34th RD50 Workshop, Lancaster, UK, June 12-14 2019

Recent studies and characterization of UFSD sensors

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Outline

- **Gain uniformity** on FBK-UFSD3 and HPK-Exx28995-Type3.1 productions:
  - gain layer depletion voltage non-uniformity
  - Collection charge

- Characterization of FBK-UFSD2 **50µm $\pm$ 1µm thick PiN diodes irradiated** at high fluences, 10^{15}-10^{16} n_{eq}/cm^2
  - Acceptor creation
  - Gain at high Electric field >100 kV/cm
  - Charge collection efficiency

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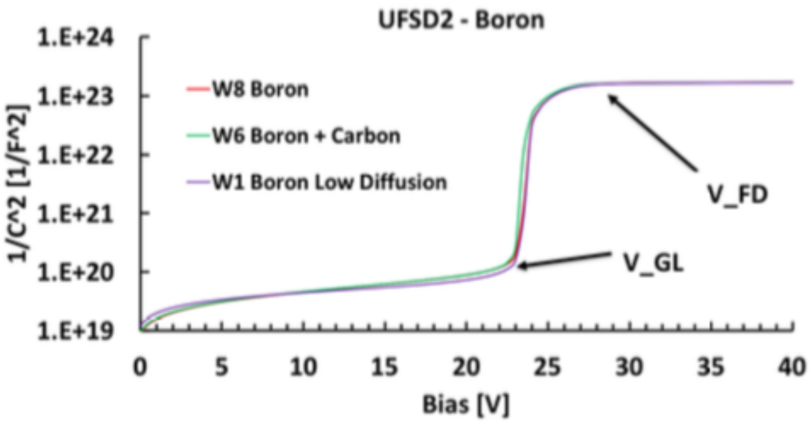
Active acceptor density into gain layer from C-V measurements

Depletion voltage of gain layer (V_{GL}) is proportional to amount of the active doping of the gain layer



$$V_{GL} = \frac{qN_A w^2}{2\varepsilon_{Si}}$$

w → gain layer thickness
N_A → Active doping concentration

Gain uniformity measurement on single wafers is based on C-V measurements on a set of sensors

Voltage foot and gain layer position

Voltage to deplete the gain layer of thickness w:

$$V_{GL} = \frac{Nqw^2}{2\varepsilon_{Si}}$$

Electric field at the end of the gain layer

$$E_{GL} = \frac{dV_{GL}}{dw} = 2 * \frac{Nqw}{2\varepsilon_{Si}}$$

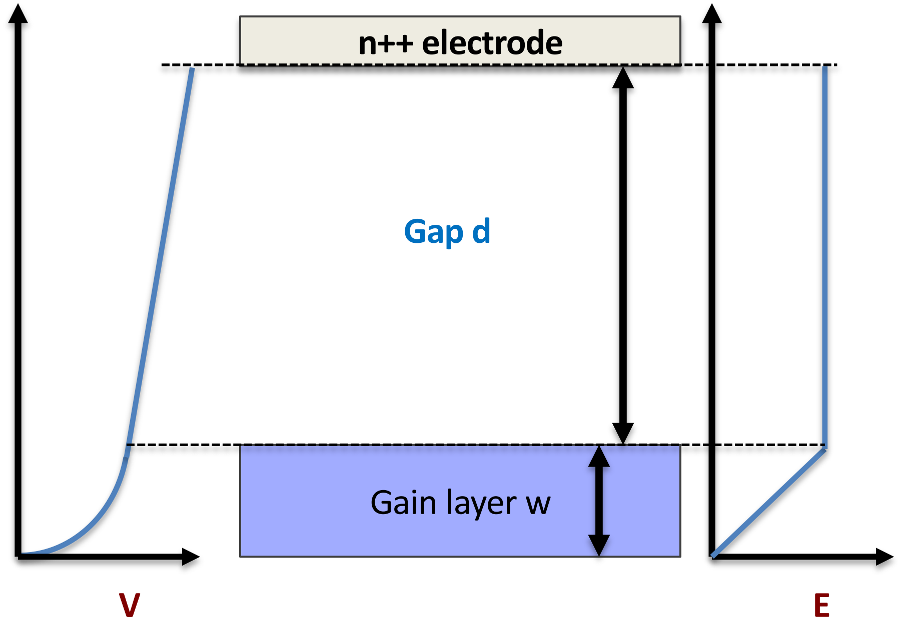
In the gap d the Electric field is a constant (assuming no doping) while the voltage increases linearly:

$$E_{Gap} = \frac{dV_{Gap}}{dw} = 2 * \frac{Nqw}{2\varepsilon_{Si}}$$

$$V_{Gap} = E_{Gap} * d = 2 * \frac{V_{GL}}{w} d$$

The voltage to deplete the foot is:

$$V_{foot} = V_{GL} * (1 + 2 * \frac{d}{w})$$



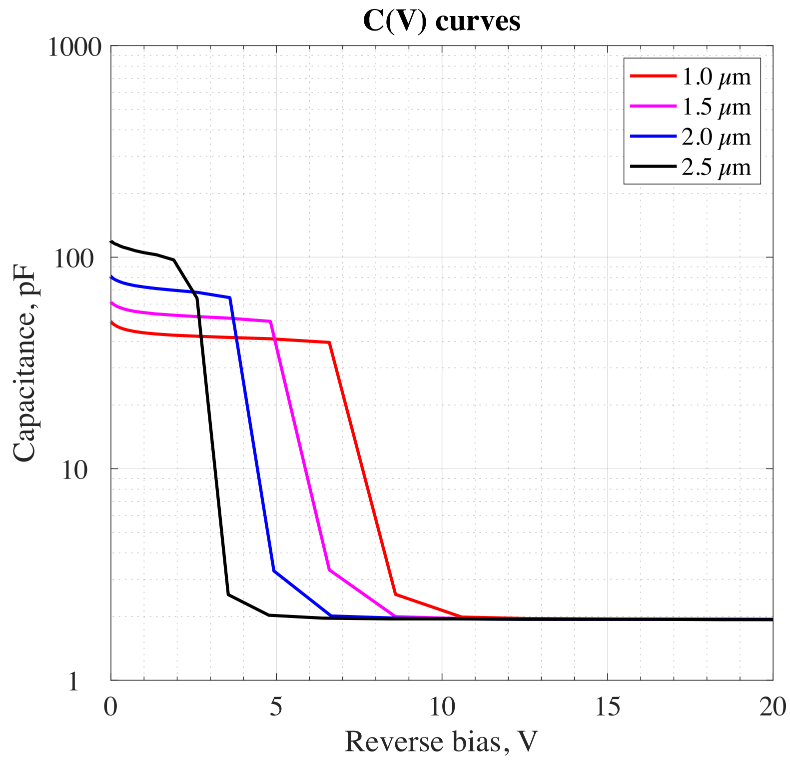
Sensors	V_{GL}	V_{GAP}	V_{FOOT}
FBK	9 V	11 V	20 V
HPK Type 3.1	6 V	30 V	36 V
HPK Type 3.2	7.5 V	49 V	57.7 V

The voltage of the foot is mostly use to create the field in the gap!

TCAD simulation of VGL_{depl} Vs GL depth

Same gain layer implanted at increasing depth:

the depletion voltage of the gain layer is linear with depth



Gain uniformity on HPK and FBK UFSDs

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FBK

- Measurements on **UFSD3 production (50 µm thick)**
- Three wafers measured W1/W2/W4

Wafer #	Dose Pgain	Carbon	Diffusion
1	0.98		L
2	0.96		L
3	0.96	A	L
4	0.96	A	L
5	0.98	A	L
6	0.96	B	L
7	0.98	B	L
8	0.98	B	L
9	0.98	C	L
10	1.00	C	L
11	1.00	D	L
12	1.02		H
13	1.00		H
14	1.02	A	H
15	1.00	A	H
16	1.02	B	H
17	1.02	B	H
18	1.04	B	H
19	1.02	C	H
20	1.04	C	H

- **Different gain layer dose** in wafer under test
- Measurement performed on array 2x2 (1x3 mm^2)

Gain uniformity on single wafer

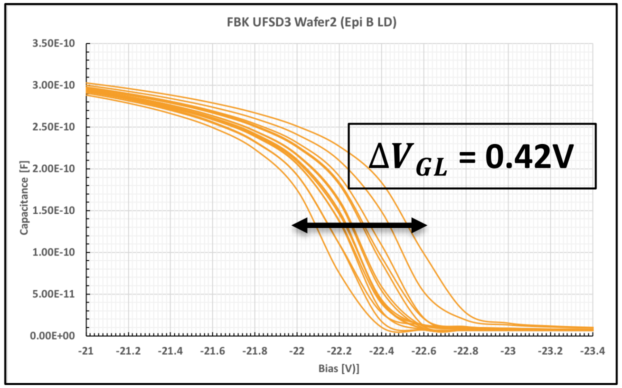
HPK

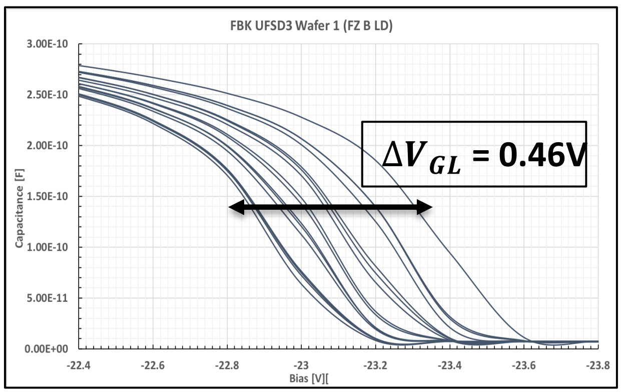
- Measurements on **production EXX28995 (type 3.1) (45 µm thick)**
- Five wafers measured W1/W2/W3/W4/W8
- **equal gain layer shape** and **dose** in all wafers
- Measurement performed on single pad (1x3 mm^2)

