Low-Gain Avalanche Diodes (LGAD) for photon science

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Collaborations

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Structure of LGADs

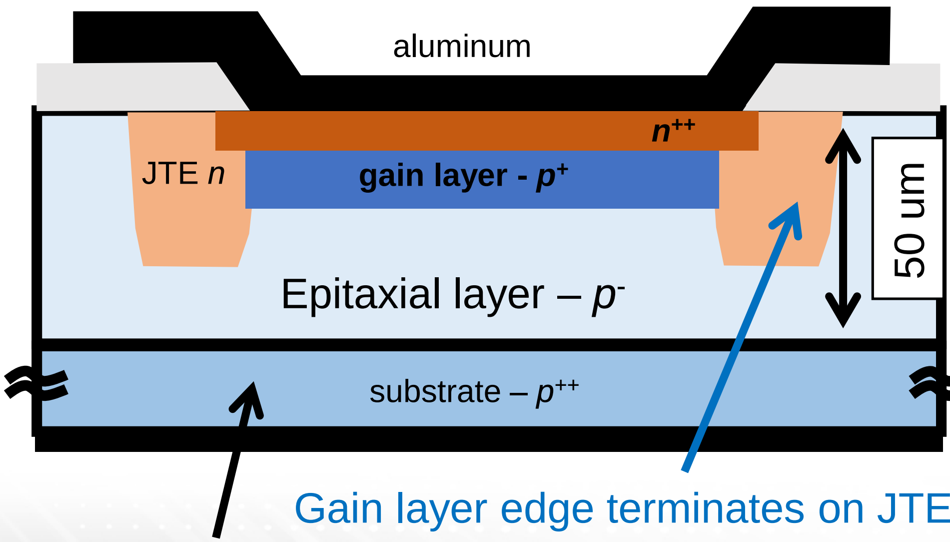
LGADs are Avalanche Diodes specifically tailored for the detection of mips in HEP
For mips: if the substrate is thin (~ 50 μm) and the gain is ~ 20 → signal is fast (~30 ps)

LGADs are 20-50um thick (only active volume!) as compared to hundreds of um of std strip/pixel sensors.
LGADs feature a p+-layer (gain layer) under the n+.
Depletion of the p+ gain layer creates intense Electric Field, high enough for electron impact ionization to occur.
Hole impact ionization ~ 0

→ LGADs operate before BreakDown (linear region)
→ gain ~ few 10s

Amplification is needed to have a good S/N when reading-out fast.

