Investigation of radiation defects

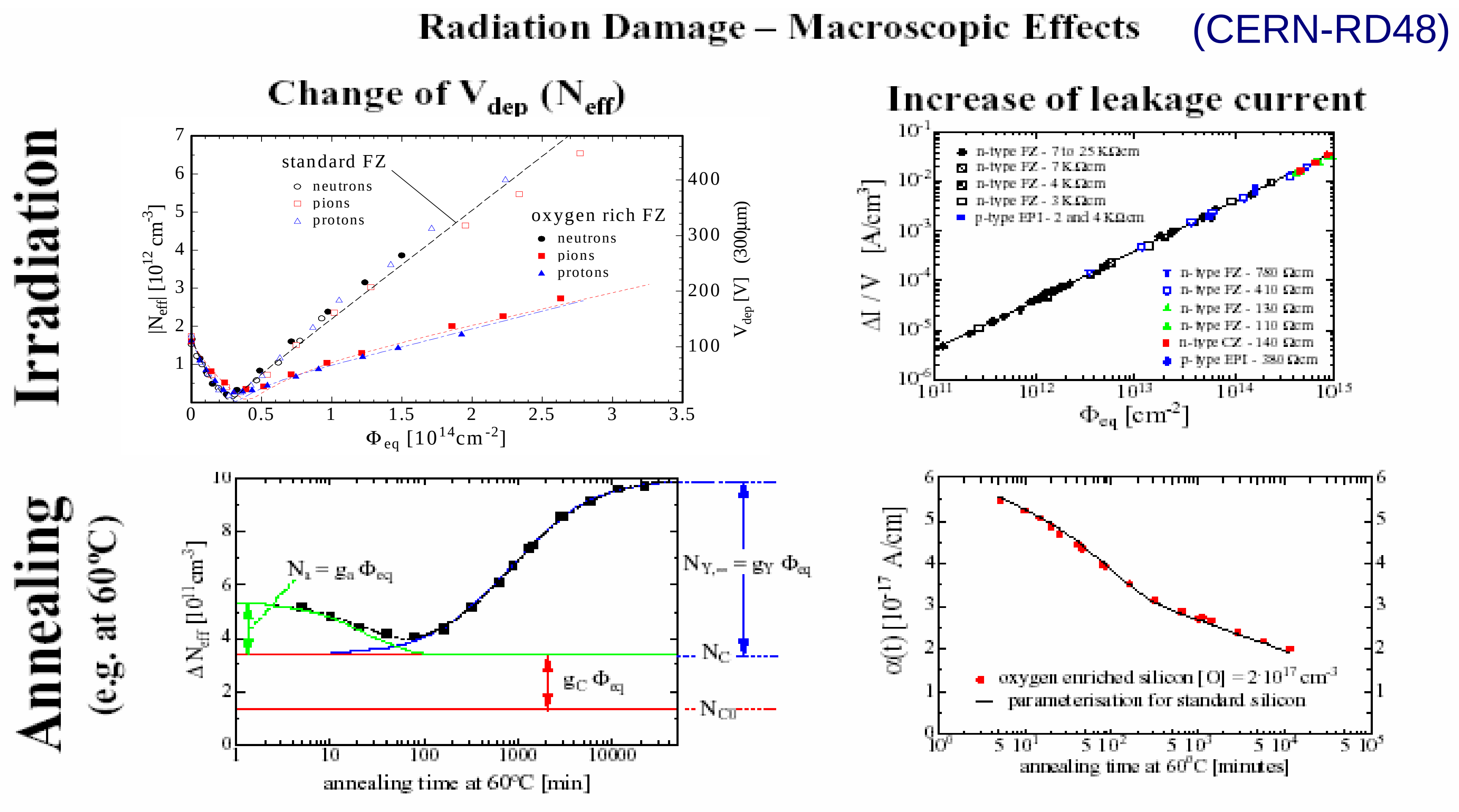
Ioana Pintilie

National Institute of Materials Physics, Bucharest, Romania

Outline

- Motivation
- Point defects
- Clasification of electrically active point defects
- Electrical properties in the space charge region
- Methods of Detection
- Radiation induced defects in Si diodes
- Summary&Conclusions

Motivation



Radiation Damage – Macroscopic Effects (CERN-RD48)

Irradiation

Change of V_{dep} (N_{eff})

Increase of leakage current

Annealing (e.g. at 60°C)

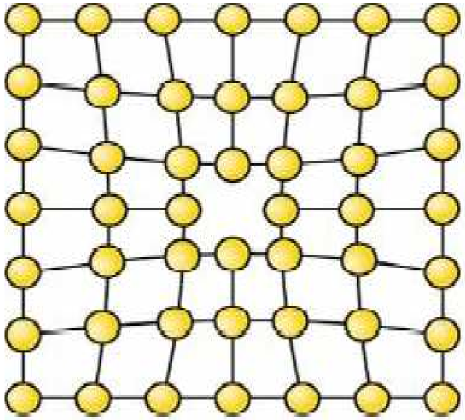
-To understand the radiation damage

- To improve the detectors radiation tolerance by “Defect engineering”

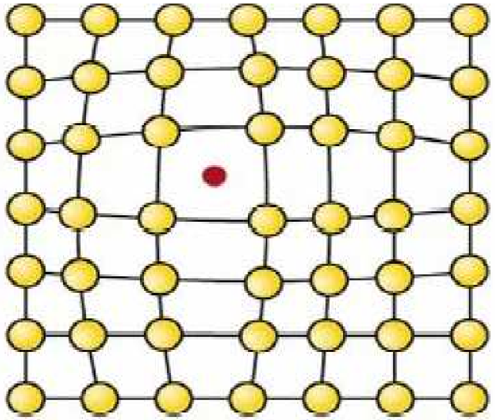
Point defects

Radiation induced

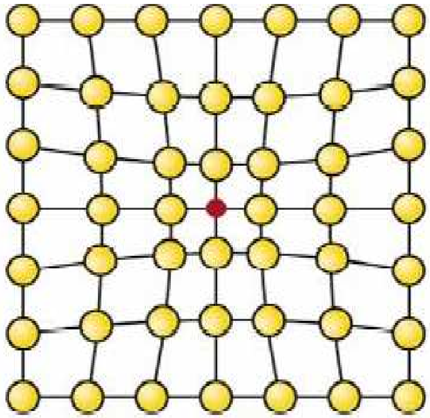
<u>vacancy</u>
- missing atom

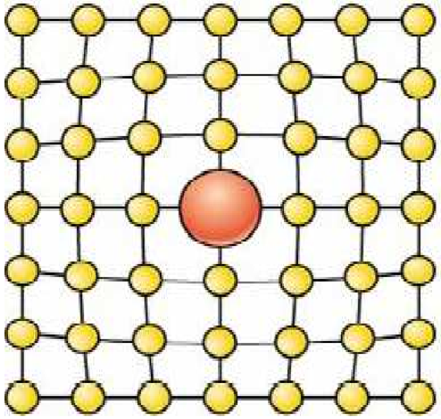


<u>interstitial atom</u>
- not in regular lattice site



<u>substitutional impurity</u>
- impurity atom in lattice

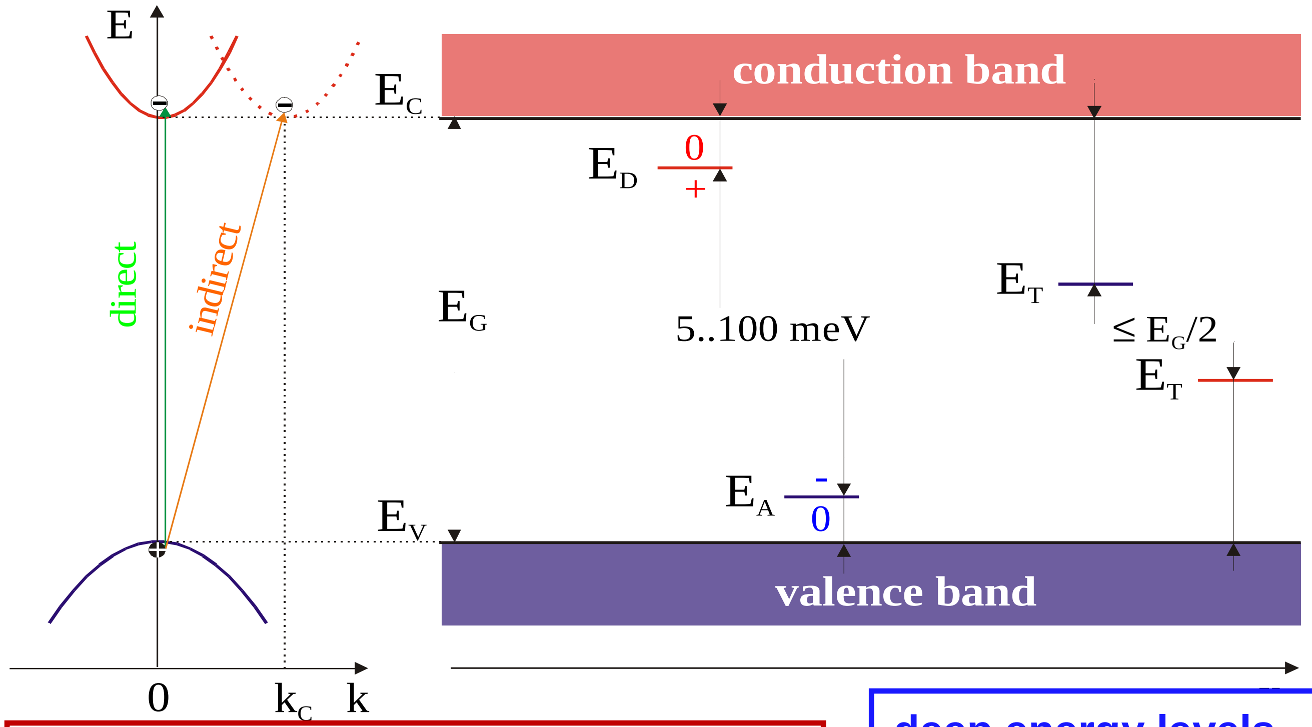




<u>Complexes</u> can form between different kinds of defects

- Local distortion of the crystalline structure
- Some defects may introduce energy levels in the band-gap of the material (electrically active defects)

