

Characterization of Irradiated APDs for Timing Applications

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⁷University of Virginia

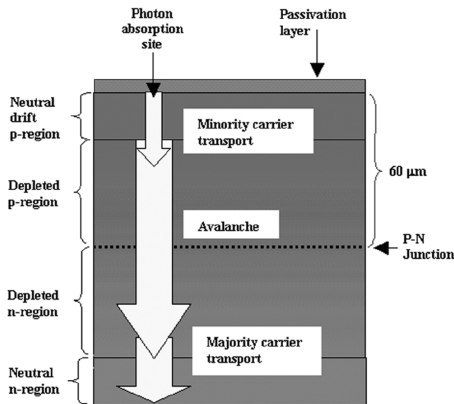
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Deep Diffused Avalanche Photo Detectors

- 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: $230\text{-}280 \mu\text{m}$
- Custom fabrication process
- Produced by Radiation
Monitoring Devices (RMD)

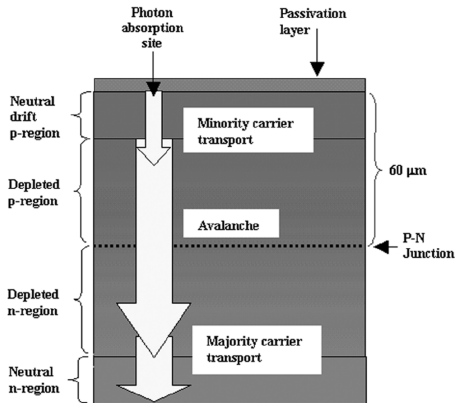
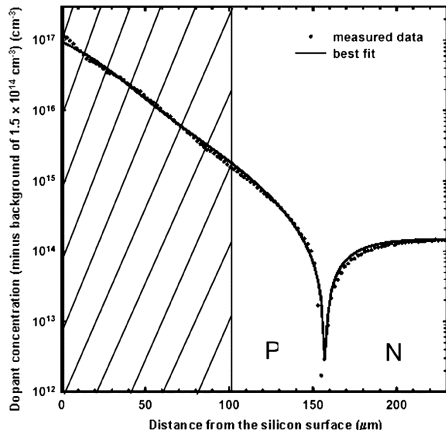


- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006

Deep Diffused Avalanche Photo Detectors

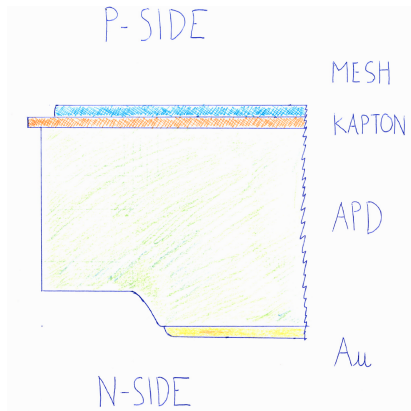
Doping profile



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

M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006

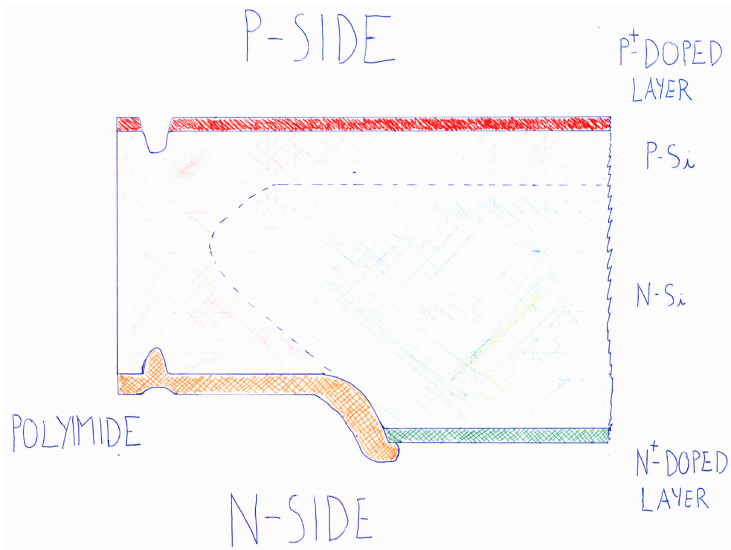
APDs with Mesh (AC coupled) Readout



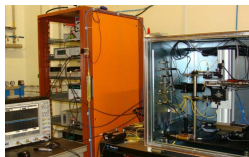
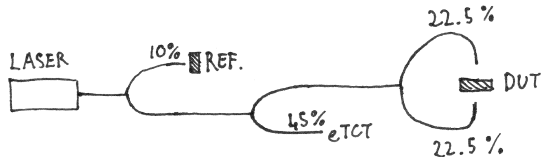
- Mesh to pick-up signal from p-side
- Au to improve conductivity of n-side
- Readout of mesh and n-side

These devices are not discussed in this talk

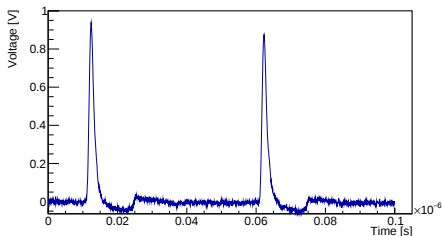
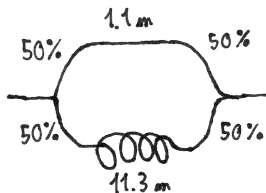
Section (not to scale)



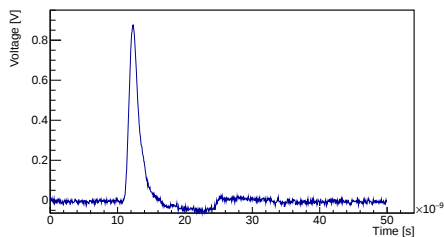
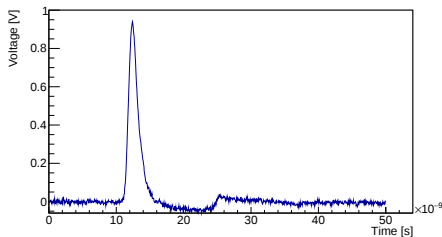
CERN SSD TCT Setup for Timing Measurements



- Pulsed 1060 nm IR laser
200 ps FWHM
- **0.8 MIPs** intensity
1 MIP := 74 eh/ μm
(Without reflections)
- 50 ns delay line between laser and first splitter
- $2 \times 2 \text{ mm}^2$ APD, non-irradiated
- 1745 V, 20°C
- 40 dB, 2 kV Cividec amplifier
- Amplitude difference of less than 5 %

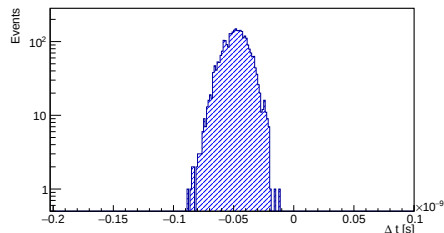


Analysis ($2 \times 2 \text{ mm}^2$ non-irradiated APD)



CFD: Thr1 0.30, Thr2 0.35, $\sigma = 10.65 \pm 0.14 \text{ ps}$, 3000 events

- Divide waveform in two parts
- Apply different thresholds to estimate time difference
- Select best threshold combination to minimize std. dev.