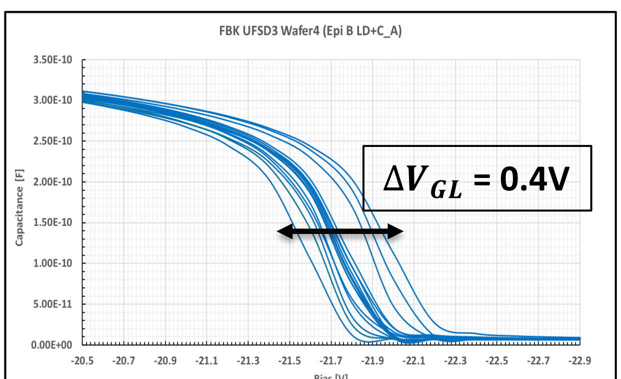
Gain uniformity on single wafer

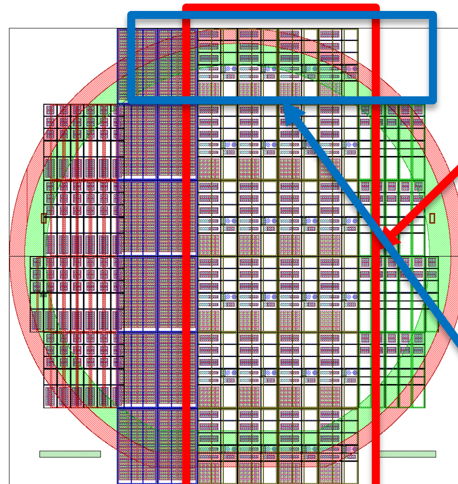
Gain non-uniformity in a multi wafers production

FBK gain uniformity on single wafer









Wafer layout

Sensors tested are distributed uniformly on the wafers

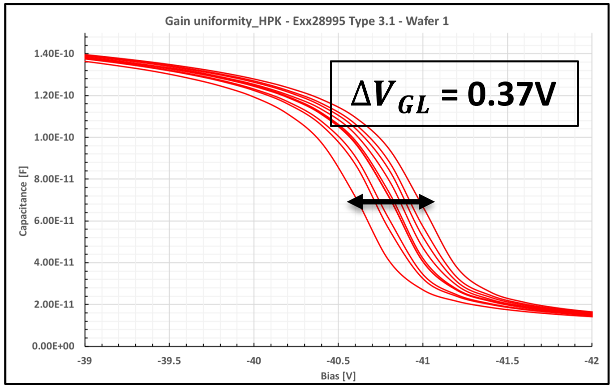
Sensors located in peripheric area on top of the wafers contributed with higher depletion voltage of gain layer

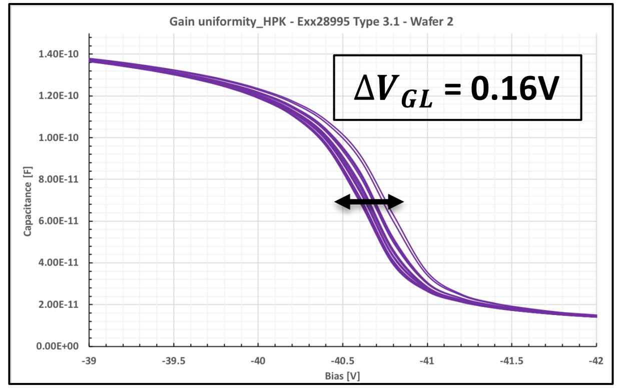
The three wafers tested show a non-uniformity of depletion voltage of gain layer of about 2%

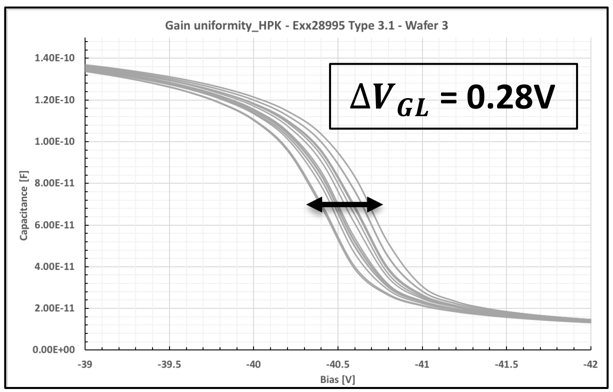
$$\Delta V_{GL}/V_{GL} \sim 2\%$$

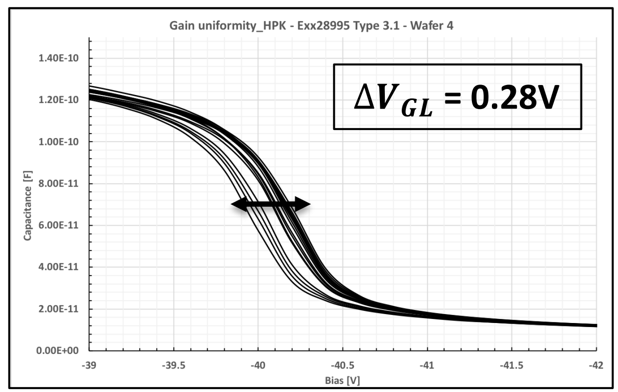
The non-uniformity is lower than 2% when excluding sensors at the periphery of the wafers

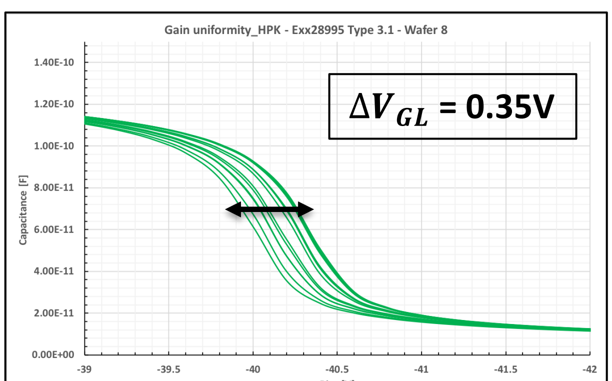
HPK gain uniformity on single wafer



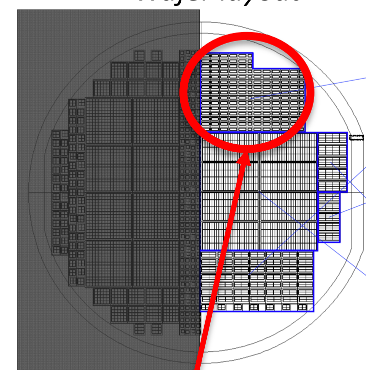








Wafer layout



Single pads tested are located in a small region of the wafers

The five wafers tested show a non-uniformity of depletion voltage of gain layer between 0.5% and 1%

