Electrically active defects in unirradiated p-type silicon detectors fabricated by different vendors

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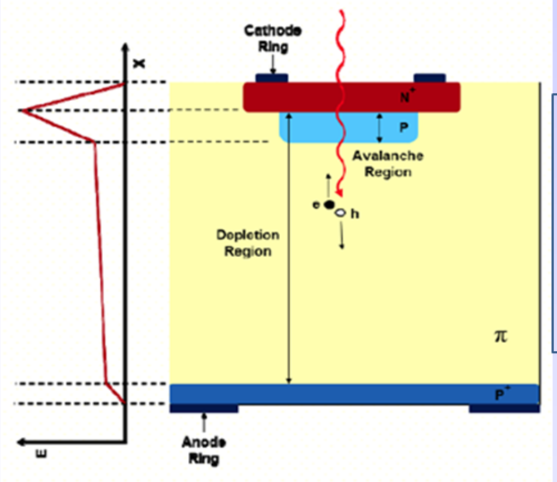
Motivation

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

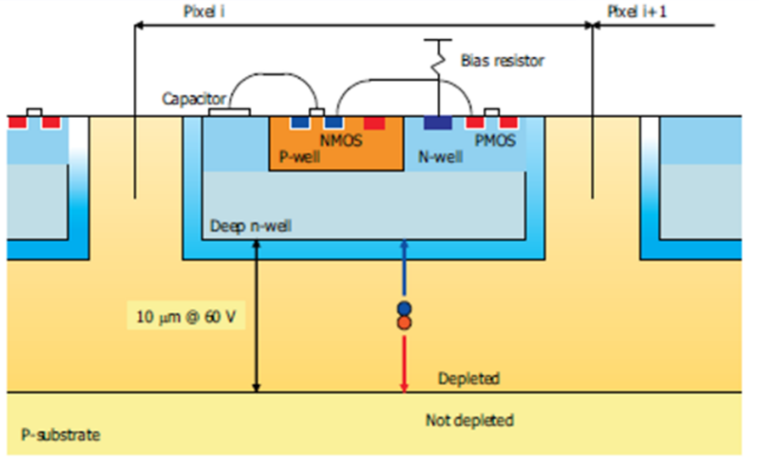
Key properties

- 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

HVCMOS (towards monolithic sensors)



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

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

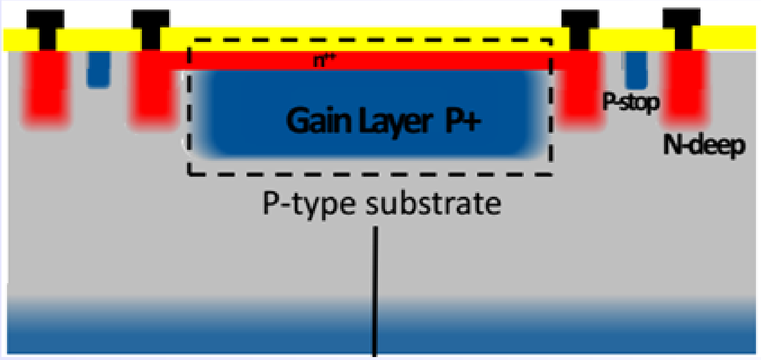
..optimizing for

- Radiation hardness
- Time resolution
- Cost effectiveness

Investigated unirradiated p-type samples

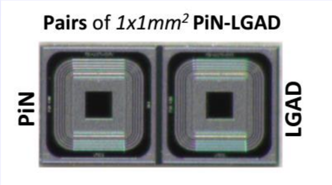
PiN pads

LGADs



20 different p-type bulk Boron doped STFZ diodes manufactured by different companies:

- ***Hamamatsu (2)***
- ***Infineon Technologies (6)***
- ***Fondazione Bruno Kessler (FBK) (12)***



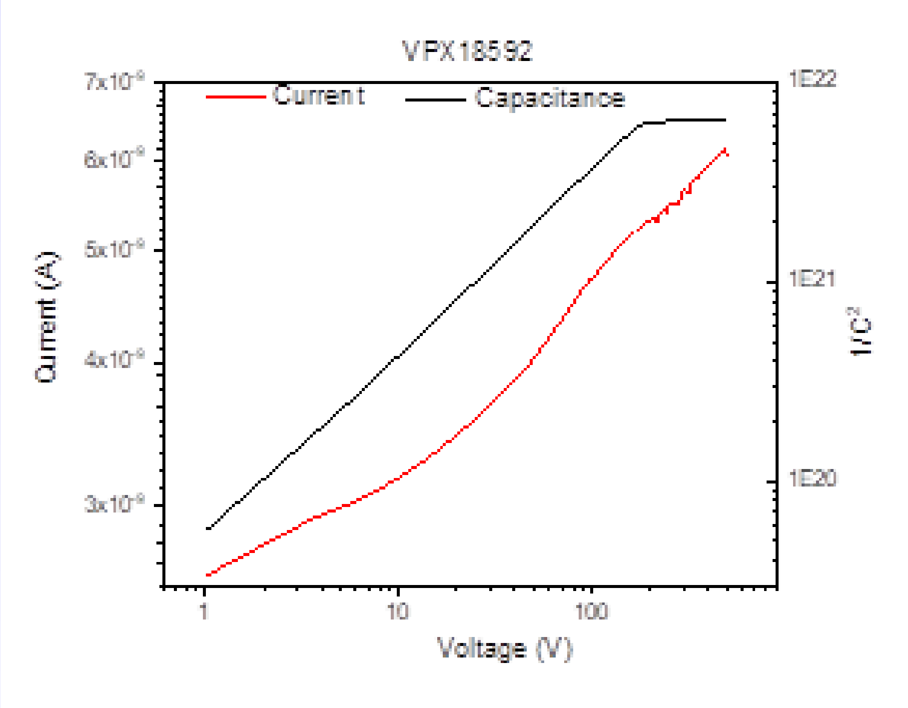
14 LGAD structures produced on STFZ silicon by
- ***Fondazione Bruno Kessler (FBK)*** with defect engineered gain layers - implantations of B or Ga alone and co-doped with C

