Low Gain Avalanche Detectors Technology Overview

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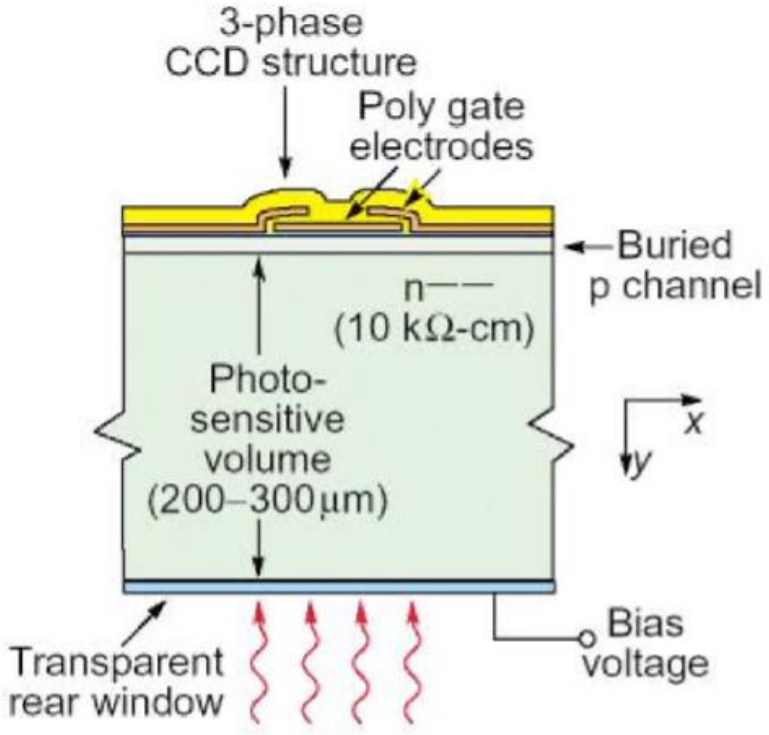
Contents

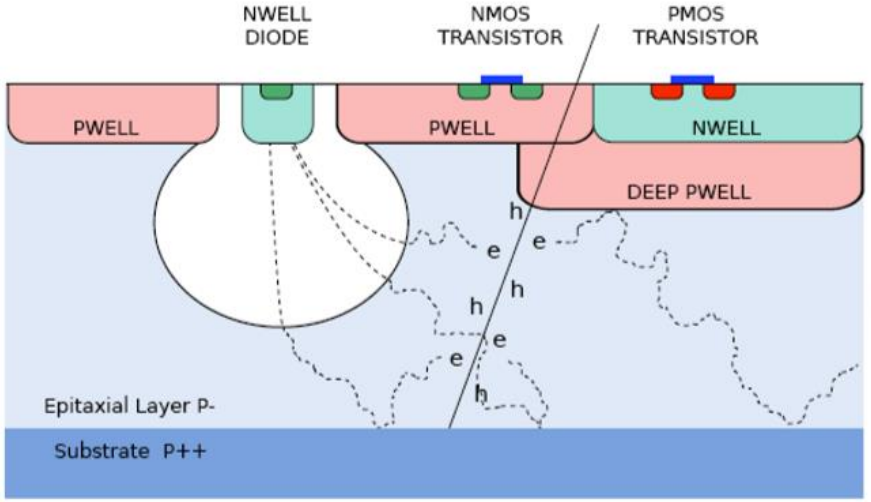
- Silicon pixel detectors
  - TimePix
- Gain
- Timing
- Micron Detectors
- Small pixels
  - The challenge
  - Two solutions

Silicon pixel detectors

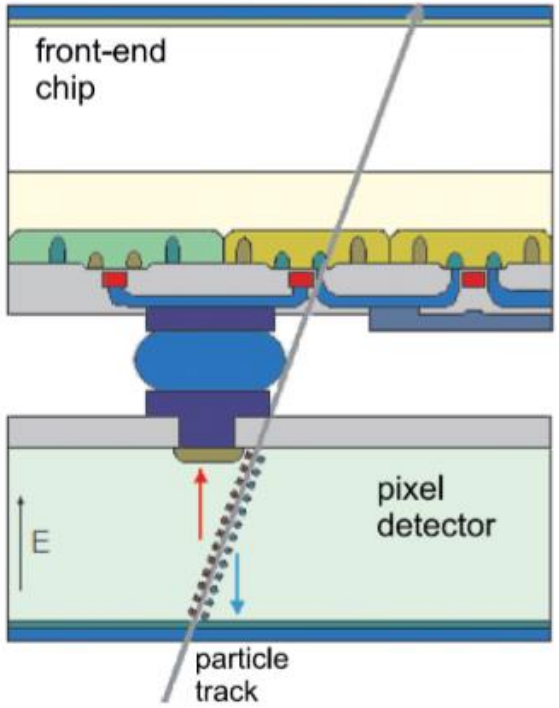
Fully depleted CCD



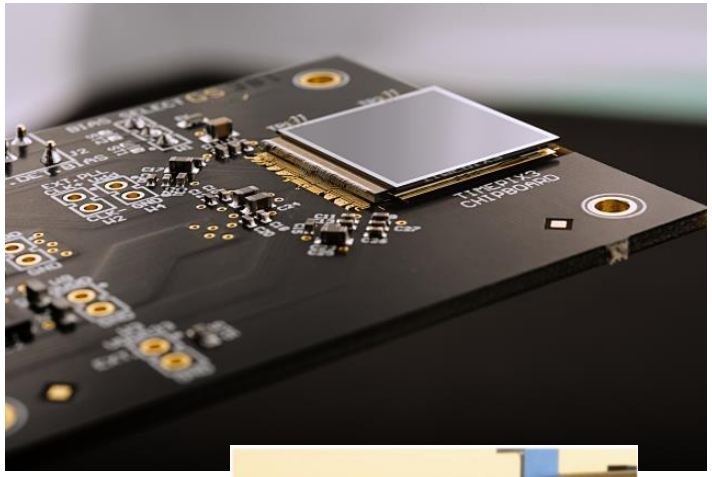
Monolithic CMOS Pixel detector



Hybrid Pixel detector



Hybrid pixel detector – An example TimePix3



The Specifications

- 256 x 256 pixels
  - 55 µm x 55 µm
- Single photon sensitivity
  - Threshold of 600e (2.2keV in Silicon)
- High frame rate
  - Continuous read-write operation @ 2000 fps
  - Maximum hit rate of 40 Mhits/s/cm^2
- Spectroscopic : Energy resolution 2keV
- Timing resolution : 1.56 ns
- 3-side buttable with TSV option

Excalibur

diamond

MIRION TECHNOLOGIES

iPIX

Applications

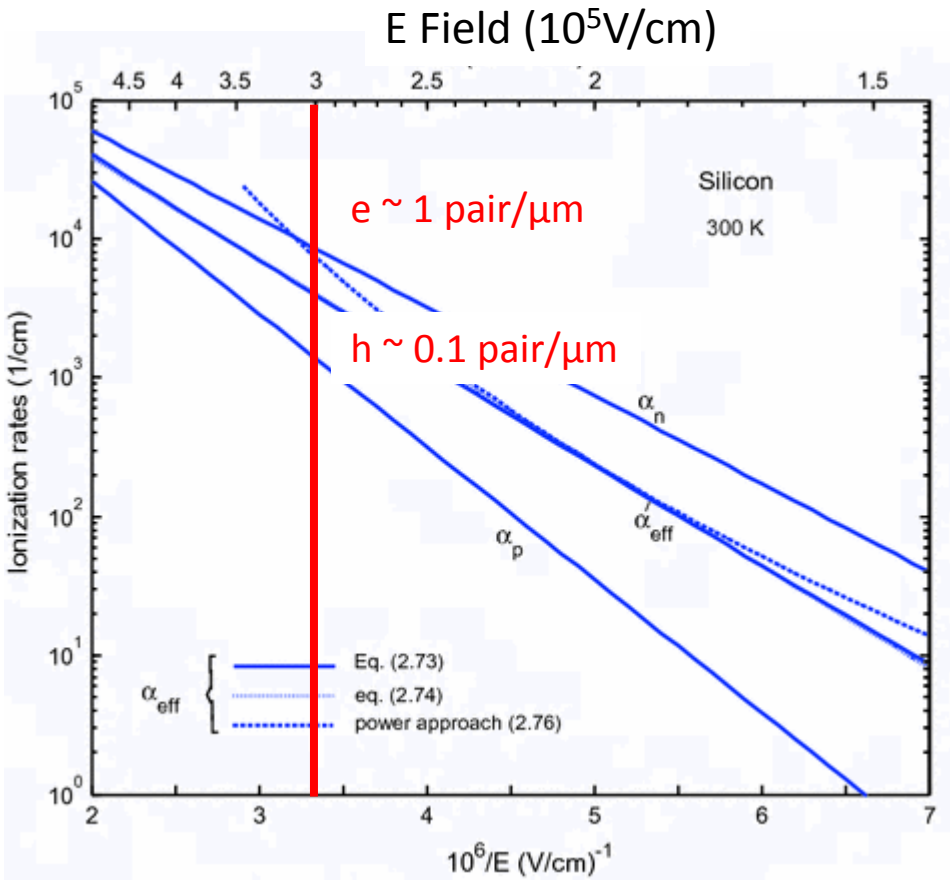
- Developed by CERN collaboration
  - Available via licence
- Gamma and neutron imaging
- (S)TEM
- Synchrotrons
- Particle tracking

