

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



Chuan Liao^a, E. Fretwurst^a, E. Garutti^a, J.Schwandt^a

^aInstitut für Experimentalphysik, Universität Hamburg

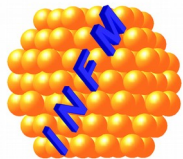


A. Himmerlich^b, Y. Gurimskaya^b, I. Mateu^b, M. Moll^b

^bConseil européen pour la recherche nucléaire (CERN)



ACCEPTOR REMOVAL TEAM



I. Pintilie^c

^cNational Institute of Materials Physics (NIMP), Bucharest

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

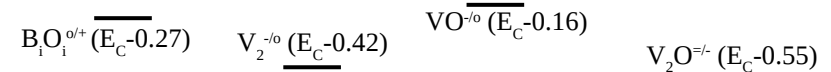
Previous work (presented on RD50 workshop [37th-39th]):

Type of Radiation

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

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

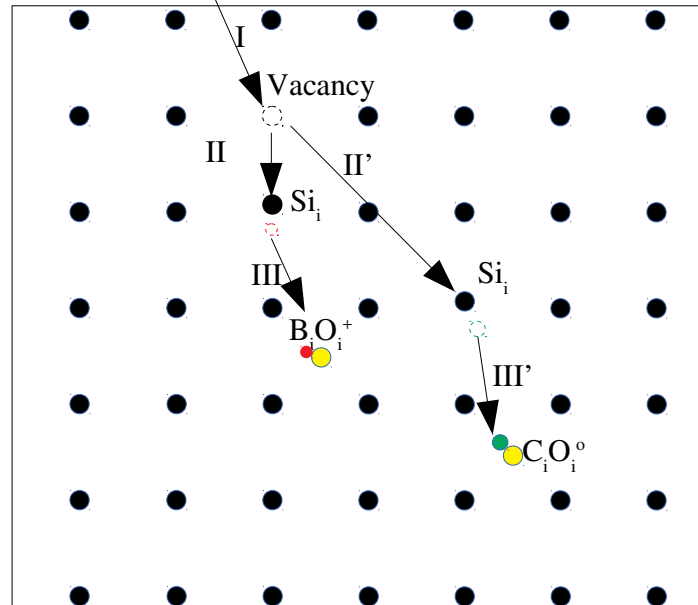
Conduction



Mid of band gap



Valence



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)

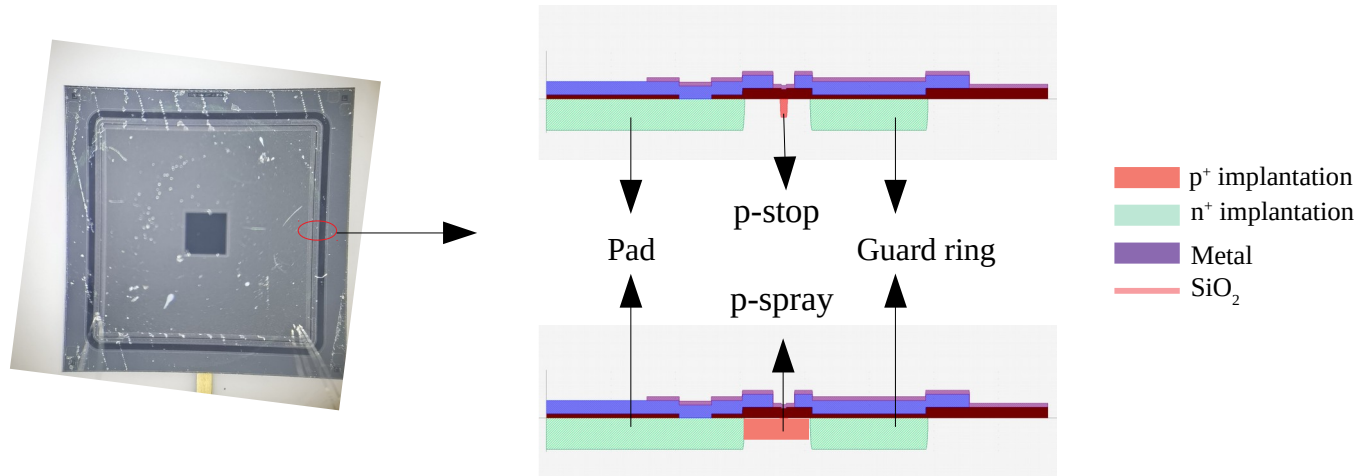
II: Si_i diffusion in the bulk and impact on lattice Boron atom (B_s)

