# From LGADs to AC-coupled LGADs for fast timing applications

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U.S. DEPARTMENT OF ENERGY

# Outline

- Low Gain Avalanche Diode (LGADs) R&D
  - High Energy Physics : TIMING
  - Photon Science : GAIN

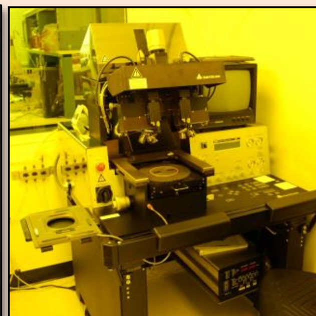
  - Fabrication
  - Measurements

Limits of LGADs

- AC-coupled LGADs
  - Fabrication
  - Measurements

All silicon process done in BNL Instrumentation Division Class-100 Clean Room

Furnaces for dry oxidations and annealings



Double-sided mask aligner

Wet bench (HF, RCA I & II, piranha, polyetch, …)


Sputtering (Al, Al1%Si, Ti)

RTA for sintering

Laser dicing

+ dry etching and thin films deposition, but we need to outsource:

- Ion implantation
- Polysilicon deposition

# LGAD Structure

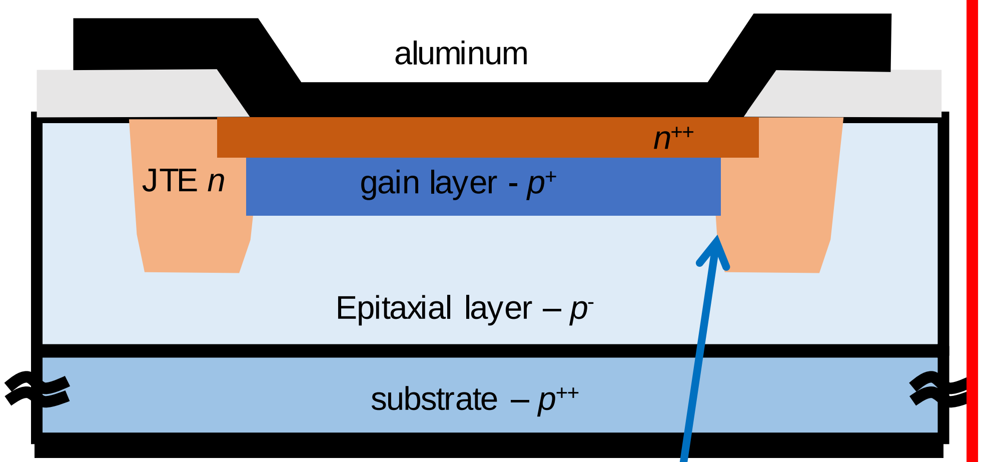
Depletion of the p+ gain layer creates intense Electric Field, high enough for electron impact ionization to occur.

Hole impact ionization ~ 0

→ no BreakDown

→ gain ~ few 10s

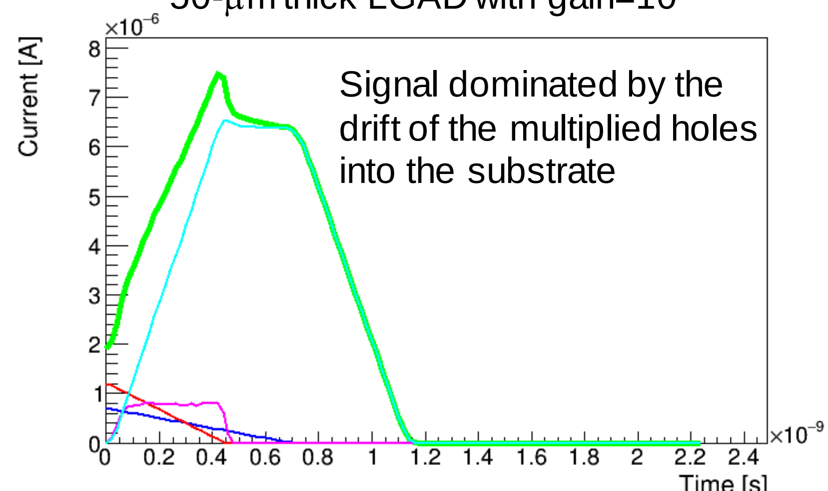
If the substrate is thin (~ 50 μm) → signal is fast (~30 ps)




Gain layer edge terminates on JTE
(not necessary, though…)

**Weightfield2 Simulation**

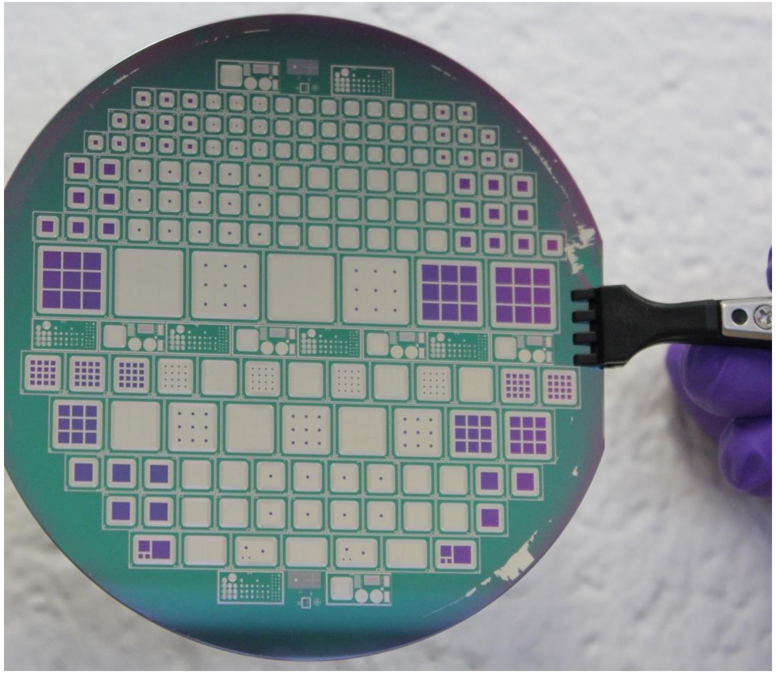
Current pulse generated by a mip in 50-μm thick LGAD with gain=10

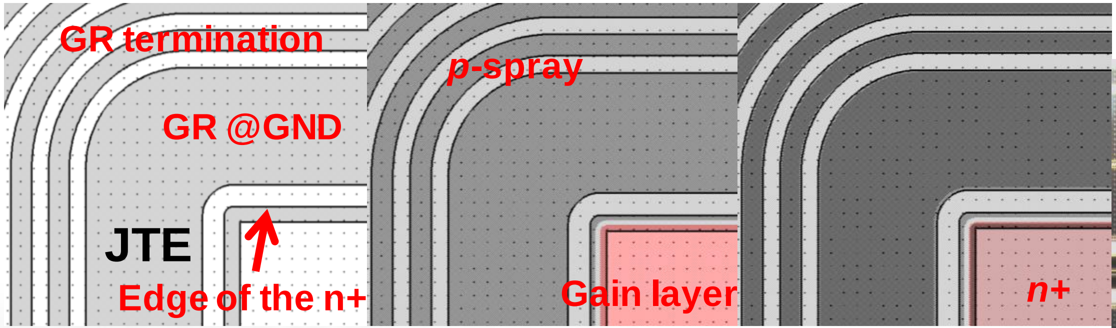


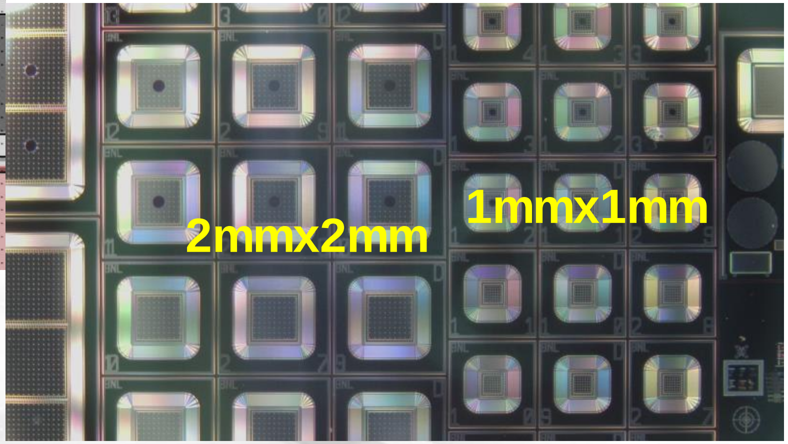

**Weightfield2:** http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

# LGAD fabrication at BNL

- 4” *p*-type epitaxial wafers (100), $N_A$~<1e14cm$^{-3}$, 50μm thick (→ $V_{depl}$ ~120V). Also FZ used.
- 4 ion implantations
  (**JTE** [Junction Termination Edge] and **gain** at high energy)
- 6 photolithographic masks
- *p*-spray isolation (patterned externally to the active area to avoid implant on gain region).
- layout with pads of 1x1 mm$^2$, 2x2 mm$^2$, 3x3 mm$^2$ and arrays.





