Diamond Edge-TCT

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The Transient Current Technique

Such setup is able to measure:
- total collected charge versus injected charge → charge collection efficiency
- drift speed and mobility of electrons and holes
- charge carrier lifetimes

Different sources of excitation possible: α-, β-sources, sub-bandgap lasers, ..
Advantages of Edge-TCT over traditional TCT

Particle traverses the whole sensor
Absorption in the first micrometers of the surface

Trapping & E-Field entangled
+ bad position resolution
+ deposited energy not easily selectable
+ screening effects in case of $\alpha$-particles
+ source handling

Multi-Photon Absorption Laser Edge-TCT solves those problems by:
✓ generate charges in a selected position with micrometer precision
✓ control the amount of injected charge through varying laser pulse energy
✓ directly measure the electric field
✓ trigger on the laser pulse
✓ do 3D scans of the sensor bulk, which is not possible with sub bandgap laser TCT
Working Principle of Edge-TCT

Extractable Quantities:

- electric field (independent of trapping) → space charge
- trapping times
- saturation velocity
- mobility of electrons and holes
- ..
Setup at ETH Zurich without electric shielding and light-tight box

1kHz, 800nm, ~100fs

1 λ/2 waveplate
2 polarizing cube
3 alignment irises
4 mirrors
5 barium borate crystal
6 focusing lenses
7 100x attenuator
8 dichroic mirror
9 short-pass filter
10 beam splitter
Oscilloscope
LV supply
DAQ PC
Amplifier
xyz-stage
xyz-stage control
high voltage supply

Setup at ETH Zurich without electric shielding and light-tight box
Charge Carrier Generation

Key Characteristic: Localized generation of charge carriers by multi-photon absorption

\[ E_Y < E_{\text{Gap}} \]

Very dense spatial and timed packing of photons required to have two photons ‘in the same place at the same time’!

→ Focal Point of Femtosecond Laser
Electronic Band Diagram of Diamond
1-, 2-, and 3-photon absorption through **indirect** and **direct** bandgap

**Direct Bandgap**
required energy = 7.3 eV / 170 nm
1-photon absorption
2-photon absorption: $E_\gamma = 3.65$ eV / 340 nm
3-photon absorption: $E_\gamma = 2.43$ eV / 510 nm

**Indirect Bandgap**
required energy $\approx 5.47$ eV / 226 nm
(minus phonon contribution and exciton energy)
1-photon absorption
2-photon absorption: $E_\gamma \approx 2.74$ eV / 453 nm

**Laser**
- photon energy **3.1 eV** (400 nm)
- $\sim$100 fs
- 0.1-5 nJ pulse energy eq. to $2 \times 10^8 - 10^{10}$ photons/pulse
- 1 kHz repetition rate
Beam Characterization

Result from beam profiling with the knife-edge technique

Beam profile from knife-edge scan in air

Better focusing $\rightarrow$ higher opening angle of the beam $\rightarrow$ smaller possible depth of scan.

Beam profile change due to refraction

Focus position: 58.215 +/- 0.004 mm
w0: 1.49 +/- 0.18 um
Rayleigh length: 49.6 +/- 6.9 um
Beam opening angle: 3.43 deg (theta=1.72deg)
M2 (beam quality): 0.7
Basic Optics
Refraction/Reflection

When light from an optically thin medium enters into a optically thick one the beam refracts toward the normal. – Snell’s law

✓ Focal point position can be modeled with Snell’s law. (Finite elements simulation does not fully agree with approximation.)
Charge Carrier’s Generation Volume
Theoretical prediction of voxel volume with current lens setup

Beam intensity profile in air

Absorbed power per volume for 2PA

2PA $\propto |I|^2$

Absorbed power per volume for 3PA

3PA $\propto |I|^3$

> 90% contribution

< 10% contribution
Selected sCVD Diamond Sample
The results shown in the following slides stem from measurements on this diamond

- bought from Element 6 (through DDL)
- Poor CCD performance
  - requires high field (0.7 V/μm) to collect full charge
- thickness – 540 μm
- Not irradiated
- pad metallized by Rutgers University (TiW sputtered with shadow mask) (we usually do Cr-Au ourselves)
- metallization distance from edge ≈400 μm (new: 150 μm)
- 2 edges polished
Presented Results

Charge Collection Map

Mobility Measurement

\[ \mu_{0,h} = 199.2 \pm 7.3, \quad \nu_{\text{sat},h} = 125.3 \pm 3.5 \]
\[ \mu_{0,e} = 126.6 \pm 2.5, \quad \nu_{\text{sat},e} = 113.1 \pm 1.5 \]

\[ v_{\text{drift}}(E) = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{\nu_{\text{sat}}} v_{\text{sat}}} \]

Waveforms

Electrical Field inside Sensor
Waveforms

hit positions

$\Delta z \approx 1 \text{ mm}$

$E_{\text{Bias}} = -2.6 \text{ V/\mu}m$

Amplitude [mV]

0  25  50  75  100  125  150  175

Time [ns]

0  1  2  3  4  5  6

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The collected charge at every scan point can be calculated as

\[ Q = \int_{t_a}^{t_b} I(x, y, z, t) dt \]

where \( t_a \) and \( t_b \) denote the integration times, and were usually chosen to be 0-200ns.
Mobility Measurement

The mobility describes the relationship between drift speed of the carriers and the electric field.

