LGAD sensors & plans for a beam telescope timing layer

A. Vauth

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DESY SiDet R&D meeting

Universität Hamburg
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DESY.

CLUSTER OF EXCELLENCE
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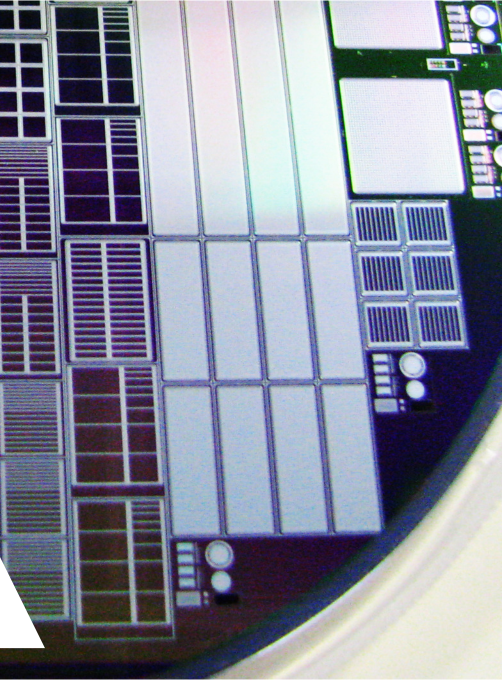


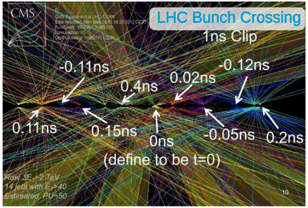
The need for new timing detectors

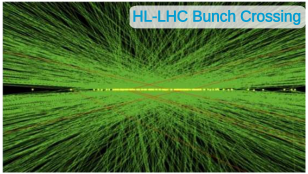
Experimental environments are evolving
→ Include track timing to address new challenging conditions

Time information complements spatial information:

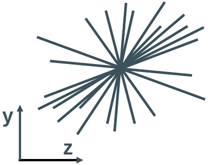
- Timing layer: timing in event reconstruction
- "4D" tracking: timing at each point along the track

Example goals/requirements: HL-LHC 50 ps, HADES 60 ps, FCC-hh 10 ps





Example



pileup tracks

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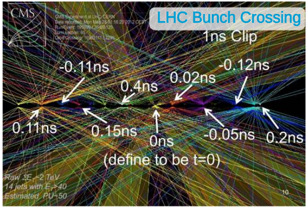
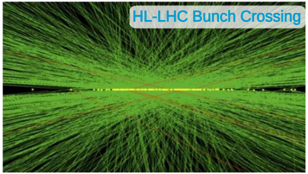
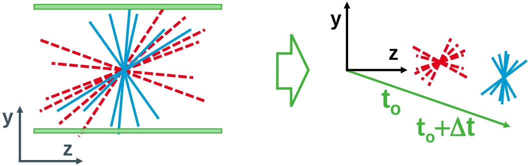




Example with timing info



added timing layer

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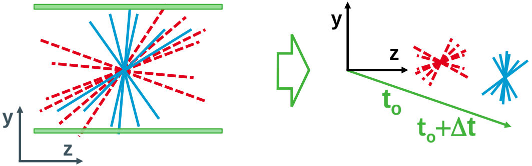

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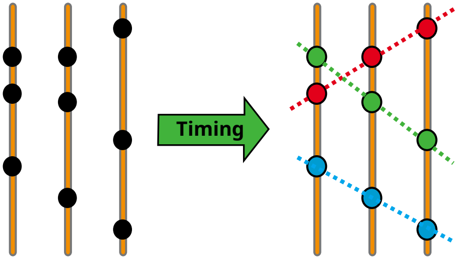
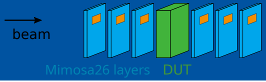


Test beam and telescopes



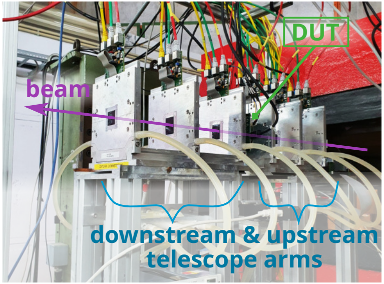
HEP detector R&D: dedicated beam tests for conceptual / technical design, calibrations, commissioning, ...

