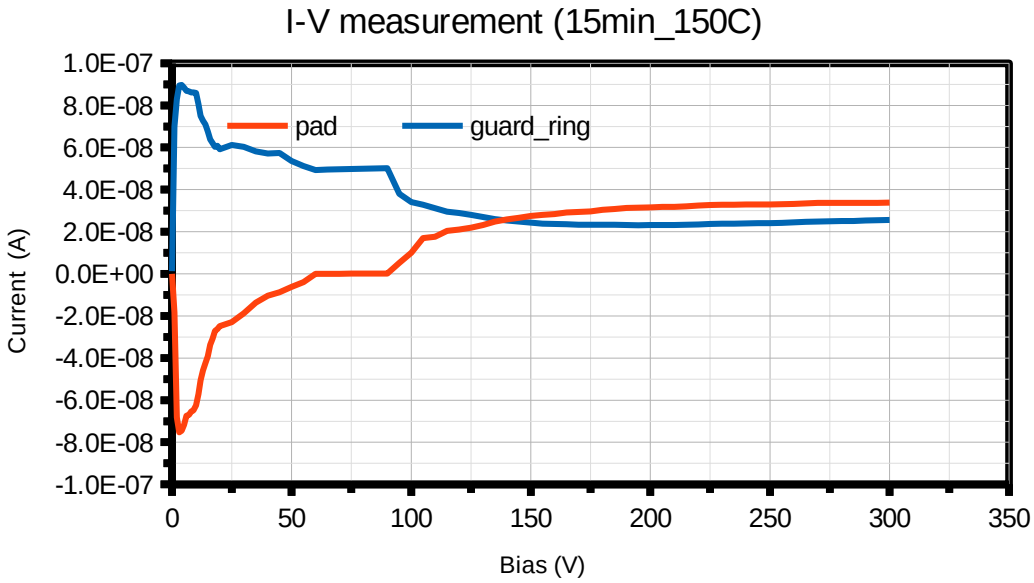
Annealing 200 - 300°C

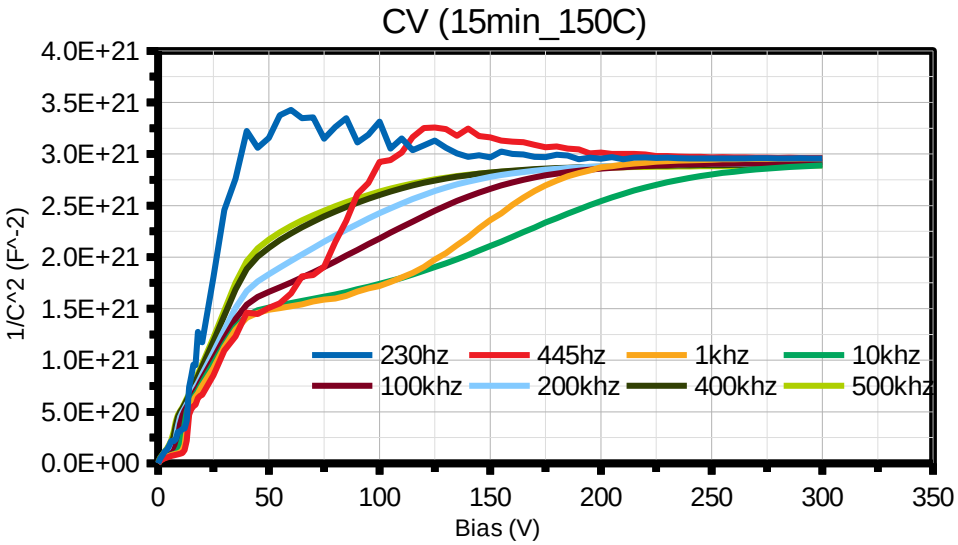


V_{bias}=-300V, T_{fill}=30K, 200 Mrad, I_{fill}=1 mA

- B_iO_i decreasing from 160°C, and disappeared at 200°C,
- I_p [2] increasing from 160°C to 200°C, decreasing from 240°C to 300°C

