Bistability of the BiOi complex – a reason for the observed large scattering in the determined acceptor removal rates in irradiated p-type silicon

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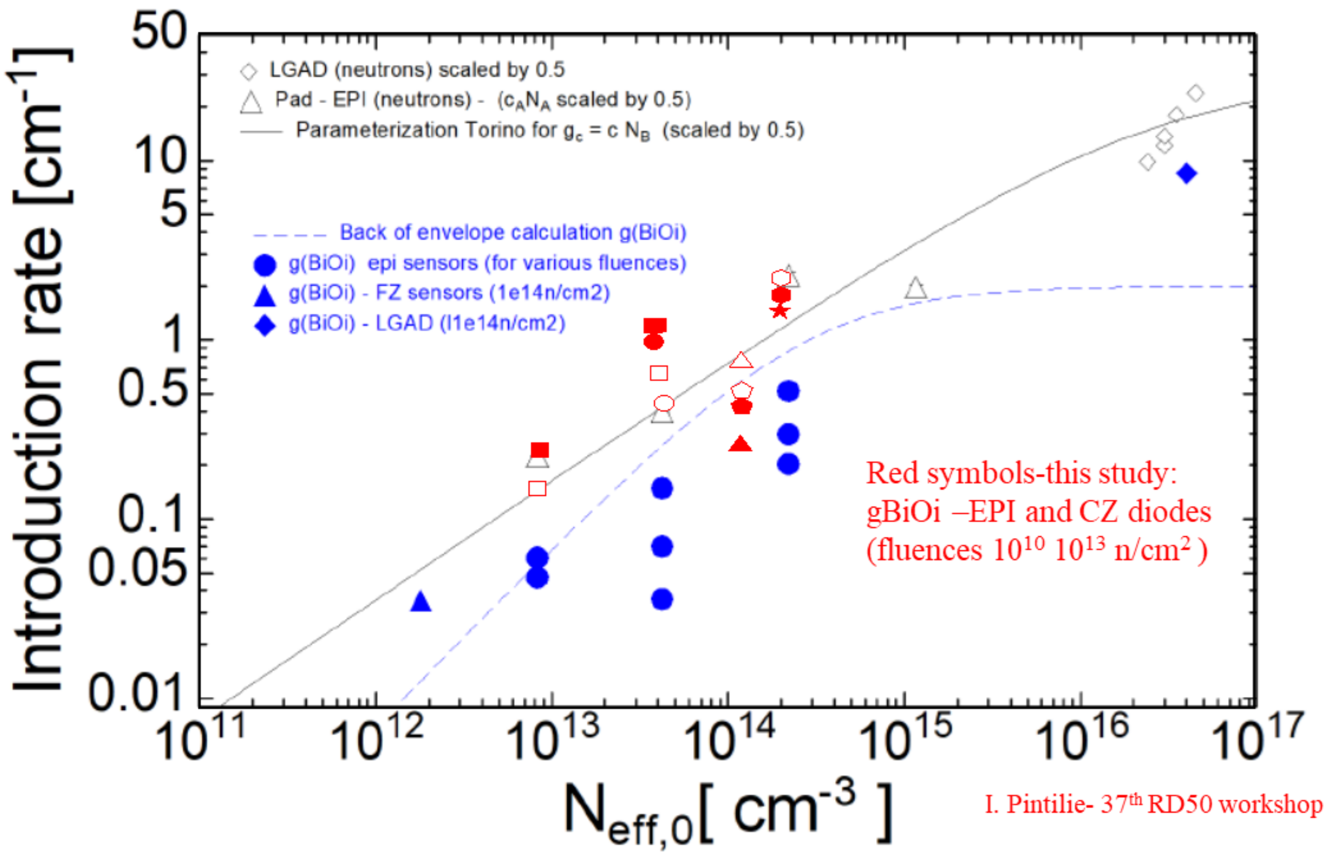
Outline

- Motivation
- Samples
- Experimental results
    - DLTS and TSC experiments
    - Bistability BiOi
    - Impact on defect generation and acceptor removal rates (V_{dep} variations)
- Summary and further work

Motivation: "Acceptor removal rate" in p-type Silicon and the BiOi defect



I. Pintilie- 37th RD50 workshop

- **strong scattering of data**, different measurement techniques used; different devices; different Silicon (e.g. [O], [C])

Possible explanation:

- Different devices and producers, sensors with different amount of impurities

- **Large differences** between B_iO_i defect generation rate and the acceptor removal rate as determined from C-V measurements

Possible explanation:

- Formation of other defects containing B or/and of other type of defects acting as donors.

What about intrinsic causes resulting in different data for the same sample measured in the same way&place ?

