Study of Deep Diffused APDs for Timing Applications

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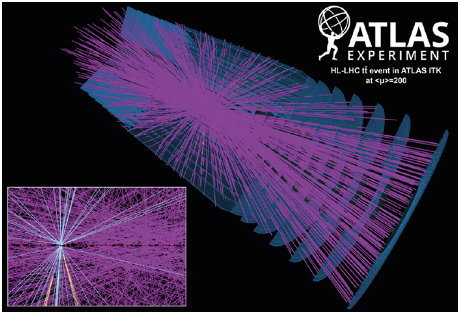
Motivation

- Tracking
- Calorimetry
- **Counteract HL-LHC pile-up**
  ⇒ 30 ps resolution for MIPs
- Particle identifications
  (time of flight)
- Different devices: silicon detectors, gas detectors, etc.
- Many active groups

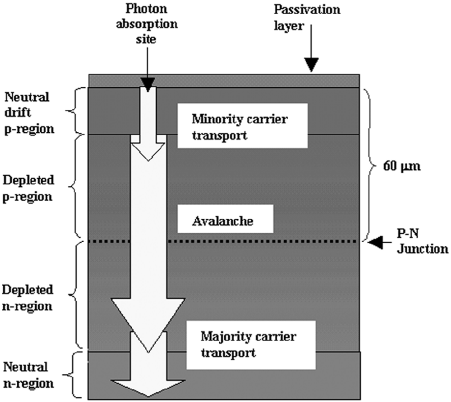
HL-LHC: With the current vertex resolution a significant fraction of the vertices will not be resolved



ATLAS and CMS are planning timing systems for HL-LHC

Deep Diffused Avalanche Photo Detectors

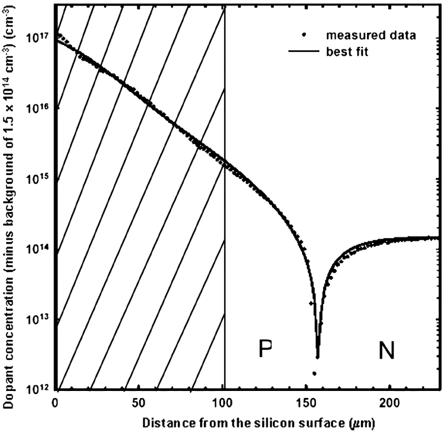
- Charge multiplication
- Gain: ≈ 500
- Bias: ≈ 1800 V
- Never fully depleted
- Die dimensions: $2.8 \times 2.8\,\text{mm}^2$ and $10 \times 10\,\text{mm}^2$
- Nominal active area: $2 \times 2\,\text{mm}^2$ and $8 \times 8\,\text{mm}^2$
- Thickness: 230-280 μm
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

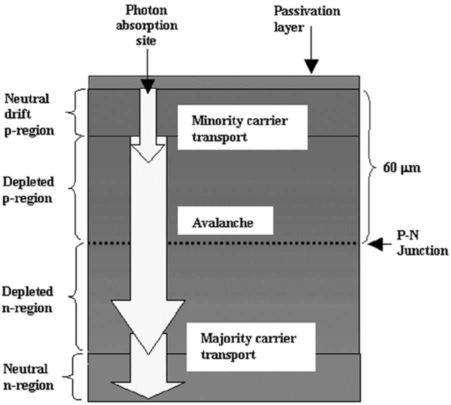


- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

Deep Diffused Avalanche Photo Detectors

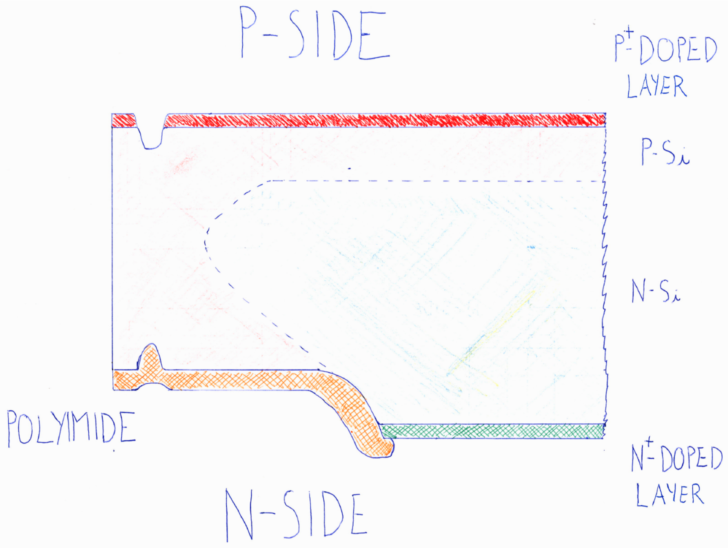
Doping profile





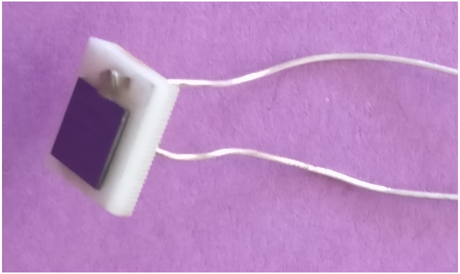
- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

Section (not to scale)