Clasification of electrically active point defects



Shallow Donors (0/+)

Deep trapping centers (acceptor or donor like)

Shallow Acceptors (-/0)

shallow energy levels

- single impurity atoms - doppants
- Donors, acceptors (e.g. Si: P or B)

➢ adjustment of conductivity,

n- or p-type

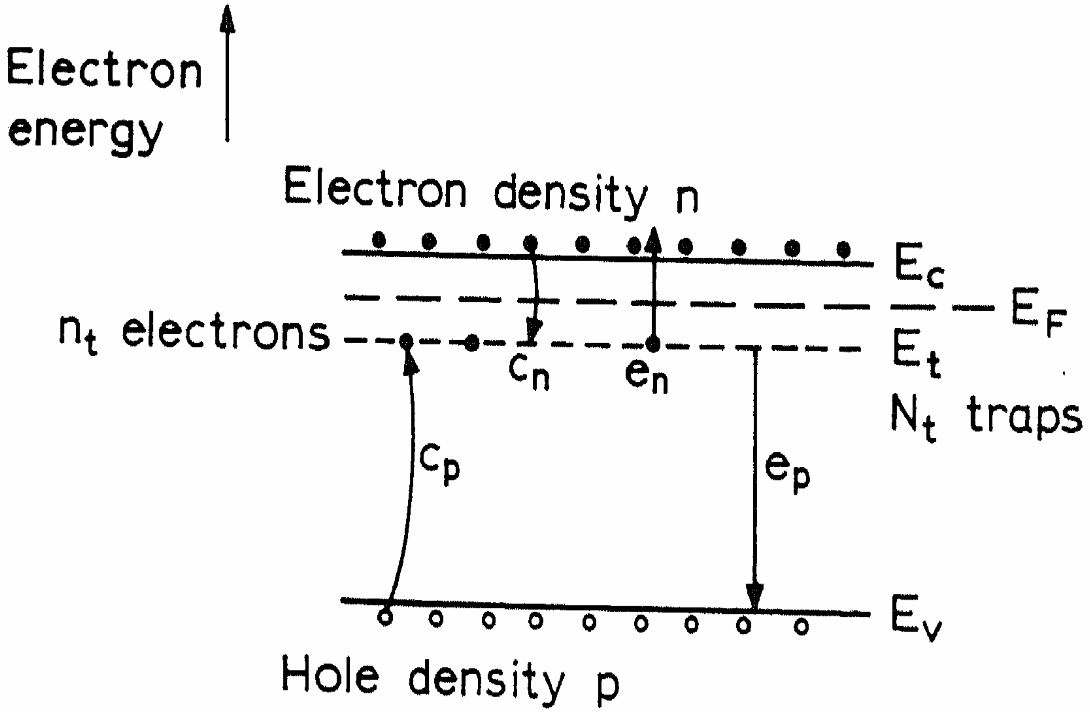
deep energy levels

- TM impurities or complex defects (intrinsic defects, radiation induced defects)
- recombination, generation or compensation

➢ even in low concentration deterioration of device characteristics (p-n junction)

Electrical properties of Point Defects

The occupancy of a defect state with an electron (hole) is determined by the competing emission and capture processes (Schockley-Read-Hall statistics).



$$c_n \sim \sigma_n * n \qquad e_n \sim \sigma_n * \exp\left(\pm \frac{E_C - E_T}{k_B T} \right)$$

Electrical properties of Point Defects - in the Space Charge Region (SCR)

Defect´ signature – emission rates

$$e_{n,p}(T) \sim \sigma_{n,p}(T) * \exp\left(\pm \frac{E_T(T) - E_{C,V}}{k_b T} \right)$$

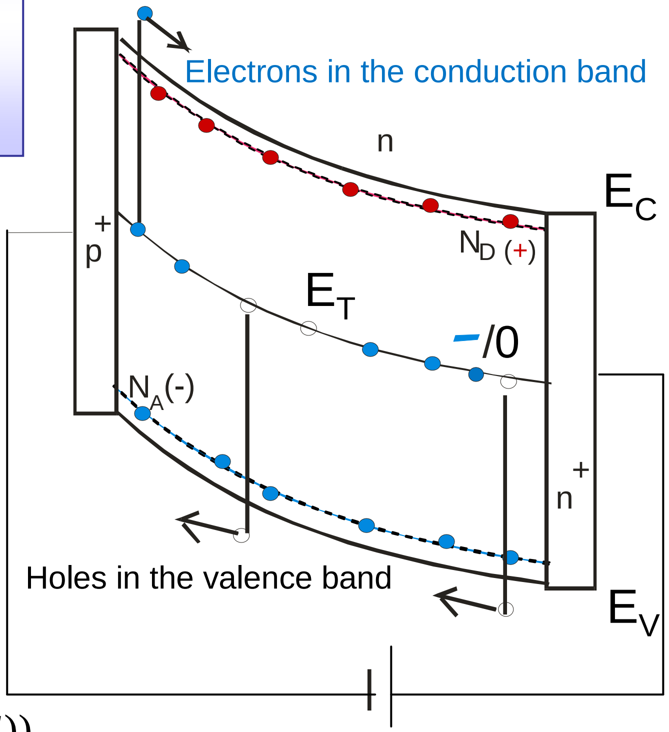
1) **Contribution to $\mathbf{N_{eff}}$** - given by the steady state ocupancy of the defect levels in SCR

$$n_T^{acceptor}(T) = N_T \frac{e_p(T)}{e_n(T) + e_p(T)}; n_T^{donor}(T) = N_T \frac{e_n(T)}{e_n(T) + e_p(T)}$$

$$N_{eff} = \sum n_T^{donor} - \sum n_T^{acceptor}$$

2) **Contribution to the leakage current**

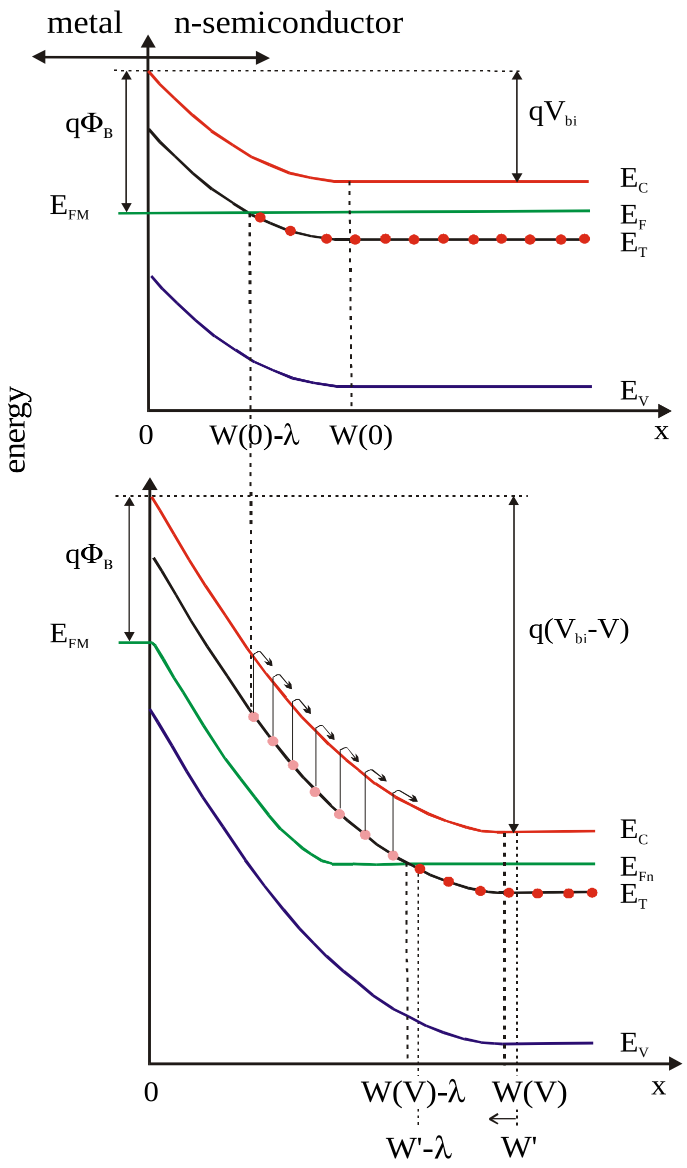
$$I_{dep}(T) = q_0 * A * d * (\sum e_n(T) * n_T^{acceptor}(T) + \sum e_p(T) * n_T^{donor}(T))$$



Methods of Detection – there is no experimental method to provide all the defects characteristics

Technique	Based on/ measures	Provided defect parameters	Limitations
Deep Level Transient Spectroscopy	Charge capture-emission / Capacitance transients	E_t, $\sigma_{n,p}$, N_t	-low density of defects ($<10^{12}$ cm^{-3}) -Chemical nature (indirect)
Thermally Stimulated Current	Charge capture-emission / Current	E_t, $\sigma_{n,p}$, N_t	-medium density of defects (10^{12} -10^{15} cm^{-3}) -Chemical nature (indirect)
Photoluminescence	Photon Absorption followed by Photon Emission / Luminescence	PL bands (E_t, τ)	-Only for radiative recombination centers - Chemical nature (indirect) - $\sigma_{n,p}$, N_t
Infrared Spectroscopy	Excitation of vibrational modes of molecules by IR absorption / Absorption of IR energy	-N_t (acc. 20-30%) - Defect structure	-Large density of defects ($> 10^{15}$ cm^{-3}) -E_t, $\sigma_{n,p}$,
Electron Paramagnetic resonance	Zeeman effect and Spins resonance / microwave photons absorption	- Chemical nature and vecinity - N_t	-Large density of defects ($> 10^{15}$ cm^{-3}) - Only paramagnetic centers - E_t, $\sigma_{n,p}$,

Deep Level Transient Spectroscopy (multiple shot technique)

