TSC measurements in the frame of acceptor removal project

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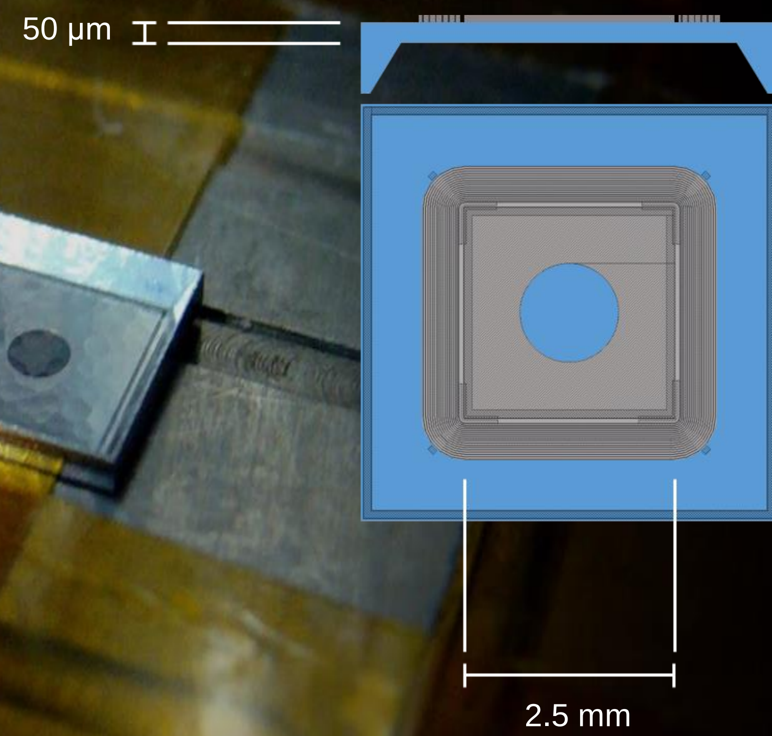
Outline

- Materials and devices
- Principle of TSC spectroscopy
- TSC setup modification
- First TSC results
- Impact of B_iO_i defect on N_{eff}
- Summary and outlook

Materials and Devices

Simple p-type Si pad diodes



Epitaxial

10 Ω·cm
50 Ω·cm
250 Ω·cm
1000 Ω·cm

Proton irradiation

1.30E14 [p/cm^2] ⟷ 7.80E+13 [n_{eq}/cm^2]

5.54E14 [p/cm^2] ⟷ 3.32E+14 [n_{eq}/cm^2]

Annealing

10 min @ 60°C

CERN IRRAD Proton Facility

CiS Forschungsinstitut für Mikrosensorik GmbH

Experimental procedure

See presentation of Pedro Almeida

CV/IV/TCT

macroscopic

- before and after irradiation
- during **isothermal annealing**

- **IV/CV :** reverse bias condition, T= -20°C (1000 Hz)

- **TCT :** reverse bias condition, at three temperatures: T= -20°C, T= -10°C, T= 0°C

Diode properties
- V_{dep}, leakage current, N_{eff}…

TSC
(Thermally Stimulated Current spectroscopy)

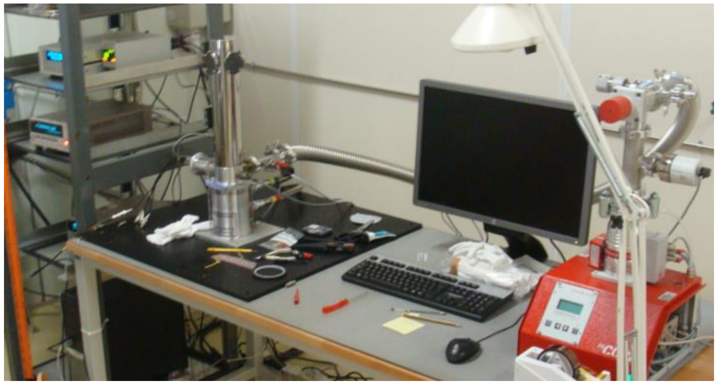
microscopic

1. **cooling**: reverse bias conditions
2. **injection**: T=20K, forward bias
3. **recording** of TSC signal, reverse bias, T↑, β = 11 K/min

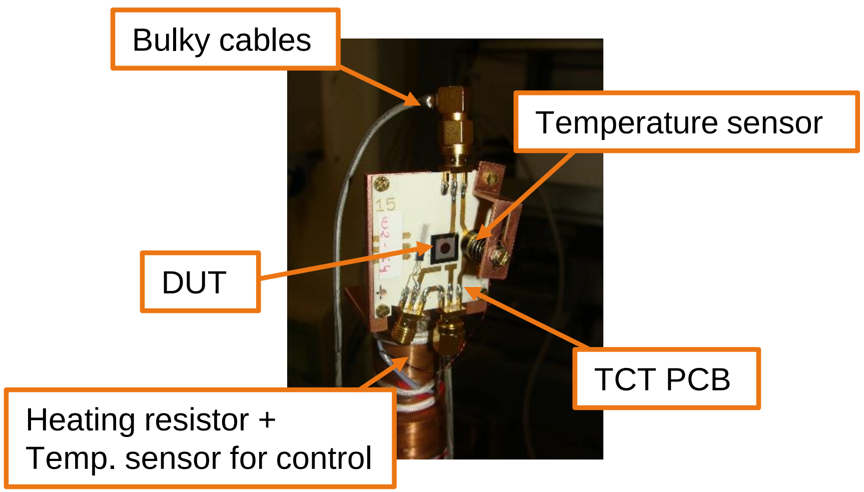
Defect properties (and impact)
- E_a, $\sigma_{n,p}$, N_c…

