Cluster related hole traps with enhanced-field-emission - the source for long term annealing in hadron irradiated Si diodes -*

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Materials

MCz-Silicon wafers: <100>, n/P, 100 µm, 1090 Ωcm, Nd = 3.96×10^{12} cm^{-3}, CiS process (samples 8556-02-25 and 8556-05-35)

EPI-Silicon wafers: <111>, n/P, 72 µm on 300 µm Cz-substrate, 169 Ωcm, CiS process

-standard Oxidation (EPI-ST) (sample 8364-02-35), Nd = 2.66×10^{13} cm^{-3},

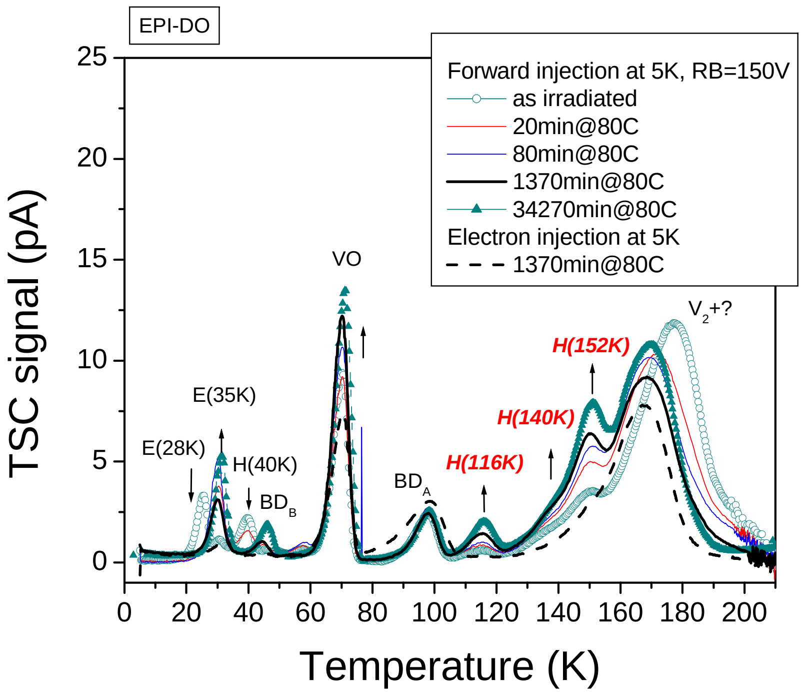
- diffusion oxygenated for 24 h/1100°C (EPI-DO) (sample 8364-05-36) Nd = 2.48×10^{13} cm^{-3}

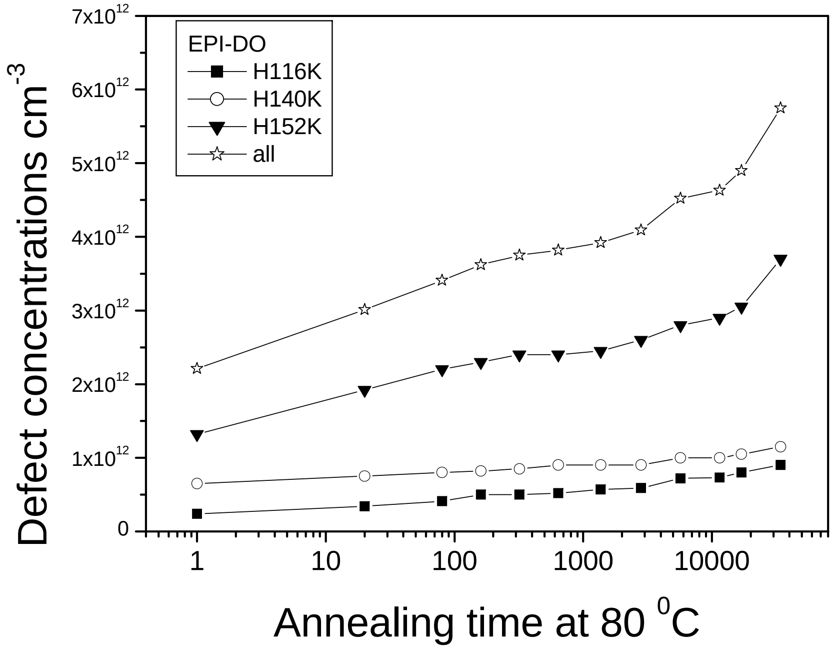
Irradiation: - 1MeV neutrons at Ljubljana; fluences of 5×10^{13} cm^{-2}
- Co^{60}- gamma irradiation at BNL (300 Mrad dose)