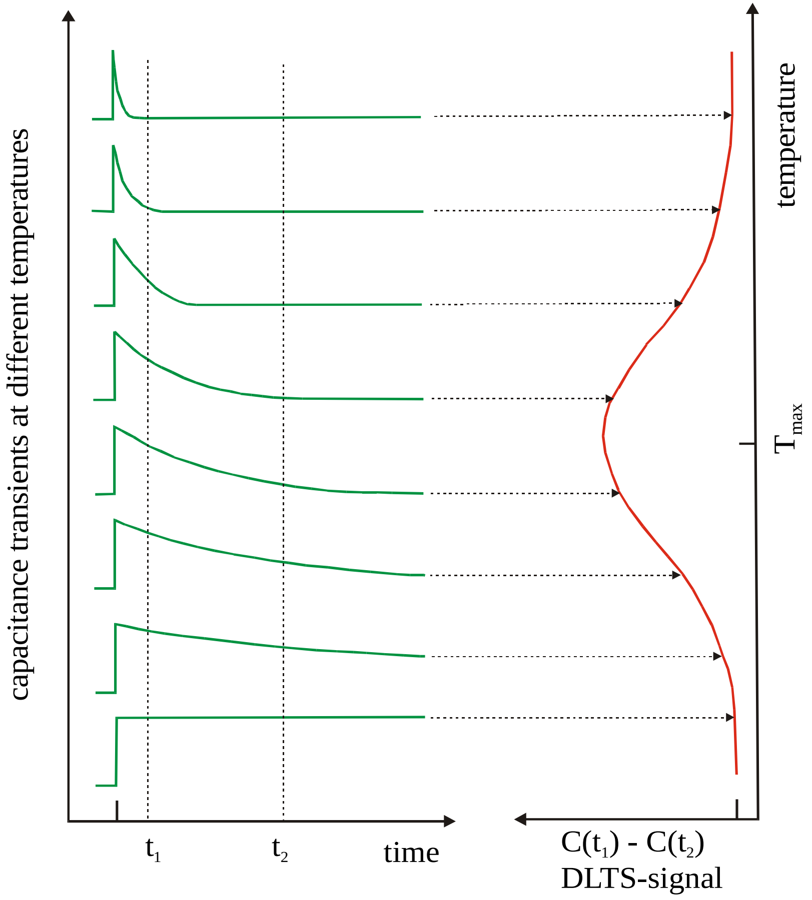


without bias

thermal equilibrium

with reverse bias

transition from
a nonstationary state
to a stationary one



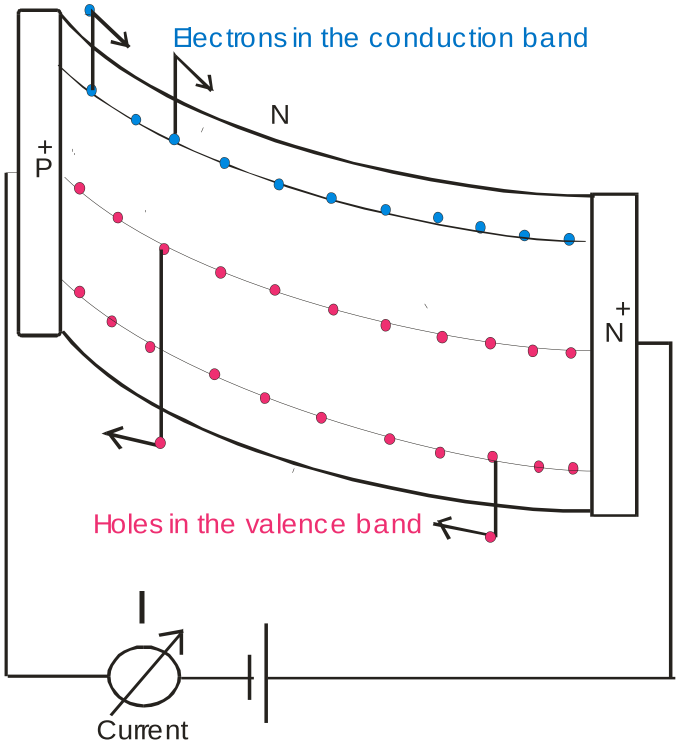
- capacitance transient:

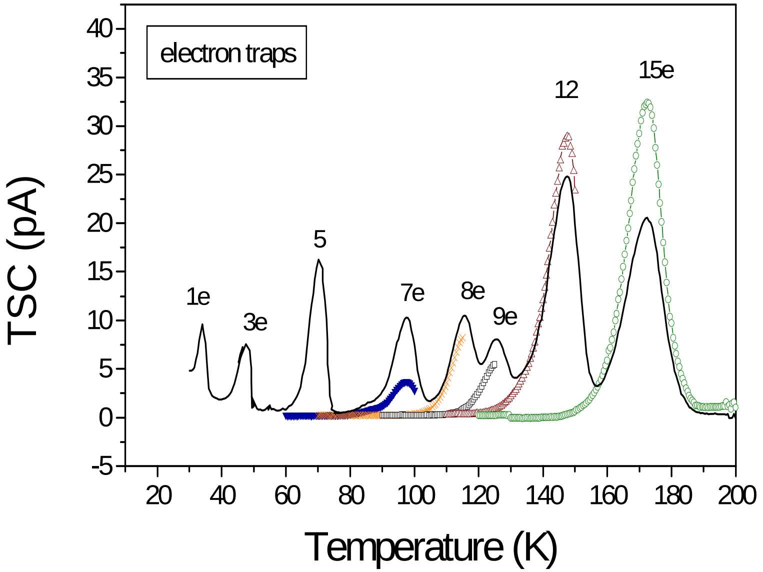
$$\Delta C = \Delta C_0 \exp\left(-e_n t\right)$$

$$N_T = 2N_D \frac{\Delta C_0}{C_0}$$

Thermally Stimulated Currents Method (single shot technique)

- Filling process -injection of carriers
- Recording – the Reverse Biased Diode is heated with constant rate and the *Current* due to the charge emission from the filled traps is recorded

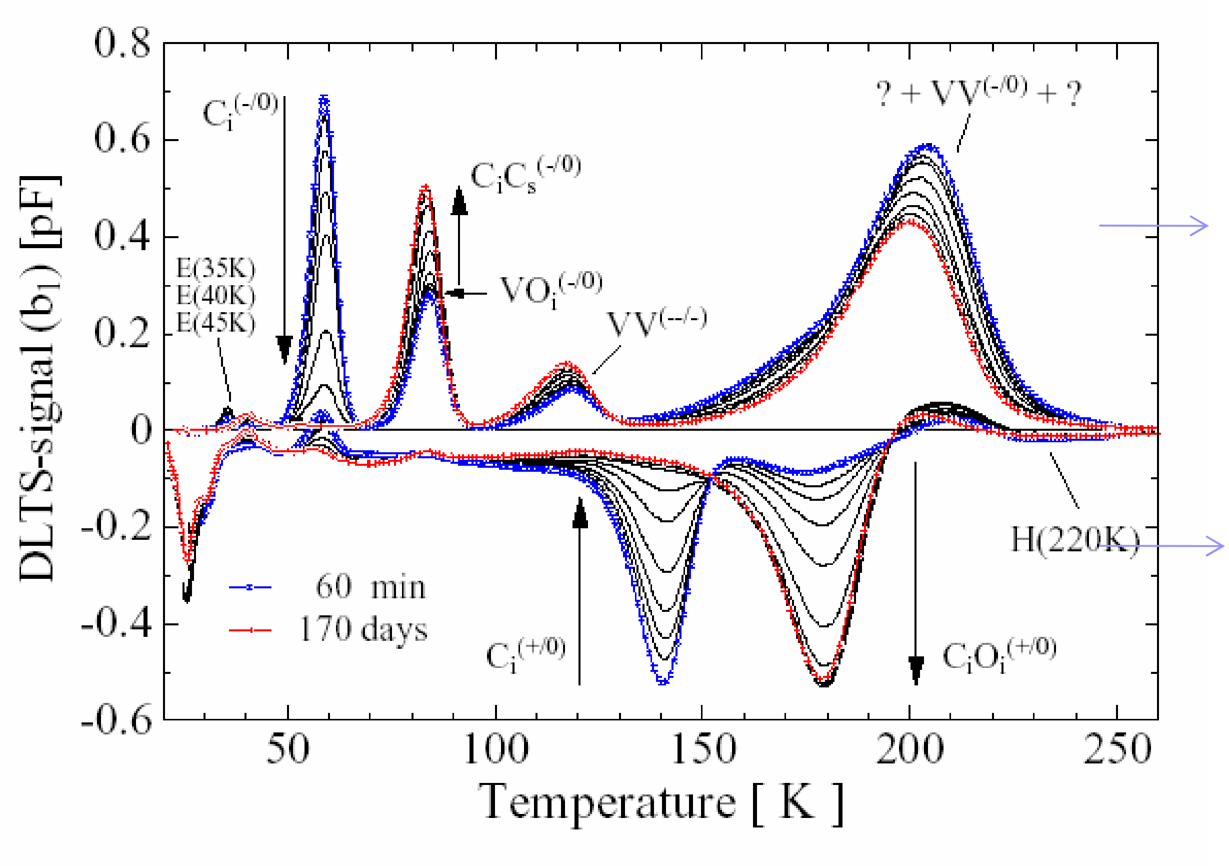



Si diodes – *typical TSC spectra (medium irradiation fluence)*

$$I_{TSC}(T) = \frac{A*d}{2} * q_0 * e_n(T) * N_t \exp(-\int_{T_0}^{T} \frac{1}{\beta} e_n(T`)dT`$$

Radiation induced defects in Si diodes

Si diodes – *typical DLTS spectra (low irradiation fluence)*



Electron traps

Hole traps

None of these defects accounts for the macroscopic effects seen at room temperature

