PERFORMANCES OF THE LATEST FBK UFSD PRODUCTION

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ULTRA-FAST SILICON DETECTORS

LOW-GAIN AVALANCHE DIODE (LGAD)

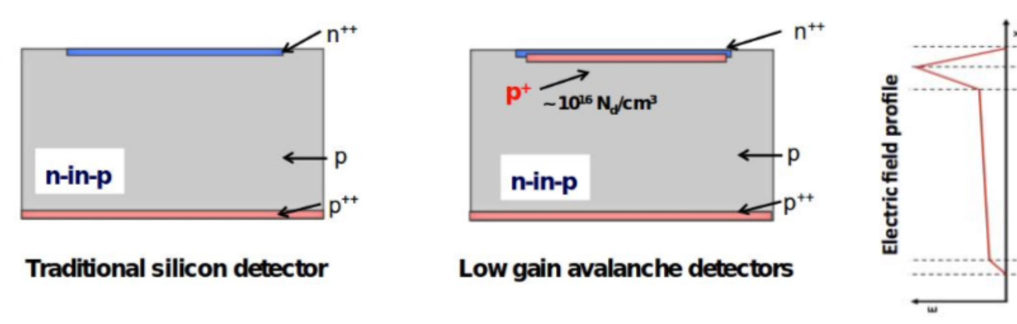
LGADs are silicon detectors with moderate gain (between 10 and 100)

They are provided with a thin highly doped layer, the so-called gain layer, near the p-n junction

→ *when the device is inversely polarized, a high local electric field is generated in the gain layer region, causing the multiplication of primary charges*

Gain absolute value must be moderate to minimize the contribution of multiplication to noise

→ *signal to noise ratio needs to be maximized*



UFSD PROJECT

Ultra-Fast Silicon Detectors (UFSD) is a project born in Torino in collaboration with the Fondazione Bruno Kessler and the University of Trento.

The aim is to develop Silicon detectors based on the Low-Gain Avalanche Diode technology optimized for timing measurements with an R&D work through various productions providing continuous design refinements.

Sensors features:

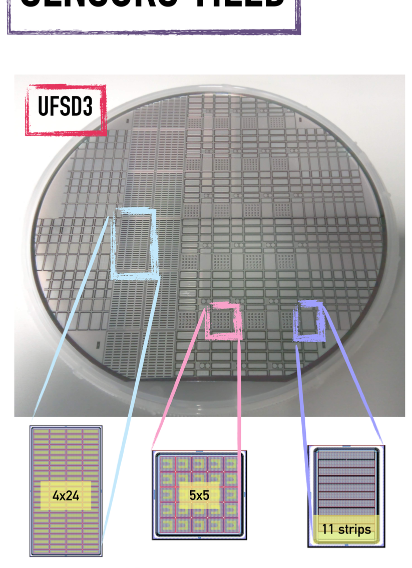
- ★ *Fine segmentation*
- ★ *Excellent timing resolution*
- ★ *Radiation resistant*

Multiple applications:

- ✦ *Timing layers for high energy physics experiments: timing information associated to events for pile-up minimization (CMS and ATLAS at High-Luminosity LHC)*
- ✦ *Particle counting: possibility to withstand very high rates*
- ✦ *3D imaging and robotic vision: improvement of reconstruction accuracy thanks spatial resolutions of few mm*
- ✦ *Positron Emission Tomography (PET): improvement of image quality and reduced dose on patients*

UFSD 3.2 PERFORMANCES

SENSORS YIELD



Devices are tested on wafer at FBK and as single structures in Torino.

For each wafer and device type, the current distribution of every single pad is plotted at a fixed value of bias.

Yield is evaluated as the ratio of good pads on the total number of measured pads, where we consider as "bad" pads or devices those that show a leakage current out of the safe range defined for a structure in each wafer.

UFSD3 production has an yield corresponding to:

- *99.9% for 4x24 matrices with 1x3 mm^2 pads*
- *99.3% for 5x5 matrices with 1.3x1.3 mm^2 pads*
- *99.8% for the 11-strips devices*

The same strategy is applied to UFSD3.2 data, whose analysis is in progress.