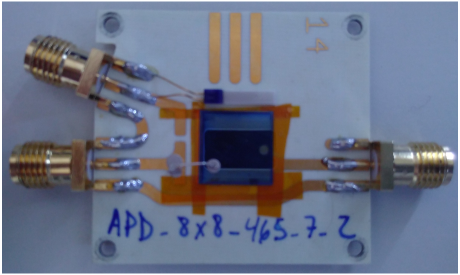


Devices

$2 \times 2\,\mathrm{mm}^2$ devices



$8 \times 8\,\mathrm{mm}^2$ devices



Radiation damage studies:

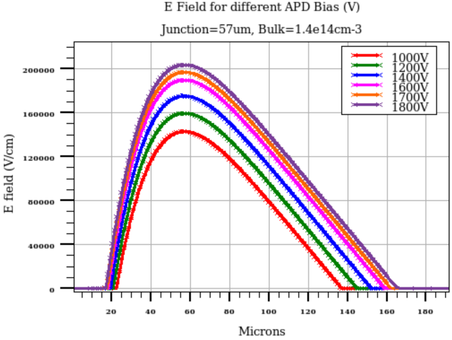
- Current (power)
- Operation voltage
- Gain
- Signal, noise

Device properties:

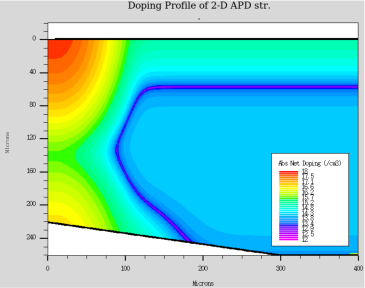
- Signal collection
- Base for timing detector

Simulation Studies

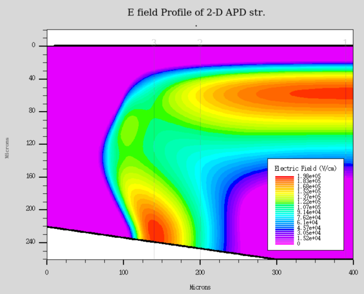
Electric field as a function of bias:



Doping distribution:

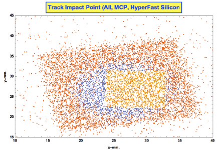


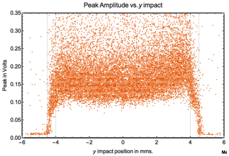
Electric field at 1700 V:

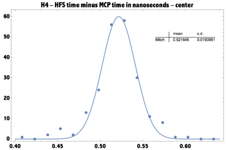


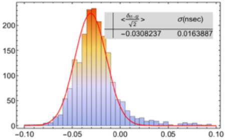
- Simulation in Silvaco TCAD
- Doping from measurement in previous slide

APDs for Timing

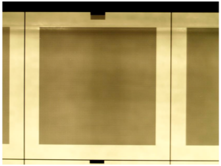




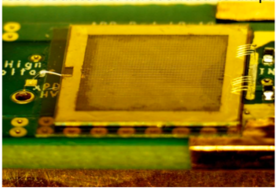




Ni/Au Electroplated mesh ---- 5um/20nm respectively



Mesh mounted & wirebonded to amplifier

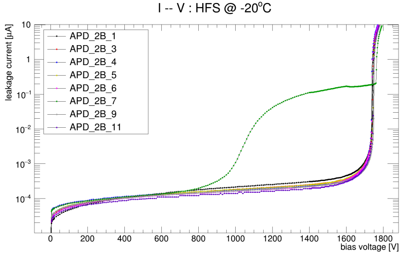


- Work on these detectors ongoing since some years
- Promising results using laser and MIPs
- Develepement of packaging and dedicated amplifier
- Radiation hardness to be demonstrated

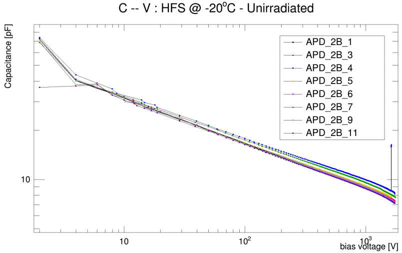
We (CERN) are the latest group joining. The operation of these detectors (1800 V on small distances) requires care.

$2 \times 2\,\mathrm{mm}^2$ APDs, IV and CV at -20°C, $\Phi_{eq} = 0$

IV:



CV:

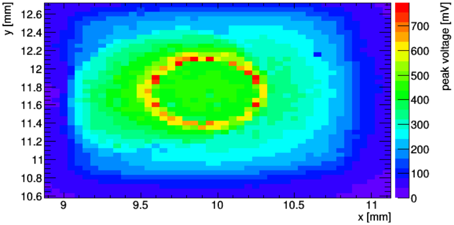


- No full depletion
- Breakdown around 1800 V
- Similar behavior for all but one detector
- Detectors irradiated in Ljubljana
  - Fluence up to $\Phi_{eq} = 10^{15}\,\mathrm{cm}^{-2}$
  - Sensors back at CERN
  - Awaiting for green light from CERN RP department