LGAD for mips, X-rays

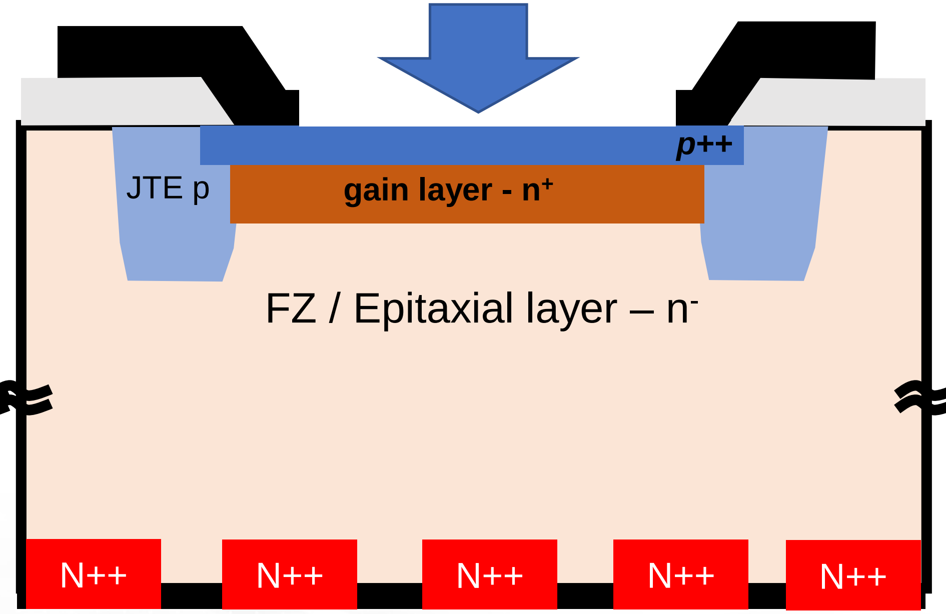


Gain layer edge terminates on JTE

Substrate is just for handling

BNL, CNM, FBK, HPK, … do LGADs

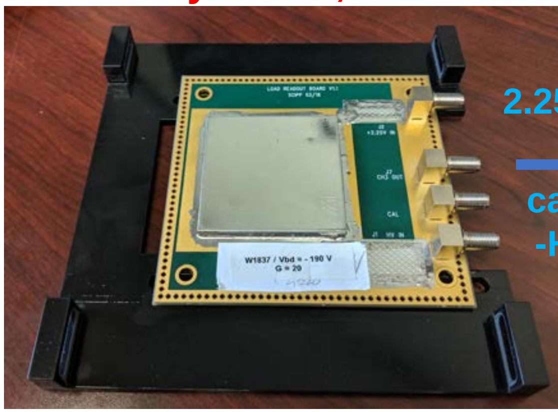
LGAD for low-penetrating particles



- Back can be pixelated.
- Single-sided processed @ BNL

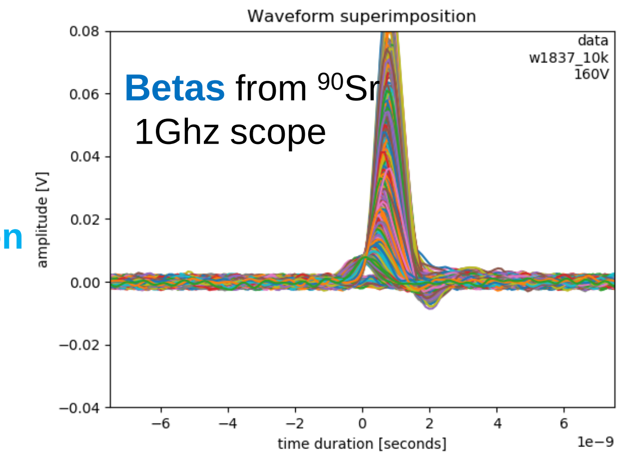
Waveforms

TA board by SCIPP, Santa Cruz



2.25V

calibration
-HV

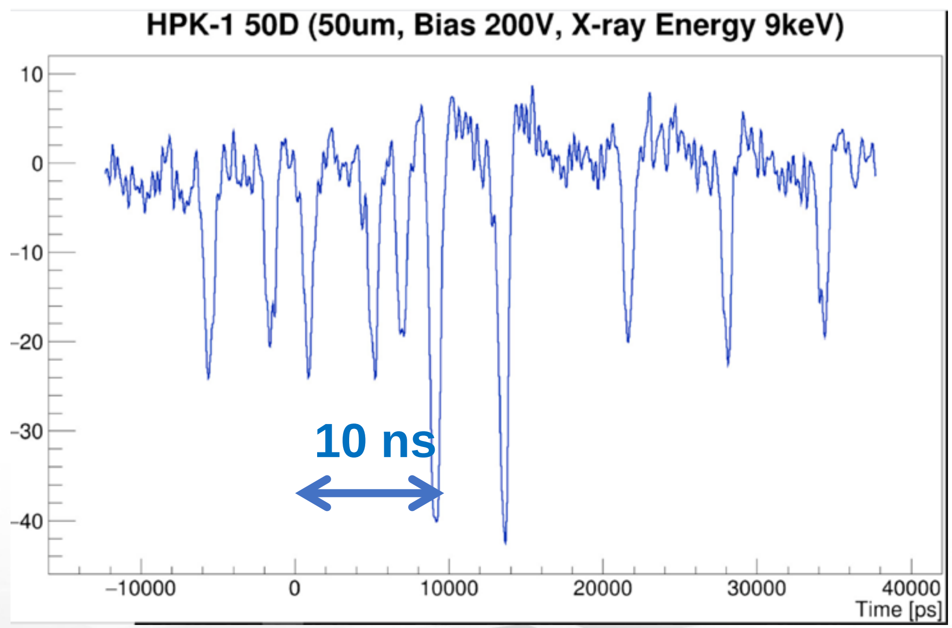


50-µm thick

Integral
[Vs] / $R_{feedback}$
→ charge[C]

High Frame rates possible

- 9keV X-rays
- 500MHz repetition rate of SSRL beam
- ~GHz bandwidth read-out
- Poor energy resolution due to multiplication noise