Annealing : Isothermal treatments at 80 ^{0}C

Investigation methods:
- I-V, C-V
- TSC

TSC results-for fully depleted diodes

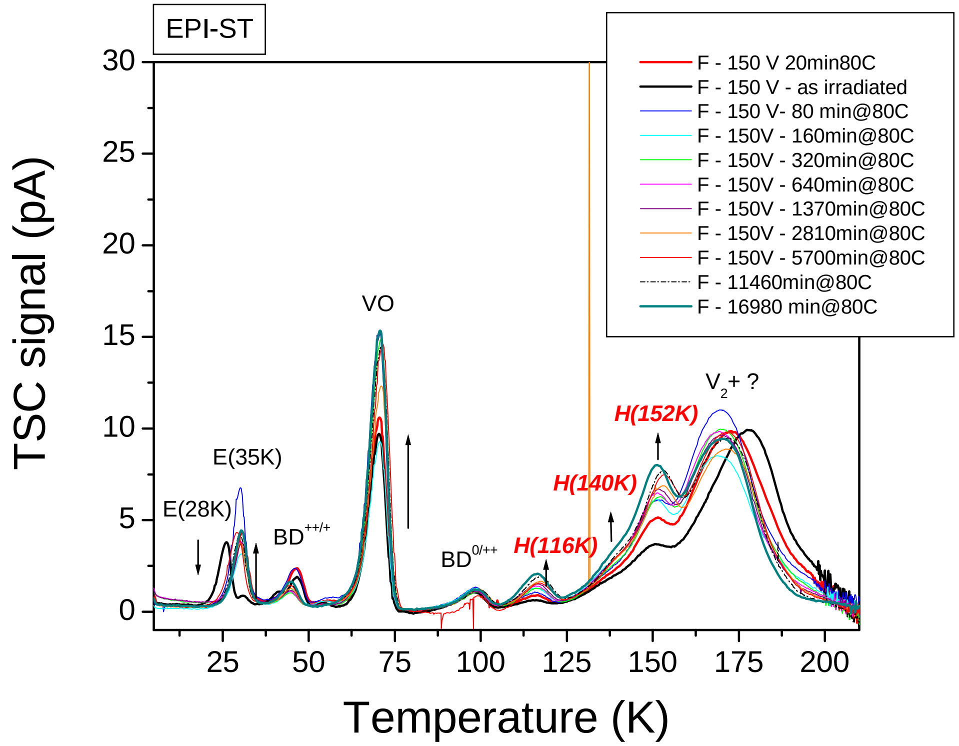


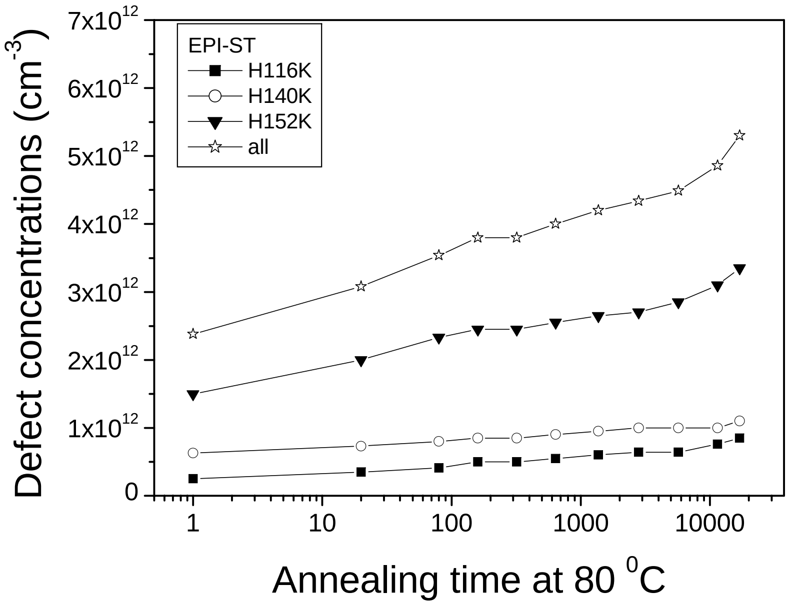


