Technology Development of LGADs at FBK

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M. Andrae, A. Bergamaschi, B. Schmitt, J. Zhang

18/02/2020 TREDI 2020

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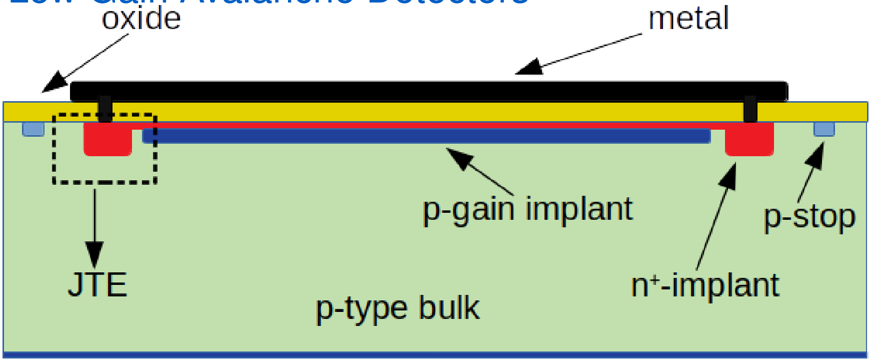
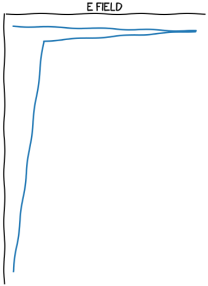
Low Gain Avalanche Detectors

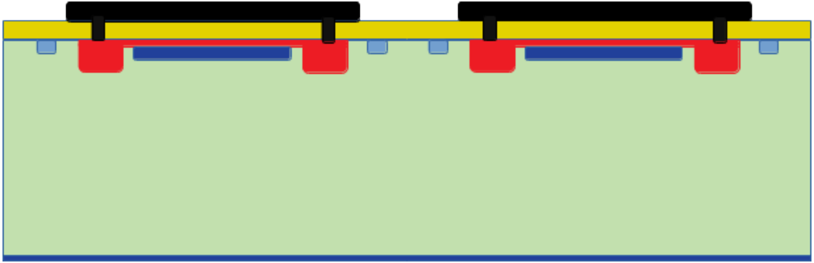




- Silicon detectors with charge multiplication
- Gain $\approx$ 10
- Gain layer provides high-field region
- Junction Termination Extension improves stability

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

Segmentation

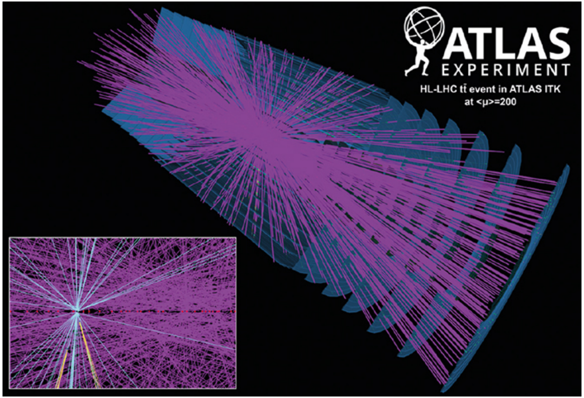


- LGAD structure is repeated
- No-gain area between channels
- JTE and channel isolation contribute to the no-gain area

High Energy Physics

HL-LHC: With the current vertex resolution a significant fraction of the vertices will not be resolved

[ATLAS simulation]

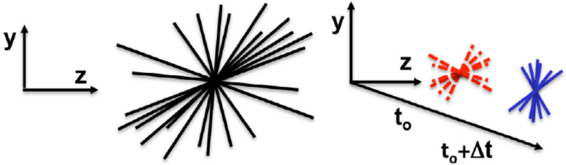


Development within the UFSD project

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

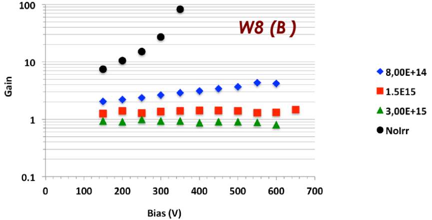
[H. Sadrozinski et al. 2018 Rep. Prog. Phys. 81 026101]