Z. Galloway, https://doi.org/10.1016/j.nima.2019.01.050

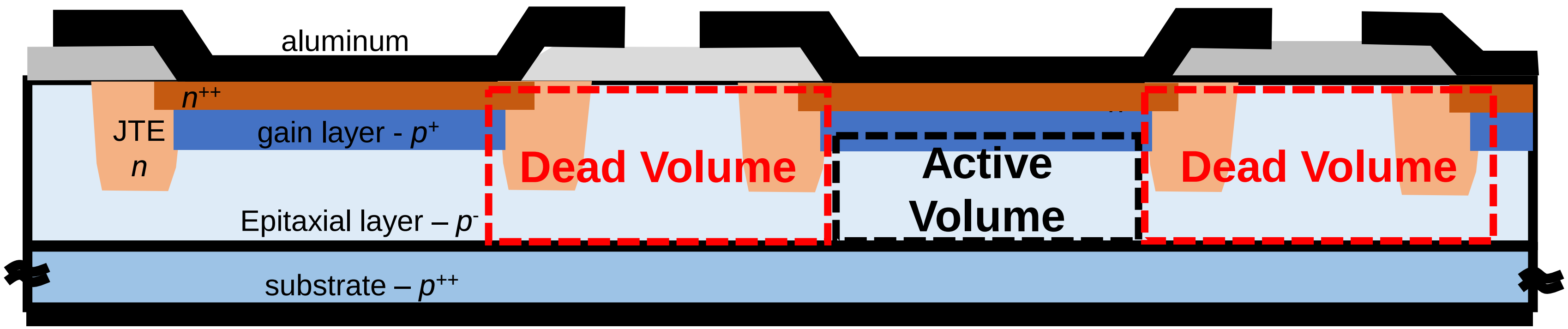
Limits of LGADs

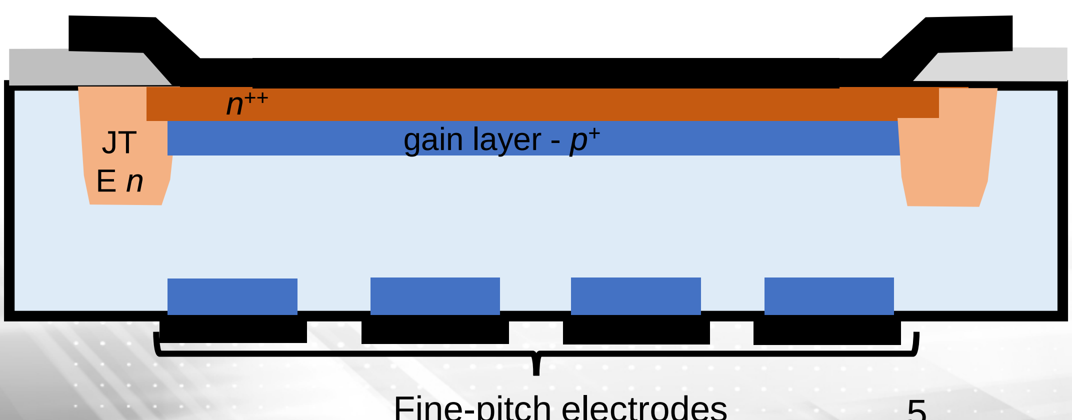
Lateral dimensions of Gain layer must be much larger than thickness of substrate, for a uniform multiplication.
Dead volume (gain~1) extends within the implanted region of the gain layer:

→ pixels/strips (pitch ~ 100 μm) 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!!!



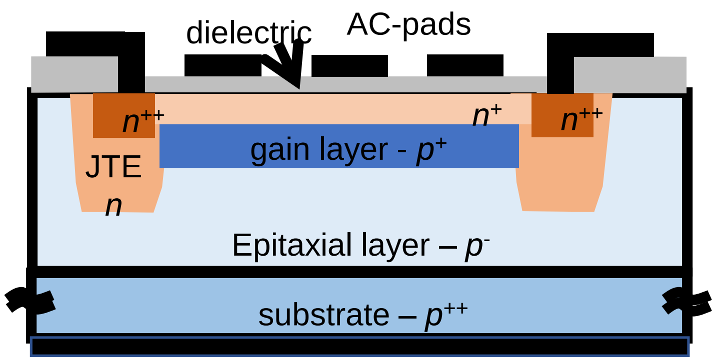


A possible Solution: Closely-spaced electrodes can be put on the opposite of the wafer (**i-LGADS**, CNM Barcelona),
but wafers must be thick to be processed.
→ not possible to associate fast-time information on a per-pixel level!