$\rightarrow$ DESY II Testbeam Faciliy

Integral part of test beam infrastructure: Beam Telescopes

$\rightarrow$ EUDET-type telescopes: 6 layers of MIMOSA26 pixel sensors

- Monolithic Active Pixel Sensor
- 1152×576 pixels, pitch: 18.4 µm
- Measured intrinsic sensor resolution: $\sigma \cong 3$ µm
- Rolling shutter readout, readout cycle 115 µs



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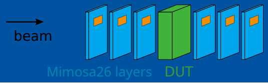

DESY TEST BEAM.

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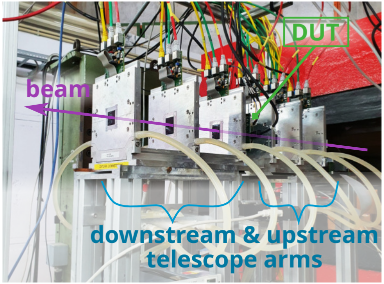
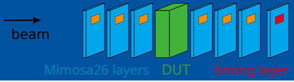
“No“ time resolution $\rightarrow$ upgrade needed
to meet requirements of future detector test campaigns

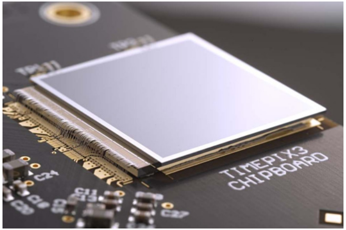


Upgrade Plans

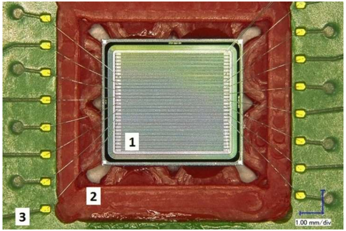


Add faster device for time stamping the tracks $\rightarrow$ timing layer

- Short term: existing sensor as intermediate solution
  - Timepix3
  - Already existing and functional
  - Timestamps $\mathcal{O}(1\,\mathrm{ns})$
- Long term: develop next-generation timing layer
  - LGAD $\rightarrow$ this talk
  - Allow for picosecond-timing
  - Requires R&D
  - Dedicated ROC? Start with Timepix3 for first prototypes



[CERN-PHOTO-201702-048-4]



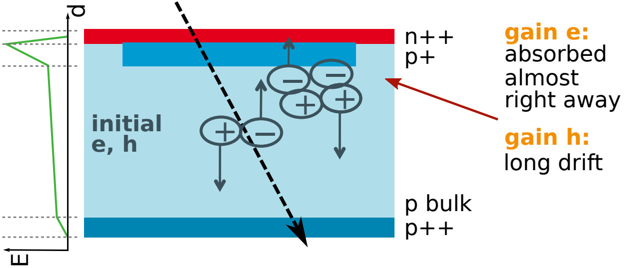
[doi.org/10.1140/epja/s10050-020-00186-w]

LGAD

Low Gain Avalanche Diodes

Ultra Fast Silicon Detectors optimised for timing measurements:

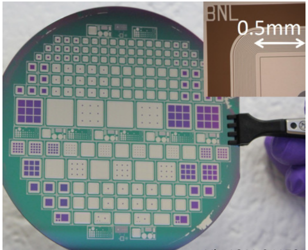
Thin multiplication layer
→ High field
→ Increase signal by factor ∼10



LGADs are routinely produced in various sizes and pad numbers

(e.g. by CNM, FBK, HPK)

$\mathcal{O}$(30 ps) time resolution possible



arXiv:1811.04152

LGADs for Timing

Time resolution is affected by:

- Each step in the read-out process
- Anything that changes the shape of the signal

$$\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \sigma_{\mathrm{LandauNoise}}^2 + \sigma_{\mathrm{Distortion}}^2 + \sigma_{\mathrm{Jitter}}^2 + \sigma_{\mathrm{TDC}}^2$$

arXiv:1704.08666

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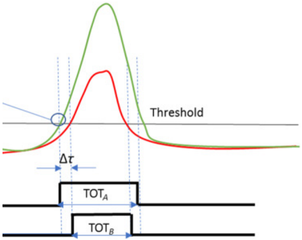
arXiv:1704.08666

Variation in time of arrival
due to different signal amplitudes

Compensation:
Constant Fraction Triggering
or amplitude-based correction (TOT)



Time walk effect OE 56(3), 031224 (2017)

LGADs for Timing

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arXiv:1704.08666

Caused by inhomogenities in
drift velocity & weighting field

Compensation:
saturated drift velocity
& optimised geometry ("parallel plate")

Time-to-digital converter
contribution $\Delta T/\sqrt{12}$ (bin width)

in most cases small contribution

LGADs for Timing

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$$\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \sigma_{\mathrm{LandauNoise}}^2 + \sigma_{\mathrm{Distortion}}^2 + \sigma_{\mathrm{Jitter}}^2 + \sigma_{\mathrm{TDC}}^2$$

arXiv:1704.08666

Energy deposit
Current fluctuations due to signal shape variations for MIP ionization

Time-Of-Arrival variations due to noise
- sensor noise
- electronics noise
- slew rates (dV/dt)

arXiv:1704.08666

= the main contributors → low gain, thin detectors (see next slides)

Why Low Gain?

