On-going studies on diminishing the acceptor removal effect by tuning the charge state of Boron containing defects in p-type irradiated PAD samples

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The *bistable behavior* of a Boron Containing Donor (BCD) related to acceptor removal (AR) effect observed in high resistivity PAD and LGAD samples[1,2]

Possible assignments of BCD:

1)**B_iO_i** formed via the reactions [1- 3]

$B_s + Si_i \rightarrow B_i$; $B_i + O_i \rightarrow$ **B_iO_i**

2) **B_sSi_i** formed via the reaction [4,5]

$B_s + Si_i \rightarrow$ **B_sSi_i**

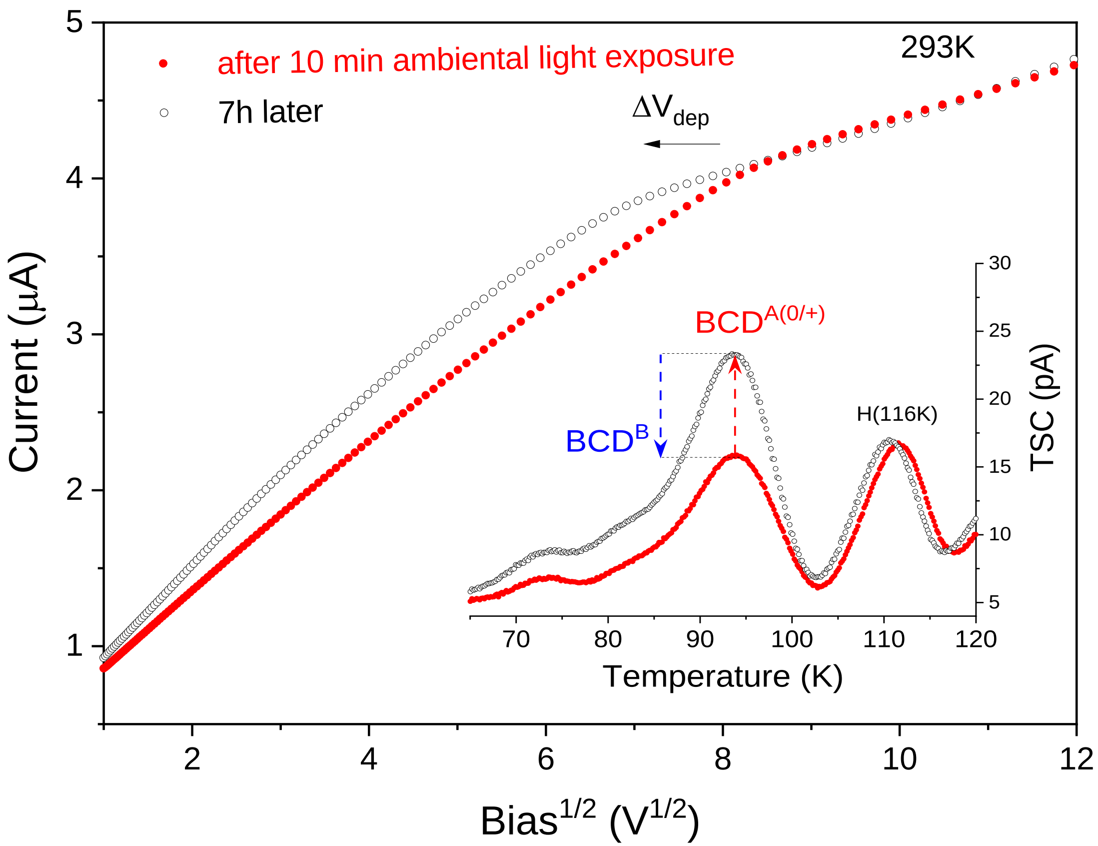
both are **deactivating the acceptor dopant (Boron substitutional)**

Configuration A- the ground state in eq. conditions, with a donor level at E_c - 0.28 eV, **contributing with positive charge to $N_{eff.}$** - maximizing the AR effect

Configuration B- the ground state in non-eq. conditions (excess of carriers), **not electrically active** and is indirectly observed via the variations in the A configuration –minimize AR

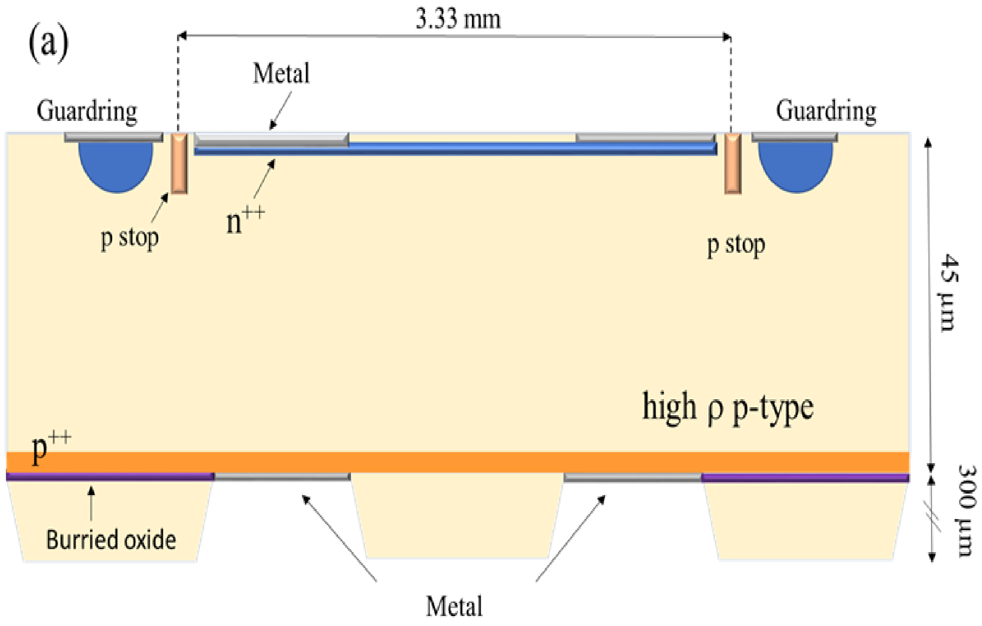
BCD^A trapping parameters:

