Defect investigations of neutron irradiated high resistivity PiN and LGAD diodes

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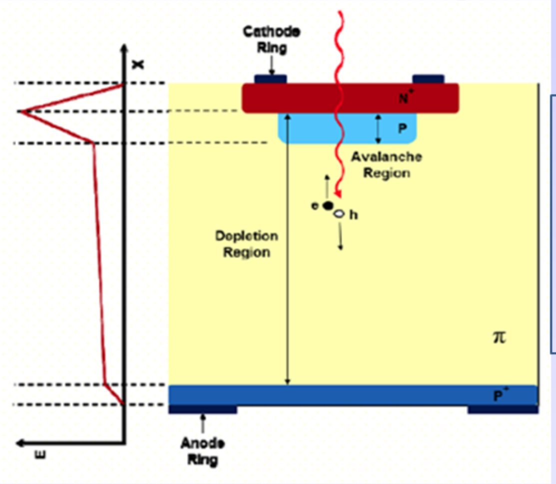
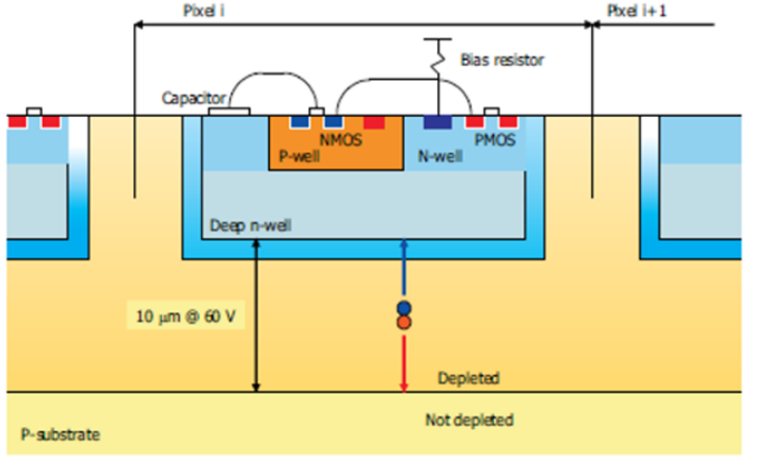
Motivation: new structures based on p-type silicon

LGAD, APD
(Sensors with intrinsic gain)



LGADS - doping levels of $10^{16} – 10^{17}$ cm^{-3} in the gain layer and of $10^{12} – 10^{15}$ cm^{-3} in the rest of the structure

HVCMOS
(towards monolithic sensors)



HVCMOS - doping levels of $10^{12} – 10^{15}$ cm^{-3}

Key properties

- Gain very sensitive to p+ layer doping and process parameters
- Gains of up to 100 achieved giving excellent timing resolution of 26 ps for thin LGADs
- Currently the best technology for achieving excellent timing measurement for mip – will be employed at ATLAS and CMS experiments after the upgrade

Limitations:

- Radiation hardness – problem of acceptor removal which decreases the gain with fluence (intensive search for solution: Ga, C and understanding removal mechanism)
- Regions without the gain around the electrodes do not have gain – fill factor improvement

Key properties

- Different substrates often limited by vendor – up to full depletion of 300 mm
- Excellent position resolution

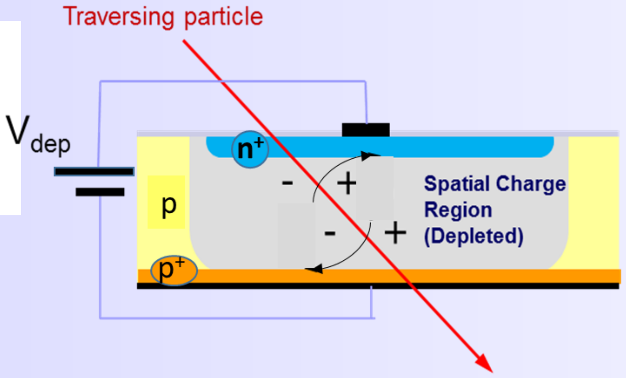
Limitations:

- Radiation hardness – problem of acceptor removal which changes detector performance
- Speed – for timing applications is not yet optimal
- SOI substrates or different other designs/processes including “Shallow Trench Isolation” affect charge collection

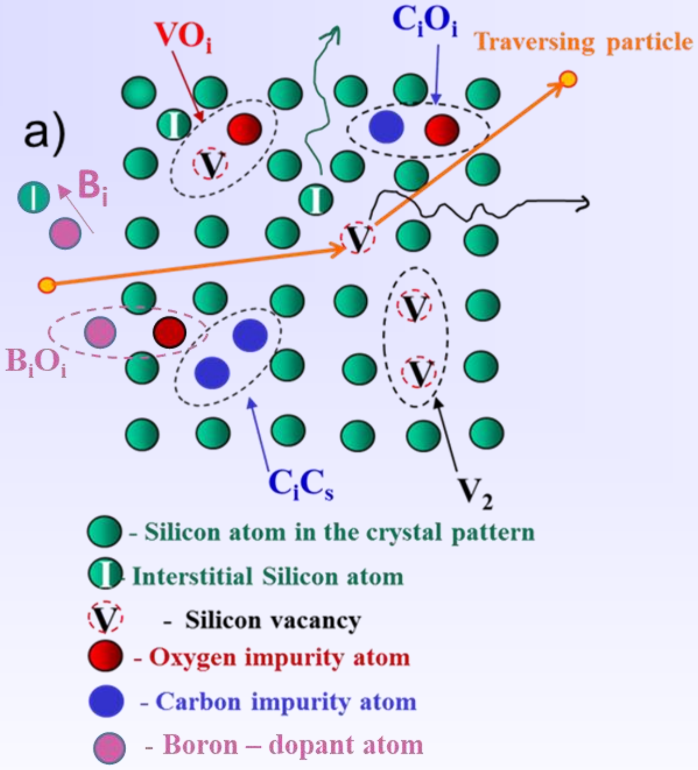
..optimizing for

- Radiation hardness
- Time resolution
- Cost effectiveness

Aim: to improve the radiation hardness of different types of silicon sensors (single pads, pixel and strips, LGAD and HVCMOS) built on **p-type silicon**



How ?: By understanding the competing defect generation involving Boron, Carbon, Si_i and O_i and find ways for balancing them



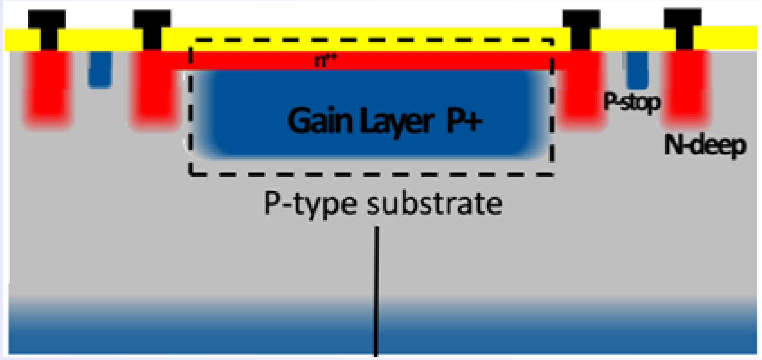
– point defects
1) V+O→VO
2) V_2
3) $I+C_s \rightarrow C_i$
4) $C_i+C_s \rightarrow C_iC_s$
5) $C_i+O_i \rightarrow C_iO_i$
6) $I+B_s \rightarrow B_i$
7) $B_i+O_i \rightarrow B_iO_i$
8) ……?……..

Investigated p-type Samples irradiated with 1 MeV neutrons

PiN pads

2 p-type bulk Boron doped STFZ diodes from *National Center for Micro-electronics (CNM)*–irradiated with 1MeV neutrons, fluences of 1x10^{14} and 1x10^{15} cm^{-2}

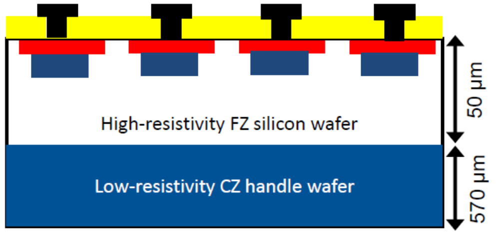
LGADs



4 LGAD structures produced on STFZ silicon from -***National Center for Micro-electronics (CNM)*** with Boron implanted gain layer– irradiated with 1MeV neutrons, fluences of 1x10^{14} and 1x10^{15} cm^{-2} - however, **only 2 could be measured**