Radiation induced defects in Si diodes

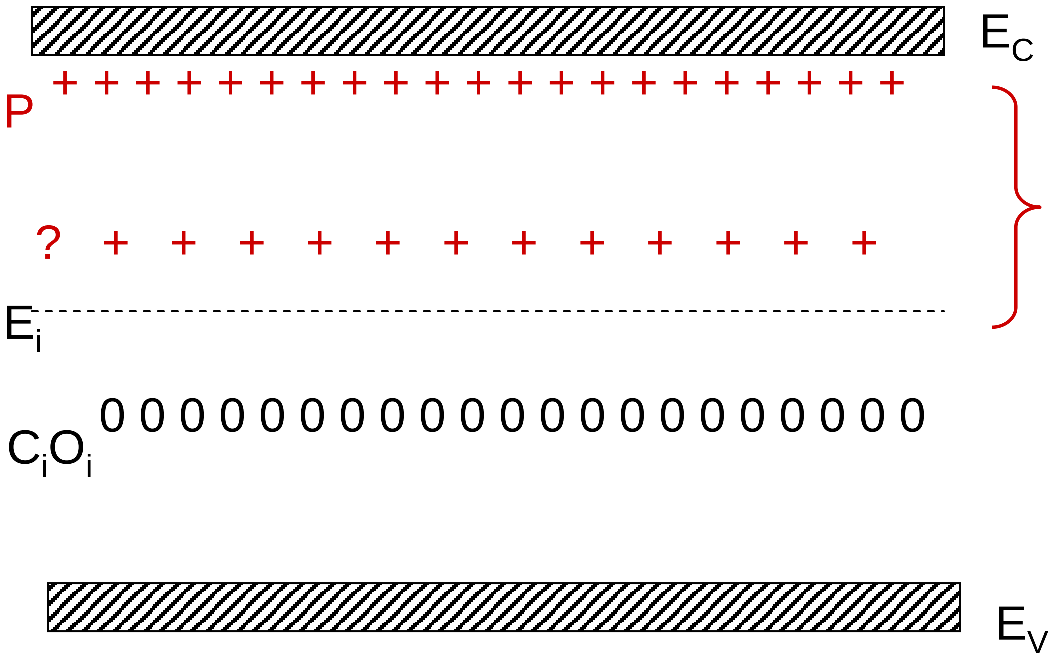
Goals

- Search for still undetected defects responsible for the radiation damage, as seen at operating temperatures
    - Point defects, predominant after gamma and electron irradiation
    - Extended defects (clusters), responsible for hadron damage

- Understand their formation and find ways to optimize the device performance

Charge state of electrically active defects at room temperature

- ***Donors (+/0)***

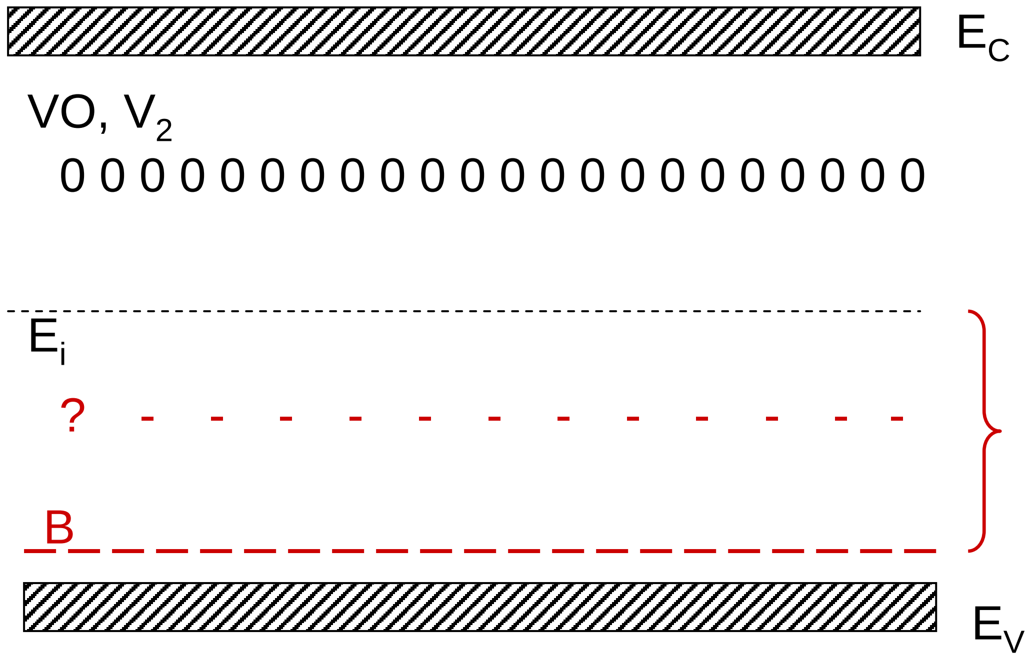


- traps for electrons
- show Poole-Frenkel effect
- Contribute with (+) to N_{eff} at RT

- traps for holes
- show no Poole-Frenkel effect
- do not contribute to N_{eff} at RT unless are near the midgap

Charge state of electrically active defects at room temperature

- ***Acceptors (0/-)***



- traps for electrons
- show no Poole-Frenkel effect
- do not contribute to N_{eff} at RT unless are near the midgap

- traps for holes
- show Poole-Frenkel effect
- contribute with (-) to N_{eff} at RT

Material

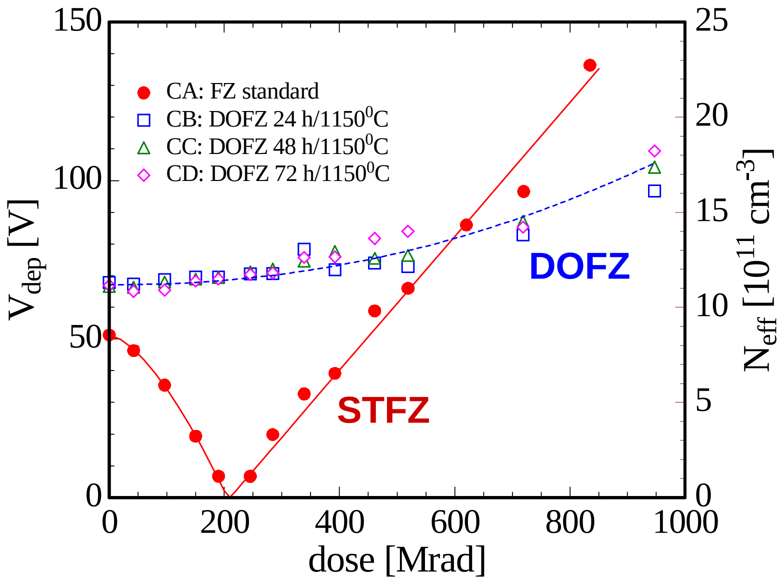
- Float zone- Silicon wafers: <111>, 300 µm, 3-4 kΩcm, N_d~10^{12} cm^{-3}
  - standard Oxidation (STFZ) - N_d~$8x10^{11}$ cm^{-3}
  - difussion oxygenated (72 h at 1150 C) (DOFZ) N_d~$1.2x10^{12}$ cm^{-3}
- MCz-Silicon wafers: <100>, 300 µm, 870 Ωcm, $N_d = 4.94x10^{12}$ cm^{-3}
- EPI-Silicon wafers: <111>
  - 25 and 50 µm on 300 µm Cz-substrate, 50 Ωcm, N_d~$7.2x10^{13}$ cm^{-3}
  - 75 µm on 300 µm Cz-substrate, 169 Ωcm
    - standard Oxidation (EPI-ST), $N_d = 2.66x10^{13}$ cm^{-3}
    - diffusion oxygenated for 24 h/1100℃ (EPI-DO) $N_d = 2.48x10^{13}$ cm^{-3}

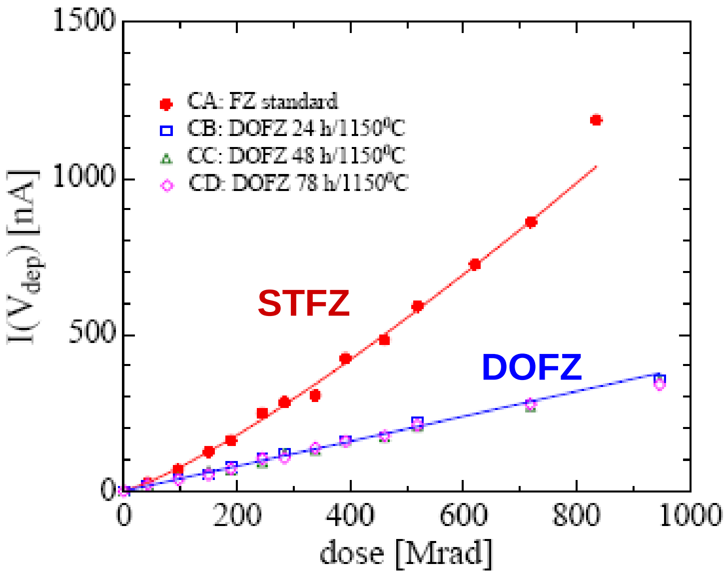
Irradiations

- **Co^{60} γ-source** at BNL, dose range 1 to 500 Mrad
- **6 -15 MeV electrons**: irradiation facility at KTH Stockhom, Sweden
- **23 GeV protons**: irradiation facility at CERN
- **1 MeV neutrons**: TRIGA reactor in Ljubljana/Slovenia

Results – Point Defects

Co^{60}- γ irradiation – only point defects are generated

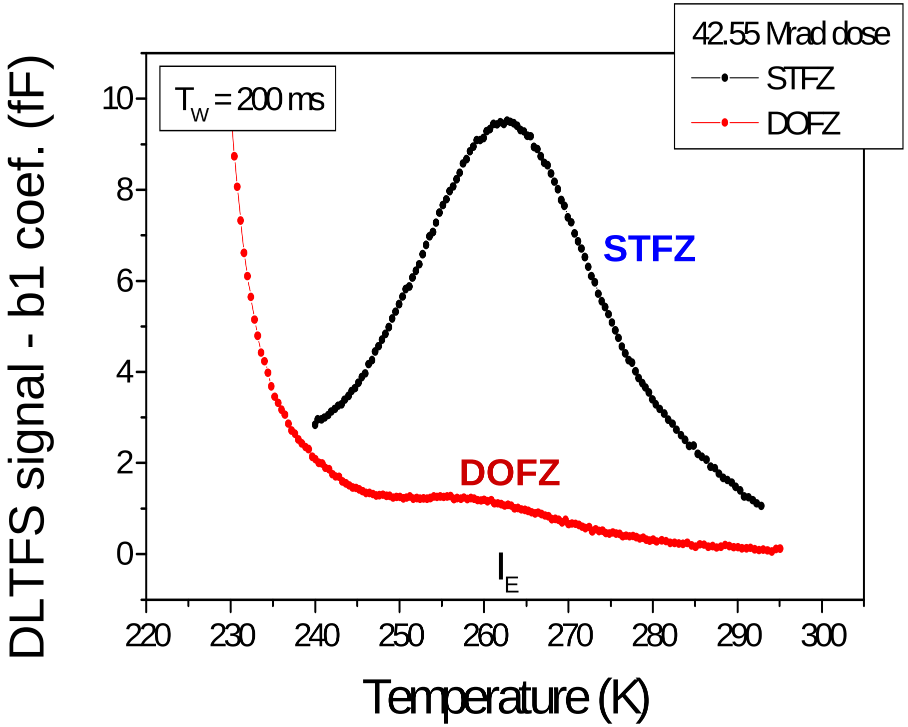




- **Very pronounced beneficial effect of oxygen on both I and V_{dep}**

- ***The change in Neff suggests the existence of a close to midgap acceptor (-/0) in O lean material and of a shallow donor in O rich silicon***