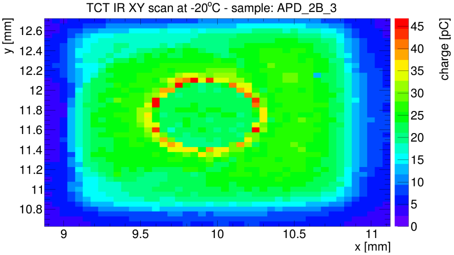
$2 \times 2\,\mathrm{mm}^2$ APDs, Infrared TCT

1700 V, -20°C, $\Phi_{eq} = 0$

Amplitude

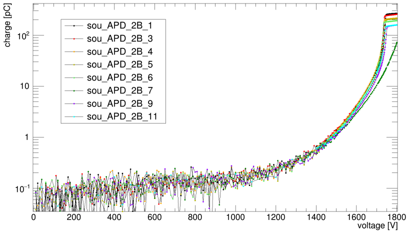


Charge collection in 25 ns



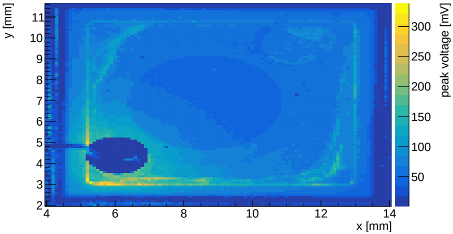
- 10 dB amplification used
- Charge collection more uniform than amplitude
- Reason: combination of E field and electrode resistivity

Charge collection vs bias:

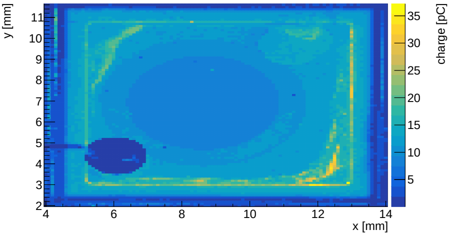


$8 \times 8\,\mathrm{mm}^2$ APD, p-side Electrode Resistivity

Amplitude

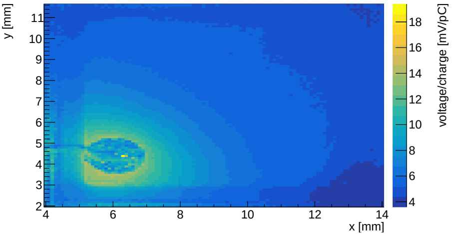


Charge in 25 ns



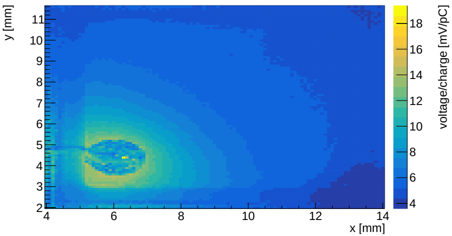
- IR front, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
  $\rightarrow$ remove charge influence on amplitude

Amplitude / charge

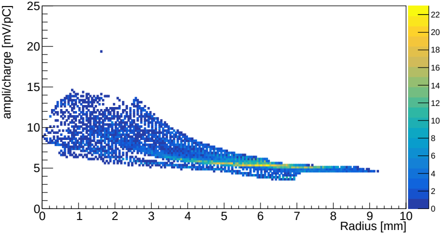


Ratio vs. Distance

Amplitude / charge



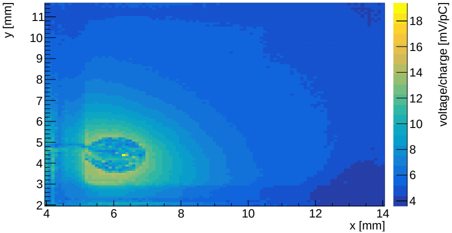
Scatter plot ratio vs distance



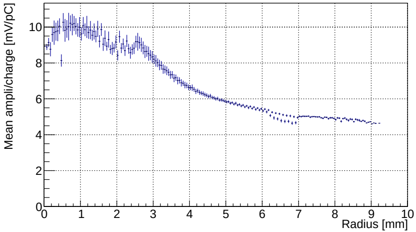
- Ratio depends on distance from contact
  $\rightarrow$ effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Ratio vs. Distance

Amplitude / charge

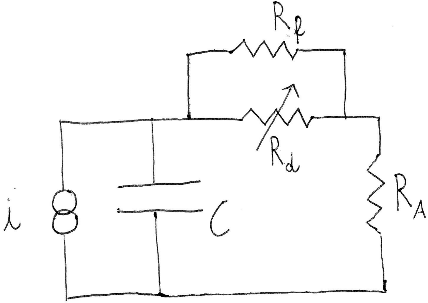


Average ratio vs distance

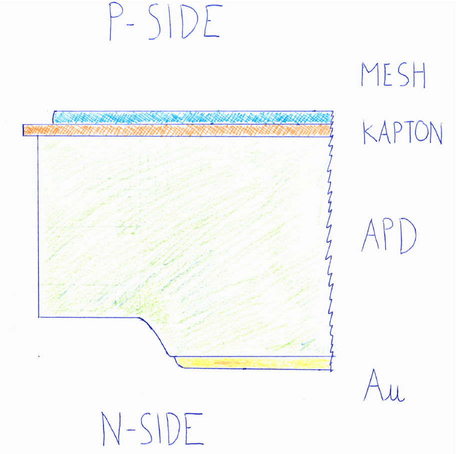


- Ratio depends on distance from contact
  $\rightarrow$ effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Electrical model:



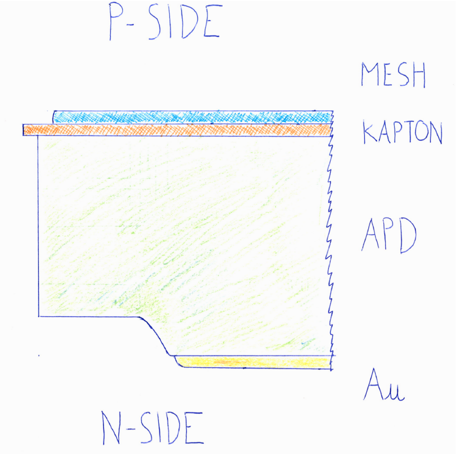
Default Mode of Operation: APD with Mesh

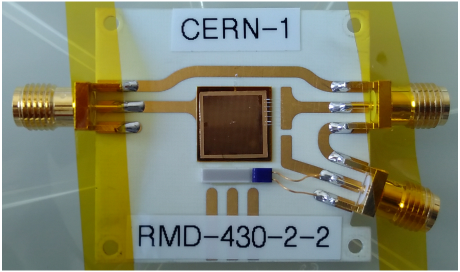


- Mesh to pick up signal from p-side
- Au to improve conductivity of n-side
- Readout of mesh and n-side

- Developed before CERN joined the collaboration
- 11 ps resolution with IR laser at MIP intensity, measured in Princeton
- Time resolution measurement to be repeated in TCT setup
- Al deposition on both sides under study

Default Mode of Operation: APD with Mesh





- Developed before CERN joined the collaboration
- 11 ps resolution with IR laser at MIP intensity, measured in Princeton
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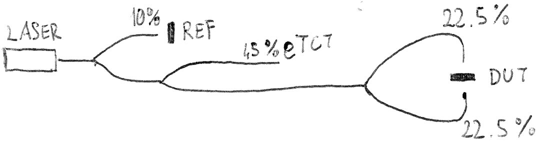
Timing Measurements with IR Laser

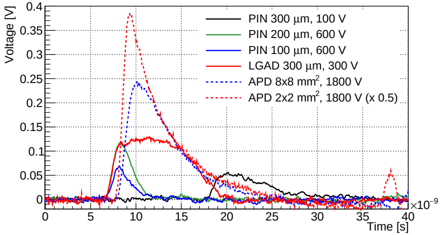


- 1064 nm laser, 200 ps pulses
- $\approx$ 12.5 MIPs
- Photodiode to monitor laser intensity $\rightarrow$ reference time
- Both diode and reference signals are amplified
- 1000 or 1500 WF per point
- CFD with thresholds optimized in analysis

Sensor	Bulk	Area [mm^2]	Thickness [μm]
PIN	n	5×5	300
PIN	n	5×5	200
PIN	p	5×5	100
LGAD	p	3×3	300
APD	-	2×2	$\approx$ 150
APD (Au n-side, w/o mesh)	-	8×8	$\approx$ 150

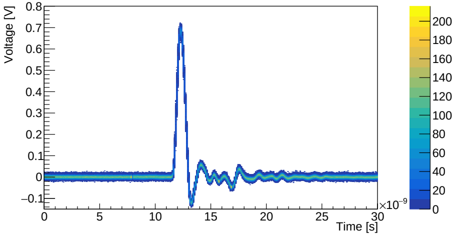
Signals

Sensors' signals:



- 10 dB amplification for APDs
- 40 dB amplification for other detectors
- $2 \times 2\,\mathrm{mm}^2$ APD signal scaled by 0.5
- Different cable lengths

Reference signal:

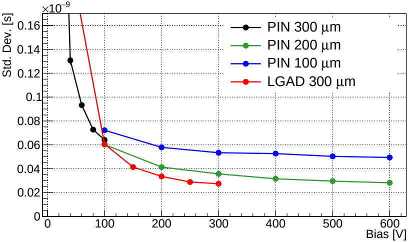


Amplitude	691 mV
Noise	6.1 mV
Risetime 20% 80%	299 ps

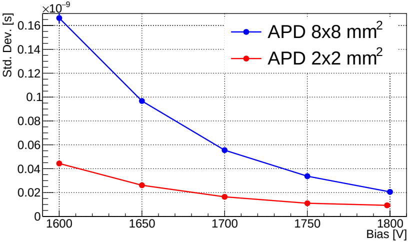
Estimated resolution $\approx$ 5 ps

Timing Measurements, PRELIMINARY

"Planar" devices:

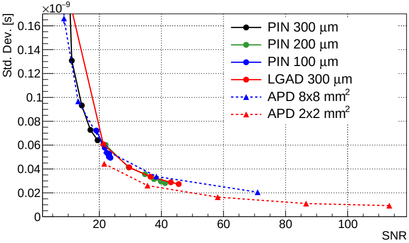


APDs:



- 300 μm LGAD: best resolution for "planar" detectors: 27.4 ps
- $2 \times 2\,\text{mm}^2$ APD: 9.3 ps
- $8 \times 8\,\text{mm}^2$ APD (Au n-side, w/o mesh): 20.6 ps
- Similar dependence on SNR for all detectors
- Improvements in optics and electronics will follow