Towards a 4D detector

AC- LGAD

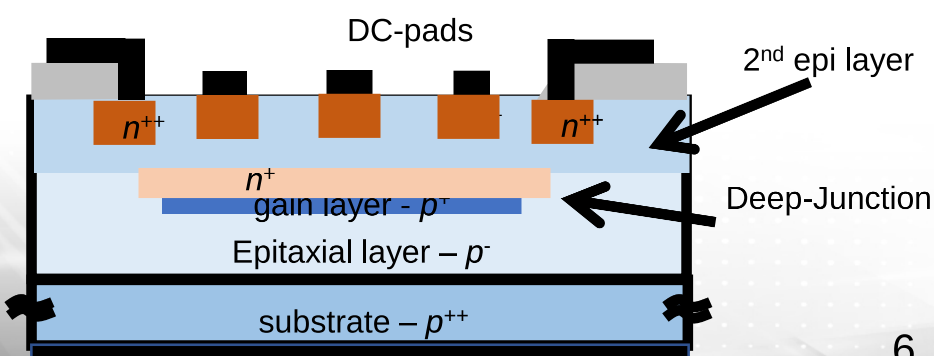
Modification of DC-LGAD, requires fine tuning of two implants (n-resistive and gain layer). Fabricated @ BNL, FBK, HPK, CNM.



- Signal spreads to several AC-pads, making occupancy high (only low event rate possible)
- Signal sharing can be used to fit hit position and hit time. Need also reconstruction algorithms.
- Optimization of AC-metal shapes are under investigation (seems however that pitch/resolution ~10)
- Slow/small signals from thicker substrates may be beyond detection?

Deep-Junction LGAD

Process on going @ BNL



- Position resolution given by pitch, as in std pixel/strip detector
- Careful: Slightly smaller electric field in the gain region in-between pads,
- need an epitaxial layer deposition after the junction is formed into the first wafer. Not standard process!!!
- Compatible with thicker substrates

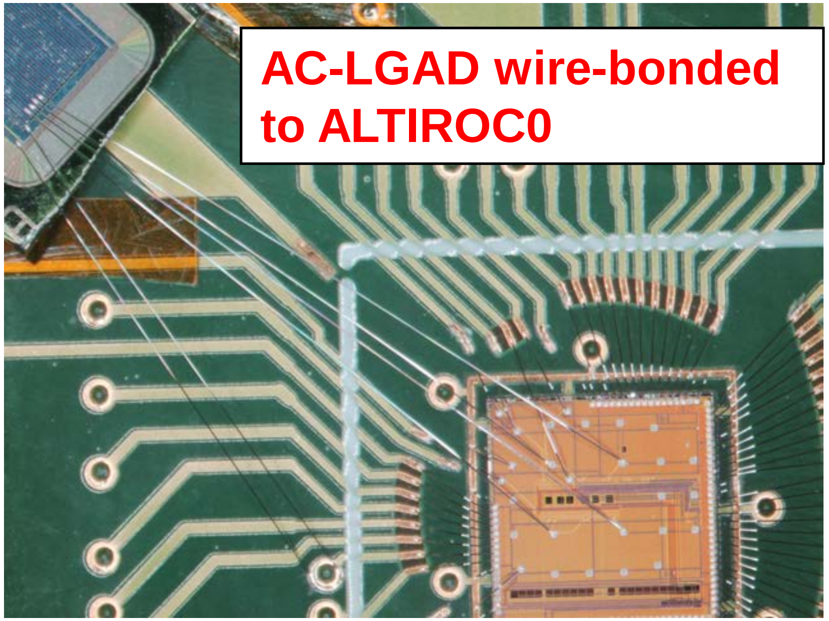
CMOS read-outs

In HEP, DC-LGADs are read-out by ALTIROC (Omega group, France), ETROC (FNAL).

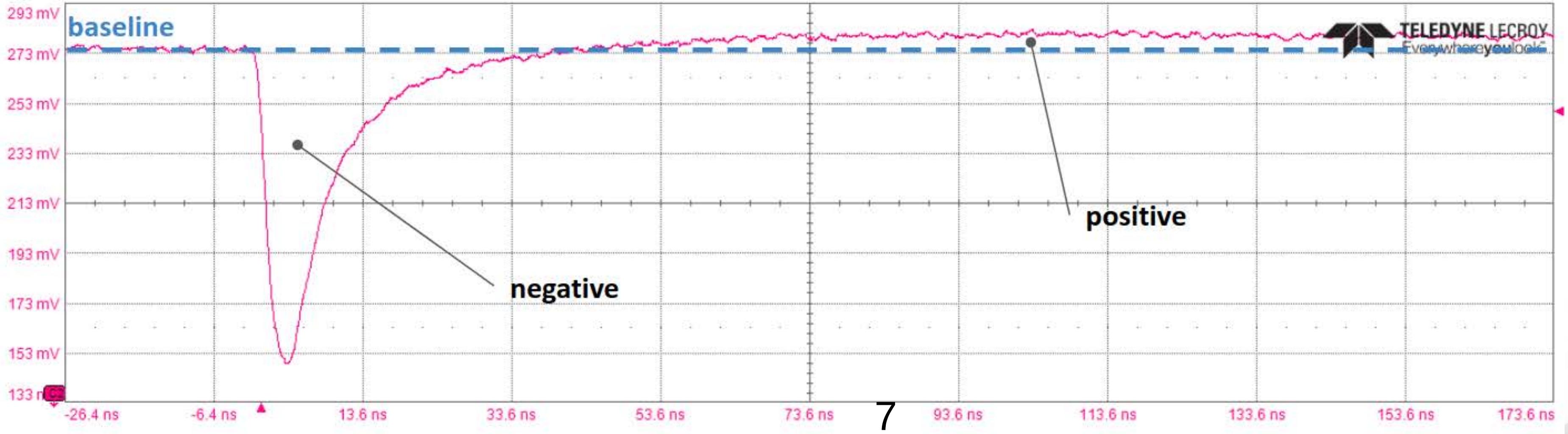
ALTIROC can read-out also AC-coupled LGAD. If we use the fact that:
Pitch/σ_x > 10, ASIC pixel may be large.

