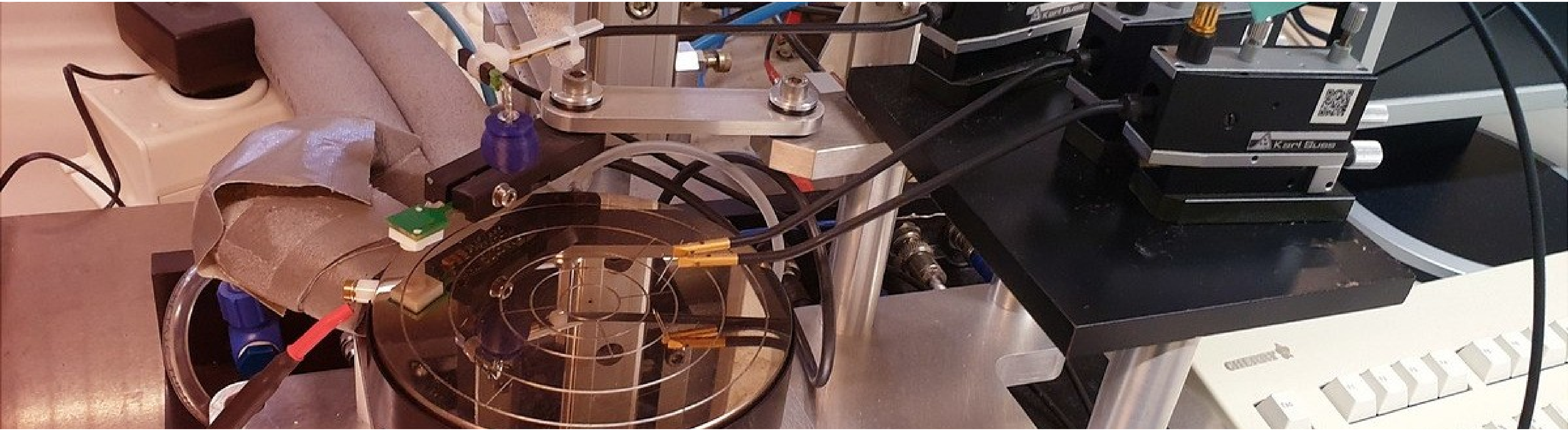
BiOi defects in LGADs



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High-D Consortium

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Outline

I. Motivation

II. Displacement damage and B_iO_i defect

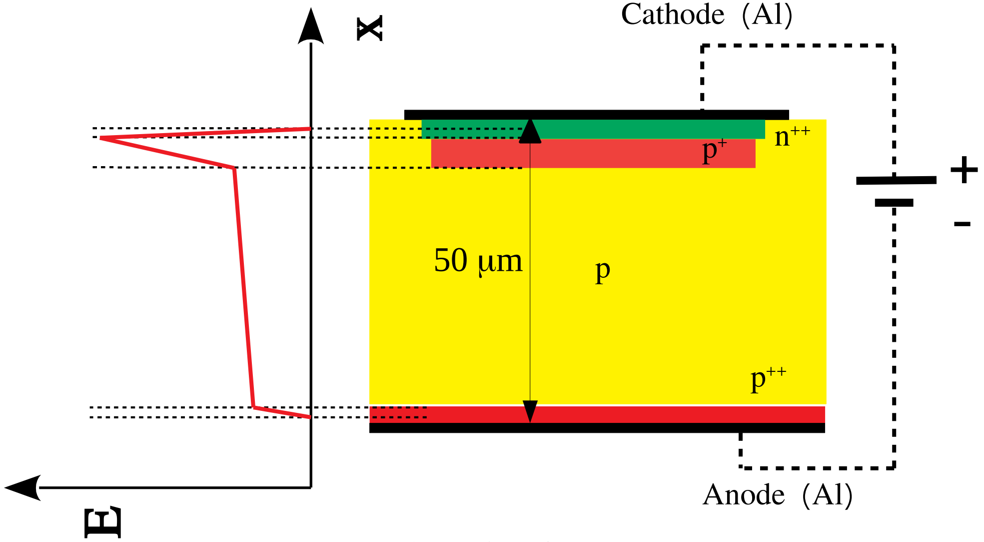
III. Experimental details

IV. Measurement results

V. Summary

Motivation

Radiation damage of LGADs [1] (Low Gain Avalanche Diodes)



Schematic of LGAD

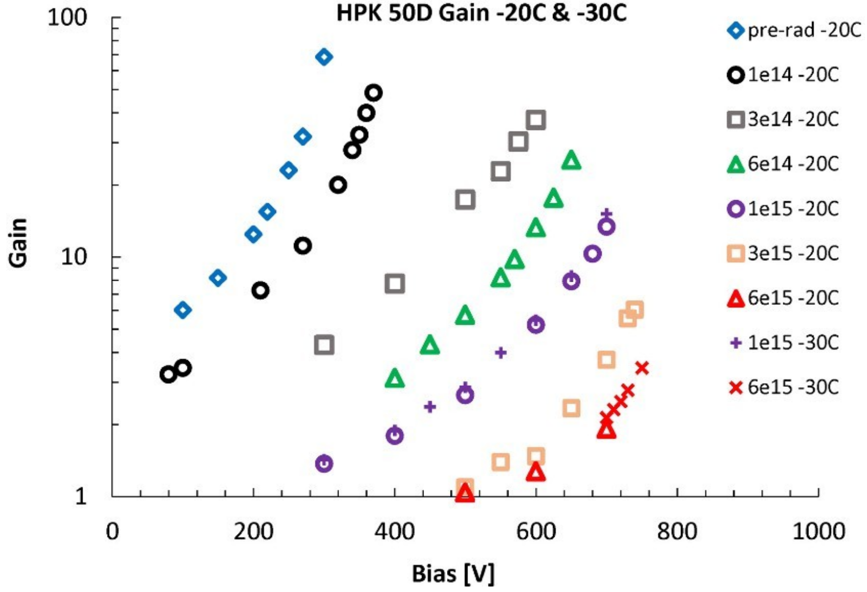
⬛ Aluminum

🟨 p type bulk (Boron doping, ~10^{13} cm^{-3})

🟥 p^{+} (Boron doping B_s^{-}, ~ 10^{16} cm^{-3})

🟥 p^{++} (Boron doping B_s^{-}, ~ 10^{19} cm^{-3})

🟩 n^{++} (phosphorus doping P_s^{+}, ~ 10^{21} cm^{-3})

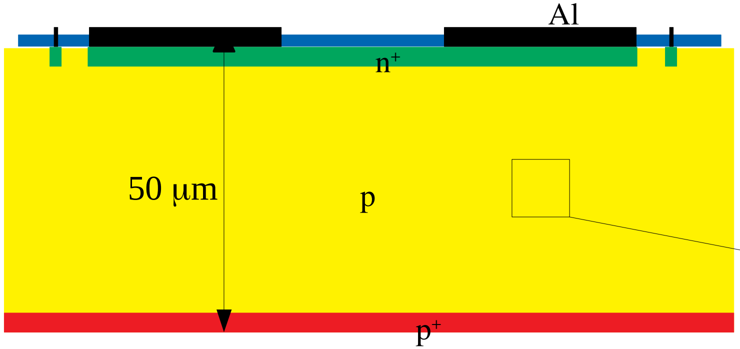


Gain value vs. bias for different fluences

Significant decrease of Gain value after irradiation

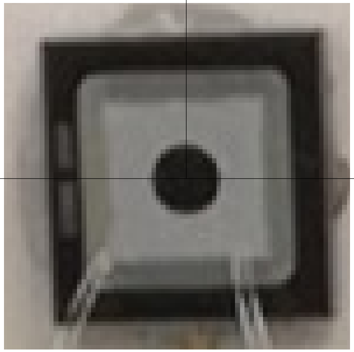
[1] Kramberger, G., et al. "Radiation effects in Low Gain Avalanche Detectors after hadron irradiations." Journal of Instrumentation 10.07 (2015): P07006.

Motivation

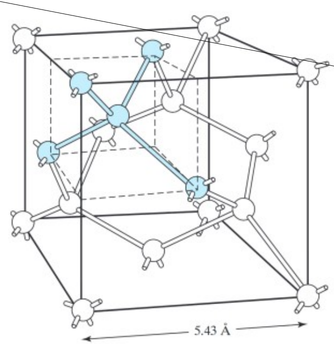


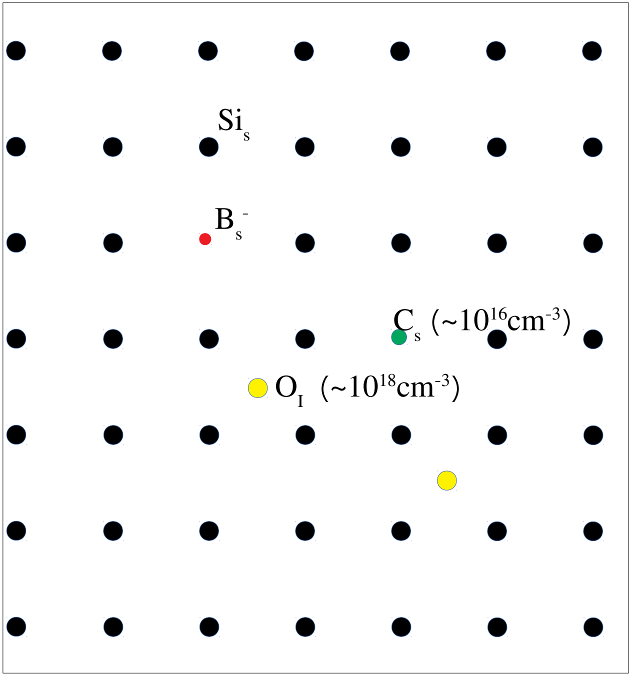
Cross section schematic of Silicon diodes (PIN diodes) we used

⬛ 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})
🟦 SiO_2



The top view of Silicon diodes (PIN diodes) we used

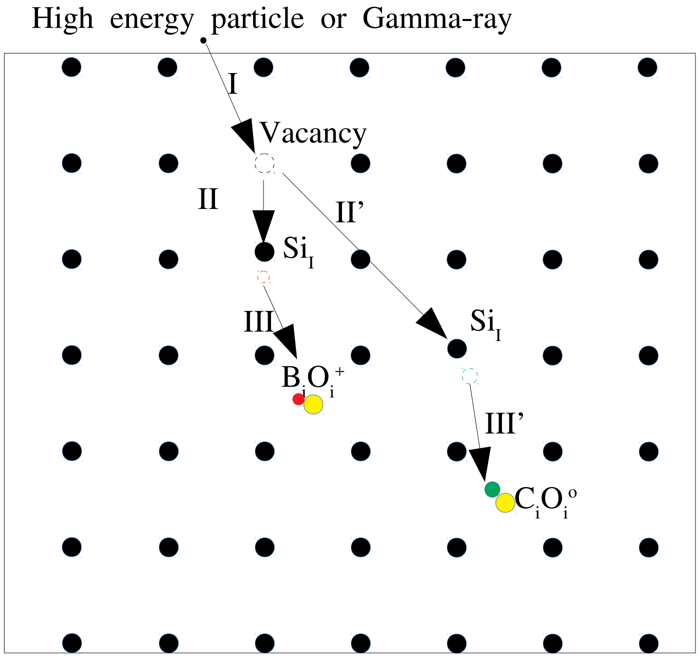




Schematic of Silicon crystal (cube side α_0=5.431 Å)

N_{eff} (space charge density in the bulk, at room temperature) was determined by concentration of B_s^- or P_s^+(p or n type)

Radiation damage in p-type silicon sensor

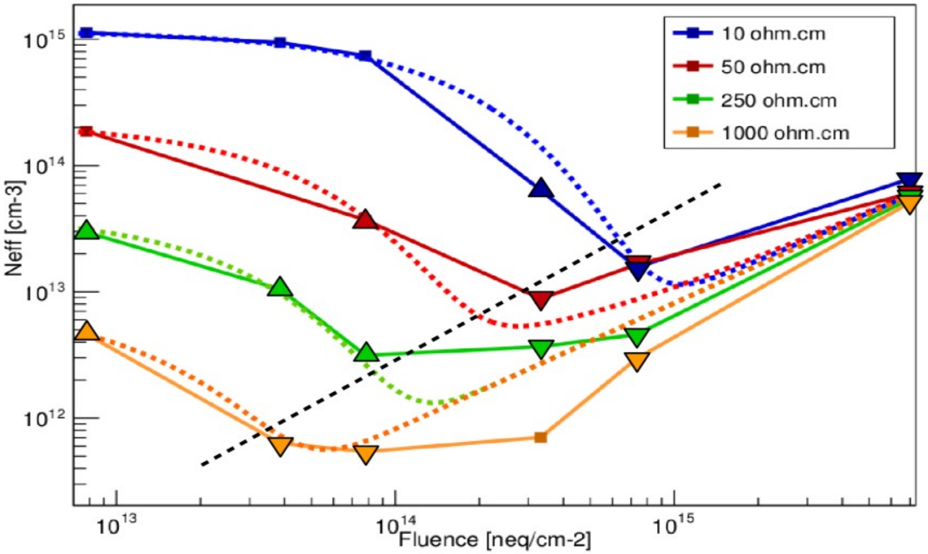


Schematic of radiation damage in p-type silicon sensor

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)



N_{eff} vs. fluence for different initial doping concentration

Radiation damage of p-type diodes is dominated by acceptor removal in the beginning and afterwards by acceptor generation [1]

B^- turn to $B_iO_i^+$

Change in N_{eff} is a factor of 2 and it will significantly affect the distribution of electric field.

