Effects of trapping on the collected signals from subsequent laser pulses in irradiated silicon sensors

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Preface:

- Known: Trapping and recombination reduce the collected charge in irradiated silicon strip sensors.
- Defects have not negligible detrapping times at operation temperatures (e.g. -20°C).
- Trapped charge has an influence on subsequent pulses.
- Open points: Is it recombination or an electric field change, necessity of a model to describe the effects.

Materials:

- P-type silicon diodes, irradiated with neutrons.
- Fluences of 1 and 2e15 \( \frac{n_{eq}}{cm^2} \).

Methods:

- (Edge and) Top-TCT measurements, using subsequent laser pulses of different intensities and time distances.
- Simulations.
Interpretation

Electric Field change model:

- Trapped charges change the eff. Doping concentration and thereby the el. Field
- Trapping of electrons reduces the depletion width, trapped holes increase it
- This would mean:
  - Intensity dependence: Amount of trapped charges determines speed of field change
  - Voltage dependence: Effect reduces if sensor is fully depleted / velocity is saturated
  - Delay dependence: Field change is only temporary, if enough charges detrap, the effect gets smaller
Top-TCT measurements

Fluence: $1 \cdot 10^{15} \, n_{eq}/cm^2$

- Higher intensity increases the slope of the decrease
  - More charge is created and trapped
  - For low intensities: Trapped charge not sufficient to change electric field

Voltage: 70V
Delay: $\sim 2.8 \, \mu s$
Top-TCT measurements

Fluence: $1 \cdot 10^{15} \, n_{eq}/cm^2$

- Low Voltages: Fast decrease, almost no pulse left
  - Peak pulse amplitude depends strongly on el. field peak amplitude
  - Low el. field vanishes fast -> flat / overturned el. field profile
- High Voltages: Decrease Vanishes
  - Velocity is already saturated, measurement is insensitive to the el. field peak amplitude decrease
Top-TCT measurements

Fluence: $1 \cdot 10^{15} \, n_{eq}/cm^2$

- Short delays: Less charge is detrapped
  - El. Field change processes faster
- Long delays: More charges detrapped:
  - El. field changes the same with each pulse, but already starts to change back to the original el. field configuration
Simulations

- Done with kDetSim
- Laser beam on sensor top, charge is created in buckets
- Buckets are followed till the junctions, calculating the amount of trapped charge
- Re-Calculation of electric field, effective doping concentration and trapped charges for each pulse
- Variables: Voltage, $N_{eff}(0)$ (fluence), laser intensity, number of defects

El. Field @200V, Neff: $7e12 \text{ 1/cm}^3$, diode

Beam spot

1st pulse
Holes
Electrons
Total charge

Position of 2D-el. field plots
Example:
- Doping Concentration $7e12 \ 1/cm^3$
- 200 V
- Total of $\sim11500$ carriers created

➢ Amplitude ca. only half in the end

*Note: Simulation is NOT considering pulse delays (more detrapping)*

Maximal Amplitudes
Higher Laser intensity:
• Doping Concentration $7e12 \text{ 1/cm}^3$
• 200 V
• Total of $\sim23100$ carriers created

➢ Faster decrease, max. Amplitude only about 1/3 in the end, “saturation” reached
Extreme case:

- Low eff. Doping concentration
- Low voltage (100V)
- High number of defects

➤ Pulse basically vanishes, el. field turned around (now field left where laser hits)
Fit Model (Work in progress)

Simulation: Observation of the change of the electric field with the trapped charge, but: neglected so far the detrapping between pulses
  ➢ (More charge trapped -> faster detrapping! → more exponential behavior)

Approach: Describe easily the current peaks following a very approximated model in order to proof that the polarization is what is really happening

Fit:
- Top- TCT
- Diodes
- Non-depleting bias voltage

Assumptions:
- Constant Neff => triangular field
- Capture of holes only, decreasing the negative space charge
- Uniform capture per depth, field independent (Error here, work in progress)
- Same trapping at every laser pulse
- Full trap occupation in the space charge (captured holes tends to emit completely)
- Current peak proportional to el. field peak $E_0$
Fit Model (Work in progress)

• At every pulse: \( n_t(t_{\text{pulse}}) = n_t(t_{\text{pulse}}^-) - \delta n_t \), where \( n_t \propto \text{intensity} \)

