ON THE BISTABILITY OF THE BORON RELATED DONOR ASSOCIATED WITH THE ACCEPTOR REMOVAL PROCESS IN IRRADIATED P-TYPE SILICON

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MOTIVATION

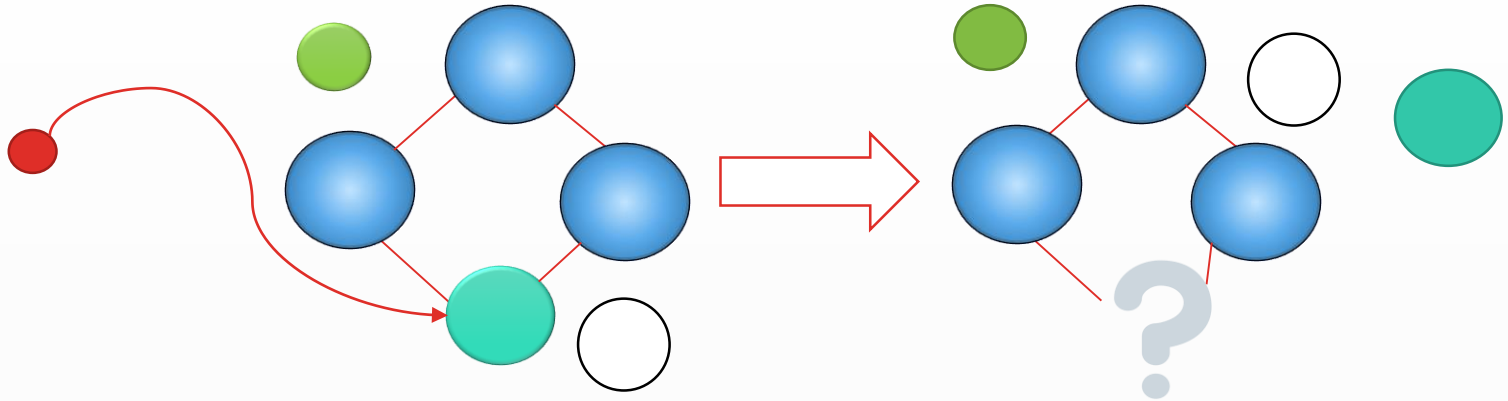


Fig1. Scheme of interaction of radiation and structure

The interaction between the structure and the irradiated sample can create a different number of defects, depending on the type of radiation and the energy of it.

$$1.\ V + O \rightarrow VO$$
$$2.\ V_2$$
$$3.\ S_i + C_s \rightarrow C_i$$
$$4.\ C_i + C_s \rightarrow C_iC_s$$

$$5.\ C_i + O_i \rightarrow C_iO_i$$
$$6.\ S_i + B_s \rightarrow B_i$$
$$7.\ B_i + O_i \rightarrow B_iO_i$$
$$and\ others\ \ldots$$

$\rightarrow lowers\ the\ doping\ of\ the\ silicon\ sample$

$(ACCEPTOR\ REMOVAL)$ → Changes to the electrical characteristics of the device

MOTIVATION & AIM

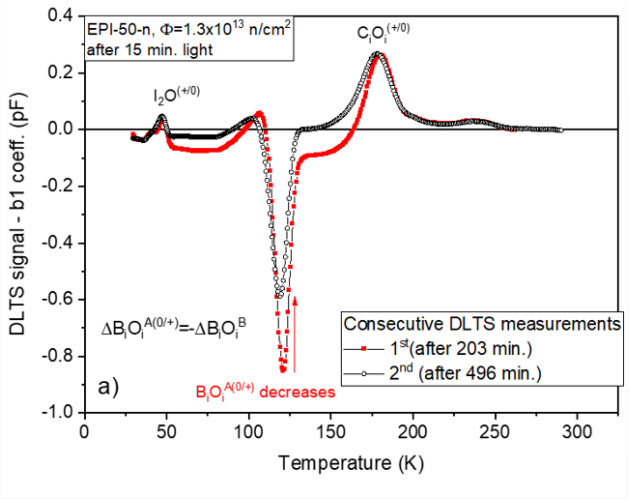


Fig2. Two consecutive DLTS spectra for electrons and holes of a $50\Omega cm$ PAD sample with a 1V pulse after 15 minutes light exposure at 293K

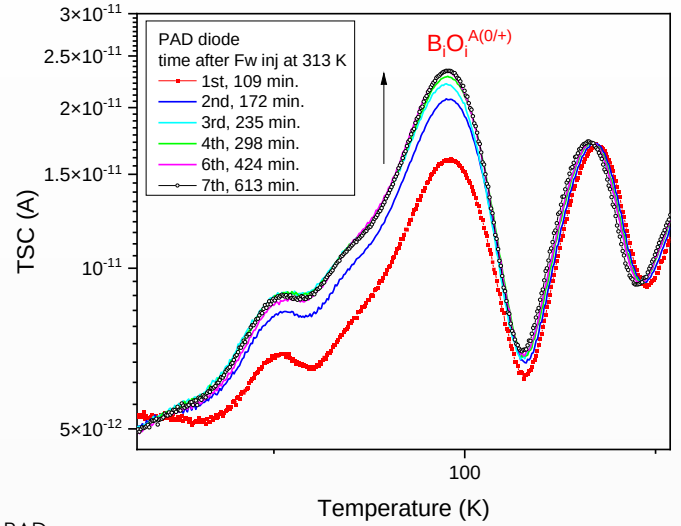


Fig3. Annealed 12 kohm cm FZ sample irradiated with Φ= 10^{15} n/cm² after 15 minutes light exposure at 293K (5.7 μA photocurrent in s.c.). Magnified TSC peak of B_iO_i showing the variation in the A configuration of the defect.

B_IO_i:
$E_c - E_A \sim 0.28eV$

Variations of 23% of the BiOi defect in diodes irradiated with $\phi_{eq} \sim 1.3 * 10^{13}\ n/cm^2$ and more than 100% for $\phi_{eq} > 10^{14}\ n/cm^2$, observable in N_{eff}. This variation is a reversible phenomena.

The donor at $120\ K$ in DLTS and 100 K in TSC has been attributed to B_iO_i(1977 by Mooney and Corbett) but lately, this identification presents some doubts.