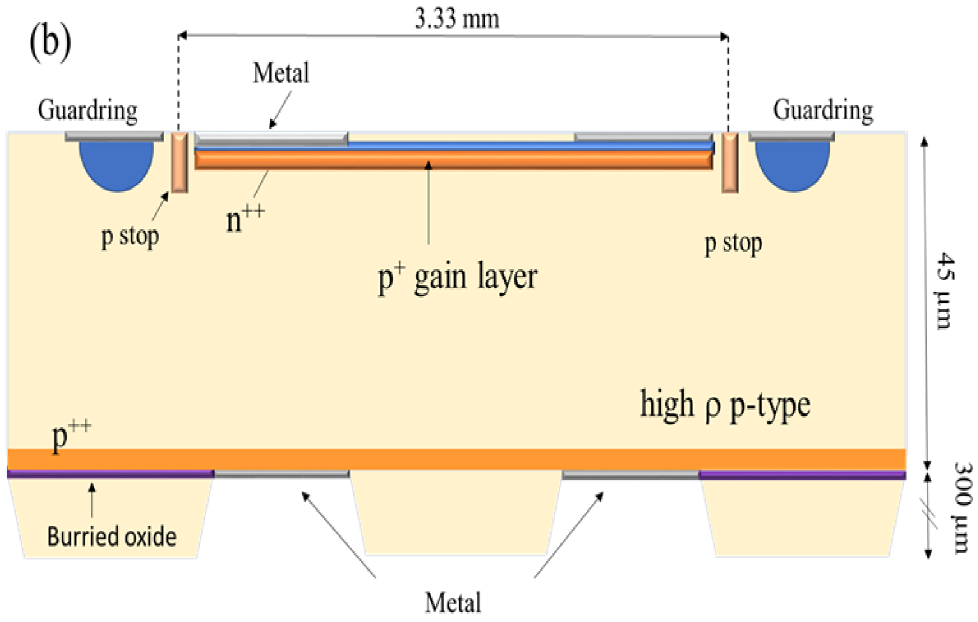
E_t = 0.28eV -$\delta E(F)$;σ_n = 1.05x10^{-14} cm^2 ; σ_p = 2.5x10^{-20} cm^2



1). C. Besleaga, et al, Bistability of the BiOi complex and its implications on evaluating the acceptor removal process in p-type silicon, Nucl. Instrum. Methods Phys. Res. A 2021, 1017, 165809. DOI: /10.1016/j.nima.2021.165809; 2). A. Nitescu et al. "Bistable Boron-Related Defect Associated with the Acceptor Removal Process in Irradiated p-Type Silicon—Electronic Properties of Configurational Transformations". Sensors **2023**, 23, 5725. https://doi.org/10.3390/s23125725; 3). Chuan Liao et al, IEEE TRANSACTIONS ON NUCLEAR SCIENCE **2022**, 69 (3) , pp.576-586, **DOI:** 10.1109/TNS.2022.3148030; 4). Möller, C.; Lauer, K. Light-induced degradation in indium-doped silicon. *Phys. Status Solidi RRL* **2013**, 7, 461. DOI: /10.1002/pssr.201307165; 5). K. Lauer, et al, Activation energies of the In_{Si}-Si_i defect transitions obtained by carrier lifetime measurements. *Phys. Status Solidi C* **2017**, 14, 1600033. DOI: /10.1002/pssc.201600033