- Low irradiation γ doses (but already high for DLTS)

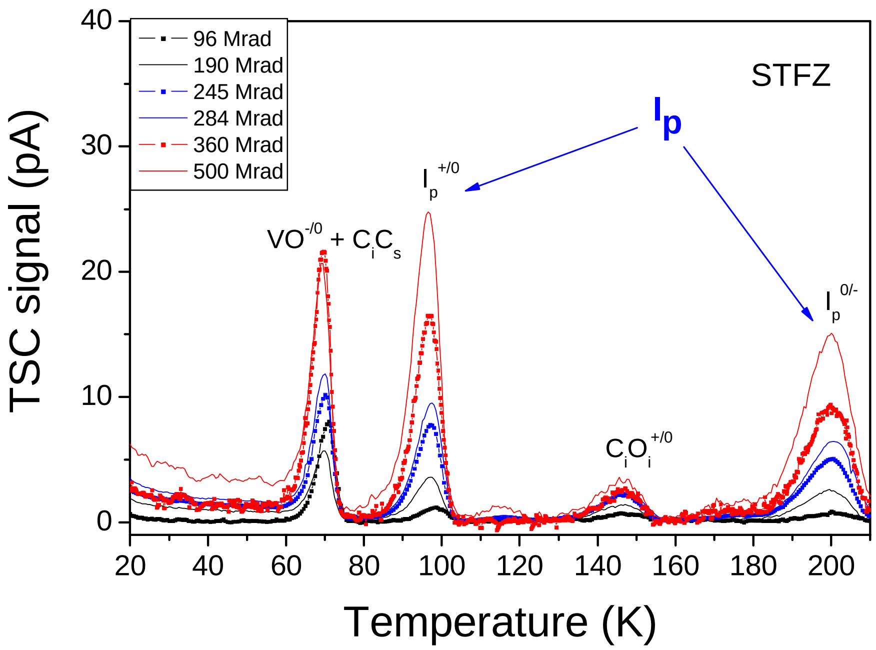


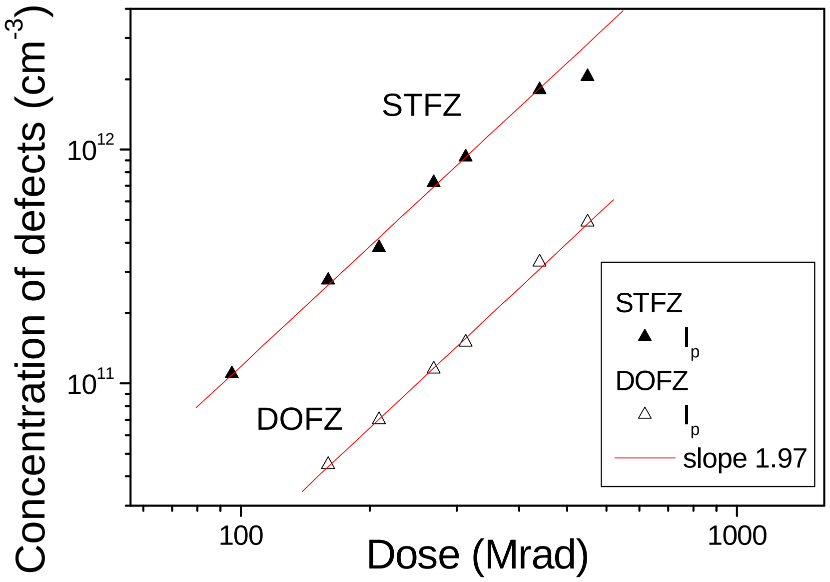
I_p center

- ***deep acceptor*** (-/0)
- Ea = Ec – 0.545 eV
- $\sigma_n = (1.7 \pm 0.2) \times 10^{-15}$ cm^2
  - direct measurement
- $\sigma_p = (9 \pm 1) \times 10^{-14}$ cm^2
  - from $N_T^{DLTS}(T)$

~ 90% occupied with (-) at RT

- Higher irradiation γ doses (TSC)





I_p centers

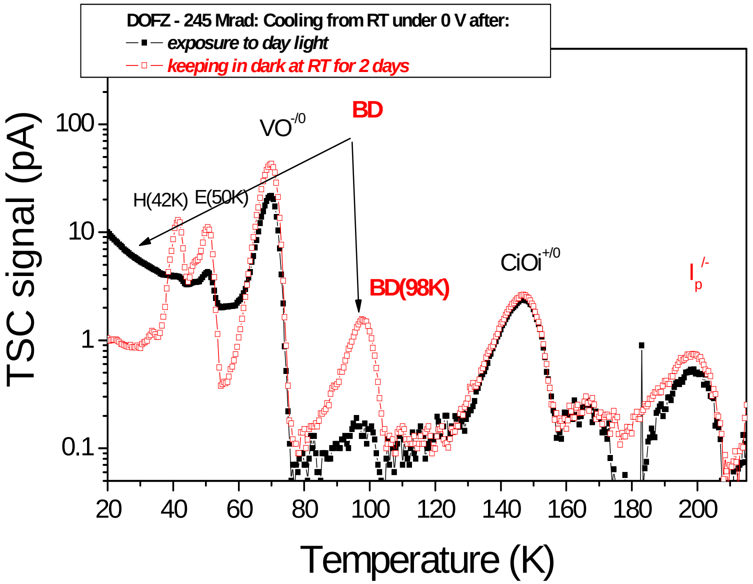
– Two levels in the gap: - a donor E_v+0.23eV (+/0) & an acceptor E_c-0.545 eV (0/-)

- Supressed in Oxygen rich material and Quadratic dose dependence

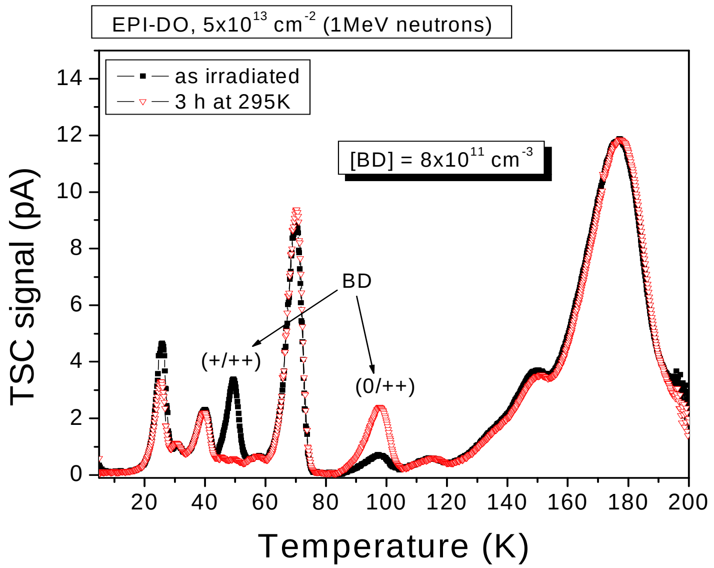
⇒ generated via a 2nd order process (V_2O?) 1) V+O → VO
2) V+VO → V_2O

<u>BD center</u> – bistability and donor activity

- In low doped n-type DOFZ



- In medium doped n-type EPI-DO



$E_i^{BD(98K)} = E_c - 0.225\ eV\ (0/++)\ ;\ E_i^{BD(50K)} = E_c - 0.15\ eV\ (+/++)$

<u>BD center</u> – donor in the upper part of the gap (+ at RT)

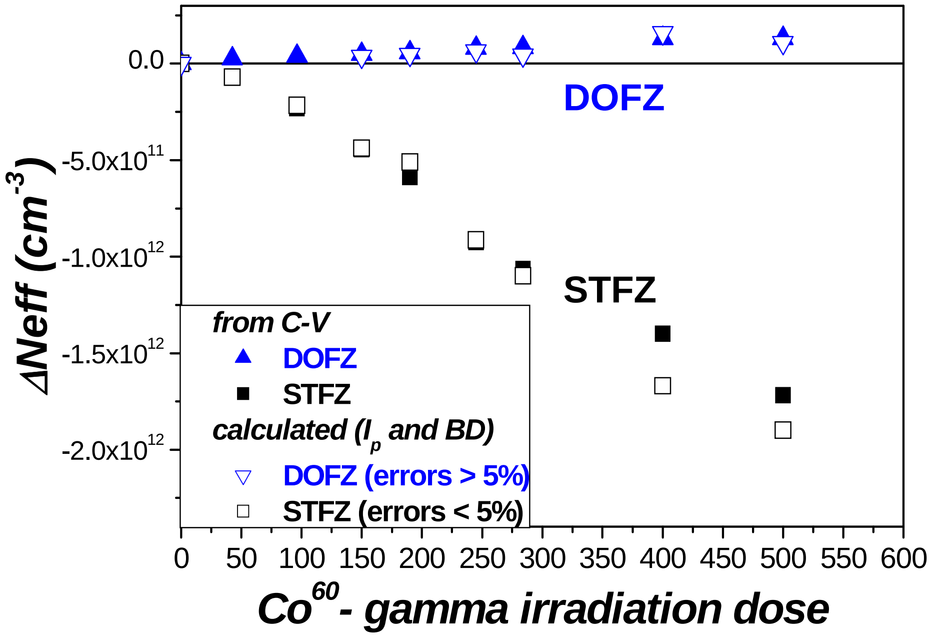
- ***generated in oxygen rich material***
- ***after $C0^{60}$- γirradiation, can even overcompensate the effect of deep acceptors!***