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

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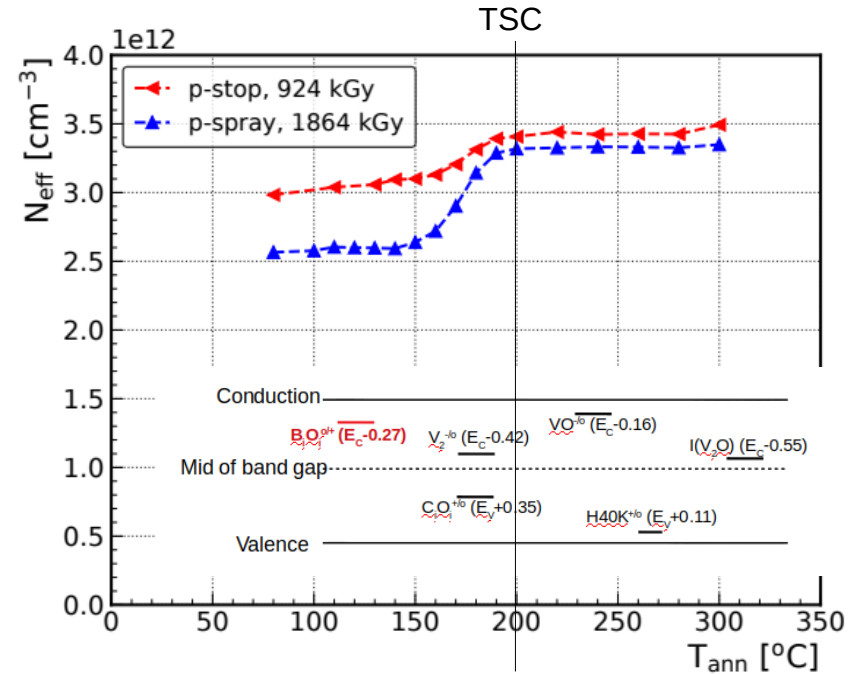
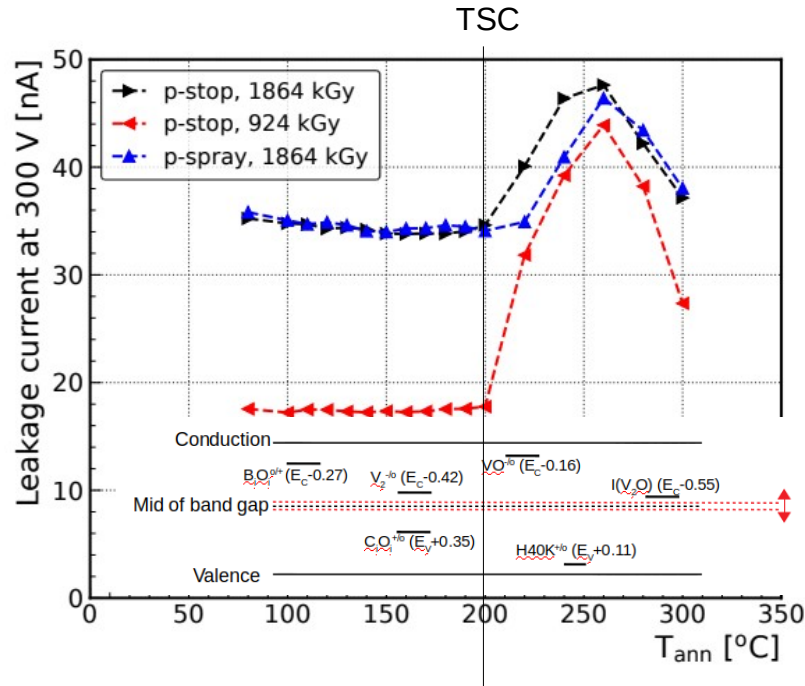
Details of investigated samples (high resistivity $\sim 3 \text{ k}\Omega\text{cm}$ p-type FZ material from Hamamatsu)

Initial doping, bulk (cm^{-3})	$\sim 3.5 \times 10^{12}$ (\approx bulk of LGADs)			
^{60}Co - γ irradiation (kGy)	94 ± 0.96	189 ± 3.9	924 ± 27	1864 ± 56
Area (cm^2)	0.25			
Thickness (μm)	150			

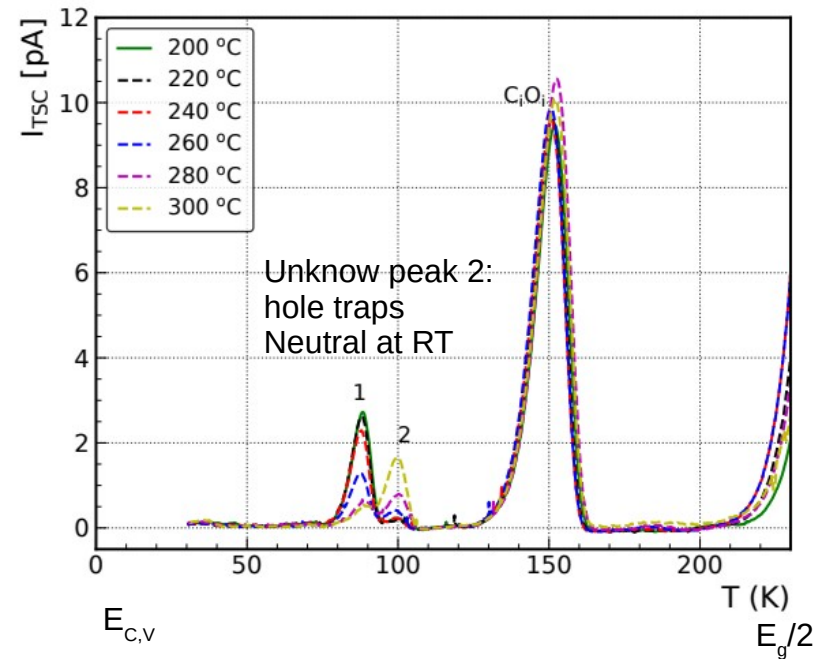
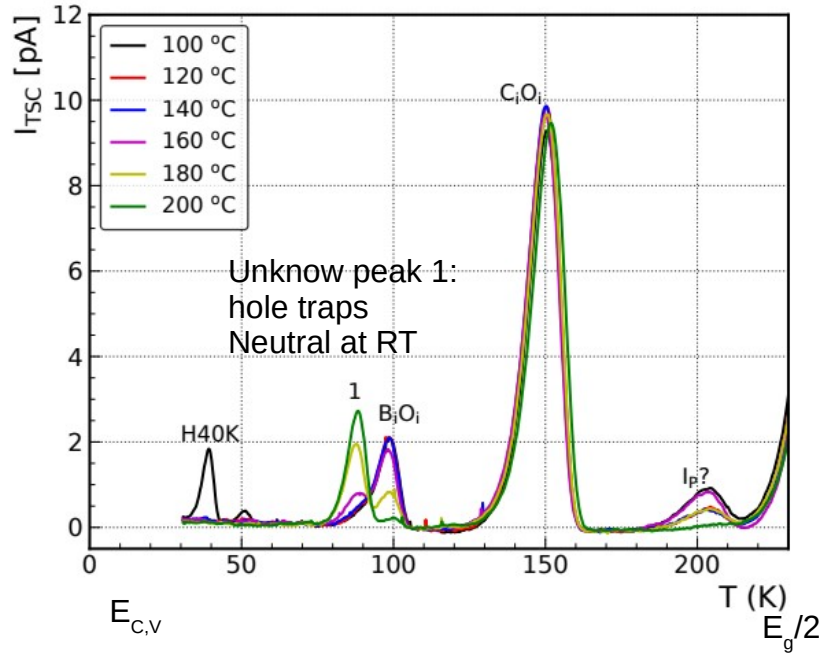