Investigated p-type Samples

$[B]_{bulk} = 2\text{-}5\text{x}10^{12}\ \text{cm}^{-3}$



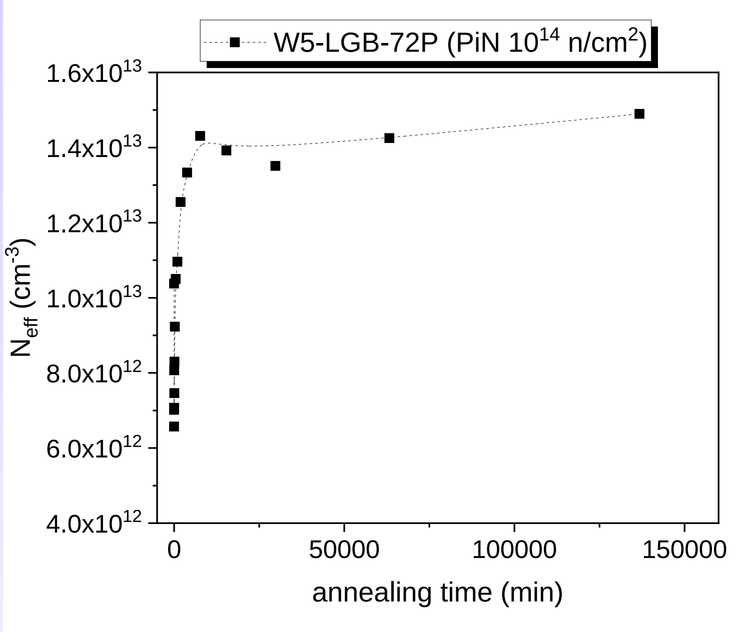
$[B]_{gain\ layer} \sim 4\text{x}10^{16}\ \text{cm}^{-3}$

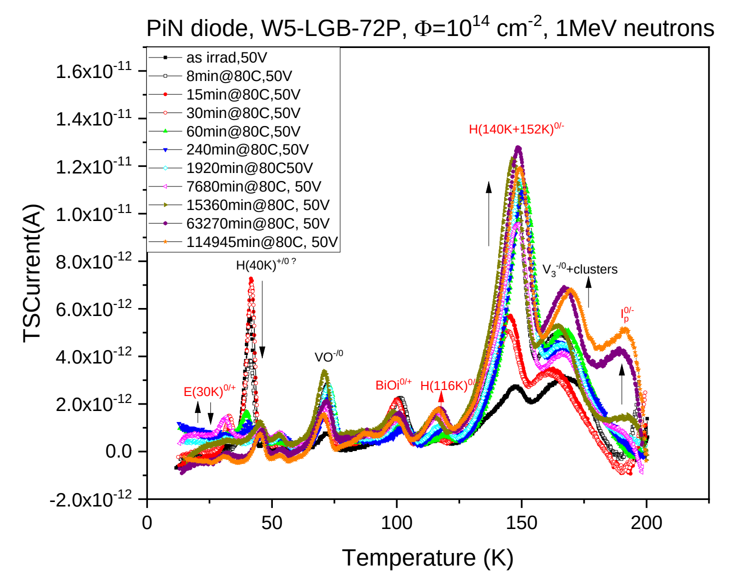
RUN 9088 neutron irradiated-for TSC measurements							
NR.	Name	Fluence n/cm2	Type	Thickness	Full depletion voltage (V)	Depletion voltage of the gain layer (V)	Leakage current at V_{dep}(20 C) (A)
1	W5-LGB-82P *RUN9088, H6TD, 10.06.2016*	1E15	PIN- no gain layer	50 µm	16.8		$1.64\text{x}10^{-5}$
2	W5-LGB-72P *RUN9088, H6TD, 10.06.2016*	1E14	PIN- no gain layer	50 µm	5.6		$1.73\text{x}10^{-6}$
3	W3-LGB-71, dose 1.8E13 *RUN9088, 29.06.2016*	1E14	LGAD	49 µm bulk, 1 µm B implanted layer	28.95	26.1	$3.78\text{x}10^{-6}$
4	W11-LGB-74, dose 2.0E13 *RUN9088, 30.06.2016*	1E15	LGAD	49 µm bulk, 1 µm B implanted layer	28.5	15.9	$2\text{x}10^{-5}$

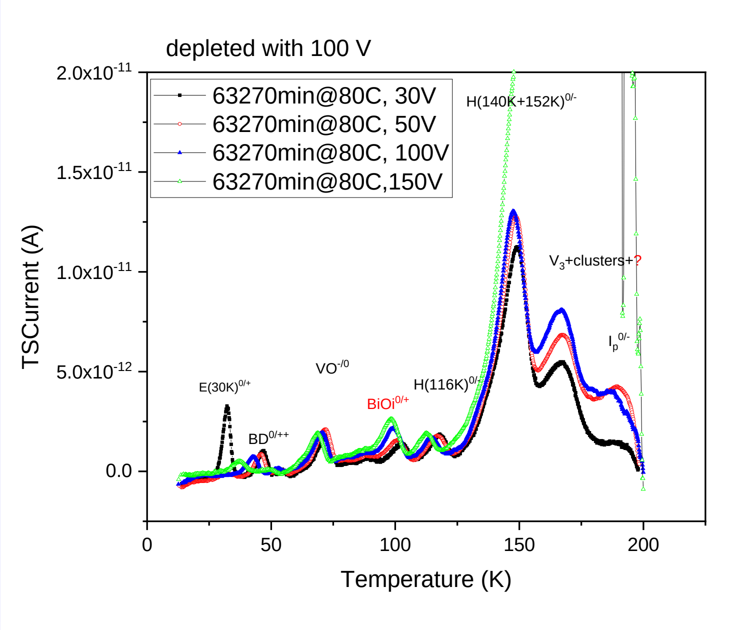
Annealing at 80^0C - PiN diodes

$\phi=10^{14}$ cm^{-2}

Diode depleted with 100V during TSC







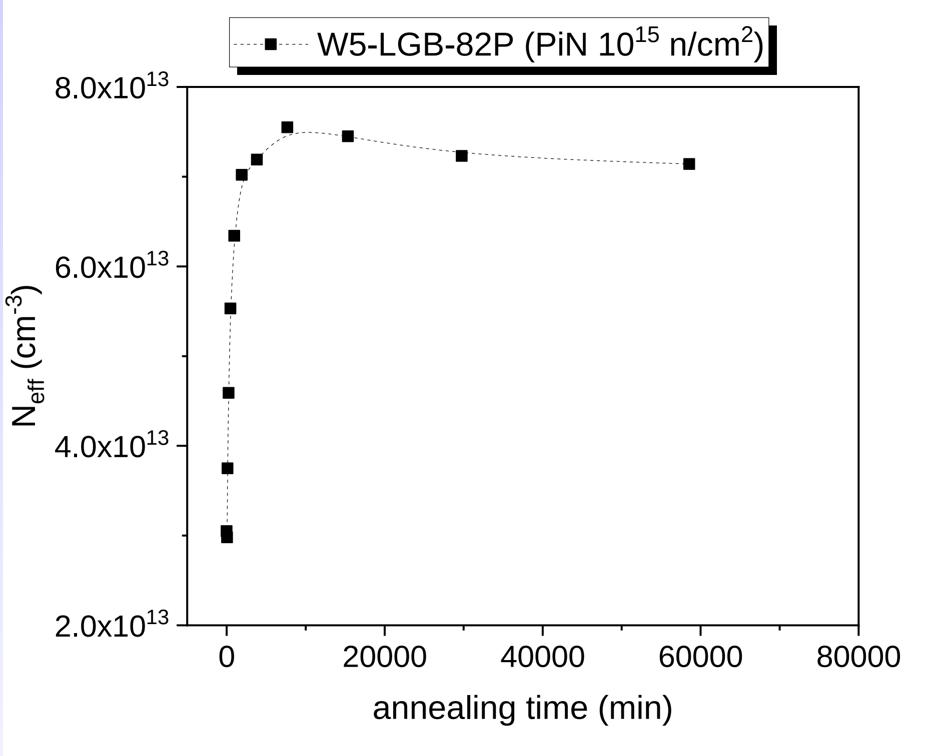
Neff from CV

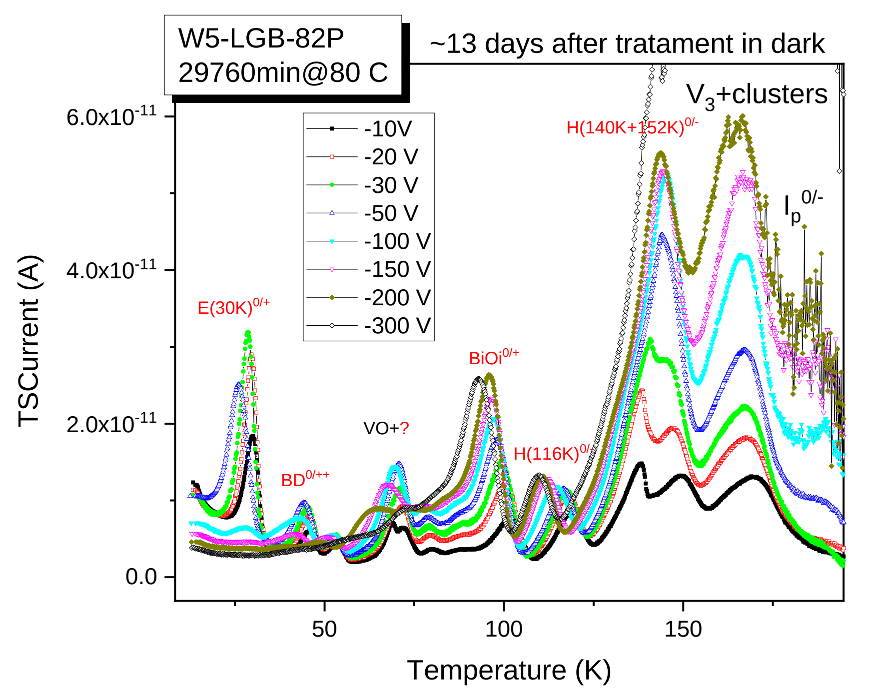
Some random variations in BiOi peak

- changes between 100V-150 V due to the actual time passed after the annealing/light exposure