Divide std. dev. by $\sqrt{2}$ to get single pulse resolution: $7.5 \pm 0.1 \text{ ps}$

No timing reference needed

Irradiated Sensors

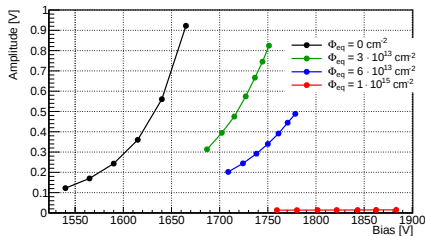
$2 \times 2 \text{ mm}^2$ APDs



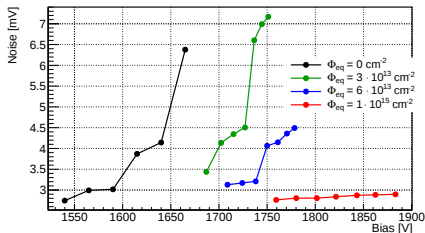
- Packaged
- Irradiated in Ljubljana (reactor neutrons)
- $\Phi_{eq} = 0, 3 \cdot 10^{13}, 6 \cdot 10^{13}, 3 \cdot 10^{14}, 10^{15} \text{ cm}^{-2}$
- Annealing of $\approx 70 \text{ min @ } 21^\circ\text{C}$
- Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14} \text{ cm}^{-2}$ is quite unstable (it eats amplifiers)

N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , 0.8 MIPs

Amplitude



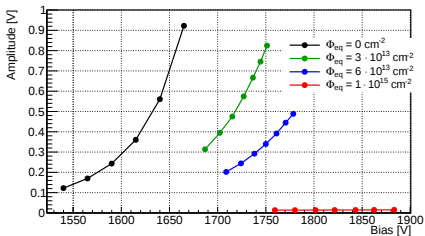
Noise



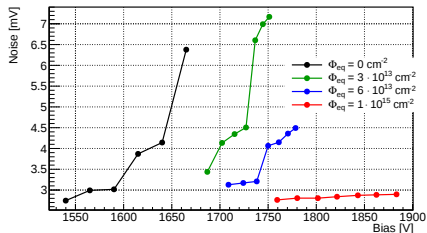
- Both dominated by multiplication
- $\Phi_{eq} \leq 6 \cdot 10^{13} \text{ cm}^{-2}$: amplitude is restored by applying bias
Here current limit of $10 \mu\text{A}$ is hit
- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: low or no multiplication

N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , 0.8 MIPs

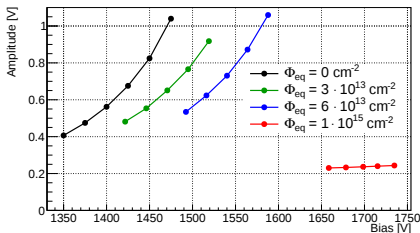
Amplitude



Noise

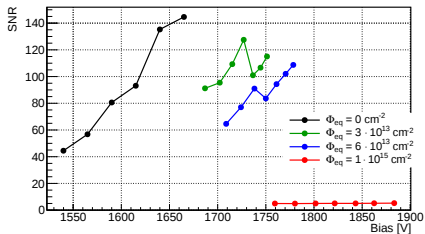


Amplitude, same detectors, 15 MIPs

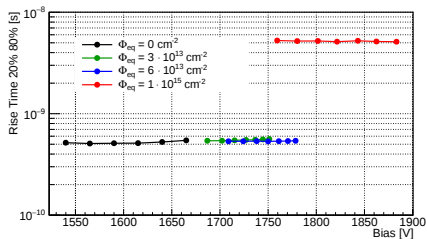


N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , 0.8 MIPs

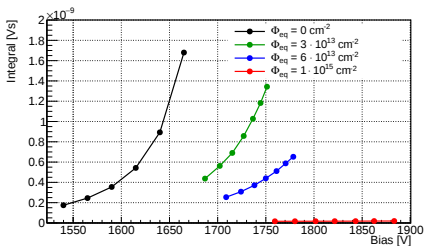
SNR



Rise Time 20% 80%



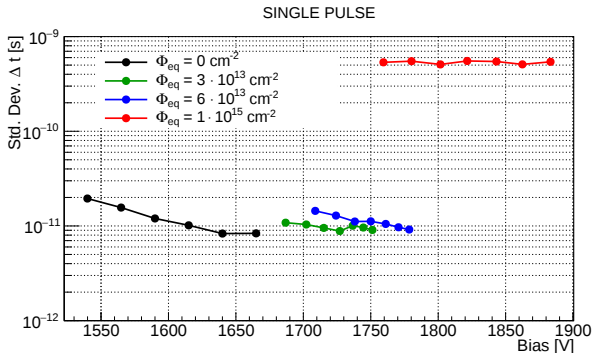
Integral



- $\Phi_{eq} \leq 6 \cdot 10^{13} \text{ cm}^{-2}$: $\approx 550 \text{ ps}$
- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: influenced by low SNR

