High resolution 3D characterization of silicon detectors using a **Two Photon Absorption Transient Current Technique**

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Outline

What is TCT and TPA?

The setup(s)

Examples of application in Si:
  Diodes
  HVCMOS  
    \{ Irradiated and non-irradiated \}

Summary
Two Photon Absorption-Transient Current Technique (TPA-TCT) is a new technique to characterize semiconductors detectors using a point-like laser probe, so called “voxel”. A voxel can be scanned in the three coordinates, thus obtaining true 3D spatial resolution.

R&D on radiation hardness of Si sensors

Test of Single Event Effects on electronics

Ultrafast molecular spectroscopy

This mixture has been possible via RD50 collaboration
What is TCT?

Technique to characterize a material via the transport of excess carriers generated typically using a laser beam. E-field profile, space charge, charge collection efficiency, trapping.. can be reached.

Induced current pulse is time resolved, measured, and analyzed.
What is TCT?

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Induced current pulse is **time resolved**, measured, and analyzed.

From **early 1990s** widely used for measurements of radiation effects in semiconductors. Workhorse for **ROSE** and **RD50** collaborations.
What is TCT?

Technique to characterize a material via the transport of excess carriers generated typically using a laser beam. E-field profile, space charge, charge collection efficiency, trapping.. can be reached.

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From early 1990s widely used for measurements of radiation effects in semiconductors.
Workhorse for ROSE and RD50 collaborations.

Sensitive to product of drift and weighting field
What is TPA?

- TPA is a **non-linear effect** shown by any material when illuminated with a **high intensity** source (for instance, a laser). For certain wavelengths, light absorption (=signal) only happens **at the focus** of the beam. No photons are absorbed “out of focus”. The more light is focused, the better “point-like” signal generation volume.

- The physical phenomena exploited is the **simultaneous absorption of 2 photons** in the material.

**OLD**

**Single Photon Absorption**

Continuous energy deposition (no spatial resolution along beam prop. dir.)

**NEW**

**Two Photon Absorption**

Energy confinement

Two photons from one laser !!
**Two Photon Absorption**

**TPA:** Conventionally, no excitation if $E_{\text{photon}} < E_{\text{gap}} \sim 1$ eV. But, if **TWO** photons arrive in $\sim 100$ attoseconds:

$$\tau_{\text{virtual}} \approx \frac{\hbar}{E_{\text{gap}}/2} \approx 0.1 \text{ fs}$$

Two Photons ($E > E_{\text{gap}}/2$) must be:

1) **coincident in time** (pulsed mode-locked fs-lasers)
2) and in **space** (microfocusing)

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**Absorption in Si**

No Single Photon Abs.: $\alpha \sim 0$ for $\lambda > 1150$ nm (Silicon)

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**Spot size**

Measured using knife edge technique.

This is the **3D probe** we scan across the volume of the detector

$$\frac{dN(r, z)}{dt} = \alpha \frac{I(r, z)}{\hbar \omega} + \beta_2 \frac{I^2(r, z)}{2 \hbar \omega}$$

---

**SPA**

Single Photon Absorption

Negligible $\lambda \geq 1100$ nm

**TPA**

Two Photon Absorption

Point-like resolution

Boosted by using short pulsed fs lasers, where $I^2 >> I$ for the same average power laser.
TPA-TCT in UPV laser facility

- **Tunable** wavelength, energy for the sensor (after attenuation) [~pJ].

Then typical **TCT readout**: top/side injection, 3D system, current amplifier and fast readout scope.

- Oscillator-Regenerative amplifier
  - 1 kHz, **4.0 mJ**, 30 fs pulses at 800 nm

- Optical Parametric Amplifier: Tunable radiation

- Intensity Autocorrelator: measurement of pulse length [~243 fs]

- Power Meter

- Pulse BW reduction to 12 nm

Marcos Fernandez – VCI 2019, Feb 18-22 2019, Vienna
TPA-TCT presented at 2016 CERN EP-Knowledge Transfer innovation day
→ It was selected for funding: Proposed Project on non-destructive QC of semiconductors

Status:

- The core of this system is a custom fibered laser working at 1.5 µm. It is being delivered this March 2019 after ~1 year development by Laser company.