Unexpected results (2000 kGy)

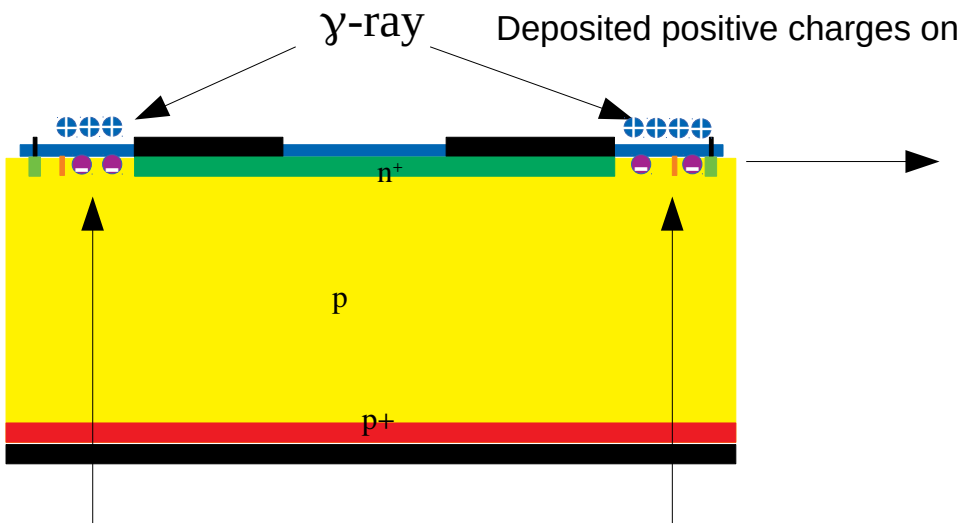




Some unexpected results happened on I-V and C-V measurements. The stander results should similar as presented on slide 4 and 11

Surface current

Surface damage due to Ionizing Energy Loss (IEL):
Oxide trapped charge – SiO_2 captured the ionizing electrons or hole
Fixed oxide charge – E' center
Interface traps in the region near to SiO_2

