Radiation induced point- and cluster-related defects with strong impact to damage properties of silicon detectors

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Outline

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- Techniques
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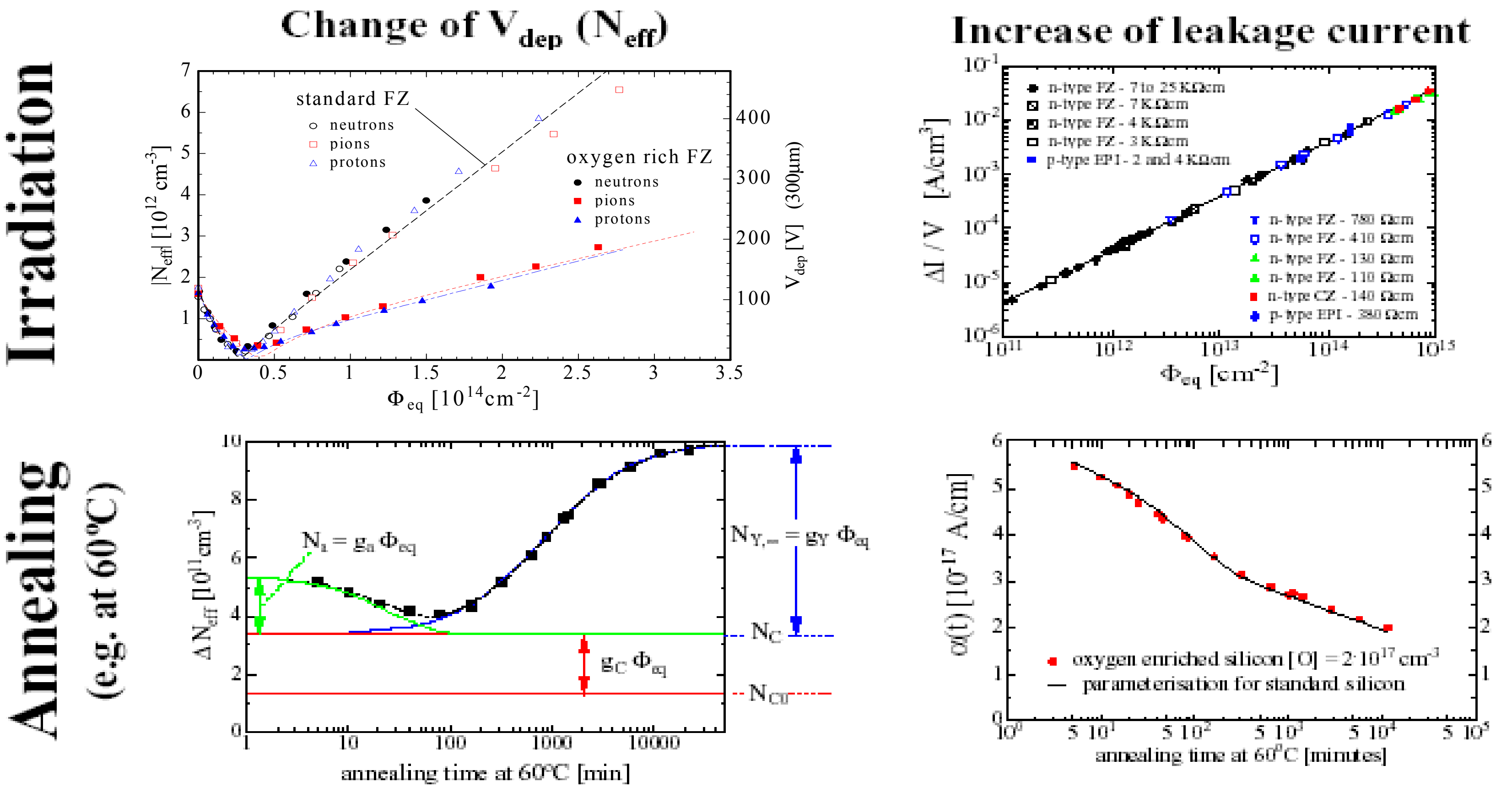
    - Extended defects
- Summary & Conclusions

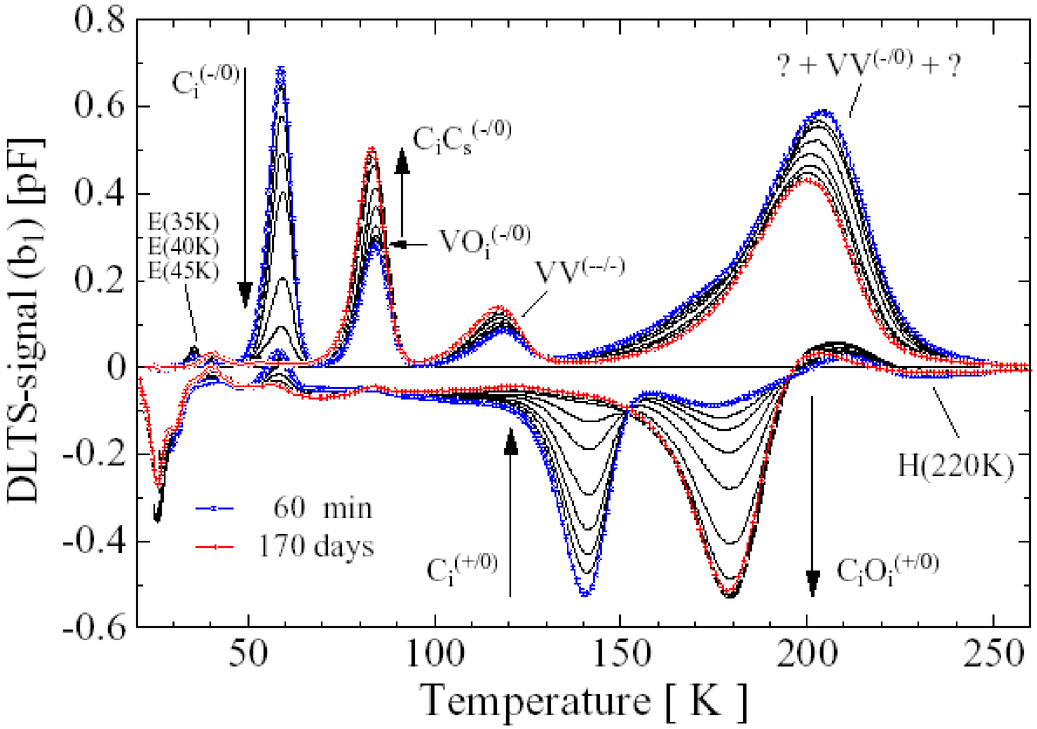
Motivation

Radiation Damage – Macroscopic Effects (CERN-RD48)



