FONDAZIONE
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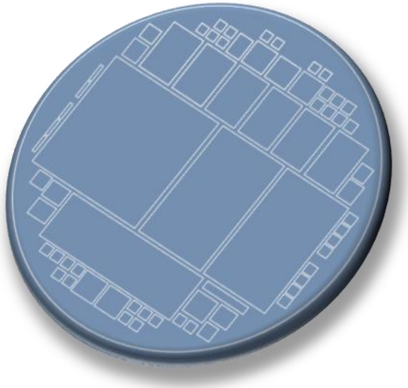


14th Trento Workshop on Advanced Silicon Radiation Detectors

25 – 27 February 2018 Fondazione Bruno Kessler, Trento, Italy

Latest Developments of Low Gain Avalanche Detectors at FBK

Giovanni Paternoster

R. Arcidiacono, G. Borghi, M. Boscardin, N. Cartiglia, G. F. Dalla Betta, M. Ferrero, F. Ficorella , M. Mandurrino, L. Pancheri, F. Siviero, V. Sola, M. Tornago

INFN Torino, Univ. Torino, Univ. Trento, TIFPA, FBK

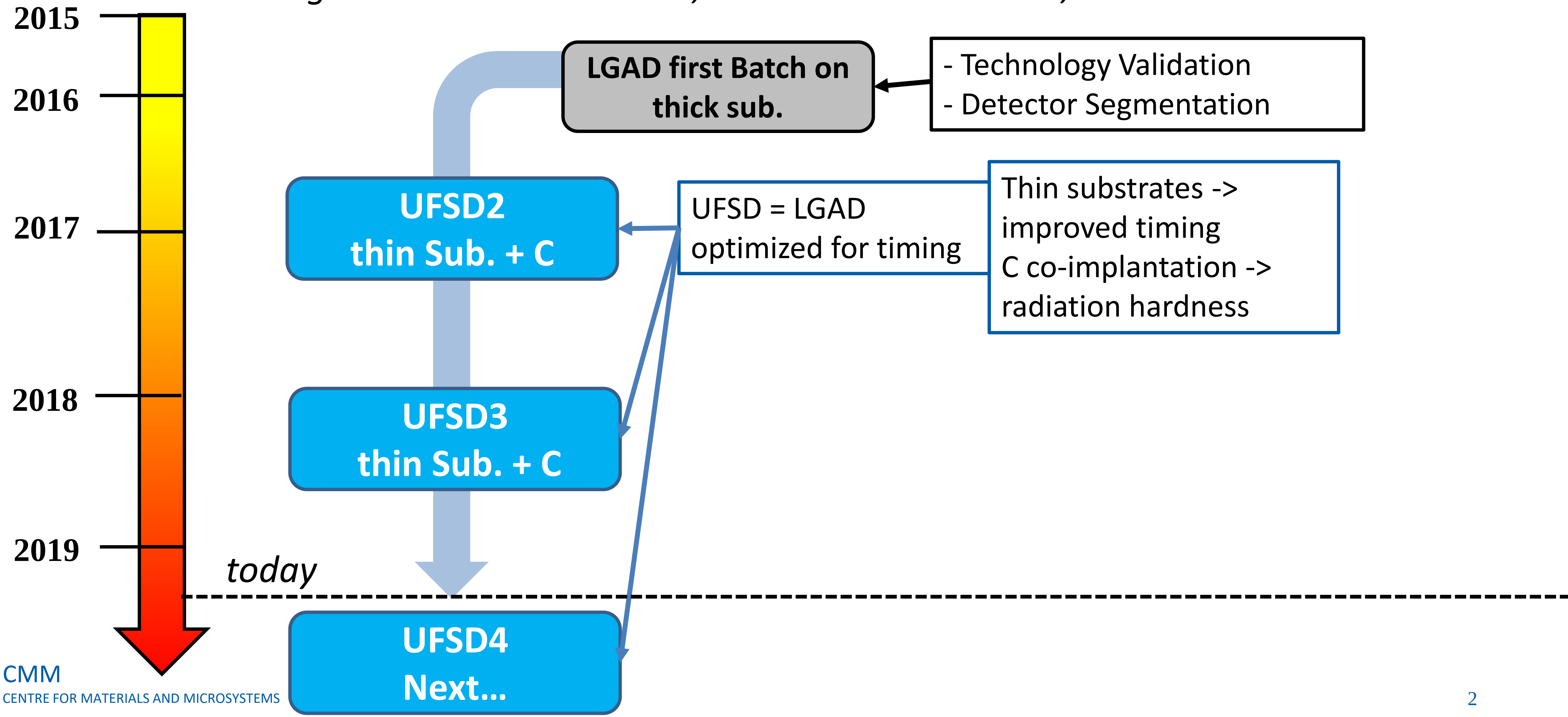
INFN

FONDAZIONE
BRUNO KESSLER

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

LGAD Technology Roadmap at FBK

a great collaboration: FBK, Univ. Trento and Turin, INFN Turin



FONDAZIONE BRUNO KESSLER

LGAD Technology Roadmap at FBK

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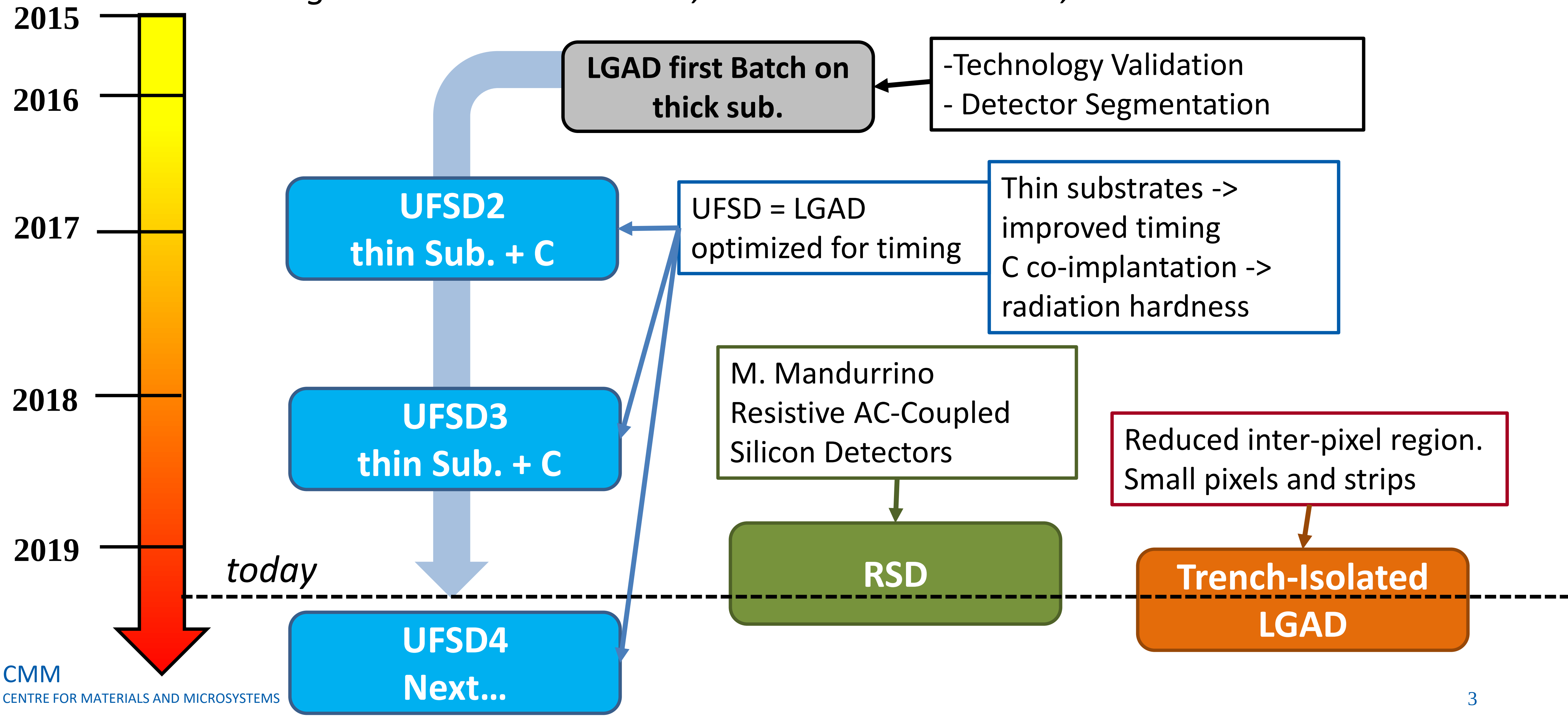

LGAD Technology Roadmap at FBK

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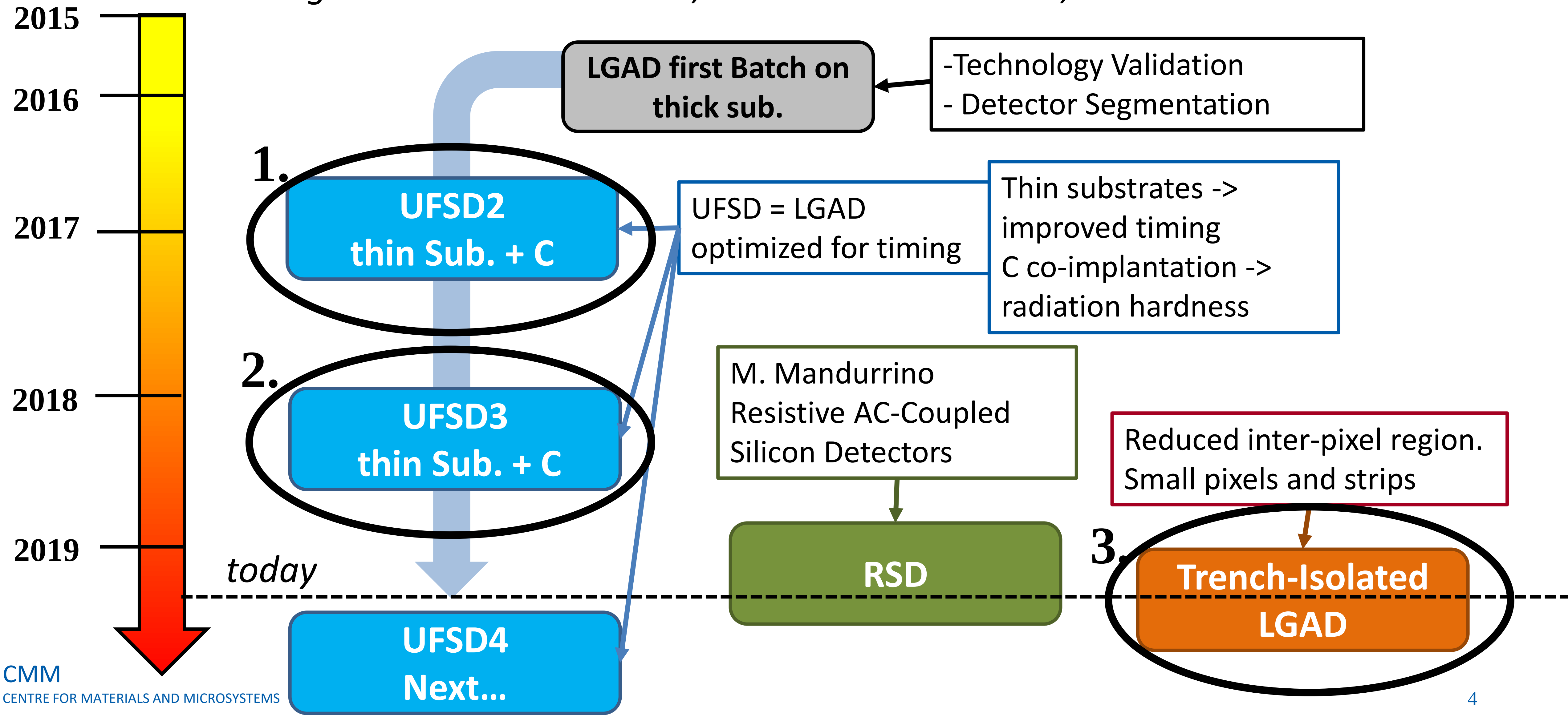
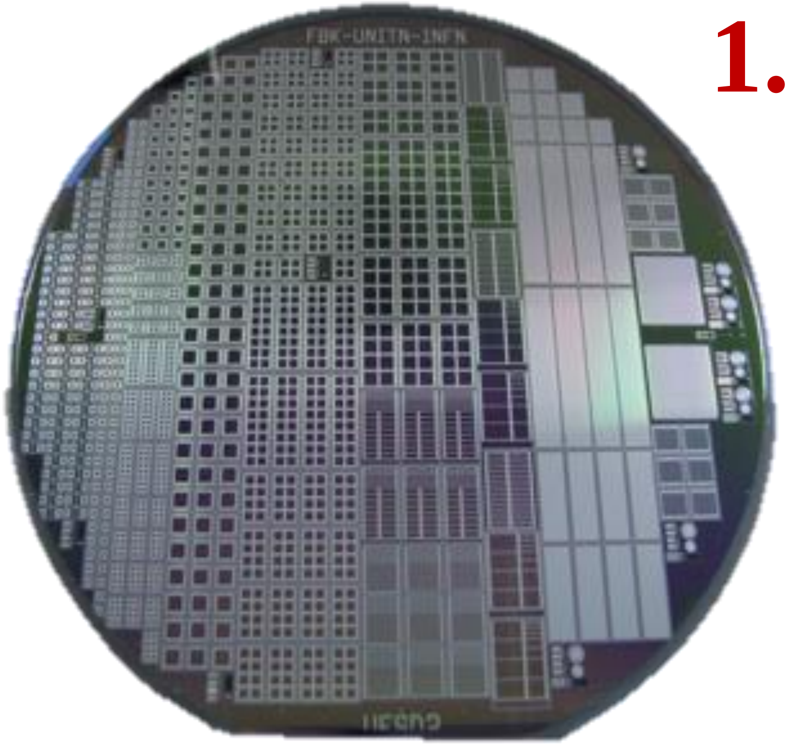
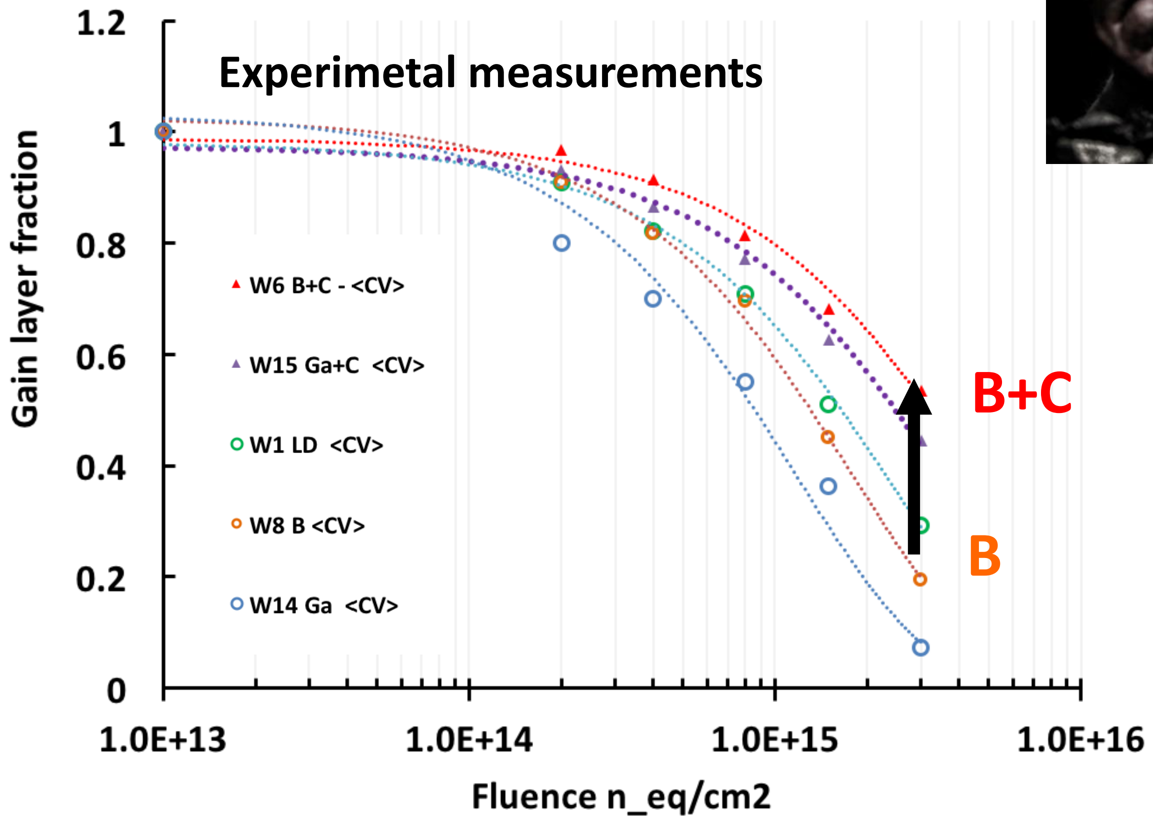