[1] Y. Gurimskaya, 31st RD50 Workshop, 20-22 of November, 2017, CERN, Geneva, Switzerland.

Radiation damage in p-type silicon sensor

Microscopic behavior :

$Si_i + B_s \rightarrow Si_s + B_i \rightarrow B_i + O_i \rightarrow B_iO_i$

$Si_i + C_s \rightarrow Si_s + C_i \rightarrow C_i + O_i \rightarrow C_iO_i$

Many other defects like the shallow defects E(30K), H(40K) and deep defects V_2, V_3

Macroscopic behavior

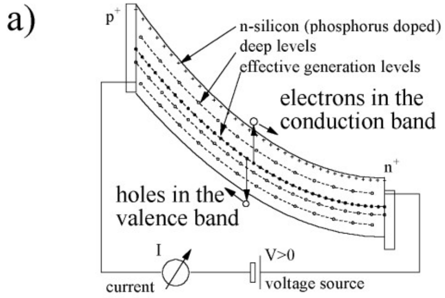
Increase of leakage current
Change of effective space charge density
Decrease of charge collection efficiency
Decrease of gain value in LGADs

1. Impurity dependence (investigate PIN diodes with different resistivity)
2. Irradiated particle dependence (investigate PIN diodes irradiated by different particles)
3. Irradiation fluence dependence (investigate PIN diodes with different irradiation fluence)
4. Annealing behavior (investigate PIN diodes after isothermal annealing at 80°C, and isochronal annealing from 100°C to 200°C)
5. LGADs sensor (investigate LGADs sensor, such observed results compare to the results given by 1-4)

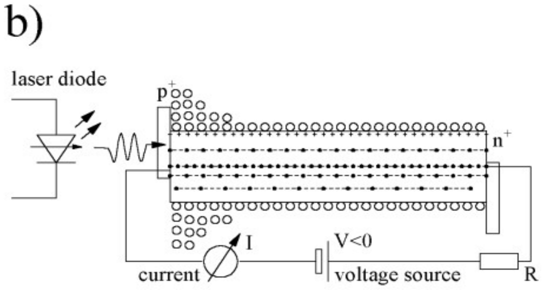
“The radiation damage induced defect in p-type silicon, BiOi is investigated”

Experimental principle

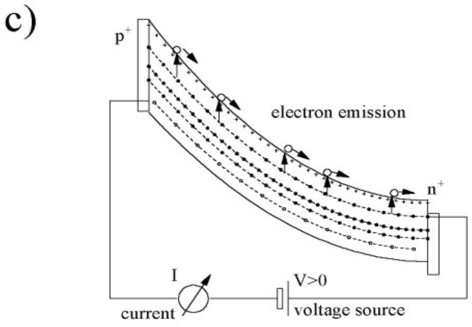
Basic Principle of Thermally Stimulated Current-TSC [2]:



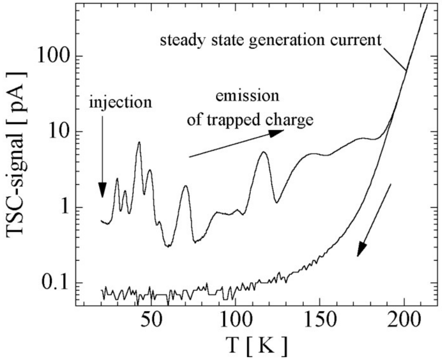
a) Cooling



b) Injection:
Forward bias injection, light injection and majority carriers injection.



c) Recording data



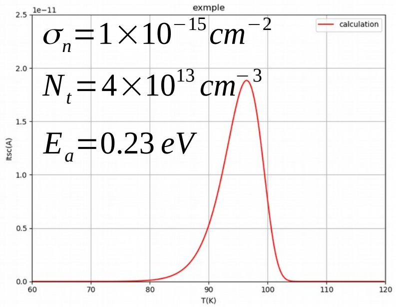
d). TSC spectrum [2]

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

$$e_n=\sigma_n v_{th,n} N_c \times \exp\left(\frac{-E_a}{K_b T}\right)$$

$$E_a=E_C-E_T$$

N_t is defect concentration; b is heating rate; s_n is capture cross section; E_a is activation energy; A is diodes area; d depleted thickness; [1]

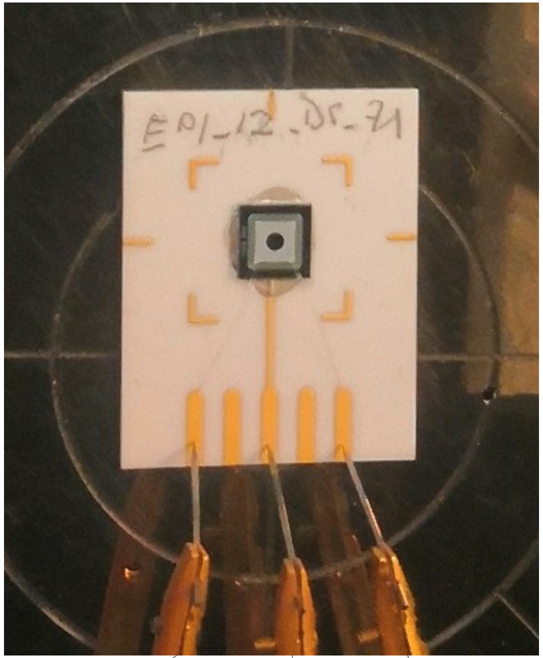


e). example of calculated TSC peak

[1] Buehler, M. G. Solid-State Electronics 15.1 (1972): 69-79.
[2] Moll, Michael. Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties. No. DESY-THESIS-1999-040. DESY, 1999.

Investigated diodes

Silicon pad
detector

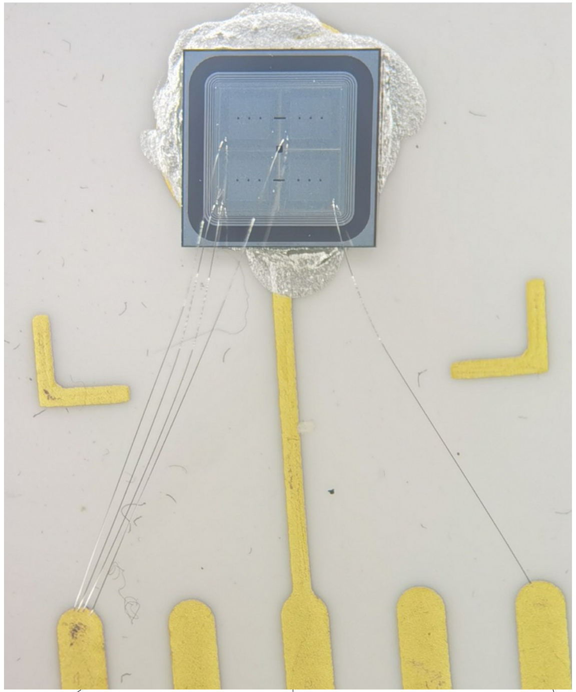


Guard ring

Back side:
bias voltage

Pad

LGADs
2×2 pixels

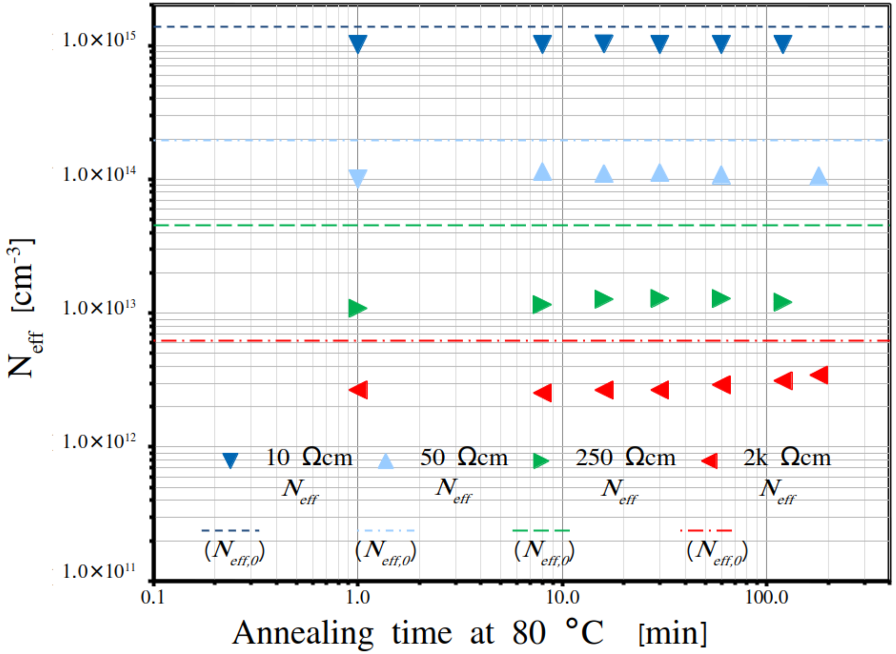


Guard ring
+3 pixels
grounded

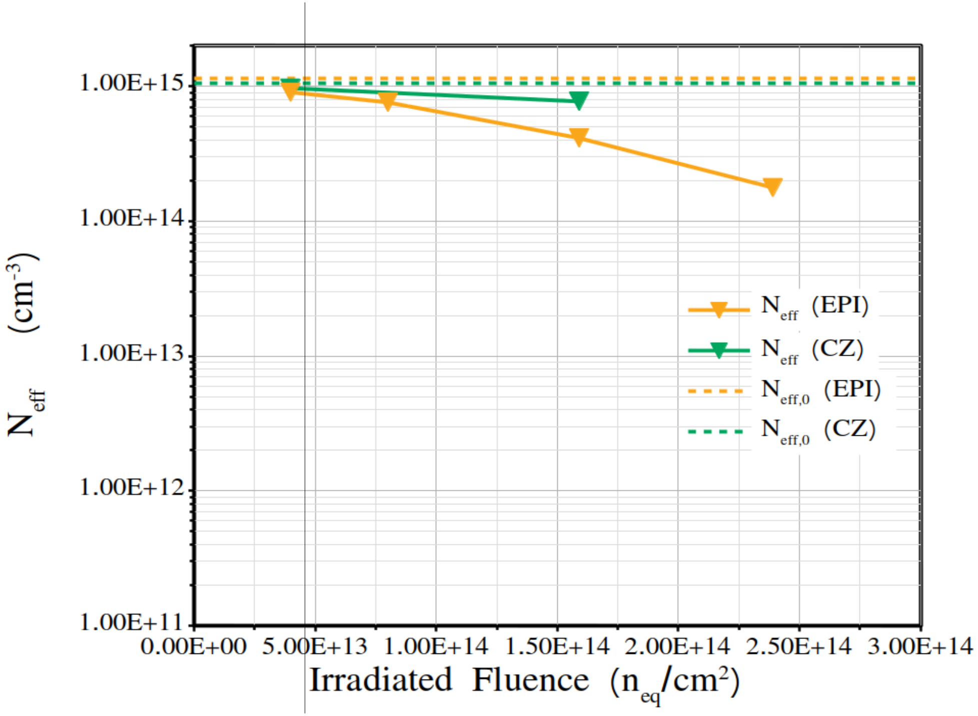
Back side:
bias voltage

Measured pixel

Effective doping



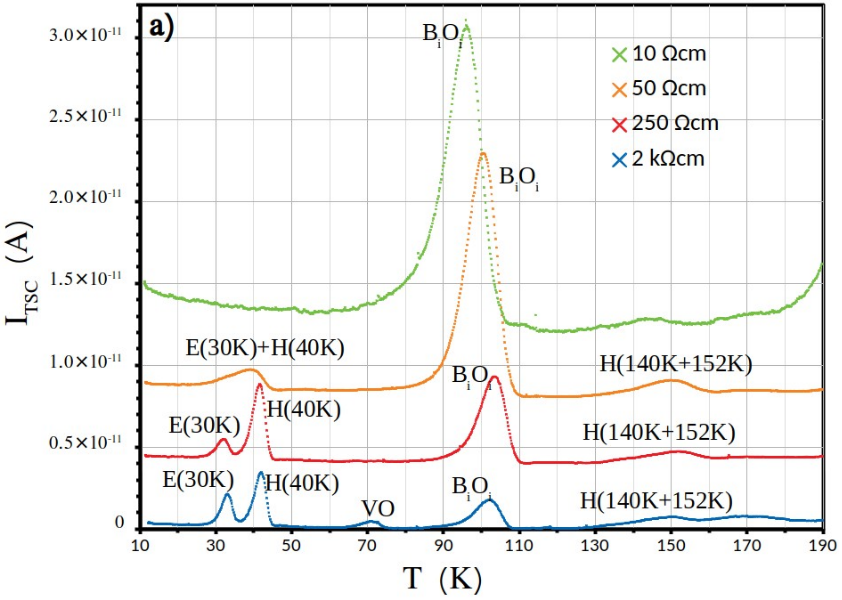
Effective doping for EPI diodes with different resistivity after irradiation by **23 GeV protons** with fluence value 4.28E13 n_{eq}/cm^2.