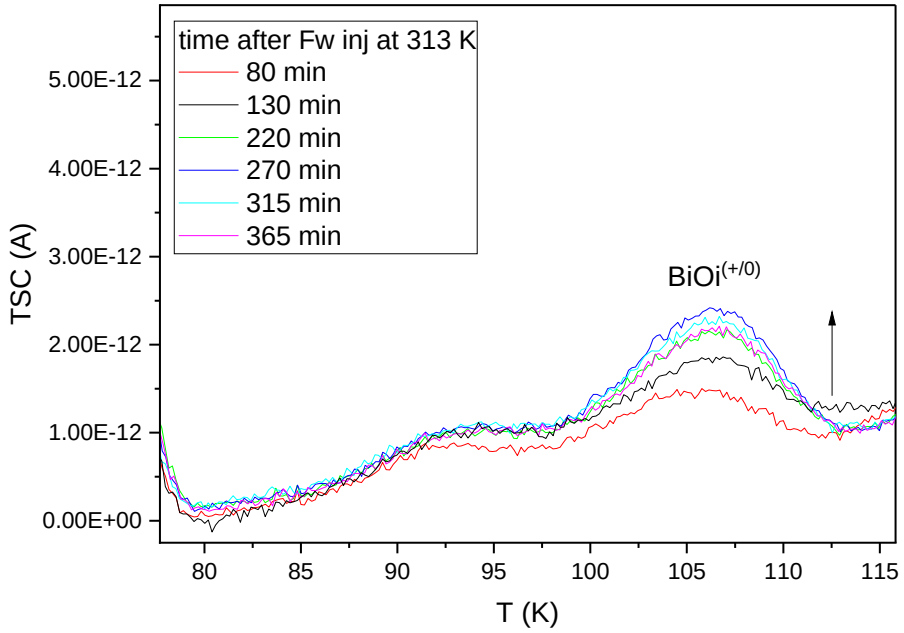
The peak variations were observed after the samples experienced an increase in the free carriers concentration at ambient temperatures caused by different factors:

- Exposure to light
- Applying a heat treatment
- Applying a forward bias current

AIM: *determine rate constants and activation energies for the defect change of configuration*

* C. Besleaga et al., doi.org/10.1016/J.NIMA.2021.165809

MOTIVATION & AIM



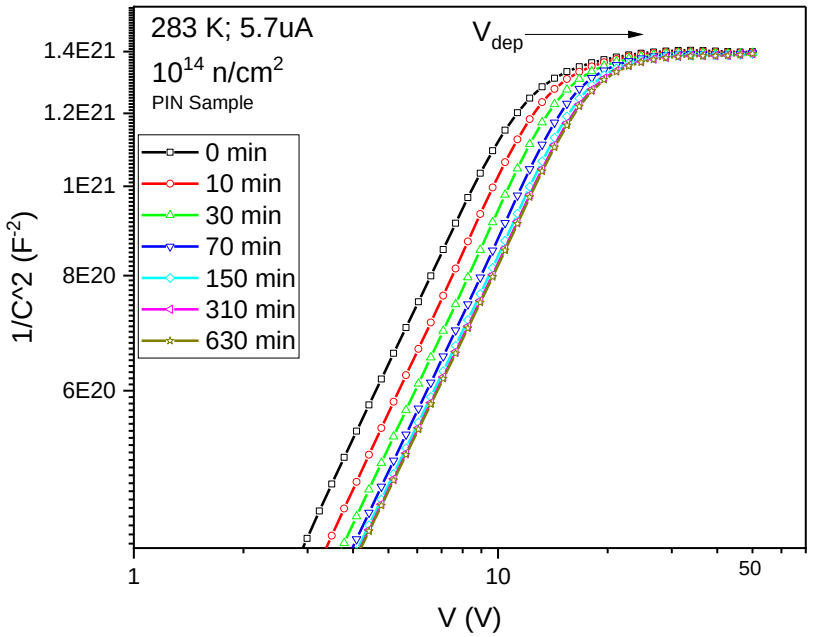


Fig4. 12 kohm cm FZ sample irradiated with $\Phi = 10^{15}$ n/cm² after changing of the defect configuration with a forward bias at 313 K and repeating TSC scans after (far left); CV measurements while charging (near left)

- The existence of configuration B is suggested by the variation of the A configuration and the changes in the depletion voltage
- Upon exposure to an excess of charge carriers, $B_iO_i^A$ transforms to the configuration $B_iO_i^B$ at ambient temperatures
- $B_iO_i^B$ is not visible through microscopic measurements but its influence can be assessed through macroscopic measurements (Capacitance and Current measurements)
- This change is reversible
- The switches between the two configurations are depedent on ambient conditions, causing a large spread of results regarding the evaluated N_{eff}

REVERSIBLE CHANGE OF DEFECT CONFIGURATION

From A to B and back

$$-\frac{dN_X}{dt} = k_i * \mathrm{N_x}; \begin{cases} N = defect\ concentration \\ t = time \\ k_i = rate\ constant \end{cases}$$

- **1st order:**

$$N = N_{t\to 0}\exp(-k * t) \to \ln[N] = \ln[N_{t\to 0}] - k * t;$$
$$Y = N_{t\to 0}[1 - \exp(-k * t)]$$

1st order reactions: Dissociations, configuration change

(each defect reacts independently)

$$k = k_0 * \exp\left(-\frac{E_A}{K_B * T}\right); \begin{cases} K_B = Boltzmann\ constant \\ E_A = activation\ energy \\ h = Planck\ constant \end{cases}$$