High resistivity PAD and LGAD samples





W5-LGB-72P

$\boldsymbol{\rho = 12\ k\Omega cm}$

$\phi = 1E14\ n/cm^2$

Guardring grounded

W3-LGB-71

$\boldsymbol{\rho = 12\ k\Omega cm}$

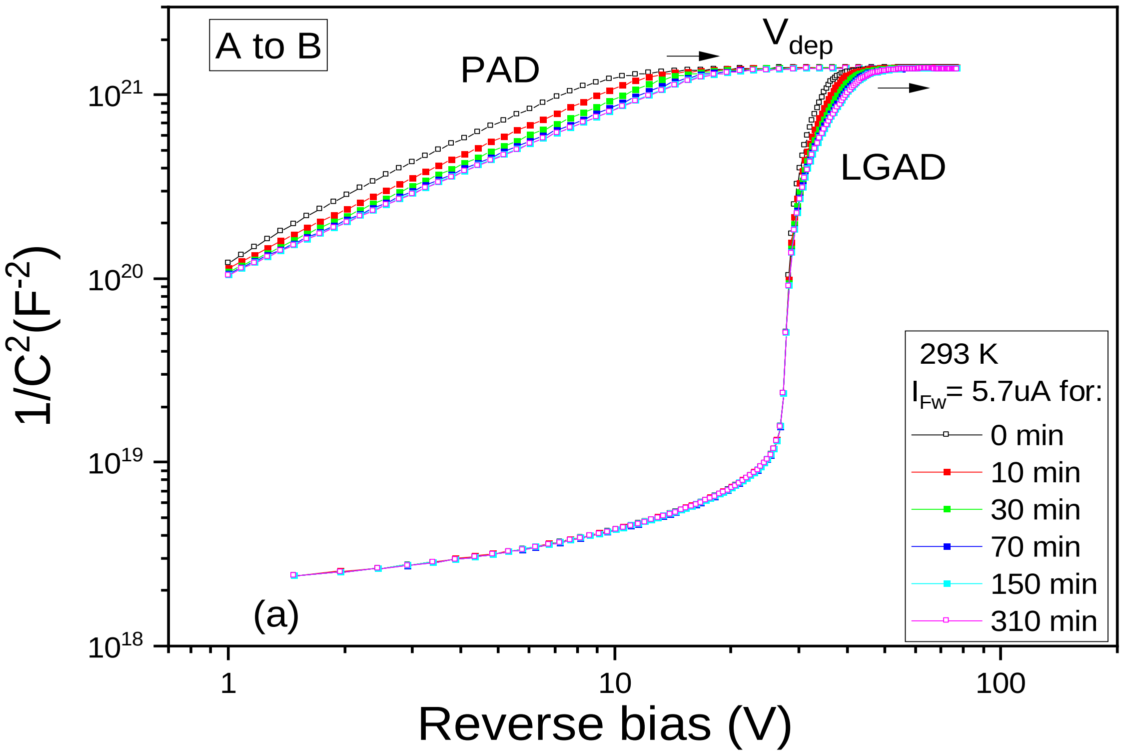
$\phi = 1E14\ n/cm^2$

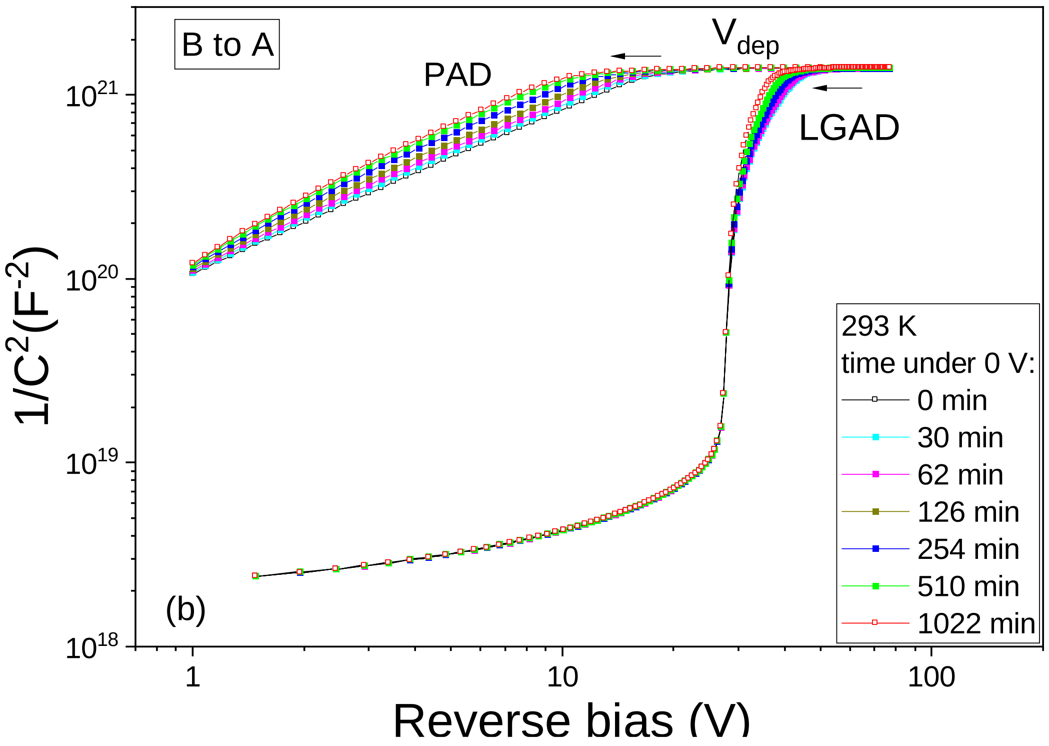
Guardring grounded

Reversible switch between the two charge configurations of BCD

As seen in CV measurements[1,2]

12 kohm·cm PAD and LGAD irradiated with 10^{14} 1MeVn/cm^2, long time annealed at 80 ^oC





A to B:

- by producing an excess of carriers in samples
- Leads to an increase in V_{dep} (with ~6.3 V)

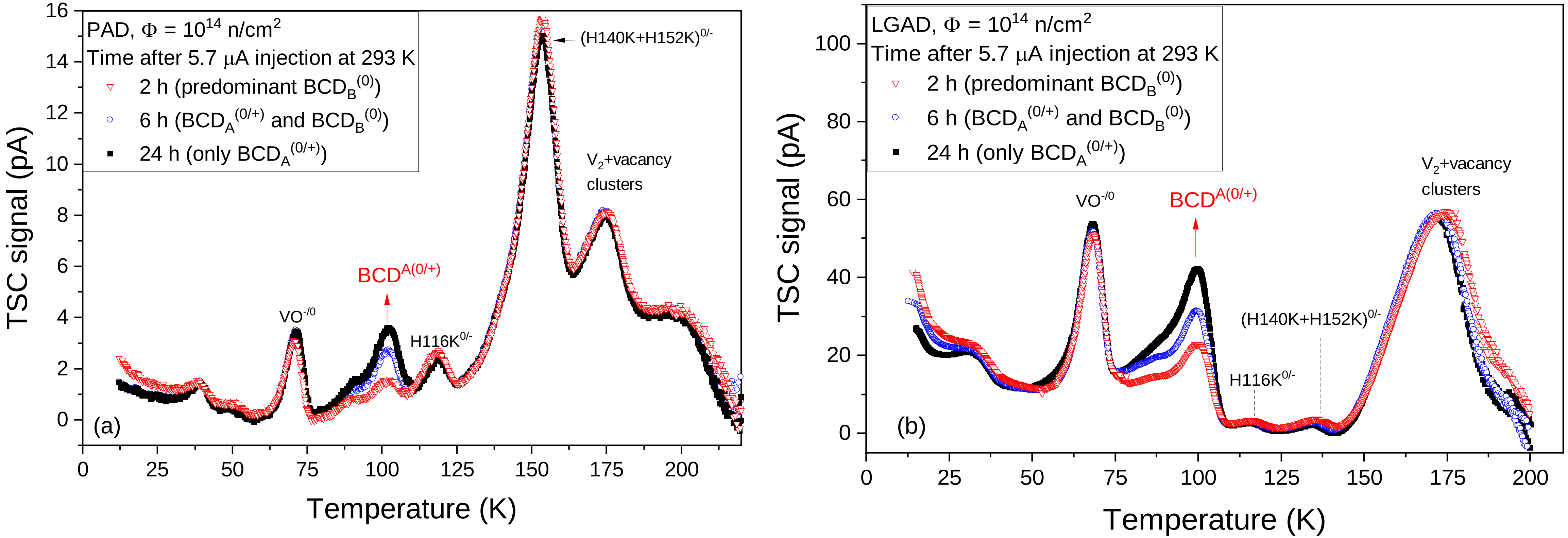
B to A:

- by keeping the sample in the dark
- V_{dep} returns back to its equilibrium value

Reversible switch between the two charge configurations of BCD

As seen in TSC measurements[1,2] - *possible only via monitoring the concentration of BCD^A*