- Rest of the system is based in our already existing SPA-TCT at CERN-SSD lab (known as TCT+).

- Some key differences / improvements:
  
  - Improved positioning system (6 degrees of freedom hexapod system)
  - Optimal cooling and sample support. It can be rotated for edge-side injection

- German Doctoral Student (M.W., Gentner Program) responsible for construction of this demonstrator.

- Upon completion of the project access to this laser via RD50 collaboration.
New CERN TPA-TCT

Status as of Feb 15th, 2019

Light injection system

6 degrees of freedom, high load capacity motion system

Laser routing, microfocusing, visible laser imaging system, cooling, stage system inside Faraday Cage.
In both illumination configurations, the focus is fixed and the detector is moved.

**Top-TPA**: detector is scanned in vertical → depth scan (10 μm resol.)

Rotating the detector by 90 degrees, we can, for instance, map the depletion region with 1 μm resolution: **edge-TPA**.
TPA top injection

- **TPA**: For simplicity, here moving the focus wrt the detector. In real measurements, the detector moves.
- Assuming fully depleted detector
- Laser probe → Excess charge carriers → Induced Current → Showing integrated current vs position

Note: dimensions exaggerated
TPA top injection

\[ Q(z) \]

Slope proportional to probe length

\[ Q_{\text{tot}} \]

\[ \sigma = 1 \mu m = 10 \mu m \]
TPA top injection

\[ \sigma = 1 \mu m \]

\[ \sigma = 10 \mu m \]

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TPA top injection

No light absorbed before/after the focus
A depth scan of the detector is done from the top!
Measurements not affected by side effects, guard rings...

\[ Q(z) \]

\[ Q_{\text{tot}} \]

\[ \sigma = 10 \mu m \]

\[ \sigma = 1 \mu m \]
TPA edge injection

\[ Q(x) \]

\[ \sigma = 10 \mu m \]

\[ \sigma = 1 \mu m \]
TPA edge injection

Very sharp transition because of 1 µm beam waist
TPA edge injection

\[ \sigma = 10 \mu m \]

\[ \sigma = 1 \mu m \]
TPA edge injection

\[ \sigma = 1 \mu m \]

\[ \sigma = 10 \mu m \]
TPA-TCT edge injection

Depth scan of the detector is done from the side with the best resolution achievable in this method.
Edge-TPA: unirradiated HVCMOS

- HVCMOS is a partially depleted sensor, built on commercial CMOS technology. Substrate of very low resistivity → very narrow depletion width (~10 μm at 100 V). Challenging detector for SPA-TCT

Standard SPA-TCT

Spatially continuous laser source, ps pulses

- Showing 2D map of the collection time of charge carriers (time lapse till 98% charge is collected).
- Very sensitive to creation point of carriers.

TPA-TCT

Point-like laser source, fs pulses

λ=1300 nm, σ=1 μm, 200 fs-pulsed laser

Substructures resolved with TPA-TCT
Edge-TPA: unirradiated HVCMOS

- HVCMOS is a partially depleted sensor, built on commercial CMOS technology.
  Substrate of very low resistivity → very narrow depletion width (~10 μm at 100 V). Challenging detector for SPA-TCT

Standard SPA-TCT

- Spatially continuous laser source, ps pulses
  \( \lambda = 1064 \text{ nm}, \sigma = 10 \mu \text{m}, \) 200 ps-pulsed laser

- Showing 2D map of the collection time of charge carriers (time lapse till 98% charge is collected)

TPA-TCT

- Point-like laser source, fs pulses
  \( \lambda = 1300 \text{ nm}, \sigma = 1 \mu \text{m}, \) 200 fs-pulsed laser

Substructures resolved with TPA-TCT
Drift/diffusion discrimination

Doping concentration

Probing the implant

Marcos Fernandez – VCI 2019, Feb 18-22 2019, Vienna
In Silicon, ionizing radiation creates **Deep Energy Levels** within the bandgap, that **increase** Single Photon **Linear Absorption**. More free charge carriers but less photons for TPA.