UFSD 3.2 PRODUCTION

UFSD PRODUCTIONS

Wafer #	Dopant	Gain dose	Carbon	Diffusion
1	Boron	0.98		Low
2	Boron	1.00		Low
3	Boron	1.00		HIGH
4	Boron	1.00	Low	HIGH
5	Boron	1.00	HIGH	HIGH
6	Boron	1.02	Low	HIGH
7	Boron	1.02	HIGH	HIGH
8	Boron	1.02		HIGH
9	Boron	1.02		HIGH
10	Boron	1.04		HIGH
11	Gallium	1.00		Low
14	Gallium	1.04		Low
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
18	Gallium	1.08		Low

UFSD2 (2017):

Focus on gain layer design (dopant and profile)

Both Boron and Gallium used as gain layer dopant

First production with Carbon implant

→ *improved radiation hardness*

UFSD3 (2018)

Produced with stepper

4 Boron doses combined with 4 Carbon doses for gain layer

3 strategies for gain layer termination structures

Production of large multipad sensors

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

Wafer #	p-stop dose
12	0,02
13	0,05
14	0,1
16	0,15
17	0,2
18	1

Structure type	Interpad width [µm]
1	16
2	21
3	21
4	24
5	25
6	28
7	28
8	28
9	38
10	49
11	21

UFSD3.1 (2019)

Optimization of p-stop doping dose

Study interpad layout

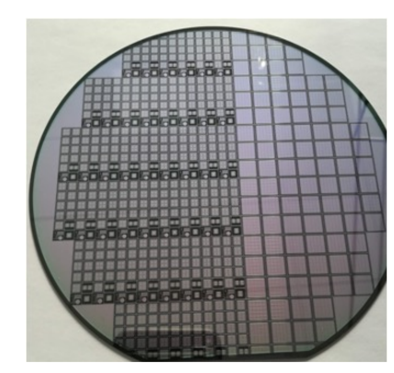
UFSD3.2 BATCH

Wafer #	Thickness	DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	0.98	1.*A	CH-BL
2	45	Standard	0.98	1.*Ab	CH-BL
3	45	Standard	0.98	0.8*A	CH-BL
4	45	Standard	0.98	0.4*A	CH-BL
7	55	Standard	0.98	1.*A	CH-BL
8	45	deep	0.70	1.*A	CBL
9	55	deep	0.70	1.*A	CBL
10	45	deep	0.70	0.6*A	CBL
11	45	deep	0.70		BL
12	45	deep	0.74	1*A	CBL
13	45	deep	0.74	0.6*A	CBL
14	45	deep	0.74	1.*A	CBH
15	55	deep	0.74	1.*A	CBH
16	45	deep	0.74	0.6*A	CBH
17	45	deep	0.74		BH
18	45	deep	0.78	A	CBH
19	45	deep	0.78	0.6*A	CBH

Latest UFSD batch produced by FBK in 2020

Production goals:

- ✓ *Optimize Carbon level*
- ✓ *Manufacture sensors with deep-carbonated gain implants*
- ✓ *Explore thinner sensors*
- ✓ *Reduce the no-gain interpad area*



Batch features:

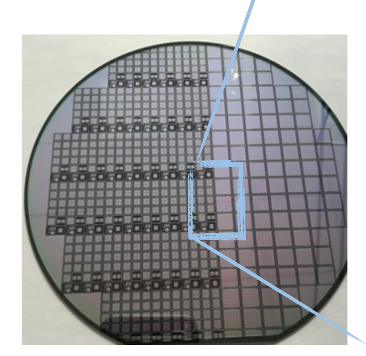
- *Produced with stepper*
- *Wafers with 2 values of thickness*
- *5 Boron doses for the gain layer*
- *4 Carbon doses*
- *2 gain layer depths*
- *3 gain layer diffusion types*
- *9 interpad designs*

PROTOTYPE DESIGN

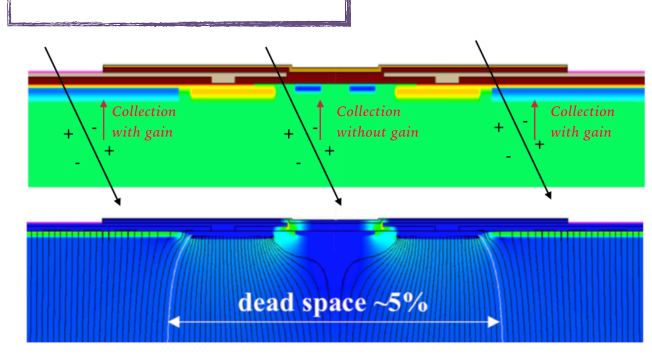
***Four different structures** are included in UFSD3.2 stepper reticle:*