12 kohm·cm PAD and LGAD irradiated with 10^{14} 1MeVn/cm^2

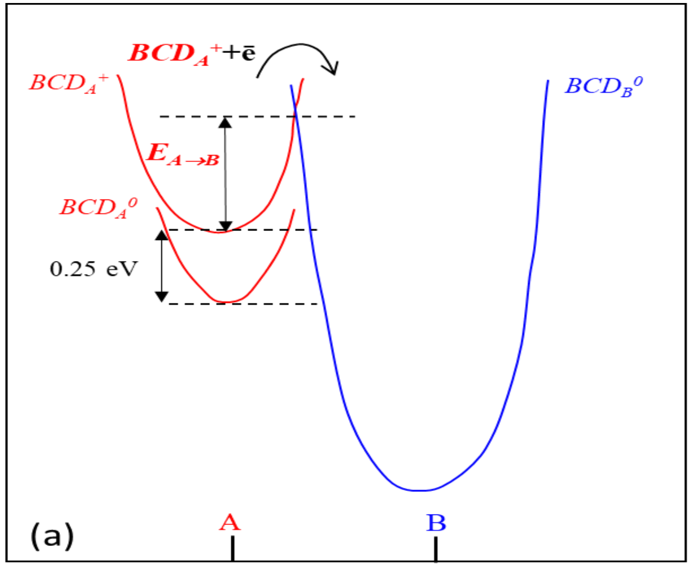


The changes from $A \rightarrow B$ is due to the excess of charge carriers. This excess of charge carriers can be stimulated through different methods:

- Thermal treatments (at $T<80°C$)
- FW current injection
- Light exposure

BCD defect kinetics, as seen in high resistivity samples[2]

A → B $BCD_A^+ + e^- \rightarrow BCD_B^0$



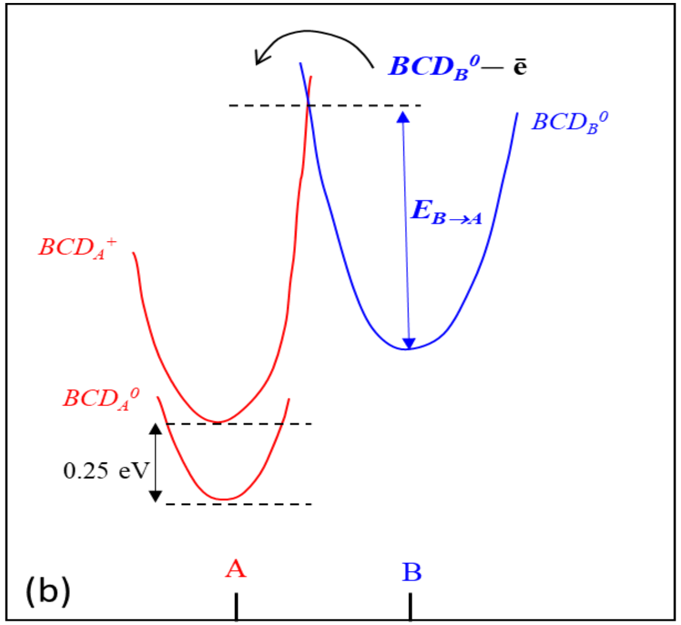
$$E_{A\rightarrow B} = 0.363\ eV$$

$$k_{A\rightarrow B} \cong 10^3 * \exp\left(-\frac{0.363\ eV}{k_B T}\right)$$

fast process, ***diminishing*** the AR effect
(*recovers* part of the removed acceptors)

$$g_B = 2 \times g_{BCD}^A + g_{BCD}^B$$

B → A $BCD_B^0 \rightarrow e^- + BCD_A^+$



$$E_{B\rightarrow A} = 0.94\ eV$$

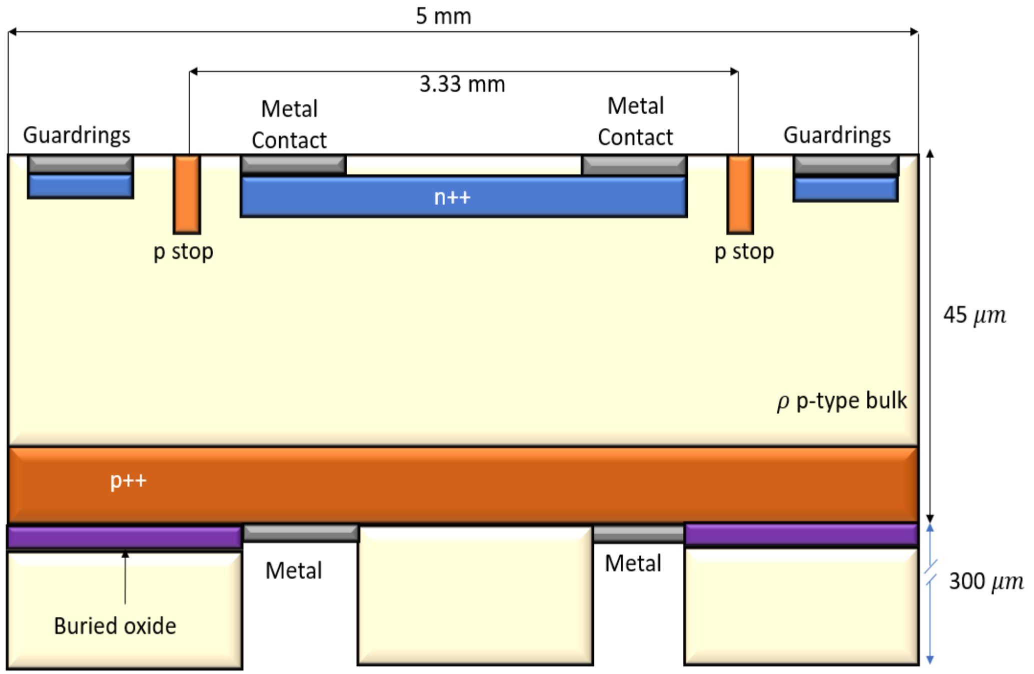
$$k_{B\rightarrow A} \cong 1.2 * 10^{12} * \exp\left(-\frac{0.94\ eV}{k_B T}\right)$$

- **slow returning process**, ***enhancing*** the AR effect (*maximize* the AR effect)
- below 273 K the B state frozen

It is possible to tune the defects configurations for *minimizing the AR effect by switching the defect from* BCD^{A+} to BCD_B^0 – diminishing the contribution of A state which is accounted twice in g_B!