N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , 0.8 MIPs

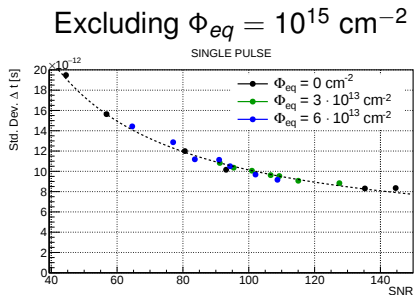
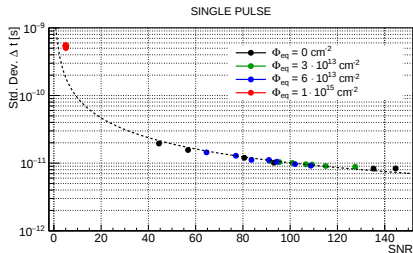
Time Resolution for one pulse



- Obtained by dividing the 2 pulses std. dev. by $\sqrt{2}$
- $\Phi_{eq} \leq 6 \cdot 10^{13} \text{ cm}^{-2}$: similar time resolution 8 – 10 ps
- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: low SNR

N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , 0.8 MIPs

Time Resolution vs. SNR



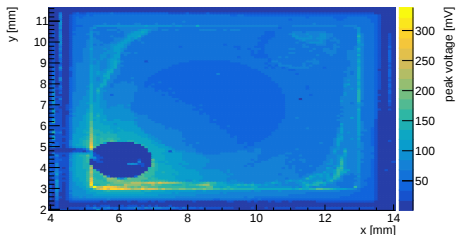
- Time resolution scales with $1/\text{SNR}$
- SNR is not a monotone function of bias for $\Phi_{eq} \neq 0 \text{ cm}^{-2}$

“Dark pulses”

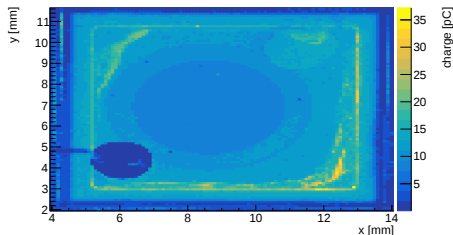
“Dark pulses” with a frequency of $\approx 3 \text{ MHz}$ are observed for the sensor irradiated to $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$.

$8 \times 8 \text{ mm}^2$ APD, Uniformity of Response

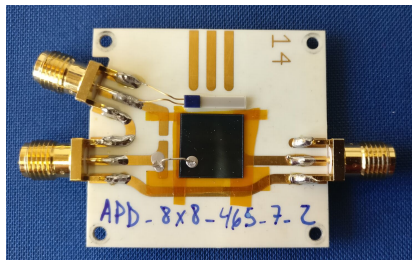
Amplitude



Charge in 25 ns



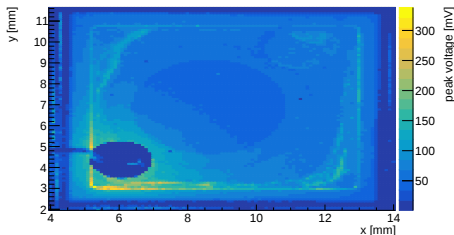
- IR laser, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
→ remove charge influence on amplitude



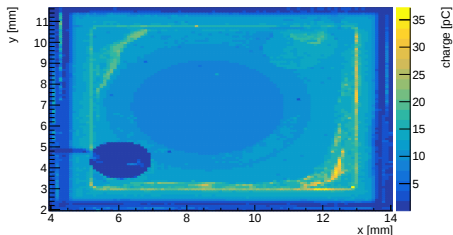
The amplitude is affected by the resistivity of the doped silicon