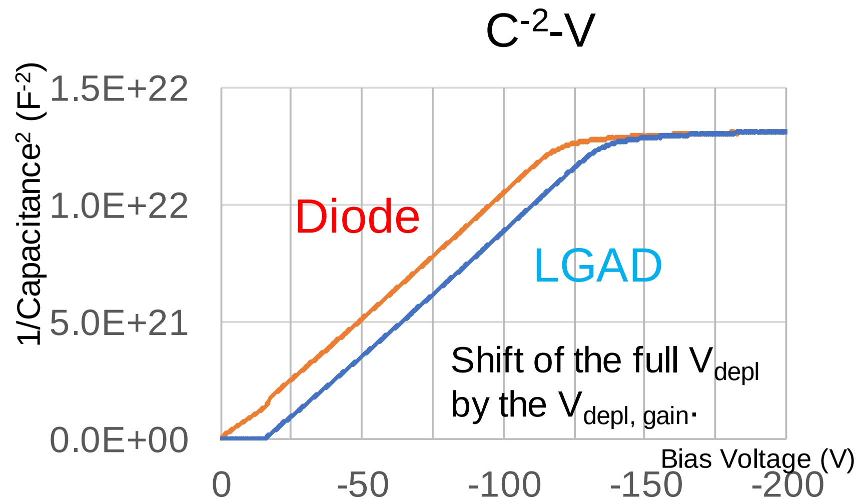



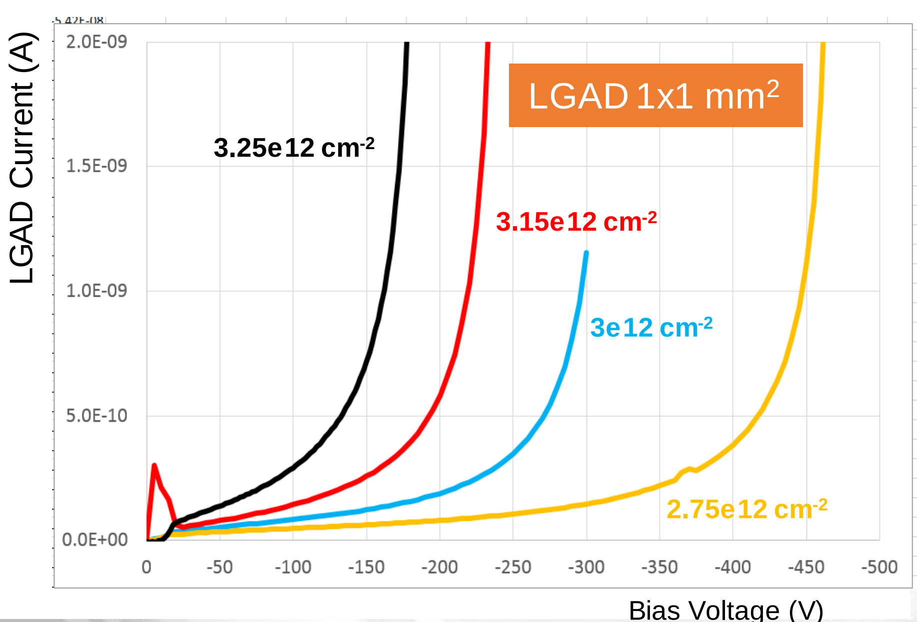

G. Giacomini, et al. “Development of a technology for the fabrication of Low-Gain Avalanche Detectors at BNL”, Nuclear Inst. and Methods in Physics Research, A 934 (2019) 52–57.

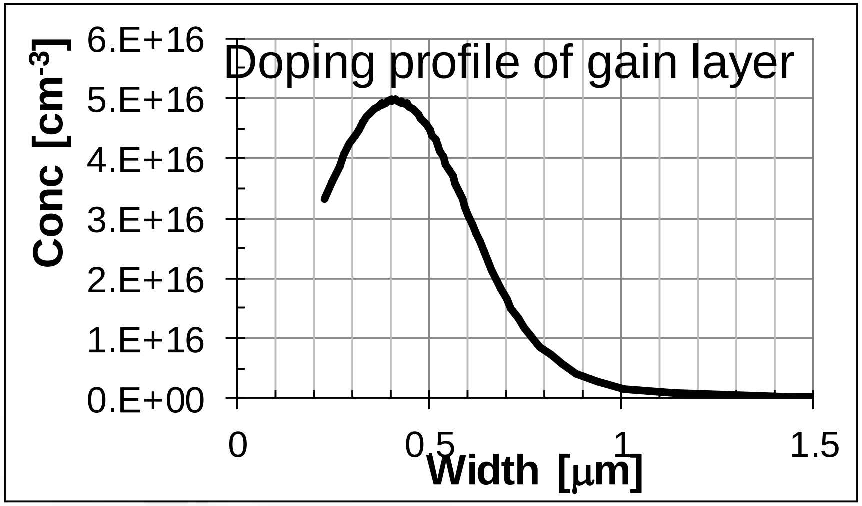
# Static Electrical Characterization

**BNL's LGADs :**

- Leakage current as measured on diodes (gain=1) 1x1 $mm^2$ is ~ 10pA (1nA/$cm^2$)
- Consistent from batch to batch
- Clearly current depends on gain layer dose, so does the breakdown voltage
- GR can stand higher voltages