- H(116K) was detected previously*
- H(152K) ~ was atributed so far to C_iO_i

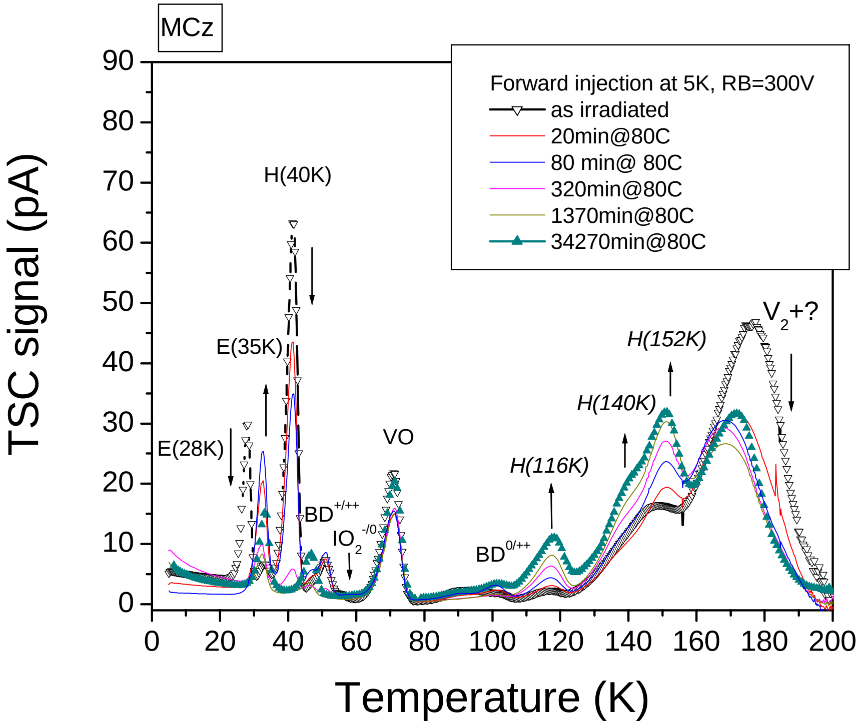
* M. Moll, H. Feick, E. Fretwurst, G. Lindstroem, Nucl. Instrum. Meth. Phys. Res. A **409,** 194 (1998)