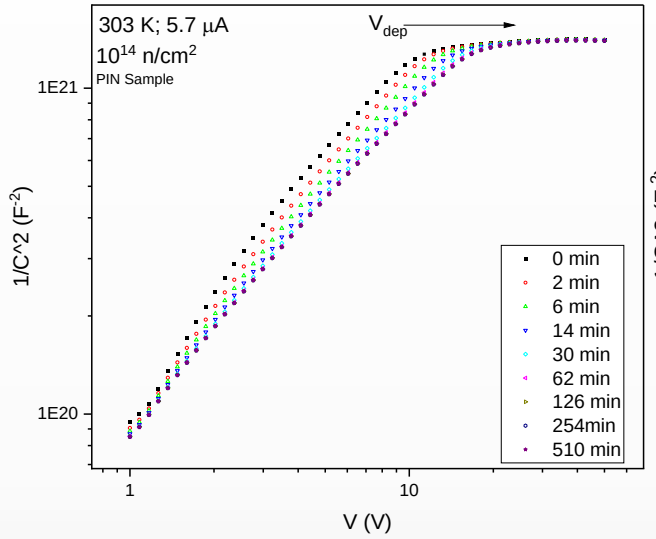
ANALYZED SAMPLE

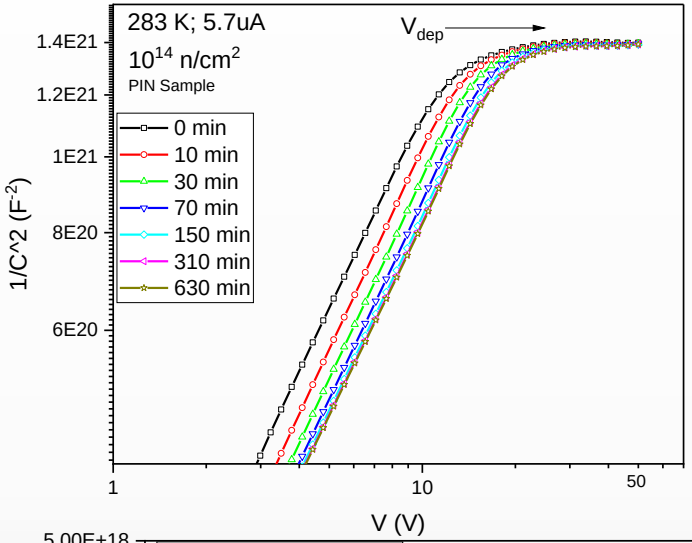
PIN sample (W5-LGP-72P**)**			
Irradiation	Thickness	Annealing Time @$80°C$	Resistivity of Float-Zone Sample
$10^{14}\ n/cm^2$	$45\ \mu m$	$136735\ min$	$12k\Omega * \mathrm{cm}$

- The long annealing time assures that the current state of the sample is stable.
- The change of the B_iO_i configuration – via monitoring the change of the depletion voltage (from C-V characteristics)for different excitation conditions of the samples – dependence on temperature
    - **Change from A to B configuration** – via exposure of the sample to an excess of free carriers for different times and at different temperatures
    - **Change from B to A configuration** – by monitoring the time needed to return from B to A configuration in dark after an initial full switch of the defect in the B configuration.

A → B

(CHARGING WITH SMALL FW CURRENT AT DIFFERENT TEMPERATURES)





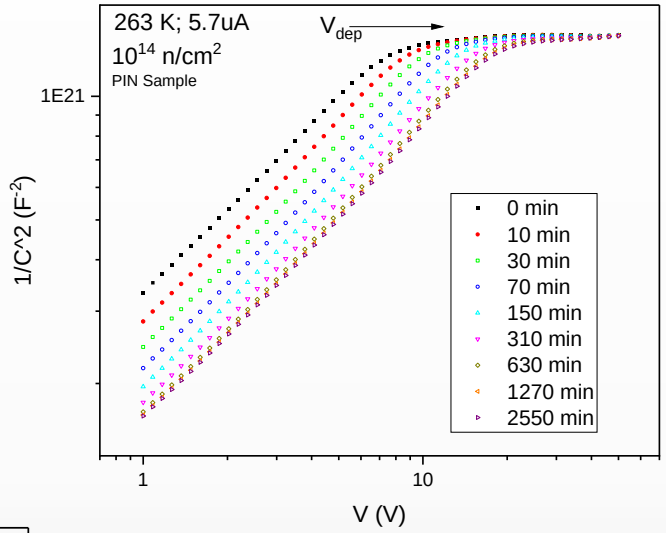
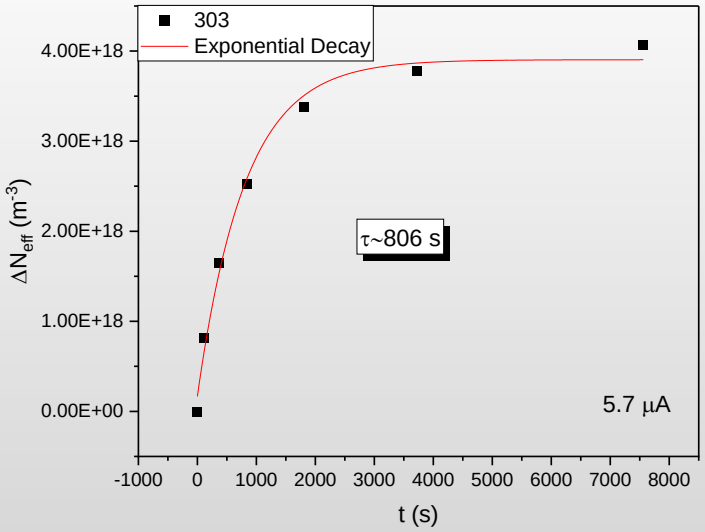
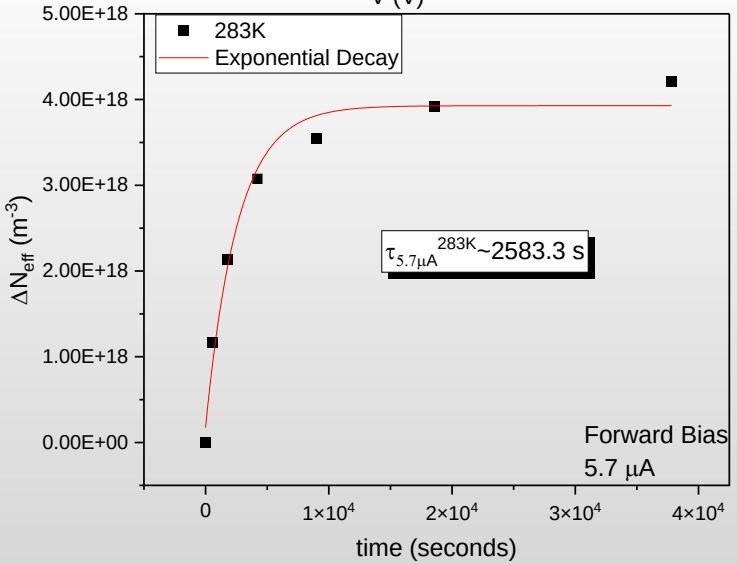
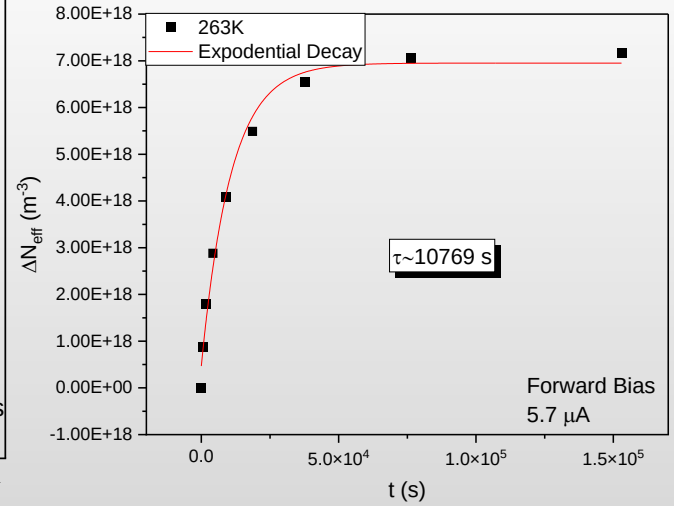