High gain has many drawbacks:
risk of breakdown, power consumption, higher noise

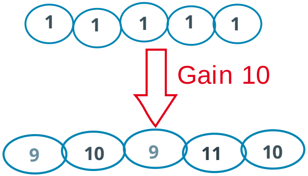
"Excess Noise Factor" (F): additional noise induced by the multiplication mechanism

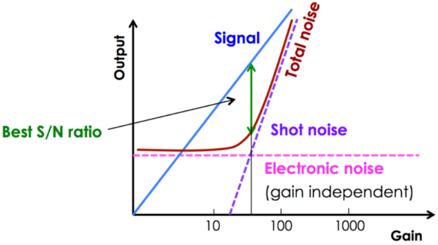
(gain not constant $\rightarrow$ additional fluctuations in current)

$F \sim G^x$

signal after multiplication: multiplied by G
current noise increases with $\sqrt{F}$
$\rightarrow$ S/N ratio deteriorates at higher gain

For a given ENF, there is an optimum gain ($10 \sim 30$)





JINST (2017) 12 C02072

Why thin sensors?

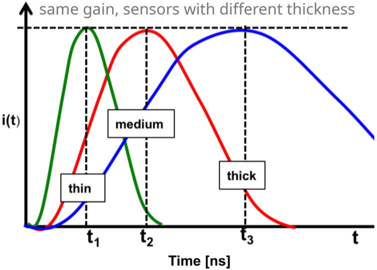
Current fluctuations are due to statistics of MIP ionization

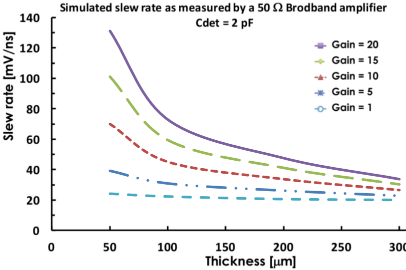
- For a fixed gain: amplitude of the signal independent of thickness d:

$$I_{max} \sim n_{eh-initial}\, G\, q\, v_{sat}$$

arXiv:1704.08666

- Slew rate (dV/dt): increases with $\frac{G}{d}$





NIMA796, (2015), 141–148

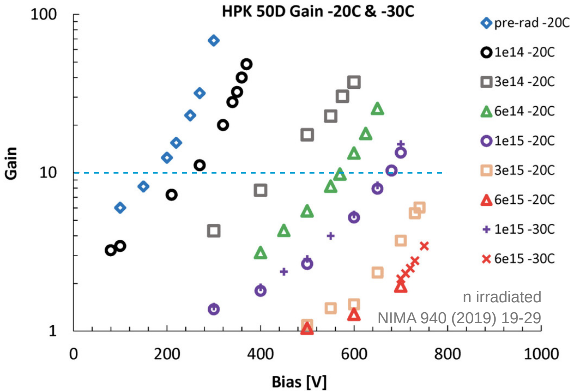
→ Thin detectors improve time resolution (35-50 μm available)

R&D Challenge: Radiation Tolerance

Irradiation causes three main effects:

- Decreased charge collection efficiency
- Increased leakage current
- Change of doping profile

Deactivation of p-doping by Boron removal
→ Gain reduction due to irradiation



R&D Challenge: Radiation Tolerance (2)

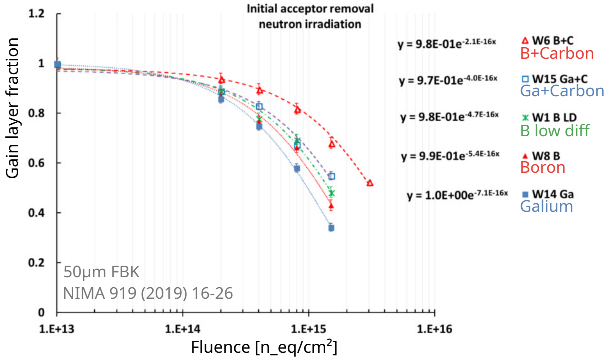
Lots of R&D ongoing, different doping profiles and ion implants:

Defect Engineering of the gain implant

- Carbon co-implantation in gain layer volume
- Boron as gain layer implant

Modification of gain layer profile

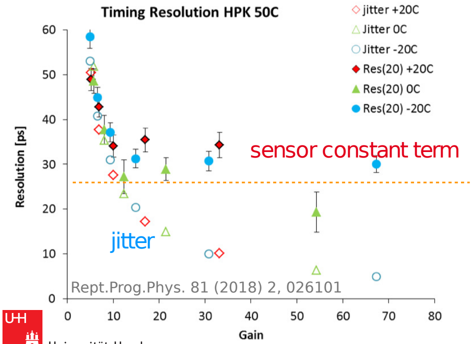
- Narrower doping layer
  with higher initial doping



Ultra-fast silicon detectors - performance

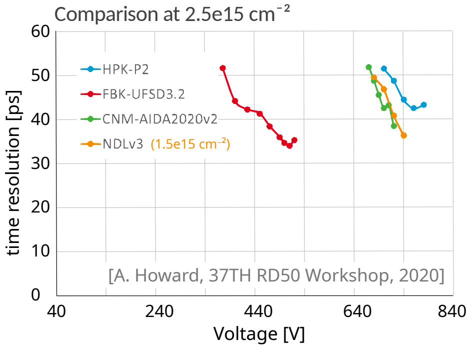
Example: UFSD from Hamamatsu

- LGAD with 50 μm thickness
- Value of gain ∼20
- 30 ps time resolution



Example: Irradiation study for HGTD

- LGAD with 45 – 55 μm thickness
- Different vendors/implantations
- ∼40 ps time resolution after irradiation



R&D Challenge: Fill Factor

Segmentation to improve spatial resolution

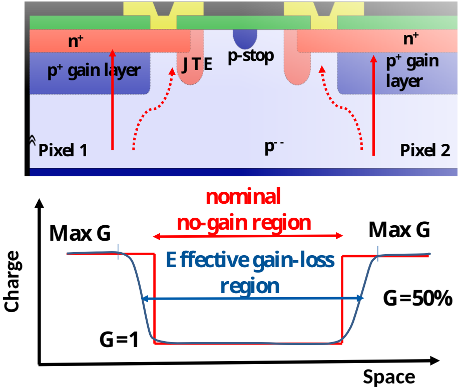
- Inter-pixel region:
  isolation and termination structures
  (p-stop, Junction Termination Extension, virtual GR)
- Carriers generated in this area not multiplied
- Interpad regions with no gain $\mathcal{O}(\approx 30\,\mu\text{m to }70\,\mu\text{m})$

$\rightarrow$ R&D challenge:
Segmentation with improved fill factor

Several technology options:

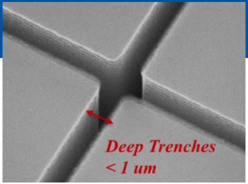
- Trench-isolated LGAD
- Inverse LGAD
- Resistive AC-Coupled LGAD
  (see talk N. Cartiglia at last week's instrumentation seminar)

Standard segmentation



[G. Paternoster , 35th RD50 workshop, Nov 2019]

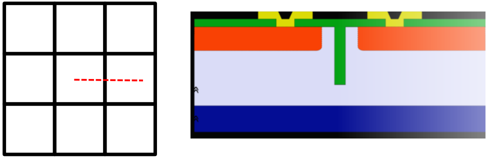
TI-LGAD



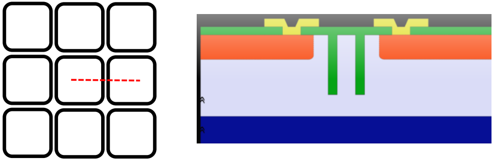
Trench isolation:

- JTE and p-stop replaced by trench to isolate the pixels
- Filled with Silicon Oxide
- Typical trench width < 1 µm
  much smaller wrt. JTE and p-stop
  $\rightarrow$ smaller no-gain region

1 Trench Layout (trench grid)



2 Trenches Layout



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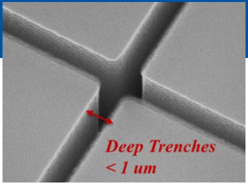