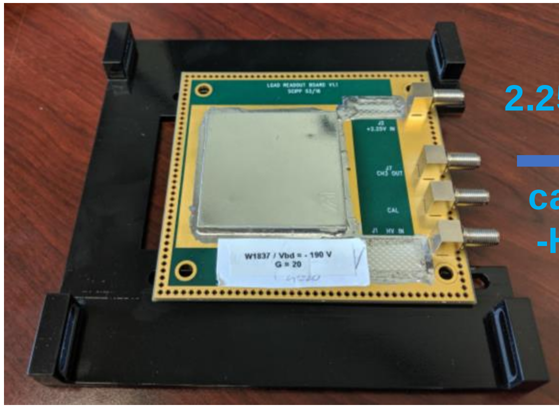


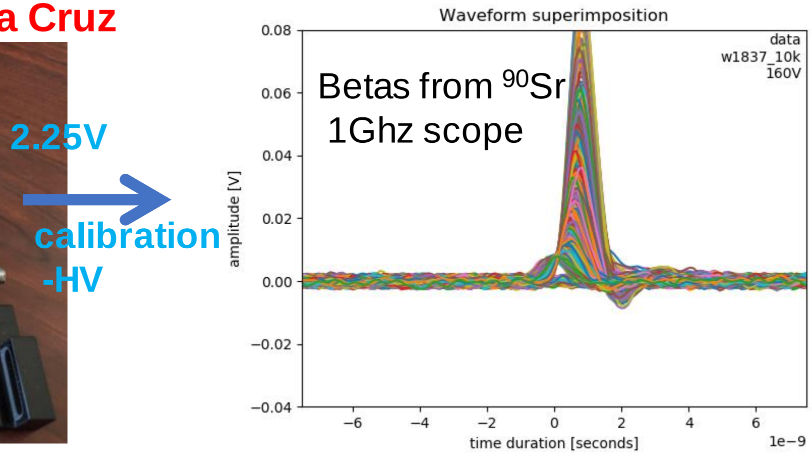



# Gain Measurements

**TA board from SCIPP, Santa Cruz**

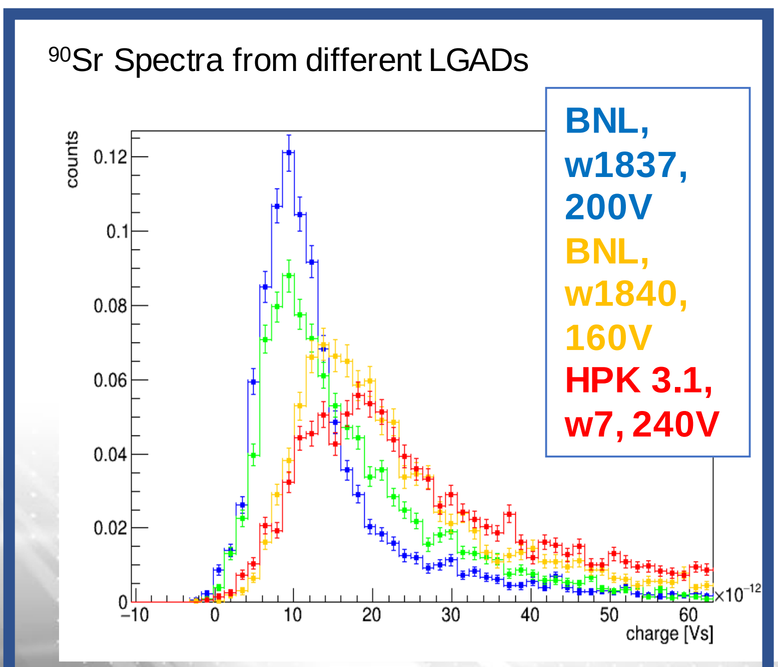


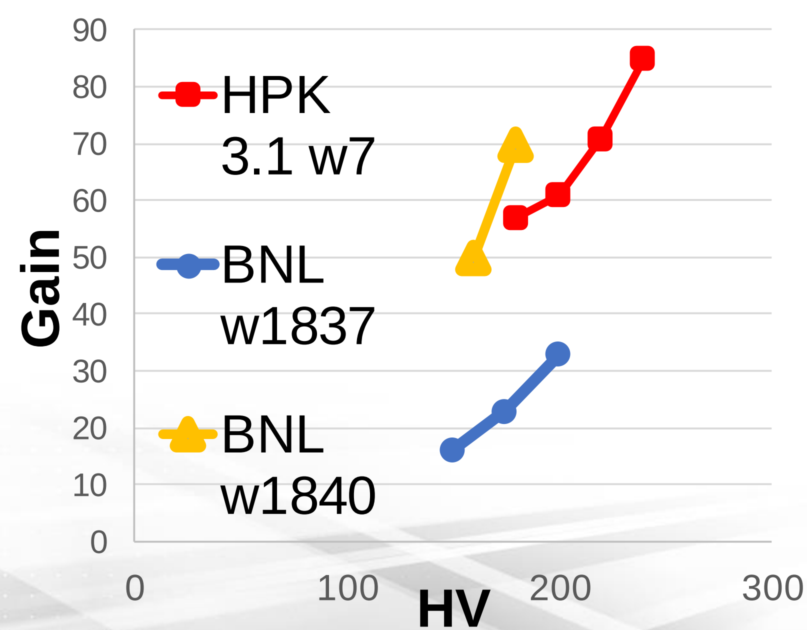



50-μm thick

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

Also Charge sensitive pre-amplifier used



# Limits of LGADs

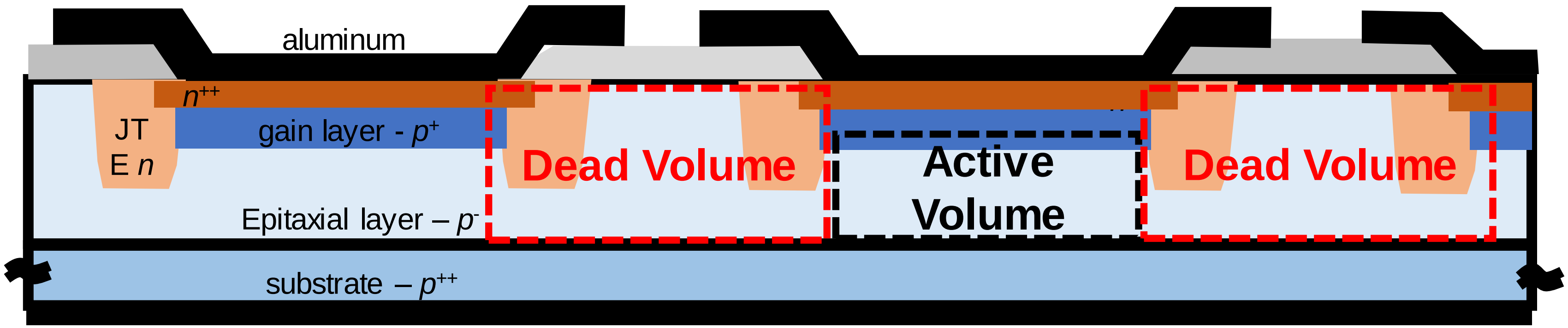
Lateral dimensions of Gain layer must be much larger than thickness of substrate, for a uniform multiplication.

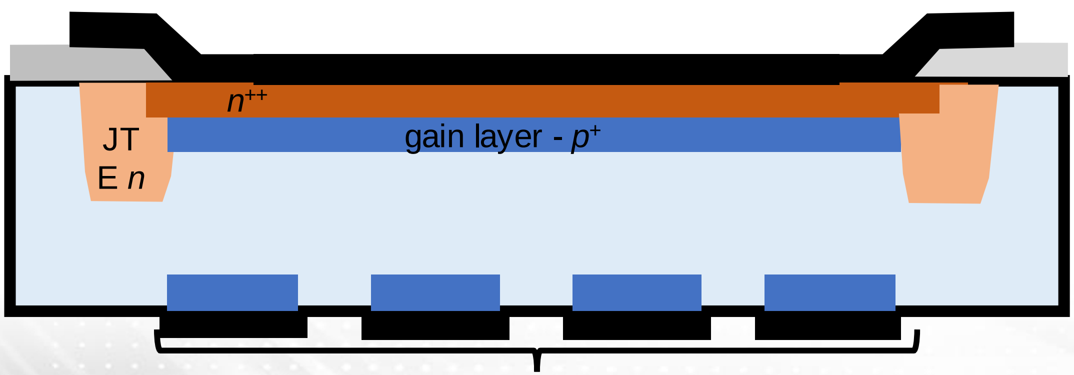
Dead volume (gain~1) extends within the implanted region of the gain layer:

→ pixels/strips (pitch ~ 100 μm) with gain layer below the implant have a FF<<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!

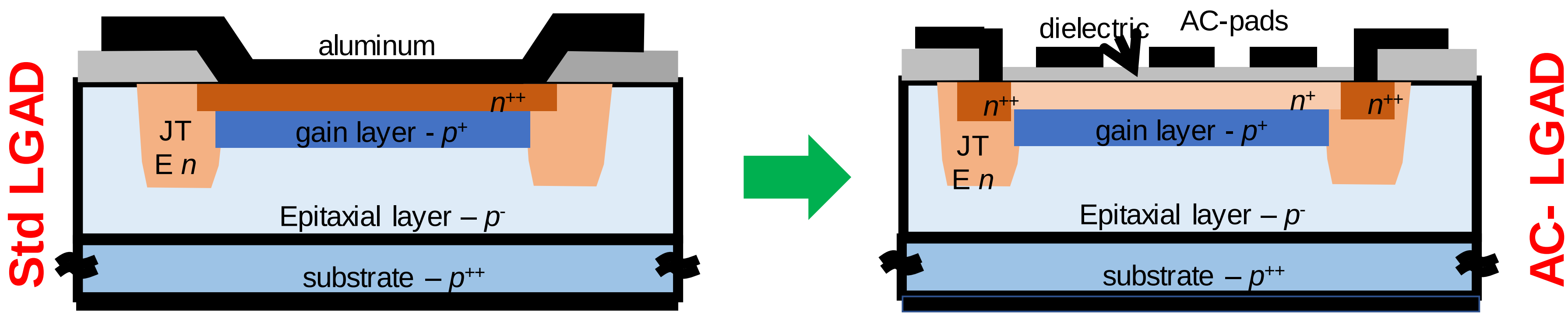
# AC-LGAD concept

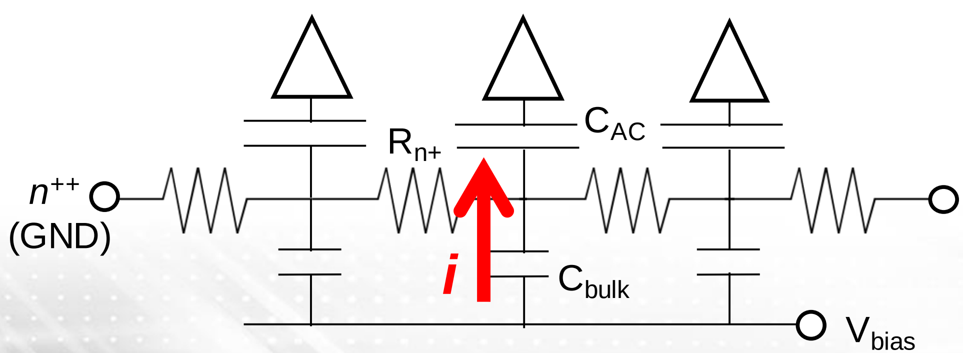
Two main differences:

1. one large low-doped high-ρ ***n*⁺** implant running overall the active area, instead of a high-doped low-ρ ***n*⁺⁺**
2. A thin insulator over the ***n*⁺**, where fine-pitch electrodes are placed.