PiN pad diodes – Hamamatsu and Infineon

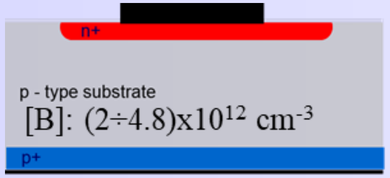
Nr	Sample	Depletion voltage (V_{dep})	Doping concentration N_{eff} (cm^{-3})	Leakage Current Normalized at 20°C (A)	Area (cm^2)	Current density (A/cm^2)
1	VPX18592	180	4.42×10^{12}	3.28×10^{-9}	0.25	1.48×10^{-8}
2	VPX21779	140	4.8×10^{12}	2.51×10^{-9}	0.065	4×10^{-8}
3a	VE711408-09	150	2.5×10^{12}	6.22×10^{-8}	0.25	2.488×10^{-7}
3b	VE711408-24	240	3.5×10^{12}	8.83×10^{-9}	0.25	3.532×10^{-8}
4a	VE543425-06	53	2×10^{12}	2.4×10^{-8}	0.25	9.6×10^{-8}
4b	VE543425-10	60	2.2×10^{12}	1.49×10^{-8}	0.25	5.96×10^{-8}
5	VL740654-18	No saturation>500V	3.5×10^{12}	Max at 500V 1×10^{-9}	0.065	1.538×10^{-8}
6	VE525852-01	66	2×10^{12}	2.32×10^{-8}	0.25	9.28×10^{-8}

