4D LGAD Technologies and their Potential Applications in Future Lepton Colliders

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Fondazione Bruno Kessler

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FONDAZIONE BRUNO KESSLER

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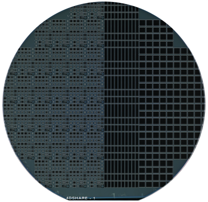
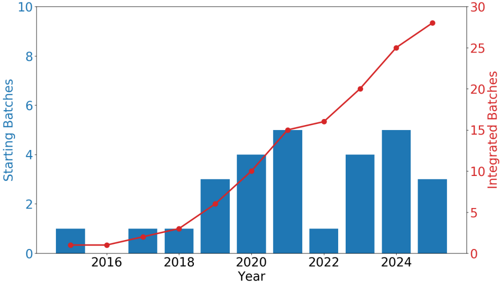
Fondazione Bruno Kessler

6 inch (150 mm)
Custom CMOS-like process

LGAD technologies:

- Standard
- Double sided (inverted)
- Trench isolated
- **AC coupled (RSD)**
- **DC-RSD**





Today: focus on FBK sensors
Other institutes also shown great results

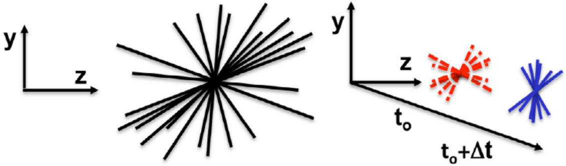
4D Tracking

Tracking with a resolution of O(10) μm and O(10) ps

- Applications:
  - Time of flight
  - Particle ID
  - Improve rate capabilities
  - High energy physics
  - Astroparticle physics
  - Medical
  - ... and more!
- Implementations:
  - Timing detector + tracker
  - **Combine timing and tracking in one sensor**

HL-LHC Application

[H. Sadrozinski et al. Rept. Prog. Phys. 81 (2018) 026101]

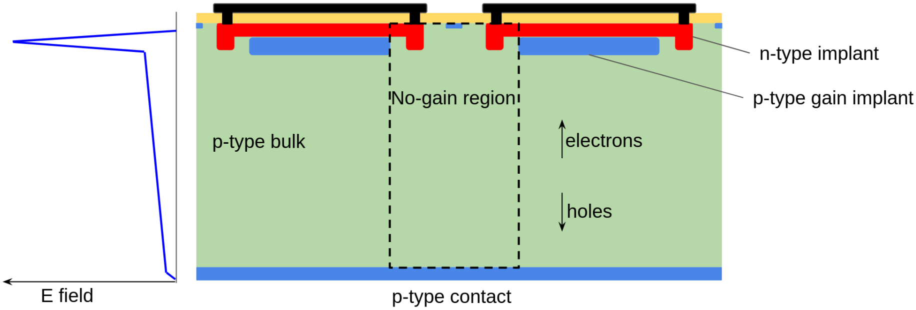


Use time coordinate to mitigate pile-up

- Track time resolution $\approx$ 30 ps
- Radiation resistance to few 10^{15} n_{eq}/cm^2
- Hit time resolution at end of life $\approx$ 50 ps

Lepton collider $\Rightarrow$ material budget $\leftrightarrow$ power consumption

(Standard) Low Gain Avalanche Diodes

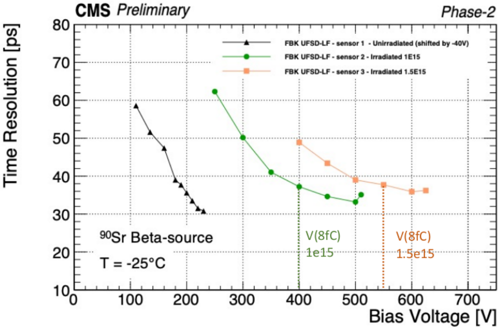


- Silicon detectors with charge multiplication
- Gain ≈ 10
- Gain layer provides high-field region
- No-gain region $\sim 30 - 80\ \mu$m
- Time resolution ~ 30 ps $\leftrightarrow$ thin $\sim 50\ \mu$m sensor

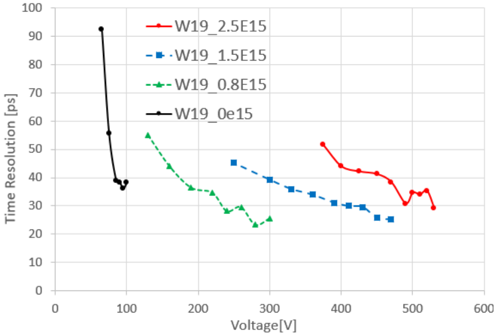
- **Improve SNR of the system**
  (When the sensor shot noise is not dominating)
- Noise and power consumption
  $\Rightarrow$ low gain