UFSD2 (2007) - What did we learn?

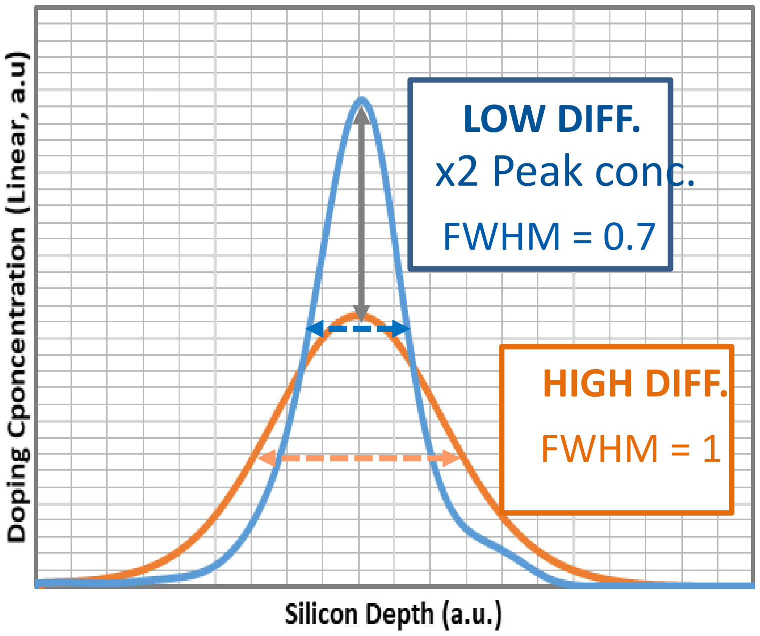


1. Carbon co-implantation mitigates the gain loss after irradiation

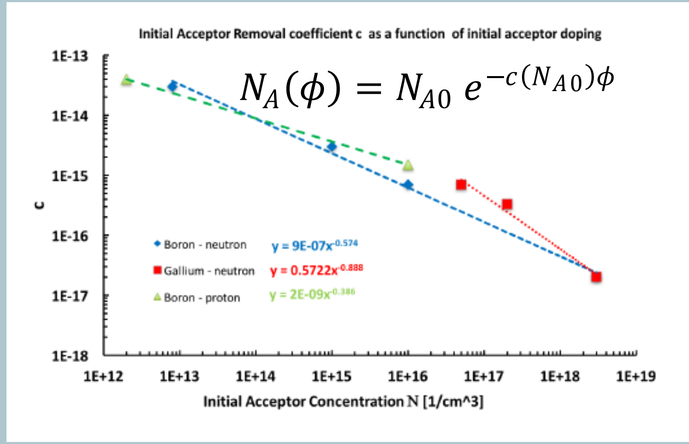


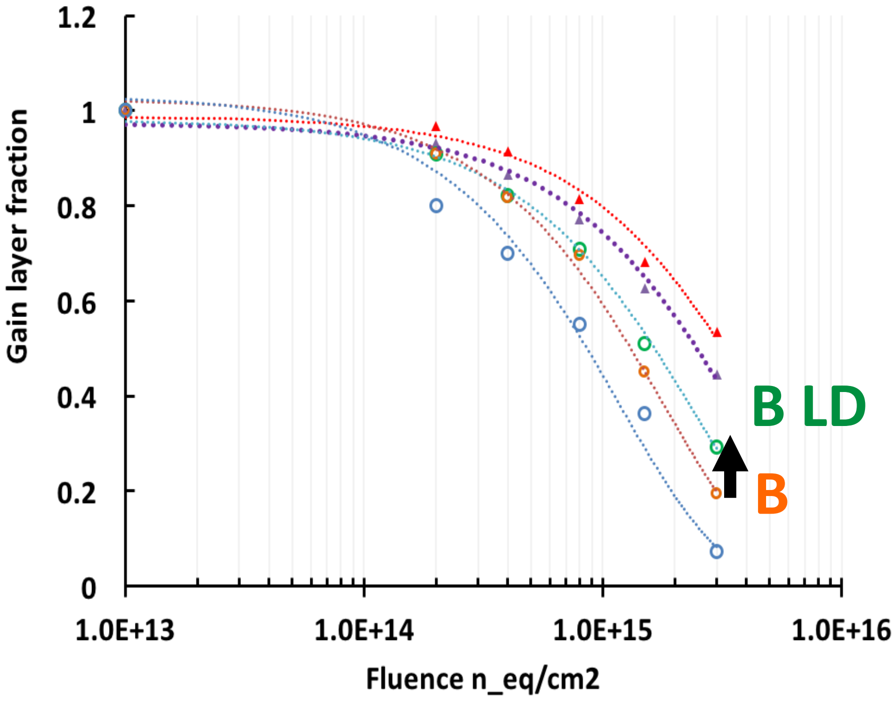
UFSD2 (2007) - What did we learn?

2 Narrower Boron doping profiles with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



higher doping densities are less affected by acceptor removal





UFSD 3 – GOALS of the Production

	Wafer #	Dose Pgain	Carbon	Diffusion
epi	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
epi	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

Improve Radiation Resistance

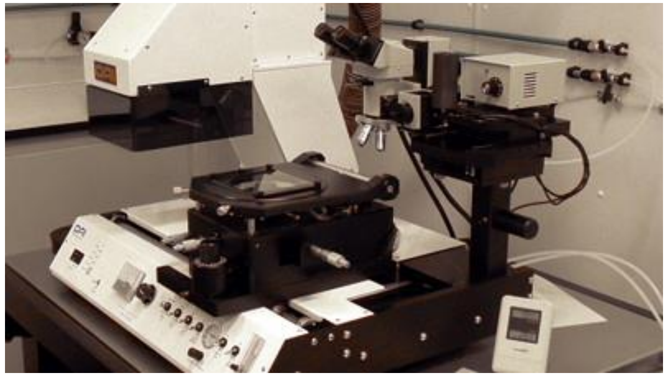
- Testing different Carbon concentrations
- Combine Carbon co-implantation with a narrower boron profiles

Demonstrate the capability of producing large-volume and large-area LGAD sensors (ATLAS and CMS HL upgrade)

- Stepper Photolithography
- Photocomposition
- Epi vs Si-Si Wafers

UFSD 3 – Stepper Photolithography

Standard technology (UFSD1 & 2)
Based on Mask Aligner



Resolution=1um.
Critical Size = 2um

New technology (UFSD 3)
Based on Stepper

Resolution = 0.35 um.
Critical Size = 0.5 um

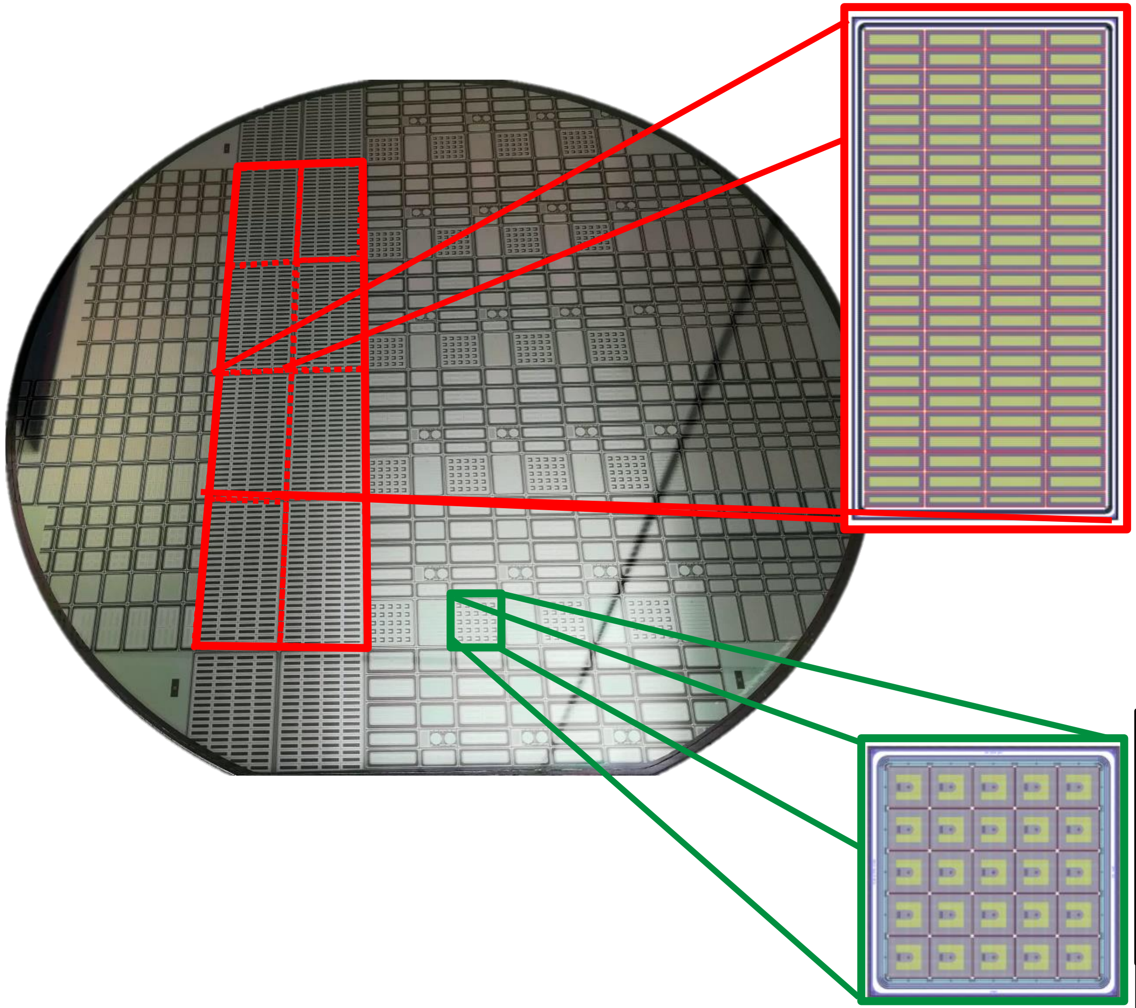
Advantages wrt Mask Aligner:

- Higher Resolution.
- Better overall quality and Reliability
- Possibility to reduce the interpixel border region
- Nanometric alignment precision -> low defectiveness due to misalignments
- Contactless exposure: less defectiveness
- Large volume production