PiN diodes – Hamamatsu

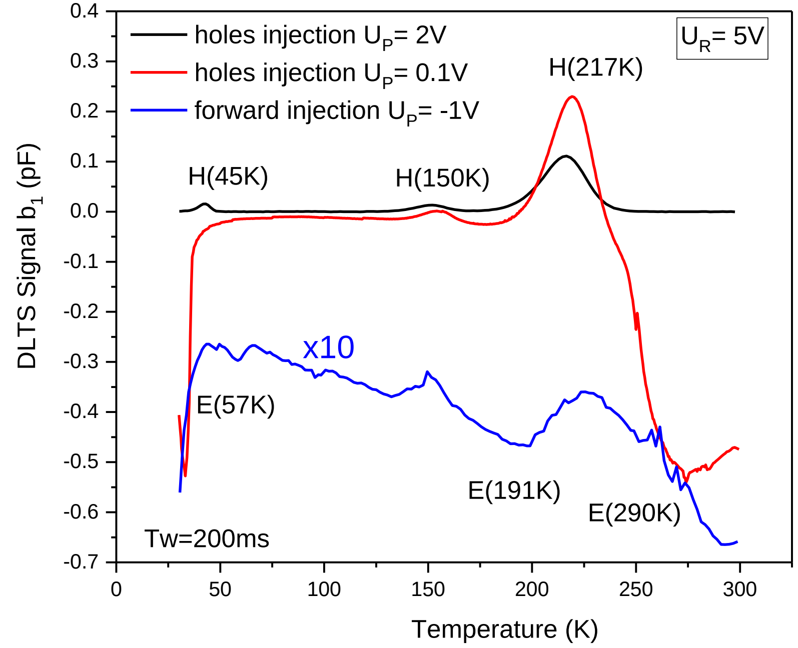
C-V, I-V characteristics



VPX samples



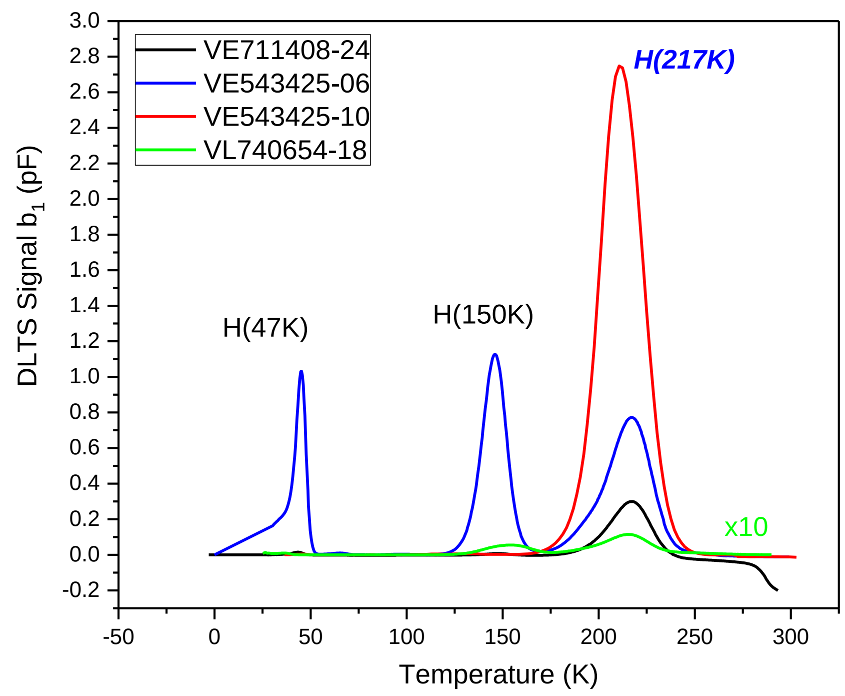
DLTS investigations

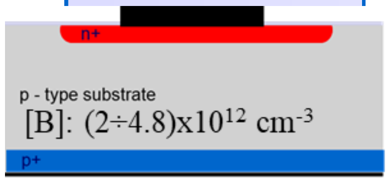


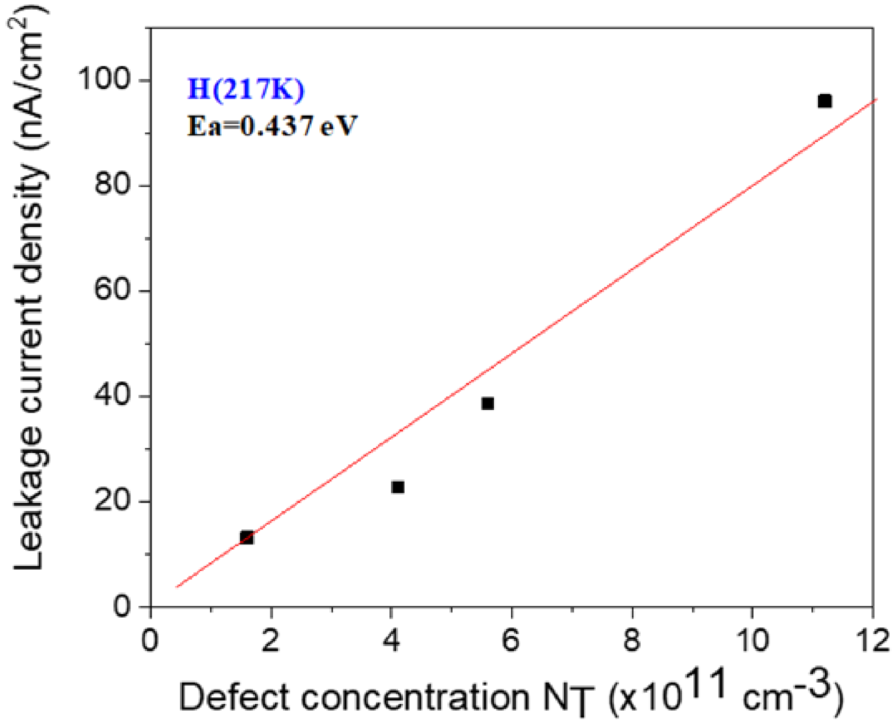
Depletion voltage (V)	180
Leakage Current at 20°C (A)	3.28×10^{-9}
Area (cm^2)	0.25
Width (um)	214
LC/vol (A/cm^2)	1.48×10^{-8}

- there are several intrinsic defects in the volume of the samples generated during the growth or processing of the wafers
- the amount of trapping centers for holes much larger than of those for electrons
- H(217K) – a trap for holes is the defect found in the highest concentration, also not homogeneous distributed in the bulk (more near the n^+ contact)

PiN diodes – Infineon





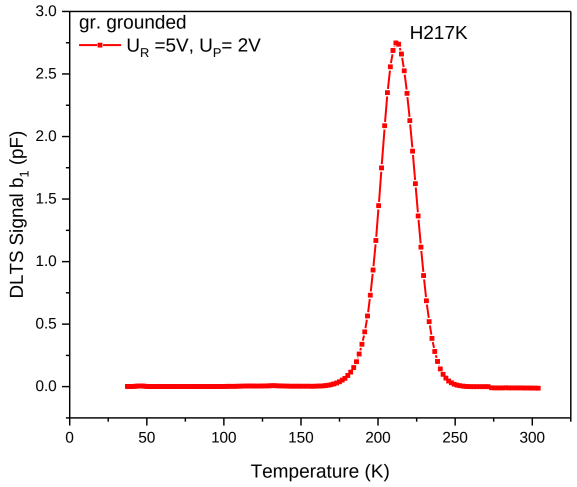


- Large differences in defect concentrations from sample to sample
- Large variations in Leakage Current - ***H(217K)*** could be the cause

PiN diodes – Hamamatsu and Infineon

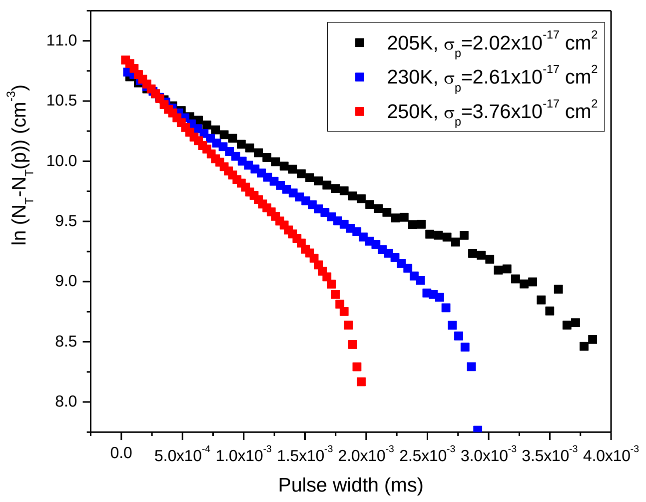
Characterization of H(217K) defect

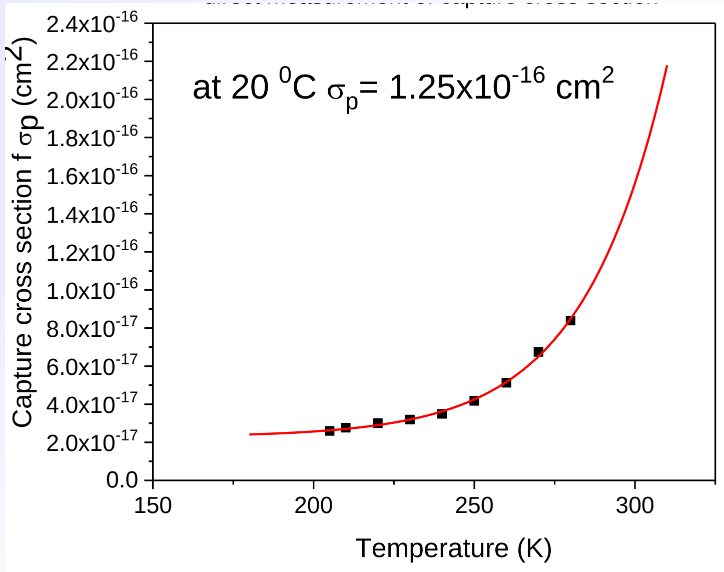
- From maxima analyses (activation energy and apparent capture cross section)



- From transient analyses at constant temperatures:
  - direct measurement of the capture cross section for holes
  - Activation energy, entropy factor

Method	Activation energy E_a (eV)	Capture cross section σ_p (cm^2) at the peak temperature
Maxima analysis	0.42	9.1×10^{-16}
Transient and capture measurement at (217K)	0.437	3×10^{-17} X_T =30.3





Impact of H(217K) defect on electrical characteristics at 20^0 C

Schockley-Read-Hall - statistics used to calculate the impact the detected defects have on the device electrical performance

$$\Delta LC(T) = q \times A \times d \times N_t \frac{e_n(T)e_p(T)}{e_n(T)+e_p(T)},$$

$$e_n(T) = v_{th,n}(T) \times \sigma_n(T) \times N_C \times \exp\left(-\frac{E_c - E_t}{k_B T}\right),$$

$$e_p(T) = v_{th,p}(T) \times \sigma_p(T) \times N_V \times \exp\left(-\frac{E_t - E_V}{k_B T}\right),$$