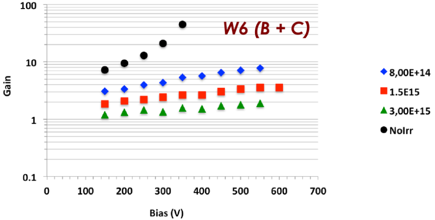


Radiation Hardening of LGADs

[R. Arcidiacono TREDI2018]

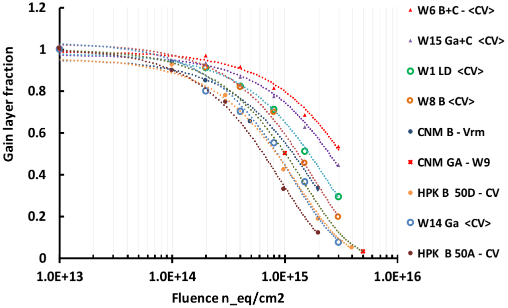
Gain = Q(LGAD) / Q(PiN)





- Thin sensors
- Mult. layer affected by acceptor removal
- Modify the mult. layer doping profile
- Use of different dopants to reduce the effect (Ga, C co-implantation)

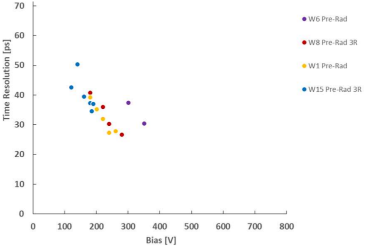
[M. Ferrero et al. NIM A 919 (2019) 16-26]



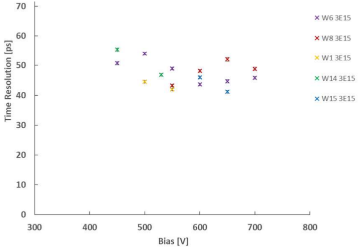
Carbon co-implantation makes the gain layer more radiation hard

LGADs for Timing

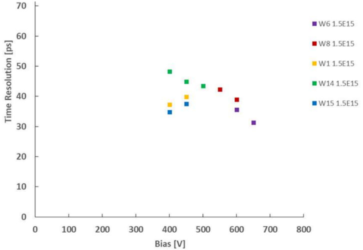
$\Phi_{eq} = 0 \text{ cm}^{-2}$



$\Phi_{eq} = 3 \cdot 10^{15} \text{ cm}^{-2}$



$\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$



- Thickness of 50-60 μm $\Rightarrow$ support wafer
- Measurements using charged particles
- **Reached required time resolution up to $\Phi_{eq} = 3 \cdot 10^{15}$ cm^{-2}**
- C coimplantation (W6): improved time resolution up to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$

[S. Mazza arXiv 2018]

LGADs for Timing

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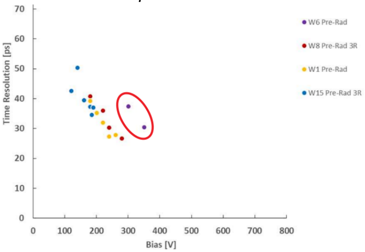
$\Phi_{eq} = 0\ \text{cm}^{-2}$



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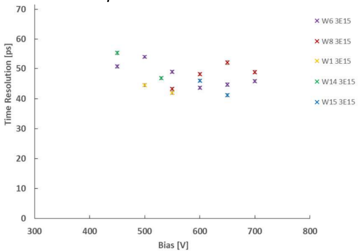

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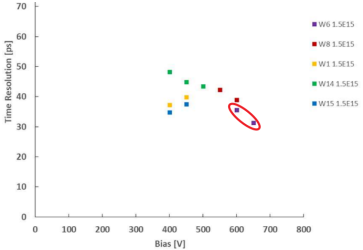

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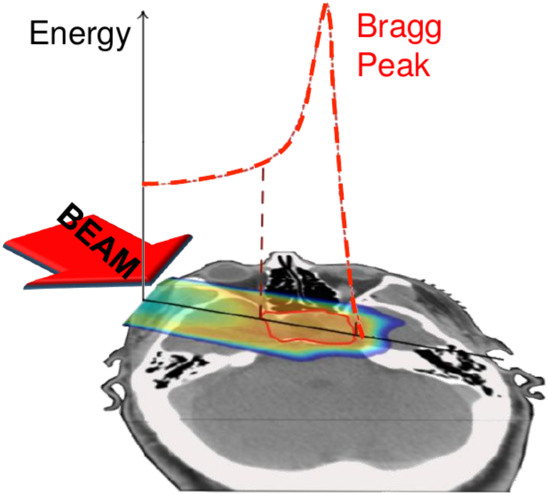
[S. Mazza arXiv 2018]