Merlin 4R

Quantum DETECTORS

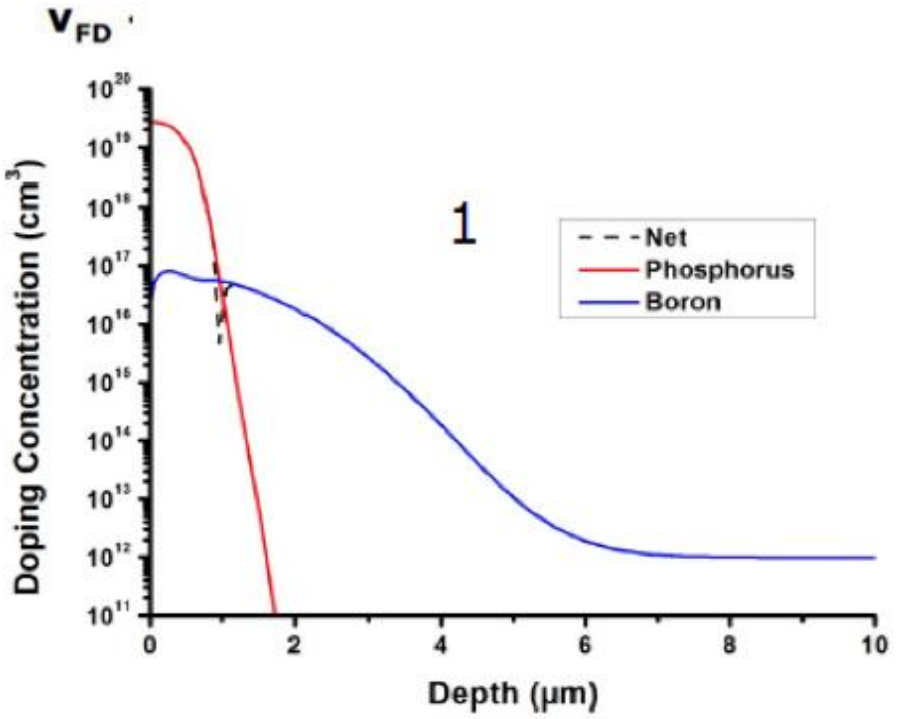
Signal

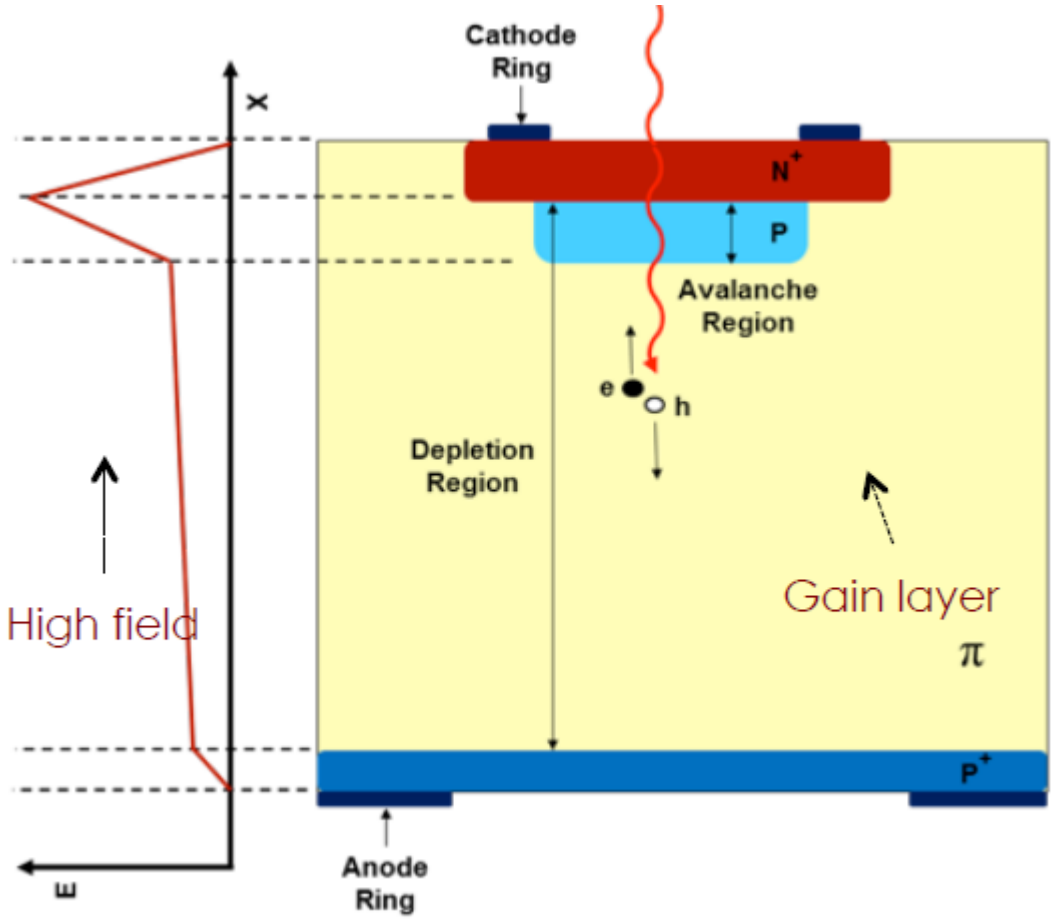
- Signal is proportional to deposited energy
  - 3.6 eV /e-h pairs (Si)
- Gain possible
  - In high electric fields electrons and holes acquire enough energy to initiate sizeable charge multiplication
- E ~ 300 kV/cm
  - Gain < 10
  - No excess noise
- E > 400 kV/cm
  - Both electrons and holes ionize
  - Geiger mode
  - Gain: infinite (breakdown)



How to get 300 kV/cm

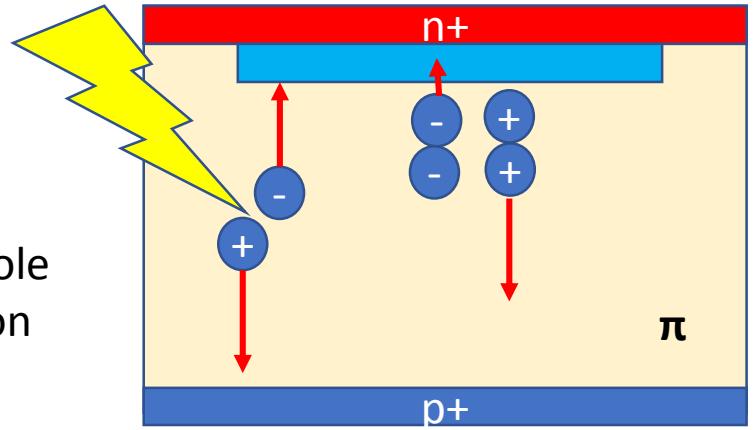
- Additional “high” doping layer under the collection electrode
  - Additional complexity to prevent breakdown - JTE
- Similar to an SiPM but with lower gain
  - No excess noise, no quenching resistors





