Defect investigations in 1 MeV neutron irradiated PiN pads and LGADs

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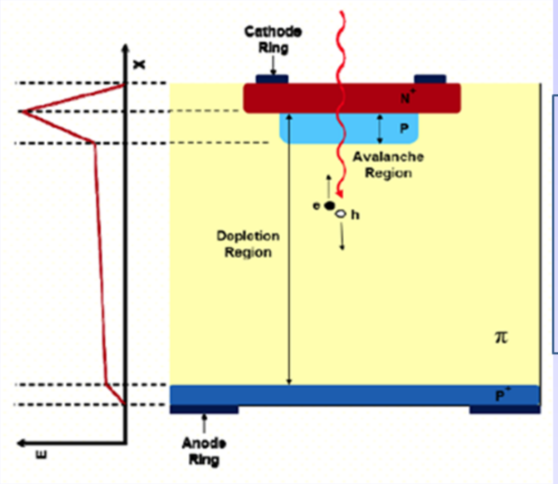
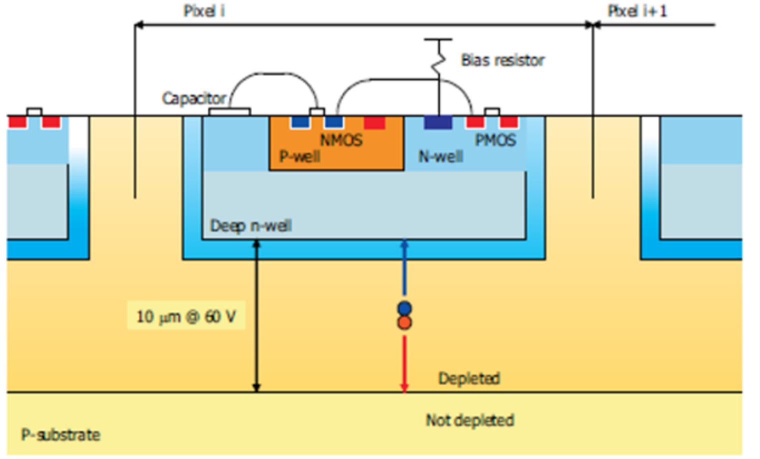
Motivation: new structures based on p-type silicon

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

The general objective is **to improve the radiation hardness** of different types of silicon sensors (single pads, pixel and strips, LGAD and HVCMOS) built on

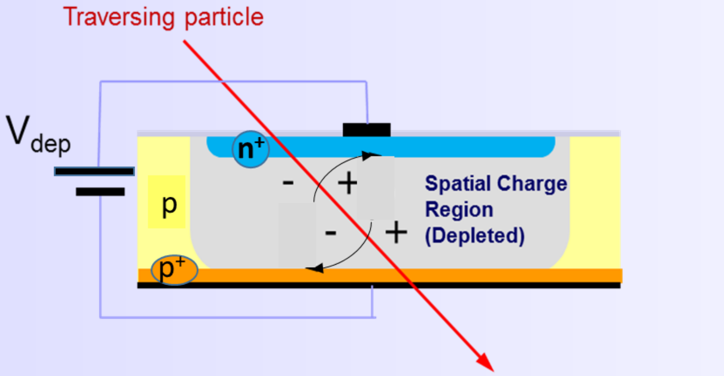
- **p-type standard float zone (different Boron content)**

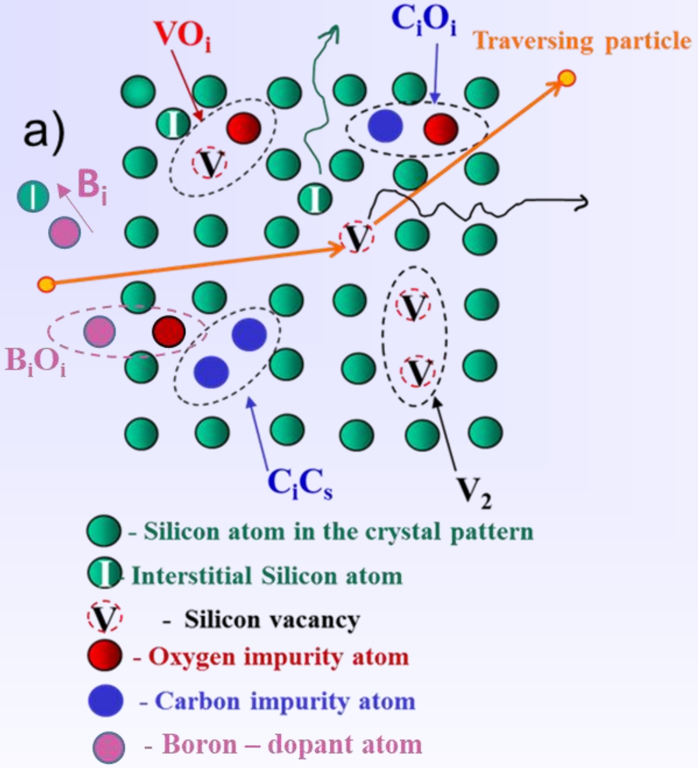
And

- **defect engineered material:**
  - **Carbon enrichment of Boron doped silicon**
  - **Gallium doped silicon, Carbon enrichment**