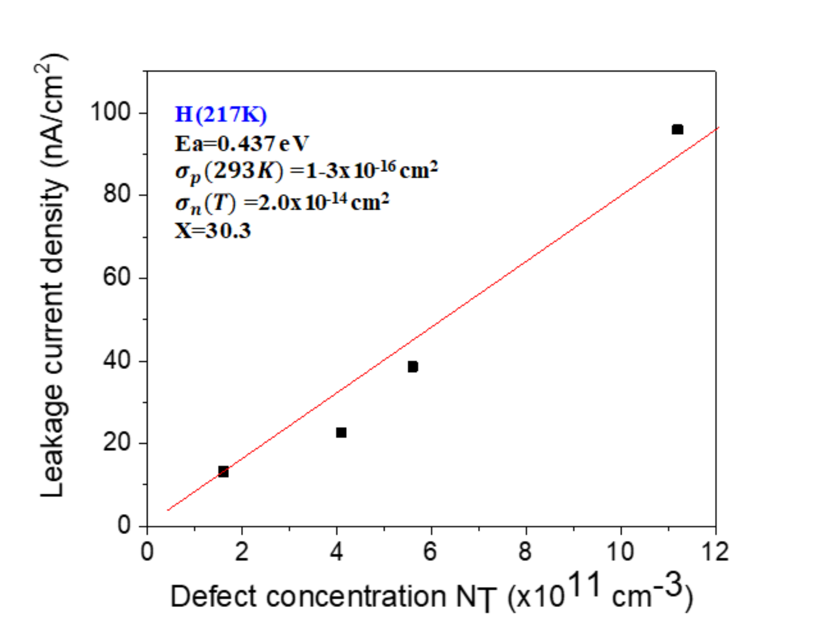
$$N_{eff}(T) = N_d + \sum_i p_{t,i}^{donor}(T) - \sum_j n_{t,j}^{acceptor}(T).$$

$$\Delta N_{eff}^{acceptor}(T) = -n_t^{acceptor}(T) = -N_t^{acceptor}\frac{e_p(T)}{e_n(T)+e_p(T)},$$

$$\Delta N_{eff}^{donor}(T) = +p_t^{donor}(T) = +N_t^{donor}\frac{e_n(T)}{e_n(T)+e_p(T)}.$$

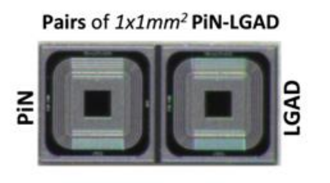
H(217K) defect – donor in lower part of the Si gap

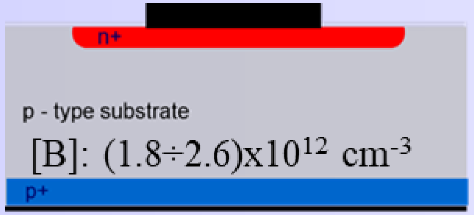
- activation energy of **0.437 eV**
- Temperature dependent capture cross section for holes (direct measurement)
- Large entropy factor (**X_T =30.3**) –strong interaction of the defect with the Si lattice (as e.g. Au in silicon)
- presuming that H(217K) determine the value of LC, the capture cross section for electrons should be **$\sigma_n(T)$ =2.0x10^{-14} cm^2**

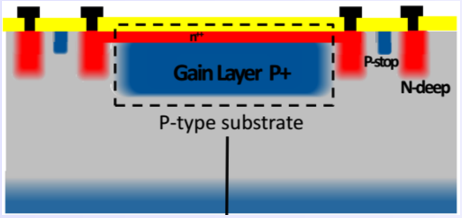


⇒ **large impact LC, not charged at 20^0 C**

PiN and LGAD diodes -FBK

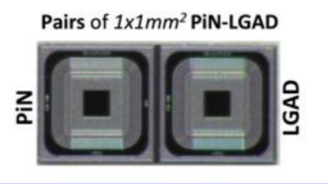


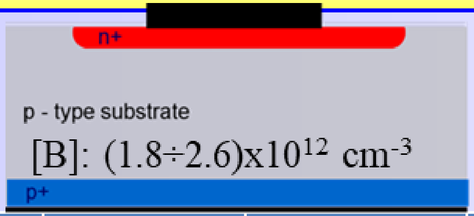




FBK UFSD2 W1 B-0.98L	Wafer 1, the gain layer implanted with B with dose 0.98 (Low diffusion-2% less)
FBK UFSD2 W6 BC-1.02 HL	Wafer 6, the gain layer implanted with B with dose 1.02(High diffusion-2% more) and co-implanted with carbon-low diffusion
FBK UFSD2 W8 B-1.02H	Wafer 8 the gain layer implanted with B with dose 1.02 (High diffusion-2% more)
FBK UFSD2 W14 G-1.04L	Wafer 14, the gain layer implanted with gallium with dose 1.04 (Low diffusion)
FBK UFSD2 W18 G-1.08L	Wafer 18, the gain layer implanted with gallium with dose 1.08 (Low diffusion)
FBK UFSD2 W15 GC-1.04LL	Wafer 15, the gain layer implanted with gallium with dose 1.04 (Low diffusion) and co-implanted with carbon-low diffusion