Annealing at 80^0C – PiN diodes

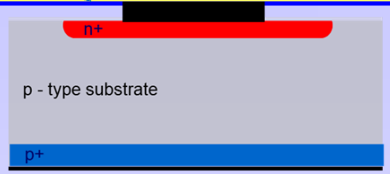
$\phi=10^{15}$ cm^{-2}





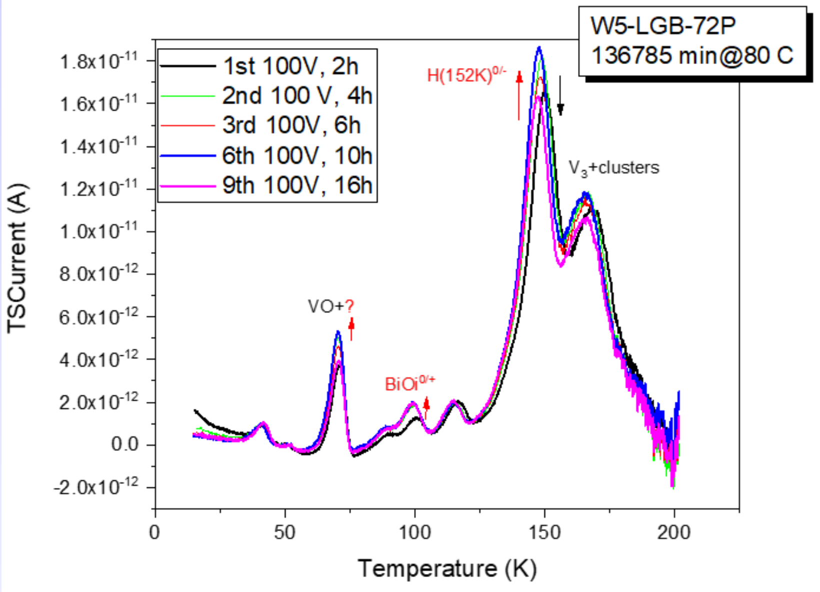
No clear indication for a type-inversion, diode depleted with 300 V

TSC investigations – BiOi electrical activity

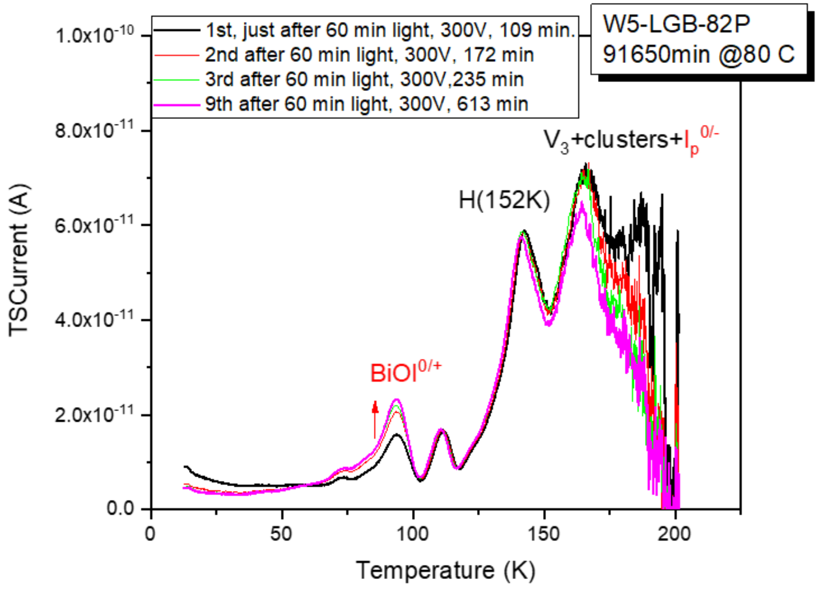


Consecutive measurements after exposure to light

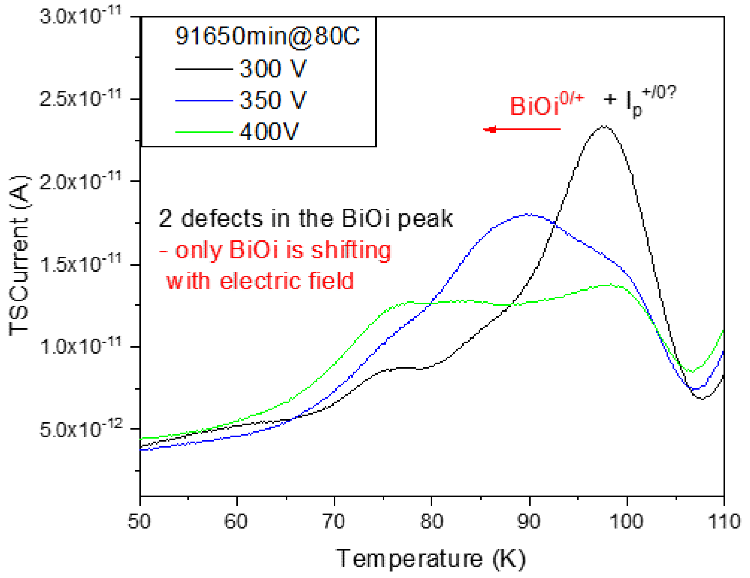
$\phi=10^{14}$ cm^{-2}



$\phi=10^{15}$ cm^{-2}



$\phi=10^{15}$ cm^{-2}

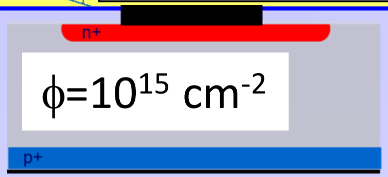


- Increase in the BiOi peak amplitude in time after heating or exposure to light

→ Bistable electrical activity

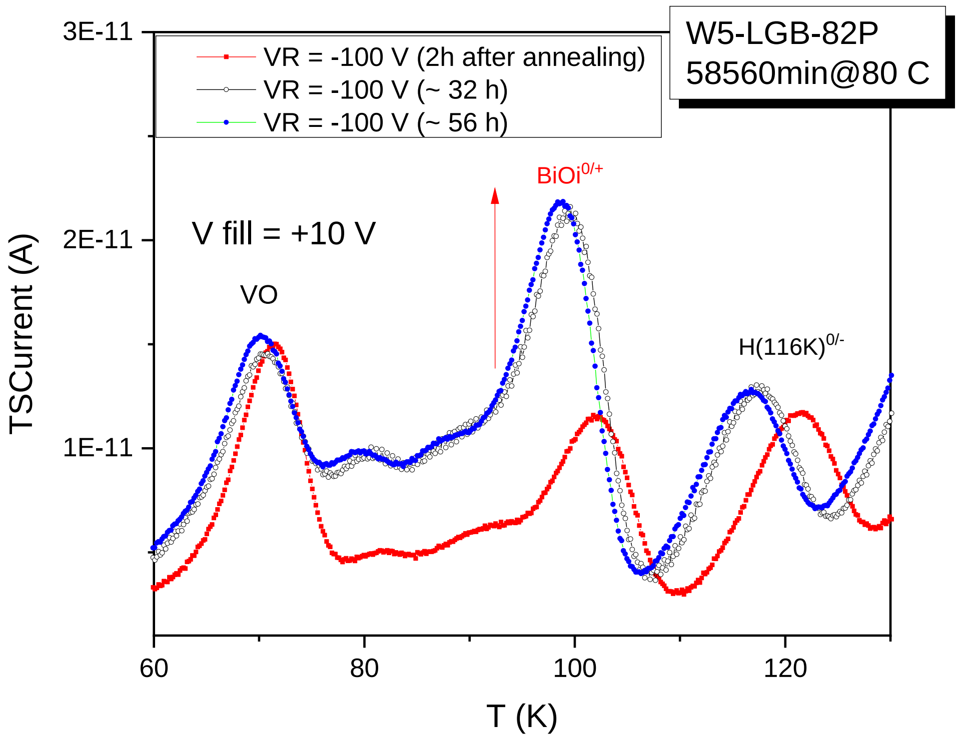
- Only half of the peak at 100 K, when measure with biases < 300 V, belongs to BiOi

