3D Laser characterization of semiconductor devices

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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**”

Outline of this talk

3D laser testing = TPA-TCT

What is TPA?  What is TCT?

TPA-TCT on:

Diodes    HVCMOS    Diamond

Not irradiated / irradiated (n)
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
Is there any technique providing 3D spatial resolution?
Is there any technique providing 3D spatial resolution?

Yes
The answer to the question is: Two Photon Absorption TCT

As of now (2016), the only existing demonstrator of the technology has been built in a laser facility in Spain.

What can it offer?

- **True 3D** spatial resolution (only technique achieving this)
- Repeatability
- Easy triggering
- High S/N

Next steps:

1) What is TCT?
2) What is TPA?
3) TPA TCT
What is TCT?

Powerpoint physics
TCT: Transient Current Technique

Allows to probe the space charge of a detector by measuring transport of induced charge carriers

\[
I(t) = N_{eh}Aq_e \nu_{drift} E_W \propto \nu_{drift} = \mu(E)E \Rightarrow I(t) \propto E(z)
\]

Assumption: overdepleted, non-irradiated diode

\[ t = -0 \text{ ns} \]
TCT: Transient Current Technique

\[ I(t) \propto E(z) \]

\[ t = 1 \text{ ns} \]
TCT: Transient Current Technique

\[ I(t) \propto E(z) \]

\[ t = 2 \, \text{ns} \]
TCT: Transient Current Technique

\[ I(t) \propto E(z) \]

\[ t = 3 \text{ ns} \]
TCT: Transient Current Technique

$I(t) \propto E(z)$

$t = 4 \text{ ns}$
TCT: Transient Current Technique

\[ I(t) \propto E(z) \]

\[ t = 6 \text{ ns} \]
TCT: Transient Current Technique

$p$-bulk $p^+ \oplus n^+\ E

\begin{align*}
I(t) & \propto E(z) \\
l(t) & = \text{Induced current pulse}
\end{align*}

\( t = 12 \text{ ns} \)
Measured pulse shows a “picture” of the electric field the carriers encountered during drift.

For an irradiated detector, the picture gets distorted due to trapping of charge carriers. Carriers do not “see” the full E-field profile.

Measured pulse convolutes:

1) EM noise
2) RC_{detector} (low pass filtering)
3) Amplifier transfer function

\[ I(t) \propto E(z) \]
Examples of TCT performance: measured waveforms

**Space Charge Sign Inversion (SCSI)**

- Before irradiation
- $1 \times 10^{14} \text{ p/cm}^2$

**Double Junction effect**

- MCZ n-on-p diode 90 V
- $3.6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

Difference between strip and diode (bottom red injection)
Most of the charge for a strip is induced near the strip → Weighting field

Depth

<table>
<thead>
<tr>
<th>Weighing Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>@Strip center</td>
</tr>
<tr>
<td>Diode</td>
</tr>
<tr>
<td>Depth</td>
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</tbody>
</table>

M. Fernández - SÉMINAIRE DE PHYSIQUE CORPUSCULAIRE, Geneva University - 30\textsuperscript{th} Nov 2016
What is TPA-TCT?
TPA-TCT: A Two Photon Absorption Transient Current Technique

- TPA-TCT is a new TCT method to characterize semiconductors.

- In standard TCT a laser is used to excite the material and create a signal. The signal is however produced across the full laser path. TPA-TCT uses a laser to create a point-like (new!) signal generation volume. This point-like probe can then be 3D scanned across the volume of the sensor.

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

OLD

Single Photon Absorption
Continuous energy deposition

NEW

Two Photon Absorption
Energy confinement
Two photons from one laser!!
TPA: physics background (I)

- TPA-TCT exploits 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 energy of each photon is **smaller than the bandgap** (so individually they can not create an e-h pair), but **the sum of both** is enough to produce one e-h pair → signal.

\[
E_{\text{photon}} \geq E_{\text{gap}} \approx 1.12 \, \text{eV}
\]

\[
E_{\text{gap}} \approx \frac{\hbar E_{\text{gap}}}{2} \approx 0.1 \, \text{fs}
\]
To have simultaneous absorption of 2 photons we need them to be “packed” in space (=focus → use high N.A. objectives) and time. Time packaging provided by **femtosecond** (fs) pulsed mode locked lasers.

**Mode locking** is a way to induce a fixed-phase relationship between the longitudinal modes of the laser’s resonant cavity.
TPA: physics background (III)

- SPA: Probability to create e-h pair is proportional to intensity $\propto I$.

In TPA we need 2 photons, so the probability is $\propto I^2$. The carrier production rate:

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

- We work in a wavelength region where $\alpha$ is very small. Since light is focused $I^2 >> I$ and the second term will be predominant.

- The power of this method depends on $\alpha I \ll \beta I^2$.

