Bistable Boron related defect associated with the acceptor removal process in irradiated p-type silicon – electronic properties of configurational transformations*

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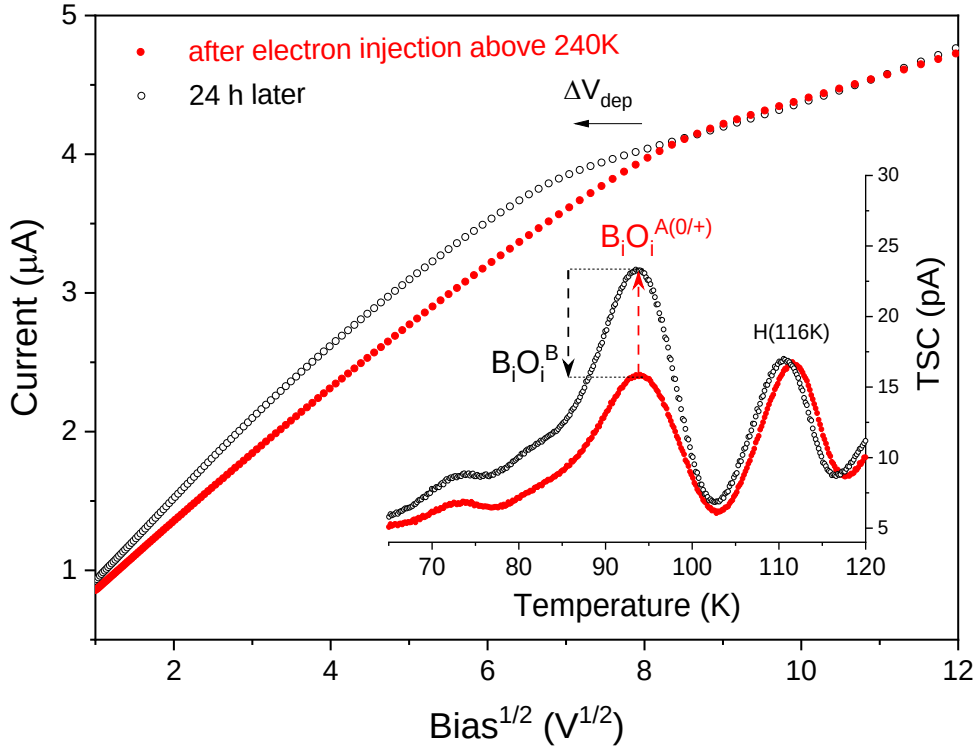
Outline

- Motivation
- Samples and Methods
- Results
  - A→B transformation
  - B→A transformation
  - Configuration Coordinate diagram
- Conclusions

Motivation

The ***bistable behavior*** of a Boron Containing Donor (BCD) related to acceptor removal effect in p-type silicon[1]



Assignments of BCD:

1) **B_iO_i** formed via the reactions[2-4]

$B_s + Si_i \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$

2) **B_sSi_i** formed via the reaction[5,6]

$B_s + Si_i \rightarrow B_sSi_i$

BCD trapping parameters:

- $\sigma_n = 1.05 \times 10^{-14}$ cm^2 ; $\sigma_p = 2.5 \times 10^{-20}$ cm^2

Due to the Poole Frenkel effect, specific to columbic centers, the defect energy level is lowering with the electric field (F)

- $E_t = E_{t,0} - \delta E(F)$

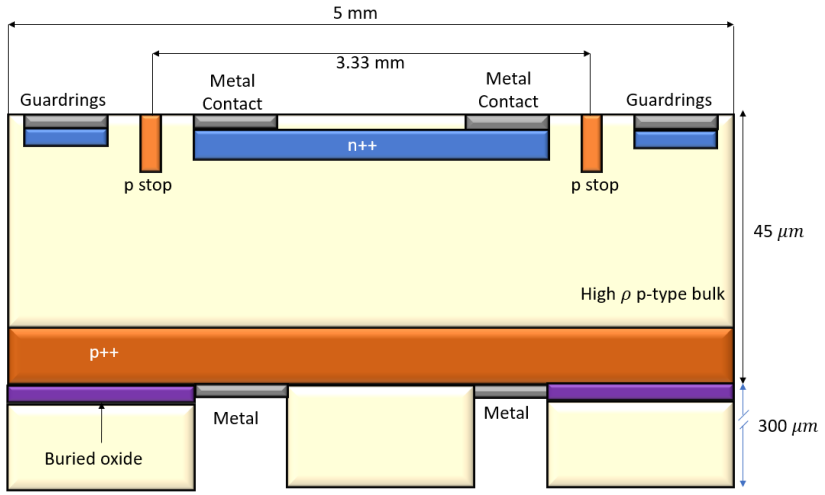
The BCD defect can exists in minimum 2 configurations:

A- the ground state in equilibrium conditions, with a donor level at about 0.28 eV from E_c of silicon. In this state the defect is contributing with positive charge to $N_{eff.}$

B- the ground state in non-equilibrium conditions (excess of carriers). This state is not electrically active and is indirectly observed via the variations in the A configuration

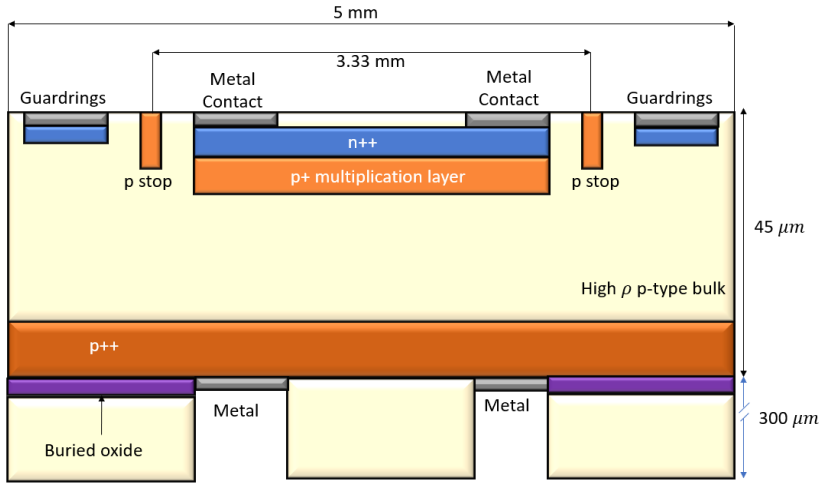
Samples

$n^{++} - p - p^{++}$ PAD (W5-LGB-72P)



Scheme of PAD sample

$n^{++} - p^{+} - p - p^{++}$ LGAD (W5-LGB-71)



Scheme of LGAD sample

- Both PAD and LGAD samples produced on high-resistivity $(12k\Omega \cdot cm)$ FZ wafers, by CNM Barcelona, and have been irradiated with $10^{14} n/cm^2$
- The samples were annealed for more than 136.000 minutes at $80°C$
- The Guardrings were grounded in all the electrical measurements

Methods

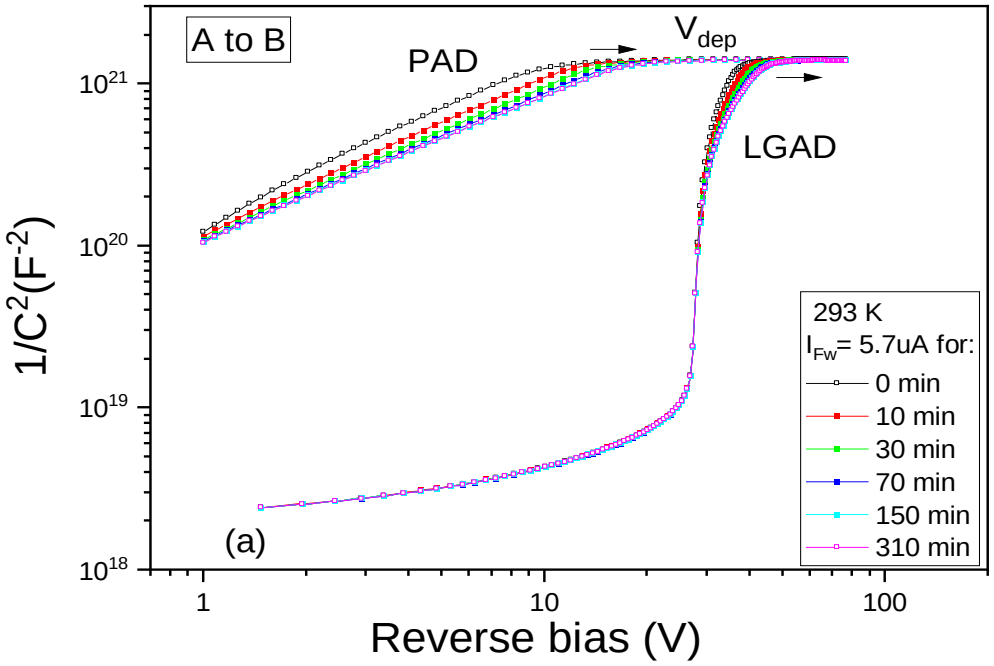
- The change of the defect configuration from A to B was achieved by performing a small forward current injection (I_{Fw} ~5.7 µA) at temperatures between 243K and 313 K.