"Defect engineering" needed for SLHC application in the tracking area to improve the detectors radiation tolerance

Radiation damage – radiation induced defects



M. Moll, PhD-thesis 1999

- None of the detected defects could explain the macroscopic behaviour of the irradiated diodes
- The defect models attributed the oxygen effect to the formation of a deep acceptor (V_2O complex), suppressed in oxygen rich silicon

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

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

Defect´ signature – emission rates

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

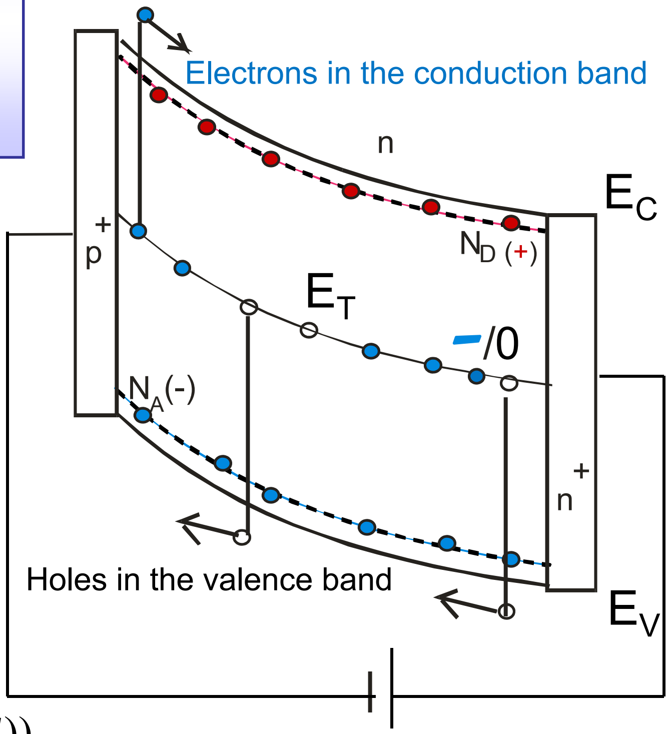
1) **Contribution to $\mathbf{N_{eff}}$** - given by the steady state ocupancy of the defect levels in SCR

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

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

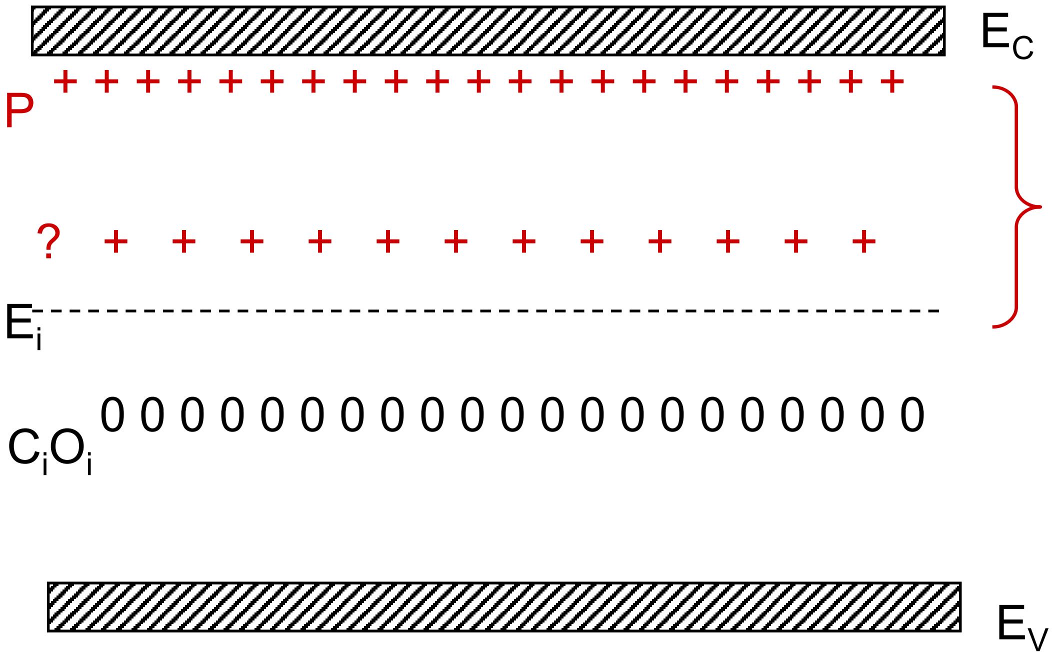
2) **Contribution to the leakage current**

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



Charge state of electrically active defects at room temperature

- **Donors (+/0)**

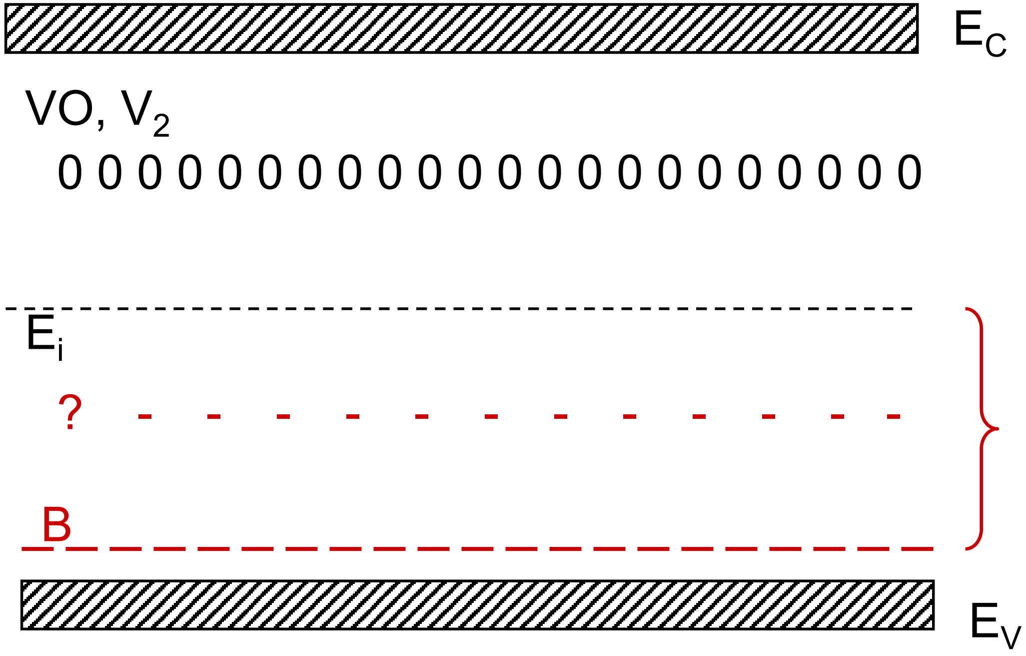


- traps for electrons
- show Poole-Frenkel effect
- Contribute with (+) to N_{eff} at RT