How gain shapes the signal

Initial electron/hole pair creation



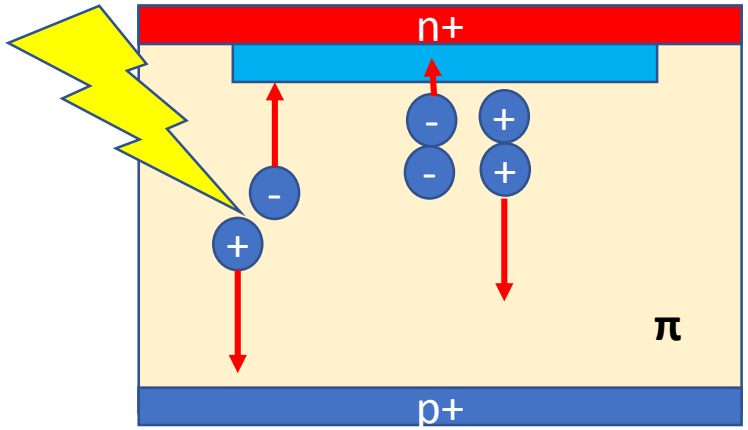
Gain electrons

Absorbed immediately

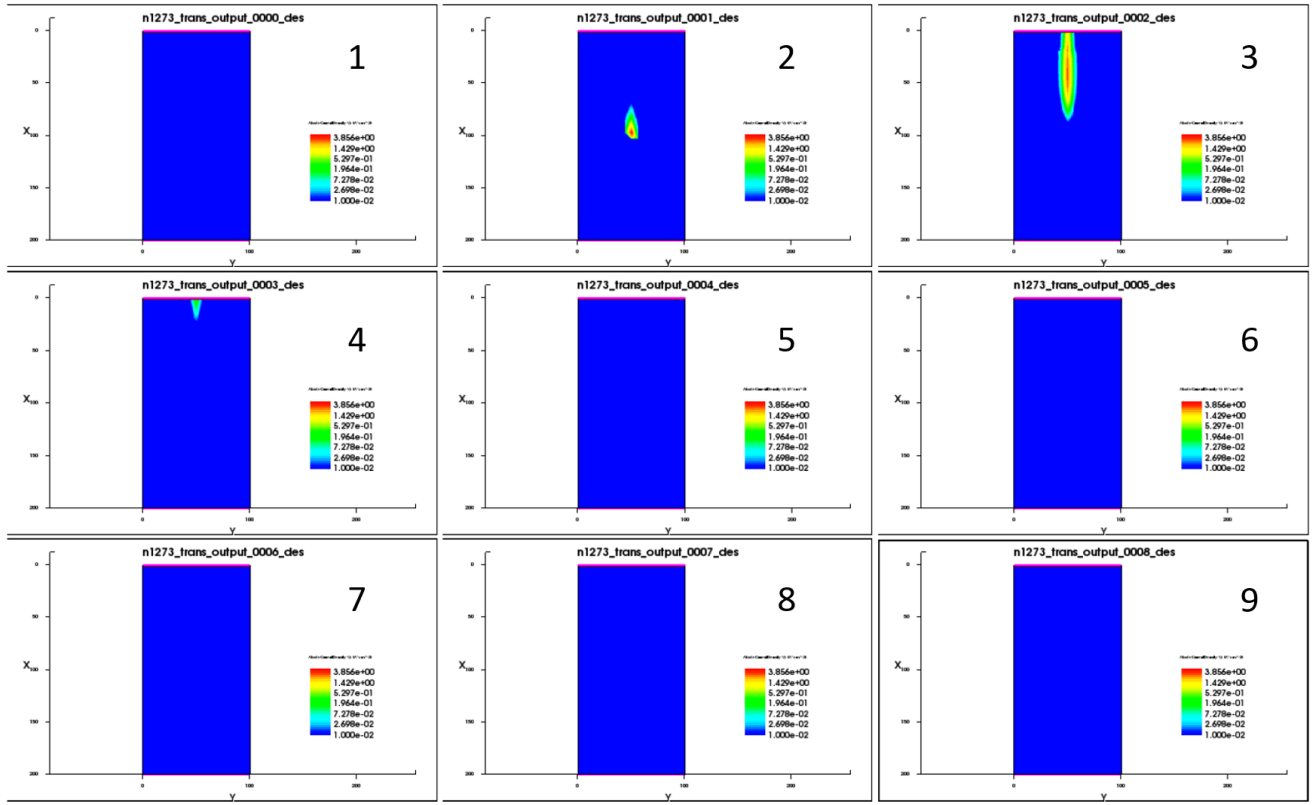
Gain holes

Long drift time

How gain shapes the signal

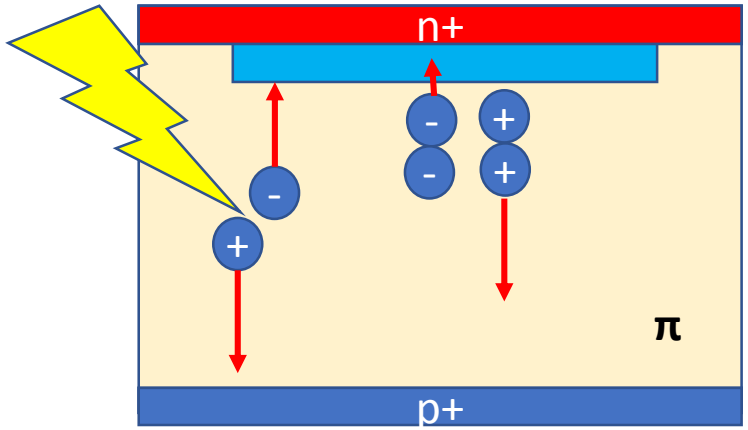


- Electron drift in the LGAD

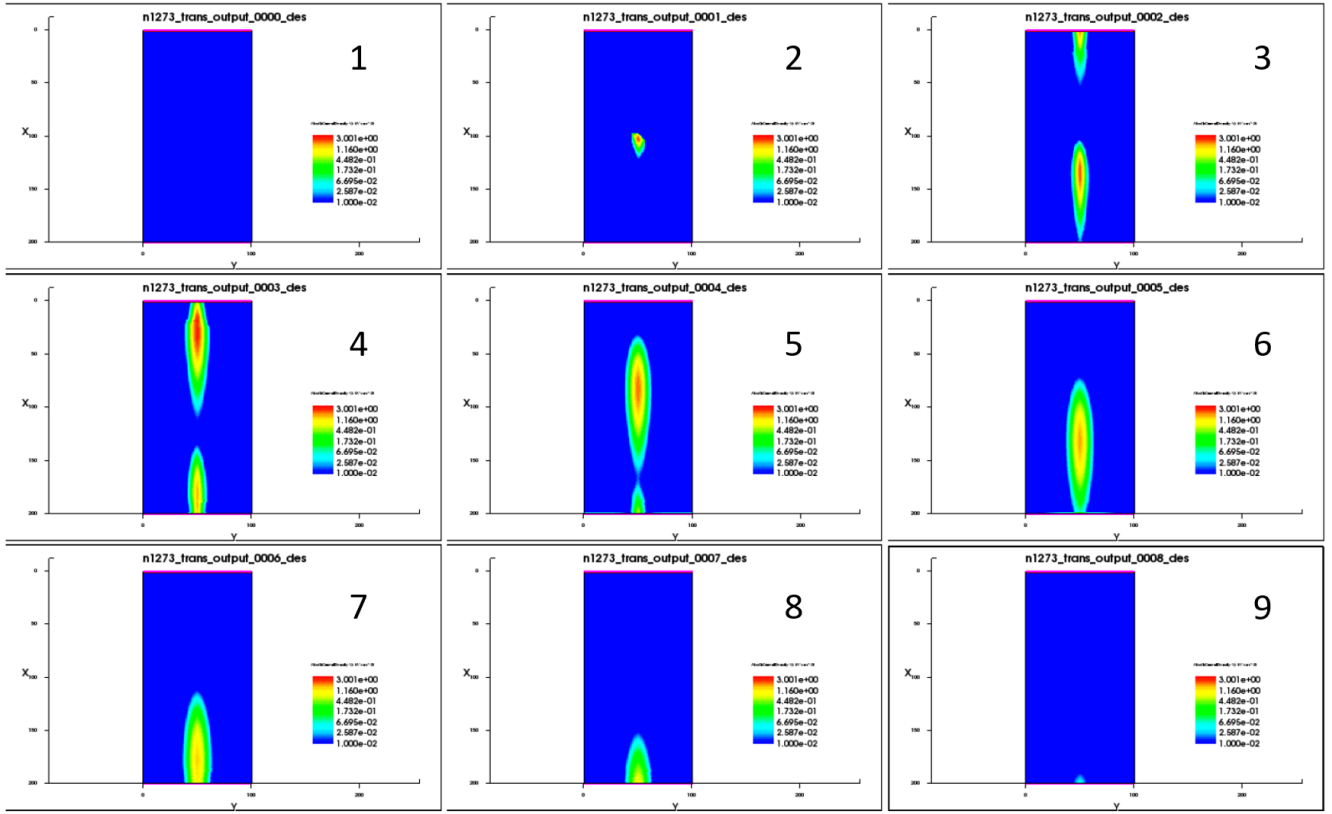


1ns time steps

How gain shapes the signal

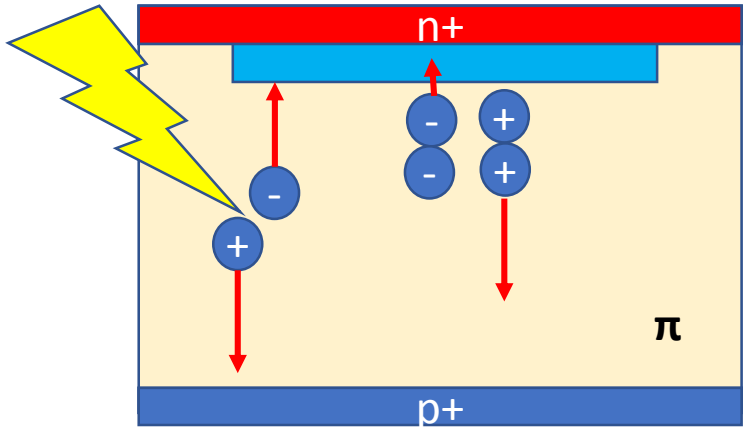


- Hole drift in the LGAD

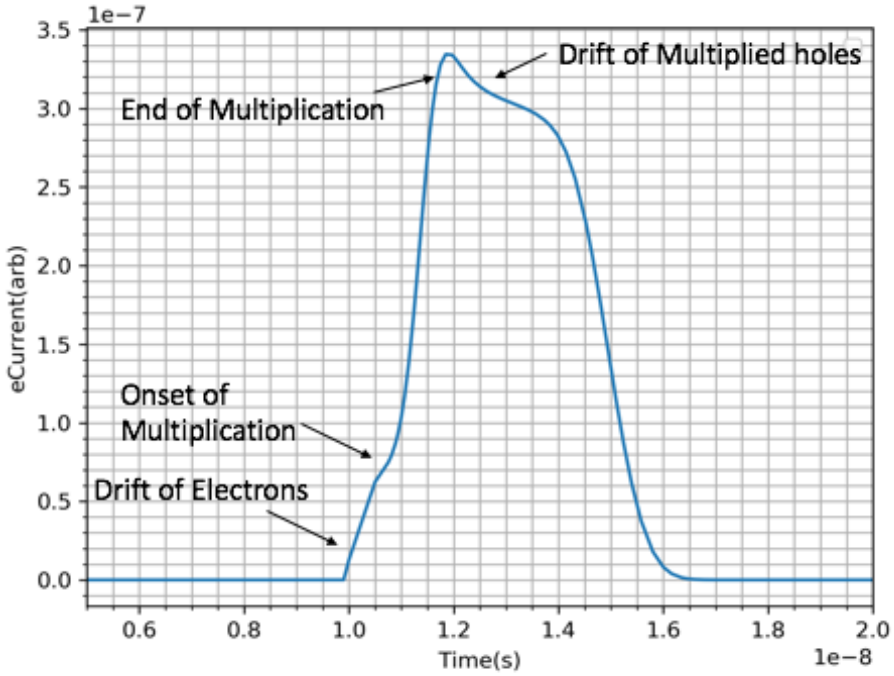


1ns time steps

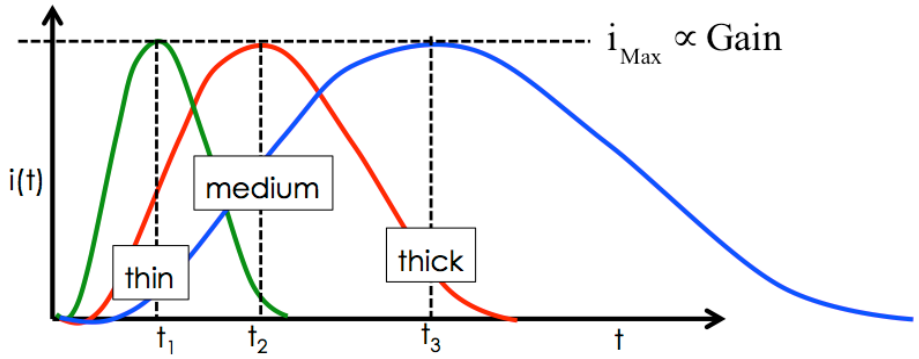
How gain shapes the signal

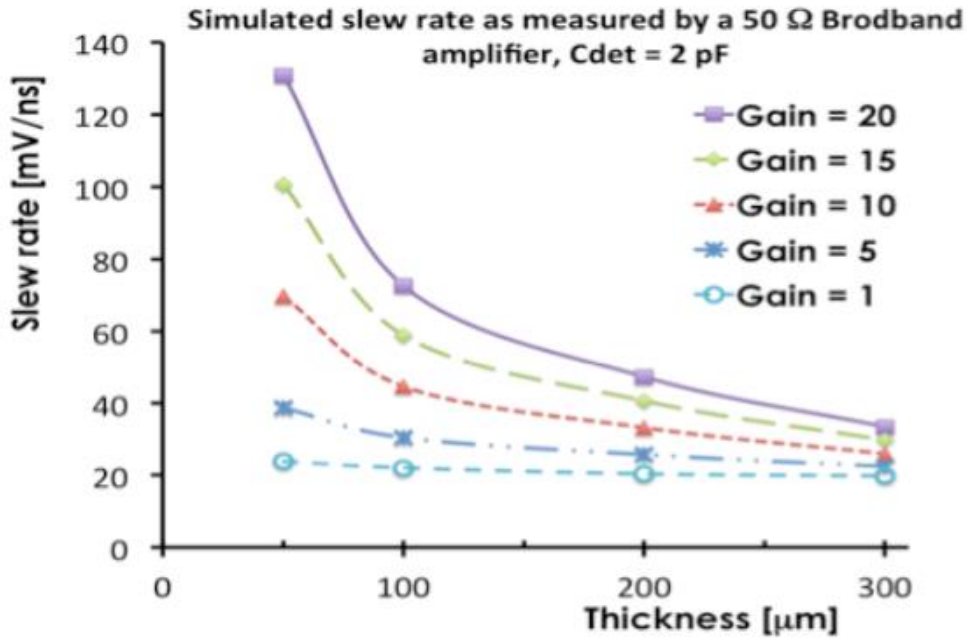


- Resulting signal



Gain gives rise to fast signals





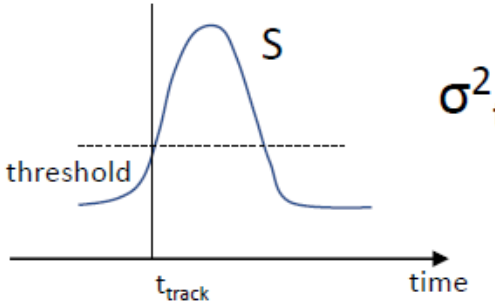
- For a fixed gain:
  - Amplitude = constant
  - Rise time ~ 1/ thickness