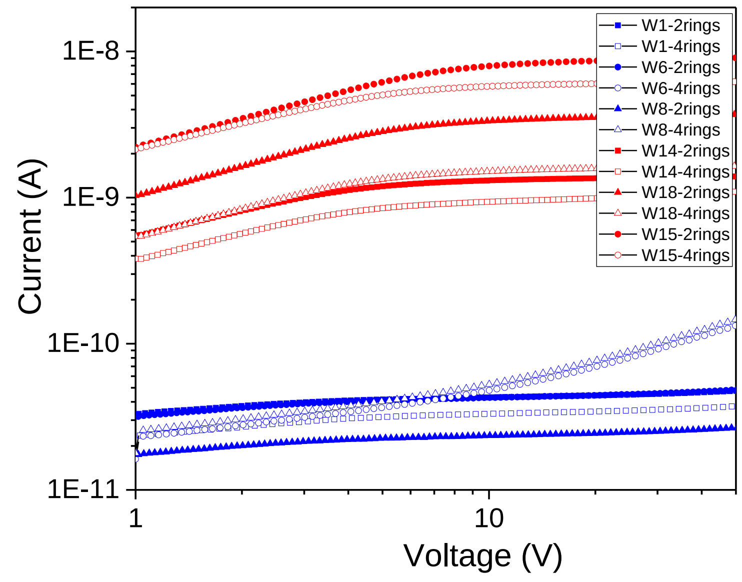
PiN diodes -FBK





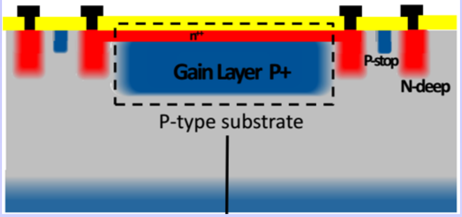
	Sample	Comments	Depletion voltage (V_{dep})	Leakage Current Normalized at 20°C (A)	Area(mm²)-thickness (µm)	N_{eff} from CV(cm^{-3})
1	FBK UFSD2 W1 B-0.98L	4 ring	3.48	$3.03x10^{-11}$	1 mm²- 50 µm	$1.83x10^{12}$
2	FBK UFSD2 W1 B-0.98L	2 rings	3.42	$4.03x10^{-11}$	1 mm²- 50 µm	$1.79\ x10^{12}$
3	FBK UFSD2 W6 BC-1.02 HL	4 rings	3.40	$3.35x10^{-11}$	1 mm²- 50 µm	$1.78\ x10^{12}$
4	FBK UFSD2 W6 BC-1.02 HL	2 rings	3.49	$2.80x10^{-11}$	1 mm²- 50 µm	$1.83\ x10^{12}$
5	FBK UFSD2 W8 B-1.02H	2 rings	3.48	$2.18x10^{-11}$	1 mm²- 50 µm	$1.83\ x10^{12}$
6	FBK UFSD2 W8 B-1.02H	4 ring	3.38	$3.55x10^{-11}$	1 mm²- 50 µm	$1.77\ x10^{12}$
7	FBK UFSD2 W14 G-1.04L	4 rings	3.51	$7.54x10^{-10}$	1 mm²- 50 µm	$1.84\ x10^{12}$
8	FBK UFSD2 W14 G-1.04L	2 rings	3.40	$1.09x10^{-9}$	1 mm²- 50 µm	$1.78\ x10^{12}$
9	FBK UFSD2 W18 G-1.08L	4 rings	3.95	$1.22x10^{-9}$	1 mm²- 50 µm	$2.07\ x10^{12}$
10	FBK UFSD2 W18 G-1.08L	2 rings	4.05	$2.81x10^{-9}$	1 mm²- 50 µm	$2.15\ x10^{12}$
11	FBK UFSD2 W15 GC-1.04LL	4 rings	4.29	$4.71x10^{-9}$	1 mm²- 50 µm	$2.25\ x10^{12}$
12	FBK UFSD2 W15 GC-1.04LL	2 rings	4.90	$6.09x10^{-9}$	1 mm²- 50 µm	$2.62\ x10^{12}$

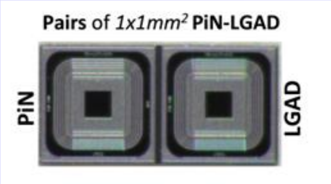
leakage current of all 12 unirradiated PiN diodes.

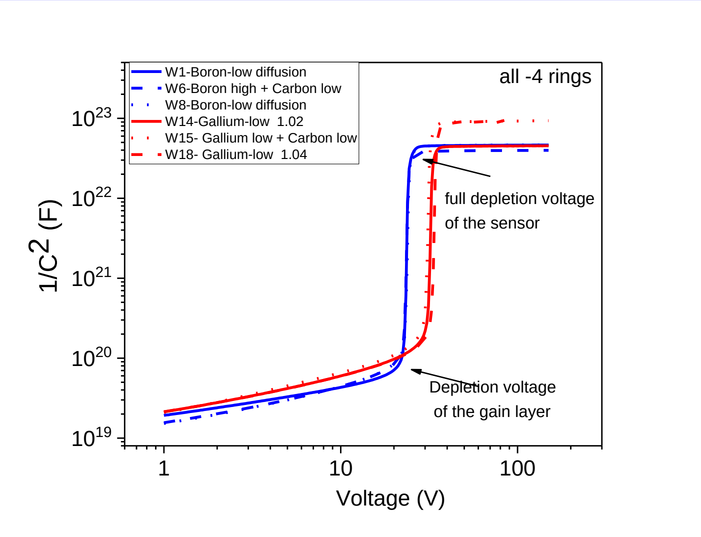


-diodes processed on W1,W6 and W8 wafers has lower LC then those processed on W14, W15 and W18 wafers