defects with an impact on the macroscopic diode parameters ⟶ TCAD simulations

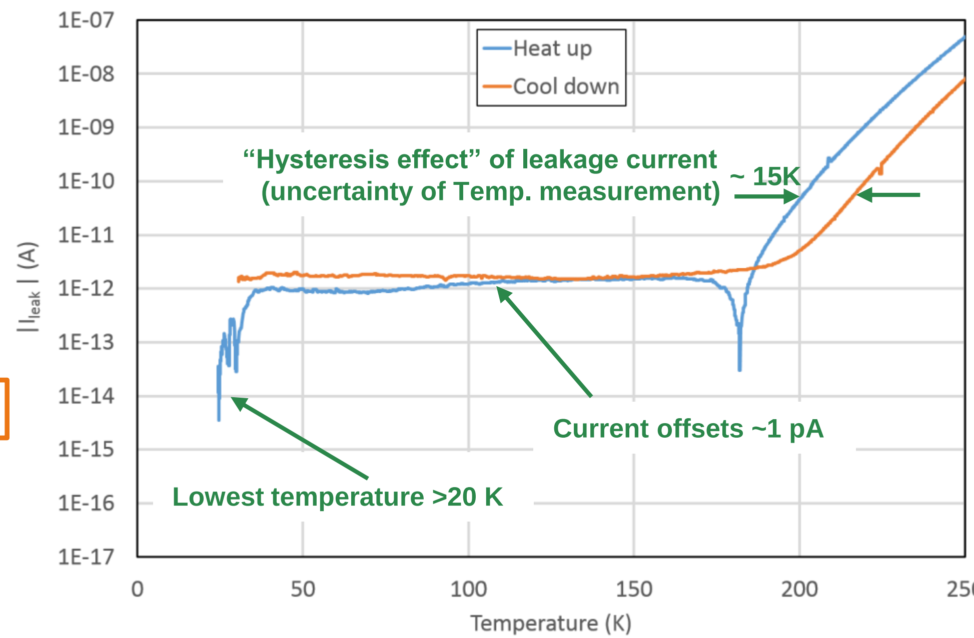
TSC setup



TSC workstation

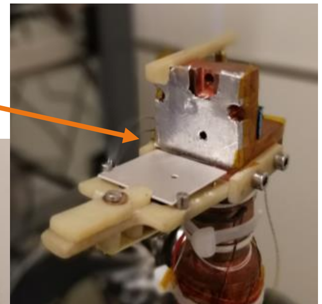


Old sample-holder (2016, not optimized for TSC)