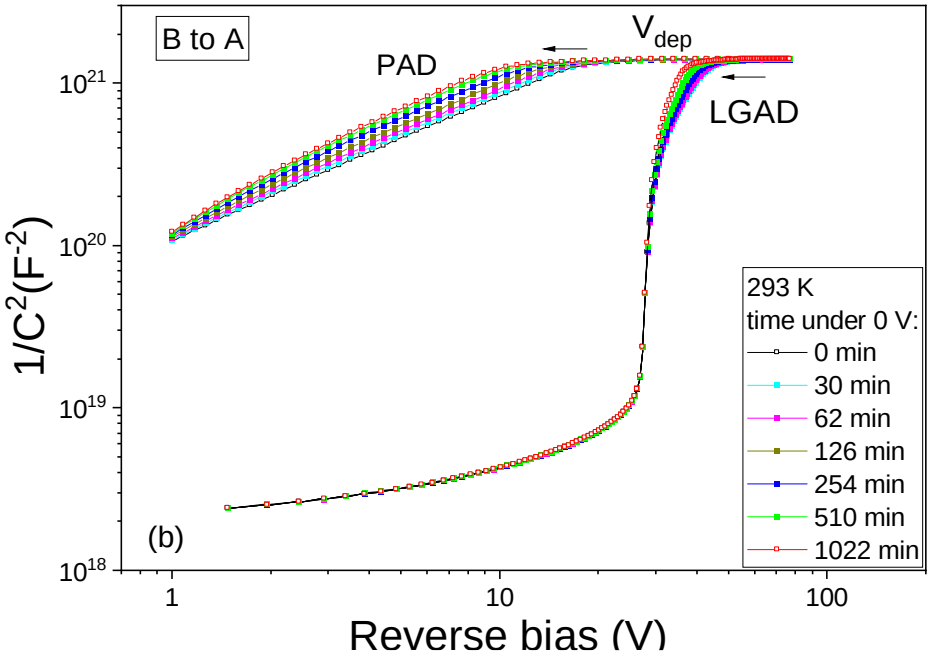
- The reverse configurational transformation (from B to A) takes place when the excess of carriers is removed and sample kept in dark

- The defect configurational transformations were studied by means of:
  - C-V/I-V measurements at different temperatures
  - TSC experiments

Results

BCD Configurational transformations as seen in C-V experiments



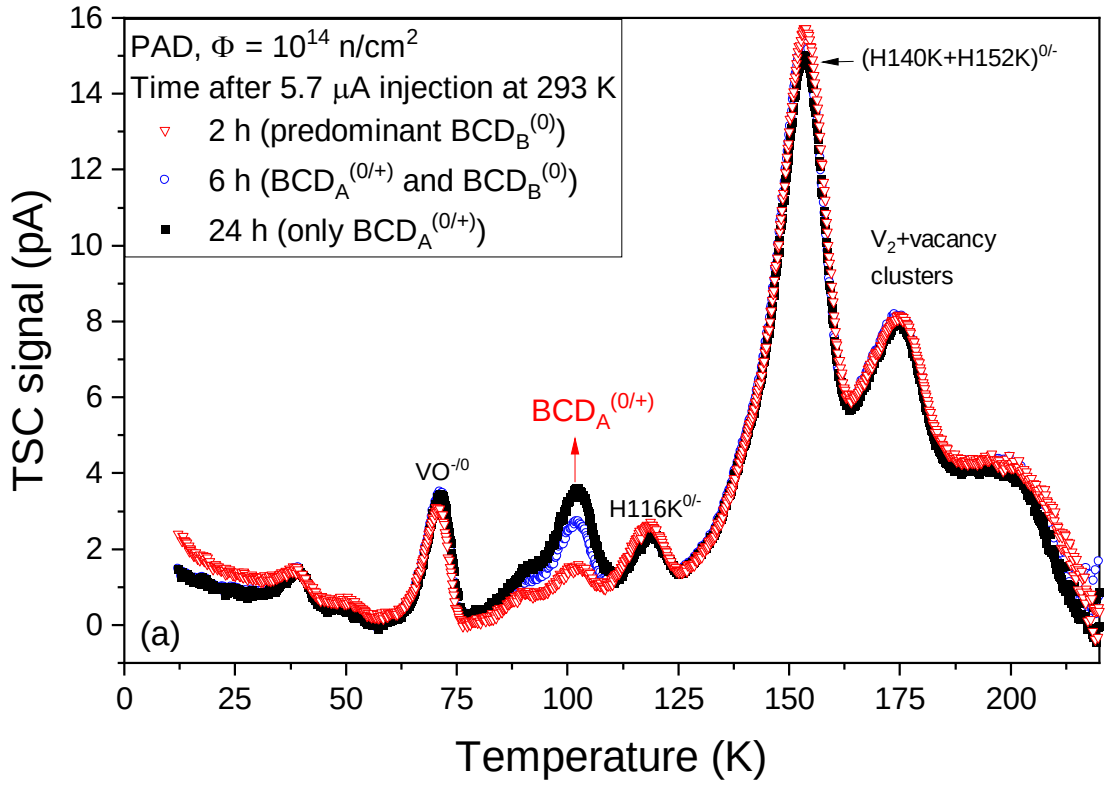


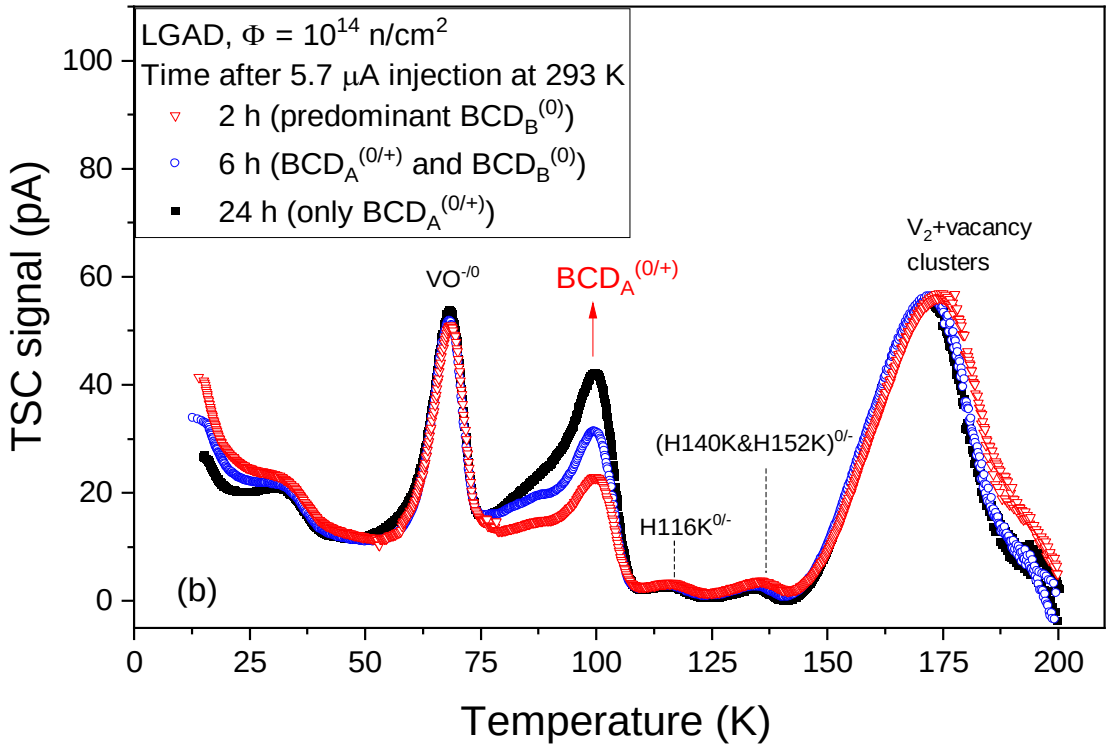
$$\frac{d\left(\frac{1}{C^2}\right)}{dV} = \frac{2}{A^2 q_0 \varepsilon \varepsilon_0 * N_{eff}}$$

- A to B (left Figure): Upon injecting a I_{fw} = 5.7 µA at 293K, an increase of up to 6.3V in depletion voltage has been measured in the PAD and LGAD samples. This corresponds to an increase in N_{eff} in the bulk of the diodes of ΔN_{eff} ~$5 \cdot 10^{12}$ cm^{-3} .
- B to A (right Figure): Removing $I_{fw,}$ the V_{dep} is slowly decreasing back to its initial value before the I_{fw} was applied.