Samples: **standard B doped and/or C co-doped , Ga doped**
- **p-type pad silicon**
- **LGAD and HVCMOS**

Irradiations with:
- **1 MeV neutrons (Ljubliana)**
- **23 GeV protons (CERN)**





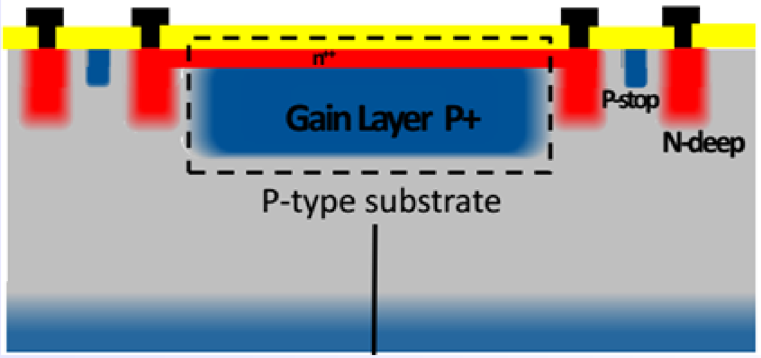
Competing reactions involving Boron, Carbon, Si_i and O_i

– 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 - Preliminary results

PiN pads

LGADs

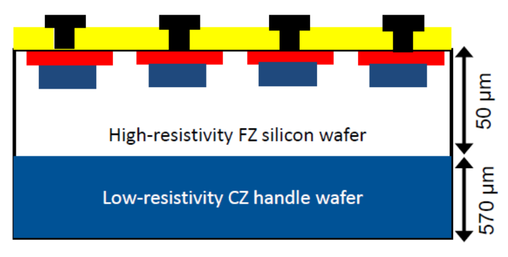


2 p-type bulk Boron doped STFZ diodes from ***National Center for Micro-electronics (CNM)***–irradiated with 1MeV neutrons, fluences of 1x10^{14} and 1x10^{15} cm^{-2}

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}

Investigated p-type Samples

$[B]_{bulk} = 2\text{-}5x10^{12}\ cm^{-3}$



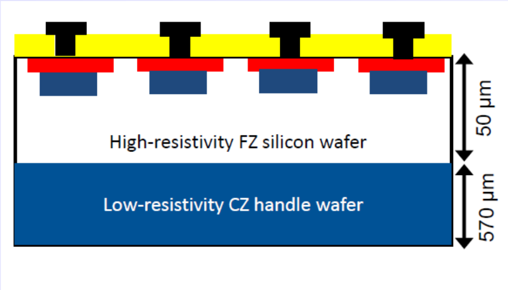
$[B]_{gain\ layer} \sim 4x10^{16}\ cm^{-3}$

RUN 9088 neutron irradiated-for TSC measurements

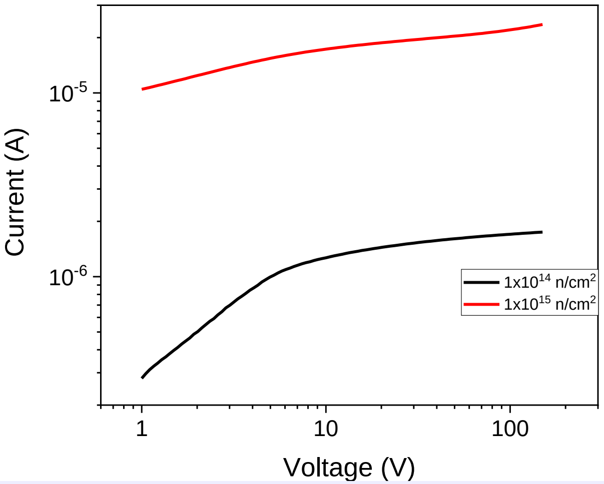
NR.	Name	Fluence n/cm2	Type	Thickness	Full depletion voltage (V)	Depletion voltage of the gain layer (V)	Leakage current at V_{dep}(20 C) (A)
1	W5-LGB-82P	$1x10^{15}$	PIN- no gain layer	50 µm	16.8		$1.64x10^{-5}$
2	W5-LGB-72P	$1x10^{14}$	PIN- no gain layer	50 µm	5.6		$1.73x10^{-6}$
3	W3-LGB71, dose 1.8E13	$1x10^{14}$	LGAD	49 µm bulk, 1 µm B implanted layer	28.95	26.1	$3.78x10^{-6}$
4	W11-LGB74, dose 2.0E13	$1x10^{15}$	LGAD	49 µm bulk, 1 µm B implanted layer	28.5	15.9	$2x10^{-5}$
5	W3-LGB74, dose 1.8E13	$1x10^{15}$	LGAD	49 µm bulk, 1 µm B implanted layer	30.4	11.6	$1.89x10^{-5}$
6	W11-LGB52, dose 2.0E13	$1x10^{14}$	LGAD	49 µm bulk, 1 µm B implanted layer	33.79	31.04	$1.03x10^{-5}$