Disadvantages:

- Smaller design area: max 1.8 x 2.2 cm^2

UFSD 3– Large Arrays



CMS ROC

Pad: 3 x 1 mm^2
Array 4 x 24 pads
Array Size: 13.2x25.0 mm^2

8 full arrays per Wafer

ATLAS ALTIROC

Pad: 1.3 x 1.3 mm^2
Array 5 x 5 pads
Array Size: 8.0x8.0 mm^2

20 full arrays per Wafer

Automatic probe station at Testing Lab, FBK. F. Ficorella

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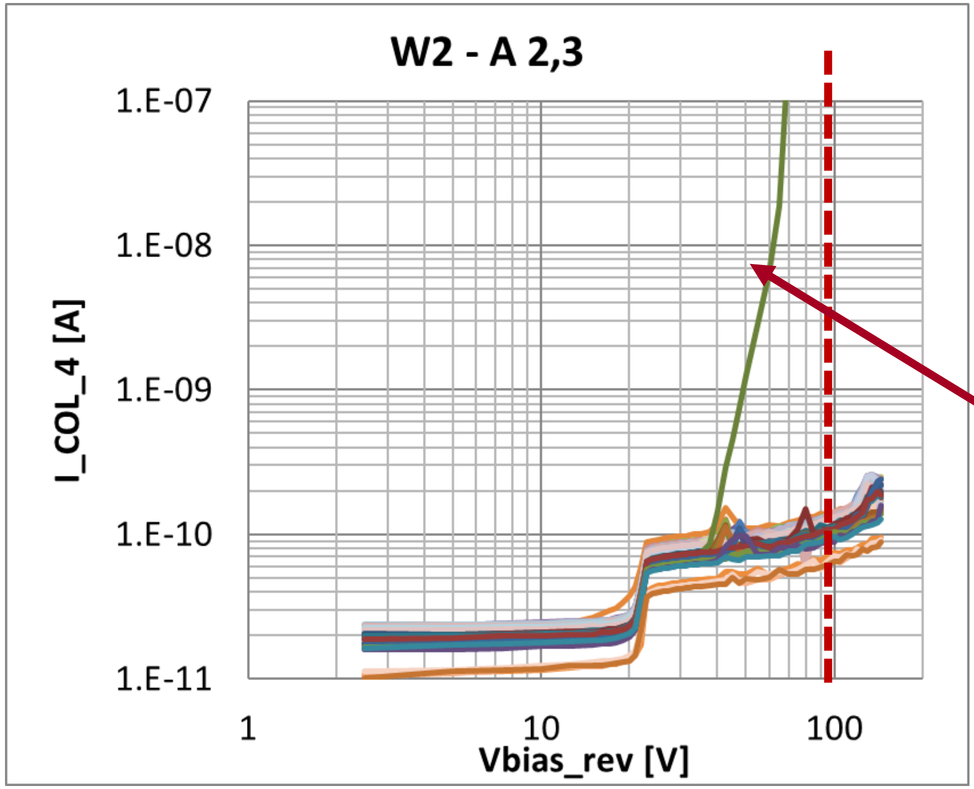
UFSD 3 – CMS Array

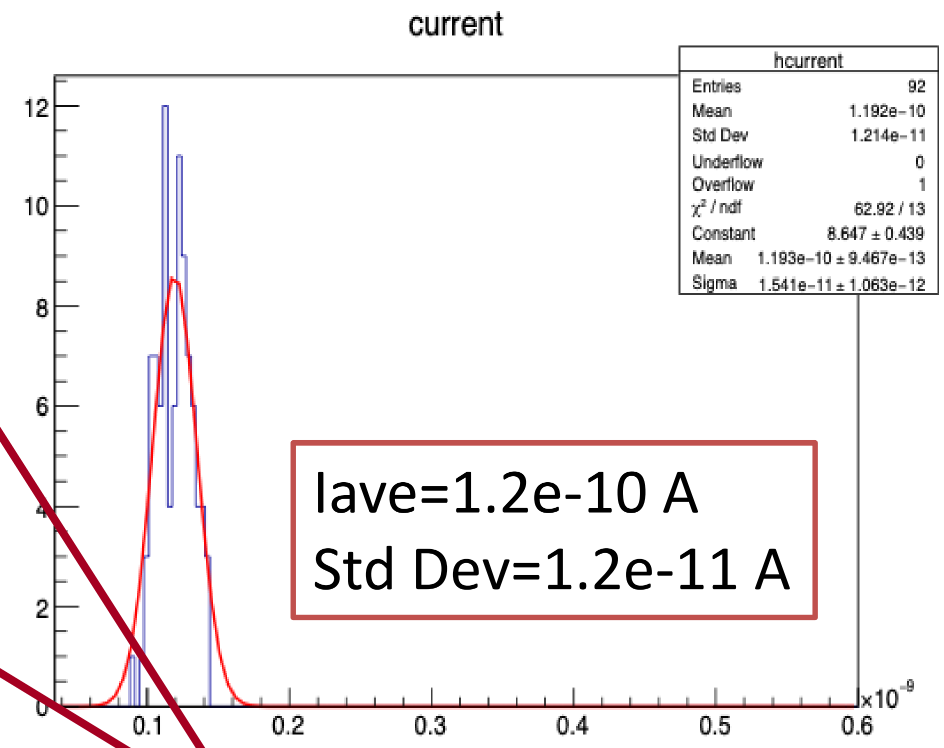
96 IV curves of a single arrays
Measurements up to 150V



Pixel Current Map
@ 100V

1.08E-10	1.20E-10	1.22E-10	1.06E-10
1.13E-10	1.21E-10	1.17E-10	1.11E-10
1.14E-10	1.34E-10	1.26E-10	1.06E-10
1.27E-10	1.38E-10	1.39E-10	1.10E-10
1.29E-10	1.39E-10	1.41E-10	1.15E-10
1.14E-10	1.33E-10	1.33E-10	1.14E-10
1.25E-10	1.40E-10	1.34E-10	1.11E-10
1.27E-10	1.37E-10	1.43E-10	1.19E-10
1.20E-10	1.24E-10	1.23E-10	3.75E-05
1.14E-10	1.35E-10	1.27E-10	1.06E-10
1.23E-10	1.35E-10	1.30E-10	1.13E-10
1.18E-10	1.27E-10	1.24E-10	9.75E-11
1.14E-10	1.28E-10	1.22E-10	1.05E-10
1.26E-10	1.33E-10	1.29E-10	1.07E-10
1.15E-10	1.19E-10	1.22E-10	1.05E-10
1.17E-10	1.28E-10	1.28E-10	1.02E-10
1.24E-10	1.29E-10	1.27E-10	1.08E-10
1.42E-10	1.20E-10	1.13E-10	1.00E-10
1.14E-10	1.21E-10	1.21E-10	1.03E-10
1.25E-10	1.35E-10	1.32E-10	1.09E-10
1.09E-10	1.13E-10	1.10E-10	1.04E-10
1.04E-10	1.04E-10	1.02E-10	8.86E-11
1.01E-10	1.05E-10	1.02E-10	9.78E-11
7.46E-11	6.60E-11	7.13E-11	6.54E-11

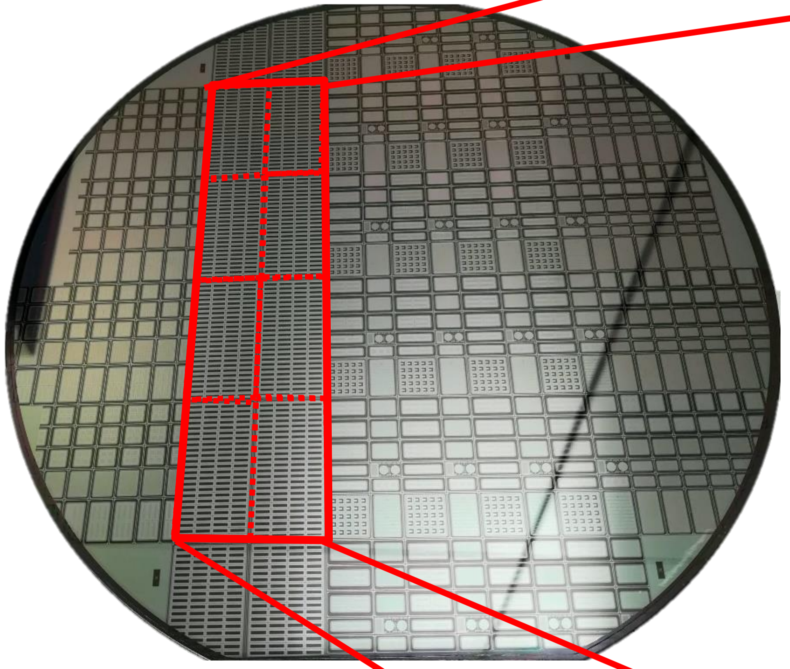
Pixel Current histogram
@ 100V



Iave=1.2e-10 A
Std Dev=1.2e-11 A

BAD pixel I ≈ 1e-5 A

CMS ARRAY – Wafer Maps



768 pixels/wafer

4.58E-10	4.31E-10	4.06E-10	3.67E-10	3.39E-10	3.36E-10	3.38E-10	3.34E-10
4.25E-10	4.08E-10	3.85E-10	3.63E-10	3.40E-10	3.46E-10	3.46E-10	3.43E-10
4.07E-10	3.90E-10	3.69E-10	3.58E-10	3.47E-10	3.49E-10	3.56E-10	3.46E-10
3.85E-10	3.90E-10	3.71E-10	3.52E-10	3.54E-10	3.69E-10	3.72E-10	3.60E-10
3.82E-10	3.73E-10	3.60E-10	3.48E-10	3.54E-10	3.72E-10	3.77E-10	3.65E-10
3.43E-10	3.42E-10	3.34E-10	3.29E-10	3.43E-10	3.67E-10	3.70E-10	3.56E-10
3.31E-10	3.42E-10	3.40E-10	3.30E-10	3.48E-10	3.73E-10	3.81E-10	3.58E-10
3.30E-10	3.33E-10	3.28E-10	3.28E-10	3.44E-10	3.70E-10	3.78E-10	3.61E-10
3.06E-10	3.13E-10	3.16E-10	5.40E-05	3.38E-10	3.50E-10	3.63E-10	5.10E-05
2.98E-10	3.05E-10	3.13E-10	3.42E-10	3.36E-10	3.48E-10	3.55E-10	3.41E-10
2.95E-10	3.11E-10	3.28E-10	3.27E-10	3.35E-10	3.54E-10	3.50E-10	3.41E-10
2.81E-10	3.02E-10	3.18E-10	3.22E-10	3.25E-10	3.39E-10	3.46E-10	3.33E-10
2.88E-10	3.18E-10	3.34E-10	3.28E-10	3.32E-10	3.59E-10	3.58E-10	3.43E-10
2.91E-10	3.21E-10	3.36E-10	3.32E-10	3.39E-10	3.59E-10	3.66E-10	3.49E-10
2.86E-10	3.21E-10	3.32E-10	3.29E-10	3.31E-10	3.57E-10	3.58E-10	3.52E-10
2.99E-10	3.31E-10	3.42E-10	3.40E-10	3.43E-10	3.65E-10	3.78E-10	3.67E-10
3.05E-10	3.39E-10	3.53E-10	3.47E-10	3.52E-10	3.75E-10	3.88E-10	3.76E-10
3.04E-10	3.30E-10	3.44E-10	3.48E-10	3.52E-10	3.72E-10	3.81E-10	3.76E-10
3.18E-10	3.48E-10	3.62E-10	3.58E-10	3.71E-10	3.89E-10	3.94E-10	3.85E-10
3.24E-10	3.54E-10	3.68E-10	3.71E-10	3.71E-10	3.89E-10	3.93E-10	3.82E-10
3.18E-10	3.49E-10	3.60E-10	3.58E-10	3.64E-10	3.76E-10	3.73E-10	3.69E-10
3.22E-10	3.51E-10	3.63E-10	3.56E-10	3.57E-10	3.63E-10	3.62E-10	3.54E-10
3.28E-10	3.53E-10	3.59E-10	3.59E-10	3.53E-10	3.59E-10	3.54E-10	3.49E-10
2.34E-10	2.49E-10	2.48E-10	2.42E-10	2.42E-10	2.42E-10	2.41E-10	2.39E-10
3.01E-10	3.26E-10	3.32E-10	3.20E-10	3.26E-10	3.32E-10	3.36E-10	3.29E-10
2.89E-10	3.20E-10	3.26E-10	3.17E-10	3.24E-10	3.35E-10	3.31E-10	3.24E-10
2.91E-10	3.16E-10	3.29E-10	3.18E-10	3.24E-10	3.35E-10	3.34E-10	3.22E-10
2.96E-10	3.32E-10	3.37E-10	3.27E-10	3.24E-10	3.43E-10	3.44E-10	3.24E-10
2.90E-10	3.29E-10	3.39E-10	3.28E-10	3.27E-10	3.41E-10	3.50E-10	3.23E-10
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3.24E-10	3.41E-10	3.43E-10	3.28E-10	3.24E-10	3.45E-10	3.37E-10	3.03E-10
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4.13E-10	3.97E-10	3.68E-10	3.49E-10	3.54E-10	3.46E-10	3.58E-10	3.54E-10
4.10E-10	4.00E-10	3.88E-10	3.63E-10	3.53E-10	3.62E-10	3.68E-10	3.69E-10
4.31E-10	4.12E-10	3.98E-10	3.73E-10	3.65E-10	3.73E-10	3.84E-10	3.78E-10
4.40E-10	4.25E-10	4.13E-10	3.88E-10	3.76E-10	3.99E-10	4.06E-10	4.03E-10
4.44E-10	4.35E-10	4.14E-10	4.00E-10	3.87E-10	4.07E-10	4.12E-10	4.04E-10
4.36E-10	4.19E-10	4.06E-10	3.89E-10	3.90E-10	3.97E-10	4.07E-10	4.01E-10
4.52E-10	4.41E-10	4.25E-10	4.10E-10	4.01E-10	4.19E-10	4.26E-10	4.03E-10
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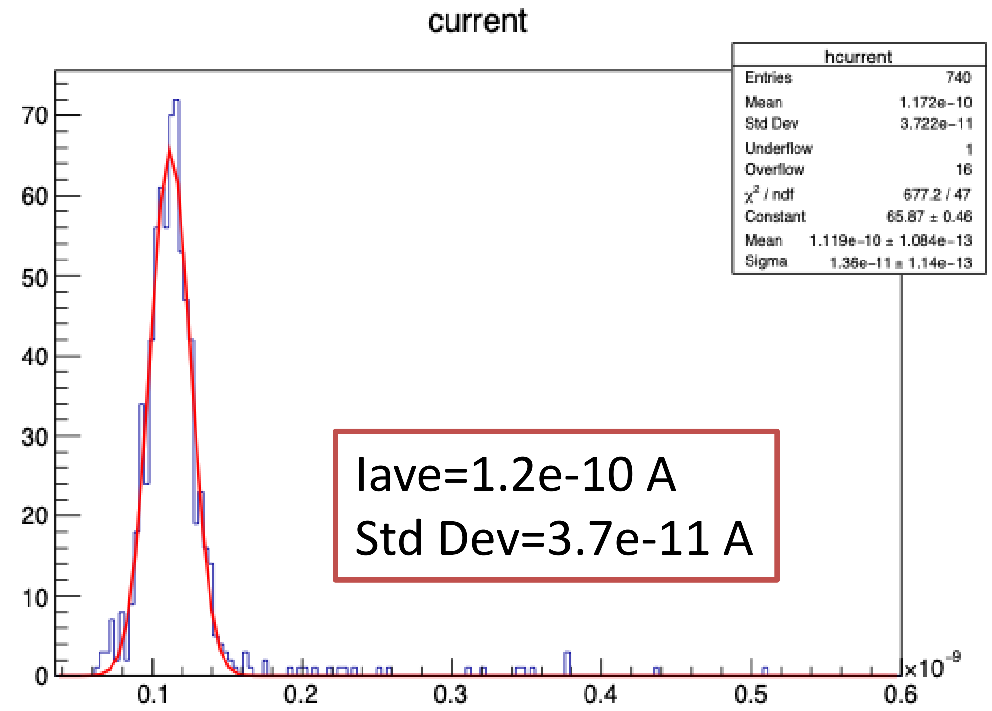
4.68E-10	4.88E-10	4.75E-10	4.50E-10	4.30E-10	4.33E-10	4.32E-10	4.17E-10
4.87E-10	2.90E-06	4.96E-10	4.66E-10	4.42E-10	4.55E-10	4.47E-10	4.26E-10
5.17E-10	1.95E-05	5.06E-10	4.76E-10	4.54E-10	4.58E-10	4.44E-10	4.32E-10
1.00E-04	1.00E-04	1.00E-04	1.00E-04	4.52E-10	4.49E-10	4.43E-10	4.28E-10
5.33E-08	5.34E-10	5.09E-10	4.87E-10	4.69E-10	4.74E-10	4.63E-10	4.39E-10
1.13E-06	5.53E-10	5.29E-10	4.97E-10	4.83E-10	4.86E-10	4.73E-10	4.50E-10
6.83E-10	7.34E-10	5.73E-10	5.80E-10	4.69E-10	4.78E-10	4.77E-10	4.57E-10
5.88E-10	6.31E-10	5.80E-10	5.16E-10	4.93E-10	5.04E-10	4.99E-10	4.79E-10
5.81E-10	6.12E-10	6.01E-10	5.38E-10	4.99E-10	5.09E-10	5.14E-10	5.00E-10
4.95E-10	6.11E-10	6.18E-10	5.45E-10	4.99E-10	5.01E-10	5.06E-10	4.99E-10
5.49E-10	6.64E-10	6.41E-10	5.79E-10	5.12E-10	5.11E-10	5.15E-10	5.11E-10
6.15E-10	6.60E-10	1.22E-07	5.81E-10	5.34E-10	5.21E-10	5.23E-10	5.15E-10
4.79E-10	4.91E-10	4.65E-10	4.38E-10	4.08E-10	3.90E-10	3.89E-10	3.81E-10

