Low-Gain Avalanche Diodes for X-ray detection

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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- **Low Gain Avalanche Diodes**
  - **Genesis**
  - **Properties**

- **Families of LGADs for 4D detection (space and time)**

- **Applications for X-rays**

Origin of LGADs

In High-Energy Physics/ Nuclear Physics, silicon detectors are extensively used with huge experiments counting on millions of channels :

But:

1- not good for timing

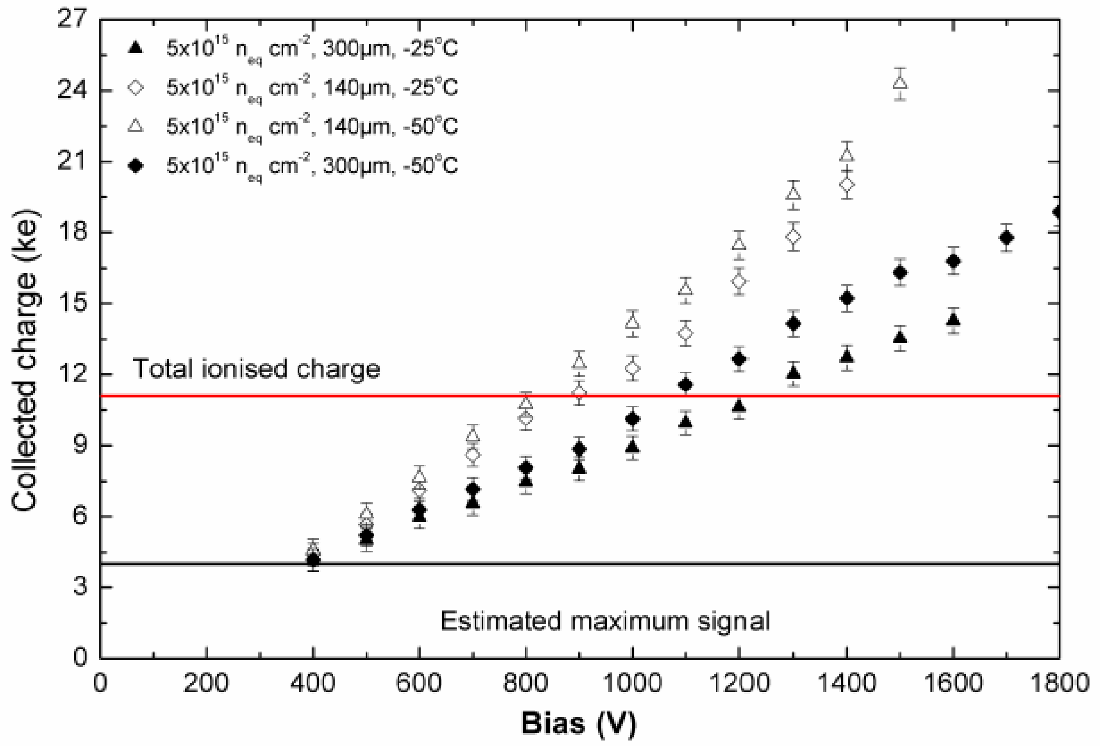
→ timing in order of tens of ps to reconstruct tracks and resolve pile-ups

2- rad-hard issues

→ signal loss in highly irradiated devices, charge trapping making thick substrates useless

3- Observation of multiplication in highly irradiated silicon strip detectors

→ yes, but at very HV and unstable…



G. Casse,2010, https://api.semanticscholar.org/CorpusID:195208891

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Solution: LGADs

Pioneered by CNM (Barcelona, Spain), funded by RD50 collaboration in 2021
(CERN R&D for Radiation hard semiconductor devices for very high luminosity colliders)

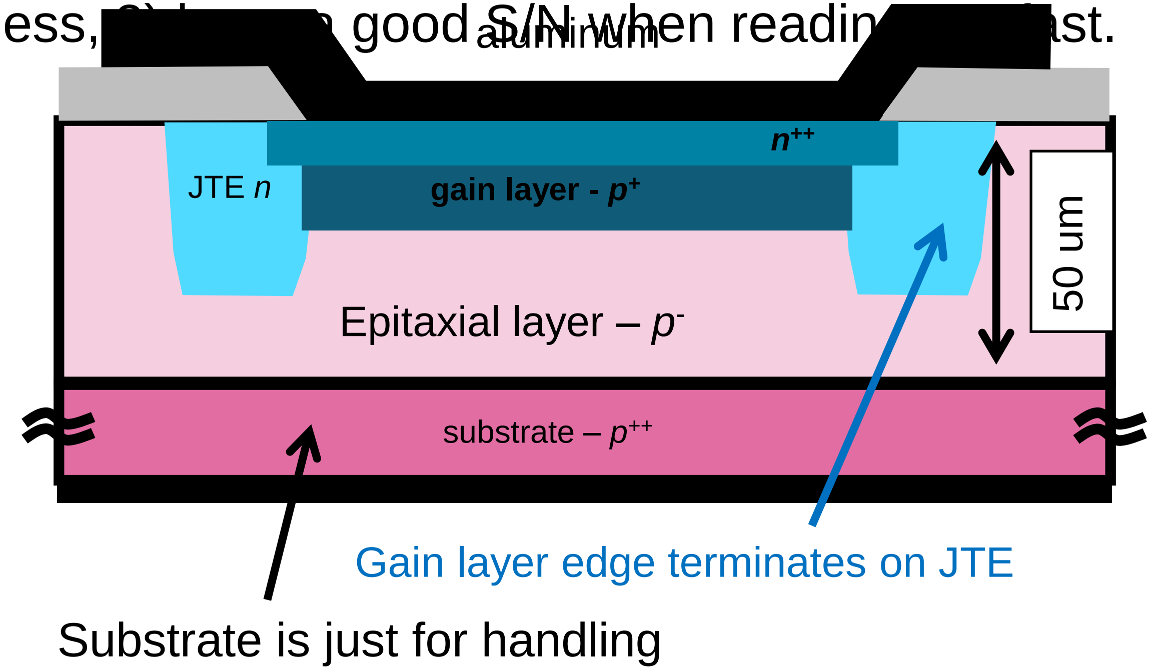
LGADs are Avalanche Diodes specifically tailored for the detection of mips in HEP

LGADs are 20-50um thick (only active volume!) as compared to hundreds of um of std strip/pixel sensors.

→ LGADs operate before BreakDown (linear region)

→ gain ~ few 10s

Amplification is needed to 1) offset the reduced thickness, [illegible] good S/N when readin[illegible]ast.



For mips:
if the substrate is thin (~ 50 μm) and the gain is ~ 20 → signal is fast (~30 ps)

LGAD producers

HAMAMATSU

FONDAZIONE BRUNO KESSLER

CNM Centre Nacional de Microelectrònica IMB

Brookhaven National Laboratory

SINTEF

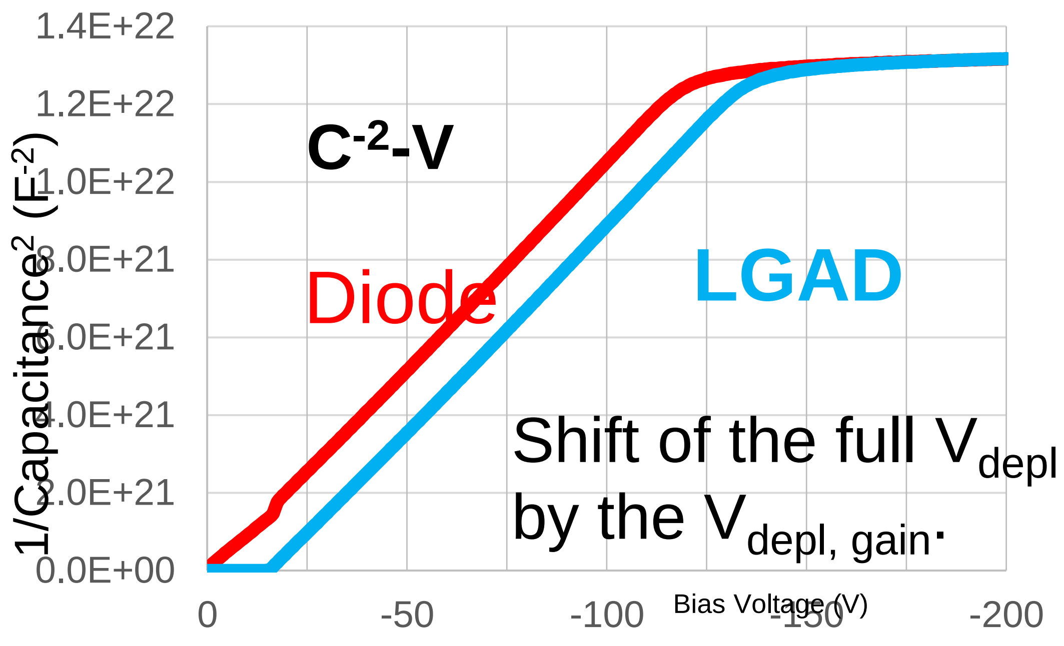
MICRON SEMICONDUCTOR LIMITED

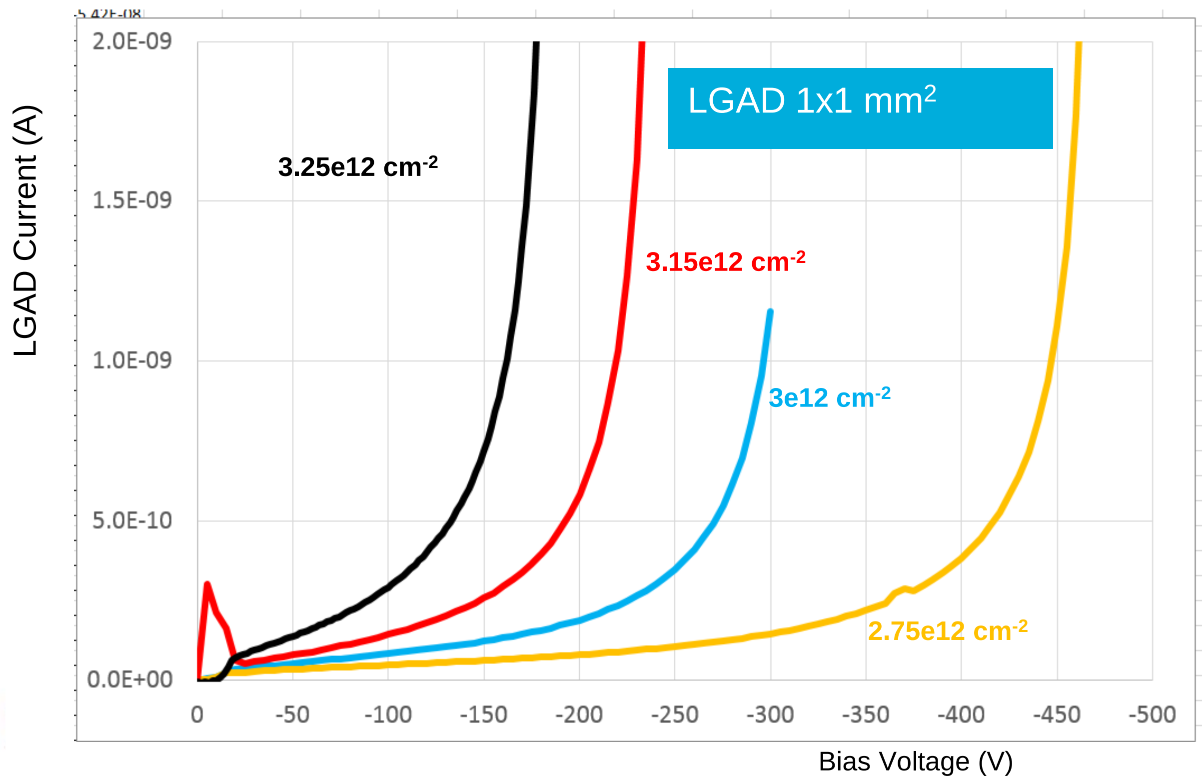
NDL

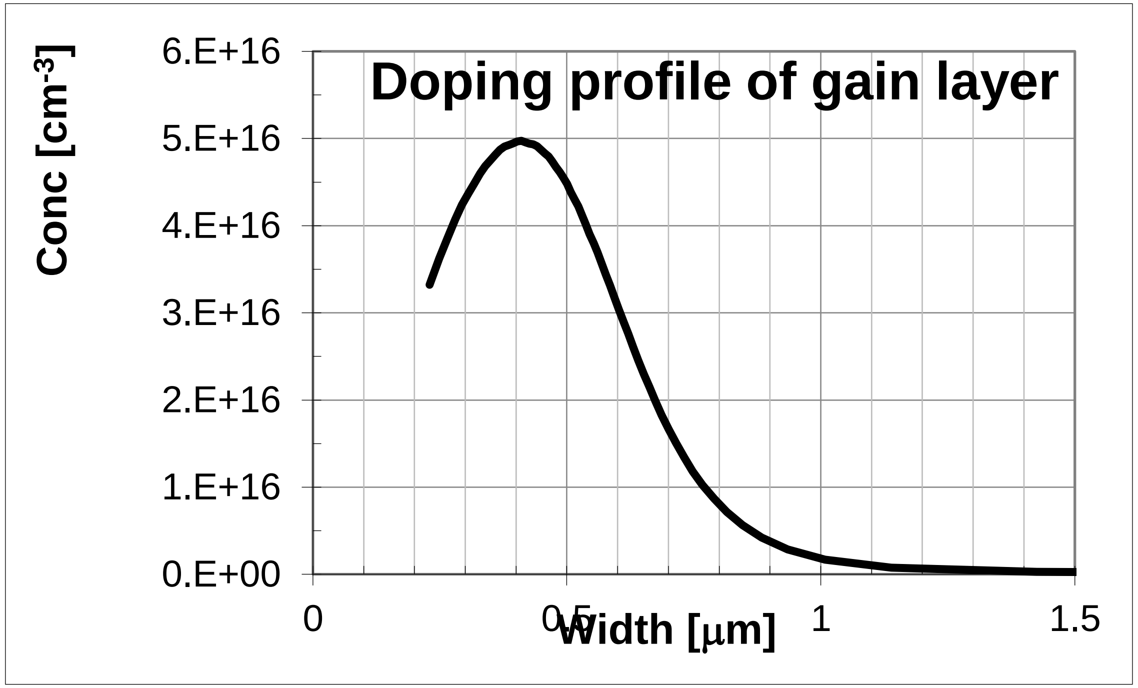
High Energy Physics (**IHEP**) **Chinese** Academic Science