LGAD diodes -FBK





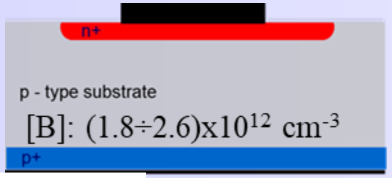


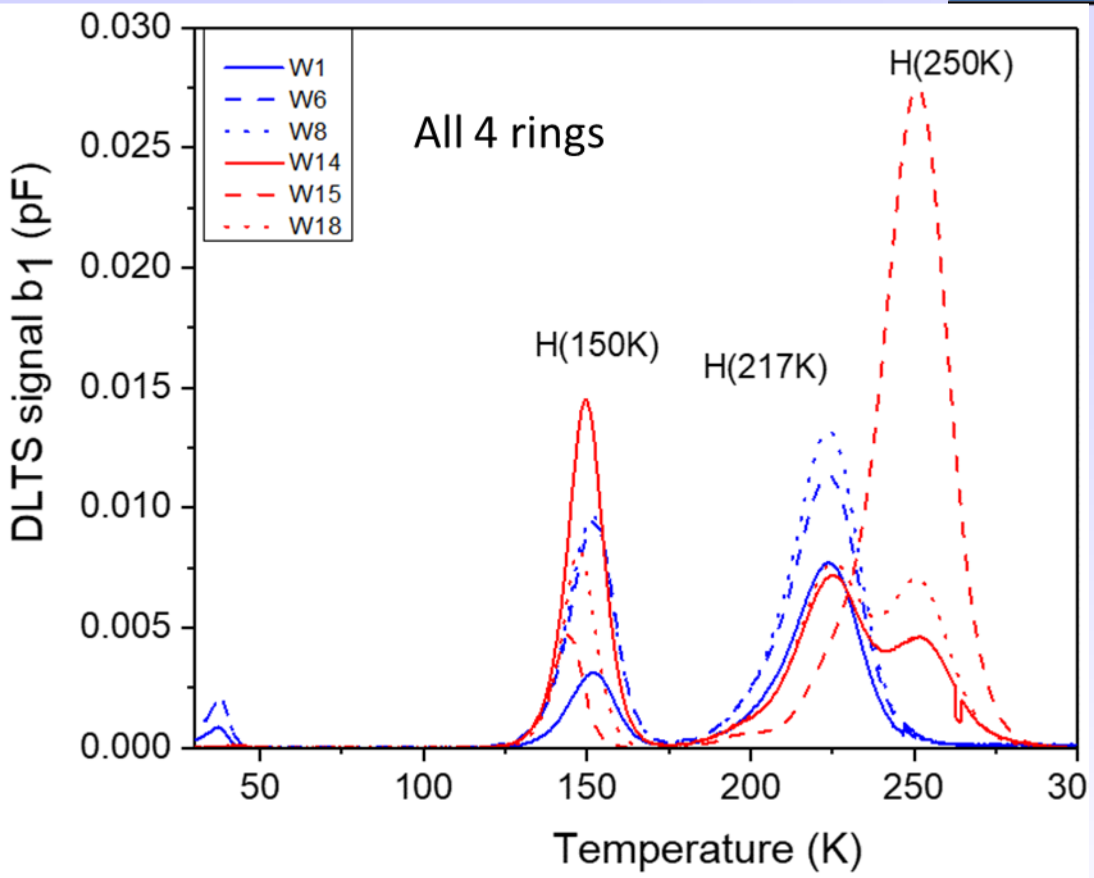
	Sample	Comments	Depletion voltage of the gain layer(V)	Full depletion voltage of sensor(V)	Leakage Current Normalized at 20°C (A) (full depletion)	Area(mm^2)-thickness (mm)	$N_{eff\ gain\ layer}$ from CV(cm^{-3})	$N_{eff\ bulk}$ from CV(cm^{-3})
1	FBK UFSD2 W1 B-0.98L	4 ring	22	25	$7.27x10^{-11}$	1 MM- 50 µm	$5.9x10^{16}$	$1.83x10^{12}$
2	FBK UFSD2 W1 B-0.98L	2 rings	22	25	$6.42x10^{-11}$	1 MM- 50 µm	$5.9x10^{16}$	$1.79\ x10^{12}$
3	FBK UFSD2 W6 BC-1.02 HL	4 rings	22	25	$2.45x10^{-10}$	1 MM- 50 µm	$5.9x10^{16}$	$1.78\ x10^{12}$
4	FBK UFSD2 W6 BC-1.02 HL	2 rings	22	25	$2.49x10^{-10}$	1 MM- 50 µm	$5.9x10^{16}$	$1.83\ x10^{12}$
5	FBK UFSD2 W8 B-1.02H	2 rings	22	25	$4.72x10^{-11}$	1 MM- 50 µm	$5.9x10^{16}$	$1.83\ x10^{12}$
6	FBK UFSD2 W8 B-1.02H	4 ring	22	25	$6.75x10^{-11}$	1 MM- 50 µm	$5.9x10^{16}$	$1.77\ x10^{12}$
7	FBK UFSD2 W14 G-1.04L	4 rings	30	35	$1.54x10^{-6}$	1 MM- 50 µm	$3.95x10^{16}$	$1.84\ x10^{12}$
8	FBK UFSD2 W14 G-1.04L	2 rings	30	35	$1.72x10^{-6}$	1 MM- 50 µm	$3.95x10^{16}$	$1.78\ x10^{12}$
9	FBK UFSD2 W18 G-1.08L	4 rings	30	35	$1.2x10^{-6}$	1 MM- 50 µm	$3.95x10^{16}$	$2.07\ x10^{12}$
10	FBK UFSD2 W18 G-1.08L	2 rings	30	35	$5.1x10^{-5}$	1 MM- 50 µm	$3.95x10^{16}$	$2.36\ x10^{12}$
11	FBK UFSD2 W15 GC-1.04LL	4 rings	30	35	$2.4x10^{-6}$	1 MM- 50 µm	$3.95x10^{16}$	$2.25\ x10^{12}$
12	FBK UFSD2 W15 GC-1.04LL	2 rings	30	35	$2.04x10^{-8}$	1 MM- 50 µm	$3.95x10^{16}$	$2.62\ x10^{12}$

Similar to PiN diodes, also the LGADs processed on W1,W6 and W8 wafers has lower LC then those processed on W14, W15 and W18 wafers

PiN diodes -FBK

DLTS investigations





Schockley-Read-Hall - statistics used to calculate the impact the detected defects have on the device electrical performance

$$\Delta LC(T) = q \times A \times d \times N_t \frac{e_n(T) e_p(T)}{e_n(T) + e_p(T)},$$

$$e_n(T) = v_{th,n}(T) \times \sigma_n(T) \times N_C \times \exp\left(-\frac{E_c - E_t}{k_B T}\right),$$

$$e_p(T) = v_{th,p}(T) \times \sigma_p(T) \times N_V \times \exp\left(-\frac{E_t - E_V}{k_B T}\right),$$

