# Defect characterization studies and modelling of defect spectra for $^{60}$Co gamma-irradiated epitaxial p-type Si diodes

EP-DT-DD
Detector Technologies
Detector Development

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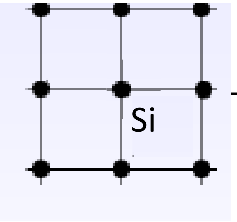
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Motivation

*Defects:*

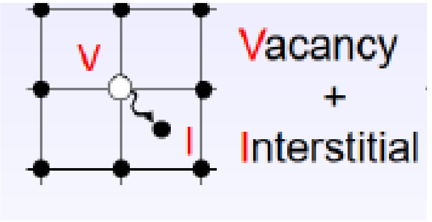
*High energy particles* →

*Si lattice*




→ ***E > 25 eV*** →

*Frenkel-pair*




*Recombination*

*Migration & formation of (stable) point & cluster defects*

*displacement damage defects*
dependent on:
**particle type**
**particle energy**
**particle fluence**

**Vacancies:**

⟹ normally low mobility at low temperatures

⟹ $V + O_i \rightarrow VO_i$ or formation of multi-vacancy-defects ($V_2$, $V_3$ …)

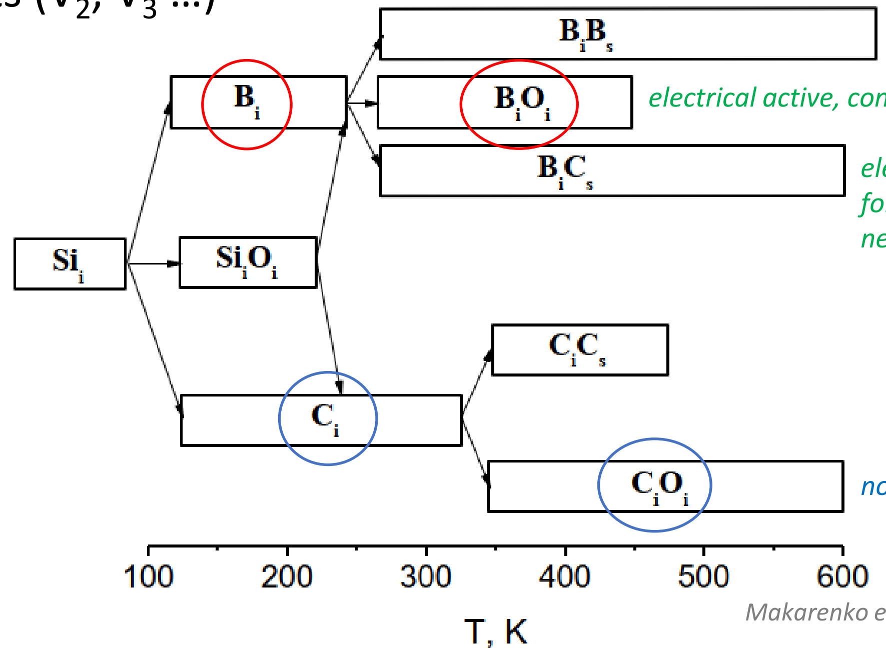
**Si-interstitials:**

⟹ very mobile even at low temperatures

⟹ interaction e.g. with impurity atoms (e.g. C, B …):

*Watkins replacement mechanism*

$$I + B_s \rightarrow Si_s + B_i$$
$$I + C_s \rightarrow Si_s + C_i$$




*not electrical active, high B content needed*

*electrical active, contributes to Neff*

*electrical active, lower formation probability due to the neutral Cs*

*no contribution to Neff*

Makarenko et al. ICDS-31, 2021

*„competition" for interstitals between C and B*
*→ increasing C content „protect" B from removal*
*→ carbon enrichment mitigates radiation damage in LGADs*

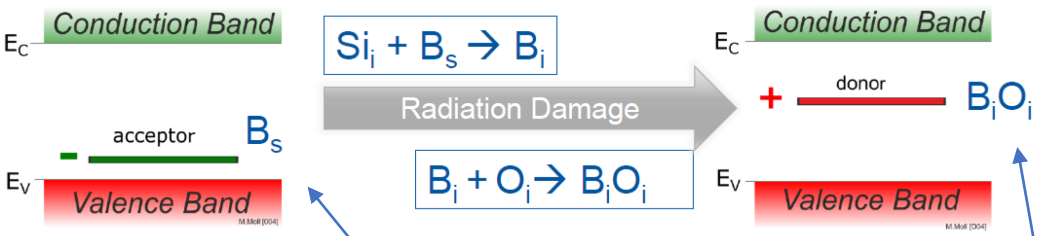
# Motivation

## Acceptor Removal Effect in B-doped silicon:

### BiOi– defect:

Moll, PoS 2019 VERTEX

- Most typical radiation induced reaction:




*induce **negative** space charge*

*induce **positive** space charge*

### $B_{Si}Si_i$ – defect:

- *B stays at its lattice place and captures a positively charged Si-interstitial that was released during irradiation*
- *in the ground state: positively charged donor*

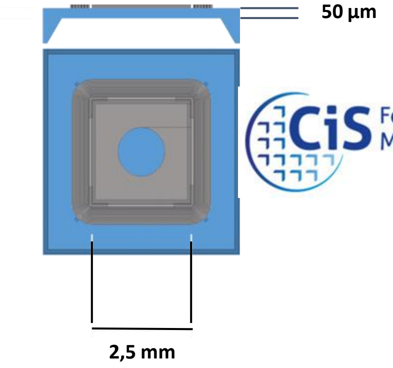
*Lauer et al. Phys. Stat. Sol. A 219 (2022)*

BiOi formation deactivated 2 active boron atoms
and should correlate with a change in Neff by a factor of 2

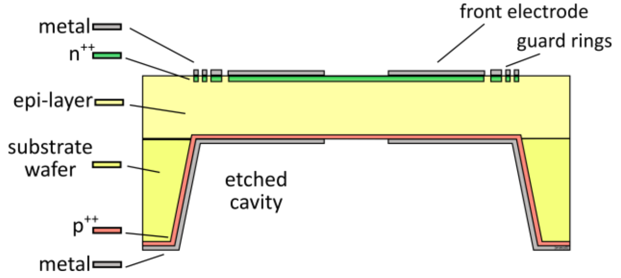
# Experimental Details

## Samples (p-type EPI diodes):

| sample | resistivity (Ωcm) | dose (Mrad) | dose (MGy) |
|---|---|---|---|
| EPI-06-DS-67 | 50 | 10 | 0.1 |
| EPI-06-DS-69 | 50 | 20 | 0.2 |
| EPI-06-DS-82 | 50 | 100 | 1 |
| EPI-06-DS-84 | 50 | 200 | 2 |
| | | | |
| EPI-10-DS-78 | 250 | 10 | 0.1 |
| EPI-10-DS-80 | 250 | 20 | 0.2 |
| EPI-10-DS-82 | 250 | 100 | 1 |
| EPI-10-DS-84 | 250 | 200 | 2 |




CiS Forschungsinstitut für Mikrosensorik GmbH




*$^{60}$Co gamma irradiation @ IRB, Zagreb* ***(100 kGy – 2 MGy)***

Institut Ruđer Bošković

# Experimental Details

## Characterization methods:

**Electrical Characterization:** C-V & I-V measurements

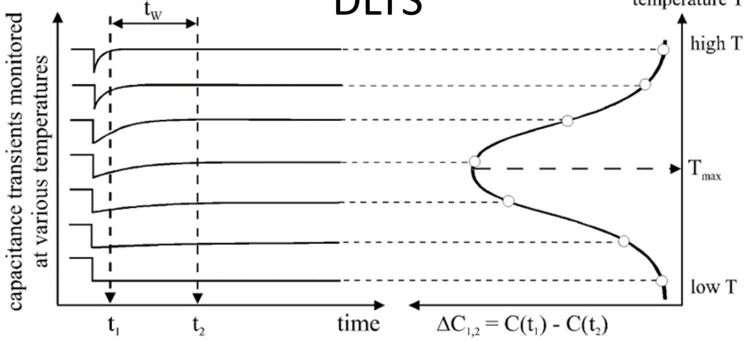
**Defect spectroscopy measurements:**

**C-DLTS: Deep Level Transient Spectroscopy**

changes in capacitance measured during the release of charge carriers from defect states