Static Electrical Characterization

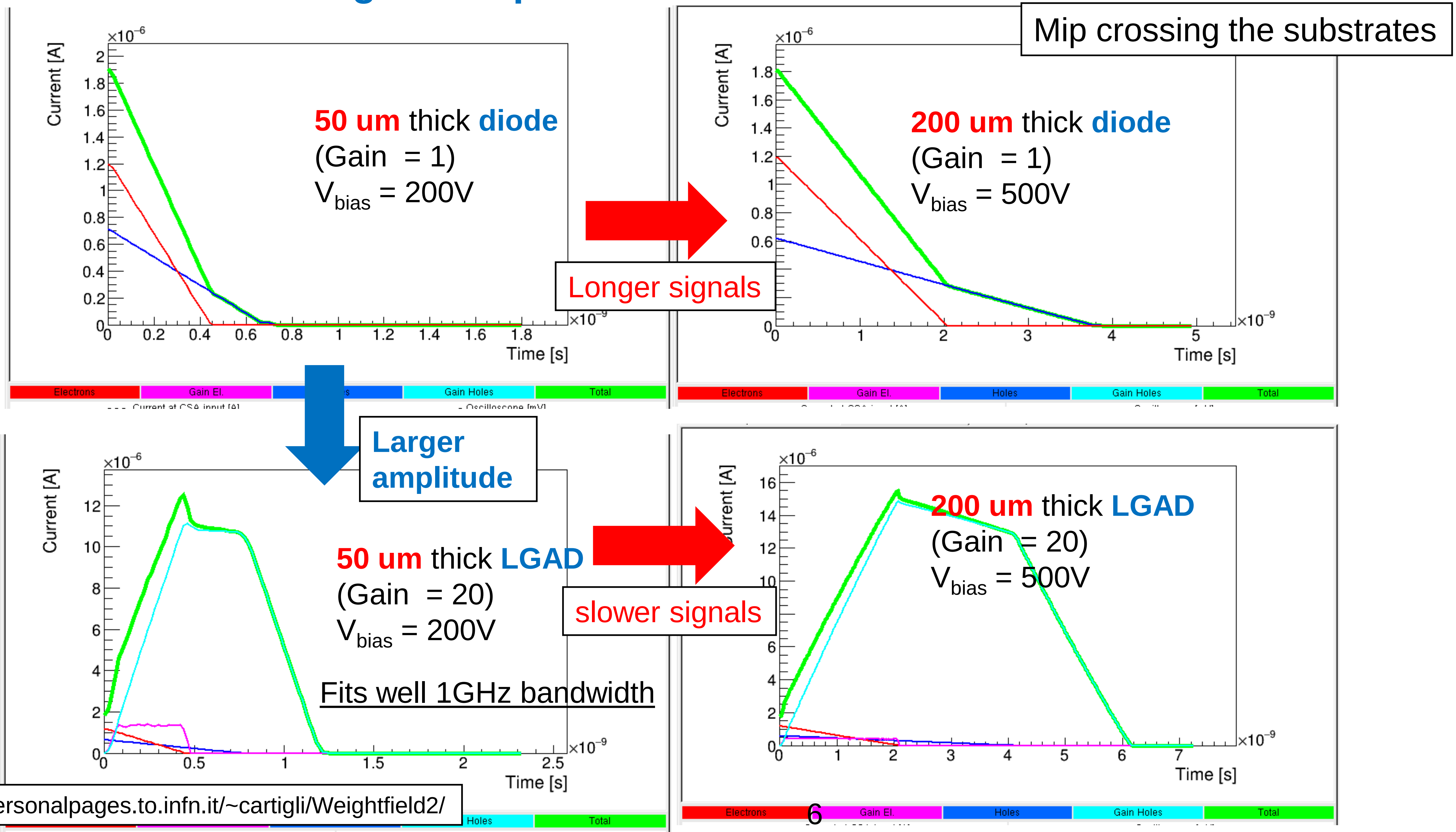
- Breakdown Voltage tunable by adjusting the dose of the gain layer
  - V_{BD} depends also on n+ doping profile, thickness and substrate doping
- For HEP/NP, VBD ~ 200 V for 50µm thick substrates







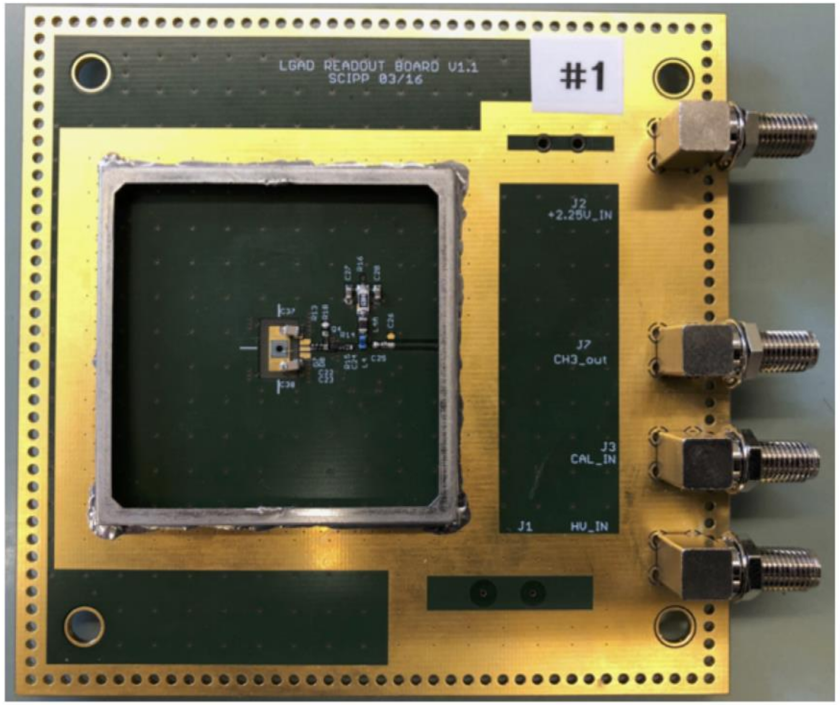
Signal shape in LGAD vs std diode



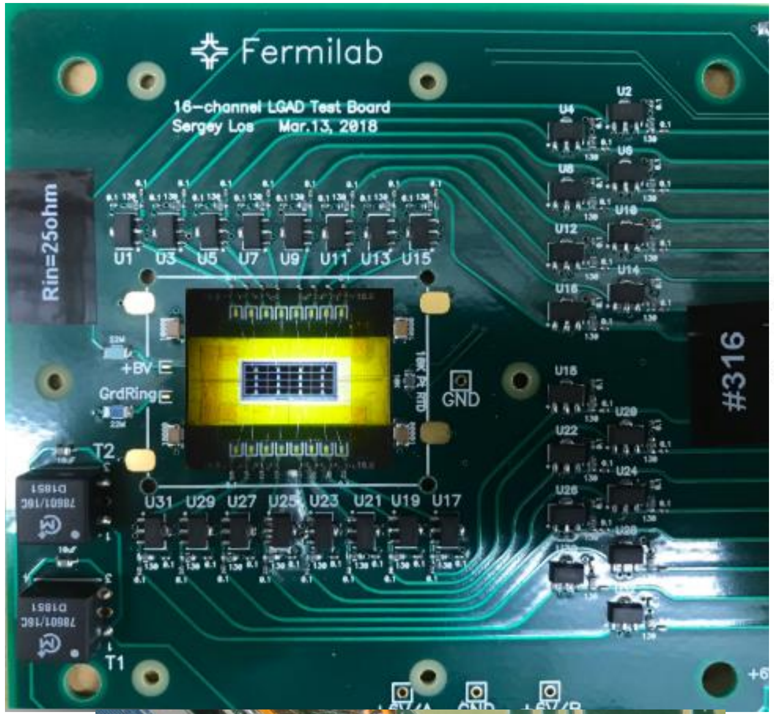
http://personalpages.to.infn.it/~cartigli/Weightfield2/

Waveforms

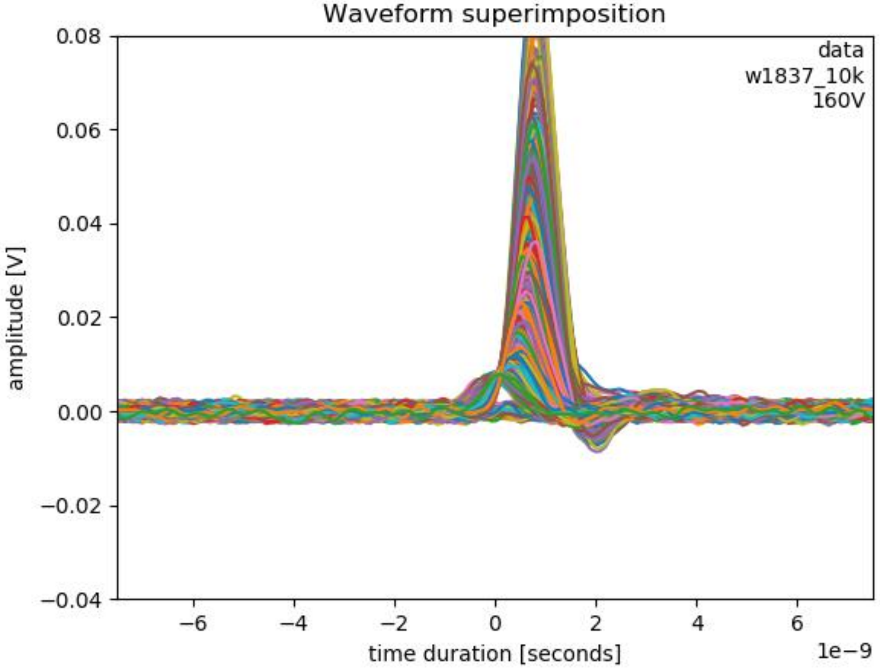
Single channel TIA by UCSC



16ch RF by FNAL

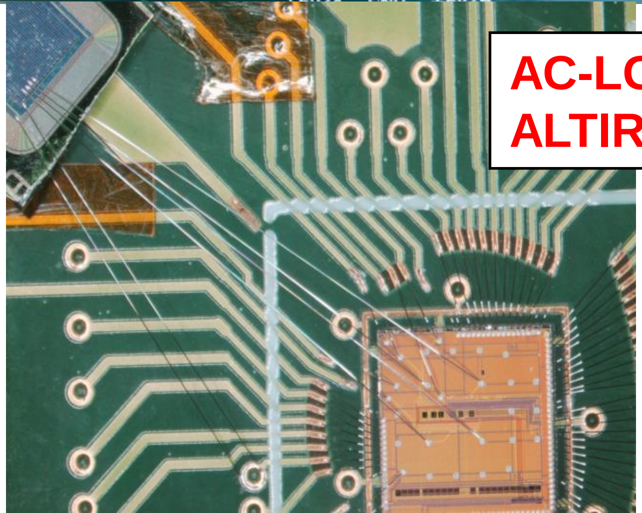


90Sr waveforms as seen on scope



Many fast ASICs developed:

- ALTIROC - ETROC
- EICROC
- FAST
- FCFD
- …



AC-LGAD wire-bonded to ALTIROC0

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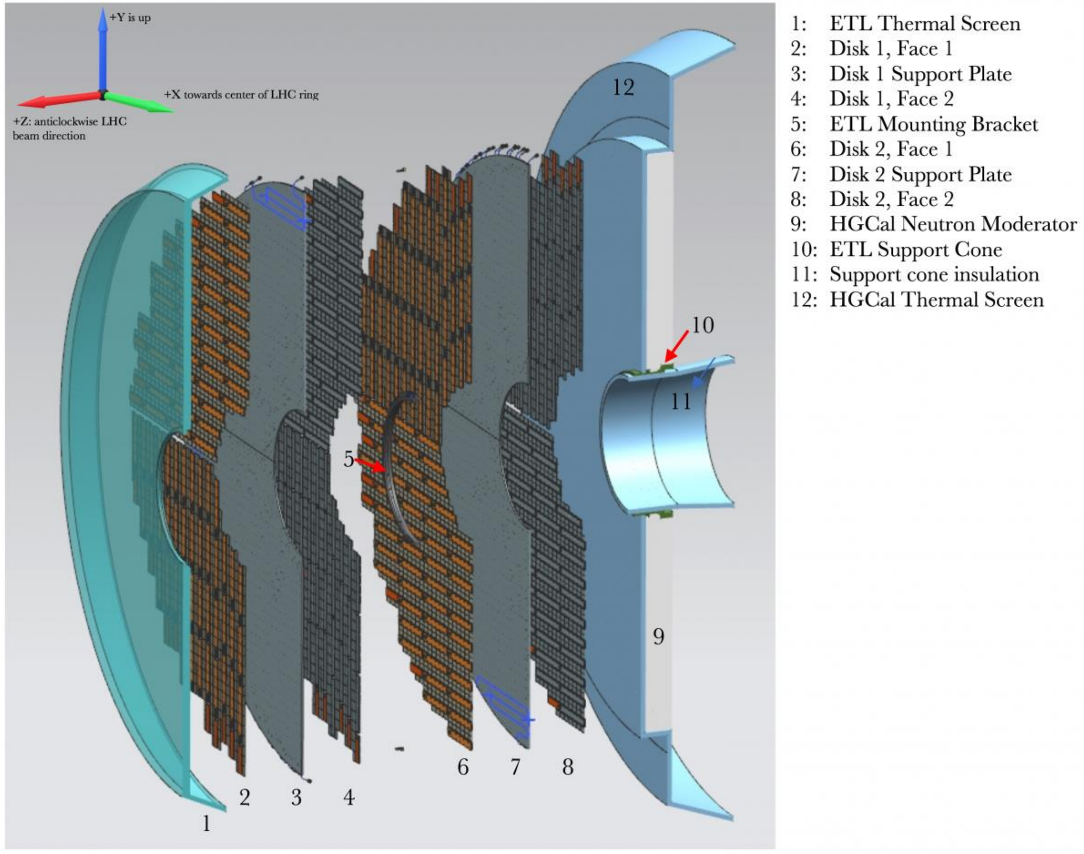
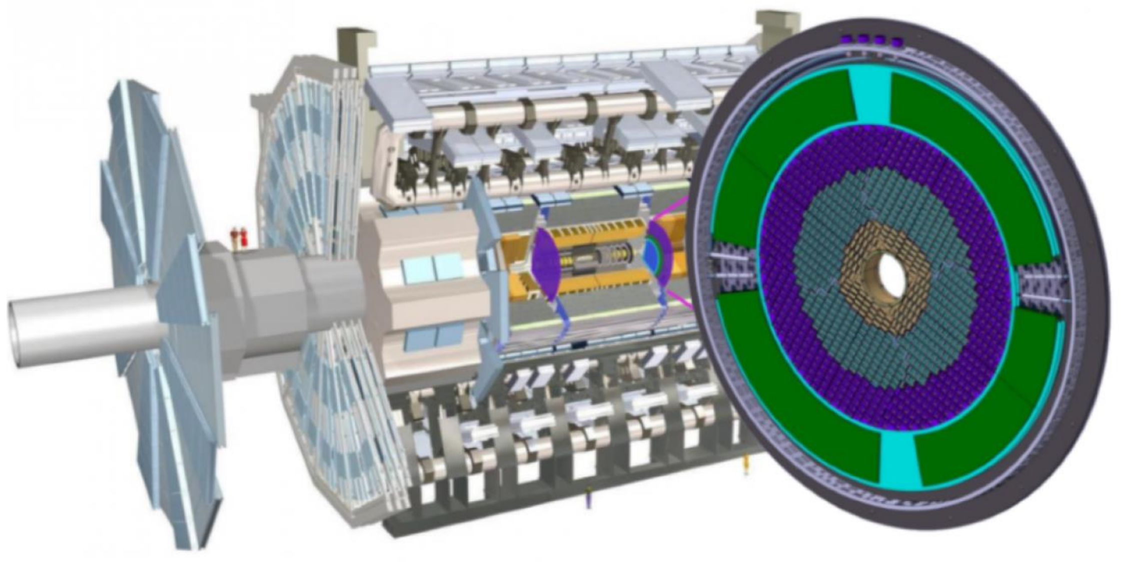
Big applications…

To help resolve/assign the many tracks originating from the multiple vertexes (same bunch crossing, close in space, separated in time by tens of ps), new timing detectors will be added.
Made by LGADs!!!

CMS Endcap Timing Layer

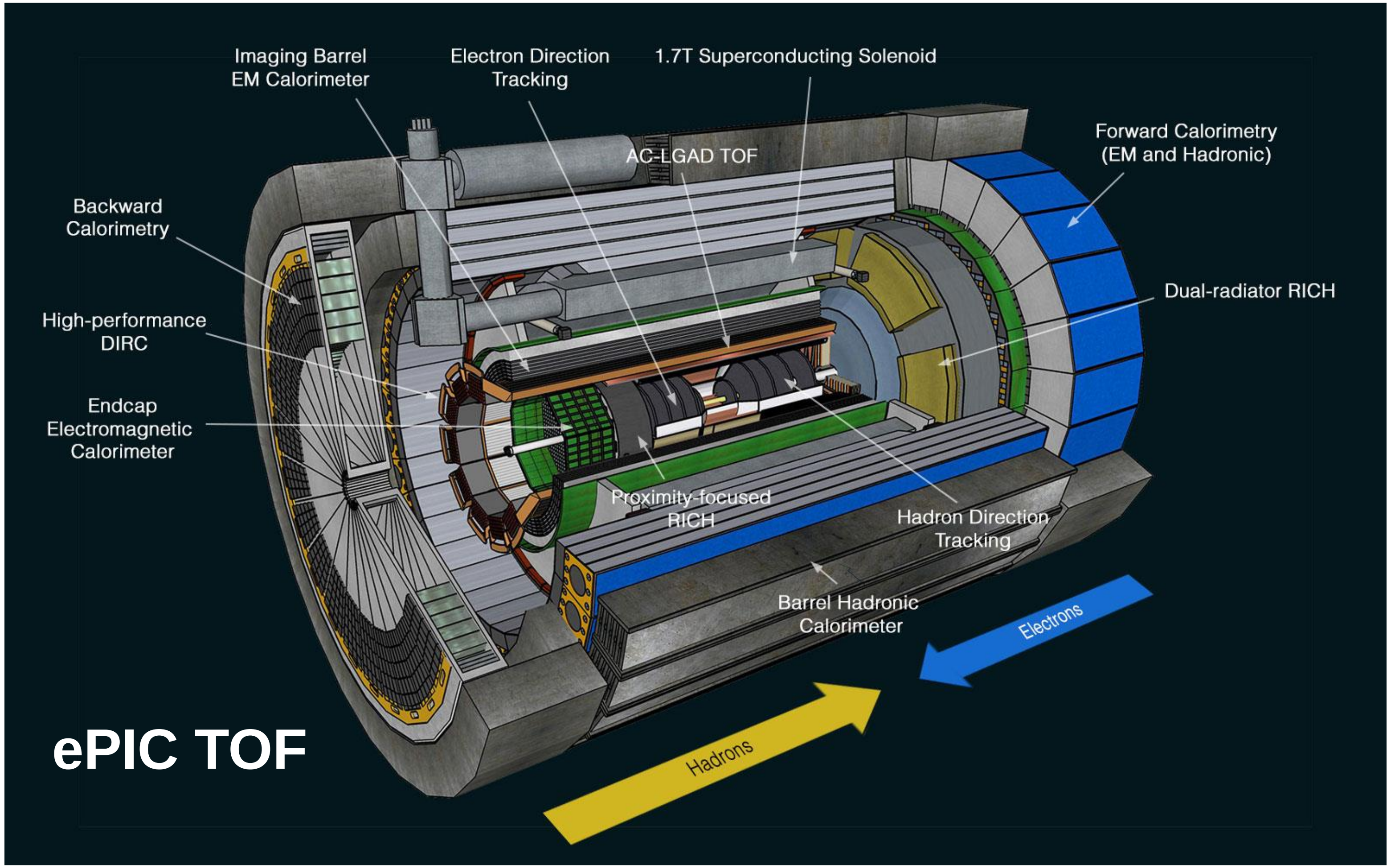


ATLAS High Granularity Timing Detector



Big applications…

EIC at BNL
Time of Flight (TOF) made by AC-LGADs
Far forward detector (Roman Pots): AC-LGADs



…for an old device

Recent developments in silicon avalanche photodiodes

R. J. McIntyre
New Products Division, RCA Inc, Box 900, Vaudreuil, Quebec, Canada J7V 7X3

What's really new?

- The application: fast detection of mips
  - requiring:
    - Rad-hardness
    - Spatial resolution
    - High channel counts
    - Substrate thickness

  - but relaxing:
    entrance window (absent)
    Bias voltage (~100s not ~1000s)
    Gain requirements (10s not 100s)

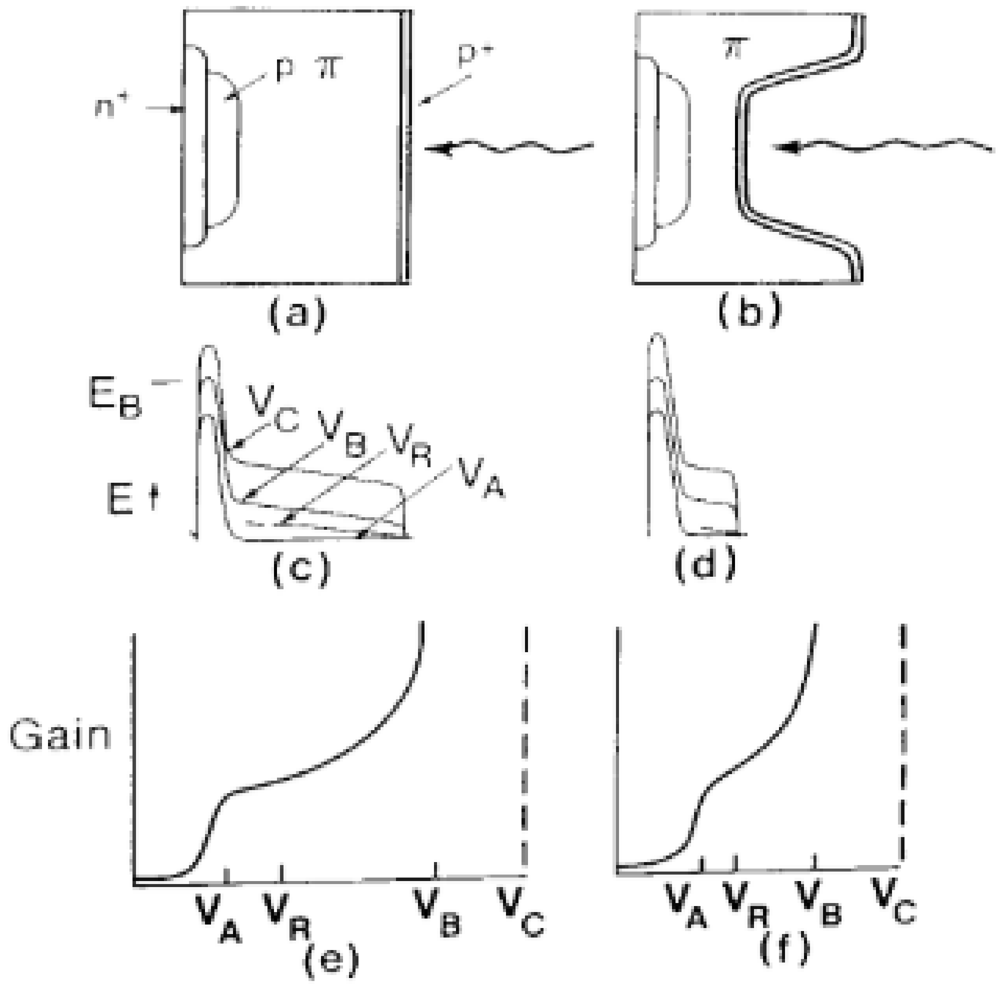


Fig 1 Two typical avalanche photodiode designs: structures (a) and (b), electric field distributions (c) and (d), and gain-voltage curves (e) and (f)