Results

BCD Configurational transformations as seen in TSC experiments





- Consecutive TSC measurements, after fully switching the defect from A to B configuration at 293 K, were performed and they show a recovery of the donor level specific to the A configuration. $T_0 = 10\ K; I_{fill} = 350\ \mu A; V_{rev} = -100\ V;\ \beta = 11\ K/min$
- The only visible variation in TSC scan is attributed to the change of $BCD_A^{(0/+)}$ to BCD_B^0

$$\Delta BCD_A^{(0/+)} \sim 3.8 * 10^{12}\ cm^{-3}$$

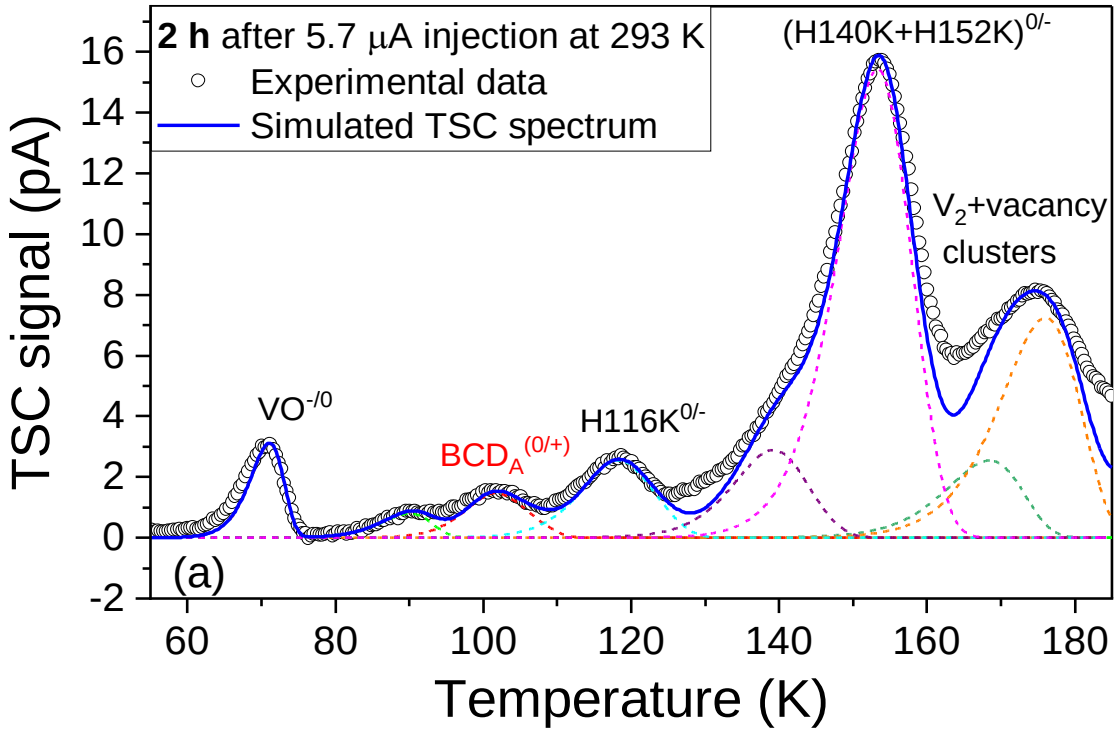
Simulation of TSC spectra & evaluation of defect concentrations in PAD

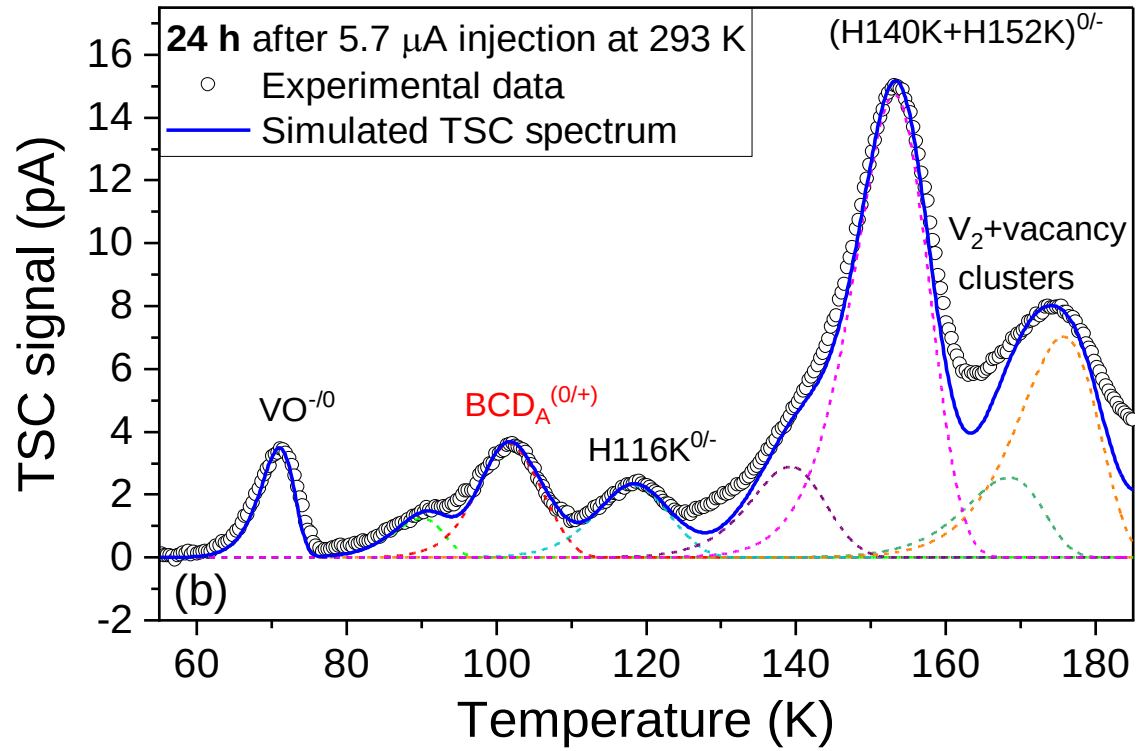
$$TSC^{e}(T) = \frac{1}{2} \times q_0 \times A_f \times N_t \times \int_0^d \left\{ e_n^{PF}(x,T) \times \exp\left(-\frac{1}{\beta} \int_{T_0}^{T} e_n^{PF}(x,T)\,dT \right) \right\} dx$$

where $e_n^{PF}(T) = e_{n,0}\left(\frac{1}{\gamma^2}\right)(e^{\gamma}(\gamma-1)+1) + \frac{1}{2}$,

$$e_{n,0}(T) = \sigma_n(T) \times v_{th,n}(T) \times N_c(T) \times \exp\left(-\frac{E_C - E_{t,0}}{k_B \times T}\right)$$

$$\gamma = \frac{q_0}{k_B \times T}\sqrt{\frac{q_0 \times |\overrightarrow{F(x,T)}|}{\pi \times \varepsilon_0 \varepsilon_r}}, \qquad F(x,T) = \frac{q_0}{\varepsilon_0 \varepsilon_r} \times N_{eff}(T) \times (d-x) + \frac{V_R - V_{dep}(T)}{d}$$