- ***Does BCD's bistability manifest also in samples of lower resistivity ?***

Samples of different resistivity (annealed 120min@60ºC)



EPI-02-50-65
$\boldsymbol{\rho = 50\Omega cm}$
$\phi = 1E14\ n/cm^2$

EPI-09-50-DS-88

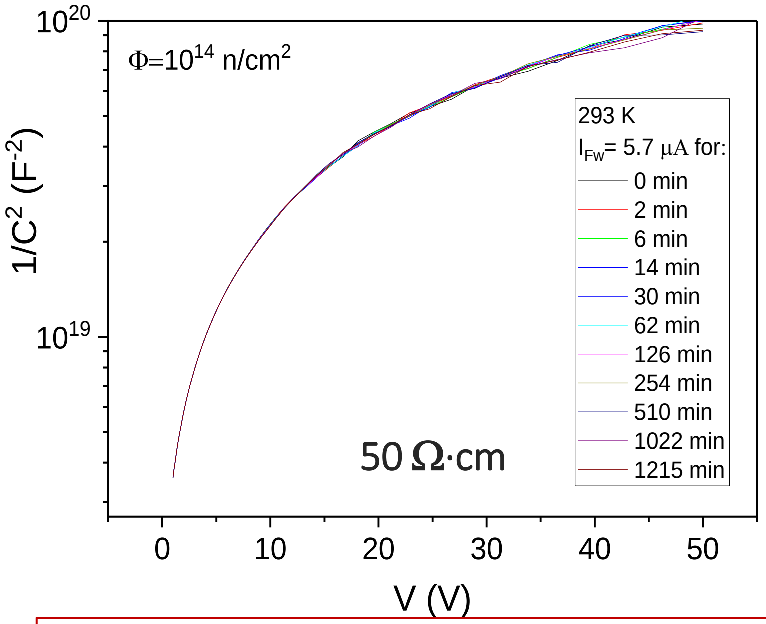
EPI-09-50-DS-89
$\boldsymbol{\rho = 250\Omega cm}$
$\phi = 1E14\ n/cm^2$

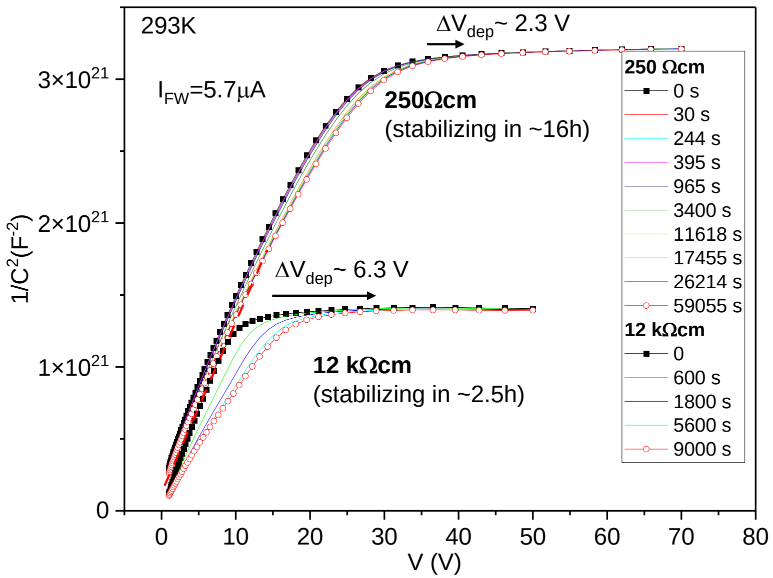
Results on the samples of different resistivity

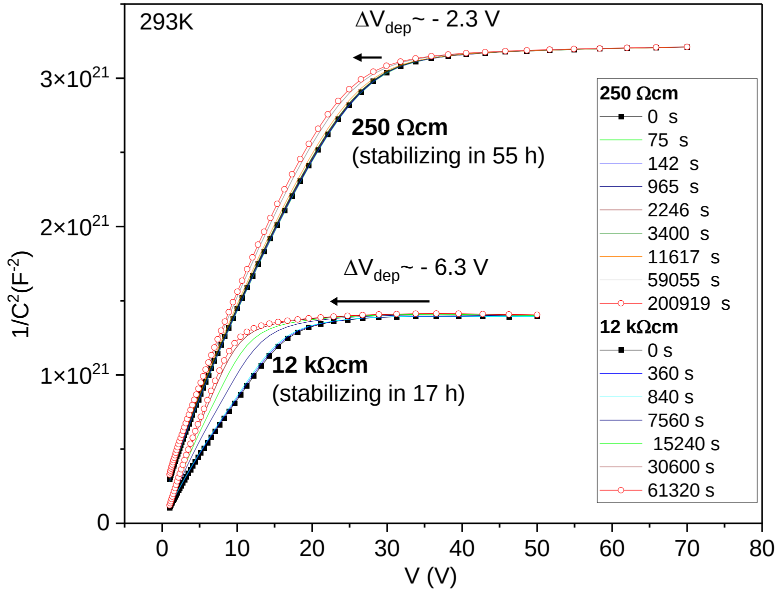
(50 Ω·cm, 250 Ω·cm and 12 k Ω·cm), $\phi = 1E14\, n/cm^2$

A → B (injecting small Fw current at 293 K, fast process)

B → A (in dark under 0V, slow process)







A to B:

For **12k Ω·cm :** ΔV$_{dep}$ ~ 6.3 V → acceptor reactivation of 3.3x10^{12} cm^{-3}

For **250 Ω·cm :** Δ V$_{dep}$ ~ 2.3 V → acceptor reactivation of 1.2x10^{12} cm^{-3}

For **50 Ω·cm :** ΔV$_{dep}$=0 , *no reactivation of acceptors*

B to A (after removing the Fw injection):

- Happen very slowly for T> 253K
- At 253K, the B state remain frozen !