- The slew rate
  - Increases with gain
  - Increases ~ 1/thickness

→ **Go thin**

→ **With Gain**

Time Resolution

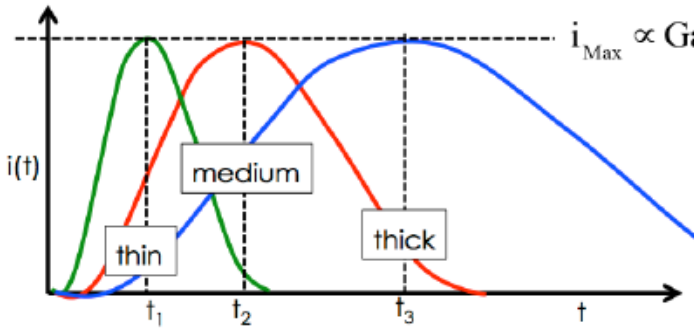


$$\sigma^2_t = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau\ Noise} + \sigma^2_{Distortion} + \sigma^2_{TDC}$$

Negligible
Optimize FE electronics

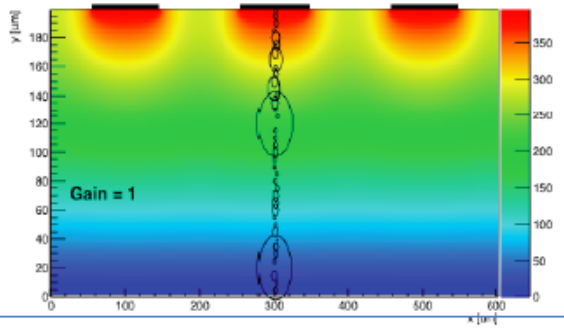
Negligible
Optimize RO electronics

$\sigma_{Jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$
➔needs **Gain** to increase S
➔needs **thin detector** to decrease t_{rise}



NB: signal amplitude DOES NOT depend on detector thickness

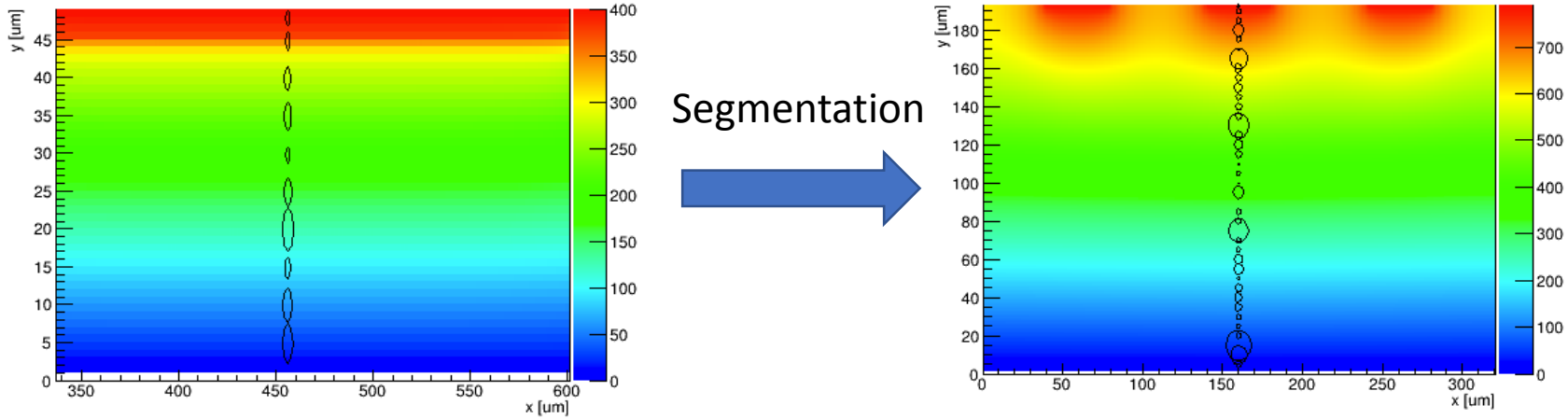
$I_{Ramo} \approx q\ v_{drift}\ E_w$
Requires **uniform v_{drift} and E_w**
➔



Decreases with detector thickness
Intrinsic Limit $\sigma_{Landau\ Noise} \approx 20ps$

