TCAD simulations of TPA-TCT measurements on PINs and LGADs

- hunting for sharks -

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Outline:

• Implementation of TPA-TCT TCAD simulations
• Experimental data and TCAD simulations
  • PIN diodes
  • LGADs
• Simulation of gain reduction in LGADs
• Conclusion and Outlook

TPA : Two Photon Absorption
TCT : Transient Current Technique
PIN : p-type intrinsic n-type
LGAD : Low Gain Avalanche Diode
shark : Sharks are a group of elasmobranch fish characterized by a cartilaginous skeleton, five to seven gill slits on the sides of the head, and pectoral fins that are not fused to the head.
Experimental Details

TPA-TCT setup

- Located in CERN EP-DT Solid State Detectors (SSD) lab
- Fyla fs laser, 1550 nm, 430 fs pulses up to 10 nJ, 8MHz to single pulse, SPA and TPA reference systems, x100 objectives with NA = 0.5 or 0.7

Inside Faraday cage

Sensors

- All used sensors
  - FZ p-type, high resistivity, not irradiated!
  - CiS (CIS16)
  - PIN diode (300 um)
  - CNM 7859, 8622 and 8665
  - PIN diodes / LGAD (~ 290 um)

Simulations

- TCAD: Synopsys vs. U-2022.12-SP1
  - 2D with rotational symmetry used
  - LGAD and Impact Ionization models
    - see [Curras and Moll IEEE TED 2023]
  - TPA charge generation
    - with analytic charge generation model (see following slides)
  - Electronics shaping
    - folding TCAD output with ‘transfer function’ (see following slides)
TCT: Excess charge generation

- Various options to produce excess charge in silicon sensors for Transient Current Technique analyses

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**Typical excess carrier volumes (in a 300 \( \mu m \) thick sensor)**

- \(^{90}\text{Sr} \): \( V_{\text{Sr}} \approx 940 \, \mu m^3 \)
- SPA (red): \( V_{\text{red}} \approx 1100 \, \mu m^3 \)
- SPA (infrared): \( V_{\text{IR}} \approx 100 \times V_{\text{Sr}} \)
- TPA: \( V_{\text{TPA}} \approx 85 \, \mu m^3 \)

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**TPA-TCT: model of excess carrier generation**

- Gaussian beam in space and time
  - with pulse length of 430 fs charge generation is "instantaneous"
- Charge distribution in space characterized by:
  - beam waist \( w_0 \)
  - Rayleigh length \( z_R \)

\[
E_p = \frac{\pi n w_0^2}{\lambda}
\]
\[
w(z') = w_0 \sqrt{1 + \left( \frac{z'}{z_R} \right)^2}
\]

- Charge generation goes with (irradiance)\(^2\)
  - 2 photons needed for one electron hole pair (2ℏ\( \omega \))
- Charge carrier density:

\[
n_{\text{TPA}}(r, z') = \frac{E_p^2 \beta_2 4 \ln 2}{\tau \omega \pi^{5/2} \sqrt{\ln 4}} \frac{1}{w^4(z')} \exp \left( -\frac{4r^2}{w^2(z')} \right)
\]
TCAD: TPA-TCT excess charge generation

- TPA charge generation example:
  - Sensor: CNM 7859 PIN (290 um)
  - Beam: NA=0.5; $w_0=1.3\mu$m, $z_R=10.5\mu$m; $Q\approx 5fC$
  - Focal plane: 250 um depth

\[ n_{\text{TPA}}(r, z') = \frac{E_p^2 \beta_2 4 \ln 2}{\tau \hbar \omega \pi^{5/2} \sqrt{\ln 4} w^4(z')} \exp \left( -\frac{4r^2}{w^2(z')} \right) \]

![Graph showing charge distribution](image)

- Log-scale on charge
- Linear-scale on charge density

- Focal plane "depth" or "z"
Simulation of TPA-TCT

- Charge cloud generated around focal depth of 250 μm (at t=1.0 ns)
- Visualisation of electron cloud moving through PIN detector (holes not shown)

• Charge cloud generated around focal depth of 250 μm (at t=1.0 ns)

• Visualisation of electron cloud moving through PIN detector (holes not shown)

1.02e-9 s

Transient Current (TC) induced by electrons and holes

Note: This example is calculated in 2D for better visibility, all shown transients calculated from 3D simulations.
Simulation: Convolution with ‘transfer function’

- Simulated TPA-TCT signal is convoluted with a measured ‘transfer function’
  - Sensor: CNM 7859 PIN (290 μm); Beam: NA=0.5; \( w_0 = 1.3 \mu \text{m}, z_R = 10.5 \mu \text{m}; Q \approx 5 \text{fC}; \) Focal plane: \( z = 50 \mu \text{m depth} \)
TPA-TCT on PIN diodes