Wafer 2



Iave=1.2e-10 A
Std Dev=3.7e-11 A

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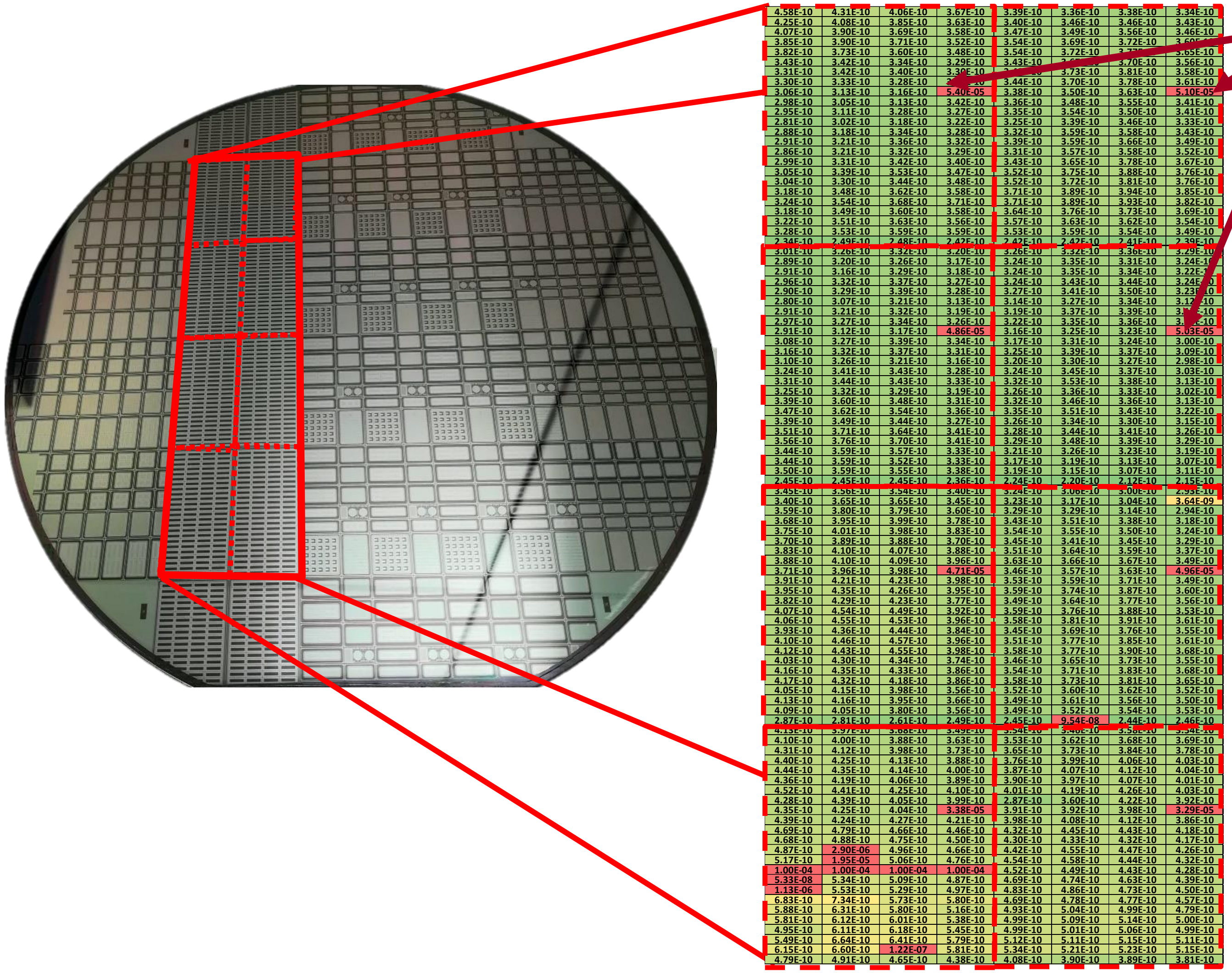
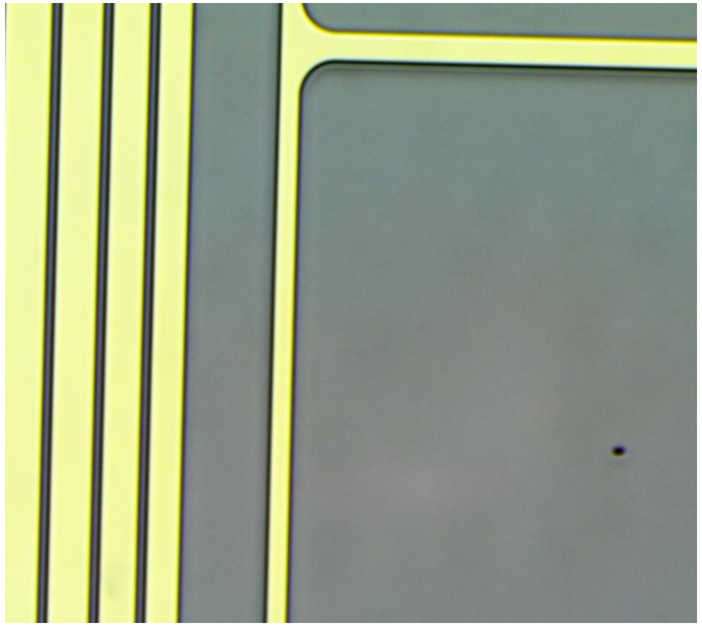
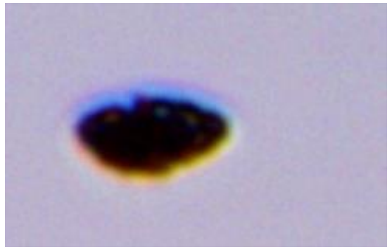
CMS ARRAY – Wafer Maps



Pixel 4,9 is BAD in all the detectors !!!

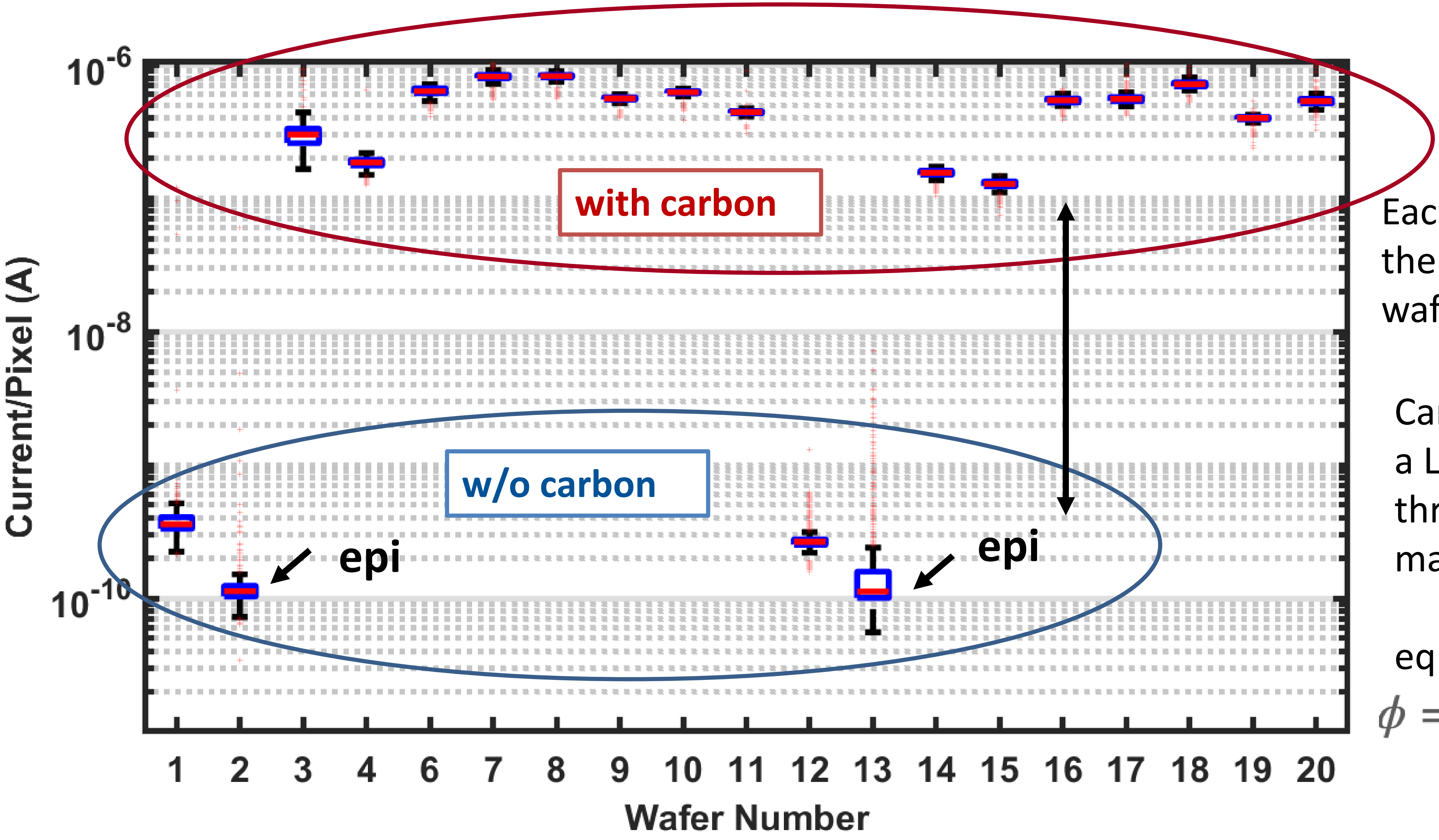
Mask Defect





If we do not consider the 4,9 pixel. 6 out 8 detector in the wafer are OK.