Position with timing

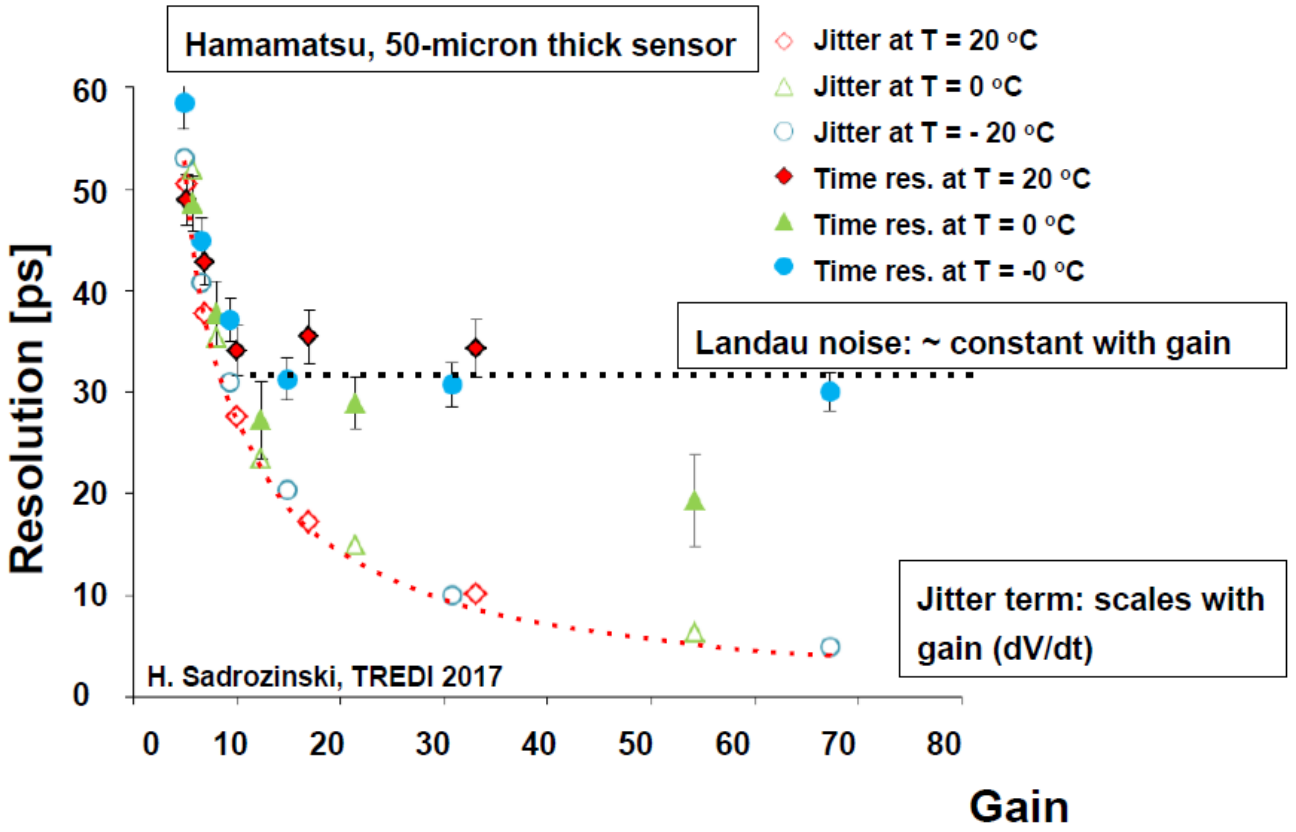
- Best to have uniform E-field for uniform timing
- Electrode segmentation makes the Drift E-field non-uniform
- Need a technology that allows electrode segmentation while not disturbing the E-field



LGAD productions

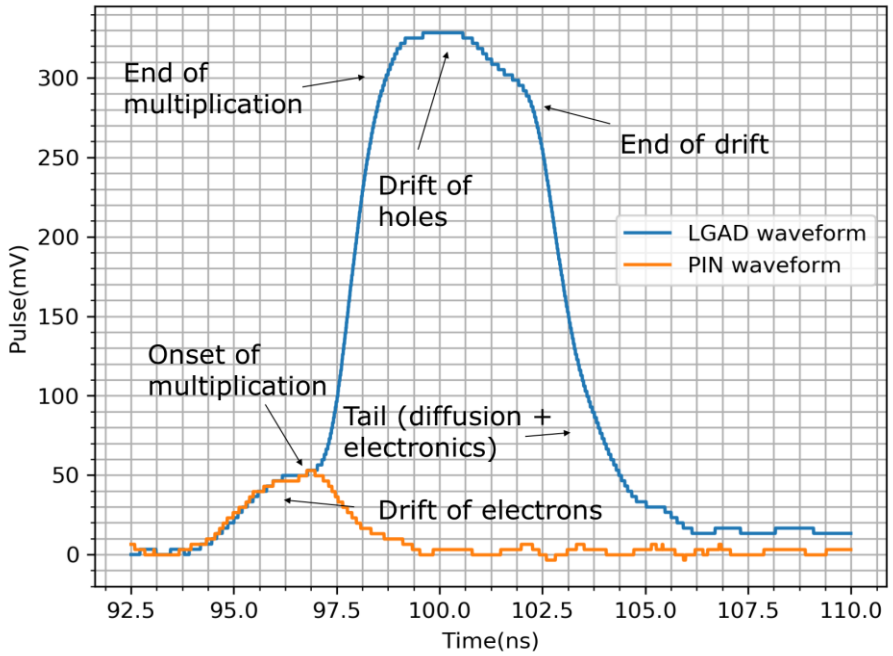
- ATLAS and CMS upgrades
  - Large pixels (1mm^2) for time tagging a track
- CERN RD50 collaboration
  - Radiation hardness
- Several manufactures
  - Micron Semiconductor, UK
  - CNM Barcelona, Spain
  - FBK Trento, Italy
  - HPK, Japan
  - BNL, USA
  - Teledyne e2V, UK

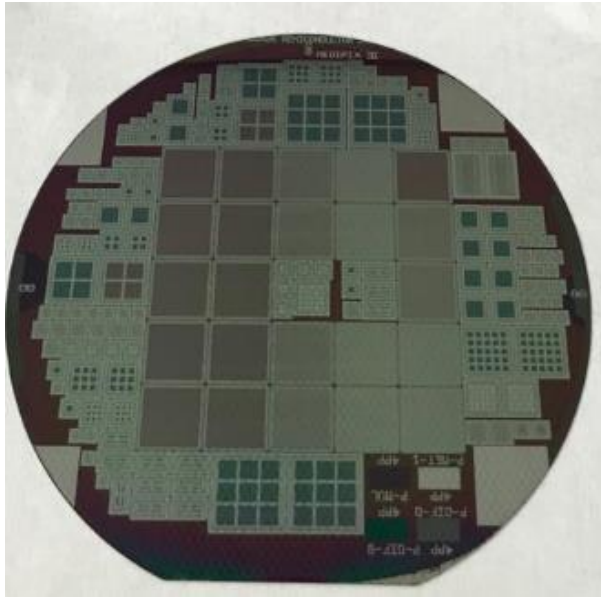
- Gain and timing measured

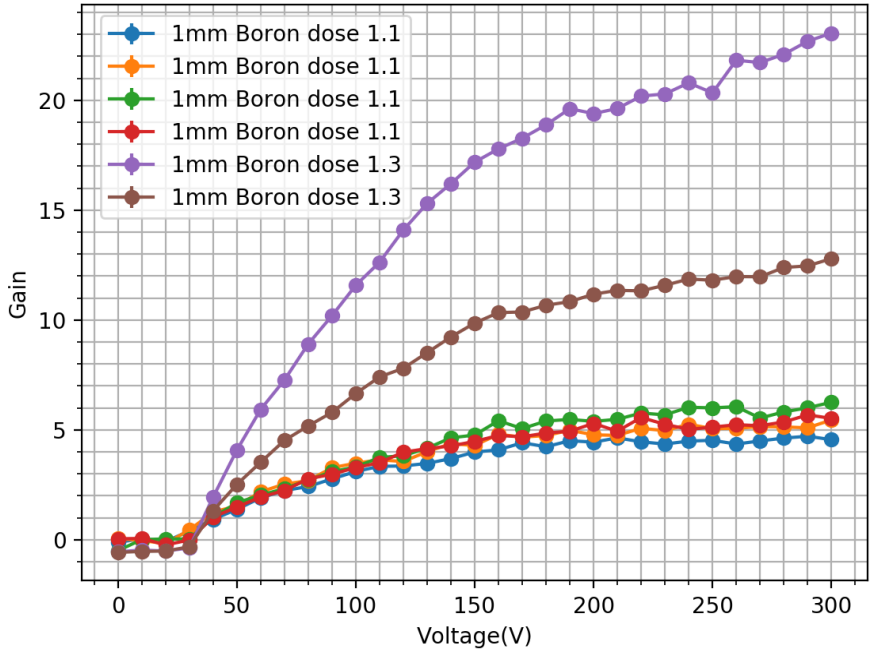


Micron Semiconductor detectors: LGAD demonstrated

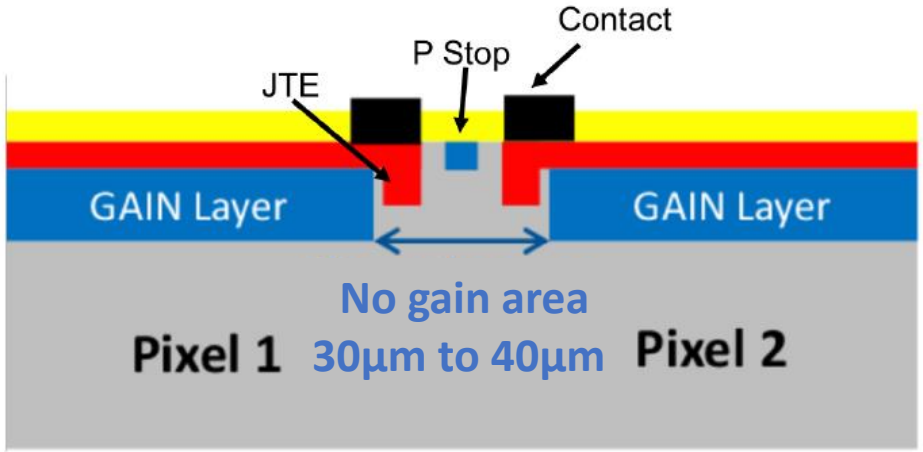
- Test wafers produced to understand gain as a function of doping
- Gain target of 10 achieved



