Investigation of high resistivity p-type FZ silicon diodes after ^{60}Co-γ irradiation

Chuan Liao[a], E. Fretwurst[a], E. Garutti[a], J.Schwandt[a]

[a]Institut für Experimentalphysik, Universität Hamburg

A. Himmerlich[b], Y. Gurimskaya[b], I. Mateu[b], M. Moll[b]

[b]Conseil européen pour la recherche nucléaire (CERN)

I. Pintilie[c]

[c]National Institute of Materials Physics (NIMP)

L. Makarenko[d]

[d]Belarussian State University

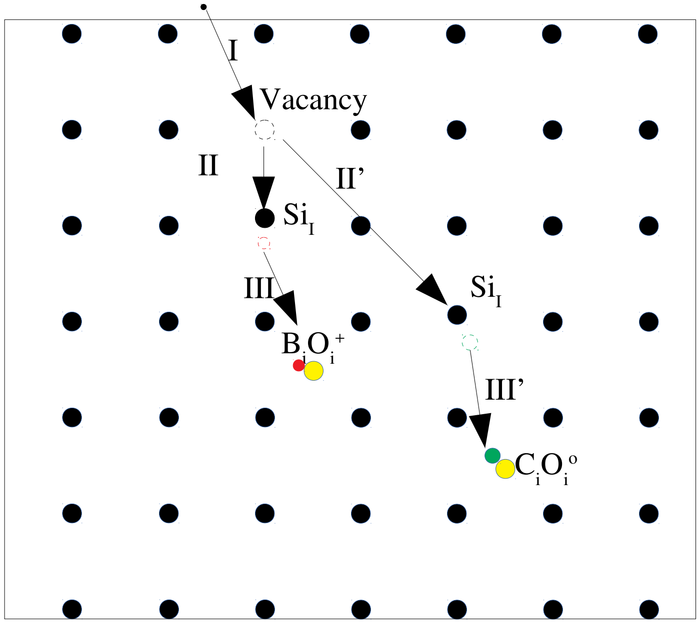
Acceptor removal team

21/06/2022

R&D 50 workshops

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)

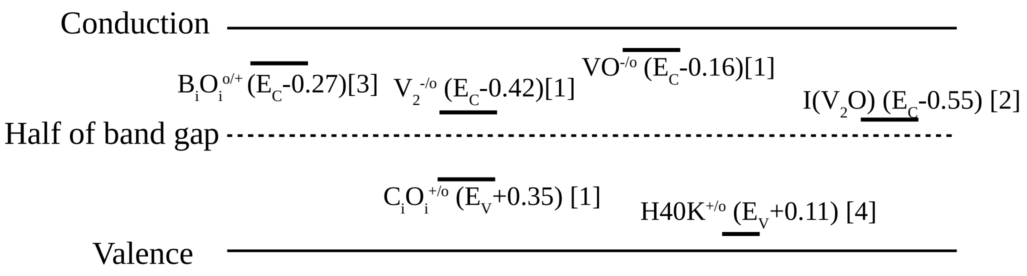
III: B_s was knocked out Si_i and turns to interstitial Boron (B_i) and finally captured by interstitial Oxygen (O_i)

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 ($[C] \approx 2 \times 10^{15}$ cm^{-3}) and EPI ($[C] \approx 3 \times 10^{16}$ cm^{-3}) diodes
- **^{60}Co – γ ?**

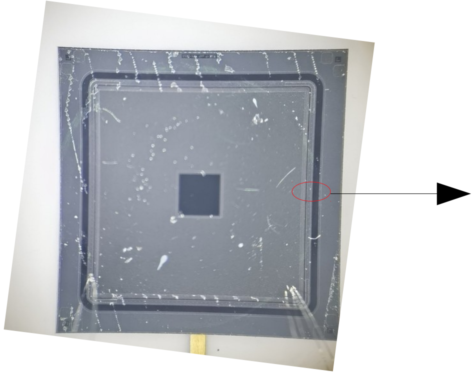
The observed results from both literature and our works(depend on initial doping, type of radiation and fluence):

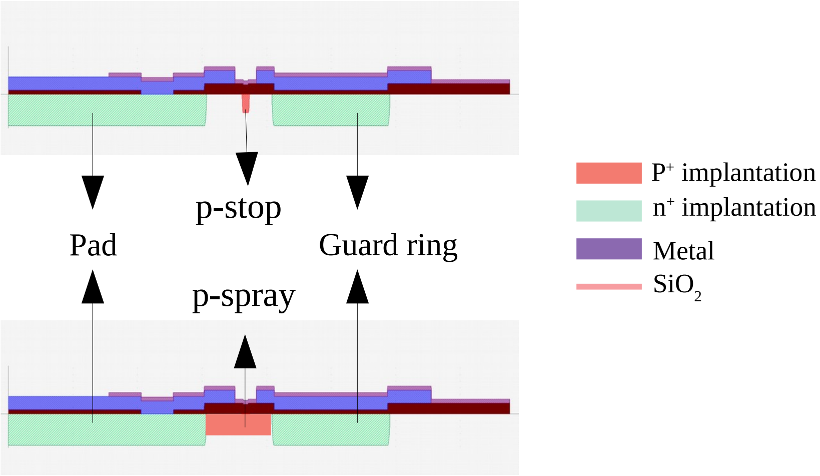


Diode Information

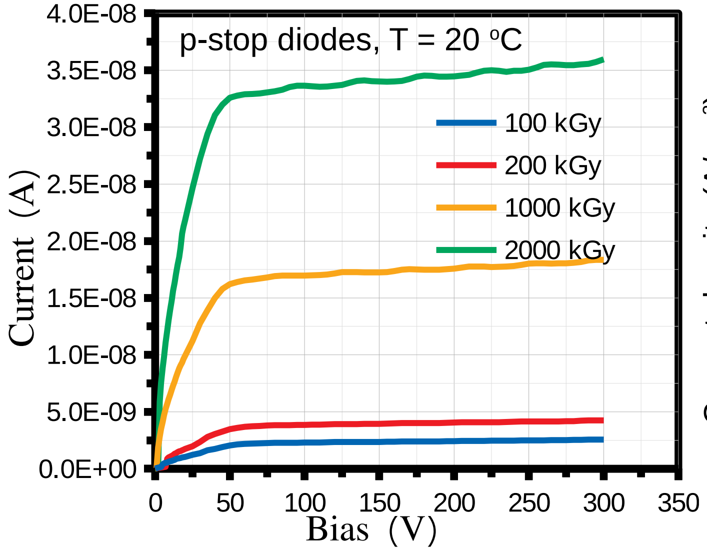
Details of samples investigated (high resistivity ~3 kΩcm p-type FZ material from Hamamatsu)