- Special attention must be payed to irradiated detectors where $\alpha$ increases with fluence!

- Our measured signal generation volume is an ellipsoid of 1 $\mu$m section and 10 $\mu$m length (see backup)

M. Fernández - SÉMINAIRE DE PHYSIQUE CORPUSCULAIRE, Geneva University - 30$^{th}$ Nov 2016
TPA: physics background (III)

- **SPA**: Probability to create e-h pair is proportional to intensity $\propto I$.

In **TPA** we need 2 photons, so the probability is $\propto I^2$. The carrier production rate:

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

- We work in a wavelength region where $\alpha$ is very small. Since light is focused $I^2 \gg I$ and the second term will be predominant.

- The **power of this method** depends on $\alpha I \ll \beta I^2$.

- Special attention must be payed to **irradiated** detectors where $\alpha$ increases with fluence!

- Our measured signal generation volume is an **ellipsoid of 1 \(\mu\)m section and 10 \(\mu\)m length** (see backup).
Understanding (nano-)women...
TPA-TCT at the SGIKER 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.
**TPA-TCT at the SGIKER laser facility**

- **SGIKER** laser facility in Bilbao (Spain) is a service of the UPV for the academic community. Granted access via RD50 to the R&D laser + 1 staff expert.

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**Diagram:**

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

- Oscillator (OSC)
- Amplifier (AMP)
- Optical Parametric Amplifier (OPA)
- Intensity Autocorrelator: measurement of pulse length (~243 fs)

- CMOS
- BS
- FSW
- OBJ
- DUT [pJ]
- 3D Motors
- DO
- PD
- Power Meter

- Visible light Imaging system

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M. Fernández - SÉMINAIRE DE PHYSIQUE CORPUSCULAIRE, Geneva University - 30th Nov 2016
TPA of an HVCMOS (CCPDv3, HV2FEI4)

\[ \lambda = 1300 \text{ nm}, \Delta t = 240 \text{ fs} \]
TPA on HVCMOS: geometry

- We measure optical test structures. Only DNW, no NMOS/PMOS inside!!

Edge-TPA scan:
- $Z$ propagation direction
- Next slides XY scans
- $\sigma = 1 \ \mu m$ (beam waist)
Application examples: unirradiated HVCMOS

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

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

**Standard SPA-TCT**

Spatially continuous laser source, ps pulses

\[ \lambda = 1064 \text{ nm}, \sigma = 10 \text{ µm}, \text{200 ps-pulsed laser} \]

**TPA-TCT**

Point-like laser source, fs pulses

\[ \lambda = 1300 \text{ nm}, \sigma = 1 \text{ µm}, \text{200 fs-pulsed laser} \]

Substructures resolved with TPA-TCT.
Substructures identified

Undepleted
Depleted ~15 μm

Collected charge map (XY)
Collection time map (XY)

In 3D!

Collected charge map (YZ)
Drift/diffusion discrimination

Probing the implant

Doping concentration

- $\chi^2$/ndf: 7.35/8
- $\rho$ [\(\Omega\) cm]: $14.71 \pm 1.348$
TPA in diamond

- Applying standard TCT to diamond because would require a UV laser.
- Using $\lambda_{\text{TPA}} = 400 \text{ nm}$ 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.
- DAQ is Labview based
TPA of neutron irradiated:
- Diodes
$(10^{13}-10^{16} \text{ n}_{eq}/\text{cm}^2)$

$\lambda=1300 \text{ nm}, \Delta t=240 \text{ fs}$
**TPA on irradiated diodes**

*FZ diodes* produced by **CNM-Barcelona**

\[ \Phi_{eq} = 10^{13} - 10^{16} \text{ n}_{eq}/\text{cm}^2 (\text{neutron irradiation at Ljubljana}) \]

Measurements at -15 °C

**What do we expect for irradiated sensors?**

For the intensity regime where we operate there are linear \((\alpha \rightarrow 0)\) and quadratic \((\beta)\) absorption terms.

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

Linear absorption in Si has been measured to grow with irradiation.

Having a sizable \(\alpha\) contribution to the signal will spoil the spatial resolution along the beam (continuous energy deposition).

Let's see how much linear absorption we have in the irradiated diodes
Irradiated diodes: intensity scan

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

TPA intensity scan done with **focus inside** the detector

SPA intensity scan done with **focus outside** the detector

M. Fernández - SÉMINAIRE DE PHYSIQUE CORPUSCULAIRE, Geneva University - 30th Nov 2016
TPA on irradiated diodes (I)

Is there a way to remove the \( \alpha \) (Single Photon) contribution?

