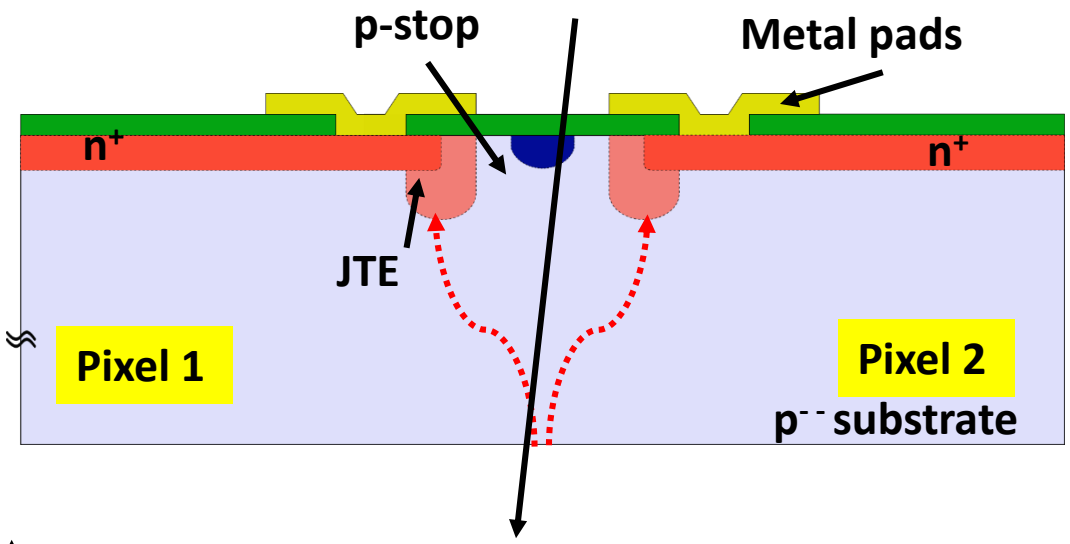
12th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking detectors (HSTD12)
Hiroshima, Japan, Dec. 15-18, 2019

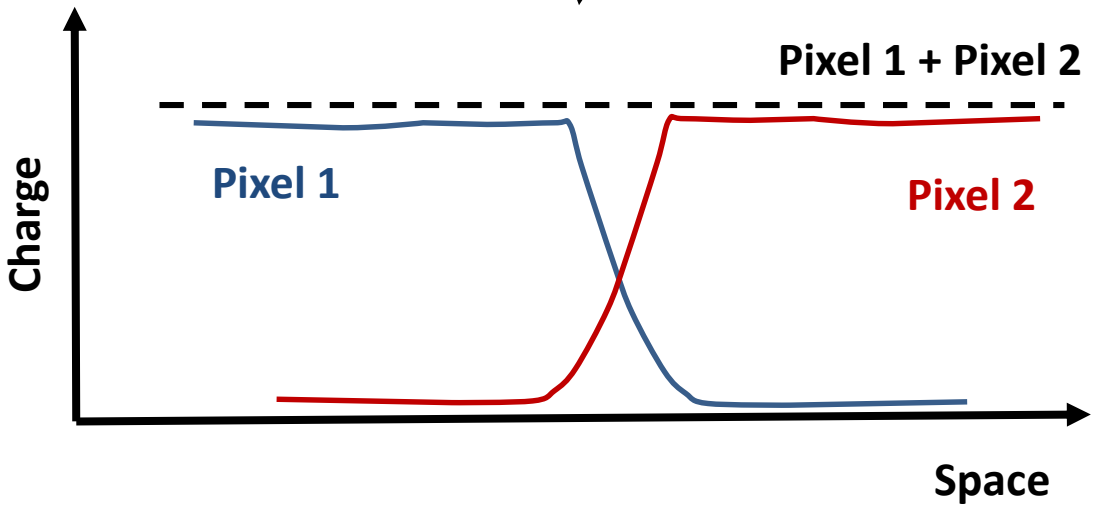
Novel Strategies for Fine-Segmented LGADs

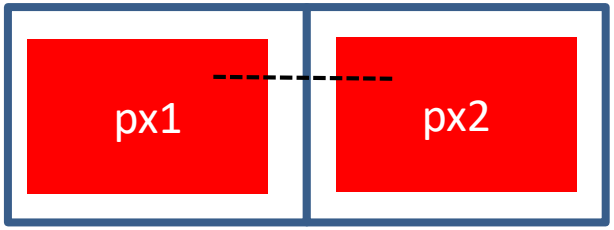
G. Paternoster, G. Borghi, M. Centis Vignali, F. Ficorella, M. Boscardin
(FBK, TIFPA)
R. Arcidiacono, N. Cartiglia, M. Mandurrino, M. Ferrero, F. Siviero, V. Sola, M. Tornago
(INFN To and University of To)
G.-F. Dalla Betta, L. Pancheri
(Universitiy of Trento, TIFPA)

1. Segmentation Issues in LGADs

Segmentation in PIN Planar Sensors

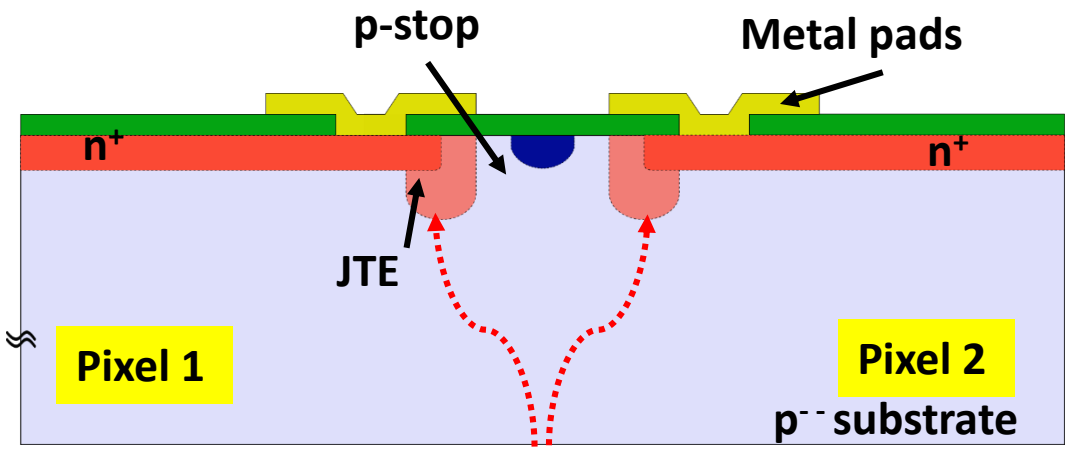


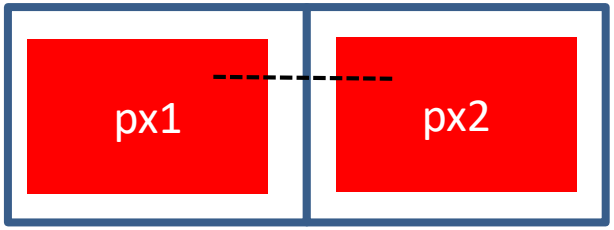




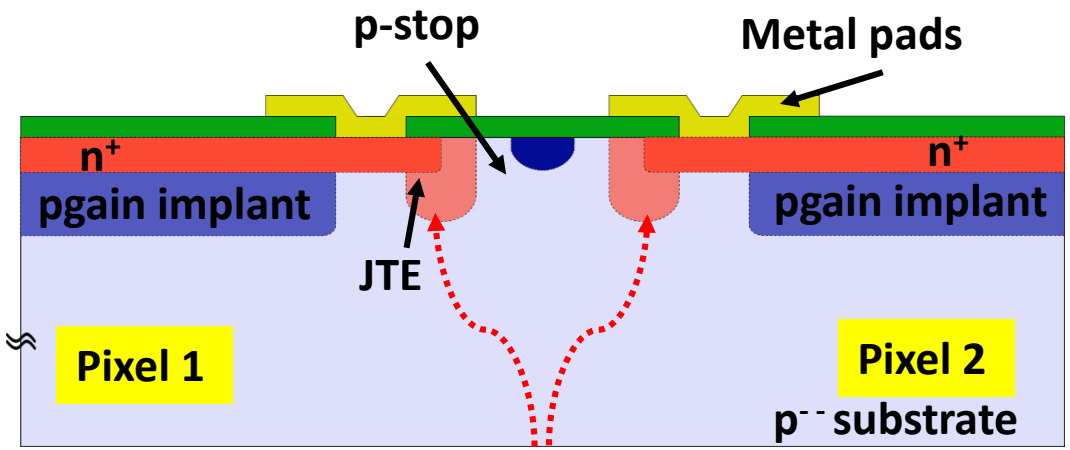
- Inter-pixel region hosts the isolation and termination structures:
  - P-stop
  - Junction Termination Extension (JTE)
- **In p-i-n sensors the charge is shared between adjacent pixels pixels but the total charge is a constant**