Initial doping, bulk (cm^{-3})	$\sim 3.5 \times 10^{12}$			
^{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			

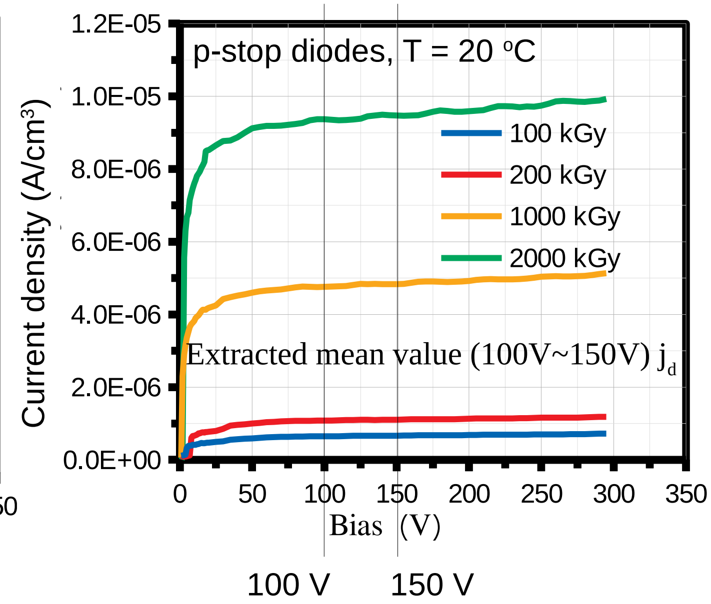




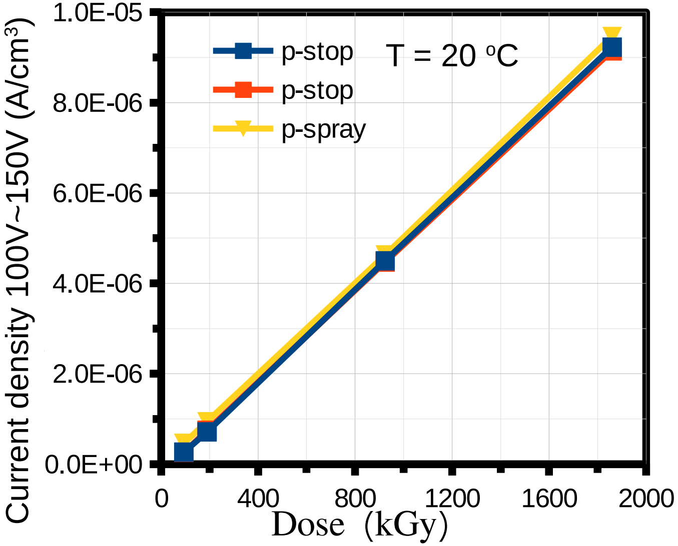
I-V measurements



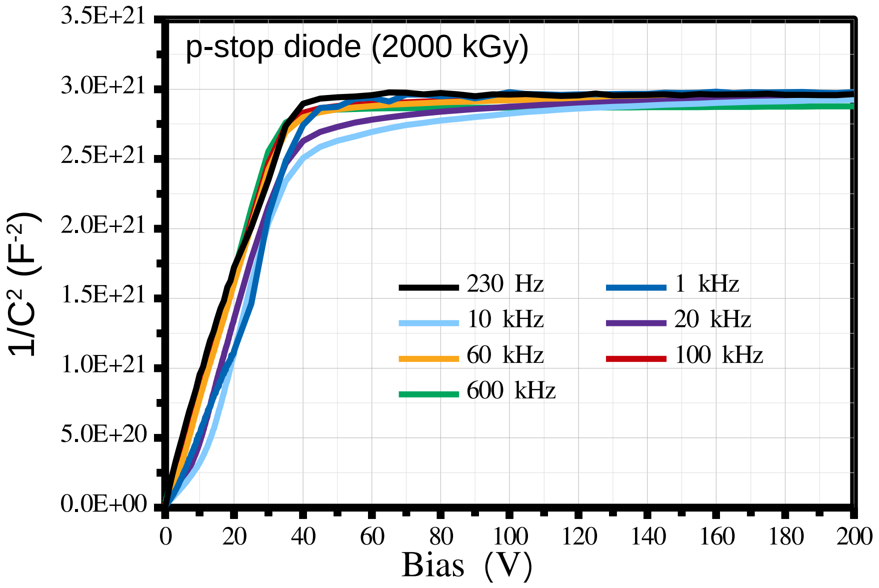
I-V measurements

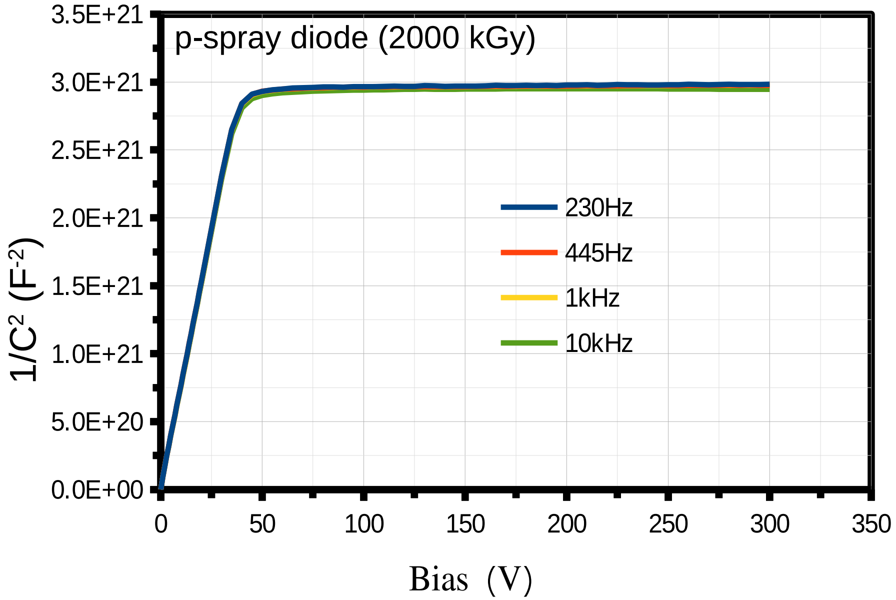


Current density given by I-V and C-V (100 kHz for p-stop diodes)