STD-LGAD Performance

[L. Lanteri TREDI2025]



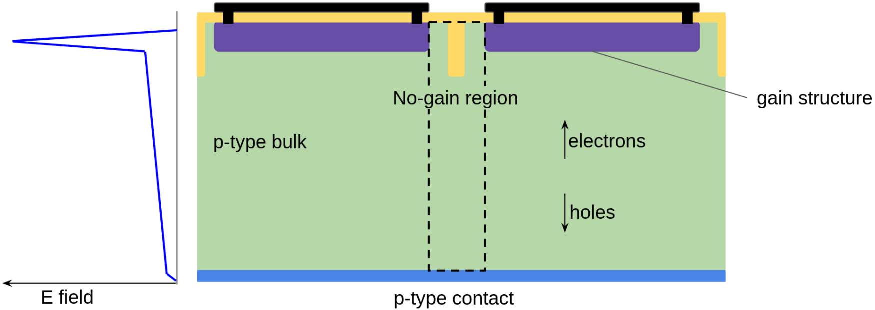
[A. Howard 37th RD50 Workshop]



- **Time resolution < 40 ps for** $2.5 \cdot 10^{15}$ **n**$_{eq}$**cm**$^{-2}$
- 1.3×1.3 mm^2 channels
- Spatial resolution = pitch$/\sqrt{12} \sim 375\ \mu$m
- 4D tracking only in conjunction with a separate system

Improve spatial resolution $\Rightarrow$ **smaller channels**

Trench Isolated LGADs

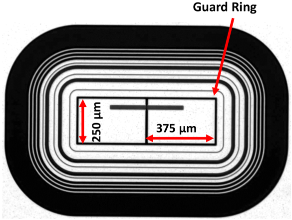


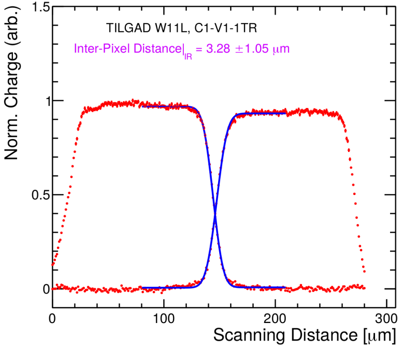
- Trenches substitute the isolation structures
- Trench width about 1 μm $\Rightarrow$ fill factor close to 100%

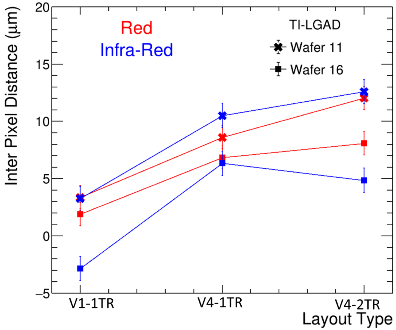
[G. Paternoster et al. IEEE EDL Vol 41 Issue 6 (2020) 884-887]

Interpad Distance

[A. Bisht Picosecond Workshop 2021]



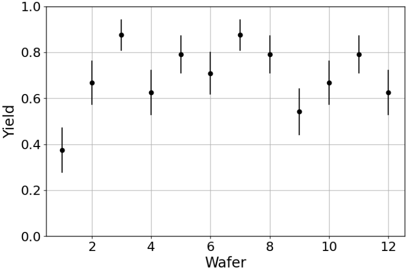




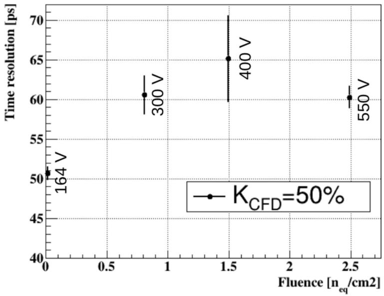
- Interpad 2-10 μm with laser
- $\sim$ 10$\times$ improvement from STD LGAD
- Some process and layout combination:
  $\rightarrow$ gain in trench region > gain of pad
  $\rightarrow$ negative interpad

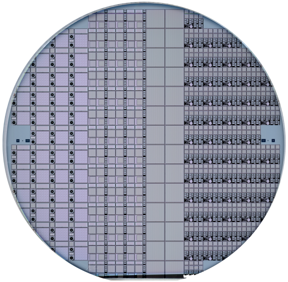
TI-LGAD Development

[A. Bisht TREDI2024]