Annealing from 100 to 200 °C in steps of 10 °C, and from 200 °C to 300 °C in steps of 20 °C (during 15 min for all steps)

I-V, C-V measurements

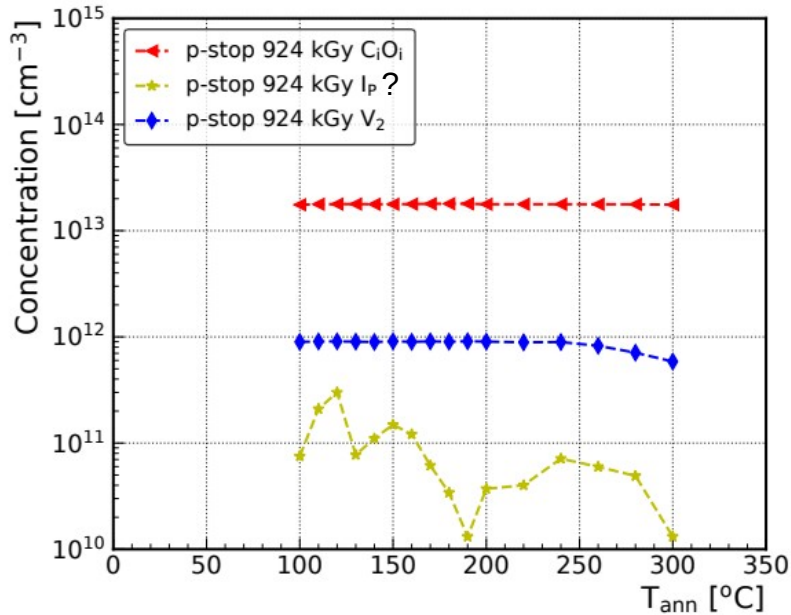


- Leakage current (LC) at 300 V vs. T_{ann} (left) and N_{eff} vs. T_{ann} (right)
- I-V, C-V are measured at room temperature, N_{eff} were extracted from C-V with frequency = 500 kHz
- The LC is firstly stable with T_{ann} up to about **200 °C**, then shows a peak at about **200 °C**, which possibly caused by the changes of deep trap with T_{ann}
- N_{eff} is firstly stable with T_{ann} up to about **150 °C**, then increasing with T_{ann} up to **200 °C**, and stable again until $T_{ann} \approx 300 \text{ °C}$

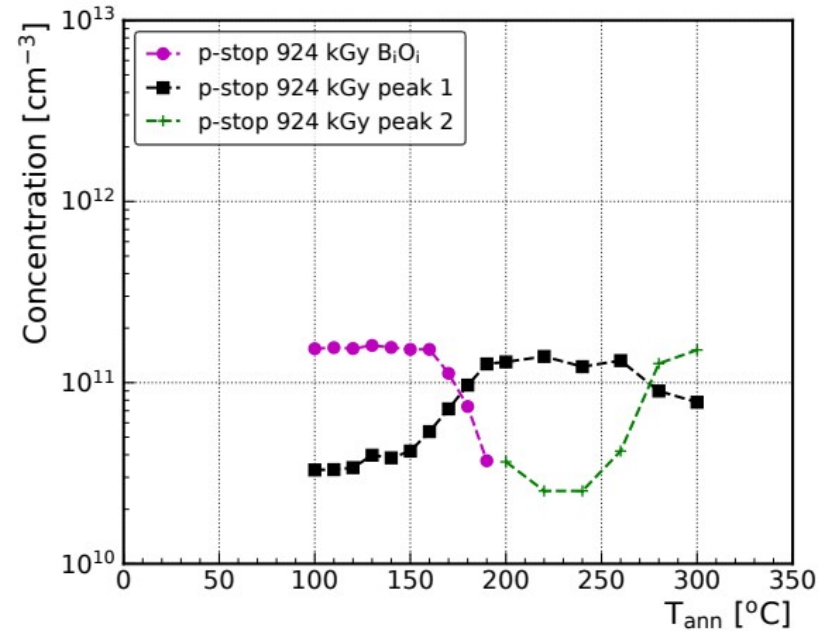


- TSC spectra ($T_{\text{fill}} \approx 30$ K, $V_{\text{bias}} = 300$ V, $I_{\text{fill}} \approx 1$ mA) for p-stop diode irradiation by ^{60}Co - γ with 1864 kGy. $T_{\text{ann}} = 100 \rightarrow 200$ °C (left) and $T_{\text{ann}} = 200 \rightarrow 300$ °C (right)
- H40K is eliminated by annealing when $T_{\text{ann}} > 100$ °C
- B_iO_i is stable with T_{ann} until 150 °C, then decreasing with T_{ann} disappeared at $T_{\text{ann}} = 200$ °C meanwhile peak 1 increasing in this range. When $T_{\text{ann}} > 200$ °C, peak 1 decreases and peak 2 increases.