Measurement Vol 3 No 4, Oct–Dec 1985

Limits of LGADs

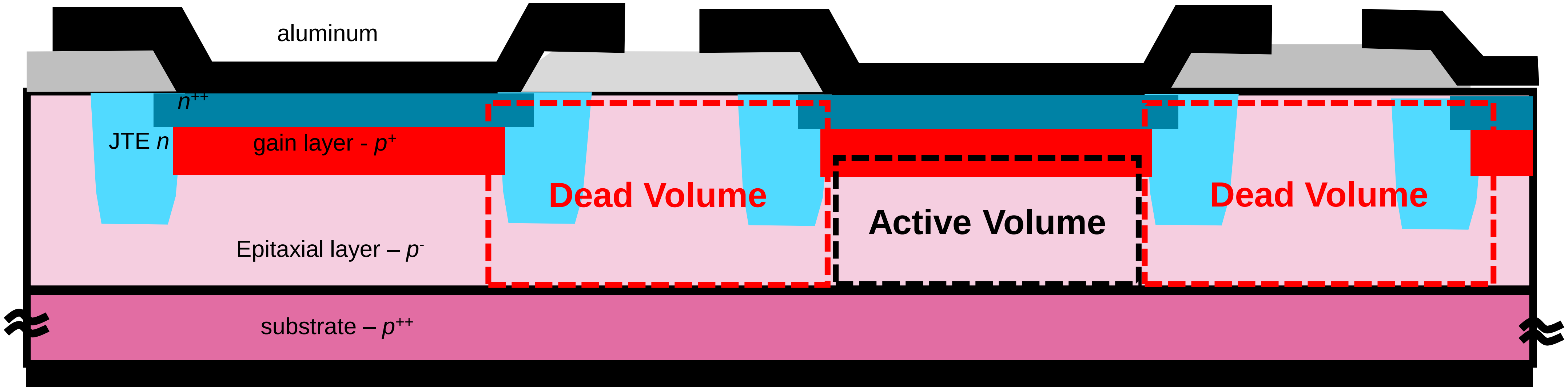
Lateral dimensions of Gain layer must be much larger than thickness of substrate, for a uniform multiplication.

Dead volume (gain~1) extends within the implanted region of the gain layer:

→ pixels/strips (pitch ~ 100 mm) with gain layer below the implant have a Fill Factor<<100% (Voltage dependent)

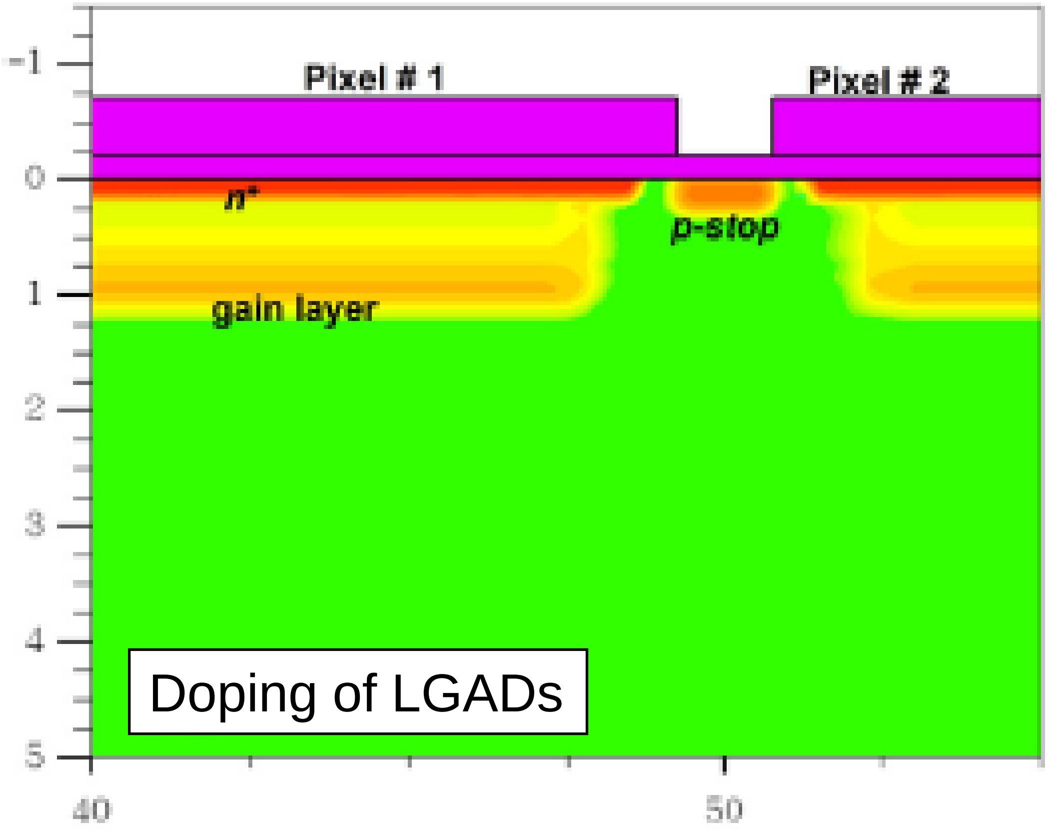
→ large pads are preferred (~ 1 mm); e.g., HGTD of ATLAS and MTD of CMS

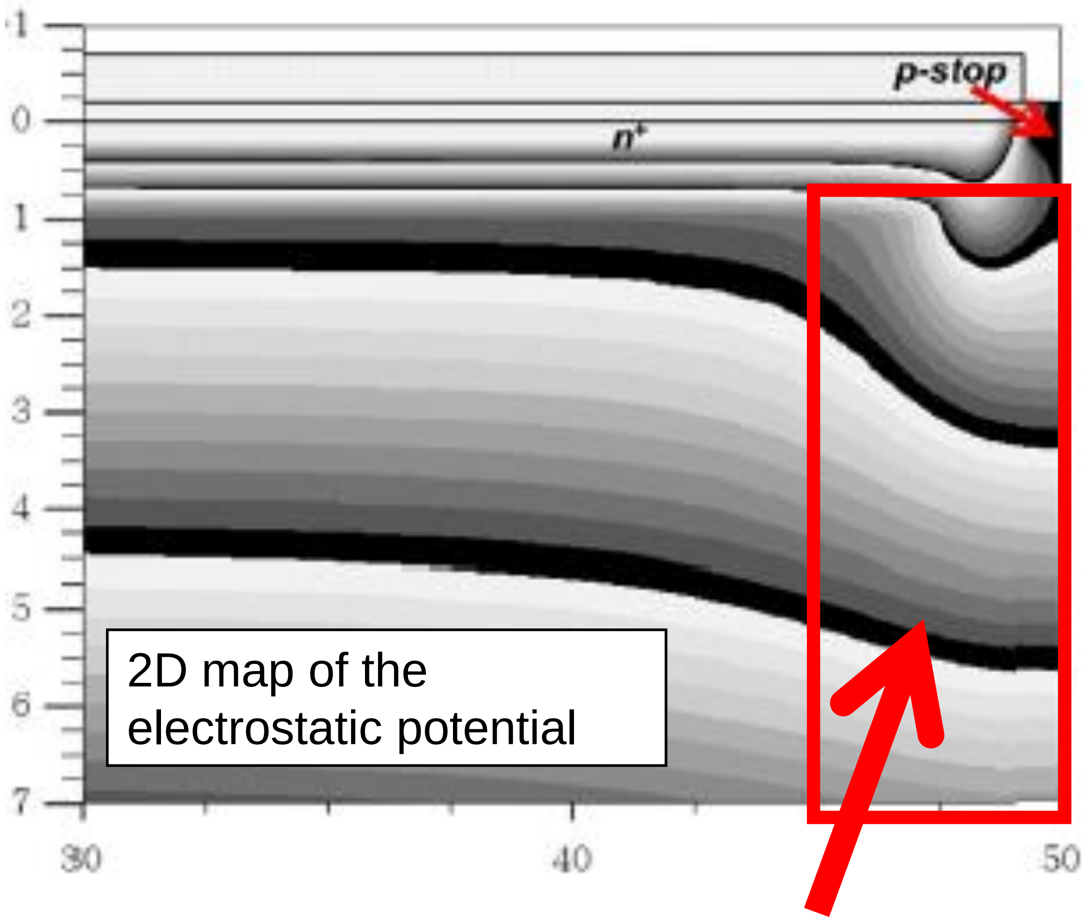
→ 4D detector not possible!!!



Origin of the dead area at the tip of the pixel

Basic electrostatic simulation shows how the potential line are bended away from the high field region