- *2x2 arrays with 1.3x1.3 mm^2 pads, one for each of the 9 UFSD3.2 interpad layout Types, chosen among UFSD 3.1 designs*
- *LGAD-PiN pairs*
- *Single pads with 1.3x1.3 mm^2 area*
- *5x5 matrices with 1.3x1.3 mm^2pads, with Type 8, 9 and 10 interpad design*

Type	Nominal width [µm]	Interpad design	Strategy
1	16	grid + extra grid	Aggressive
2	21	grid	Medium
4	24	grid	Safe
5	25	grid	
7	28	grid + extra grid	
8	28	grid + extra grid	
9	38	2 p-stops	Super safe
10	49	2 p-stops + bias grid	
11	21	grid	Medium



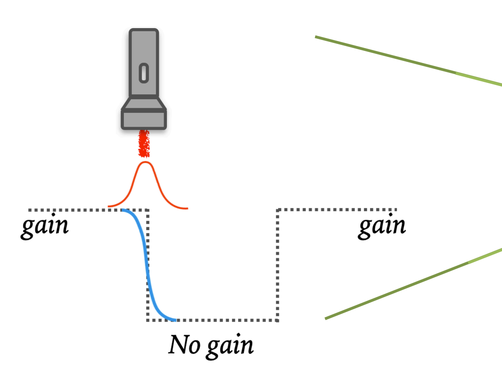
INTERPAD STUDIES

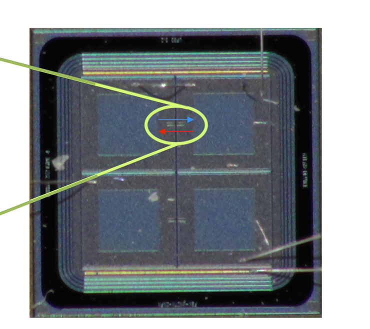


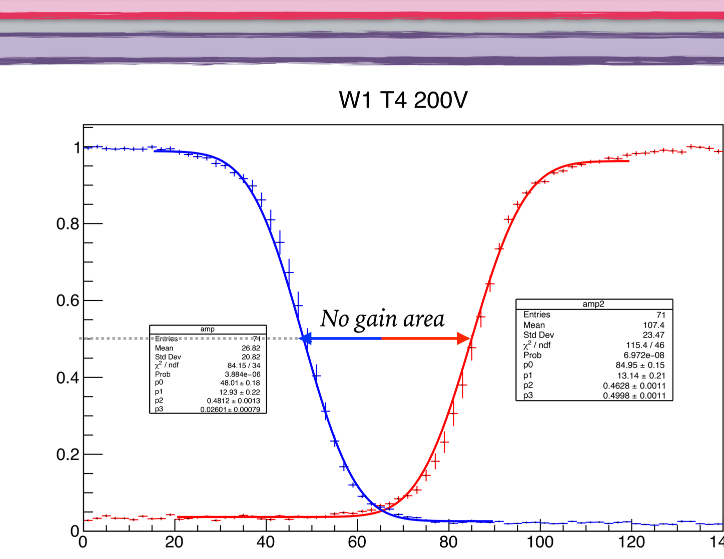
In UFSDs it is necessary to implement gain termination structures which determine a no gain region in which multiplication does not occur.

The number of collected charges in this area depends on the termination structures layout and the implants properties.

UFSD3.2 interpad designs aim to reduce the no-gain area while maintaining a good production yield.



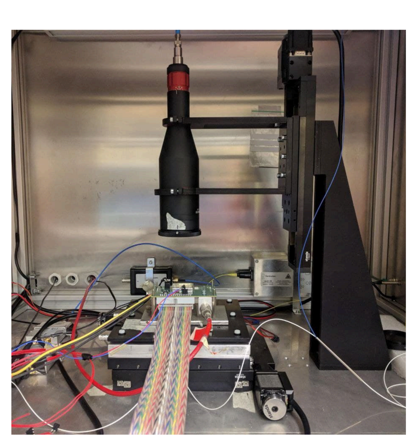




The Transient Current Technique Setup (TCT) by Particulars is used to perform precision measurements on Silicon Detectors thanks to the analysis of the current signal induced in the device under test by an infra-red picosecond laser.

The setup is provided with moving stages with micrometrical precision and an optical system that allows reaching a minimum laser spot of ~10 µm.