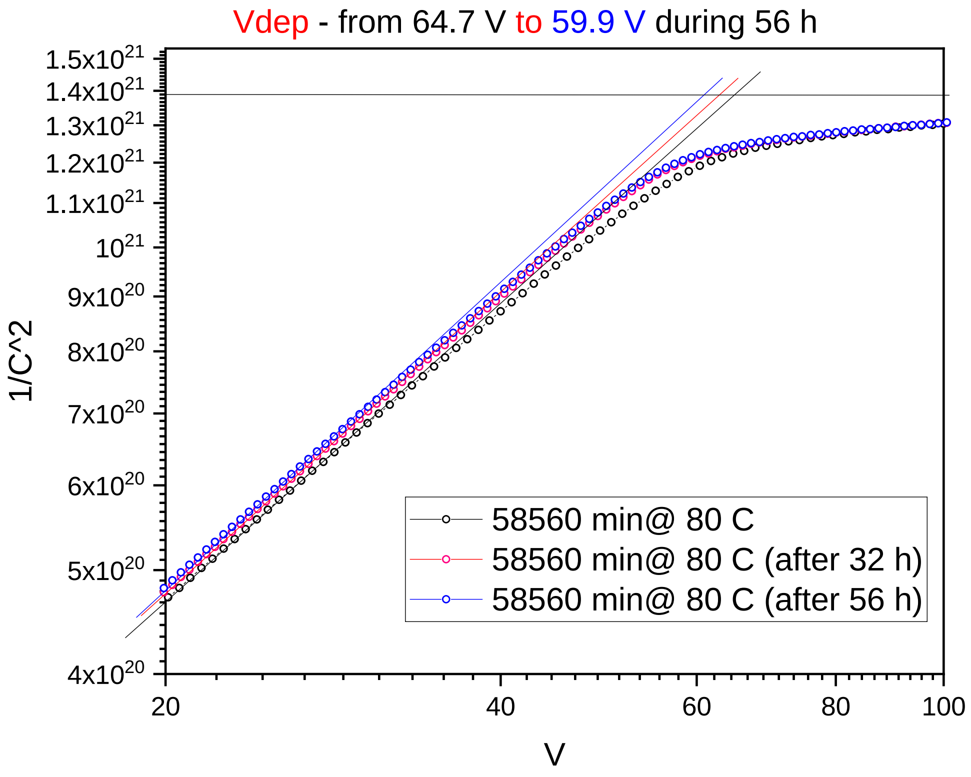
Instability of BiOi electrical activity after annealing/exposure to light



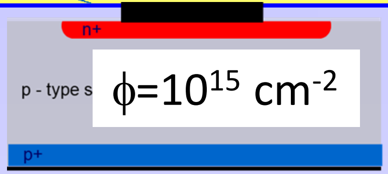
$\phi=10^{15}$ cm^{-2}

Consecutive measurements after heat treatment



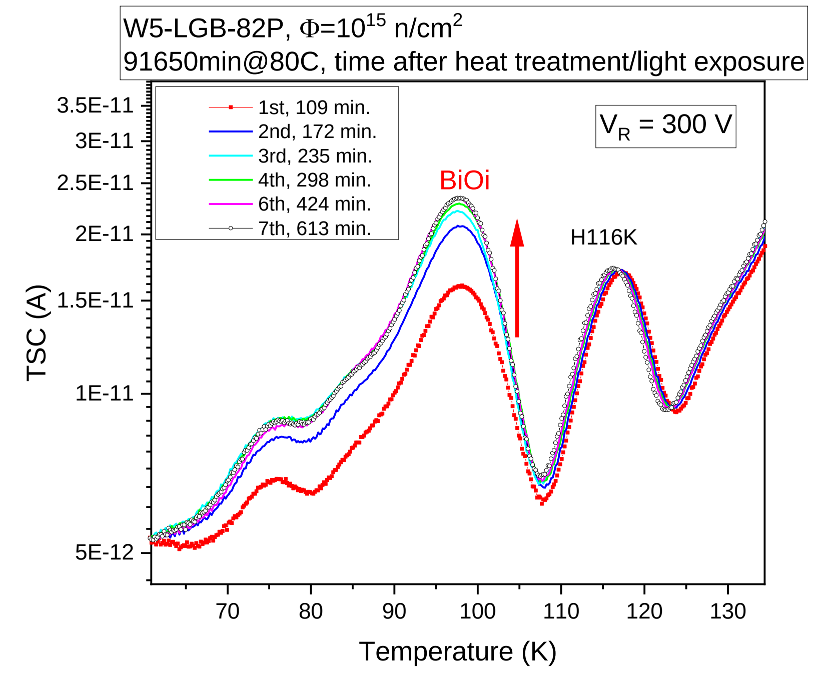


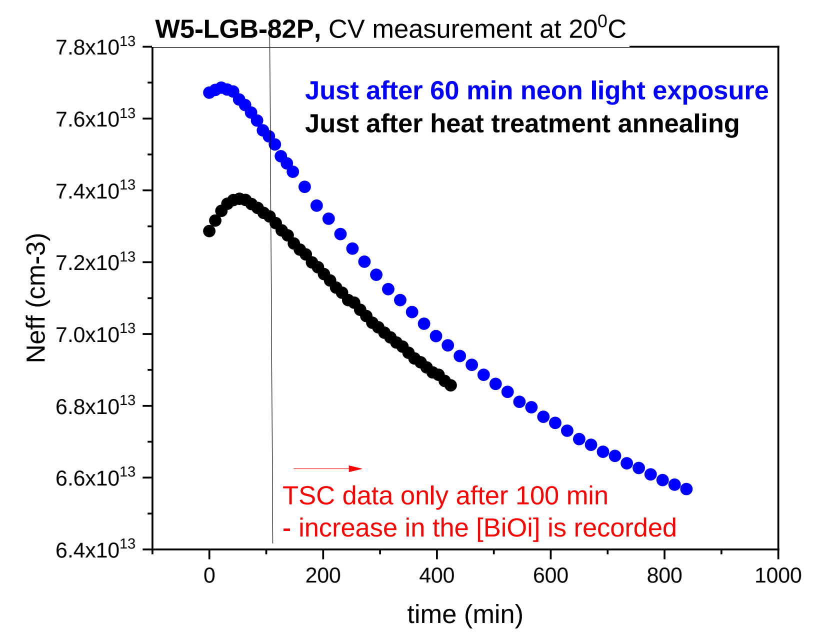
The increase in the BiOi concentration may cause the decrease in V_{dep}



$\phi=10^{15}$ cm^{-2}

Instability of the electrical activity of BiOi after annealing/ light exposure



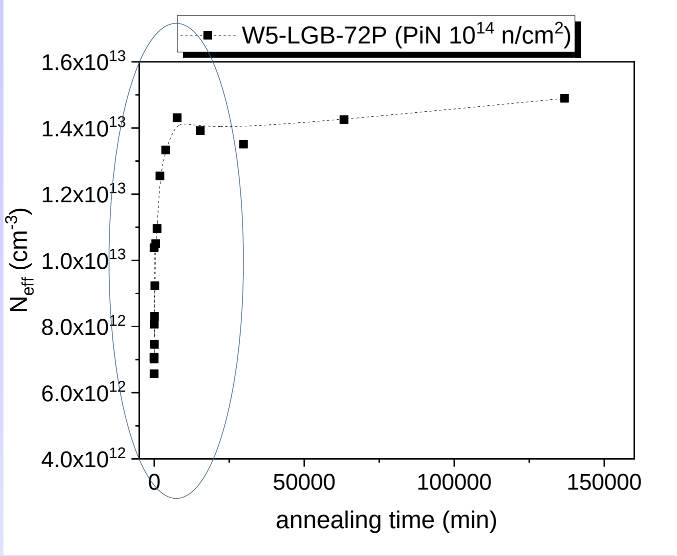


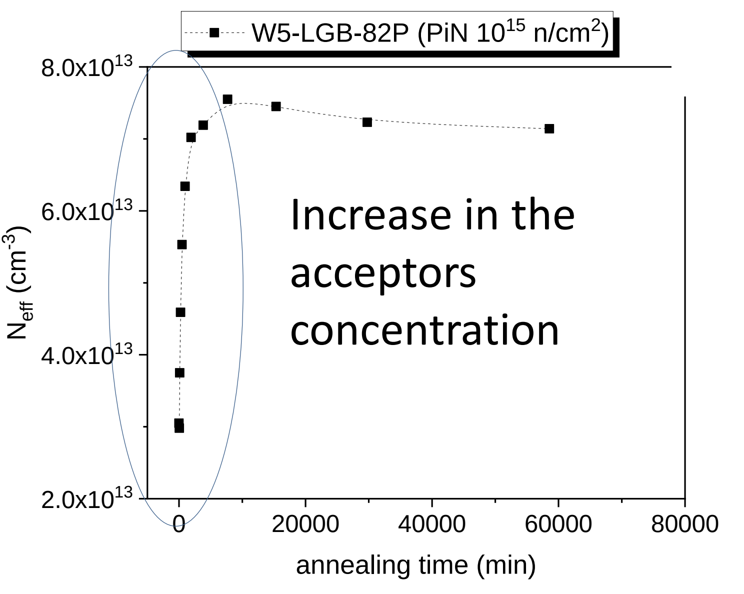
TSC data only after 100 min
- increase in the [BiOi] is recorded