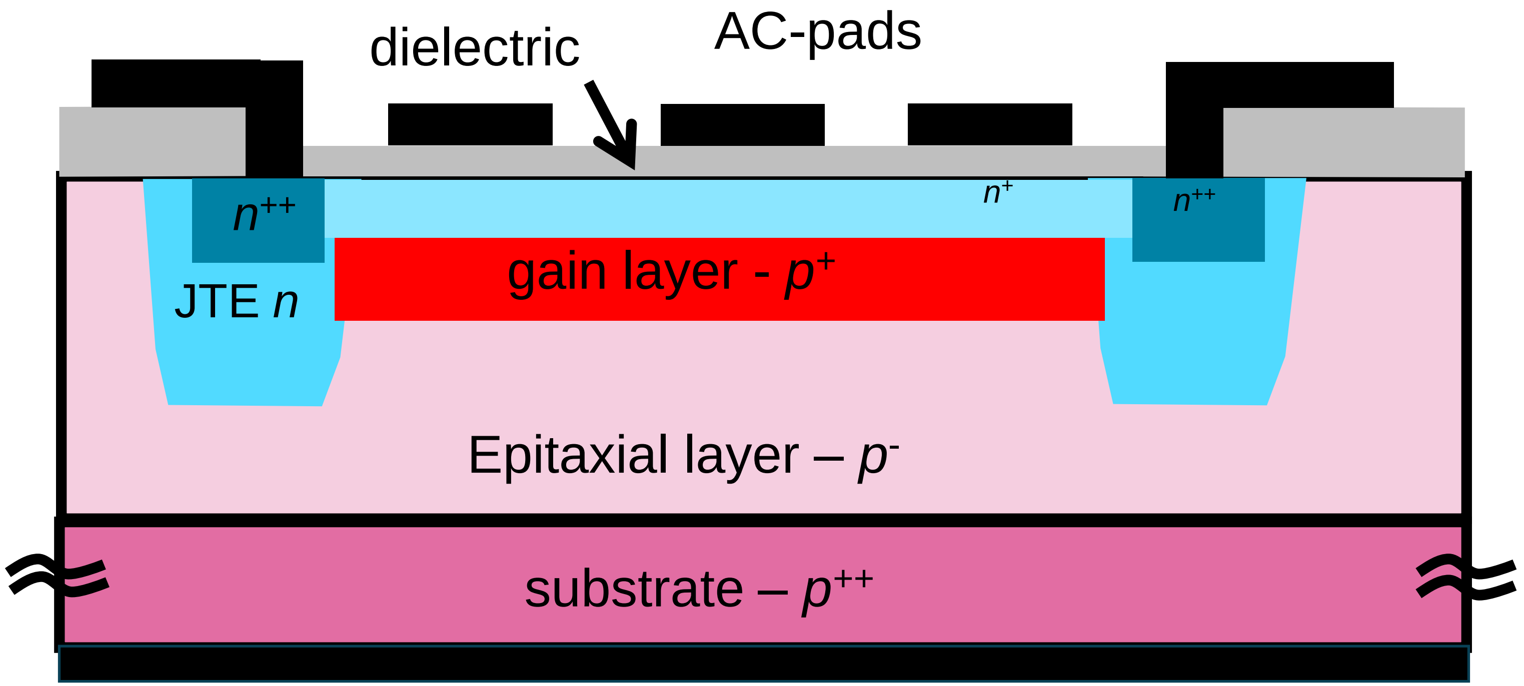




Electrons are collected by the tip of the n+, where electric fields are low

Towards a 4D detector

AC- LGAD

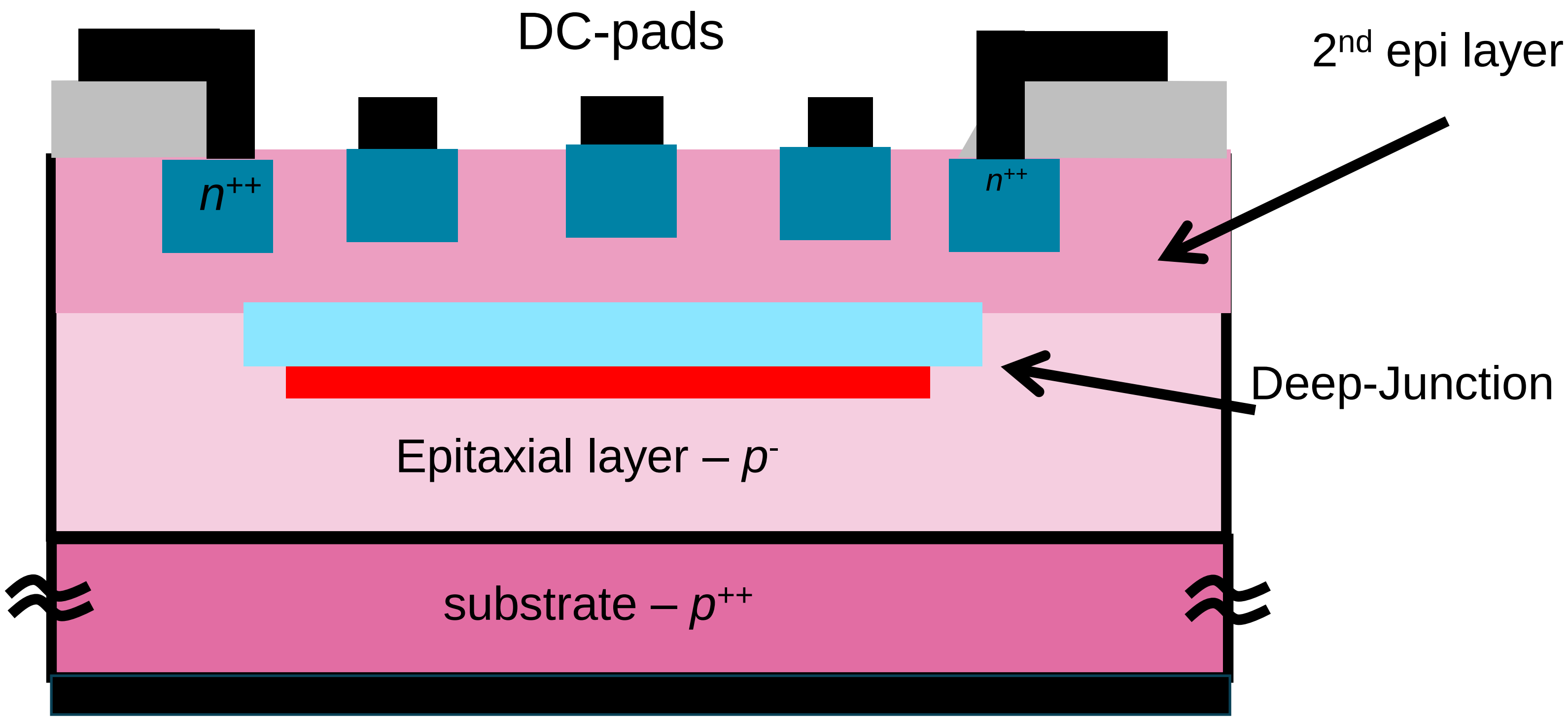


- Large area, uniform n+ and gain layer for 100% fill factor (FF)
- Signal capacitively induced to AC-coupled electrodes placed on insulator
- Signal spread to several AC-pads, making occupancy high
- Signal sharing can be used to fit hit position and hit time.

Metal electrodes can be of arbitrary shape.
Spatial resolution ~ pitch/20 (channel count low)
For example, for ePIC TOF strips will be at a pitch of 0.5 mm (or more)

Towards a 4D detector

Deep-Junction LGAD



- Large area, uniform, buried n/p gain junction, for 100% fill factor (FF)
- Position resolution given by pitch, as in std pixel/strip detector
- need an epitaxial layer deposition after the junction is formed into the first wafer. Not standard process!!!

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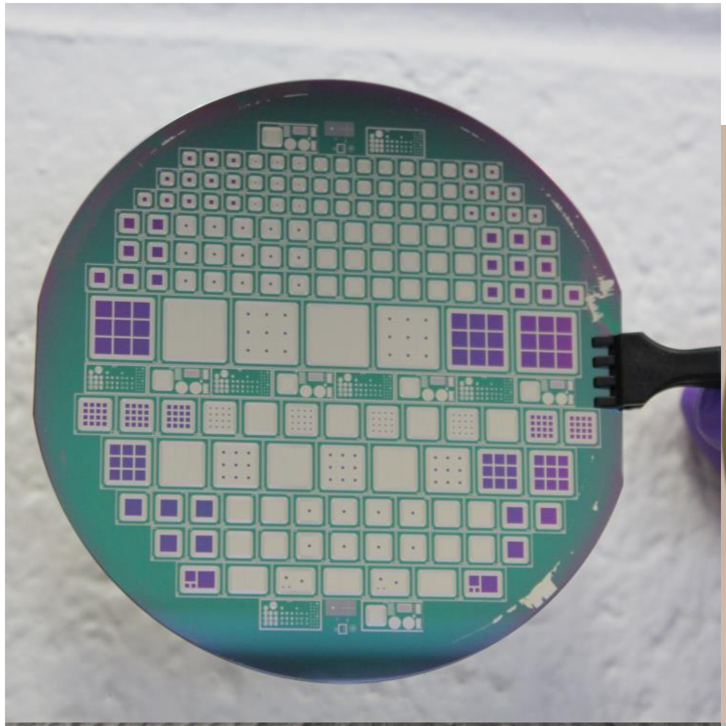
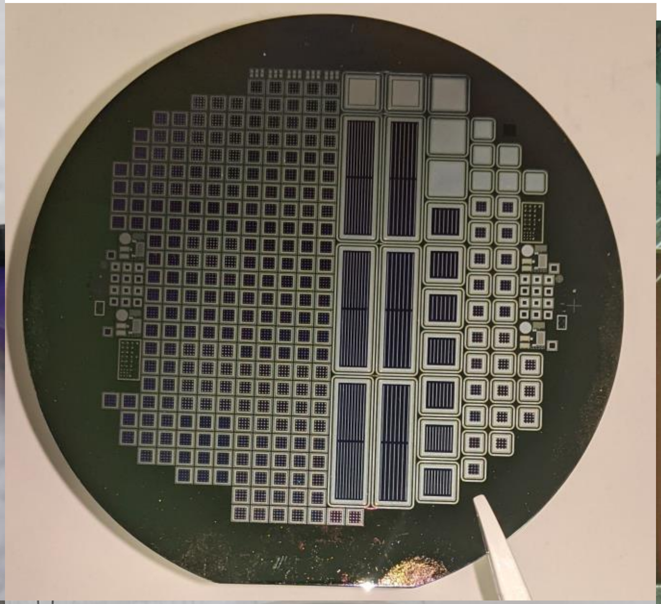
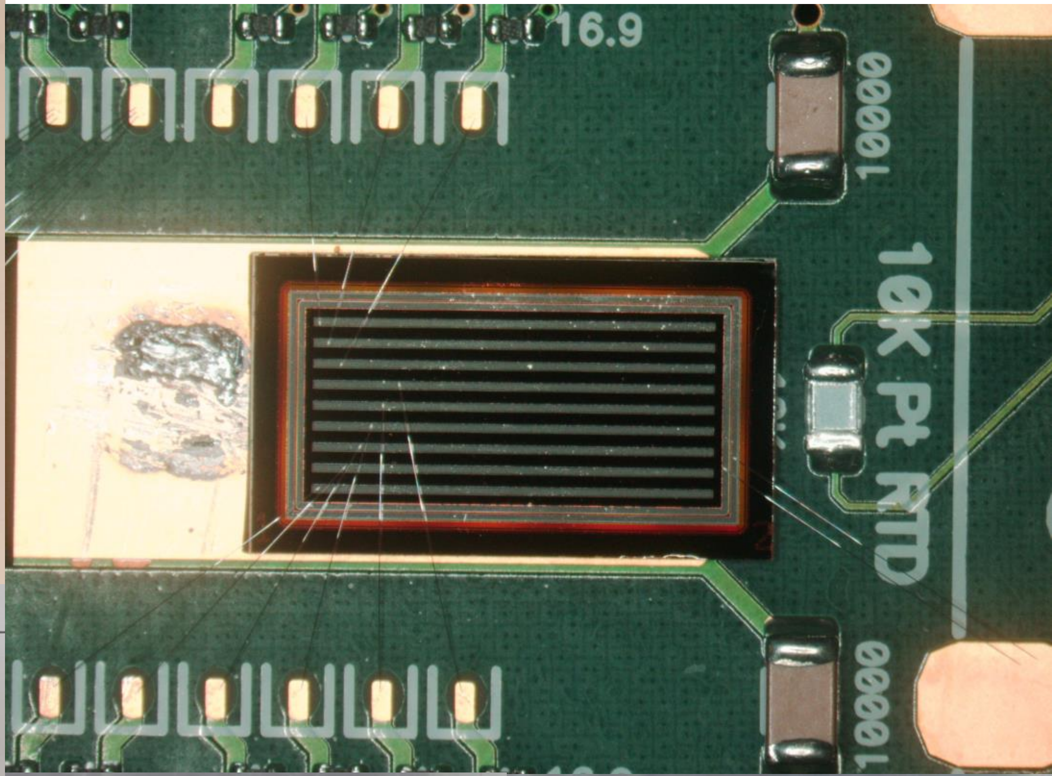
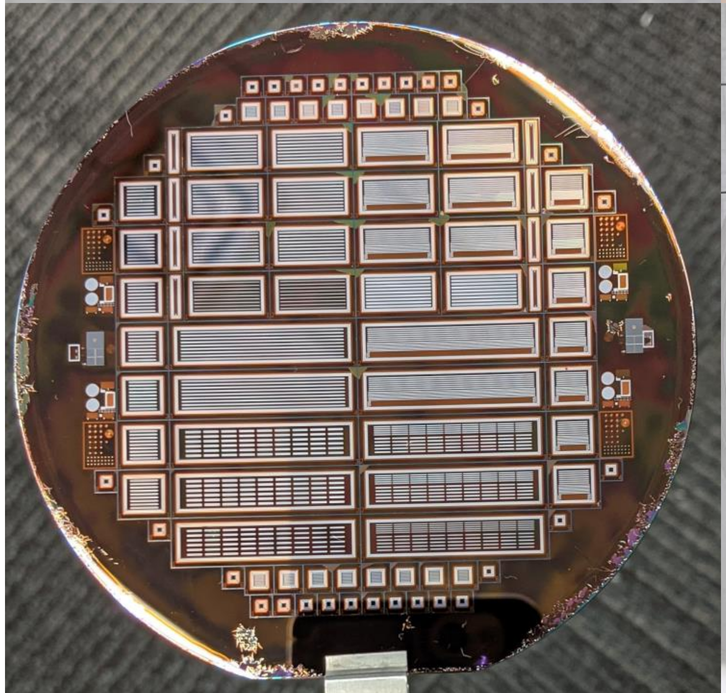
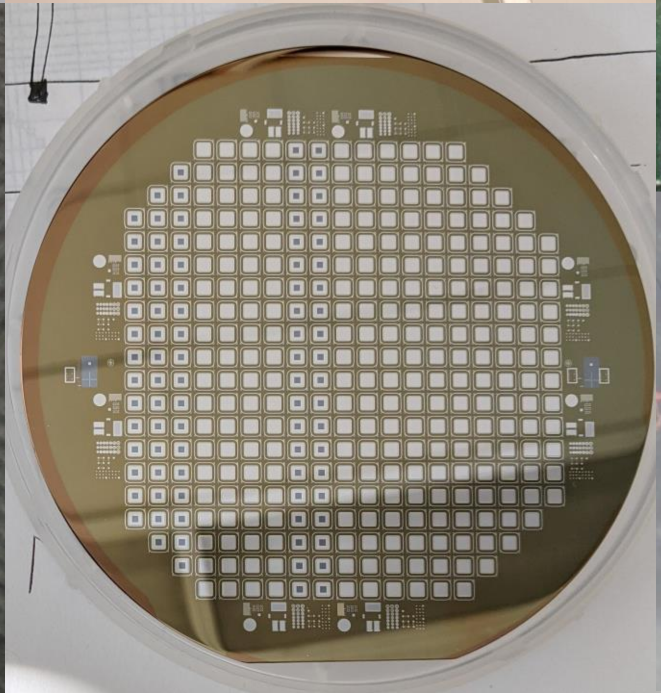
Several fabrication at BNL