Fig5. Capacitance measurements at different temperatures during charging under a 5.7μA forward bias(up) and extracted effective dopage variation (down)







$\Delta V_{fd}\ (V) \in (7, 10)V$

We chose 5.7 μA injection current because of the short-circuit current under ambient laboratory light.

A → B

(CHARGING WITH DIFFERENT FW CURRENT AT THE SAME TEMPERATURE)

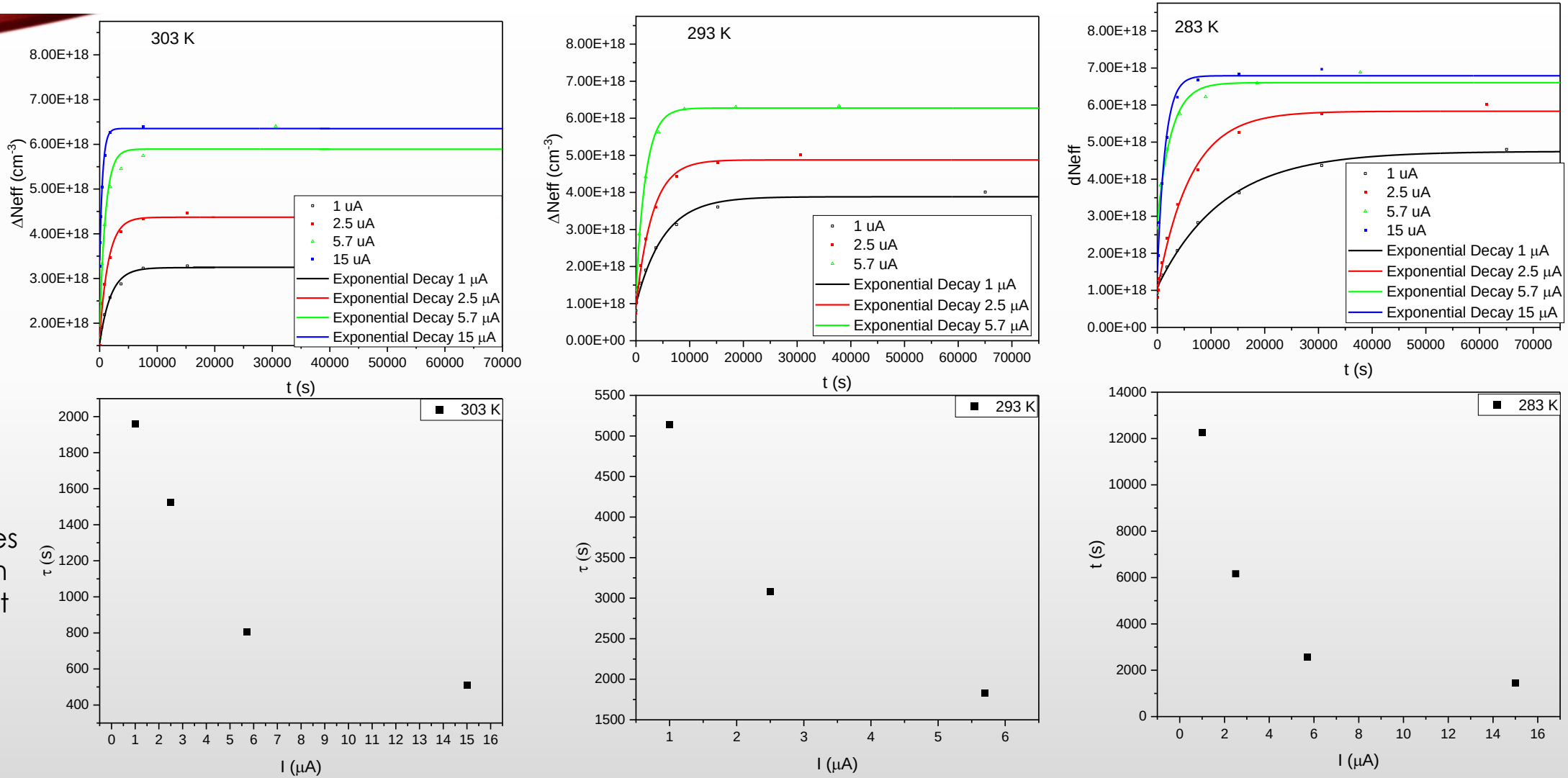
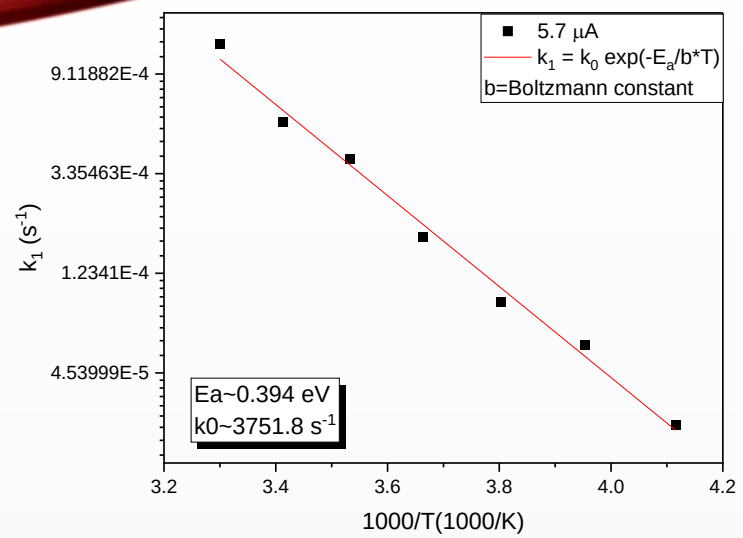


