CPAD Instrumentation Frontier Workshop

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LGAD Prospects: Granularity and Repetition Rate

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UCSC Launchpad Initiative

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Outline of Talk

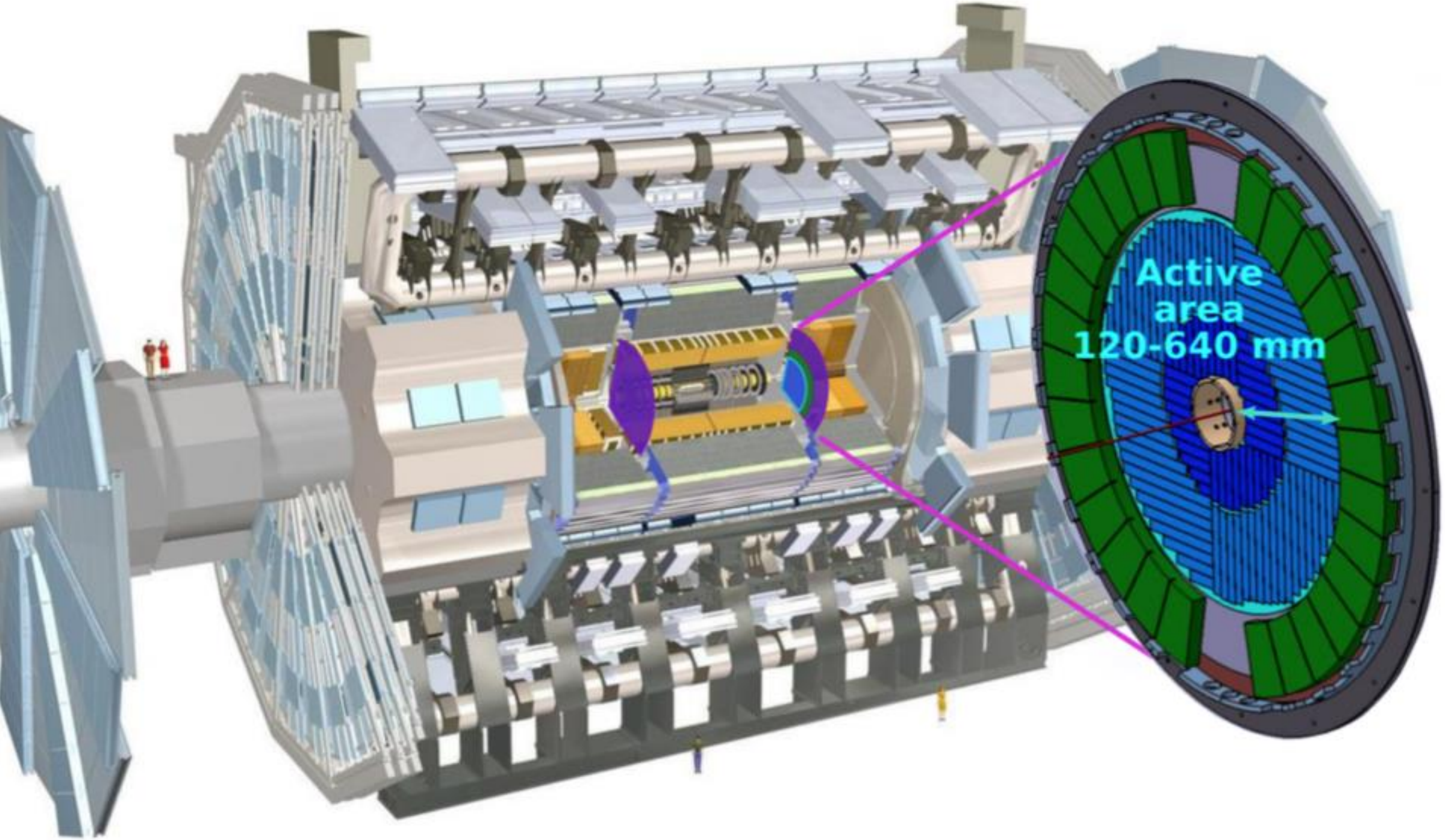
LGAD Granularity

- Current limitations and goals
- AC (AC-coupled) LGAD
- TI (Trench-Isolated) LGAD
- iLGAD (inverted junction structure)
- DJ (Deep-Junction) LGAD 

Diode Detectors in High Frame-Rate Applications

- Motivated by need for advanced accelerator diagnostics

Initial Application: CMS/ATLAS Timing Layers



ATLAS HGTD

- Two layers (front and back of frame) on each side of IP
- Covers forward region $2.4<|\eta|<4.0$
- Pixel dimension of $1.3x1.3mm^2$

Complementary instrument under design by CMS, with a more central coverage

Granularity and the JTE

JTE = Junction Termination Extension

Needed to avoid large fields and breakdown between segmented implants

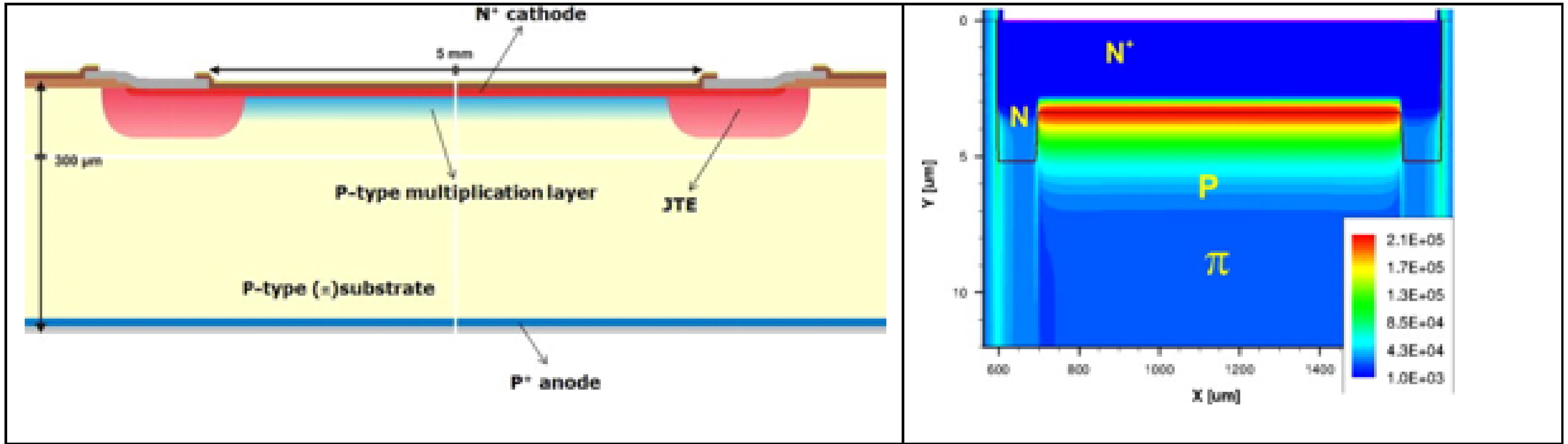


Figure 1.: (Left) Schematic cross-section of the LGAD pad design with a JTE structure protecting the junction edge termination. (Right) Simulated electric field distribution throughout the multiplication junction of an LGAD terminated with a JTE. The legend gives the field strength in V/cm [G.Pellegrini et al., NIMA, 2014,12-16]

Conventional LGAD Coverage Gaps

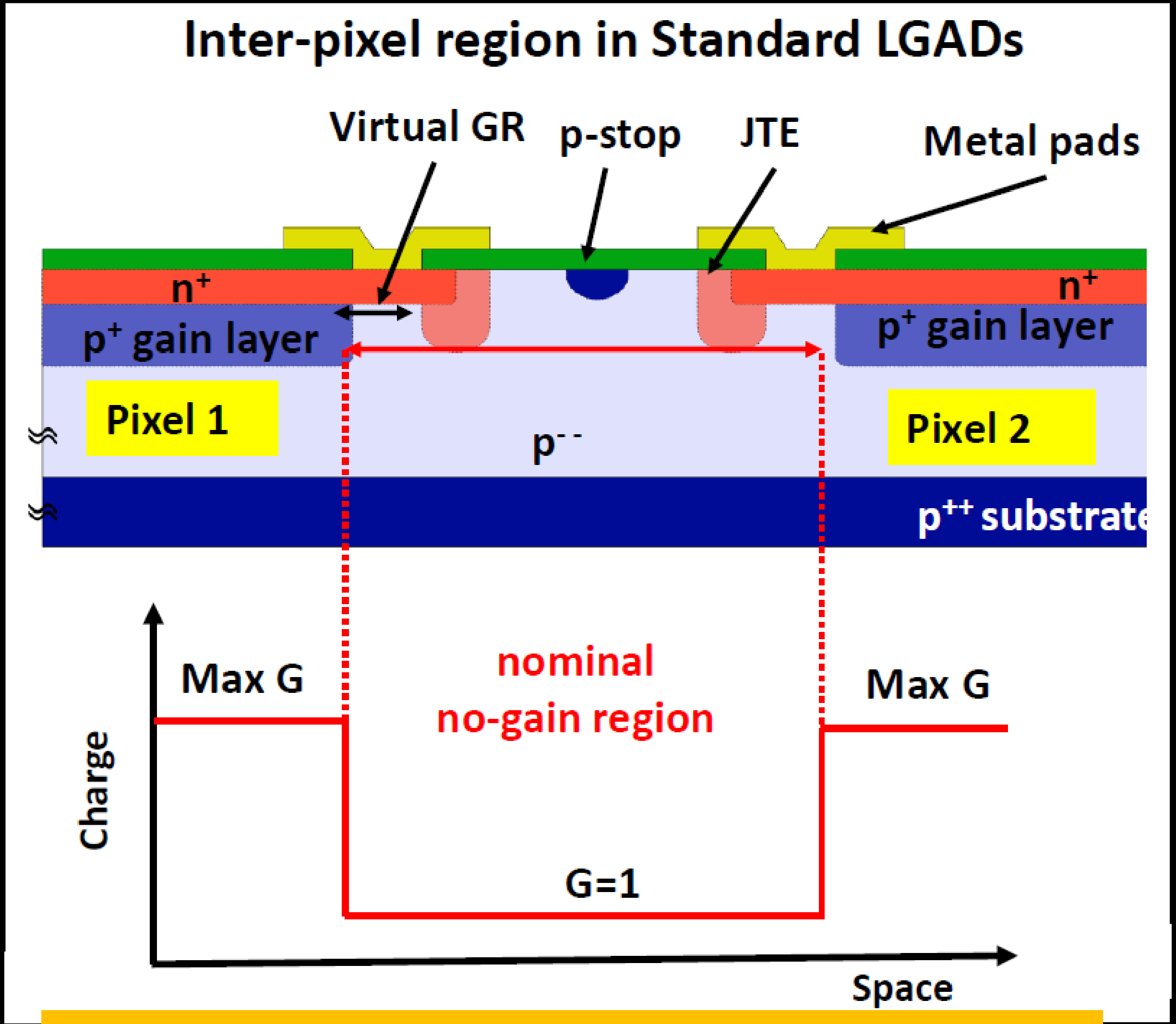
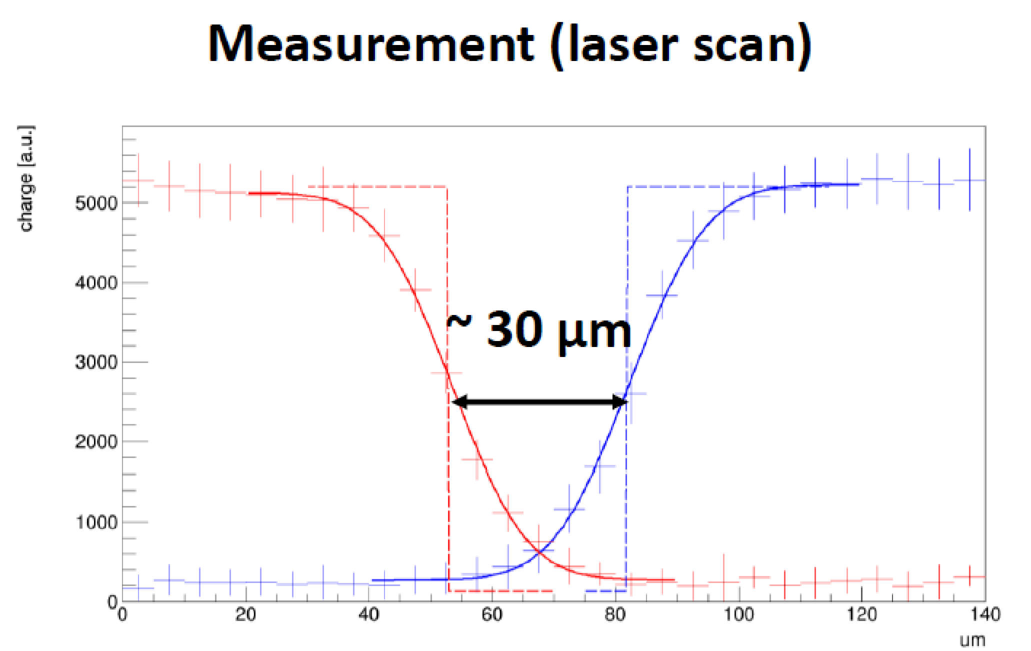