- The increase in BiOi concentration accounts for the variation in V_{dep}

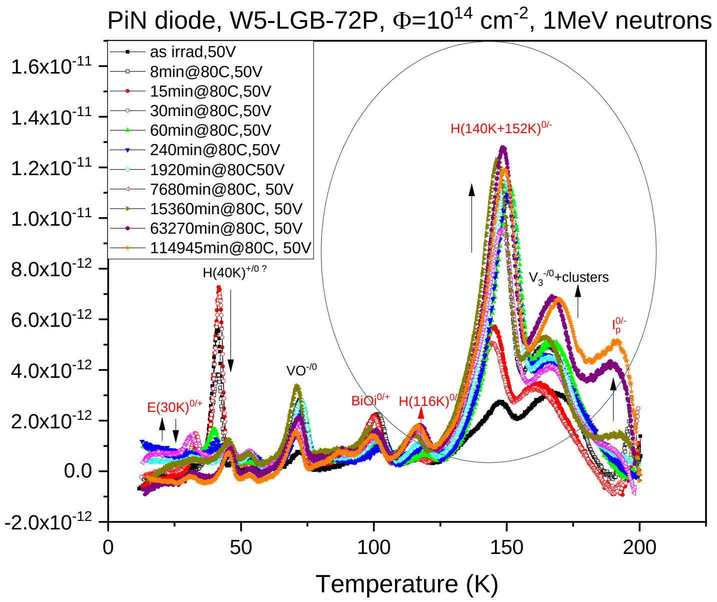
→ **the diode is not inverted ?**

Annealing behaviour after 1 MeV neutrons irradiation





Increase in the acceptors concentration



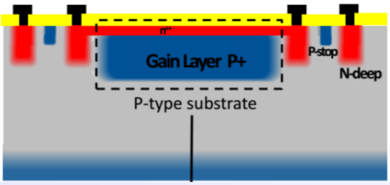
$\Phi=10^{14}$ cm^{-2} of high resistivity p-type STFZ Si

- **Generation of donors**: generation rate of BiOi is 0.03 cm^{-1} (maximum) and of E(30K) donor is 0.017 cm^{-1}.The amount of acceptor removal caused by BiOi is 6x10^{12} cm^{-3} (counted as twice the amount of BiOi) and of 1.7x10^{12} cm^{-3} by E(30K)
- **Generation of acceptors:** The amount of H(11K), H(140K+152K) acceptors created by irradiation ~1.3x10^{13} cm^{-3} (total generation rate of ~ 0.13 cm^{-1}) / I_p not counted

$\Phi=10^{15}$ cm^{-2} **Generation of donors**: generation rate of BiOi is 0.016 cm^{-1} (maximum) and of E(30K) donor is 0.017 cm^{-1} .The amount of acceptor removal caused by BiOi is 3.2x10^{13} cm^{-3} (counted as twice the amount of BiOi) and of 1.7x10^{13} cm^{-3} by E(30K)

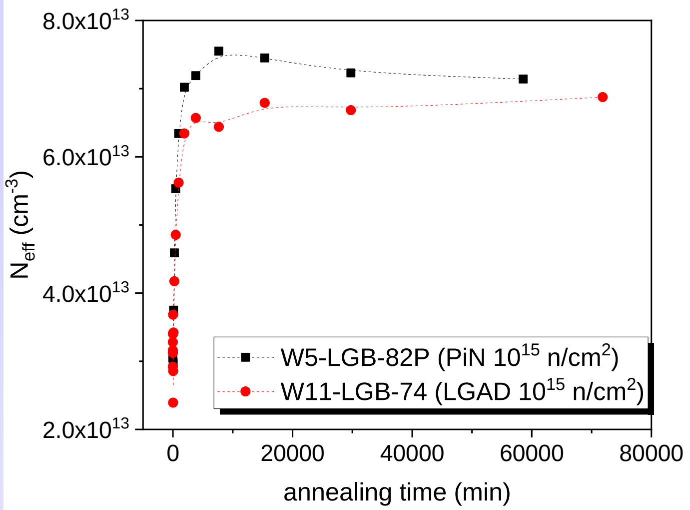
- **Generation of acceptors:** The amount of H(11K), H(140K+152K) acceptors created by irradiation 1.23x10^{14} cm^{-3} (total generation rate of ~ 0.123 cm^{-1}); I_p not counted

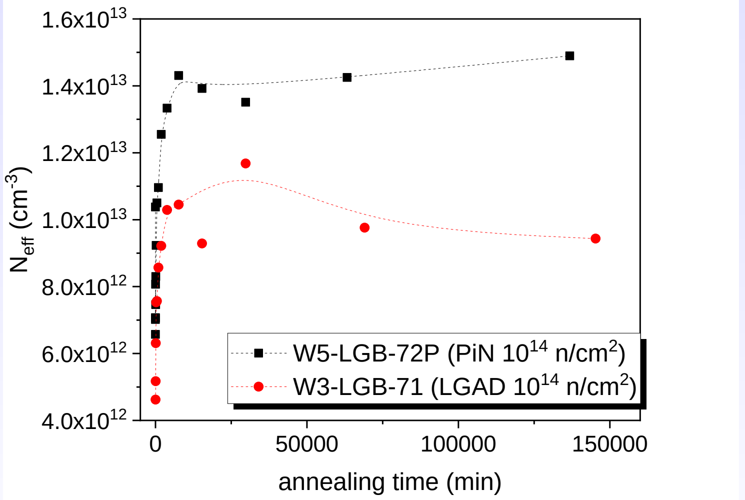
Similar trends in LGADS



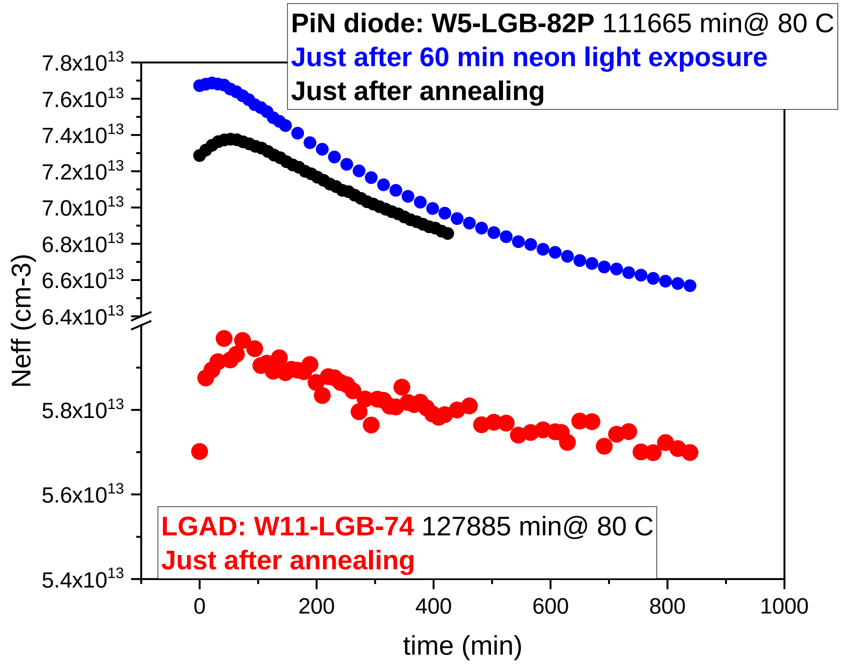
In the bulk of the LGADs

Dependence on the annealing time at 80 C



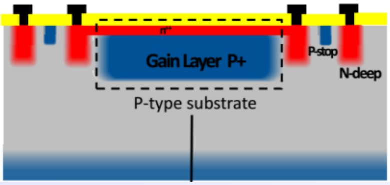


Dependence on the time after annealing at 80 C or exposure to light

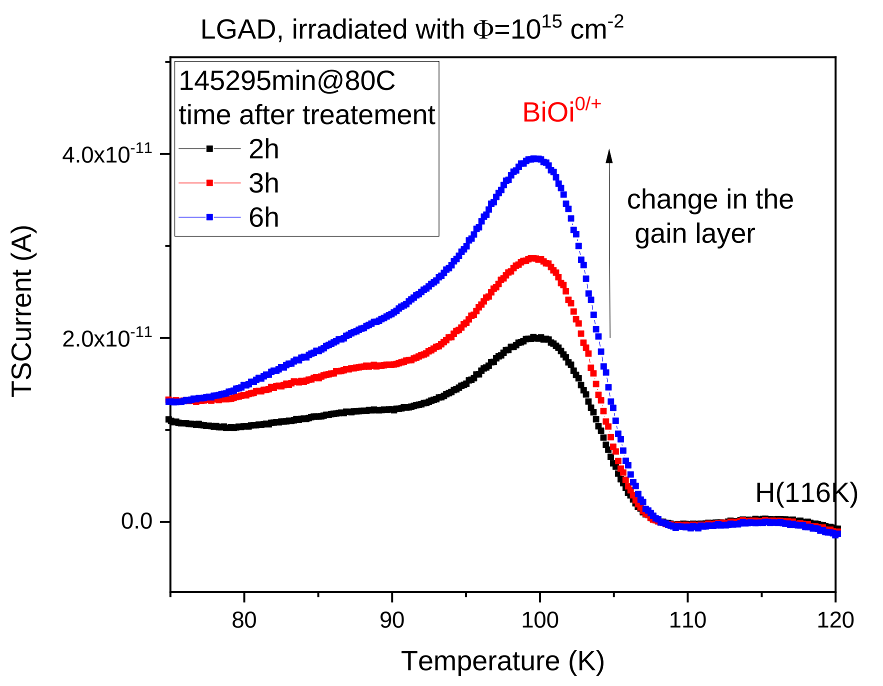


Instability of BiOi in the bulk – reflected in Neff variations (from CV)