Hadron Therapy

A. Vignati [Picosecond Workshop 2018]



Development within the MoVeIT project

MoVe IT

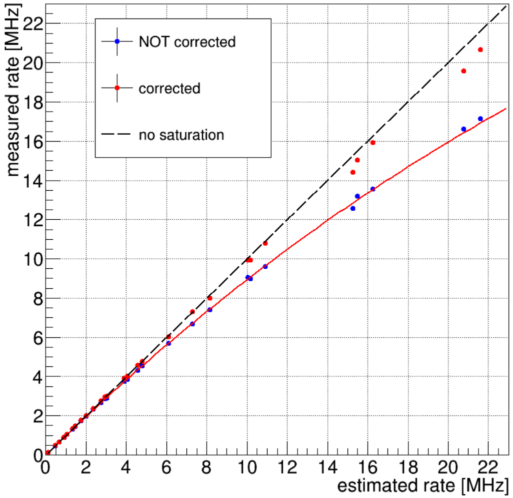
Beam monitoring during treatment

- Quality assurance
- Energy (TOF measurement)
- Particle count
- Beam profile

Sensor requirements similar to HEP **but** TOF measurement using several particles

Particle Counting

A. Vignati [MMND 2020]

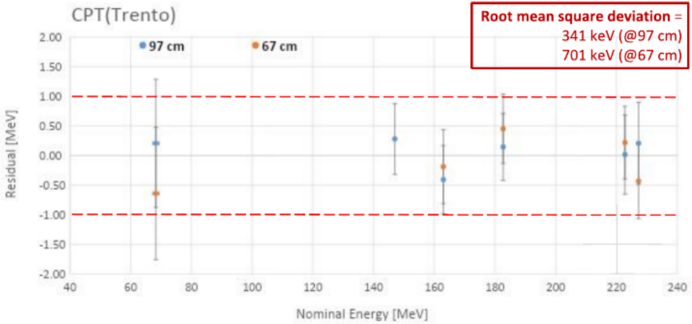


- LGAD strip sensor
- Rate on one strip
- Goal rate: 1-2 MHz/strip
- Pile-up correction with paralizable model extends linearity

Particle counting accuracy meets expectations

Energy Measurement

A. Vignati [Picosecond Workshop 2018]



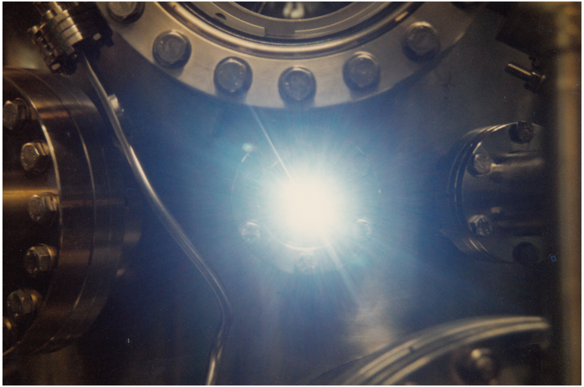
- LGAD strip sensor
- TOF measurement
- L = 67, 97 cm

Energy resolution meets expectations

Production for full scale prototype will start soon

X-ray Detection

[Wikipedia CC BY-SA 2.0]



Development in collaboration with PSI

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Detection of soft X-rays: 250 eV - 2 keV

- K-edges of bio elements
  $\rightarrow$ pharmaceuticals, cell imaging
- L-edges of 3d-transition metals
  $\rightarrow$ magnets, superconductors, quantum materials ...