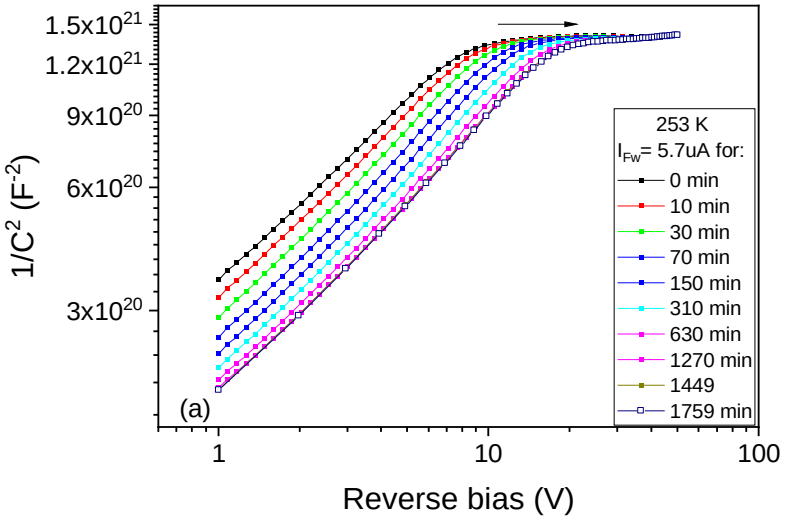


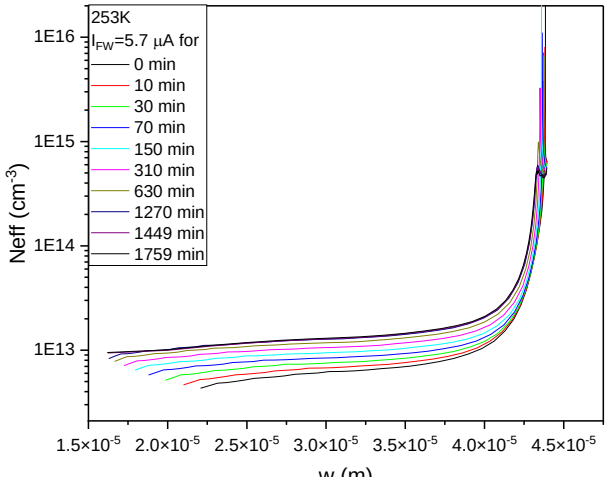
$E_{t,0} \cong 0.286\ eV$, *zero field activation energy of the BCD defect in the A configuration*

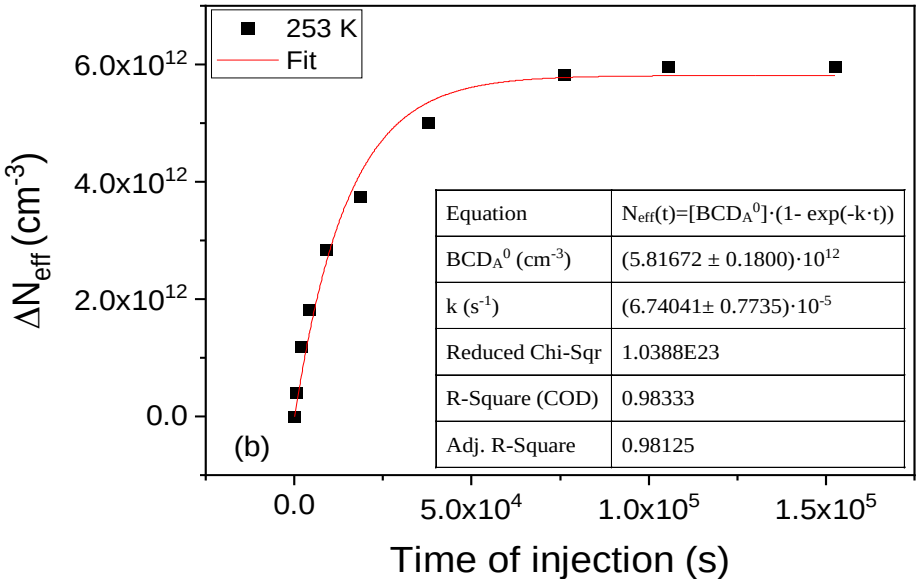
A→B transformation

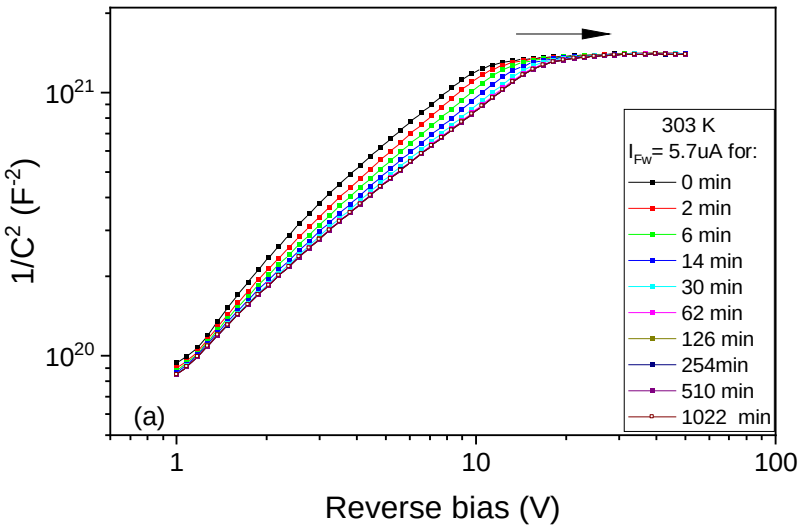
via Cyclic CV measurements at different temperatures. In between the C-Vs a small forward injection, I_{fw}= 5.7μA, is applied for different times

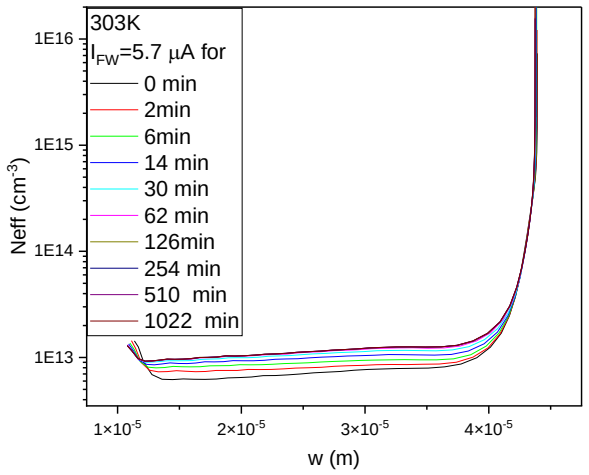
$$\Delta Neff(T) = -\Delta[BCD_A(t)] = BCD_A^0(1 - \exp(-k * t))$$