$8 \times 8 \text{ mm}^2$ APD, Uniformity of Response

Amplitude

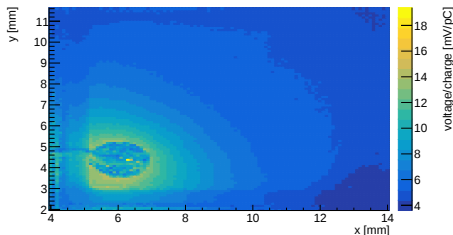


Charge in 25 ns



- IR laser, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
→ remove charge influence on amplitude

Amplitude / charge

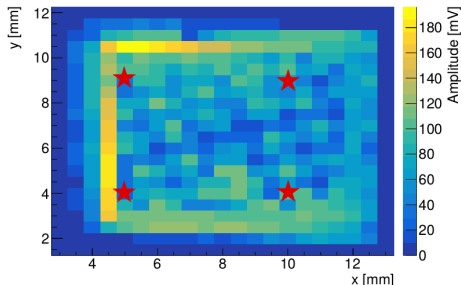
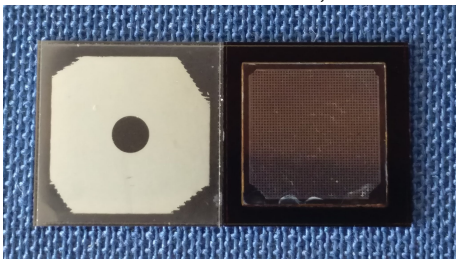


The amplitude is affected by the resistivity of the doped silicon

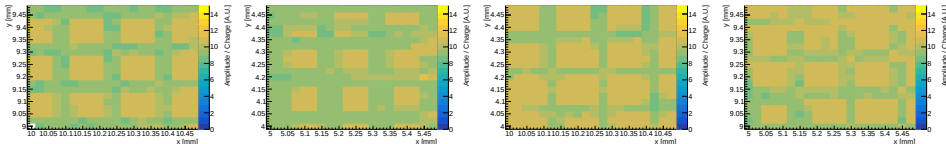
Metallized $8 \times 8 \text{ mm}^2$ APD, Uniformity of Response

1800 V, 20 C

Metallization at EPFL-CMi, Lausanne



Ratio between charge and amplitude ($0.5 \times 0.5 \text{ mm}^2$ areas at stars position)

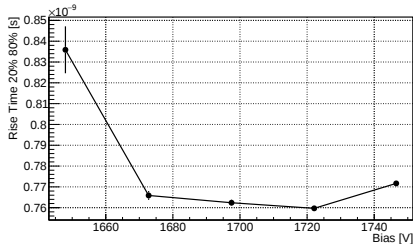


Good uniformity over the detector

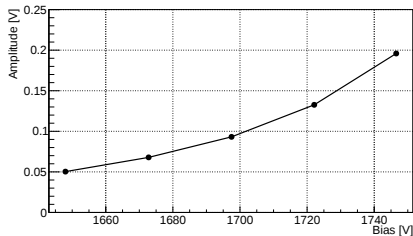
Thank you J. Bronuzzi for the help in the metallization procedure!

Metallized $8 \times 8 \text{ mm}^2$ APD, 20°C , 0.8 MIPs

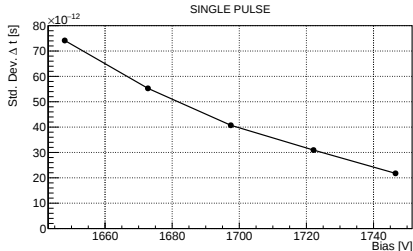
Rise Time 20% 80%



Amplitude



Time Resolution for one pulse



- Rise time $\approx 770 \text{ ps}$
- Lower amplitude than $2 \times 2 \text{ mm}^2$ APDs
- Best single pulse resolution: $21.8 \pm 0.3 \text{ ps}$

The metallized APDs are often unstable. To be investigated.