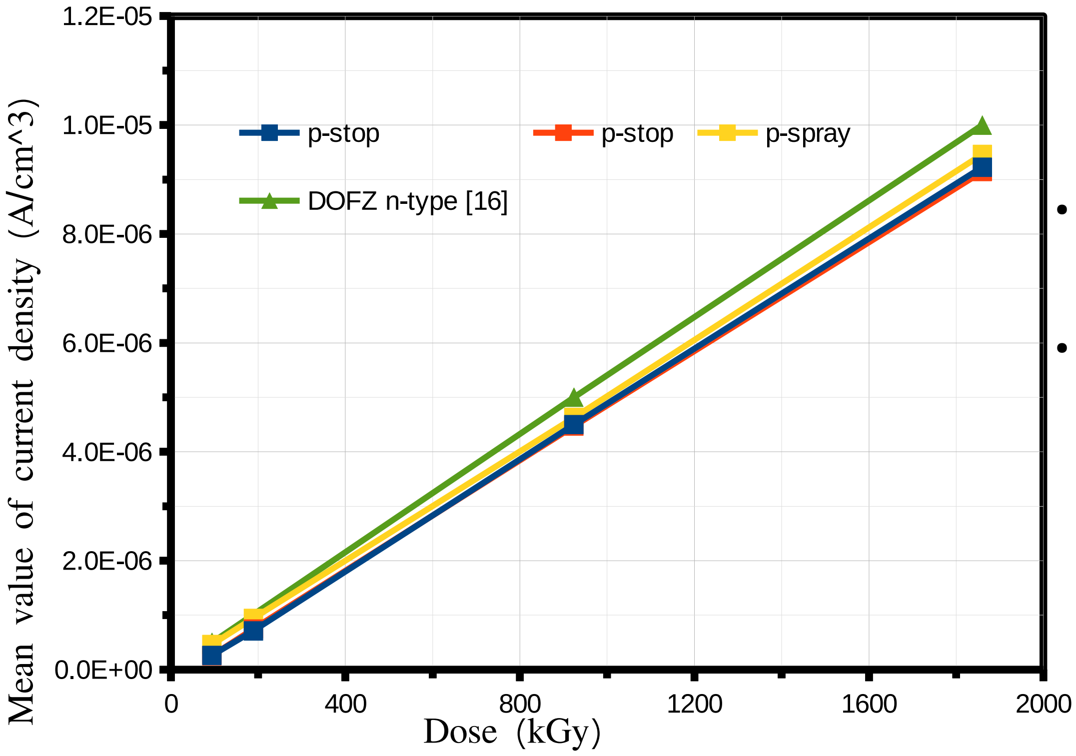
C-V measurements





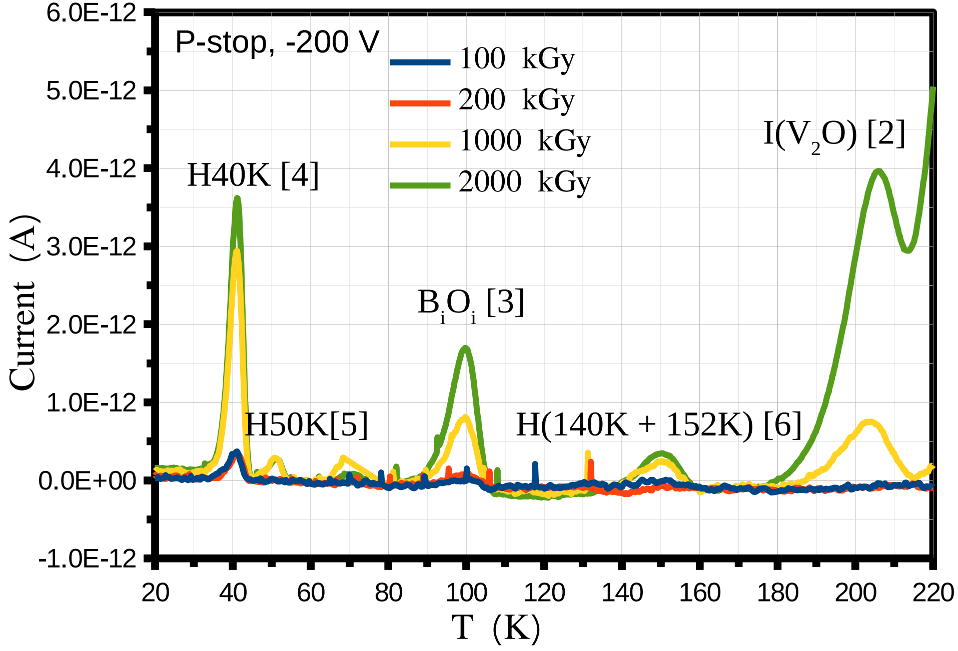
- C-V measurement for p-stop diode (left, 2000 kGy, freq = 230Hz ~ 600 kHz) and p-spray diode (right, 2000 kGy, freq = 230Hz ~ 10 kHz)
- Measured at room temperature, V_{AC} = 0.5 V
- Observation:
  – No frequency dependence for p-spray diode
  – Frequency dependence for p-stop diode

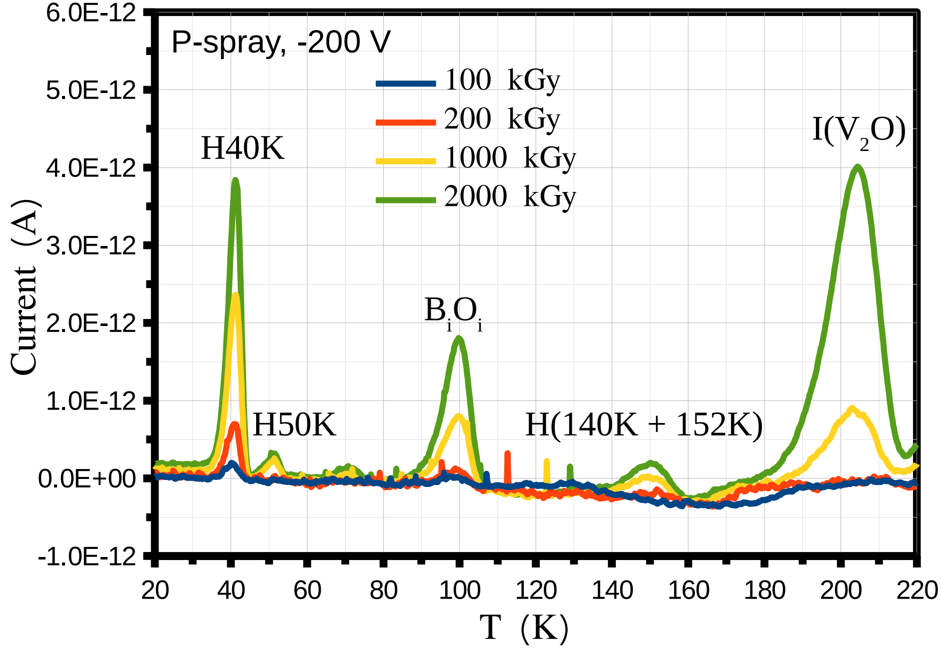
Comparison with other materials (I-V)