$$0.5\% < \Delta V_{GL}/V_{GL} < 1\%$$

HPK gain uniformity on multi-wafers production

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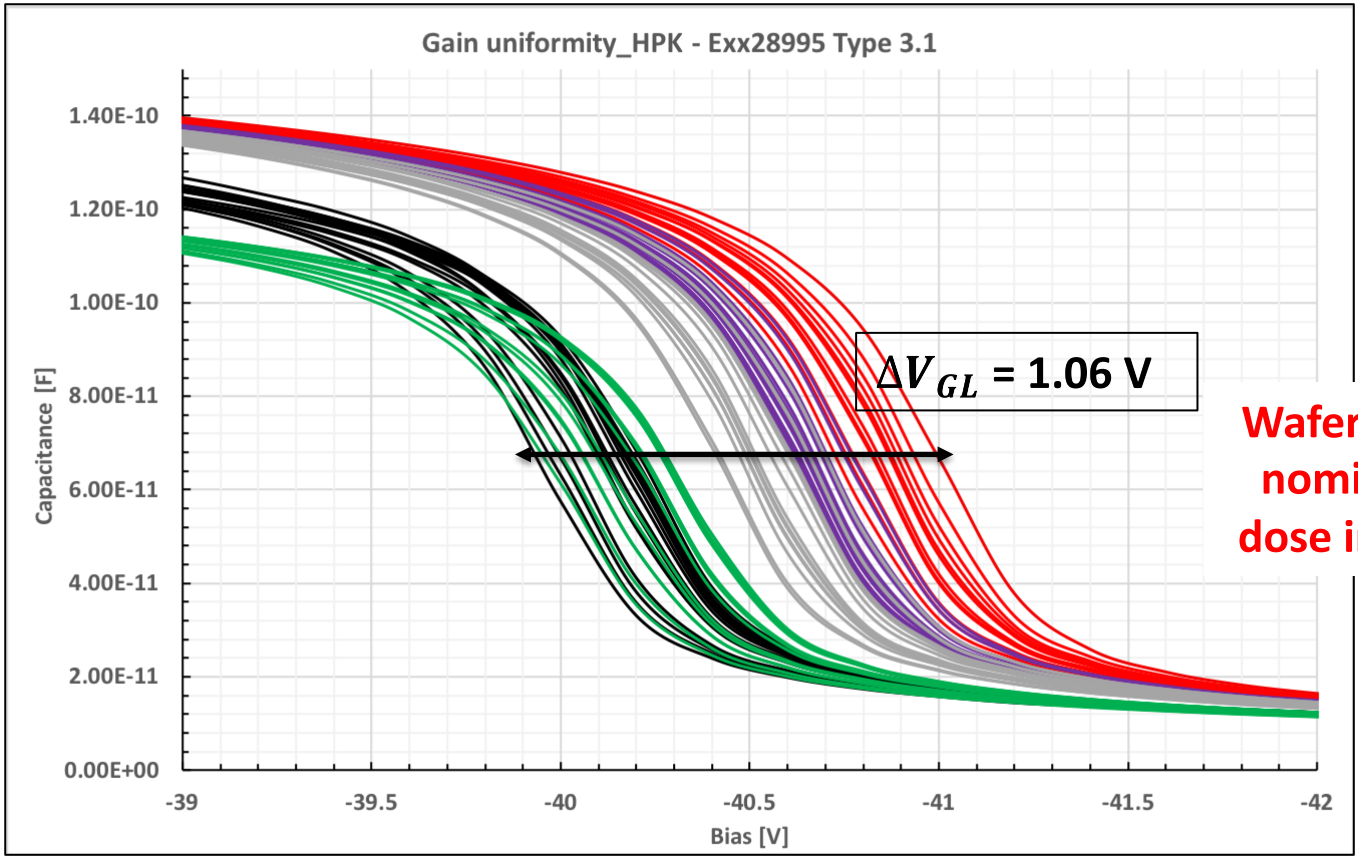
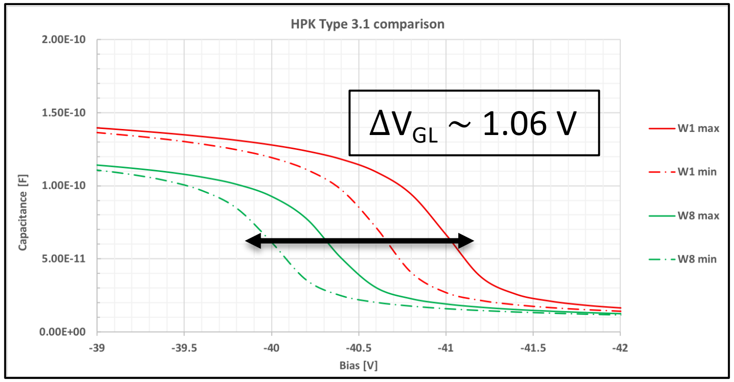


Wafer with the same nominal implanted dose in the gain layer

In a multi-wafers production a non-uniformity of p-gain dose between the wafers is summed to the non-uniformity on the single wafer

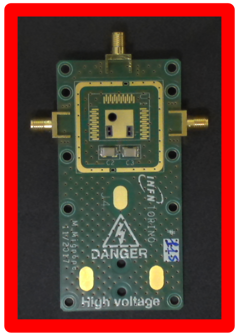
HPK shows an overall non-uniformity of ∼2.7%

Effect of gain non-uniformity on charge collection in HPK UFSD

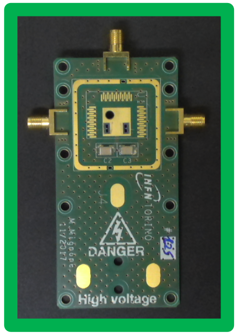


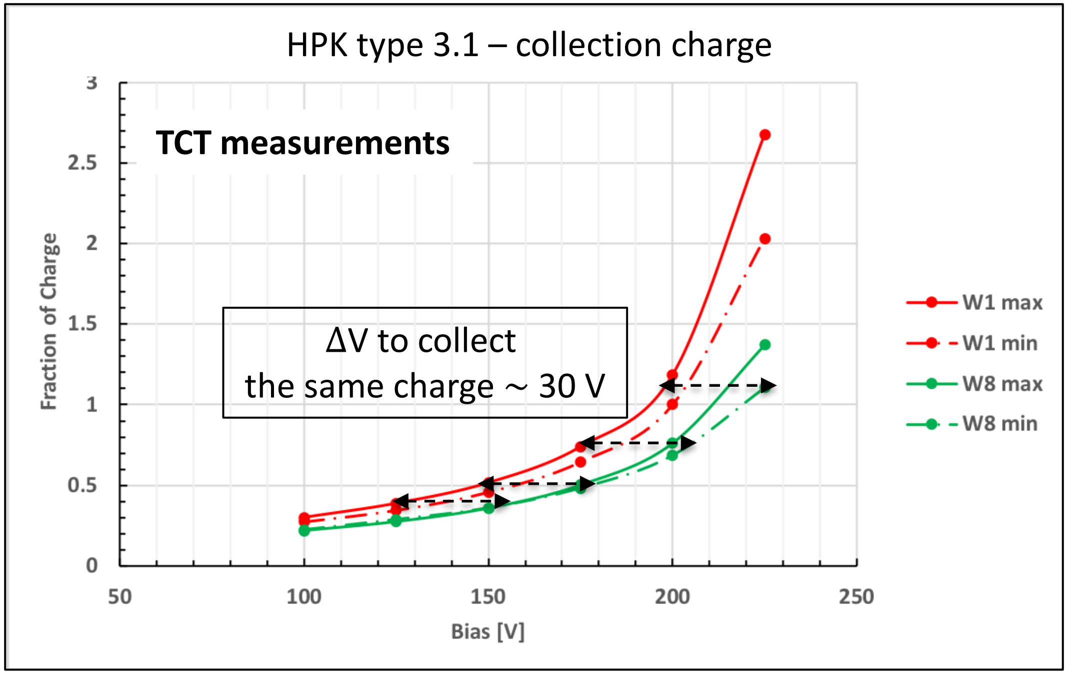
Four sensors selected for charge collection measurements

Wafer 1



Wafer 8

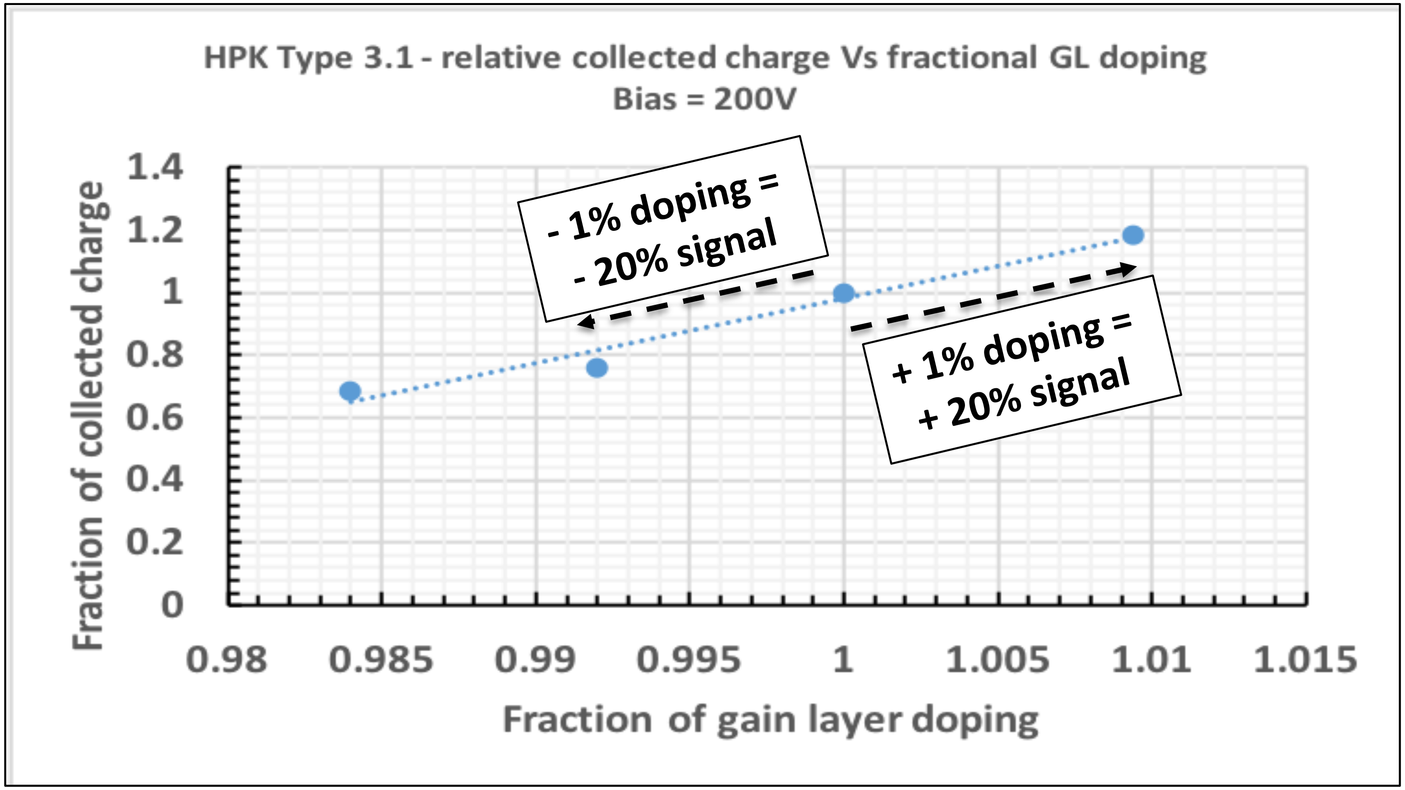




A bias increment of 30V is required to collect the same amount of charge in UFSD with lower p-gain dose