CMS ARRAY – BOXPLOT



Each box represents all the 768 pixels in the wafer

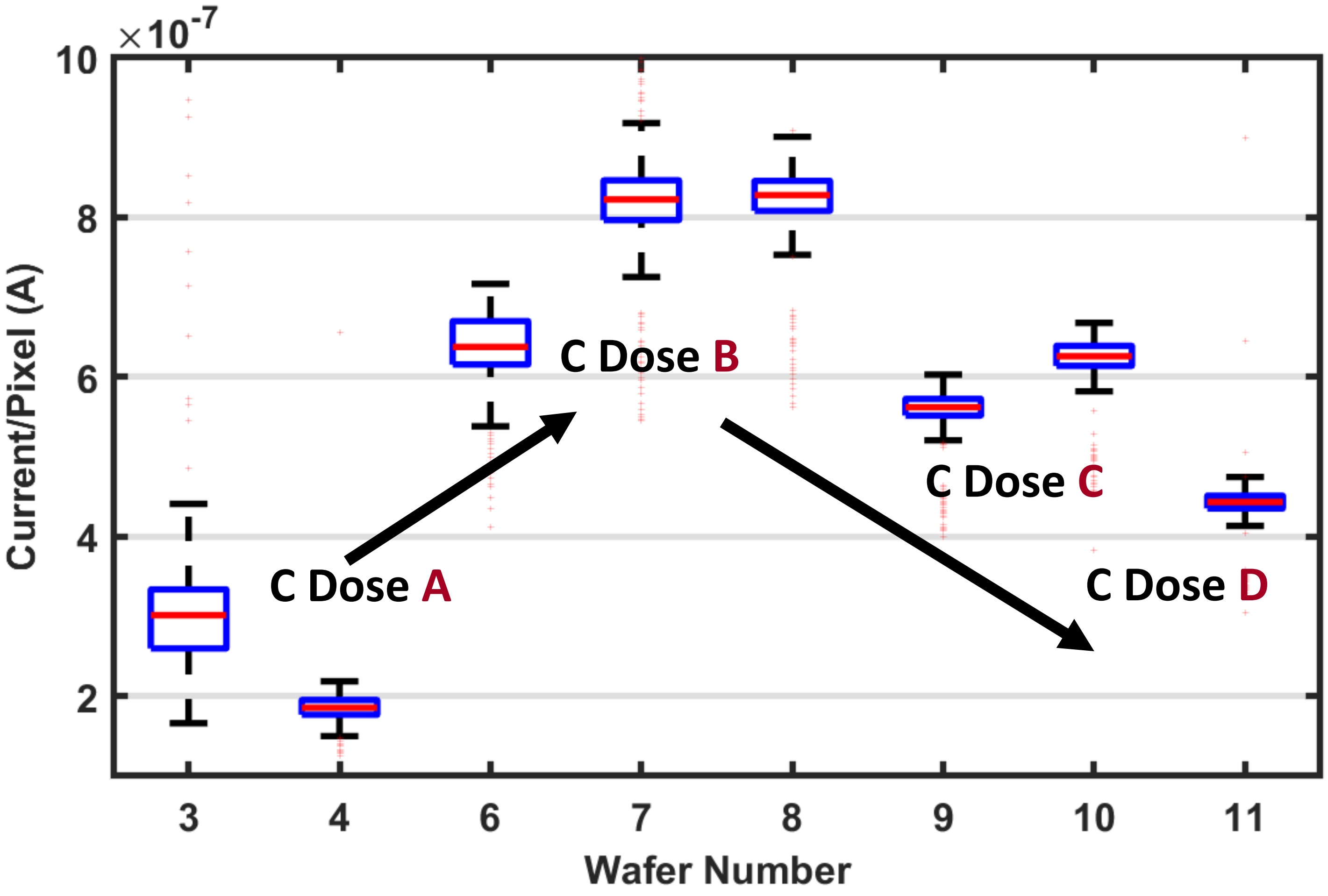
Carbonated wafers have a Leakeage Current three order of magnitude higher.

equivalent to

$$\phi = 10^{13} n_{eq}/cm^2$$

CMS ARRAY – BOXPLOT

Wafers with carbon – Low Diffusion



Splits with higher Carbon Doses show lower Leakage current!

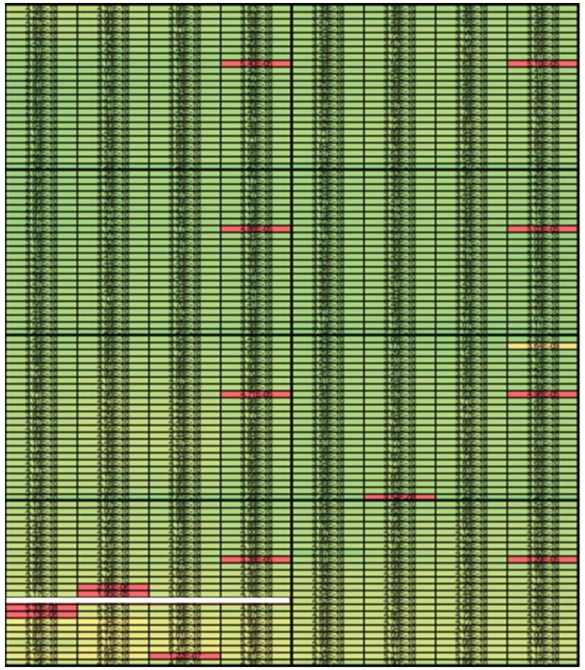
This could be explained with a gain reduction at highest Carbon Doses.

See M. Ferrero Talk!

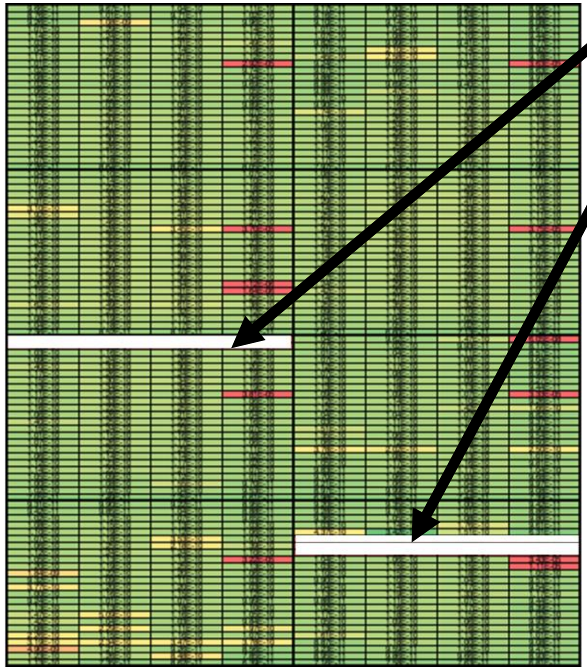
CMS ARRAY – Wafer Maps

Wafers without carbon

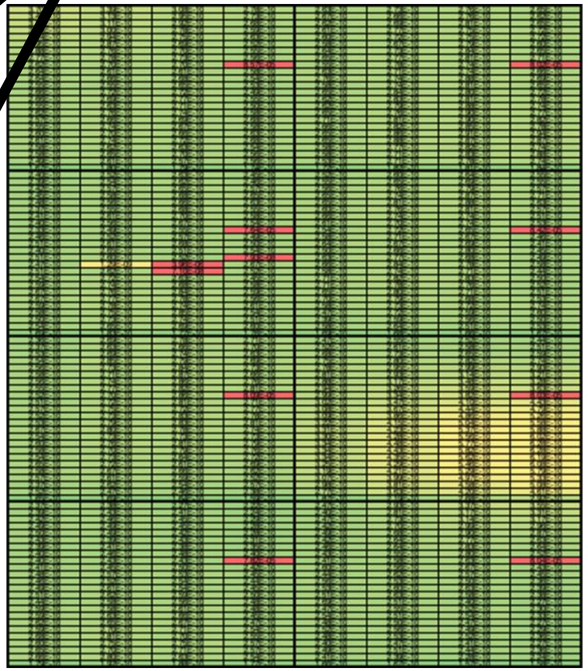
Values not acquired due to software issue



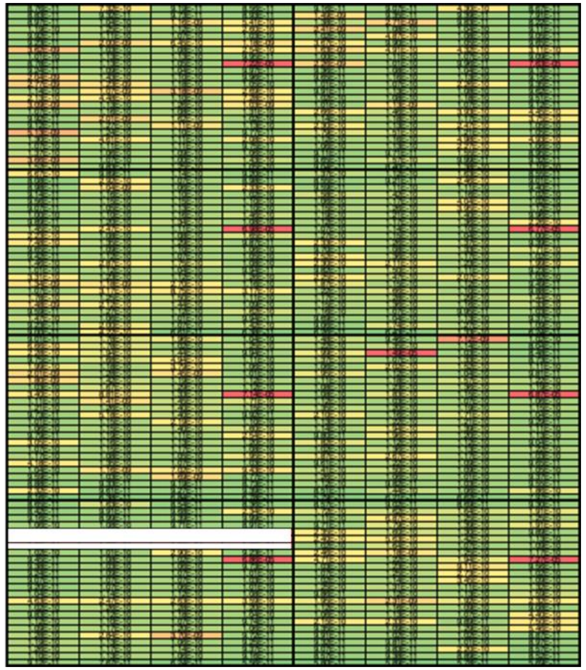
W1 - SiSi



W2 - Epi



W12 - SiSi



W13 - Epi

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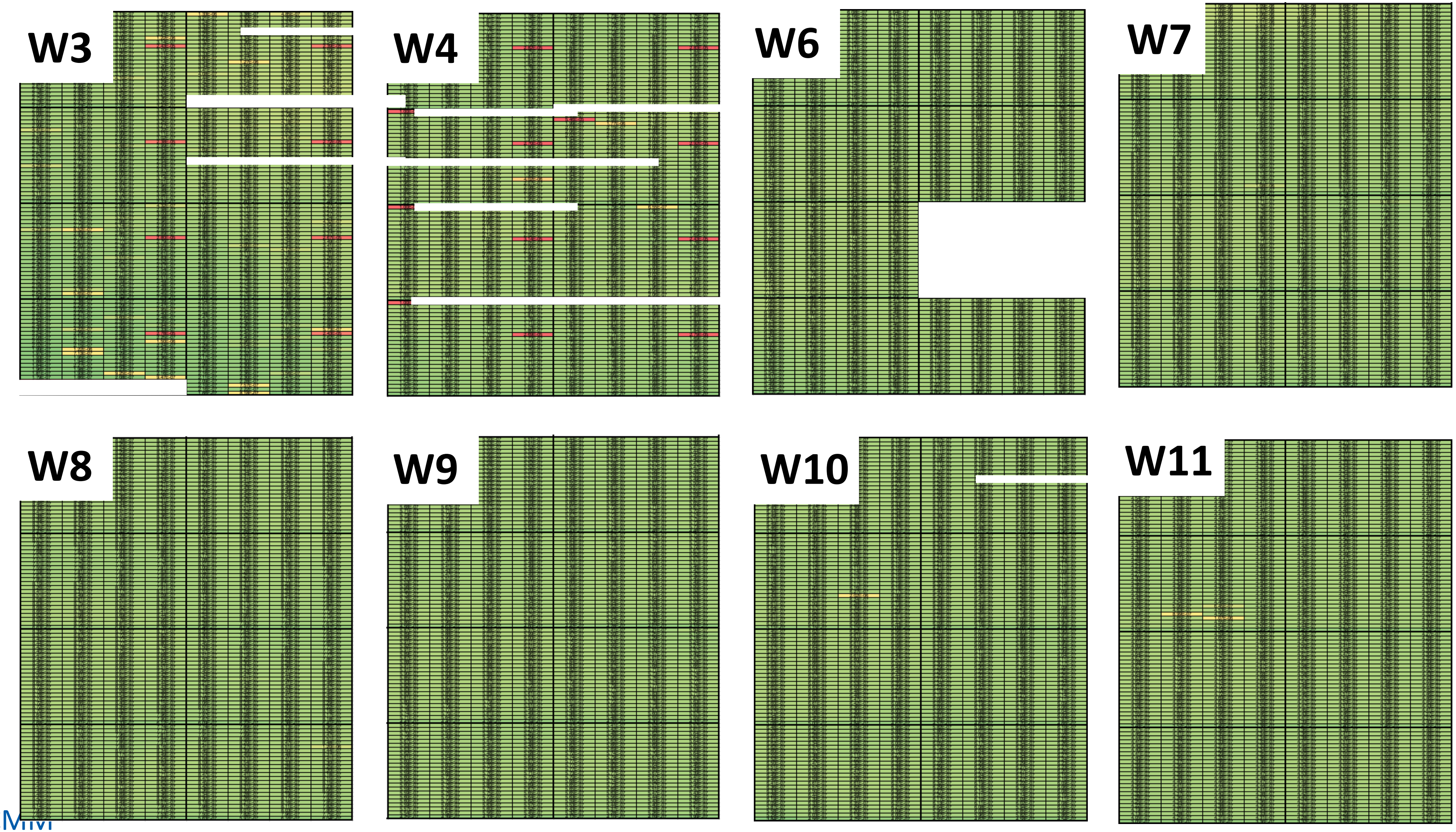
CMS ARRAY – Wafer Maps

