Investigation of the BiOi defect in EPI and Cz silicon diodes using Thermally Stimulated current (TSC) and Thermally Stimulated Capacitance (TS-Cap)

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

RD50

Nov 17, 2021

Outline

I. Motivation

II. Experimental details

III. Measurements

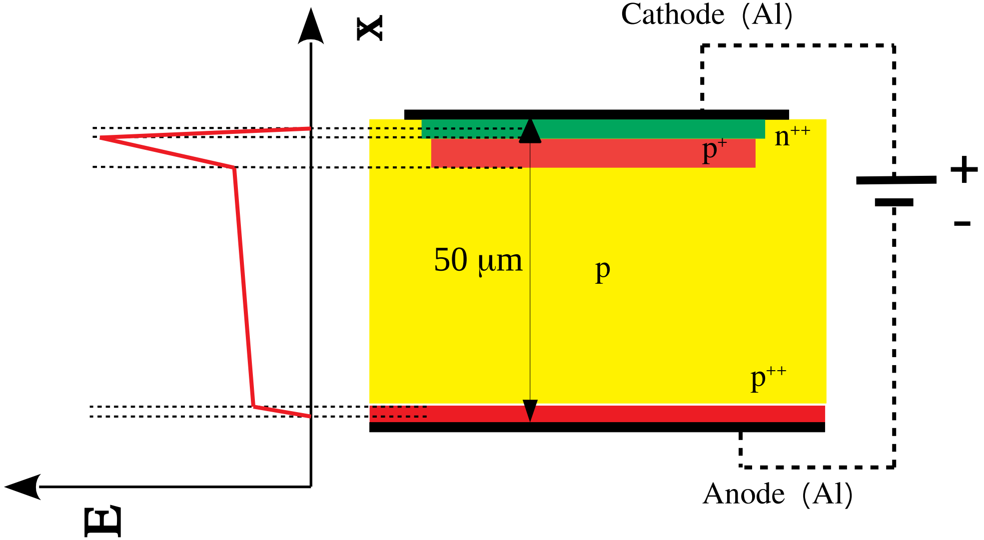
IV. Simulation

V. Summary

Motivation

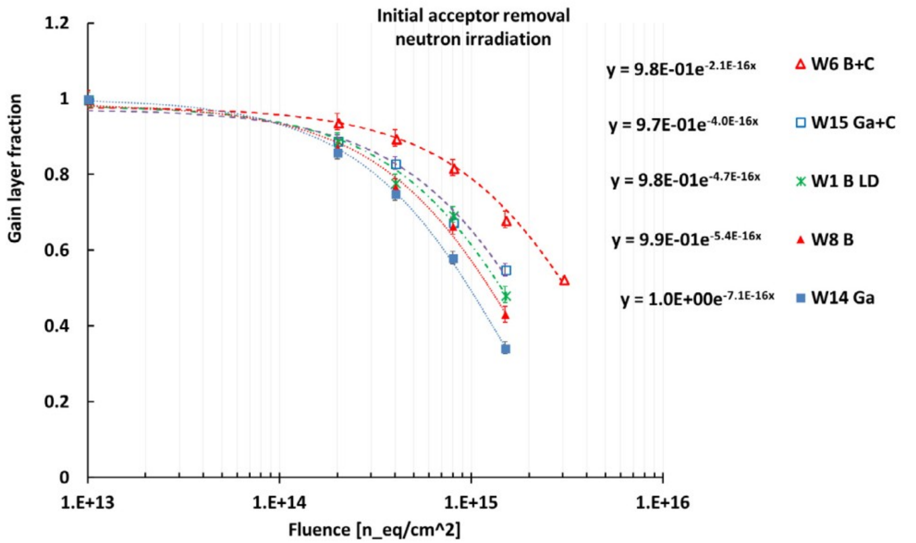
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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})