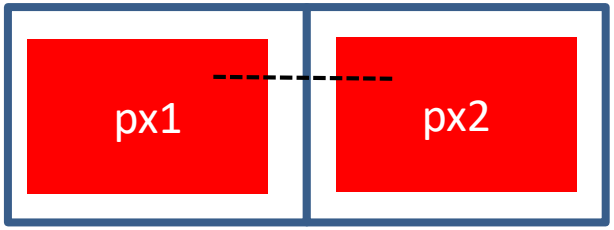
Segmentation in LGADs



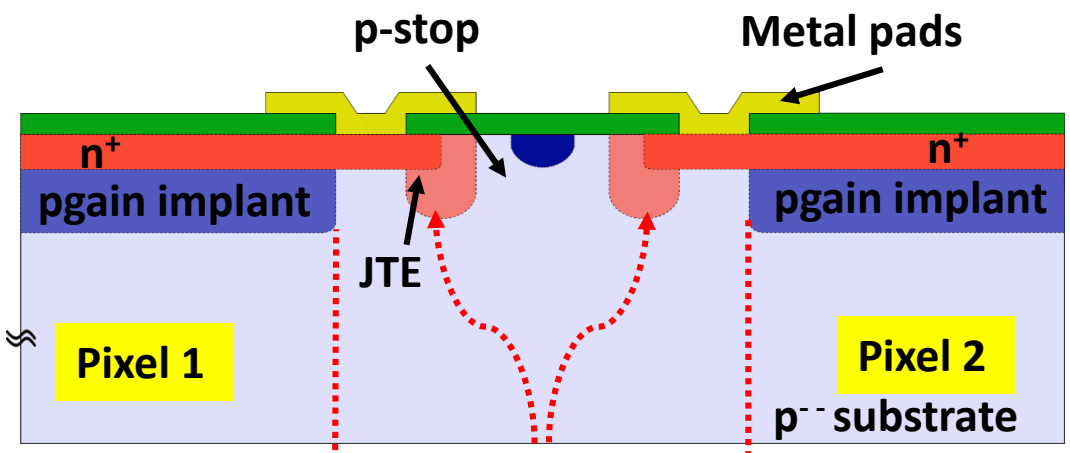


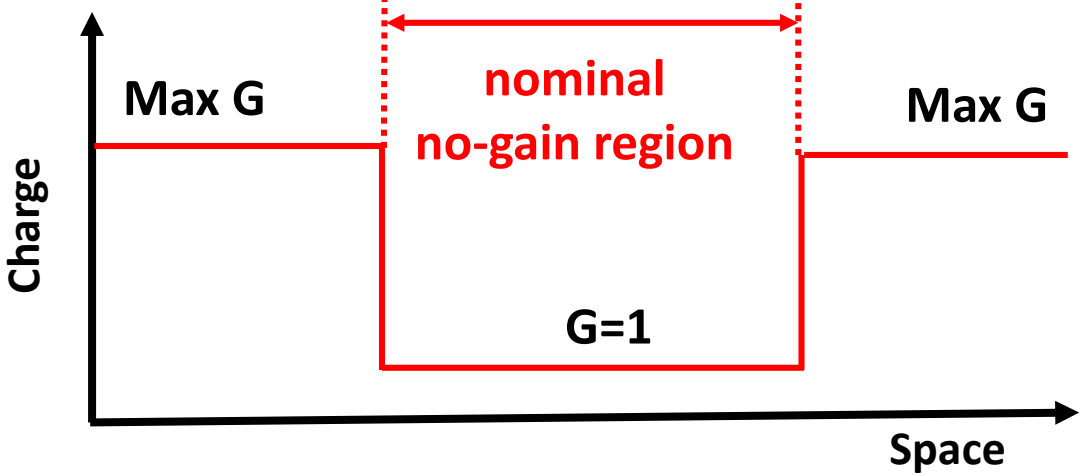
Segmentation in LGADs

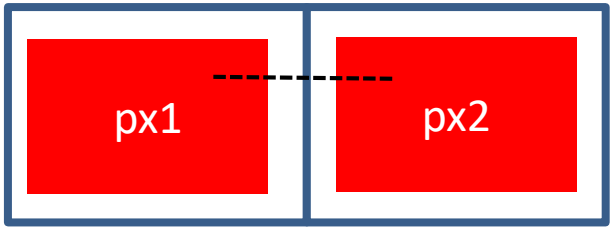




Segmentation in LGADs







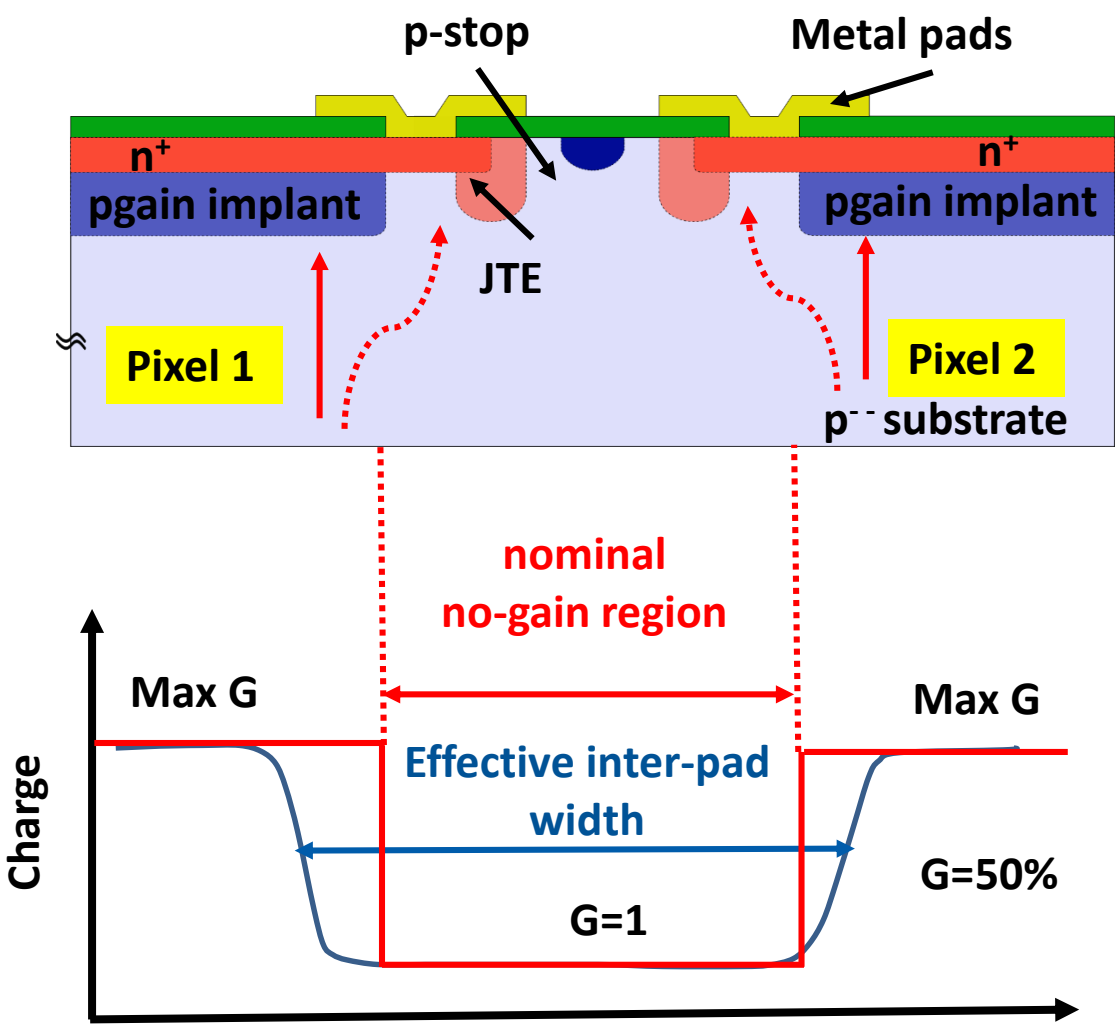
The pixel border is a dead-region. The carriers generated in this area are not multiplied.

Nominal NO-GAIN region

(PGAIN-PGAIN distance defined by layout)

Segmentation in LGAD

The collection and drift mechanisms also play a role in the no-gain region.



- Some carriers, generated at the periphery of the gain implant, are collected by the dee JTE and do not pass through the gain layer.
- **These carriers are multiplied with reduced gain**

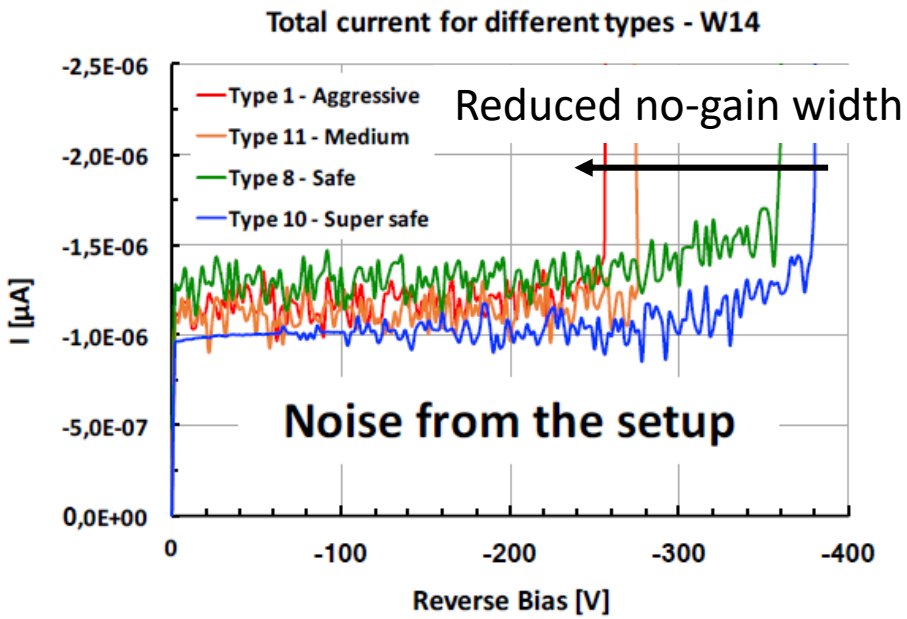
Effective interpad width
>=
nominal no-gain

Segmentation in LGAD

- The nominal no-gain width depends on:
  - **Fabrication technology**
  - **Physical limits** (maximum E fields) to fulfill operational requirements (V_{BD} , etc.)

Layout	No-gain width
UFSD 2 – Super Safe	66 um
UFSD 3 - Safe	31 um
UFSD 3 - Medium	20.5 um
UFSD 3 Aggressive	11 um

HPK (LGAD 3.1 2019) => 60um

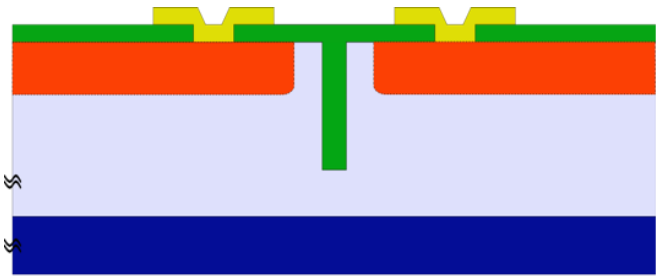


V. Sola – 35th RD50 Workshop, November 2019

There is an **intrinsic limit in reducing the inter-pad region**. A too small distance between n-doped regions and p-stop leads to early edge-BD and pop-corn noise

New Segmentation Strategies under development at FBK and INFN

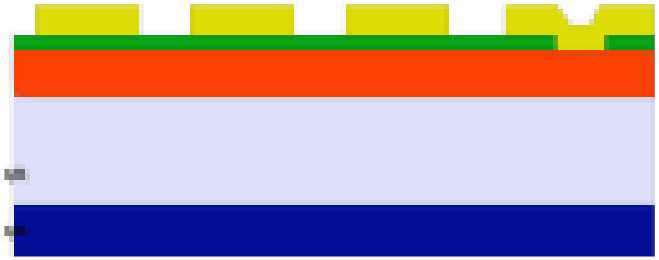
Trench-Isolated LGADs (TI-LGAD)



- DC readout
- Patterned p-gain
- Compact isolation structure based on Deep Trench Isolation technology

Resistive AC-coupled Silicon Detectors (RSD)

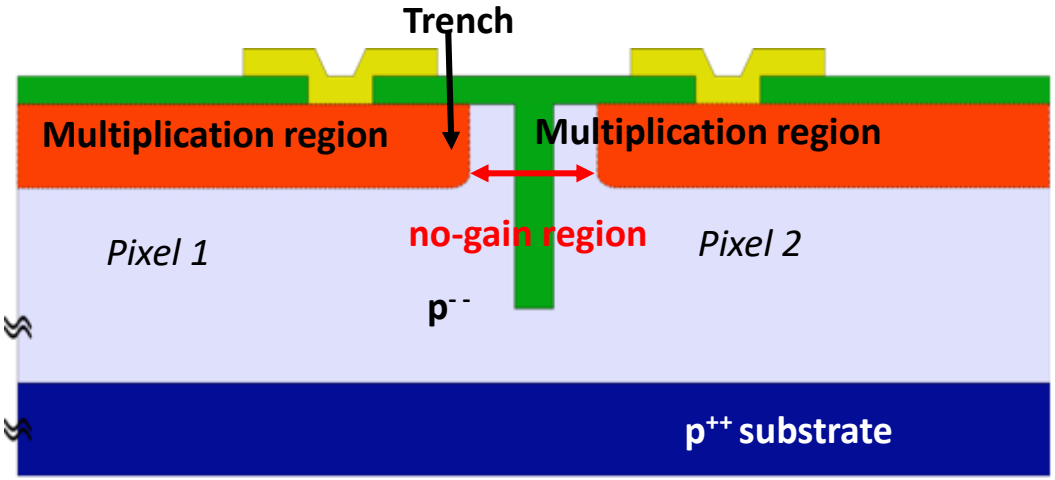
(M. Mandurrino INFN To)