Wafers with carbon - LD



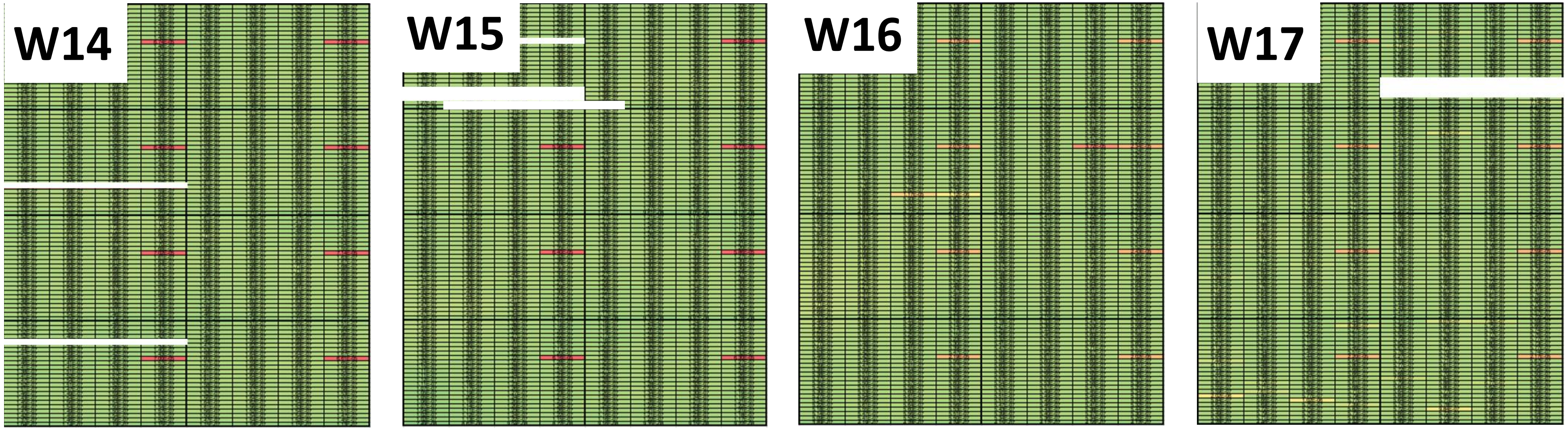
- In the last wafers **BAD pixel disappears.** **But the defect is still there...**

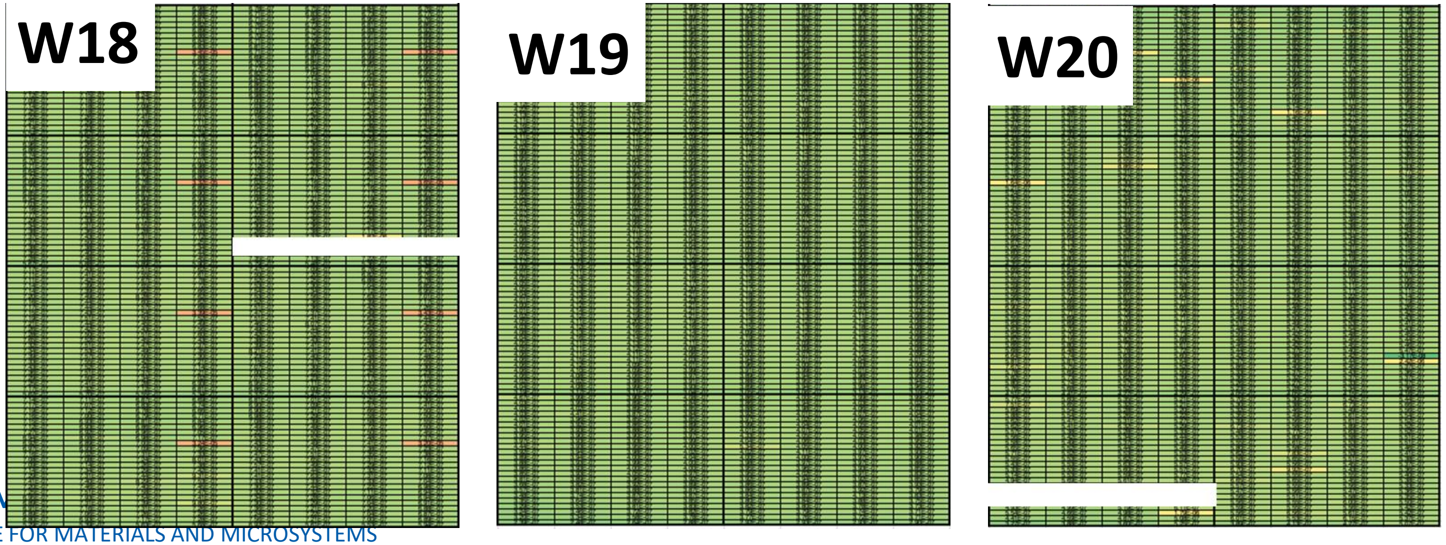
- These are the wafers with the **higher Carbon content,** thus the lower gain.

Are sensors with low or no-gain **less sensitive** to some fabrications defect?

CMS ARRAY – Wafer Maps

Wafers with carbon - HD





14 bad channels out of 15.100
→ 0.1%

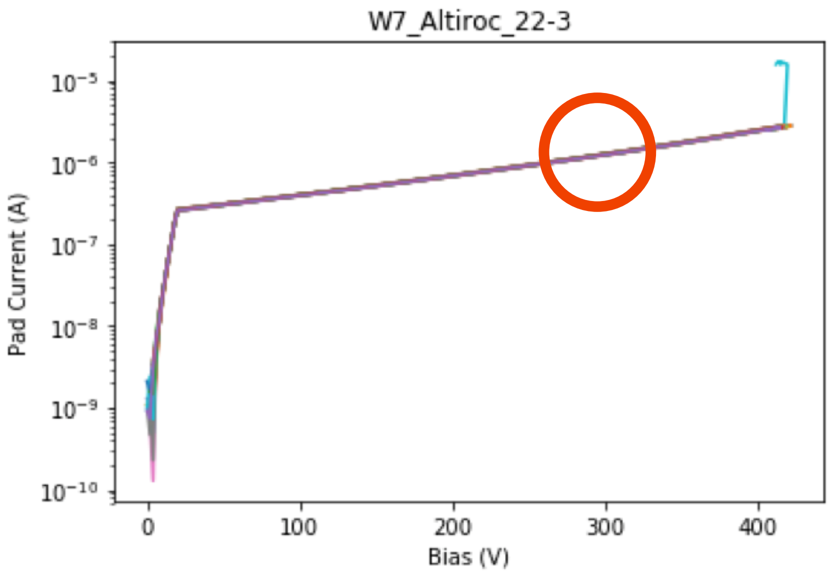
(64 bad pads due to mask defect)

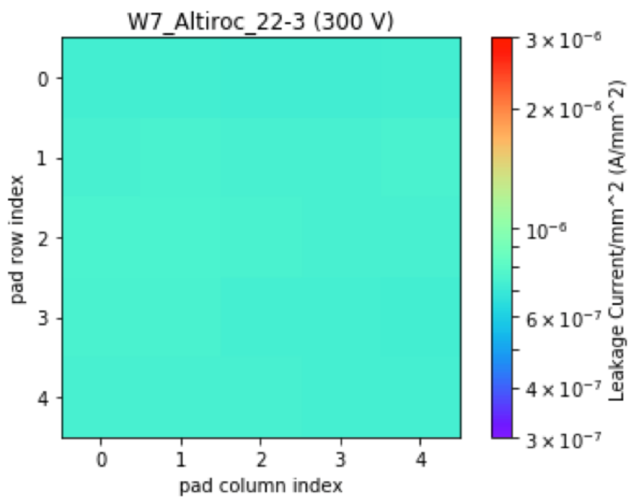
All the 14 bad pixels are in the wafers w/o Carbon or with the lowest Carbon Dose (higher gain)

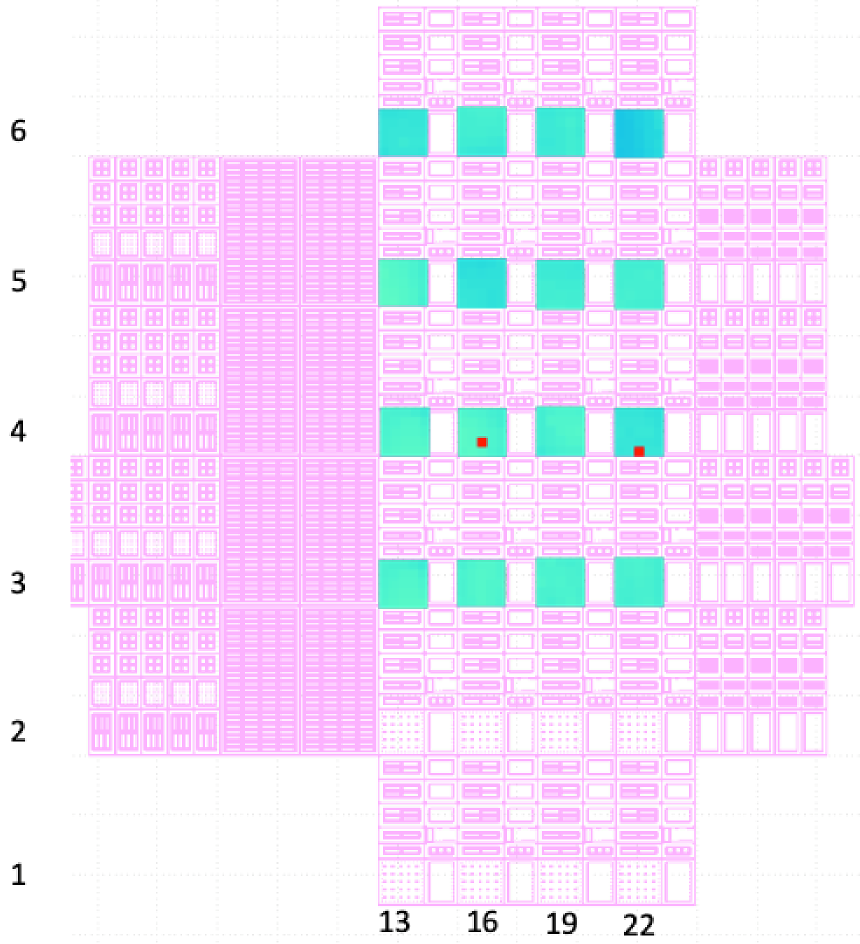
ALTROC ARRAY – Wafer Maps

Every pad is connected, higher voltage reached.

Leakage current @**300V** for each pad of **W7** ALTIROC structure







→ *In total 4 bad pads out of 575*~***0.7%***

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Large Area Sensors - Photocomposition

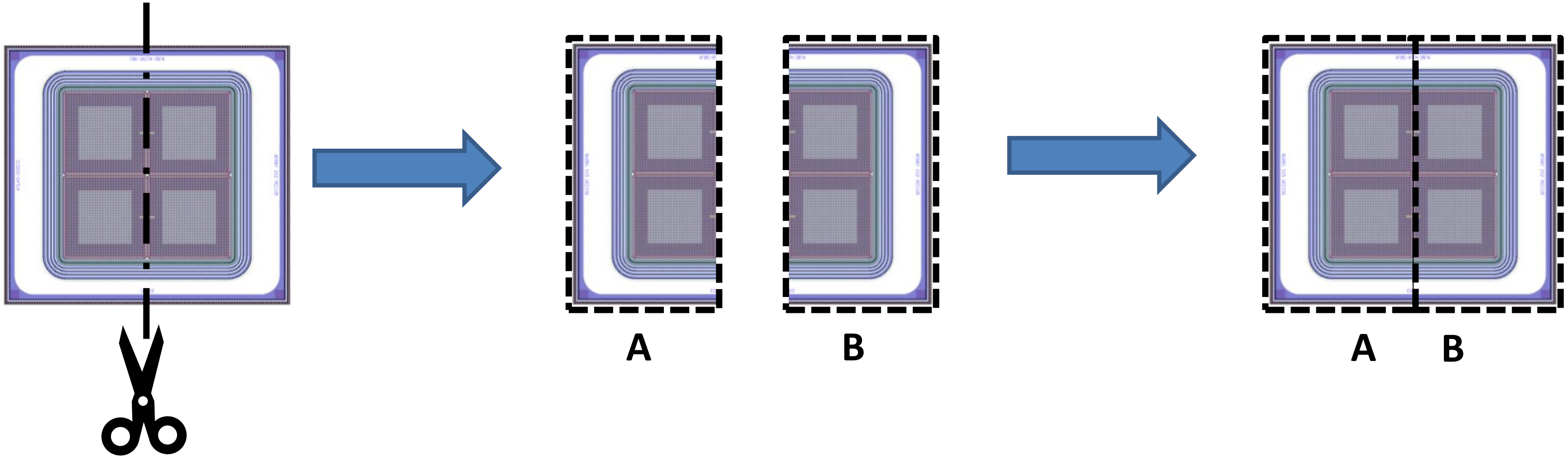
Problem: Stepper constraints allow to produce monolithic sensors not larger than 2.2 x 1.8 cm^2

Photocomposition is being considered to produce large-area devices with stepper.