**100% Fill Factor** and **fast timing information at a per-pixel level** both achieved!!!

- Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric
- Electrons collect at the resistive ***n*⁺** and then slowly flow to a ohmic contact at the edge.

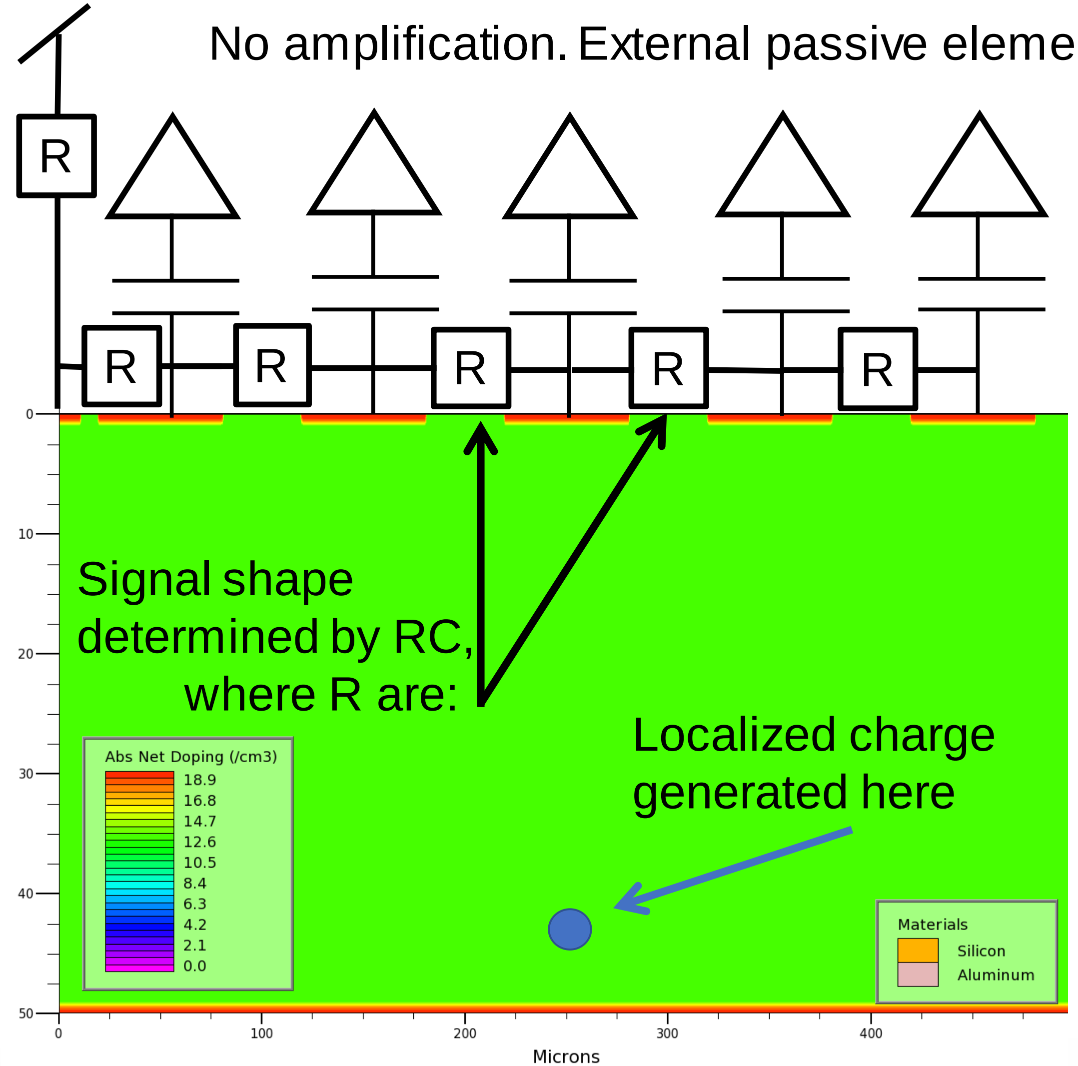


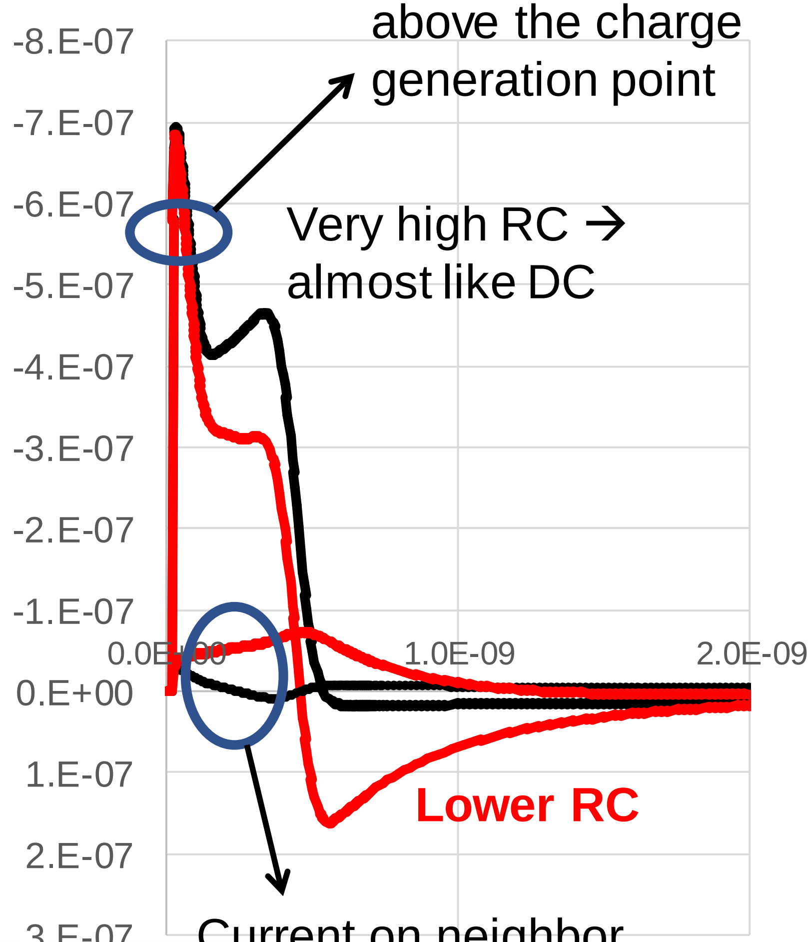




In a simple lumped model, signal current ***i*** goes to the readout electronics if $Z(R_{n+}) >> Z(C_{AC})$