Diagram credit: FBK, Trento, Italy

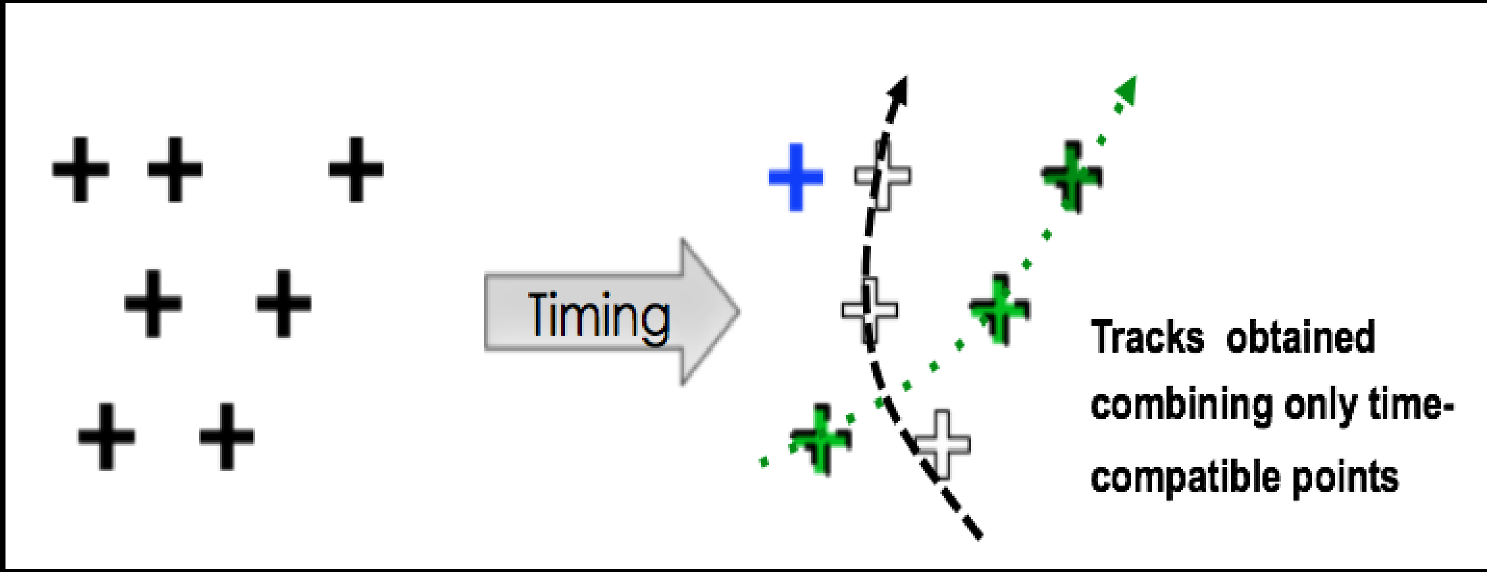


Measurements performed in Torino Silicon Lab (University of Torino - INFN)

- Smallest achievable gap (50% criterion) is ~30µm
- Limits granularity to ~mm scale

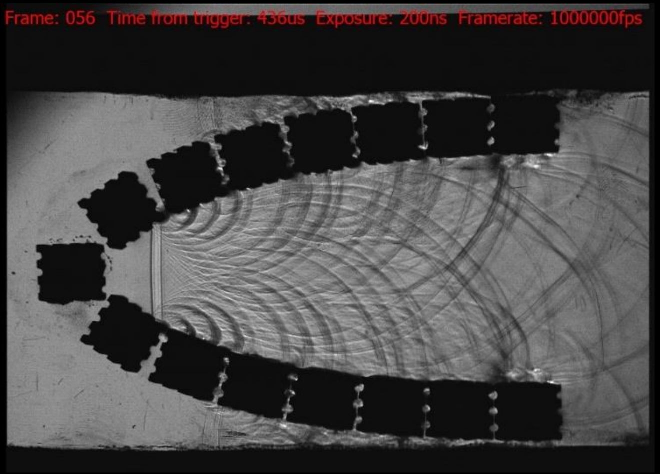
LGAD Granularity Wish List

4D tracking: relevant scale is ~50 μm in rϕ (e.g. ATLAS pixel layers)



X-Ray Imaging: again relevant scale is ~50 μm

e.g. Z. Wang, *On the Single-Photon-Counting (SPC) modes of imaging using an XFEL source*, JINST 10, C12013 (2015).

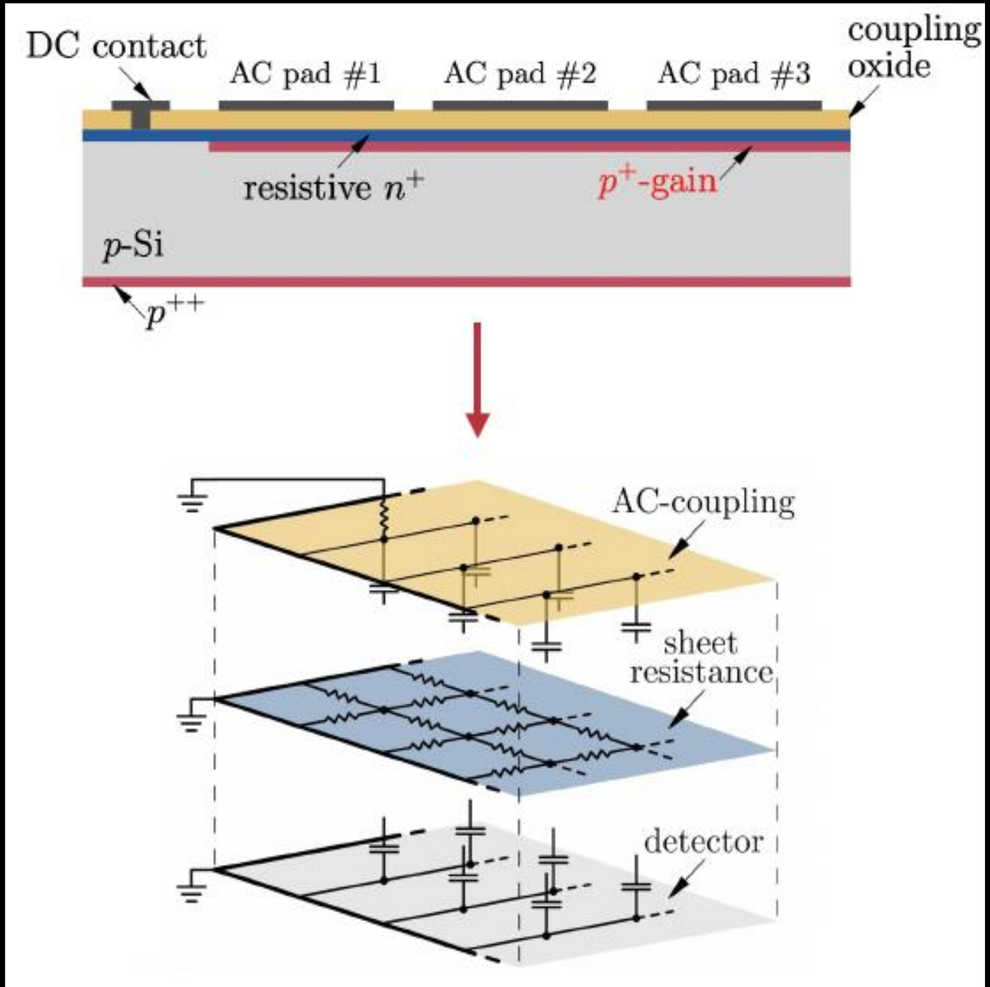


Towards Higher LGAD Granularity

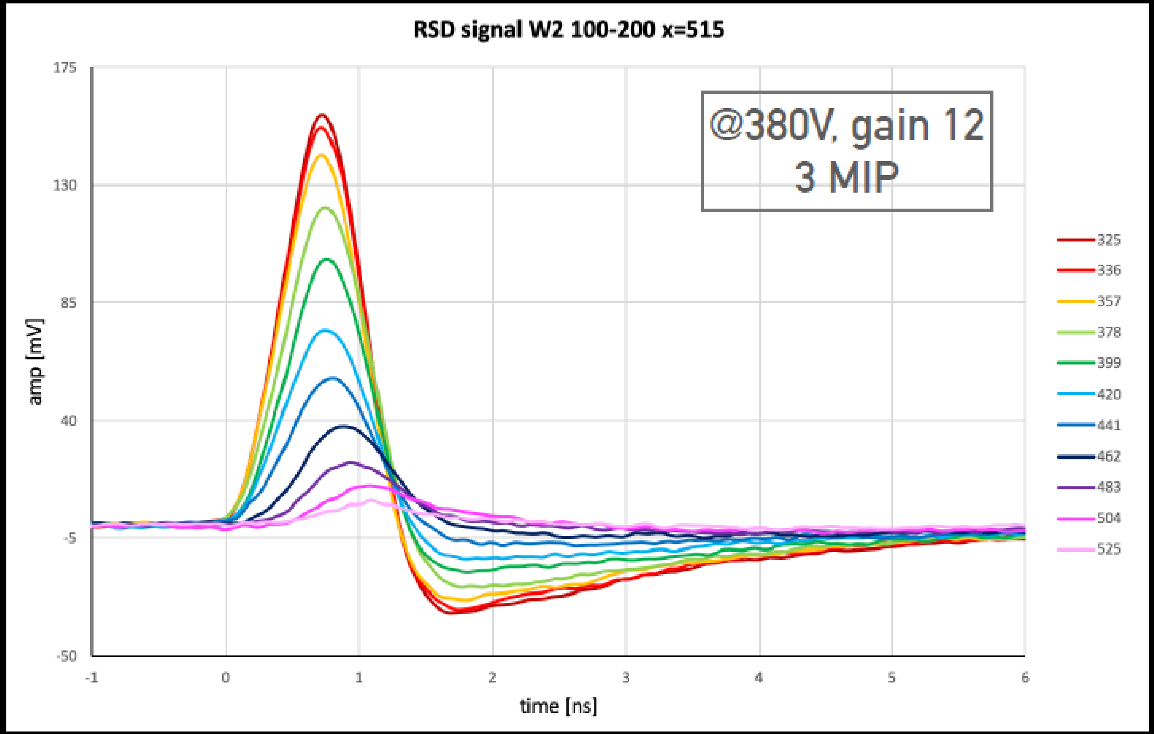
- AC (AC-coupled) LGAD
- TI (Trench-Isolated) LGAD
- iLGAD (inverted junction structure)
- DJ (Deep-Junction) LGAD 