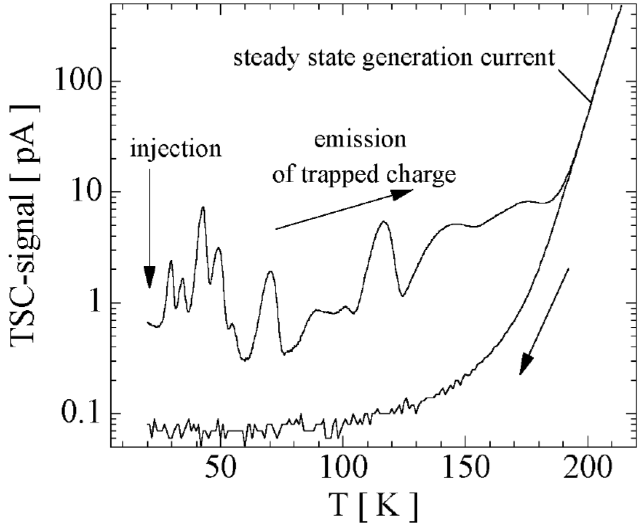
- *Thermal activation energy of defect levels*
- *Capture cross section for electrons or holes*
- *Defect concentration*

DLTS




*Moll thesis 1999*

TSC




**TSC: Thermally Stimulated Current Technique**

monitoring the discharging current due to thermal emission of charge carriers from defect levels

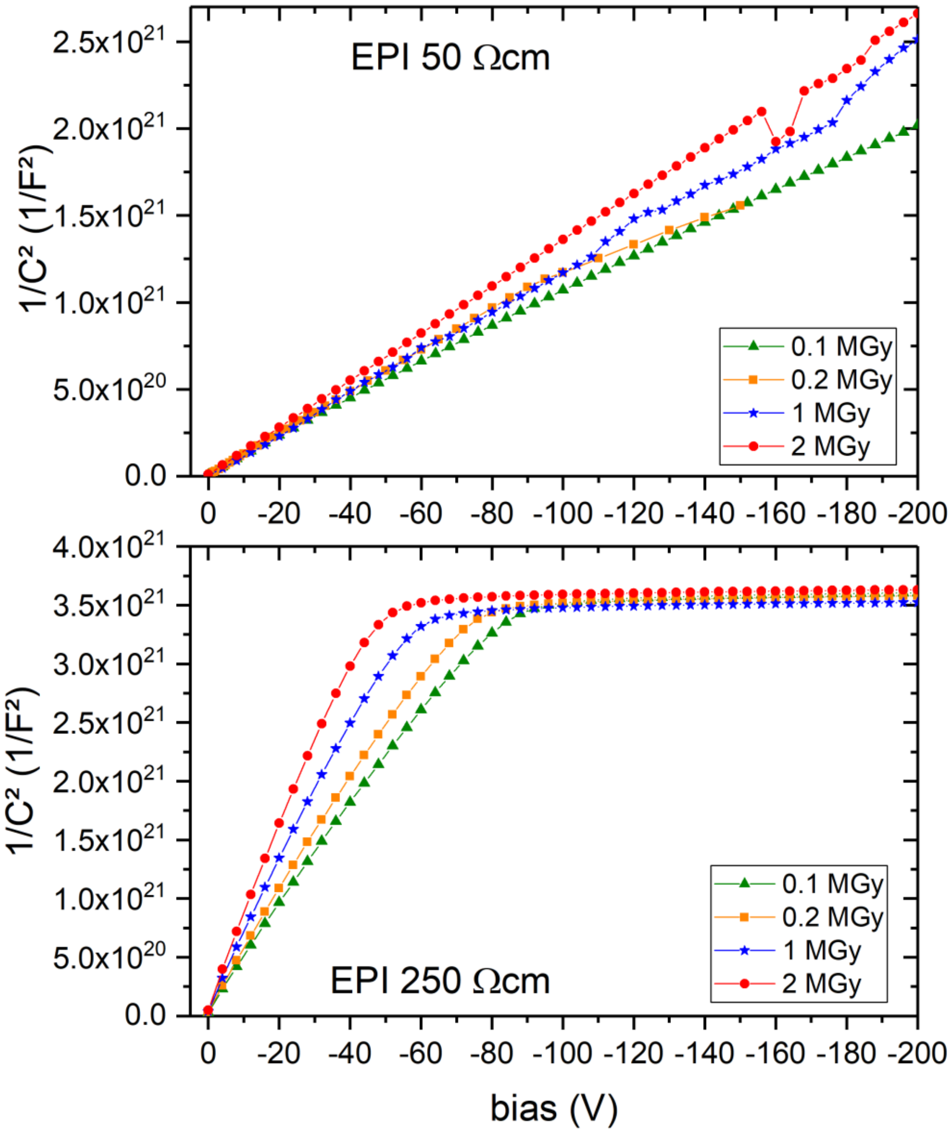
**Modelling of TSC spectra using *pytsc* (Python-based analysis software):**

$$I_{TSC}(t) = q_0 A \int_0^{W(t)} \sum_{\text{all defects}} \frac{e_n(t)n_t(t) + e_p(t)p_t(t)}{2} dx$$

*$e_n(t)$, $e_p(t)$ : emission rate for electrons/ holes*
*$n_t$, $p_t$ : defect states occupied by electrons/ holes*

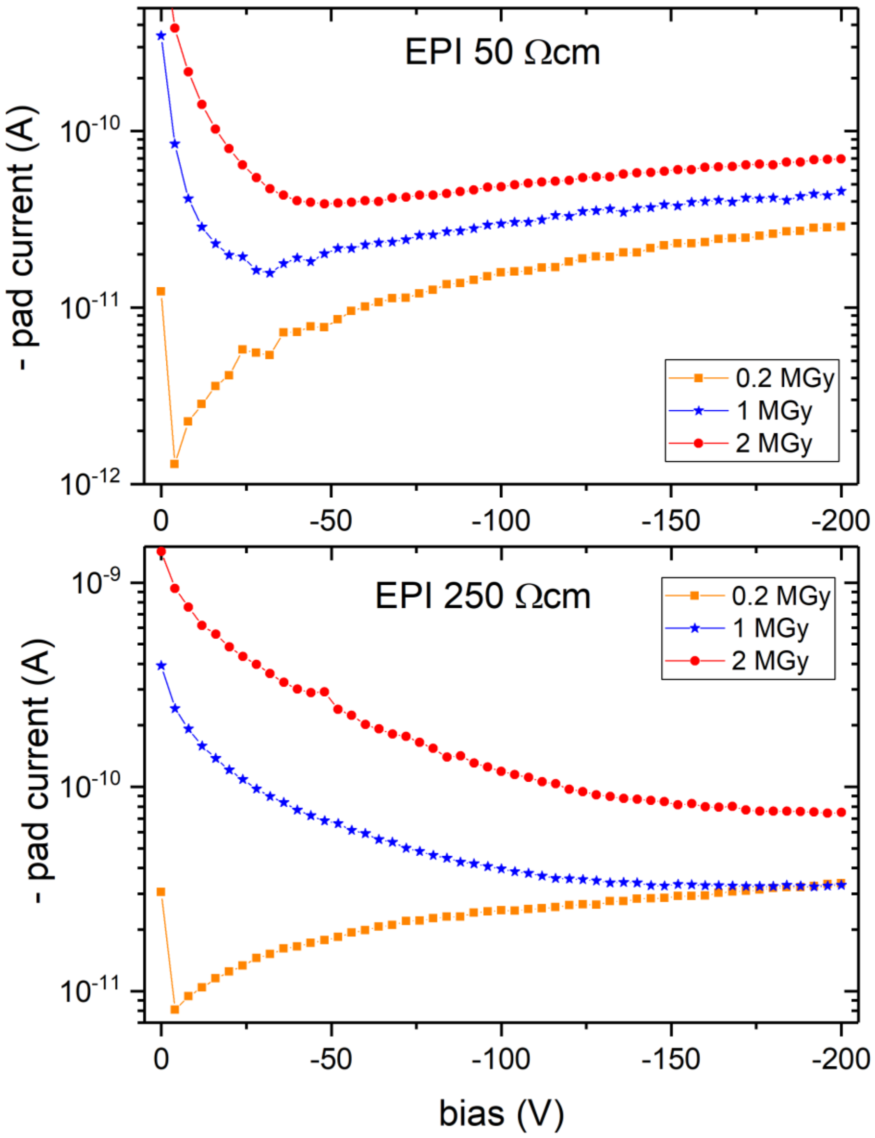
*$W(t)$ : depletion depth*
*$\beta(t) = dT/dt = const.$ : heating rate*

# Electrical characterization : C-V and I-V after irradiation




With increasing radiation dose:

- Depletion voltage decreases
- Effective doping concentration decreases
  → Deactivation of active boron
- Ileak increases (surface damage induced currents)



# DLTS measurements

- **Peak 1:**

($I_2O$ )

$E_v$+ 0.09 eV

$\sigma_p$: 2E-14 cm²

- **Peak 2:**

(vacancy related)