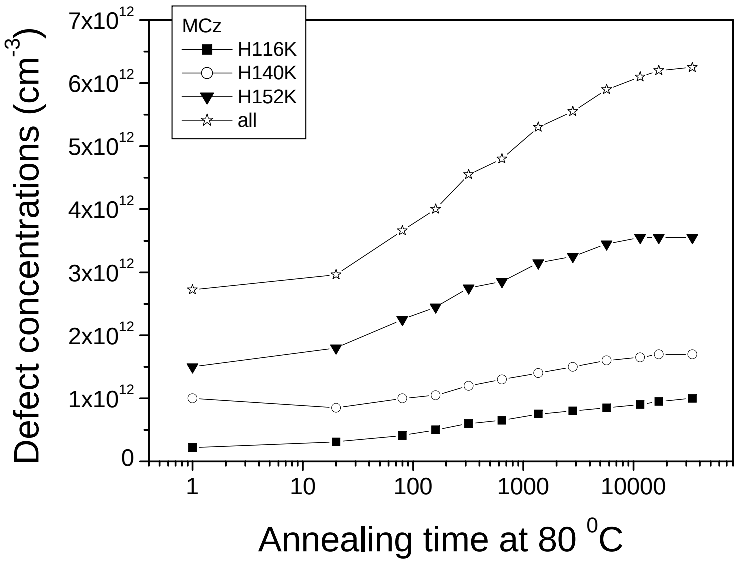
TSC results-for fully depleted diodes



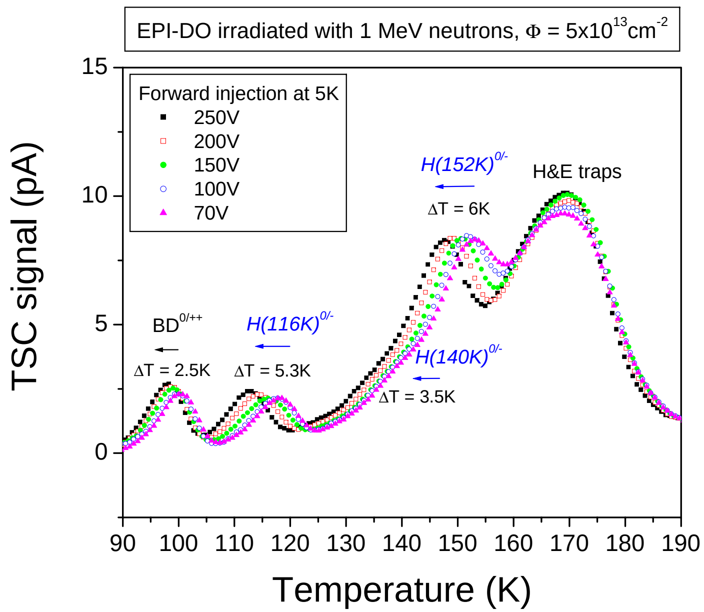


TSC results-for fully depleted diodes

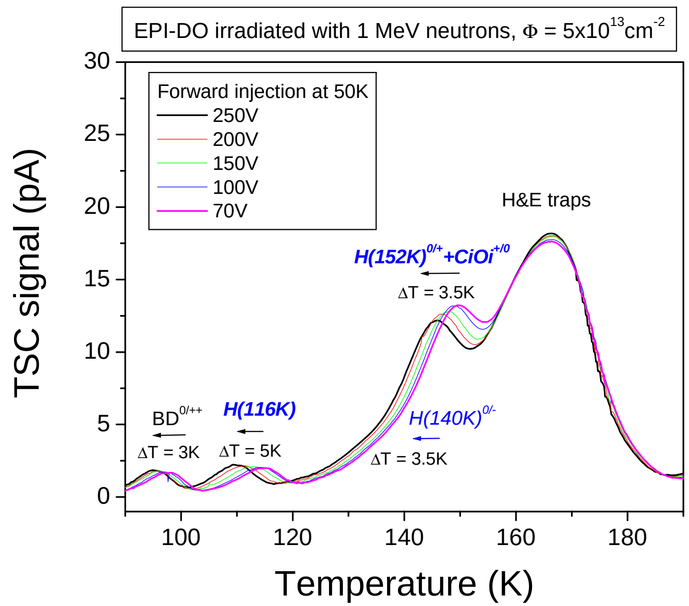




H(116K), H(140K) and H(152K)- hole traps with enhanced field emission

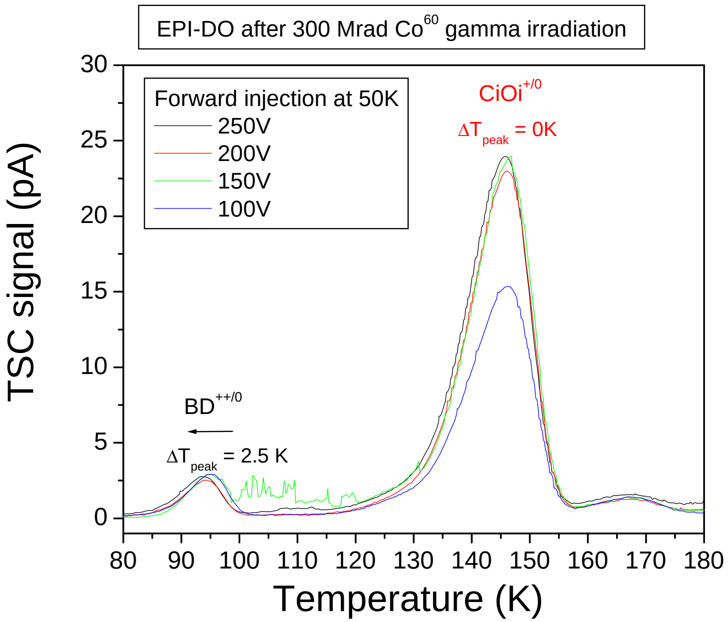