- bistability of B_iO_i, what trigger it and how is impacting the measured data ?
- Possible differences in the time scale of measuring CVs and perform microscopic defect investigations

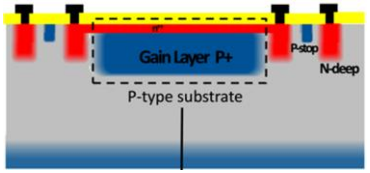
Investigated p-type Samples

PiN pads produced and processed by CiS, Germany and few PiN and LGADs from CNM

50 µm thick P-type substrate:

- EPI, 50 ohm cm (4 samples)
- EPI, 250 ohm cm (4 samples)
- EPI, 1000 ohm cm (4 samples)

- Pairs of PiN and LGAD FZ diodes



Irradiation with 23 GeV protons and 1 MeV neutrons

- with 23 GeV protons and 1 MeV neutrons
- eq. fluences $<1.3\times10^{13}$ n/cm^2

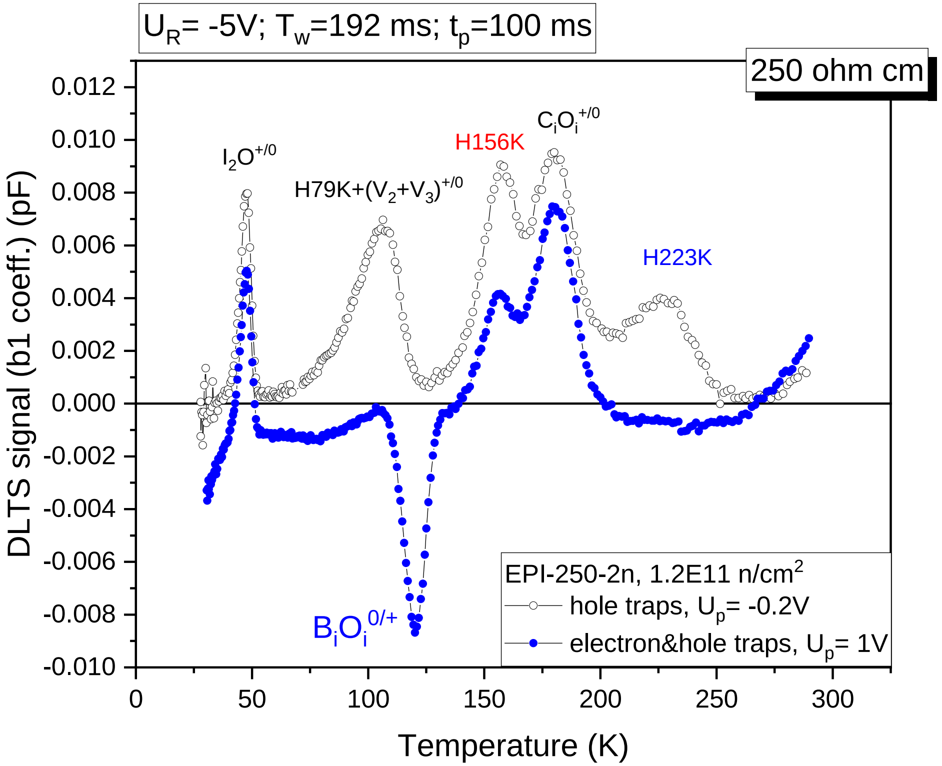
- with 1 MeV neutrons, fluences of 10^{14} and 10^{15} n/cm^2