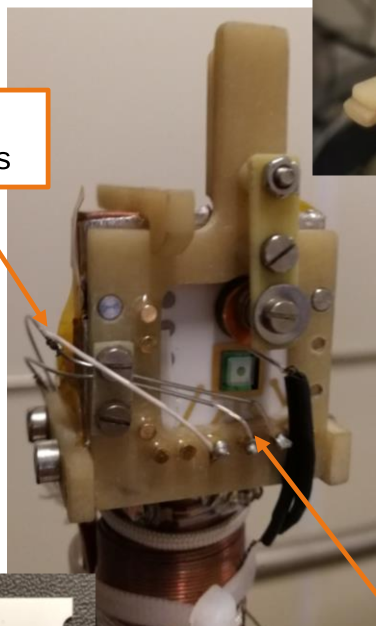


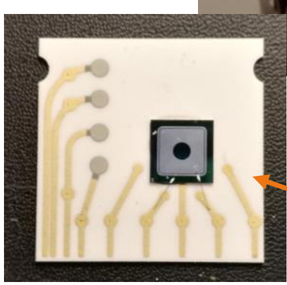
TSC setup optimization

Easy system to change samples



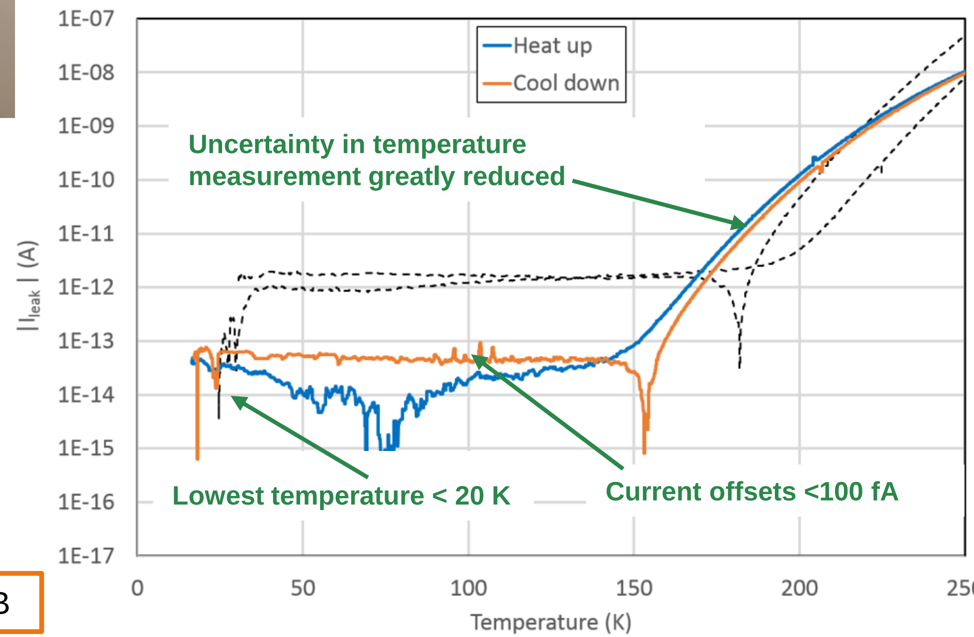
Lightweight coaxial cables





Spring loaded contacts to PCB

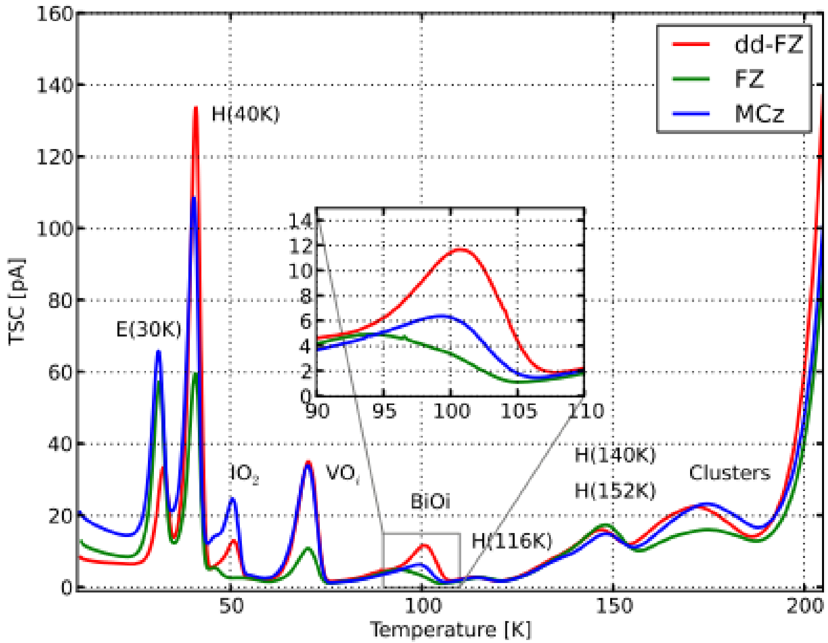
New ceramic PCB for better thermal conductivity
(No connectors to reduce thermal mass)



New TSC sample holder (inspired by the Hamburg concept / Design by Robert Loos (CERN))

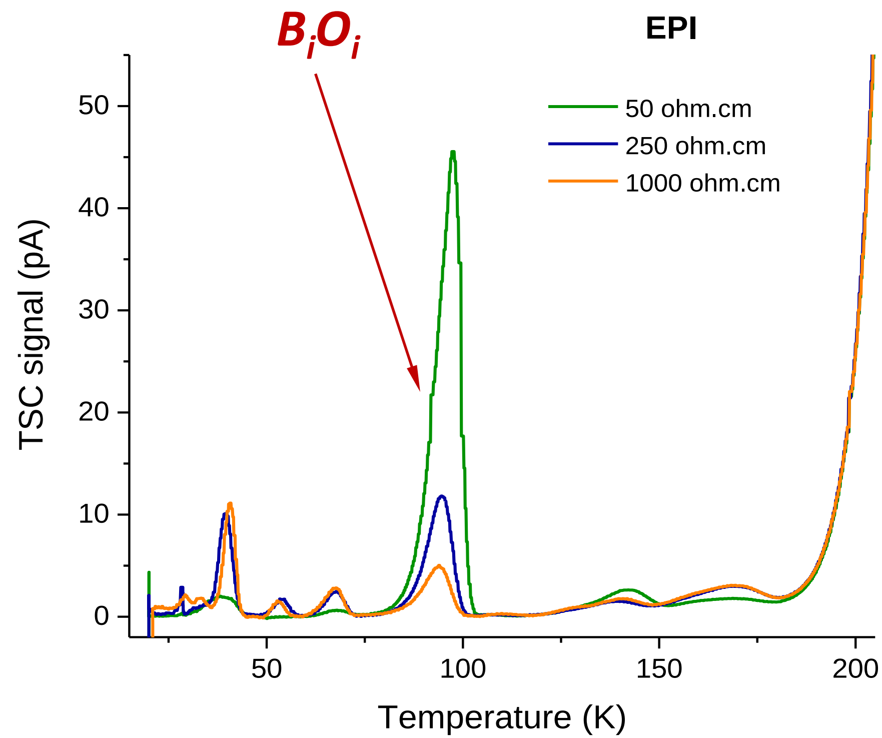
Standard TSC scans

- E. M. Donegani, E. Fretwurst, E. Garutti, University of Hamburg, Germany, *RADECS 2016*