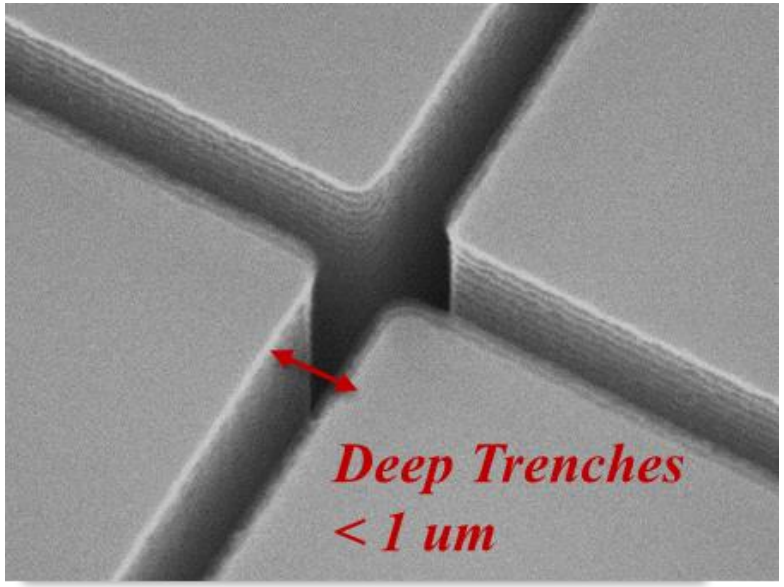
- Metal Pads AC-coupled to the resistive n+ via dielectric coupling layer
- Not-segmented PGAIN -> virtually 100% FF

2. Trench-Isolated LGADs (TI-LGADs)

Deep Trench Isolation technology



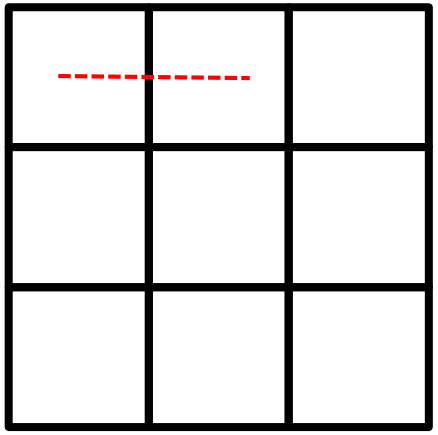
- **JTE and p-stop are replaced by a single trench.**
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.

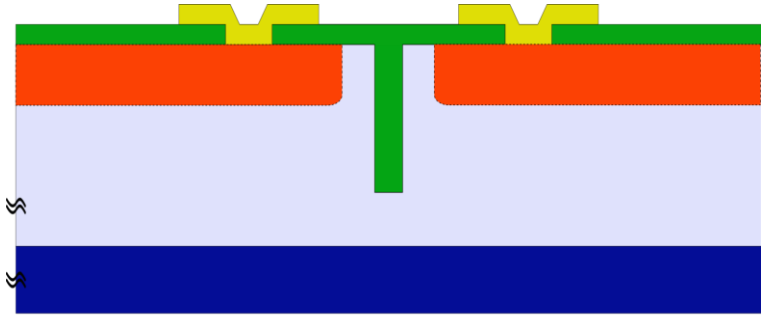


- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

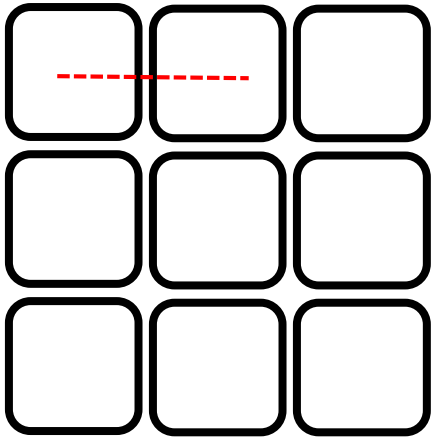
TI-LGAD Design & Simulations

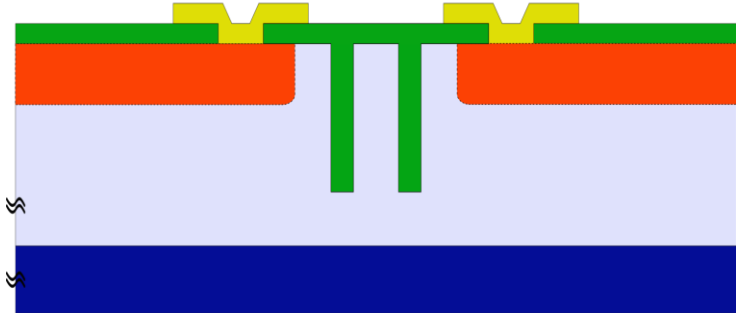
- **1 Trench Layout (trench grid)**





- **2 Trenches Layout**

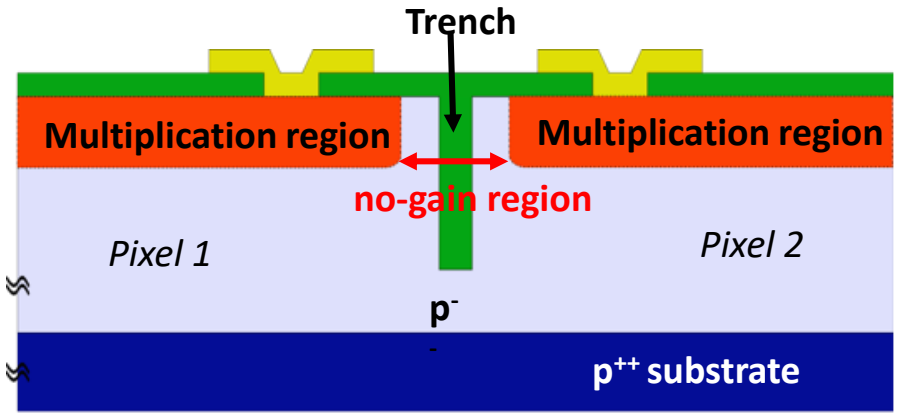




- **A TCAD simulations campaign** was carried out in order to optimize the TI-LGAD design in terms of:
  - Trench geometry (1 trench, 2 trenches)
  - Trench depth

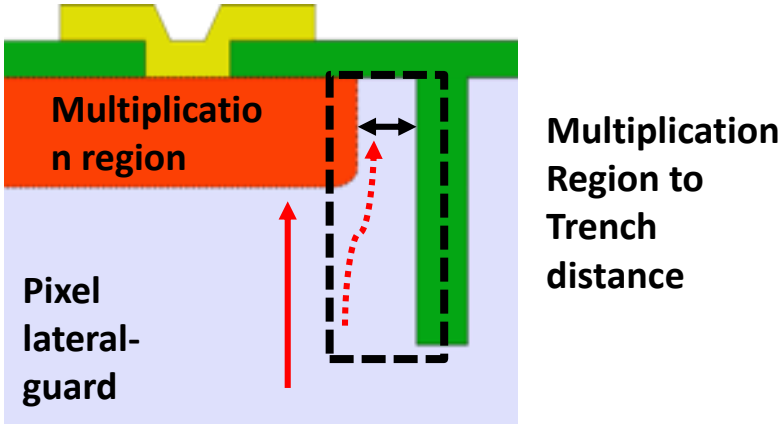
Layout	Nominal no-gain width
1 Trench	~ 4 um
2 Trenches	~ 6 um

Deep Trench Isolation technology



Two-fold advantage with respect to standard LGADs:

- Trenches are much smaller wrt JTE and p-stop => smaller nominal no-gain region (**from 20-60 um to 4-6um**)
- The E-field at the pixel border could be optimized to reduce the transition region width



Smaller gain-loss region is expected

1st Test Run of TI-LGADs (RUN 0)

First test run of TI-LGADs produced at FBK in 2019.

Sensor geometry:

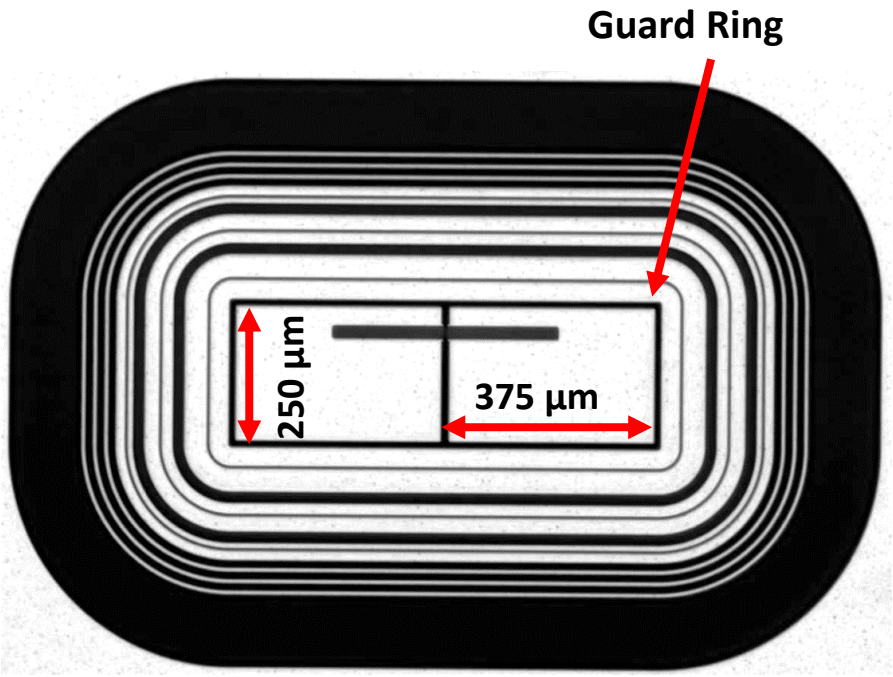
- 2x1 pixels (250 µm × 375 µm)

Layout splits (~30):

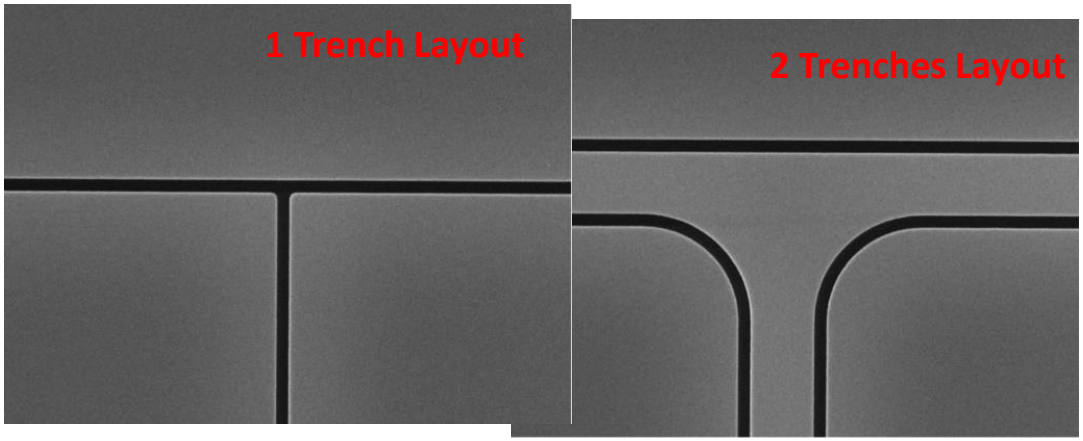
- Trench layout (1T and 2T)
- Pixel Lateral border (trench-multiplication region distance)

Process splits:

- trench fabrication process.
- Trench depth
- PGAIN implant doses



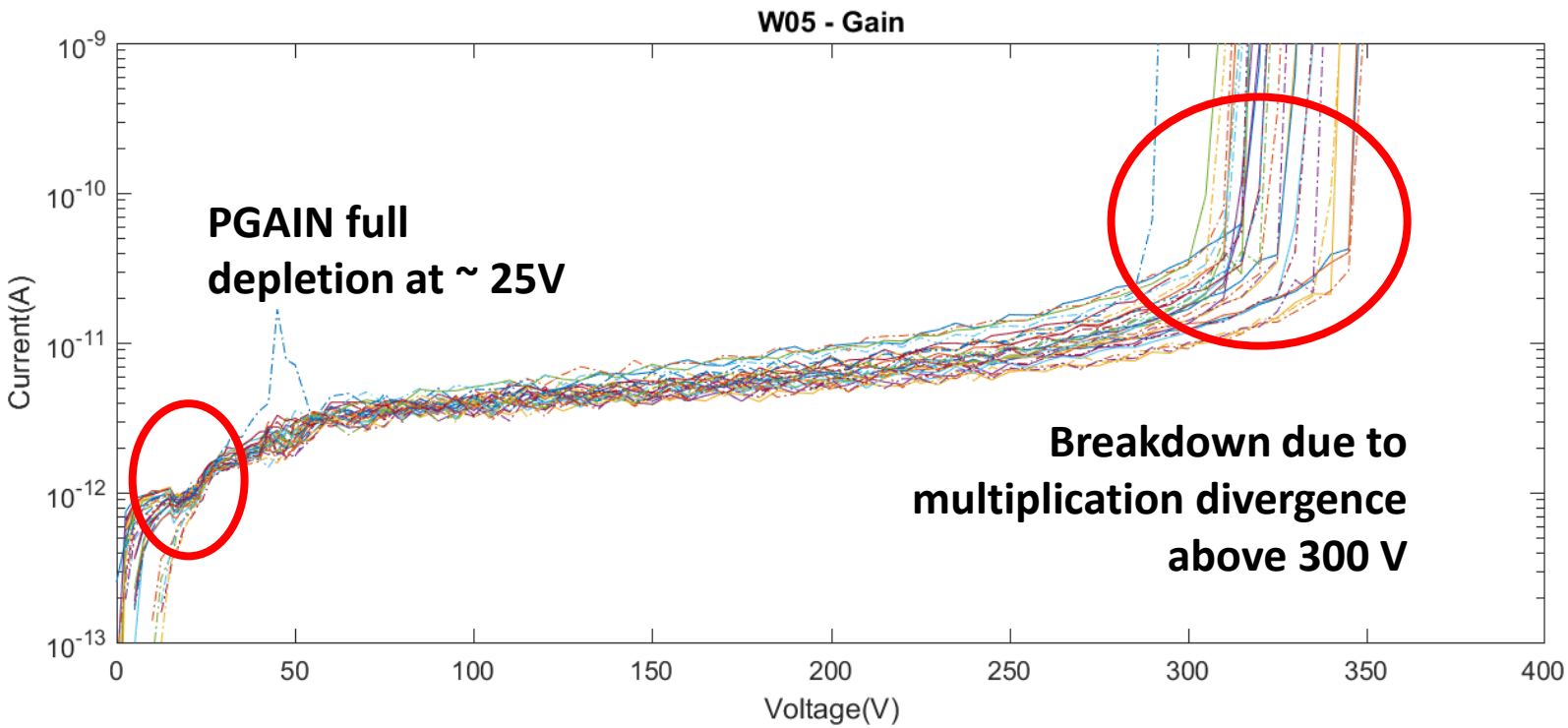
SEM images after trench etching



TI-LGAD Parametric Characterization (IV)

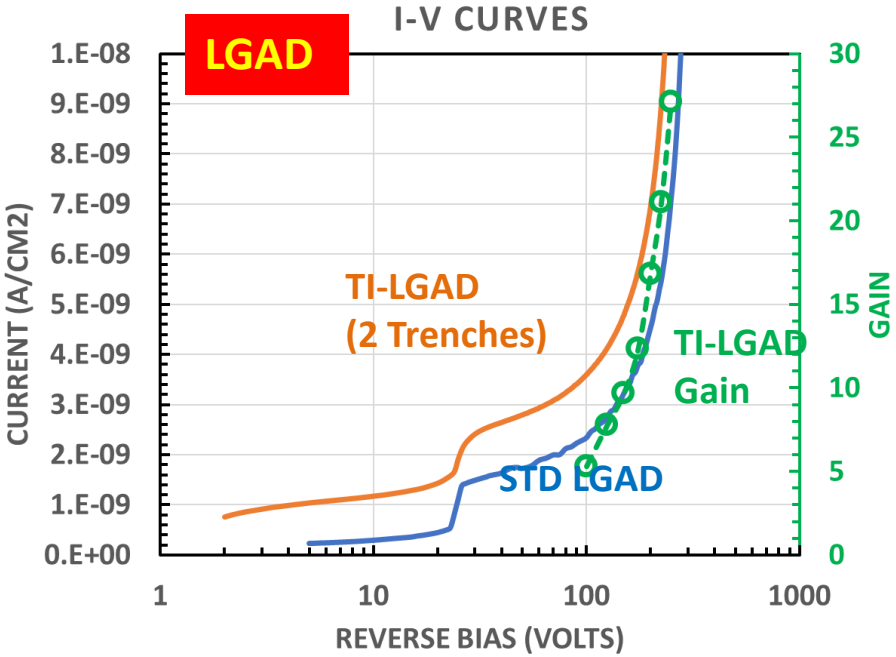
First IV curves show expected behaviour of TI-LGAD sensors:

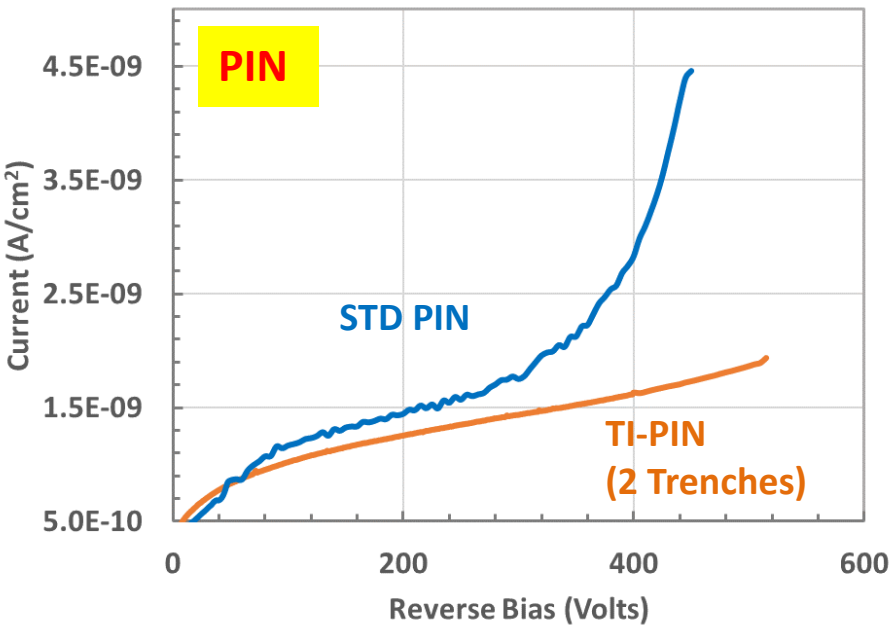
- Gain “knee” @ ~ 25 V
- Breakdown > 300 V



TI-LGAD Parametric Characterization (IV)

TI-LGAD vs STD LGADs (produced in the same batch with the same junction technology)

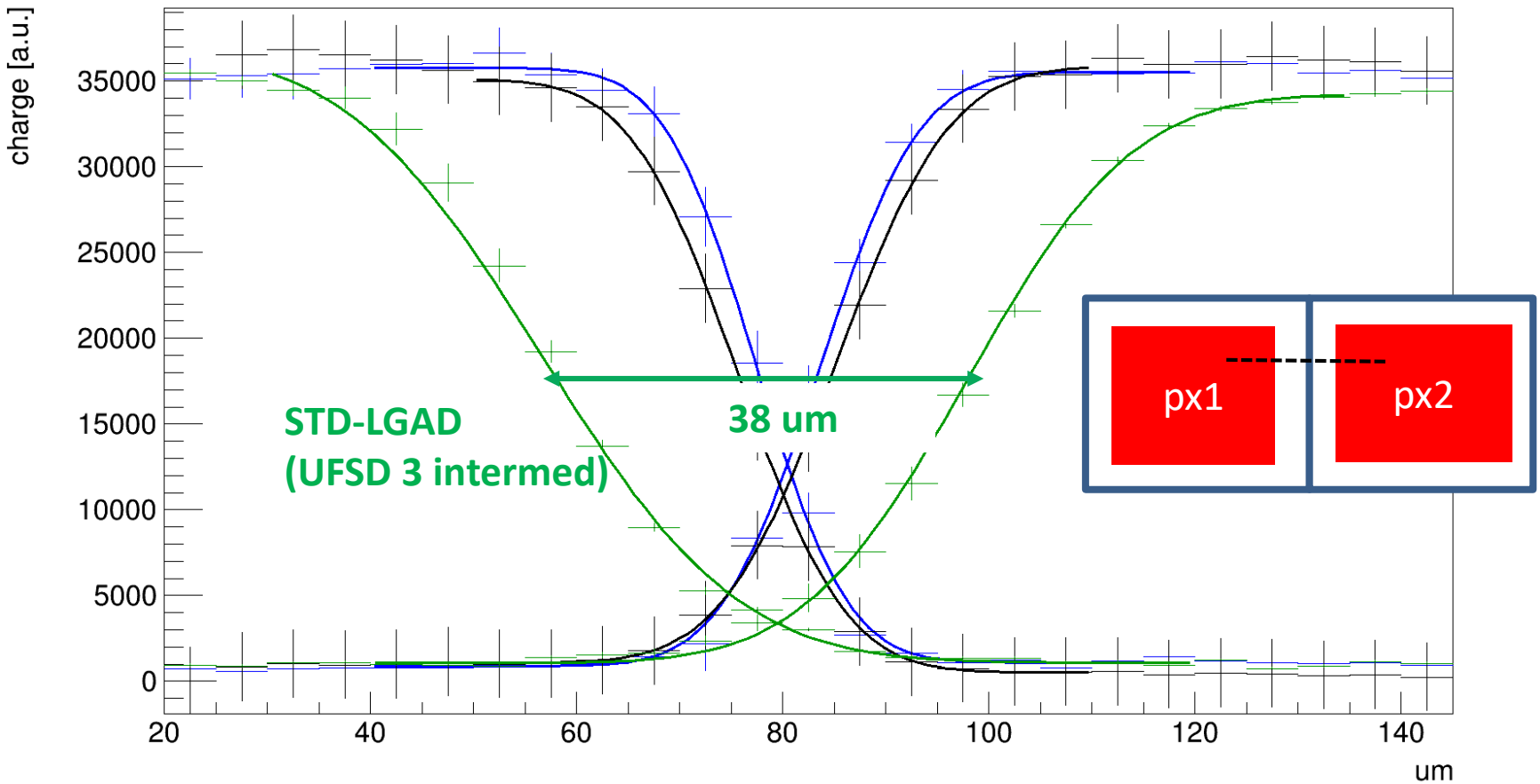




- Electrical behavior is compatible with STD LGADs
- Same knee Voltage and BD Voltage
- Difference in dark current is not significant