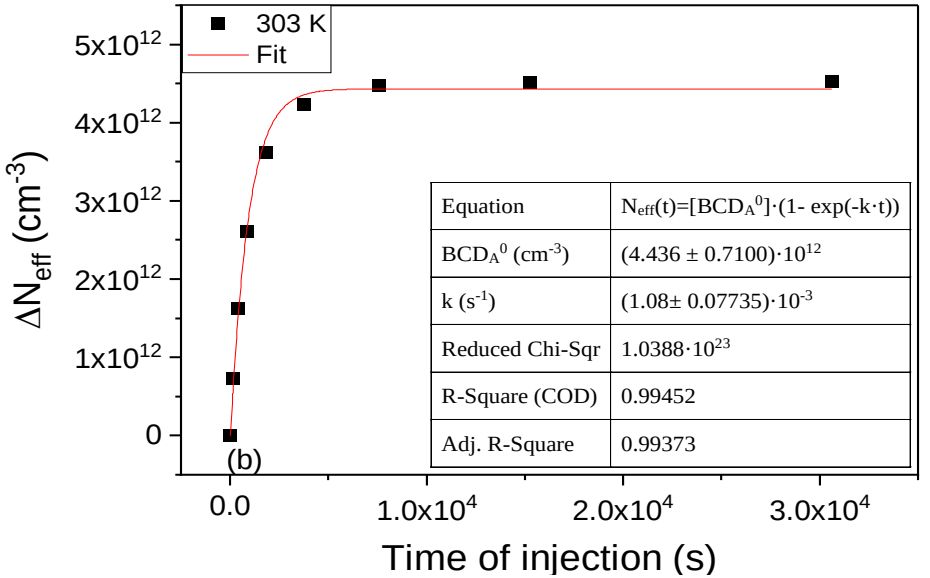




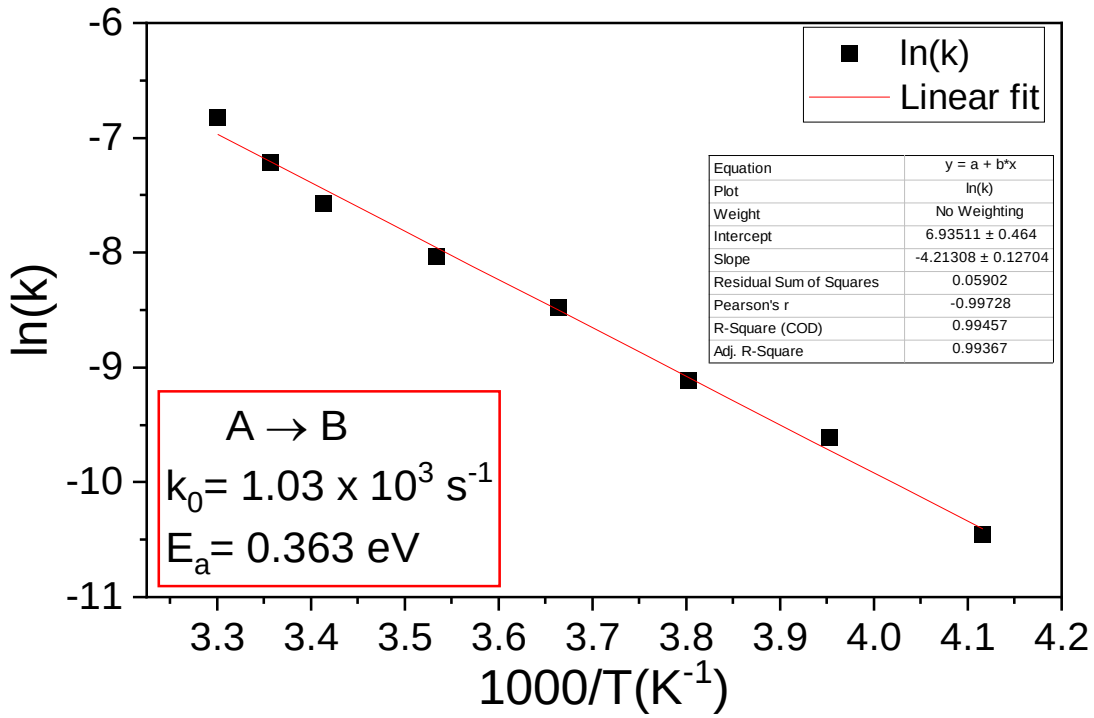


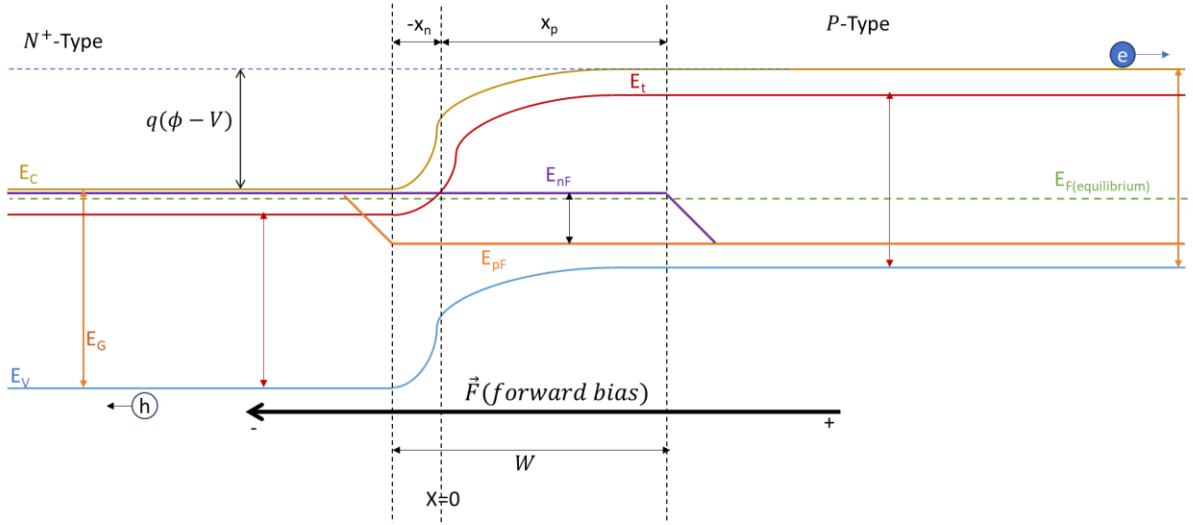






Electronic properties of A→B transformation





Schematic quasi-Fermi levels in a silicon sample

- Because the energy level of the defect lies above the Fermi level, the value of k_0 is much smaller than that expected for a free carrier capture $(\text{of } 10^7\ s^{-1})$
- This is due to the position of the fermi energy level, which remains below the donor energy level of defect during the small Fw injection, affecting thus the population of donor defect [7]

$$k \cong \sigma_n * Nt * v_{th} * \left(1 + \exp\left(\frac{E_t - E_{nF}}{k_B * T}\right)\right)^{-1};$$