Experiment vs. Simulation

... gaining confidence into the simulations
PIN-Diode – TPA-TCT z-scan

- Experimental and simulation settings
  - Sensor: CNM 7859 WL-A63-PIN4 (p-type, 290 µm) operated at 200V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with $z_R=10.5 \mu m$, $w_0=1.3 \mu m$

Experiment

Simulation

reflection at sensor backside (not considered in simulation)

[S.Pape, PhD thesis, 2024]
PIN-Diode – TPA-TCT z-scan

- TPA-TCT transients after charge injection at various depth ("z-scan")

- $z < 280 \, \mu m$ : very good agreement between experiment and simulation
- $z > 280 \, \mu m$ : for injection close to the backside the experimental transients are influenced by reflection
  - higher signal in experiment due to reflection at back side
- $z > 290 \, \mu m$ : no signal in simulation while in the experiment we get a signal
  - even beyond the sensor thickness a signal is obtained in the experiment because of the reflection at the back side
PIN-Diode – TPA-TCT z-scan

• TPA-TCT transients (simulation & data) after charge injection at various depth (“z-scan”)
  • same data as previous slide

![Diagram showing TPA-TCT transients at various depths with red points representing simulated data and black lines representing measured data.]

- Note: same scaling factor for signal heights used for all simulated data!
- ….. some room for improvement, but quite good agreement
PIN-Diode – TPA-TCT z-scan

- Experimental and simulated transients undergoing the same analyses procedures

29.11.2023 - RD50 Workshop
Michael Moll, CERN
TPA-TCT on LGADs

Experiment vs. Simulation

... finally, we arrive to the SHARKS
PIN and LGAD – TPA-TCT z-scan

- TPA-TCT measurements on CNM 8622 devices (illumination from top)
  - **PIN**: p-type, 280\(\mu\)m, operated at 200V, 20°C; **LGAD**: 280\(\mu\)m, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with \(z_R=11.9\mu\)m, \(w_0=1.3\mu\)m

**PIN diode:** Beam intensity has no influence on charge collection profile

**LGAD:** Beam intensity has influence on charge collection profile:
“shark fin effect”

1 MIP \(\approx 3.6\) fC

[S. Pape, RD50 Workshop Nov. 2021]
[S. Pape et. al, NIMA 2022]
Reminder: LGAD gain suppression

**LGAD gain** depends on operational parameters:
- Applied voltage
- Temperature
- **Charge carrier density (“gain suppression”)**
  - Excess charge carriers enter the gain layer (i.e. the high field region) and undergo impact ionization.
  - The charge carriers build up a temporal counter directed electric field that reduces the field strength in the gain layer.
  - Following charge carriers entering the gain layer see a lower field and produce less impact ionization.
  - The gain depends on the amount of charge carriers being amplified. The higher the free charge carrier density in the gain layer the lower is the gain.
  - **Gain depends on the excess charge carrier density**

- More details on LGAD impact ionization and gain suppression:
  - Curras et al., NIMA 2022, *Gain reduction mechanism in LGAD* (first observation, IR-TCT, Sr90)
  - Curras and Moll, IEEE TED 2023 (impact ionization coefficients)
  - Kramberger et al., NIMA 2023, (IR-TCT, modelling)
  - S.Pape et al. NIMA 2022 (TPA-TCT); Femke de Wit, Bachelor thesis 2023 [link]; Sebastian Pape, PhD thesis 2024 [soon]
LGAD gain suppression in TPA-TCT

- More details on experimental results:
  - Sebastian Pape, 27.11.2021, RD50 Workshop
  - S.Pape et. al, NIMA 2022
  - S.Pape, PhD thesis 2024

Focus close to backside

1 MIP $\approx$ 3.6 fC

Focus close to frontside

Charge injected: 250 $\mu$m depth +2.0 ns +4.0 ns

1 MIP $\approx$ 3.6 fC
PIN – TPA-TCT z-scan

- TPA-TCT measurements on CNM 8622 devices (illumination from top)
  - **PIN**: p-type, 286μm, operated at 200V, 20°C
  - **TPA-TCT optics**: NA=0.5 (x100) resulting in a beam with $z_R=11.9\mu m$, $w_0=1.3\mu m$

**PIN diode:** Beam intensity has no influence on charge collection profile

**PIN:** Reflection at back side not included in simulation.

[S.Pape, RD50 Workshop Nov.2021]
[S.Pape et. al, NIMA 2022]
LGAD – TPA-TCT z-scan

- TPA-TCT measurements and simulations on CNM 8622 devices (illumination from top)
  - **LGAD**: 280 μm, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with $z_R=11.9$ μm, $w_0=1.3$ μm

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**LGAD**: Beam intensity has influence on charge collection profile: “shark fin effect”