200 µm, Φ_{neq} =0.5·10[14] cm[−2], 8 minutes @ 80°C annealing

- our preliminary results for fully-depleted diodes

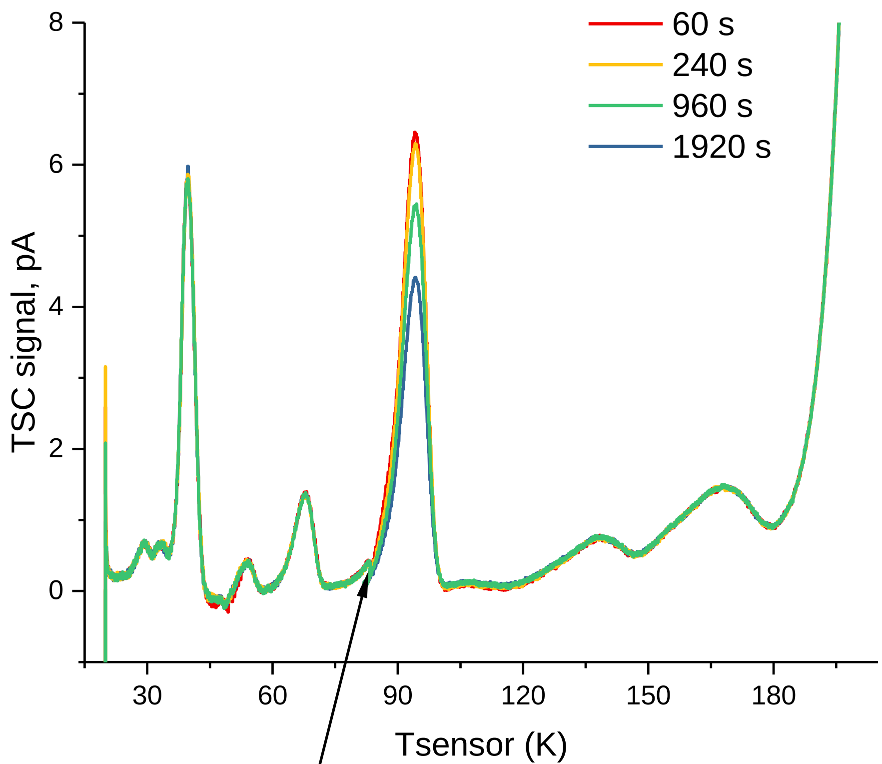


50 µm, Φ_{neq} = 7.80 · 10[13] cm[-2], 10 min @ 60°C annealing

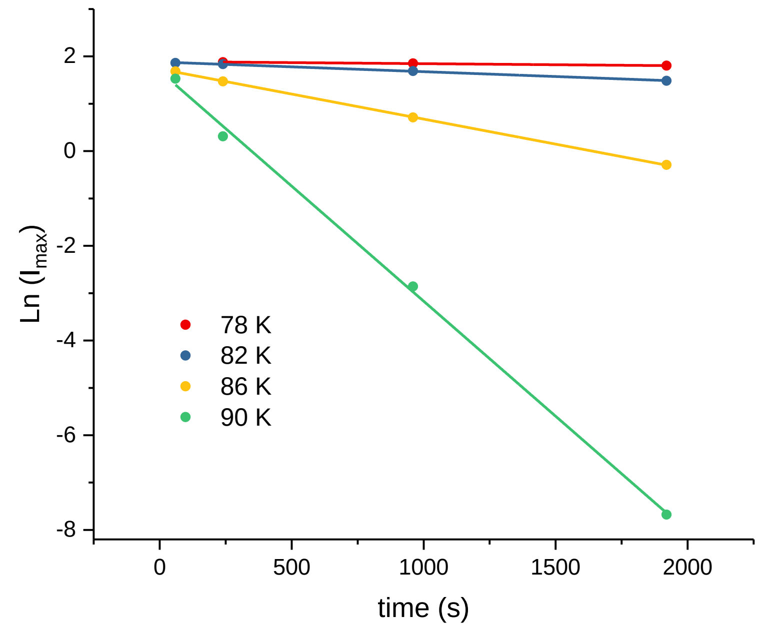
TSC. Delayed Heating Method

$$I_{peak}(t_d) = I_{peak}(0)\exp\left(-\frac{t_d}{\tau_e}\right), \qquad \tau_e = \frac{1}{\sigma v_{th} N_c} \exp\left(\frac{E_t}{k_B T_i}\right)$$

t_d – de-excitation time (delay time)



Delay at T_i=78 K



Slope = τ_e at different delay T (78, 82, 86 and 90K)