Approach 1: AC LGAD

The AC-coupled LGAD (AC-LGAD)

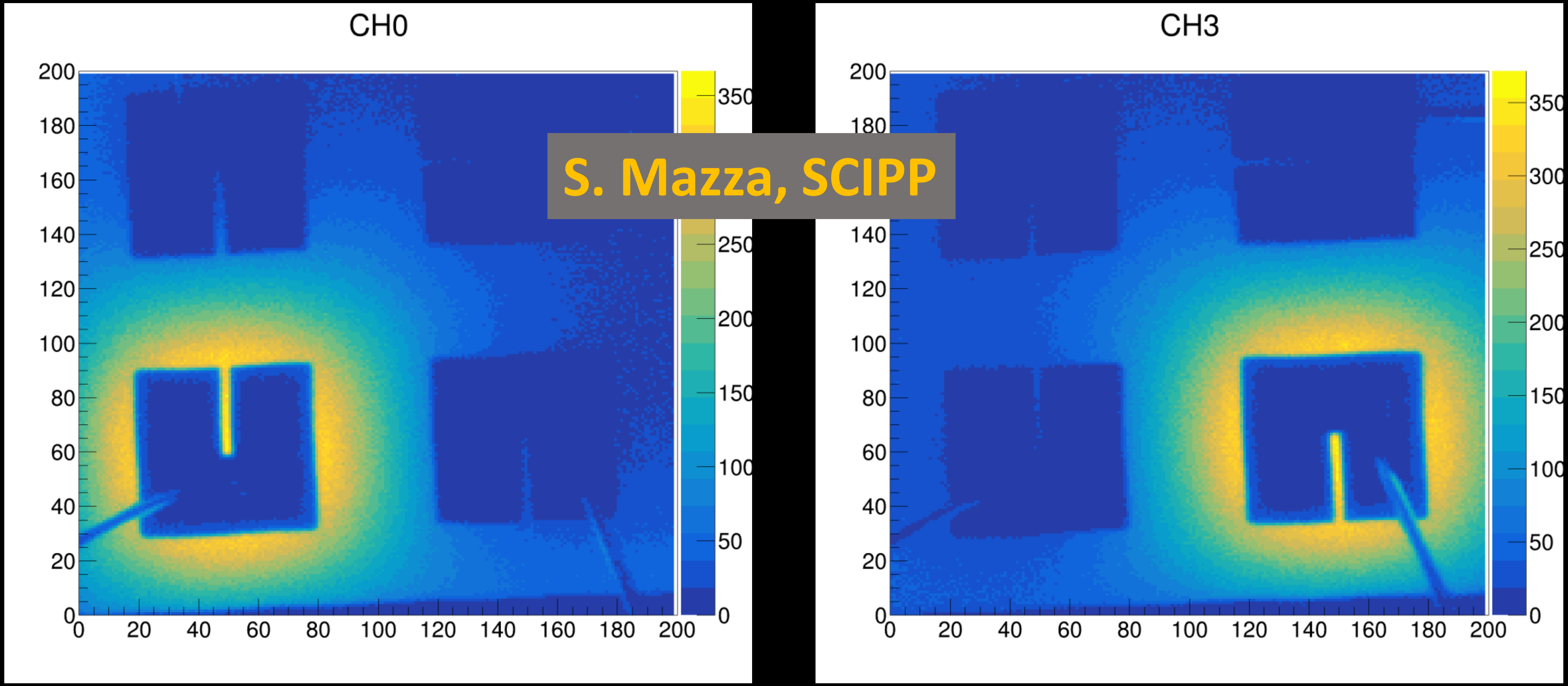


US patent No.: 9,613,993 B2, granted Apr. 4, 2017: *"Segmented AC-coupled readout from continuous collection electrodes in semiconductor sensors"* Hartmut Sadrozinski, Abraham Seiden (UC Santa Cruz), Nicolo Cartiglia (INFN Torino).



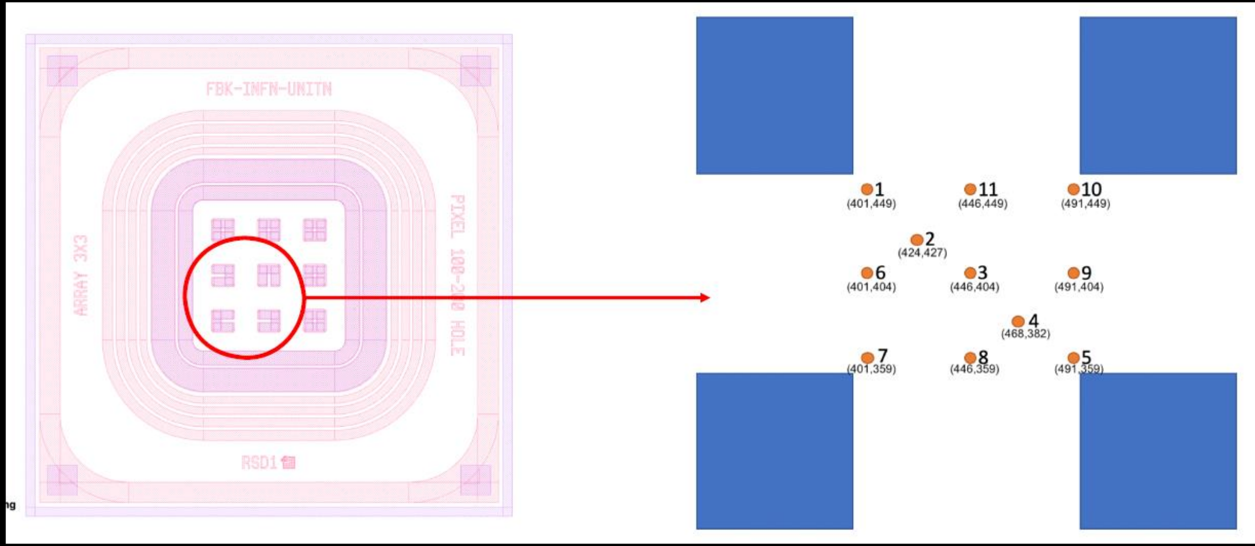
Since signal is AC-coupled, must integrate to 0

AC LGAD: Response Envelope

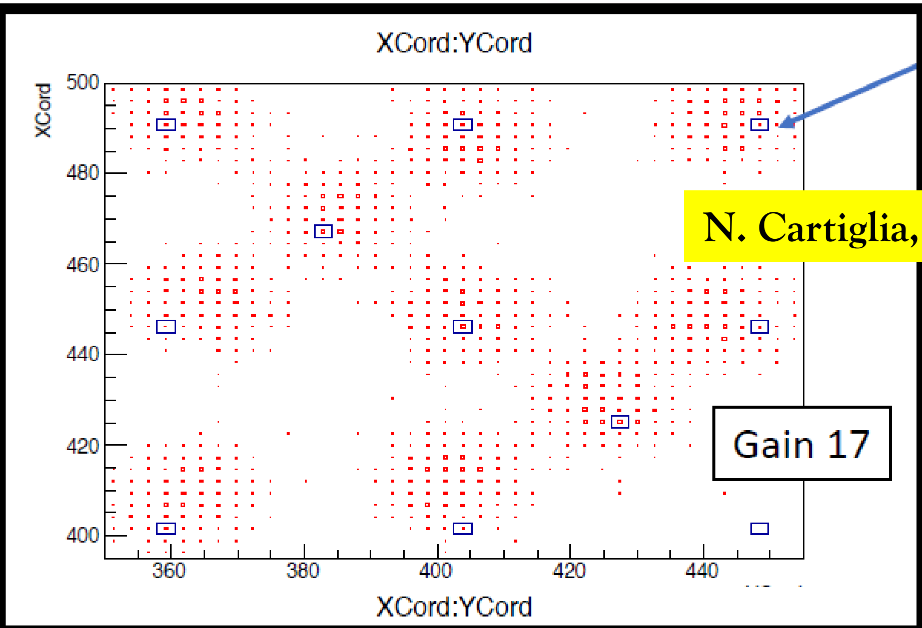


- Pulsed laser measurements at SCIPP
- Coordinates represent position of laser spot
- Read-out channel is the illuminated channel