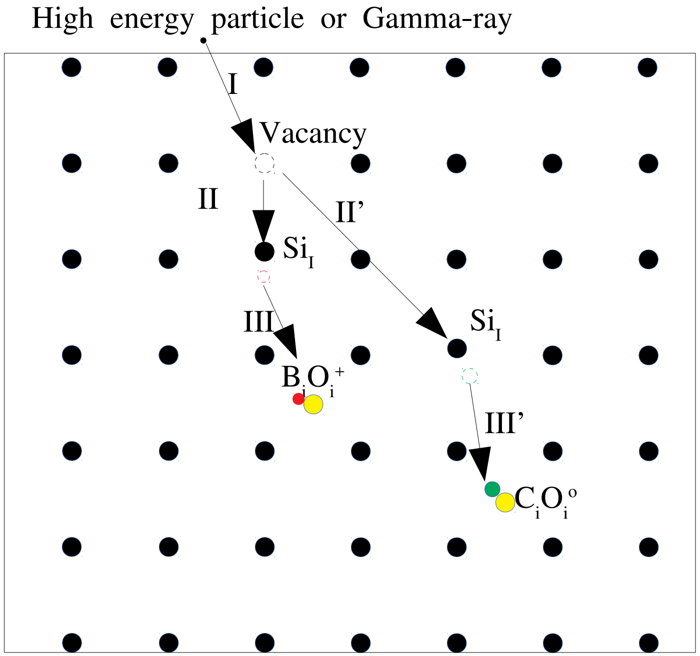


Gain fraction vs. Fluence for different doping

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

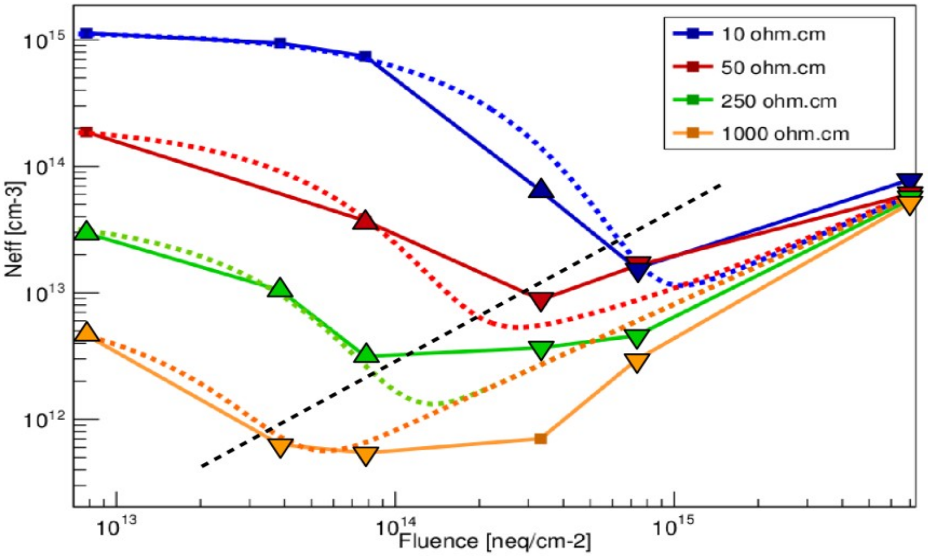


Schematic of radiation damage in p-type silicon material

I: Lattice Silicon atom (Si_s) is knocked out by incident particle and Si_s gets 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 is knocked out by 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.

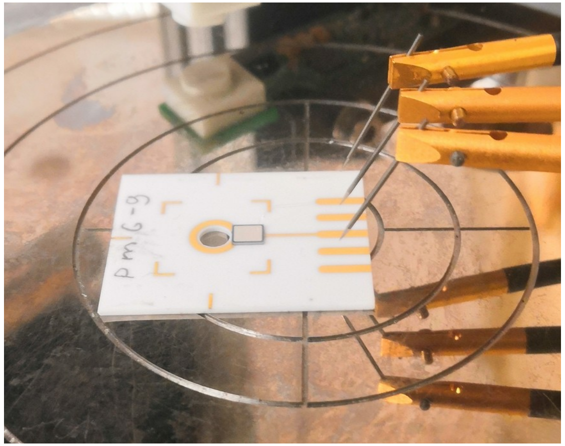
[1] Y. Gurimskaya, 31st RD50 Workshop, 20-22 of November, 2017, CERN, Geneva, Switzerland.

Experimental details

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:



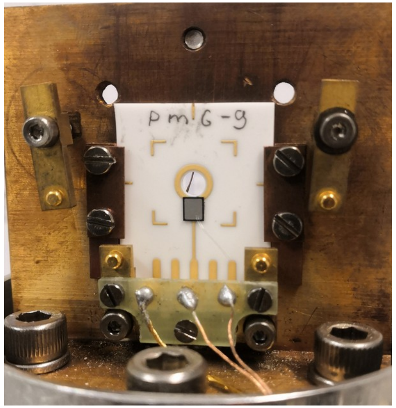
Experimental parameter (C-V, I-V):

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):

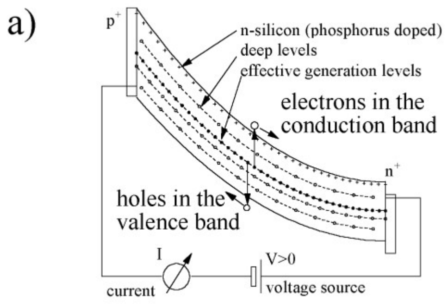
Cooling down bias: 0 V
Filling temperature: typical 10 K
Filling: Forward bias filling, 0 V filling or light injection
Filling time: 30 s
Delay time: 30 s
Heating rate: 0.183 K/s

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

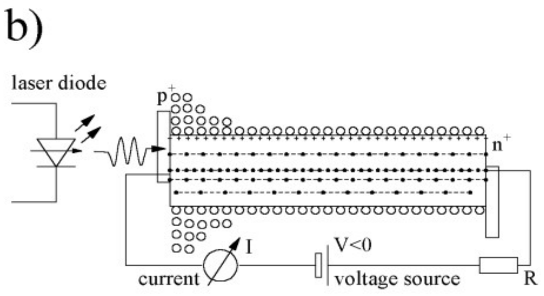


Experimental details

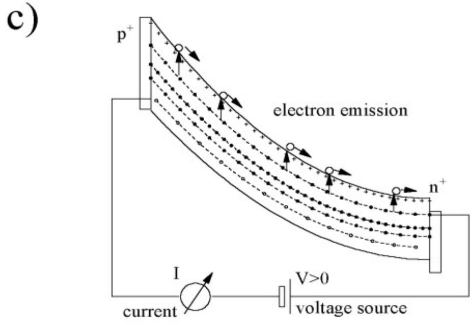
Basic Principle of Thermally Stimulated Current-TSC (or TS-Cap) [2]:



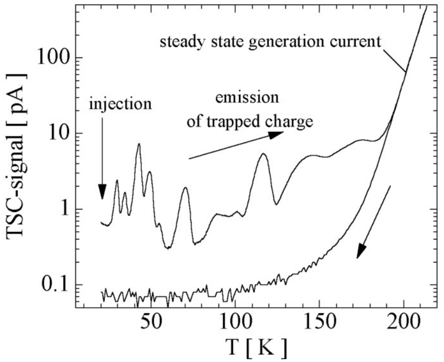
a) Cooling



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



c) Recording data



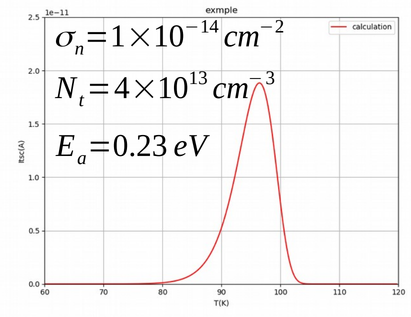
TSC spectrum [2]