Concentration vs. T_{ann} (p-stop, 924 kGy)



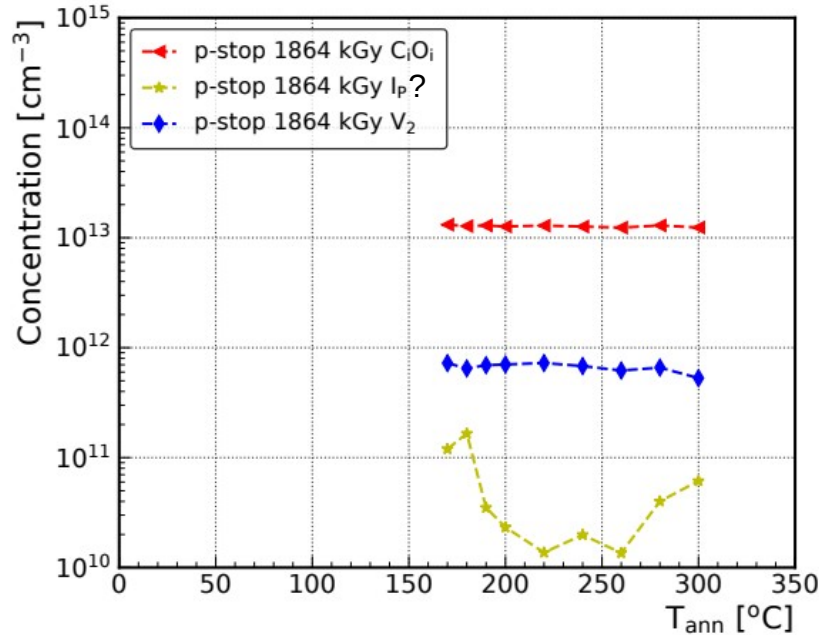
TSC spectra ($T_{\text{fill}} \approx 100 \text{ K}$, $V_{\text{bias}} = 300 \text{ V}$, $I_{\text{fill}} \approx 1 \text{ mA}$)
 C_iO_i , I_p , V_2



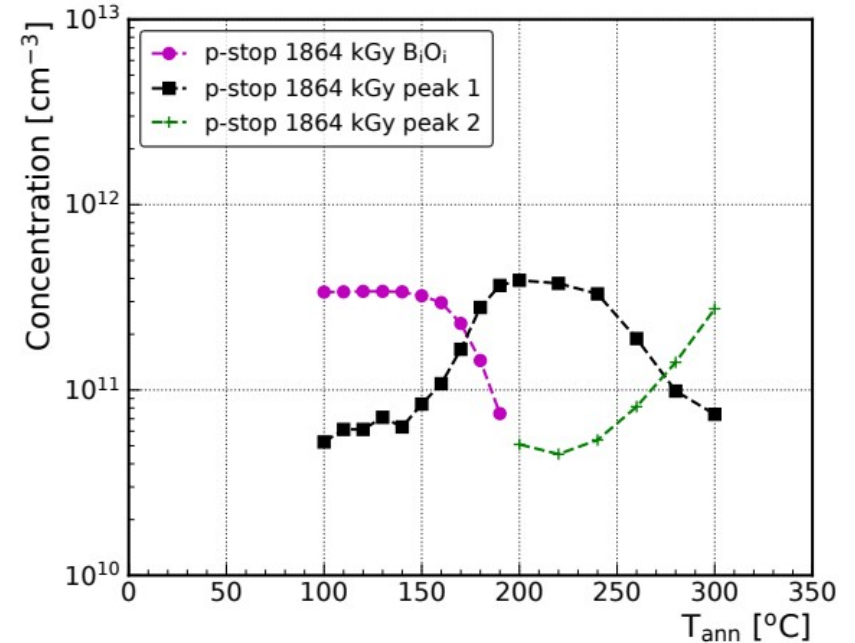
TSC spectra ($T_{\text{fill}} \approx 30 \text{ K}$, $V_{\text{bias}} = 300 \text{ V}$, $I_{\text{fill}} \approx 1 \text{ mA}$)
 BiO_i , peak 1 and 2

- C_iO_i , V_2 stable with annealing up to 300 °C
- BiO_i , peak 1 and 2 strongly correlated with each other

Concentration vs. T_{ann} (p-stop, 1864 kGy)



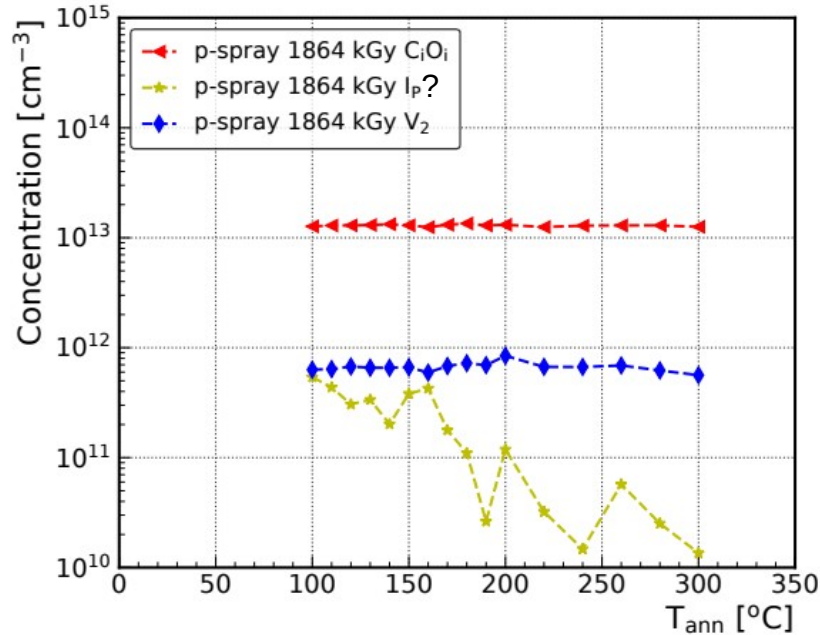
TSC spectra ($T_{\text{fill}} \approx 50$ K, $V_{\text{bias}} = 300$ V, $I_{\text{fill}} \approx 1$ mA)
 C_iO_i , I_p , V_2