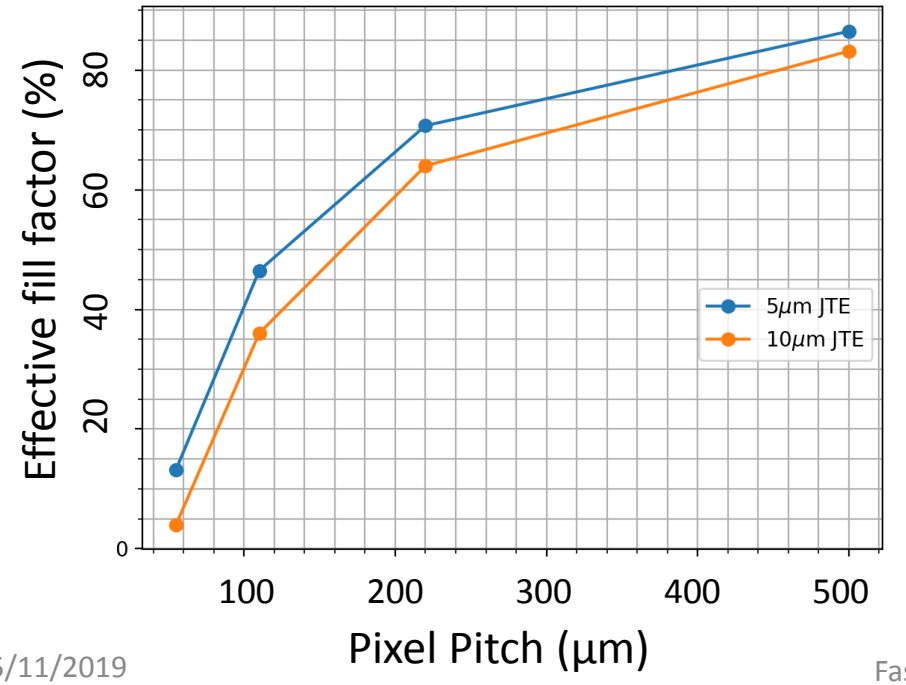




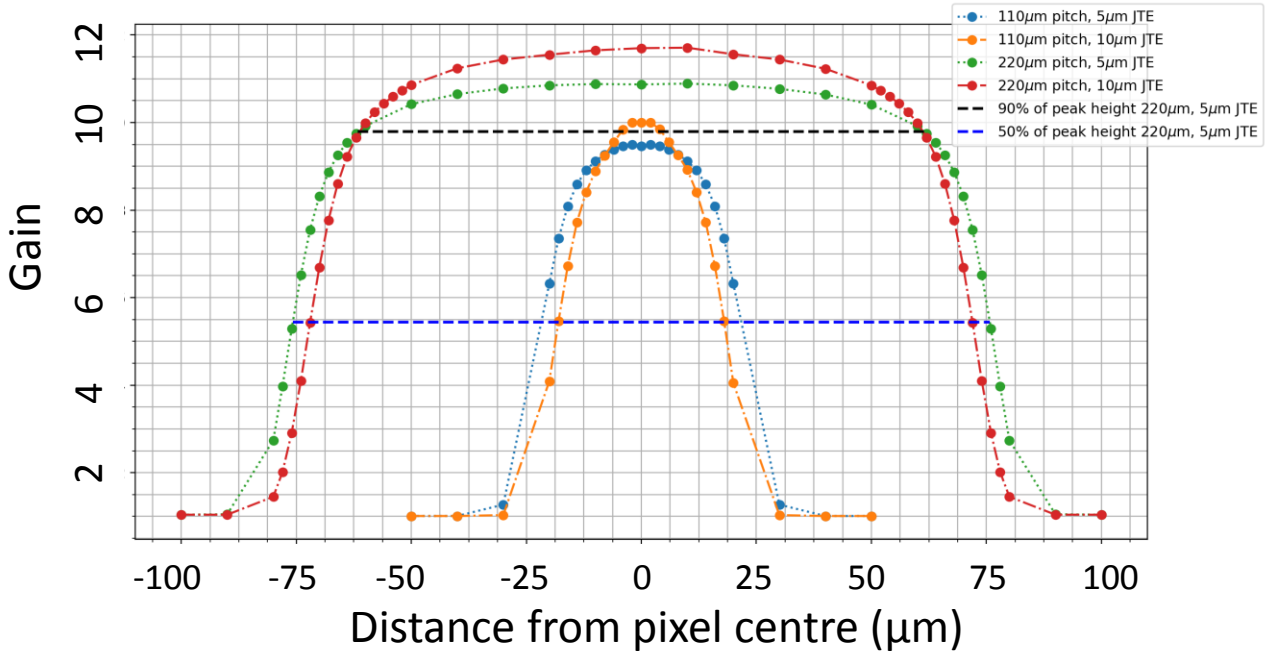
Small pixel challenge



Effective fill factor

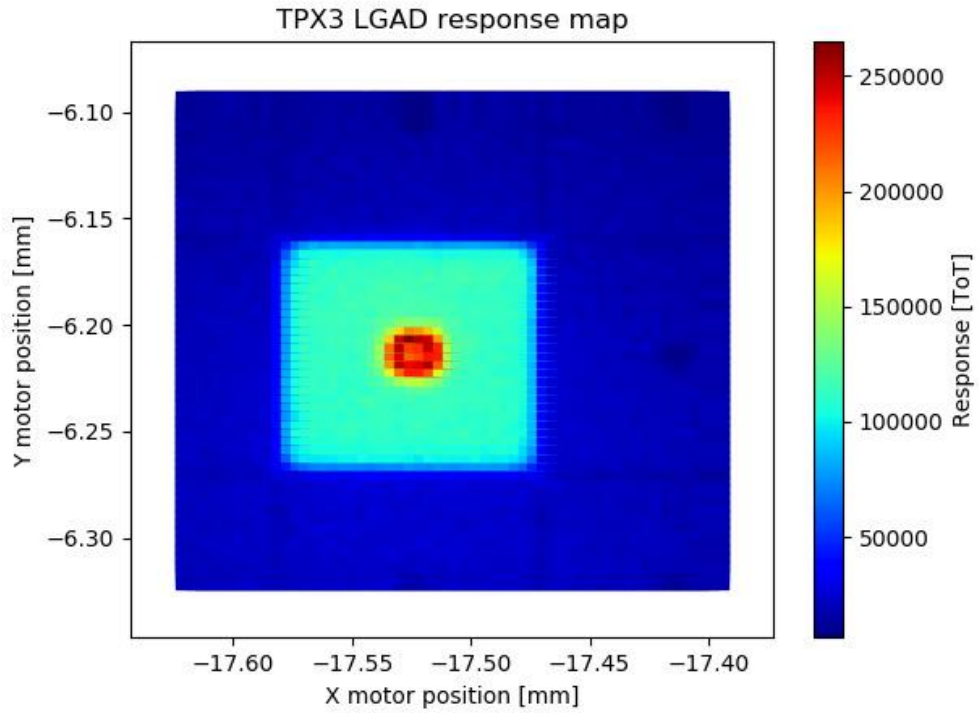


Gain non-uniformity

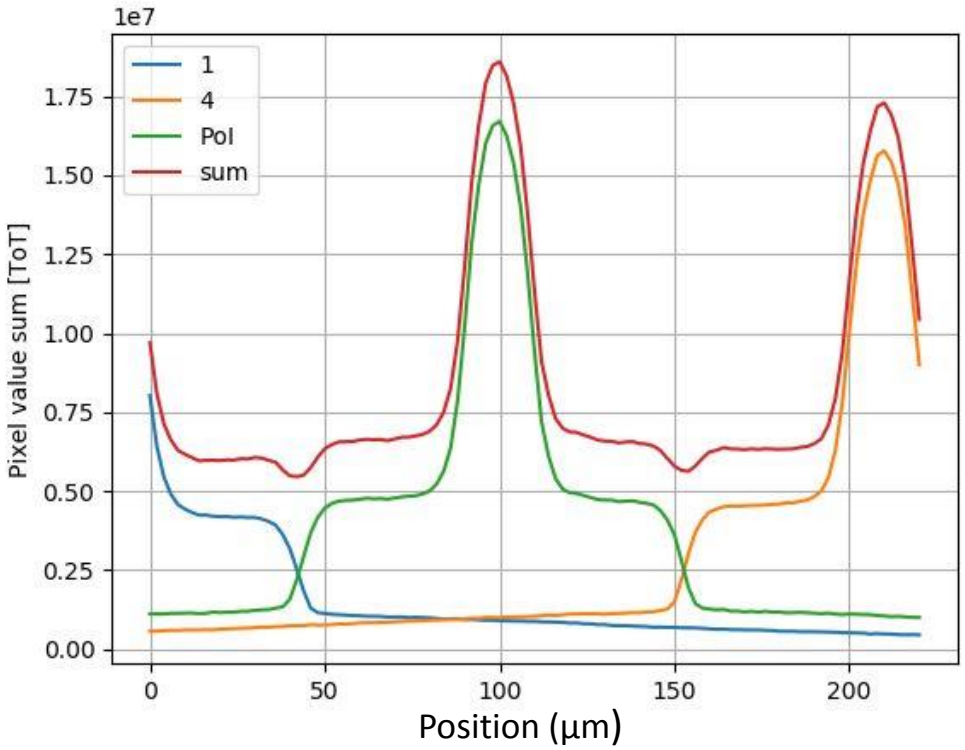


Small pixel challenge

110um pixel response to 15keV photons

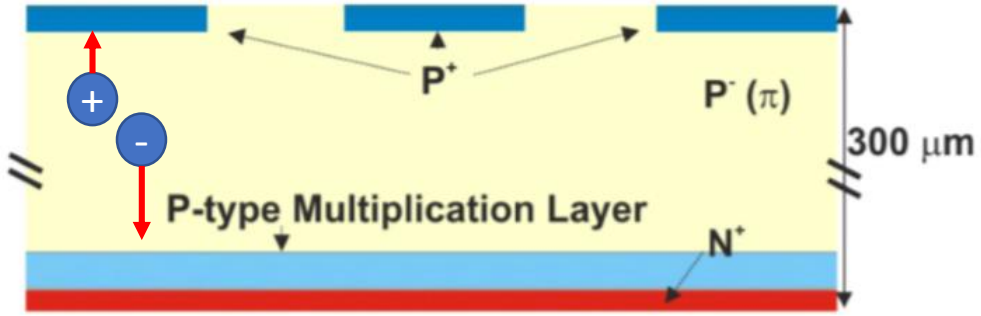


Gain in central 25µm region of pixel



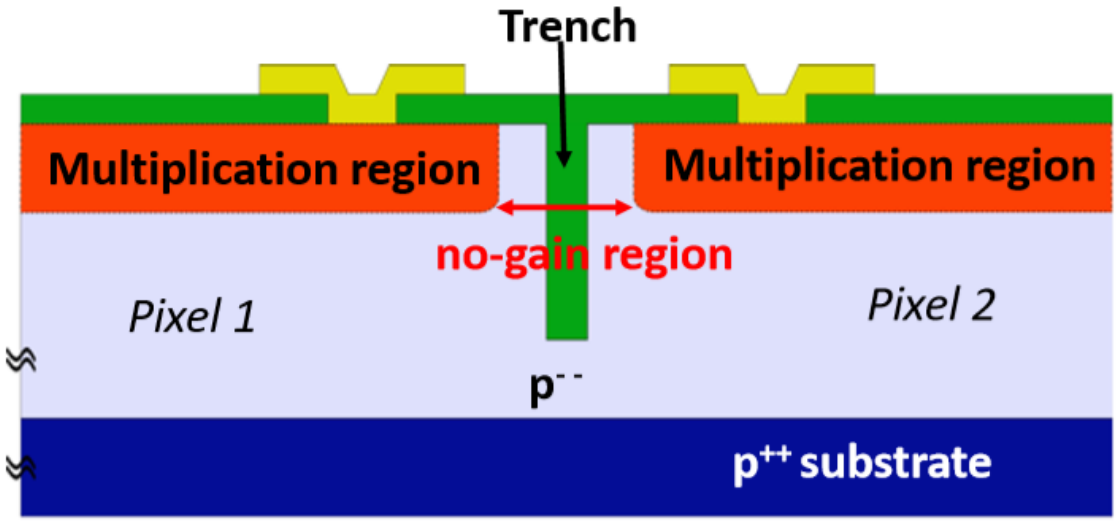
Small pixel solutions

iLGAD



- Move the gain layer to the opposite side to the segmented side
- Electron multiplication at rear