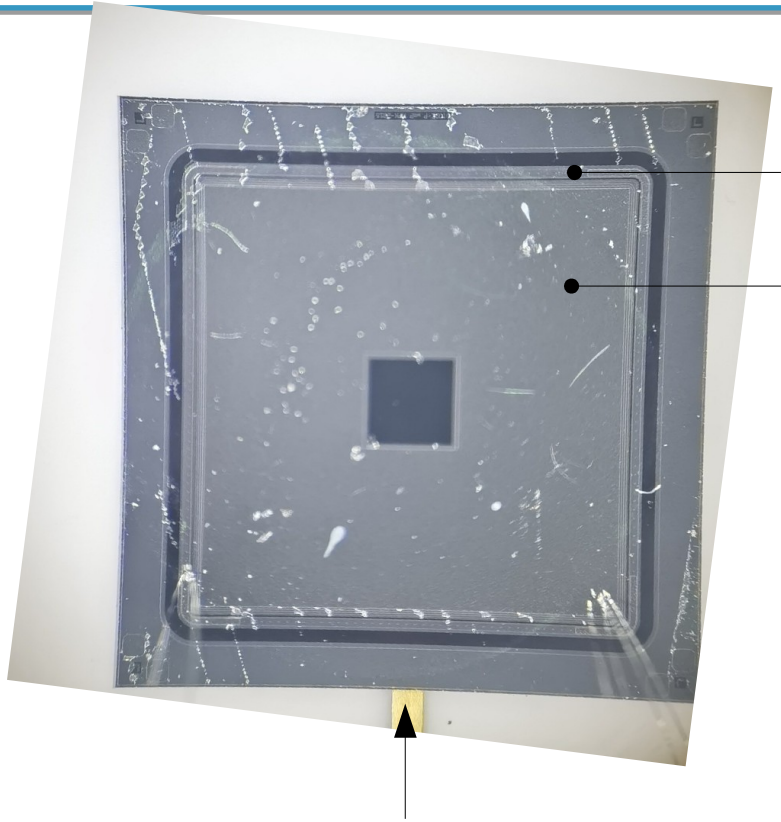


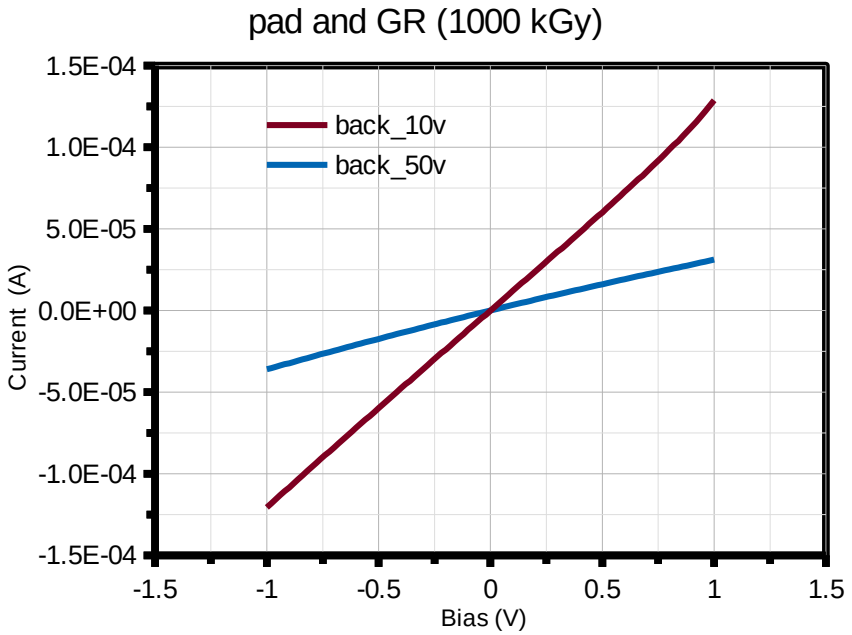
As the accumulation of positive charges on the SiO_2, The resistivity between guard-ring and pad are changed.

- Frequency dependent C-V
- Current goes to guard-ring

Aluminum
p type bulk (Boron doping, 10^{13}~10^{15} cm^{-3})
p^+ (Boron doping B_s^-, ~ 5×10^{19} cm^{-3})
n^+ (Phosphorus doping P_s^+, ~ 1×10^{21} cm^{-3})
p^+ (Boron implantation, P-stop or P-spray ~ 10^{11} cm^{-3})
n^+ (Phosphorus implantation, guard ring)
SiO_2