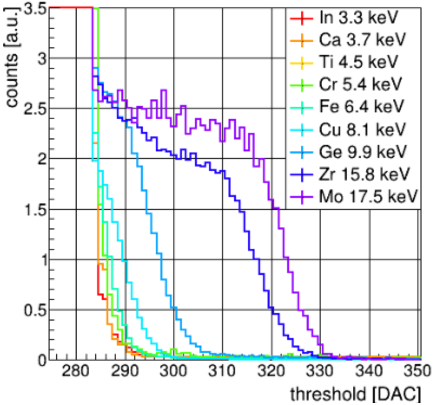
Use LGADs:

- Gain to lower the detection limit of photon counting detectors
- Gain to improve SNR of integrating detectors
- Thin entrance window must be developed

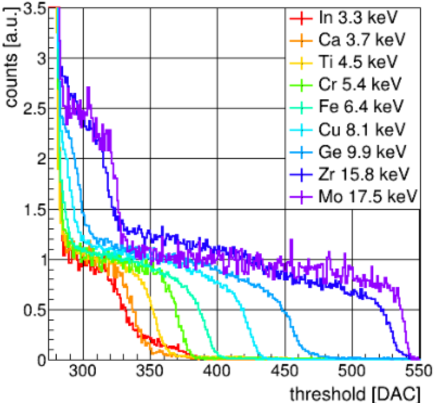
Low Energy X-ray Detection

Photon counting strip detectors, fluorescence X-rays

PiN sensor (zoomed)



LGAD sensor



E $>$ 8 keV visible

E $<$ 3.3 keV visible

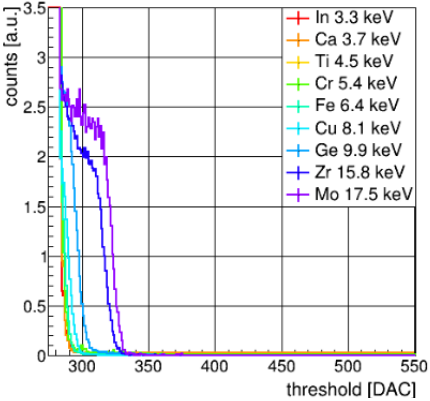
Improvement in detection threshold

[A. Bergamaschi TREDI2019]
[M. Andrae, J. Zhang, et al. J. Synchrotron Rad. (2019)]

Low Energy X-ray Detection

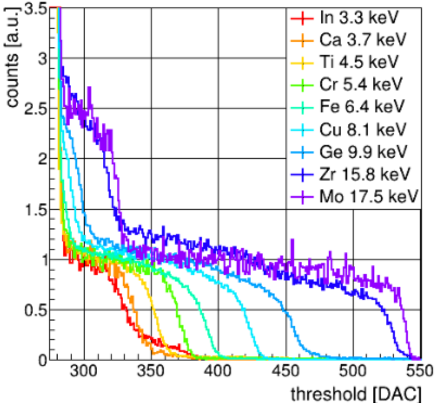
Photon counting strip detectors, fluorescence X-rays

PiN sensor



E > 8 keV visible

LGAD sensor



E < 3.3 keV visible

Improvement in detection threshold

[A. Bergamaschi TREDI2019]
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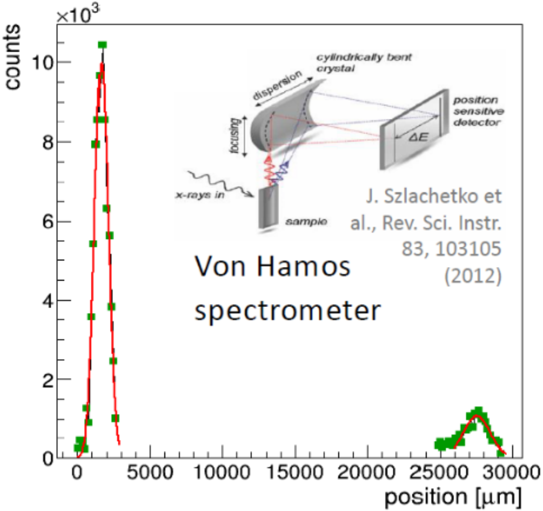
Low Energy X-ray Detection



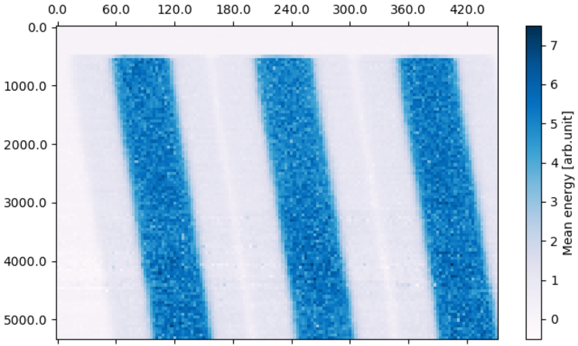
- Photon counting LGAD strip detector
- Fluorescence X-rays
- Sulfur target
- K_α = 2.31 keV
- K_β = 2.46 keV
- Von Hamos spectrometer