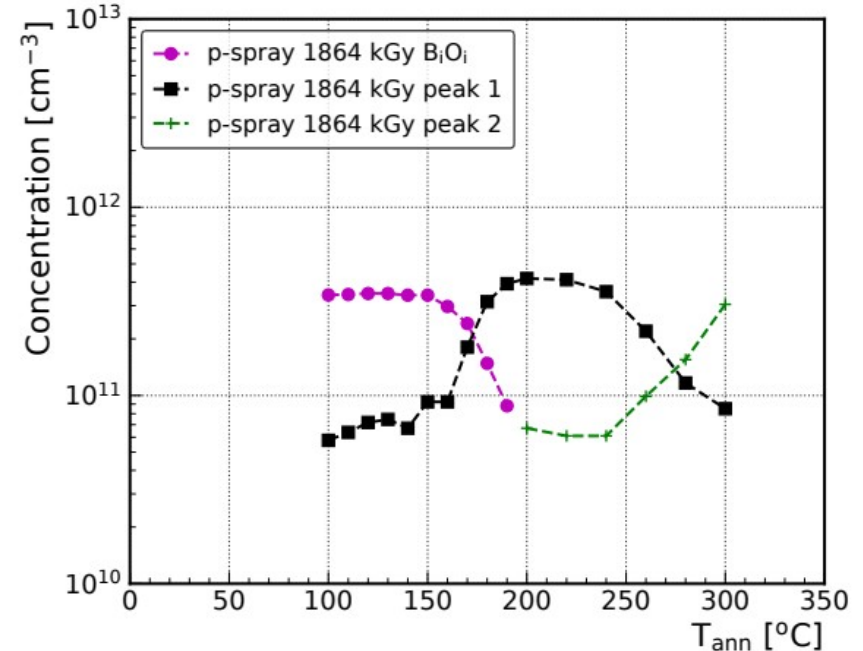
TSC spectra ($T_{\text{fill}} \approx 30$ K, $V_{\text{bias}} = 300$ V, $I_{\text{fill}} \approx 1$ mA)
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- BiO_i , peak 1 and 2 strongly correlated with each other

Concentration vs. T_{ann} (p-spray, 1864 kGy)



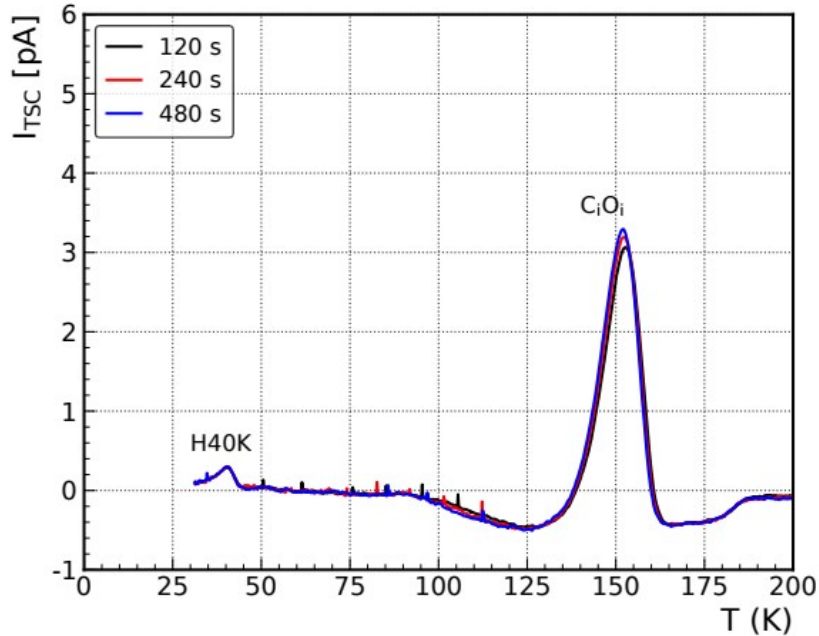
TSC spectra ($T_{fill} \approx 50$ K, $V_{bias} = 300$ V, $I_{fill} \approx 1$ mA)
 C_iO_i , I_p , V_2



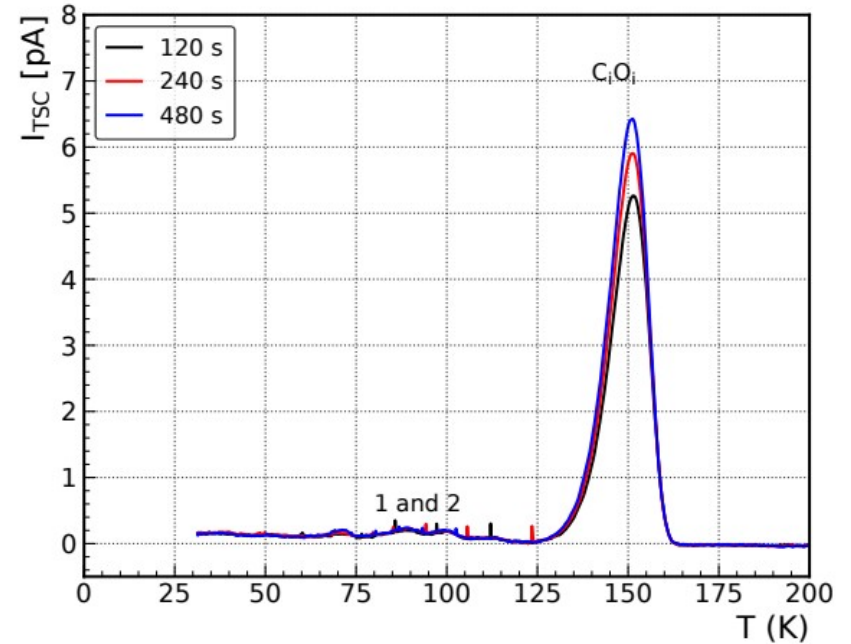
TSC spectra ($T_{fill} \approx 30$ K, $V_{bias} = 300$ V, $I_{fill} \approx 1$ mA)
 BiO_i , peak 1 and 2

- C_iO_i , V_2 stable with annealing up to 300 °C
- BiO_i , peak 1 and 2 strongly correlated with each other