4 (τ_e, T_i) pairs

Sensor: CIS16-EPI-08-50-DS-93

$\Phi = 7.80 \cdot 10^{13}\ n_{eq}/cm^2$

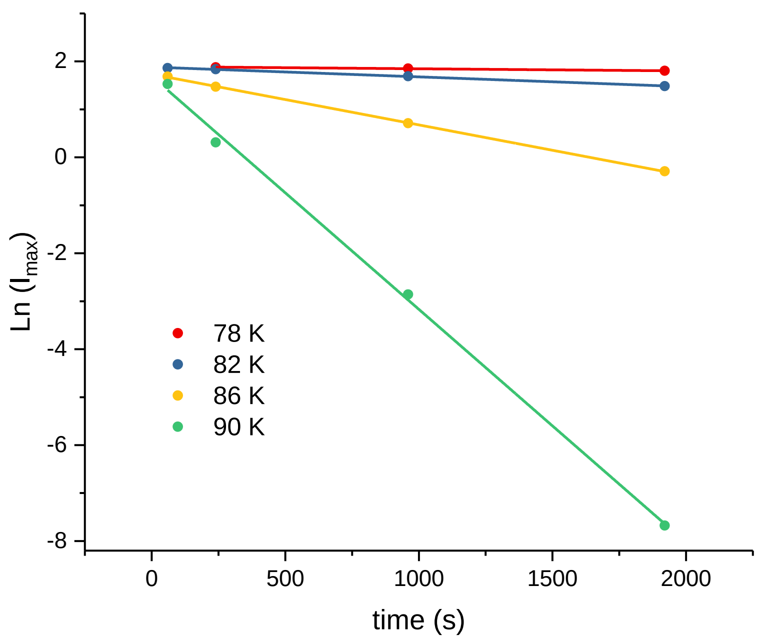
$\rho = 250\ \Omega$ cm

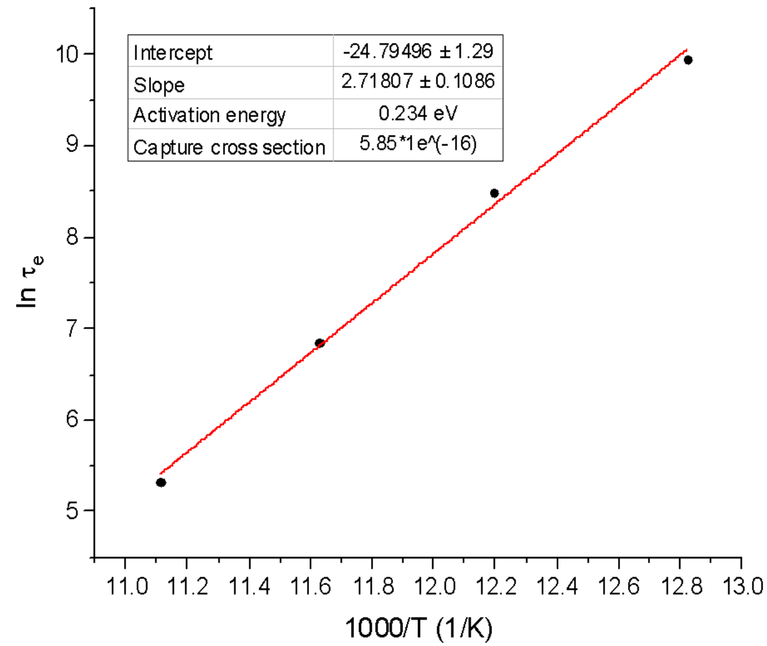
annealing = 10 min @ 60°C

TSC. Delayed Heating Method

$$I_{peak}(t_d) = I_{peak}(0)\exp\left(-\frac{t_d}{\tau_e}\right),\ \tau_e = \frac{1}{\sigma v_{th} N_c} - \exp\left(\frac{E_t}{k_B T_i}\right)$$

t_d – de-excitation time (delay time)





Slope = τ_e at different delay T
(78, 82, 86 and 90K)

4 (τ_e,T_i) pairs ⟹ **(E_a,σ)**

Sensor: CIS16-EPI-08-50-DS-93

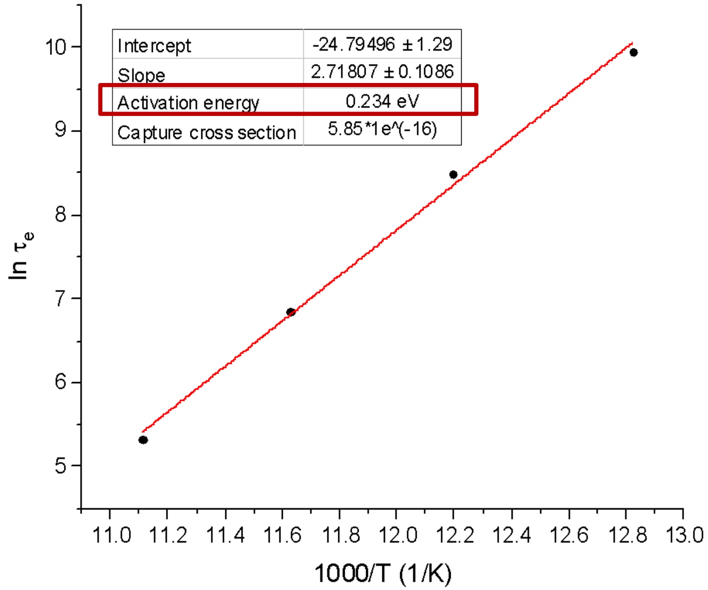
$\Phi = 7.80 \cdot 10^{13}\ n_{eq}/cm^2$