- 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

Techniques

I) Deep Level Transient Spectroscopy **- for $N_T < 10\% \ N_d$**

- based on measuring capacitance transients: $\Delta C = \Delta C_0 \exp(-e_{n,p}t)$

► emission rates - $e_{n,p}(T)$ - position in the bandgap - ΔE_T
- capture cross sections - σ_n , σ_p

► defect concentration: $N_T \sim 2 \cdot N_d \cdot \Delta C/C_0$

II) Thermally Stimulated Currents Method **– improved for $N_T > N_d$ and for centers with enhanced field emission**

- based on measuring the current due to emission from the filled traps

► emission rates - $e_{n,p}(T)$ - position in the bandgap - ΔE_T
- apparent capture cross sections - σ_n , σ_p

► defect concentration: N_T

Material & Irradiations

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°C (EPI-DO) $N_d = 2.48x10^{13}$ cm^{-3}

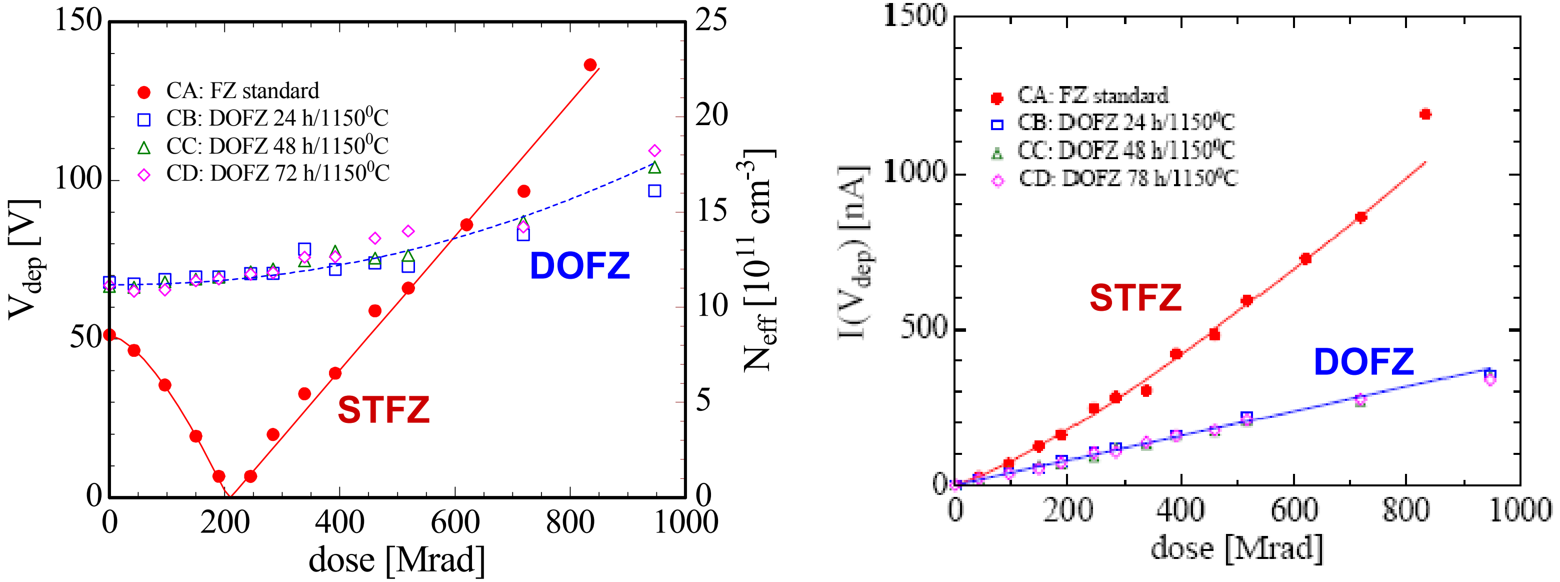
Irradiations

- **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

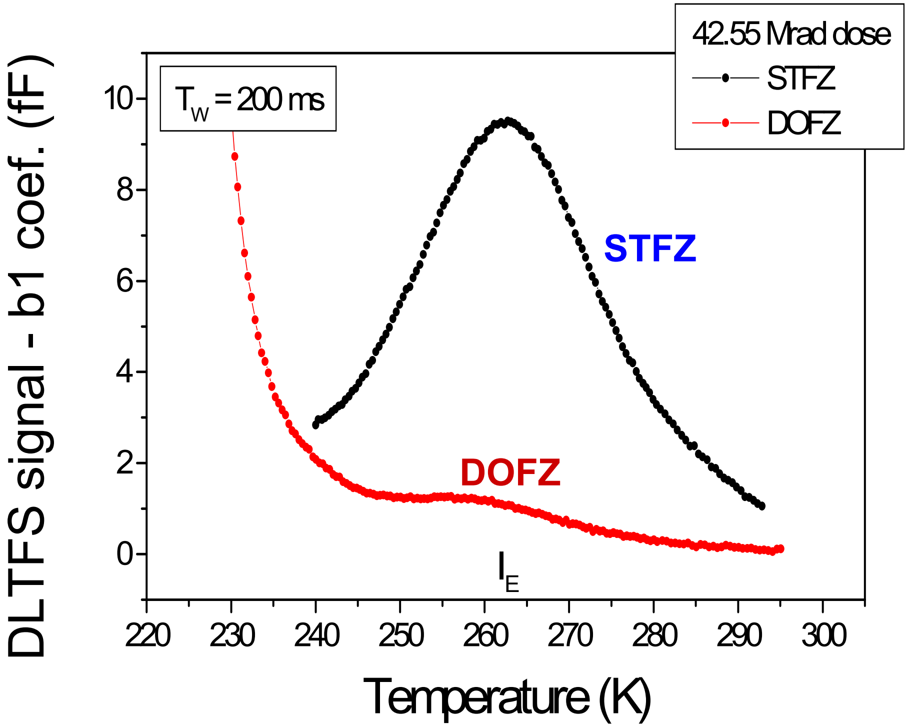
Results – Point Defects (Ref. 1-6)

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



- **Very pronounced beneficial effect of oxygen on both I and V_{dep}**
- ***Close to midgap acceptor correlated with [O] responsible ?***