$E_v$+ 0.19 eV

$\sigma_p$: 4E-16 cm²

- **CiOi**

$E_v$+ 0.36 eV

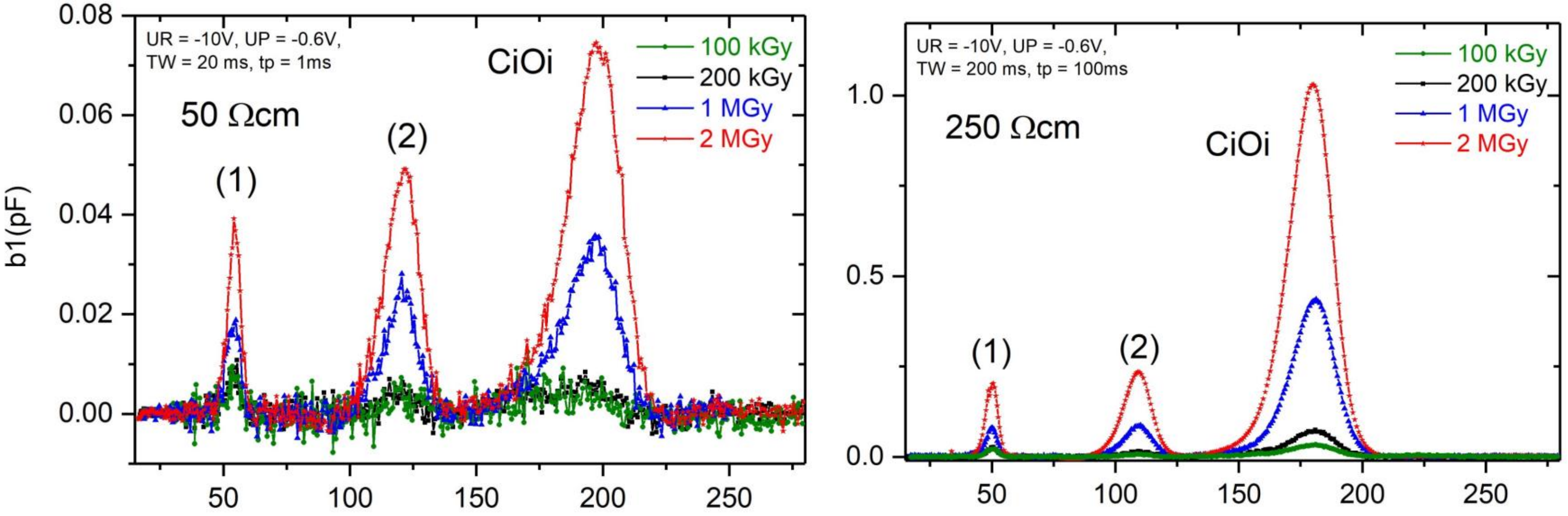
$\sigma_p$: 2E-15 cm²

- **BiOi**

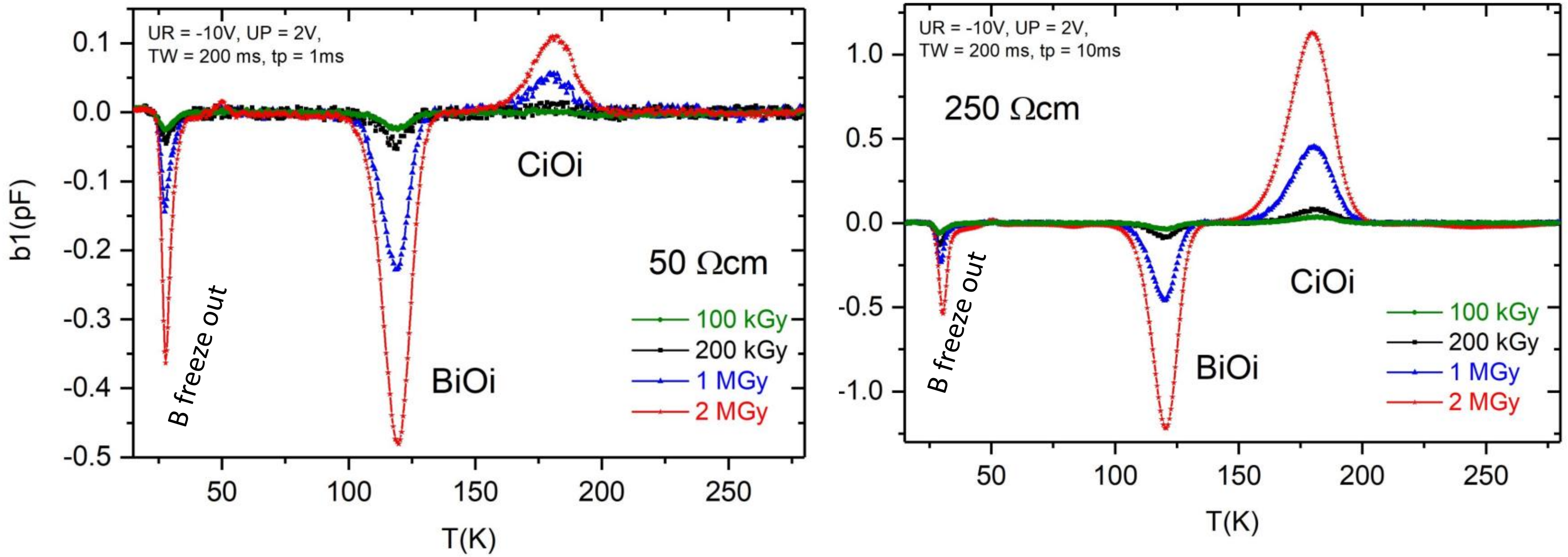
$E_c$-0.25 eV

$\sigma_n$: 6E-15 cm²

Majority carrier injection:



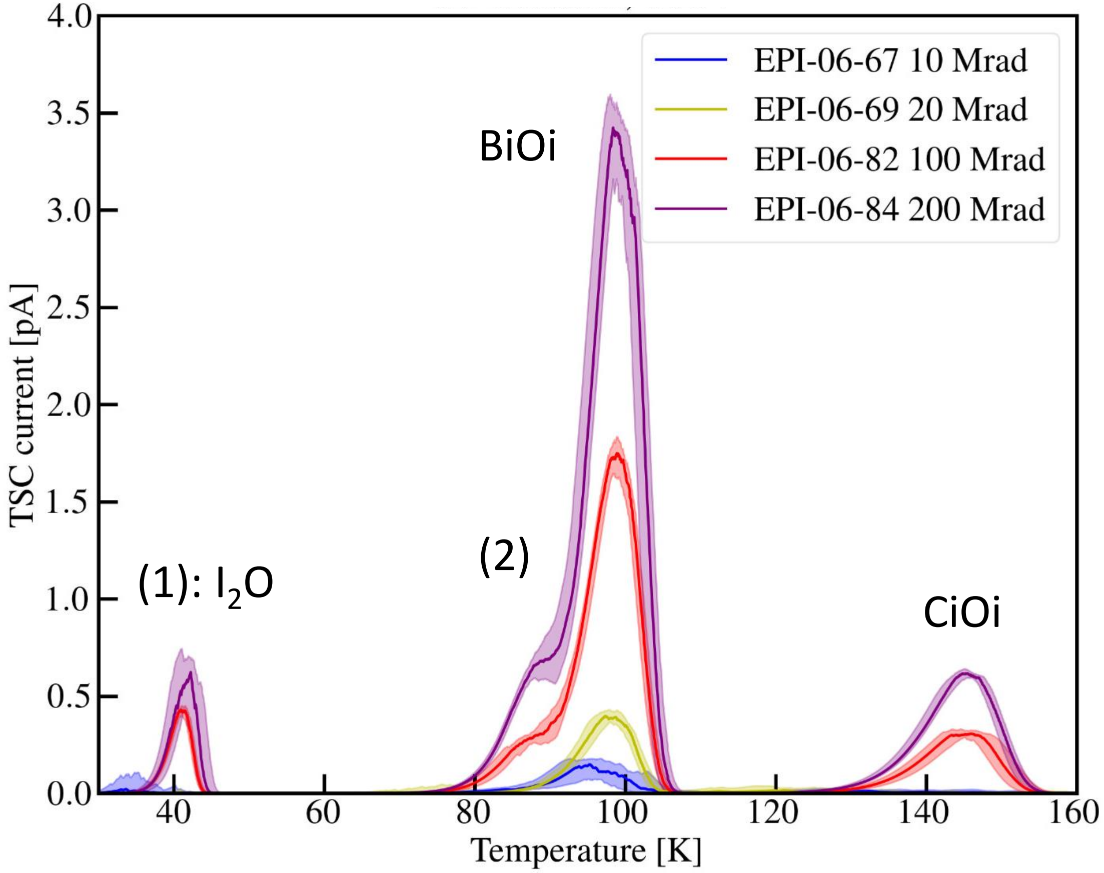

Majority & minority carrier injection:



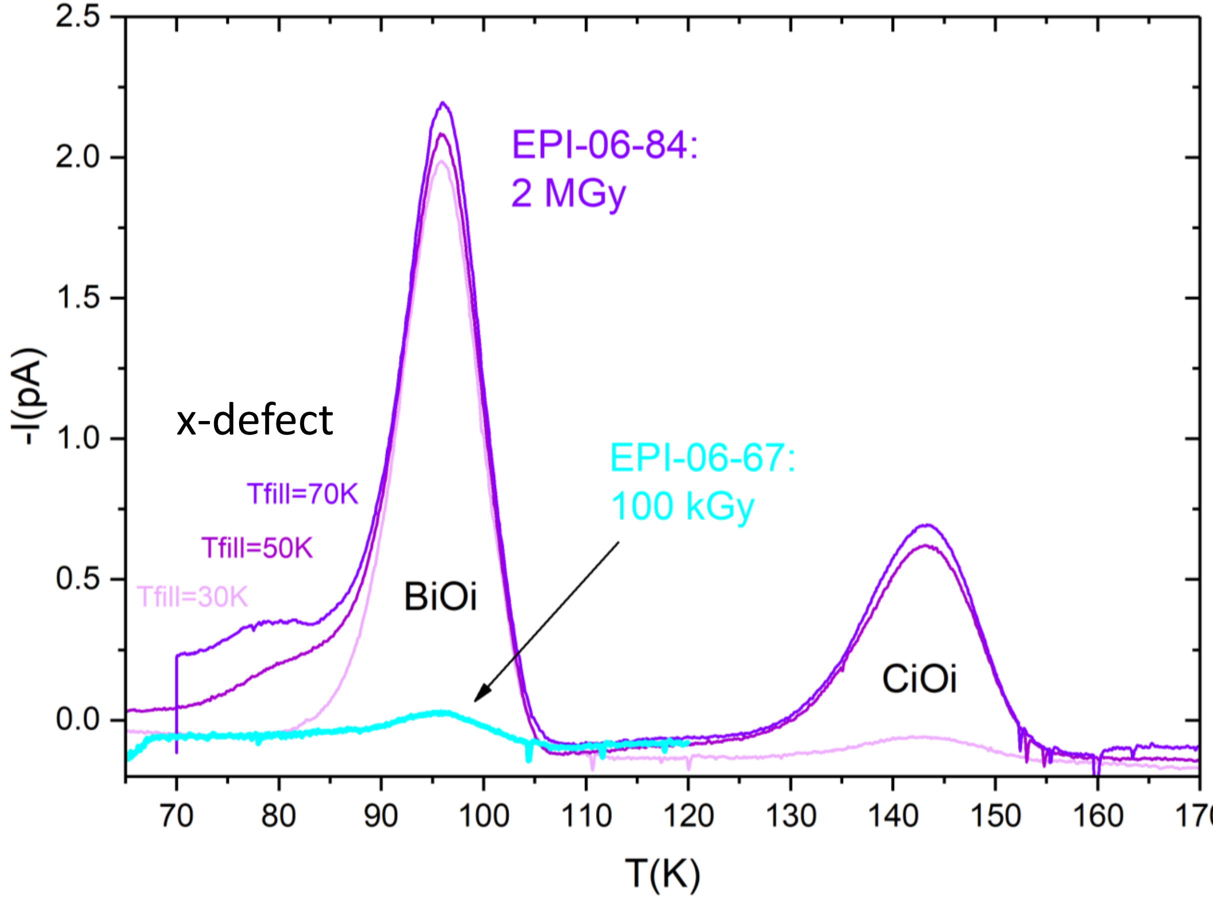
# pytsc spectra & TSC measurements

## EPI 50 Ωcm

pytsc spectra (VR=-100V)
with DLTS parameters:

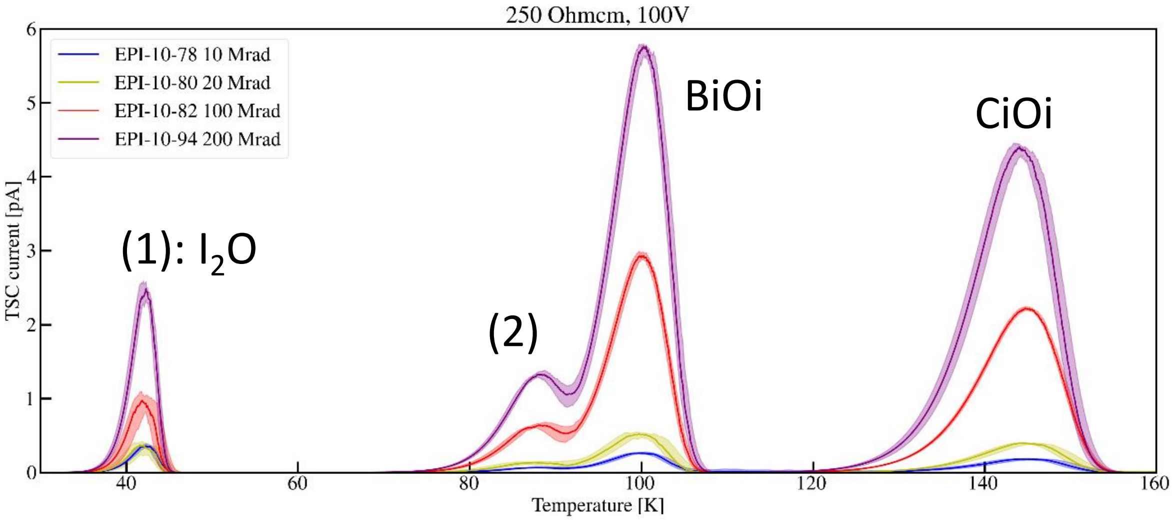



measured TSC spectra (VR=-100V, Vfill=+20V, Tfill >40K):