Light injection



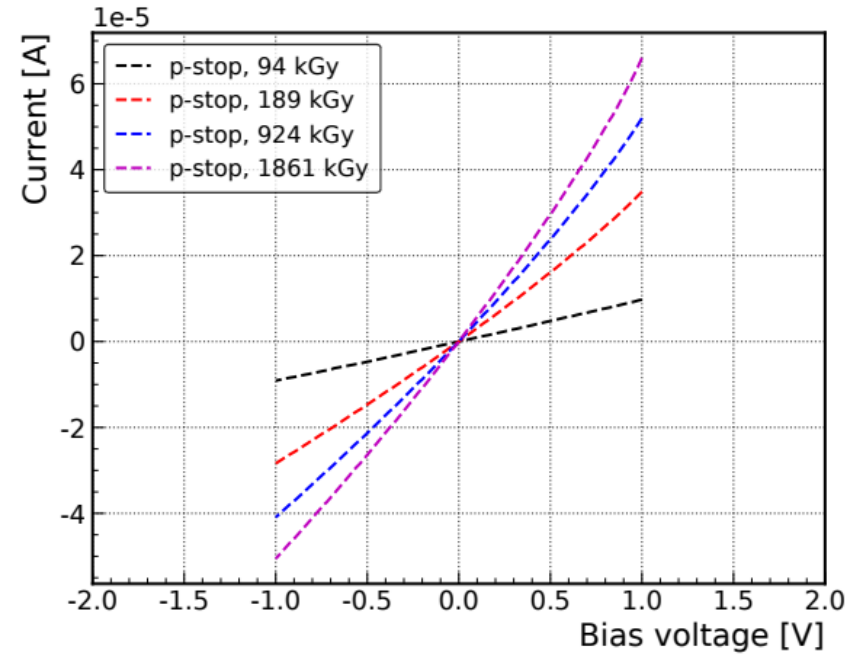
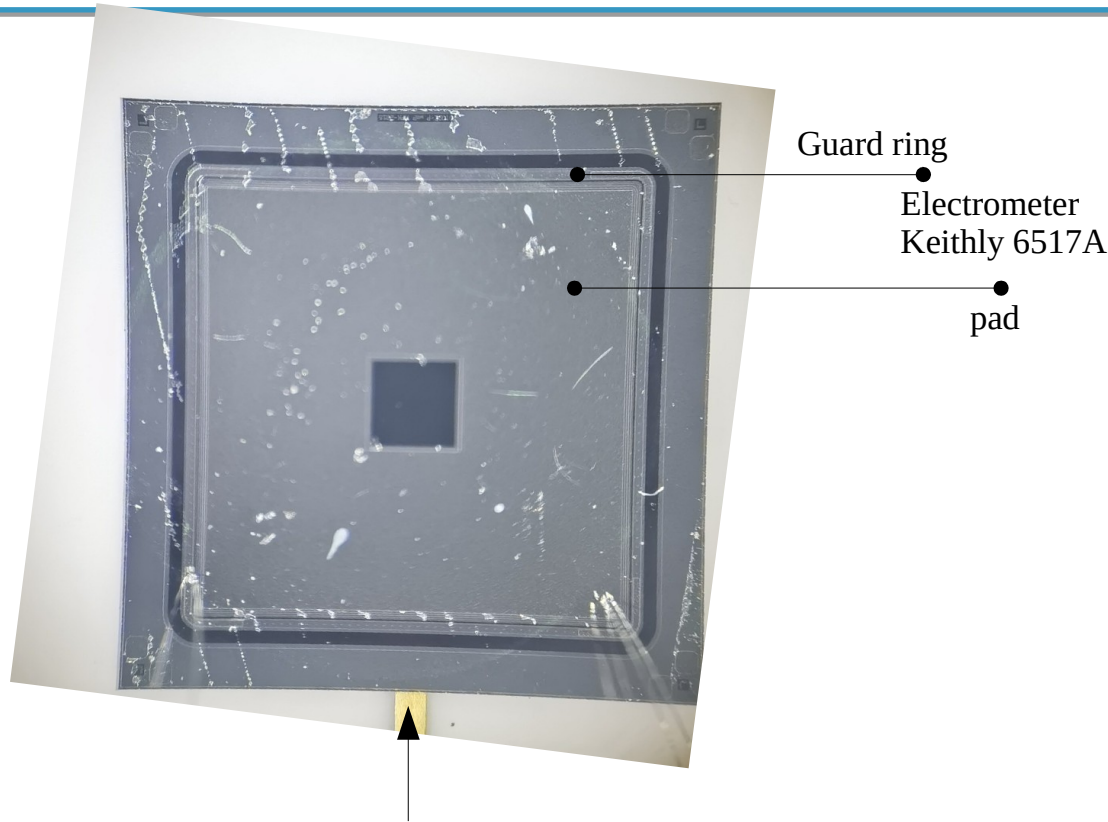
TSC, p-spray, 924 kGy, as-irrad