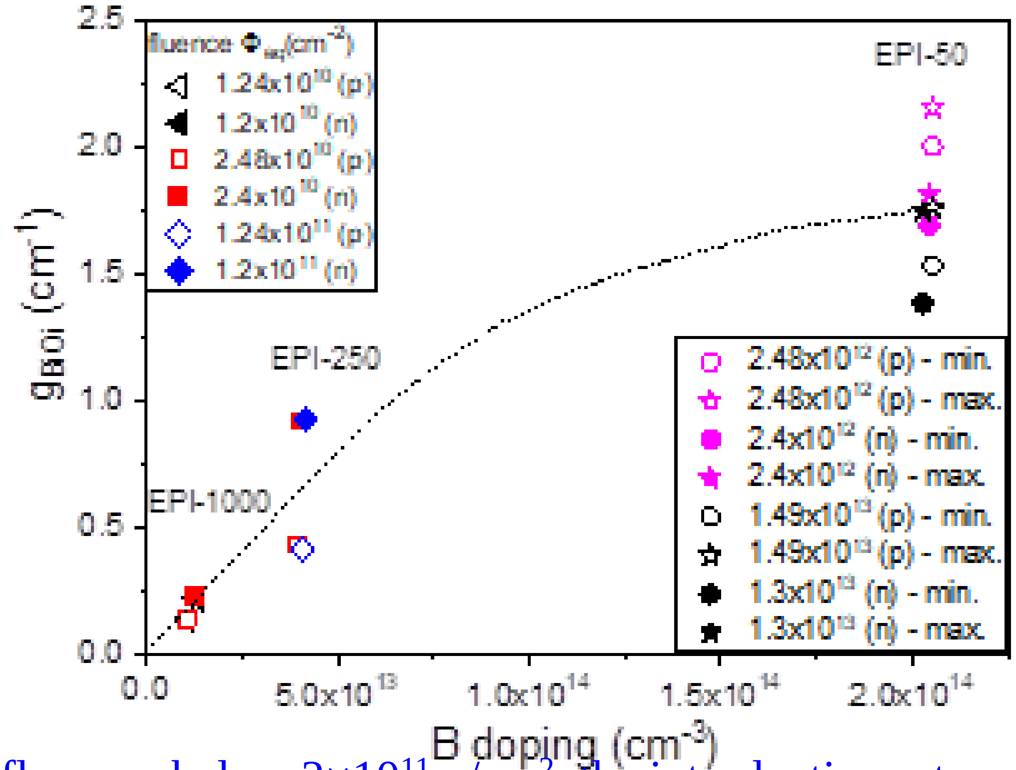
Type of investigations

- Electrical characterization by DLTS & CV/IV

- Electrical characterization via TSC & IV

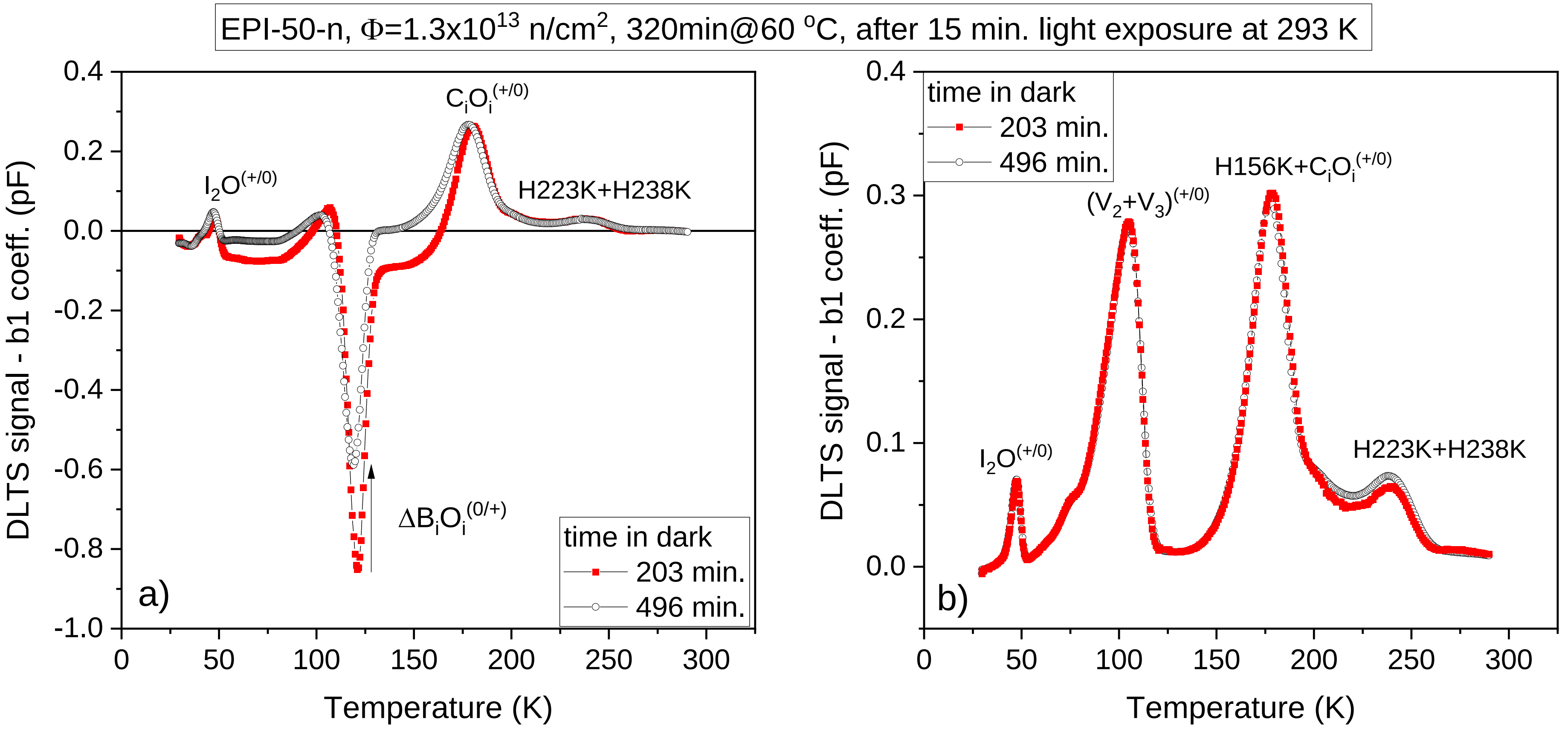
DLTS characterization of EPI diodes – B_iO_i defect generation rate for eq. fluences $<1.3\times10^{13}$ n/cm^2*