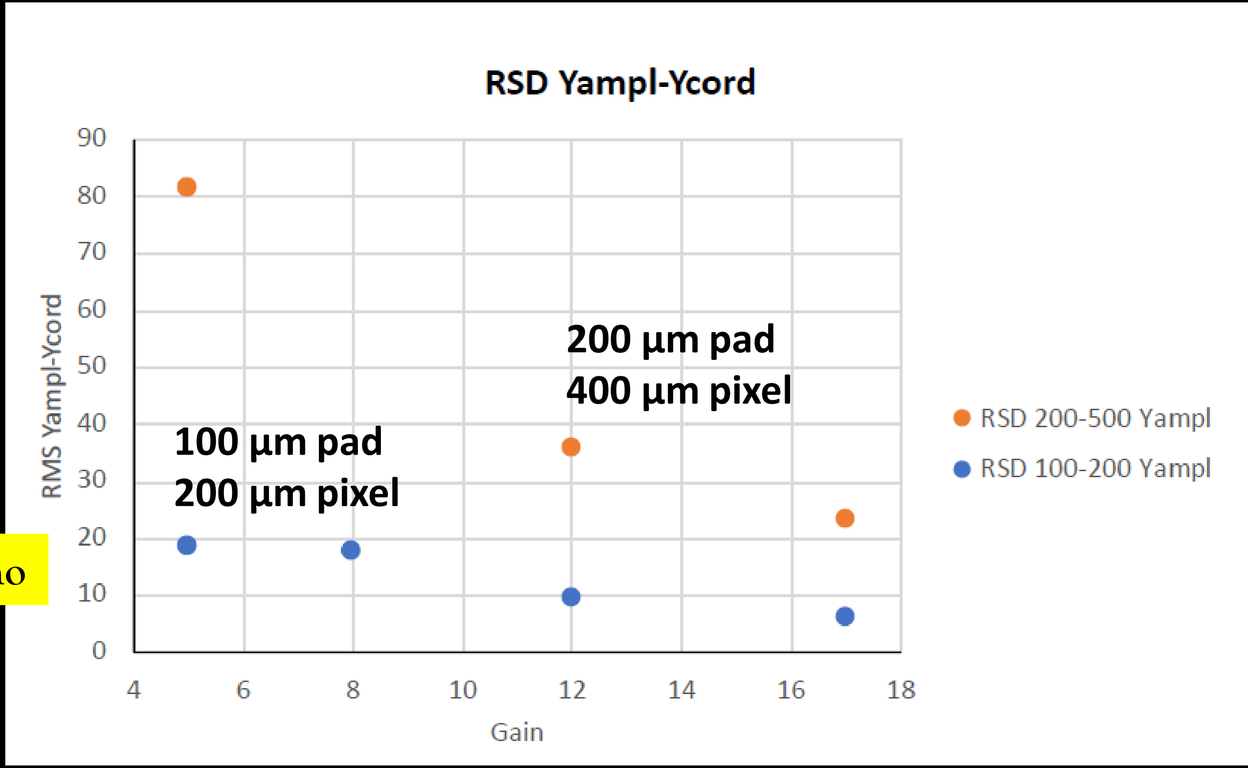
AC LGAD: Position Resolution



Illuminate with precision pulsed laser
Intensity adjusted to ~1 MiP

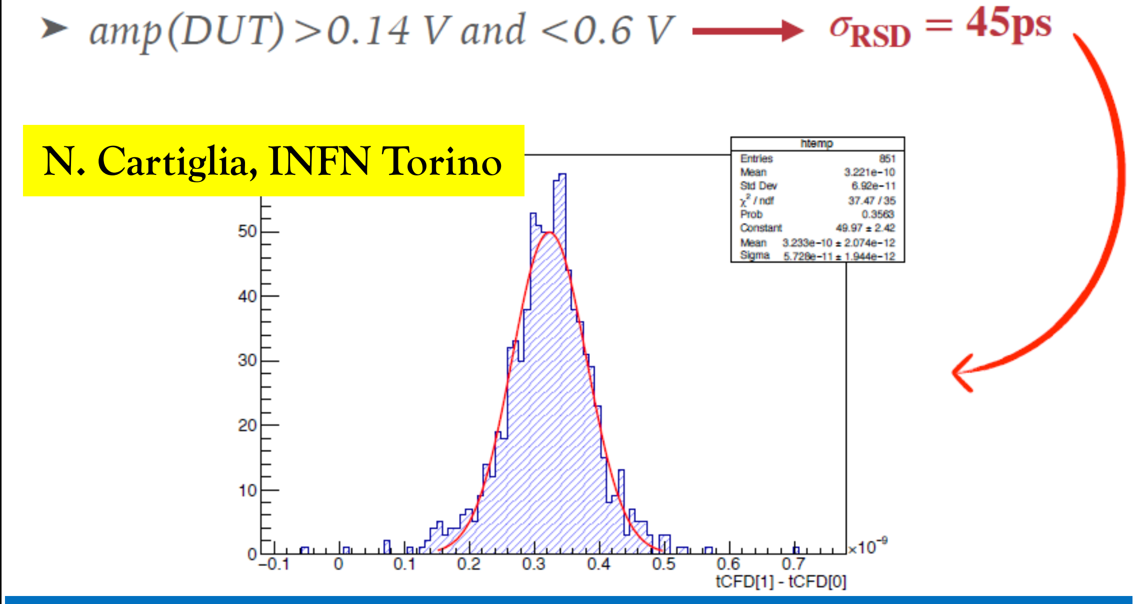


N. Cartiglia, INFN Torino



For small-pixel prototype, can approach 5 µm ➔ Promising for 4D tracking!

AC LGAD: Timing and "Workplan"



Temporal resolution already approaching that of conventional LGADs (45ps vs 20ps)

Split table (with breakdown voltage)

wafer	*n*-plus dose	*p*-gain dose	dielectric thickness	*p*-stop dose	substrate	Vbd
1	A	0.92	L	B	Si-Si	480
2	A	0.94	L	A	Si-Si	440
3	A	0.94	L	B	Epi	460
4	A	0.94	H	B	Si-Si	440
6	B	0.92	L	B	Epi	525
7	B	0.94	L	A	Si-Si	460
8	B	0.94	L	B	Si-Si	460
10	B	0.96	H	B	Si-Si	430
11	C	0.92	L	B	Si-Si	515
12	C	0.94	L	B	Epi	490
13	C	0.94	L	B	Si-Si	465
15	C	0.96	H	C	Si-Si	445

Parameter space currently under exploration

AC LGAD R&D Threads

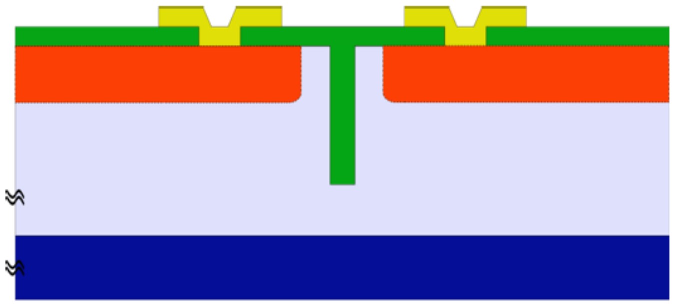
- **N^{++} layer resistivity**
- **N^{++} termination**
- **Signal coupling (dielectric width; pad fill-factor)**
- **Gain layer properties**
- **Timing resolution and signal-to-noise**
- **Point-spread function and cross talk**
- **Fabrication technique**

Approach 2: TI LGAD

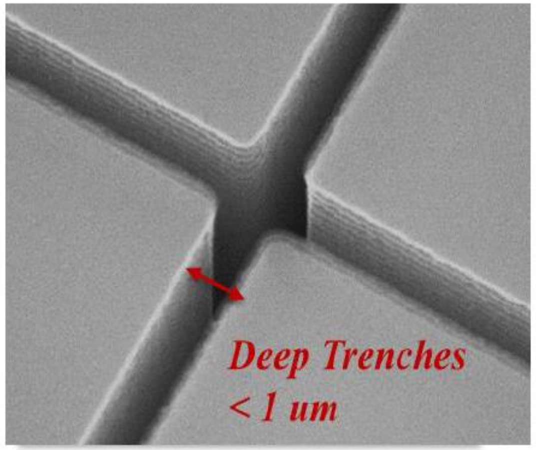
Trench-Isolated ("TI") LGAD

- Straightforward idea: Avoid breakdown by interposing a physical barrier (trench) between semiconductor junction segments (implants)
- Trench of depth 1μm or less
- Filled with insulator (SiO)

Trench-Isolated LGADs (TI-LGAD)



- DC readout
- Patterned p-gain
- Compact isolation structure based on Deep Trench Isolation technology

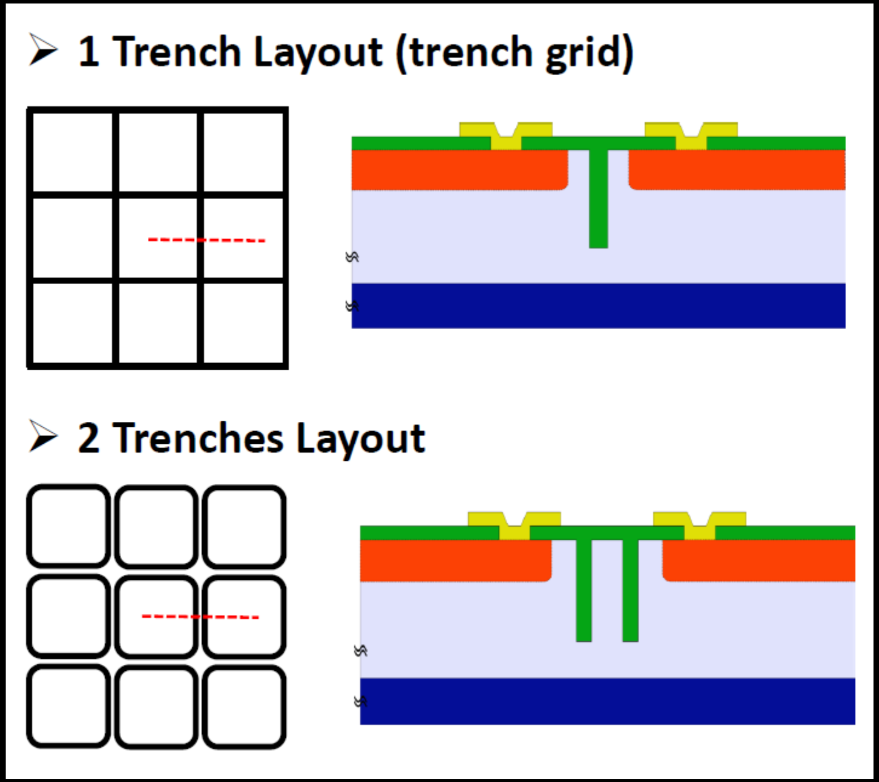


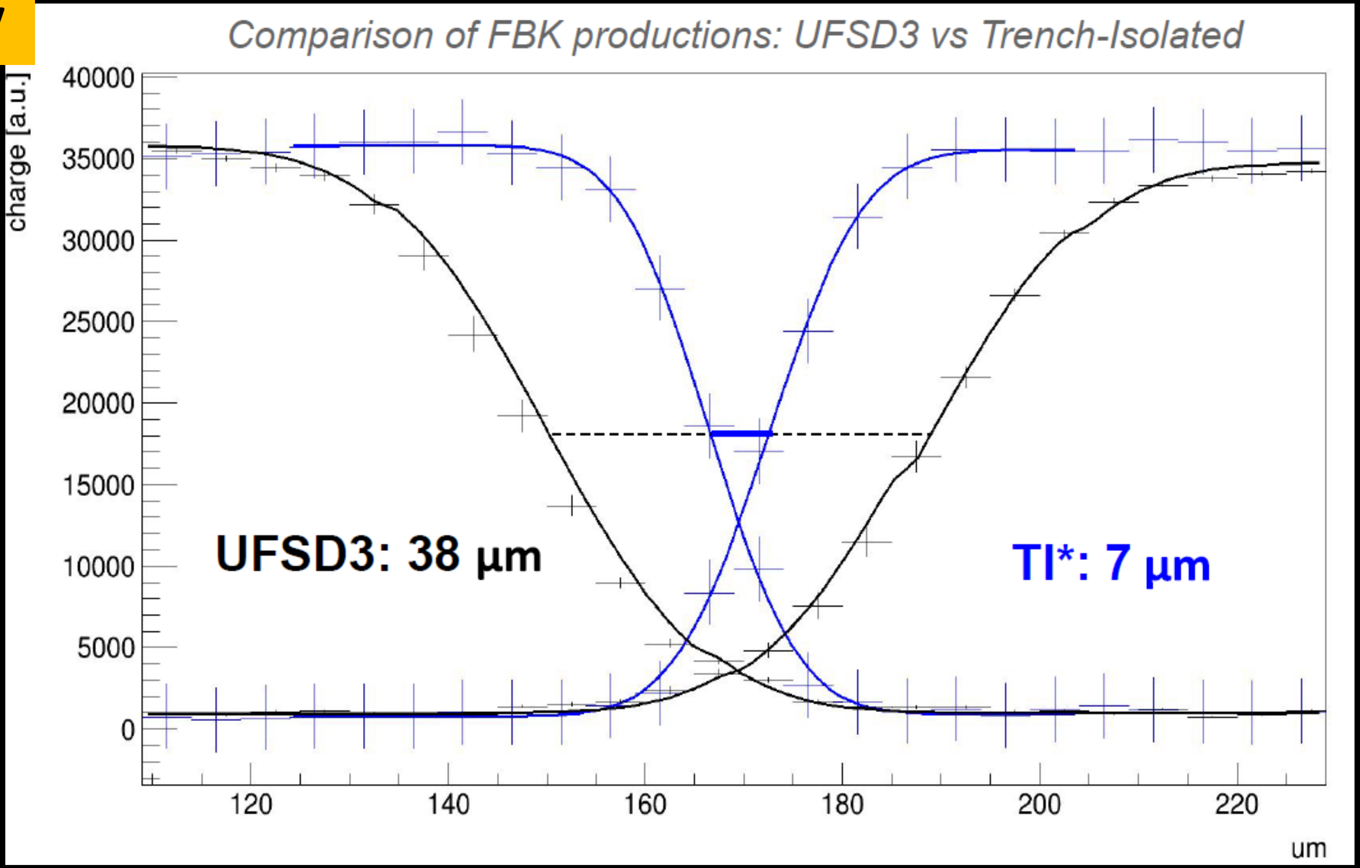
- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

