Radiation Damage Effects on LGADs and Deep Diffused APDs

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Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: $\approx 500$
- Bias: $\approx 1800 \text{ V}$
- Never fully depleted
- Die dimensions: $2.8 \times 2.8 \text{ mm}^2$
- Nominal active area: $2 \times 2 \text{ mm}^2$
- Thickness: $230 - 280 \mu\text{m}$
- 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

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
  $\Rightarrow$ no timing measurements
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 × 2 mm²** APD, non-irradiated
- 1745 V, 20°C
- 40 dB, 2 kV Cividec amplifier
- Amplitude difference of less than 5%
Analysis (2 × 2 mm² non-irradiated APD)

- 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: $7.5 \pm 0.1$ ps

No timing reference needed
N-irradiated $2 \times 2 \text{ mm}^2$ APDs, $-20^\circ\text{C}$, 0.8 MIPs

- 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, $-20^\circ \text{C}$, 0.8 MIPs

Amplitude

Bias [V]

Noise

Bias [V]

Amplitude, same detectors, 15 MIPs

Bias [V]
N-irradiated $2 \times 2$ mm$^2$ APDs, $-20^\circ$C, 0.8 MIPs

- Non-monotone function of bias voltage

- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm$^{-2}$:
  $\approx 550$ ps, all points within 11%

- $\Phi_{eq} = 10^{15}$ cm$^{-2}$:
  around 5.1-5.3 ns, influenced by low SNR
N-irradiated 2 × 2 mm² APDs, −20°C, 0.8 MIPs

Time Resolution for one pulse

Time Resolution vs. SNR

- Obtained by dividing the 2 pulses std. dev. by \(\sqrt{2}\)
- \(\Phi_{eq} \leq 6 \times 10^{13} \text{ cm}^{-2}\): 8 – 10 ps
- \(\Phi_{eq} = 10^{15} \text{ cm}^{-2}\):
  around 508-553 ps, low SNR

“Dark pulses”

“Dark pulses” with a frequency of \(\approx 3\) MHz are observed at −20°C, 1700 V for the sensor irradiated to \(\Phi_{eq} = 10^{15} \text{ cm}^{-2}\).
Radiation Effects in 285 μm Thick LGADs

- CNM run 7859
- Thickness: 285 μm
- Area: 3 × 3 mm²
- Multiplication layer dose: 1.8 and 2.0 · 10^{13} cm^{-2}
- \( I < 0.3 \, \mu A \) @ 20° C, full depletion
- Irradiated with 24 GeV/c protons
- Initial annealing: 80 min at 60° C
Charge Collection from “Red Back” Illumination

\[ \lambda = 660 \text{ nm}, \ 25 \text{ ns integration time}, \ -20^\circ \text{C} \quad 80 \text{ min} @ 60^\circ \text{C} \]

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$

Mult. layer dose $2.0 \cdot 10^{13} \text{ cm}^{-2}$

- Charge collection reduced by irradiation
- Two “steps” present in the $\Phi_{eq} = 10^{13}, 10^{14} \text{ cm}^{-2}$ curves for mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$
  \[ \Rightarrow \] the shape indicates that the depletion starts from the back of the detector

The sensors irradiated to $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$ were studied further.

S. Otero Ugobono, VERTEX 2017
Waveforms “Red Back” Illumination $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$

The depletion region develops from the back of the device before the effects of multiplication can be seen in the collected charge.

This can influence the measurement of the effective doping of the multiplication layer after irradiation.

S. Otero Ugobono, VERTEX 2017
Two Photons Absorption TCT
For details about this technique, see talk from M. Fernandez Garcia.

- Point-like generation of charge carriers
- Generation point moved along detector thickness

Mult. layer dose $1.8 \cdot 10^{13}$ cm$^{-2}$, $\Phi_{eq} = 10^{14}$ cm$^{-2}$, $T = -20^\circ$C

Electric field develops from the back side until $\approx 95$ V
Afterwards, the field starts to increase from the front of the detector

M. Fernandez Garcia, 31$^{st}$ RD50 workshop, 2017
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13}$ cm$^{-2}$, $\Phi_{eq} = 10^{14}$ cm$^{-2}$, $T = -20^\circ$C
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
Waveforms “Red Back” Illumination