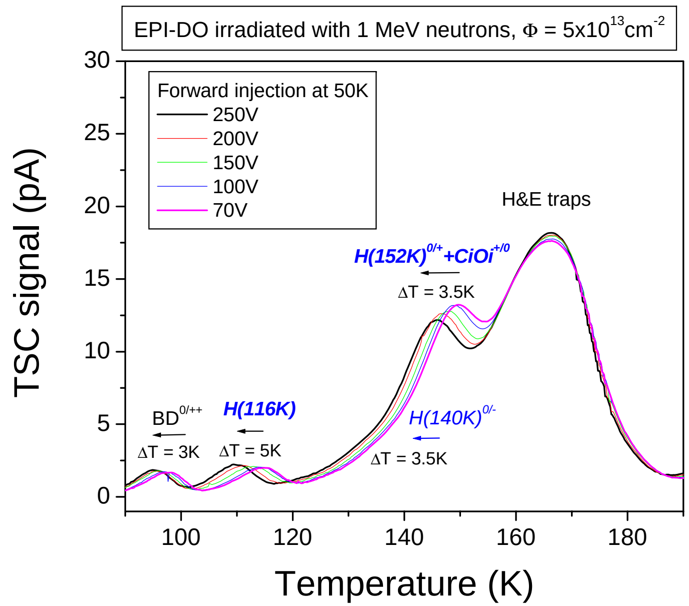
Filling of traps at 5 K



Filling of traps at 50 K

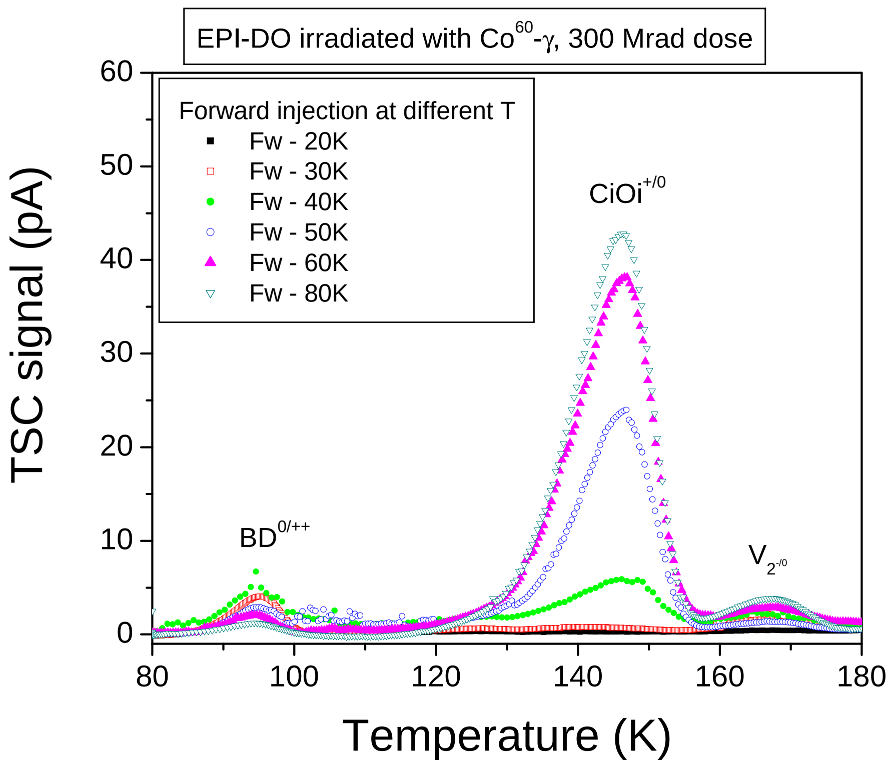
Point defects and cluster related defects





All H(116K), H(140K) and H(152K) are cluster related defects

How much C_iO_i can overlap to H(152K) peak ?