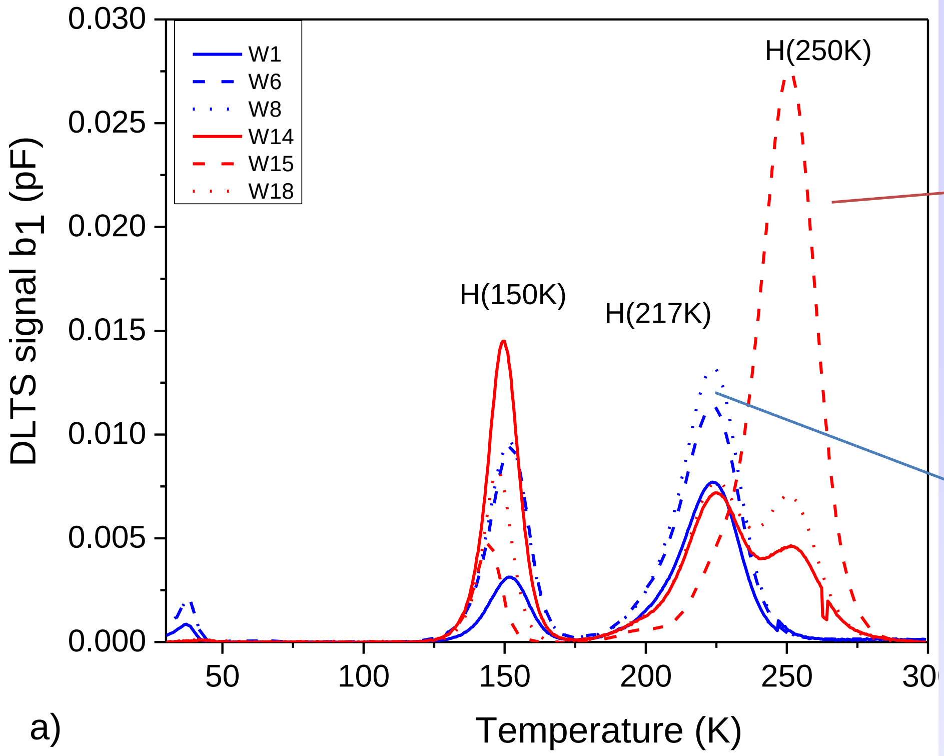
$$N_{eff}(T) = N_d + \sum_i p_{t,i}^{donor}(T) - \sum_j n_{t,j}^{acceptor}(T).$$

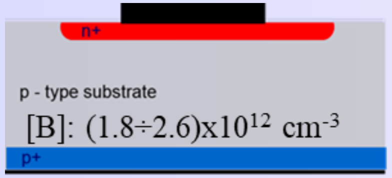
$$\Delta N_{eff}^{acceptor}(T) = -n_t^{acceptor}(T) = -N_t^{acceptor} \frac{e_p(T)}{e_n(T) + e_p(T)},$$

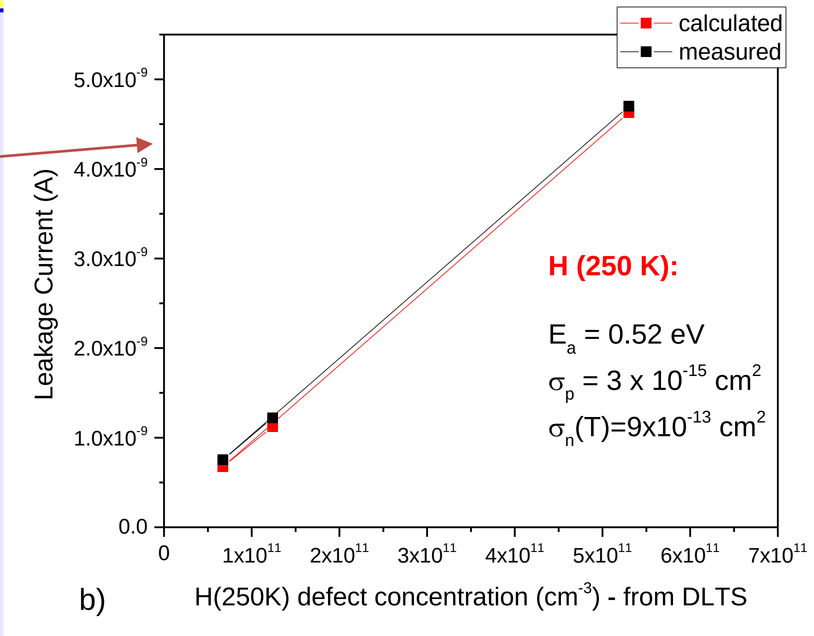
$$\Delta N_{eff}^{donor}(T) = +p_t^{donor}(T) = +N_t^{donor} \frac{e_n(T)}{e_n(T) + e_p(T)}.$$

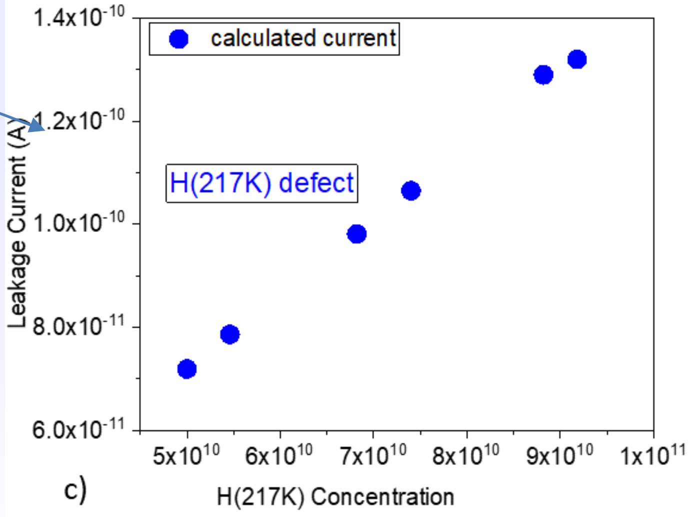
H(250K) trapping parameters: E_a=0.52 eV, σ_p= 3x10^{-15} cm^2 (direct measurement constant with T)

PiN diodes -FBK







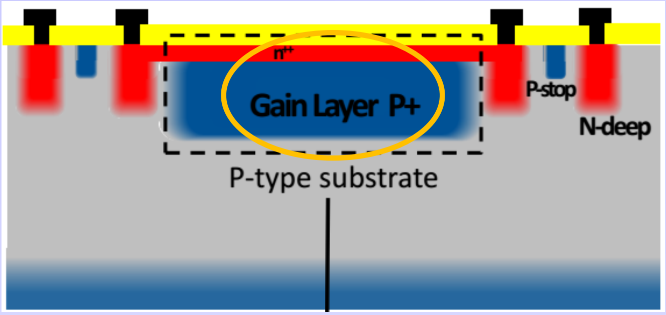


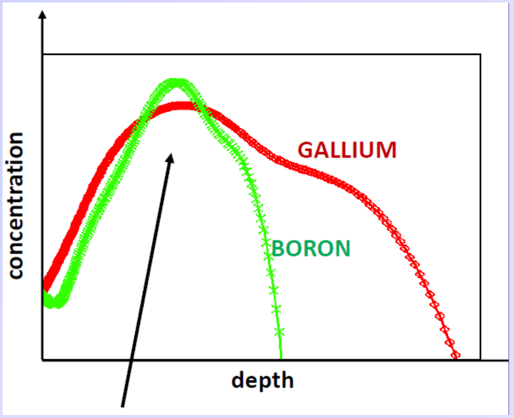
- Similar defects as in Hamamatsu and Infineon samples (H150K) and **H(217K)**
- **H(217K) can explain the low values of LC (<1.5x10^{-10} A) in W1, W6 and W8**
- **H(250K) in W14, W15 and W18 if $\sigma_n(T)$ =9x10^{-14} cm^2**