Similar trends in LGADS



In the gain layer – differs only the generation of BiOi



Similar instability of BiOi

Generation of BiOi donors:

Φ=10 ^{14} cm^{-2} LGAD

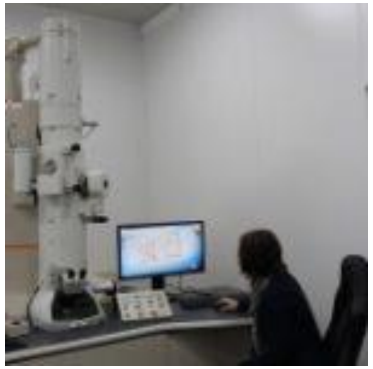
- generation rate of BiOi is 8.6 cm^{-1}.The amount of acceptor removal caused by BiOi in the gain layer is 1.72x10^{15} cm^{-3} (counted as twice the amount of BiOi)

Φ=10 ^{15} cm^{-2} LGAD

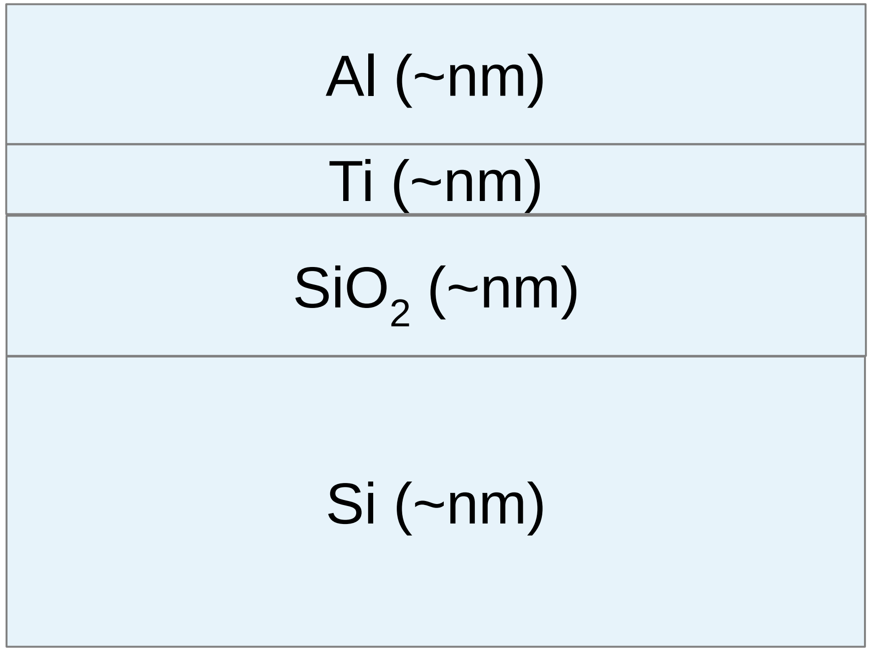
- generation rate of BiOi is ~8 cm^{-1}.The amount of acceptor removal caused by BiOi in the gain layer is 1.6x10^{16} cm^{-3} (counted as twice the amount of BiOi)

TEM on irradiated Silicon : current issues and future challenges

$\phi=10^{15}\ \text{cm}^{-2}$



TEM perspective on the sample (after cross-sectional preparation):



Al (~nm)

Ti (~nm)

SiO_2 (~nm)

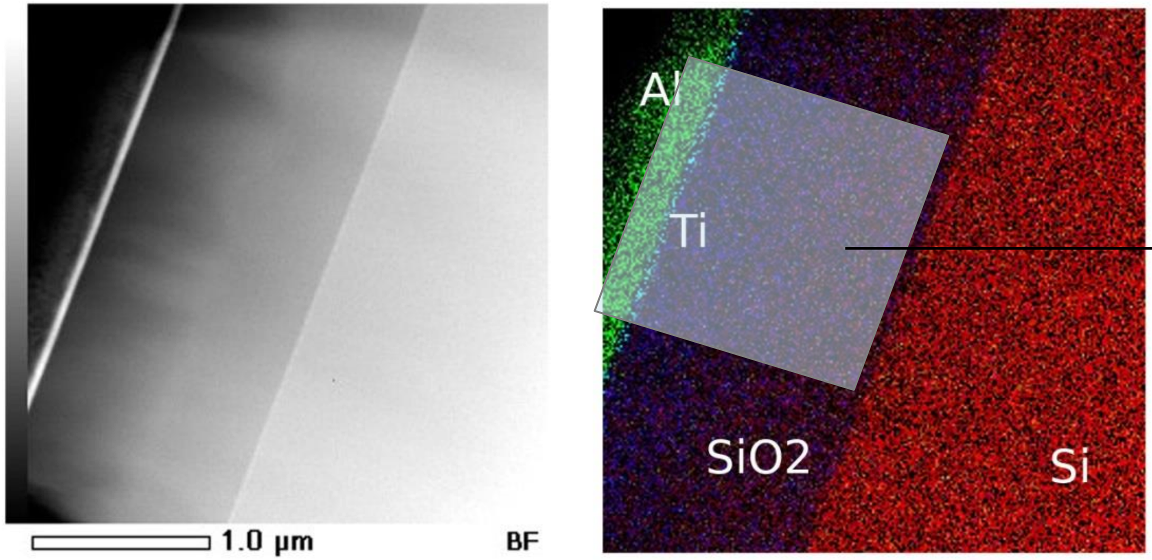
Si (~nm)

Important: Prior to observations, sample has been treated for 80 min @ 160 C

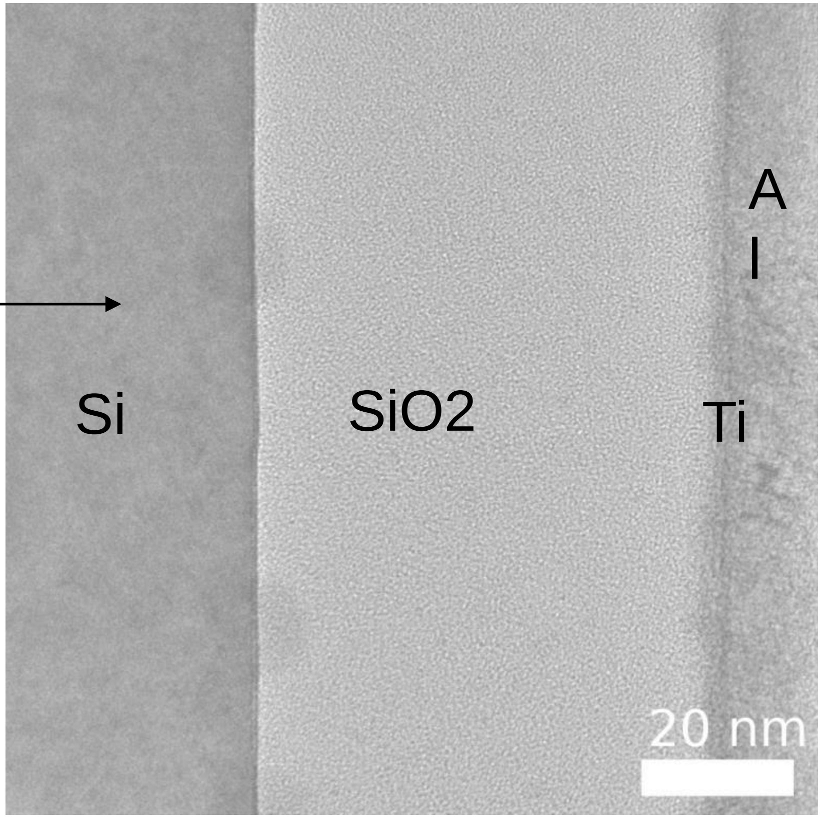
Transmission Electron Microscope JEOL2100

- Scanning Transmission Electron Microscopy (STEM) unit with Annular Dark Field and Bright Field detectors;
- Energy dispersive X-ray spectrometer (EDS),
- Movie-recording CCD camera
- Analytical holder with two tilting axis (double tilt);
- Holder with two tilting axis (double tilt) for in-situ heating of the sample;
- Tomography kit for TEM/STEM including electron tomography holder
- ASTAR crystalographic mapping unit
- Accelerating voltage range: 80kV-200kV
- LaB6 filament