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



I_p center

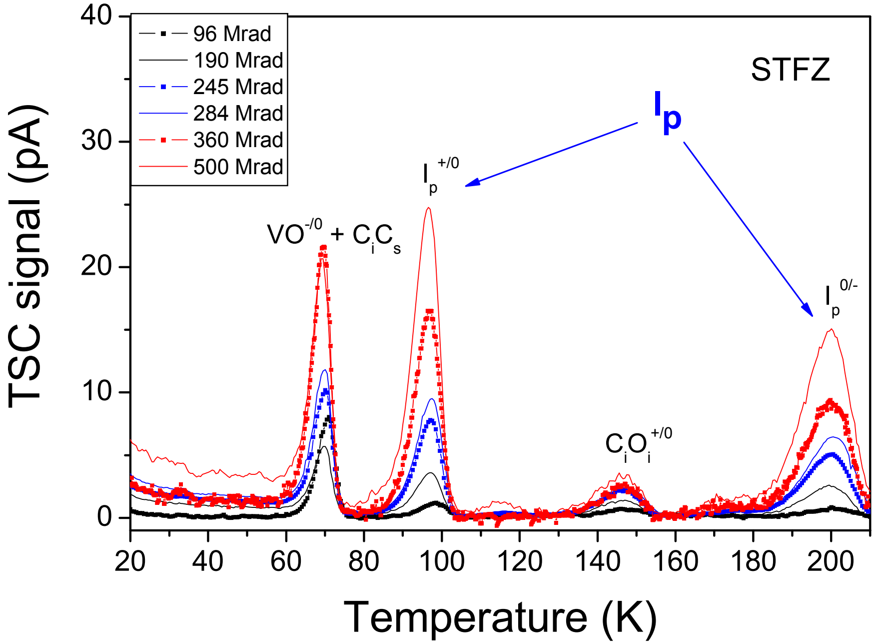
- ***deep acceptor*** (-/0)
- Ea = Ec – 0.545 eV
- $\sigma_n = (1.7\pm0.2)\times10^{-15}$ cm^2

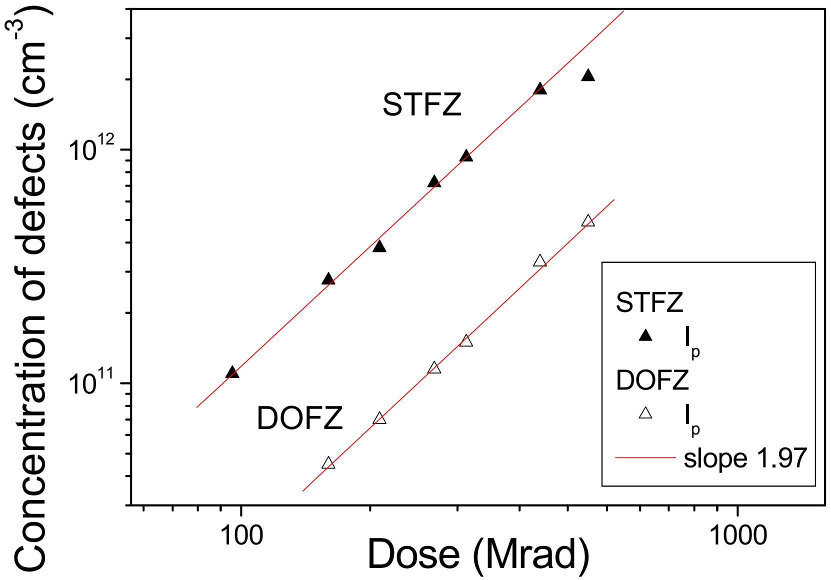
  - direct measurement
- $\sigma_p = (9\pm1)\times10^{-14}$ cm^2

  - from $N_T^{DLTS}(T)$

~ 90% occupied with (-) at RT

- Higher irradiation γ doses (TSC)





I_p centers

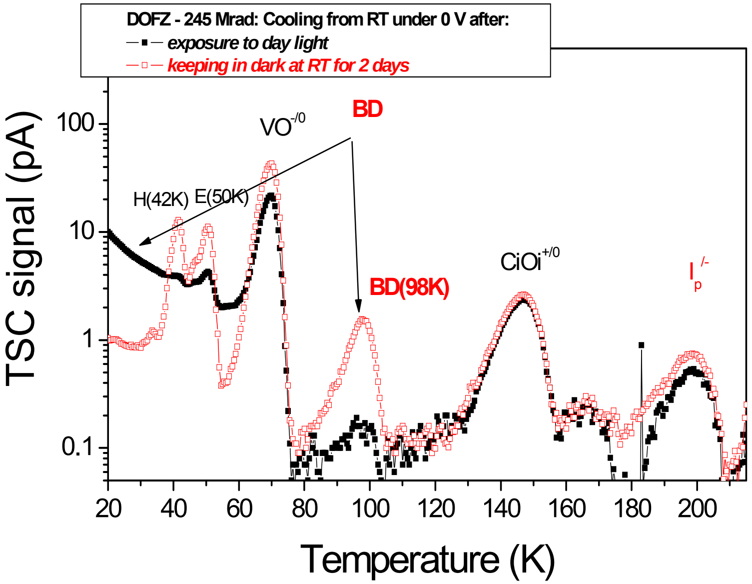
– Two levels in the gap: - a donor E_v+0.23eV (+/0) & an acceptor E_c-0.545 eV (0/-)

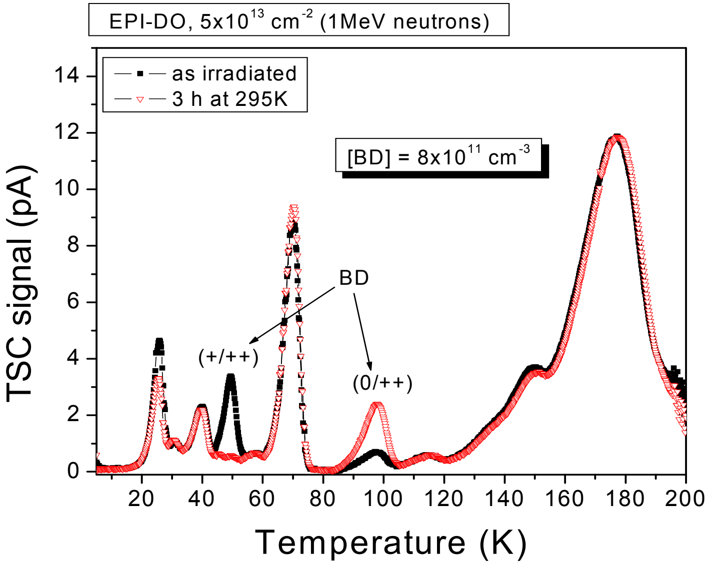
- Supressed in Oxygen rich material and Quadratic dose dependence