[I. Velkovska TREDI2025]

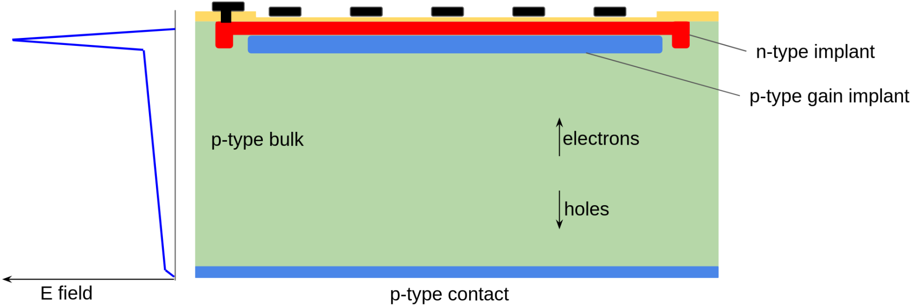




- First carbonated TI-LGAD in AIDA Innova batch
- **Demonstrated promising yield for $\sim$1$\times$1 cm^2 sensors**
- Pitch down to 55 μm
- Beam test of irradiated test structures (250$\times$375 μm^2)
- **$\sim$60 ps resolution after** 2.5 $\cdot$ 10^{15} **n$_{eq}$/cm^2**

Possible 4D tracking using small pitch $\rightarrow$ large power density

AC-LGADs (Resistive Silicon Detectors)



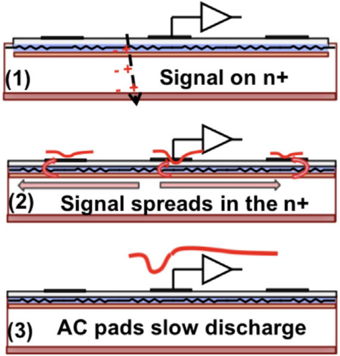
- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Readout channels capacitively coupled $\Rightarrow$ resistive layer to limit signal spreading
- No restrictions on channel dimension

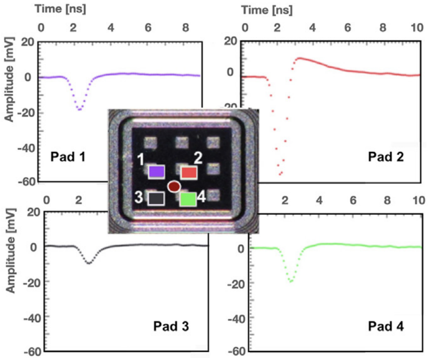
[M. Mandurrino et al. IEEE EDL Vol 40 Issue 11 (2019) 1780-1783]

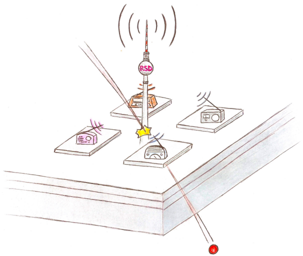
Resistive Signal Sharing

[M. Tornago et al. NIMA 1003 (2021) 165319]

[M. Tornago 36th RD50 Workshop]



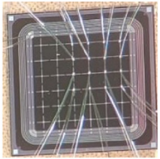


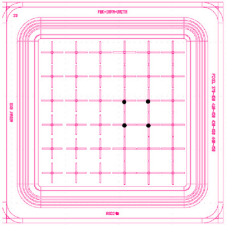


- Ionization is amplified and signal induced on resistive layer
- Signal propagates on the resistive layer
- AC-coupling to readout provides lower impedance path than resistive layer $\rightarrow$ signal is read out
- The capacitance of the electrodes discharge

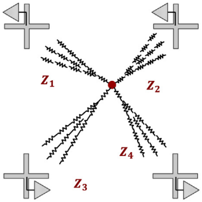
Resistive Signal Sharing

[R. Arcidiacono et al. NIMA 1057 (2023) 168671]



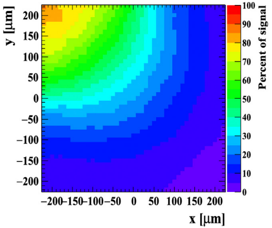


- Cross electrodes
- 450 μm pitch

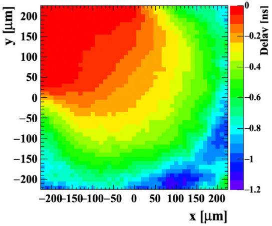


[L. Menzio et al. NIMA 1065 (2024) 169526]