- Signal due to hole collection
  - Must have thin, over depleted sesnor

Trench isolation



- 1-5μm wide trench replaces termination structures
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels
- Increases fill factor: 55um pixel:>80% cf 15%

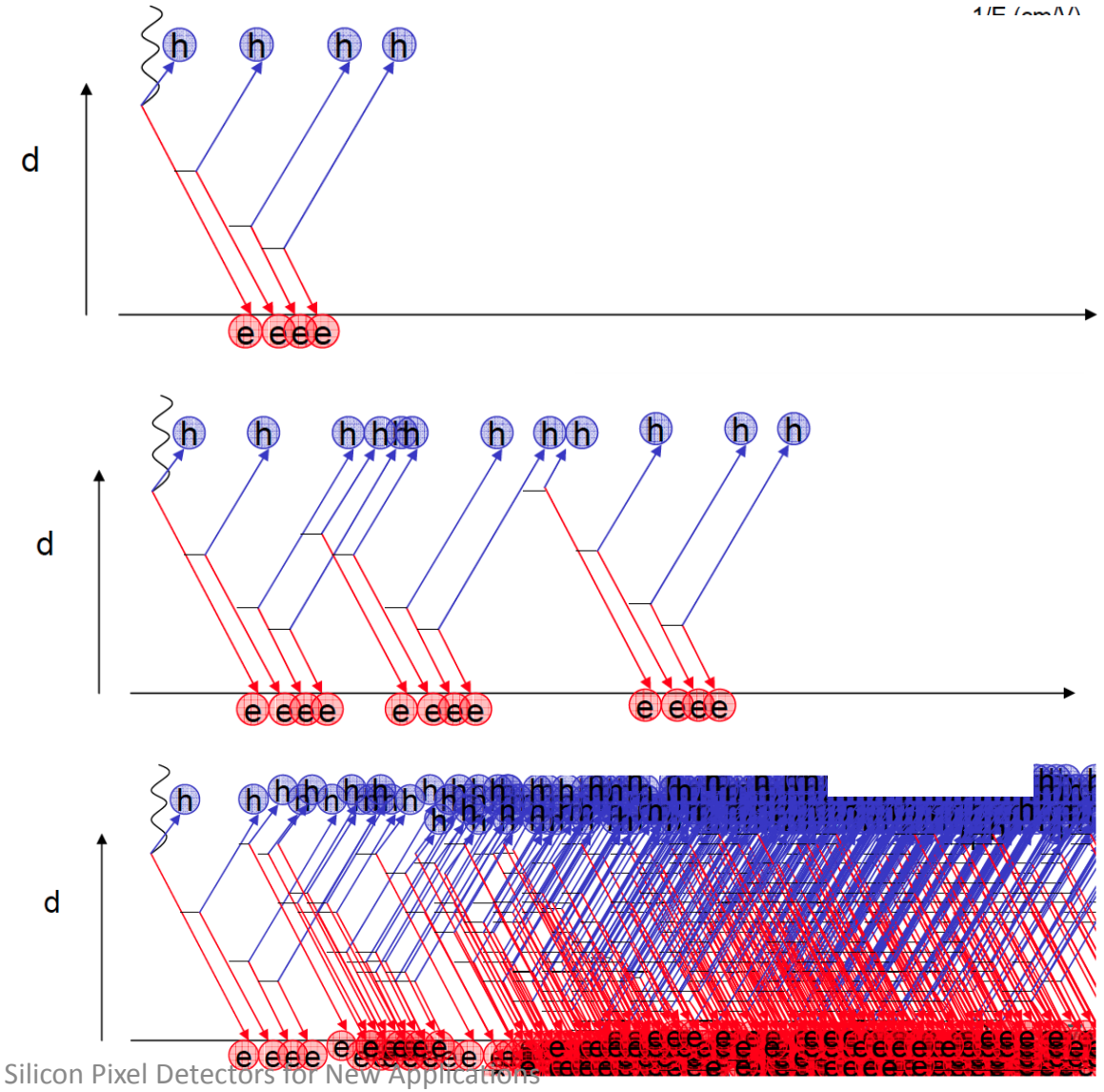
Summary

- Low Gain Avalanche Detectors (LGAD) enable
  - Sub-threshold X-ray detection hybrid pixel detectors
  - Timing detectors (30ps resolution)
- Modest Gain
  - Reduces noise
  - Reduces E-field -> Allow segmentation
- Small pixel challenge
  - iLGAD or Trench Isolation