But generally speaking, hard to fit fast electronics in small pixels. Efforts on-gong:

- **FCFD0 (FNAL)** (
- Timespot (https://web.infn.it/timespot/), although for the read-out of 3D pixel sensors



AC-LGAD wire-bonded to ALTIROC0

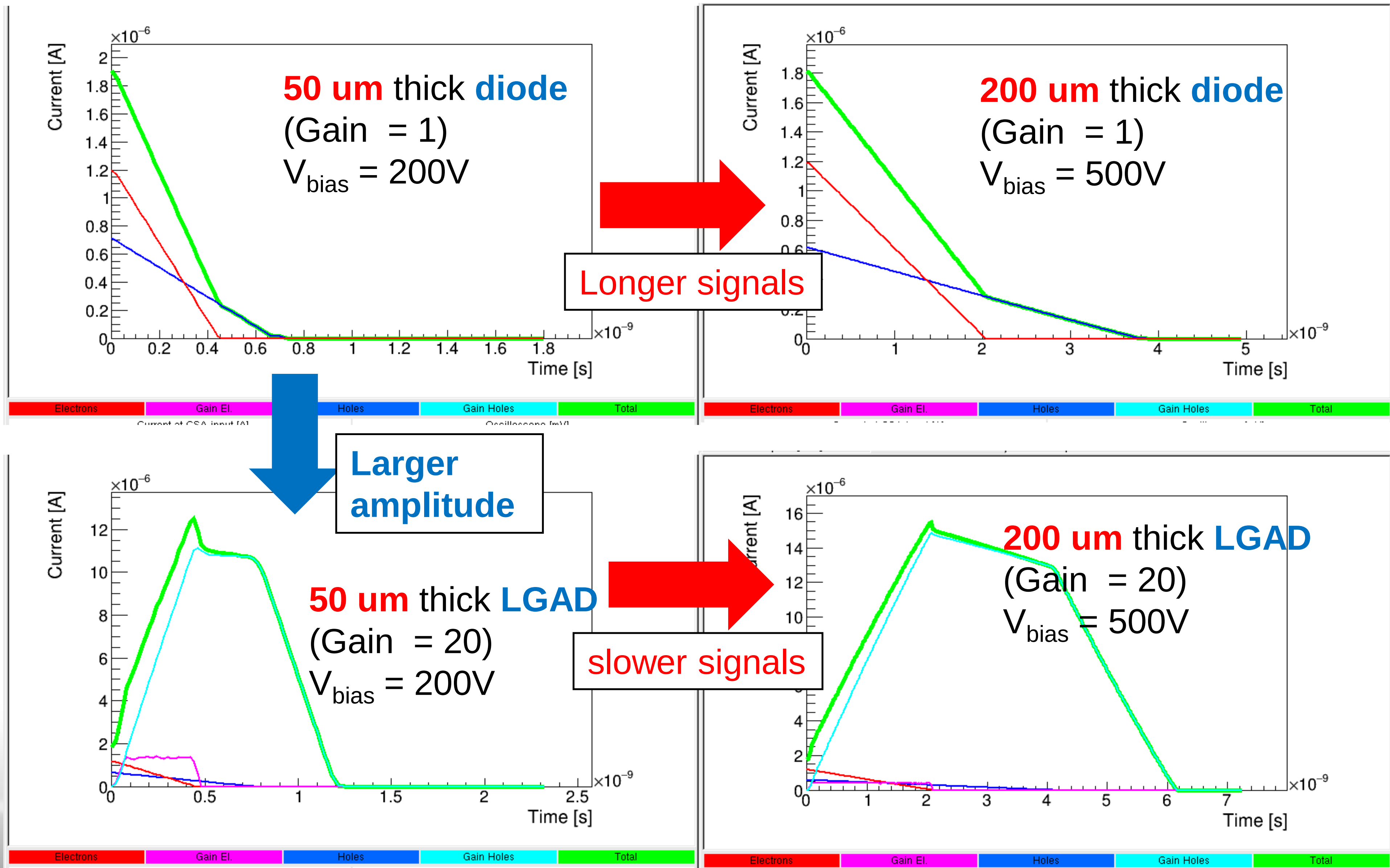


Summary

- LGADs have been developed for detection of mips in HEP.
- LGADs can have a σ_t < 30ps (for mips), once a few design rules are met
- While poor spectroscopic properties, good for fast detection of X-rays
- OK also for the detection of low-energy X-rays, but need to reverse the sign of the doping.
- Established technology: a few foundries (BNL, CNM, FBK, HPK) can do them
- If we want σ_x ~ 100um, LGADs are not good enough and other LGADs families must be used (or developed): AC-LGADs, Deep-Junction …work in progress
- CMOS read-out with small pixel pitch is challenging. Work in progress.