![Graph showing charge vs. stage z (mm)](image1)

![Graph showing collected charge vs. depth in silicon (μm)](image2)

[S.Pape, RD50 Workshop Nov.2021]
[S.Pape et. al, NIMA 2022]
LGAD – TPA-TCT z-scan

- TPA-TCT measurements and simulations on CNM 8622 devices (illumination from top)
  - **LGAD**: 280µm, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with \( z_R = 11.9 \mu m \), \( w_0 = 1.3 \mu m \)

**LGAD**: Beam intensity has influence on charge collection profile: “shark fin effect”

[S. Pape, RD50 Workshop Nov.2021]
[S. Pape et. al, NIMA 2022]
Gain as function of depth

- **Experimental Data**
  - Sebastian Pape, 27.11.2021, RD50 Workshop
  - $\text{gain}(z) = \frac{Q_{\text{LGAD}}(z)}{Q_{\text{PIN}}(z)}$
  - 1 MIP = 3.6 fC

- **TCAD simulation**
  - CNM 8622 $\frac{Q_{\text{LGAD}}(z)}{Q_{\text{PIN}}(z)}$

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![Graph showing gain as function of depth](image)

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Simulation: LGAD, PIN

Experiment: LGAD, PIN

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**TPA-TCT depth-scan: CNM 8622 LGAD**

Sensor: 900V, TPA: 1.3um, 11.9um

- 1fC [0.3 MIPs]
- 10fC [2.8 MIPs]
- 30fC [8.3 MIPs]
- 65fC [18 MIPs]
- 360fC [100 MIPs]
- 1000fC [300 MIPs]
Gain as function of depth

- Experimental and Simulated Data
  - \( \text{gain}(z) = \frac{Q_{\text{LGAD}}(z)}{Q_{\text{PIN}}(z)} \) (collected within 25ns)
  - 1 MIP = 3.6 fC

Carriers deposited at \( z=150 \) um
Gain as function of depth

- Experimental and Simulated Data
  - \[ \text{gain}(z) = \frac{Q_{\text{LGAD}}(z)}{Q_{\text{PIN}}(z)} \] (collected within 25ns)
  - 1 MIP = 3.6 fC

**Figure 4.2.2:** Gain reduction mechanism observed in the CNM LGAD 8622-WA18-2 by in-depth scans (a) and gain profiles (b) at different laser intensities. The laser intensity is given in units of the generated charge, which is extracted from measurements in a pad detector. The top side is located at \( z = -300 \mu m \) and the coordinates in the z-axis of both plots match. The gain reduction becomes more pronounced when charge is generated inside or close to the top side junction. All measurements are performed with a bias voltage of 900 V.

Carriers deposited at \( z = 150 \) um
Outlook: SPA-TCT (Infrared)

• Study of LGAD gain suppression using SPA-TCT

• June 2022 RD50 Workshop
  • 1D simulation on gain suppression: Factor >10 mismatch in laser intensity between simulated and experimental data

• Repeated simulation with 3D laser beam
  • 1064nm, $z_R=50\mu m$, $w_0=8\mu m$, absorption length 1.5 mm
  • Good agreement (preliminary data)

TCT: Variation of laser pulse intensity

• TCT: IR and red laser pulses, top and bottom illumination

Data: 900 V; 20°C

Experimental Data

1D simulation: 900 V; 20°C

1D: IR top (900V)
1D: red top (900V)

Increasing laser intensity

Gain = (with gain)/(without gain)
MIP$^*=\text{Intensity to create charge of 1 MIP}$

large triangles = TCAD simulation
TPA generated charge profiles included in TCAD simulation
- good agreement between measured and simulated transients
- reflections of the beam are seen in the experimental data but not included in the simulations
- simulations help to understand several features of z-scans on PIN diodes (see Sebastian Pape talk)

Simulated transients undergo same analyses procedures as measured transients:
- Access to: Time-over-Threshold (ToT), Prompt-Current (PC), Weighted Prompt-Current (WPC),…
- Simulations proved already a powerful tool to understand several features of z-scans on PIN diodes

TCAD simulations reproduces the “shark-fin” effect for LGADs
- confirmation that diffusion is the origin of the effect
- gain suppression can be successfully simulated in TCAD simulators with ‘standard physics models’
- absolute values of gain suppression in this work agree within 20% with experimental results

OUTLOOK
- Consolidation of simulations: study LGAD transients, meshing integrity, absolute numbers of charge generated
- Gain suppression in LGADs as seen with infrared and red lasers
- Development of an analytic model for LGAD gain suppression in Monte Carlo solvers
  - very tricky, see Femke de Wit thesis [link]
- Study of plasma effects in PIN diodes (experimental results covered by TCAD simulations??)