- The estimated value of leakage current density of n-type was included (DOFZ – Oxygen enriched diodes. [O] ≈ 1×10^{17} cm^{-3}).
- Similar behavior on development of j_d with dose value, possibly due to both are oxygen-enriched (10^{17} cm^{-3}) [2] compare to standard FZ (Standard FZ [O] = 5×10^{15} cm^{-3}) [2]

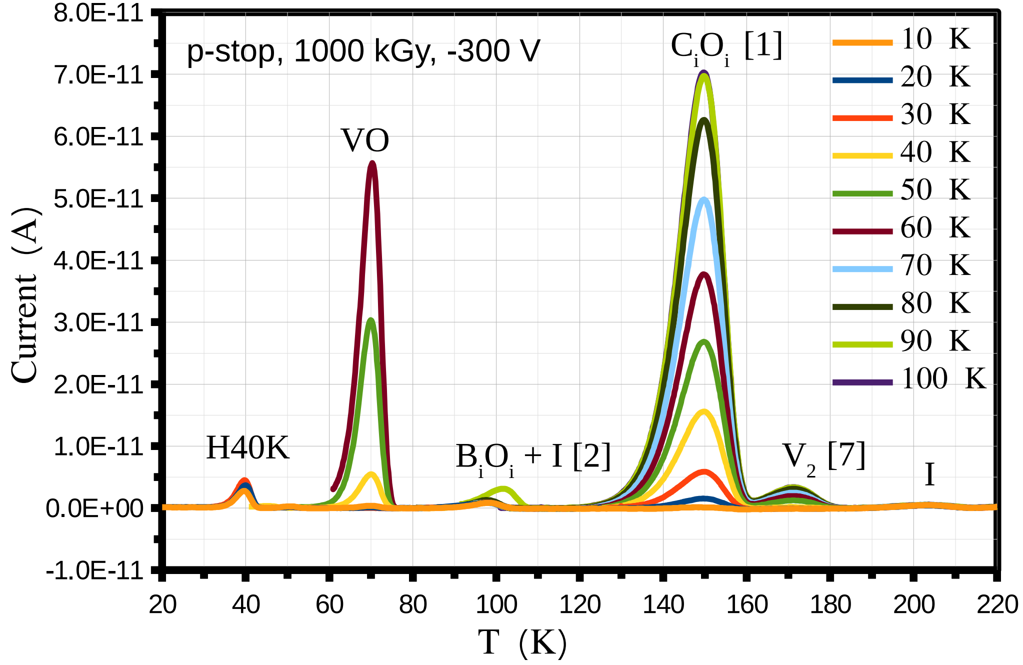
TSC measurement (-200 V)

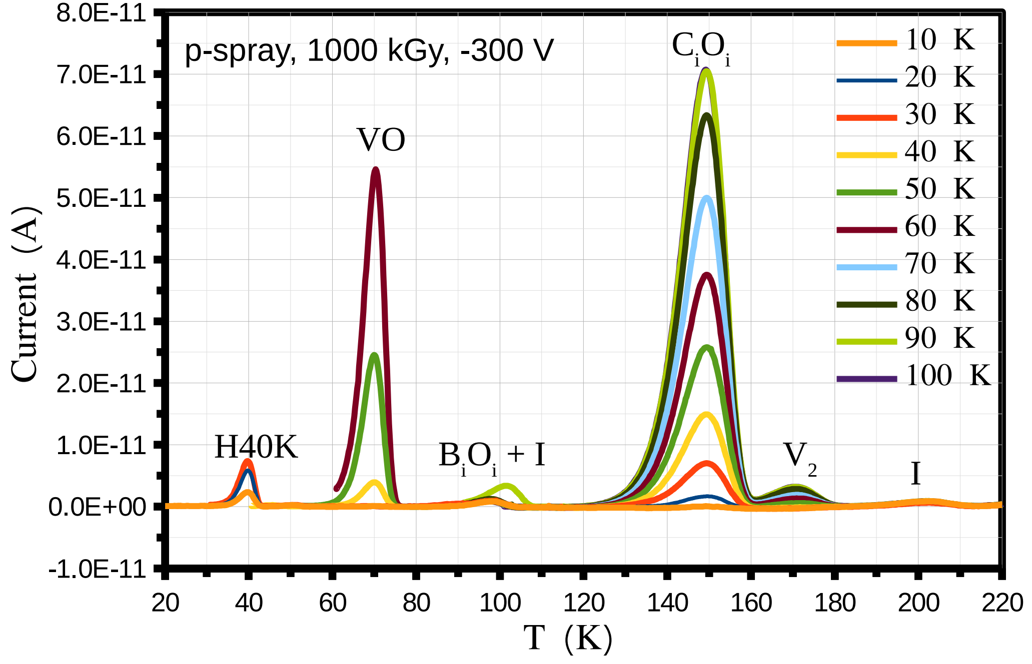




- Forward bias filling, filling current I_{fill} = 0.8 mA, filling temperature at T_{fill} = 10 K for 30 s, heating rate β = 0.183 K/s and $V_{heat\ up}$ = -200 V