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

BD center – 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/++) ; $E_i^{BD(50K)} = E_c - 0.15\ eV$ (+/++)

BD center – donor in the upper part of the gap (+ at RT)

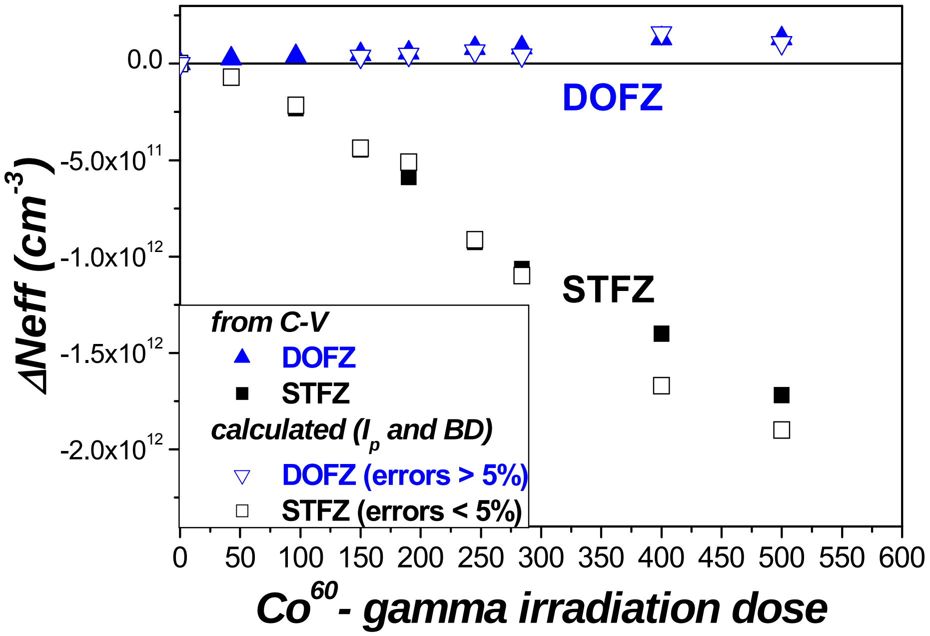
- ***generated in oxygen rich material***
- ***after $C0^{60}$- γ irradiation, can even overcompensate the effect of deep acceptors!***

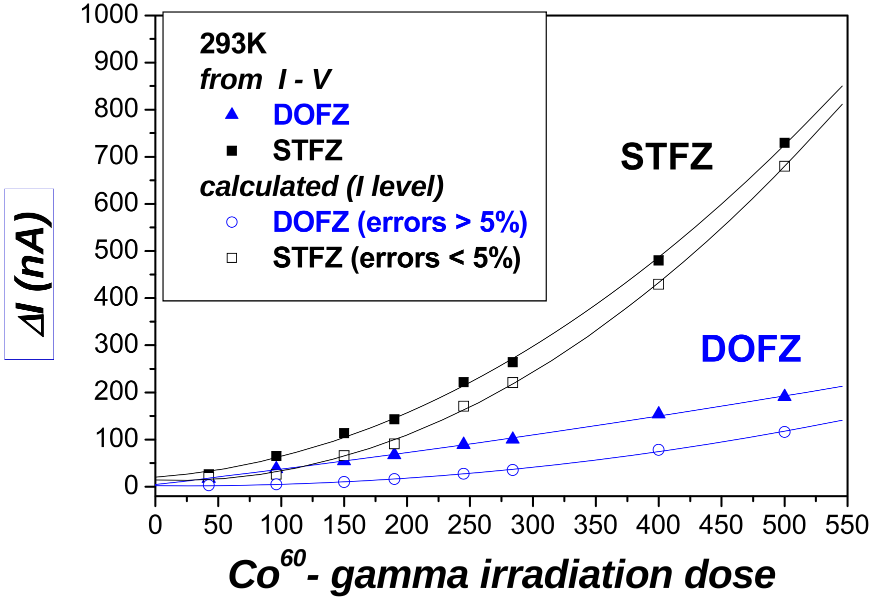
The bistability, donor activity and energy levels associate the BD centers with TDD2 $\Rightarrow$ oxygen dimers are part of the defect structure

Impact of I_p and BD defects on detector properties

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

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



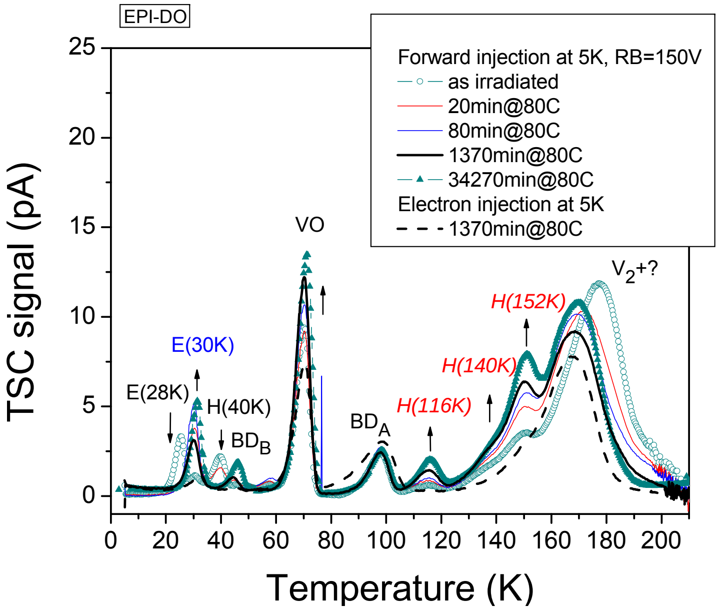


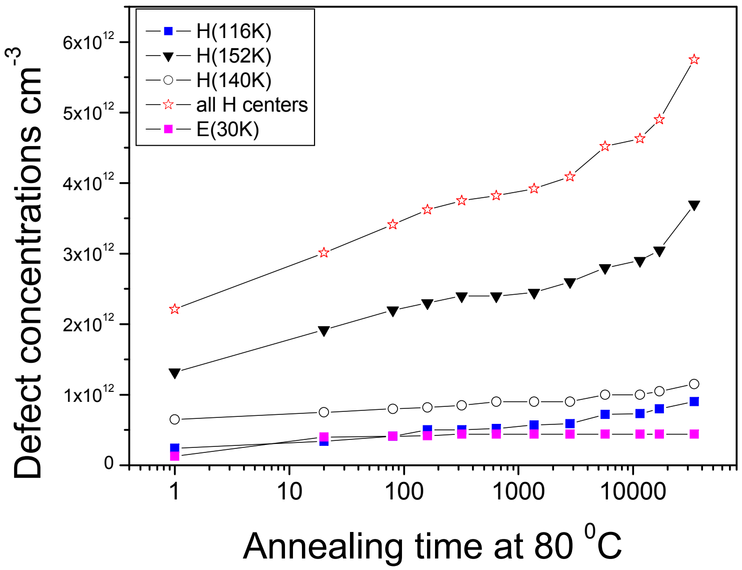
change of N_{eff} and leakage current well described