- Linear absorption **smears** spatial resolution along the beam propagation direction.
- Clear signature:
  1) carriers collected even when focus is outside the detector.
  2) Linear increase of signal as power increases

\[
\frac{dN(r,z)}{dt} = \alpha \frac{I(r,z)}{\hbar \omega} + \beta_2 \frac{I^2(r,z)}{2 \hbar \omega}
\]
In TPA, the increase of linear absorption can be subtracted exploiting the fact that it is Z-invariant.

Solution:
1) place focus outside the detector → measure $\alpha$-induced signal: $I(t,\alpha)$
2) Subtract $I(t,\alpha)$ (waveform-by-waveform) to measurements with focus inside the detector
TPA in irradiated HVCMOS

Raw data: $Q(6 \text{ ns})$

$7 \times 10^{15} \text{ n}_{\text{eq}} / \text{cm}^2$

- No sharp decrease of $Q(y)$ or collection time, due to $\alpha$-contamination.

- edge-TPA can overestimate depletion width in irradiated devices if this effect is not accounted for.
Due to strong beam focusing/divergence, the $\alpha$-contribution can overflow the depleted region:

Diode-like correction method not applicable $\Rightarrow$ Developed a different one (see backup) based on 2 consecutive scans of the same region at different powers

Because of $\alpha$ correction, collection time drops to zero behind depleted region

Marcos Fernandez – VCI 2019, Feb 18-22 2019, Vienna
Summary

- TPA-TCT is a new material characterization technique providing 1 µm resolution in 2D and up to 10 µm along the beam direction → Optimal configuration for edge injection

- Physical phenomena exploited is the simultaneous absorption of two photons at the focus of a fs-laser beam.

- Demonstrated performance on a low resistivity HVCMOS with 15 um depletion depth

- Increase of linear absorption with irradiation in Si (intrinsic to Si) reduces TPA contrast. This smearing can be corrected either by moving the focus outside of the sample (diodes) or by dual scan at different power (devices with very small depletion width).

- From the experience gained on the demonstrator system in Bilbao, we are building an optimized setup for Silicon measurements at CERN. Laser delivery this next month. Project funded by 2016 CERN Knowledge Transfer Program.

- All these activities have been carried out in the framework of CERN-RD50 collaboration
TPA - TCT extra information

1) NIMA Vol 845, 11 February 2017, Pages 69-71
https://doi.org/10.1016/j.nima.2016.05.070

2) Journal of Instrumentation, Volume 12, January 2017
http://iopscience.iop.org/article/10.1088/1748-0221/12/01/C01038

3) I. Vila, CERN Detector Seminar, 26th January 2018
https://indico.cern.ch/event/697958/

4) M. Fernandez, Seminaire de physique corpusculaire, University of Generva, 30th Nov 2016
http://dpnc.unige.ch/seminaire/talks/fernandez.pdf
BACKUPS
3D microfabrication: using **focused ultrashort laser pulses** on the volume of a **photoresist**, the pulses initiate **polymerization**. After illumination of the structure and **development** (washing out the non-illuminated regions) the **polymerized** material remains in the prescribed **3D** form.