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Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13}$ cm$^{-2}$, $\Phi_{eq} = 10^{14}$ cm$^{-2}$, $T = -20^\circ$C

[Graphs showing waveforms and integral vs bias voltage, voltage vs time]
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
Waveforms “Red Back” Illumination

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Waveforms “Red Back” Illumination

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Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \times 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ C$
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \, \text{cm}^{-2}$, $\Phi_{eq} = 10^{14} \, \text{cm}^{-2}$, $T = -20^\circ \text{C}$
Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
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Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ \text{C}$
Qualitative Simulation

Triple junction

- J1: Reverse biased
- J2: Forward biased
- J3: Reverse biased

- Qualitative TCAD simulation can reproduce the features of the measurements
- The model and observations suggest the presence of three junctions

Further studies are needed.
Annealing Effects on $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$ Samples

Room temperature annealing due to measurements and samples handling

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $-20^\circ \text{C}$

- Multiplication onset voltage (red front illumination) decreases with annealing
- Gain at 400 V (defined using PiN diodes) increases with annealing
- Both mult. layer doses show similar results
- Strong dependence on annealing, origin to be understood

S. Otero Ugobono, VERTEX 2017
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S. Otero Ugobono, VERTEX 2017
Summary & Outlook

- Measured time resolution of neutron irradiated $2 \times 2$ mm$^2$ APDs
- Performance at det. center not degraded by neutron irradiation of at least $\Phi_{eq} = 6 \cdot 10^{13}$ cm$^{-2}$ $\Rightarrow \sigma_t = 8 - 10$ ps @ 0.8 MIPs
- $\Phi_{eq} = 10^{15}$ cm$^{-2}$: very low or no gain, “dark pulses” are observed

- Studied the properties of proton irradiated 285 $\mu$m thick LGADs
- In some cases the electric field develops from the back of the detector
- The measurements suggest the presence of three junctions in the detectors

Outlook:

- New APD irradiation to explore region $6 \cdot 10^{13} \leq \Phi_{eq} \leq 7 \cdot 10^{14}$ cm$^{-2}$
- Characterization of irradiated LGADs from CNM run 8622 and CNM run 10478 50 $\mu$m thick quad-diodes. Irradiation with 24 GeV/c protons is completed
- Extend study of annealing effects
Backup Material
APD Section (not to scale)

P-SIDE

P\textsuperscript{+}-DOPED LAYER

P-Si

N-Si

POLYIMIDE

N-SIDE

N\textsuperscript{+}-DOPED LAYER
IV and Signal Amplitude $2 \times 2 \text{ mm}^2$ APDs

$T = -20^\circ\text{C}$, $\lambda = 1060 \text{ nm}$, **15 MIPs** equivalent intensity, 10 dB amplification, 256 averages in the scope

- Increase in bulk generation current
- Reduction of gain
Difference Pulses $2 \times 2 \; \text{mm}^2$ APDs

Amplitude

![Amplitude Graph]

Noise

![Noise Graph]

Integral

![Integral Graph]

Rise Time 20% 80%

![Rise Time Graph]

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

Properties of pulses equal within 5 %

M. Centis Vignali

Radiation Damage LGADs and APDs

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

Continuos line: first pulse, Dashed: second pulse
Similar values, difference due to statistical fluctuations of the $\Delta t$ std. dev.
$\Phi_{eq} = 10^{15} \, \text{cm}^{-2}$: jumps due to low SNR
Calibration IR back TCT+, without Amplifier

- 100 µm p-type FZ sensor, $V_{\text{dep}} \approx 2$ 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 $\mu$m, 74 eh pairs / $\mu$m

Fit: $y = ax$

Without amplifier

IR Back on 92 $\mu$m Detector, 1 MIP = 6808 eh pairs

With amplifier

IR Back on 92 $\mu$m Detector, 1 MIP = 6808 eh pairs

$3.189 \pm 0.007$ MIPs/mV

$3.1113 \pm 0.0009$ 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 $\mu$m, 74 eh pairs / $\mu$m

Fit: $y = ax$

Without amplifier

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

3.562 ± 0.006 MIPs/mV

3.6 MIPs/mV

12 % difference with respect to IR back
Annealing Effects

Red back Illumination

Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $-20^\circ \text{C}$

(Right): IV from 28.04.2017, TCT from 12.05.2017