• Trap occupation evolution between pulses:

\[
\frac{dn_t}{dt} = e_p (N_t - n_t) \rightarrow -\frac{dp_t}{dt} = e_p p_t
\]

\[
p_t(t) = p_t(\infty) - [p_t(\infty) - p_t(t_{\text{pulse}})] e^{-\frac{t}{\tau}}, \quad \tau = e_p \propto T^2 e^{\frac{E_{\text{act}}}{K_b T}}
\]

• From the assumptions: \( p_t(\infty) = 0 \rightarrow p_t(t) = p_t(t_{\text{pulse}}) e^{-\frac{t}{\tau}} \)

• At every pulse \( i \), after pulse repetition time \( \Delta T \):

\[
p_t(iT) = p_t((i - 1)\Delta T) e^{-\frac{\Delta T}{\tau}} + \delta n_t
\]

\[
\rightarrow p_t(i) = \sum_{k=0}^{i} \delta n_t e^{\frac{kT}{\tau}} - \delta n_t
\]

\[
\rightarrow p_t(i) = \delta n_t \frac{1-e^{-\frac{\Delta T(i+1)}{\tau}}}{1-e^{-\frac{\Delta T}{\tau}}} - \delta n_t
\]

with \( p_{MAX} = N_t \)

• El. Field peak: \( E_0 = \sqrt{2e(N_{eff} - p_t(i))V} \)

• Current peak:

\[
I_{PK} \propto \left[ n_e \frac{v_{se} E_0(i)/E_{ce}}{\sqrt{1+(E_0(i)/E_{ce})^2}} + n_h \frac{v_{sh} E_0(i)/E_{ch}}{1+(E_0(i)/E_{ch})^2} \right]
\]

where \( n_e = n_h \propto \text{intensity} \), for \( v_{se}, E_{ce}, v_{sh}, E_{ch} \)

see [Scharf, Klanner, NIM A 2005]
Currently: Study of the dependencies of the slope to confirm the model:

- vs pulse repetition time
- vs bias voltage
- vs intensity

Note: Parabolic dependence on intensity means no recombination but trapping!
• Observation: Assuming constant trapping density does not reproduce the results
  ➢ Larger voltage results in a lower slope

• Improvement: Considering lower trapping densities for larger carrier velocity as expected
  ➢ Work in progress!
Conclusion

- Trapping has a significant impact on the signals created by subsequent laser pulses

- Systematic measurements proofed the dependence on laser intensity, delay time and voltage

- Explained by a change of el. field in the sensor: polarization effect
  - Confirmed by simulations

- Work in progress
  - Fitting a trapping-detrapping model to the data
  - Extract trapping and detrapping parameters

- More studies and simulations are necessary to investigate the possible impacts for applications
  - MIP – like particles, electrons and holes created through the entire sensor
  - Charge multiplicative sensors (e.g. LGADs), large amount of charge carriers, possible impact on multiplication layer?
Conclusion

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Thanks for your attention!
Backup

Irradiated Sensor, 2e15, 500V

Graphs showing current vs. time for different voltages and delays.
Extreme case:

- Low eff. Doping concentration
- Low voltage (200V)
- High number of defects

- Pulse basically vanishes, el. field turned around (now field left where laser hits)
• **Charge multiplication**
  
  • High field close to strip implants saturates carrier speed and produces “hot” carriers.
  • Hot carriers cause impact ionization: electron-hole pair creation.
  • Avalanche mechanisms: charge collection diverges.

• **Plasma effect**
  
  • Free carriers are not negligible and influence the electric field distribution: screening effect -> charge „clouds“ travel slower.
  • Carriers drift apart due to diffusion and electrostatic repulsion -> lateral spread.
    • Increases charge collection time by so-called plasma time.
Bacup: Setups and Techniques

Edge-TCT Measurements

Use of a fiber splitter and cables of different lengths to alter the delay of one pulse
Small intensity loss due to cable length and junctions
Otherwise no difference between the pulses

- 30 single pulses send
- Measured for different laser intensities
- Besides small artifacts at low intensity, no change visible for all pulses

Measured with non irradiated sensor, fully depleted, at one depth
Signal Generation

- If sensor not fully depleted → no signal expected from non depleted area
- Signal pulse time expected to be approximately constant
- In Charge Multiplication: Additional contribution to the signal first from multiplied electrons, then from multiplied holes
Irradiated Sensor, 2e15

- Different delay: Impact on the charge decrease
- For longer delay: Detrapping already in progress
- Small fluctuations due to resolution, but trend is stable

All measurements at 1100 V, temperature of ~-30°C, ~50 μm beneath strips