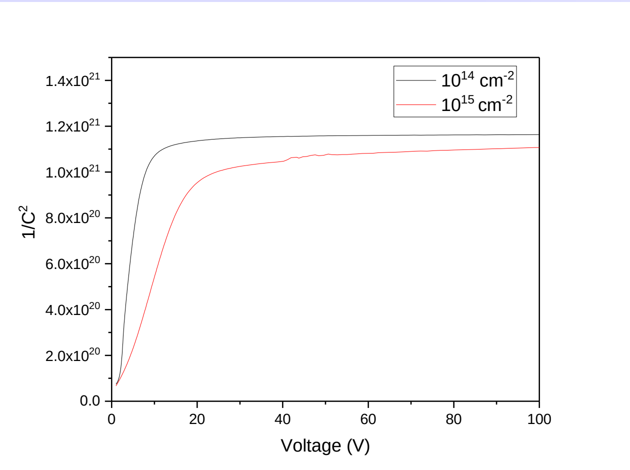
Electrical characteristics

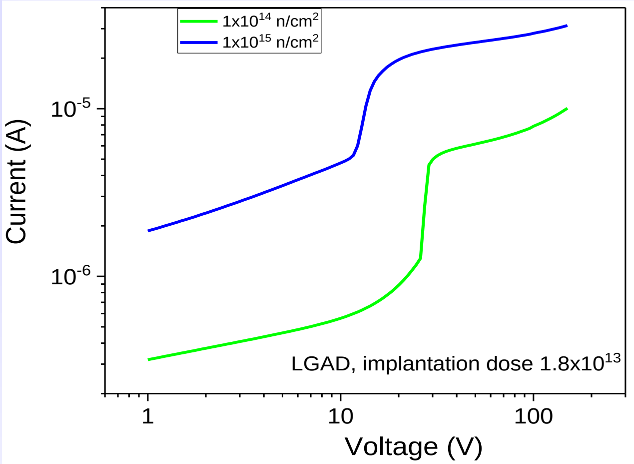
$[B]_{bulk} = 2\text{-}5\mathrm{x}10^{12}\ \mathrm{cm}^{-3}$