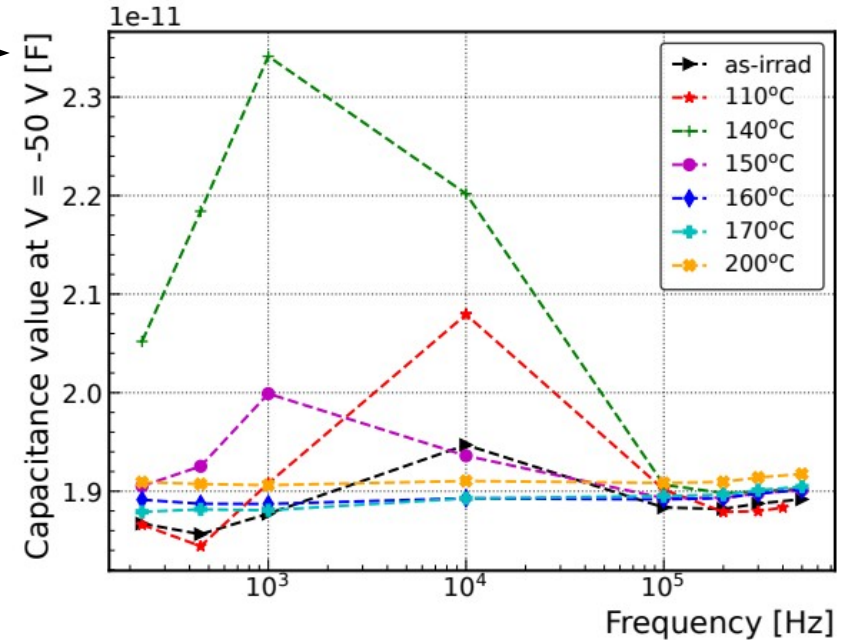
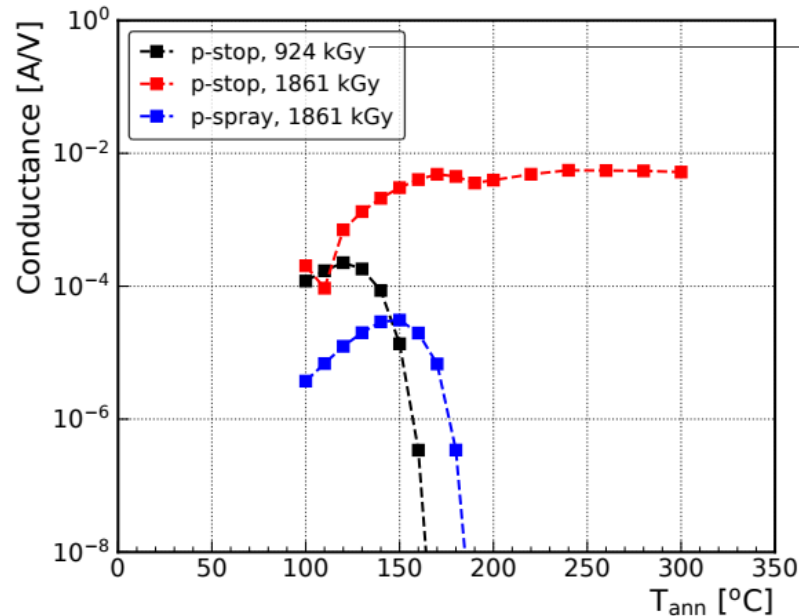
TSC, p-spray, 1864 kGy, 300 °C@15min

- TSC spectra ($T_{\text{fill}} \approx 30 \text{ K}$, $V_{\text{bias}} = 300 \text{ V}$)
- Illuminated by green light (520 nm) at front (n+) – hole trap filling
- Peak 1 and 2 are hole traps, and doesn't show poole frenkel effect (see back up) – peak 1 is not the X-defect

Surface current



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



- Left: Conductance vs. T_{ann} for F150P-7 (p-stop, 924 kGy), F150P-8 (p-stop, 1864 kGy) and F150Y-8 (p-spray, 1864 kGy)
- Right: Capacitance value at $V = -50$ V vs. frequency for different T_{ann} (p-stop, 924 kGy)
- Conductance of F150P-7 (p-stop, 924 kGy) is firstly increasing with T_{ann} and decreases for $T_{ann} > 120$ °C
- Conductance of F150P-8 (p-stop, 1864 kGy) is increasing with T_{ann} and saturated when $T_{ann} > 150$ °C
- Conductance of F150Y-8 (p-spray, 1864 kGy) is firstly increasing with T_{ann} and decreases for $T_{ann} > 150$ °C

I. Results of isochronal annealing at 100 – 300 °C during 15 min, for Fz p-type diodes irradiated by ^{60}Co γ with dose value (924 kGy and 1864 kGy):

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

- A strange peak appeared on saturated leakage current vs T_{ann}
- Extracted N_{eff} from corresponded to the changes of B_iO_i after annealing

b). Microscopic measurement (TSC):

- C_iO_i and V_2 are stable up to 300 °C
- B_iO_i was annealed out from 150 to 200°C. Meanwhile, two unknown peaks (1 and 2) appeared at following annealing steps
- Peaks 1 and 2 are hole traps and neutral at room temperature

II. Surface current:

- Conductance increases with dose value
- For p-stop 924 kGy and p-spray 1864 kGy diodes, conductance is first increasing, and decreasing after 120 °C and 150 °C
- For p-stop 1864 kGy diode, conductance keeps increasing and saturated when $T_{\text{ann}} > 150$ °C