Data are acquired with a dedicated LabView software.



No gain distance is measured by performing a 1D scan with the laser along the optical window between two pads.

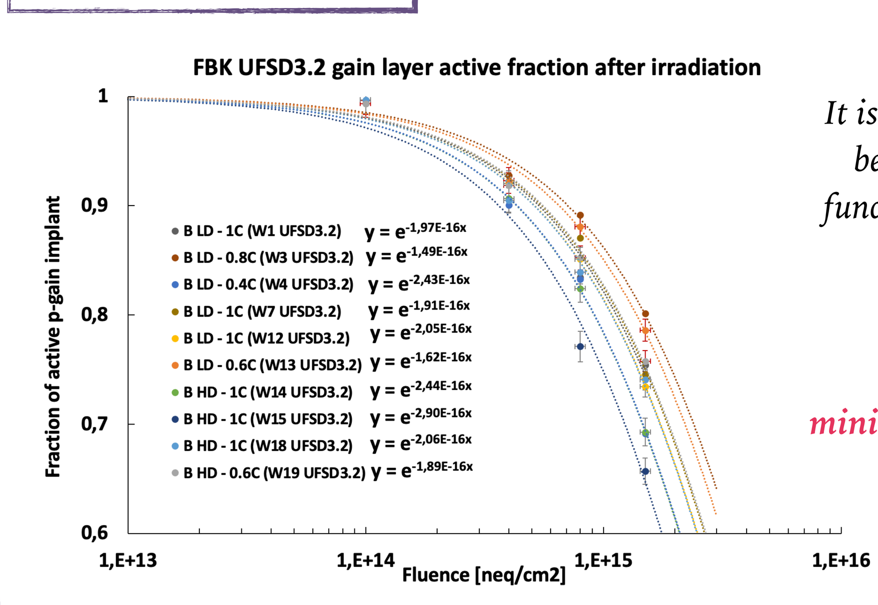
The resulting behavior of collected charge as a function of laser position in an S-curve, representing the convolution of the gain layer step function and the gaussian beam profile of the laser.

Interpad area is evaluated as the distance between the points at 50% of the S-curve maximum for the two measured pads.

wafer	type	interpad [µm]	nominal no gain distance [µm]
W1	T4	37	23,5
W2	T4	38	23,5
W4	T4	35	23,5
	T10	68	49
W7	T4	34	23,5
W10	T4	39	23,5
	T10	65	49
W14	T4	42	23,5
	T10	71	49

RADIATION TOLERANCE

In an n-in-p device, one of the main radiation effect is the deactivation of Boron acceptors in the gain layer: $N_A(\phi) = N_A(0)e^{-c\phi}$.

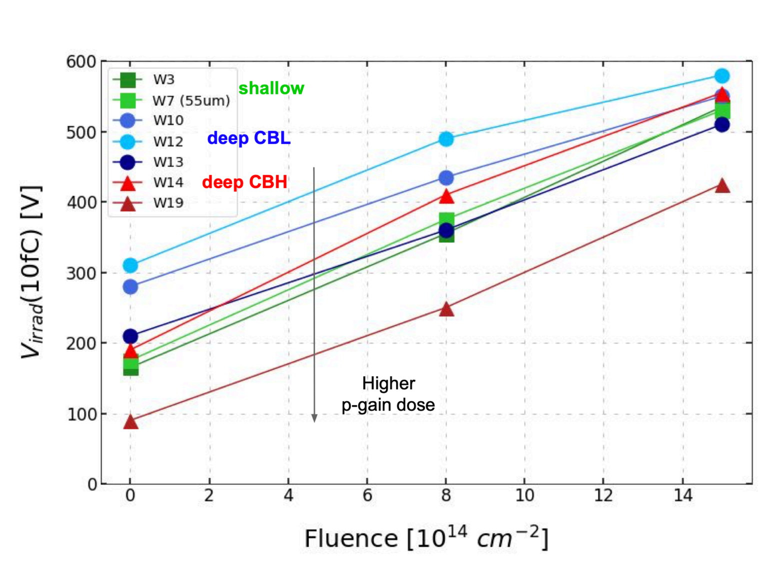


It is possible to extract the "c" factor for each wafer from the behavior of the gain layer active fraction represented as a function of fluence. The gain layer active fraction is calculated using the gain layer depletion voltage at each fluence, obtained from CV measurements.