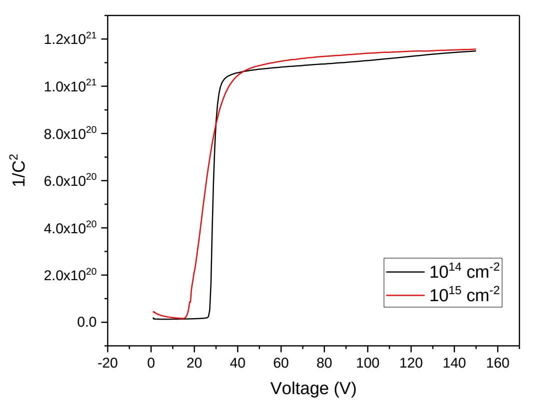


$[B]_{gain\ layer} \sim 4\mathrm{x}10^{16}\ \mathrm{cm}^{-3}$







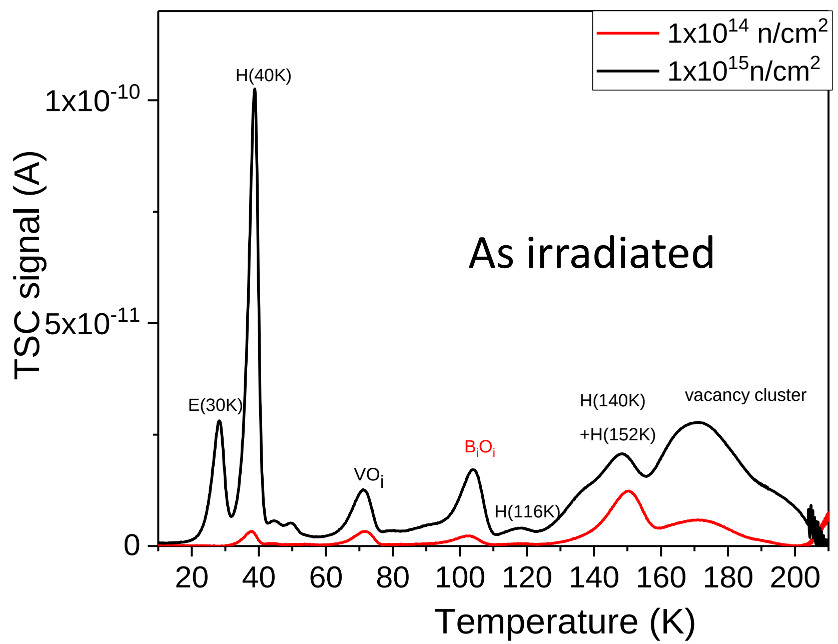


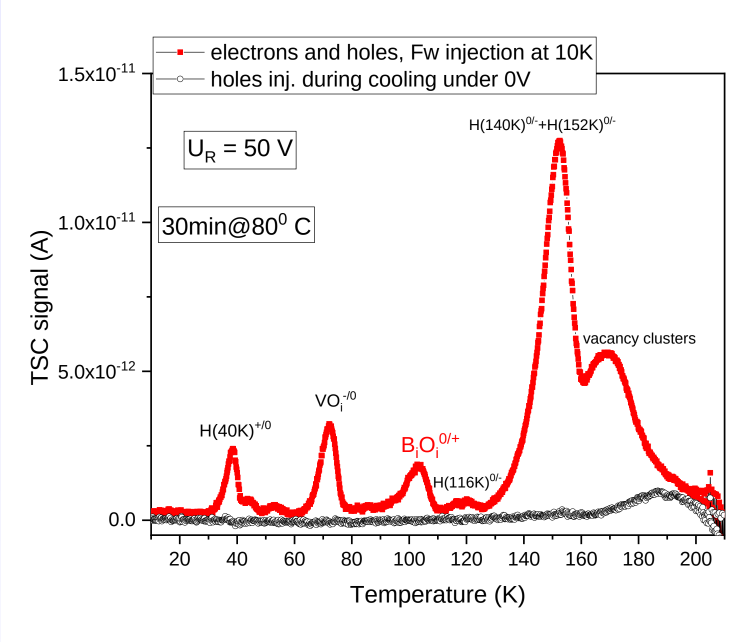
- Bulk LC LGADs > bulk PiN

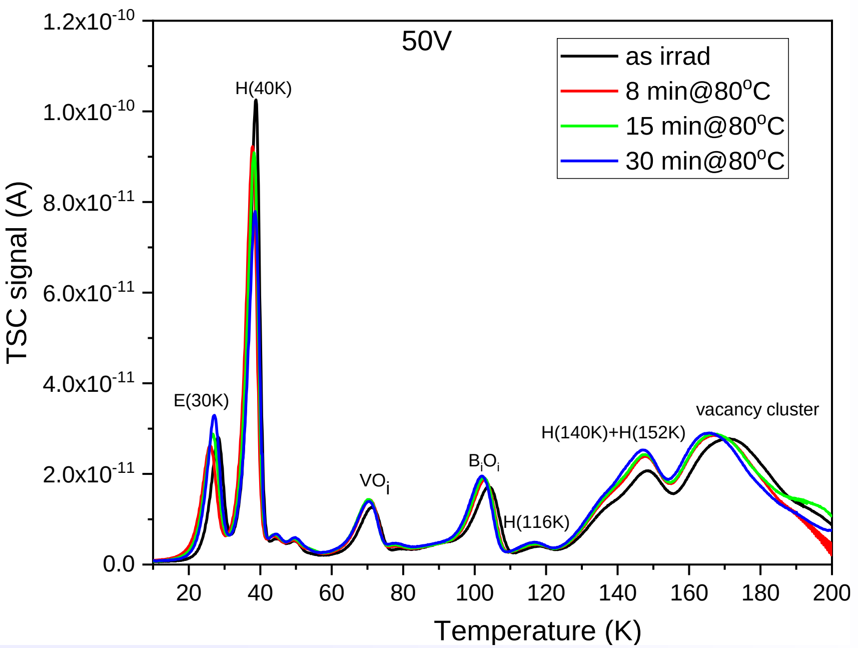
TSC investigations

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

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