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

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

$$E_a=E_C-E_T$$

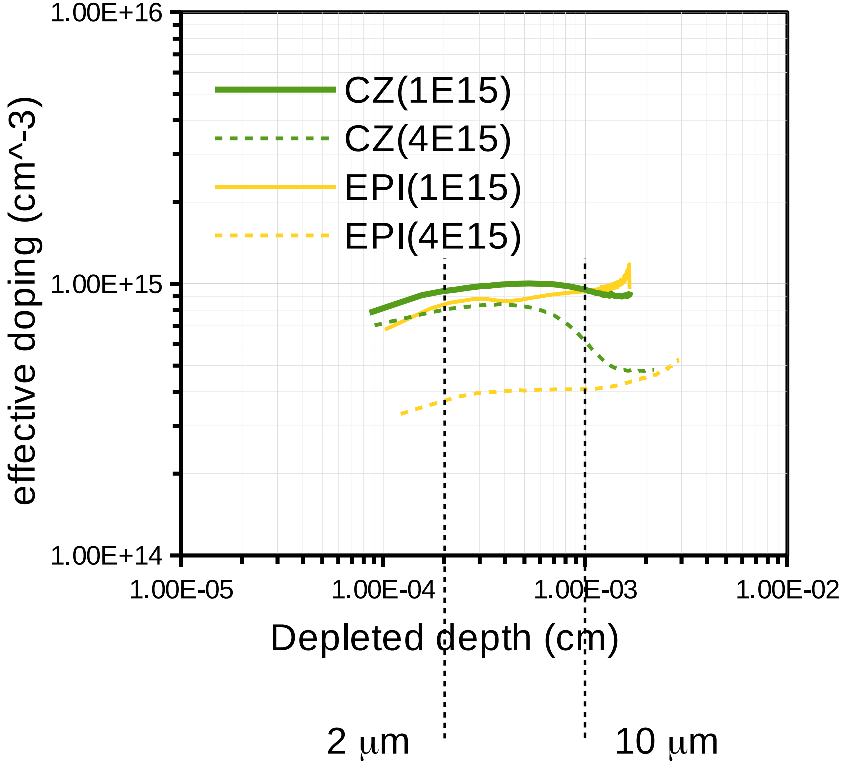
N_t is defect concentration; β is heating rate; σ_n is capture cross section;
E_a is activation energy; A is diodes area; d depleted thickness; [1]

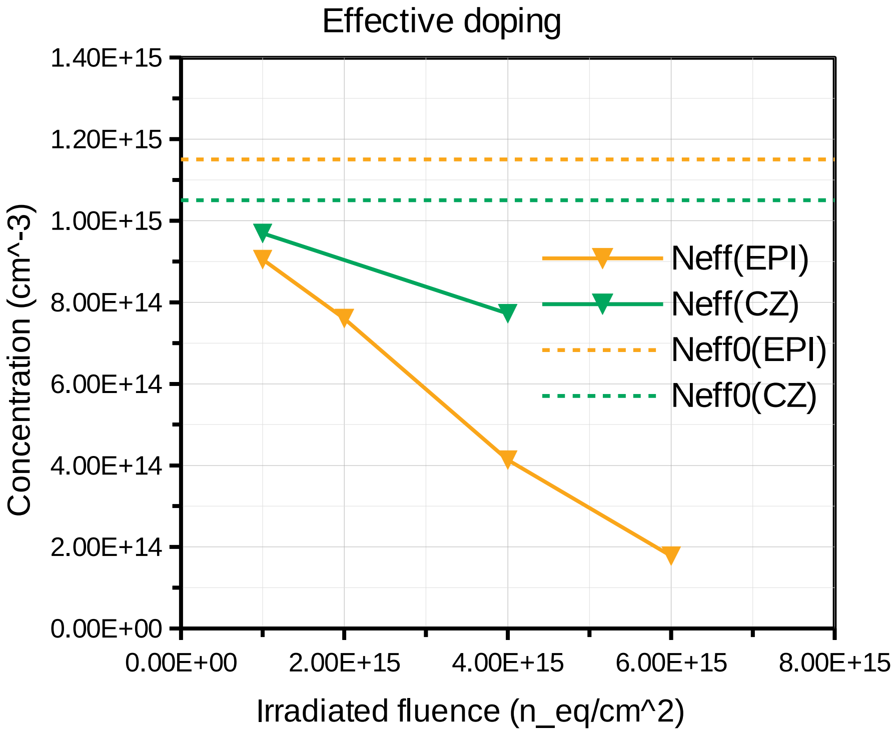


example of calculated TSC peak

[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.