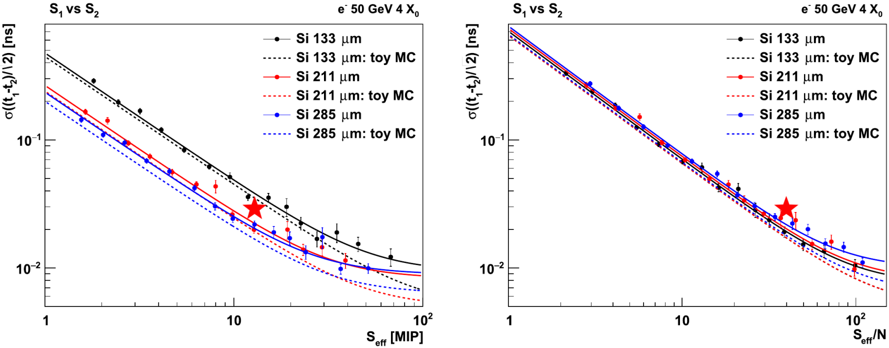
Timing vs SNR:



Comparison with Beam Test for 200 μm Diode

The timing resolution of the 200 μm diode was measured in TB

https://doi.org/10.1016/j.nima.2017.03.065



- Diode represented by red markers
- Laser measurement at 600 V, 12.5 MIPs: Res. 28 ps, SNR 41
- Close to beam test result

Summary

- Deep diffused APDs w/ mesh shown promising timing results (11 ps with IR laser @ MIP intensity)
- Radiation hardness is to be demonstrated
- Gaining experience in detector operation and understanding of detector structure
- Irradiation study of devices without mesh:
  - Set of $2 \times 2\,\mathrm{mm}^2$ APDs characterized before irradiation (previous study shown reproducibility problems)
  - Sensors irradiated in Ljubljana and back at CERN
- First timing measurements in the TCT setup:
  - Comparison of different detectors in same conditions
  - For $\approx$ 12.5 MIPs the results are close to beam test measurements

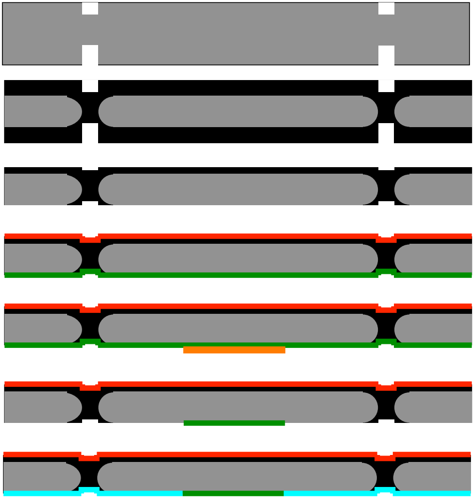
Outlook:

- Characterize the irradiated $2 \times 2\,\mathrm{mm}^2$ APDs
- Improve the TCT optics to inject 1 MIP in the sensor
- Improve TCT electronics

Backup Material

Fabrication

Starting from neutron transmutation n-doped $< 100 >$ Si wafers



Saw cut grooves added to n-type silicon

Deep p-type diffusion (black)

Polishing defines p-n junction depth

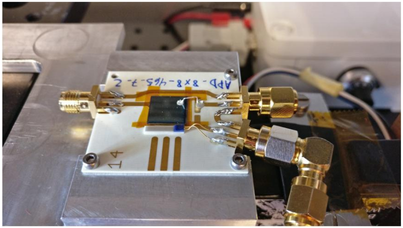
The p^+ (red) and n^+ (green) layers are diffused into the front and back surfaces

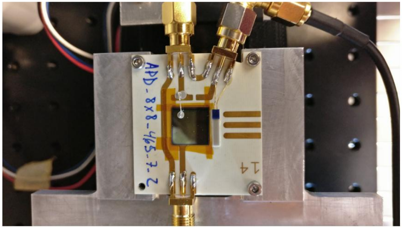
Part of the n^+ region is masked with an etch resist polyimide (orange)

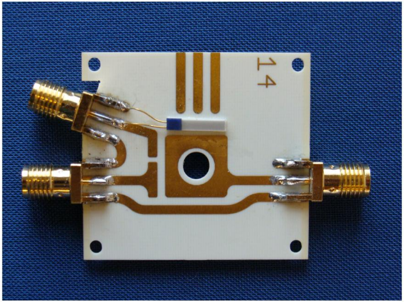
The masking polyimide is removed, leaving residual n+ material that forms the contact electrode.

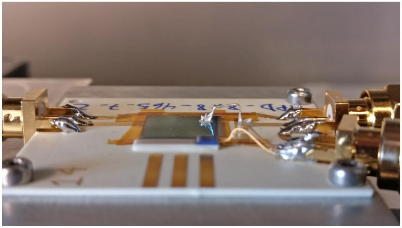
Wafer cleaned. Passivation polyimide applied photolithographically on entire back side except n+ pads.