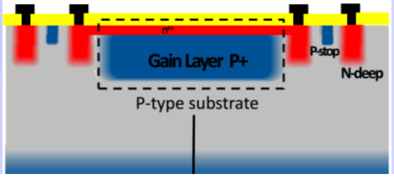


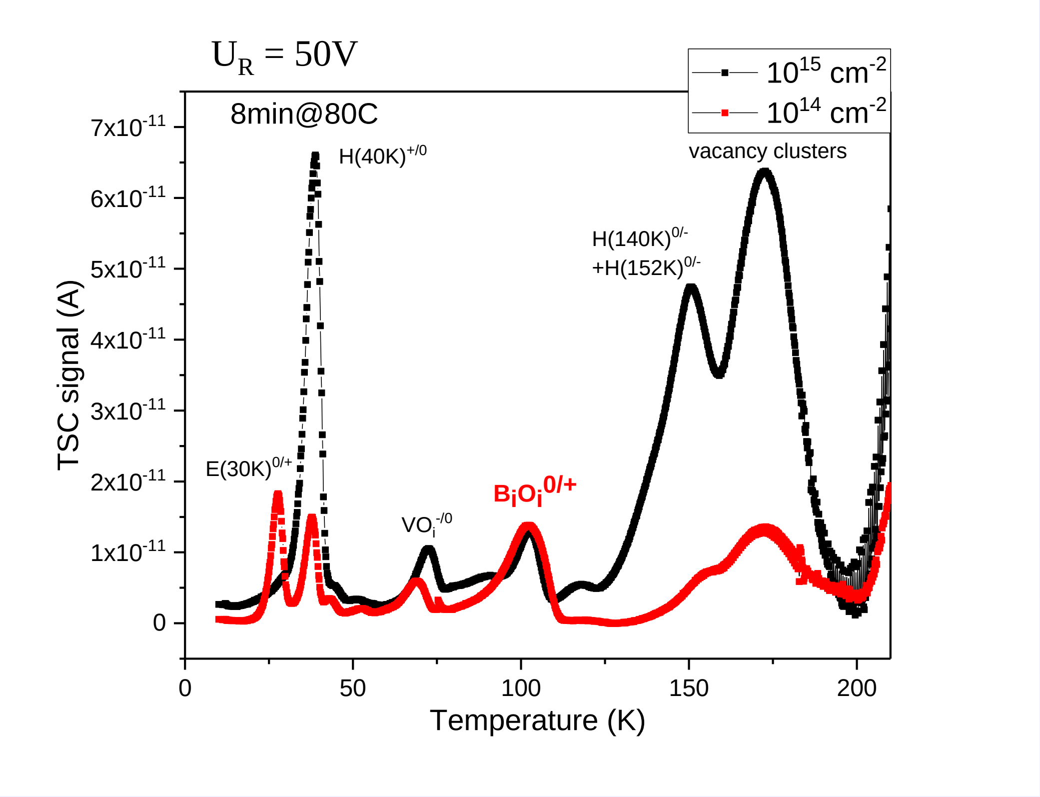




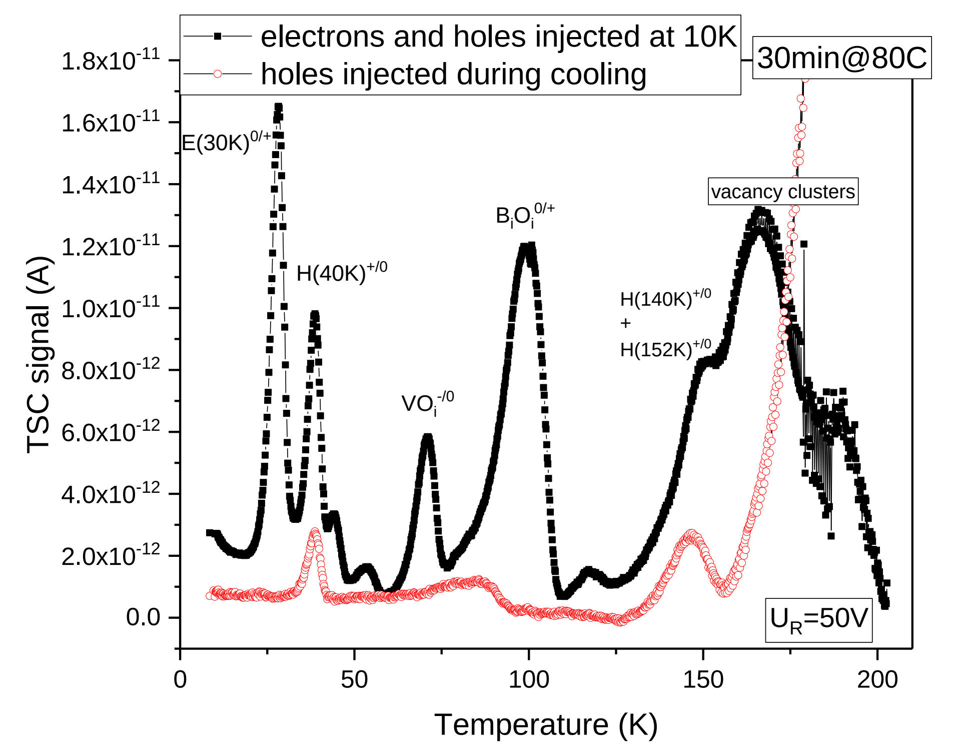
- In PiN diodes all defects increase in concentration with fluence (including BiOi)

TSC investigations





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



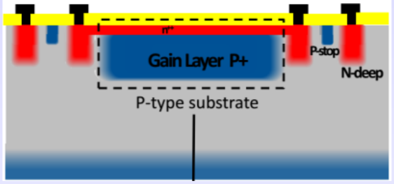
- In LGAD diodes most of the defects increase in concentration with fluence but the BiOi