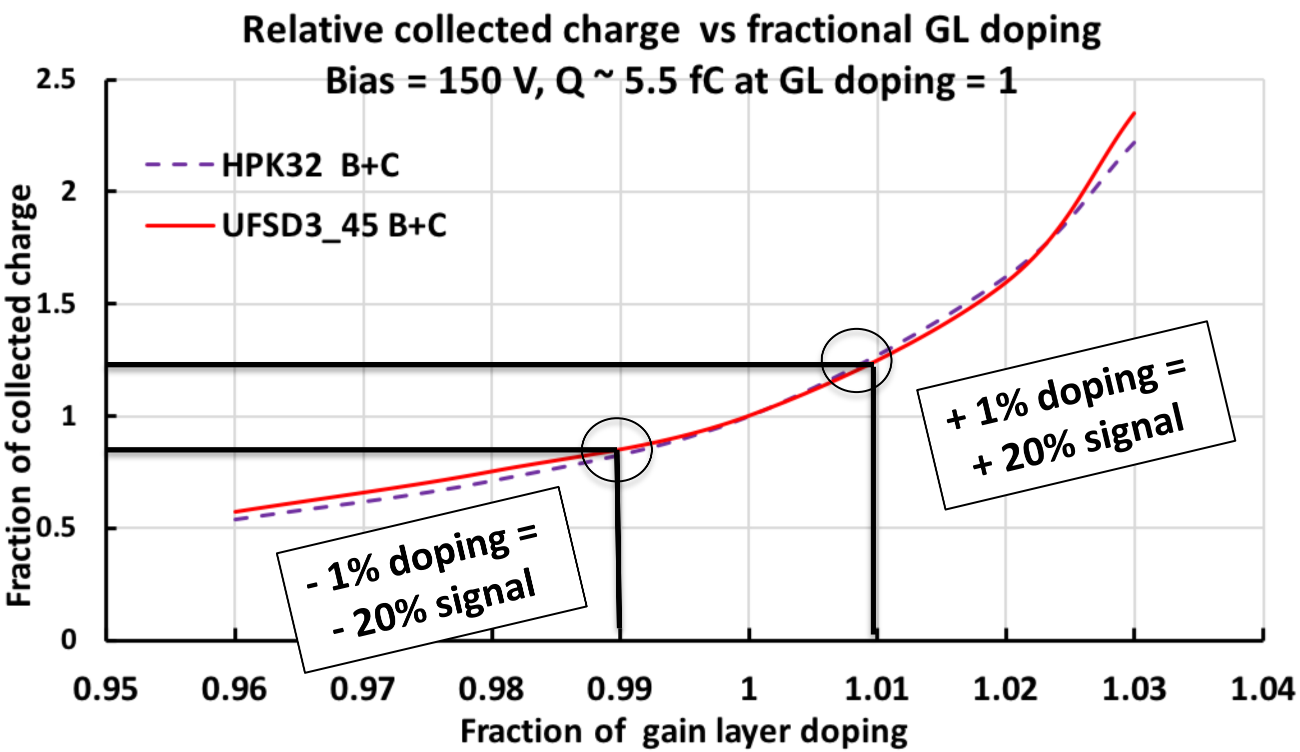
30V/2.7% = 11 V/%
It takes ~ 11V to compensate for a 1% doping difference

Effect of gain layer doping variation on charge collection in HPK UFSD



Gain layer doping variation of few % induces a charge collection variation of 10s%

Simulation of gain vs doping



Very good agreement of data and simulation

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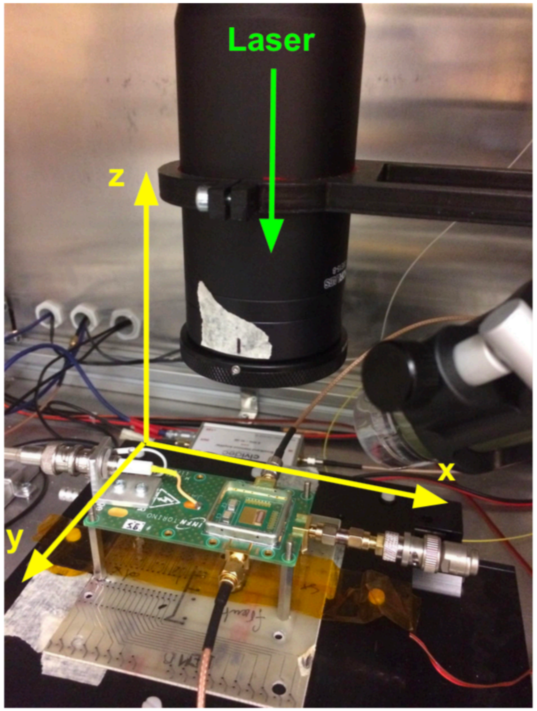
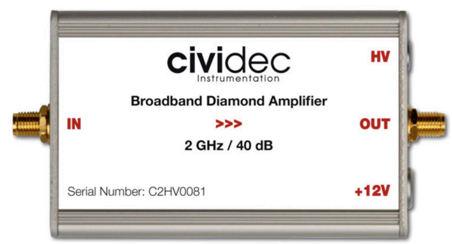
Measurement setup



Reference diode

BB Amplifier



Lauda Chiller

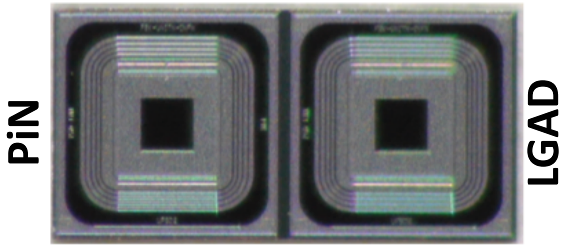
Lecroy oscilloscope

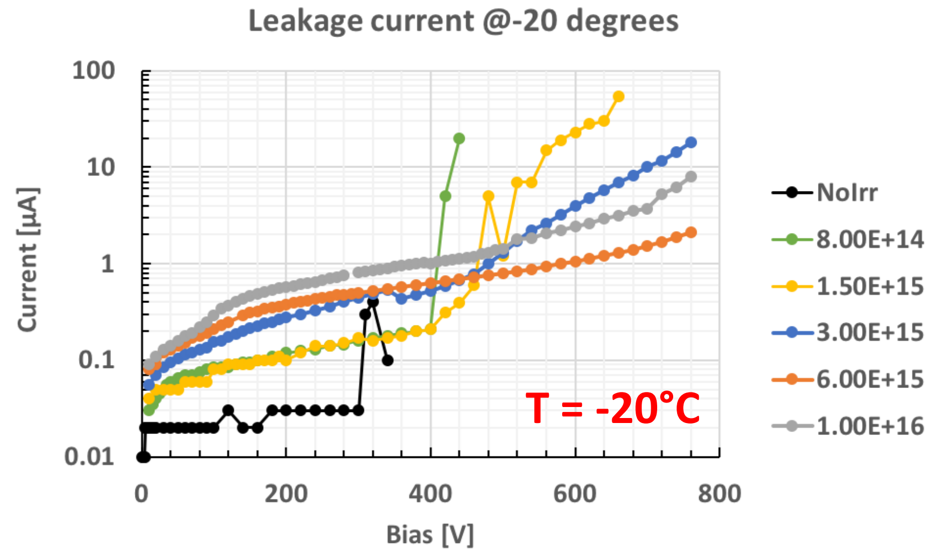
- Particulars TCT setup:
- IR pulsed laser 1064nm → 10-20 µm spot diameter
- Chiller Lauda Eco Silver Re1050 for cooling
- InGaAs Reference diode + laser splitter 10%-90% to check laser stability
- CIVIDEC Broadband amplifier → 40dB
- Lecroy Oscilloscope (BW 4GHz, 40Gsample/s) for data acquisition

Irradiation campaign

- FBK UFSD2 single pad PiN sensors:
  FZ bulk with active thickness of 50μm ± 1μm (from CV measurements)
- Neutron irradiation in Ljubljana (2018 irradiation campaign)
  (AIDA2020) → thank you GK and friends!
- Fluence steps: 0,8/1,5/3/6/10*10^{15} n_{eq}/cm^2