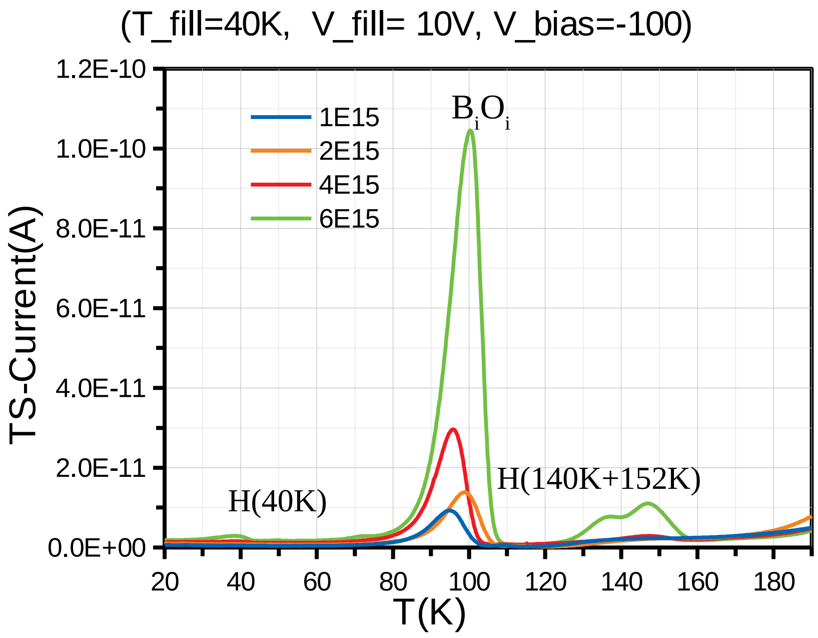
N_{eff} profile (10 Ωcm, as-irrad)



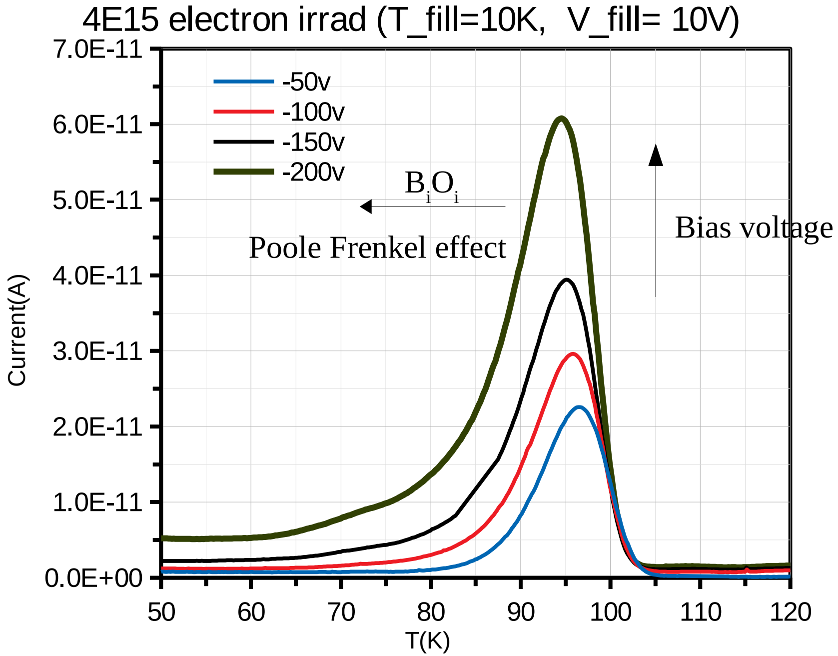


Doping profile for CZ and EPI diodes with fluence 1E15 and 4E15 e/cm^{-2}. (left figure)
Figure on the right: Decreases of the N_{eff} is smaller for CZ diodes compared to EPI devices (If edge effects can be ignored)

Example of TSC on BiOi (10 Ωcm, as-irrad)



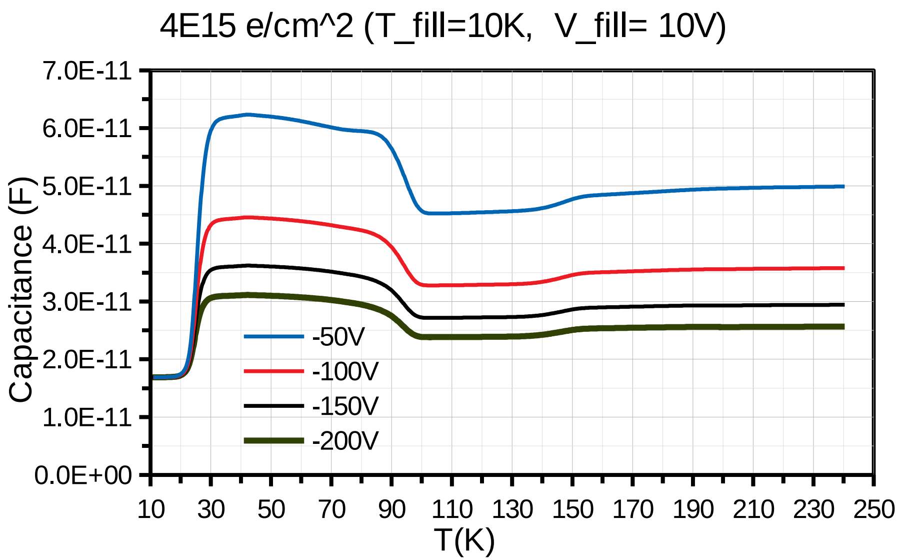
TSC spectra for diodes with different irradiation fluence