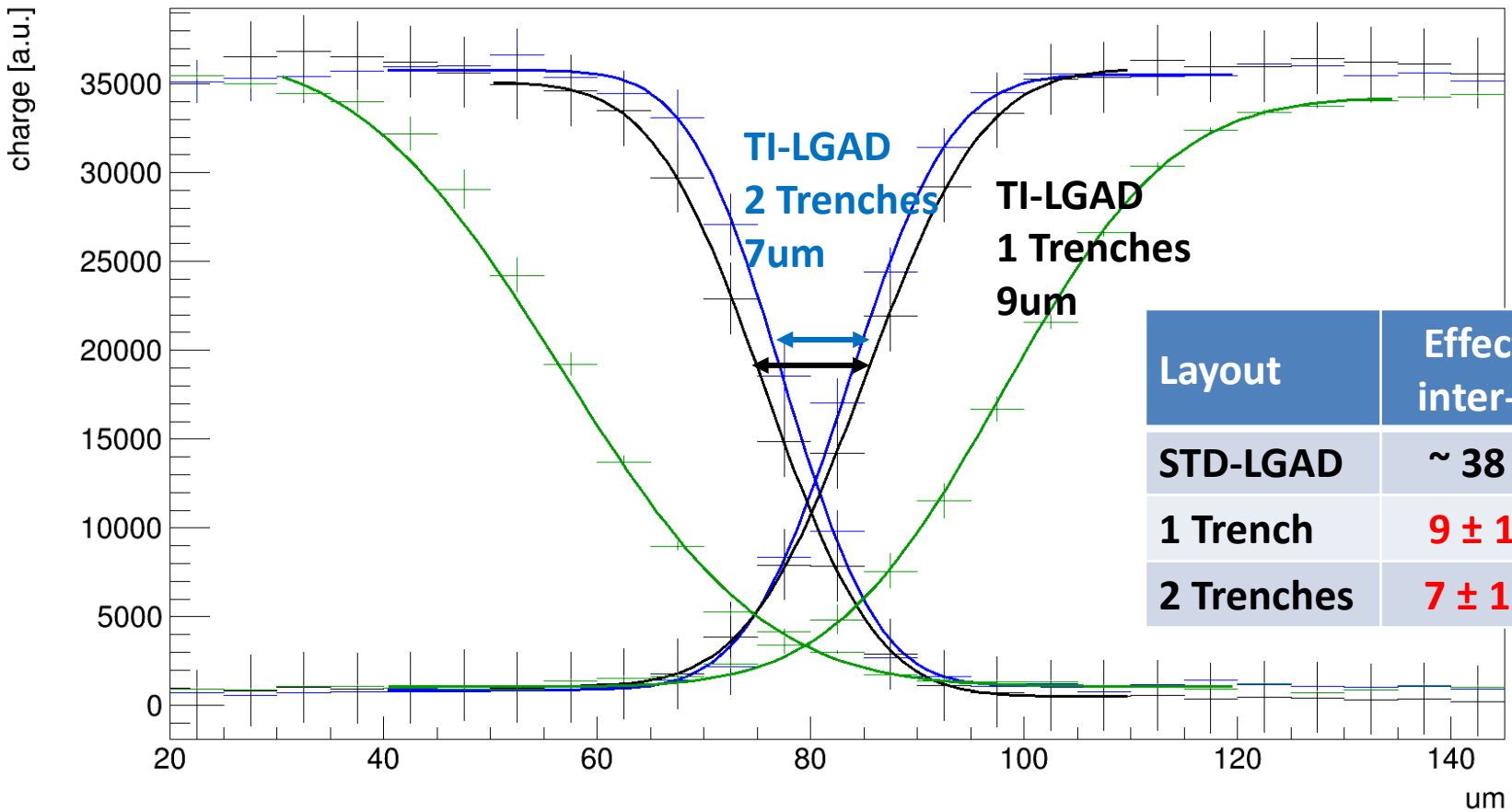
- STD PIN breakdown at 420 Volts (most likely at the pixel border).
- NO BD in TI-PIN up to 500V

TI-LGAD inter-pad Characterization (TCT laser Setup)



Measurements performed in Torino Silicon Lab (University of Torino - INFN)
F. Siviero – 35th RD50 Workshop, November 2019

TI-LGAD inter-pad Characterization (TCT laser Setup)

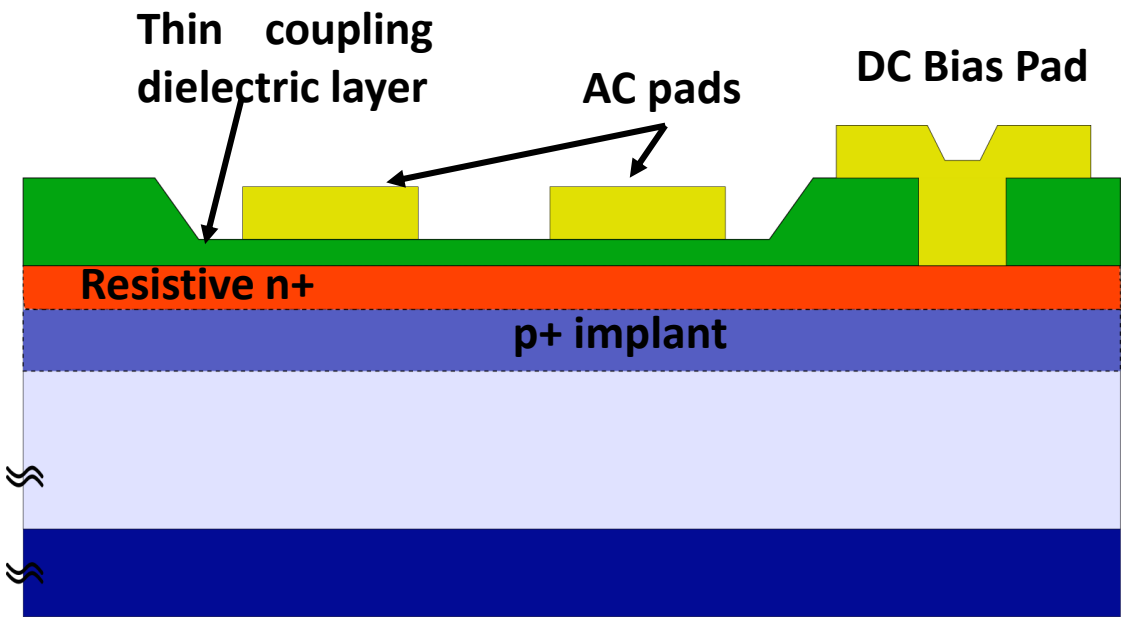


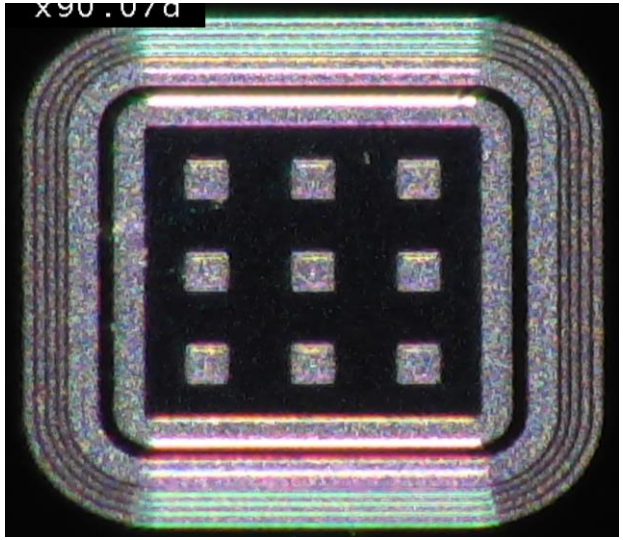
Layout	Effective inter-pad
STD-LGAD	~ 38 um
1 Trench	9 ± 1um
2 Trenches	7 ± 1 um

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
F. Siviero – 35th RD50 Workshop, Nove,ber 2019

3. Resistive AC-Coupled Silicon Sensors (RSD)

Resistive AC-coupled Silicon Detectors

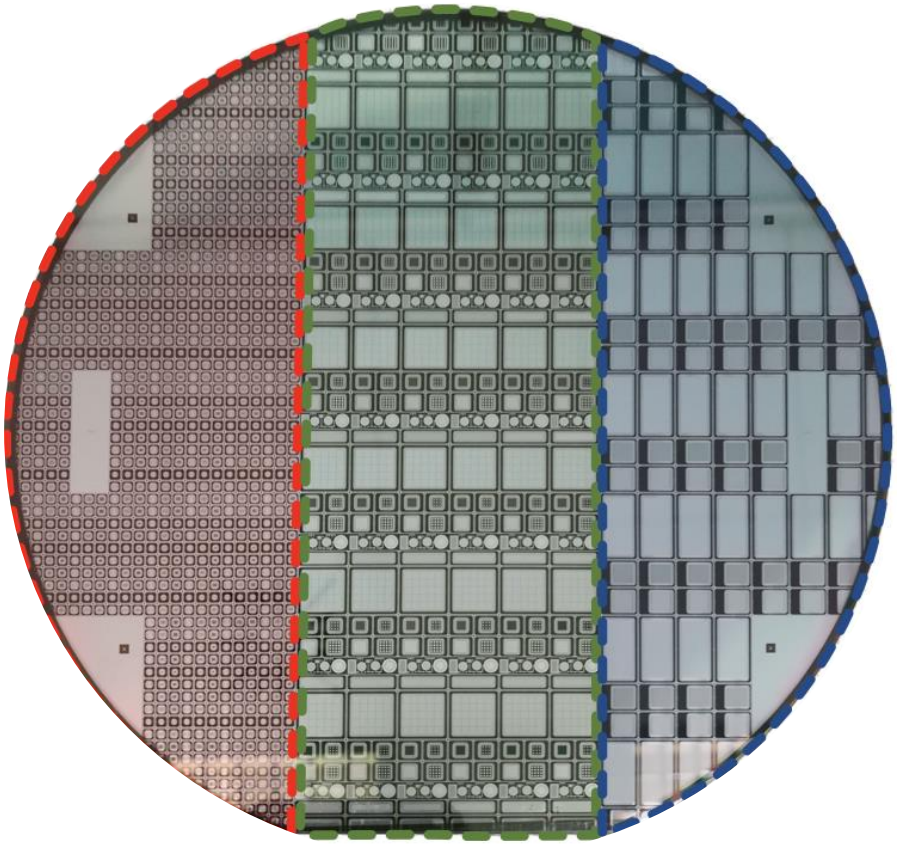




Main Technological Features

- Not-segmented p-gain implant
- Resistive n+ implant
- AC Metal pads
- Segmentation of the AC pads defines the pitch
- Thin coupling dielectric layer under yhe AC pads

First production of RSD at FBK



First RSD Production delivered in Q2 2019

Layout Splits:

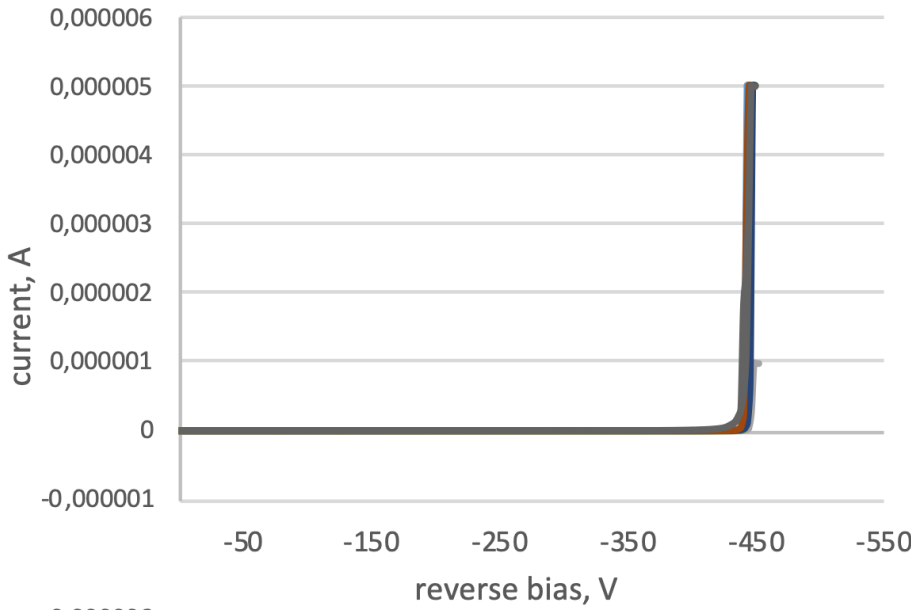
- Pad arrays (from 50 to 500 um pitch)
- Strips
- ALTIROC arrays