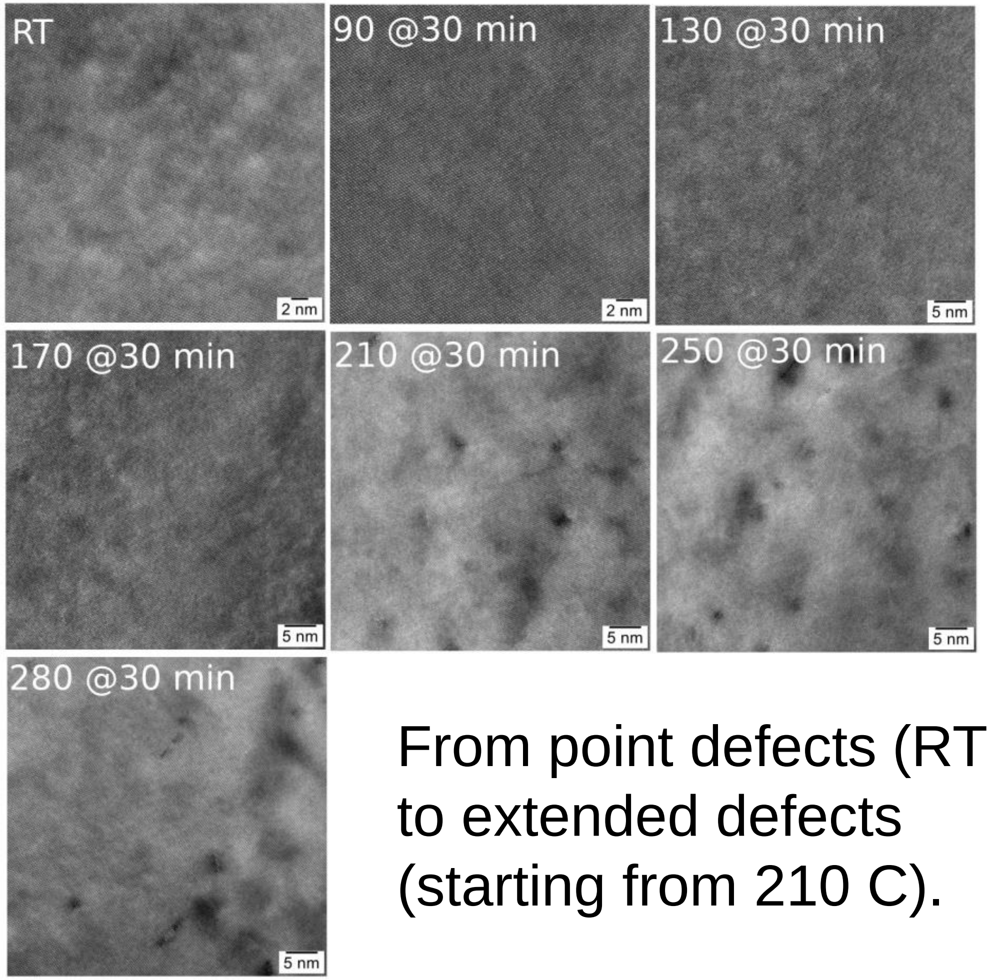
Choosing area @200kV



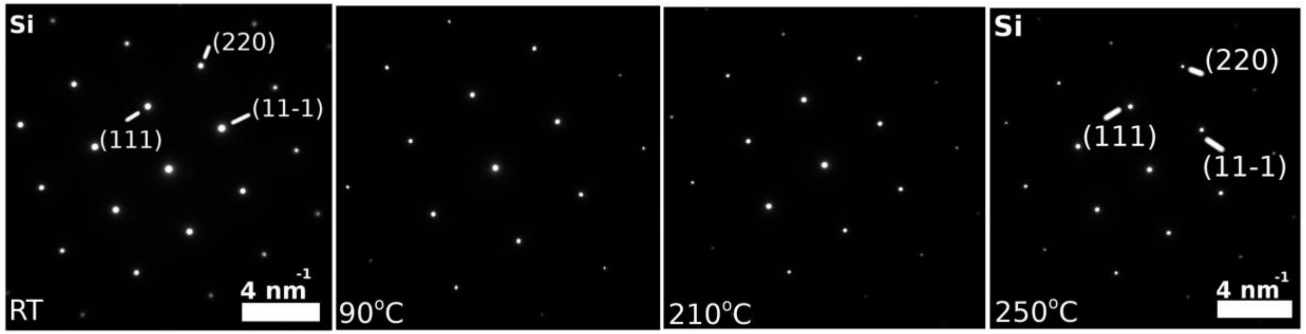
Scanning image(left) and
EDS map (right)



In situ evolution with temperature.
Q&A: Reality or beam damage?



From point defects (RT) to extended defects (starting from 210 C).



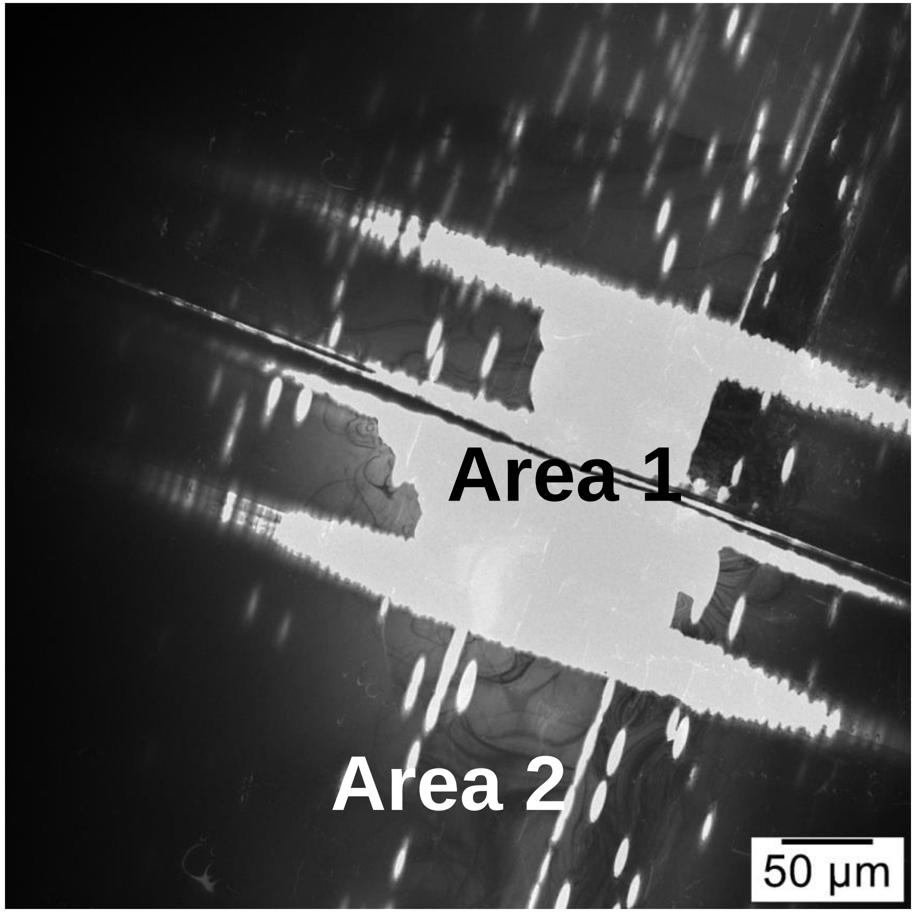
No structural changes observable by Selected area electron diffraction – Si is still crystalline

On a fresh sample, electron beam has been focused on a clean sillicon area. Beam damage has been observed within seconds (defect accumulation). Thus, the structural evolution @200kV is not concludent !!!