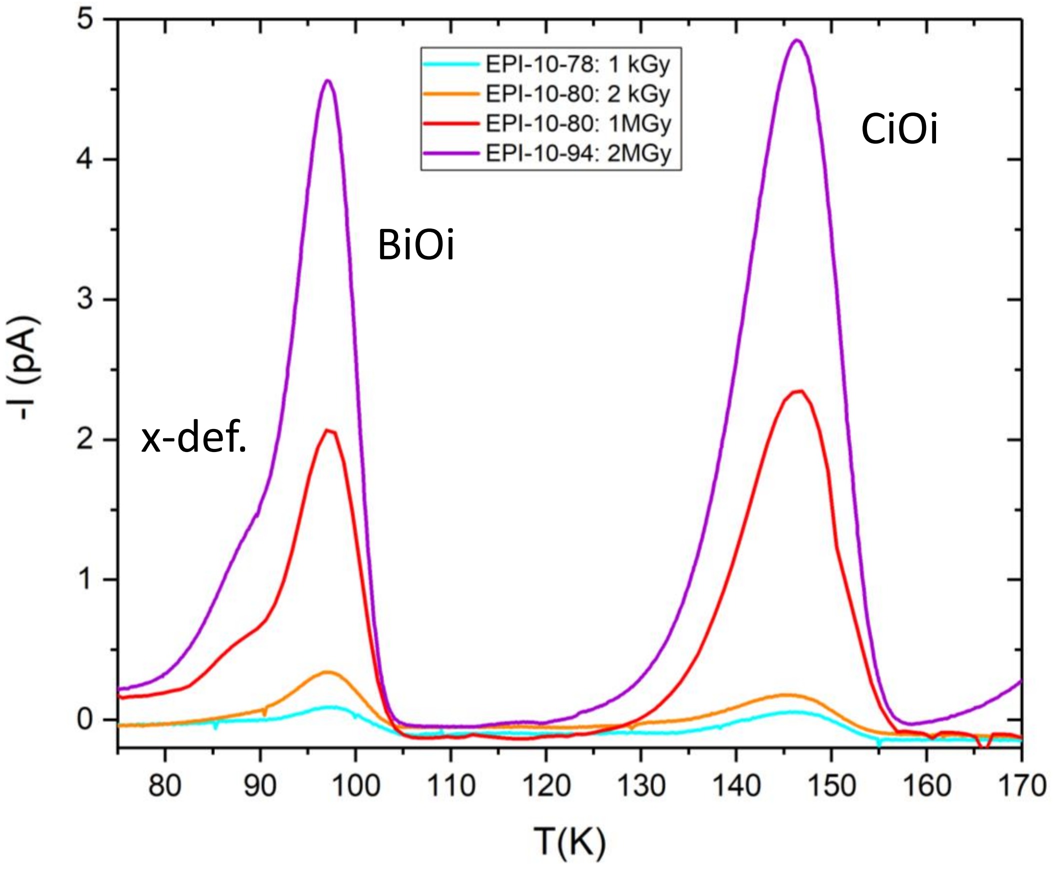


# pytsc spectra & TSC measurements

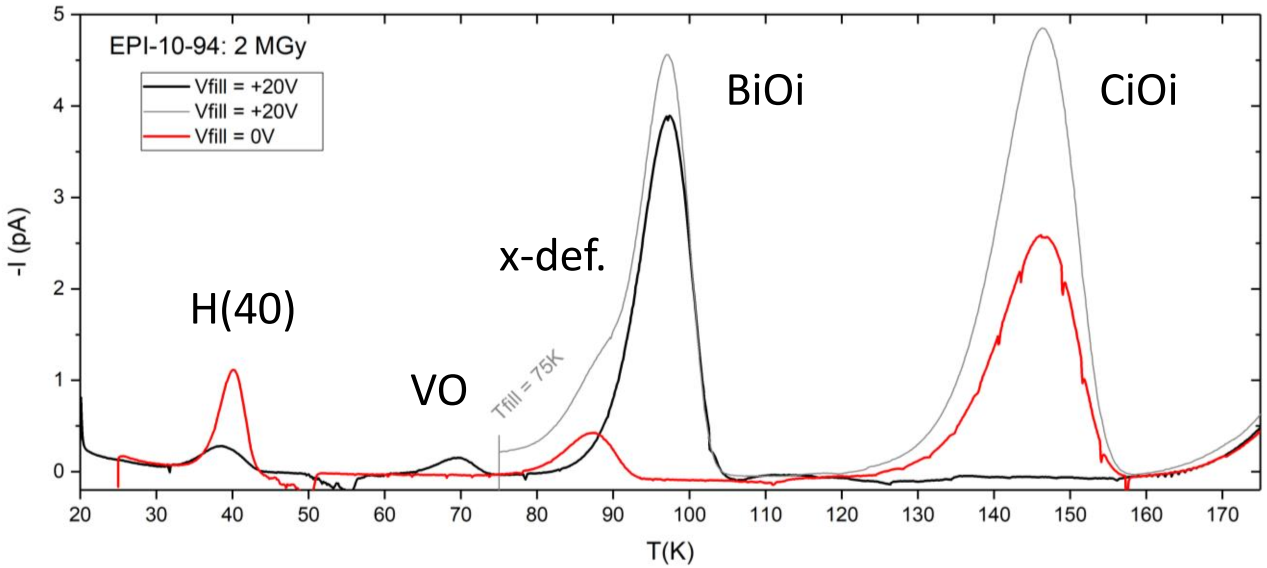
## pytsc spectra (VR=-100V) with DLTS parameters: EPI 250 Ωcm




## measured TSC spectra (VR=-100V, Vfill=+20V, Tfill >40K):



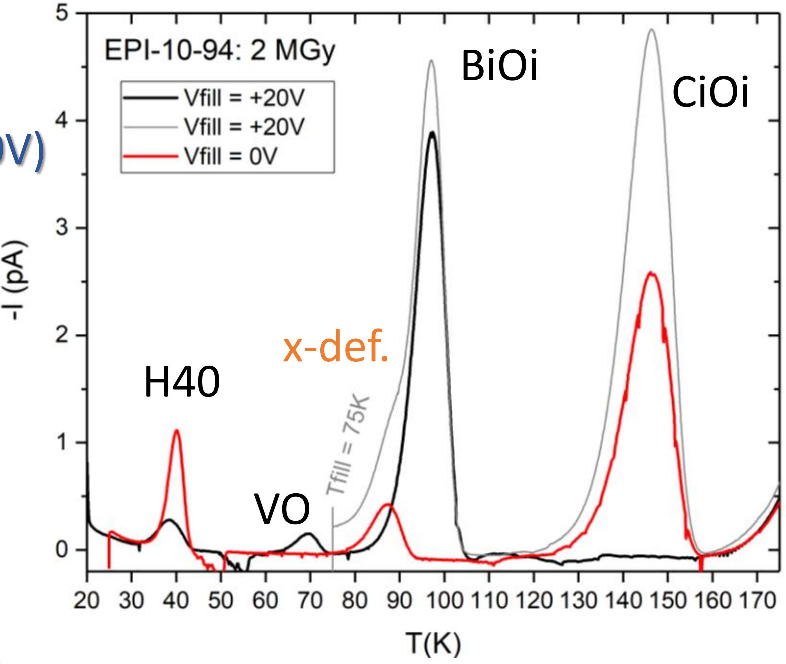

## measured TSC spectra 2 MGy irradiation (VR=-100V):



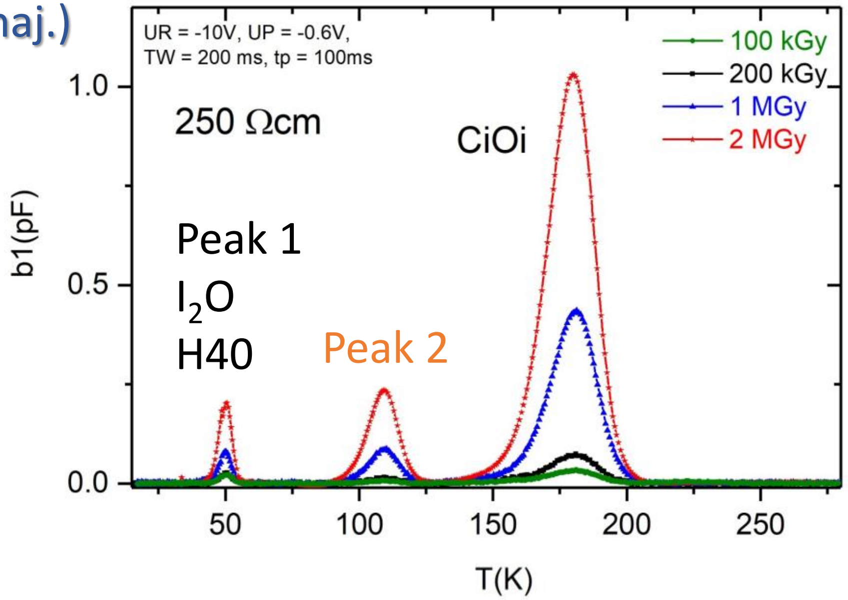
# x-defect



TSC (-100V)




DLTS (maj.)

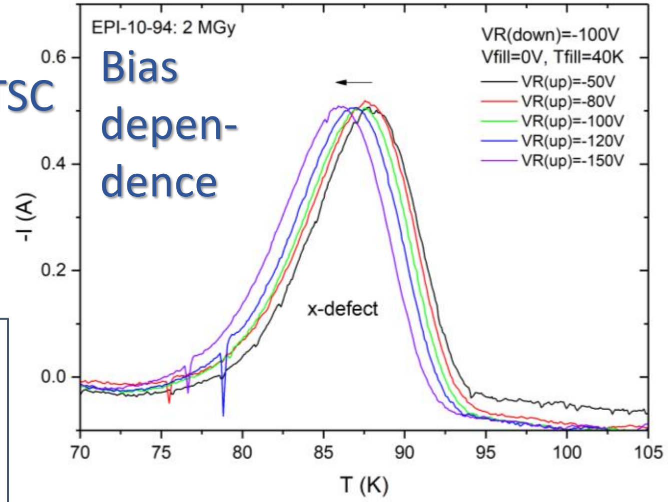



## x-defect:

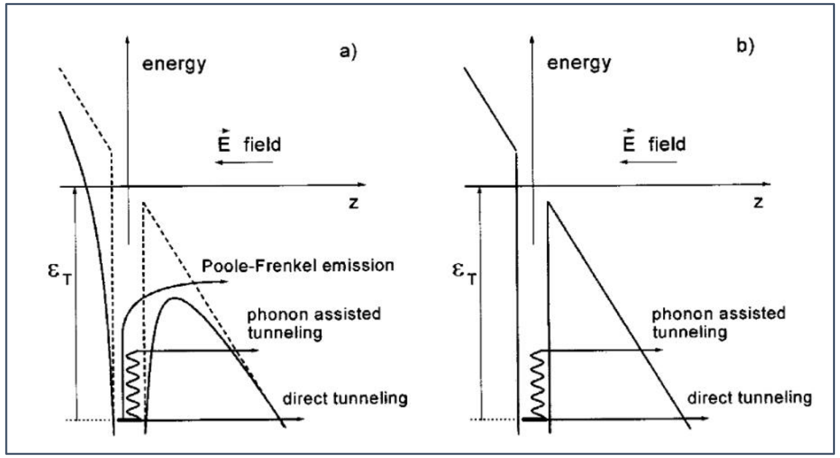
*Chuan Liao 37th RD50 WS Nov.2020*
*& Chuan Liao et al. IEEE 69,3 (2022)*