Summary & Outlook

- Measured time resolution of neutron irradiated $2 \times 2 \text{ mm}^2$ APDs
- Performance at det. center not degraded by neutron irradiation of at least $\Phi_{eq} = 6 \cdot 10^{13} \text{ cm}^{-2} \Rightarrow \sigma_t = 8 - 10 \text{ ps @ } 0.8 \text{ MIPs}$
- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: very low or no gain, “dark pulses” are observed
- Modified the TCT setup for timing without external references
- Improved the uniformity of response of $8 \times 8 \text{ mm}^2$ APDs by applying a metal layer, stability is under study
- Time res. of metallized $8 \times 8 \text{ mm}^2$ APDs: $\sigma_t = 22 \text{ ps @ } 0.8 \text{ MIPs}$

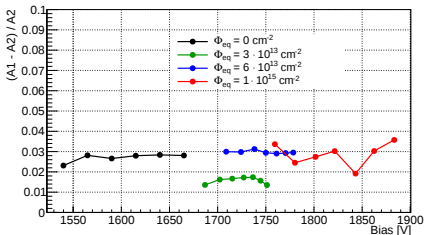
Outlook:

- Test different devices in the TCT setup
- New irradiation to explore region $6 \cdot 10^{13} \leq \Phi_{eq} \leq 7 \cdot 10^{14} \text{ cm}^{-2}$
- Use faster amplifiers to improve the time resolution
- Test the detectors in beam tests

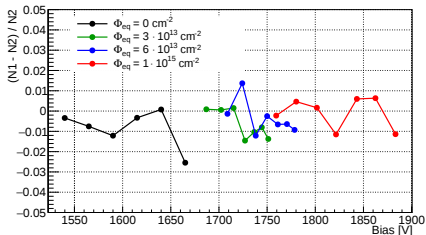
Backup Material

Difference Pulses $2 \times 2 \text{ mm}^2$ APDs

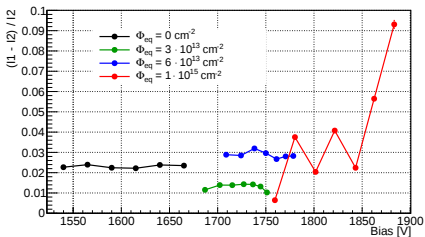
Amplitude



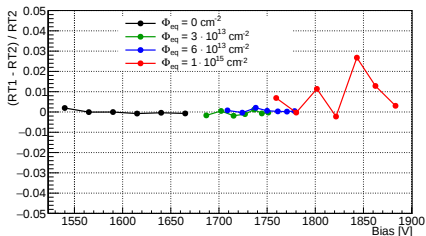
Noise



Integral



Rise Time 20% 80%

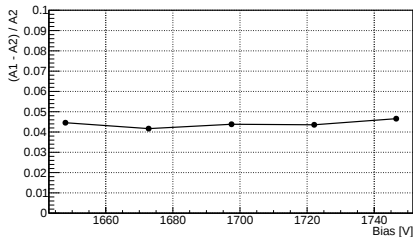


Data for $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$ influenced by low SNR