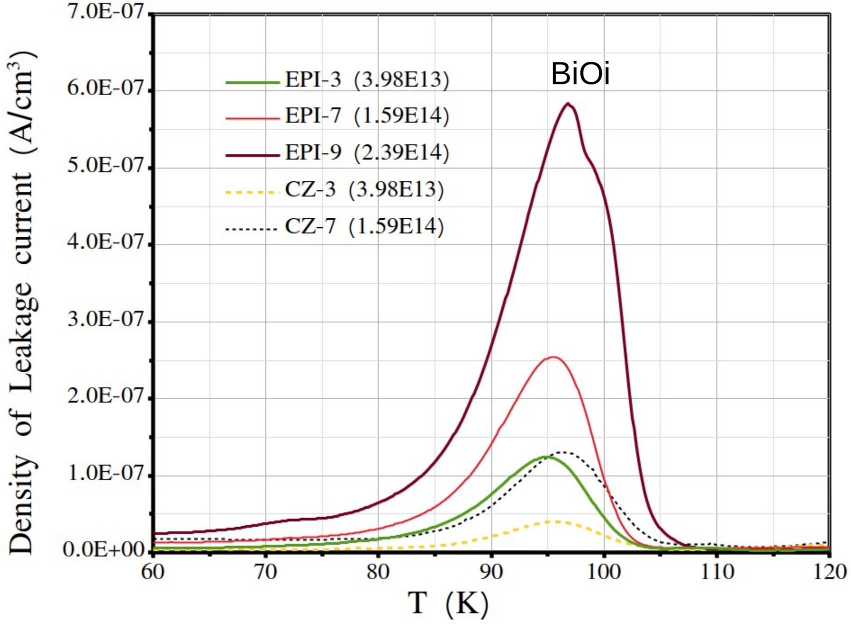


4.28E13

Effective doping for EPI- and CZ-diodes (~ 10 Ωcm) after irradiation with **6 MeV electrons** with fluence values in the ranges between 3.98E13 ~ 2.39E14 n_{eq}/cm^2.

Thermally Stimulated Current

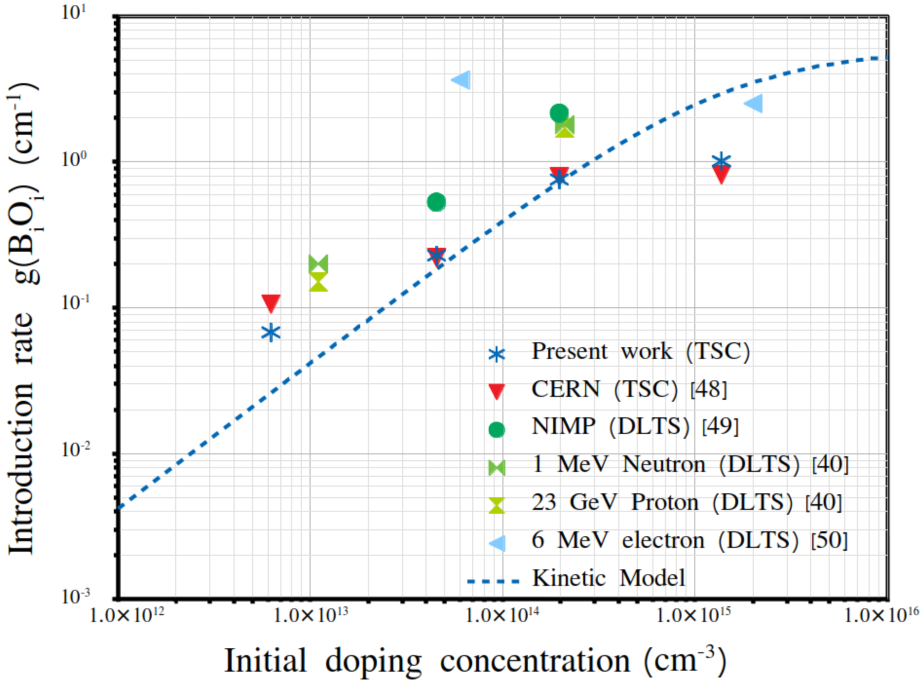




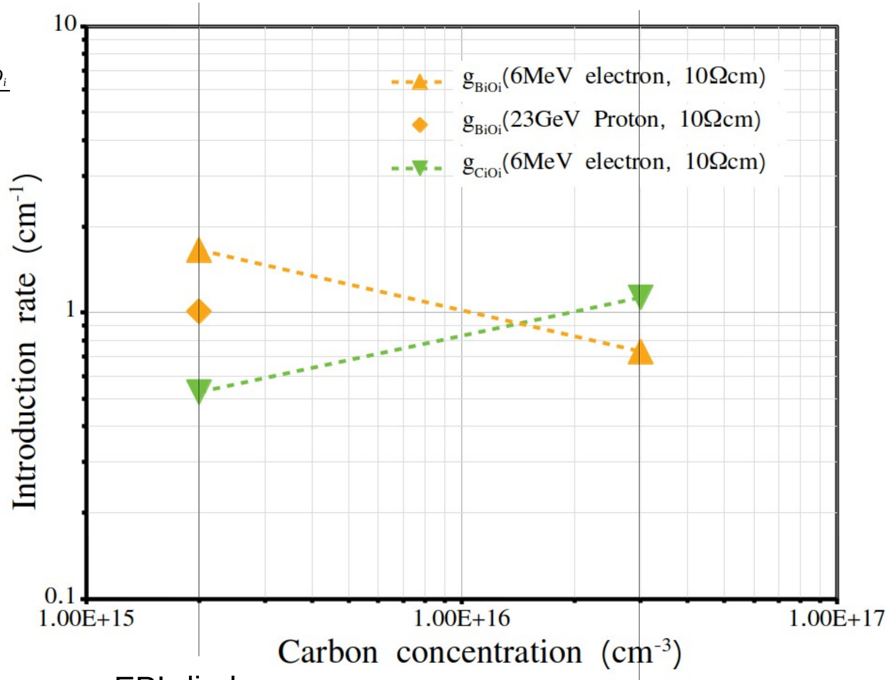
TSC spectra of diodes with different resistivity after **23 GeV protons** irradiation to Φ_{eq} = 4.28E13 n_{eq}/cm^2 for reverse bias 20 V (2 kΩcm), 40 V (250 Ωcm), 200 V (50 Ωcm) and 100 V (10 Ωcm, spectra normalized to d/w(100 V)).

TSC spectra of diodes produced by **different processing** – Epitaxial (EPI-3, 7, 9) and Czochralski (CZ-3, 7) with 10 Ωcm resistivity, and after **6 MeV electrons** irradiation with fluence Φ = 1, 4, 6 × 10^{15} cm^{-2}. The diodes were measured with applied reverse bias 100 V, and spectra are normalized by a factor 1/(Aw(T)). A = active area, w(T) = temperature dependent depletion depth at constant bias voltage

Introduction rate



$$g(B_iO_i)=\frac{N_{t,B_iO_i}}{\phi_{eq}}$$



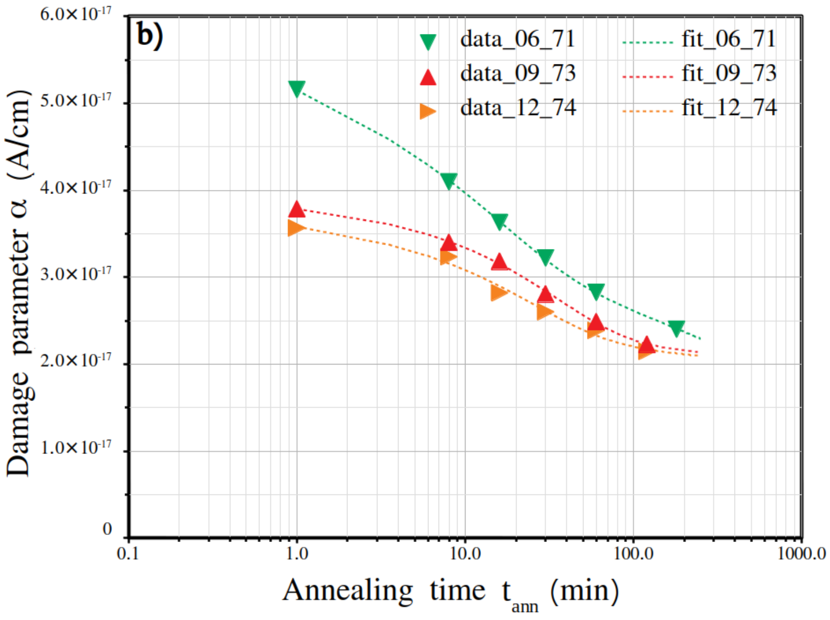
EPI-diodes

Cz-diodes

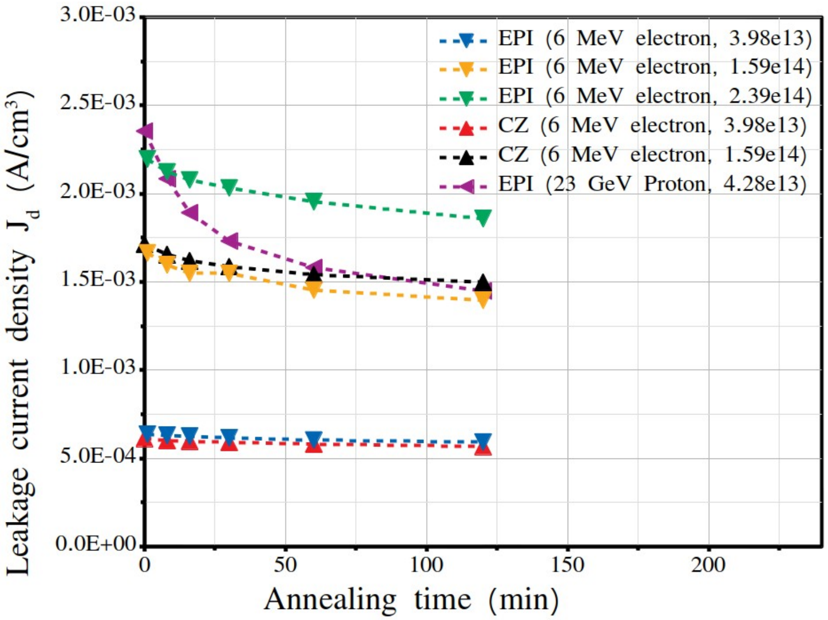
Introduction rate of B_iO_i as function of initial doping (~$[B_s]$) for EPI-diodes

Introduction rate of B_iO_i and C_iO_i as function of Carbon concentration (~$[C_s]$)

Annealing behavior (80^{o}C)

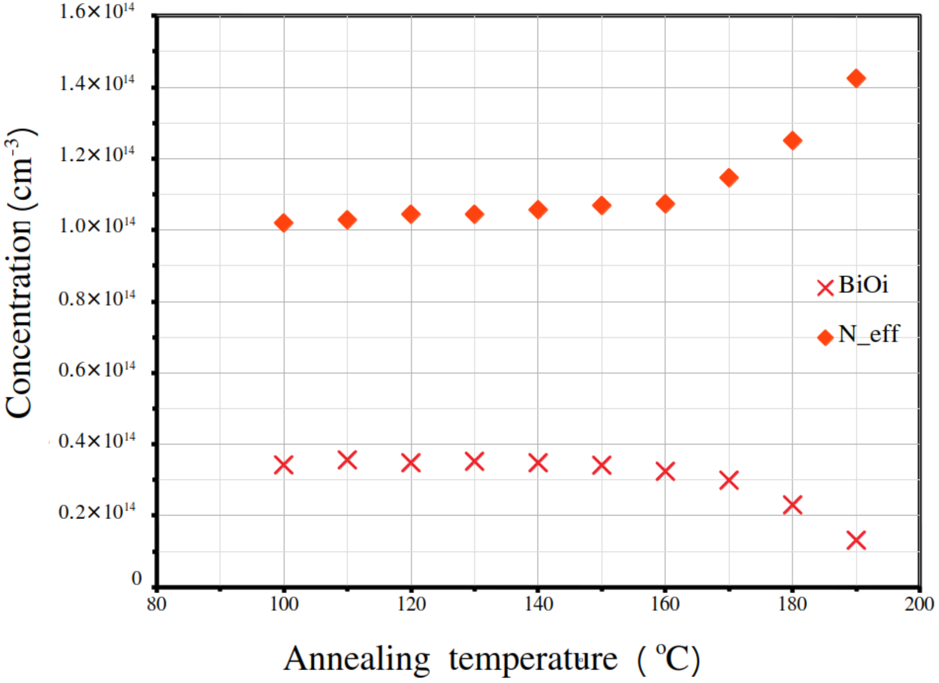


Annealing behavior of current related damage parameter for EPI-diodes with resistivity 2 kΩcm (12_74), 250 Ωcm (09_73) and 50 Ωcm (06_71), which were irradiated by 23 GeV protons with fluence Φ_{eq} = 4.28E13 cm^{-2}