For $T_{filling}$< 30K no C_iO_i can be filled

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As long as the forward injection is performed at T_{fill}< 30K the magnitude of H(152K) peak is not affected by the C_iO_i defect

TSC spectra analysis for traps with enhanced field emission

In general, the TSC signal resulting from a hole trap in the diode is given by:

$$TSC(T) = \frac{q \cdot A \cdot w \cdot P_t \cdot e_p(T)}{2} \cdot \exp\left\{ -\frac{1}{\beta} \int_{T_0}^{T} e_p(T) \cdot dT \right\}$$

where P_t is the concentration of the filled traps, e_p is the emission rate of holes, w the depleted width of the diode, A is the active area of the diode.

- This formalism is not suited for traps with enhanced electric-field-emission, it may lead to huge errors in evaluating the defect level position in the band gap
- An identification of the mechanism behind the enhanced-field-emission depends on how the experimental data fits when different potentials are accounted for the defect

Mechanisms leading to an enhanced-electric-field-emission

- Poole Frenkel effect is characteristics to coulombic wells
  - where the carrier climbs over a barrier lowered by the electric field
  - seen for electric fields 10^3 - 10^6 V/cm
  - gives a clear indication about the charge state of the defect

- pure tunneling
  - the carriers are tunneling the barrier at high energy
  - possible only for electric fields > 10^7 V/cm
  - gives no indication about the defect charge state

- phonon assisted tunneling

– the carriers absorb thermal energy from the latice and then tunnel through the barrier at a higher energy

– seen for electric fields 10^4 - 10^6 V/cm

– gives no indication about the defect charge state

Poole Frenkel effect

$V(r) = -q^2/4\pi\varepsilon_0\varepsilon_r - qFr\cos\theta,$

$\Delta E_i = V(r_{max}) = -q(qF\cos\theta/\pi\varepsilon_0\varepsilon_r)^{1/2}$

- For one dimensional PF effect $\theta=0$ and $e_p^{PF} = e_{p0}\exp(-\Delta E_i/kT)$
- For three dimensional PF effect $0 < \theta < \pi/2$ and

$$e_p^{PF} = e_p^{0}(1/\gamma^2)\left[e^{\gamma}(\gamma-1)-1\right]+1/2$$

where, $\gamma = (qF/\pi\varepsilon_0\varepsilon_r)^{1/2} q/k_B T$

- for F has to be considered the local electric field in the p^+n diode:

$F(x) = qN_{eff}(d-x)/\varepsilon_0\varepsilon_r + (V-V_d)/d$ if $V>V_d$

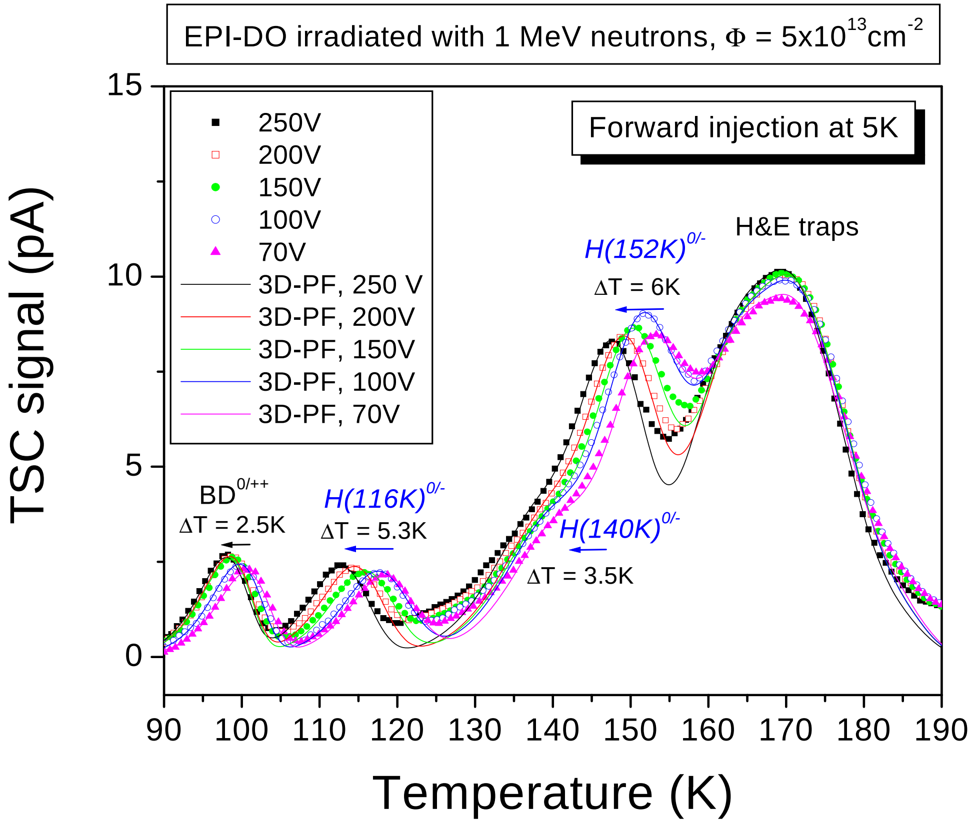
$F(x) = qN_{eff}(w-x)/\varepsilon_0\varepsilon_r$ if $V<V_d$

TSC spectra analysis for traps with enhanced field emission

For Coulombic wells the emission rate depends on the local electric field and the corresponding TSC peak should be calculated according to:

$$TSC^{PF}(T) = \frac{q \cdot A \cdot P_t}{2} \int_0^w e_p^{PF}(x,T) \cdot \exp\left\{ -\frac{1}{\beta} \int_{T_0}^{T} e_p^{PF}(x,T) \cdot dT \right\} dx$$

Results for the fit of TSC peaks with 3D-PF



The 3D-PF effect formalism describes the experiments

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The H(116K), H(140K) and H(152K) centers have acceptor levels in the lower part of the gap

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The H(116K), H(140K) and H(152K) centers contribute with their full concentration as negative space charge to N_{eff}^{0} in the initially n-type silicon diodes

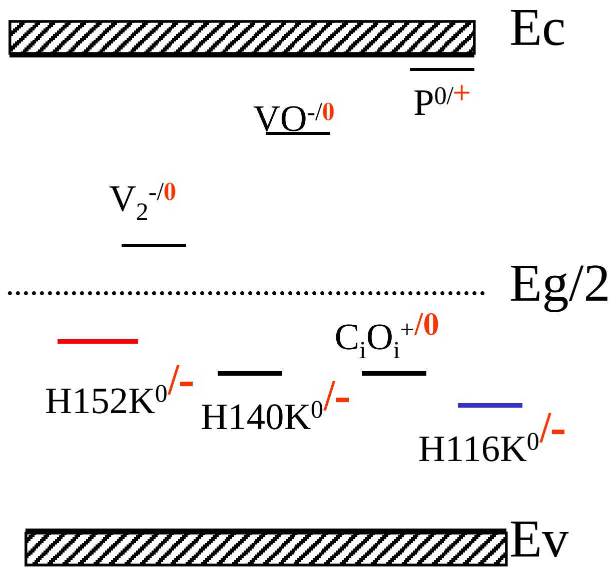
The levels position in the bandgap

The parameters for the zero field emission rates describing the experimental results are:

$E_i^{116K} = E_v + 0.33eV$ (0.285eV*) and
$\sigma_p^{116K} = 4\cdot10^{-14}$ $(4\cdot10^{-15}*)cm^2$