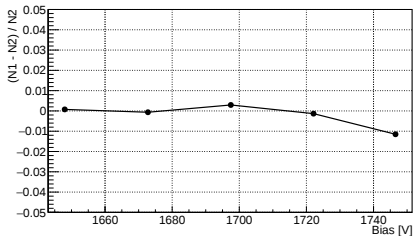
Properties of pulses equal within 5%

Difference Pulses Metallized $8 \times 8 \text{ mm}^2$ APD

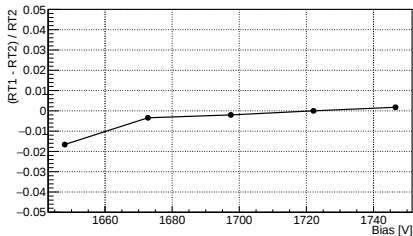
Amplitude



Noise



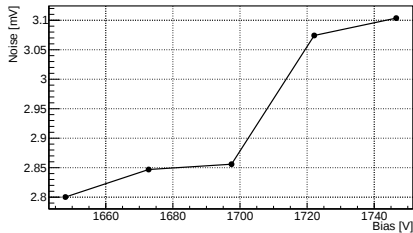
Rise Time 20% 80%



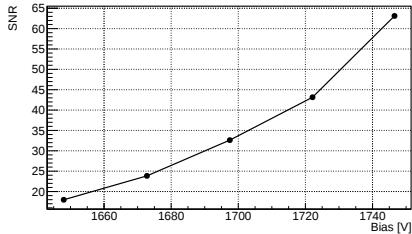
Properties of pulses equal within 5 %

Pulses Metallized $8 \times 8 \text{ mm}^2$ APD

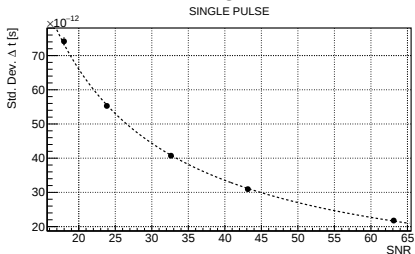
Noise



SNR

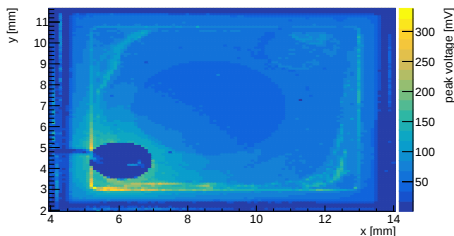


Timing SNR

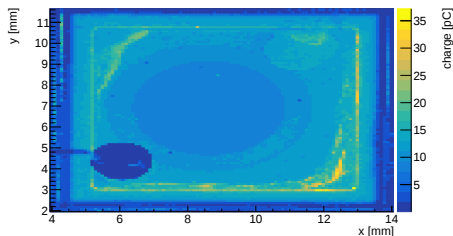


$8 \times 8 \text{ mm}^2$ APD, p-side Electrode Resistivity

Amplitude

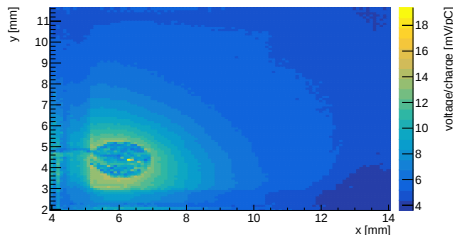


Charge in 25 ns



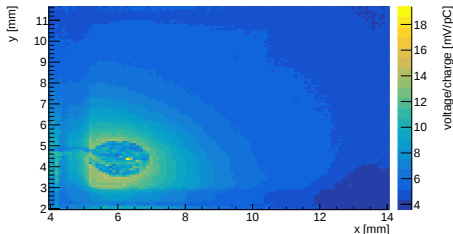
- IR front, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
→ remove charge influence on amplitude

Amplitude / charge

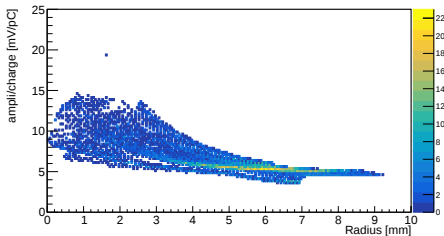


Ratio vs. Distance

Amplitude / charge



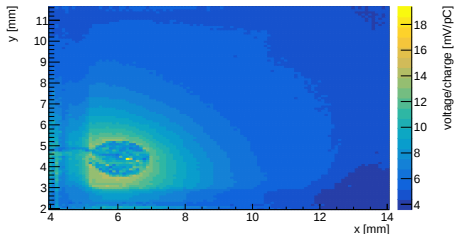
Scatter plot ratio vs distance



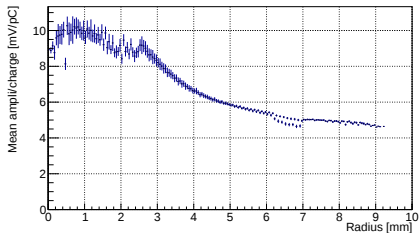
- Ratio depends on distance from contact
→ effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Ratio vs. Distance