Process Splits:

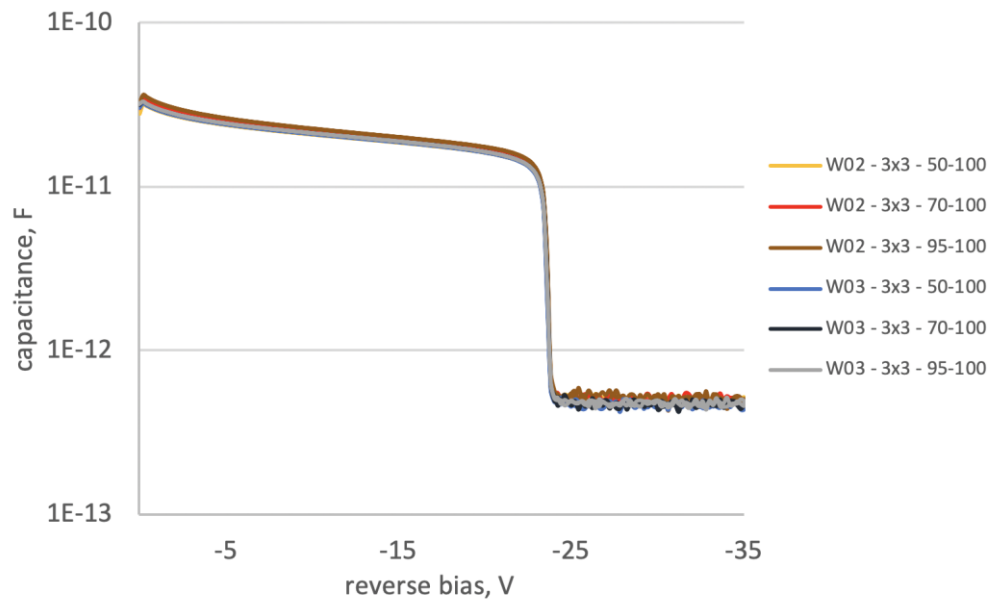
- Sheet resistance of the n+ implant
- PGain Implant Dose
- Coupling Dielectric Layer Thickness

RSD: Parametric Characterization

I-V



C-V



- Electrical behavior is compatible with STD LGADs
- High BD Voltage (~450 Volts)
- Very good homogeneity

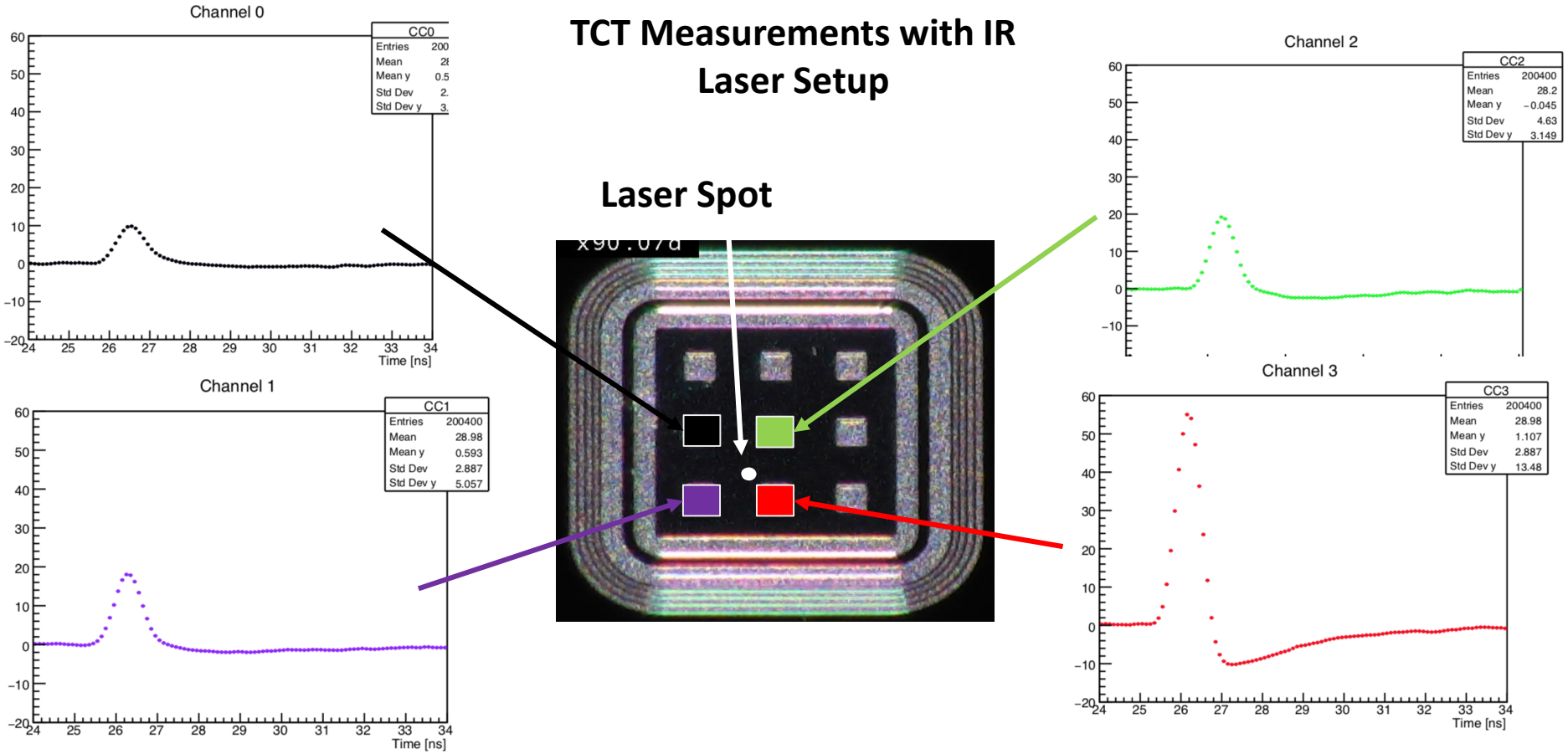
- Full-depletion of the pgain implant at ~ 25V

M. Tornago – 35th RD50 Workshop, November 2019

RSD: Spatial resolution

TCT Measurements with IR Laser Setup

Laser Spot



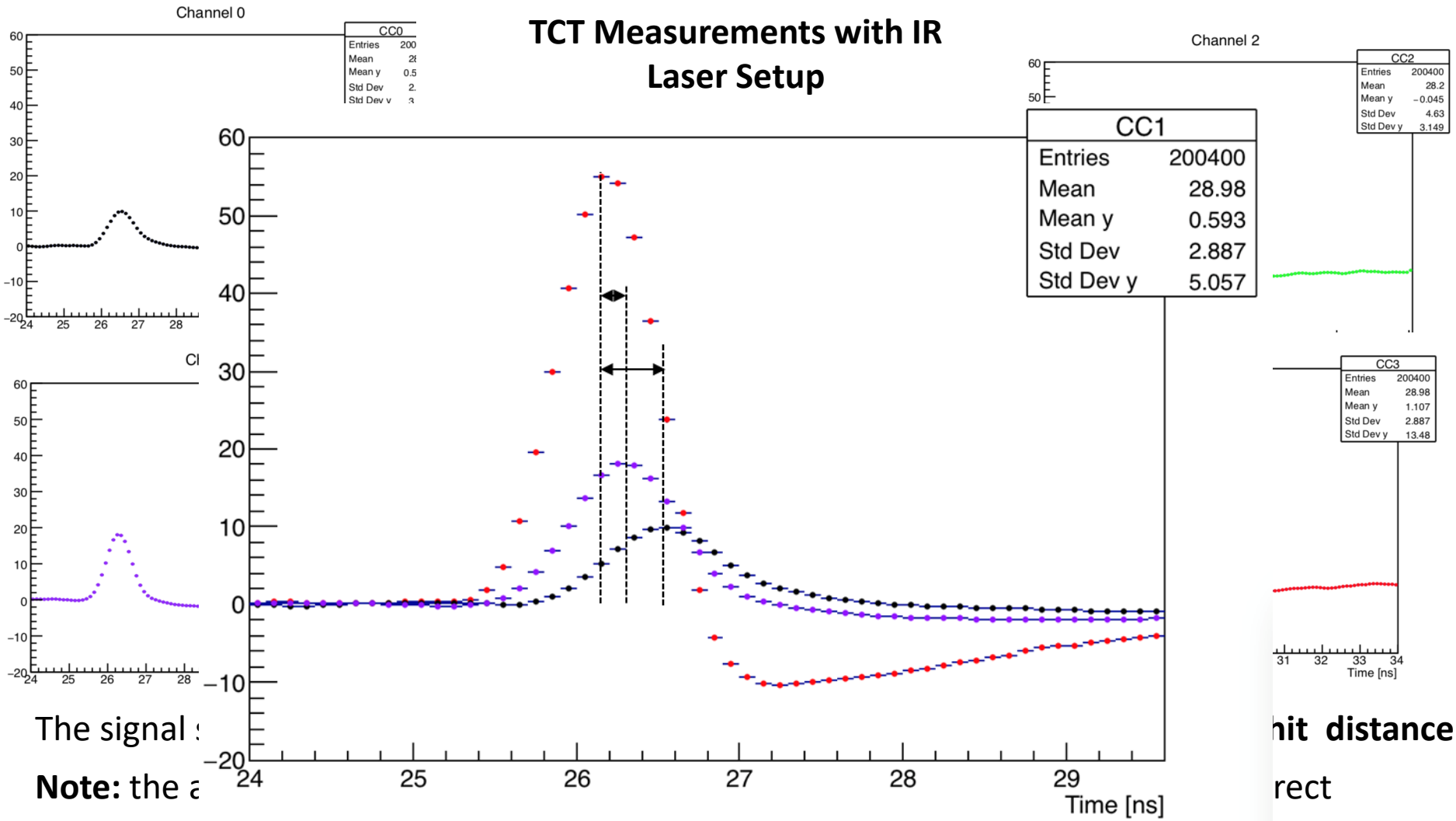
The signal spreads on several pads, with **amplitude inversely proportional to the hit distance**

Note: the amplitudes on far away pads is much larger than what is predicted by direct induction