Surface current



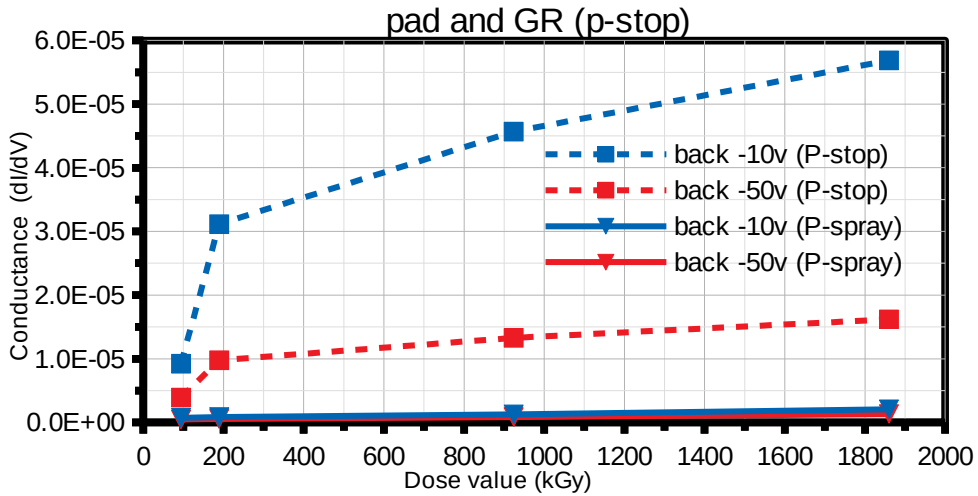


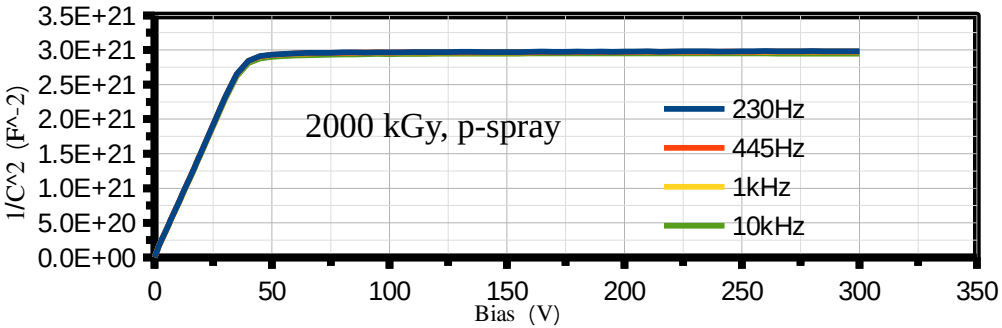
The definition of conductance(σ): $\sigma = dI/dV$

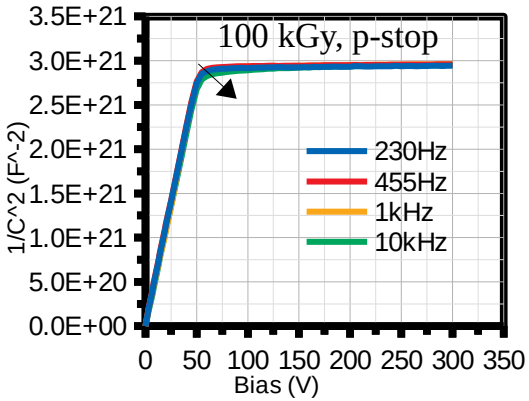
In semiconductor, σ was determined by: $\sigma = q_0(\mu_e n + \mu_h p)$

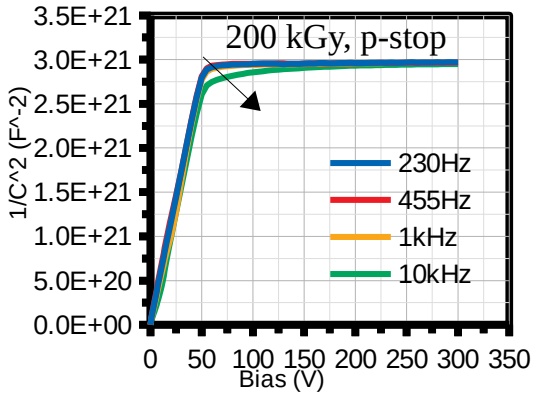
Where the n and p are the free charge carriers concentration