Pairs of *1x1mm²* **PiN-LGAD**

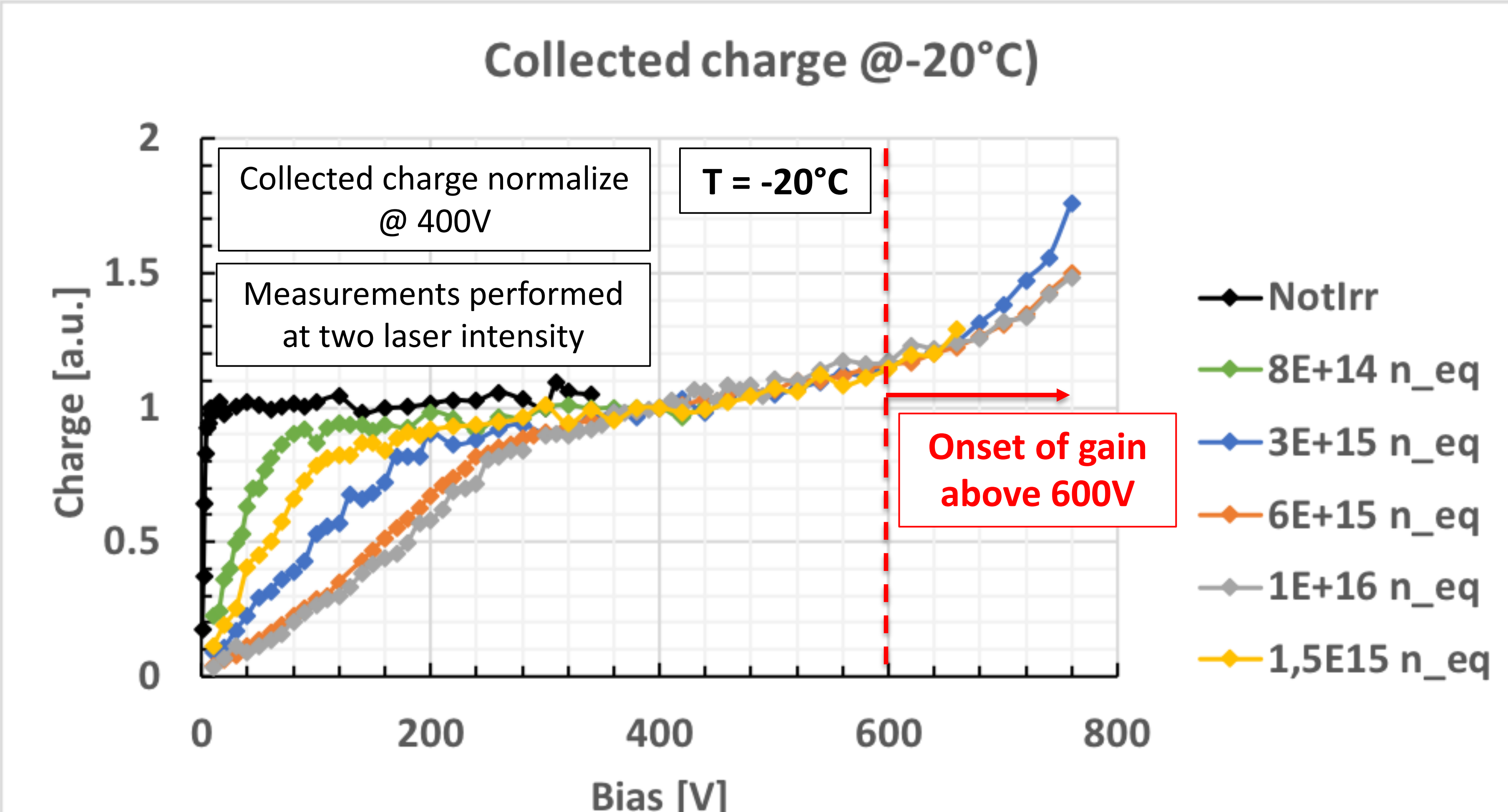




PiN 's operating range @-20°C:

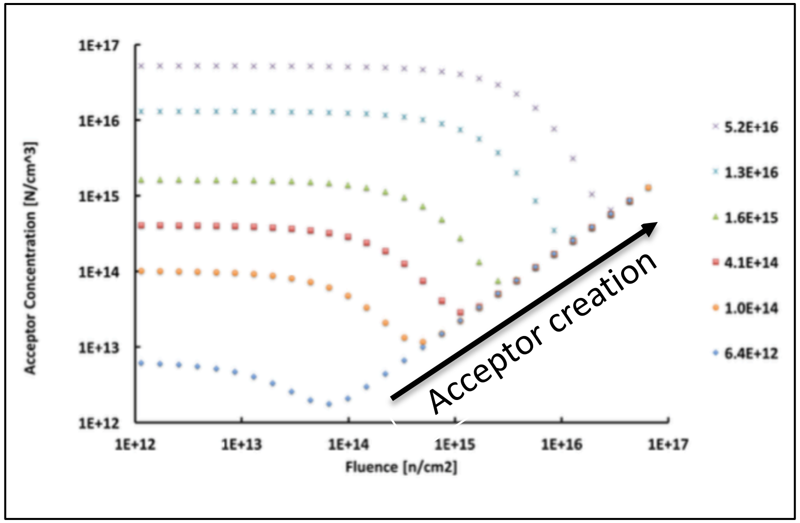
- Not irradiated and irradiated at 8E14 → Breakdown at ~ 400V
- Irradiated above 8E14 → Breakdown at ~ 750V

Gain in irradiated 50µm PiN diodes



- **Onset of gain at 600V** in irradiated sensors **above fluences of 1.5E15 n_{eq}/cm^2**
- **Same gain** appears in sensors irradiated **at 6E15 and 1E16 n_{eq}/cm^2**
- **Higher gain** occurs **at fluence 3E15 n_{eq}/cm^2** than at 6E15 and 1E16 n_{eq}/cm^2

Acceptor creation in irradiated 50µm FZ bulk



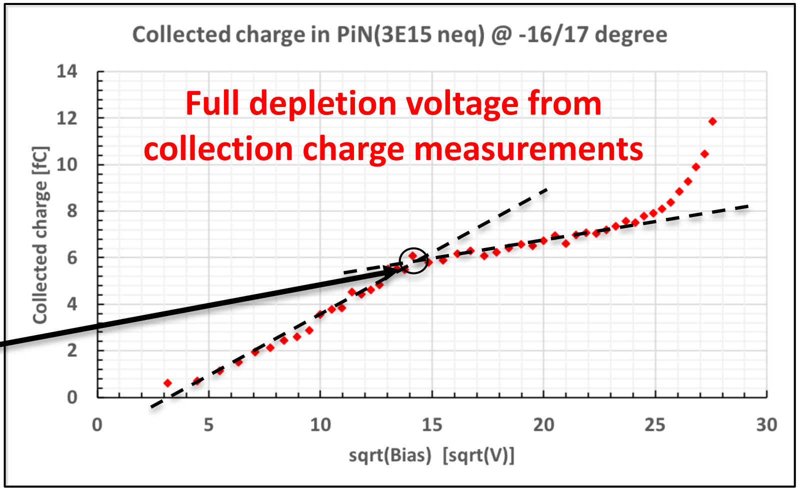
$$N_A(\emptyset) = g_{eff}\emptyset$$

$g_{eff} \sim 0.02\ cm^{-1}$

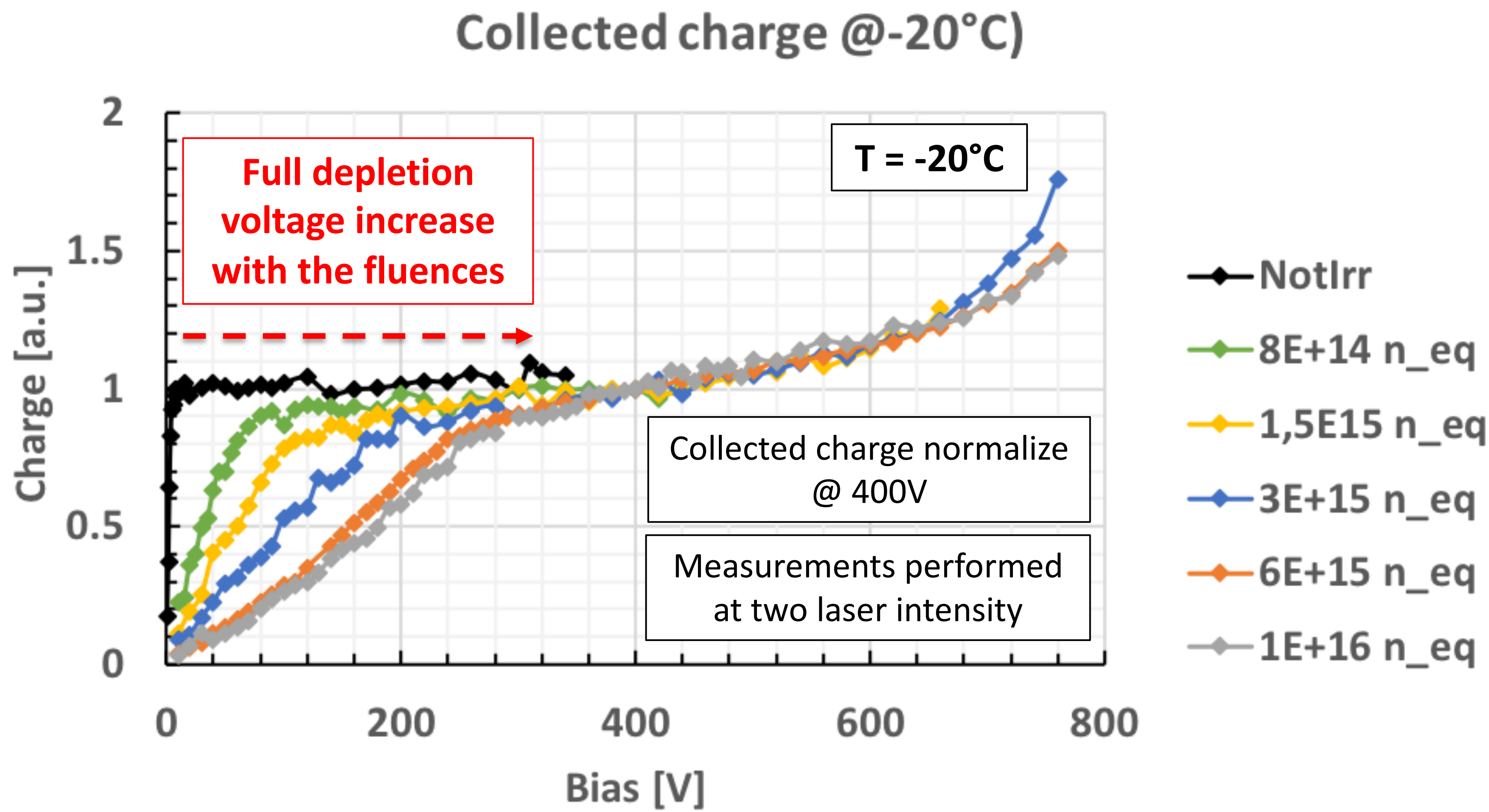
Expected linear acceptor creation as a function of fluence