1. \( 10^{13} \) \( n_{eq}/cm^2 \) for TPA+SPA, \( \sim 40 \) Q

2. \( 10^{14} \) \( n_{eq}/cm^2 \) for SPA

3. \( 10^{15} \) \( n_{eq}/cm^2 \) at \( T = -20^\circ C \) for TPA+SPA, \( \sim 1.6 \) Q

4. \( 10^{16} \) \( n_{eq}/cm^2 \) for SPA at \( T = -20^\circ C \), \( \sim 1.4 \) Q

Marcos Fernandez, 2nd TCT Workshop, Ljubljana, October 17th 2016
Let's do a vertical scan. How does it look like in case of SPA for non irradiated?

TCT $\rightarrow$ **induced current** $\rightarrow$ $Q(z) = \text{integrated current as a function of detector position}$
SPA: vertical scans

- **SPA**: IR vertical \((z)\) scan. Assuming depleted detector.
SPA: vertical scans

- **SPA**: IR vertical ($z$) scan. Assuming depleted detector.

Collected charge is $Z$ invariant!
TPA: Ellipsoidal excitation volume. In reality the detector is moved. Here, moving the laser voxel. Detector not irradiated: $\alpha I \ll \beta I^2$.

Note: dimensions exaggerated
TPA: vertical scans

(not Erf(z) since $N(z) \propto I^2$)
TPA: vertical scans

\[ \text{Q}_{\text{tot}}(z) \]

Si
SPA: vertical scans

- **TPA**: Vertical Z-scan: no light absorbed before/after the focus!!
**TPA**: In case of irradiated detectors, $\alpha(\lambda)$ increases with fluence, leading to a reduced $\beta/\alpha$ contrast.
Subtraction of linear absorption

- SPA contribution can be removed cause it is z-invariant!

Two correction algorithms are possible

1) If the depletion width > beam diameter:  
   **Z-scan method**
   - Focus beam outside → measure $\alpha$ contribution.
   - Focus beam inside → measure $\alpha + \beta$ contribution
   - Correct data (focus inside) at waveform level.

2) If the beam diameter is bigger than the depletion region:  
   **Intensity method**
   - Focus beam inside the detector
   - Reduce intensity (so $\alpha I \geq \beta I^2$) → measure $\alpha$ contribution
   - Do not move the focus. Increase intensity and measure $\alpha + \beta$.
   - Subtract $\alpha$
SPC Z-scan correction works
Corrections are done at waveform level
TPA of neutron irradiated:
- HVCMOS (CCPDv3)
  \( (7 \times 10^{15} \text{ n}_{eq} / \text{cm}^2) \)

[no SPA correction accomplished yet]

\[ \lambda = 1300 \text{ nm}, \ \Delta t = 240 \text{ fs} \]
Charge map shows a **rectangular region** with increased charge collection shifted away from junction border. Most likely due to **full beam** there being **inside** the depleted region.
Depletion depth

- **Criteria**: End of depletion region is calculated fitting the rightmost “bump” in rise time. **PN junction** origin assigned to minimum of rise time bump.

\[ \Phi = 7 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \]
\[ N_{\text{eff}} (80\text{ V}) = 5.4 \times 10^{13} \text{ cm}^{-3} \]

Non-irradiated:
\[ N_{\text{eff}} (80\text{V}) = 1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \]
\[ \chi^2 / \text{ndf} = 7.35 / 8 \]
\[ \rho [\Omega \text{ cm}] = 14.71 \pm 1.348 \]

Acceptance removal

\[ \chi^2 / \text{ndf} = 8.325 / 7 \]
\[ \rho [\Omega \text{ cm}] = 320.3 \pm 20.5 \]

**Note**: using other estimators for depleted width (collection time, for instance), we arrive to different numbers. Resistivity can change up to Δρ=100 Ω.cm
Idea of TPA-TCT came during a seminar about TCT (!!) in 2012. Sometimes, seminars are more useful for the speaker than for the audience.

Simulation of the system and first measurements accomplished by 2014. TPA officially presented at 25th RD50 workshop at CERN (Nov. 2014).

Since then we measured: silicon diodes, LGADs, diamond, HVCMOS.

Some improvements to current setup are on the way:
- Sub-\(\mu\)m stepping motors
- Pitch and Jaw platforms

TPA presented in EP-Knowledge Transfer day → Selected and presented for KT Fund Selection Committee. Now waiting an answer:
- TPA can be used in industry as a doping/E-field profiler
- Design debugger
- Live imaging of functioning device
- ...

Alternatively, we would also like to have a TPA-TCT setup at CERN. Market survey of components to setup a desktop TPA-system at CERN.
This mixture has been possible via CERN-RD50 collaboration
Summary

▶ The opening question of this talk “Is there any technique providing 3D spatial resolution?” has been answered positively:

▶ **Two Photon Absorption-TCT** is a new semiconductor characterization technique that allows for 3D spatial resolution \((1 \times 1 \times 10 \text{ \(\mu\text{m}^3\)})\).