TI-LGAD slide credits: FBK, Trento, Italy

Low-Gain Region Characterization for TI-LGAD

TI-LGAD slide credits: FBK, Trento, Italy

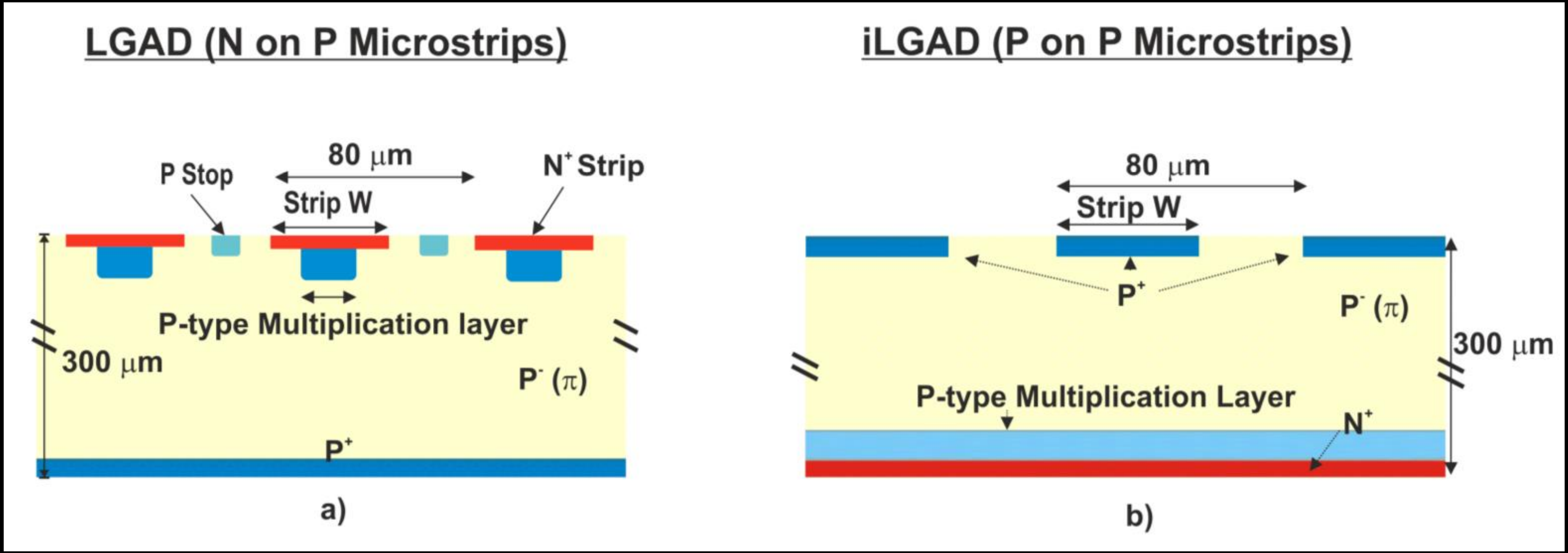




- Low-gain region reduced from ~30 μm to 5-10 μm (50% criterion)
- Timing resolution, irradiation properties still to be assessed

Approach 3: iLGAD

Inverted Architecture (iLGAD)

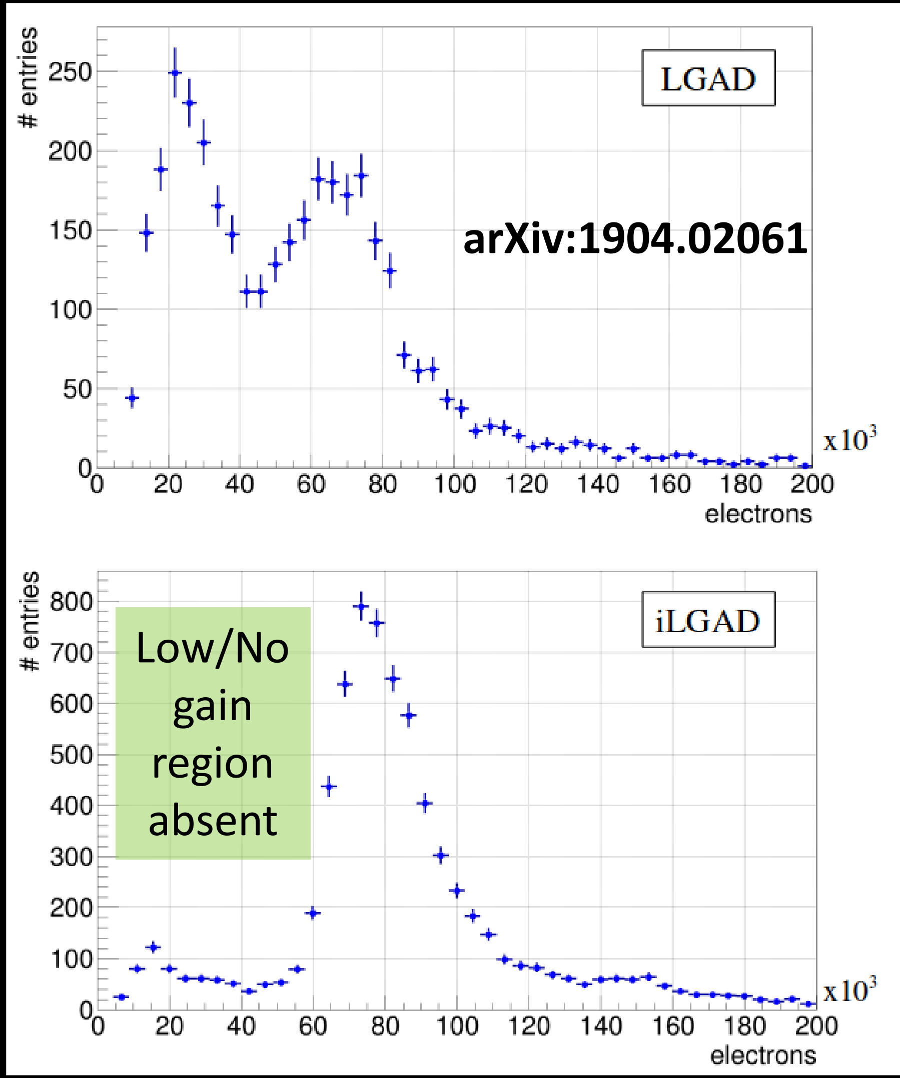


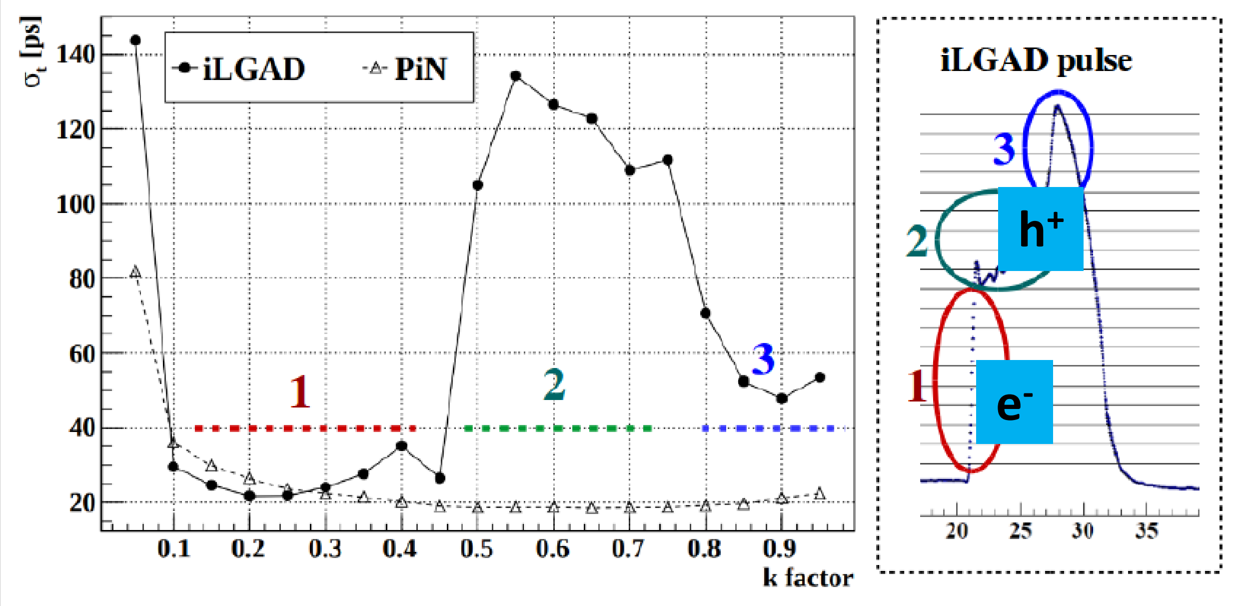
Junction/Gain layer at back of device

→ Low fields at upper surface, so conventional segmentation

→ Inverted architecture ("iLGAD")

Prototype iLGAD Characterization



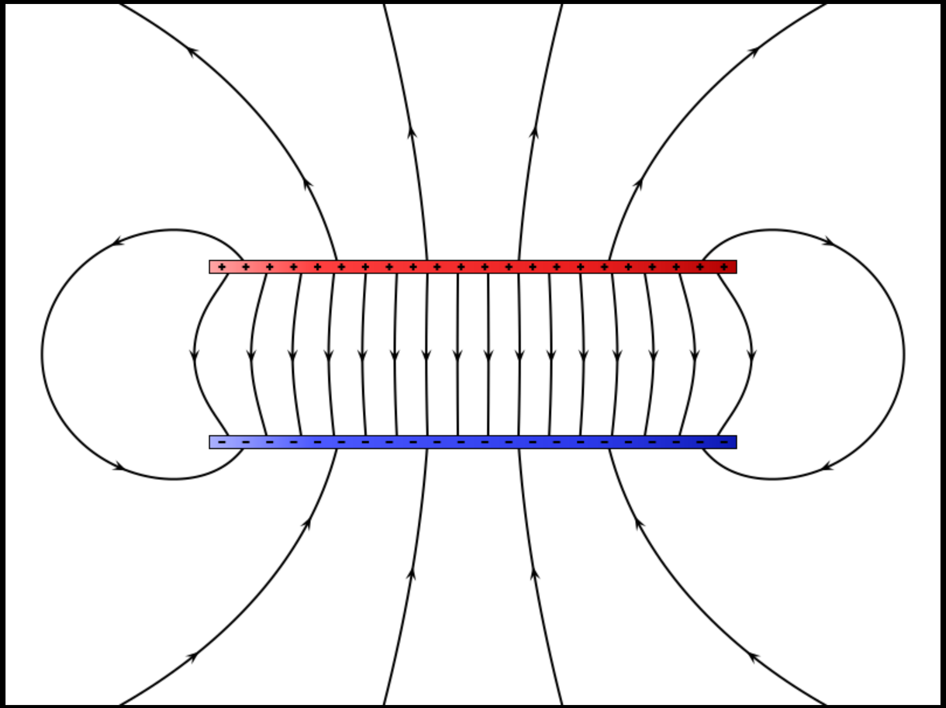


PiN and iLGAD Timing Comparison

- Large signal ("saturated") regime
- Fast rise region shows PiN-like turn-on (effective charge collection)
- MIP timing resolution under study