Screenshots from “**Is this the world's smallest sculpture?**” CNN “**Ones to watch**”

# Common characterization techniques of semiconductor radiation detectors

<table>
<thead>
<tr>
<th>Technique</th>
<th>Type</th>
<th>Spatial resolution</th>
<th>Efficiency</th>
<th>Reach</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV/CV</td>
<td>Electrical</td>
<td>Not applicable</td>
<td>No</td>
<td>( I_{\text{leak}}, V_{\text{dep}}(\propto N_{\text{eff}}), V_{\text{br}}, C_{\text{end}} )</td>
<td>Needle system, Cold chuck, pA-meter, LCR meter...</td>
</tr>
<tr>
<td>TCT (Transient Current Technique)</td>
<td>Optical</td>
<td>2D</td>
<td>Yes</td>
<td>( N_{\text{eff}}, \tau_{e,h} ) (low ( \Phi_{\text{eq}} )) uniformity</td>
<td>ps-pulsed laser stepper motors, Amplifier, scope</td>
</tr>
<tr>
<td>Radioactive source</td>
<td>Source</td>
<td>None</td>
<td>Yes</td>
<td>( V_{\text{dep}}, \text{CCE} )</td>
<td>Radioactive source, trigger system</td>
</tr>
<tr>
<td>IBIC</td>
<td>Source</td>
<td>2D</td>
<td>Yes</td>
<td>2D CCE</td>
<td>Accelerator</td>
</tr>
<tr>
<td>Test beam</td>
<td>Source</td>
<td>2D</td>
<td>Yes</td>
<td>Setup/sensor dependent: 2D CCE,...</td>
<td>Accelerator, beam time, telescope, trigger,</td>
</tr>
</tbody>
</table>

MIP capabilities: Test beam, infrared TCT
Two Photon Absorption (TPA-TCT)
Point-like energy deposition → 3D spatial resolution
Novel technique developed by IFCA, CERN, US, UPV
2 photons=1 e-h pair

SPA-TCT Red
Employing short absorption length laser (red for Si), all carriers deposited in few µm from surface.
Allows to study drift of one kind of carriers.
No spatial resolution along beam direction.
1 photon=1 e-h pair
SPA: Single Photon Absorption
TCT: Transient Current Technique

SPA-TCT Infrared
Using long absorption length laser (infrared for Si). Homogeneous distribution along “Rayleigh length”.
Similar to MIPs, though different dE/dx.
Incidence can be from top, bottom or edge.
Edge: lateral spatial resolution.
1 photon=1 e-h pair

Two Photon Absorption (TPA-TCT)
Point-like energy deposition → 3D spatial resolution
Novel technique developed by IFCA, CERN, US, UPV
2 photons=1 e-h pair

Transient Current Techniques
Applicable to both pad/segmented detectors
Simple readout
DAQ directly on digital scope
**TCT: Transient Current Technique**

\[ I(t) = N_{eh} A q_e v_{\text{drift}} E_W \propto v_{\text{drift}} = \mu(E) E \Rightarrow I(t) \propto E(z) \]

**Assumption:** 1D, overdepleted, non-irradiated diode
Evidences for TPA process

1) Collected charge varies quadratically with power
2) Z-scan is not Z-invariant.

Then characterize the excitation volume:

Ellipsoid is completely described by waist \( w_0 \), \( \lambda \) and \( \beta \).

\[
W_0 = 0.95 \pm 0.05 \, \mu m
\]
\[
\text{Ellipsoid length} = 13 \, \mu m
\]

An edge-TPA scan is optimum, because spatial resolution is \( \sim 1 \, \mu m \)

Try to scan pads from the edge \( \rightarrow \) Get active area very close to the border
Work in a power regime where $\beta \gg \alpha$ but **without** producing **plasma**.

- For this detector. Laser power $< 80$ pJ $\Rightarrow$ no plasma effect
The primary equations governing pulse propagation and carrier generation in a semiconductor material are \[15, 16\]

\[
\frac{dI(r, z)}{dz} = -\alpha I(r, z) - \beta_2 I^2(r, z) - \sigma_{\text{ex}} N I(r, z) \tag{1}
\]

\[
\frac{d\Phi(r, z)}{dz} = \beta_1 I(r, z) - \gamma_1 N(r, z) \tag{2}
\]

\[
\frac{dN(r, z)}{dt} = \frac{\alpha I(r, z)}{\hbar \omega} + \frac{\beta_2 I^2(r, z)}{2\hbar \omega} \tag{3}
\]