Assuming an uniform acceptor creation in 50µm thickness, the **acceptor density is proportional to full depletion voltage** (V_{FD}) of PiN diode

$$N_A(\emptyset) \propto V_{FD}$$

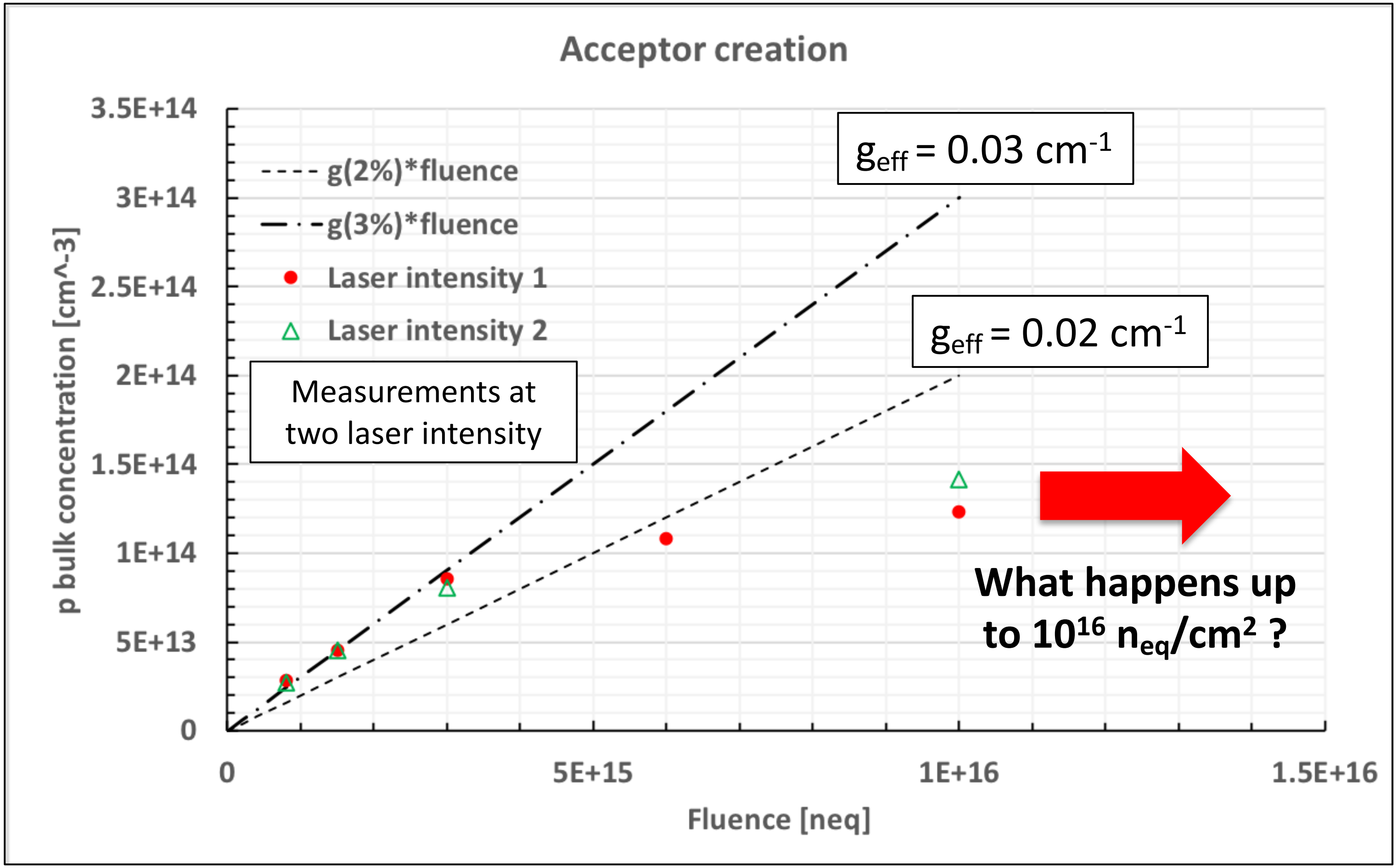


Full depletion voltage in irradiated 50µm PiN diodes



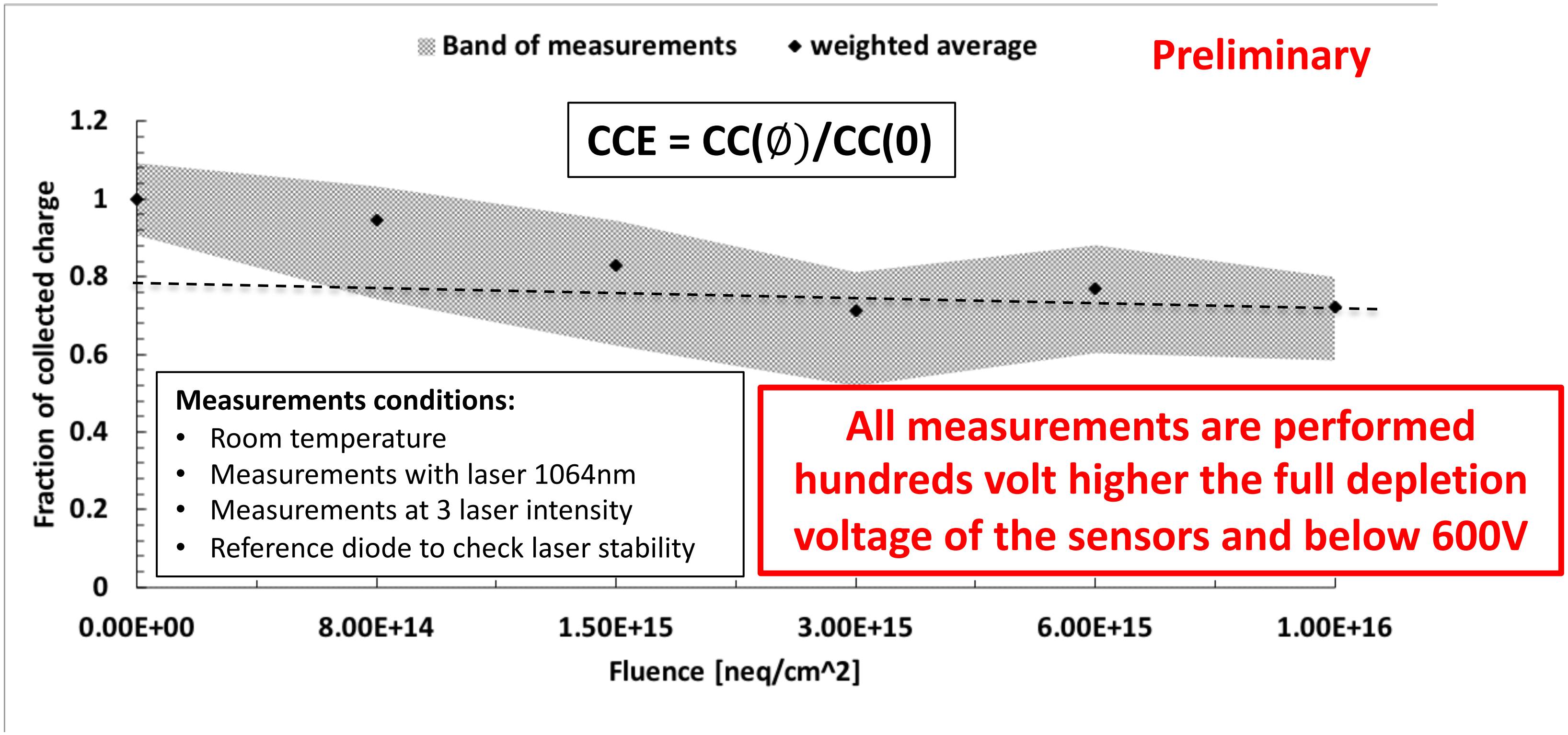
Full depletion voltage in **PiN diodes (50µm thick, -20°C) irradiated at 6E15 and 1E16 n_{eq}/cm²** are very close, not in agreement with the expected trend by acceptor creation law.

Acceptor creation in 50μm PiN diodes



Acceptor creation saturation above 6E15 n_{eq}/cm^2?