(the acceptor removal effect remains reduced to its minimum)

The efficiency of switching the defect' charge configuration *is increasing with the sample' resistivity*

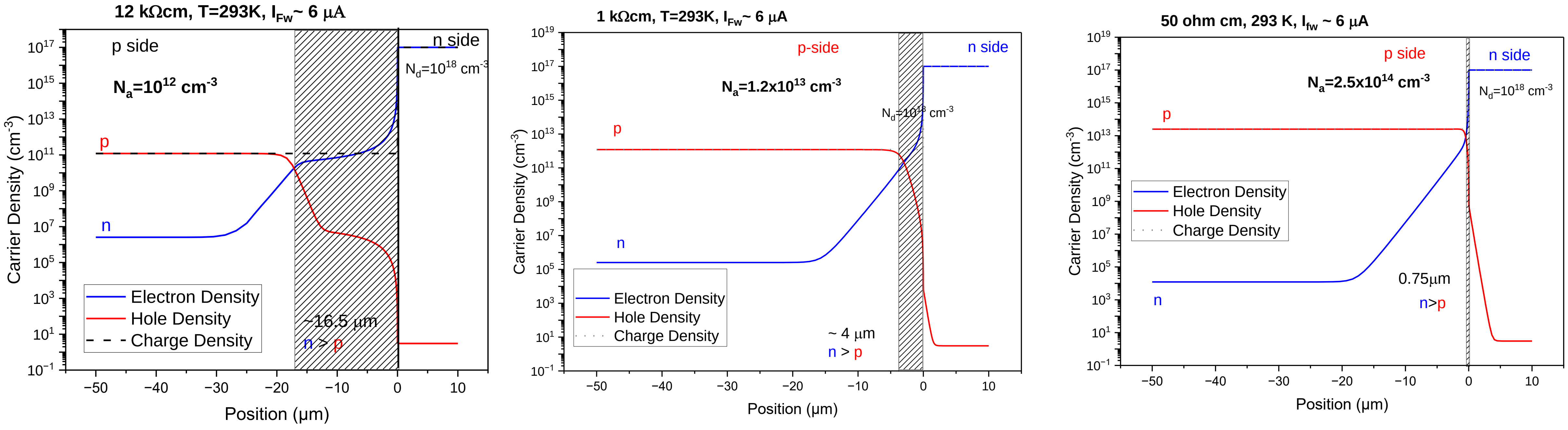
• Why can be reactivated more acceptors in high resistivity than in low resistivity samples after the same small Fw current injection ?

A → B

$$BCD_A^+ + e^- \rightarrow BCD_B^0$$

$$E_{A\rightarrow B} = 0.363\ eV$$

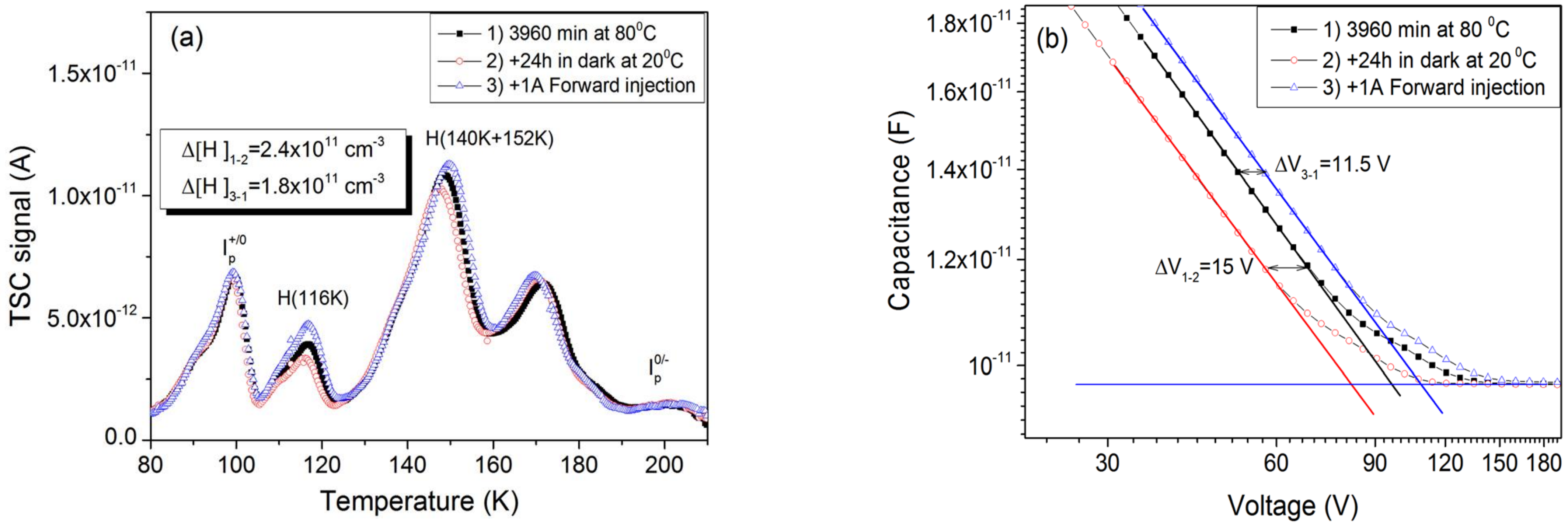
$$k_{A\rightarrow B} \cong 10^3 * \exp\left(-\frac{0.363\ eV}{k_B T}\right)$$



The volume in which the density of free electrons is larger than that of holes increases with resistivity → the change of the BCD configuration from A to B (with some recovery of acceptors) after small Fw current injection is observed in high resistivity diodes.

• Are other bistable effects that may overlap to that of BCD ?