⇒ first breakthrough in understanding the damage effects

Results – Extended Defects (clusters) (Ref. 7)

- **After irradiation with 1 MeV neutrons, Φ= $5x10^{13}$ cm^{-2}**





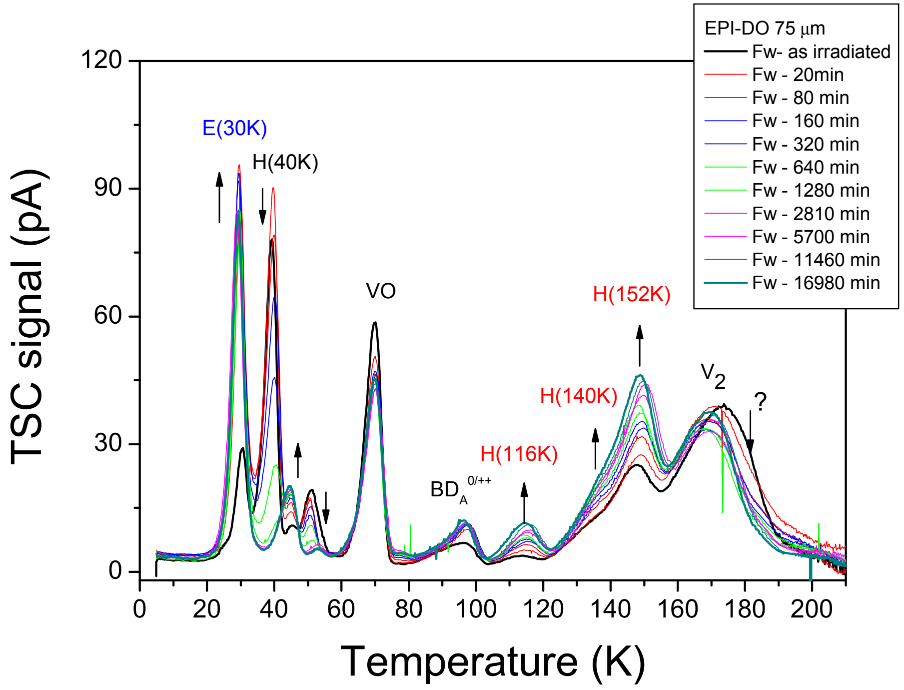
- H(116K), H(140K) and H(152K) traps for holes
- E(30K) trap for electrons

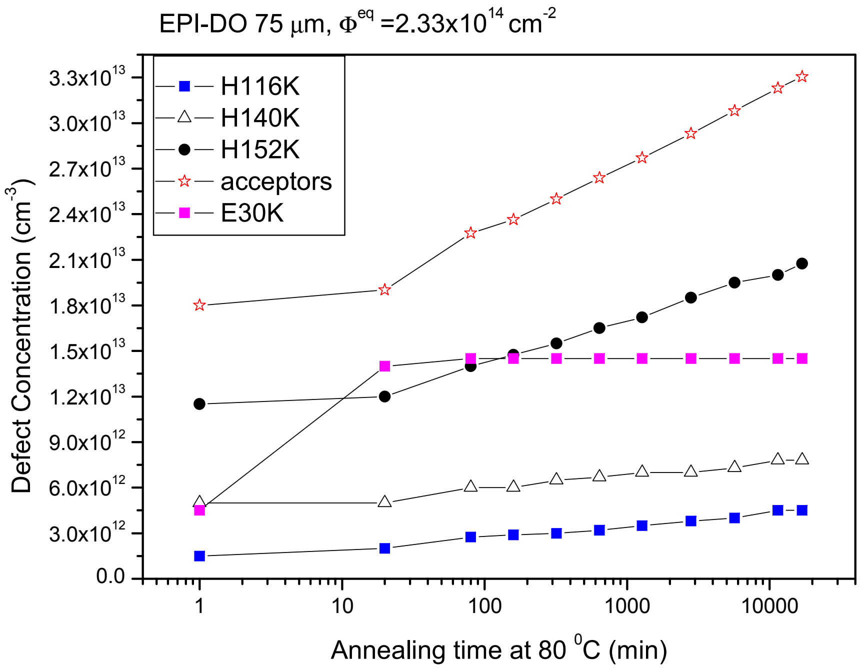
} Independent on the material

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

▪ 23 GeV protons

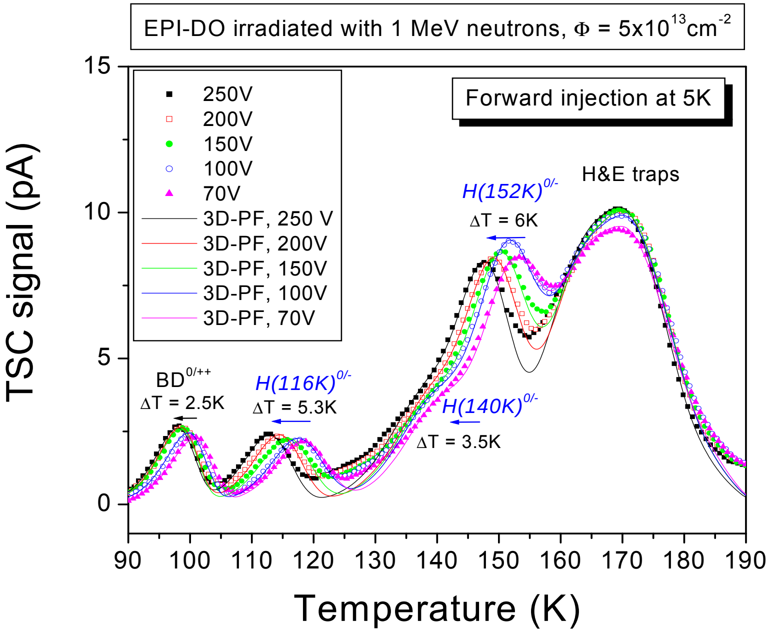
EPI-DO, 75 µm, $\Phi_{eq}= 2.33\mathrm{x}10^{14}\ \mathrm{cm}^{-2}$