Fig6. Capacitance measurements at different temperatures during discharging in dark and short circuit conditions after charging

The time constant for transformation A to B depends on the injection current at the same temperature. The higher the injection current, the faster is the transformation.

$A \rightarrow B$
(DETERMINATION OF THE REACTION RATE AND ACTIVATION ENERGY)



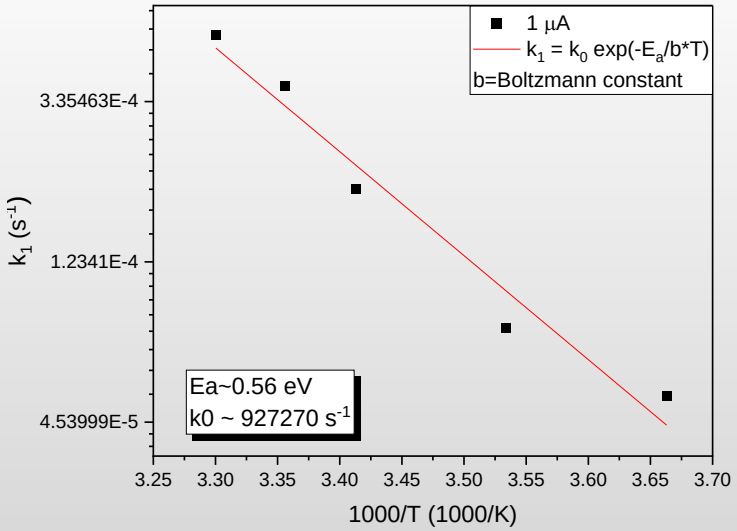
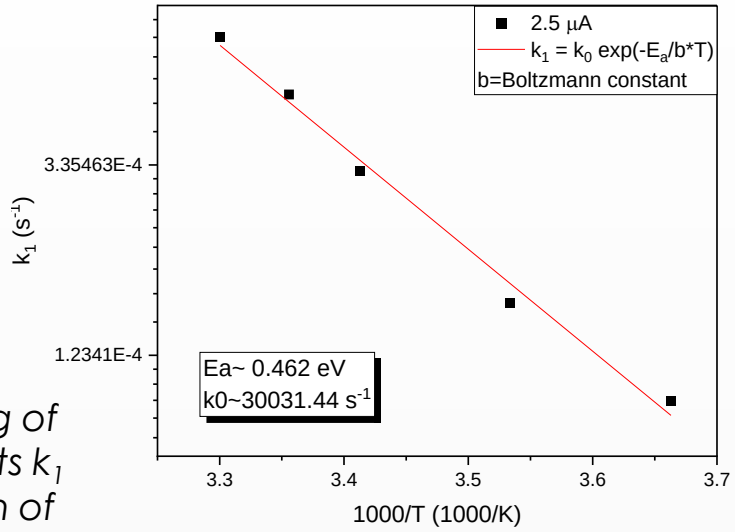
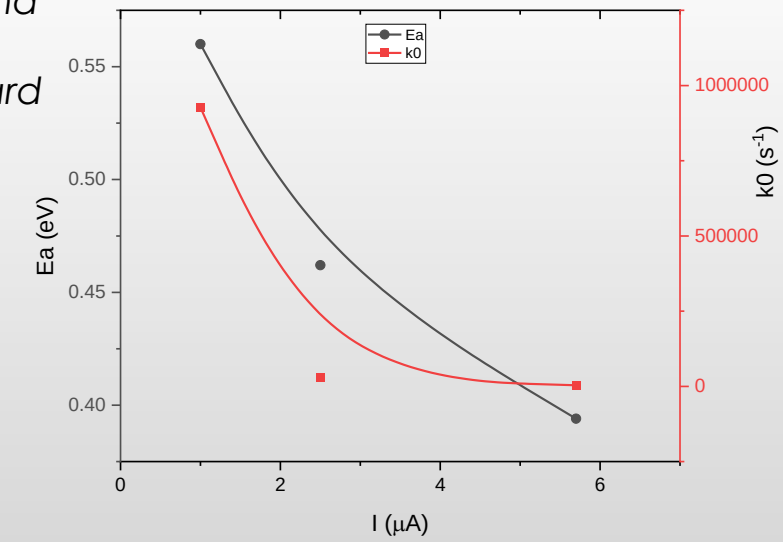


Fig7. Linear Fitting of the time constants k_1 for the extraction of activation energy and k_0 at different magnitudes of forward bias





The higher the injection level, the lower is the process activation energy

B → A

(DISCHARGING IN DARK AND UNDER 0 V AT DIFFERENT TEMPERATURES)