- yes, we know that the cluster related hole traps, responsible for the magnitude of reverse annealing in n-type Silicon, show a bistable behavior after high irradiation levels



R. Radu et al, J. Appl. Phys. 117, 164503 (2015)

Bistability of H(116 K), H(140 K), and H(152 K) defects and corresponding change in V_{dep} of a 300 μm thick STFZ diode irradiated with 27MeV electrons, Φ=10^{14} cm^{-2} (type inverted) and annealed for 3960 min at 80 C: (a) TSC spectra; (b) C-V curves measured with a frequency of 10 kHz and 0.5V small ac signal;

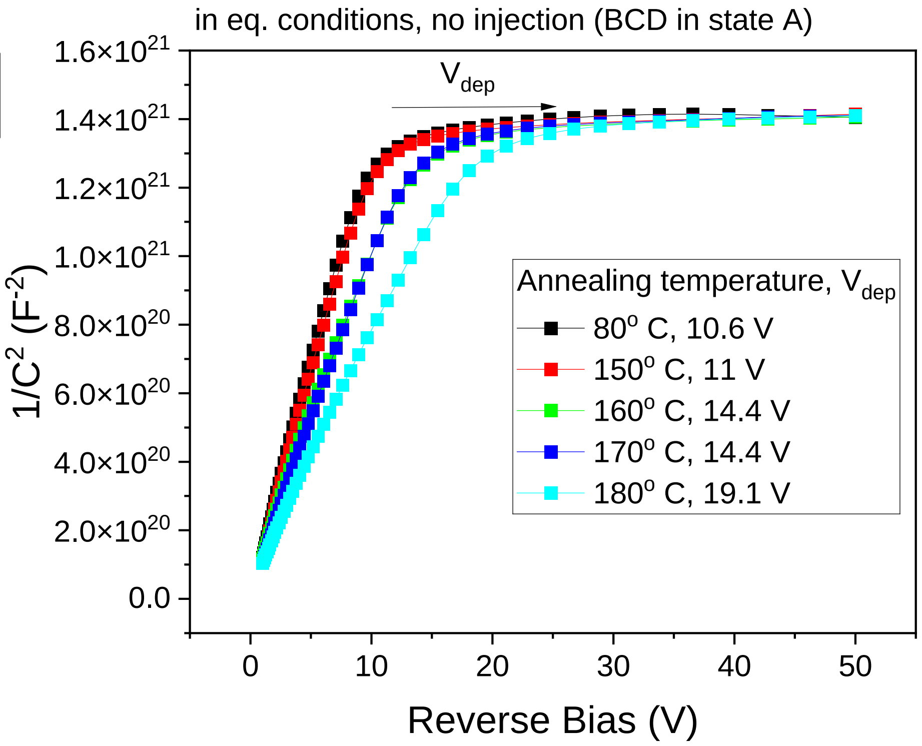
As acceptors in the lower part of the gap the impact of H116K, H140K and H152K clusters on N_{eff} in p-type Silicon is opposite to that of BCD (donors in the upper part of the gap)

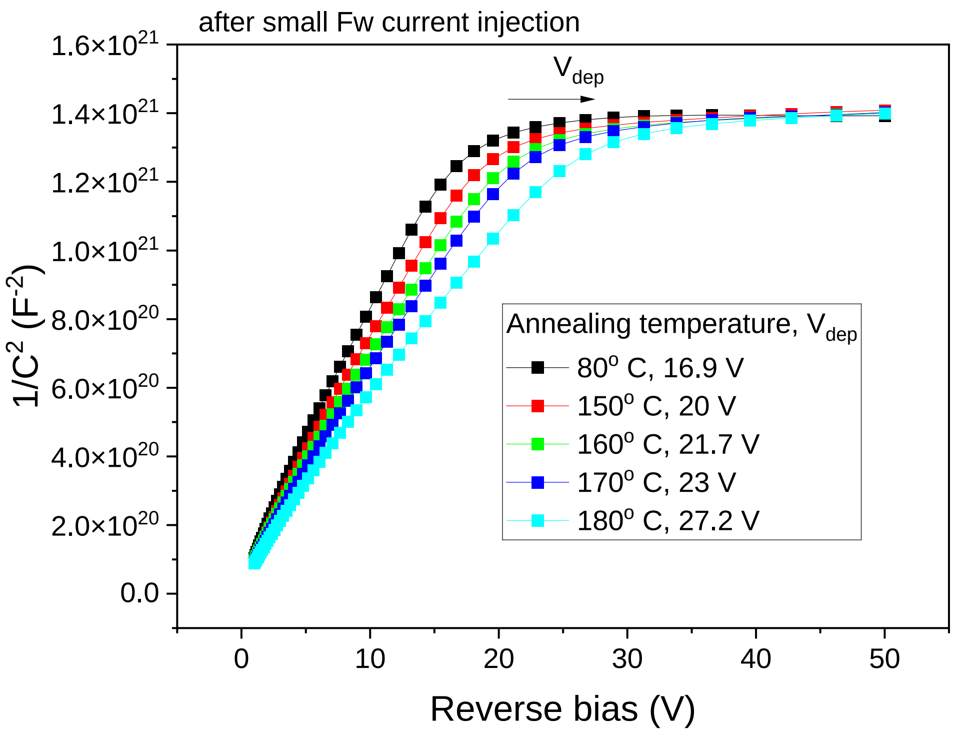
Annealing studies on 12 kΩcm PAD samples

We know that: - BCD defect dissociates in (160° C - 200° C) the temperature interval[4]