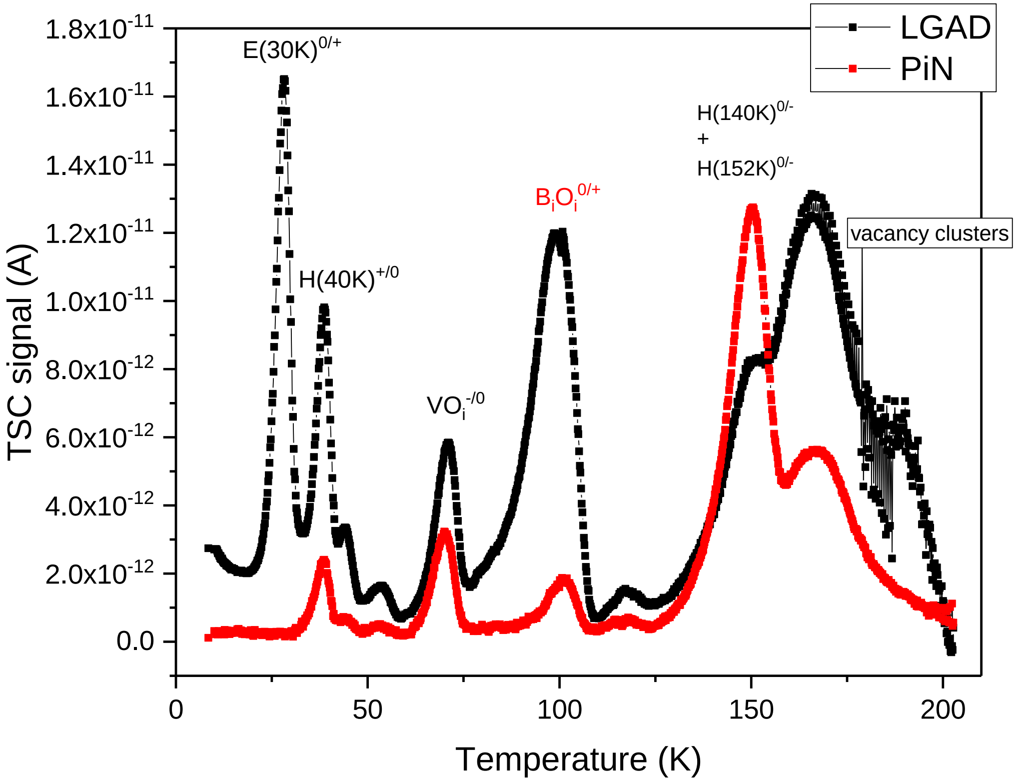
⇒ A saturation of BiOi possible caused by the limited amount of Oi

TSC investigations

Comparison between LGAD and PiN

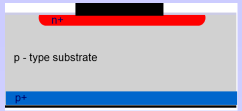
$\phi=10^{14}\ \mathrm{cm}^{-2}$, 30min@80C



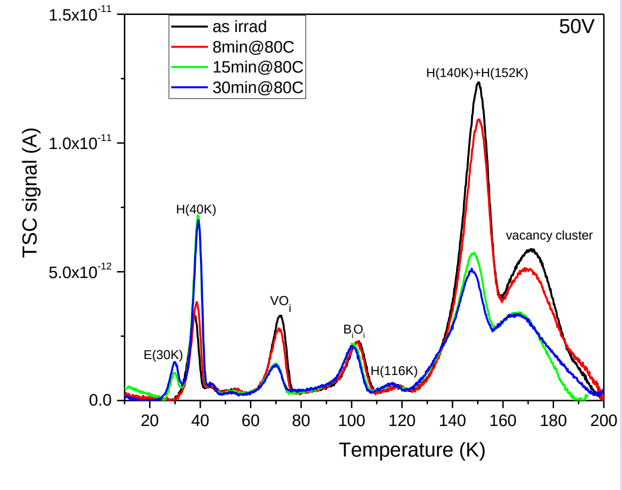


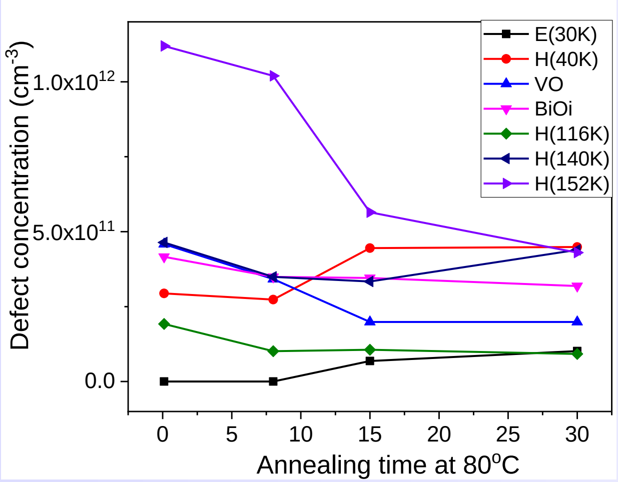
- point defects and clusters are detected in both PiN and LGAD diodes.
- The generation rates are different in the gain layer compared with the bulk (measured on PiN pad diodes) –e.g. more BiOi in LGAD
- All these defects and their impact on the electrical performances of the PIN and LGAD diodes are now under evaluation.