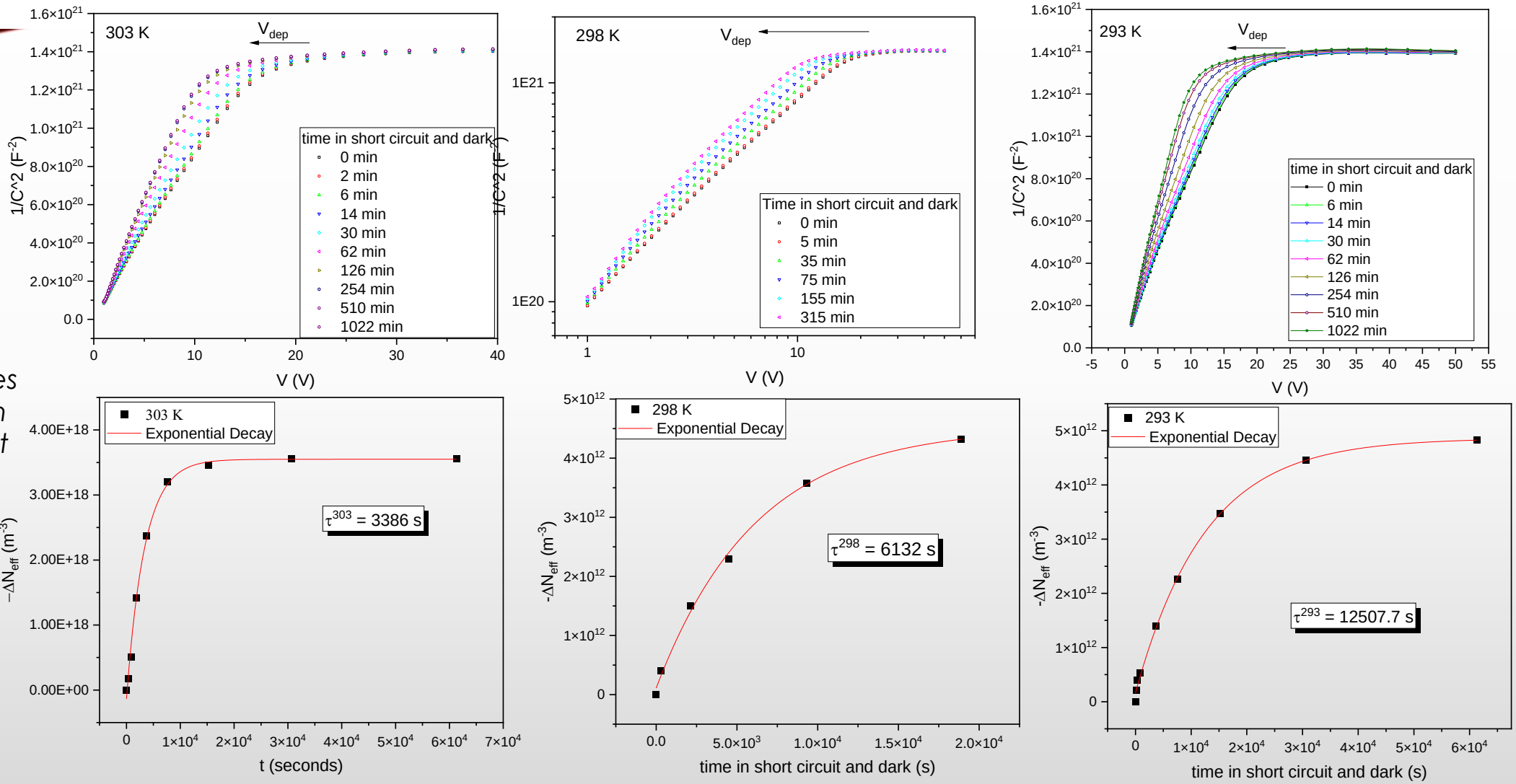
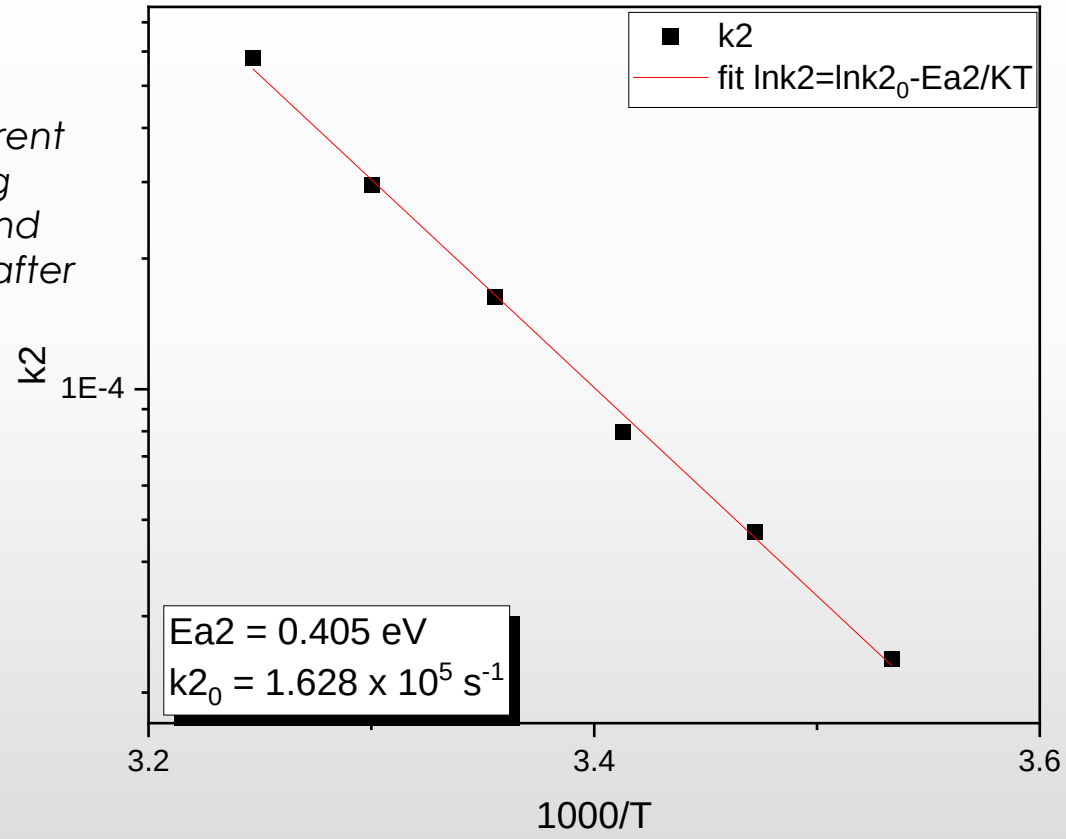


Fig6. Capacitance measurements at different temperatures during discharging in dark and short circuit conditions after charging

The reverse transformation (B→A) takes place faster with higher temperatures.
At 30°C, the transformation takes around 1 h while at 20°C, it takes about 4 hours.