Detection of 2.31 keV photons

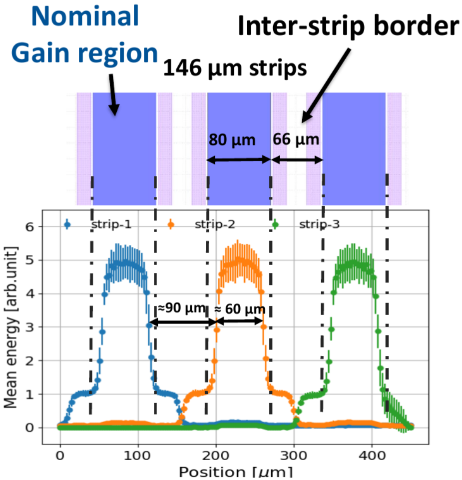
[A. Bergamaschi TREDI2019]
[M. Andrae, J. Zhang, et al. J. Synchrotron Rad. (2019)]

Segmentation: Fill Factor

Focused 20 keV x-ray beam



- Measured FF: $\approx$ 40%
- Impact on detection efficiency

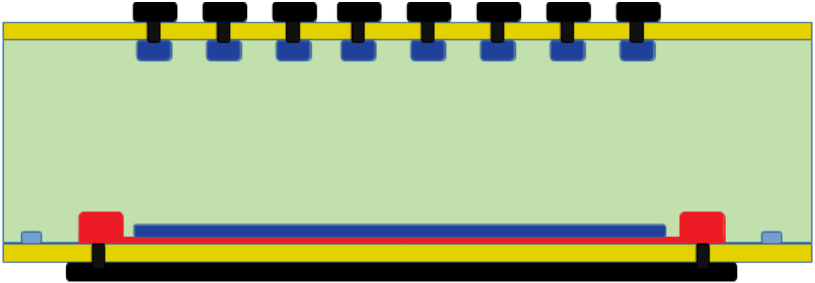


Signal vs position for 3 strips

Fill factor needs improvement

[M. Andrae, J. Zhang, et al. J. Synchrotron Rad. (2019)]

Double Sided LGADs

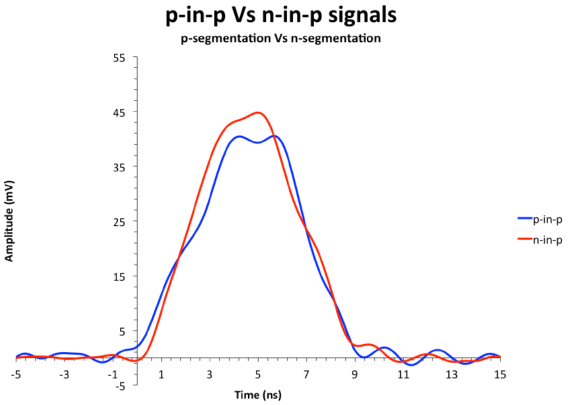


- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Double sided process
- Active thickness is the wafer thickness
- Readout side is ohmic
- Design not optimal for timing applications
- Readout side separated from LGAD side $\Rightarrow$ no restrictions on channel dimensions

[G.F. Dalla Betta et al. NIM A 796 (2015) 154]

Double Sided LGADs

[M. Ferrero 29th RD50 Workshop 2016]



Proof of concept in first FBK LGAD production

- Signal of regular vs double sided LGAD
- Pad size $\gg$ thickness
- Laser illumination
- Signals are similar
- A difference is expected for smaller pads

- Production to start soon dedicated to X-ray detection
- Optimization for thin entrance window (LGAD side)

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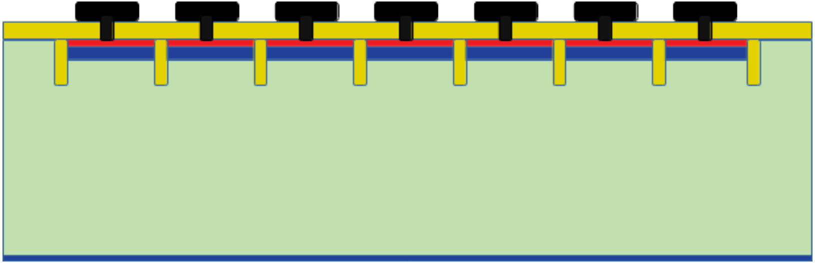
AC Coupled LGADs

- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Readout channels capacitively coupled
- Resistive layer to limit signal spreading
- No restrictions on channel dimension
- One production optimized for timing $\Rightarrow$ results in N. Cartiglia talk (this session)
- One future production to start in summer 2020

[M. Mandurrino et al. IEEE EDL, vol. 40, no. 11, 2019]

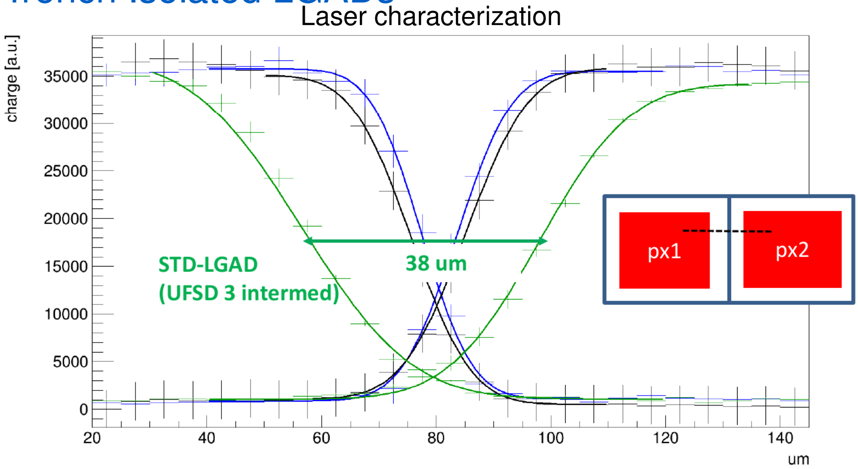
Trench Isolated LGADs

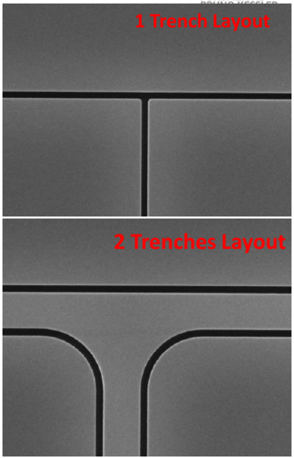


- Trenches substitute the JTE and isolation structures
- Trench width about 1 μm $\Rightarrow$ fill factor close to 100%
- One production optimized for timing

[G. Paternoster et al. IEEE EDL (2019) in revision]

Trench Isolated LGADs





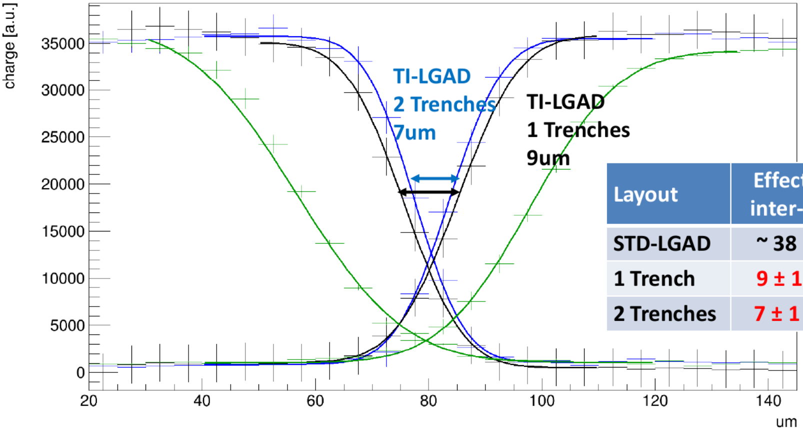
Factor 5 reduction in no-gain area

Production optimized for timing to start soon

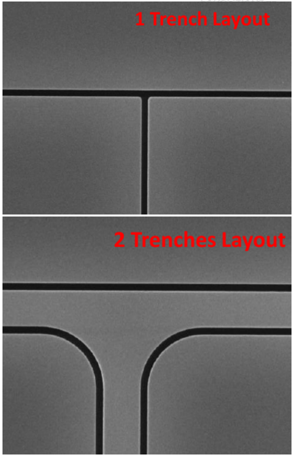
[G. Paternoster HSTD12 2019]