- only for low boron content, when samples were irradiated with fluences below 2×10^{11} n/cm^2, the introduction rates of BiOi are nicely grouped according to the type of irradiation (neutrons or protons) – no “scattering”
- for 50 Ωcm resistivity samples, irradiated with fluences in the 10^{12} – 10^{13} n/cm^2 range, gBiOi data becomes irreproducible when the samples with the same history behind in terms of irradiation and annealing stage are re-measured

* C. Besleaga et al., Bistability of the BiOi complex and its implications on evaluating the acceptor removal, arXiv:2102.06537



DLTS spectra on irradiated EPI-50 diode recorded after exposing the sample to the ambiental laboratory light at 293K, corresponding to different storage times in dark, for: a) electrons&holes traps (1 V forward bias pulses); b) majority carriers (0 V filling pulses).*

- Variation of up to 23% for the detected [B_iO_i] in diodes irradiated with Φ_{eq} = 1.3x10^{13}n/cm^2 (and of ~10% for Φ_{eq} =2.5x10^{12}n/cm^2), in the first ~8h after exposure to ambient light
- Such changes are reversible:
  - bistable nature of BiOi defect: existence of min. two defect configurations, A and B
  - only configuration A is detectable in DLTS measurements

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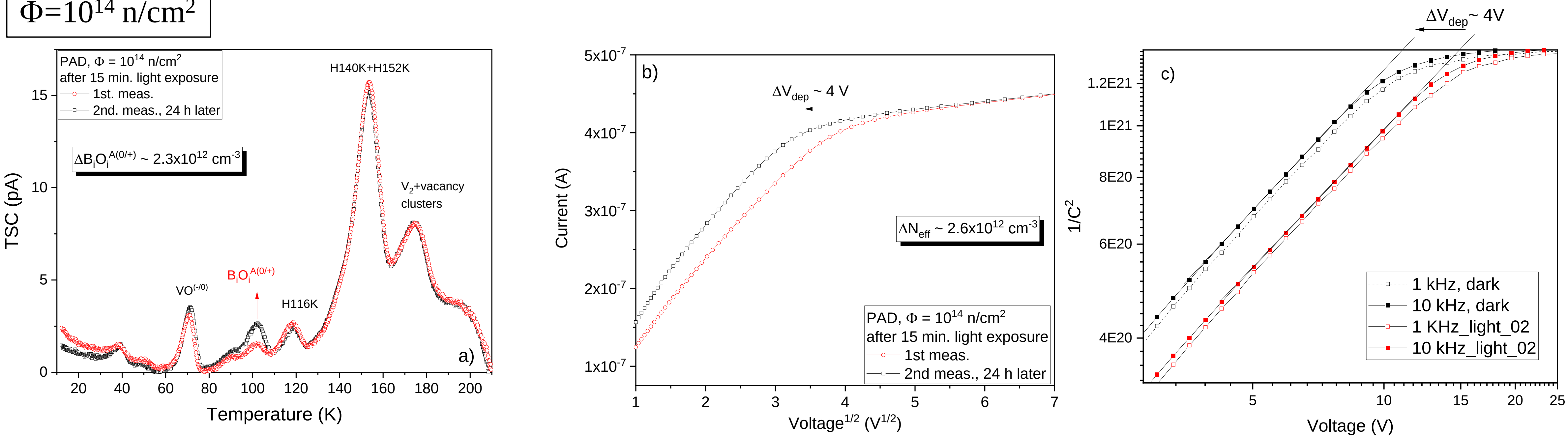
Irradiation fluence of 10^{14} and 10^{15} n_{eq}/cm^2 – TSC and IV/CV investigations*

Examples of variations in B_iO_i concentration, as seen via the A configuration, caused by heating the diodes to 80 °C or by exposure to ambient light (laboratory neon for ~ 15 minutes) in PAD diodes annealed for 91650 min@80 °C

$\Phi=10^{14}$ n/cm²



- The variation in B_iO_i concentration is in good agreement with the variation of V_{dep} from IV and CV at 293K.
- Variation up to 80% for the detected [B_iO_i] defect in diodes irradiated with $\Phi_{eq} = 10^{14}$n/cm²

→ B_iO_i exist in minimum 2 configurations, A and B
→ only the A one is charged at ambient temperature
→ the defect reversibly passes from one configuration to another after exposing the samples to an excess of carriers at ambiental temperatures