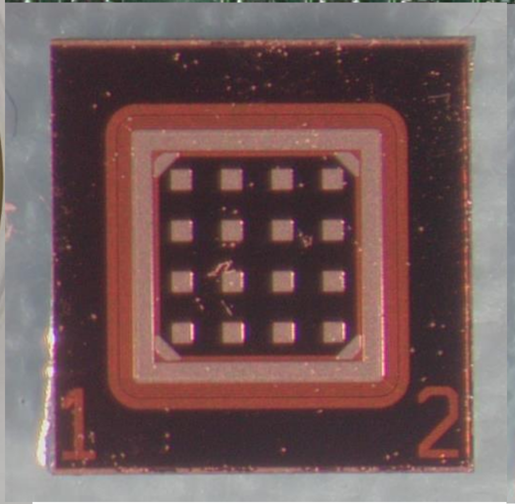


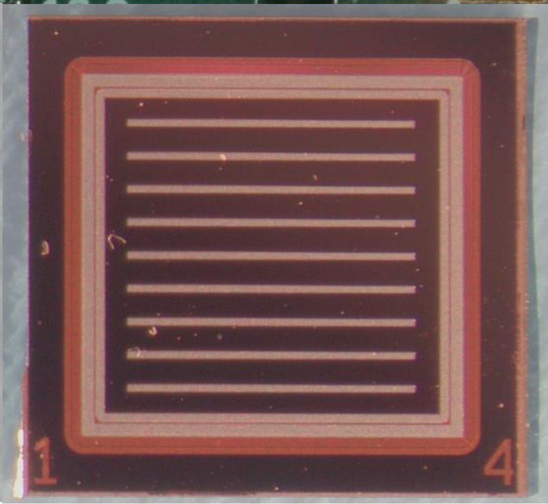








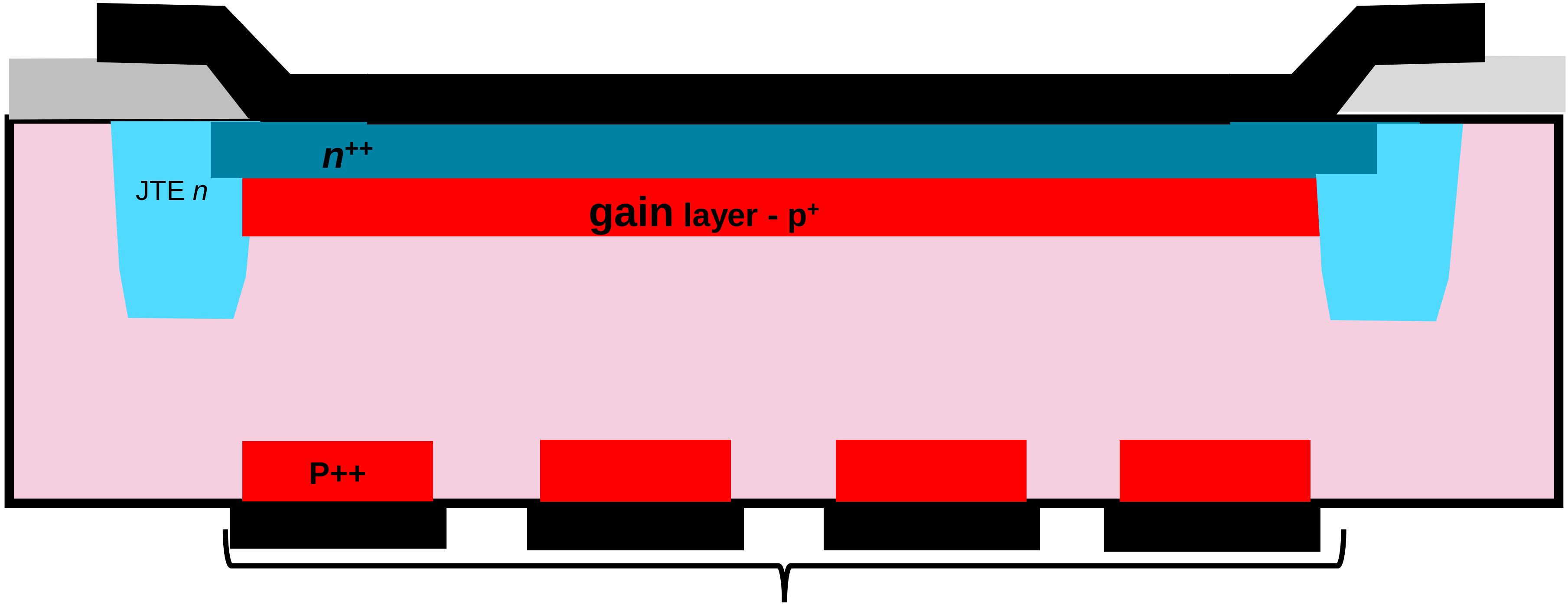




Towards a 4D detector

iLGAD

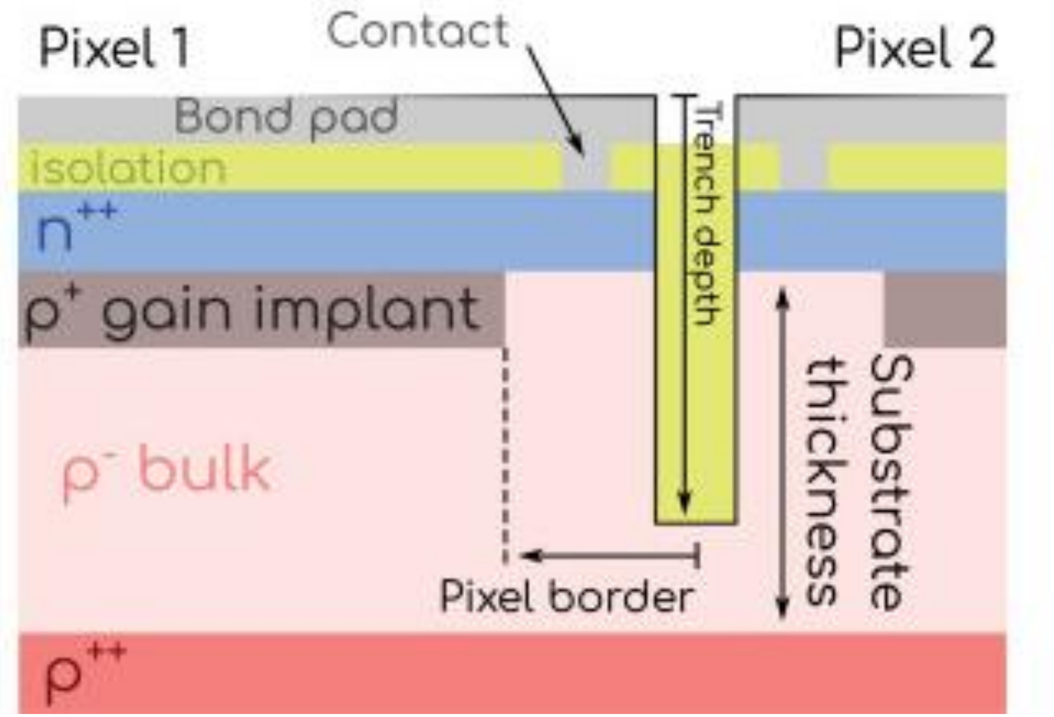
Another Solution: Closely-spaced electrodes can be put on the opposite of the wafer (inverted LGAD - **i-LGADS**, CNM Barcelona),
but wafers must be thick to be processed.
→ not possible to associate fast-time information on a per-pixel level!



Fine-pitch electrodes

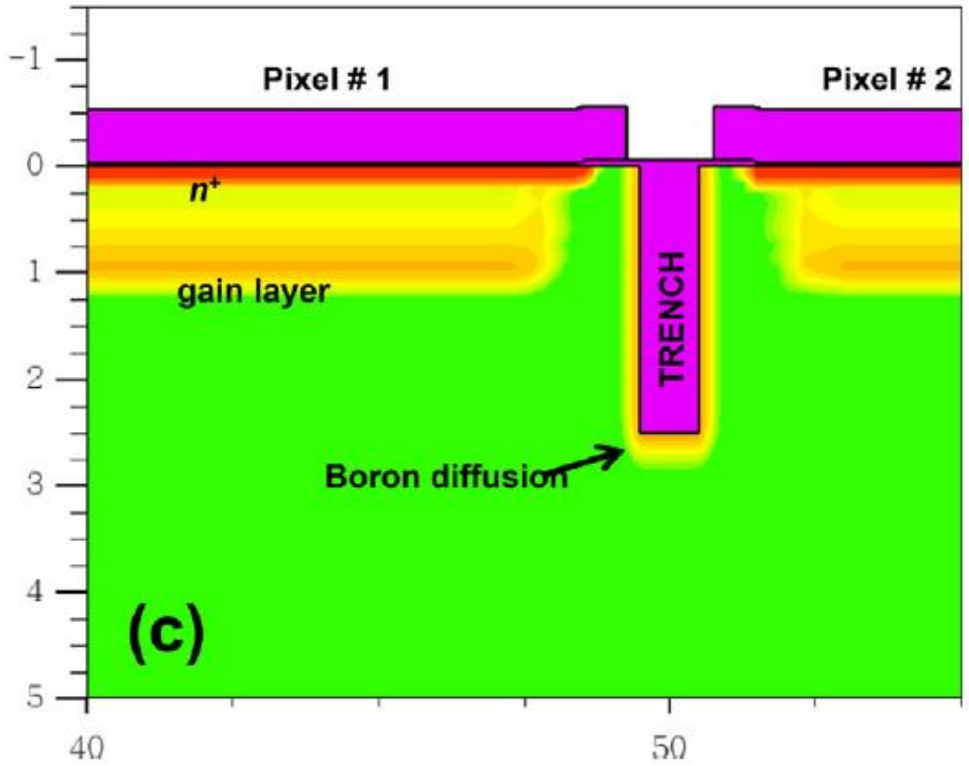
Trench-Isolated LGADs

Tech by FBK
By modifying the tip of the pixels and isolating them by trenches, dead areas of only a few μm can be achieved.



https://doi.org/10.1016/j.nima.2022.167030

Tech by BNL
Trench doped by boron to push the drifting electrons toward the high gain region