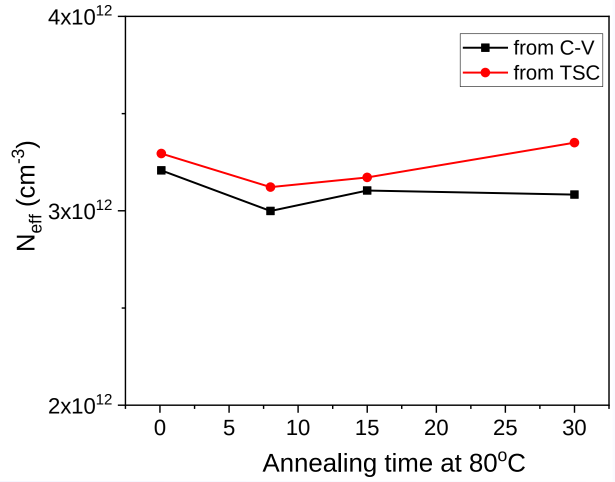
Impact on Neff



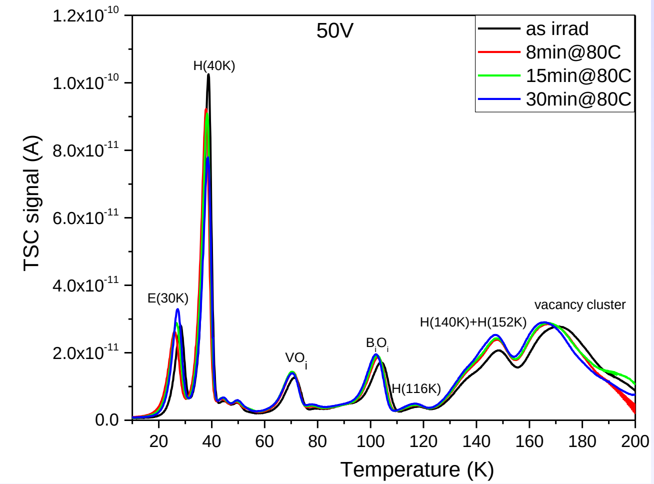
$\phi=10^{14}$ cm^{-2}

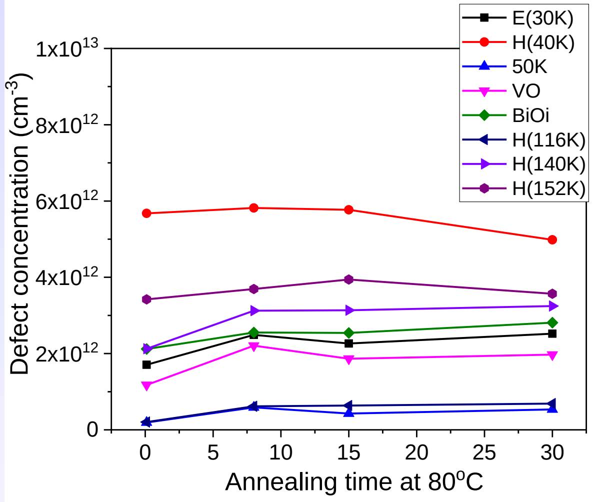


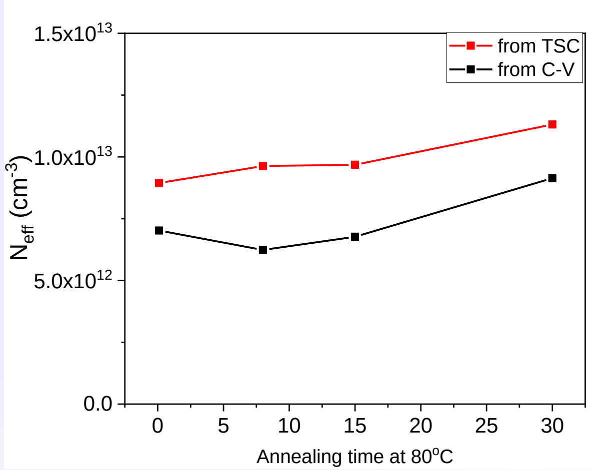




$\phi=10^{15}$ cm^{-2}



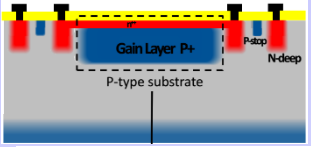




- Neff evaluated with defect concentrations determined from TSC > Neff evaluated from CV
- The missing acceptors concentration from TSC increase with the fluence

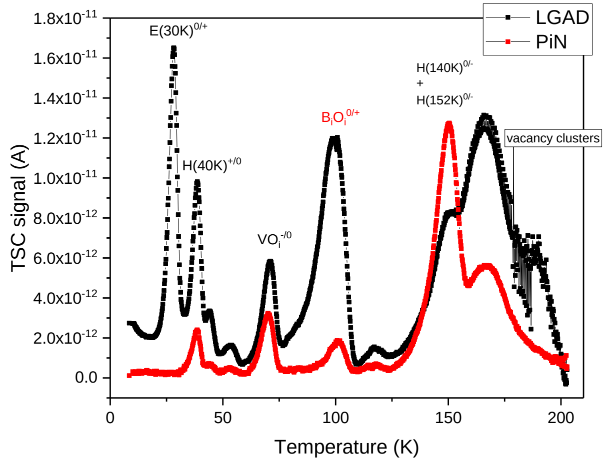
⇒ possible cause - the existence of Bi – not electrically active (cannot be determined by TSC and deactivates the B dopant)