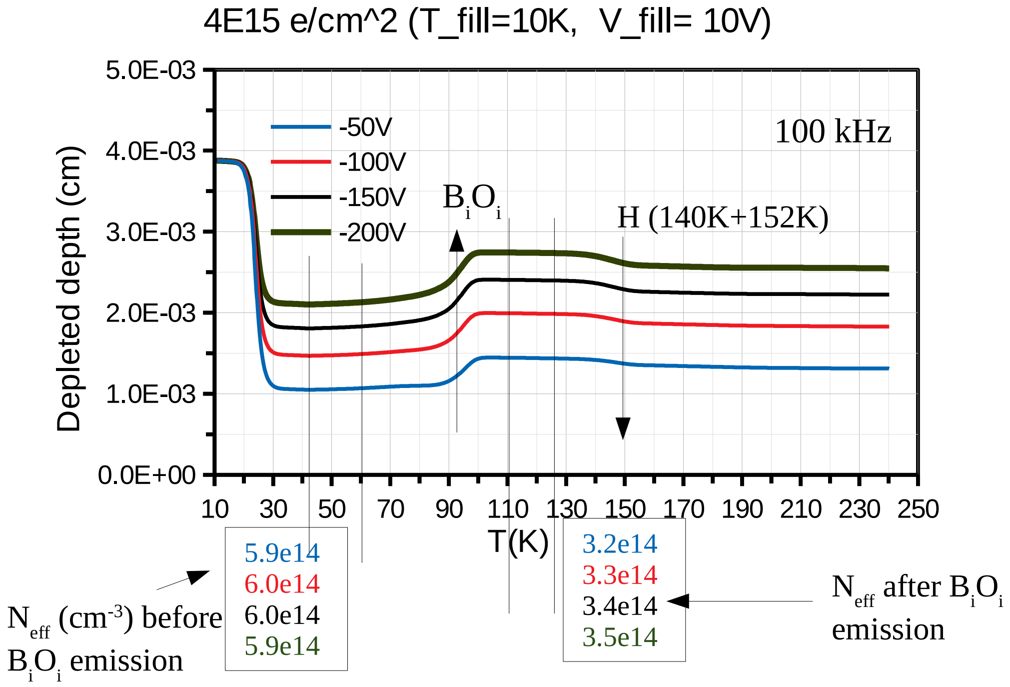


TSC spectra for different reverse bias heating up

- Dominant B_iO_i signal, which depends on the fluence.
- Shift 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

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

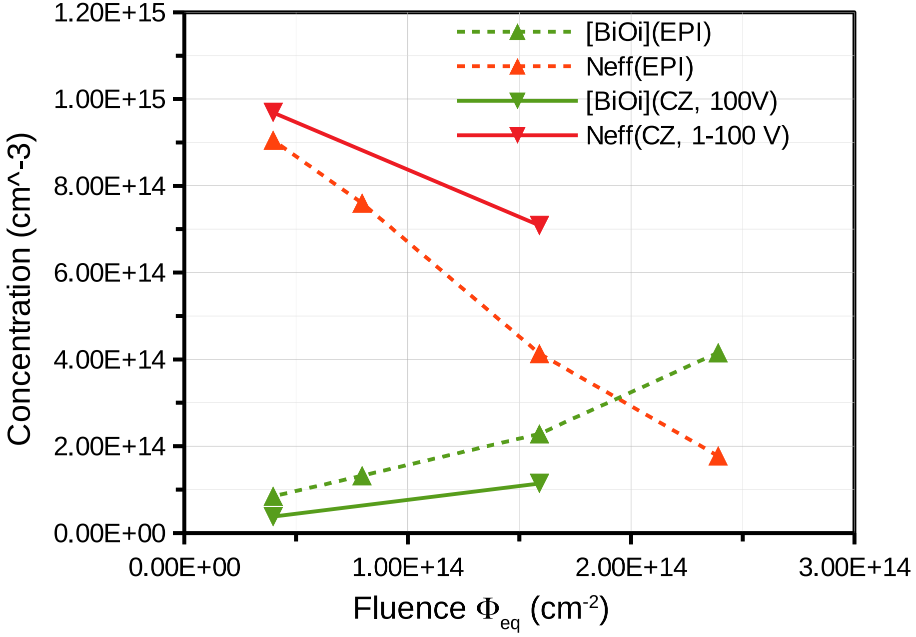




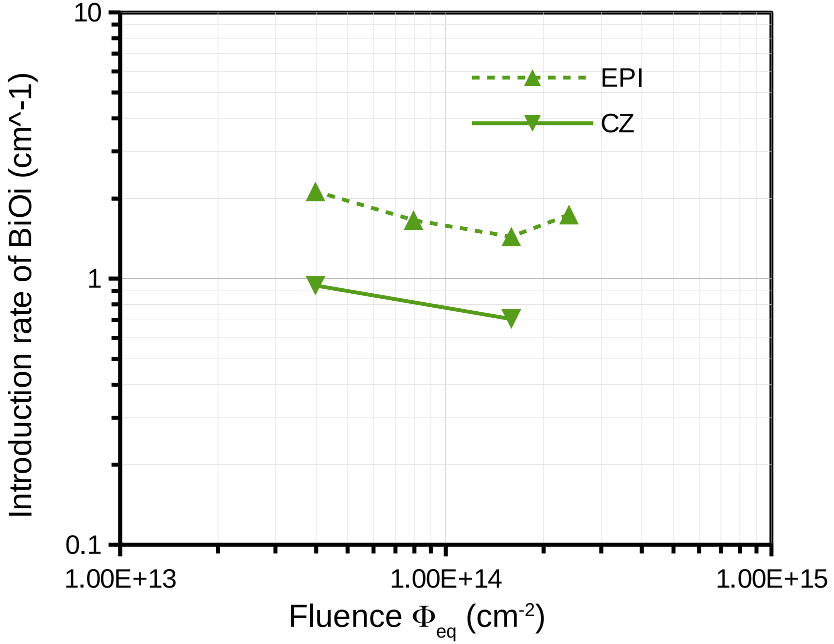
- Depleted depth was extracted from TS-cap with $d = \varepsilon_{si}\varepsilon_0 A/C$
- The shift of B_iO_i peak temperature versus V_{bias} can also be observed in TS-Cap measurement
- Freeze-out of free charge carriers for T < 30 K
- Effective doping concentration can be extracted only if the diode is not fully depleted