- hole trap
- capture cross section is strongly T-dependent
- for proton, neutron & electron irrad.: clearly identified for lower fluences (< 7E+13 $n_{eq}/cm^2$)
- shows electrical field dependence

TSC Bias depen-dence




## Poole-Frenkel-Effect:




charged defect

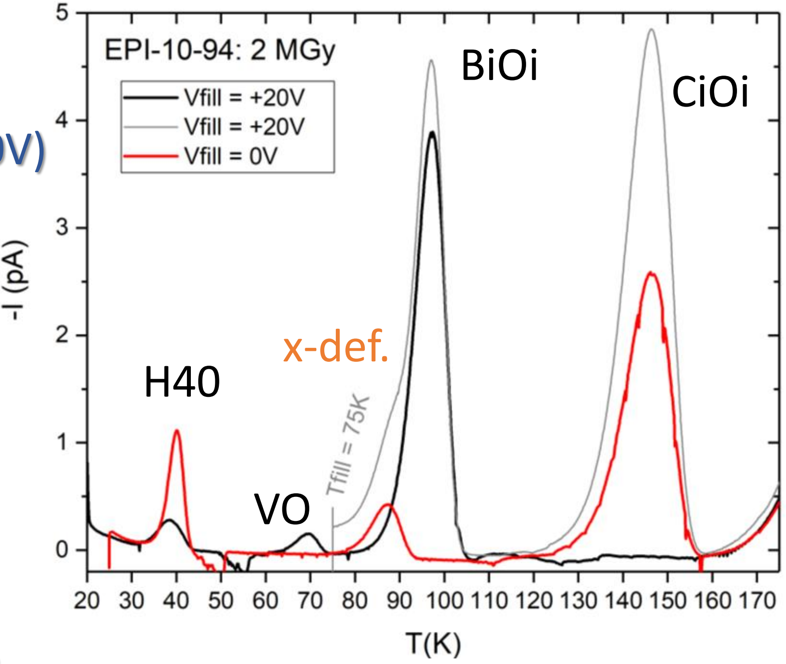
neutral defect

*Zangenberg et al.*
*NIM B 186 (2002)*

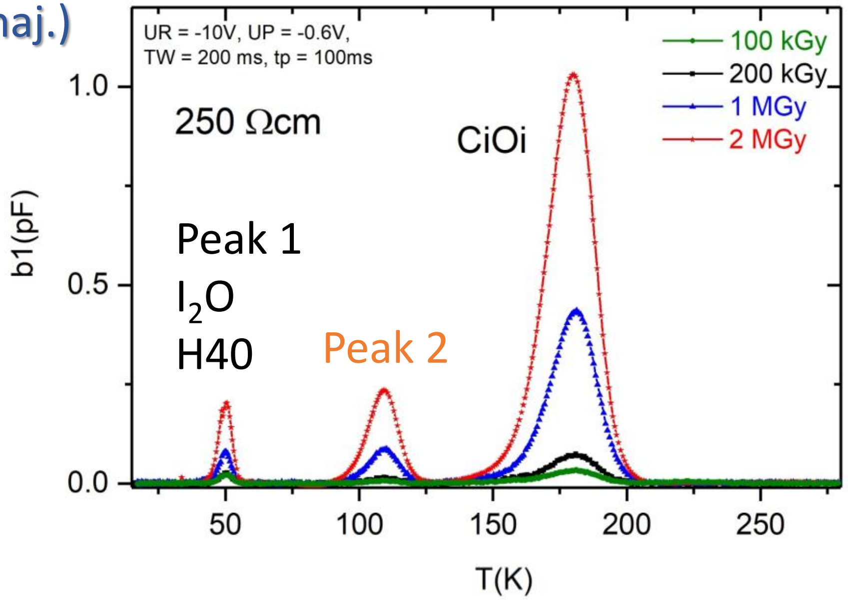
# x-defect



TSC (-100V)




DLTS (maj.)

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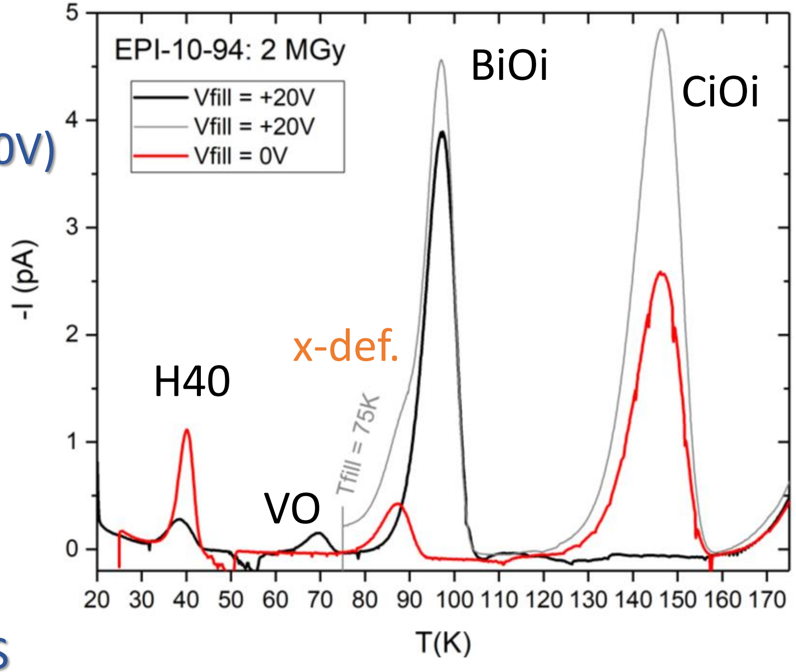
- shows electrical field dependence

**peak (2) DLTS:**
- hole trap
- activation energy: $E_v$+ 0.19 eV
- capture cross section $\sigma_p$: 4E-16 cm²

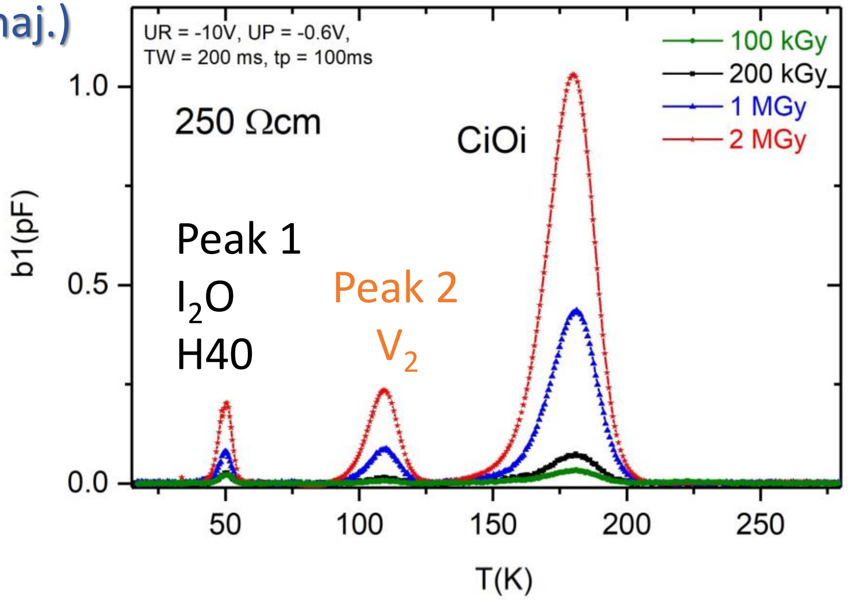
# x-defect



TSC (-100V)




DLTS (maj.)