Successfully tested on Si and diamond detectors

▶ On **unirradiated** devices TPA shows its full power. We resolved the deep implant of an HVCMOS and even measured inside of it.

▶ In **irradiated** devices, the **radiation-induced** linear absorption smears the contrast of TPA-TCT. Corrections tested and working.

Can we try to minimize \(\alpha\)-contribution? We are commissioning the fs-laser facility in Bilbao to operate at \(\lambda=1.5 \text{ \(\mu\text{m}\)}\), because of the lower linear absorption.

▶ Access to a **fs-laser** is still reduced in our community. We will try to have a table-top fs-laser (fixed \(\lambda\)) at CERN-SSD.

▶ **New RD50 project** to measure non-irradiated / irradiated HV/HRCMOS (different resistivities, collecting electrode geometries...). Institutions welcome to join.
THANK YOU FOR YOUR ATTENTION
fs laser facts for ps laser users

- **Pulse stretching**: Short pulse $\rightarrow$ Wide spectrum $\rightarrow$ different frequencies travel at different speed $\rightarrow$ dispersion. When a fs pulse **traverses material**, the pulse length **increases**. This is not important for ps pulses.
  - Luckily, this broadening **can be corrected** (within limits). Careful choice of optics is needed. Lenses are forbidden. Use mirrors.

- **Wavelength tunability**: Non-linear effects allow to tune the wavelength of the pulse. Second ($2\omega$) and higher order **harmonics** ($3\omega$...) are easily generated. NIR $\rightarrow$ Vis ($2\omega$) $\rightarrow$ UV ($3\omega$)
  - Getting higher wavelengths from a lower one needs of expensive hardware: parametric amplifiers and sufficient energy ($\geq \mu\text{J}$). Table-top (cheap) lasers will be bounded to the wavelength chosen and to the harmonics below.

Careful: fs-laser can **vaporize** the detector ($\text{Si ablation} \sim 45 \, \mu\text{J}/\mu\text{m}^2$, $\mu\text{J}/\text{fs} = 1 \, \text{GW}$)

**In general, do not reach nJ pulses for Silicon**

Pulse width broadening after 20 mm of BK7 for an input pulse of 100 fs
Evidences for TPA process

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

Then characterize the excitation volume:

\[ dN(r, z) = \frac{\beta_2 I^2(r, z)}{2 \hbar \omega} \]

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

\[ w(z) = w_0 \sqrt{\frac{\lambda z}{\pi w_0^2 n}} \]

\[ I(z) = \frac{2P}{\pi w^2(z)} e^{-2r^2/w^2(z)} \]

\[ t \sim t_p \rightarrow N(z) = \int_{-\infty}^{\infty} 2\pi r \cdot t_p \cdot N(r, z) \, dr \]

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

**New RD50 project to perform edge-TPA on irradiated diodes**
Differences between TPA and SPA scans (I)

TPA: collected charge increases quadratically with power.

SPA: collected charge increases linearly with power.

⇒ Work in a power regime where $\beta \gg \alpha$ but without producing plasma.

- For this detector.
- Laser power $< 80\ pJ$
⇒ no plasma effect.
Tested device: HVCMOS HV2FEI4 (aka CCPDv3)

- HVCMOS sensors are partially depleted MAPS implemented in **low resistivity** CMOS technology, able to withstand voltages **up to 100 V**.

- The deep n-well (DNW) is both the substrate for shallow transistors and the collecting diode.

- Due to the low resistivity and maximum voltage granted by the technology, the maximum depletion depth is of the order of **10 µm** ← Tough for SPA methods

- For this experiment, laser illumination from the **edge of the detector**.
Beam reflection at interfaces

TPA carrier generation volume (focus) does not produce a signal cause it is outside the active region.

Reflected beam

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!

YZ=side view of the implant
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 can not be easily resolved because the beam is continuous.


Marcos Fernandez - 29th RD50 meeting – CERN – 21-23 November 2016
Irradiated HVCMOS, time variables

In irradiated Si, linear absorption $\alpha$ grows:
3D resolution in TPA of irradiated detectors looks more like a 2D resolution

Collection time map is smeared by charges coming from above/below focus point.

Testing Rise Time (RT, 10-90%) as estimator to identify junction position.

E-field $\propto$ Rise Time:
Higher E-field $\rightarrow$ faster pulses $\rightarrow$ Smaller RT

Expecting lowest RT at junction border.
E-field comparison

- Biased to -60V, operating voltage of device
- All electric fields are roughly the same:
  - higher value at edges of the deep n-well
  - Lower value in deep n-well and outside depletion
- One difference: 2D full model has a higher electric field value in the oxide because of the metal layer
**SubSurface Laser Engraving (SSLE)**
Tipically 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/