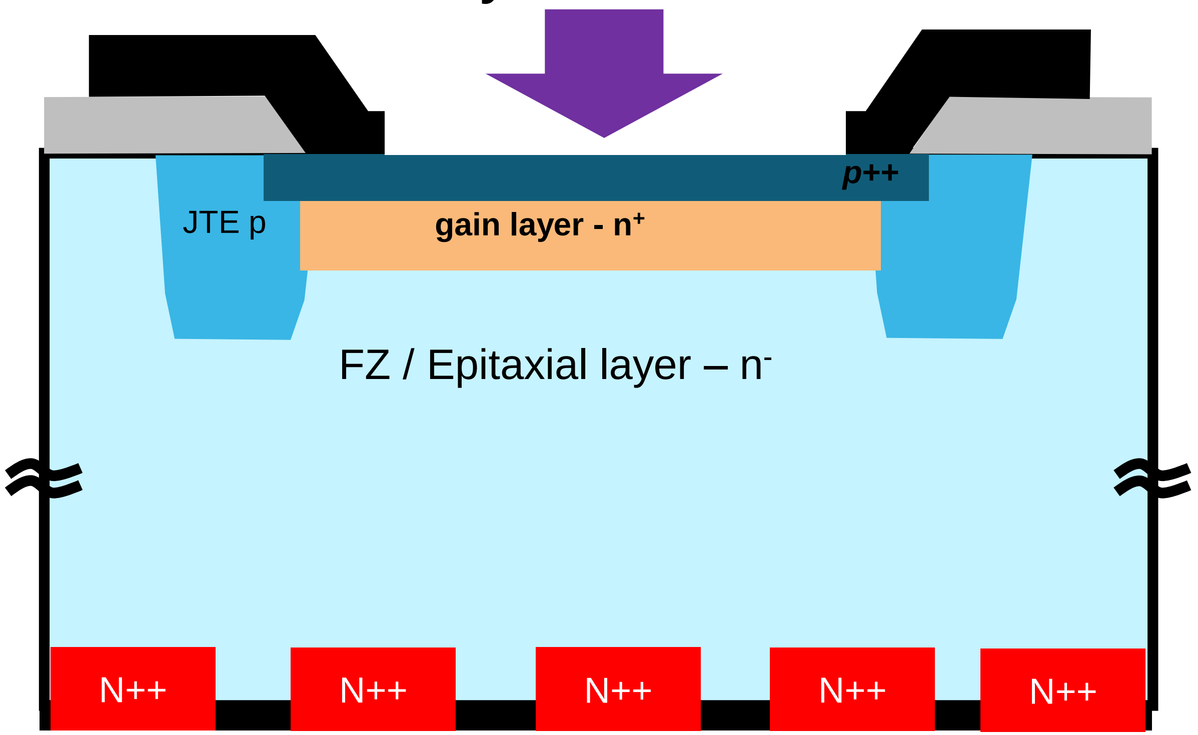


https://doi.org/10.1016/j.nima.2023.168497

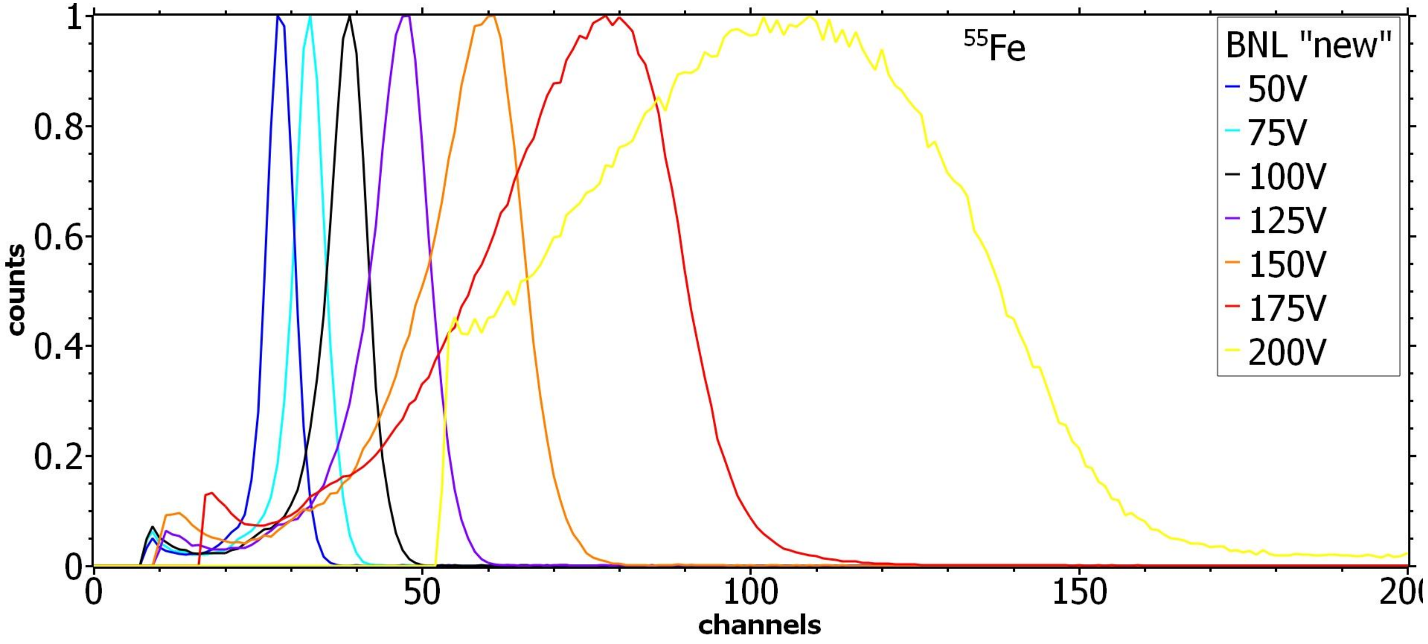
nLGAD

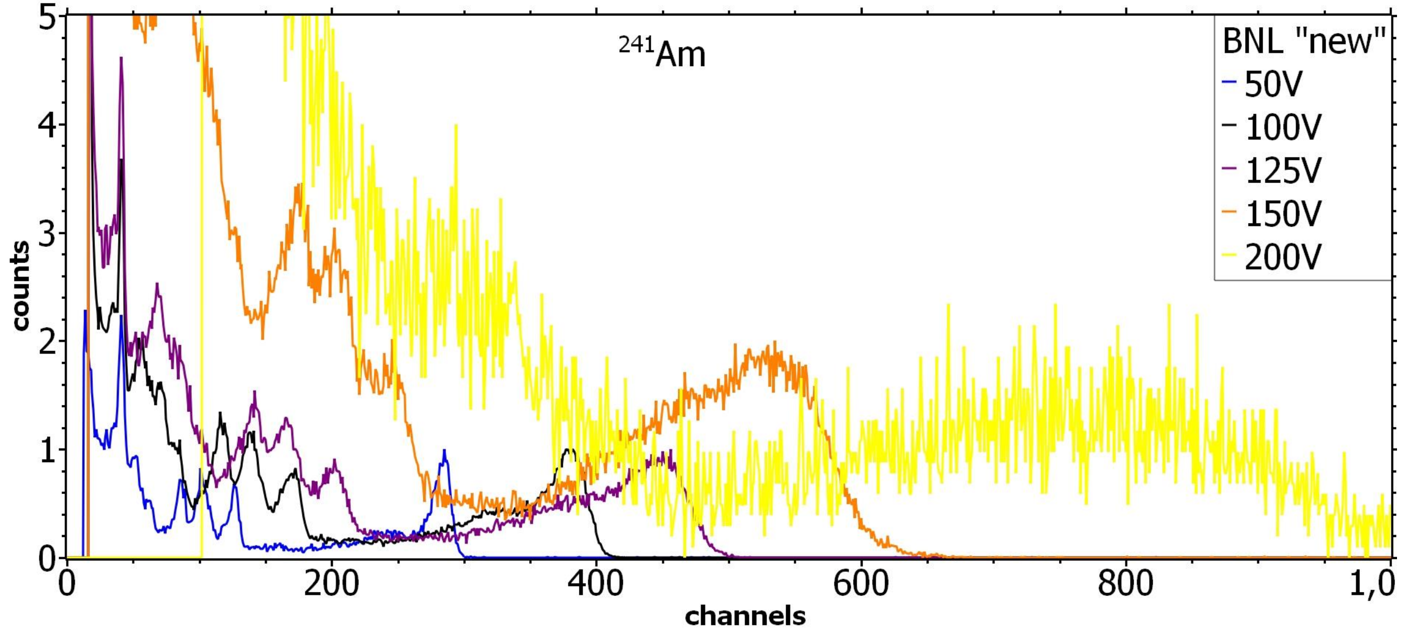
nLGAD has all the doping of the opposite sign with respect to std LGAD
LGAD for low-penetrating particles.
Ionization coefficient in silicon are higher for electrons than for hole: the electrons must initiate the avalanche crossing the high electric field.

UV, low-energy electrons, soft X-rays have small penetration depth in silicon:
Signa electrons cross the high field to be collected by the n+ on the back.
Requires thin entrance window



Spectroscopic properties





Pulse height spectra acquired with CSA (A250, Amptek).

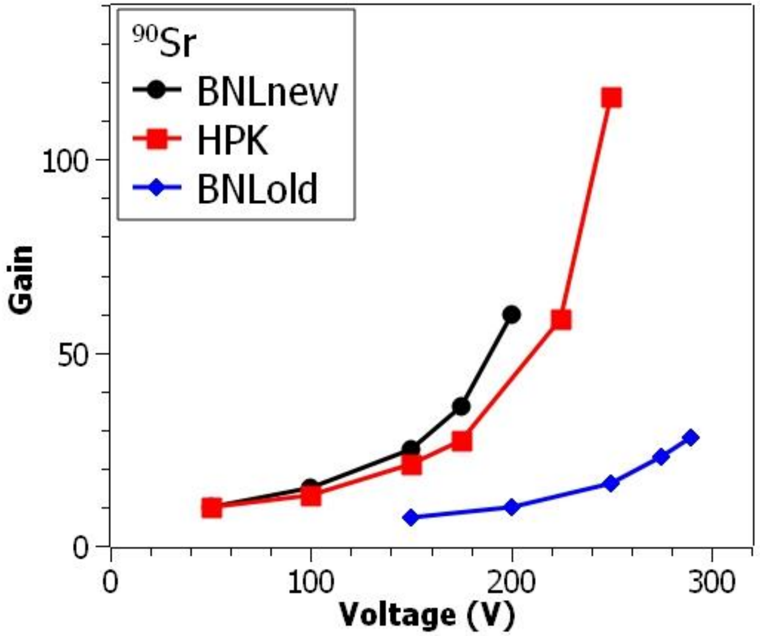
- Gain increase with voltage
- Gain dependent on radiation
- Skewness towards lower gains
- Multiplication noise increase more than signal