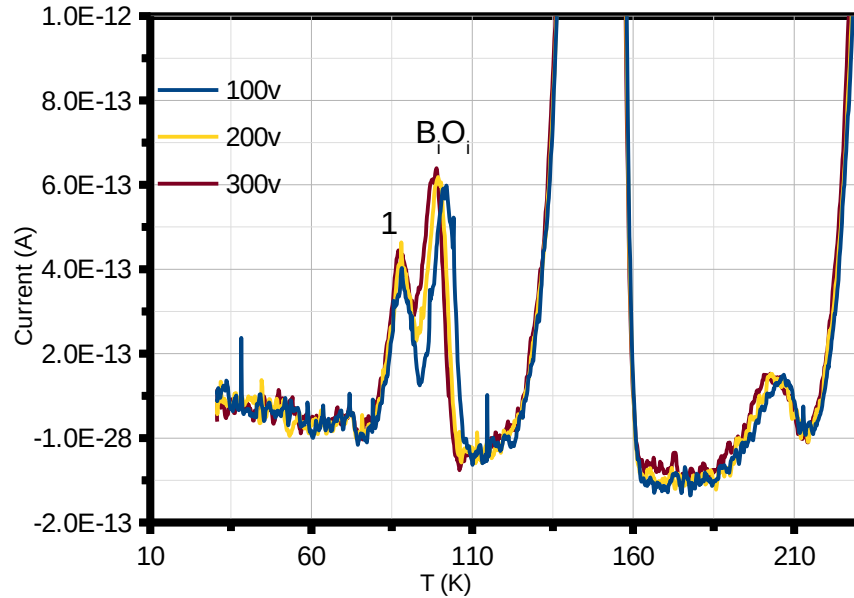


BACKUP

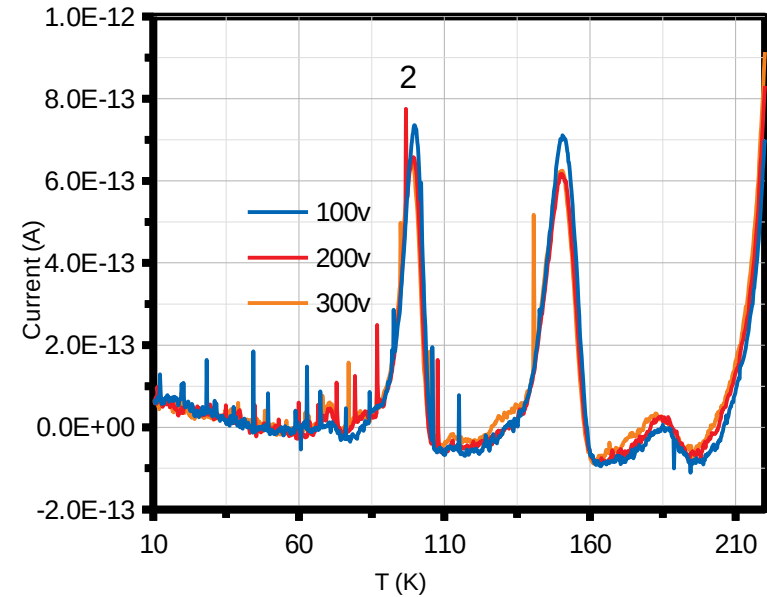
TSC with different V_{bias}

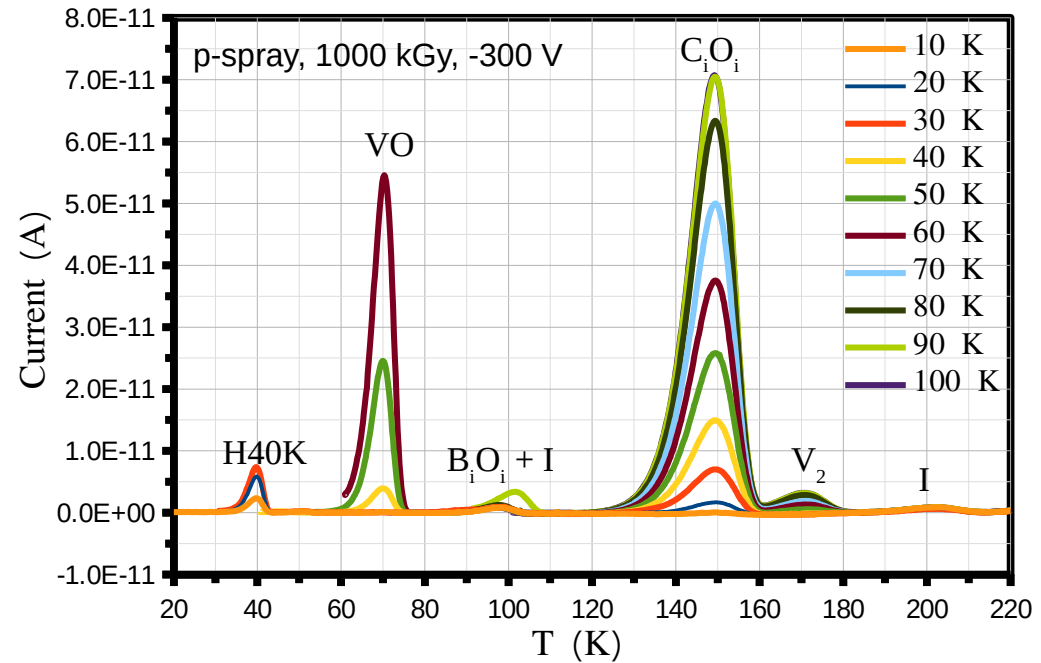
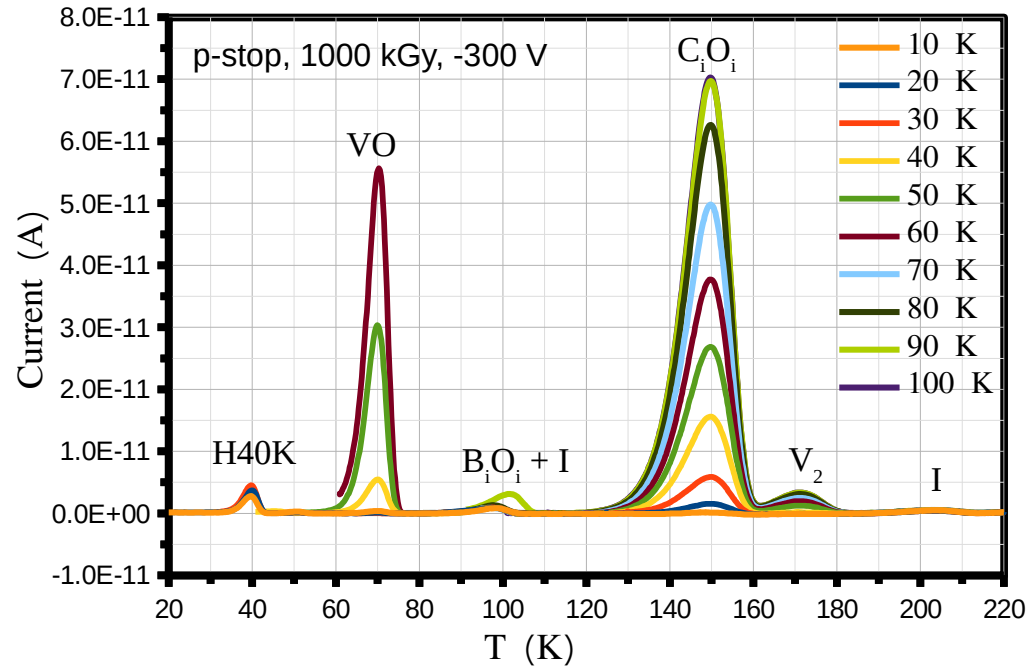


p-stop, 100 Mrad, $T_{\text{ann}} = 170^\circ\text{C}$



p-spray, 200 Mrad, $T_{\text{ann}} = 280^\circ\text{C}$





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