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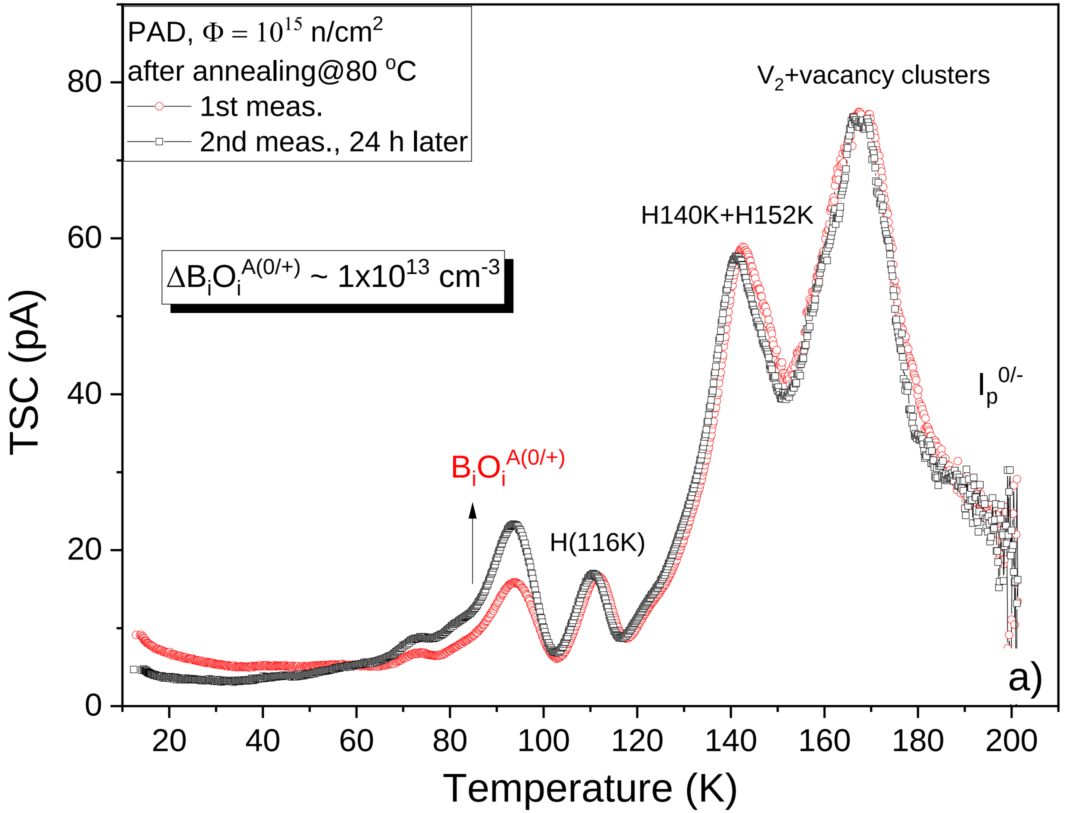
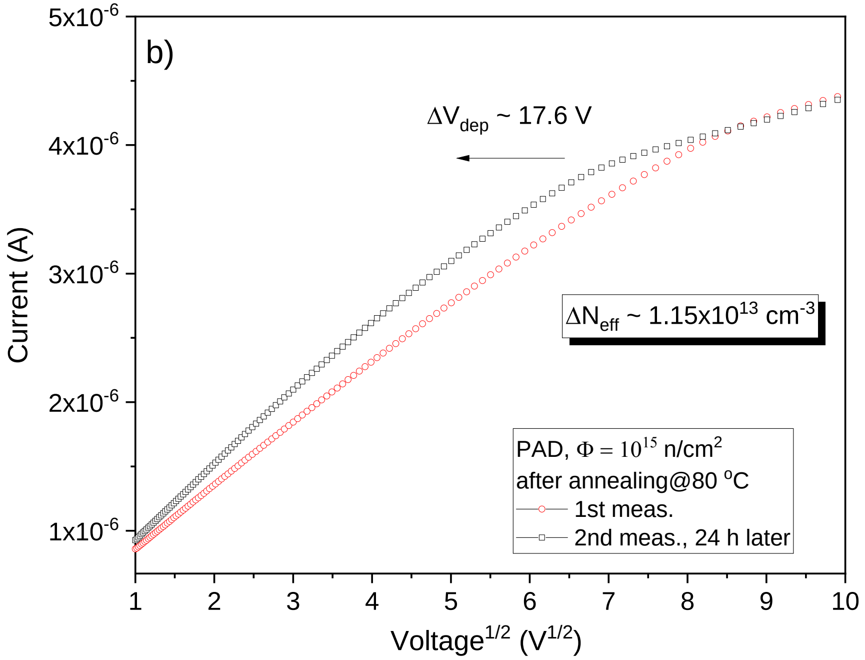
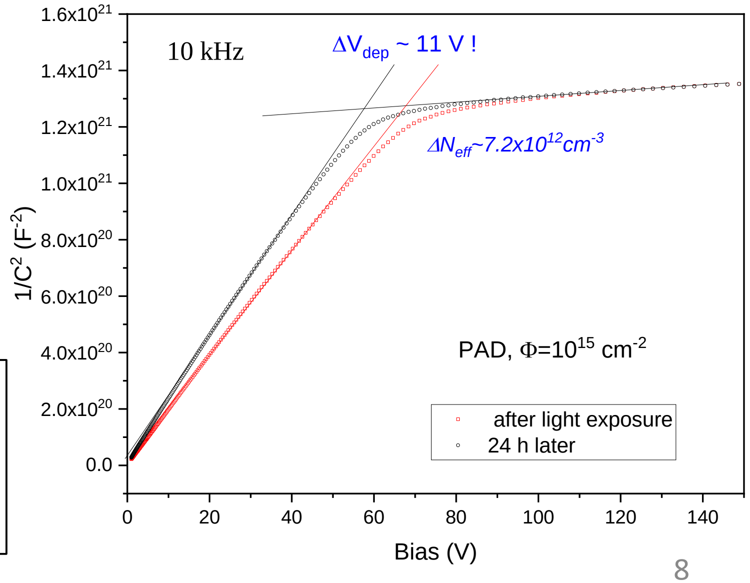
$\Phi=10^{15}$ n/cm^2