$\rho = 250\ \Omega$ cm

annealing = 10 min @ 60°C

TSC results vs Literature

Defect	Emission parameters: E_a(eV), σ (cm^2), T_{TSC} (K),T_{DLTS} (K)	Reference
B_iO_i	-0.23	L. C. Kimerling et al., "Interstitial Defect Reactions in Silicon", Materials Science Forum, Vols. 38-41, pp. 141-150, 1989
B_iO_i	-0.25	P. M. Mooney, L. J. Cheng, M. Süli, J. D. Gerson, and J. W. Corbett Phys. Rev. B 15, 3836, 1977
B_iO_i	-0.24,4E-15, 98, 118	Trauwaert, Radiation and Impurity Related Deep Levels in Si, PhD thesis, IMEC-KUL, Leuven, 1995
B_iO_i	-0.27, 3E-13, 96, 113	Schmidt, J., Berge, C., Aberle, G., Appl. Phys. Lett. 73, 2167, 1998



B_iO_i – donor level at about E_c-0.23 eV, stable at RT; begins to anneal around 150°C

Sensor: CIS16-EPI-12-50-DS-93

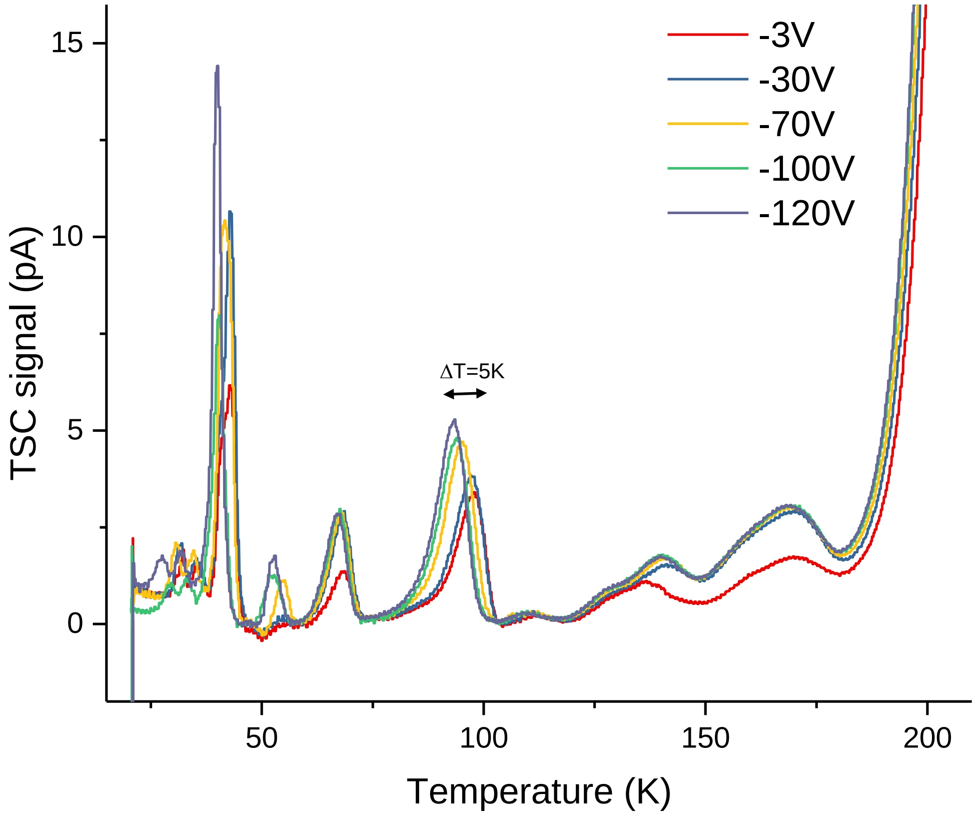
$\Phi = 7.80 \cdot 10^{13}\ n_{eq}/cm^2$

$\rho = 1000\ \Omega$ cm

annealing = 10 min @ 60°C

TSC. Poole-Frenkel Effect

- is a characteristic of coulombic wells
- seen for electric fields 10^3-10^6 V/cm
- in TSC doesn't give a clear indication of the charge state of defect



PF observed for the peak at 98K

defect charged after carrier emission

In line with identification of [B_iO_i]

$\bar{e}$ and *h* injection by red light illumination from back and front sides is planned to be performed