Picture bare APD 8x8 and PCB

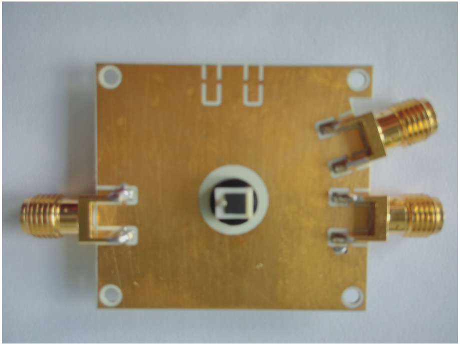


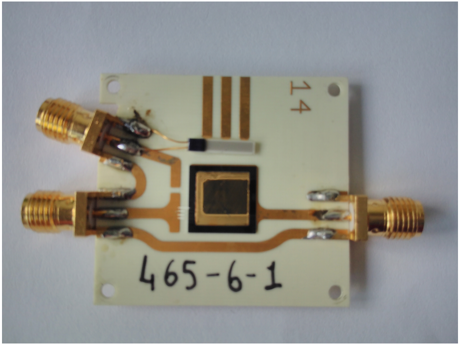






2 $\times$ 2 and Au Plated APD on PCB

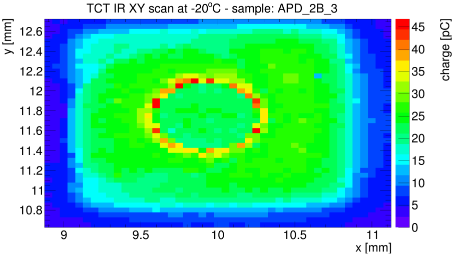




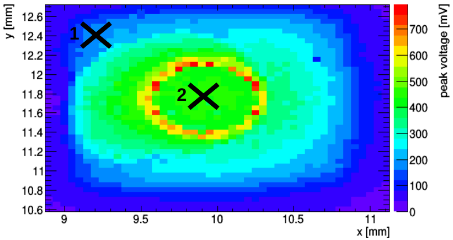
$2 \times 2\,\mathrm{mm}^2$ APDs, Infrared TCT Front

Infrared laser, 1700 V, -20°C, $\Phi_{eq} = 0$

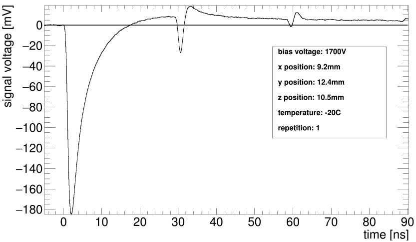
Charge collection in 25 ns



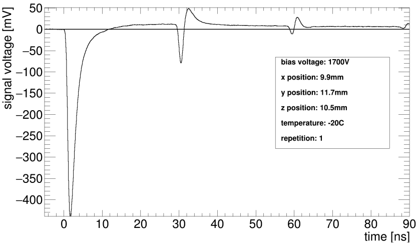
Amplitude



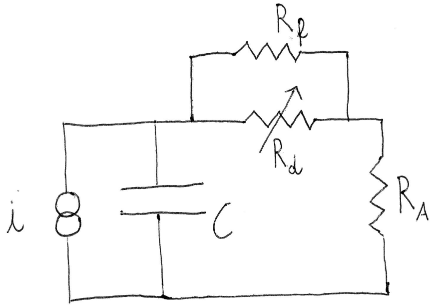
1



2



Electrical Model $8 \times 8\,\mathrm{mm}^2$ APD, p-side Electrode Resistivity



Assuming a delta current pulse of charge Q

$$V_C(t=0) = V_R = \frac{Q}{C}$$

Voltage at the amplifier terminals

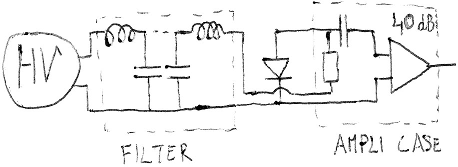
$$V_A = V_R \left(1 + \frac{R_f}{R_A(1 + R_f/R_d)}\right)^{-1}$$

$$R_d = k \cdot d$$

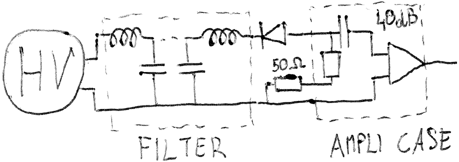
- $C \rightarrow$ det capacitance
- $R_d \rightarrow$ p-side resistance (distance dependent)
- $R_f \rightarrow$ fixed resistance (contribution from trenches??)
- $R_A \rightarrow$ amplifier input

Readout schematics

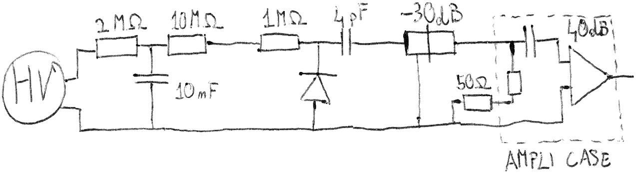
Front readout and bias



Back bias, front readout

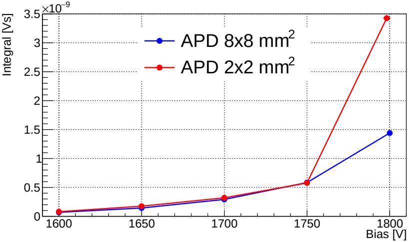


APD readout:

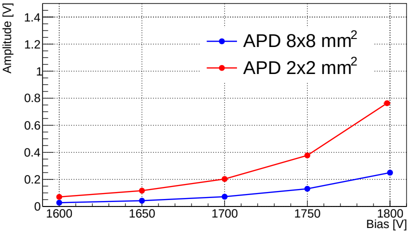


APD Signal

Integral:

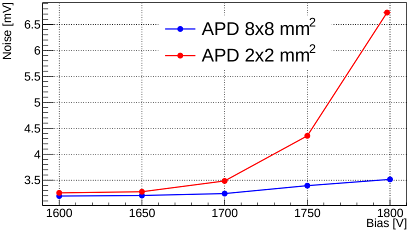


Amplitude:



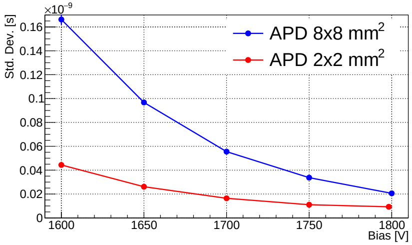
- Similar integral for both
  $\rightarrow$ Similar charge deposition and amplification?
- Different amplitude and noise
  $\rightarrow$ To be checked if amplitude scales with capacitance

Noise:

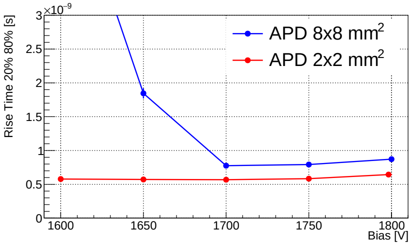


APD Timing

Time resolution:

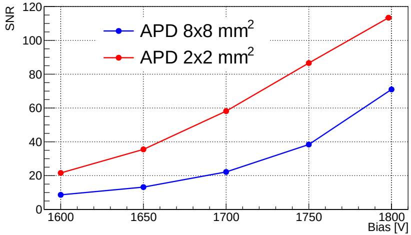


Rise time 20% 80%:



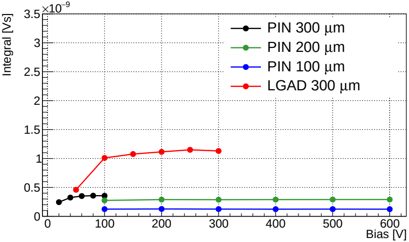
- Better resolution and SNR for the 2×2
- Smaller rise time for the 2×2

Signal to noise ratio:

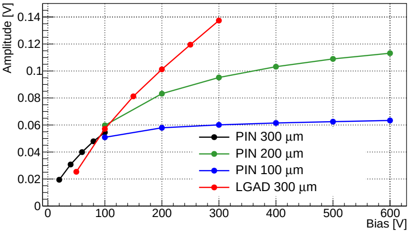


“Planar” Devices Signal

Integral:

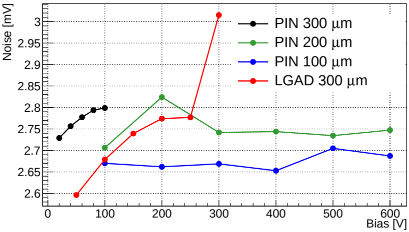


Amplitude:



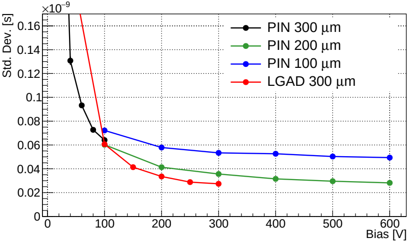
- LGAD has largest signal amplitude and integral
- Integral almost constant, amplitude increase due to drift velocity

Noise:

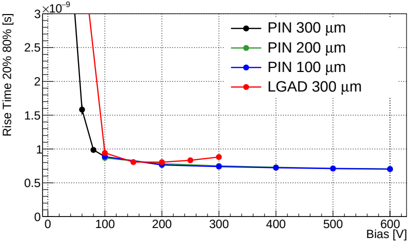


“Planar” Devices Timing

Time resolution:

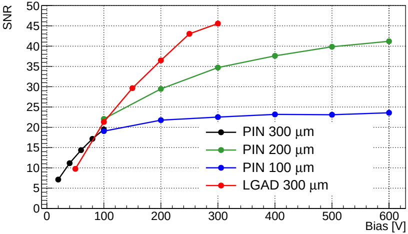


Rise time 20% 80%:

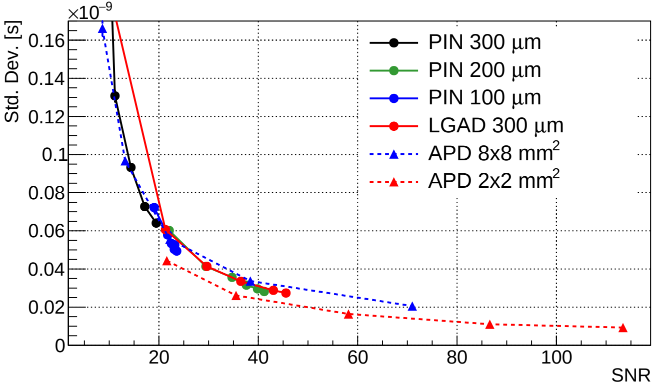


- Best timing resolution for LGAD
- What would be the resolution for a 50 μm LGAD?

