Determination of E-field in Two-Photon TCT: application to the E-field mapping of irradiated LGADs

Marcos Fernández(1), Richard Jaramillo, Iván Vila

Raúl Montero

Michael Moll

Rogelio Palomo

(1) Also visiting scientist at CERN
Outline

Motivation

Transient Current Techniques: TPA-TCT

Calculation of E-field, the scaling problem

Examples of E-field calculation

Edge-TCT on diodes
TPA-TCT on diodes
TPA-TCT on LGAD

Work carried out within RD50 collaboration
Motivation

Two (not excluding) hypothesis for gain reduction in LGADs:

1) **Acceptor removal** in the gain layer or

2) **Double Junction mechanism**

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Two-Photon-Absorption TCT measurement of CNM-LGAD irradiated to $10^{14}$ $n_{eq}$/cm$^2$ shows:

- **0-95 V**: depletion starting from the backside
- **96-100 V**: double junction shape
- **>100V**: junction at the front and develops to the backside

How sound is this E-field calculation?
Transient Current Techniques
Technique that allows to study the **current induced** by excess charge carriers produced, typically, by a **laser**.

**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
Two Photon Absorption-TCT

SPA
Single Photon Absorption
Continuous energy deposition

TPA
Two Photon Absorption

Fluorescent solution

Spot size

Two Photons \((E > E_{\text{gap}}/2)\) must be coincident in time (pulsed mode-locked lasers) and in space (microfocusing) \(\times 100\) objective

Laser facility at Bilbao (Spain) UPV
Access granted thanks to RD50 collaboration

Absorption in Si

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

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

Single Photon Absorption
No spatial resolution along the beam propagation direction

Two Photon Absorption
Point-like resolution
Boosted by getting away from SPA region and increasing irradiance so \(I_2 \gg I\).

Handle: use fs laser

13\textsuperscript{st} Trento Workshop – Marcos Fernández
The problem: calculate E-field in absolute units

Detector response to a pulse of light

\[ I_{\text{total}}(t) = N_{e,h} q_e A \cdot e^{-t} \cdot \vec{v} \cdot \vec{E}_W \]

**Charge** scale can be fixed comparing with a MIP and using 1 MIP=76 e-h/µm.
This does not hold for irradiated detectors
Scaling for drift velocity is not straightforward
Systematics for the calculation of E-field scale

SPA edge-TCT:

**Reflections** at the air-surface interface (inward and outward) → number of photons is not constant.

**Attenuation** depth along direction of propagation (mm) modify number of photons

Mitigated using strip detectors + weighting field

**Illumination** below GR and unactive regions for detection

TPA-TCT:

Only normal reflections.

**Attenuation** along beam direction is **minimal** because of small detector thickness.

A diode is the best geometry because of **constant weighting** field.
Scaling of drift velocity (I)

As a **first approach**, we will use the prompt method (Kramberger, IEE TNS vol57 4, 2010), based on Ramo's current. For a diode ($E_{w} = 1/d$) and constant mobility, the total induced current is:

$$I_{\text{total}}(t) = \frac{N_{e,h} q_{e} A}{d} \cdot \frac{e^{-t}}{\tau} \cdot (\mu_{e} E(z) + \mu_{h} E(z))$$

**First simplification**: mobility is constant. $I_{\text{total}}(t) = k e^{-\frac{t}{\tau}} (\mu_{e} + \mu_{h}) E(z)$

For a fixed bias $E<1 \text{ V/\mu m}$ in a diode→ $\mu_{e} (\mu_{\eta})$ typically varies ~20%(10%).

Better applicability for overdepleted detectors with "flat" velocity profiles ("small" Neff, high resistivity)

(faster variation for $e$ than $h$)

13th Trento Workshop – Marcos Fernández
Scaling of drift velocity (II)

For $t \sim 0$:

$$I_{\text{total}}(t \sim 0) = k \left( \mu_e + \mu_h \right) E(z) = k' E(z) \quad \Rightarrow \quad E(z) = \frac{I_{\text{total}}(t \sim 0)}{k'}$$

**Prompt method:**
Drift velocity profile can be calculated except for a proportional factor from the rising edge of the induced current.