Backup

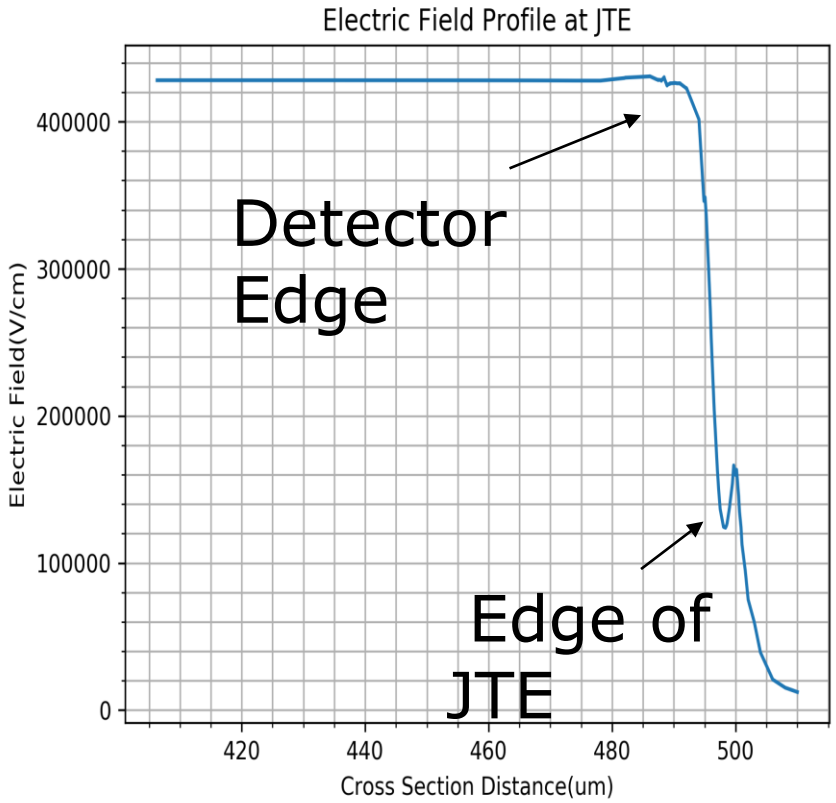
Three Gain modes

- 300 kV/cm < E < 400 kV/cm
  - Only electrons ionize
  - Linear mode
  - Gain < 10
  - N(l) = exp(αl) with l=path length in high electric field
- E ~ 400 kV/cm
  - Both electrons and (rarely) holes ionize
  - Still linear mode
  - Gain: 50 – 300
  - Excess noise: σ(N) ~ k N, k=αh/αe
- E > 400 kV/cm
  - Both electrons and holes ionize
  - Geiger mode
  - Gain: infinite (breakdown)



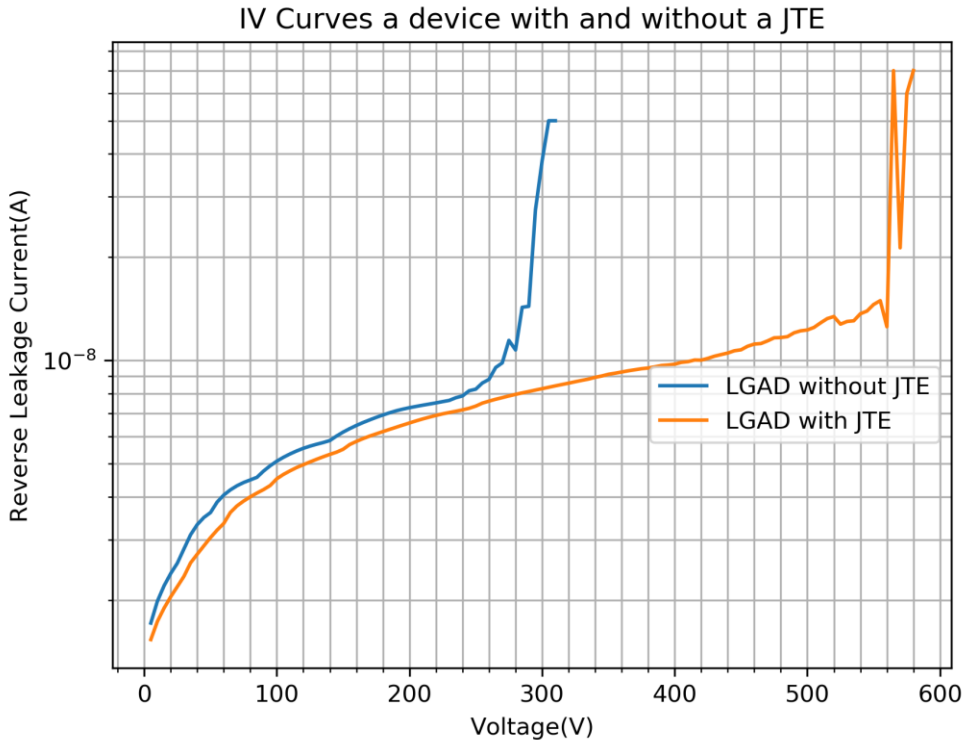
Junction termination Extension (JTE)

- Deep peripheral implant to control electric field at active area edge



JTE

- Reduces detector leakage current.
- Increases detector breakdown voltage.



- Breakdown voltage without JTE < 300 V.
- Breakdown voltage with JTE > 500 V.

Timepix3 → Timepix4

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	3.5x
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	33%
		Max rate	0.43x10^6 hits/mm^2/s	**3.58x10^6 hits/mm^2/s**	8x
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	5x
TOT energy resolution			< 2KeV	**< 1Kev**	2x
TOA binning resolution			1.56ns	**195ps**	8x
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	4x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**	32x
Target global minimum threshold			<500 e^-	<500 e^-	

What is the signal of one e/h pair?

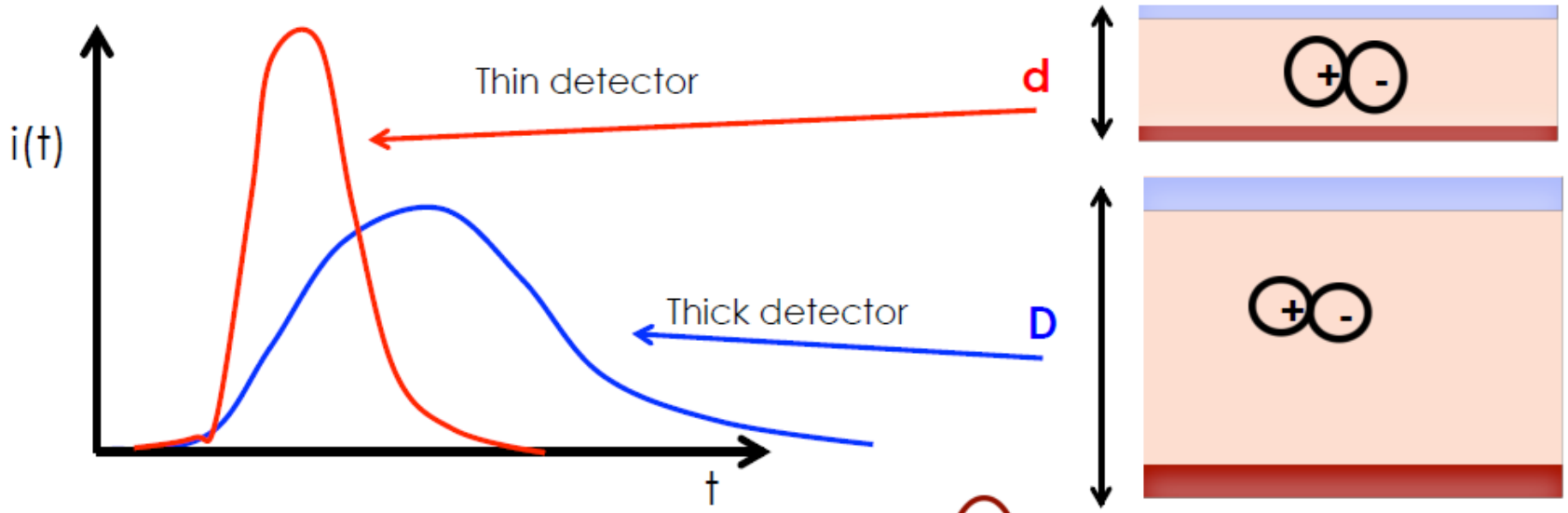
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair.**

The integral of their currents is equal to the electric charge, q:

$$\int [i_{el}(t)+i_h(t)]dt = q$$

However **the shape of the signal depends on the thickness** d:
thinner detectors have higher slew rate



➔ **One e/h pair generates higher current in thin detectors**

$$i \propto qv\frac{1}{d}$$

Weighting field

Possible approaches for timing systems

We need to minimize this expression:

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2$$

- **APD** (silicon with gain ~ 100): maximize dV/dt
  - Very large signal
- **Diamond:** minimize N, minimize dt
  - Large energy gap, very low noise, low capacitance
  - Very good mobility, short collection time t_r
- **LGAD** (silicon with gain ~ 10): minimize N, moderate dV/dt
  - Low gain to avoid shot noise and excess noise factor

Shot noise

$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk})M^2F\right]$$

$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

k = e/h ionization rate

x = excess noise index

M = gain