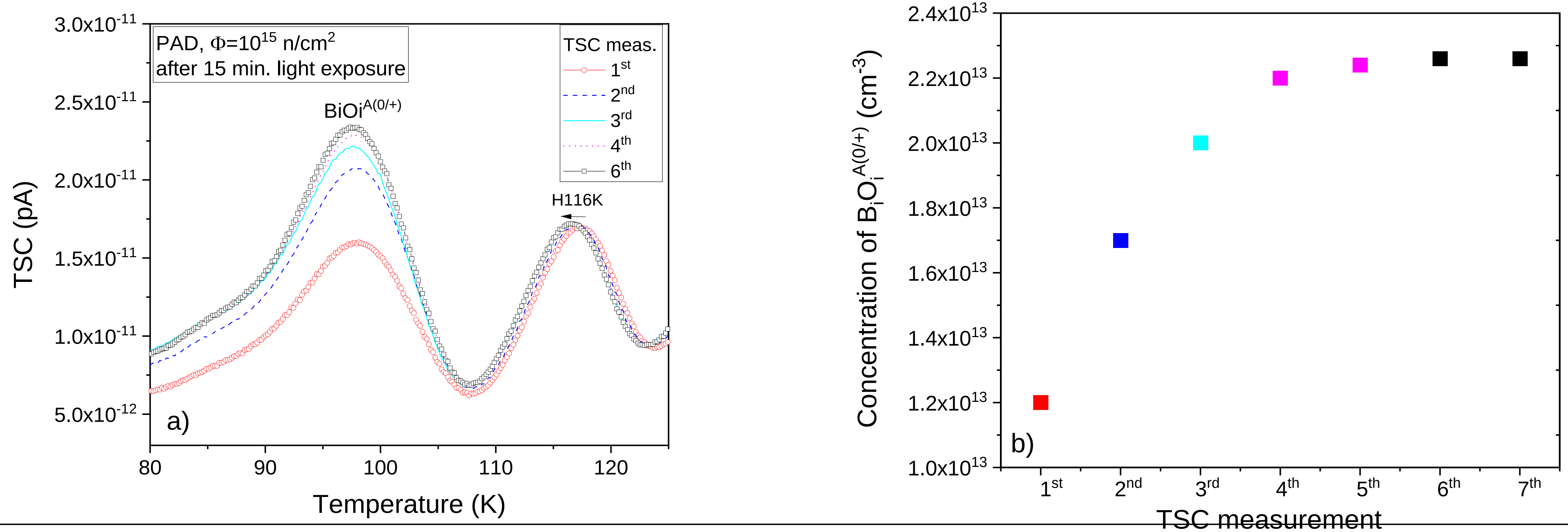






- The variation in B_iO_i concentration is also in good agreement with the variation of V_{dep} at 293K as seen in IV but in CV
- CV measurements underestimate ΔV_{dep} for fluences of 10^{15} n/cm^2 (or larger).

Consecutive TSC measurements after laboratory light (neon) exposure*



- Variation of 120% for the detected concentration of B_iO_i defect, for $\Phi_{eq} = 10^{15}$ n/cm^2
- The concentration of $B_iO_i^{A(0/+)}$ is stabilized in the sixth TSC measurement, recorded at ~ 7h after the exposure to light

→ The $B_iO_i^{A(0/+)}$ generation rate can be strongly underestimated if measurements are performed before 7h after heat treatment or exposure to light; the $B_iO_i^{B}$ generation rate cannot be estimated

→ The B_iO_i generation rate ($g_{BiOi} = g_{BiOi}^{A} + g_{BiOi}^{B}$) estimated from electrical measurements may always be underestimated, and so does also the acceptor removal rate!

→ Acceptor removal rate ~ $g_{Bi} = 2g^{A}_{BiOi} + g^{B}_{BiOi}$, where g^{B}_{BiOi} is unkown yet!