Amplitude template



Delay template

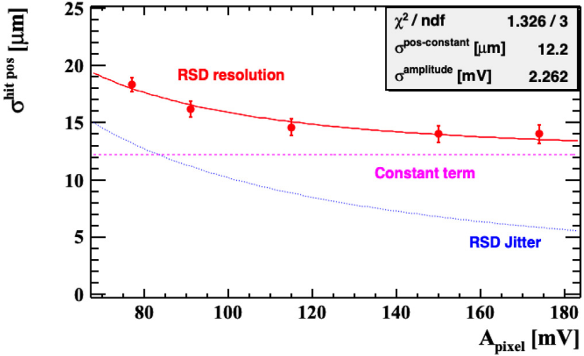


- Signal shared proportionally to the impedance to each surrounding electrode
- Response templates are created using beam test data (space and time)
- Position estimated using space template
- Time estimated starting from hit position (propagation on resistive layer)

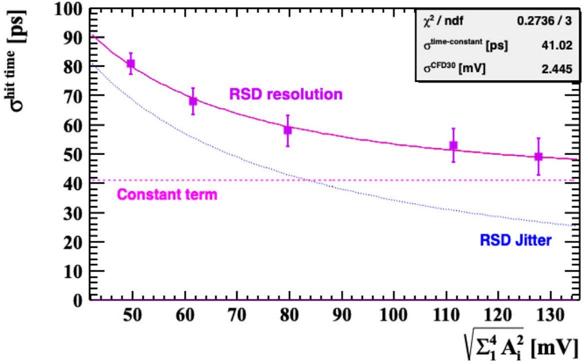
Results

[L. Menzio et al. NIMA 1065 (2024) 169526]

Space



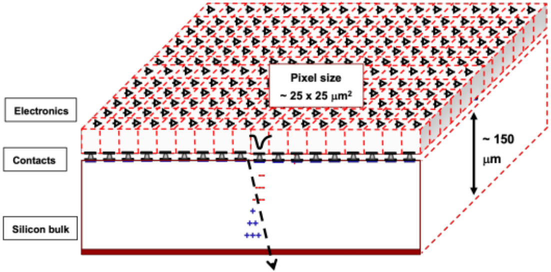
Time



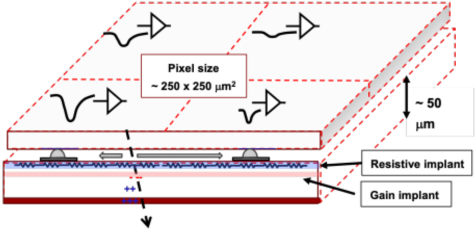
- Cross electrodes 450 μm pitch
- 14 μm spatial resolution
- 50 ps time resolution
- **Spatial resolution is $\sim$3-4% of pitch**
- **4D tracking**

Consequences

[N. Cartiglia et al. JPS Conf. Proc. 42, 011029 (2024)]



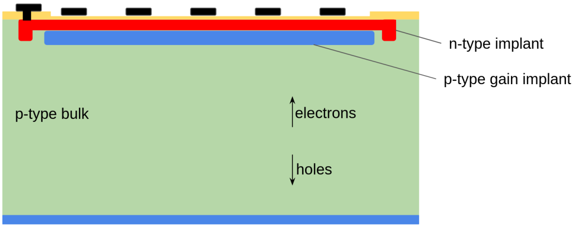
Standard Silicon Detector



Resistive Silicon Detector

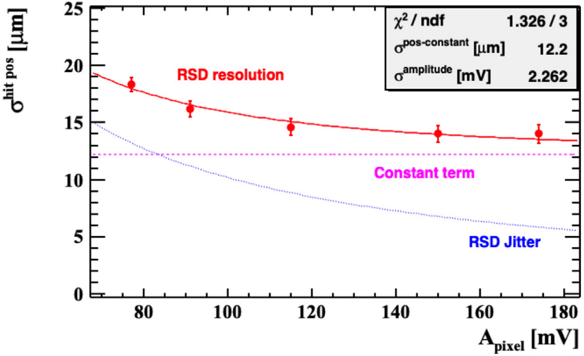
- Time resolution $\Rightarrow$ thin sensors with gain
  $\Rightarrow$ no charge sharing through Lorentz or incidence angle
- 14 μm resolution without signal sharing $\Rightarrow \sim$ 50 μm pitch
  $\Rightarrow \sim$ **80 times channel count reduction with resistive sharing**
  $\Rightarrow$ Power consumption reduction
- **Thin sensors and decreased power consumption $\Rightarrow$ lighter 4D tracker**