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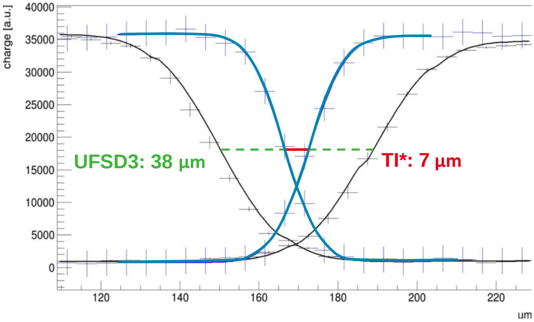
Layout	Nominal no-gain	Effective gain-loss
1 Trench	~ 4 um	~6 um
2 Trenches	~ 6 um	~3 um

[G. Paternoster , 35th RD50 workshop, Nov 2019]

Trade-off between minimizing gain-loss region and reducing E-field at the border

Comparison of FBK productions: UFSD3 vs Trench-Isolated

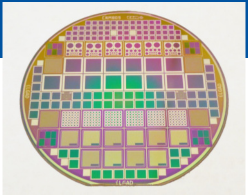


[F. Siviero, 35th RD50 workshop, Nov 2019]

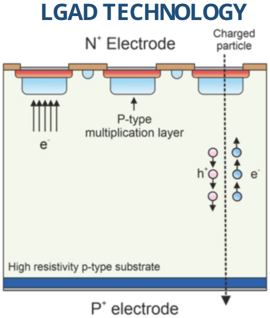
iLGAD

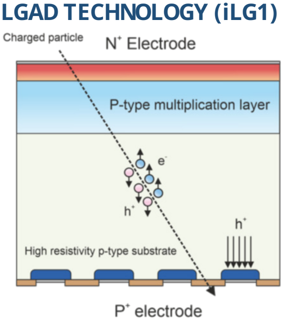
Inverse LGADs:

- No segmentation of the multiplication layer
- Hole collection
- Complex double side process (first generation)



[D. Flores, SIMDET '16, Sep 2016]



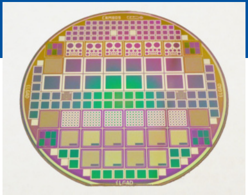


[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

iLGAD

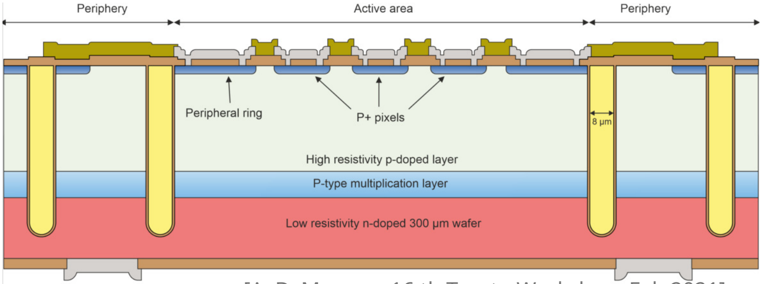
Inverse LGADs:

- No segmentation of the multiplication layer
- Hole collection
- Trenches to isolate the active area (third generation)
- Single-side process



[D. Flores, SIMDET '16, Sep 2016]

inverse LGAD (third generation)



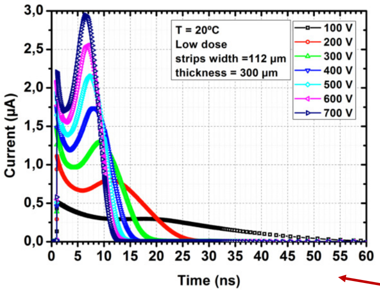
[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

iLGAD for Timing

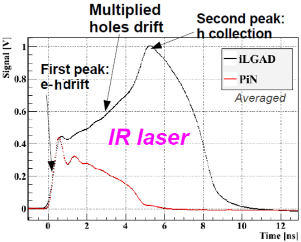
To use iLGADs for timing applications → Reduce the thickness of the detector
CNM: fabrication with two different approache

1. Epitaxial wafer + epitaxial multiplication
2. Si-Si wafers + implanted multiplication

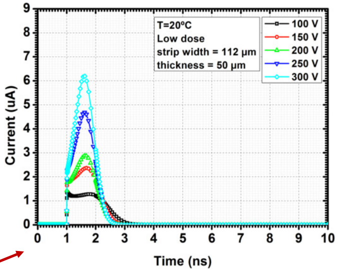
TCAD Simulation 300 µm thick iLGAD



Experimental 300 µm thick iLGAD



TCAD Simulation 50 µm thick iLGAD



Different scale!