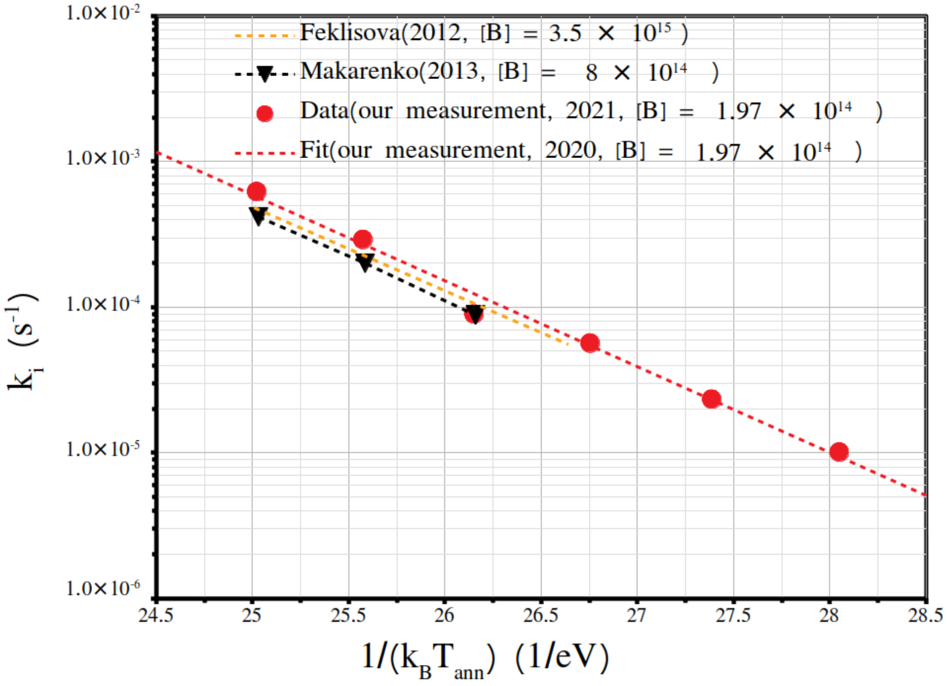


Annealing behavior of leakage current for EPI- and Cz- diodes with resistivity 10 Ωcm, and irradiated by different particles and fluence values

Isochronal annealing behavior of B_iO_i



Defect concentration [BiOi] and Neff vs. annealing temperature. For each temperature step the duration of annealing was 15 min



The frequency factors for annealing out of BiOi vs. $1/(k_BT_{ann})$; from the slope the corresponding activation energy of BiOi is extracted to $E_A = 1.35 \pm 0.01$ eV

Summary

I. Impurity dependence:

- Higher initial doping concentration leads to higher B_iO_i introduction rate after the same fluence value, but the increase is limited
- The diodes with high carbon concentration restrain the generation of B_iO_i and, thus, depress the deactivation of $[B_s]$

II. Fluence dependence:

- The higher irradiation fluence value leads to higher B_iO_i concentration (up to now)
- The higher irradiation fluence value leads to higher leakage current, and the annealing out of ΔI increasing with irradiation fluence value

III. Particle dependence:

- The generation of B_iO_i for 23 GeV proton approx equal to half of value for 6 MeV electron
- The larger annealing out value of ΔI was observed on 23 GeV proton irradiated diodes compare to 6 MeV electron irradiated

IV. Annealing behaviors:

- If $T_{ann} > 150\ {}^{o}C$, $[B_iO_i]$ decrease, N_{eff} increase
- The change $\Delta N_{eff} \approx 2 \times \Delta N_t$ ($[B_iO_i]$) as expected from $B_s(-) \rightarrow B_iO_i\ (+)$

V. LGAD diodes:

- The measurements of the pixel sensors with and without wire-bond were performed in our lab
- Up to now the analysis of the data was not as we expected

Back Up

Experimental details

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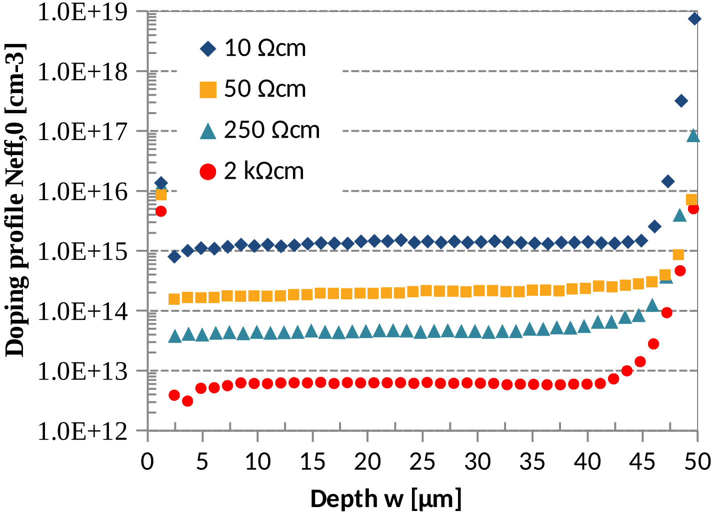
Experimental detail

Information of measured expitaxial silicon diodes (PIN)

Label	EPI50P_01_DS_73	EPI50P_06_DS_71	EPI50P_09_DS_73	EPI50P_12_DS_74
$N_{eff,0}$	1.37E15 cm^{-3}	1.97E14 cm^{-3}	4.53E13 cm^{-3}	6.24E12 cm^{-3}
Irradiation	23 GeV proton, Φ = 6.91E13 cm^{-2}, neutron equivalence Φ_{eq} = 4.28E13 cm^{-2}			
Area	6.927E-2 cm^2			
Thickness	50 μm			



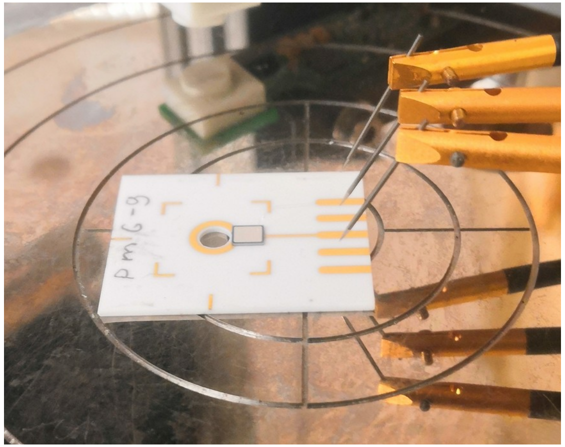
$N_{eff,0}$ vs. Depth from ITME(Institute of Electronic Materials Technology)

Experimental detail

Information of measured silicon diodes

Label	EPI50P_06_DS_3	EPI50P_06_DS_7	EPI50P_06_DS_9	CZ300P_06_DS_3	CZ300P_06_DS_7
$N_{eff,0}$	Expitaxial silicon, P-type 1.15e15 cm-3			Cz silicon, P-type 1.05e15 cm^{-3}	
Initial resistivity	~ 10 Ωcm			~ 10 Ωcm	
Irradiation (6 MeV electrons)	1e15 e/cm^2 (3.98e13 n_{eq}/cm^2)	4e15 e/cm^2 (1.59e14 n_{eq}/cm^2)	6e15 e/cm^2 (2.39e14 n_{eq}/cm^2)	1e15 e/cm^2 (3.98e13 n_{eq}/cm^2)	4e15 e/cm^2 (1.59e14 n_{eq}/cm^2)
Area	6.21E-2 cm^2			2.9E-2 cm^2	
Thickness	50 μm			350 μm	

C-V, I-V:



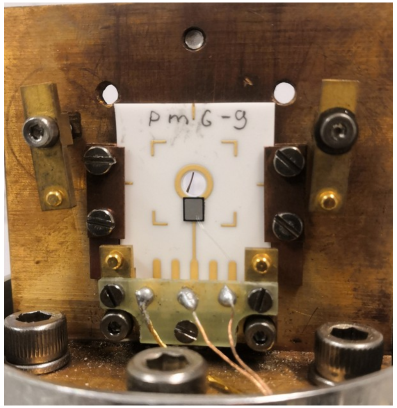
Experimental parameter (C-V, I-V):

Temperature: 20 °C
Humidity: < 10%
Frequencies for C-V: 230 Hz, 455 Hz, 1 kHz, 10 kHz
AC voltage for C-V: 0.5 V

Experimental parameter (TSC and TS-Cap):

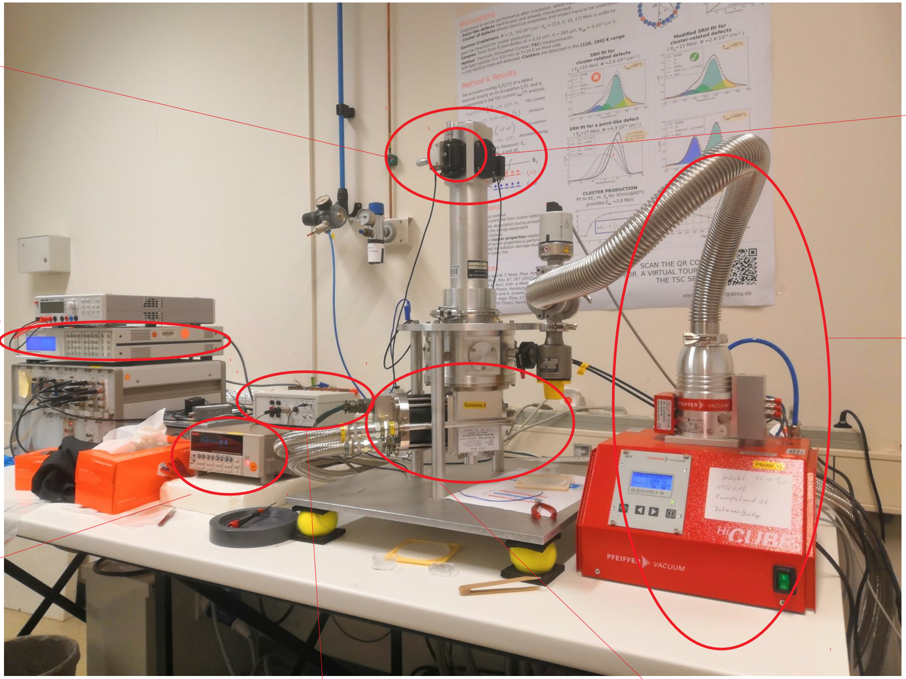
Cooling down bias: 0 V
Filling temperature: typical 10 K
Filling: Forward bias filling, 0 V filling or light injection
Filling time: 30 s
Delay time: 30 s
Heating rate: 0.183 K/s

Thermally stimulated current and Thermally stimulated capacitance (TSC, TS-Cap):



Experimental detail

Thermally Stimulated Current-TSC:



LED support for light injection

Temperature controller

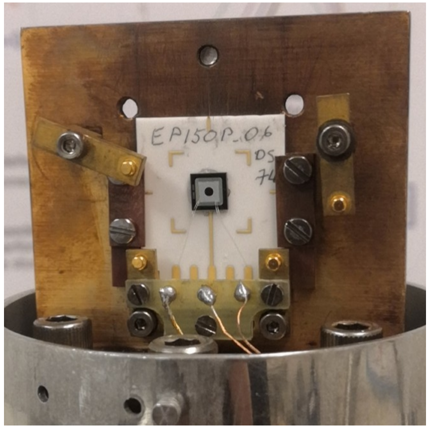
Keithly 6517A Electrometer

Switch box for PC control of He compressor and power supply for light injection

Cooling system

High vacuum pump system

Hot stage with sample holder, temperature sensor and heater

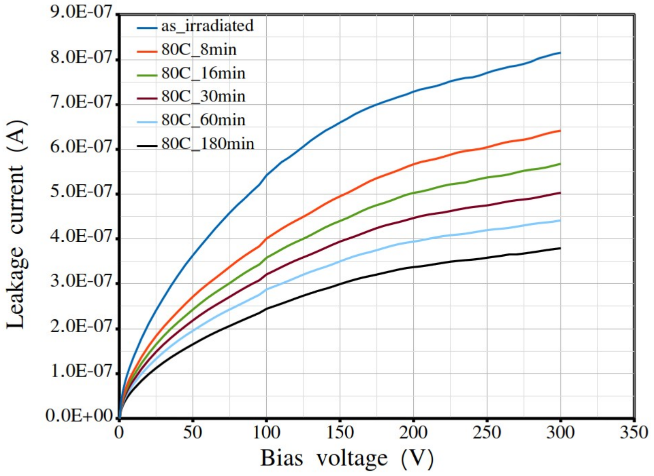


Experimental parameter (TSC):

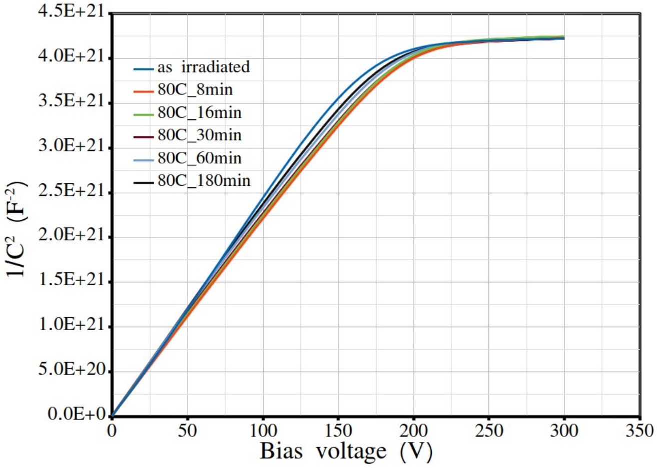
Cooling down bias: 0 V
Filling temperature: typical 10 K
Filling: Forward bias filling, 0 V filling or light injection
Filling time: 30 s
Delay time: 30 s
Heating rate: 0.183 K/s
Heating up bias: depends on effective space charge concentration after irradiation

Methods for I-V and C-V measurements

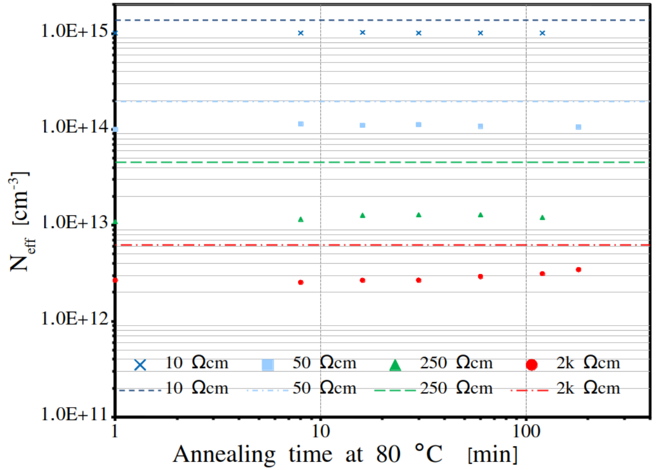
C-V, I-V measurement – isothermal annealing