- H116K, H140K and H152K continue forming

CVs at 293 K

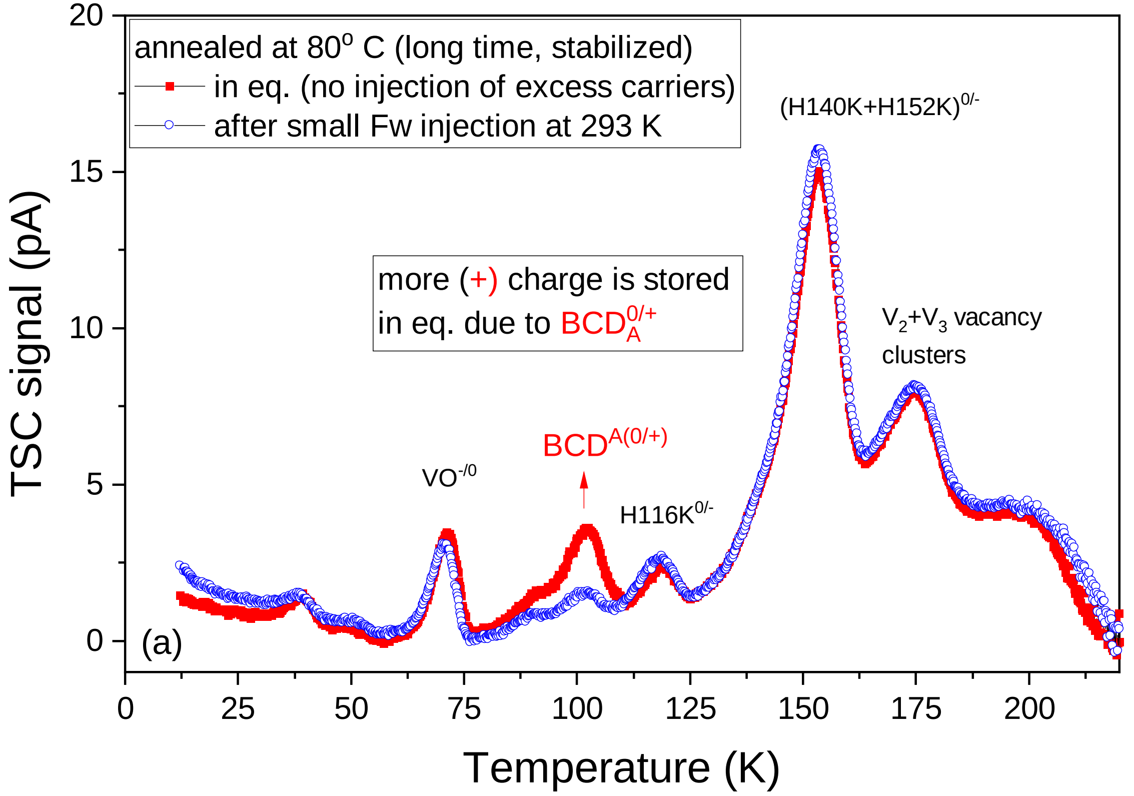


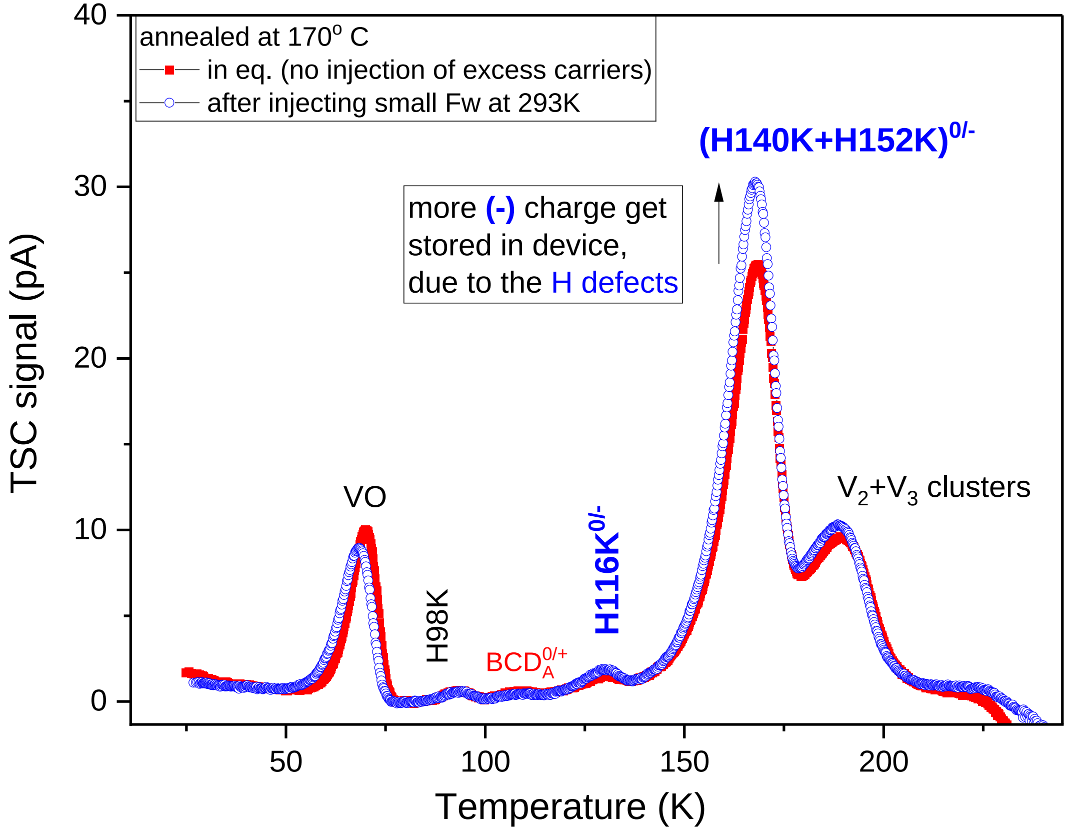


- During annealing, V_{dep} increases both, in eq. conditions and after small Fw injection
- While after annealing at 180⁰ C an increase of ~ 10 V in V_{dep} is measured , only a 6.3 V can be attributed to the dissociation of BCD, the rest is due to the *H116K, H140K and H152K defects*

Annealing studies on 12 kΩcm PAD samples

TSC experiments





- before the annealing the observed bistability is mainly due to BCD (ΔV_{dep} ~ 6.3 V)
- after annealing at 180°C (where BCD signal vanishes) the amount of *H-type cluster defects increases twice* becoming the main source for the observed bistabilities (ΔV_{dep} ~ 4 V)

Conclusions

- The acceptor removal effect can be minimized by switching the BCD from its stable, positively charged configuration A, to the neutral one B. Such a process is very efficient in high resistivity p-type Silicon.
- The more favorable B state can be achieved by small injection of carriers. The B state froze-in at 253K.
- Isochronal annealing at temperatures below 200 ^{o}C reveals that also the cluster defects, acceptors in the lower part of the gap, manifest bistability – small Fw injections increase the negative charge stored on these defects and so, their bistability can also be used to minimize the acceptor removal effect.
- The study on *H116K, H140K and H152K* clusters just started and will continue for establishing the kinetics behind bistability and whether the more favourable configuration with respect to AR effect can be frozen-in

Thank you for your attention!