Back up

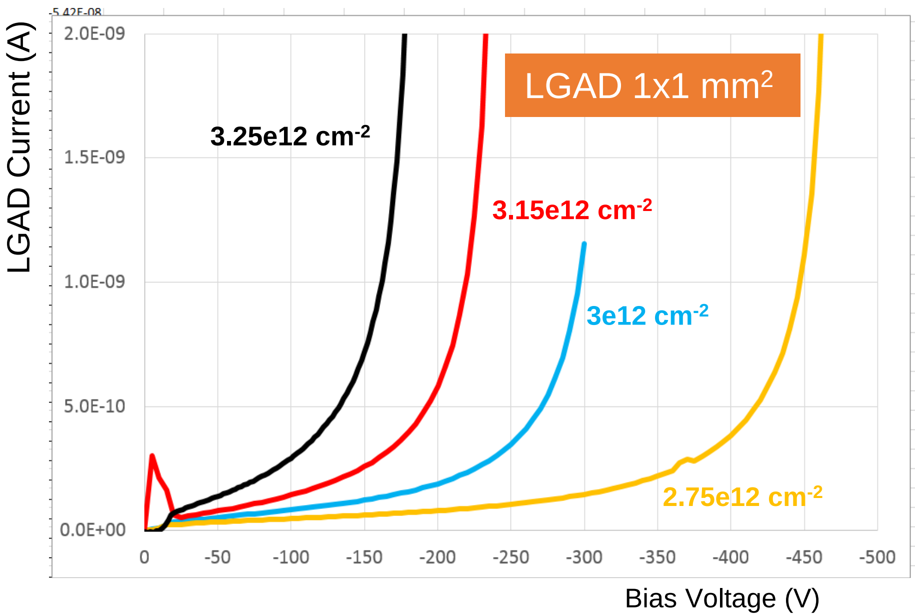
Signal shape in LGAD vs std diode

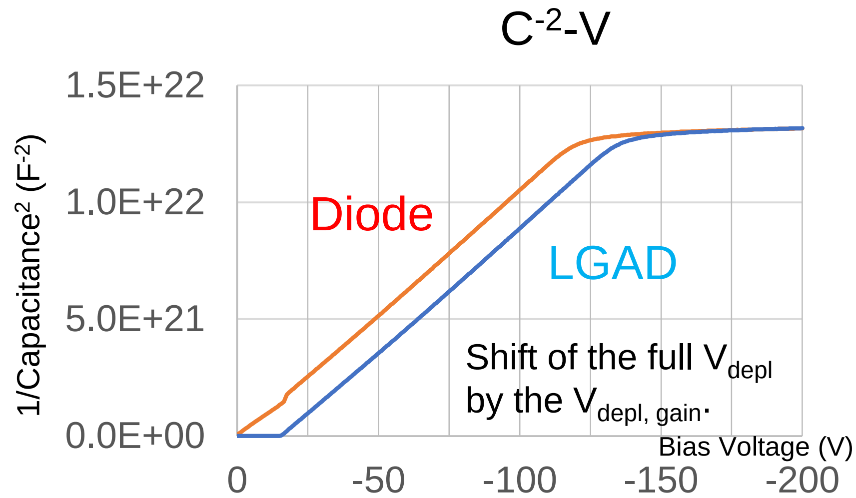


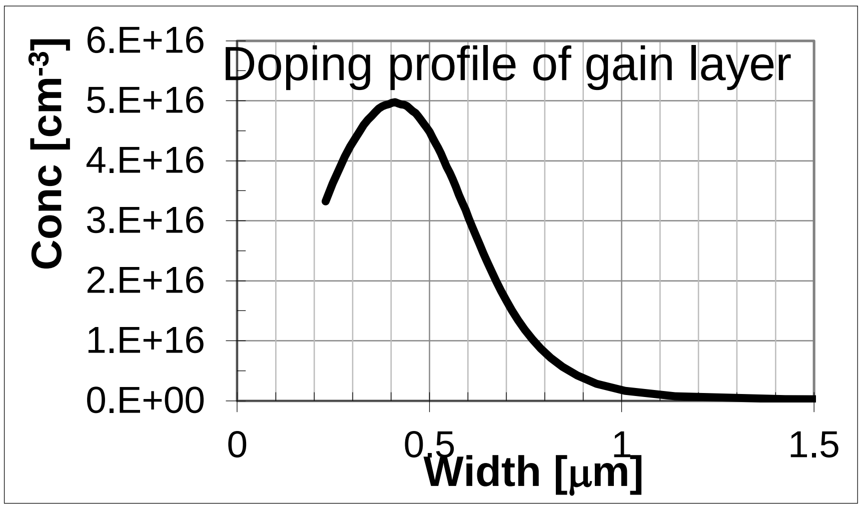
Static Electrical Characterization

BNL's LGADs :

- Leakage current as measured on diodes (gain=1) 1x1 mm² is ~ 10pA (1nA/cm²)
- Consistent from batch to batch
- Clearly current depends on gain layer dose, so does the breakdown voltage
- GR can stand higher voltages



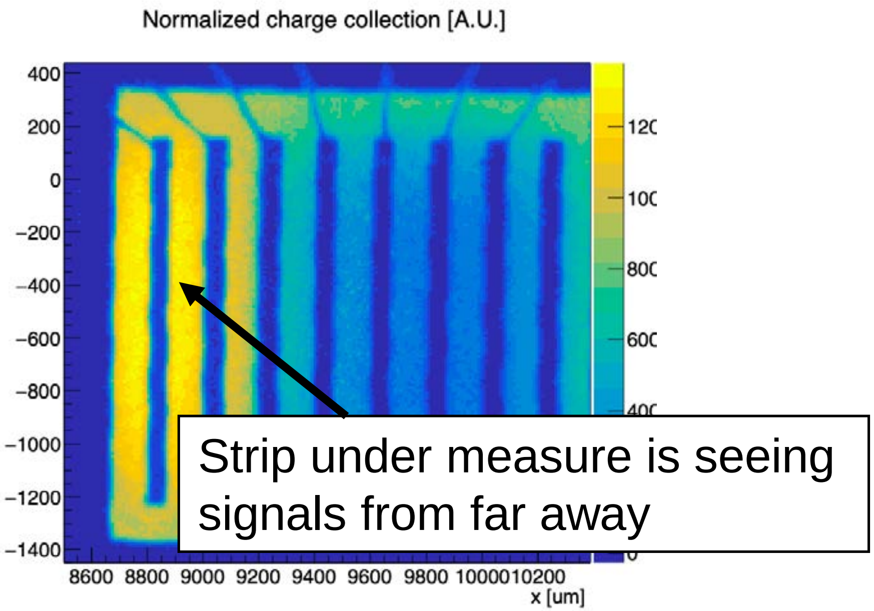