Defect concentration and introduction rate (as-irrad)

Defect concentration



Introduction rate



- B_iO_i concentration of 1e15 diode and 2e15 diode are given by integration with constant depletion depth (w, which is given by C-V measurment) from 80 K to 110 K
- Defect concentration of 4e15 diode and 6e15 diode are given by the eq.(1) and sum from 80 K to 110 K.
- Effective doping (N_{eff}) is extracted from doping profile

$$N_t(V)=\sum_i \frac{2Q_i}{q_0 A w(T_i)} \quad (1)$$

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

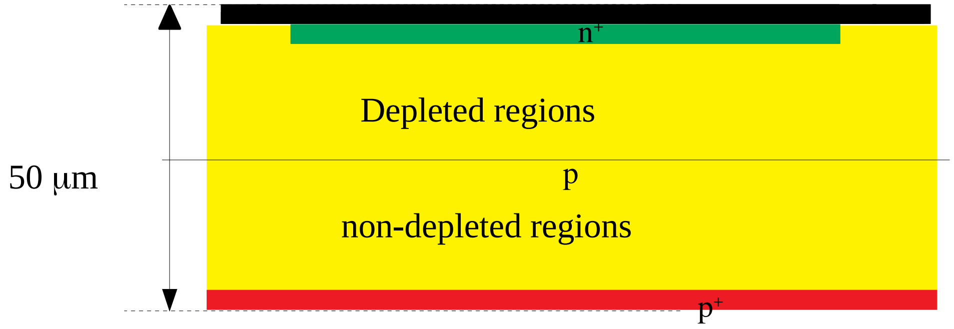
$$e_n=\sigma_n v_{th,n} N_c\times\exp(\frac{-Ea_0}{K_b T})[(\frac{1}{\gamma^2})(e^{\gamma}(\gamma-1)+1)+\frac{1}{2}]$$

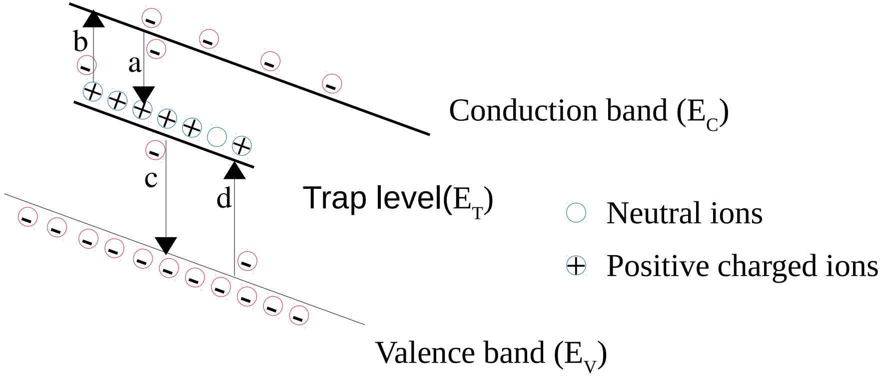
TS-Capacitance:

$$C=\frac{\varepsilon\varepsilon_0 A}{d(T)}$$

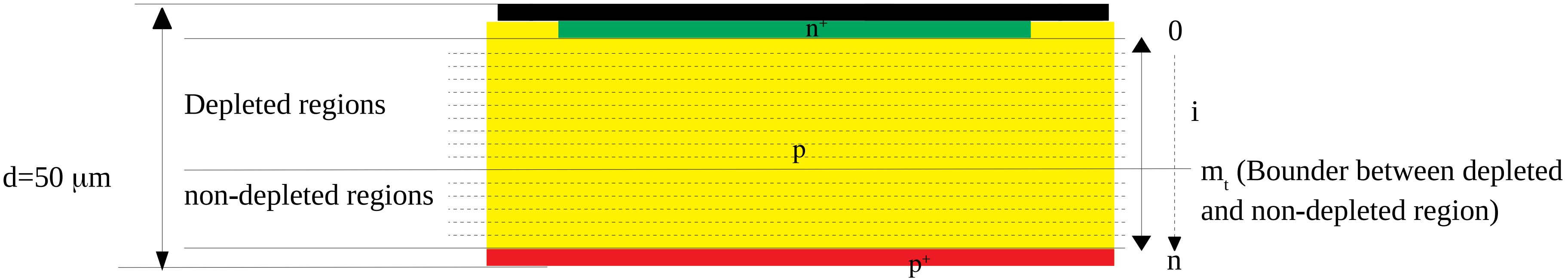
TS-Current:

$$I_{tsc}=q_0 A N_t\int_0^{d(T)} e_n f(T)\frac{d(T)-x}{d(T)}dx$$





Finite element (Basic principle)



Occupation fraction:

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

Simplification (t = index for temperature T_t(K) in the region of interest, i stands for position):

Poisson equation ($i<m_t$):

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

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

Effective doping during emission:

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

N_t is defect concentration

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

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

σ_n is capture cross section; $v_{th,n}$ is thermal velocity of electron; N_C is state density on conduction band; E_{a0} is zero field activation energy; k_B is Boltzmann constant

Simulation procedure (Matrix)

During emission 1 (example, t = 1) :