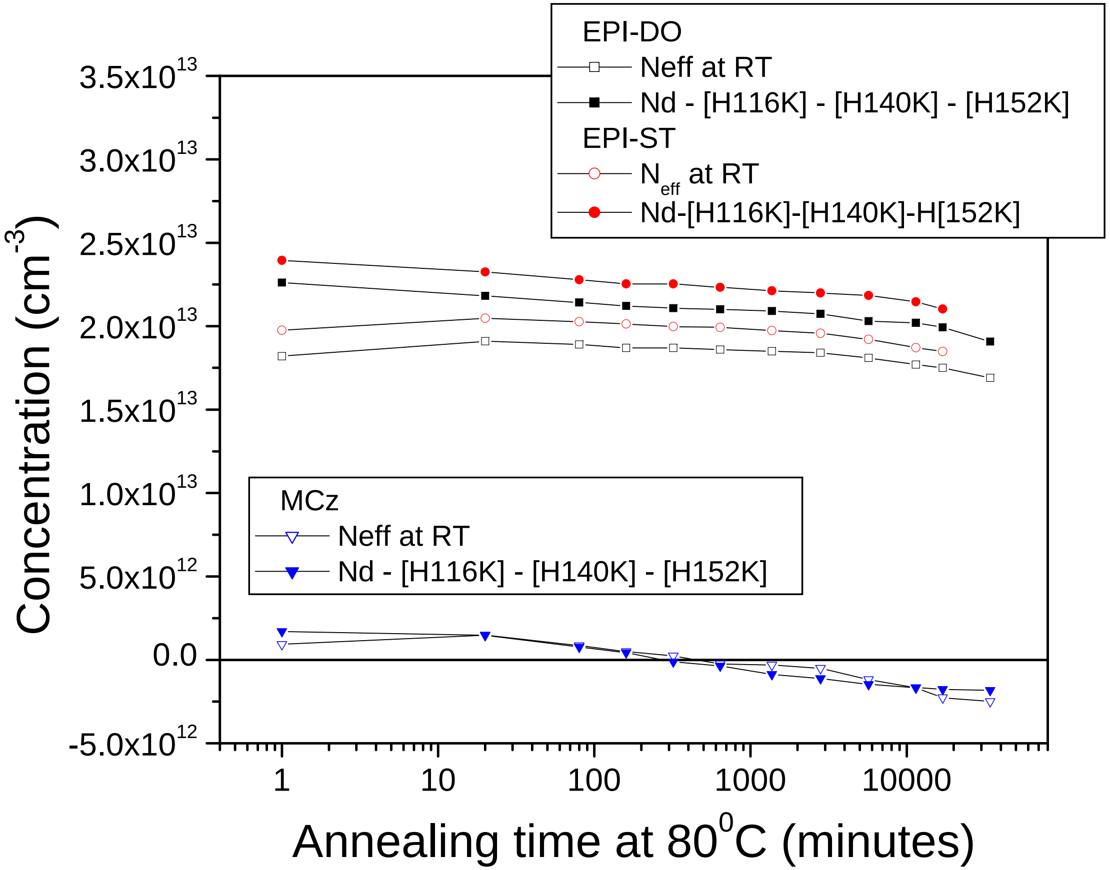
$E_i^{140K} = E_v + 0.36eV$ and $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

$E_i^{152K} = E_v + 0.42eV$ (0.36eV*) and
$\sigma_p^{152K} = 2.3\cdot10^{-14}$ $(2\cdot10^{-15}*)$ cm^2



* - aparent ionization energy and capture cross sections when no field dependence of emission rates is accounted

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



These defects are responsible for the long term annealing of N_{eff}

Summary

- Three cluster related acceptors in the lower part of the gap have been detected by TSC experiments.
- Their zero field activation enthalpies resulted from modelling the TSC peaks with the 3D-Poole Frenkel model and taking into account the spatial distribution of the diode electric field.
- It is shown that these acceptors are responsible for the long term annealing of N_{eff} in hadron irradiated silicon diodes.