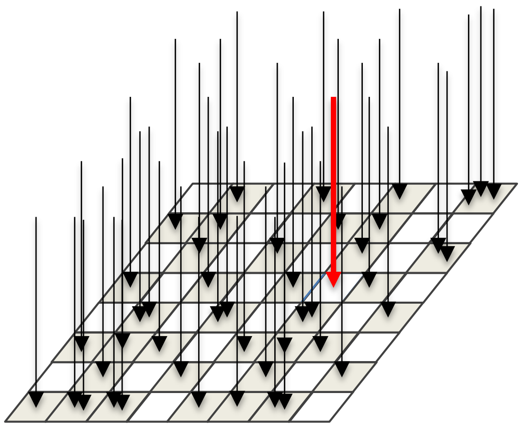
Charge collection efficiency in 50µm PiN diodes

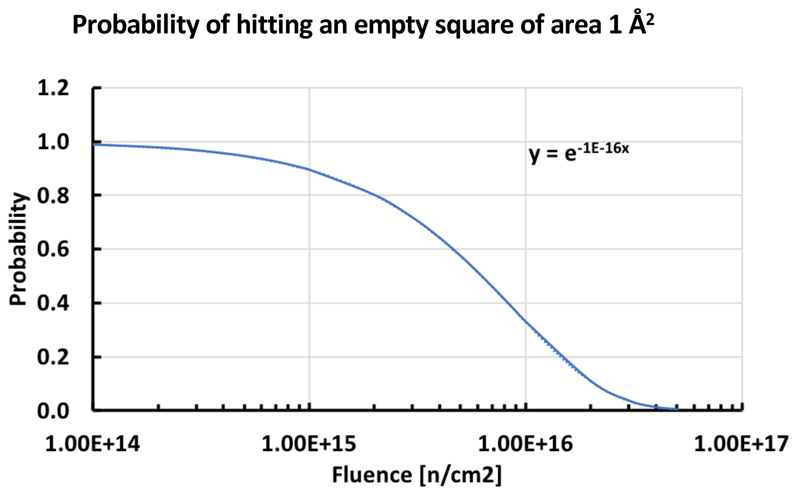


- CCE decreases until fluence 3E15 n_{eq}/cm^2
- CCE of about 60%-80% at 1E16 n_{eq}/cm^2
- **CCE saturation above 3E15 n_{eq}/cm^2**

2D calculation of superposition

- Define a particle hit on the surface by a small square a_o (for example 1 $Å^2$)
- Calculate the probability for the $(n+1)^{th}$ particle to hit an empty square





1) Probability for a particle to hit a square = a_o / cm2 = 1E-18

2) Probability for a particle to miss a square: 1 – 1E-18

3) Probability for a particle to hit a square that has been missed by the previous n = $(1 – 1E\text{-}18)^n$

4) This is a Poisson probability problem, with parameter a_o

After 5E15 n/cm2, the probability of hitting an Amstrong square already hit is 50%

Conclusion

Gain uniformity:

- **FBK**-UFSD3: gain layer implant uniformity on **single wafer ~ 2%**
- **HPK**-Type3.1: gain layer implant uniformity on **single wafer 0.5%-1**
  gain layer implant uniformity on **production ~ 2.7%**
- Variation of ~ % on fraction of gain layer doping is equivalent at tens% of variation in collected charge

Irradiated PiN diodes:

- **Onset of gain above 600V**, up to fluences of **3E15 n_{eq}/cm^2, at -20°C**
- Same gain in PiN diodes irradiated at 6E15 and 1E16 n_{eq}/cm^2, lower than sensors irradiated at 3E15 n_{eq}/cm^2
- Onset of **acceptor creation saturation above** fluence of **6E15 n_{eq}/cm^2**
- Onset of **CCE saturation above** fluence of **3E15 n_{eq}/cm^2**

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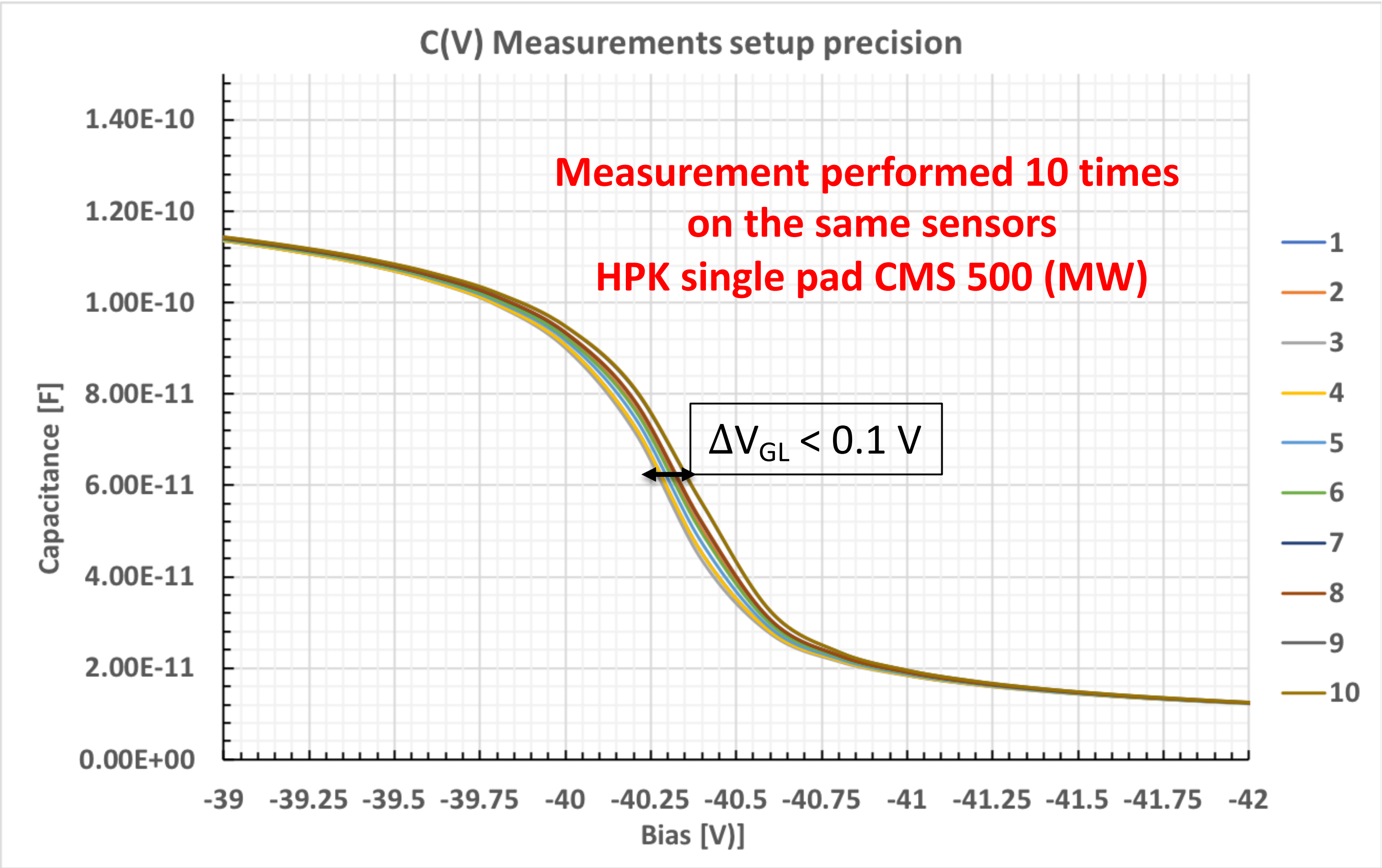
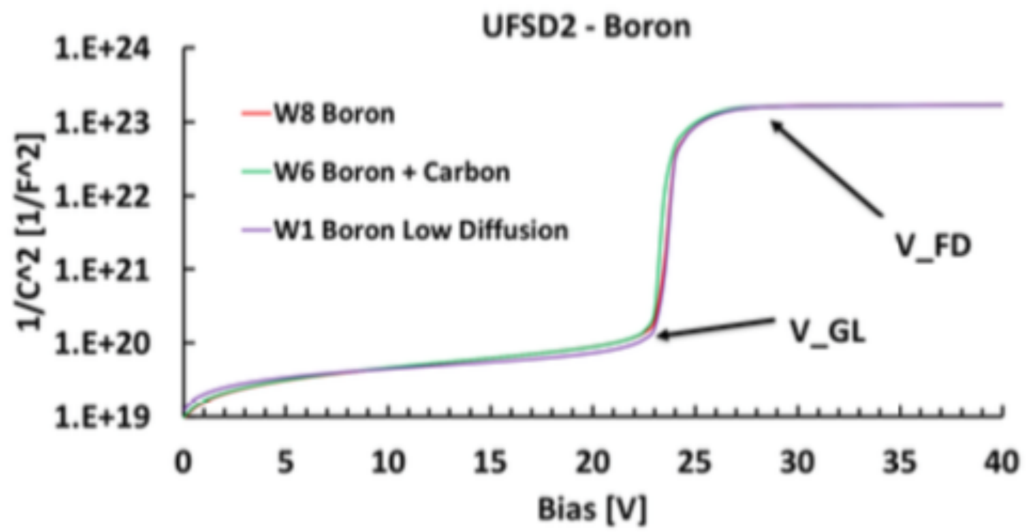
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant no. 654168 (AIDA-2020)
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)