AC-LGADs (Resistive Silicon Detectors)



- Continuous gain layer
- Time resolution
- Resistive charge division
  $\Rightarrow$ Larger channel pitch for same resolution
- Bipolar signal with recharge tail
- Biasing only at sensor edge
- Poor signal confinement

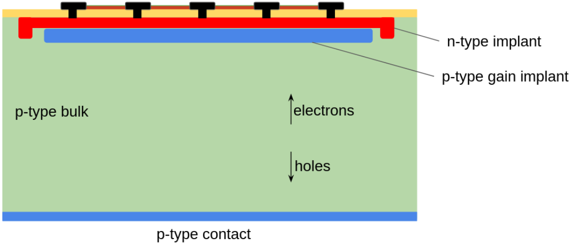
[L. Menzio et al. NIMA 1065 (2024) 169526]

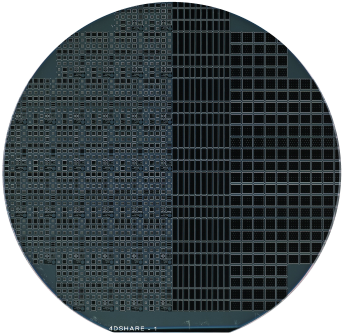


$\sim$15 μm resolution with 450 μm readout pitch
$\sim$50 ps time resolution

Resolution about 3-4% of readout pitch

DC Resistive Silicon Detectors





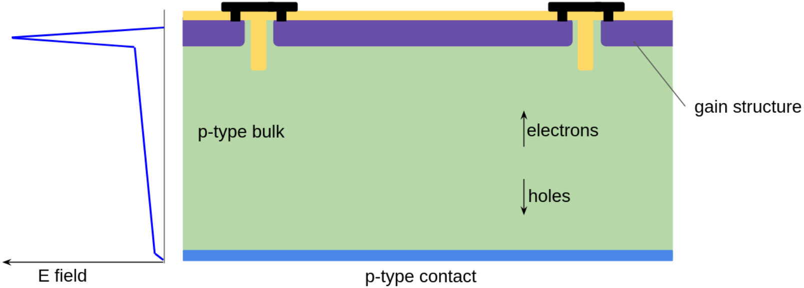
- Continuous gain layer
- Time resolution
- Resistive charge division
  $\Rightarrow$ Larger channel pitch for same resolution
- ~~Bipolar signal with recharge tail~~
- ~~Biasing only at sensor edge~~
- ~~Poor signal confinement~~

Variations of:

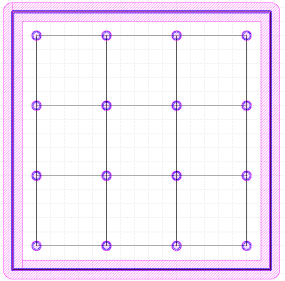
- Resistivity
- Contact fabrication
- Geometry: pixels, strips, square, triangular

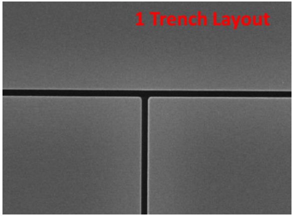
Trenches used for signal confinement

Trench DC-RSD



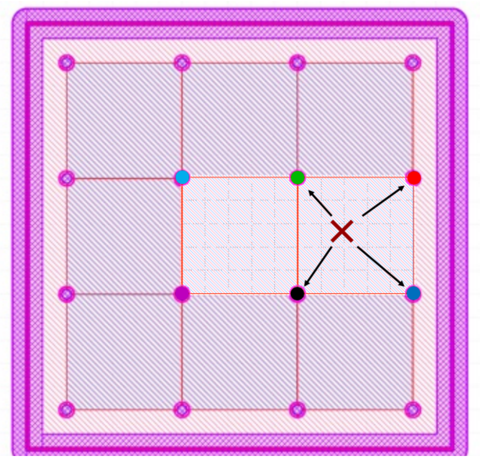
- Trench to contain the signal
- Segmented gain layer
- Pads read out neighboring regions