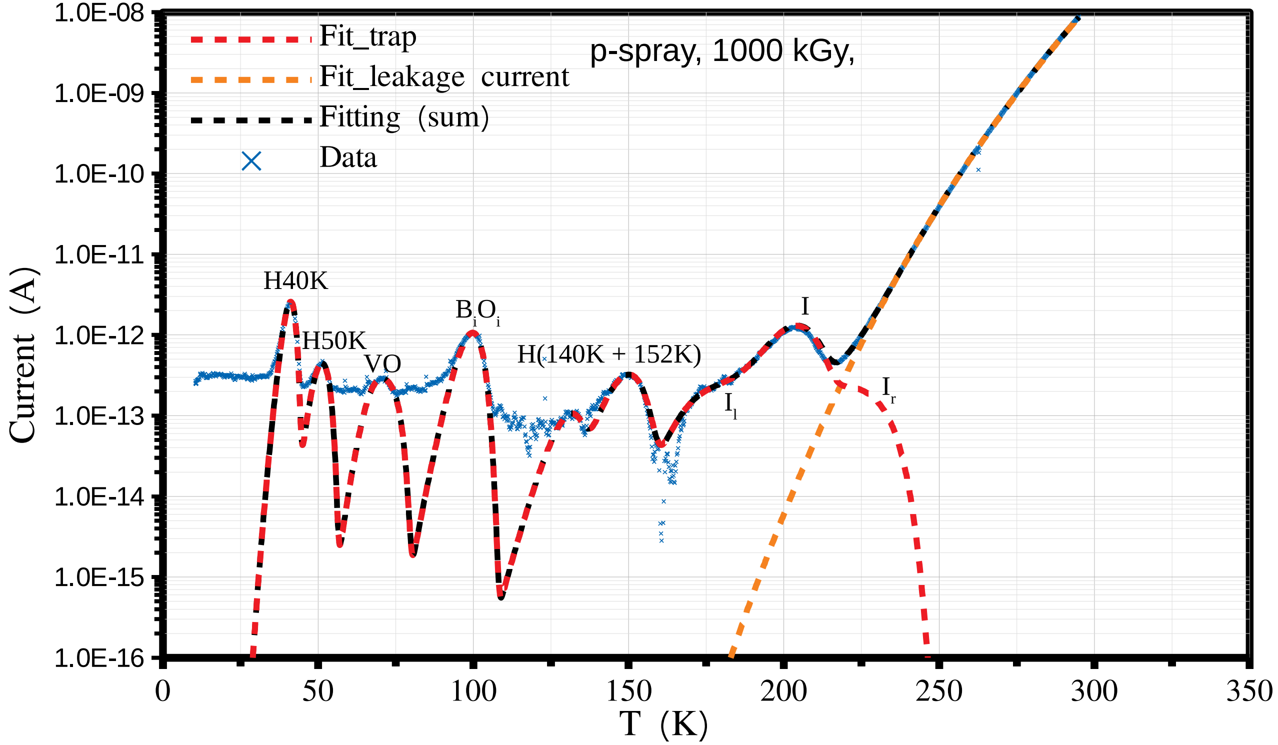
TSC measurement (T_{fill} dependent)





- p-stop diode, 1000 kGy (left) / p-spray diode, 1000 kGy (right)
- Same experimental parameters as presented before, except for $V_{heat\ up}$ = -300 V and T_{fill}
- The amplitude of H40K, VO, C_iO_i and V_2 appeared strongly dependent on T_{fill}

Fitting TSC spectra to extracted defect information



Peak fitting example of TSC spectra (1000 kGy, p-spray diode, T_{fill} = 10K, $V_{heat-up}$ = -200V)

Fit_trap[8-12]:

$$I_{tsc}=\frac{1}{2}q_0\,A\,d\,N_t\,e_n\exp\left(-\frac{1}{\beta}\int e_n(T)\,dT\right)$$

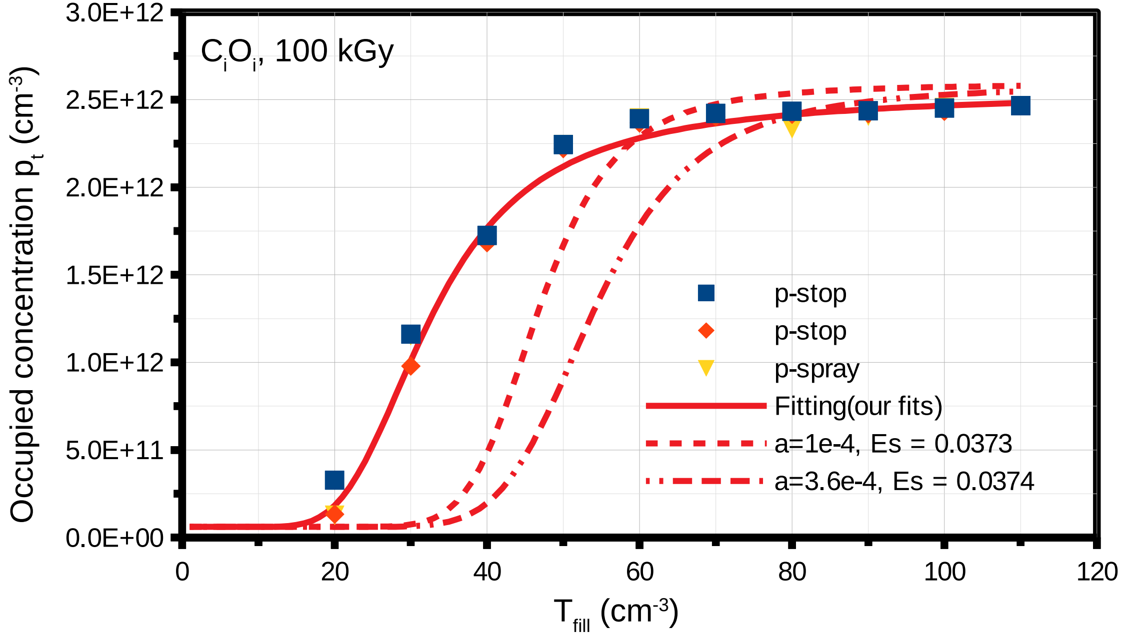
Three free parameters: The defect concentration N_t with two factors implanted into emission rate e_n – the capture cross section σ and activation energy E_a.

Fit_leakage current (high temperature range):

$$I_{LC}=C\cdot T^n\cdot\exp\left(-\frac{\delta E}{k_B T}\right)$$

Three free parameters: C; n (1~3); δE(~0.73, voltage dependent – Poole Frenkel and tunneling).

Temperature-dependent capture



Such fitting procedures only work for lower dose values (~100 kGy and ~200 kGy) and only for C_iO_i

Conclusion: determine the concentration in saturation – Details on the next slides

Occupied state during filling can be estimated by:

$$n_t = N_t \times \frac{1}{1 + \frac{c_p(T) \cdot p}{c_n(T) \cdot n}} \quad \text{or} \quad p_t = N_t \times \frac{1}{1 + \frac{c_n(T) \cdot n}{c_p(T) \cdot p}}$$