Courtesy of N. Cartiglia

RSD: Spatial resolution

TCT Measurements with IR Laser Setup



The signal s … **hit distance**

Note: the a … rect

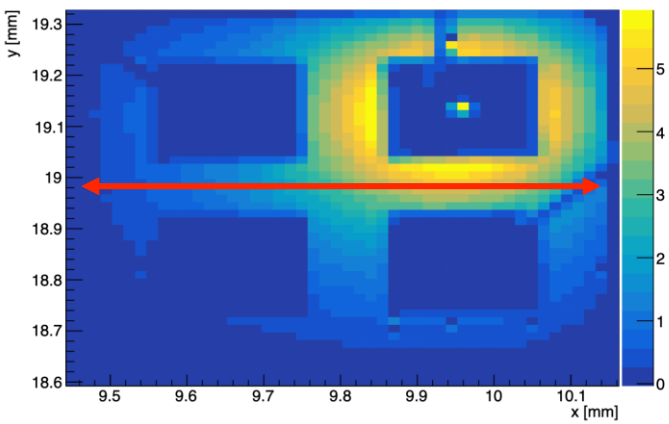
induction

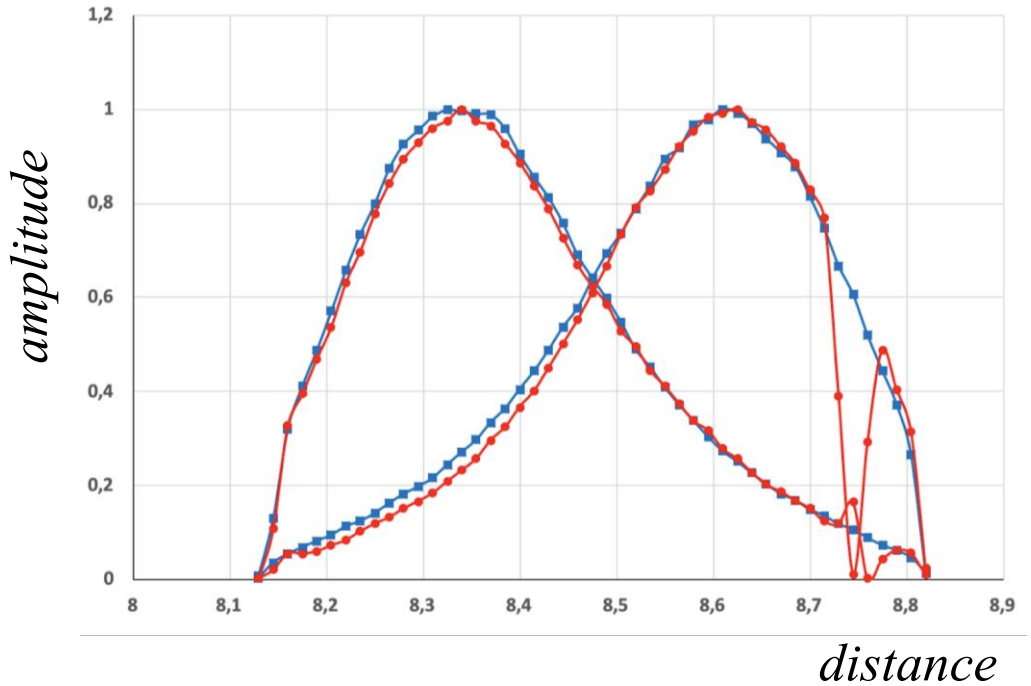
Courtesy of N. Cartiglia

RSD: Spatial resolution

Study of signal projections along a scan line (in red) for two neighboring pads

2x2 Pixels 300 um pitch





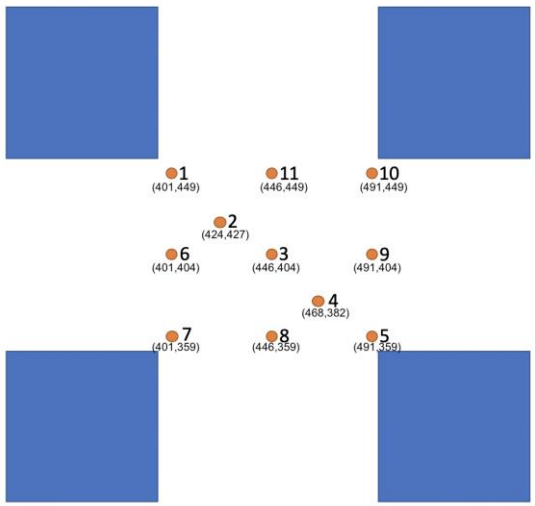
M. Tornago – 35th RD50 Workshop, November 2019

RSD: Spatial resolution

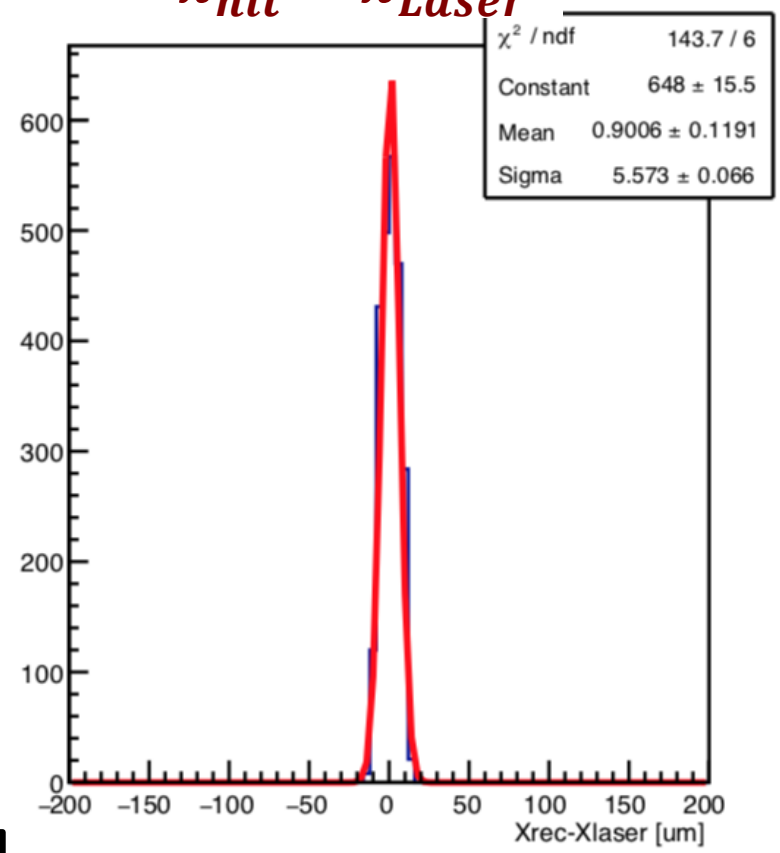
The position of the hit is obtained as:

(amplitude>10 mV)

$$x_{hit} = \frac{\sum_{i=1}^{i=4} x_{pad}(i) * Amp(i)^{Cor}}{\sum_{i=1}^{i=4} Amp(i)^{Cor}}$$



$x_{hit} - x_{Laser}$



100um pitch Array:

x resolution: 6 um, with an offset of 1 um

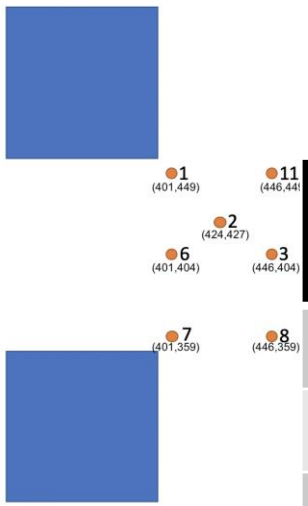
Courtesy of N. Cartiglia

RSD: Spatial resolution

The position of the hit is obtained as:

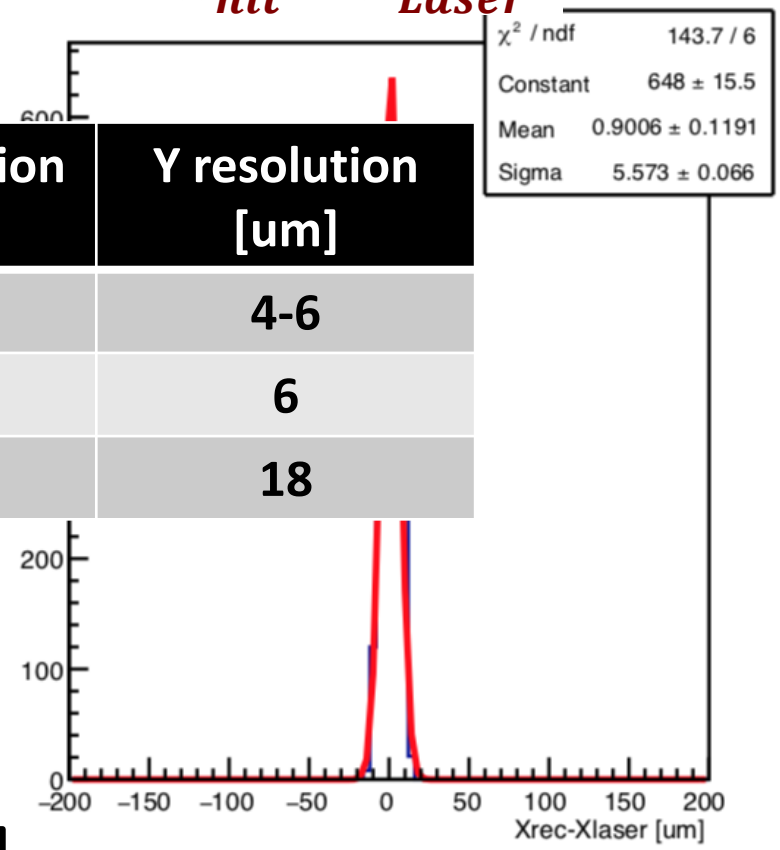
(amplitude>10 mV)

$$x_{hit} = \frac{\sum_{i=1}^{i=4} x_{pad}(i) * Amp(i)^{Cor}}{\sum_{i=1}^{i=4} Amp(i)^{Cor}}$$



	x resolution [um]	Y resolution [um]
100 um	4-6	4-6
200 um	6	6
500 um	19	18

$$x_{hit} - x_{Laser}$$



100um pitch Array:

x resolution: 6 um, with an offset of 1 um

Courtesy of N. Cartiglia

Conclusions

- The segmentation issues of the Standard LGAD technology has been presented. Inter-pad width is > 30 um
- Two development strategies have been introduced (**TI-LGADs** & **RSD**)
- First Samples of **Trench-isolated LGAD** have been successfully produced at FBK
- Preliminary electrical measurements showed the expected behavior in terms of knee Voltage, BD voltage, and IV-CV shapes
- TCT Characterization shows that the Interpad of TI-LGADs is reduced down to 7-9 um.
- Promising results also from **RSD** development. The RSD shows a sub-pixel spatial resolution down to 6 um (sigma).