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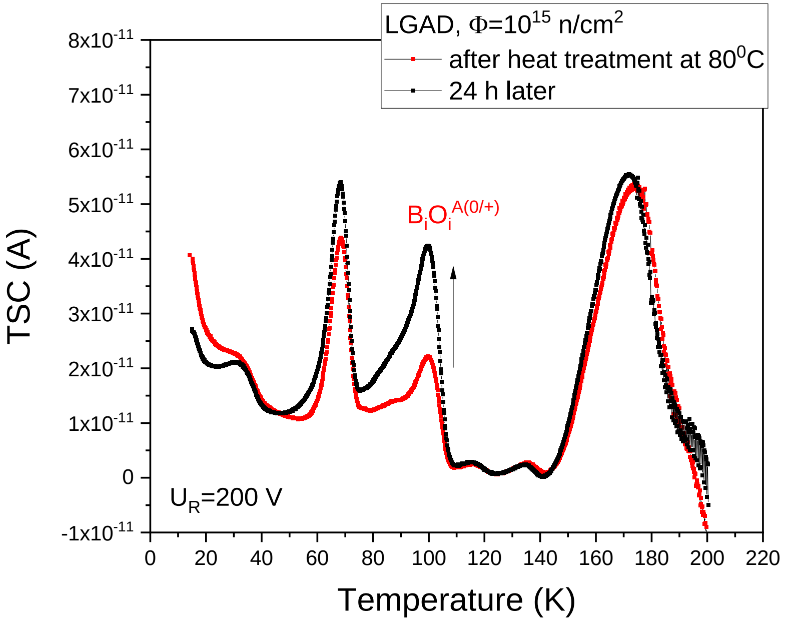
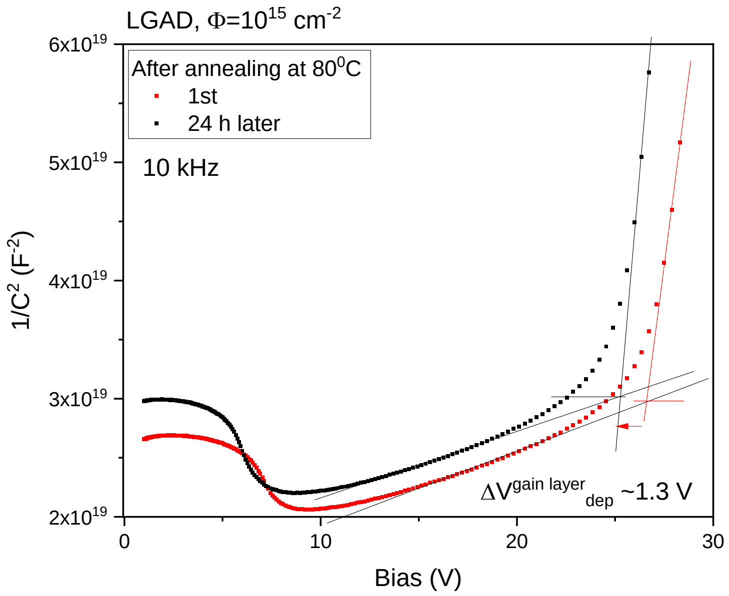
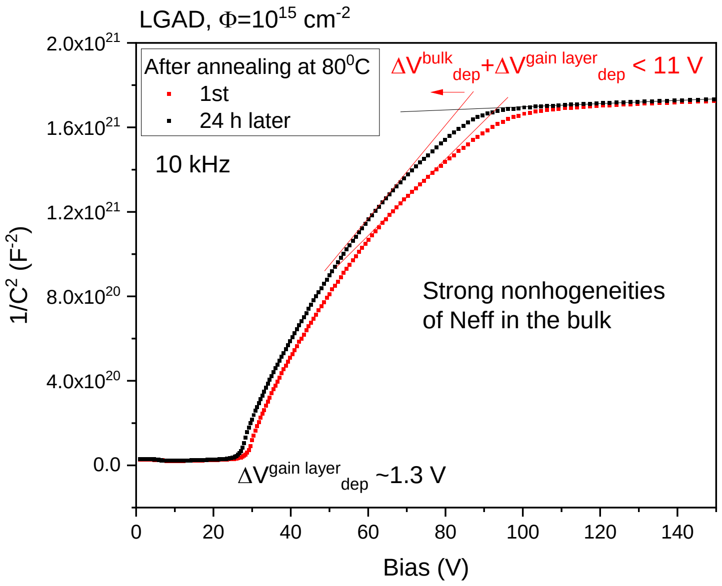
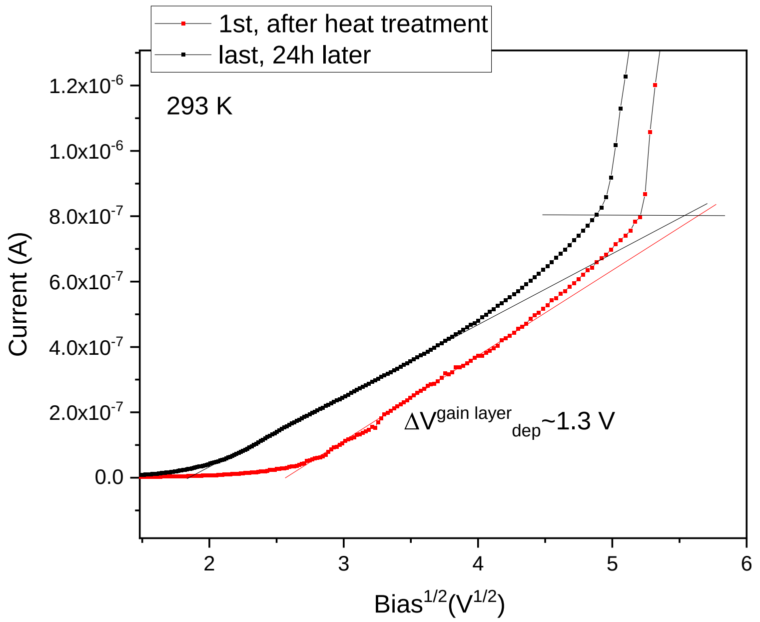
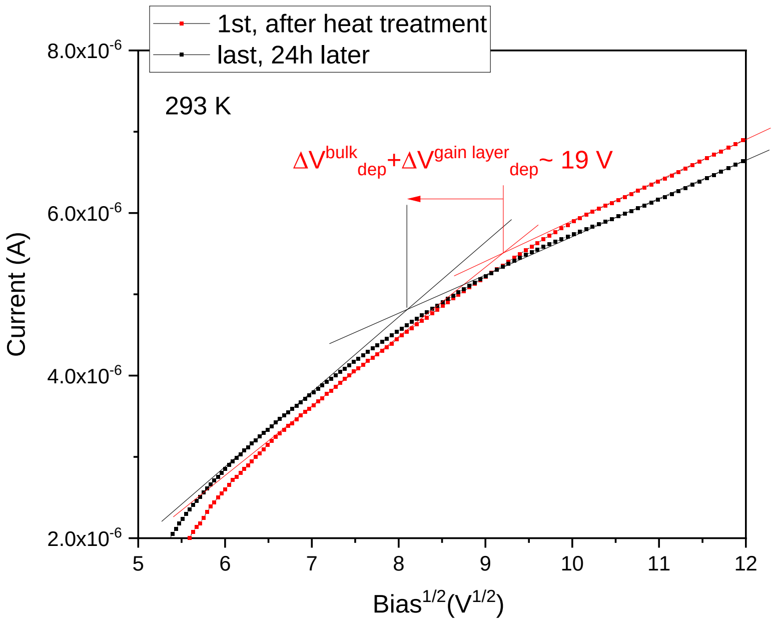
Similar features seen in LGAD samples