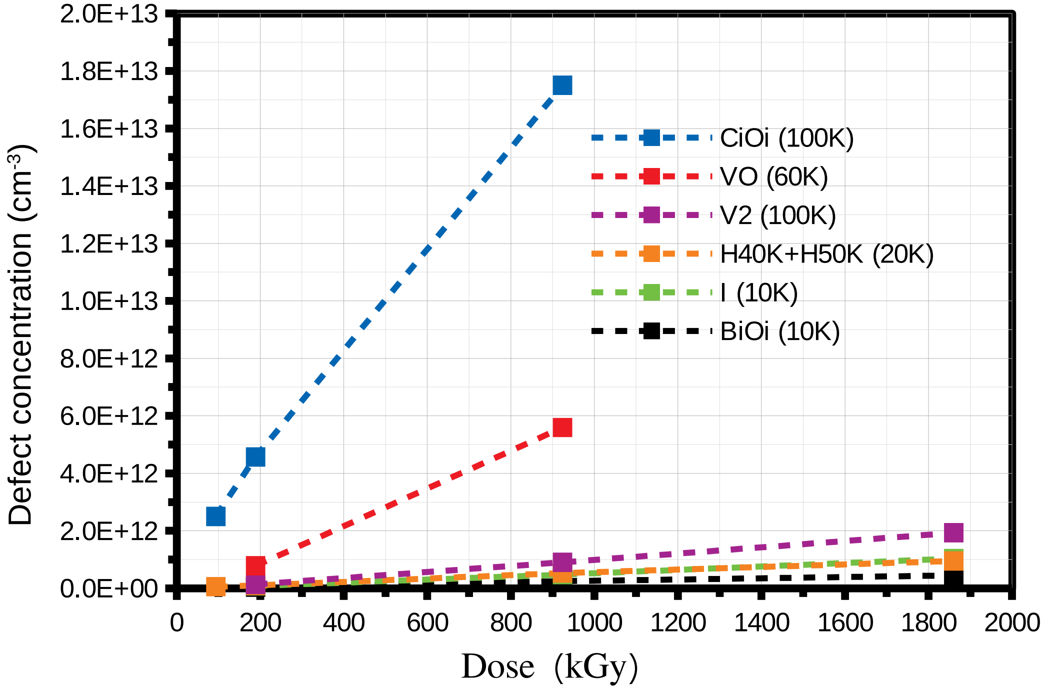
Forward bias filling n ≈ p, the occupation was determined by the ratio between C_p and C_n.

Filling function given by multi-phonon captured[13]:

$$p_t = N_{offset} + N_t \times \frac{1}{1 + a \cdot \exp\left(\frac{E_S}{k_B T_{fill}}\right)}$$

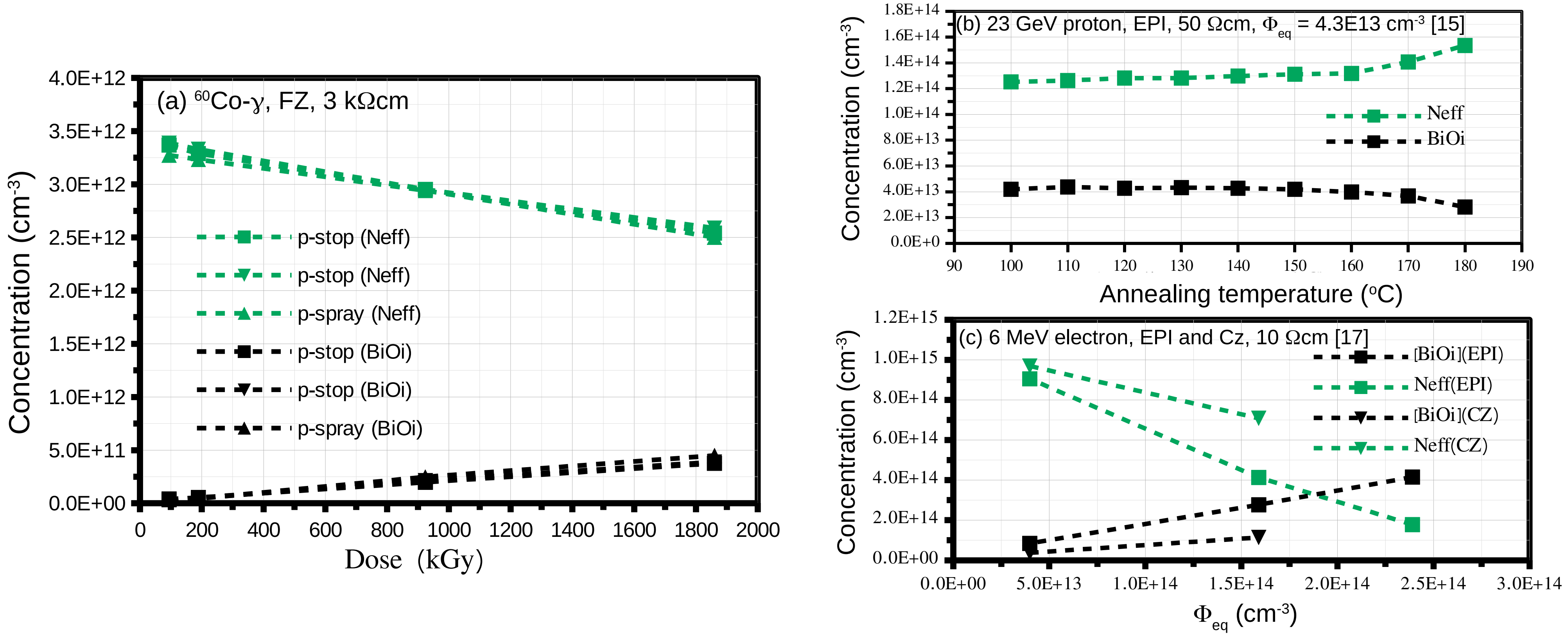
	Our fits	Reference value (neutron)
N_{offset} (cm^{-3})	6.061×10^{10}	
N_t (cm^{-3})	2.531×10^{12}	
a	0.0118	1e-4[1] or 3.4e-4[14]
E_S (eV)	0.013	0.0373[1] or 0.0374[14]

Extracted defect concentration



- The first formation of trap is C_iO_i, H40K+H50K (Possibly vacancy related) and B_iO_i (or X-defect [15]?)
- The concentration of C_iO_i should be proved by further experiments e.g electron or hole injection

$[B_iO_i]$ 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 Neff given by CV measurement
- ΔNeff ≈ 2×Δ$[B_iO_i]$ (for all figure presented in this slide)

Summary

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):

- T_{fill} dependence of amplitude was observed on the defects (H40K, VO, C_iO_i and V_2) and analyzed with multi-phonon captivation
- The development of defect concentration with dose value
- $\Delta N_{eff} \approx 2\times\Delta[B_iO_i]$