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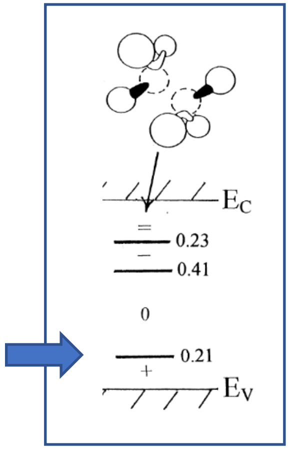



*Watkins Mater. Sci. Semicond. Proc. 3 (2000)*

## From literature:

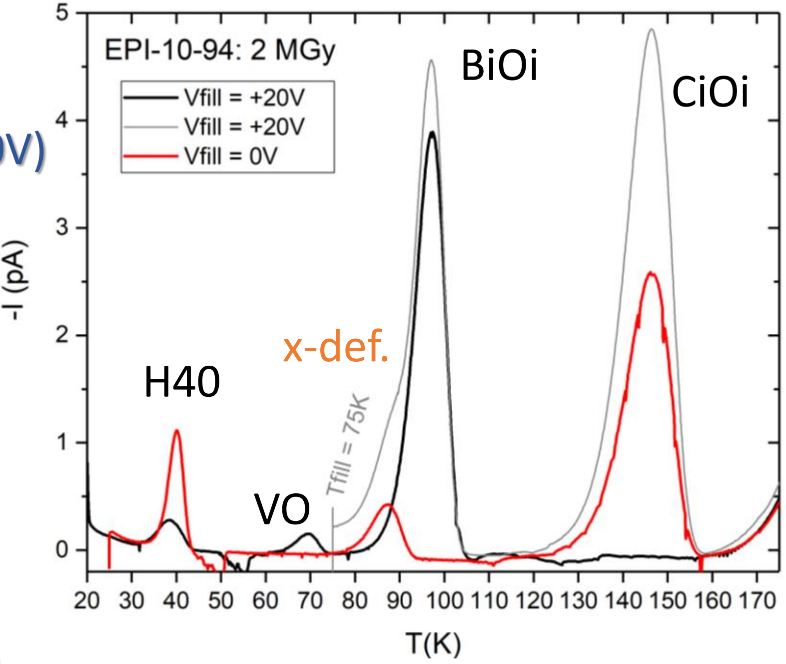
## Peak 2 => Divacancy $V_2(0/+)$

- Ev + 0.19 eV, $\sigma_p$: ~E-16 cm² — *Kolevatov et al. Phys. Stat. Sol. A 216 (2019)*
- Ev + 0.19 eV, $\sigma_p$: 5E-16 cm² — *Zangenberg et al. Appl. Phys. A 80 (2005), NIM B 186 (2002)*

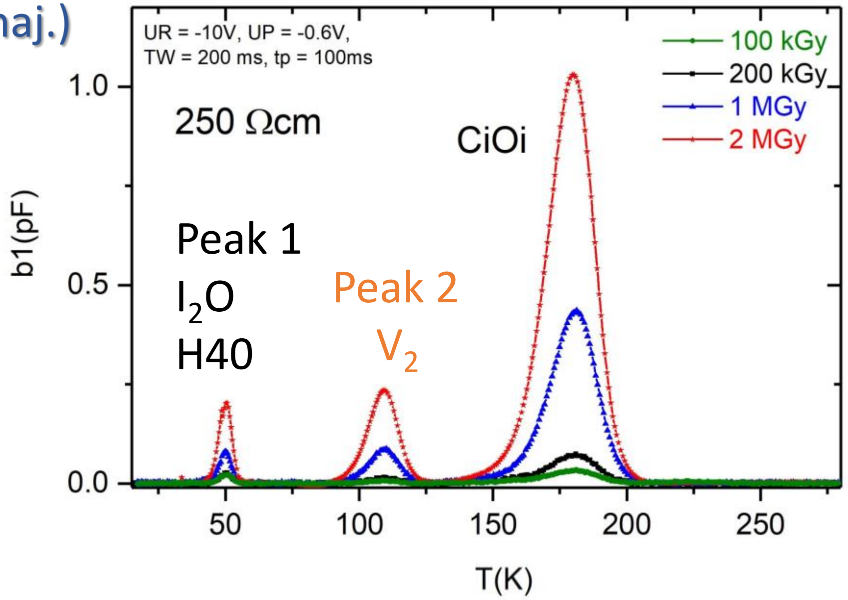
# x-defect



TSC (-100V)




DLTS (maj.)

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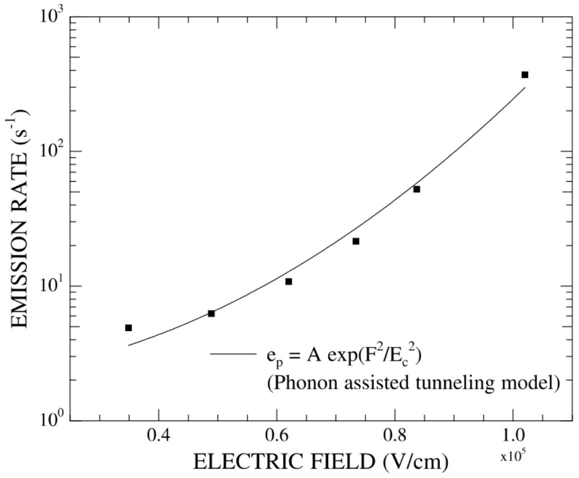


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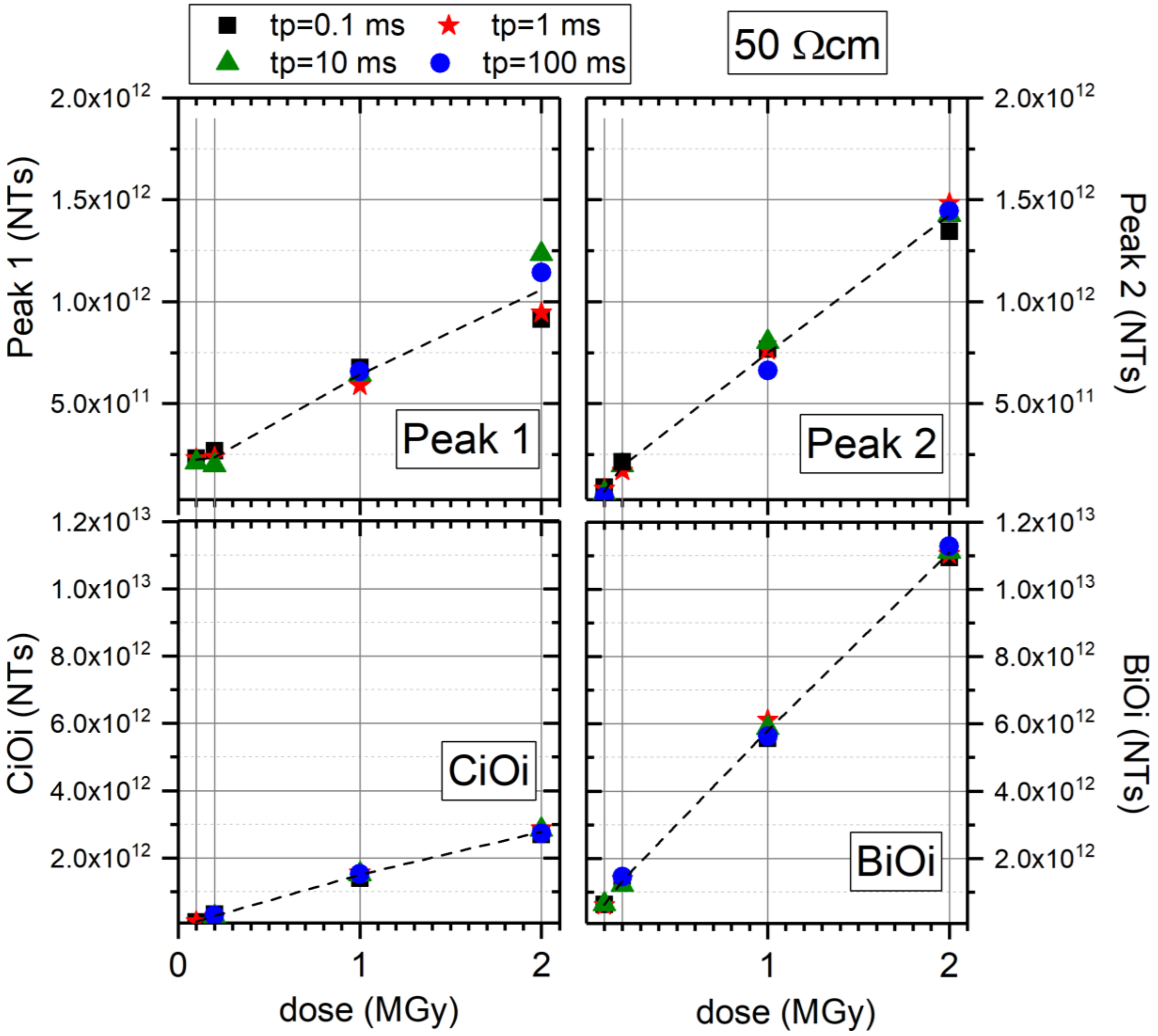
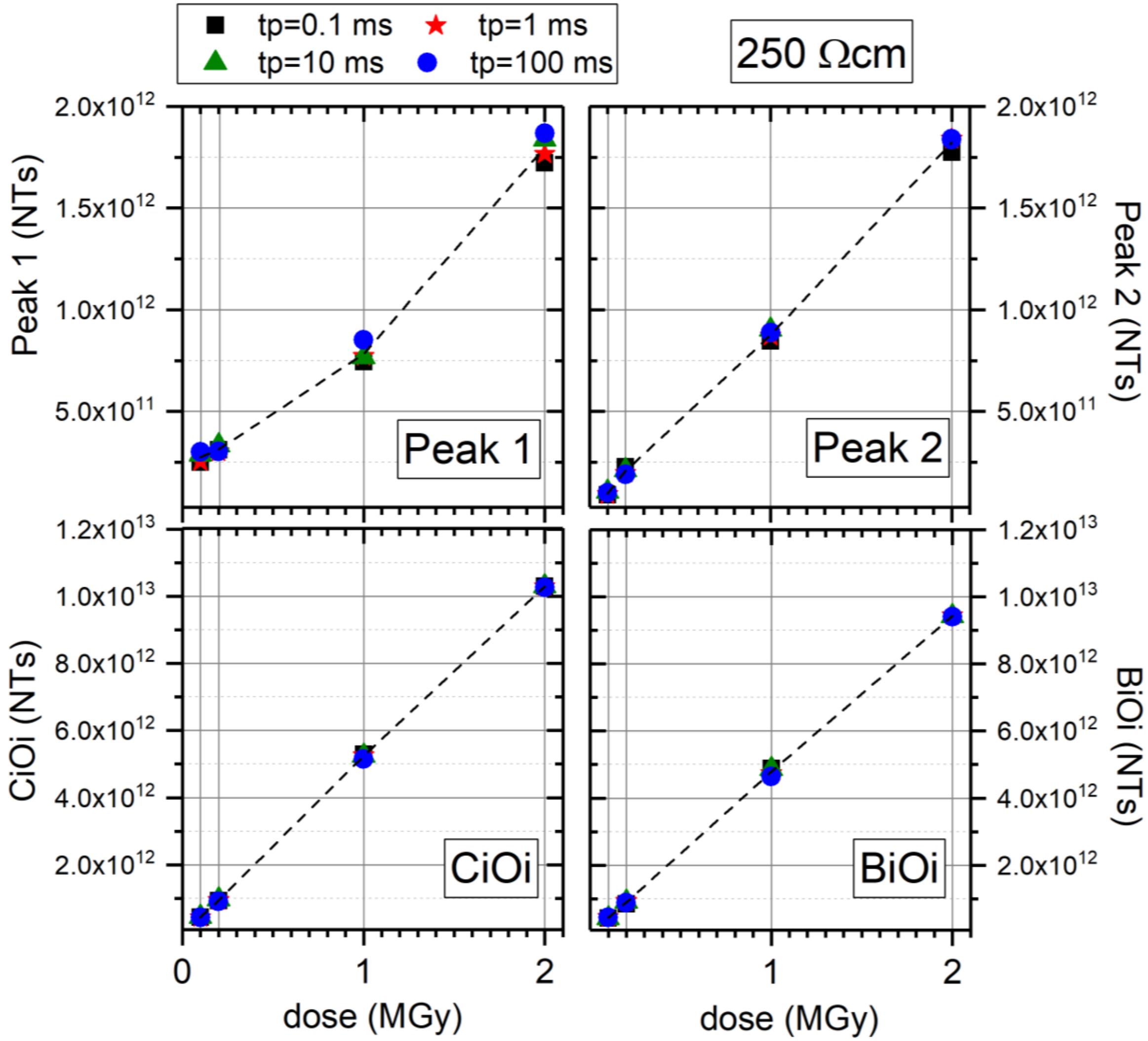
- Ev + 0.19 eV, $\sigma_p$: ~E-16 cm² *Kolevatov et al. Phys. Stat. Sol. A 216 (2019)*
- Ev + 0.19 eV, $\sigma_p$: 5E-16 cm²
- large field dependence reported (phonon assisted tunnelling)