where \( I \) is pulse irradiance, \( N \) is the density of free carriers, and \( \Phi \) is the phase. \( \alpha \) is the linear absorption coefficient, \( \beta_2 \) is the two-photon absorption coefficient that is proportional to the imaginary part of \( \chi^{(3)} \) (the third-order nonlinear-optical susceptibility), \( \sigma_{\text{ex}} \) is the absorptivity of laser-generated free carriers, \( \beta_1 \) is proportional to the real part of \( \chi^{(3)} \), \( \gamma_1 \) describes the refraction due to free carriers, and \( z \) is the depth in the material.

\[
N_{1P}(z) = \frac{\alpha}{\hbar \omega} \exp(-\alpha z) \int_{-\infty}^{\infty} I_0(z, t) \, dt
\]

\[
N_{2P}(z) = \frac{\beta_2}{2\hbar \omega} \int_{-\infty}^{\infty} I^2(z, t) \, dt
\]

The longitudinal dependence of the beam radius \( w(z) \) is

\[
w(z) = w_o \left[ 1 + \left( \frac{\lambda z}{\pi w_o^2 n} \right)^2 \right]^{1/2}, \quad z_o \left( \frac{\pi w_o^2 n}{\lambda} \right).
\]

The parameter \( 2z_o \) defines the propagation distance over which the beam is reasonably well collimated in the vicinity of \( w_o \). In silicon \((n \approx 3.51)\), for 1.26 \( \mu \)m light and 0.8 \( \mu \)m beam radius (that of the present study), \( 2z_o \) is \( \approx 11.2 \) \( \mu \)m.
TPA: Needed two (simultaneous) photons to produce 1 e-h pair. Mediated by virtual state.

Resonant TPA: Two (sequential) photons to produce 1 e-h pair. Mediated by Deep Level (DL)

Two SPA: Unpaired holes (in BV) or electrons (BC). Generation is proportional to number of DLs (it grows with fluence) and laser intensity (more photons available for transition).
HVCMOS: correction of radiation induced SPA signal

Generation rate of e-h pairs per unit volume:
\[
\frac{dN(r, z; i)}{dt} = \alpha \frac{I(r, z; i)}{\hbar \omega} + \frac{\beta_2 I^2(r, z; i)}{2 \hbar \omega}
\]

with
\[
I(r, z) = \frac{2P}{\pi w(z)^2} \exp \left( -\frac{2r^2}{w(z)^2} \right)
\]

A Ge photodiode (linear response at 1300 nm) is used to measure laser power, which is proportional to the integral of the irradiance: \( I(r, t; i) \)

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(r, z) \, dr \, dz \propto P \quad \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(r, z)^2 \, dr \, dz \propto P^2
\]

Then:
\[
Q_{DUT} = q_e \int r \int z N(r, z; i) \, dr \, dz = q_e N(i)
\]

This is the charge measured in the detector (easy to calculate)
**HVCMOS: correction of radiation induced SPA signal**

Assuming a “rectangular” laser pulse of duration \( t_p \) (~30 fs)

\[
\int \alpha \frac{I(r, z; i)}{\hbar \omega} \, dt + \int \frac{\beta_2 I^2(r, z; i)}{2 \hbar \omega} \, dt = \alpha \frac{P t_p}{\hbar \omega} + \frac{\beta_2 t_p P^2}{2 \hbar \omega}
\]

So finally:

\[
Q_{DUT} = \frac{q_e \alpha t_p}{\hbar \omega} \, P + \frac{q_e \beta_2 t_p}{2 \hbar \omega} \, P^2
\]

\[
\begin{align*}
Q_\alpha &= \frac{q_e \alpha t_p}{\hbar \omega} \\
Q_\beta &= \frac{q_e \beta_2 t_p}{2 \hbar \omega}
\end{align*}
\]

With \( Q_\alpha \) and \( Q_\beta \) the SPA and TPA contributions to the signal (they should be constants)