Emission ($\gamma_{i,0}=(qE_{i,0}/\pi\varepsilon_0\varepsilon_r)^{1/2}q/(k_BT_0)$):

$$e_{n,i,1}=\sigma_n v_{th,n} N_c \times \exp\left(\frac{-E_{a0}}{k_B T_0}\right)\left[\left(\frac{1}{\gamma_{i,0}^{2}}\right)\left(e^{\gamma_{i,0}}(\gamma_{i,0}-1)+1\right)+\frac{1}{2}\right]$$

$$f_{i,1}=\exp(-(e_{n,i,0}+e_{n,i,1}))$$

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

$$V=\left(\sum_{0}^{m_1} i\cdot\left(\frac{q_0 Neff_{i,1}}{\varepsilon\varepsilon_0}\cdot\frac{d}{n}\right)\right)\cdot\frac{d}{n}$$

$$E_{i,1}=\sum_{0}^{m_1}\frac{q_0 Neff_{i,1}}{\varepsilon\varepsilon_0}\cdot\frac{d}{n}-\sum_{0}^{i}\frac{q_0 Neff_{j,1}}{\varepsilon\varepsilon_0}\cdot\frac{d}{n}$$

m_t:

0 ....t

m_0			

Electric field ($E_{i,t}$):

0 .... j ....t

n ..... i 0

0	0		
$E_{0,0}$	$\Sigma q_0 Neff_{i,1} d/(\varepsilon\varepsilon_0 n)$		
$E_{1,0}$	$\Sigma q_0 Neff_{i,1} d/(\varepsilon\varepsilon_0 n)$ - $q_0 Neff_{1,0} d_0/\varepsilon\varepsilon_0 n$		

Emission rate:

0 ....t

n ..... i 0

0	$en_{0,1}$		
0	$en_{1,1}$		
0	$en_{2,1}$		

Occupation fraction:

0 ....t

n ..... i 0

1	$\exp(-(en_{0,0}+en_{0,1}))$		
1	$\exp(-(en_{1,0}+en_{1,1}))$		
1	$\exp(-(en_{2,0}+en_{2,1}))$		

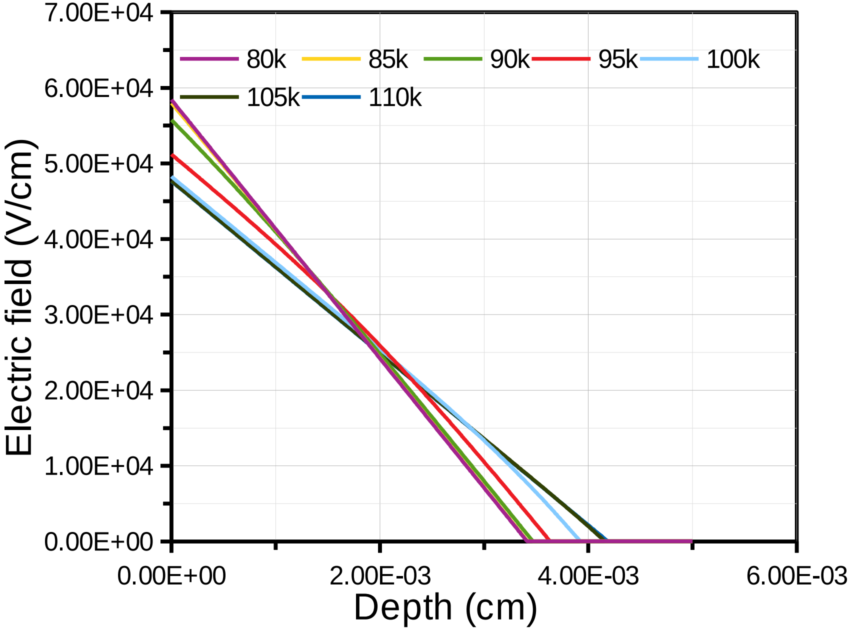
Effective doping ($Neff_{i,t}$):