1. Layout of a test structure (QUAD) was divided into two parts

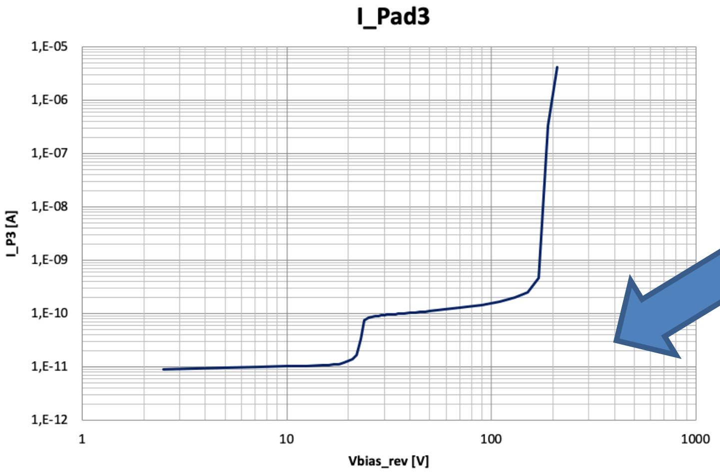
2. placed in two different shots

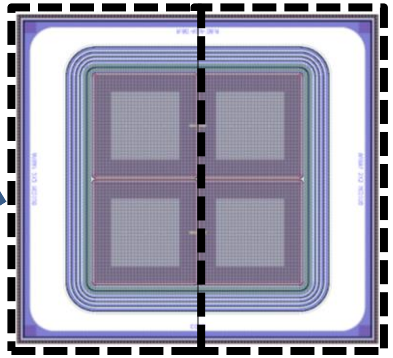
3. And printed close to reconstruct the device



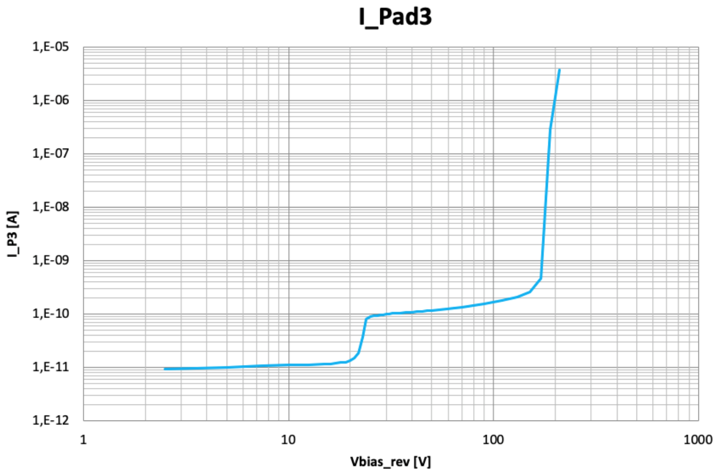
Large Area Sensors - Photocomposition

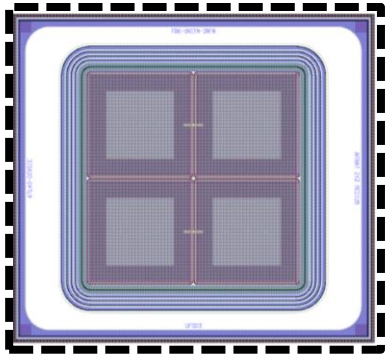
Photocomposed structures



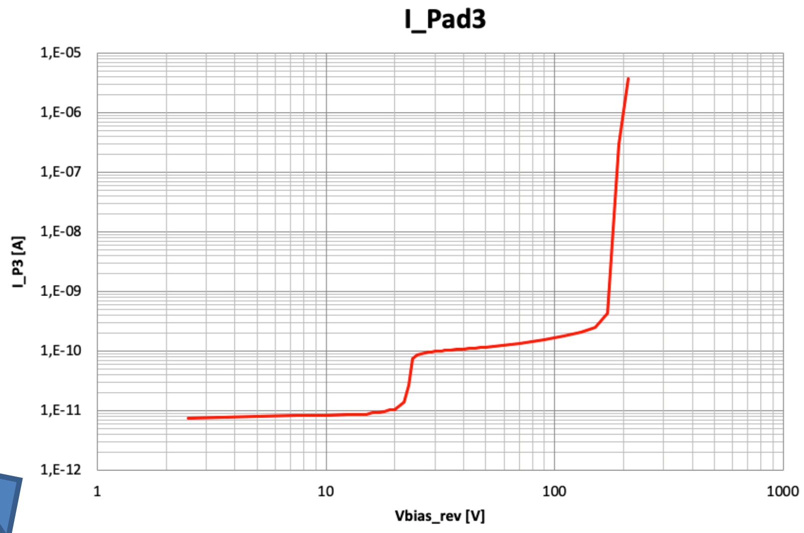


A B





Reference structure



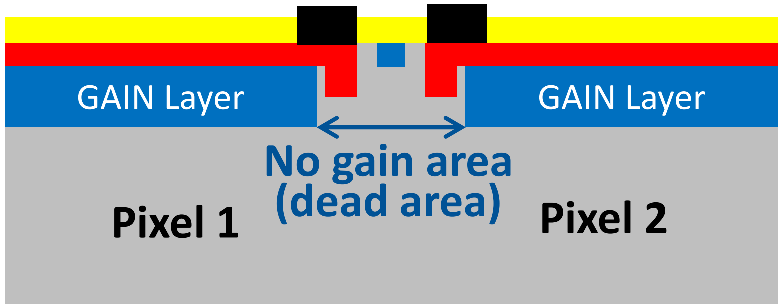
Extremely good results.

Photocomposed sensors are indistinguishable from the reference one

LGAD Sensor Segmentation

LGAD Segmentation problem: Fill Factor losses

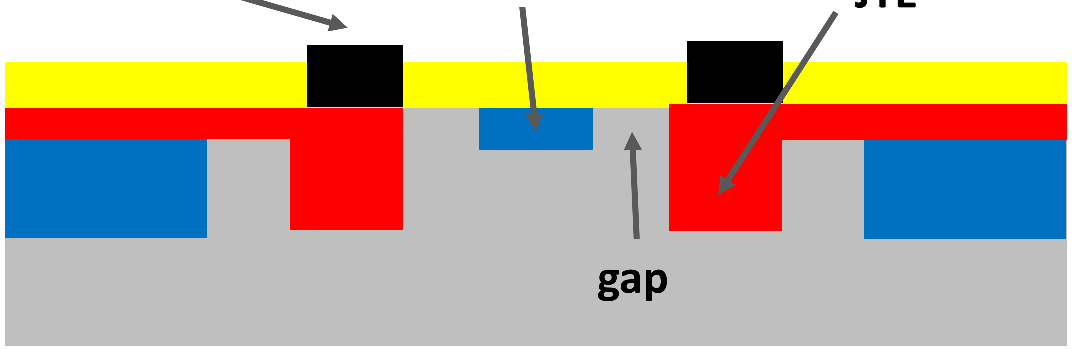
technology
(FBK UFSD2)



- Detectors with internal gain are typically affected by Fill Factor reduction.
- Two regions are present :
  - i) GAIN region (pixel core)
  - ii) NO-GAIN region (pixel border)

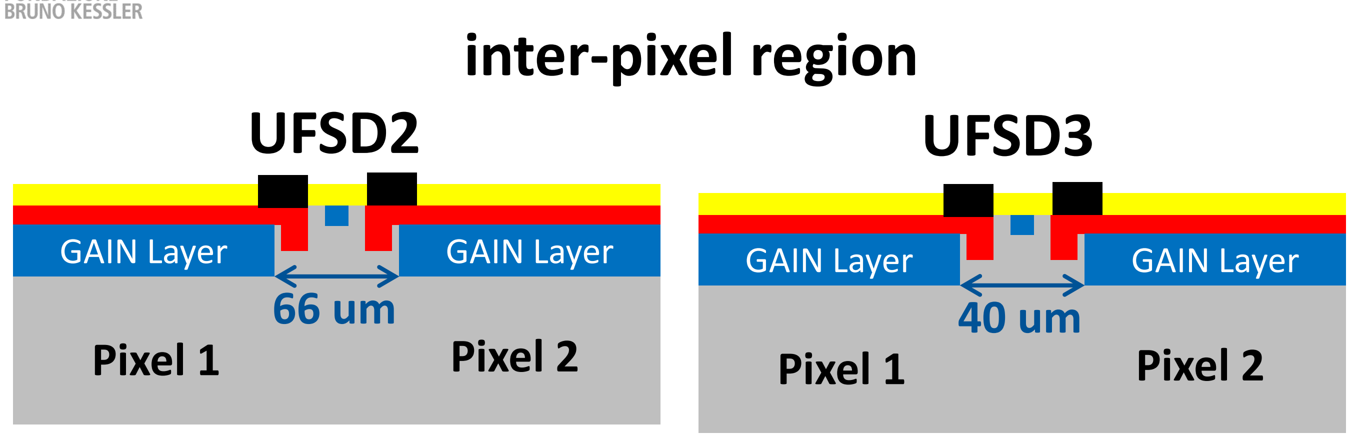
$$\text{Fill Factor} = \frac{\text{gain area}}{\text{total area}}$$

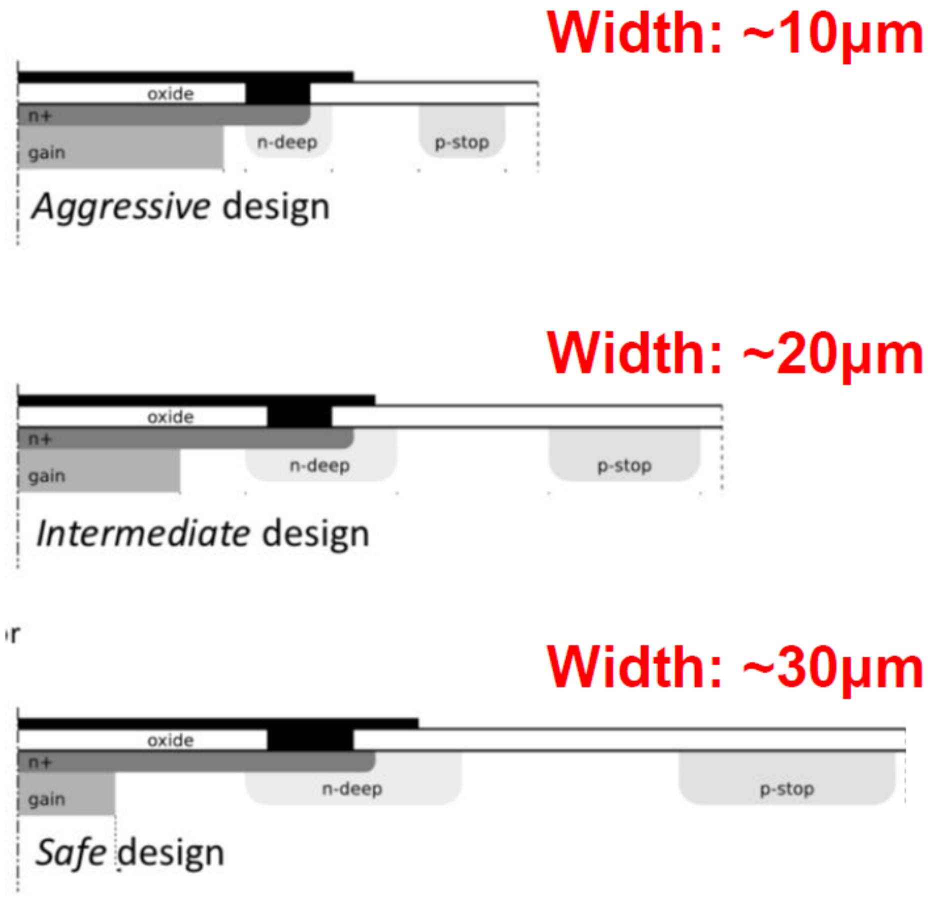
- The pixel border is a dead-region. The carriers generated in this area are not multiplied.



- The pixel border region is necessary to host all the structures to control the E field (JTE, p-stop, etc..). Its dimensions are due to design and technology constraints

Inter-pixel area in UFSD3





UFSD3 R&D Structures (in scale)

R&D structures in UFSD3

➢ **4 solutions for the inactive area** between gain layers (pads/strips):

1) "SUPER-SAFE" 40um
2) "AGGRESSIVE"
3) "MEDIUM"
4) "SAFE"

Inter-pixel area in UFSD3

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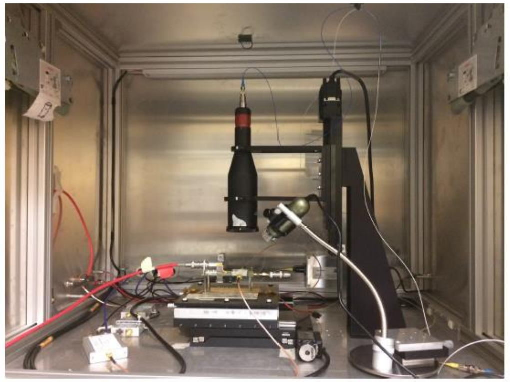
TCT