TSC. Defect Concentration

Sensor: CIS16-EPI-08-50-DS-93

$\Phi = 7.80 \cdot 10^{13}\ n_{eq}/cm^2$

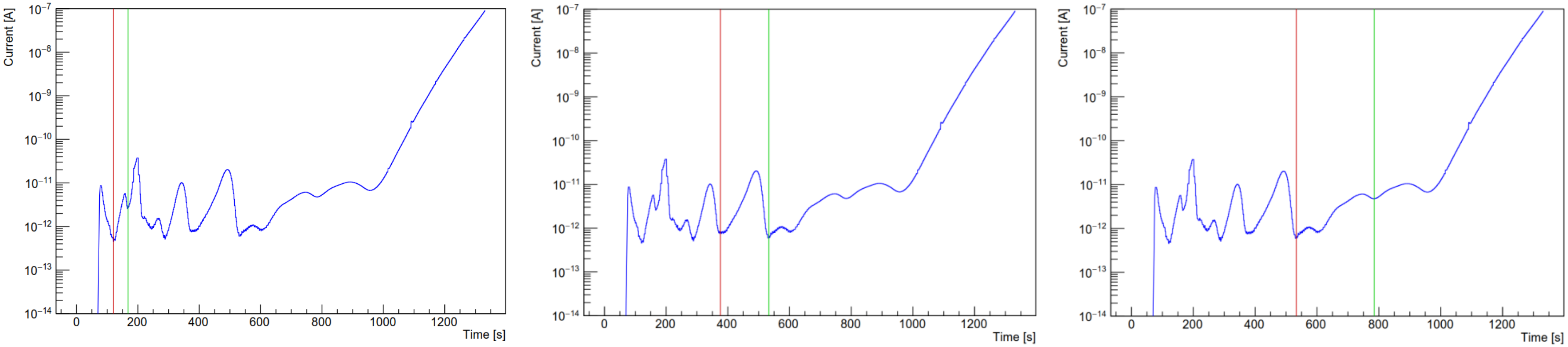
$\rho = 250\ \Omega$ cm

annealing = 10 min @ 60°C

Preliminary results

Integration over the observed TSC peak in time allows us to calculate the defect concentration:

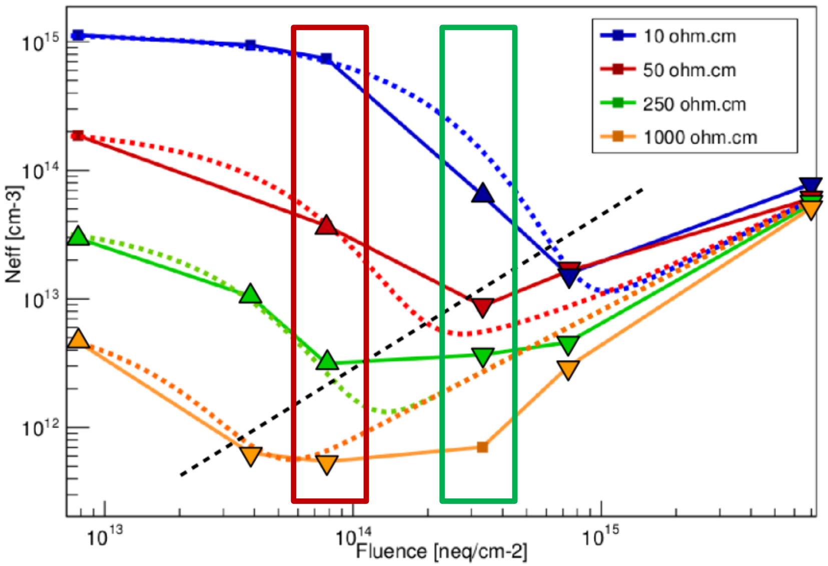
$$Q_t = \int I_{TSC}(t).dt \qquad n_{t,0} = 2\frac{Q_t}{q_0 AW}$$