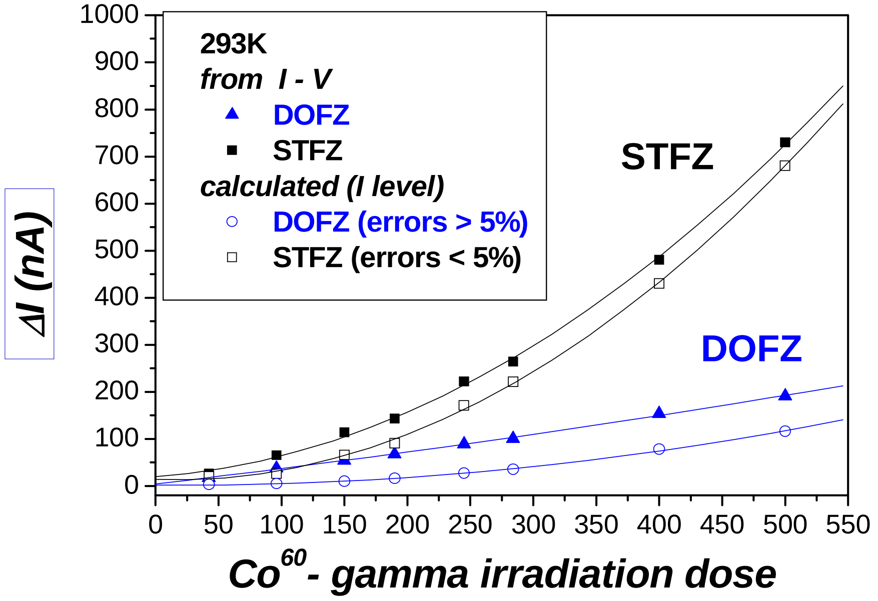
The bistability, donor activity and energy levels associate the BD centers with TDD2 $\Rightarrow$ oxygen dimers are part of the defect structure

Impact of I_p and BD defects on detector properties

$$\Delta N_{eff}(T) = -n_T(T)$$

$$\Delta I(T) = q_0 \cdot e_n(T) \cdot n_T(T) \cdot Vol$$



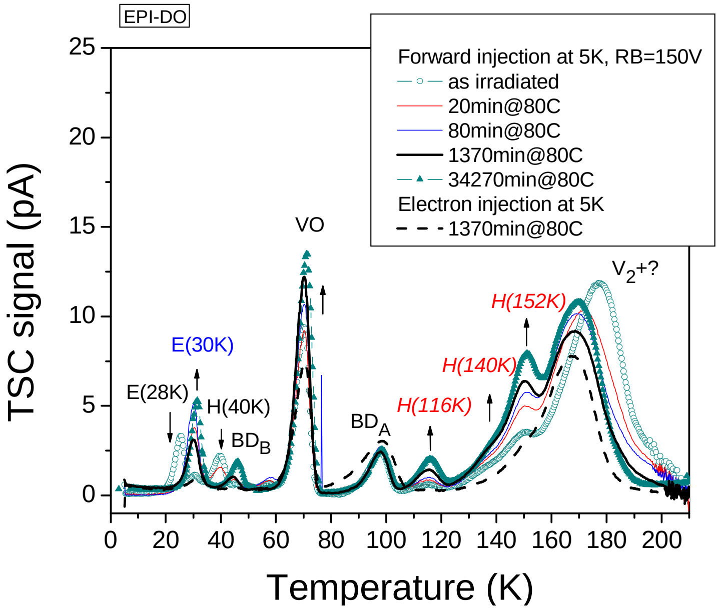


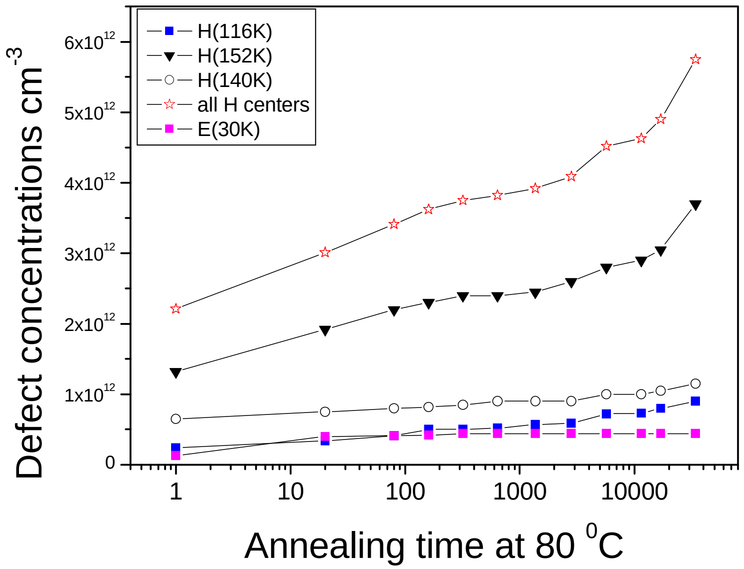
change of N_{eff} and leakage current well described

⇒ first breakthrough in understanding the damage effects

Results – Extended Defects (clusters)

- **After irradiation with 1 MeV neutrons,** $\Phi = 5\text{x}10^{13}\ \text{cm}^{-2}$





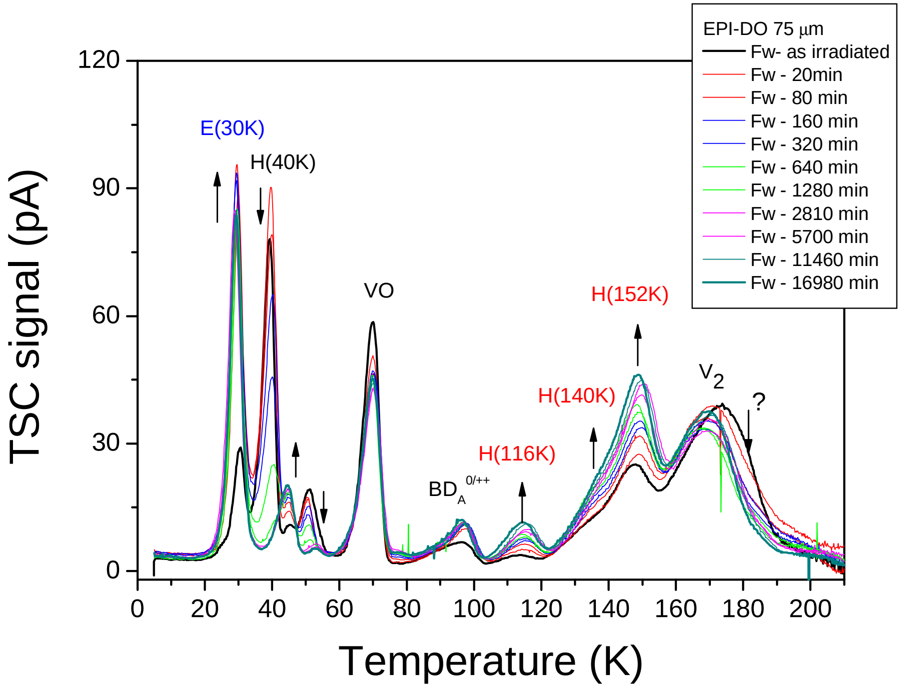
- H(116K), H(140K) and H(152K) traps for holes
- E(30K) trap for electrons