Backup

CV measurements
Setup precision



Extrapolation of active acceptor density into gain layer (Method)



V_{GL} = Depletion Voltage for Gain Layer

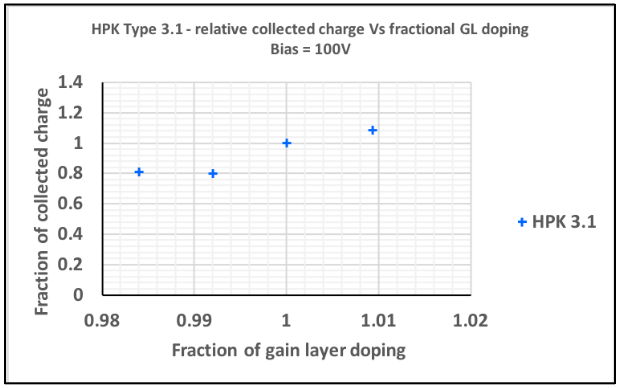
V_{FD} = Full Depletion Voltage of sensor

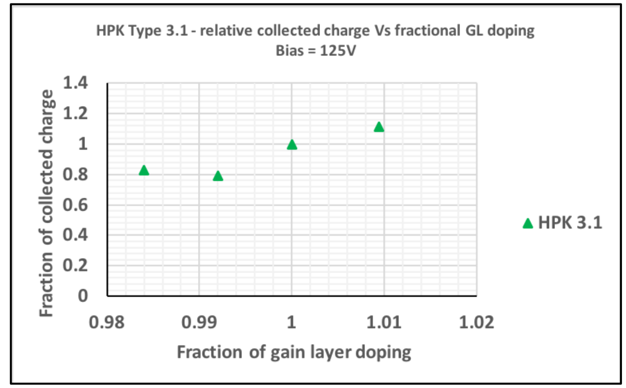
V_{GL} is proportional to the amount of the active doping of the gain layer

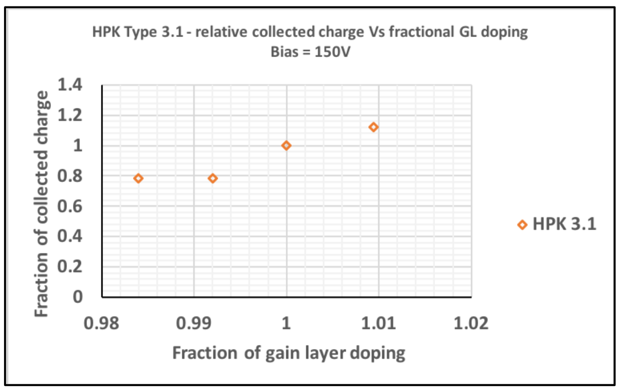
$$V_{GL} = \frac{qN_A}{2\epsilon}w^2$$

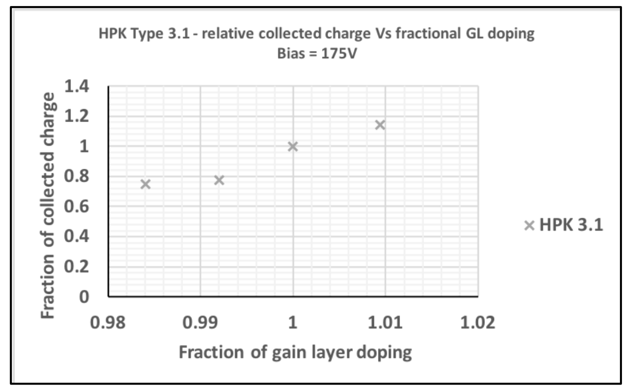
N_A = Active doping concentration
ω = thickness of the gain layer (~1 µm)
q = electron electric charge
ε = Dielectric constant of Silicon

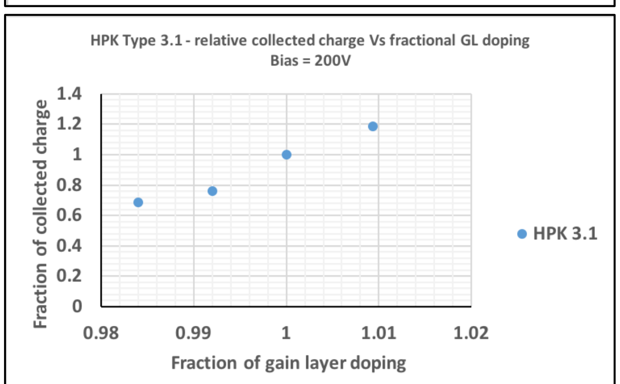
Effect of gain layer doping variation on charge collection in HPK UFSD @ different bias

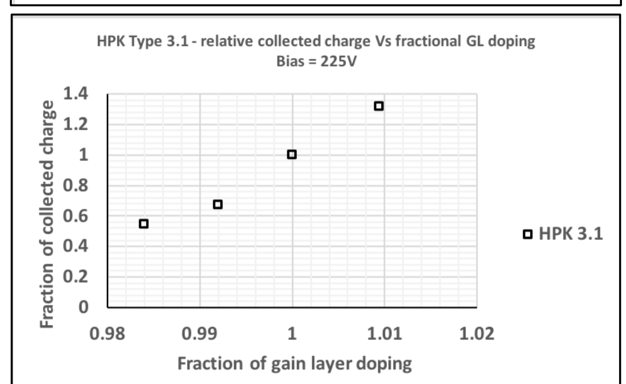




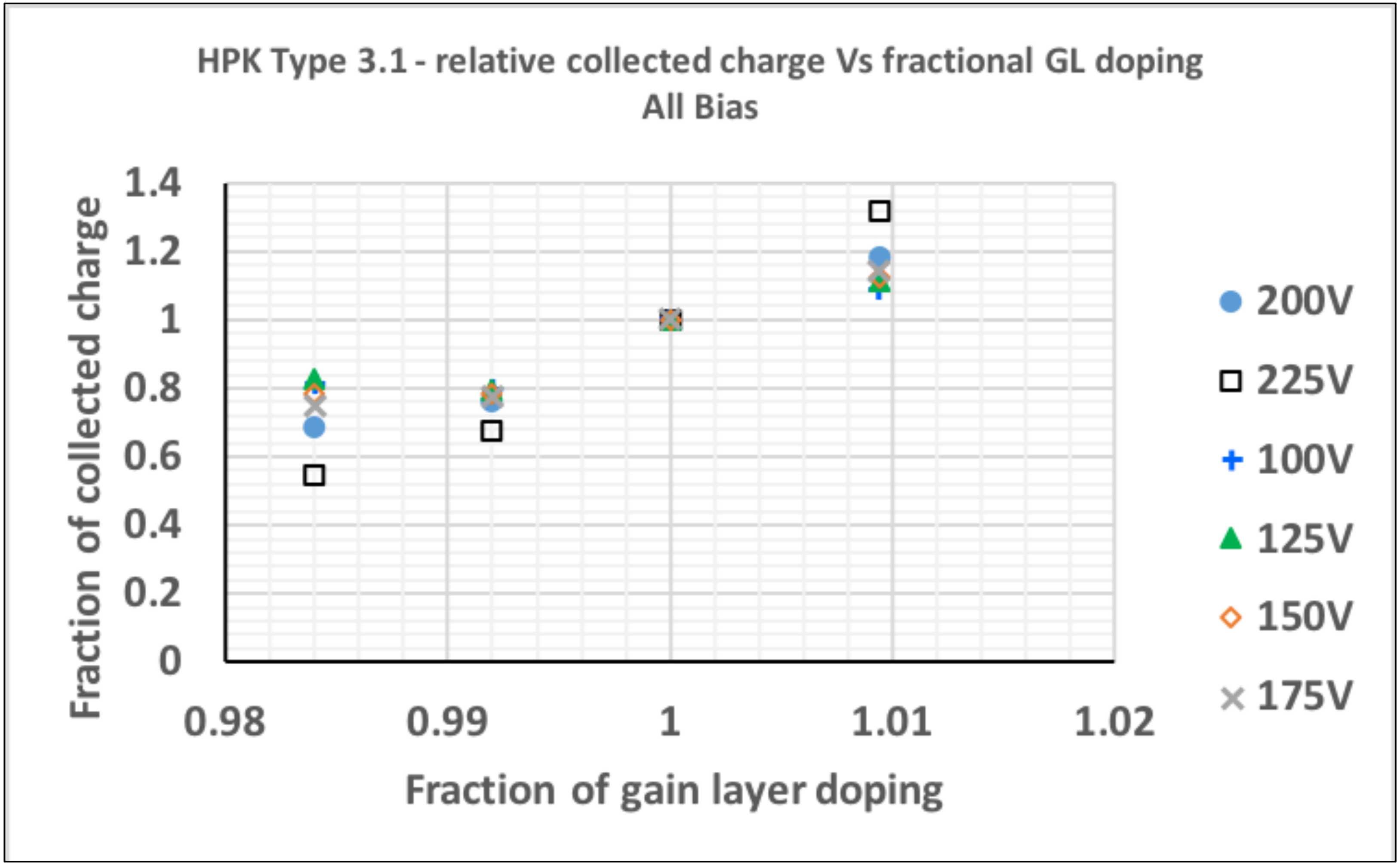








Effect of gain layer doping variation on charge collection in HPK UFSD @ different bias



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