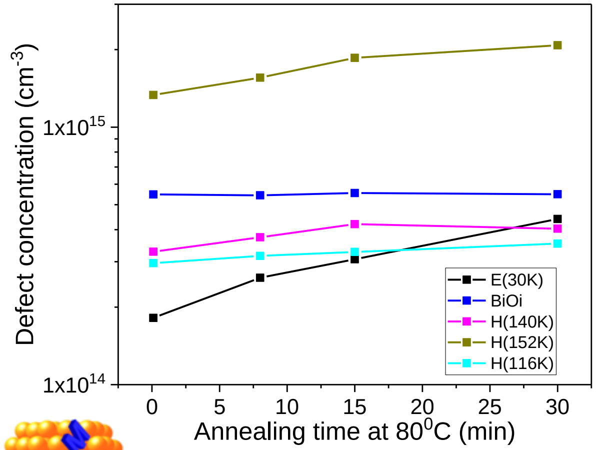
Impact on Neff

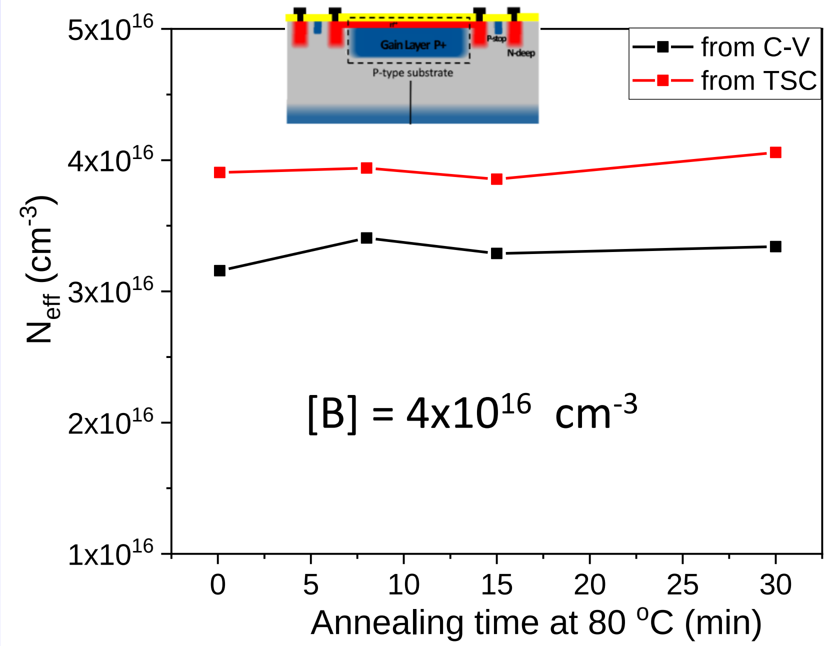


$\phi = 10^{14}\ \mathrm{cm}^{-2}$

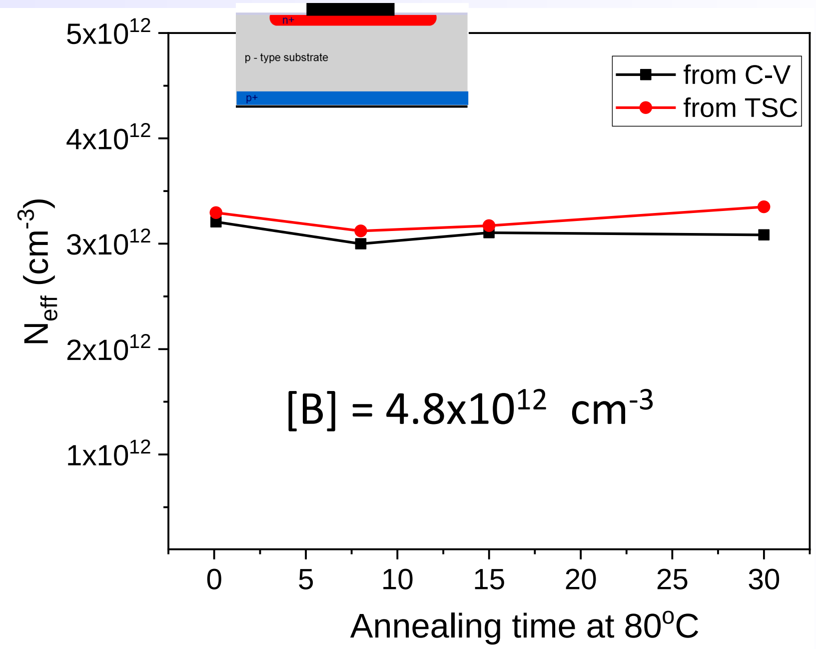
Defect concentrations – comparison between gain layer and bulk







[B] = 4x10^{16} cm^{-3}



[B] = 4.8x10^{12} cm^{-3}

For the gain layer even large differences between Neff from TSC and that from CV – suggesting the same cause, the generation of B_i (not electrically active), in larger amount in the implanted layer than in the bulk

Conclusions and further work

- A saturation of BiOi defect in the gain layer is observed starting with a fluence of 10^{14} cm^{-2}
- The TSC evaluation underestimate the acceptor removal process (cannot determine also the Bi defect) and underestimation increases with the amount of B dopant
- Annealing studies on 1 MeV CNM samples to be continued up to 10.000 min@80^0 C
- TSC investigations after 1MeV neutrons irradiation, fluences of 10^{15} cm^{-2} are reliable – one can try to go for higher fluences.
- Start the investigations on irradiated defect engineered FBK samples
- Start investigation on irradiated EPI PiN pad samples (STFZ has large amount of processing induced defects)

Thank you for your attention !