H(250K) – with Ea=0.52eV, σ_p= 3x10^{-15} cm^2 and $\sigma_n(T)$ =9x10^{-14} cm^2

⇒ large impact on LC and ~ 53% of its concentration is positively charged at 20^0 C

Un-irradiated LGAD sensors



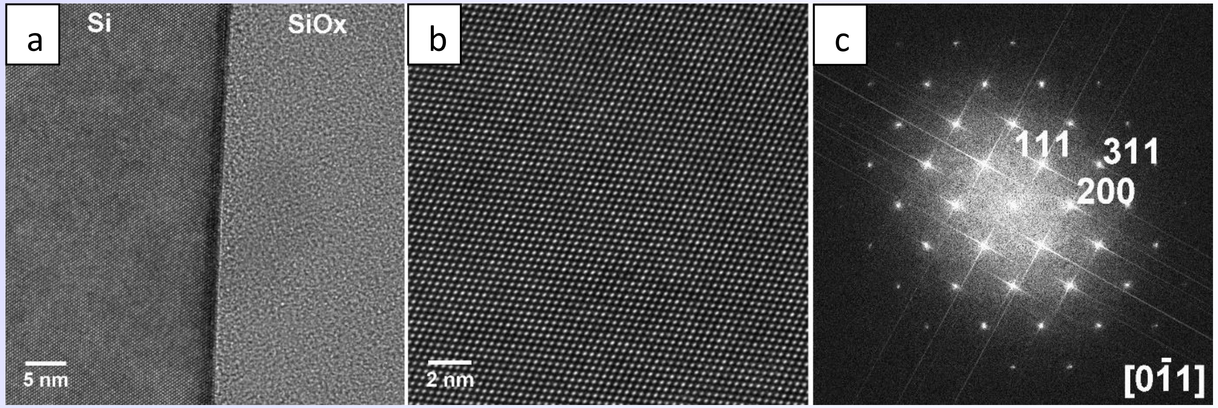


Examples on FBK STFZ Si with gain layer implanted with:

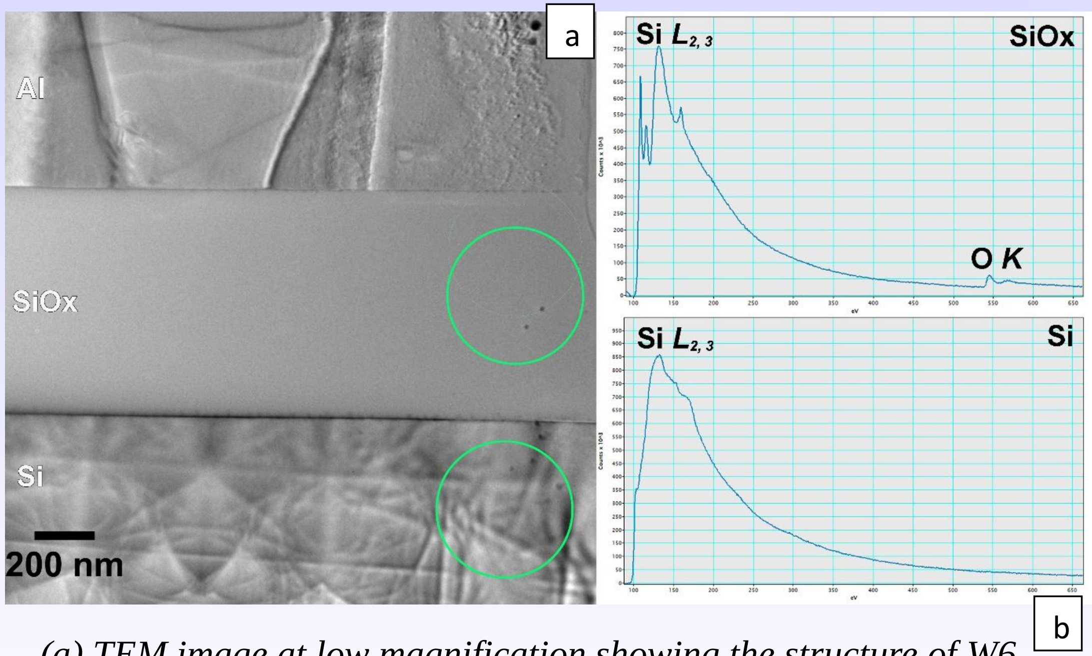
- **B and co-implanted with C**

and

- **Ga and co-implanted with C**.



a) HRTEM images at the SiOx-Si interface and (b) a detail from the Si; (c) FFT pattern corresponding to the image (a).



(a) TEM image at low magnification showing the structure of W6 sample(LGAD implanted with B&C) and (b) EELS spectra extracted from the areas inside of green circles.

The HRTEM analyses on samples implanted with boron, gallium or co-implanted with carbon reveal a continuous pattern of high resolution fringes, without any obvious structural defects.

Conclusions

- we found several electrically active defects in as-grown/processed samples manufactured by different vendors

Defect/impact	Activation energy (eV)	Capture cross section for holes at 20^0 C (cm^2)	Capture cross section for electrons at 20^0 C (cm^2)
H(150K)	0.31 eV	$7x10^{-15}$	
H(217K) Impact on LC	0.437 eV	$1.25x10^{-16}$ (XT=30.3)	$2.0x10^{-14}$ cm^2
H(250K) Impact on both LC and Neff	0.52 eV	$3x10^{-15}$	$9x10^{-14}$ cm^2

Common to p-type Si

Most likely due to accidental impurification of the wafers

Near future research activities

- Proceed with DLTS measurements on LGAD samples produced by FBK (DLTS not available for the moment)
- Irradiation of the existing defect engineered FBK sensors (neutrons and/or protons) – this year with 1MeV neutrons
- Start investigation on EPI PiN pad samples (STFZ has large amount of processing induced defects in different concentrations even when processed on wafers from the same batch)

Thank you for your attention !