- The variation in B_iO_i concentration as seen in TSC measurements is reflected in the variation of V_{dep} as seen in IV but in CV (ΔV_{dep} determined from CV measurements is underestimated for fluences of 10^{15} n/cm^2 or larger).

Summary

- We performed dedicated experiments in order to understand the **large scattering** in the results reported for acceptor removal and BiOi generation rates in p type Si.
- We evidenced that even when measuring the same sample, **scattering of the BiOi generation rates occurs**, starting to be visible for irradiation fluences above 10^{12} n_{eq}/cm^2 and becoming significant large at high fluences.
- We demonstrated that the main reason behind is **the bistable character of the B_iO_i defect** which can exists in at least two configurations, labelled as A and B. The switch between A and B configurations is observed only through variations detected in the A configuration of the defect, characterized by a donor energy level at ~0.25 eV from the conduction band in both, high and low resistivity silicon.
- We have shown that the **defect reversibly passes from one configuration to another** after exposing the samples to an excess of carriers (thermal treatments or inherent exposure to the ambient light when manipulating the samples). This process is accompanied by a change in the defect electrical activity, causing not only significant long time variations in both, N_{eff} and [B_iO_i], but also to an **underestimation of the true introduction rate of the B_iO_i defect** and **of the calculated "acceptor removal" rate**.
- The steady state, giving the maximum concentration of the B_iO_i in the A configuration, is achieved by keeping the sample some time in the dark. **Any electrical measurement performed before the $B_iO_i^{A(0/+)}$ configuration is stabilized will give a different result.**
- We conclude that **procedural reasons are contributing significantly to the large scattering** in both, the reported values concerning the "acceptor removal" as determined from C-V/I-V measurements and the B_iO_i introduction rate as detected in DLTS and TSC measurements.

Further work

- **[BiOi] and acceptor removal process**: we expect that the magnitude of BiOi variations and the corresponding time constants depend on the impurity content in the samples (*Boron*, *Carbon*, *Oxygen*), on the light intensity, on the damage status of the samples (e.g. *Fermi level position in the bandgap*, *leakage current*) and on *temperature*, and such dependencies **shall be studied further**.
- For the cases presented here, it takes about 7 h for the detectable $B_iO_i^A$ defect configuration to reach the steady state concentration. Since not always it is possible to wait such long times, **further investigations are needed for parametrizing the variations in time of both, B_iO_i defect concentrations and N_{eff}, for different situations**.

Thank you for your attention !