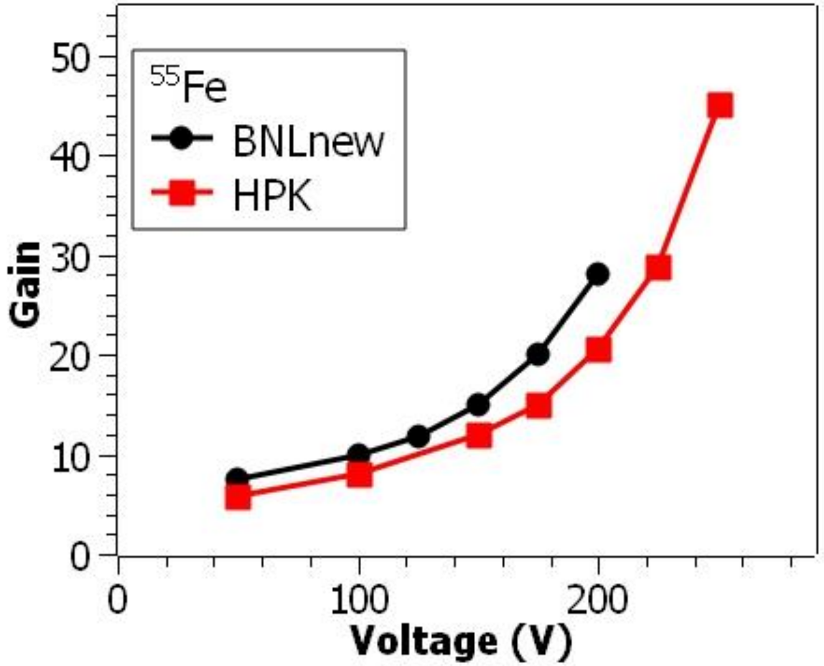
  → Worst S/N at higher gains

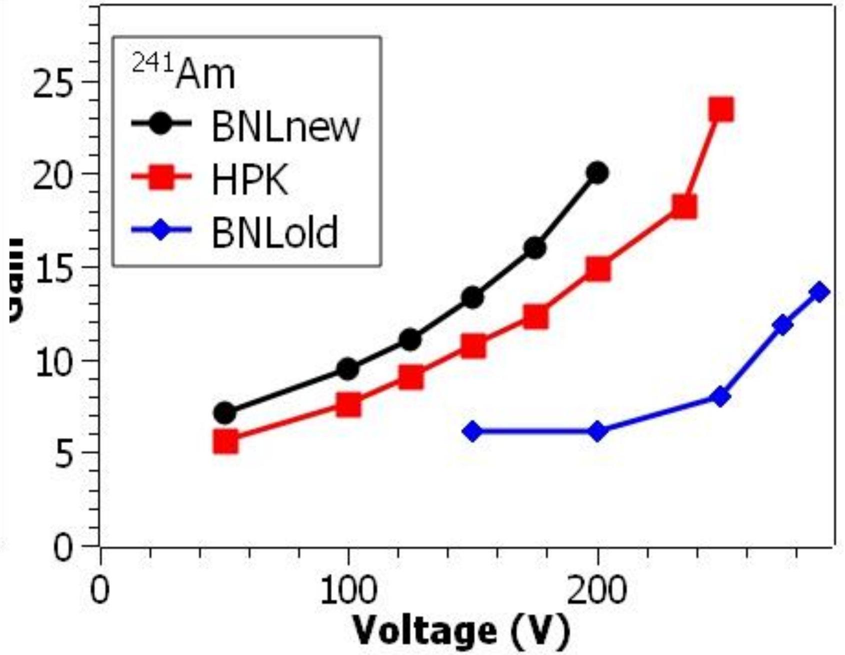
FWHM by pulsing a C_{test} ~ negligible

Gain

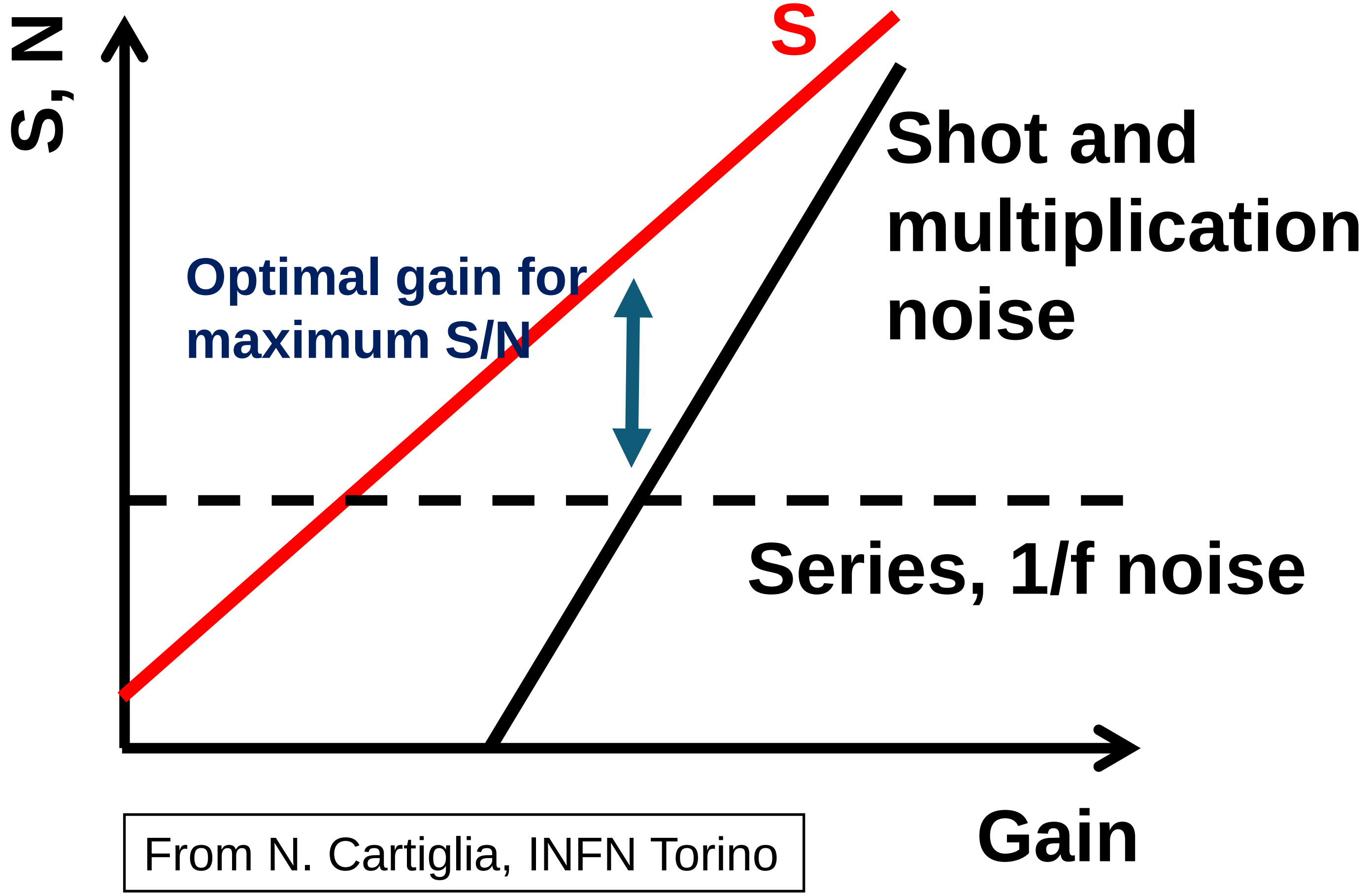
- Higher gain for mips than for X-rays
  - Charge density plays a role
- Several process parameters affect the max gain (doping profiles, …)







Noise



Signal ~ gain

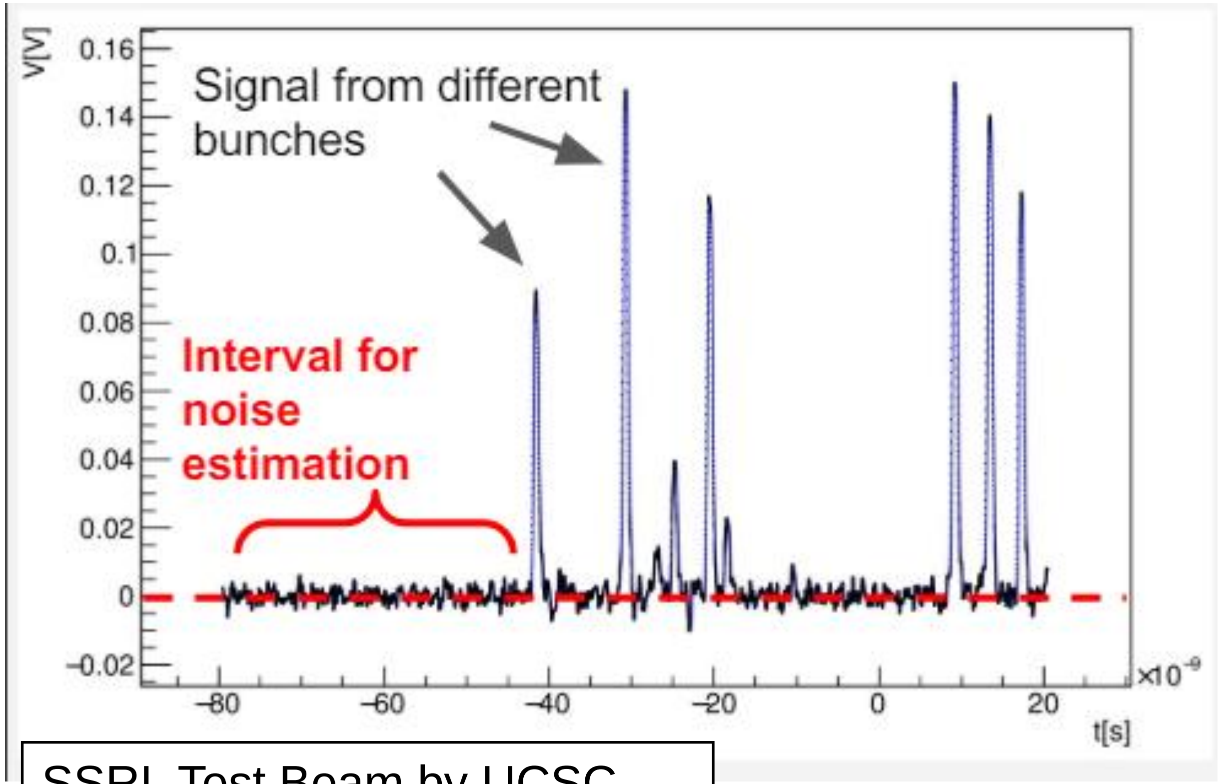
LGAD introduces a parallel noise:
$di^2/df \sim$ shot * gain^2 *F(gain)

APD/LGAD can achieve better S/N than no-gain diode only because of the electronic noise baseline

Timing

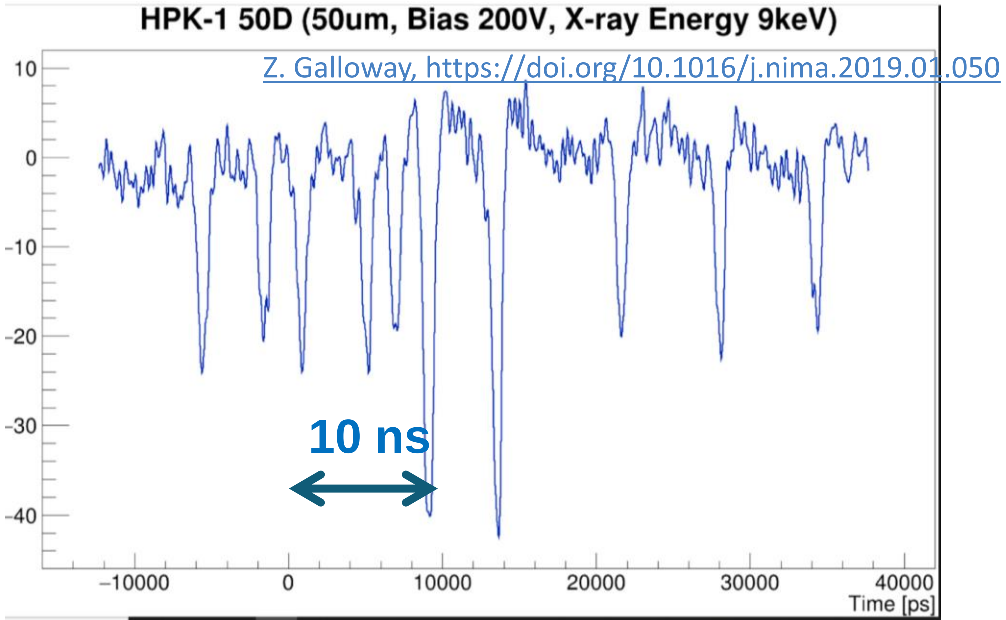
When detecting mips, LGADs show timing resolution of 20-30 ps, depending on substrate thickness and limited by Landau fluctuation.

For X-rays, timing is worse as there exists a time-walk effect from photon absorption at different depth.
> ~100ps (Y. Zhao, CPAD 2023)



SSRL Test Beam by UCSC

As signal develops in ~ 1ns, can detect 500MHz repetition rate.
Up to 1GHz (per channel) seems possible.



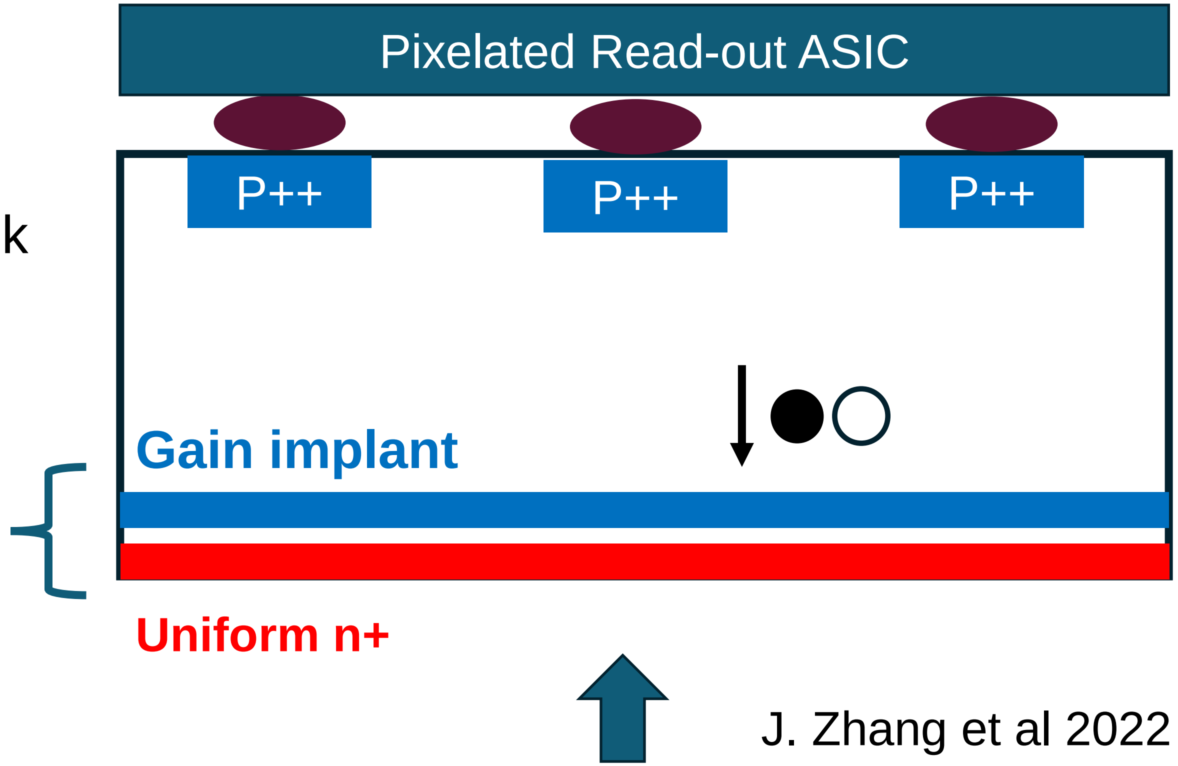
LGAD for Soft X-rays

We can use the LGAD gain to bring the signal comfortably above the noise level (due to FFE).
Gain should be small as not to trigger the multiplication noise and high excess noise.

Soft X-rays – as their penetration depth is small – need modified LGAD structures.

Signal electrons ● drift back to the n+ to cross the gain region and get multiplied

<u>Ultra-shallow gain region</u>



J. Zhang et al 2022 JINST 17 C11011

Summary

- LGADs have been developed for detection of mips in HEP
  - Established technology: a few foundries are in the game

- LGADs can have a σ_t < 30ps (for mips), once a few design rules are met
  - For 4D detection, other LGADs families must be used (or developed): AC-LGADs, Deep-Junction …work in progress

- While poor spectroscopic properties, good for fast detection of X-rays

- OK also for the detection of low-energy X-rays but need different structures