[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

Timing layer timeline

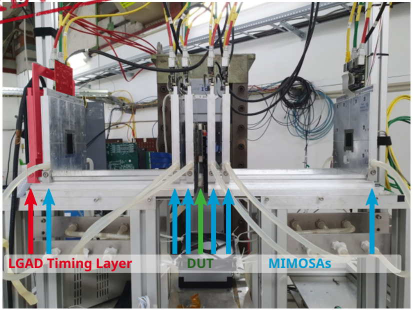
- Trench-isolated LGADs: part of RD50 run @ FBK
Pixel pitch: 55 µm × 55 µm, number of pixels 55 × 55
Production to finish end of this month

- Inverse LGADs: part of RD50 run @ CNM
Pixel pitch: 55x55 µm^2, number of pixels 256x256
Mask design/fabrication ongoing,
Production to be finished in September

Other ingredients for improved timing?
Trigger Logic Unit, DAQ software
→ **AIDA-2020 TLU, EUDAQ 2**

Summary & Outlook

- Low Gain Avalanche Diodes to measure both time and space - with improved signal-to-noise ratio
- For timing: 30-50 μm thickness, gain $(O)(10)$
- R&D ongoing on
  - radiation hardness (doping profile, ion implantats)
  - segmentation (Trench / Resistive AC / i-LGAD)
  - and more (uniformity, electronics, ...)
- More and more R&D on fast timing detectors
  $\rightarrow$ growing need for timing layer to test them



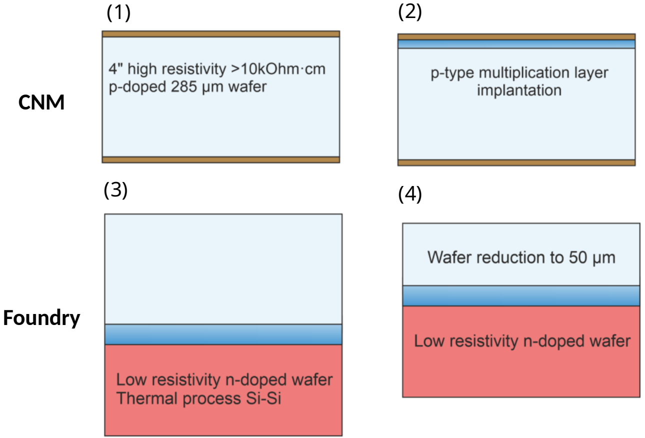
$\rightarrow$ **LGAD layer for beam telescopes**
for the next decade of successful testbeam operation

Backup Slides

iLGAD Third Generation (iLG3): Fabrication Process

We are planning to carry out this fabrication with two different approaches:

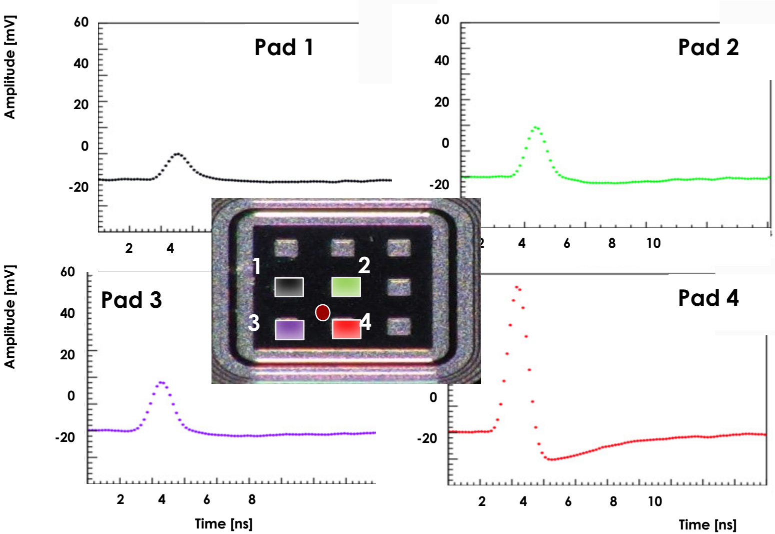
1. Epitaxial wafer + epitaxial multiplication
2. **Si-Si wafers + implanted multiplication**



Dose/energy multiplication layer is adapted to the Si-Si thermal process

After (4), the profile is the same as standard LGAD runs. This is the starting point for the fabrication.

Example of signal sharing



50-mm thick RSD,
Gain ~ 20

The laser is shot at the position of the red dot: the signal is seen in 4 pads