FONDAZIONE
BRUNO KESSLER

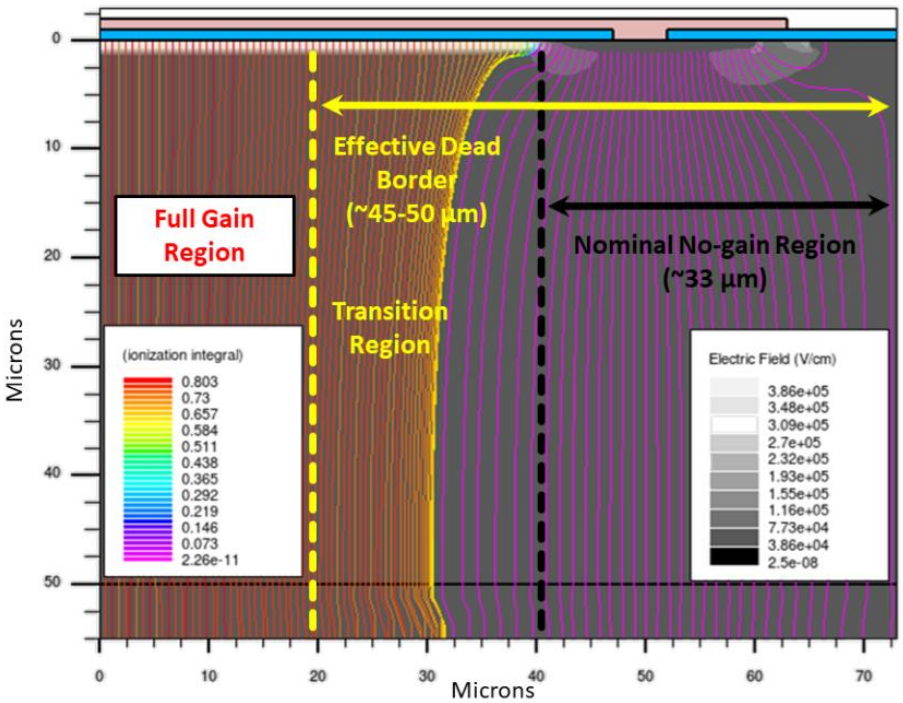
Thank you for your attention

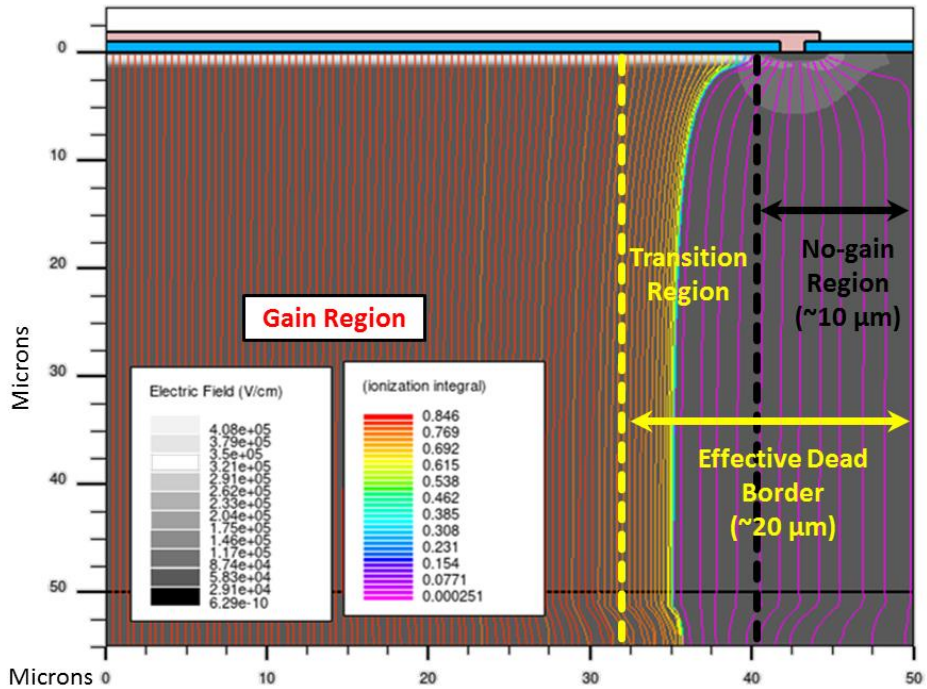
Acknowledgements

We kindly acknowledge the following funding agencies:

- INFN - Gruppo V
- INFN RSD Project
- Horizon 2020, grant UFSD669529
- H2020 project AIDA-2020, GA no. 654168
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- RD50 Collaboration, CERN
- Fondazione Bruno Kessler, Trento, ITALY

BACKUP Slides

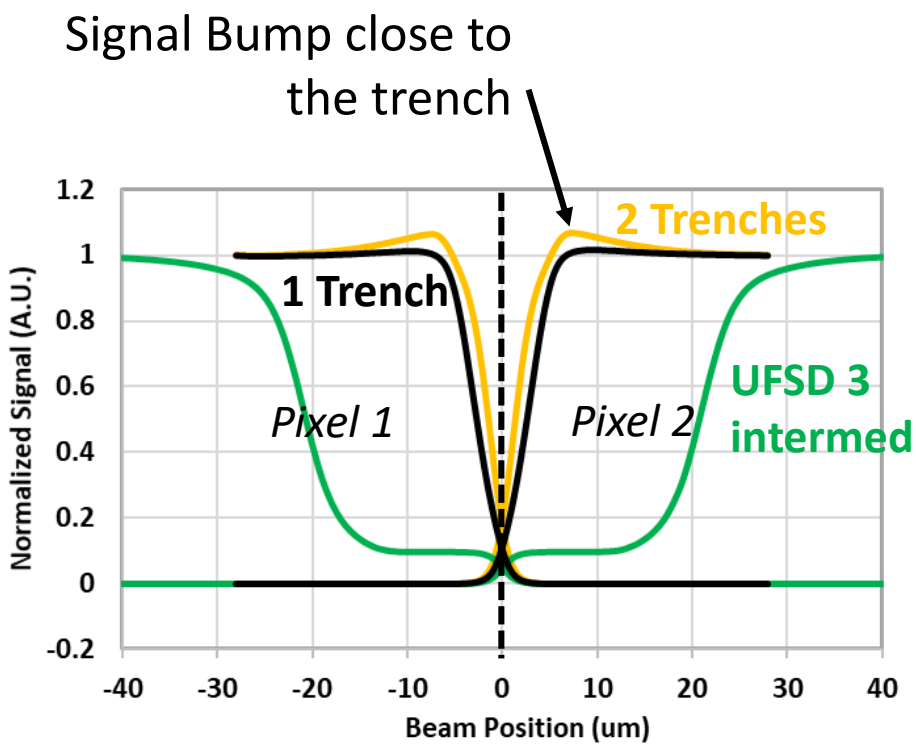




TCAD simulation of the pixel border in a UFSD2 structure (left) and UFSD3-intermediate structure (right)

TI-LGAD Design & Simulations

TCAD Simulated laser scan at the inter-pixel region (1um wide IR laser spot)

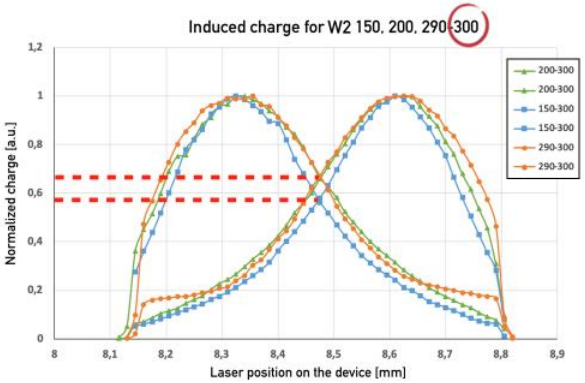


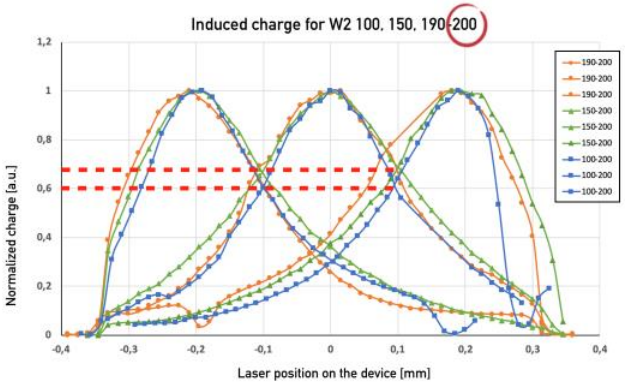
Layout	Nominal no-gain	Effective gain-loss
1 Trench	~ 4 um	~6 um
2 Trenches	~ 6 um	~3 um

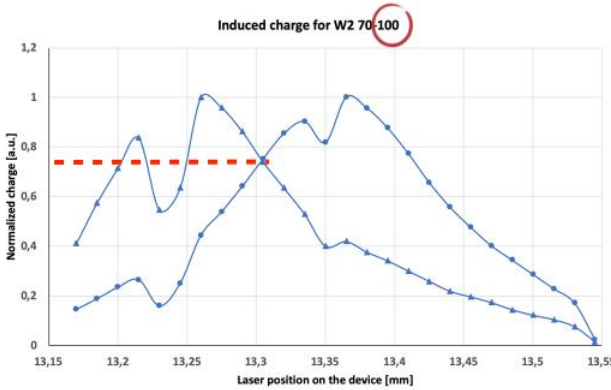
- Even if 2T Layout has larger nominal no-gain region the effective gain-loss width is less wrt to 1T layout
- 2T layout shows increased signals at the border (high local E-field)

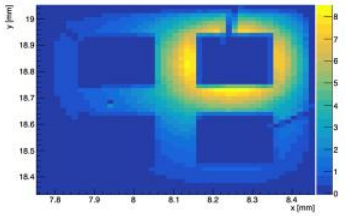
Design optimization trade-off between minimization of the gain-loss region and reduction of E-field at the border.

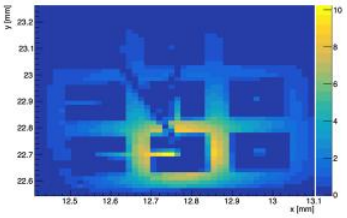
The induced charge shape depends on the pitch and the AC pad size in the DUTs

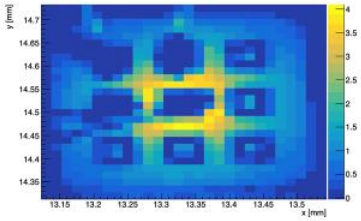








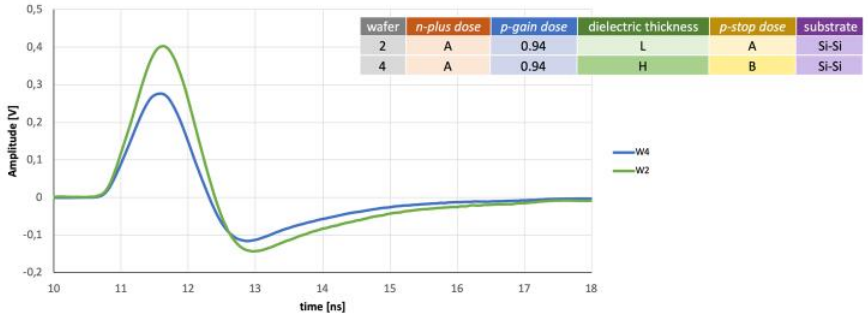




FONDAZIONE
BRUNO KESSLER

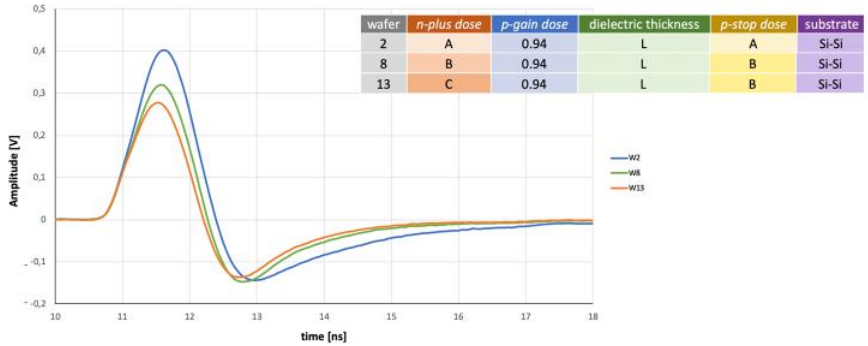
Waveforms change with the sensors RC, depending on n+ dose, oxide thickness and also AC pad size and pitch

Signal RSD 70-100 different oxide thickness



wafer	n-plus dose	p-gain dose	dielectric thickness	p-stop dose	substrate
2	A	0.94	L	A	Si-Si
4	A	0.94	H	B	Si-Si

Signals RSD 70-100 different n+ dose



wafer	n-plus dose	p-gain dose	dielectric thickness	p-stop dose	substrate
2	A	0.94	L	A	Si-Si
8	B	0.94	L	B	Si-Si
13	C	0.94	L	B	Si-Si

RSD signals W2 150, 200, 290-300, 70-100