$B \rightarrow A$
(DETERMINATION OF THE REACTION RATE AND ACTIVATION ENERGY)

Fig8. Capacitance measurements at different temperatures during discharging in dark and short circuit conditions after charging



- The change from configuration B to configuration A requires more time than the other (from A to B).
- It is influenced by temperature (the larger the temperature, the faster the change of configuration)

(also valid for charging: the higher the temperature, the faster is the change from configuration A to B!)

CURRENT MEASUREMENTS

Similar behaviors of charging and discharging mechanism as seen in CV measurements are observed in IV characteristics.

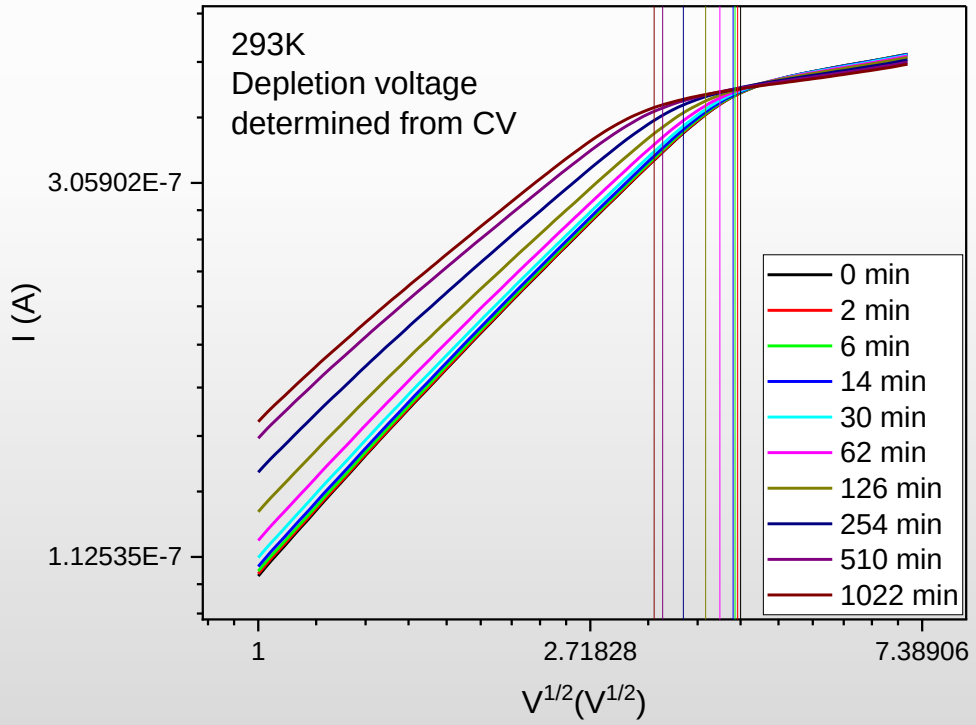
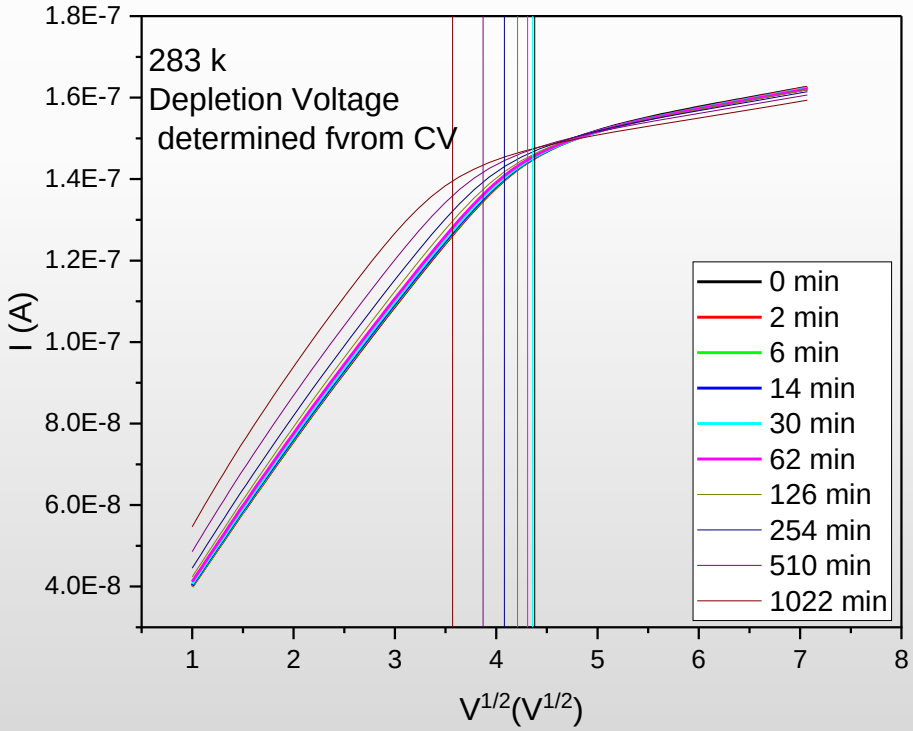


Fig9. Extraction of current depletion utilizing the full-depletion voltage from CV measurements at 283 K (left) and 293 K (right)



CONCLUSIONS

We have studied the bistability of B_iO_i defects via the changes in macroscopic characteristics (Capacitance and current measurements)

We found that:

- The lower the injection current, the slower the change from configuration A to B at a given temperature:
$\tau_{1\mu A}(283\ K)\sim 12270\ s < \tau_{5.7\mu A}(283\ K)\sim 2580\ s$
- For the same injection current, the transformation $A \rightarrow B$ is faster with the increasing temperature:
$\tau(303\ K)\sim 1015\ s > \tau(283\ K)\sim 2583\ s$
- The time constant for $A \rightarrow B$ transformation is much smaller than for $B \rightarrow A$:

$$\tau_{charging}\sim 2583\ s \ll \tau_{discharging}\sim 41839\ \text{s (for 283 K)}$$

- A higher injection than 5.7 μA didn't brought a larger variation to the extracted reaction rate and activation energy:
$\tau(5.7\mu A) = 1451\ s \qquad \tau(15\mu A) = 2583\ s\ (for\ 283\ K)$
- To reduce the scattering of the N_{eff} results, one has to avoid the exposure of the sample to the ambient light and also avoid keeping the sample at temperatures exceeding 20°C

THANK YOU FOR THE ATTENTION!