I-V for $N_{eff,0}$ = 1.97E14 cm^{-3} diodes



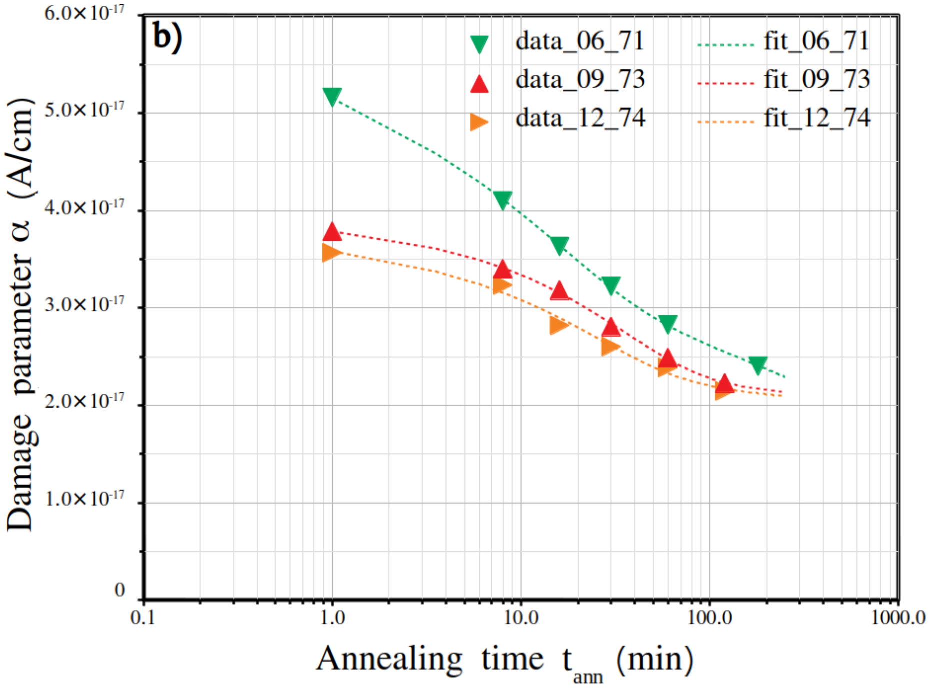
C-V for $N_{eff,0}$ = 1.97E14 cm^{-3} diodes



N_{eff} vs t_{ann} for $N_{eff,0}$ = 1.97E14 cm^{-3} diodes

I. The decreases of leakage current after isothermal annealing
II. Stability of effective doping concentration N_{eff} (full depeleted voltage V_{fd}) during isothermal annealing

Annealing of current and full depletion voltage

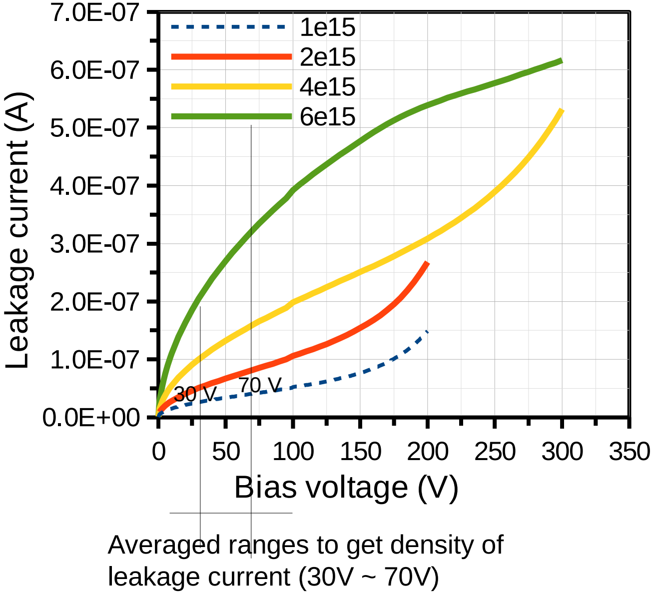


$$\alpha = \frac{I}{V\,\phi_{eq}}$$

Fitting functions[1]: $\alpha(t) = \alpha_I \cdot \exp\left(\frac{-t}{\tau_I}\right) + \alpha_0 - \beta \cdot \ln\left(\frac{t}{t_0}\right)$ $t_0 = 1\,min$

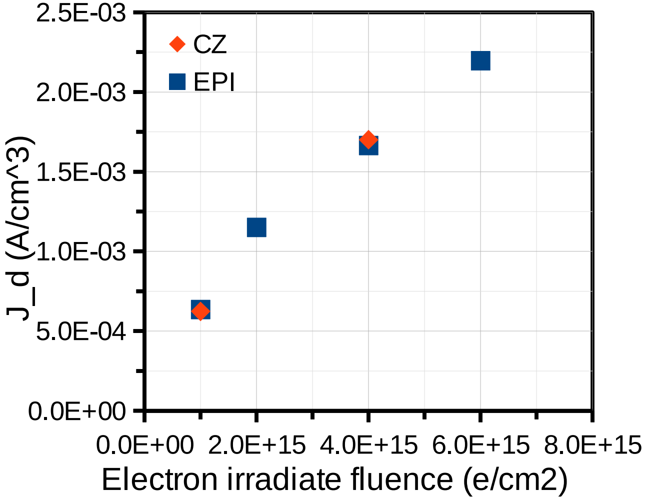
Fit parameter(50 Ωcm):	Ref. [1]:
$\alpha_I \approx 1.14 \times 10^{-17}\,A/cm$	$\alpha_I \approx 1.13 \times 10^{-17}\,A/cm$
$\tau_I \approx 18\,min$	$\tau_I \approx 9\,min$
$\alpha_0 \approx 5.48 \times 10^{-17}\,A/cm$	$\alpha_0 \approx 4.23 \times 10^{-17}\,A/cm$
$\beta_0 \approx 4.51 \times 10^{-18}\,A/cm$	$\beta_0 \approx 2.83 \times 10^{-18}\,A/cm$

I-V and N_{eff} profile (10 Ωcm, as-irrad)

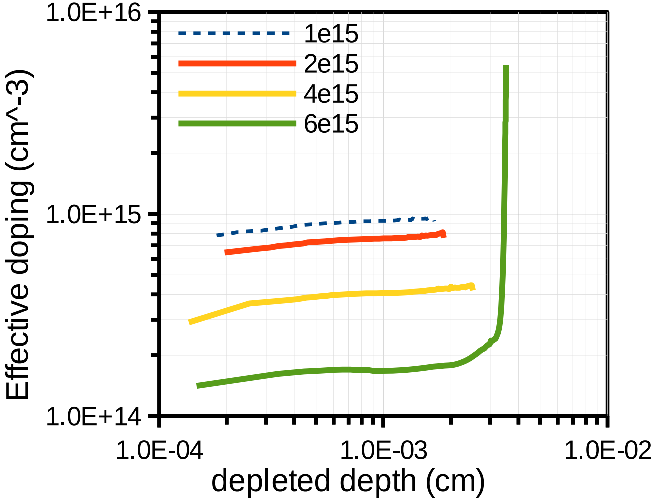


Averaged ranges to get density of leakage current (30V ~ 70V)

Leakage current for different fluence



Mean value of leakage current density J_d as function of irradiation fluence



Doping profile

- Leakage current increases with fluence. In order to observe the mean value of leakage current density (J_d), the current in the range from 30V to 70V was chosen for calculate J_d (the depleted volume is taken from C-V measurement)
- Doping profile is taken from C-V measurement with frequency equal 10 kHz and V_{AC}=0.5V. Effective doping decrease with fluence

TSC Data analyze

BiOi in TSC spectra (1.97E14 cm^{-3})

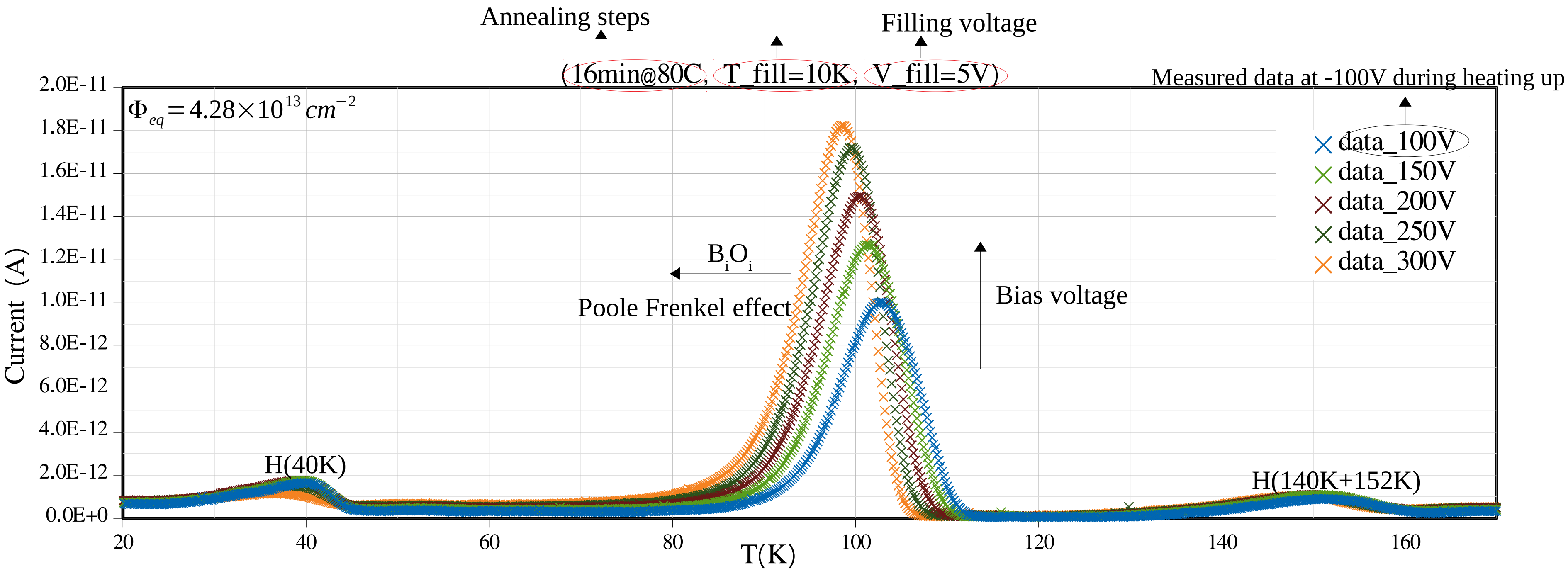
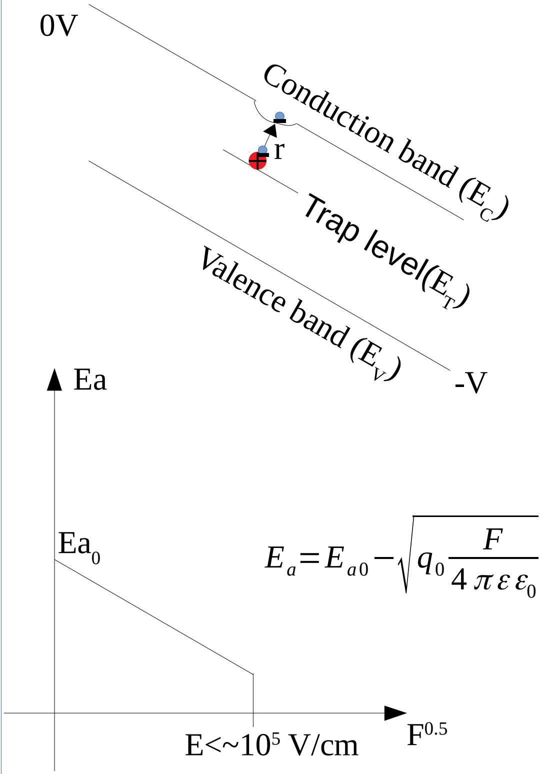


Fig 6. TSC spectra for different bias voltages of 50 Ωcm diode after 23 GeV proton irradiation

- Dominant B_iO_i signal
- Shift of peak maximum with V_{bias} → Poole-Frenkel effect; electron trap B_iO_i (o/+) donor defect
- Peak amplitude increases with bias voltage due to increasing depletion depth and after full depletion extending into the p+ region

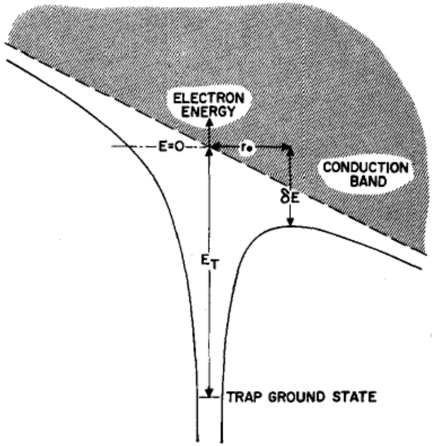
Poole Frenkel effect

Example for 1-D[1]:



$$E_a = E_{a0} - \sqrt{q_0 \frac{F}{4\pi\varepsilon\varepsilon_0}}$$

3-D [2]:



$$E_a = E_{a0} - \sqrt{\frac{q_0 F\cos\theta}{4\pi\varepsilon\varepsilon_0}}$$

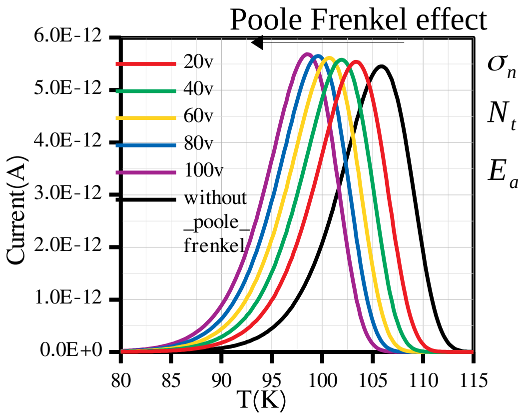
$$e_n = \sigma_n v_{th,n} N_c \times \exp\left(\frac{-Ea_0}{K_b T}\right)\left[\left(\frac{1}{\gamma^2}\right)\left(e^{\gamma}(\gamma-1)+1\right)+\frac{1}{2}\right]$$

$\gamma = (qF/\pi\varepsilon_0\varepsilon_r)^{1/2} q_0/(k_B T)$

Describe TSC peak:

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

q_0: elementary charge; A: area; d: depleted thickness; N_t: defect concentration; e_n: emission rate; T: temperature; x: position; β: heating rate; σ_n: electron captured cross section; $v_{th,n}$: thermal velocity of electron; N_C density of state in the conduction band; E_{a0}: zero field activation energy; k_B: Boltzmann constant; F(x): electric field.