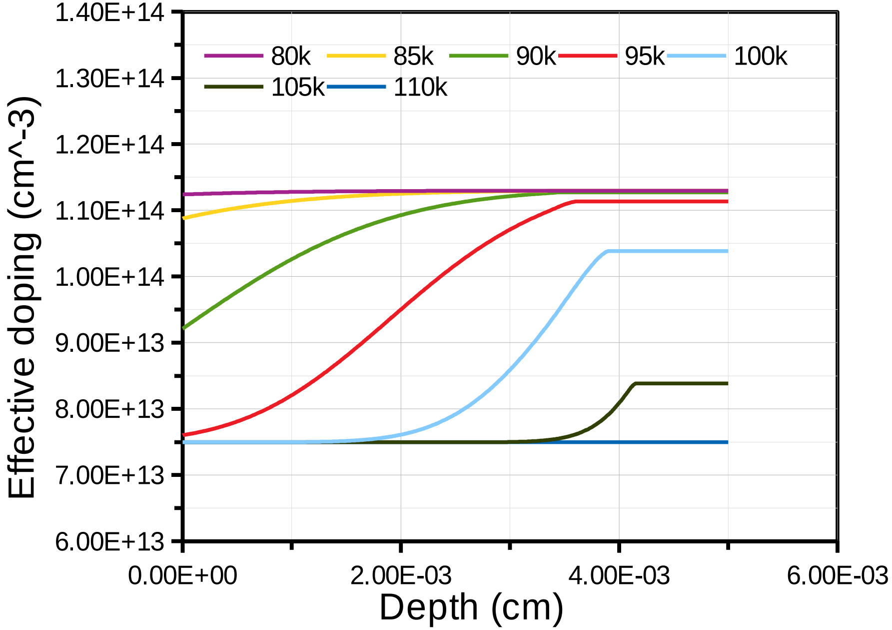
0 ....t

n ..... i 0

1.12964E14	$Neff_{0,1}$		
1.12964E14	$Neff_{1,1}$		
1.12964E14	$Neff_{2,1}$		

Electric field and Doping profile for V_{bias}=-100V



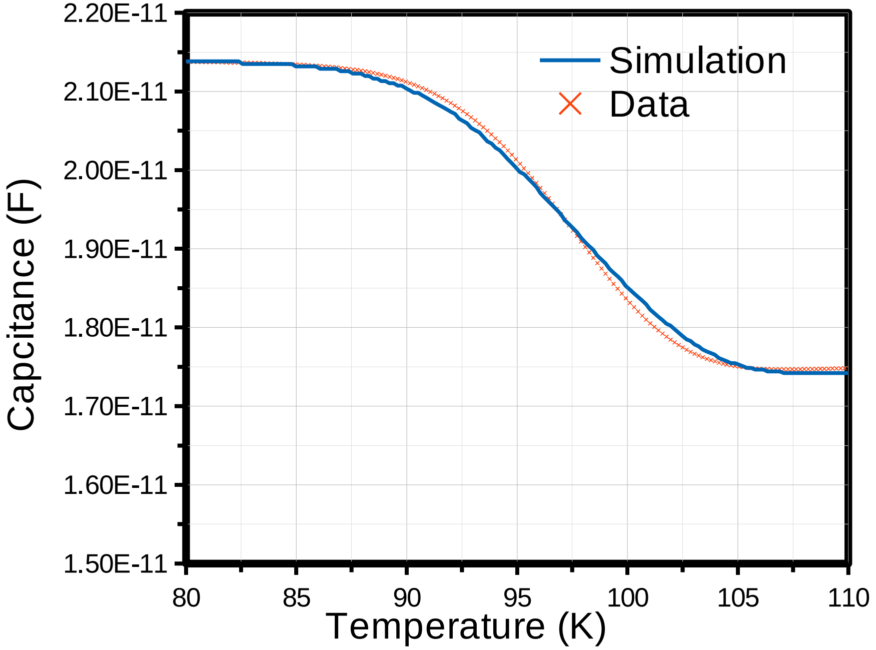


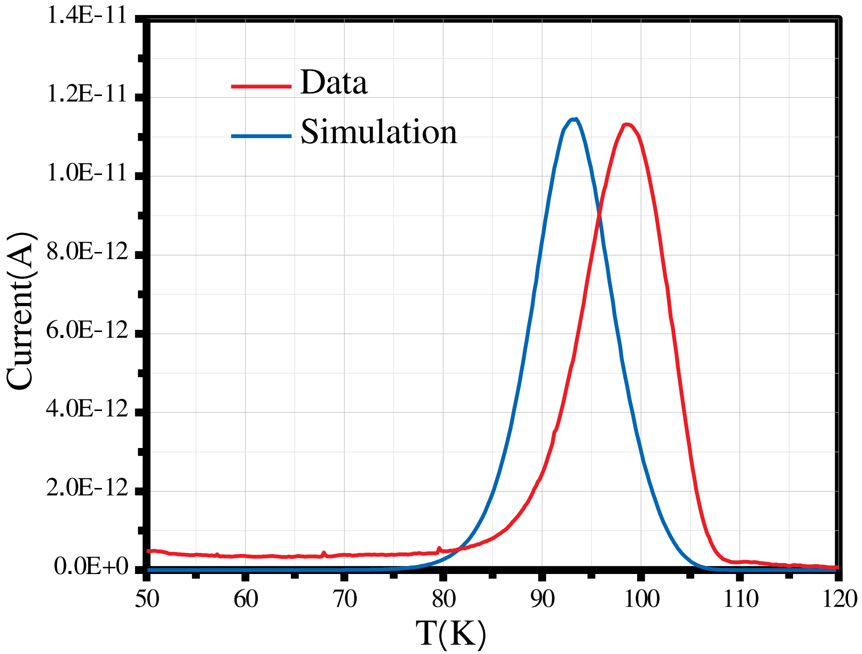
The distribution of electric field and doping profile for different temperatures. During B_iO_i emission, the changes of electric field and doping profile is observed.

BiOi defect information:

σ_0 = 1e-14 cm^2, Ea0 = 0.269 eV, N_t = 3.8e+13 cm^{-3}, $N_{eff,0}$ = 1.13e+14 cm^{-3}

TS-Cap and TSC simulated and compared with data





Comparison of simulation and data for TS-Cap (left) and TSC spectrum (right). Possible reasons for the difference between simulation and data:

- Effect of non-depleted region

Summary

I. Results for ~10 Ωcm diodes irradiated by 6 MeV electron with fluence (1e15 e/cm^2, 2e15 e/cm^2, 4e15 e/cm^2 and 6e15 e/cm^2):

a). Macroscopic measurement (C-V):

- Effective doping decreases as fluence increases

b). Microscopic measurement (TSC, TS-Cap):

- B_iO_i peak on TSC spectra: 3-D Poole Frenkel effect (shift with bias voltage)
- B_iO_i concentration proportional to irradiated fluence
- B_iO_i introduction rate (g_{BiOi}) is nearly the same for the different fluence values
- Different B_iO_i concentration extracted from TSC and TS-Cap

c). The comparison of CZ and EPI diodes:

- Cz material shows smaller decrease of N_{eff} and lower BiOi concentration compared to EPI material for the same fluence

II. Results of simulation:

- Considering the Poole Frenkel effect, the changes of electric field and doping profile has been simulated
- The simulated TS-Cap values agree quite well with the experimental data. The small differences between simulation and experiment might due to an effect from non-depleted region
- The difference between the simulated and measured TSC spectrum is quite large. This finding has to be investigated further in more detail.

[1] C. Liao 37th RD50 Workshop, Nov 2020, Zagreb.