Signal Confinement

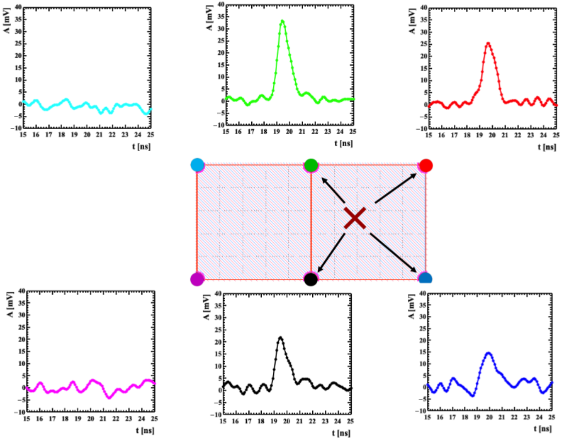
[N. Cartiglia et al. TREDI2025]



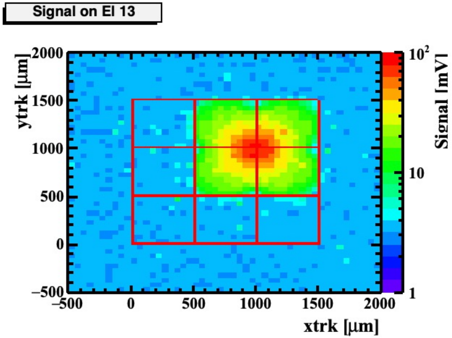
- Square cells 500 μm
- **Signal is contained**

Signal Confinement

[N. Cartiglia et al. TREDI2025]



- Square cells 500 μm
- **Signal is contained**

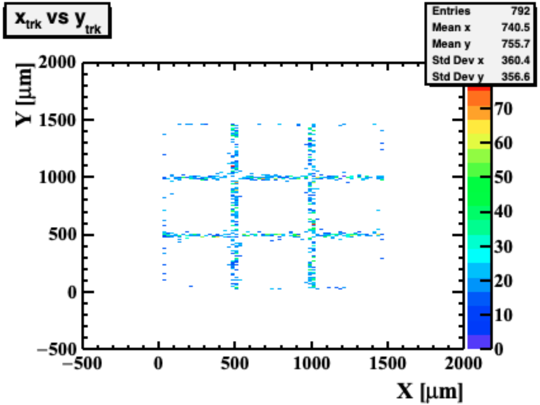


Trench Effect

- Hits with reduced amplitude
- Lower gain in trench region
- 500 μm pitch $\Rightarrow$ **fill factor $\sim$ 99%**

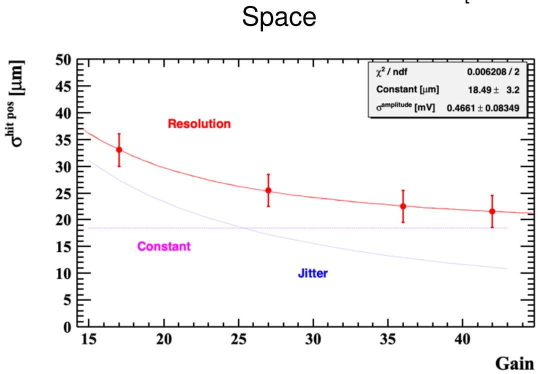
[R. Arcidiacono VCI2025]

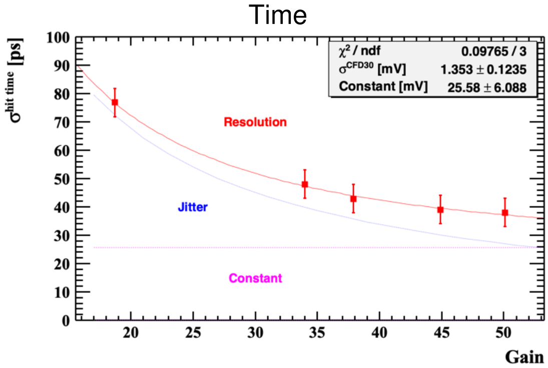
Map of hits with reduced amplitude



Resolution

[R. Arcidiacono VCI2025]



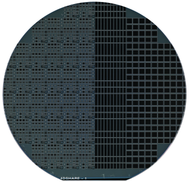


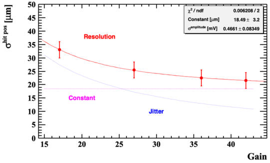
- Square cells 500 μm side
- 20 μm spatial resolution
- 40 ps time resolution
- **Spatial resolution is $\sim$5% of pitch**
- **4D tracking**