# Mixed mode TCAD simulation

No amplification. External passive elements

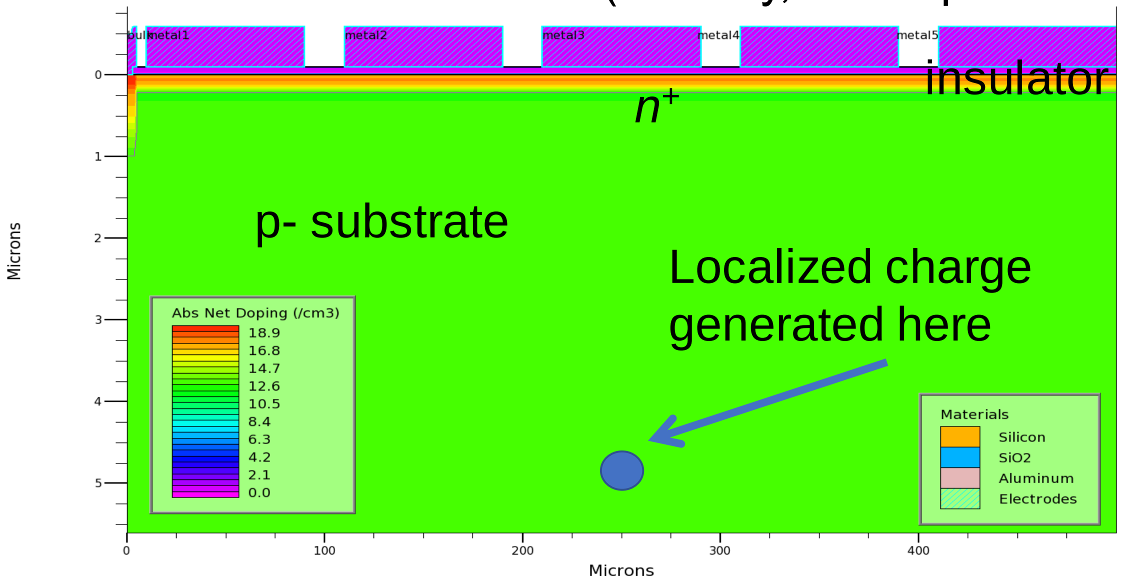


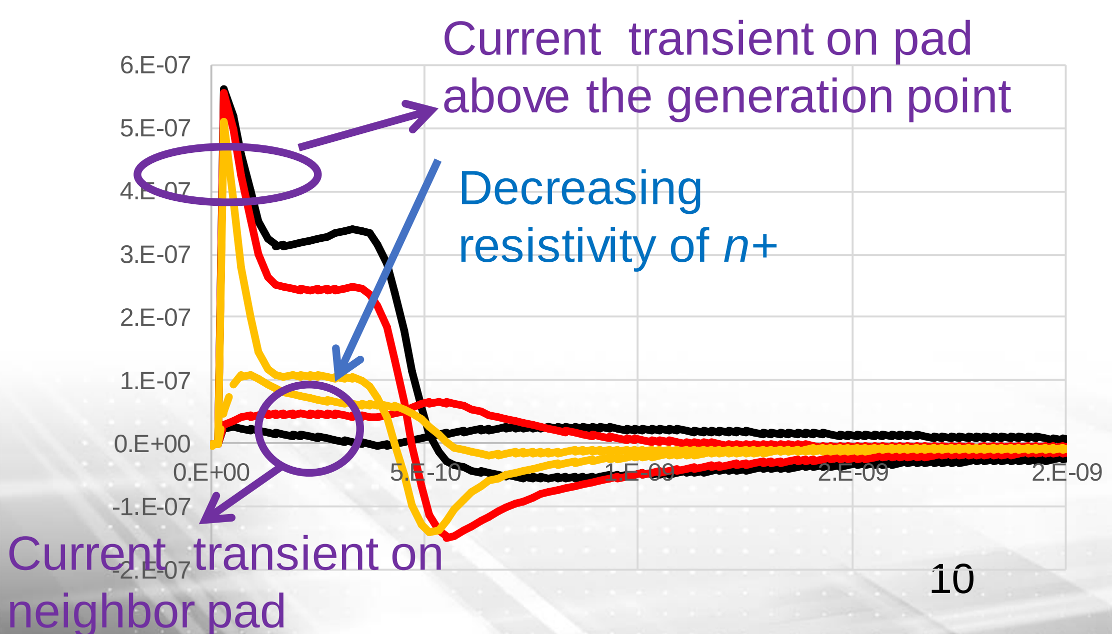

To maximize the signal fed to the electronics, maximize RC.
but smaller RC increase crosstalk in neighbor pixels

# Mixed mode TCAD simulation -2

Simulation of AC-LGAD (actually, no amplification…)




Device geometry and process simulated with SILVACO




- Signal fed to the read-out electronics strongly depends on R(C)
- Higher crosstalk if RC is small

# Fabrication of AC-LGAD

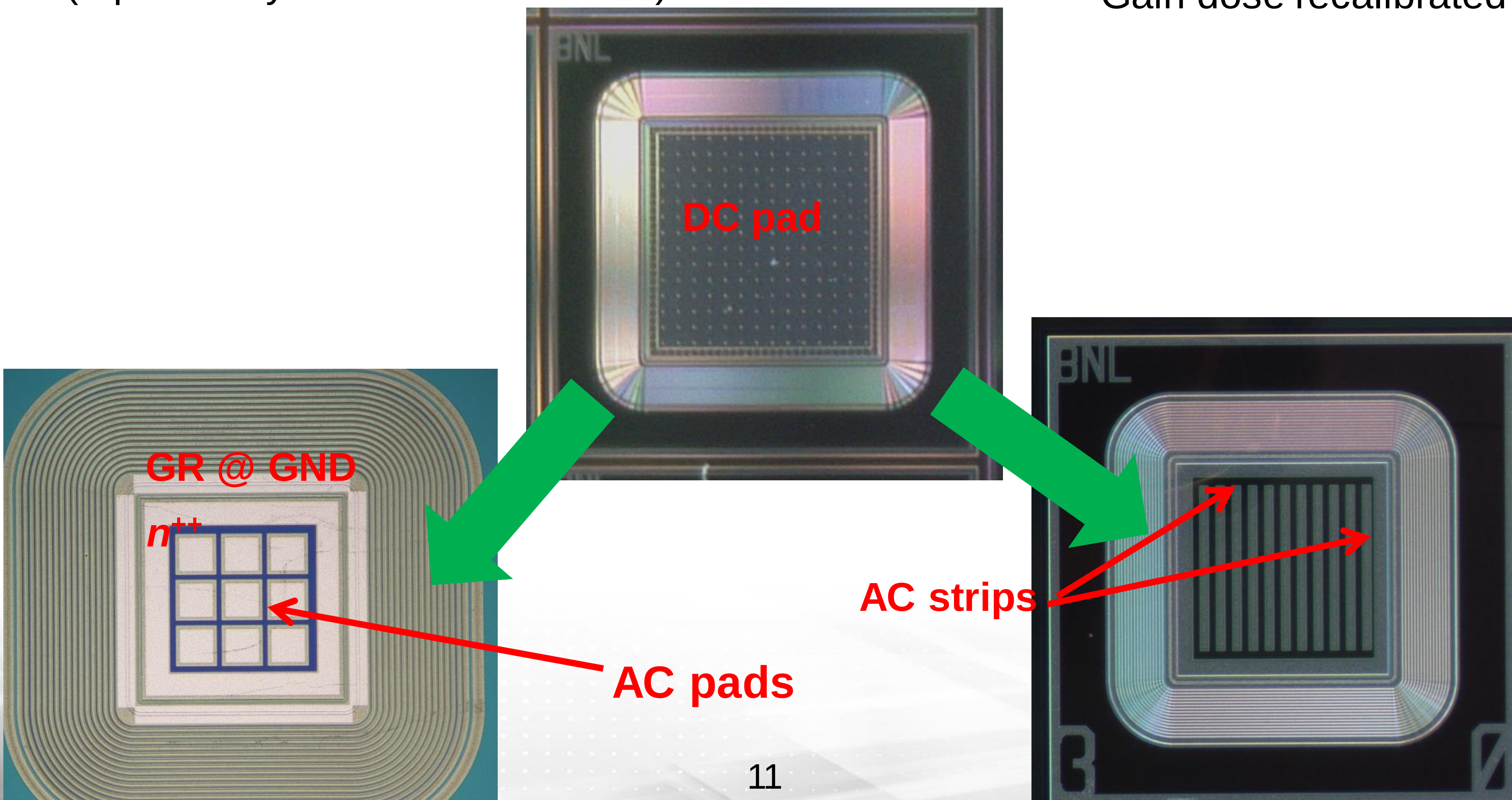
Starting point: LGAD

Design:

- Change METAL (and thus Contacts)
- ***n***$^{++}$ runs at the periphery only
  (replaced by ***n***$^{+}$ in the active area)

Process:

- Resistive ***n***$^{+}$ in the active area 10/100 less dose
- Thin insulator over the ***n***$^{+}$ (100nm SiN)
- Gain dose recalibrated