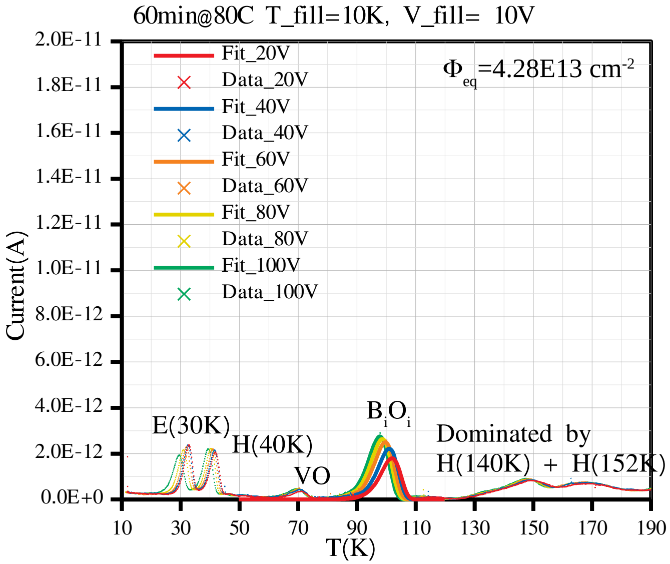
$\sigma_n = 1\times10^{-15} cm^{-2}$

$N_t = 1.2\times10^{13} cm^{-3}$

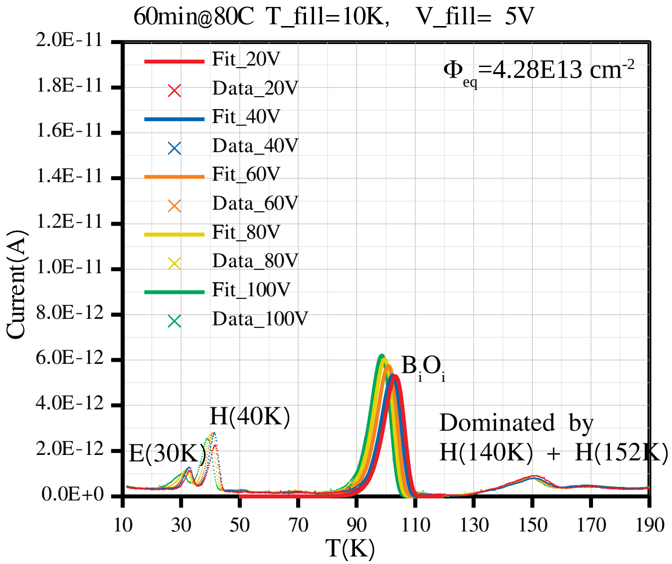
$E_{a0} = 0.255\, eV$

[1] J. L. Hartke, J. Appl. Phys. 39, 4871 (1968).
[2] Pintilie, I., E. Fretwurst, and G. Lindström. Applied Physics Letters 92.2 (2008): 024101.

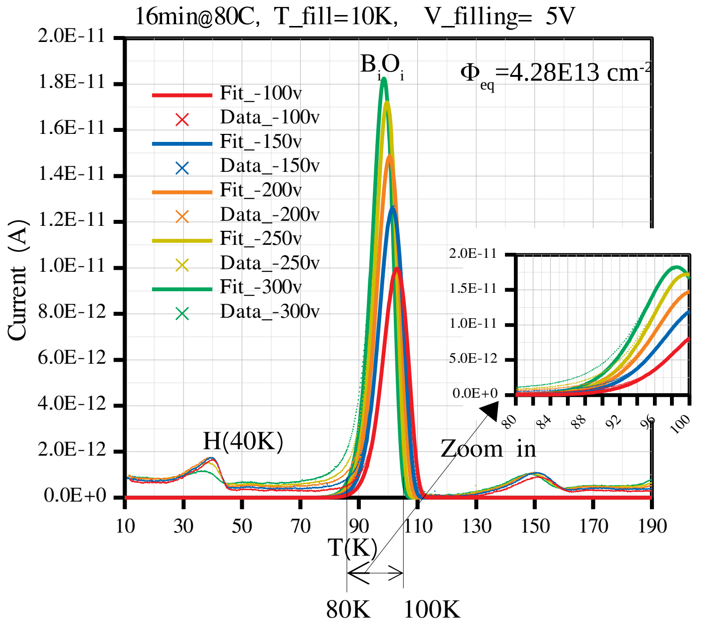
Fit B_iO_i peak in TSC spectra



TSC spectra for $N_{eff,0}$ = 6.94E12 cm^{-3} diodes with different V_{bias}



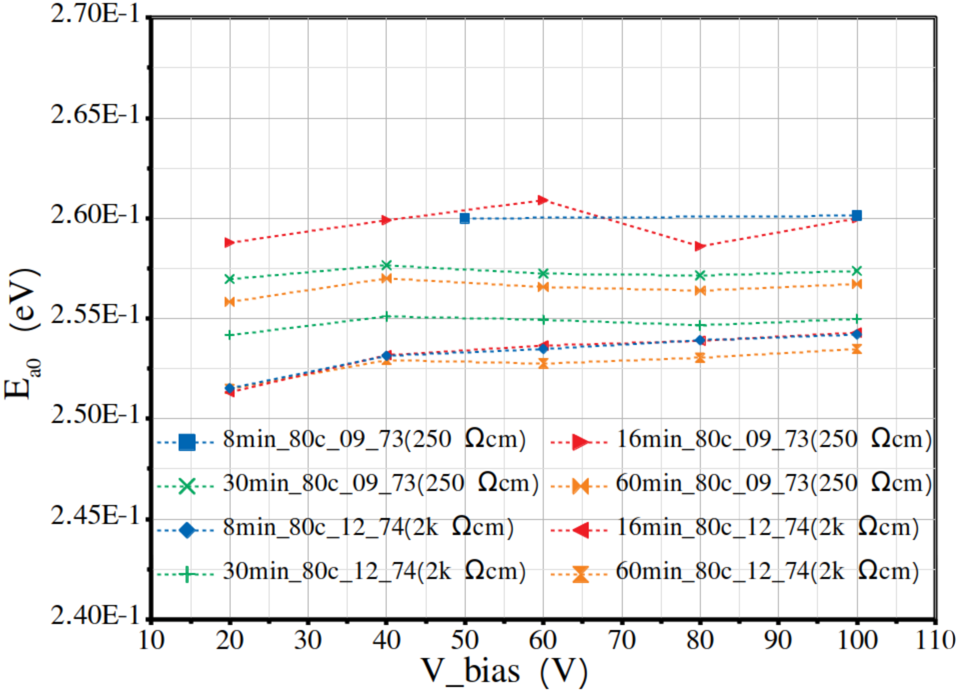
TSC spectra for $N_{eff,0}$ = 4.53E13 cm^{-3} diodes with different V_{bias}



TSC spectra for $N_{eff,0}$ = 1.97E14 cm^{-3} diodes with different V_{bias}

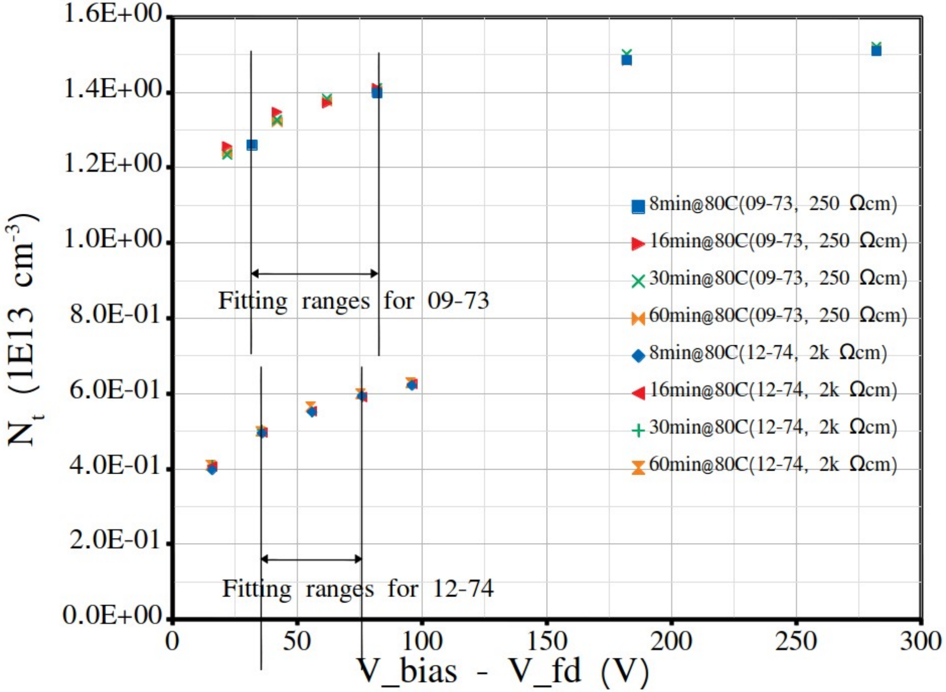
For same irradiation fluence, the BiOi concentration increase as $N_{eff,0}$ increasing. And if most of the recoil energy deposited forms B_iO_i defect, the concentration of other defects will decrease

Activation energy and defect concentration



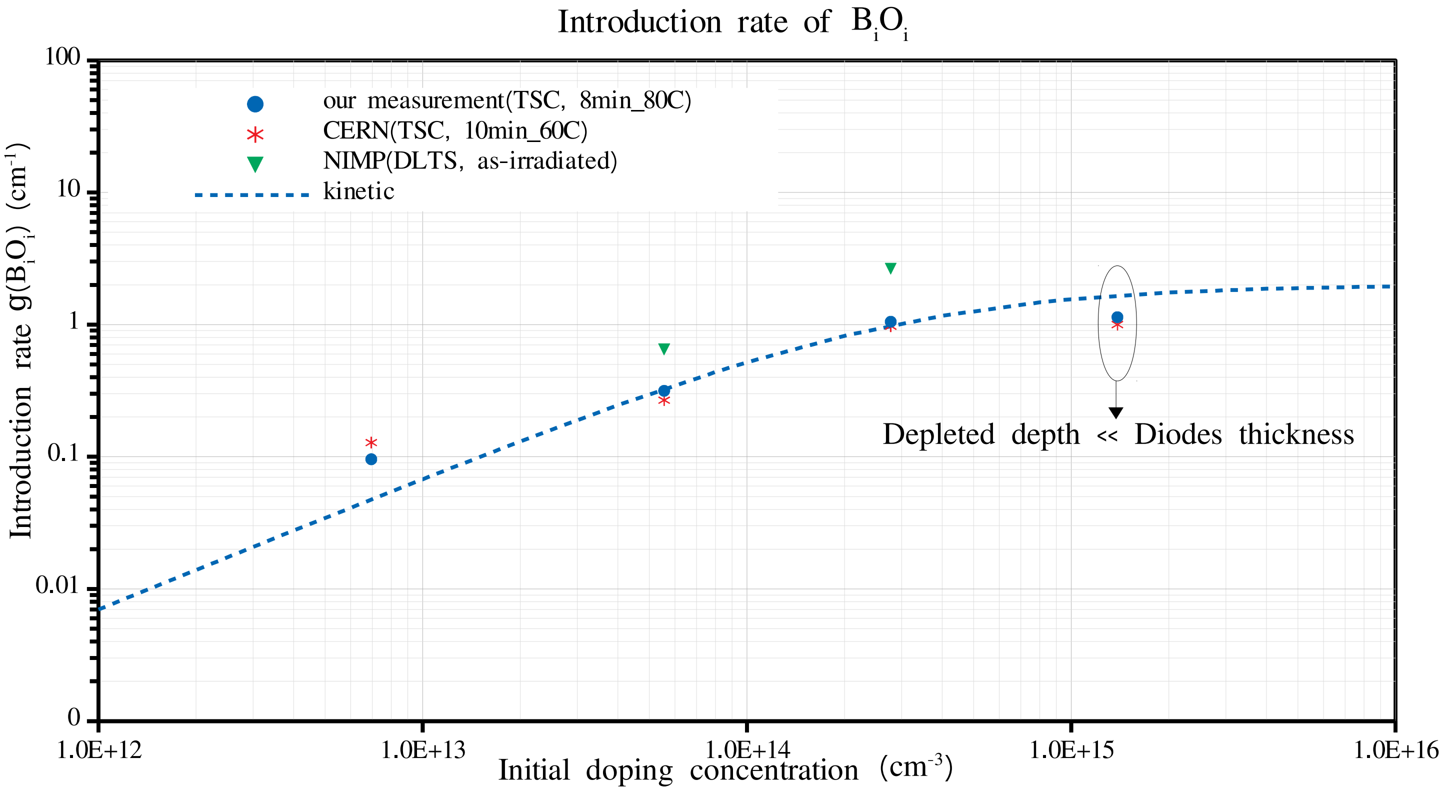
Zero field activation energy E_{a0} versus bias voltage of BiOi defect extracted from TSC spectra of 250 Ωcm and 2K Ωcm

$$\sigma_n \approx 1\times10^{-15}\, cm^{-2}$$



B_iO_i concentration as function of excess voltage (V_{bias} - V_{fd}) for the 250 Ωcm and 2k Ωcm extracted from TSC spectra measured after annealing steps between 8 min and 60 min at 80°C. The ranges for a linear fit to the data are indicated for both diodes in order to get the B_iO_i concentration at $V_{bias} = V_{fd}$