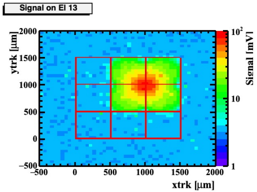
Summary

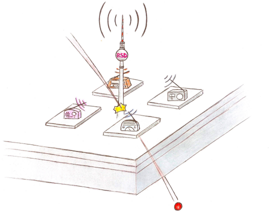
- Several mature LGAD technologies
- Thin sensors show good time resolution
- No signal sharing
  - STD-LGADs: poor position resolution
  - TI-LGADs: position resolution improved through segmentation
- Resistive signal sharing
  - AC-LGAD: 4D tracking sensor
  - DC-RSD: 4D tracking sensor
- Resitive signal sharing improves position resolution for a given pitch

AC-LGAD and DC-RSD sensors are promising technologies for lightweight 4D trackers





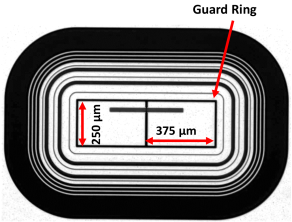


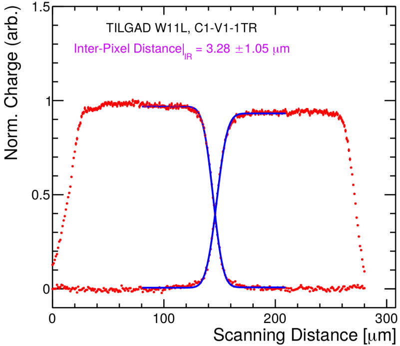


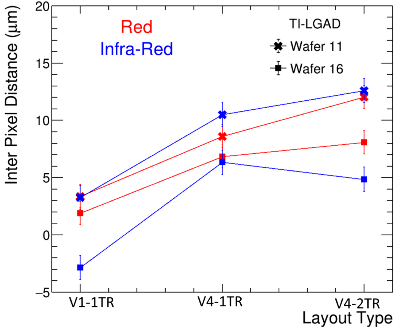
Backup Material

Interpad Distance

[A. Bisht Picosecond Workshop 2021]



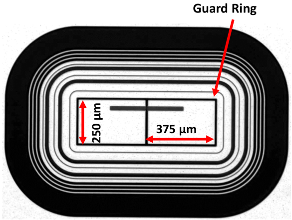


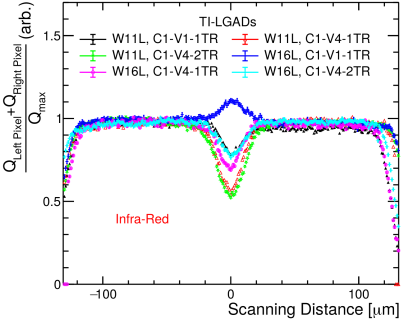


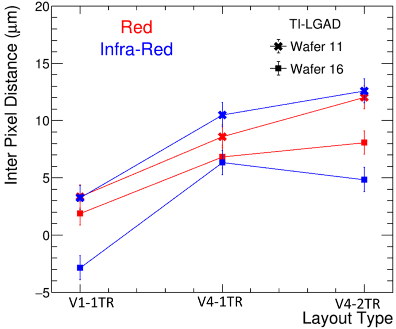
- Interpad 2-10 μm with laser
- $\sim 10\times$ improvement from STD LGAD
- Some process and layout combination:
  $\rightarrow$ gain in trench region > gain of pad
  $\rightarrow$ negative interpad

Interpad Distance

[A. Bisht Picosecond Workshop 2021]







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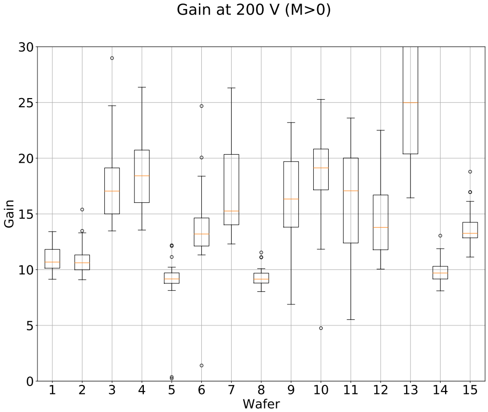
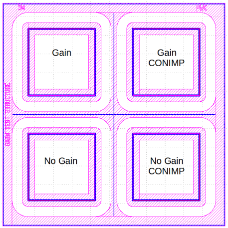
Median Gain 200 V