II. Comparison with n-type materials:

- Current density increase with fluence is the same for p-type and n-type

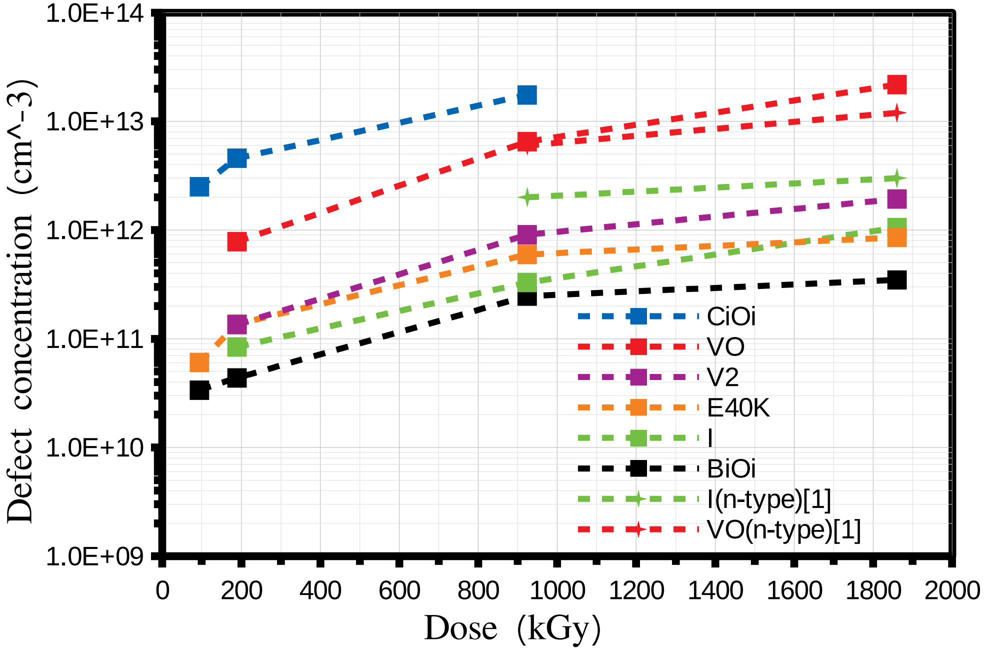
Further plans :
I. annealing behavior
2. identified surface traps

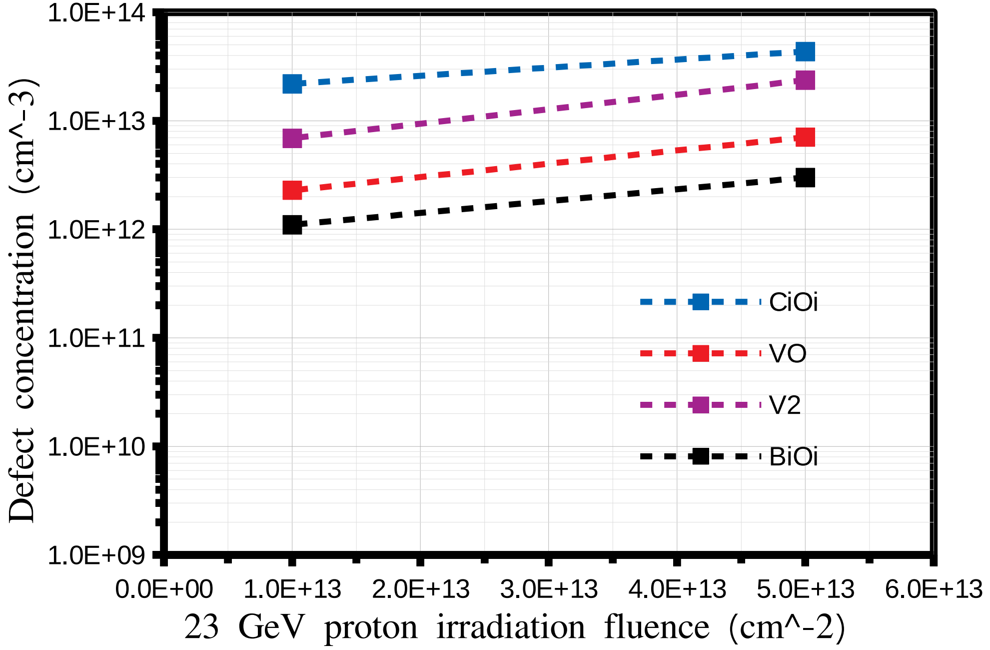
Back up

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] Hallén, Anders, et al. "Lifetime in proton irradiated silicon." Journal of Applied Physics 79.8 (1996): 3906-3914.
[8] C. T. Sah et al., Solid State Electron, vol. 13, no. 6, pp. 759–788, 1970
[9] I. Pintilie et al., Appl. Phys. Lett., vol. 78, p. 550, Jan. 2001
[10] M. G. Buehler, Solid State Electron, vol. 15, no. 1, pp. 69–79, 1972
[11] M. Moll, Ph.D. dissertation, Dept. Phys., Univ. Hamburg, Hamburg, Germany, 1999
[12] I. Pintilie et al., Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip., vol. 556, no. 1, pp. 197–208, Jan. 2006
[13] C.H. Henry, D.V. Lang, “Nonradiative capture and recombination by multiphonon emission in GaAs and GaP’ Phys. Rev. B 15(2) 989 (1977)
[14] H. Feick “Radiation tolerance of silicon particle detectors for high-energy physics experiments,” Ph.D. dissertation, Dept. Phys., Univ. Hamburg, Hamburg, Germany, 1997
[15] 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
[16] Fretwurst, E., et al. "Bulk damage effects in standard and oxygen-enriched silicon detectors induced by ^{60}Co-gamma radiation." Nucl. Instrum. Methods Phys. Res. A, 514.1-3 (2003): 1-8.
[17] 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

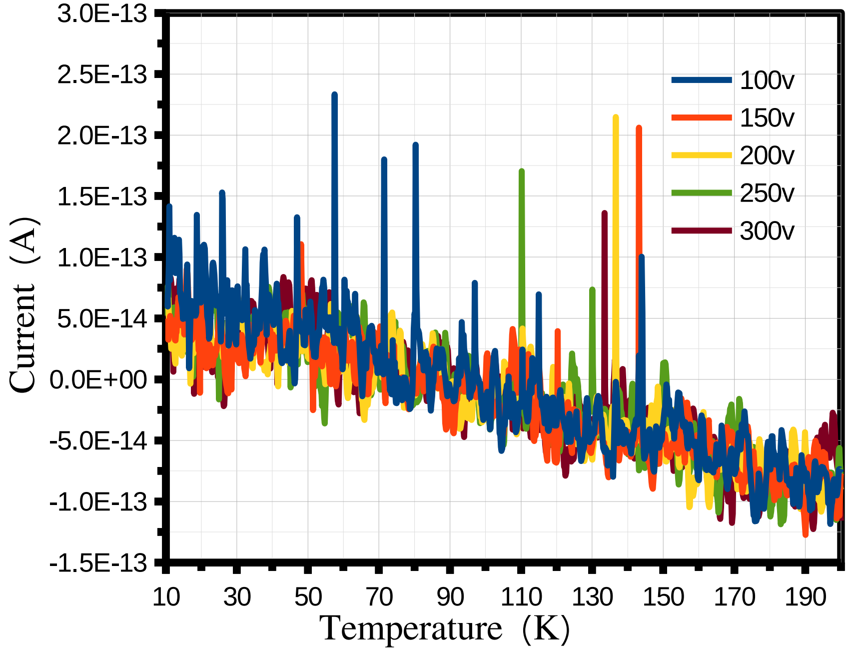
Compare with other materials (defect)