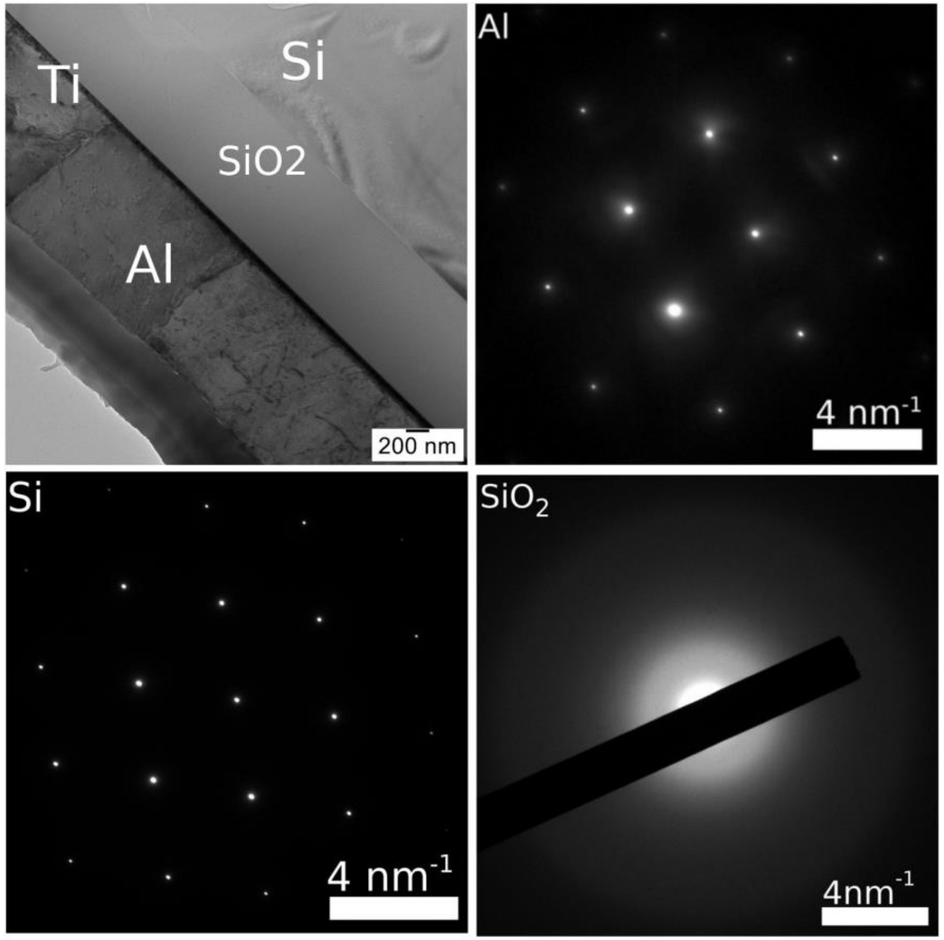
Answer: Beam damage is significant @ 200kV.

Switching to 80kV accelerating voltage

- No beam damage has been observed at 80kV.
- In-situ heating has been observed both at the Al-Ti-SiO2 interface (area1) and deep inside the Si substrate (area 2, ~100 um depth)
- Sample has been heated for 30 min @ 150 C, then the temperature has been increased @250 and kept constant for another 30 min.

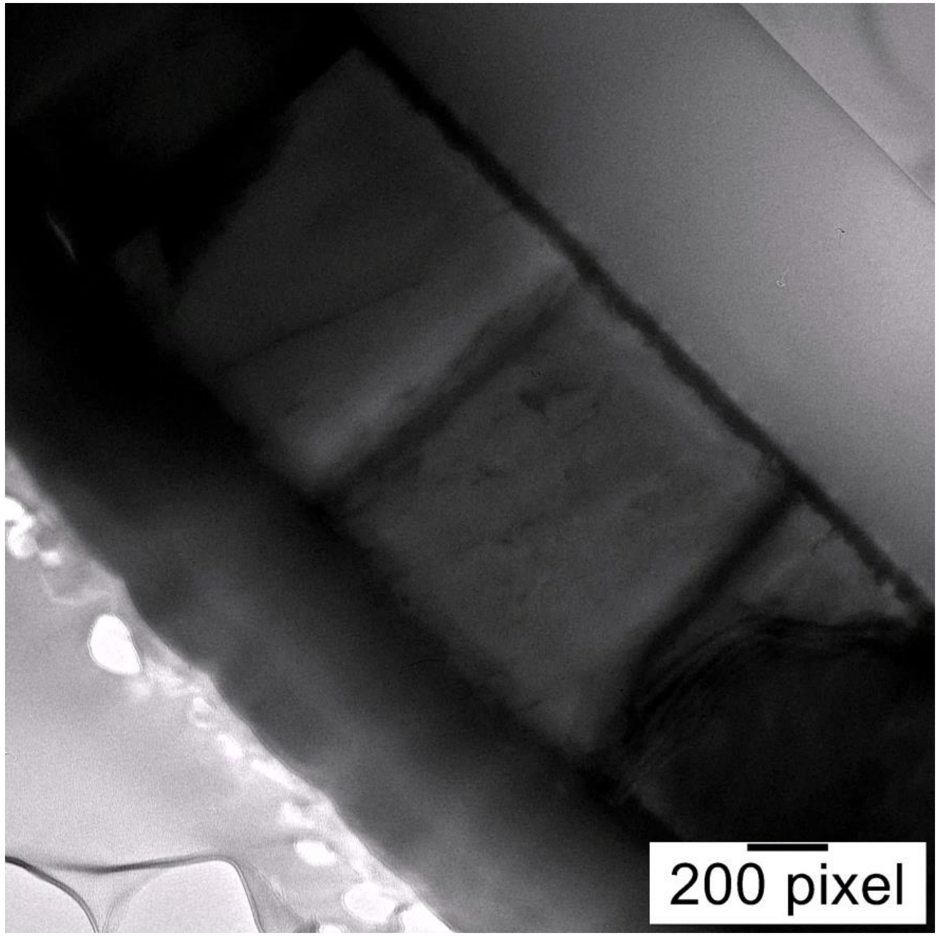


At the surface (area1)



150C-250C transition

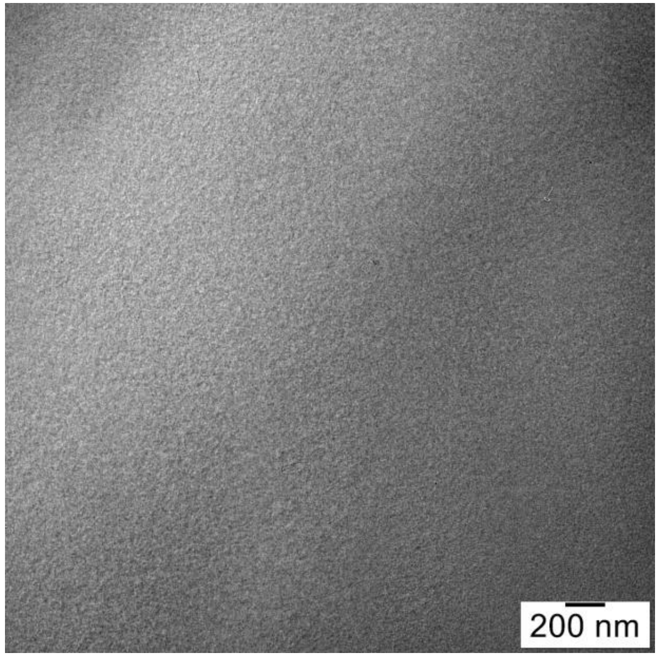
→



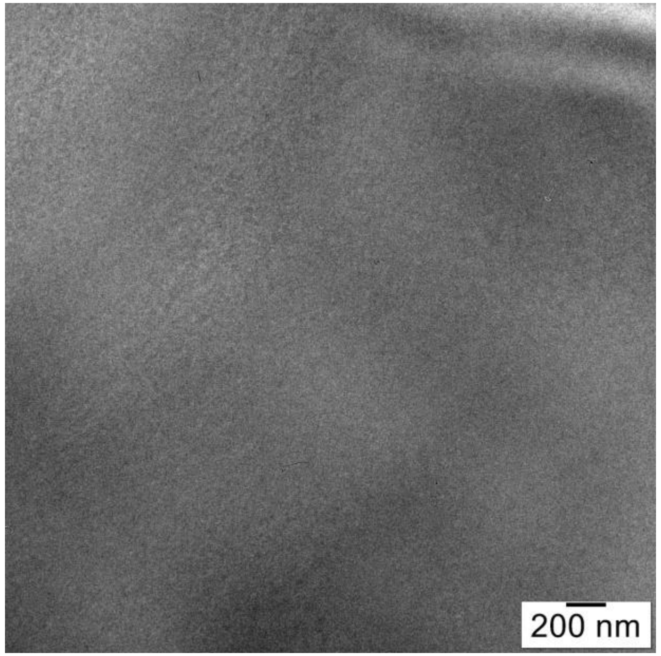
Extended defects (dislocations) dynamics in the Al coating as observed during 150-250 C heating.

Deep (area2)

After 30 min @ 150



After 30 min @ 250



Apart from lattice bending (sample is extremely thin, electron transparent), no defects have been observed.

Future perspectives and challenges:

1. Observe the cross-sectional sample at higher temperatures, for longer times
2. In-situ observations of the Silicon film at atomic resolution

Conclusions and further work

- We have performed a long –term annealing at 80 C
- The investigated high resistivity PiN diodes are not inverted after a fluence of 10^{15} cm^{-2}
- The variation of Neff in these samples are due to the increase of acceptor concentration during the annealing rather than to a generation of donors.
- Due to the instability of the BiOi defect, it is difficult to precisely follow the annealing behavior, the CV measurements are usually performed just after heat treatment while the earliest TSC can be obtained after 2 h.
- TEM investigations could not reveal changes due to irradiation (too low the fluence)

Further work:

- look for the reasons of BiOi instability and find a way to correlate with the CV results

- similar studies on different resistivity materials (higher fluences for TEM) and LGADs

Thank you for your attention !