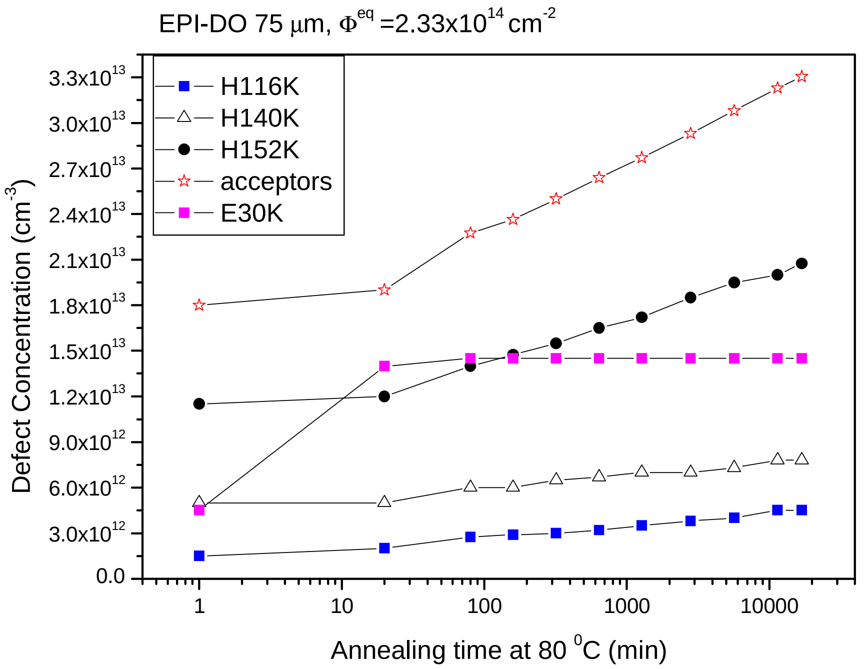
} Independent on the material

- H(116K) was detected previously
- H(152K) ~ was atributed so far to C_iO_i

■ 23 GeV protons

EPI-DO, 75 µm, $\Phi_{eq} = 2.33 \times 10^{14}$ cm^{-2}



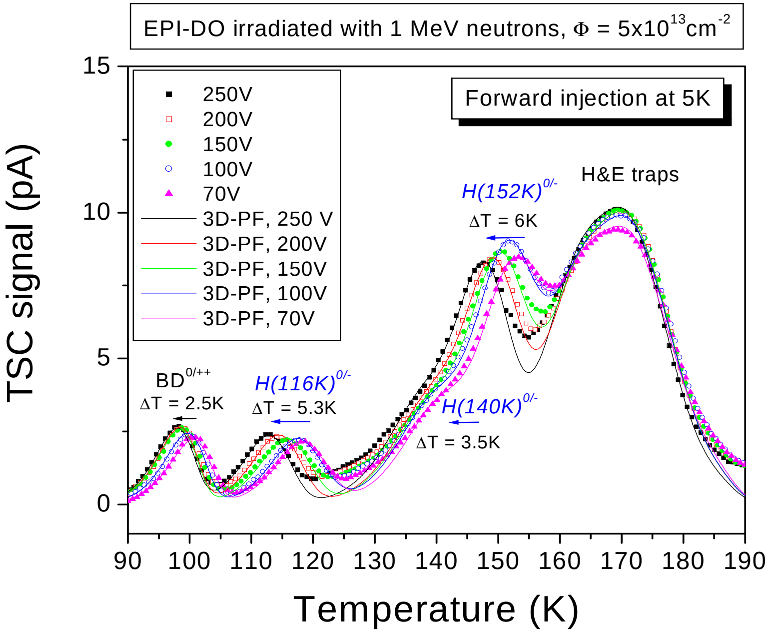


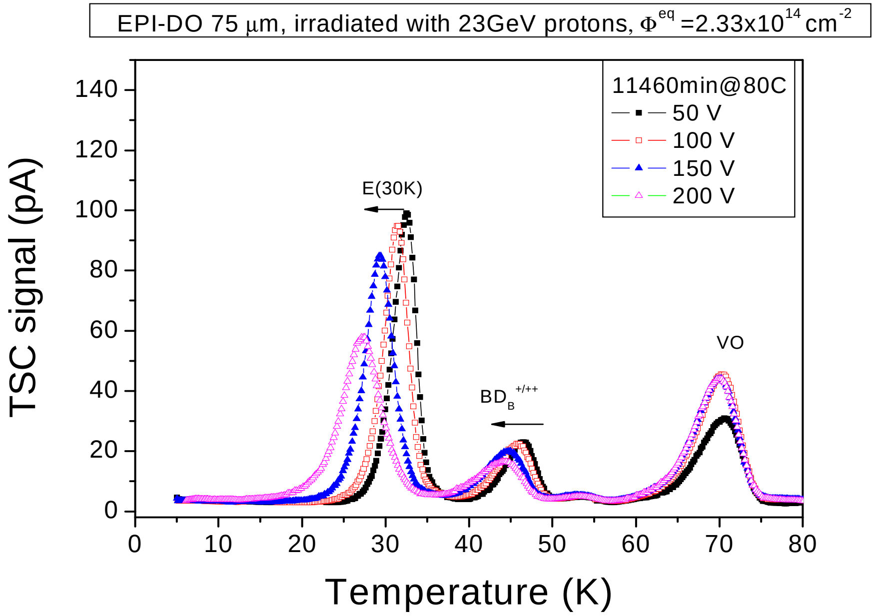
E(30K) center:

- Compared to neutron irradiation its generation is much enhanced relative to of the H centers!

- 20% less generated in EPI-ST than in EPI-DO

H(116K), H(140K), H(152K) and E(30K) - cluster related traps with enhanced field emission





- The 3D-Poole Frenkel effect formalism describes the experiments

$E_i^{116K} = E_v + 0.33eV, \sigma_p^{116K} = 4 \cdot 10^{-14}\ cm^2$
$E_i^{140K} = E_v + 0.36eV, \sigma_p^{140K} = 2.5 \cdot 10^{-15}\ cm^2$
$E_i^{152K} = E_v + 0.42eV, \sigma_p^{152K} = 2.3 \cdot 10^{-14}\ cm^2$

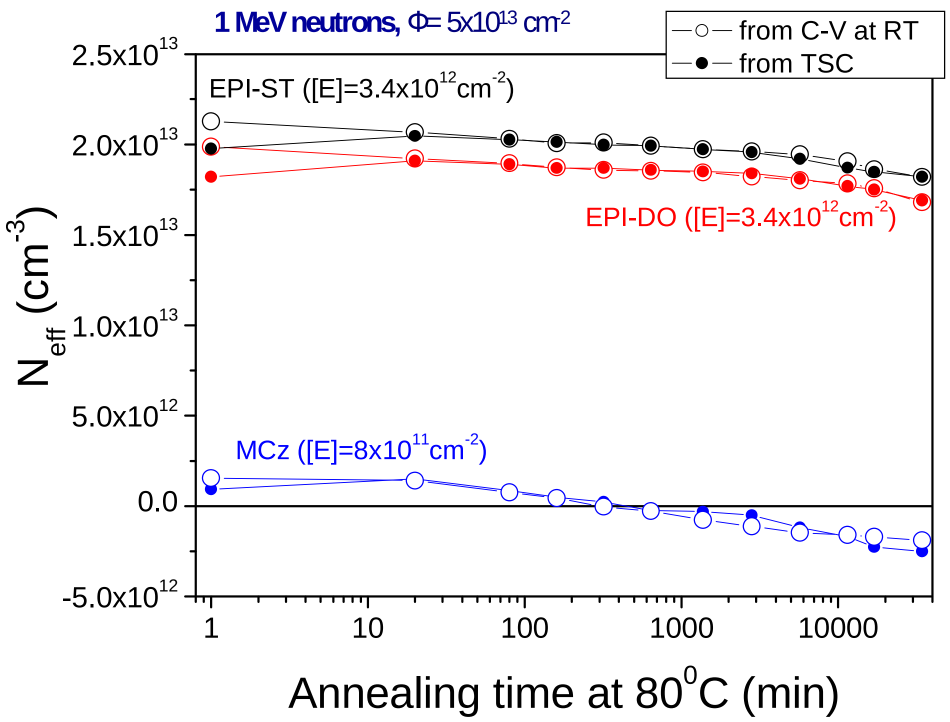
Are acceptors in the lower part of the gap and contribute with (-) space charge at RT

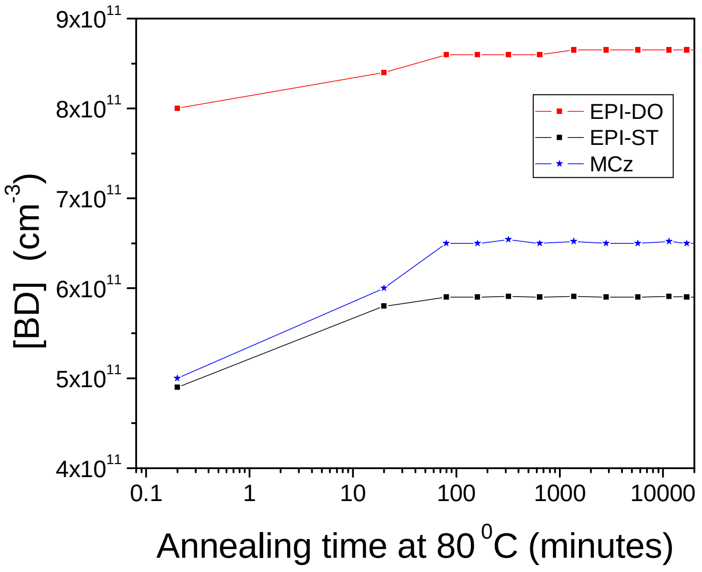
$E_i^{30K} = E_c - 0.1eV, \sigma_n^{30K} = 2.3 \cdot 10^{-14}\ cm^2$

Are donors in the upper part of the gap and contribute with (+) space charge at RT

The impact of BD, E(30K), H(116K), H(140K) and H(152K) on N_{eff}

EPI-ST: $N_d = 2.66\times10^{13}$ cm^{-3}; EPI-DO: $N_d = 2.48\times10^{13}$ cm^{-3}; MCz: $N_d = 4.94\times10^{12}$ cm^{-3}



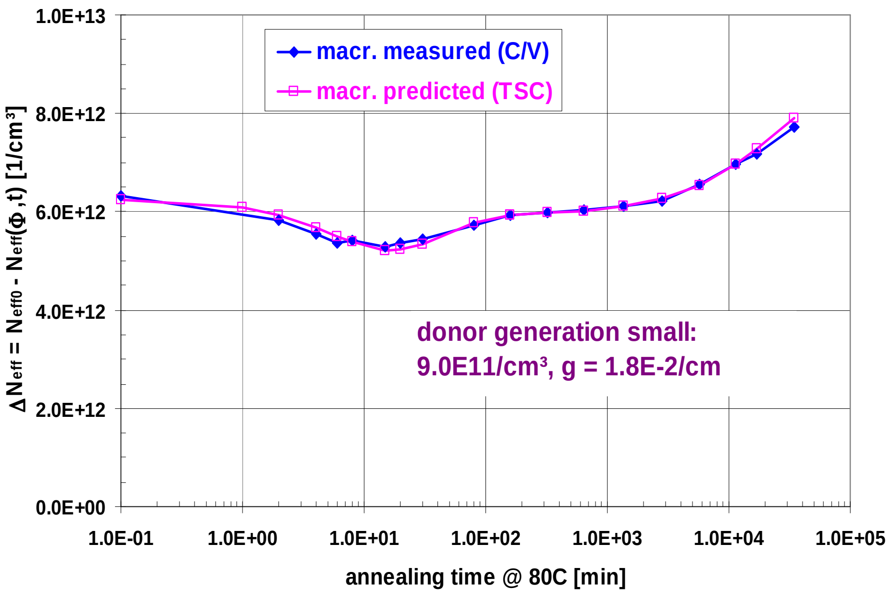


Differences between materials given by the initial doping (N_d) and [BD], only!

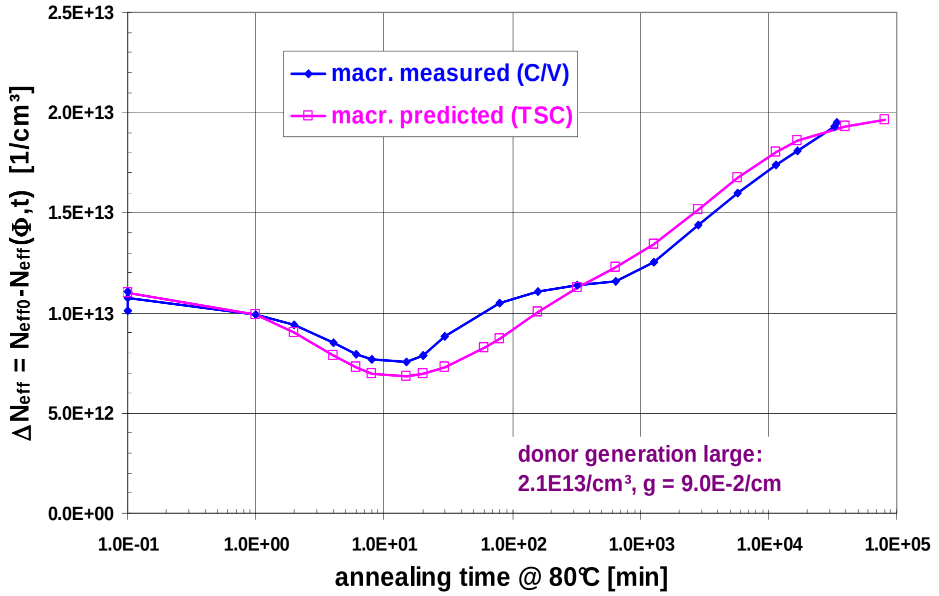
⇒ These are the defects responsible for the annealing of N_{eff} at RT!