This is how it was measured:

1) **Find the edges of the sensor:**
   By plotting the charge of several y-scans (red curve=average) the edges can be fitted with complementary error functions.

2) **At a given voltage inject charges at different y-positions** and measure their drift time by fitting the resulting current pulses.
3) Speed Measurement

By fitting leading and trailing edge of the pulses the drift time can be extracted. Naturally the drift speed is \( \text{drift distance} / \text{drift time} \).

One problem is the electric field profile, that directly affects the measurement:

One solution is to measure the average drift speed from one detector edge to another (similar to surface injection).

4) Extrapolation
5) Error Propagation ..

Do this for many different bias voltages
Mobility Result

\[ \mu_{0,h} = 199.2 \pm 7.3, \; v_{sat,h} = 125.3 \pm 3.5 \]
\[ \mu_{0,e} = 126.6 \pm 2.5, \; v_{sat,e} = 113.1 \pm 1.5 \]

\[ v_{\text{drift}}(E) = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}} \]

A comparison plot of mobility results from ‘Pernegger (JAP)’, ‘Pomorski (PSS)’ and ‘IJS Ljubljana’ can be found in the Backup.
Electric Field Measurement

For every averaged waveform in a y-scan we look at the rising edge of the pulse.

The integral of the rising edge (red square) is a measure for the immediate carrier drift after the laser pulse.

\[ I_{\text{prompt}} \propto I(t=0) \]

Drift distance only 20 – 40μm during rising time.

→ ignoring carrier trapping
Electric Field Measurement

\[ I_{e,h} = A \cdot e_0 \cdot N_{e,h} \cdot e^{-\frac{t}{\tau_{eff}}} \cdot v_{e,h} \cdot W \]

\[ I_{e,h}(t = 0) = A \cdot e_0 \cdot N_{e,h} \cdot v_{e,h} \cdot \frac{1}{d} \]

\[ I_{e,h}(t = 0) = \text{constant} \cdot \mu_{e,h}(E) \cdot E \cdot \frac{1}{d} \]

\[ 0 = I_{e,h}(t = 0) - \text{constant} \cdot \mu_{e,h}(E) \cdot E \]

Use ‘Bisection Method’ to solve for \( E \) with the constraint that:

\[ V_{Bias} = \int_0^d E \, dy \]
Results

Electrical field map at constant bias voltage

Electrical field profiles at constant bias voltage

Electrical field profiles at different bias voltages for the same position → does not vary much with electric field
Future Studies: Measurements of 3D pCVD Diamond Detectors

**Parameters**
- Cell size: 150μm x 100μm
- Bias voltage: +45V
- Laser pulse Energy: 0.6 nJ
Conclusions

 ✓ Edge-TCT proofed to be a viable option for sCVD (and pCVD) diamond detectors
 ✓ We have a fully automated and working setup to measure
 ✓ The analysis techniques were worked out together with people from Ljubljana (Marko Mikuž and Gregor Kramberger)

Outlook

 o Find the origin of rate dependence in irradiated sCVD diamonds
 o Is there a correlation between dislocations/lattice defects and the electric field in the sensor?
 o Do the measurements change at different temperatures?
 o How does the electric field change under a strong β-source over time?
Detector Simulation with KDetSim

Example: Charge injection example along a linear path

No RC filter applied!
- Injection along a laser beam line
- No space charge
- Diffusion = on
- No RC filter
- No trapping

Simulation allows to model signal’s shape:

holes
(2200, 300) → (2300, 400) MIP Track

electrons

- Laser beam

holes ≈ 7.7 µm/ns
electrons ≈ 5.8 µm/ns
Detector Simulation
Effect of the electric field close to the edge of the metallization

Effects due to non-uniform electric fields become apparent close to the edge of the metallization.
Space Charge Experiments with KDetSim
The goal was to find a space charge distribution that would resemble the waveforms seen in reality.

Another way to modify the signal shape is with space charge

→ cubic space charge distribution
→ Injection along a line
→ No RC filtering
→ No trapping

Very preliminary!

Cubic toy space charge model!

y=50µm

y=450µm

slowly falling

Very preliminary!
Comparison of Mobility Results

![Graph showing comparison of mobility results](image-url)
Other Projects
In-House Sensor Making

Procedure for making strip- and pad-detectors developed at ETH’s FIRST cleanroom
Order of Photon Absorption

Purely quadratic dependence between beam power and signal $\rightarrow \text{2 PA}$

Fit Function: $p_0 \cdot x^{p_1} + p_2$

$\chi^2 / \text{NDF} = 1.892 / 11$

$p_0 = 31.89 \pm 3.01$

$p_1 = 2.07 \pm 0.10$

$p_2 = 0.04 \pm 0.06$