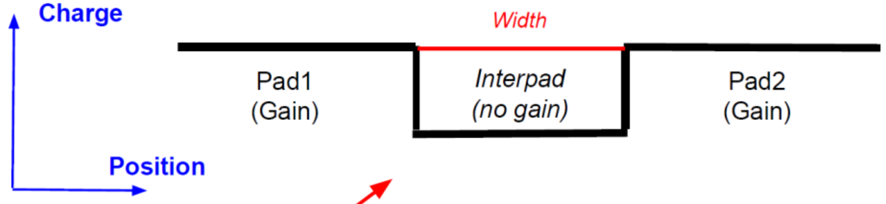


TCT Setup in Torino

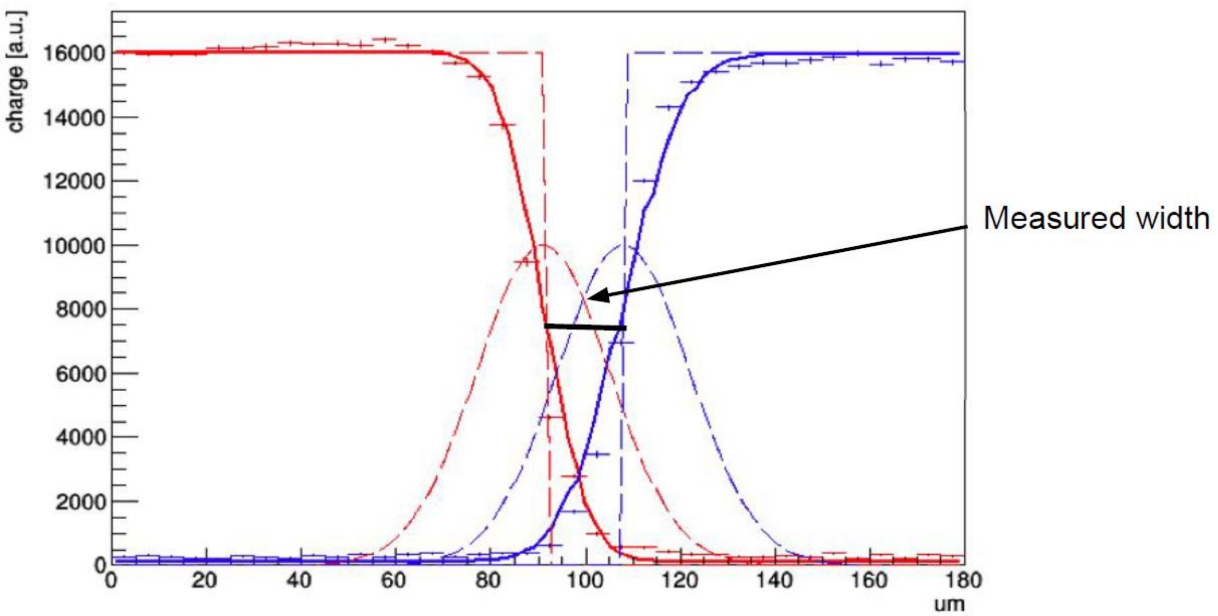
Particulars TCT setup:

- IR pulsed **laser** (1060 nm) → **10-15 µm spot**
- xy-stage with sub-µm precision
- Stage control and DAQ via Labview software
- **Automatic xy-scan + Small laser spot:**

➔ **Very precise mapping of the DUT**



Result with a point-like spot → our spot is 10-15 µm with a gaussian shape

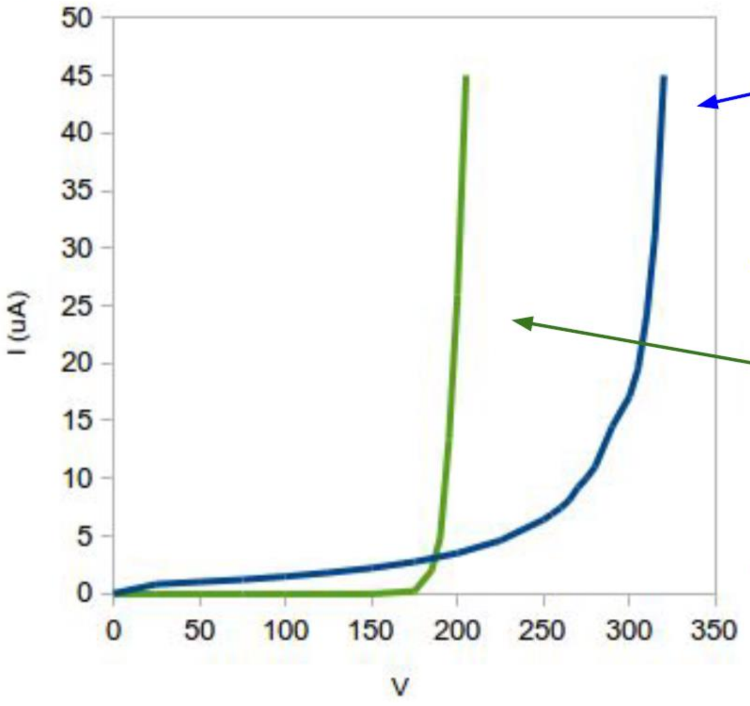


Structure	Measured distance (µm)
AGGRESSIVE	16.4
INTERMEDIATE	16.7
SAFE	30.4
SUPER SAFE	38.3

F. Silviero
33rd RD50 workshop

Inter-pixel area in UFSD3

Problem: smaller interpixel regions shows early breakdowns, not due to the gain. Probably this problem could be mitigated by reducing p-stop doping concnetration



"SUPER-SAFE"

- Breakdown Voltage (V_{BD}) > 300V
- I(V) exponential

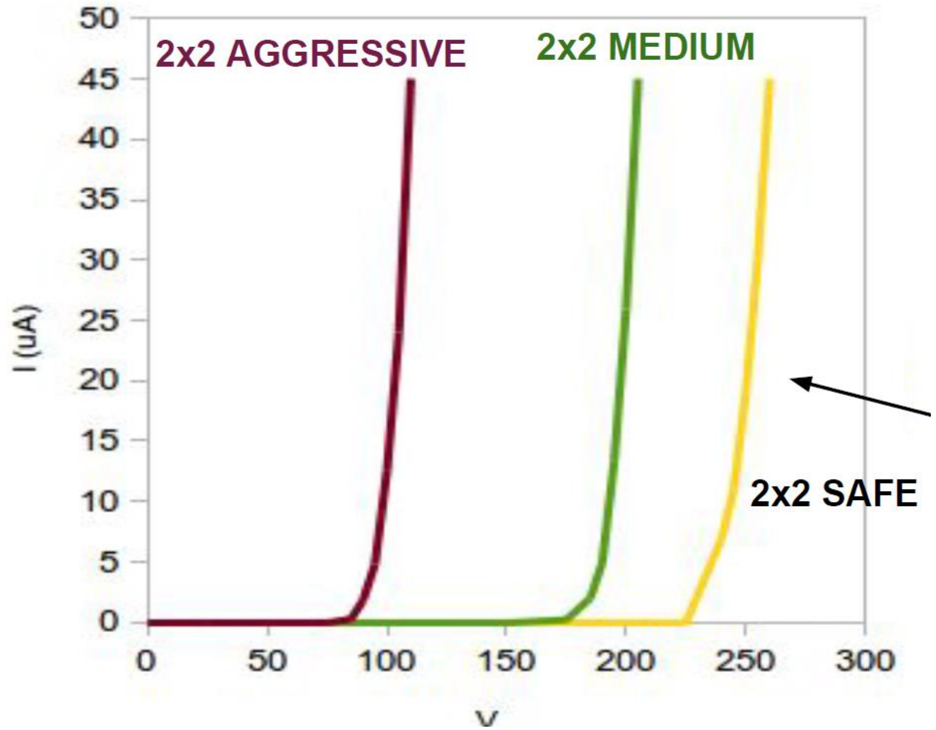
➔ Breakdown due to internal gain

➔ This is the kind of Breakdown we like

R&D Structures

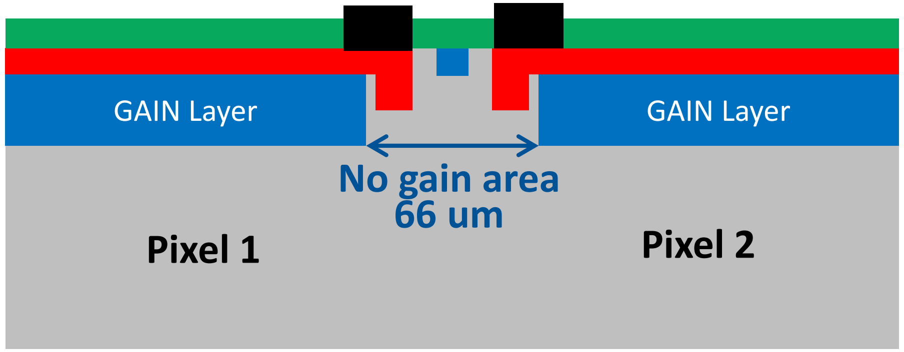
- V_{BD} < 300V
- I(V) is not an exponential

➔ Early Breakdown, not due to the gain

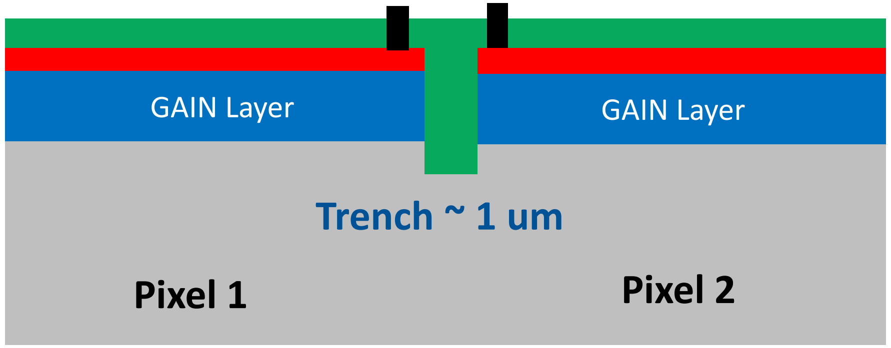


New strategies to improve FF

Standard JTE + p-stop isolation



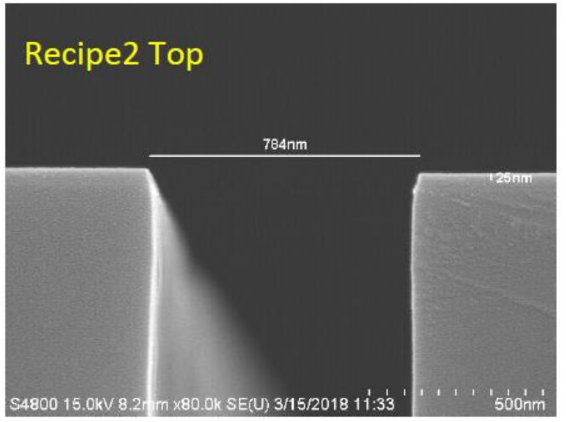
Trench Isolation LGAD

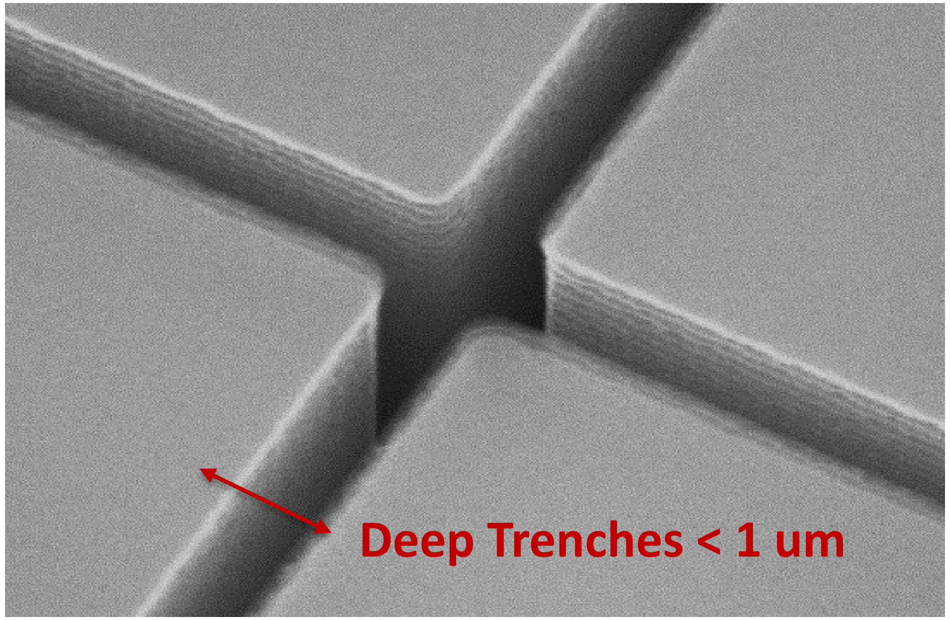


- Trench isolation could drastically reduce the inter-pixel border region down to few microns

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi





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Trench Isolated LGAD – RD50 project

TITLE: Segmented LGAD with small pixels and high Fill-Factor (Trench Isolated LGAD, TI-LGAD)

GOAL: Design and production of thin segmented LGAD sensors with small pixels (<= 100 um) and high Fill Factor (> 80%)

RD50

Involved institutes:

1. Fondazione Bruno Kessler
2. INFN Torino (Nicolo Cartiglia)
3. KIT (Michele Caselle, Alexander Dierlamm)
4. University of Zurich (Ben Kilminster)
5. Paul Scherrer Institut (Tilman Rohe, Anna Bergamaschi)
6. Institut "Jozef Stefan" (Gregor Kramberger)
7. University of Birmingham (Phil Allport)
8. UC Santa Cruz (Hartmut Sadrozinski)

Conclusions

- Radiation Hardness: in UFSD 3 batch new efforts have been done to optimize Carbon co-implantation and Gain layer doping profile to mitigate the initial acceptor removal effect.

- Capability to fabricate large-area and large-volume sensor productions has been demonstrated.
  - Pixel yield on the UFSD 3 batch is > 99%
  - Photocomposition can be used to produce large devices > 4 cm^2

- Sensors with different inter-pixel distances have been tested. UFSD3 sensors features a reduced dead-border (40um) wrt previous batches. Further reductions led to early breakdown.

- Trench-isolated LGAD is a novel detector design, which promises to reduce the inter-pixel region down to a few microns.

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Thank you for your attention!

UFSD Collaboration

INFN Torino, Univ. Torino, Univ. Trento, TIFPA, FBK

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