Now, we can take 2 identical measurements at 2 different intensities and calculate \( Q_\beta \)

\[
\begin{align*}
Q_1 &= Q_\beta P_1^2 + Q_\alpha P_1 \\
Q_2 &= Q_\beta P_2^2 + Q_\alpha P_2
\end{align*}
\]

\[
Q_\beta = \frac{Q_1 - Q_2}{P_1 - P_2}
\]

\[
Q_\alpha = \frac{Q_1}{P_1} - \frac{Q_2}{P_2}
\]

The \( \alpha \) corrected signal is:

\[
Q_\beta P_1^2 = Q_1 - Q_\alpha P_1
\]
Fun: High Resolution imaging inside implant

-5 V
-8 V
-20 V

Collection time [ns]

-5 V
-8 V
-20 V

Bulk

1.35 1.351 1.352 1.353 1.354 1.355 1.356 1.357 1.358 1.359
1.36 1.361 1.362 1.363 1.364 1.365 1.366 1.367 1.368 1.369

-0.008 -0.006 -0.004 -0.002 0 0.002 0.004 0.006 0.008

M. Fernández - TPA-TCT, Seminar über Teilchenphysik - 21th Dec 2017
TPA in diamond

- Applying standard TCT to diamond because would require a UV laser.
- Using $\lambda_{\text{TPA}} = 400$ nm we did TPA-TCT in diamond
- Picture to the left is just a proof of principle: we got a signal in a diamond device.

That's a first laser TCT in diamond ever!

DAQ, simulation and analysis packages

- We have developed a simulation package called TRACS:
  
  https://github.com/JulesDoc/Tracs

  that simulates any TCT, including TPA-TCT.

- We also have a complete ROOT-based software package to do 3D analysis of TPA data.
Beam coupling to deep motifs

Shallow motif to scan
Small loss due to reflection at the borders
Approximately constant coupling of energy to focus.
**Good layout** for TPA measurement

Deep motif to scan
Very asymmetric coupling to the focus
**Bad layout** for TPA measurement

Si/air reflection affects only near the interface. Elsewhere full beam is contained inside the detector.

Beam is chopped almost everywhere.
Beam reflection at interfaces

TPA: Material is transparent to $\lambda$ before/after the focus

SPA: Direct and reflected beam contribute to signal

Reflection “ghost image” of the beam produces a signal!

Metal layers or Air/Passivation/Si interface

YZ=side view of the implant

Marcos Fernandez - 29th RD50 meeting – CERN – 21-23 November 2016
Comparison of direct and ghost signals

Choosing pairs of waveforms:
1) at the interface
2) ±2 μm away
3) ±10 μm away

Seen reflection of pulses well inside the bulk.

In SPA-edge-TCT this reflection cannot be easily resolved because the beam is continuous.

Top-TPA on LGADs

- Top TPA on LGAD PS protons: $10^{14} \text{n}_{eq}/\text{cm}^2$

Proofs existence of double junction mechanism in LGADs. Impact on Acceptor Removal interpretation
Fig. 1. Setup of the dispersion-managed, Er-doped seed laser.

Fig. 3. Schematic of the complete CPA setup.
SubSurface Laser Engraving (SSLE)
Typically in BK7 Glass (Borosilicate doped with potassium)
Also with pure quartz (SiO₂)
Pico or FemtoSecond Laser, 1064 nm (SiO₂), 532 nm (BK7)
Multi-Photon Absorption
Free electron creation in the focus point
FotoChemistry in Solids:
Index of refraction changes.
Color centers


TJDP-532K Machine (532 nm, BK7 crown glass)
http://www.tianjunlaser.com/
w1f8, 1.3 um, 1e14, -20C
W1D2, $\lambda = 1300$ nm, $10^{15}$ $n_{eq}$/cm$^2$, $-20$ °C (SPA correction)
tleft = 26.8; 
tright = 40.0;

Some values missing! 
Go file by file

Check 200,400 V