CNM (Barcelona, Spain), FBK (Trento, Italy), Hamamatsu (Japan), IHEP-NDL (Beijng, China) are also producing LGADs.

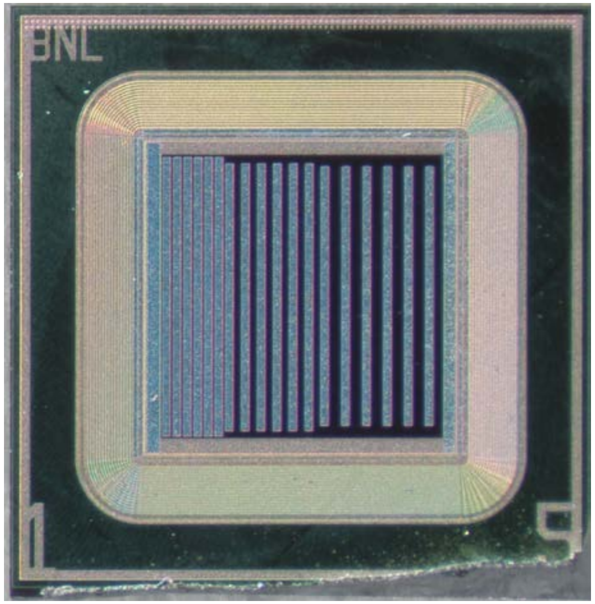
Signal sharing in AC-LGAD

- signal is shared among several electrodes.
  → interpolation allows to enhance position/timing resolution.
- Since multiple electrodes see a mip, not the best choice in a high event rate environment. EIC is ok.
- **Pitch/σ_x > 10** (https://arxiv.org/abs/2007.09528)
- **σ_t ~ 35 ps.**