Introduction rate of B_iO_i for different doping



Definition of $g(B_iO_i)$:

$$g(B_iO_i)=\frac{N_{t,B_iO_i}}{\phi_{eq}}$$

Defect Kinetics Model [1-2]:

$$g(B_iO_i)\approx g_I\times\left(1+\frac{k_{IC}[C_s]}{k_{IB}[B_s]}\right)^{-1}$$

$$g_I\approx 2\,cm^{-1}$$

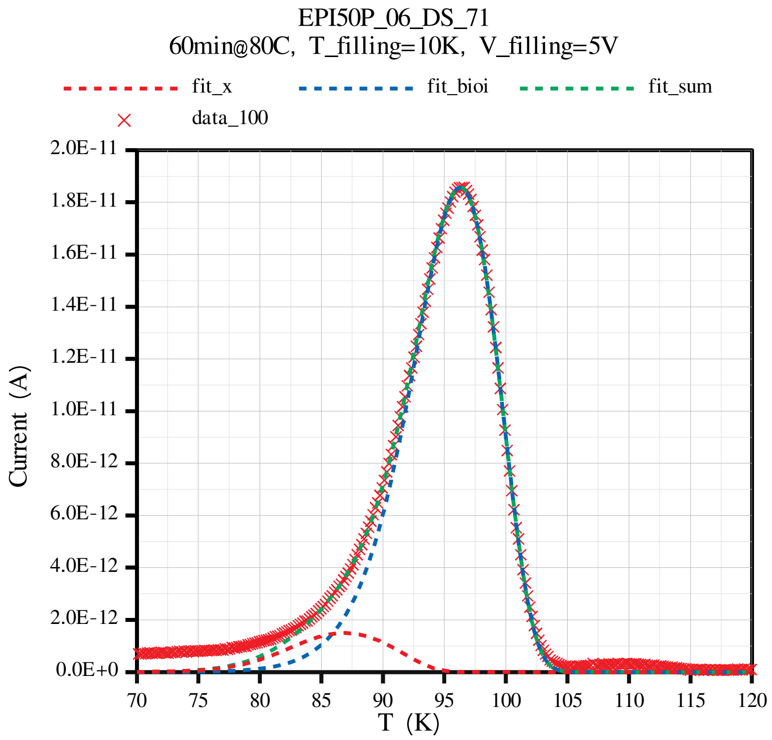
$$\frac{k_{IB}}{k_{IC}}\approx 7$$

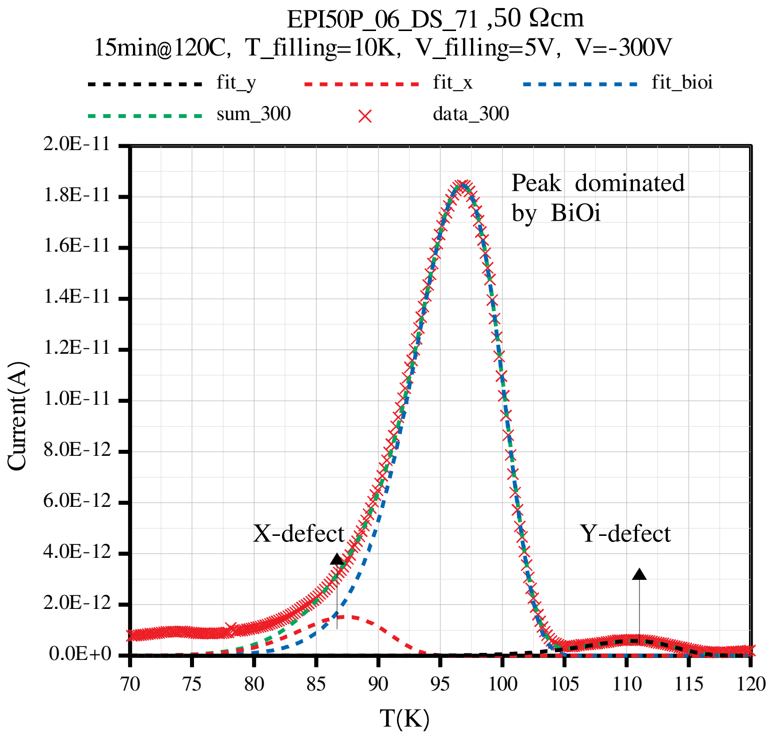
$$[C_s]\approx 2\times10^{15}\,cm^{-3}$$

For higher initial doping ($N_{eff,0}$ > 1E15 cm^{-3}), There appears to be some limit for the increase of $g(B_iO_i)$ --> for higher $N_{eff,0}$ > 1E15 cm^{-3}, If $N_{eff,0}$ improved, the radiation hardness improves as well

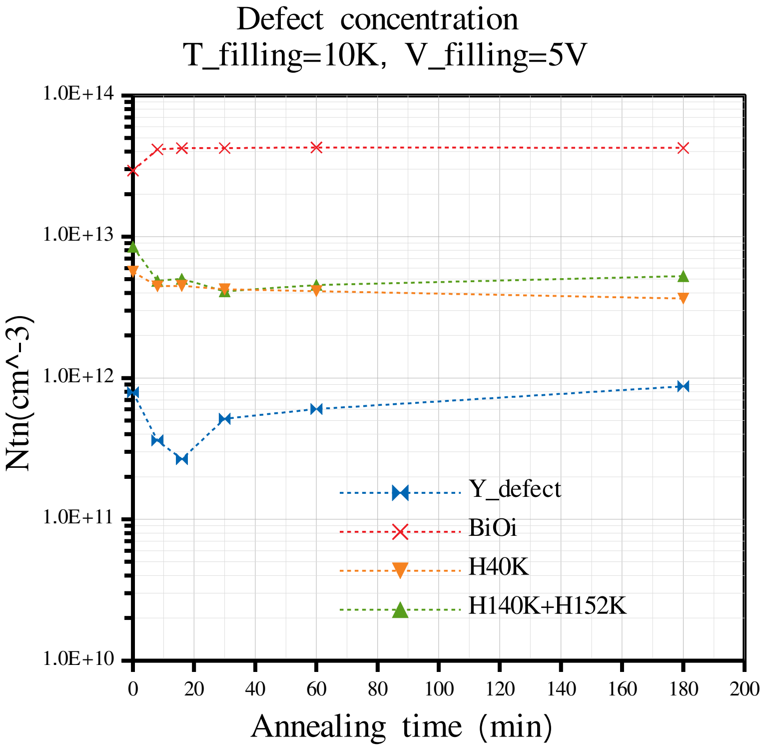
[1] Makarenko, Leonid F., et al. physica status solidi (a) 216.17 (2019): 1900354.
[2] Moll, Michael. "Acceptor removal-Displacement damage effects involving the shallow acceptor doping of p-type silicon devices." (2019).

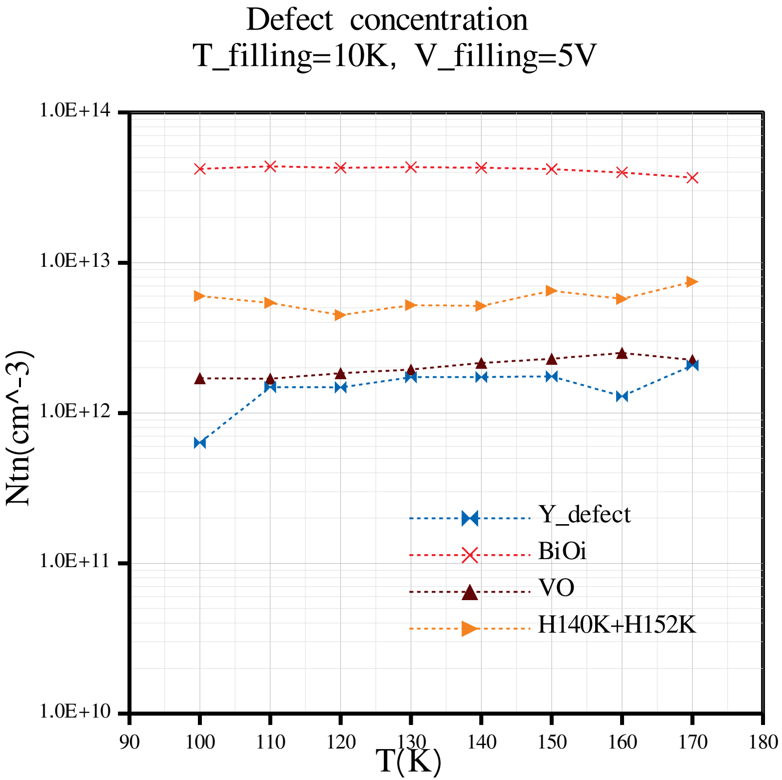
Annealing behavior of TSC measurements



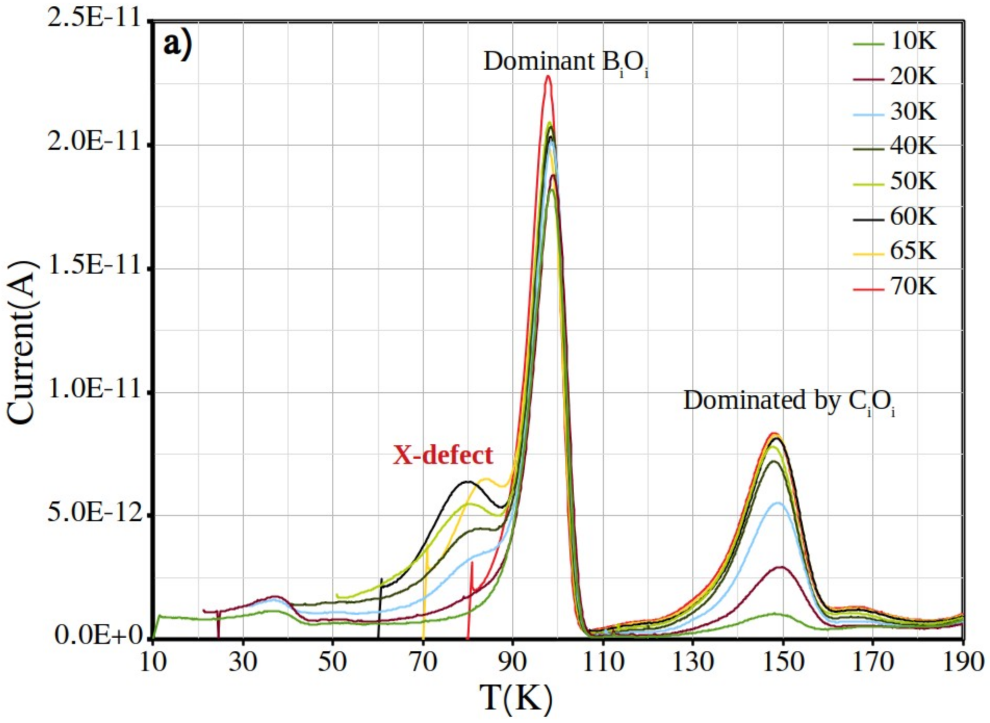


Annealing behavior of TSC measurements

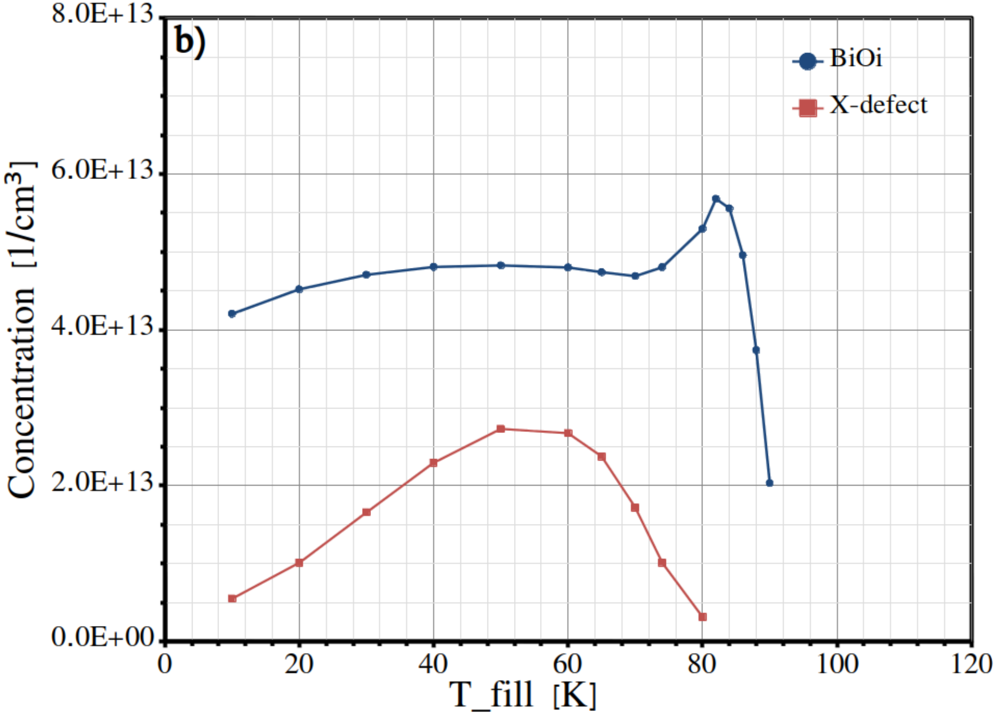




Indication for X-defect (1.97E14 cm^{-3})