To calculate $k'$ we use the constraint that the electric field integrated over the thickness of the detector gives the bias. **Experimentally** this can be realized as a Z-scan in edge-TCT or a normal scan in TPA.

$$V_{\text{bias}} = \int_0^{w(V)} E(z) \, dz = \int_0^{w(V)} \frac{I_{\text{total}}(t \sim 0)}{k'} \, dz \quad \Rightarrow \quad k' = \frac{\int_0^{w(V)} I_{\text{total}}(t \sim 0) \, dz}{V_{\text{bias}}}$$

Different $k'$ for each bias.

By construction:

$$V_{\text{bias}} = \int_0^{w(V)} E(z) \, dz$$
Meaning of $t \sim 0$

The picture obtained for different $(t \sim 0)$ is the same except for a normalization constant.
The resistivity calculated from Vdep~5 V gives a resistivity of 14.5 kΩ.cm.

Nominal is >10 kΩ.cm.
Doping resistivity can be calculated from the slope of the E-field, once the scale is known.

\[ E(x) = \frac{2V_{di}}{d} \left(1 - \frac{x}{d}\right) + \frac{V_b - V_{di}}{d} \Rightarrow \text{slope} = 2V_{\text{dep}} / d^2 \rightarrow N_{\text{eff}} = \frac{\epsilon}{e} \cdot \text{slope} \]

The result for this detector is 14 kΩ.cm

However this method is not robust. A small change in the slope gets amplified by the \( \epsilon/e \) factor (error is roughly x10 bigger than from Vdep method).
E-field calculation in TPA top-TCT

From depletion voltage: \( V_{\text{dep}} = 35.7 \) V
\( \text{Neff} = 8 \) k\( \Omega \).cm

From slope: 7.8 k\( \Omega \).cm

PiN 7859_W1_A6_3 (different detector)

Two independent estimations of the nominal resistivity (12 k\( \Omega \).cm):
- From depleted width (CV-like): 8 k\( \Omega \).cm
- From E-field slope: 7.8 k\( \Omega \).cm
E-field calculation in LGAD p-irradiated $1\times10^{14}$ n$_{eq}$/cm$^2$

Gain at the front does not seem to impact drift velocity/charge profiles.

Drift velocity scaling calculated discarding Gain.
Conclusions

Thanks to the point-like excitation volume inherent to TPA the problem of calculation of Electric field inside a detector using Ramo theorem is simplified.

As a first attempt, we used the current prompt method and the bias constraint to extract the proportionality factor. Electric field and doping concentration calculated for diodes and an irradiated LGAD.

Next: use simulation package TRACS to account for mobility changes with E-field and fit for effective space charge.

A TPA-TCT system is being built at CERN-SSD and will be commissioned at the end of 2018, thanks to CERN-KT funding.
Backup
Mult. layer dose $1.8 \cdot 10^{13} \text{ cm}^{-2}$, $\Phi_{eq} = 10^{14} \text{ cm}^{-2}$, $T = -20^\circ\text{C}$
Sweeping vs averaging

Short sweeps average laser power oscillations
Two Photon Absorption-TCT

SPA
Single Photon Absorption
Continuous energy deposition

TPA
Two Photon Absorption
Energy confinement

Two Photons must be coincident in time (pulsed mode-locked lasers) and in space (microfocusing)

σ = 1 μm

σ = 10 μm

x100 objective

Setup
3D stages
N₂ cooling

Two Photon Absorption
E_{gap}/2
E_{gap}/2
0.1 fs

Non-irradiated

Fluorescent solution

Objective
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 \( \beta \).

\[
\begin{align*}
W_0 &= 0.95 \pm 0.05 \, \mu m \\
\text{Ellipsoid length} &= 13 \, \mu m
\end{align*}
\]

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

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

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

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

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**