Trench Isolated LGADs

Laser characterization



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



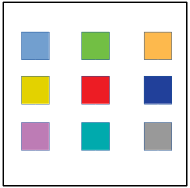
Factor 5 reduction in no-gain area

Production optimized for timing to start soon

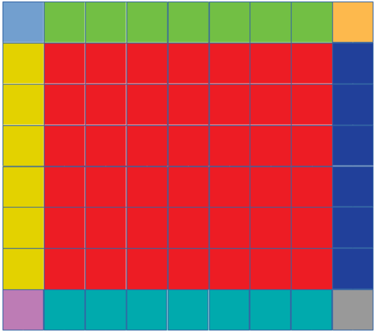
[G. Paternoster HSTD12 2019]

Process Capabilities

Recticle $\approx 2 \times 2$ cm^2 on wafer



Sensor



Stitching

- Stepper machine to reduce min feature size with respect to mask aligner
- Recticle constraints the sensor size
- Stitching overcomes this limitation

Tested successfully in one LGAD production

[G. Paternoster TREDI2019]

Wafer thinning

- Handle wafer ($\approx$ 300 μm) used in production of thin ($\approx$ 50 μm) LGADs
- Material budget constraints in several application
- Thinning to reduce handle wafer thickness

Capability to be acquired in the next 1.5 years

Summary

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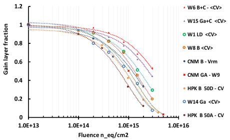
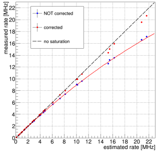
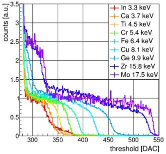
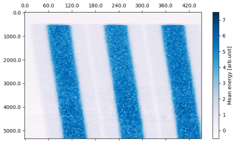
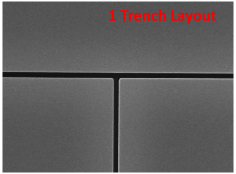
- Active development of LGADs at FBK
- Several projects benefit from the sensors
- Development and evolution of different LGAD “flavors” to solve different measurement problems
- Several LGAD productions foreseen in the future





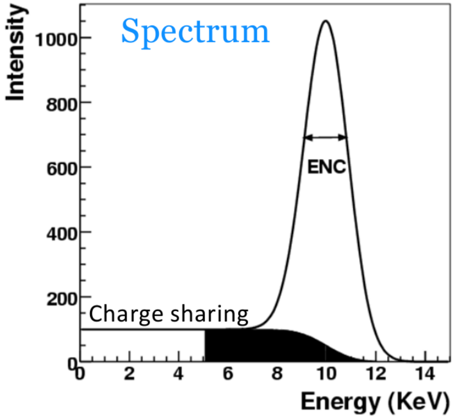


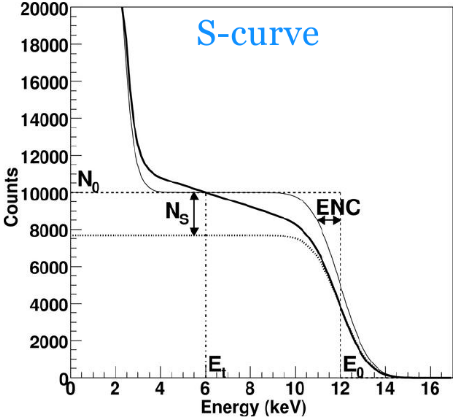




Backup Material

Photon Counting Detectors Characterization



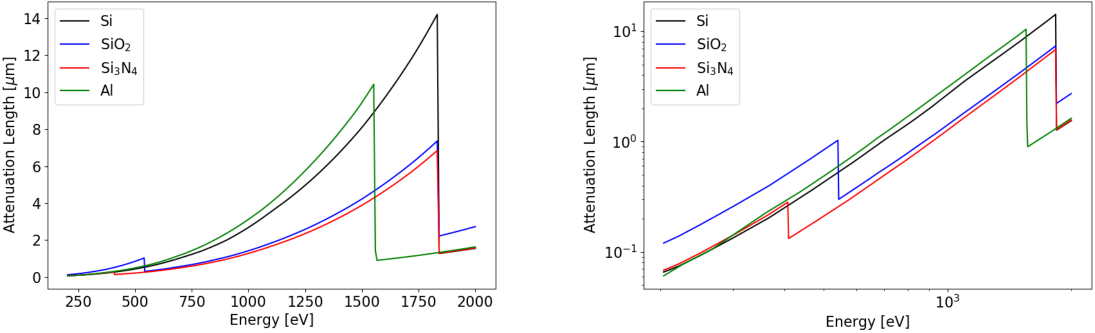


- Monochromatic x-rays
- Can be fluorescence

- S-curve by scanning the threshold
- S-curve is the running integral of the spectrum