$\sigma_n = capture\ cross - section$

$v_{th} = electron\ thermal\ velocity$

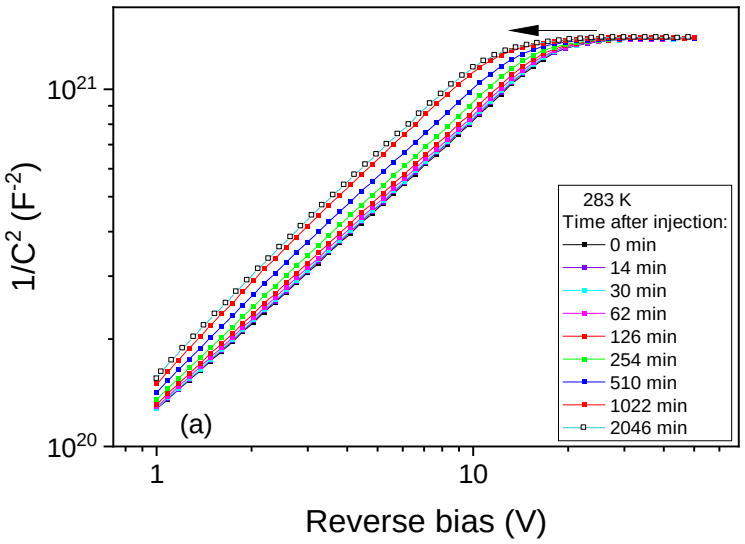
$E_t = \ donor\ energy\ level$

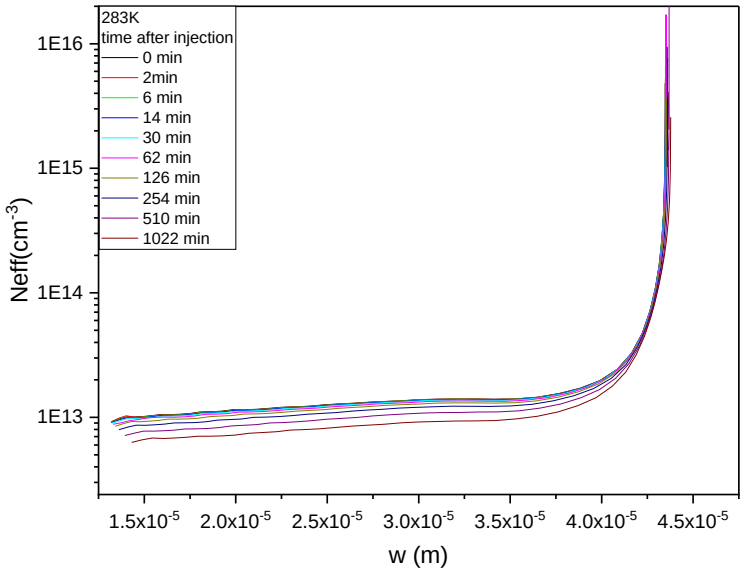
$E_{nF} = quasi - Fermi\ energy\ level$

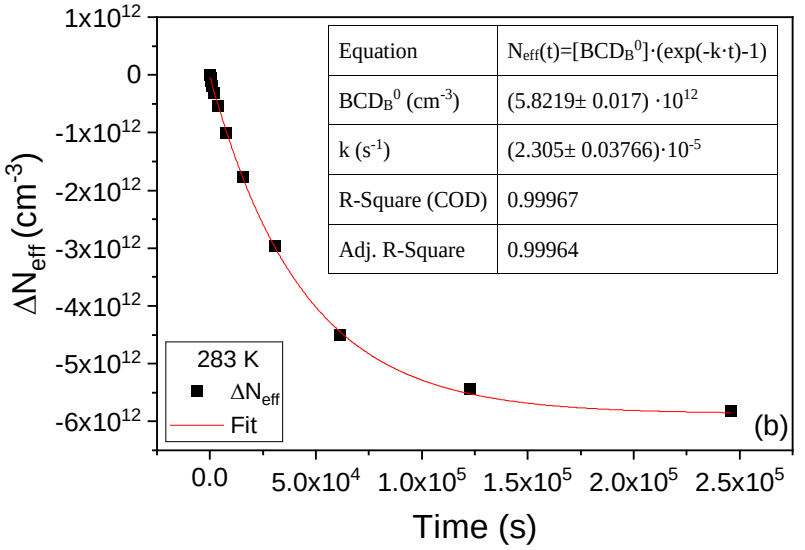
B→A transformation

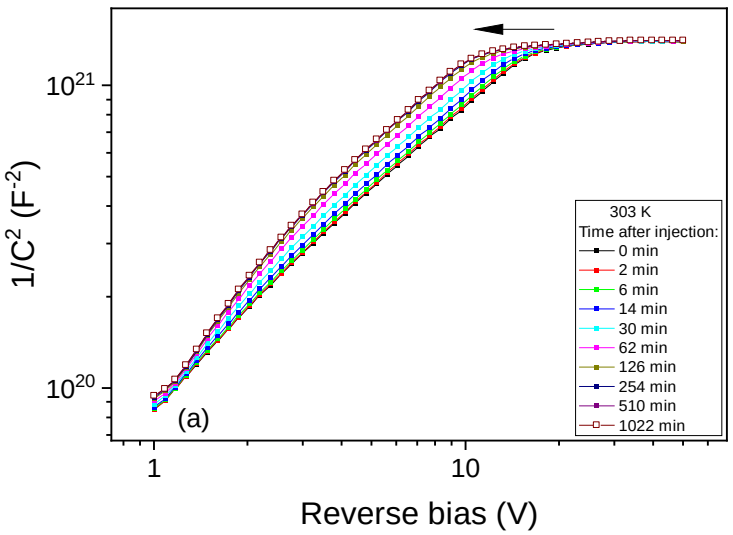
via cyclic CV measurements at different temperatures
different times after the I_{Fw} injection has stopped

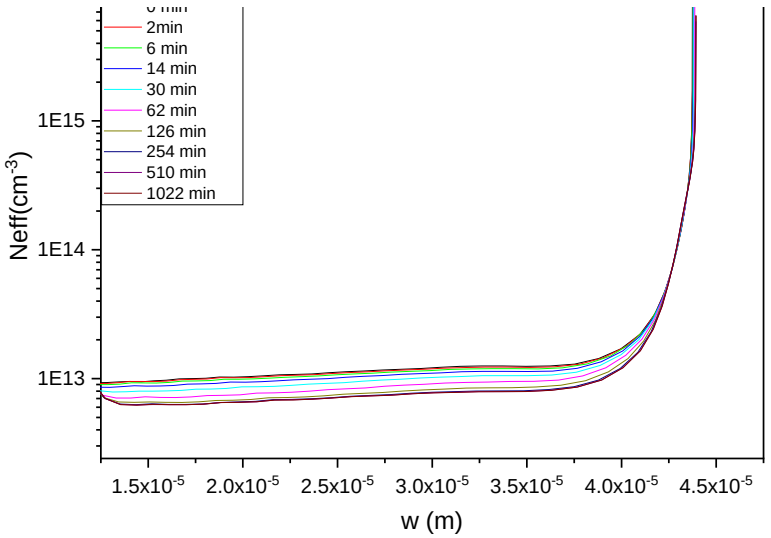
$$\Delta Neff(T) = \Delta[BCD_B(t)] = BCD_B^0(\exp(-k*t) - 1)$$