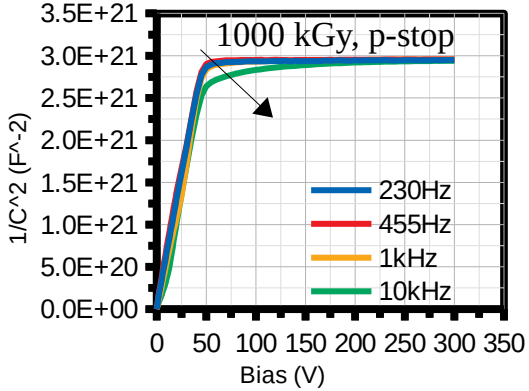
Measurement results

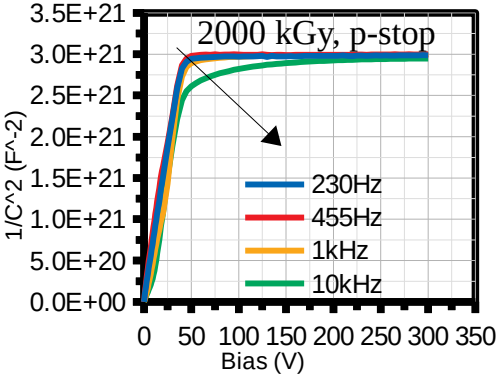






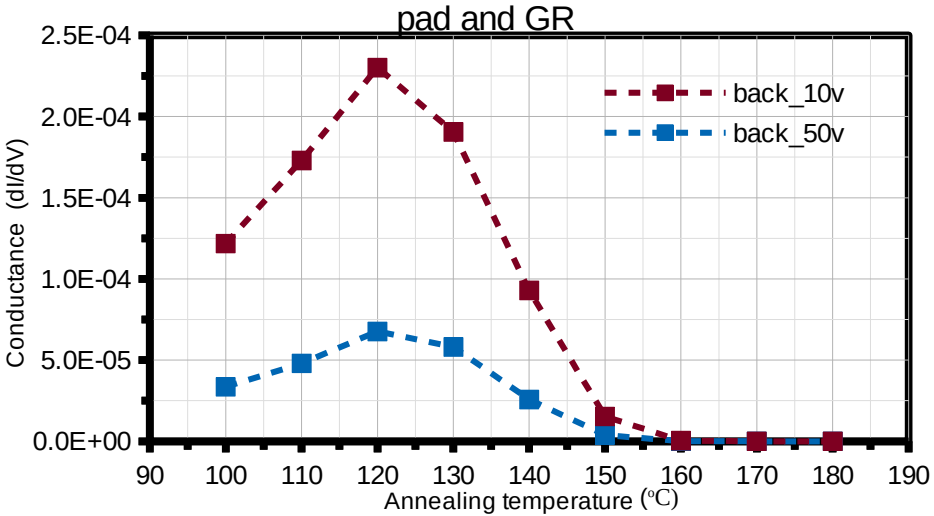




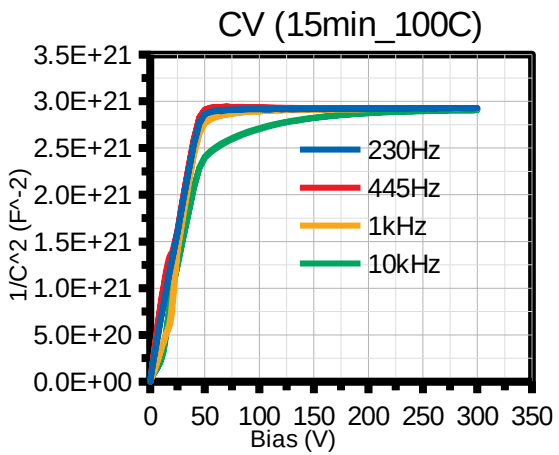


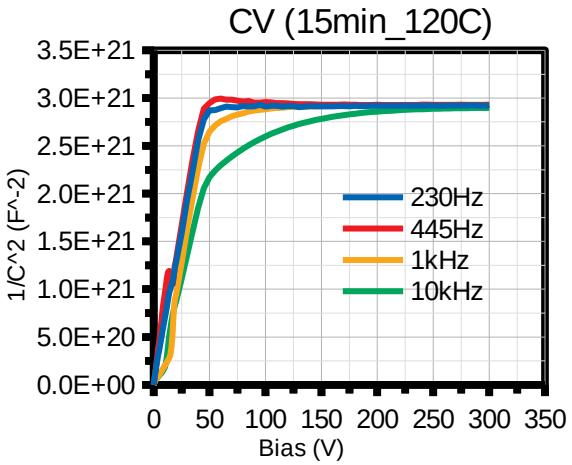
- Conductance increasing with Dose values
- Frequency depends on the conductance