TCT laser scan (measure of signal amplitude as a function of the laser hit position)

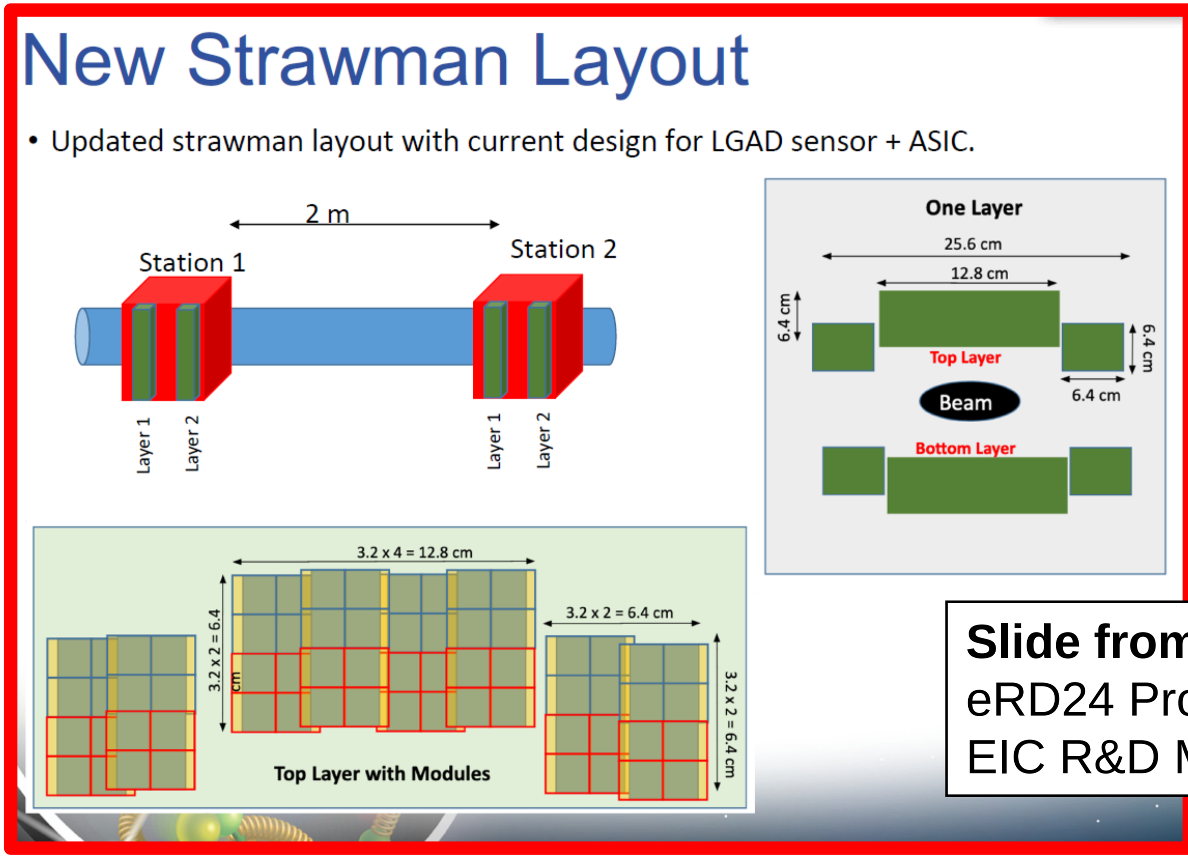
- **Signal sharing**



BNL AC-LGAD strip sensors, at pitch of 100, 150, 200 um.
In a recent beamtest at FNAL:

1. **σ_x<15um**
2. **σ_t ~ 35ps.**
3. **100% fill factor**

AC-LGADs are the baseline for detectors in EIC Roman Pot



Slide from A. Jentsch
eRD24 Progress Report
EIC R&D Meeting, 3/25/2021

Also, consortium of 14 international institutes with interests in the LGAD technology for EIC detectors.
See Expression of Interest on "Fast timing silicon detectors for EIC detectors"
https://indico.bnl.gov/event/8552/contributions/43183/attachments/31235/49294/EIC.EoI_LGAD_consortium.pdf
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