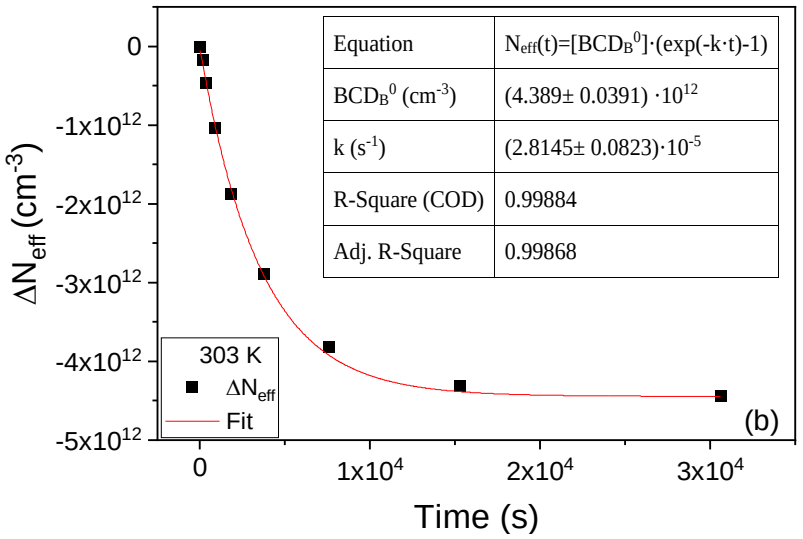




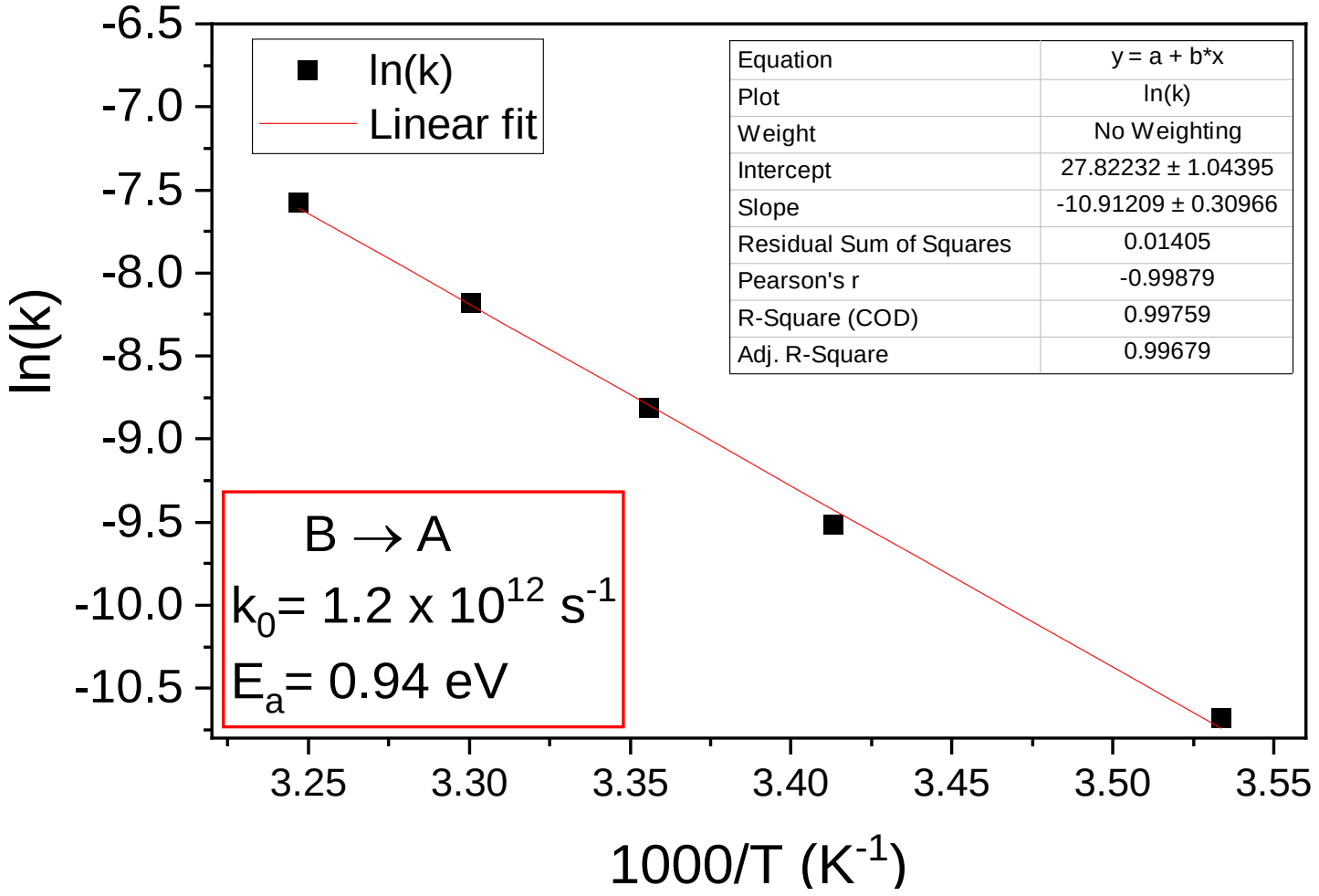








Electronic properties of B→A transformation



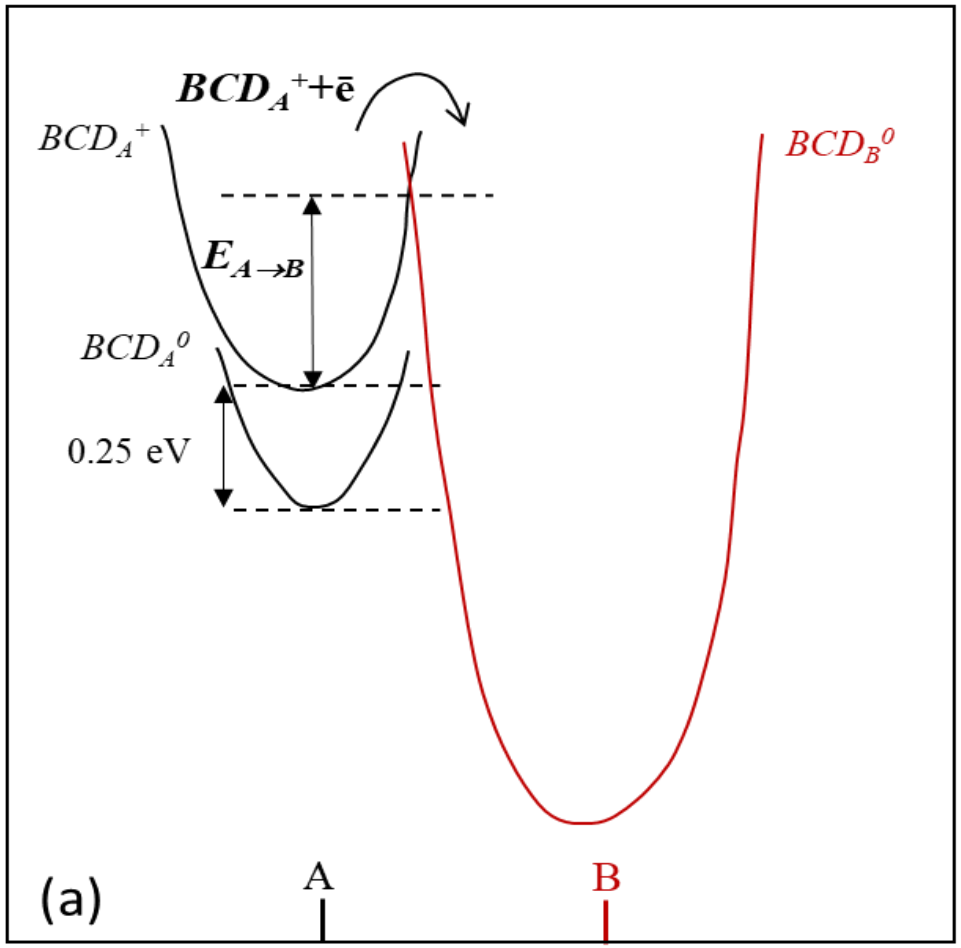
Equation	y = a + b*x
Plot	ln(k)
Weight	No Weighting
Intercept	27.82232 ± 1.04395
Slope	-10.91209 ± 0.30966
Residual Sum of Squares	0.01405
Pearson's r	-0.99879
R-Square (COD)	0.99759
Adj. R-Square	0.99679

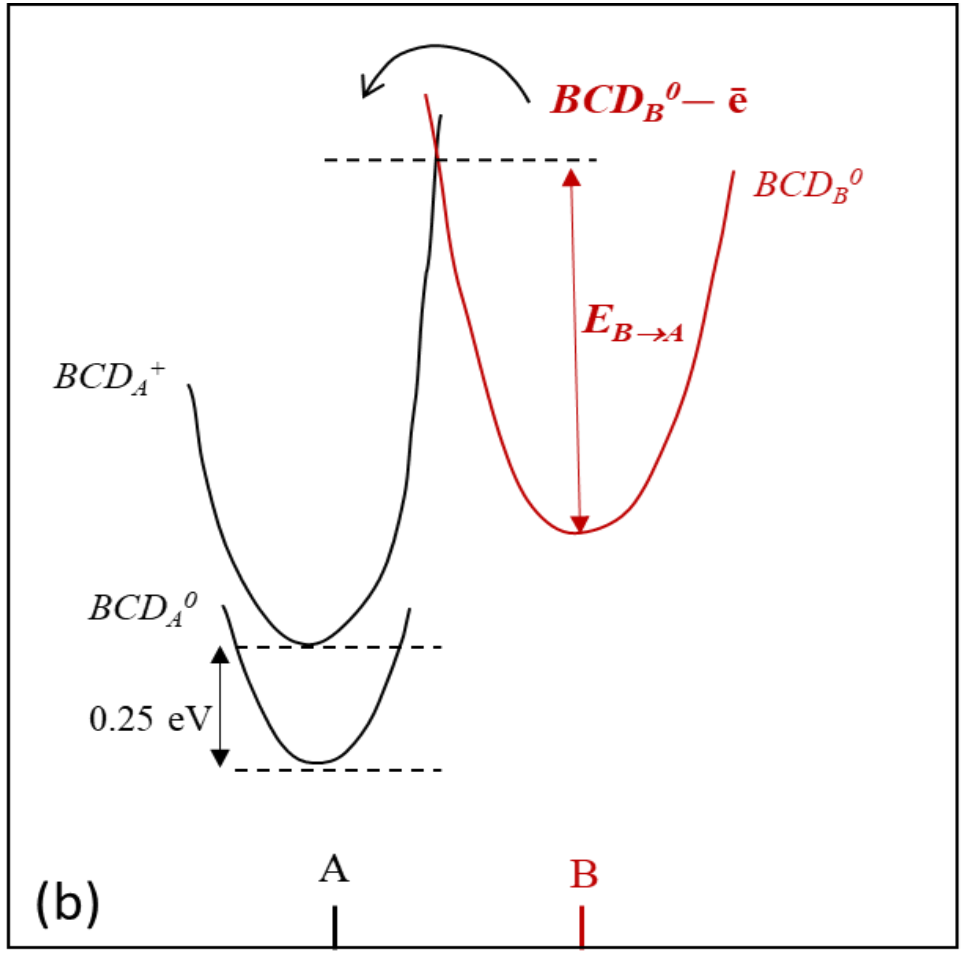
- The value of $k_0 = 1.2 * 10^{12} s^{-1}$ is in the range for a free carrier emission process
- The large energy barrier of $E_a = 0.94\ eV$ also explains the long times requires for the full recovery of the BCD_A configuration

Configuration Coordinate Diagram

for $A \rightarrow B$ transformation
(when electrons in excess are injected)

for B →A transformation
(when excess electrons are removed)





Conclusions

- ***In equilibrium conditions, the BCD defects are found in the A configuration***. Through TSC measurements, the corresponding zero field energy level for $BCD_A^{(0/+)}$ donor state has been determined to be at $E_{t,0} \cong 0.286\ eV$ from the conduction band of silicon
- ***In non-equilibrium conditions,*** when electrons exist in excess in high resistivity samples***, the defect can transform in configuration B*** (BCD_B^0) ***at ambient temperatures,*** by capturing a free electron and overpassing the energy barrier of $E_{A\to B} = 0.363\ eV$. The defect remains in B state as long as there is an excess of electrons.
- ***Removing the source of excess carriers, the defect returns to its donor state A*** $(\boldsymbol{BCD_A^{(0/+)}})$ by emitting an electron while surmounting the large energy barrier of $E_{B\to A} = 0.94\ eV$
- ***The*** $\boldsymbol{A \to B}$ ***defect configurational change***, as observed here also in CV measurements, ***is not detected in low resistivity diodes***. In high resistivity samples, the small forward injection current, comparable with the photocurrent generated by the ambient light, is larger than that of injected holes and on longer distances inside the diodes. Therefore, the transformation $A \to B$ in low resistivity samples is expected to occur in a much smaller volume, causing negligible variations in C-V measurements.

References

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Thank you for your attention!