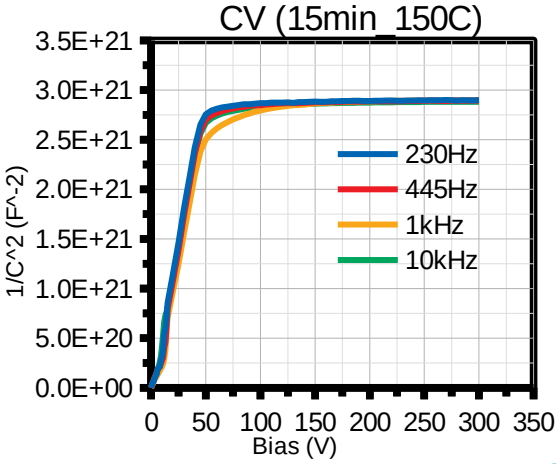
Annealing behaviors
(p-stop, 100 kGy, 15 min for each T_{ann})

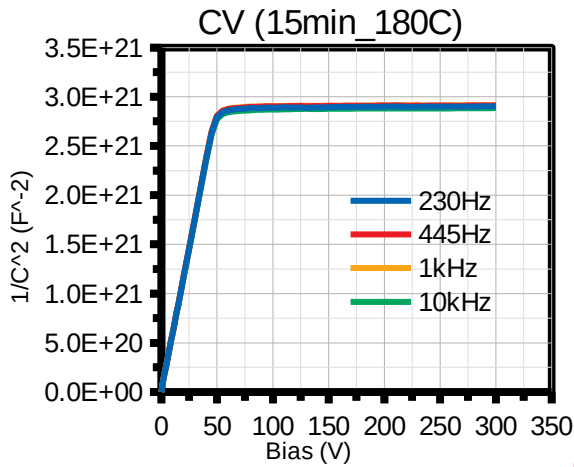


When T_{ann} > 170°C, frequency dependent disappeared.









Conclusion

I. Results for FZ p-type diodes irradiated by ^{60}Co γ with dose value (100 kGy, 200 kGy, 1000 kGy and 2000 kGy):

a). Macroscopic measurement (I-V, C-V):

- j_d linear increasing with dose value
- Frequency-dependent of C-V didn't appear on p-spray diodes

b). Microscopic measurement (TSC):

- Introduction rate of defect increases with dose
- $\Delta Neff \approx 2\times\Delta[B_iO_i]$
- B_iO_i was annealing out from 150 to 200^{o}C. Meanwhile V_2O was formed.

II. Surface current:

- Surface current increasing with Dose value
- For 1000 kGy γ-ray irradiated diode, surface current can be annealing out when T_{ann} > 160^{o}C

Literature

[1] M. Moll, “Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties,” Ph.D. dissertation, Dept. Phys., Univ. Hamburg, Hamburg, Germany, 1999
[2] Pintilie, Ioana, et al. "Radiation-induced point-and cluster-related defects with strong impact on damage properties of silicon detectors." Nucl. Instrum. Methods Phys. Res. A, 611.1 (2009): 52-68.
[3] Liao, C., et al. "The Boron–Oxygen (B_iO_i) Defect Complex Induced by Irradiation With 23 GeV Protons in p-Type Epitaxial Silicon Diodes." IEEE Transactions on Nuclear Science 69.3 (2022): 576-586.
[4] Wodean project. Summary Report, 2010
[5] Pintilie, I., et al. "Second-order generation of point defects in gamma-irradiated float-zone silicon, an explanation for “type inversion”." Applied physics letters 82.13 (2003): 2169-2171
[6] I. Pintilie, E. Fretwurst, and G. Lindström, “Cluster related hole traps with enhanced-field-emission—The source for long term annealing in hadron irradiated Si diodes,” Appl. Phys. Lett., vol. 92, no. 2, Jan. 2008
[7] C. Liao et al., “The boron-oxygen (BiOi) defect complex induced by irradiation with 23 GeV protons in p-type epitaxial silicon diodes,” presented at the 37th RD50 Workshop, Zagreb, Croatia, 2020. [Online]. Available: https://indico.cern.ch/event/896954
[8] C. Liao et al., “Investigation of the BiOi defect in EPI and Cz silicon diodes using Thermally Stimulated current (TSC) and Thermally Stimulated Capacitance (TS-Cap),” presented at the 39th RD50 Workshop, Valencia, Spain, 2021. [Online]. Available: https://indico.cern.ch/event/1074989