*Results on UFSD3.2 show that the Carbon dose which minimizes radiation damage is between 0.6*A and 1.*A.*

Measurements performed with a beta source on UFSD3.2 devices allowed to identify the bias voltage increment that needs to be applied to irradiated detectors to be operated at their optimal working point at each fluence

The working point has been here defined as the bias voltage at which a charge of 10 fC is collected



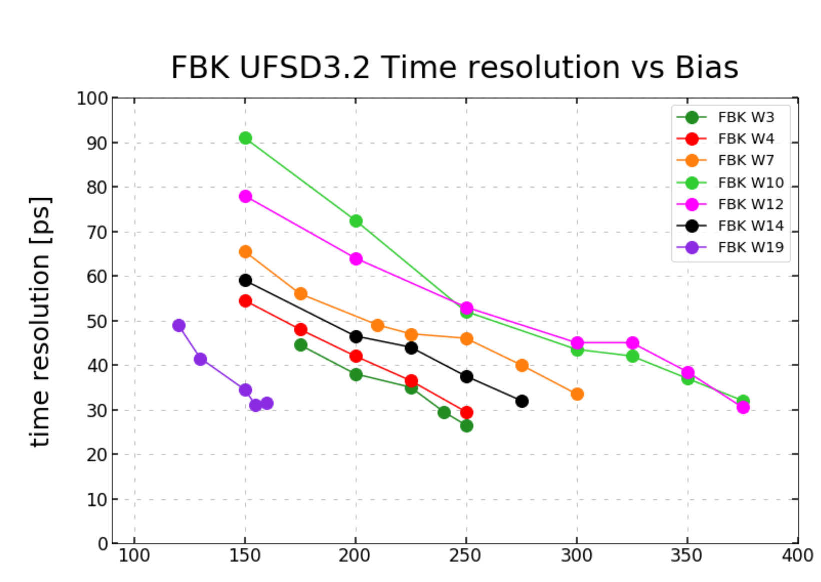
See M. Ferrero talk on 26 May
https://indico.cern.ch/event/981823/contributions/4293561/

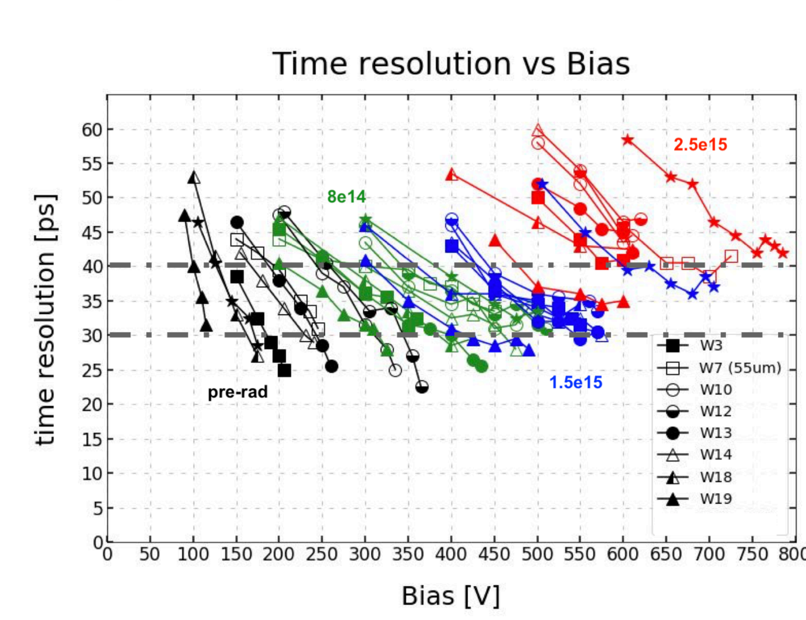
TIME RESOLUTION

Measurements performed with the Torino Beta-source setup provided with a DUT+trigger telescope in a climate chamber and an automated DAQ and analysis system.

All UFSD3.2 wafers can deliver a charge >20 fC and reach a time resolution of ~30 ps when new. The best choice are wafers operating at high voltage in which carriers drift velocity is saturated and with a smooth gain curve, so that non-uniformities between sensors affect performances less.

All irradiated sensors deliver a charge >10 fC and reach a time resolution of ~30 ps up to 1.5e15 n_eq/cm^2, while they reach ~5 fC of charge and 40 ps resolutions at 2.5e15 n_eq/cm^2.





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