[A. Bergamaschi TREDI2019]

X-ray Attenuation Length

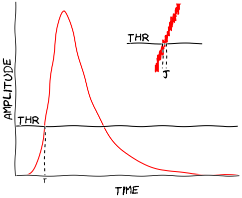


http://henke.lbl.gov/optical_constants/atten2.html

Time Resolution

$$\sigma_t^2 = \sigma_{\text{jitter}}^2 + \sigma_{\text{time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{distortion}}^2 + \sigma_{\text{TDC}}^2$$

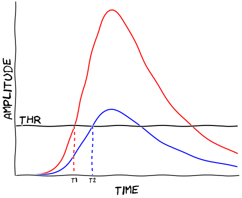
Jitter



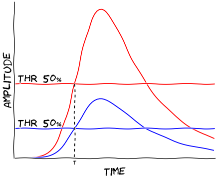
$\sigma_{\text{jitter}} = \sigma_n / \frac{dV}{dt}$

Increase $\frac{dV}{dt}$, SNR

Time walk



Correct for it, e.g. CFD

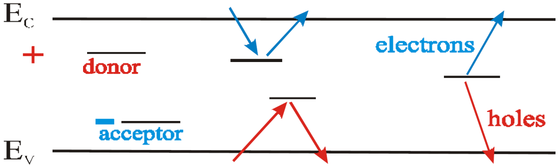


- Landau noise: non-uniformity in the energy deposited per unit length
- Distortion: change in signal shape due to detector non-uniformities
- TDC: resolution of the TDC, if no other effects: bin$/\sqrt{12}$

Radiation Damage in Silicon Detectors

Bulk damage

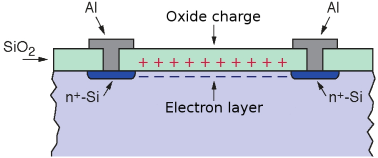
- Non ionizing energy loss (NIEL)
- Defect generation in the lattice
- Change of V_{dep}
- Increase in leakage current
  $\rightarrow$ noise
- Decrease in signal



Damage expressed as
equivalent fluence of 1 MeV neutrons Φ_{eq} [cm^{-2}]

Surface damage

- Ionizing energy loss in SiO_2
- Traps at the Si-SiO_2 interface
- Build up of positive charge
- Modification of electric field
  $\rightarrow$ charge losses
  $\rightarrow$ noise
  $\rightarrow$ breakdown
- Conductive layers
- Affects sensors and electronics

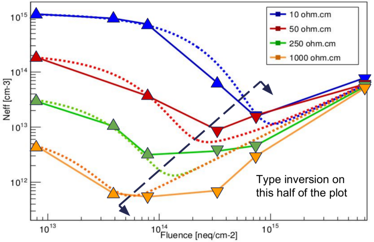


Relevant quantity: dose in SiO_2

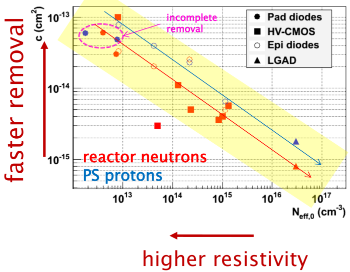
Acceptor Removal

Change in doping in boron-doped p-type silicon

[P. de Almeida, TREDI2018]



[G. Kramberger, HSTD11 2017]



Affects:

- p-type silicon sensors
- LGADs $\rightarrow$ gain reduction
- CMOS sensors $\rightarrow$ change in depletion region

$$N_{eff}(\Phi) = N_{eff}(0) - N_c(1 - e^{-c\phi}) + g_c\Phi$$

$N_{eff} \rightarrow$ effective doping concentration
$N_c \rightarrow$ "removable" dopants
$c \rightarrow$ acceptor removal constant
$\Phi \rightarrow$ fluence
$g_c \rightarrow$ introduction rate