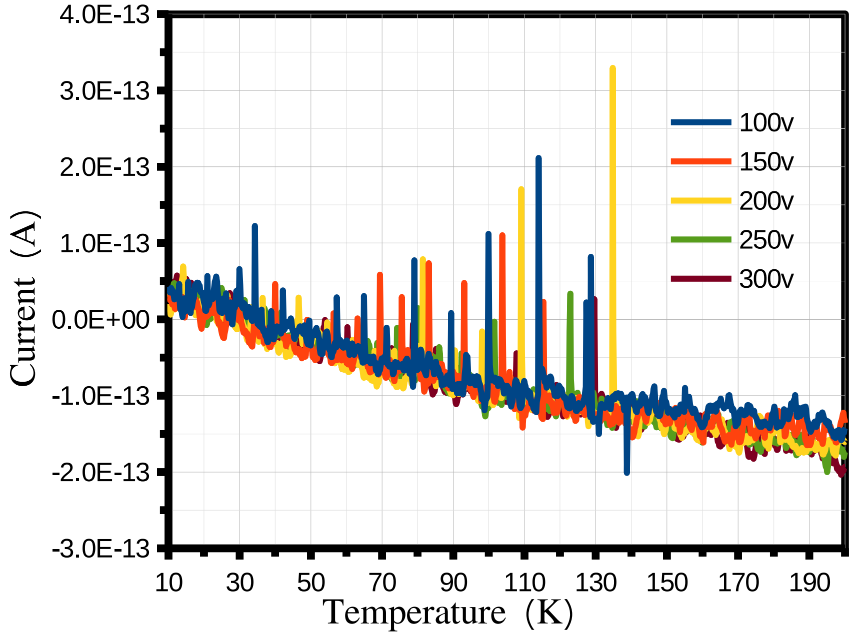




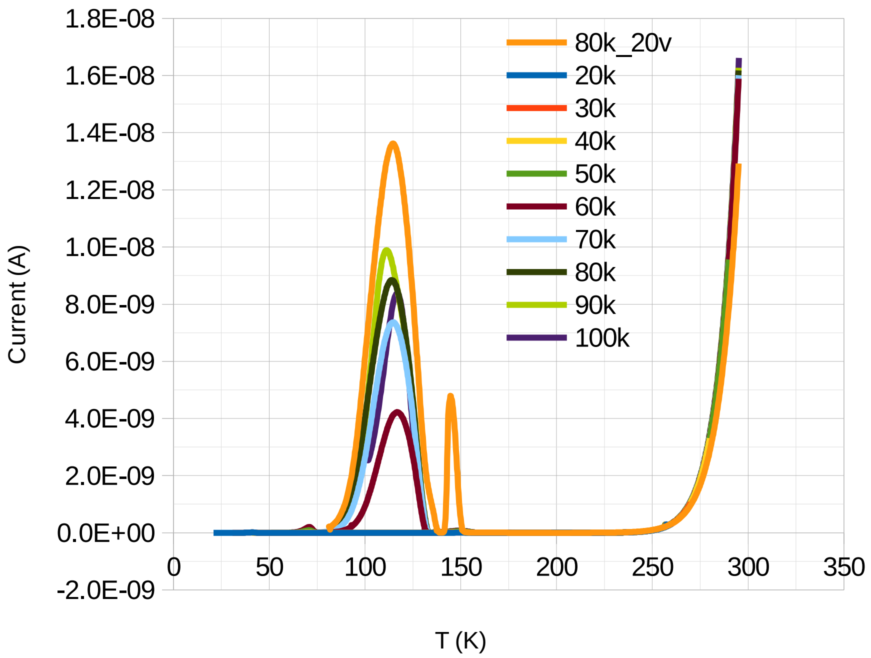
- Defect concentration extracted from TSC for different material and particle irradiation. (left) the n-type also is FZ sample
- I (possibly VO_2) higher and VO lower on n-type diodes than to p-type for 100 Mrad and 200 Mrad irradiation
- V_2 concentration higher than VO for proton irradiation

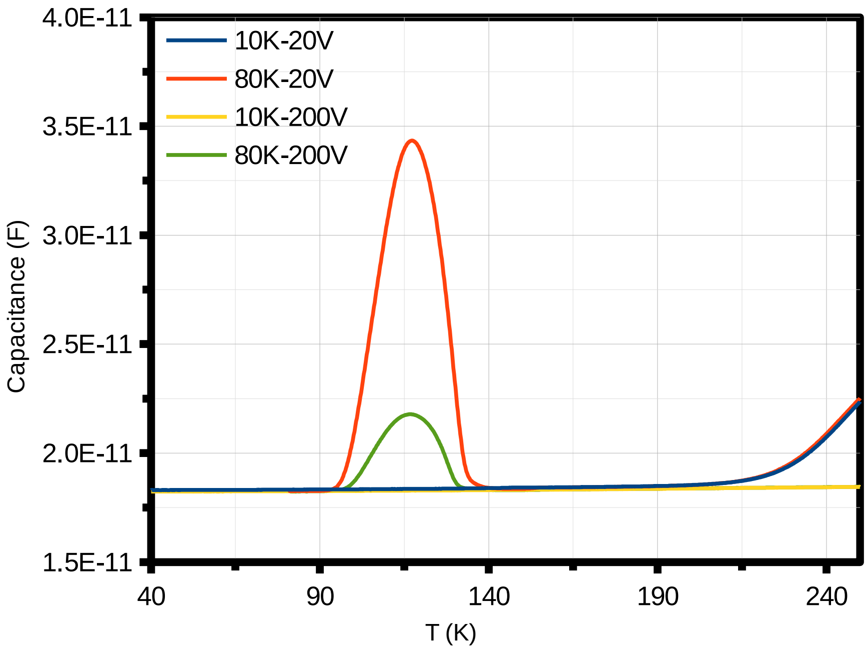
Noise


3.0E-13
2.5E-13
2.0E-13
1.5E-13
1.0E-13
5.0E-14
0.0E+00
-5.0E-14
-1.0E-13
-1.5E-13
Current (A)
10
30
50
70
90
110
130
150
170
190
Temperature (K)
100v
150v
200v
250v
300v


4.0E-13
3.0E-13
2.0E-13
1.0E-13
0.0E+00
-1.0E-13
-2.0E-13
-3.0E-13
Current (A)
10
30
50
70
90
110
130
150
170
190
Temperature (K)
100v
150v
200v
250v
300v

Strange peak





I-V for proton irradiation