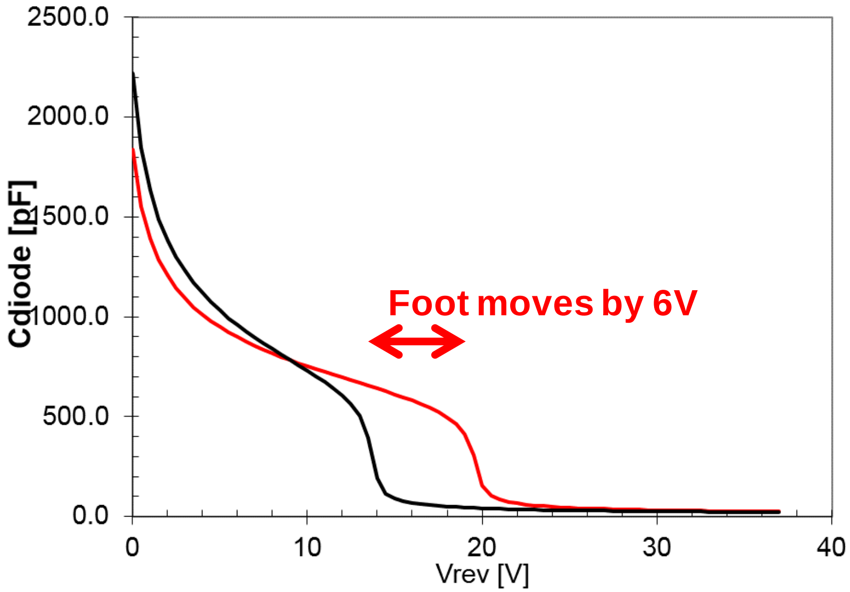
# Recalibration of Gain Layer

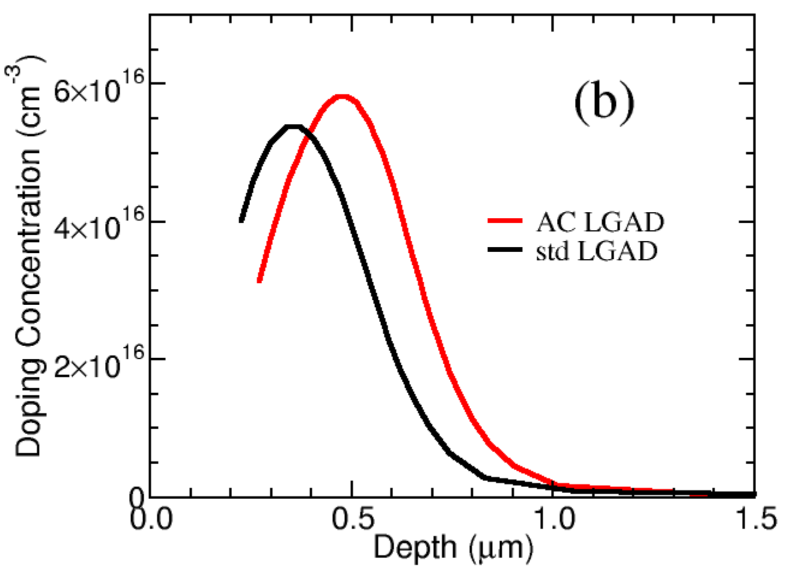
In the very first AC-LGADs wafers, used the same gain layer dose as in LGADs.

**Problem:** the ***n*⁺** is little doped, and its depleted thickness is not negligible

the $p^+$ gain layer is deeper, **GAIN is HIGHER**

<u>LOWER BREAKDOWN VOLTAGE</u>




Gain layer dose has been lowered in following production, while keeping the process flow very similar.

# Signal amplitude in LGADs vs AC-LGADs

- LGAD: same AC-LGAD device where the ***n***$^{++}$ is read-out by the TA.
- AC-LGAD: one of the 3x3 200μm x 200μm AC-coupled pads

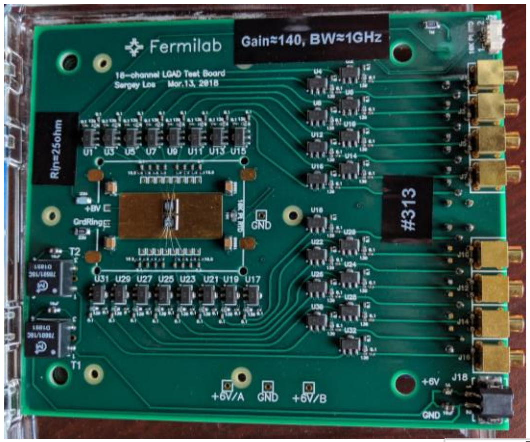
→ Bias conditions and gain are the same

Comparison of pulse amplitudes of betas from $^{90}$Sr.

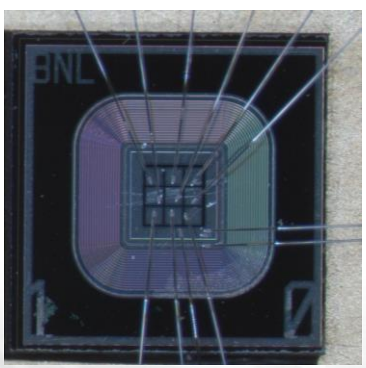
Essentially equal distribution (same gain) for LGAD and AC-LGAD Amplitudes

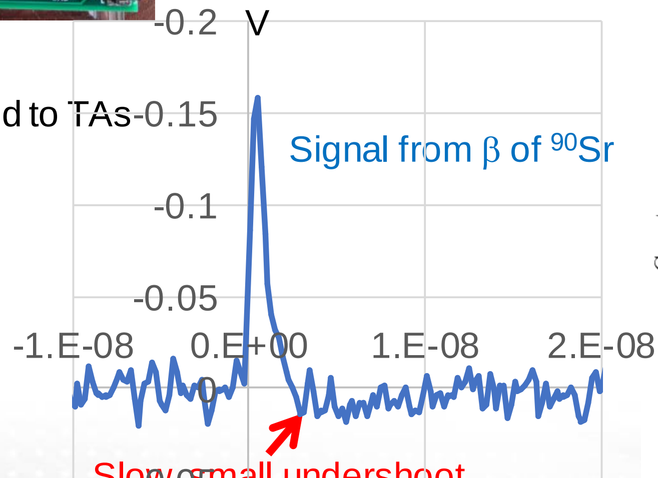
→ all signal goes through $C_{AC}$ (=20pF)

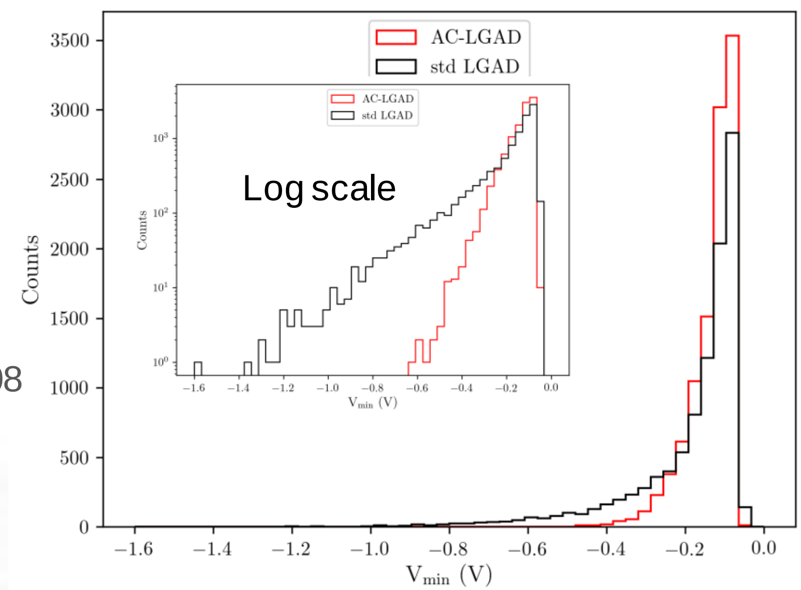
16 channel TA board by FermiLab




3x3 200μm x 200μm
AC-pads wired bonded to TAs



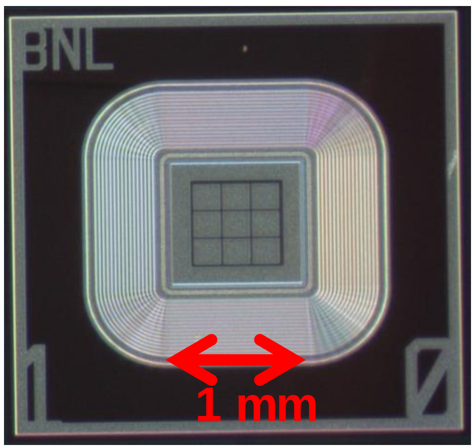



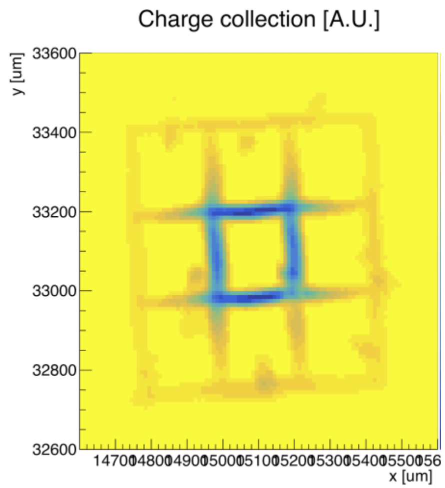



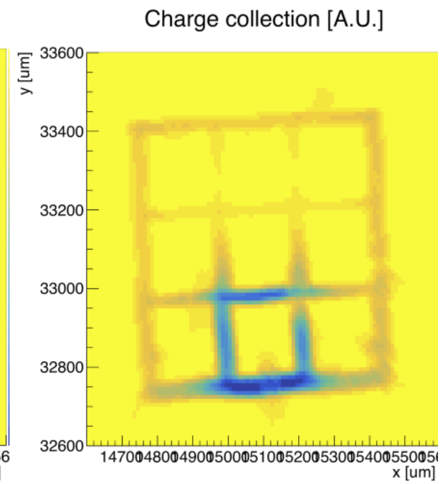
# Cross-talk

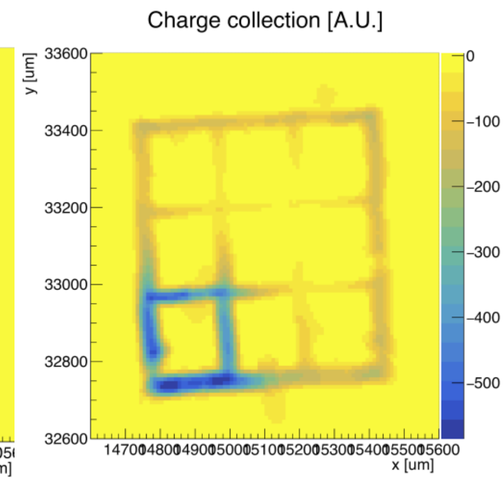
Response of a single pixel as a function of shining position of IR or red laser (TCT scan).