Amplitude / charge

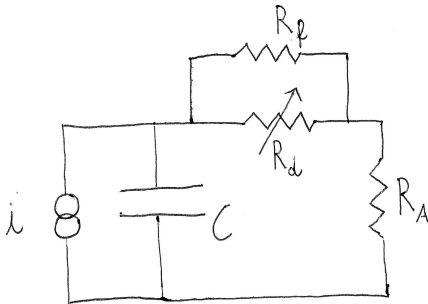


Average ratio vs distance



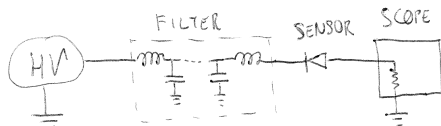
- Ratio depends on distance from contact
→ effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Electrical model:

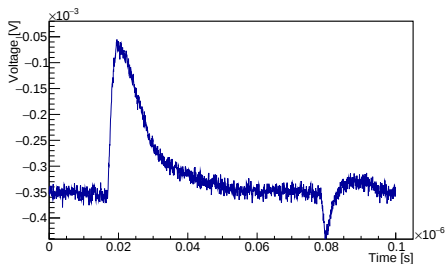


Calibration IR back TCT+, without Amplifier

- 100 μm p-type FZ sensor, $V_{\text{dep}} \approx 2\text{ V}$
- 5 V bias from sensor back
- Long bias cable to avoid reflections
- 1024 averages in scope
- 20 repetitions
- Integrate (15 - 70) ns
- Intensity varied using shutter



20 mV amplitude on ref.
photodiode



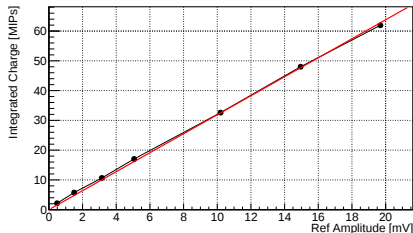
Calibration IR Back TCT+

Real det thickness 92 μm , 74 eh pairs / μm

Fit: $y = ax$

Without amplifier

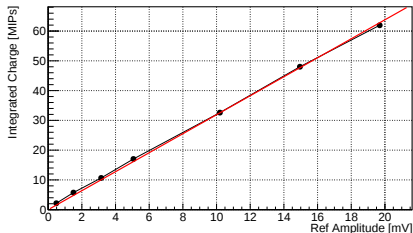
IR Back on 92 μm Detector, 1 MIP = 6808 eh pairs



3.189 ± 0.007 MIPs/mV

With amplifier

IR Back on 92 μm Detector, 1 MIP = 6808 eh pairs



3.1113 ± 0.0009 MIPs/mV
(No error due to ampli gain measurement considered)

Results in agreement within 3 %

3.2 MIPs/mV

Also, the calibration of the ampli worked fine.

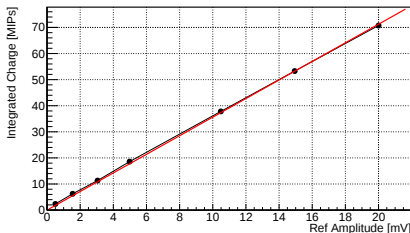
Calibration IR Front TCT+

Real det thickness $92\text{ }\mu\text{m}$, 74 eh pairs / μm

$$\text{Fit: } y = ax$$

Without amplifier

IR Front on $92\text{ }\mu\text{m}$ Detector, 1 MIP = 6808 eh pairs



$$3.562 \pm 0.006 \text{ MIPs/mV}$$

3.6 MIPs/mV

12 % difference with respect to IR back