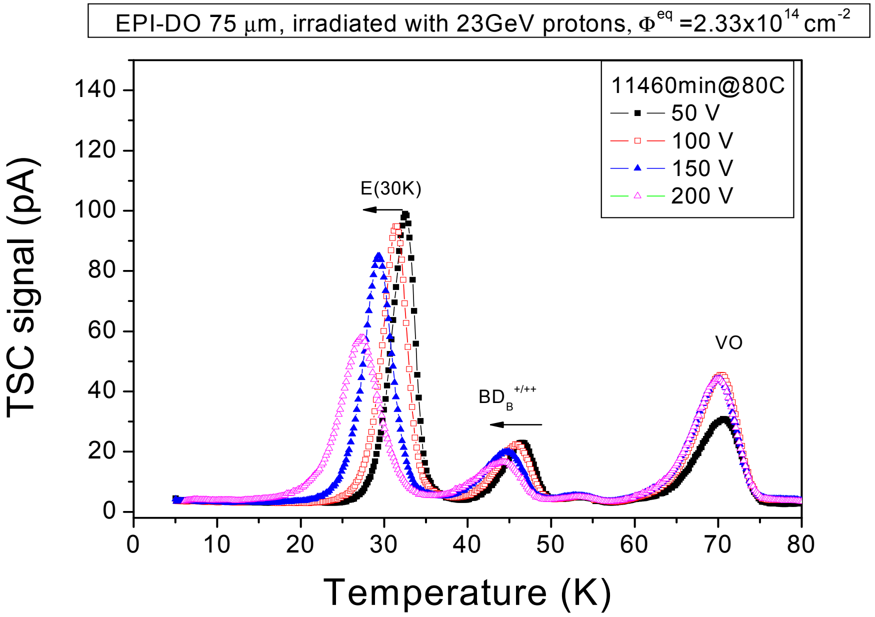




The generation of E(30K) center is much enhanced relative to of the H centers !

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

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

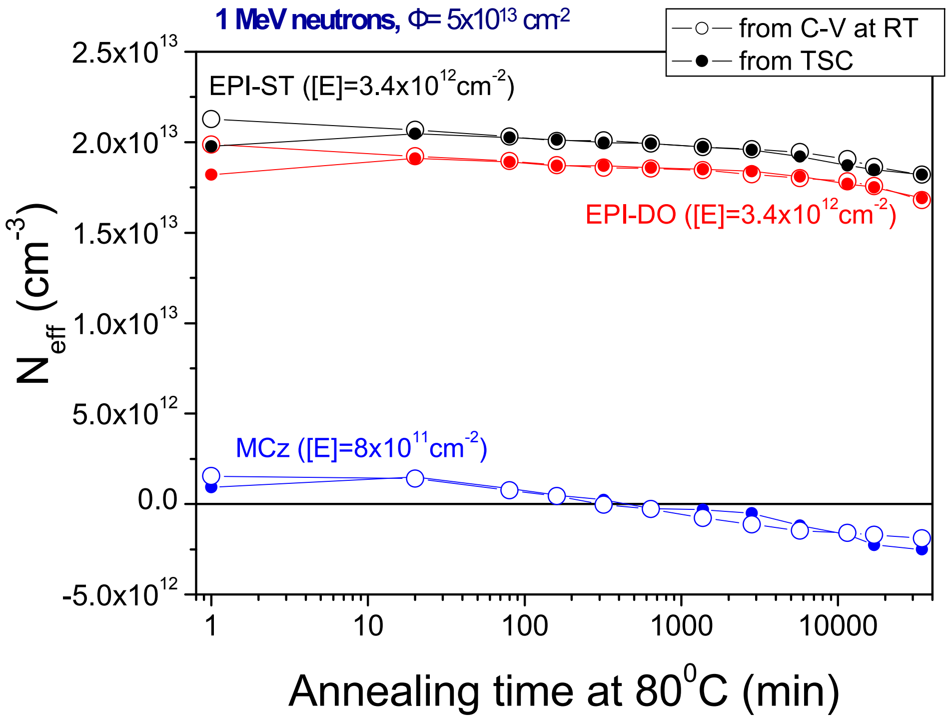
Are acceptors in the lower part of the gap and contribute with (-) space charge at RT

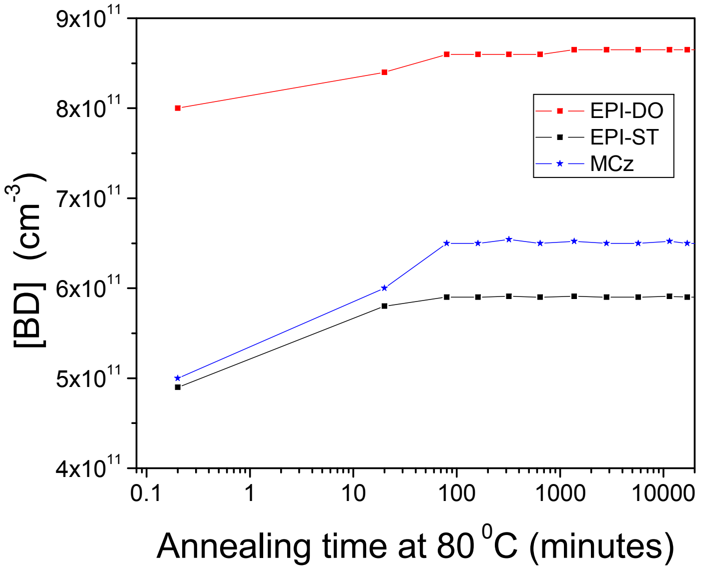
$E_i^{30K} = E_c - 0.1eV, \sigma_n^{30K} = 2.3\cdot 10^{-14}\ cm^2$

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: $N_d = 2.66 \times 10^{13}$ cm^{-3}; EPI-DO: $N_d = 2.48 \times 10^{13}$ cm^{-3}; MCz: $N_d = 4.94 \times 10^{12}$ cm^{-3}