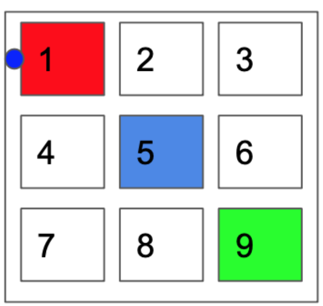
- **Border effect**: the $n^{++}$ is a low resistance path that couples the signals back to the pixel under measure.



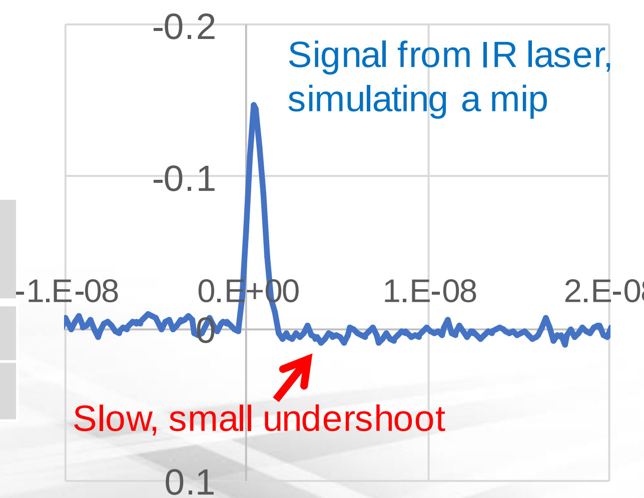




Measurement of cross-talk in several point.
In this case:

| | Dose $n^+$ 1/10th | Dose $n^+$ 1/100th |
|---|---|---|
| $Amplitude_5$ / $Amplitude_1$ | 9% | 7% |
| $Amplitude_9$ / $Amplitude_1$ | 16% | 11% |



# Conclusions

- Low-Gain Avalanche Diodes (LGADs) have been fabricated at BNL
- LGADs are the starting point for AC-LGAD development
- By changing a few photolithographic masks and tuning process flow parameters, AC-LGADs have been fabricated as well.
- Positive and similar results from the two devices,
  - experimental results have shown margins of improvement, e.g. cross-talk along periphery of device.
  - Optimization is ongoing.

# BACK-UP

## Timing

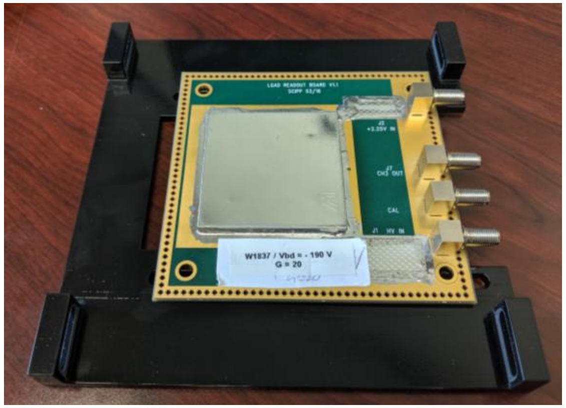
AC-LAGDs and LGADs have very similar waveforms.
Same timing performance expected.

Calculating the **Jitter** on $^{90}Sr$ waveforms, $\sigma_t = \sigma_n / (dS/dt) \sim$ **20 ps** .

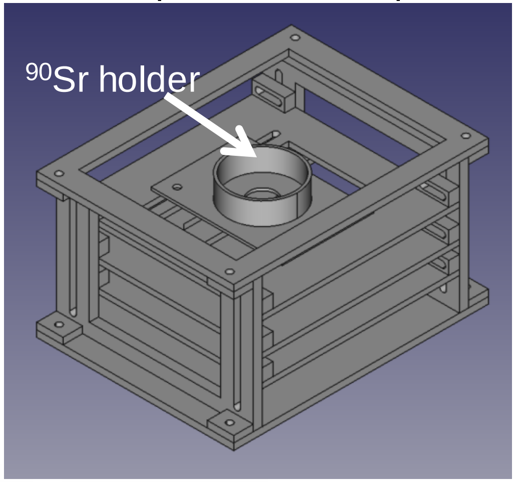
NEXT: Measuring timing with beta scope.