EXTRA

LGAD sample (W3-LGP-71P**)**			
Irradiation	Thickness of Gain Layer	Thickness of the sample	Annealing Time @80°C
$1.8 * 10^{14}\ n/cm^2$	$1\ \mu m$	$45\ \mu m$	

CAPACITANCE MEASUREMENTS

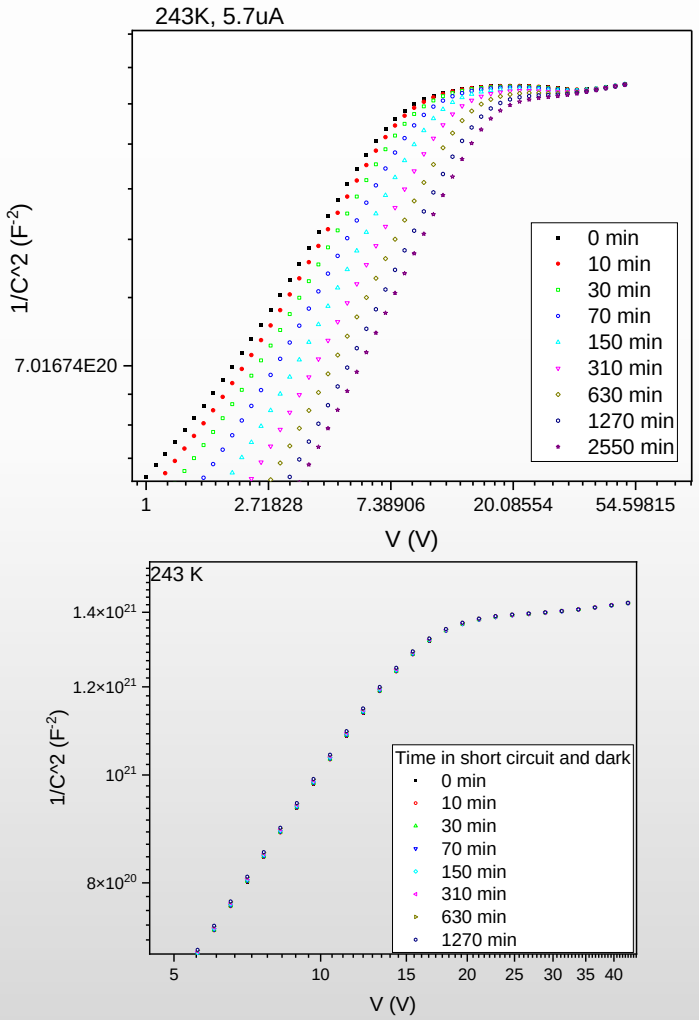


Fig10. Variation of CV measurements at 243 K

A->B

B->A

At low temperatures ($example\ at\ 243\ K$), the variation of the CV measurements in short circuit and dark was very small.

CAPACITANCE MEASUREMENTS

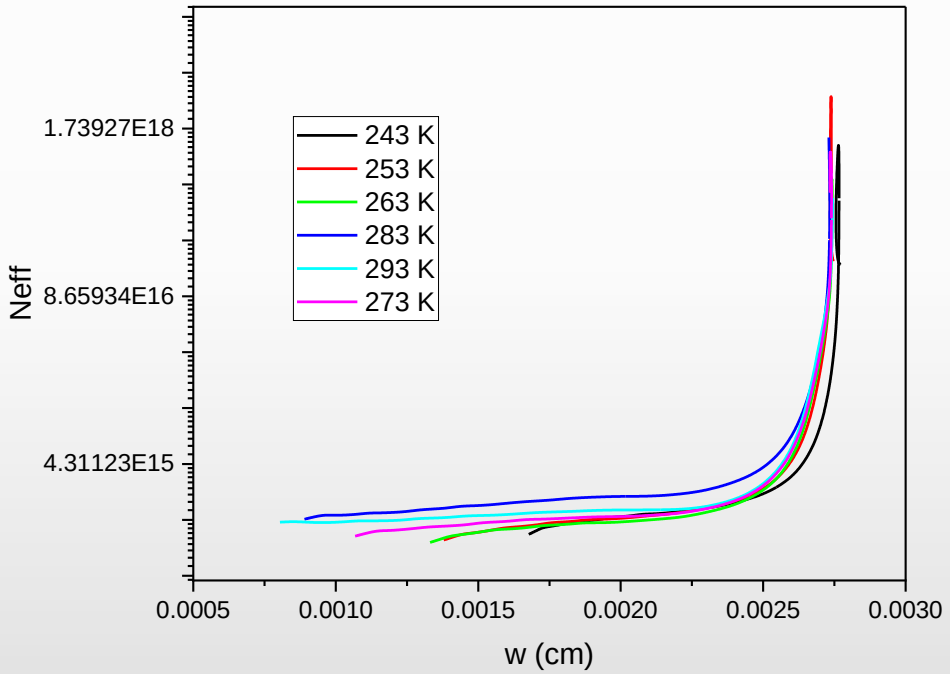


Fig4. Variation of effective dopage with the thickness of the space charge region (∝ applied voltage) – arrival to full depletion

$$N_{eff} = \frac{2\epsilon_0 \epsilon_r V_{fd}}{q_0 d^2}$$

$$N_{eff}(V) = \frac{2}{\epsilon_0 \epsilon_r A^2 q_0 \frac{d(1/C^2)}{dV}}$$

$$w(V) = \frac{\epsilon_0 \epsilon_r A}{C(V)}; V < V_{fd}$$

$$\begin{cases} \epsilon_0 = permittivity\ of\ vacuum \\ \epsilon_r = relative\ permittivity\ (11.9\ for\ Si) \\ q_0 = elementary\ charge \\ V_{fd} = full - depletion\ voltage \\ d = thickness\ of\ the\ sample \\ w = thickness\ of\ the\ limited\ space\ charge\ region \\ N_{eff} = effective\ dopage \\ A = area\ of\ the\ sample \\ C = capacitance \end{cases}$$