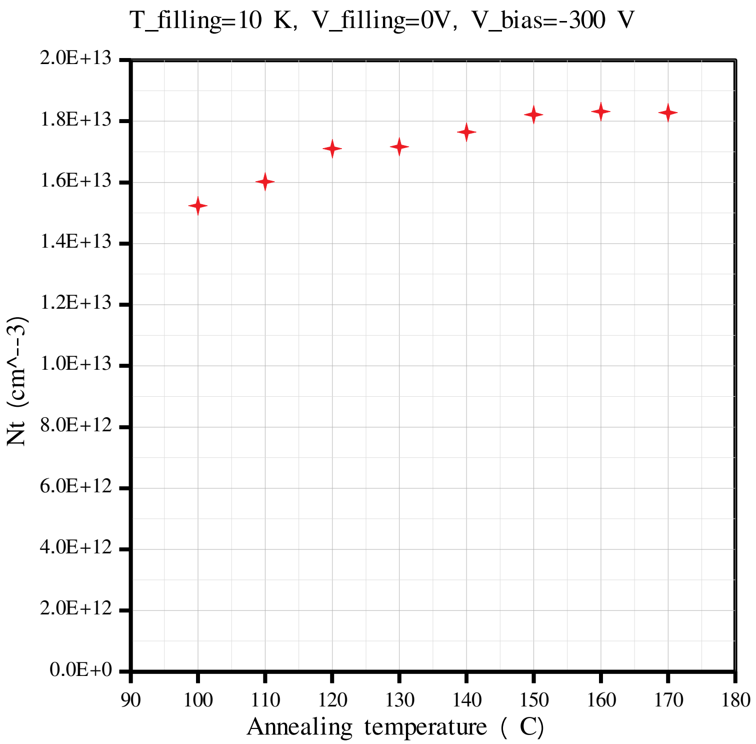
TSC spectrum of $N_{eff,0}$ = 1.97E14 cm^{-3} p-type diodes after 30 minutes isothermel annealing at 80°C. Different T_{fill} from 10K to 70K, V_{fill} = 5V



Concentration of BiOi and X-defect versus filling temperature T_{fill} extracted from the TSC spectra

Forward bias injection: $$p_t = \frac{N_t}{\left(1 + \frac{c_n}{c_p}\right)}$$

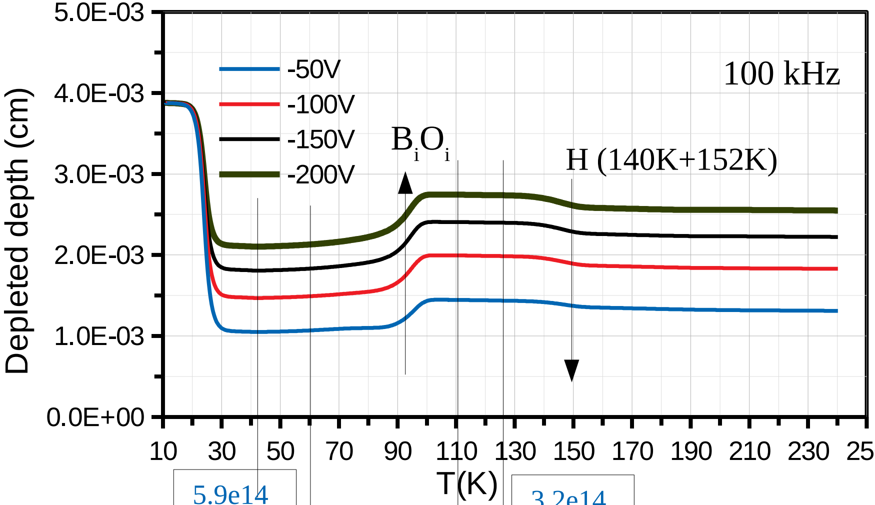
Annealing behavior of X-defect



TS-Cap measurement analysis

Example of TS-Cap on B_iO_i (10 Ωcm, as-irrad)

4E15 e/cm^2 (T_fill=10K, V_fill= 10V)



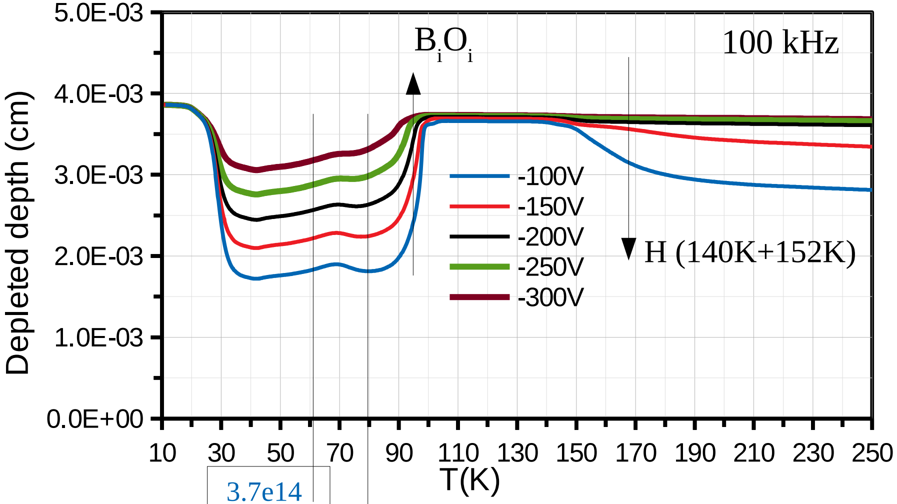
N_{eff} (cm^{-3}) before B_iO_i emission

5.9e14
6.0e14
6.0e14
5.9e14

3.2e14
3.3e14
3.4e14
3.5e14

N_{eff} after B_iO_i emission

6E15 e/cm^2 (T_fill=10K, V_fill= 10V, 100 kHz)



3.7e14
3.8e14
3.8e14
3.8e14
3.7e14

N_{eff} (cm^{-3}) before B_iO_i emission

- Depleted depth was extracted from TS-cap with $d = \varepsilon_{si}\varepsilon_0 A/C$
- The shift of B_iO_i peak temperature versus V_{bias} can also be observed in TS-Cap measurement
- Freeze-out of free charge carriers for T < 40 K
- Effective doping concentration can be extracted only if the diode is not fully depleted

Basic principle(1-D)

Poisson equation: $\frac{dE}{dx}=\frac{q_0 N_{eff}}{\varepsilon \varepsilon_0}$

Occupation fraction: $f(T)=\exp(-\frac{1}{\beta}\int e_n dT)$

Effective doping during emission:

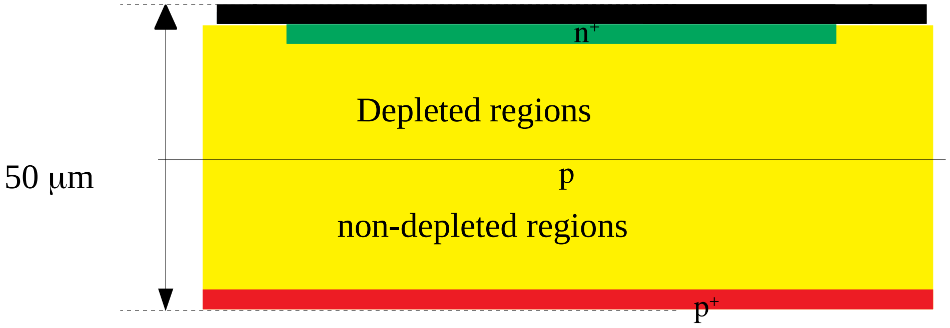
$$N_{eff}=N_0+N_t\cdot(1-f(T))$$

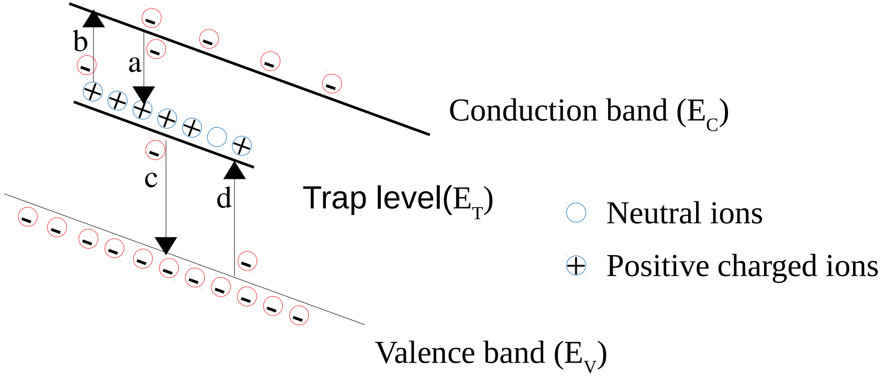
3-d Poole Frenkel ($\gamma=(qE/\pi\varepsilon_0\varepsilon_r)^{1/2}q/(k_B T)$):

$$e_n=\sigma_n v_{th,n} N_c \times \exp(\frac{-Ea_0}{K_b T})[(\frac{1}{\gamma^2})(e^{\gamma}(\gamma-1)+1)+\frac{1}{2}]$$

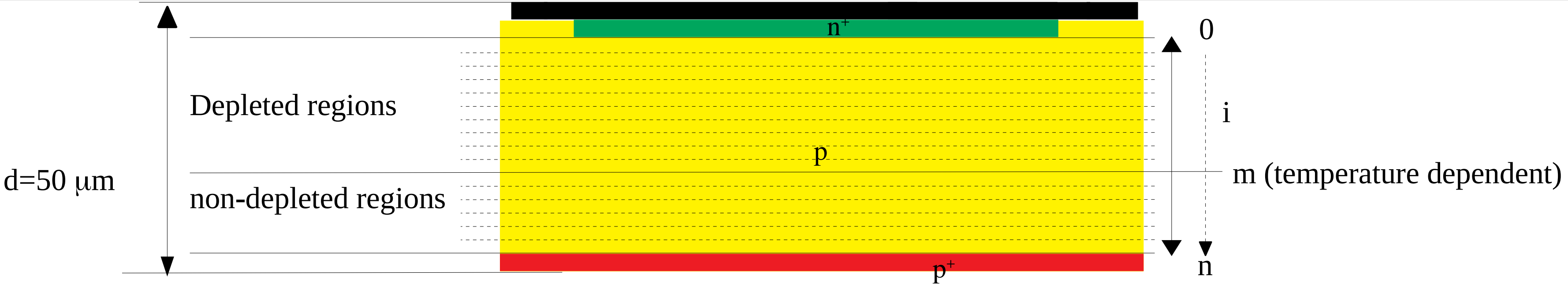
Capacitance:

$$C=\frac{\varepsilon\varepsilon_0 A}{d}$$





Finite element (Basic principle)



Simplification (t for temperature T(K), i stands for position):

Poisson equation ($i<m_t$):

$$E_{i+1,t}-E_{i,t}=\frac{q_0 Neff_{i,t}}{\varepsilon\varepsilon_0}\cdot\frac{d_t}{n}$$ and $$E_{i,t}=\sum_{i=0}^{m_t}\frac{q_0 Neff_{i,t}}{\varepsilon\varepsilon_0}\cdot\frac{d}{n}-\sum_{j=0}^{i}\frac{q_0 Neff_{j,t}}{\varepsilon\varepsilon_0}\cdot\frac{d}{n}$$

$$\downarrow$$

$$\sum_{i=0}^{m_t}E_{i,t}\cdot\frac{d}{n}=V$$

Occupation fraction:

$$f_{i,t}=\exp\left(-\sum_t e_{n,i,t}\right)$$

Effective doping during emission:

$$Neff_{i,t}=N_0-N_t\cdot(1-f_{i,t})$$

3-d Poole Frenkel ($\gamma_{i,t}=(qE_{i,t}/\pi\varepsilon_0\varepsilon_r)^{1/2}q/(k_B t)$):

$$e_{n,i,t}=\sigma_n v_{th,n}N_c\times\exp\left(\frac{-E_{a0}}{k_B t}\right)\left[\left(\frac{1}{\gamma_{i,t}{}^2}\right)\left(e^{\gamma_{i,t}}(\gamma_{i,t}-1)+1\right)+\frac{1}{2}\right]$$