Approach 4: DJ LGAD

DJ-LGAD: A NEW! Approach to LGAD Granularity



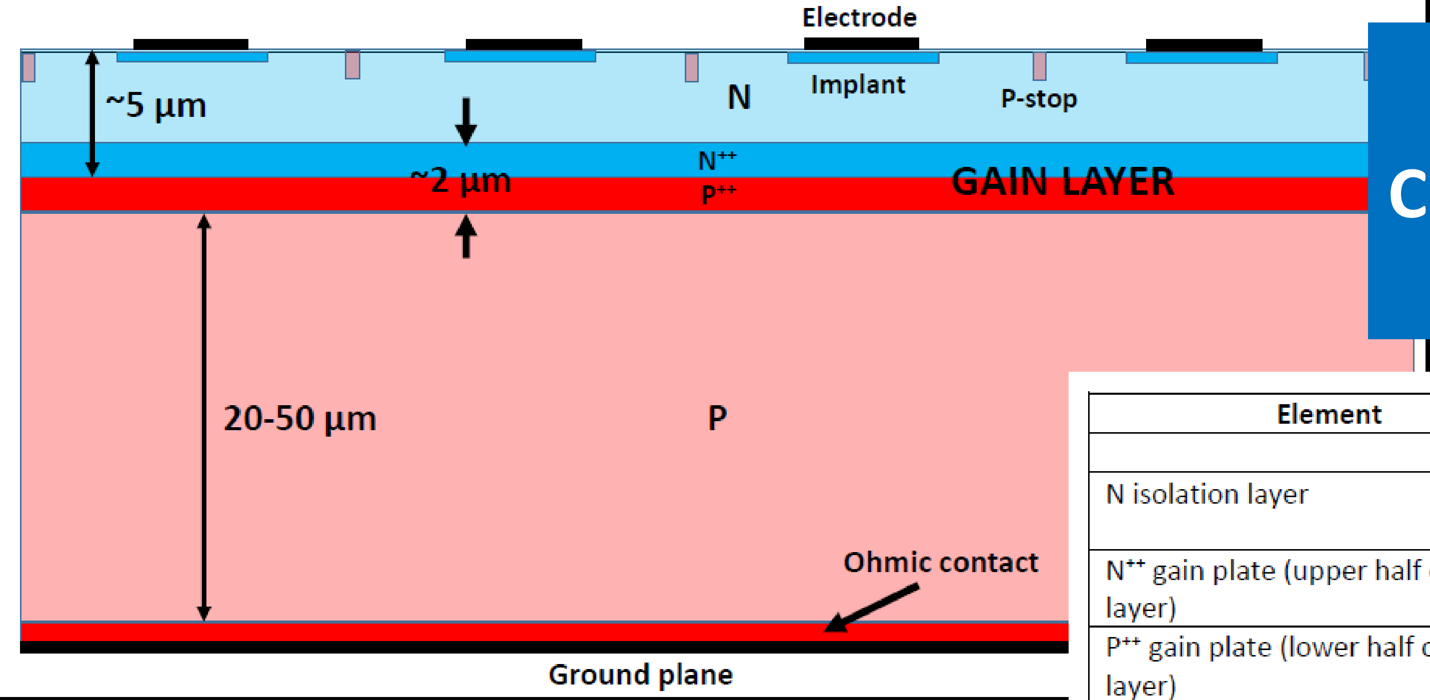
Basic inspiration is that of the capacitive field: Locally large, but surrounded by low-field region beyond the plates.

Idea:

- Use symmetric P-N junction to act as an effective capacitor
- Localized high field in junction region creates impact ionization
- Bury the P-N junction so that fields are low at the surface, allowing conventional granularization

➔ **"Deep Junction" LGAD (DJ-LGAD)**

DJ-LGAD Baseline Design



Patent Application SC 2019-978

C. Gee, S. Mazza, B. Schumm, Y. Zhao

UC Santa Cruz

Element	Doping Level	Extent in Depth
N isolation layer	Constant doping of density 3e12 N/cm^3	From 0 µm (surface) to beginning of N++ "gain plate" layer
N++ gain plate (upper half of gain layer)	Gaussian doping, peak of 3.0e16 N/cm^3	Peak at 4 µm, Gaussian width of 0.17 µm
P++ gain plate (lower half of gain layer)	Gaussian doping, peak of 3.0e16 N/cm^3	Peak at 5.5 µm, Gaussian width of 0.17 µm
P drift region	Constant doping of density 3.0e12 N/cm^3	End of P++ "gain plate" layer to 50 µm
P stop	Constant doping of density 1.0e13 N/cm^3	1 µm deep, 1µ wide
N++ implant	Constant doping of density 1.0e19 N/cm^3	At surface
Gain layer doping tolerance (N++ and P++ varied together)	Effective operation between 2.9e^16 and 3.5e^16	

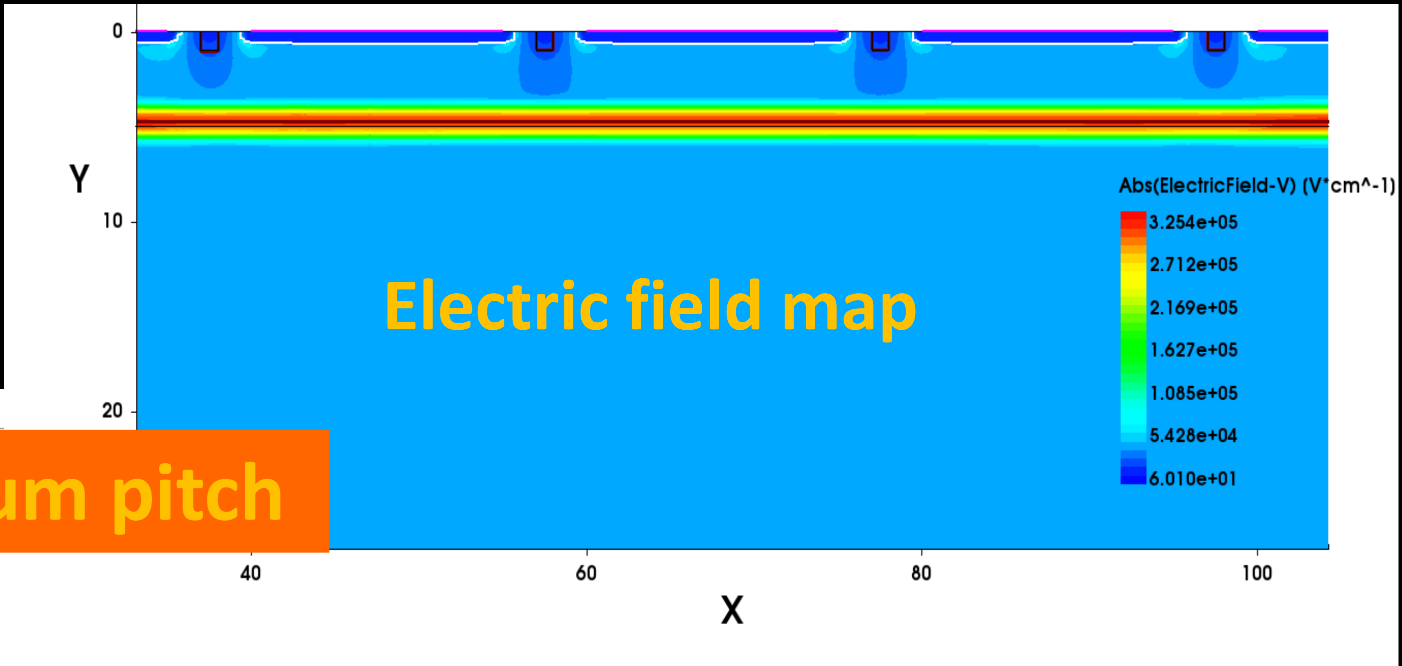
DJ-LGAD Baseline Design

Implementation of concept requires significant tuning of design parameters

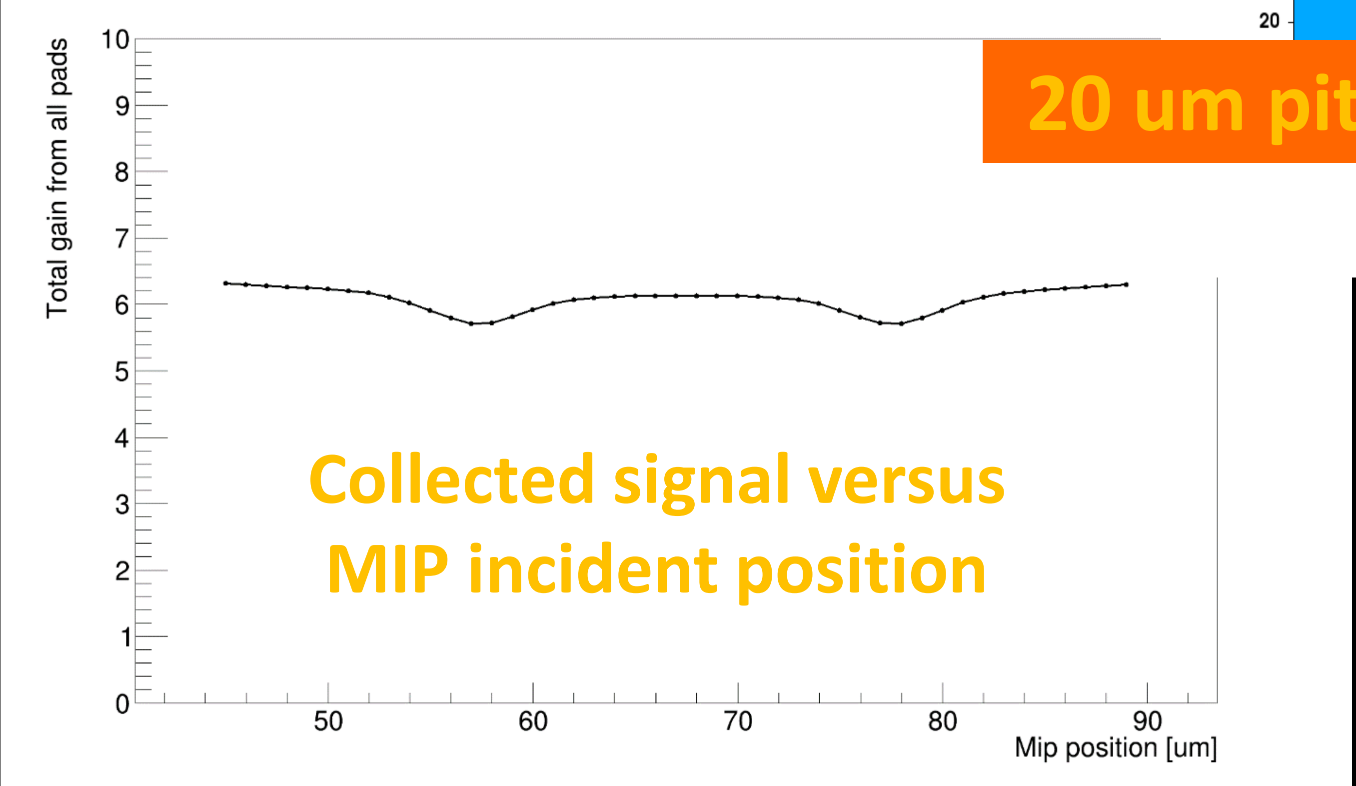
DJ LGAD Simulated Performance

Field Configuration

- Junction creates gain region
- Low field at surface and in bulk
- Drift velocity saturated everywhere