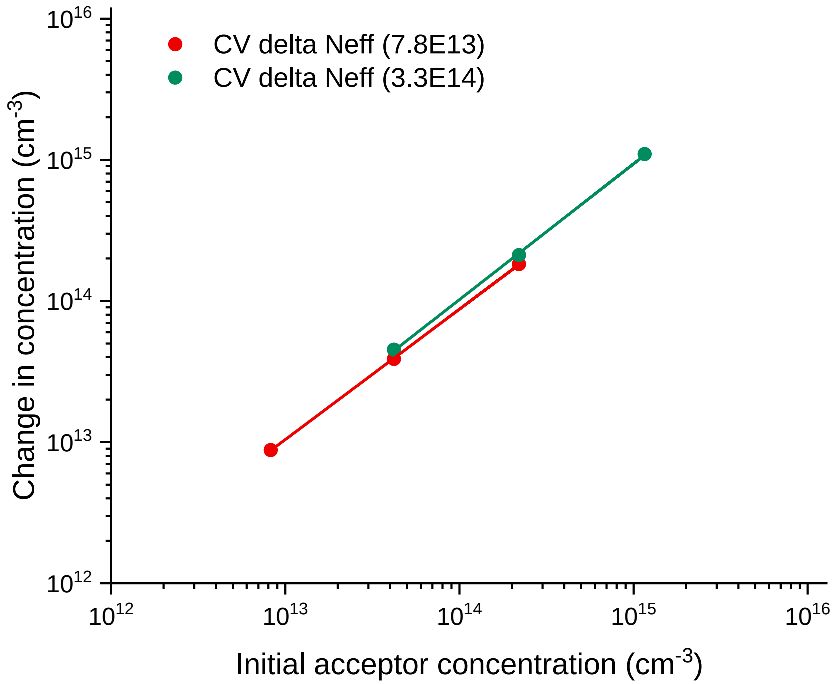


Sensor			TSC		
Name	Fluence	Resistivity	E[30]	[BiOi]	[H116+H140+H152]
EPI-05-94	7.80E+13	50		3.80E+13	1.01E+13
EPI-08-93	7.80E+13	250	9.30E+11	4.65E+11	7.09E+12
EPI-12-93	7.80E+13	1000	3.22E+12	1.61E+12	7.25E+12
EPI-01-101	3.32E+14	10	1.22E+13	6.10E+12	5.28E+13
EPI-05-98	3.32E+14	50	4.80E+12	2.40E+12	3.74E+13
EPI-08-97	3.32E+14	250	3.12E+13	1.56E+13	3.06E+13

Assuming B_iO_i is double-charged

ΔN_{eff} vs $N_{eff,0}$

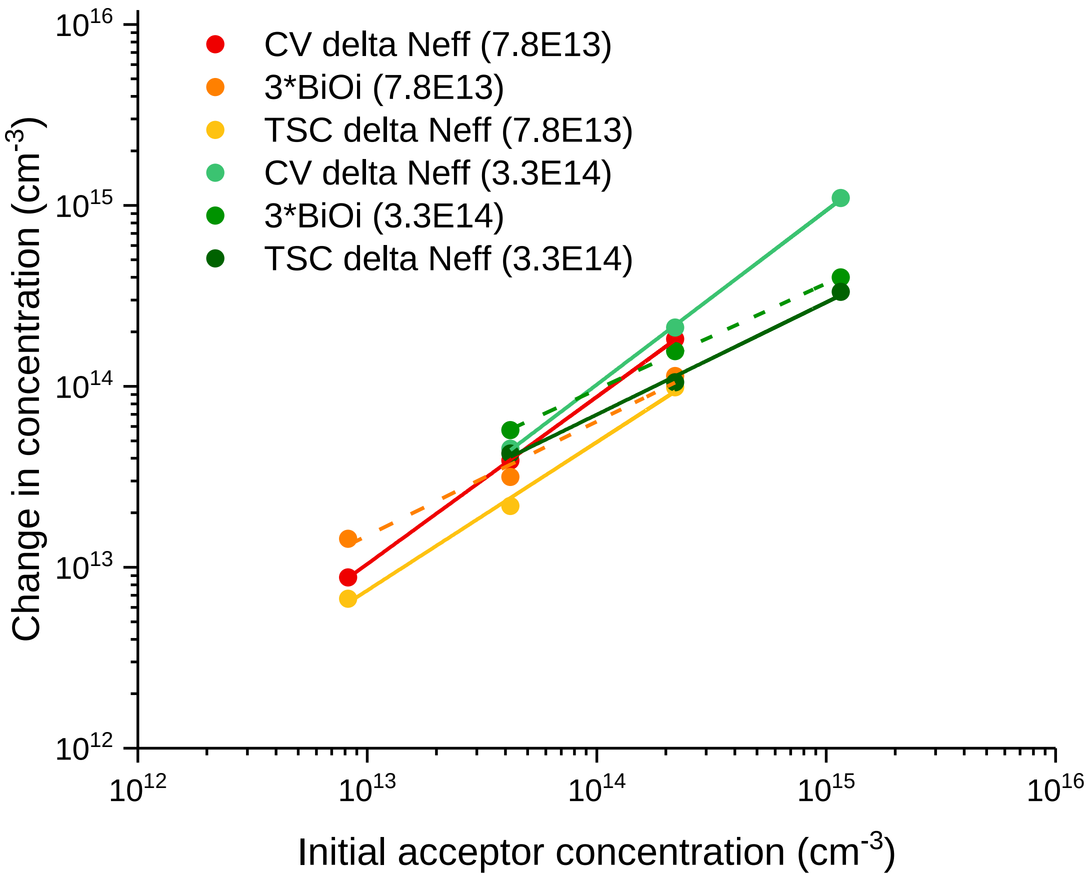




<u>Type inversion?</u>

See Pedro's presentation

Concentration of defects with impact on N_{eff} (space charge)



$$\begin{cases} I + B_s \longrightarrow B_i \\ B_i + O_i \longrightarrow B_i O_i \\ B_i + B_s \longrightarrow B_i B_s \quad \textbf{?} \end{cases}$$

$3\times B_iO_i$ +E(30)-H(116)-H(140)-H(152)

Summary and outlook

- Strong dependence between B_iO_i production and resistivity was detected
- Defects contributing to the space charge (V_{dep}, N_{eff}) were investigated with CV/IV and TSC measurements
- Impact of *E(30)* and B_iO_i, introducing “+” space charge and of three deep acceptors *H(116K)*, *H(140K)* and *H(152K*), introducing “-” space charge was taken into account
- We observed promising correlation between ΔN_{eff} extracted from CV and TSC measurements obtained for two proton fluences

- Results should be checked for other materials, higher fluences and different types of irradiation. Additional annealing study, TSC with red light illumination, determination of parameters for other observed defects should be presented to complete existing result