1st-order defect kinetics

$$-\frac{\partial[N]}{\partial t} = k[N] \rightarrow [N] = [N]_{t\rightarrow 0} * \exp(-k * t)\,; \begin{cases} [N] = concentration\ of\ defect \\ t = time \\ k = constant\ rate \end{cases}$$

$$k = k_0 * \exp\left(-\frac{Ea}{k_B T}\right); \begin{cases} k_0 = frequency\ factor \\ Ea = activation\ energy \\ k_B = Boltzmann\ constant \\ T = temperature \end{cases}$$

$$k_0 \sim \begin{cases} 10^7 s^{-1} \rightarrow capture\ of\ free\ carrier\ by\ multiphonon\ emission \\ 10^{12} s^{-1} \rightarrow emission\ of\ free\ carriers \end{cases}$$

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Poole-Frenkel (PF) Thermally Stimulated Current Signal simulation for electron traps in diodes

$$TSC_{PF}^{e}(T) = \frac{1}{2} * q * A * N_t * \int_0^d e_n^{PF}(x,T) * \exp\left(-\frac{1}{\beta}\int_{T_0}^{T} e_n^{PF}(x,T)dT\right)dx$$

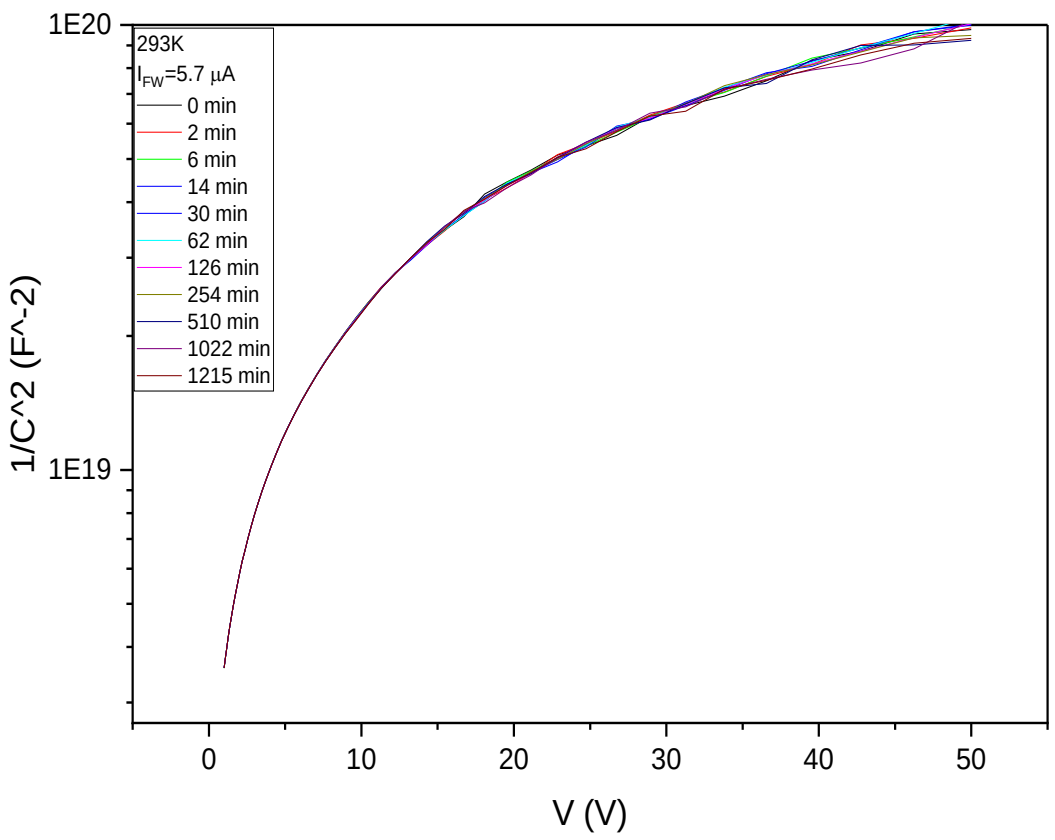
$$e_n^{PF}(T) = e_n\left(\frac{1}{\gamma^2}\right)(e^{\gamma} * (\gamma - 1) + 1) + \frac{1}{2}; \gamma = \frac{q}{k_B T}\sqrt{\frac{q|\vec{F}|}{\pi * \varepsilon_0 \varepsilon_r}}; en = \sigma * v_{th} * Nc * \exp\left(-\frac{Ec - Et}{k_B T}\right)$$

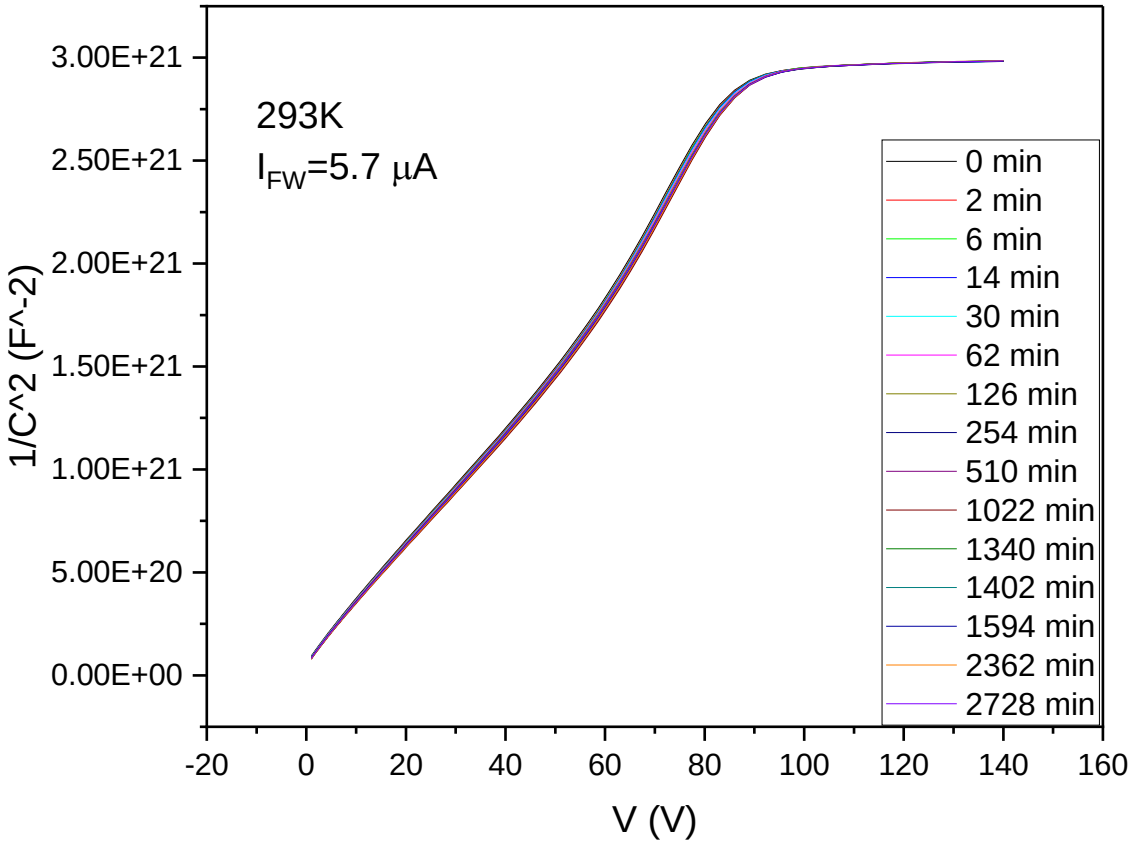
$$\begin{cases} q = elementary\ charge \\ d = thickness\ of\ the\ sample \\ A = active\ surface\ of\ the\ sample \\ N_t = defect\ concentration \\ \beta = heating\ rate \\ T_0 = filling\ temperature \\ e_n = electron\ emission\ rate \\ \vec{F} = electric\ field\ in\ sample\ (sample\ is\ fully\ depleted) \\ \varepsilon_0\varepsilon_r = dielectric\ constant\ of\ silicon \end{cases}$$

In diodes: $F(x,T) = \frac{q_0}{\varepsilon_0\varepsilon_r} \times N_{eff}(T) \times (d - x) + \frac{V_R - V_{dep}(T)}{d}$, for $V > V_{dep}$

EPI-02-50-65, **50 Ω·cm**

Φ =1E14 n/cm^2



CZ-03-100-DS-81, **100 Ω·cm**

Φ =1E15 n/cm^2