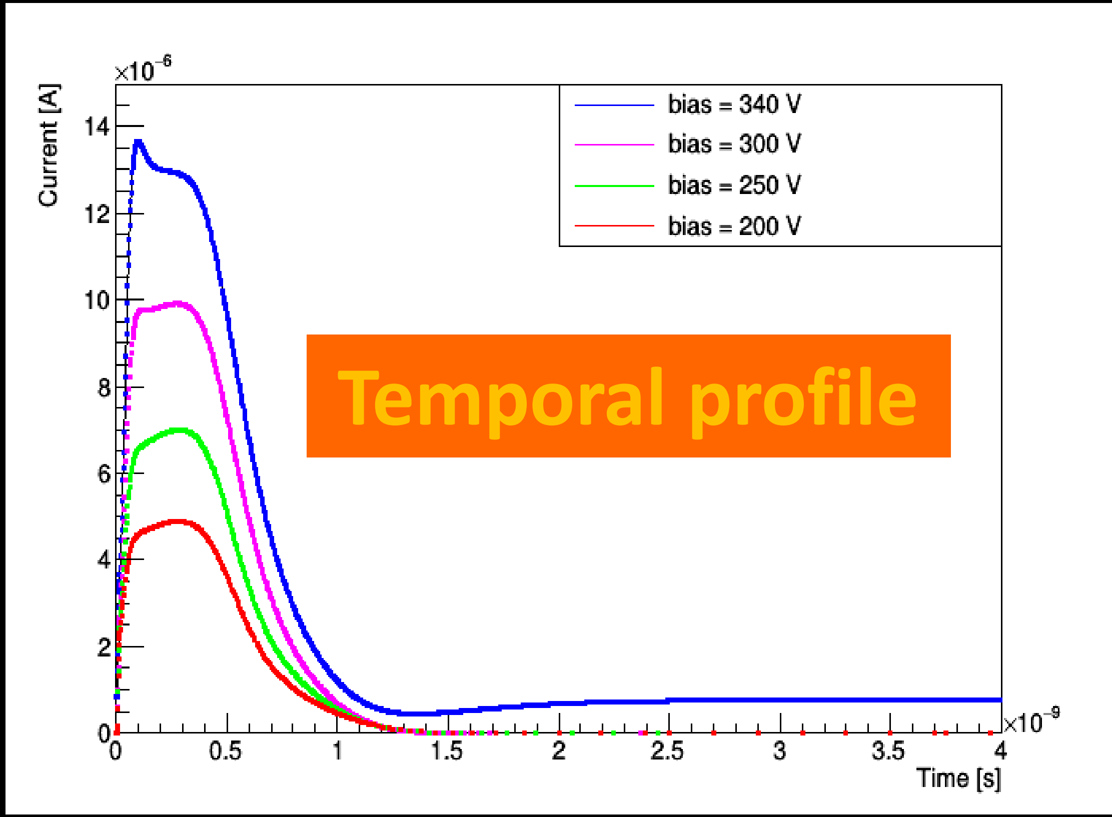
20 um pitch

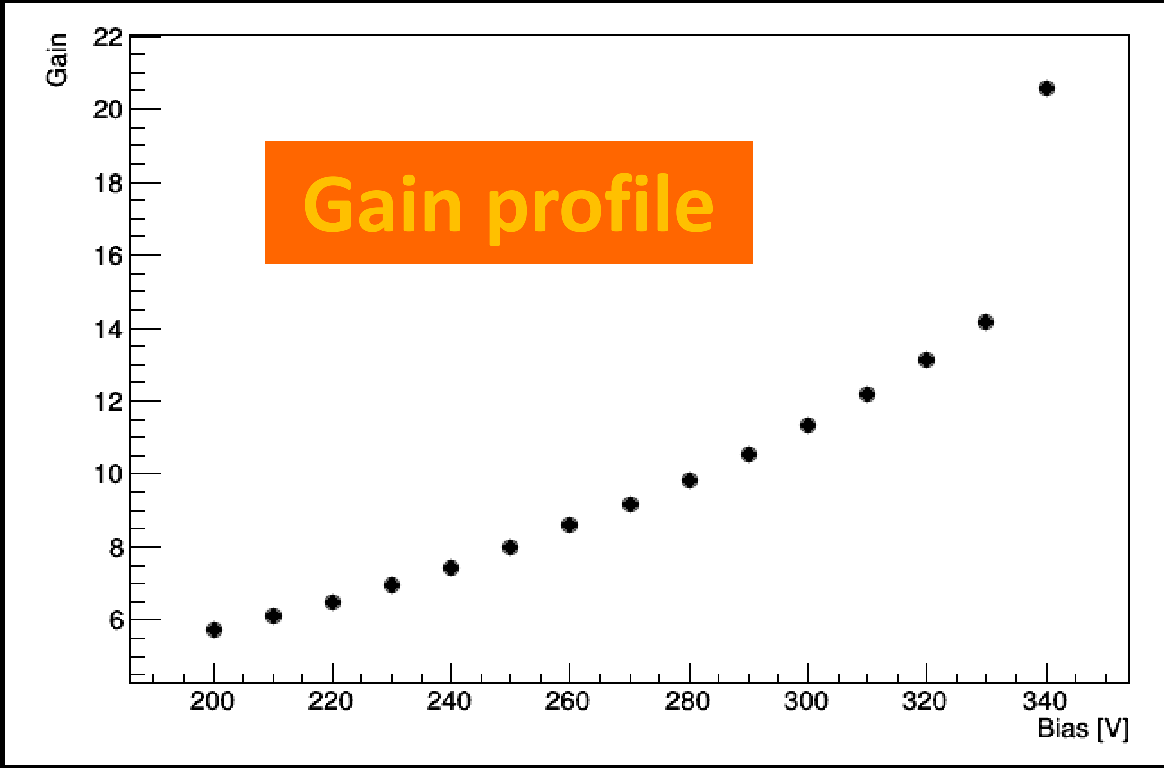


Gain Uniformity

- 20 µm pixels simulated
- ± 4% across full device
- DC coupled to readout pads

DJ-LGAD Performance and Prototyping





First prototype (if funded) will be rudimentary planar prototype to confirm the Deep Junction principle

SBIR-STTR Grant Submitted
Cactus Materials, Inc.
Title: A New Approach to Achieving High Granularity in Low-Gain Avalanche Detectors
PI: Rafiqul Islam, PhD. Rafiqul.islam@cactusmaterials.com
Topic Number/Subtopic Letter: 34b

LGADs and High Frame-Rate Applications

LGADs and Ultra-High Frame Rate

Next-generation photon sources will likely strive towards multi-GHz frame rate

C. Barnes, *The Dynamic Mesoscale Materials Capability*, P/T Colloquium, Los Alamos National Laboratory, Feb 14, 2019, https://204.121.60.11/science-innovation/sciencefacilities/dmmsc/_assets/docs/PTColloq%2020190214_public.pdf

Q: Do LGADs provide any advantage at high frame rate? Note that impact ionization is a secondary process, so takes time to develop

Consider signal development in the "saturated" regime (essentially uniform e/h plasma deposited instantaneously in the detector bulk)

B. Schumm, *Signal Development for Saturated Ultrafast Sensors with Impact Ionization Gain*, arXiv:1908.04953, August 2019; submitted to JINST

Signal Development in Saturated Regime

Consider flux Φ of X-rays of energy E_γ (eV) incident on a sensor of thickness d with attenuation length λ and e/h drift speed $v^s_{e/h}$. At leading order the signal charge collected after time t contains two terms: A linear direct term and a quadratic term from impact ionization (gain):

$$Q_{e/h}(t) = \frac{\Phi E_\gamma v^s_{e/h}}{3.66\,\lambda}\left[t + \frac{1}{2}\sum_{e/h} A_{e/h} v^s_{e/h} t^2\right]$$

$$A_{e/h} = \frac{1}{d}\int dz\, \alpha_{e/h}(z)$$

Impact ionization factor = number pf e/h pairs created per cm of travel of extant carrier

If amplified with a circuit with collection time τ, the total collected charge will be approximately

$$Q_{e/h} = \frac{K\Phi E_\gamma v^s_{e/h}\tau}{3.66\,\lambda}\left[1 + \frac{1}{2}\sum_{e/h} K A_{e/h} v^s_{e/h}\tau\right]$$

Gain contribution

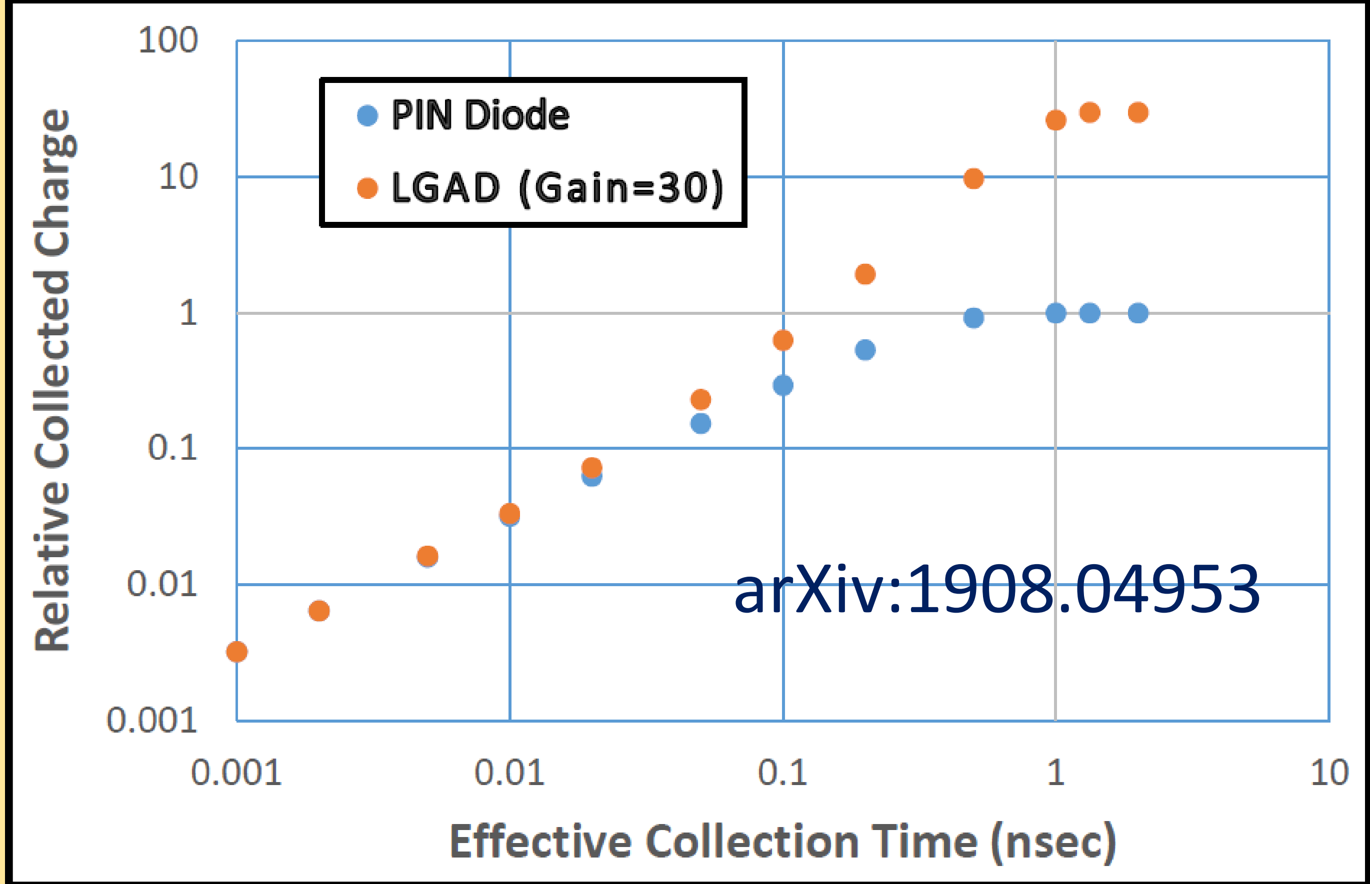
where $K \cong 1$ relates the circuit shaping time to the effective charge collection time. If the circled term is greater than 1 then the gain provides a benefit.

arXiv:1908.04953

Saturated Sensors: Elemental Simulation

Develop elemental simulation with

- Planar 50µm thick sensor
- saturated drift speed
  $v_{e/h}$=100/60 µm/nsec
- 2µm thick gain layer
- α=0.61µm mean free path per
  impact ionization in gain layer
- leads to a gain of 30.



➔ LGADs provide benefit to ~10 GHz frame rate (maximum under consideration in next generation photon sources)

Summary

Granularity

Conventional LGAD limited to ~1mm^2 granularity by junction termination requirements
→A number of approaches under development to reach 50 μm (or better) scale
→AC-LGAD most advanced idea but still much R&D to do
→DJ-LGAD new (first public presentation) has potential to provide high granularity in DC-coupled mode with no gain-free regions

Frame Rate

Study of fundamental properties of impact ionization and solid-state charge collection suggests that LGADs advantageous to frame rates of 10 GHz or more

- Accelerator diagnostics (R&D funded by 3 year University of California "Lab Fees" grant to begin in Spring, with LANL, LBNL, UC Davis, UC Santa Barbara, UC Santa Cruz)
- X-ray imaging
- … ?