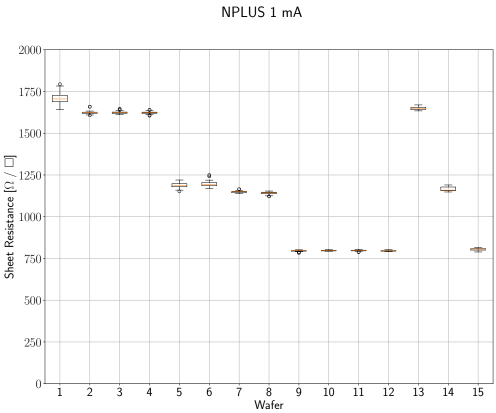


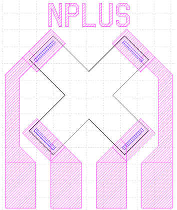
Wafer	NPLUS dose	CONIMP	PGAIN dose	EPI batch
1	0,25		1.02	A
2	0,25	Y	1.02	A
3	0,25	Y	1.06	A
4	0,25	Y	1.06	A
5	0,5		1.02	A
6	0,5		1.06	A
7	0,5	Y	1.06	A
8	0,5	Y	1.02	A
9	1		1.02	A
10	1		1.06	A
11	1	Y	1.02	A
12	1	Y	1.06	A
13	0,25	Y	1.06	B
14	0,5	Y	1.02	B
15	1	Y	1.06	B

- **Gain has the right values**
- NPLUS affects the gain
- High dispersion due to defects in starting material (wafer 7, 9, 10, 11, 12)



Median Sheet Resistance NPLUS





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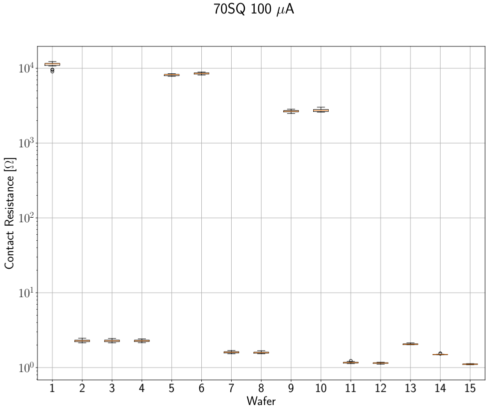
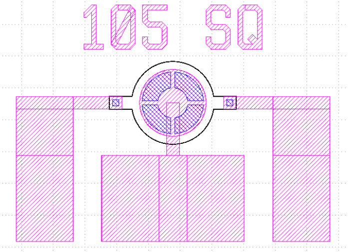
3	0,25	Y	1.06	A
4	0,25	Y	1.06	A
5	0,5		1.02	A
6	0,5		1.06	A
7	0,5	Y	1.06	A
8	0,5	Y	1.02	A
9	1		1.02	A
10	1		1.06	A
11	1	Y	1.02	A
12	1	Y	1.06	A
13	0,25	Y	1.06	B
14	0,5	Y	1.02	B
15	1	Y	1.06	B

Resistance values in the correct range

Median Contact Resistance Pad 70 μm





TRENCH, CONTACT, METAL

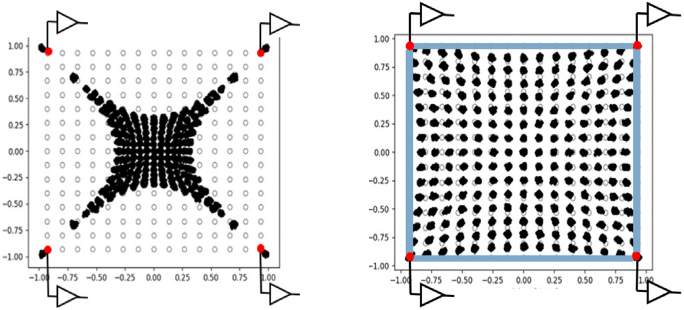
- 4 point measurement
- 100 μA current

Effects from NPLUS and CONIMP

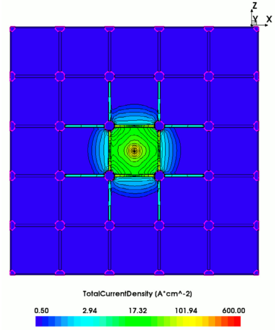
CONIMP reduces contact resistance from 10k to a few Ω

Future DC-RSD: from Trenches to Resistors?

[L. Menzio et al. NIMA 1041 (2022) 167374]



MIP Signal
Resistors between readout pads



[F. Moscatelli et al. NIMA 1064 (2024) 169380]

- Charge COG $\Rightarrow$ Pincushion distortion
- Resistors reduce distortion
- Connection to readout pads and resistive layer

Resistors reduce distortion and provide signal confinement