*Zangenberg et al. Appl. Phys. A 80 (2005), NIM B 186 (2002)*

# DLTS : defect concentrations

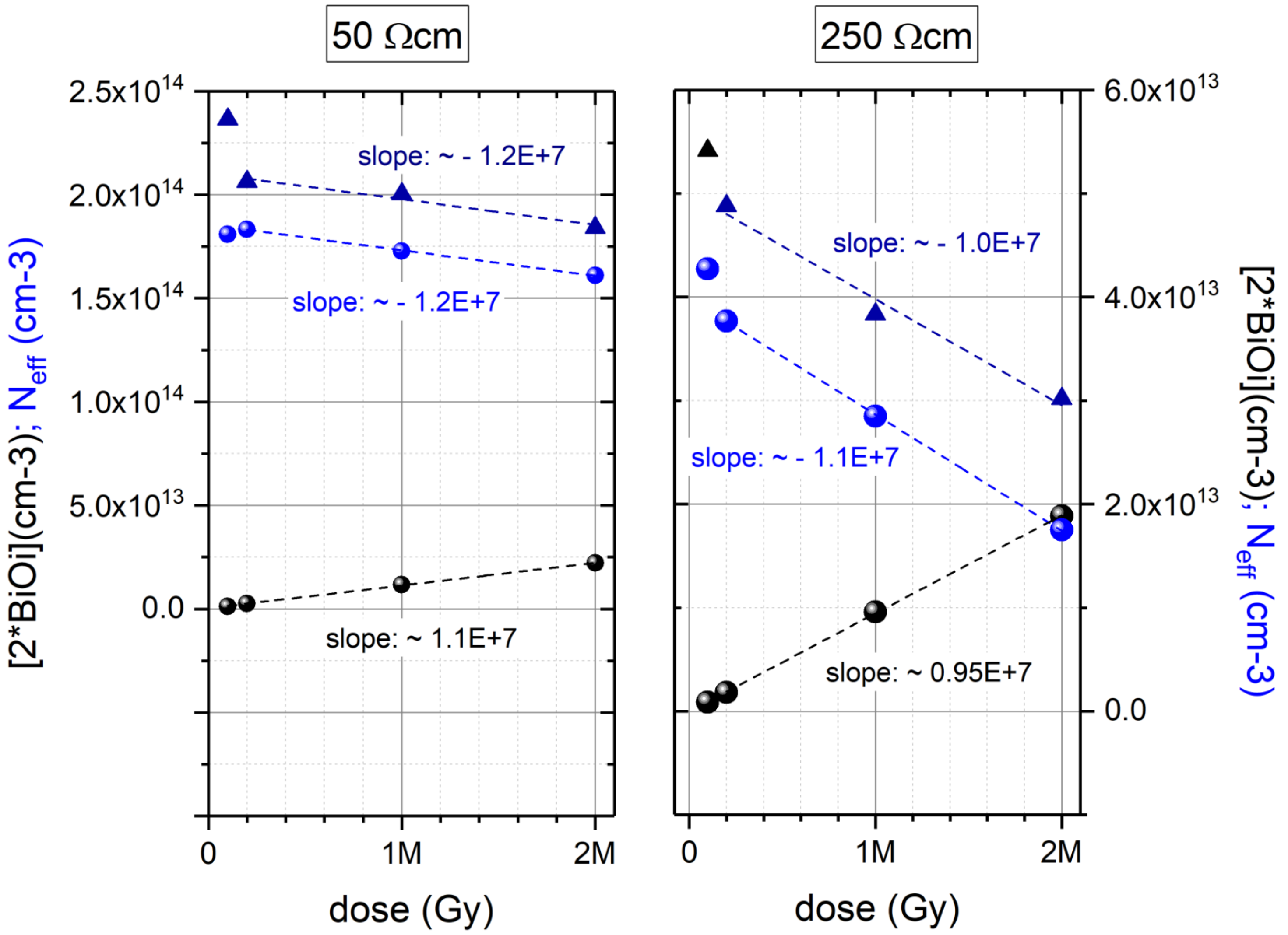
## Defect concentrations vs. radiation dose:



# Correlation wih $N_{eff}$

## Correlation between the change in the effective doping concentration and BiOi concentration:




- $N_{eff}$ from C-V curves taken at: T = 253K and T = 108 – 130K

- Change in $N_{eff}$ correlates with change in the BiOi concentration (dose > 200 kGy) → one BiOi deactivates two active B atoms

*Consistent with measurements on proton irrad. EPI diodes: Chuan Liao et al. IEEE 69,3 (2022)*

# Summary

- Defect characterization on $^{60}$Co – gamma irradiated Si pad diodes
- DLTS, TSC and TSC modelling (pytsc)
- Identify and characterize the main defects

  **$I_2O$ (DLTS) / H(40) (TSC)** : $E_v$+ 0.09 eV, $\sigma_p$: 2E-14 cm²

  **$V_2$ (DLTS)** : $E_v$+ 0.19 eV, $\sigma_p$: 4E-16 cm²

  **x-defect (TSC)**

  *… ongoing discussion about correlations* (applies to $V_2$ and x-defect)

  **CiOi** : $E_v$+ 0.36 eV, $\sigma_p$: 2E-15 cm²

  **BiOi** : $E_c$-0.25 eV, $\sigma_n$: 6E-15 cm²

- BiOi defect:
  - Donor type defect level in the upper part of the band gap that deactivates 2 active boron atoms
  - Correlates with a factor of about 2 with the changes in the effective space

*Thank you for your attention!*