Signal to noise ratio:



Timing vs SNR

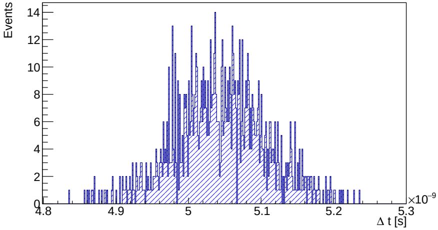


- Similar behavior for all sensors

"Planar" Devices Δt Distribution

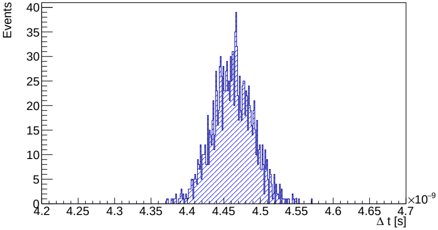
PIN 300 μm 100 V:

CFD: Thr1 0.50, Thr2 0.20, σ = 64.07 $\pm$ 1.47 ps, 1000 events



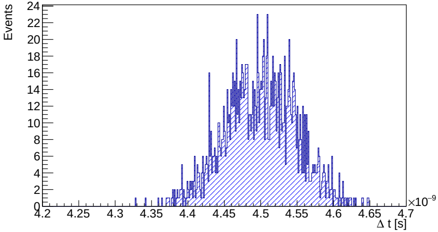
PIN 200 μm 600 V:

CFD: Thr1 0.45, Thr2 0.20, σ = 28.18 $\pm$ 0.54 ps, 1500 events



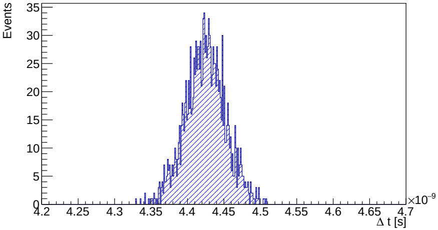
PIN 100 μm 600 V:

CFD: Thr1 0.55, Thr2 0.45, σ = 49.39 $\pm$ 0.87 ps, 1500 events



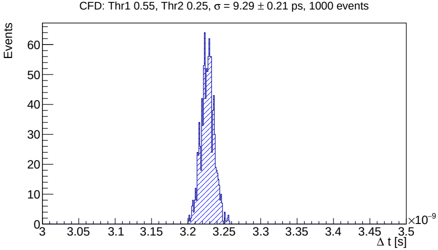
LGAD 300 μm 300 V:

CFD: Thr1 0.45, Thr2 0.20, σ = 27.40 $\pm$ 0.51 ps, 1500 events

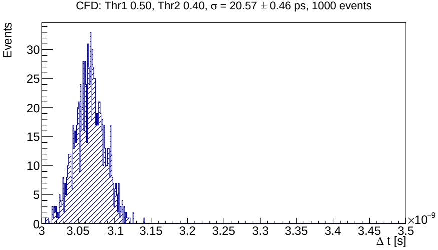


APD Δt Distribution

APD 2 $\times$ 2 mm^2 1800 V:

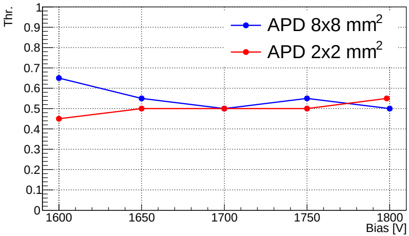


APD 8 $\times$ 8 mm^2
(Au n-side, w/o mesh) 1800 V:

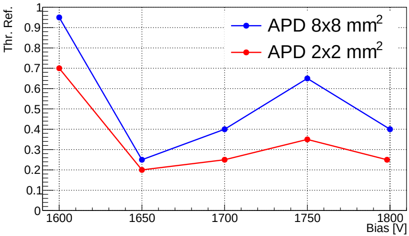


APD Thresholds

APD threshold:



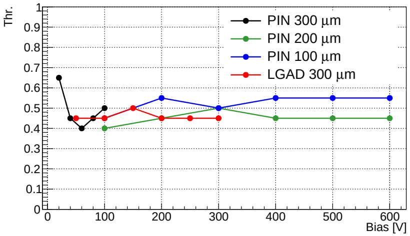
Reference threshold:



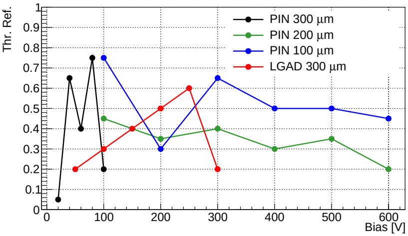
- The ref. threshold has no big impact on the time resolution
- The ref. threshold swings more due to statistical fluctuations

“Planar” Devices Thresholds

Device threshold:



Reference threshold:



- The ref. threshold has no big impact on the time resolution
- The ref. threshold swings more due to statistical fluctuations

Reference Signal Amplitude