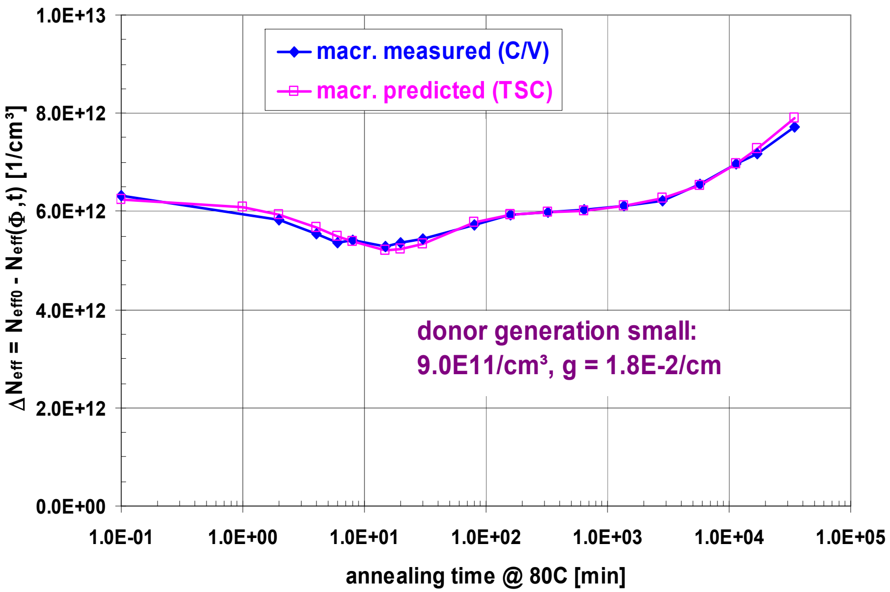


Differences between materials given by the initial doping (N_d) and [BD], only!

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

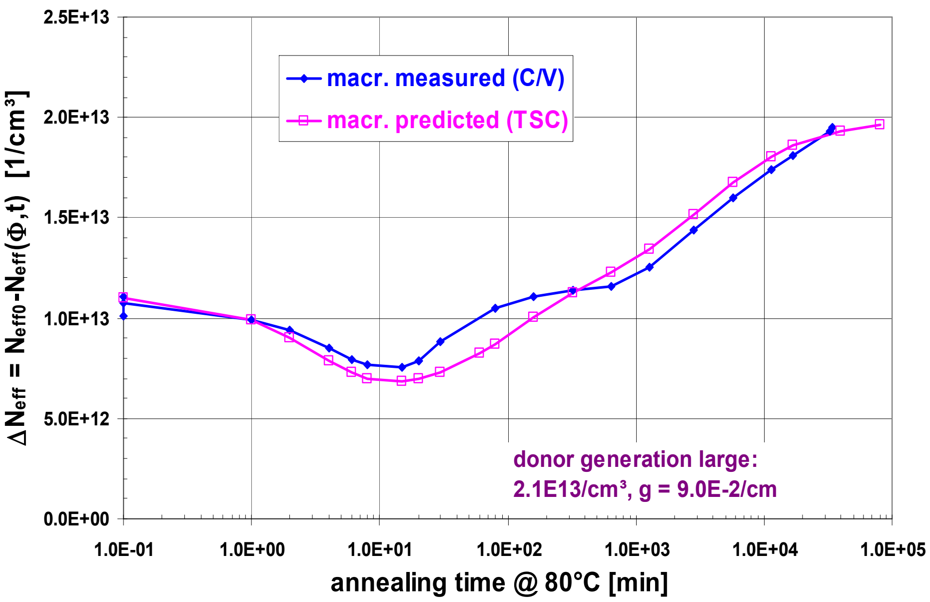
EPI-DO 75 μm: $N_d = 2.48\text{x}10^{13}$ cm^{-3}

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



donor generation small:
9.0E11/cm³, g = 1.8E-2/cm

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



donor generation large:
2.1E13/cm³, g = 9.0E-2/cm

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

Summary – defects with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{I} = E_c - 0.545$ eV
  - ☐ $\sigma_n^{I} = 2.3 \cdot 10^{-14}$ cm²
  - ☐ $\sigma p^{I} = 2.3 \cdot 10^{-14}$ cm²

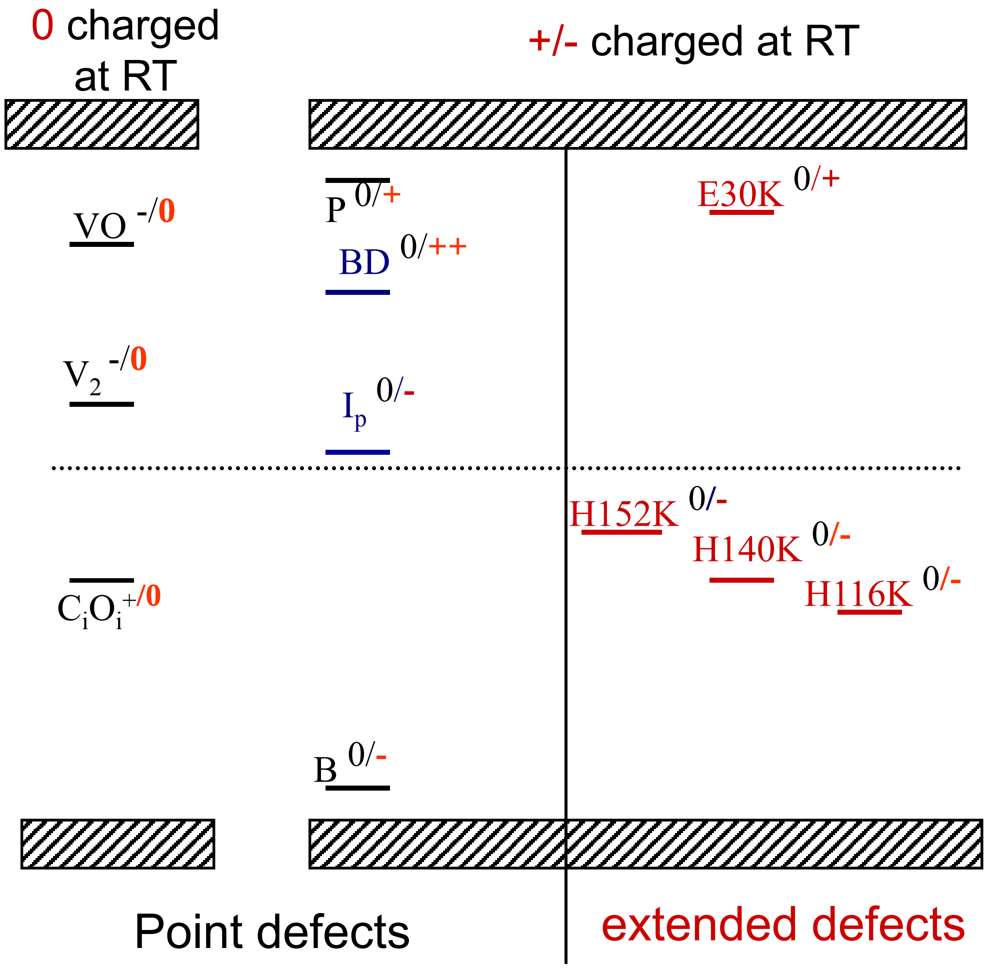
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm²



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**

Acknowledgements

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