**Telescope for timing measurements: Beta scope**

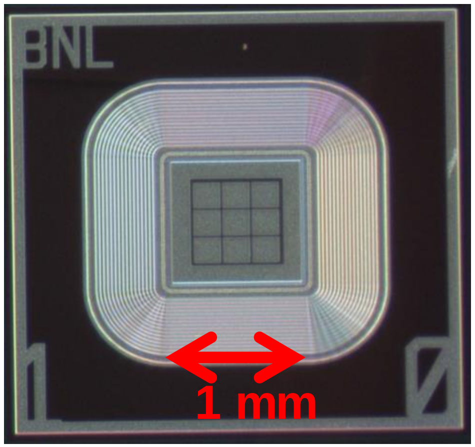
SCIPP TA on 3D-printed support

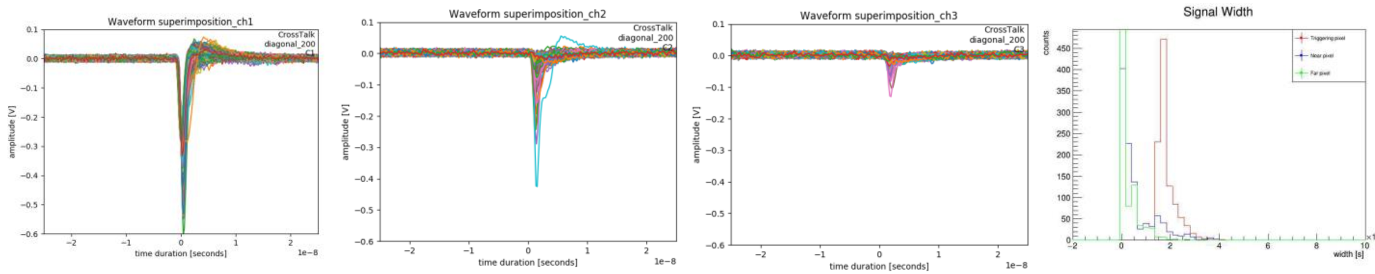


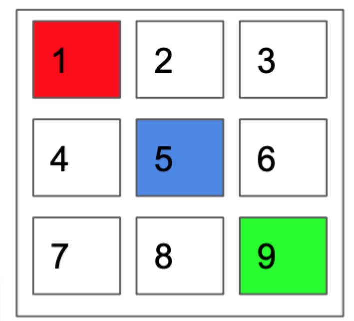

3D-printed telescope



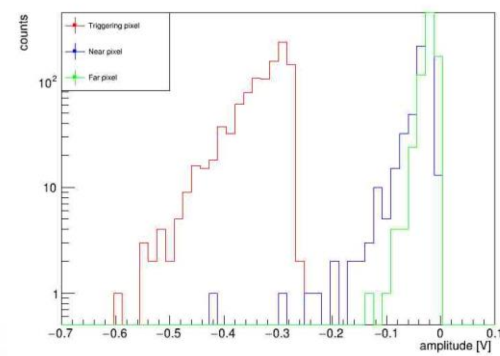
# Cross-talk strontium



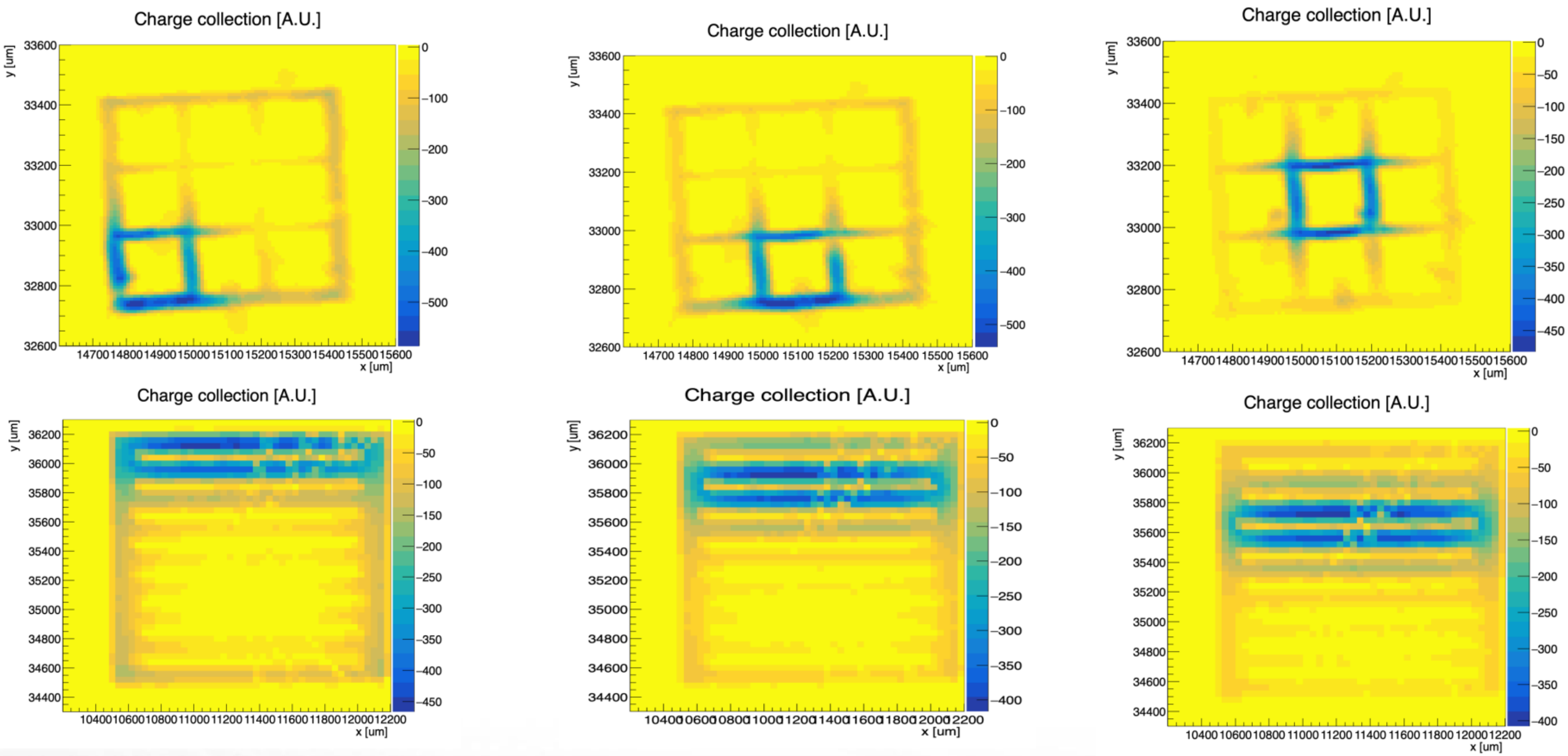




| | |
|---|---|
| $\text{Amplitude}_5 / \text{Amplitude}_1$ | 10% |
| $\text{Amplitude}_9 / \text{Amplitude}_1$ | 6% |



# RED laser


Charge collection [A.U.]
y [um]
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Charge collection [A.U.]
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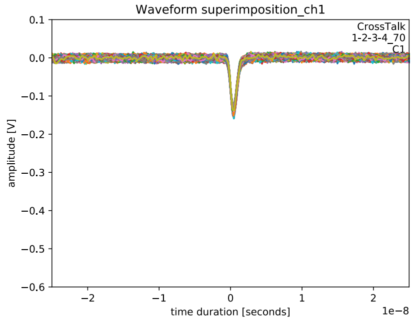
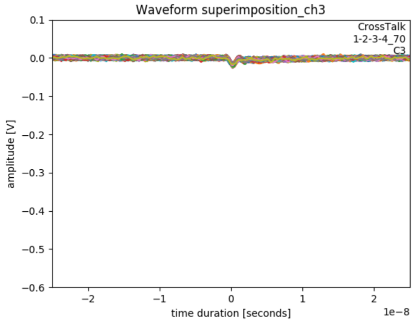
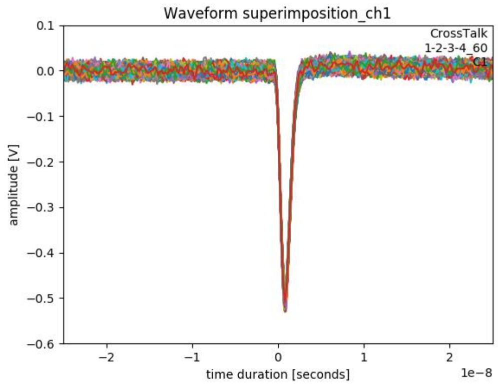
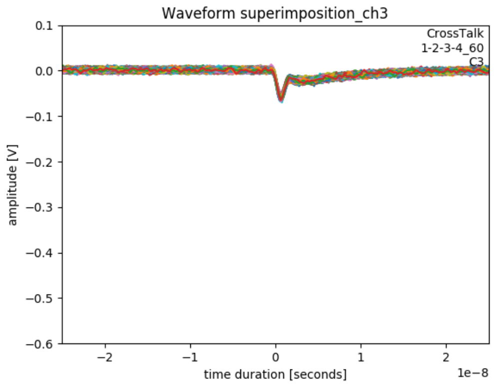


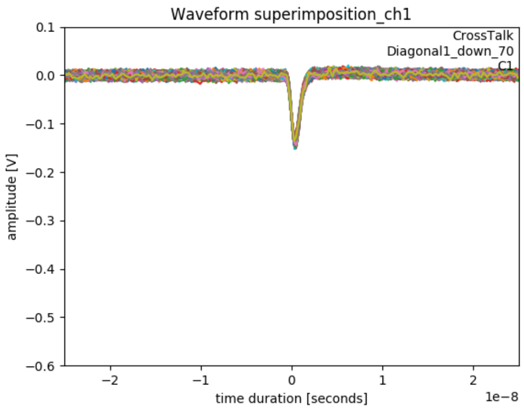



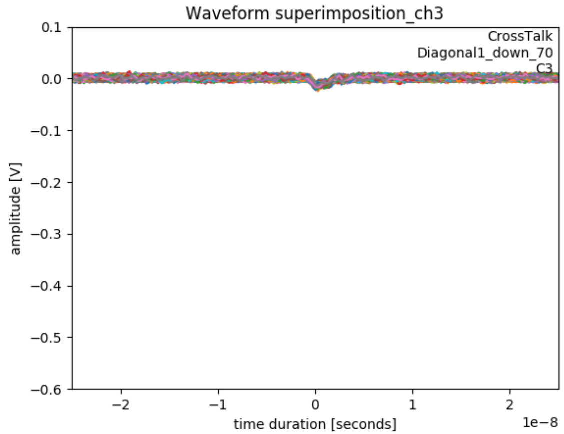

Strip 1 and strip 3 as in slide13



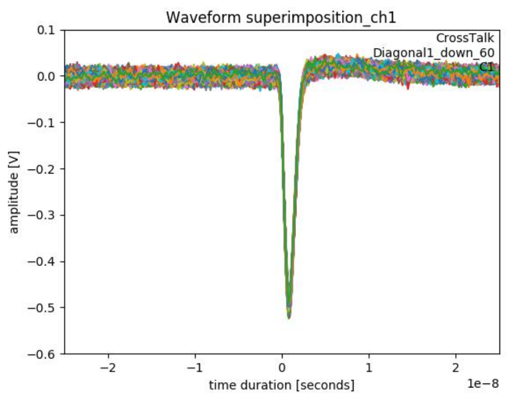

strip 1 e 3 , laser more intense

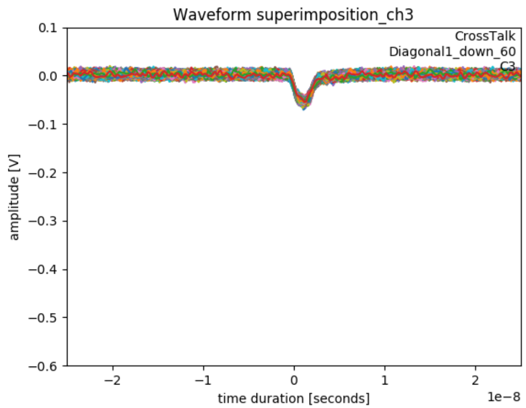



Triggering and far pixel per l' AC-LGAD
A few mips

IR laser




Triggering and far , many mips