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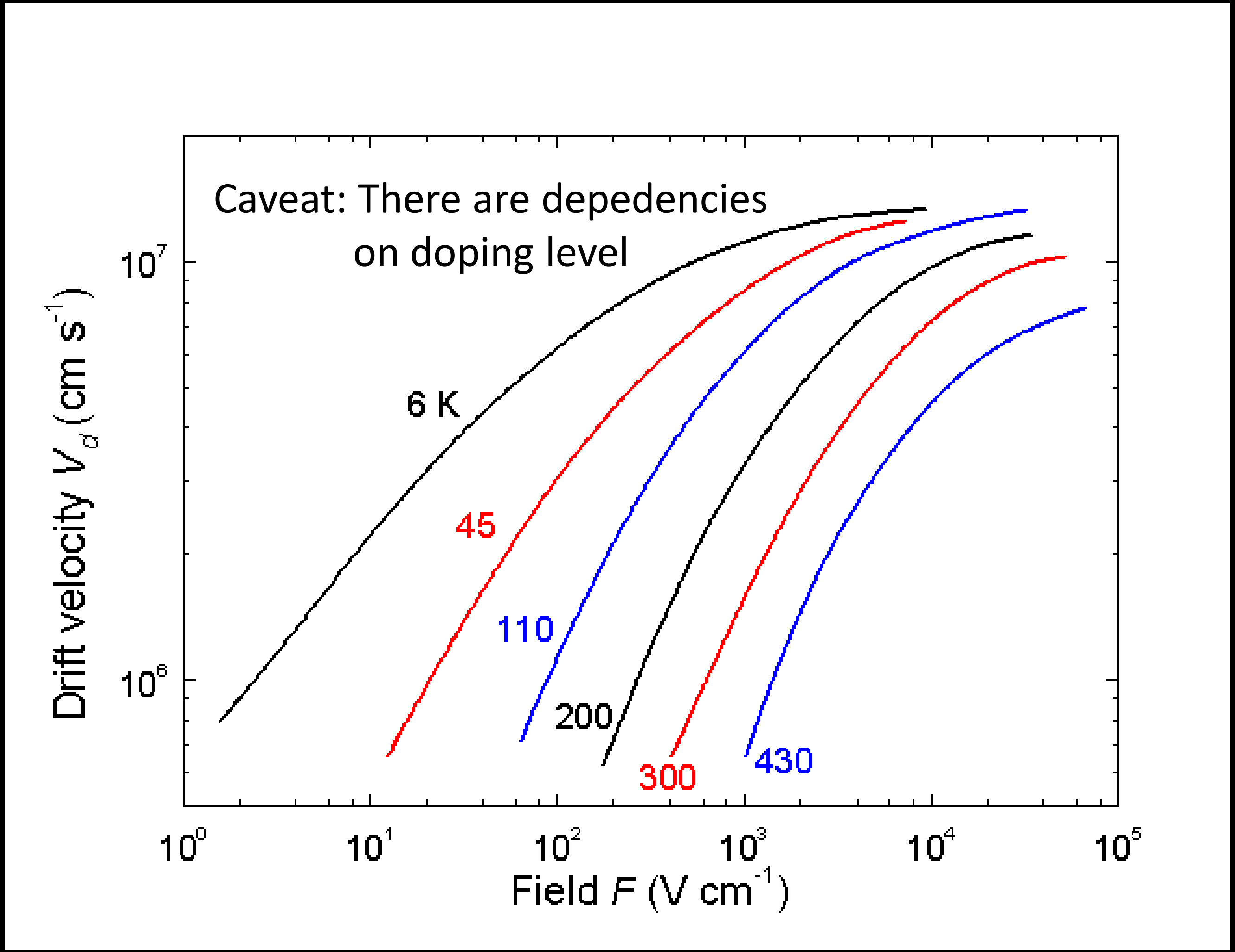
BACKUP

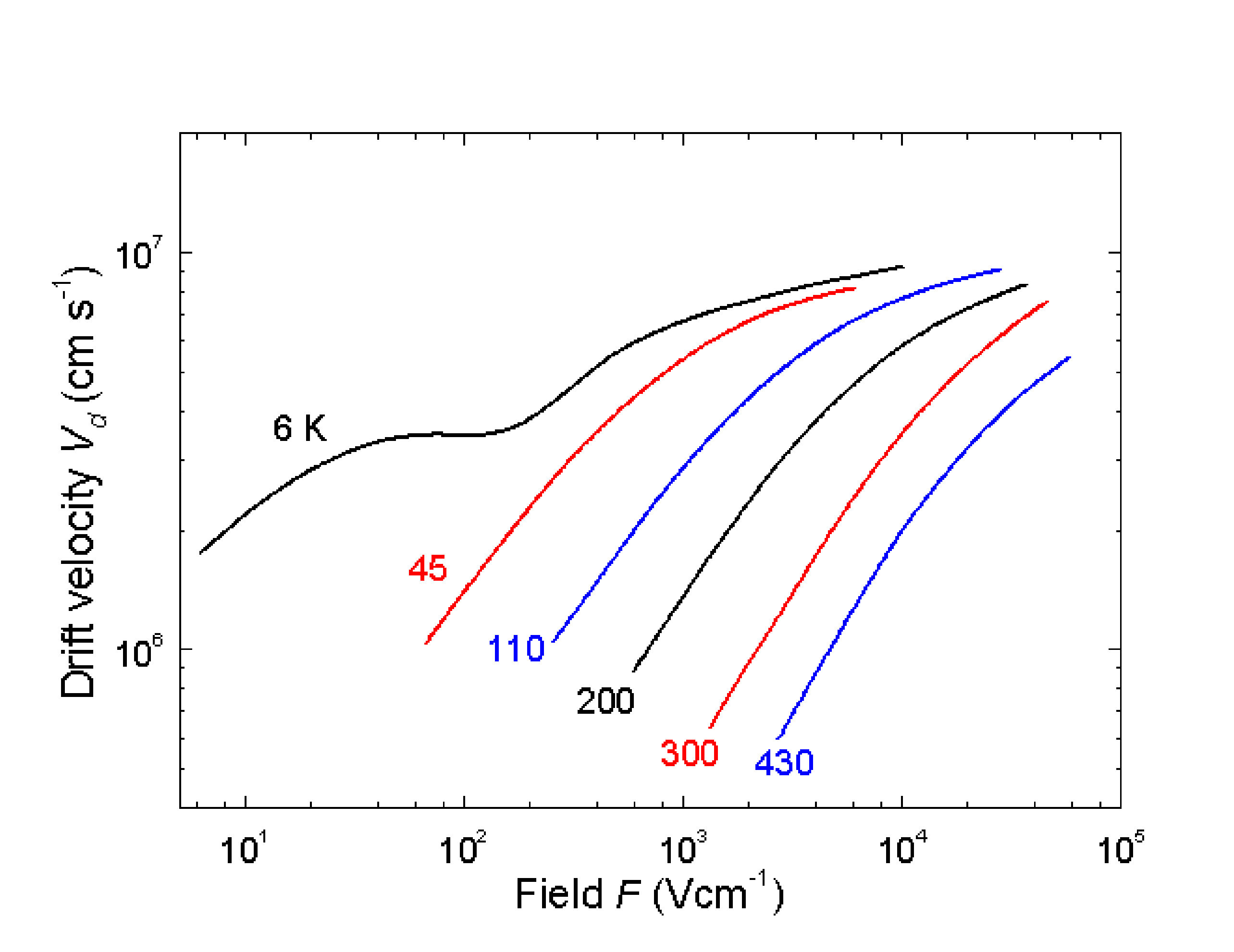
Basic Properties: Electron Drift Velocity



Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, *Solid State Electron.* **20, 2**(1977) 77-89.

- For fields approaching 10^4 V/cm, velocity saturates at ~10^7 cm/s
- Transit time for 100 μm of silicon is ~1 nsec
- Transit time and temporal resolution are NOT one and the same, but it sets a scale
- Thinner sensors generally associated with more precise timing

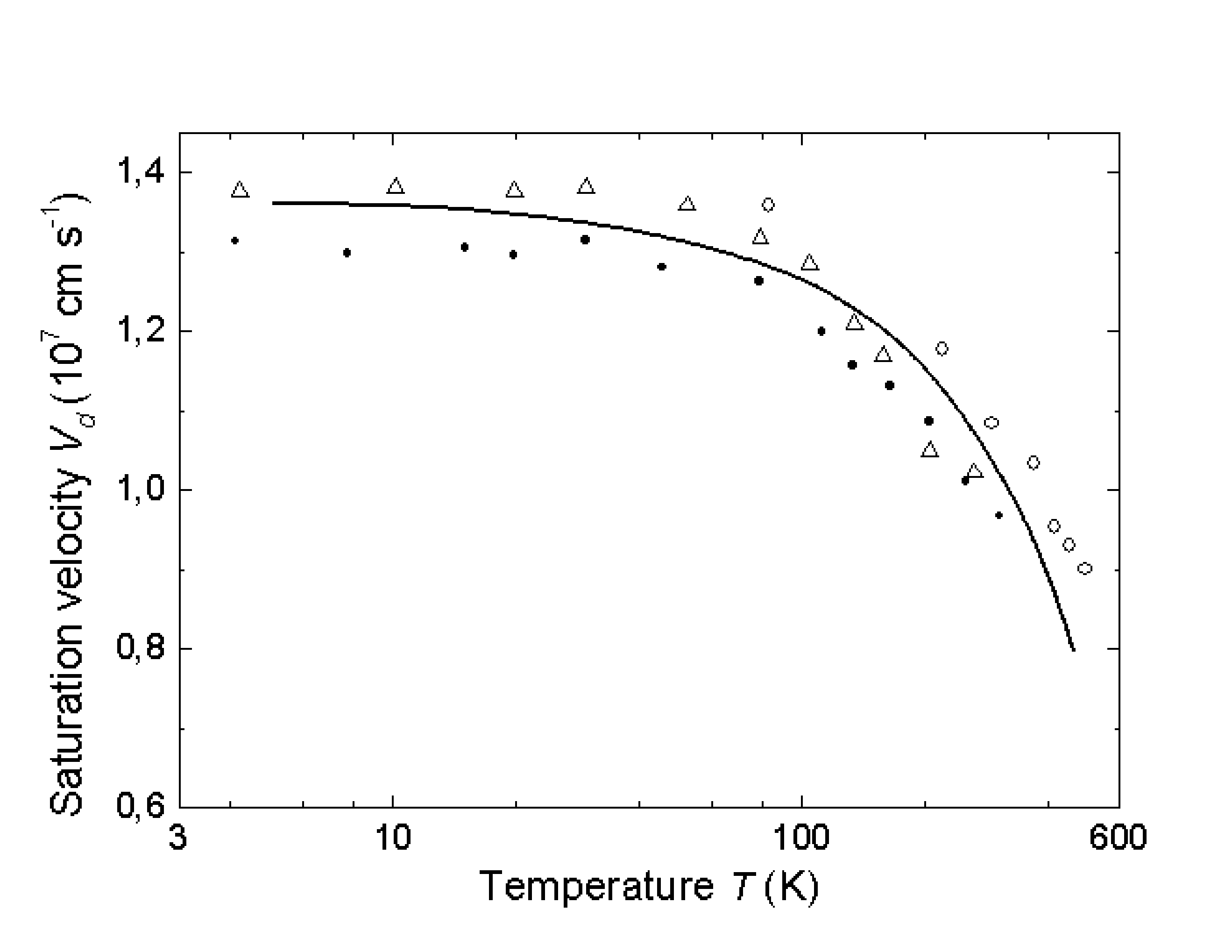
Basic Properties: Hole Drift Velocity



- Saturated speed a bit less than for electrons
- Saturation occurs at higher fields
- Note that 10^4 V/cm over 100 μm is 100 V

Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, *Solid State Electron.* **20, 2**(1977) 77-89.

Electron drift velocity



Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, *Solid State Electron.* **20, 2**(1977) 77-89.