EPI-DO 75 μm: $N_d = 2.48 \times 10^{13}$ cm^{-3}

1 MeV neutrons, $\Phi = 5 \times 10^{13}$ cm^{-2}

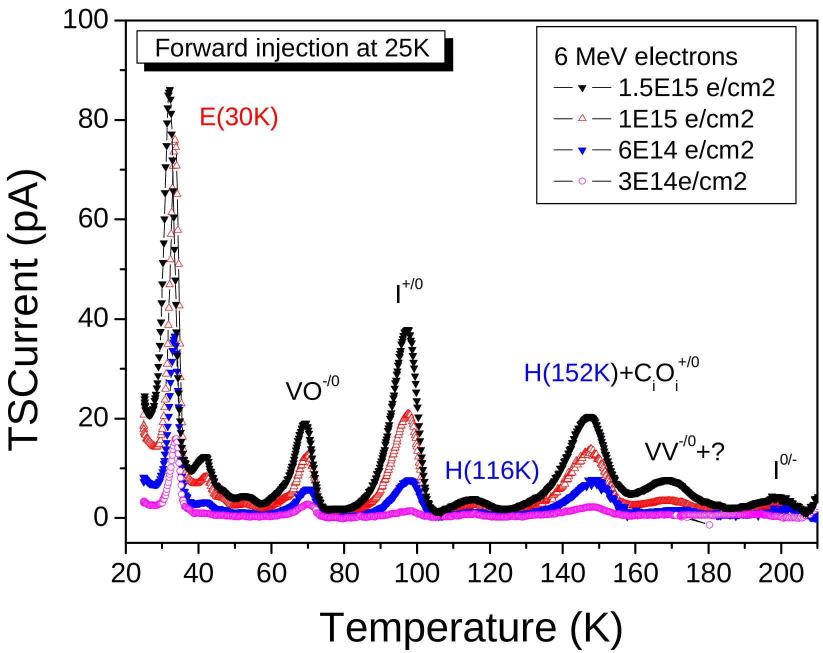


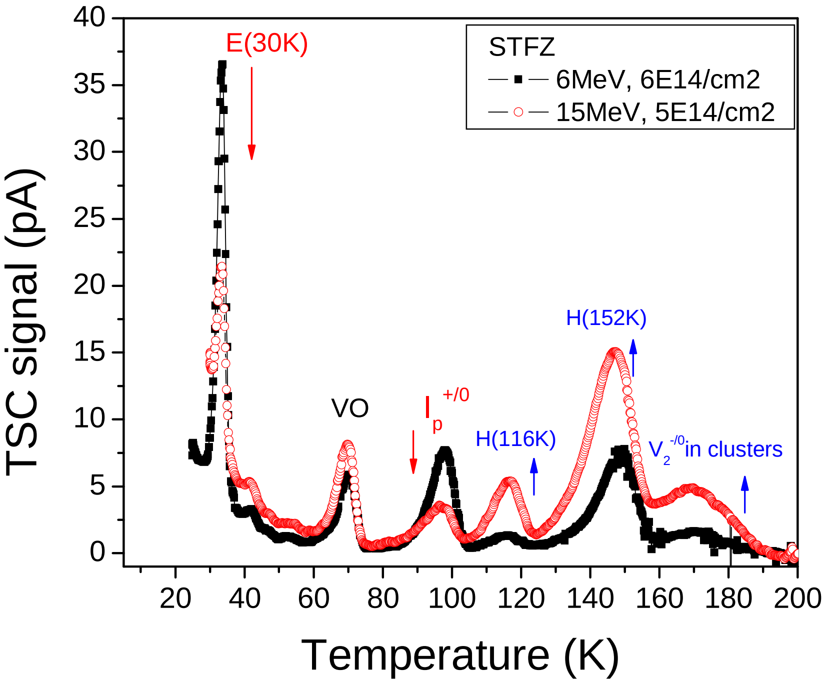
23GeV protons, $\Phi_{eq} = 2.33 \times 10^{14}$ cm^{-2}



Larger donor generation (E(30K) and BD) after 23GeV protons than after 1 MeV neutrons (~4.5 times) !

Defects due to electron irradiation (6 and 15 MeV)





- E(30K), H(116K), H(140K) and H(152K) – defects not seen after irradiation with gammas up to 500 Mrad dose ⇒ they are extended defects
- I_p, E(30K) defects decrease in concentration with increasing the electron energy ⇒ E(30K) may be a complex but not extended defect (~ I_3)

⇒ Clusters of defects (H(116K), H(140K) and H(152K)) start to form already for electron energies of 6 MeV

Summary

Identified point defects induced by irradiation

Defect	$E_{V,C}\pm E_t$ [eV]	$\sigma_{n,p}$ [cm^2]	T_{anneal} [°C]	g [cm^{-1}] N_t/Φ_{eq}	Material
IO_2(-/0)	–0.143	3.8×10^{-14}	≈100	≈ 0.21	MCz, EPI-DO
C_i(-/0)	–0.114	5.9×10^{-15}	≈80		FZ, EPI-ST
$C_iC_s^A$(-/0)	–0.171	1.4×10^{-14}	≈260		FZ, EPI-ST
VO_i(-/0)	–0.176	1.4×10^{-14}	≈300 / >300	0.73	MCz, EPI / FZ
X(=/-) V_2O(=/-)	–0.241	1.1×10^{-14}	≈260 in		MCz, EPI
V_2(=/-)	–0.224	7×10^{-16}	≈260 / 340	0.37	MCz,, EPI / Fz
L, V_3O(=/-)	–0.328	1.23×10^{-15}	≈240 in		MCz, EPI
E4, V_3(=/-)	–0.36	4×10^{-15}	≈240	0.19	MCz, EPI / FZ
E(205a)	–0.393	1.3×10^{-15}	≈180		MCz, EPI / FZ
V_2(-/0)	–0.424	2.1×10^{-15}	≈260 / 340	0.37	MCz, EPI / FZ
X(-/0), V_2O(-/0)	–0.467	1.1×10^{-14}	≈260 in		MCz, EPI
E5, V_3(-/0)	–0.456	5×10^{-15}	≈240	0.19	MCz,, EPI / FZ
C_iO_i(+/0)	+0.360	$2{,}45\times10^{-15}$	≈380	1.3	MCz, EPI / FZ

Summary

not identified defects but with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 1.7\cdot10^{-15}$ cm^2
  - $\sigma p^{I} = 9\cdot10^{-14}$ cm^2

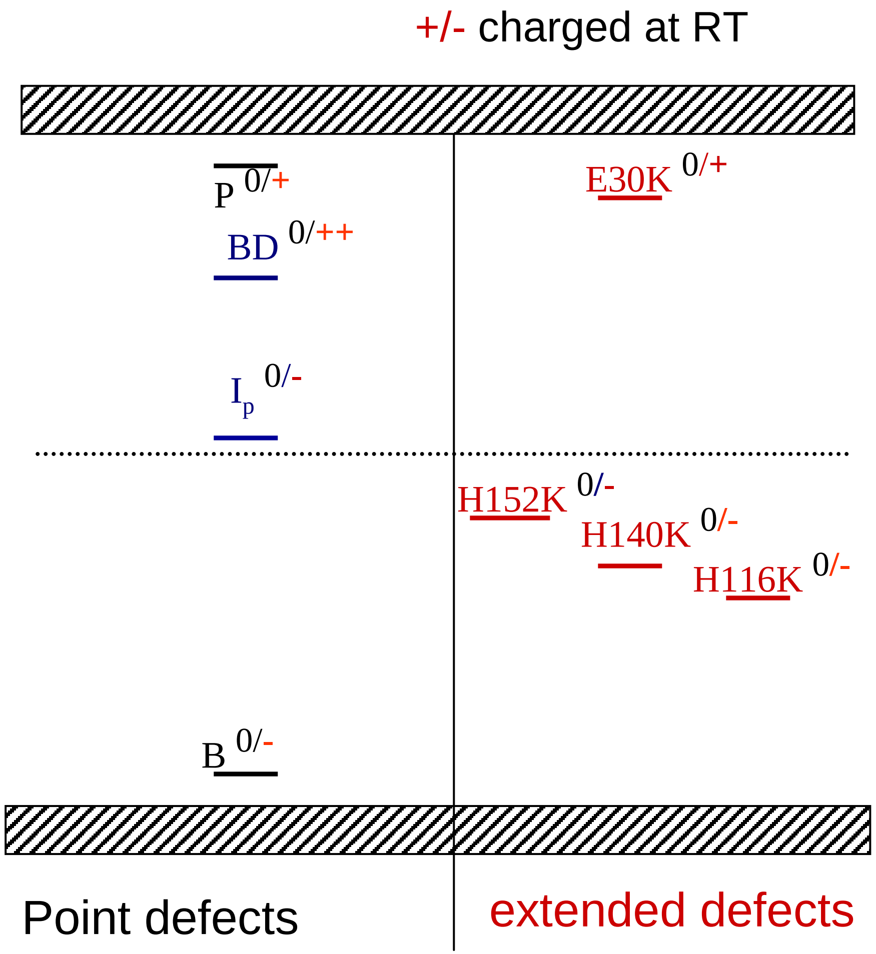
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2



Conclusions

- **Direct correlation between defect investigations and device properties can be achieved!**
- **Point defects – dependent on the material ⇒ defect engineering does work**
- **Cluster related defects – independent on the material ⇒ Possibility of compensation with point defects via defect engineering**
- ***Still missing the identification of the chemical nature of the defects that deteriorates the device characteristics***