Investigation of the amplitude decrease in subsequent pulse detection in irradiated silicon sensors

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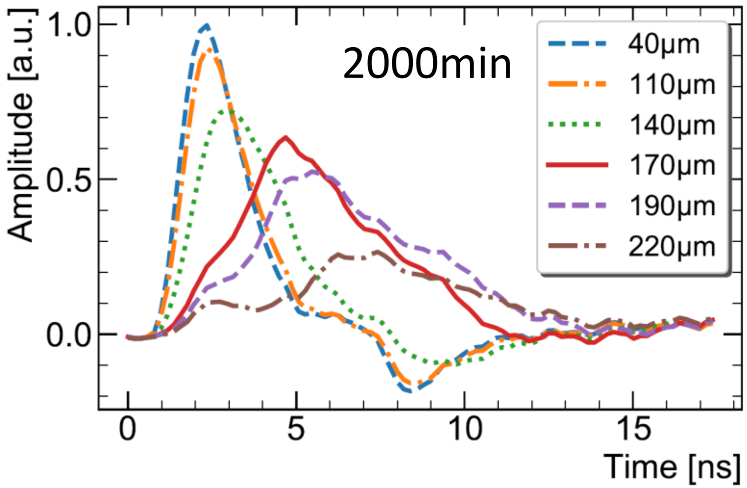
Recap:

$\mathbf{1 \cdot 10^{15}\ n_{eq}/cm^2}$,
annealed at 70°C, 1100 V

- Signal change in edge-TCT measurements observed during annealing
- Increase of signal duration in enhanced CM
- Appearance of signal from the undepleted sensor back
  - Exhibiting the most significant changes
  - Longer and slower than expected
- Explanation: charge created previously changes the electric field in the sensor + multiplied charges screen themselves from the present field (plasma effect)



- Goal of new study: Investigate the effect of charge created previously on the electric field

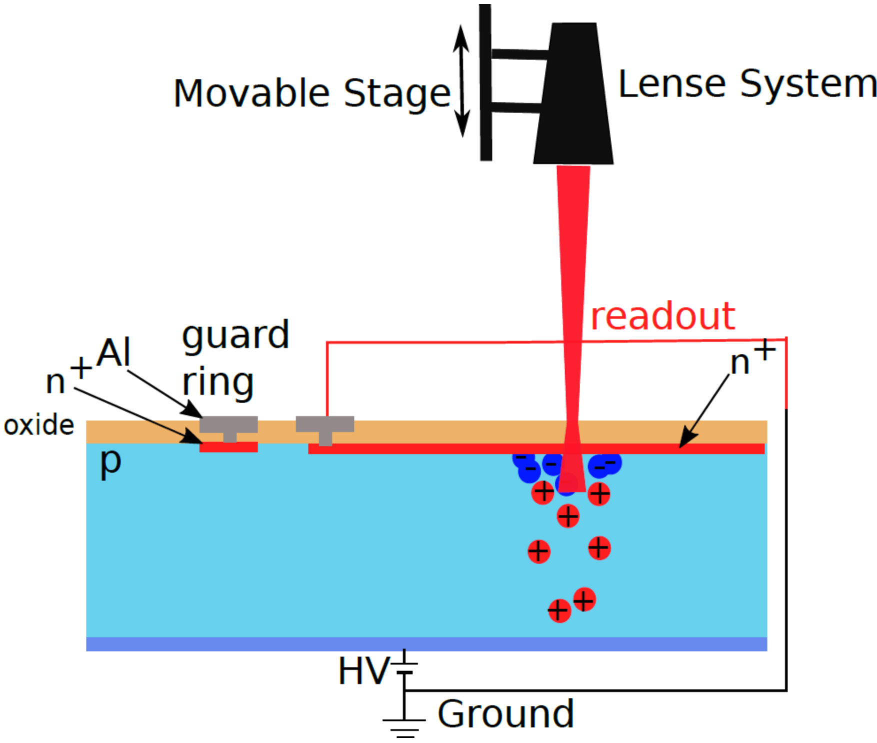
Measurement Setup

Transient Current Technique

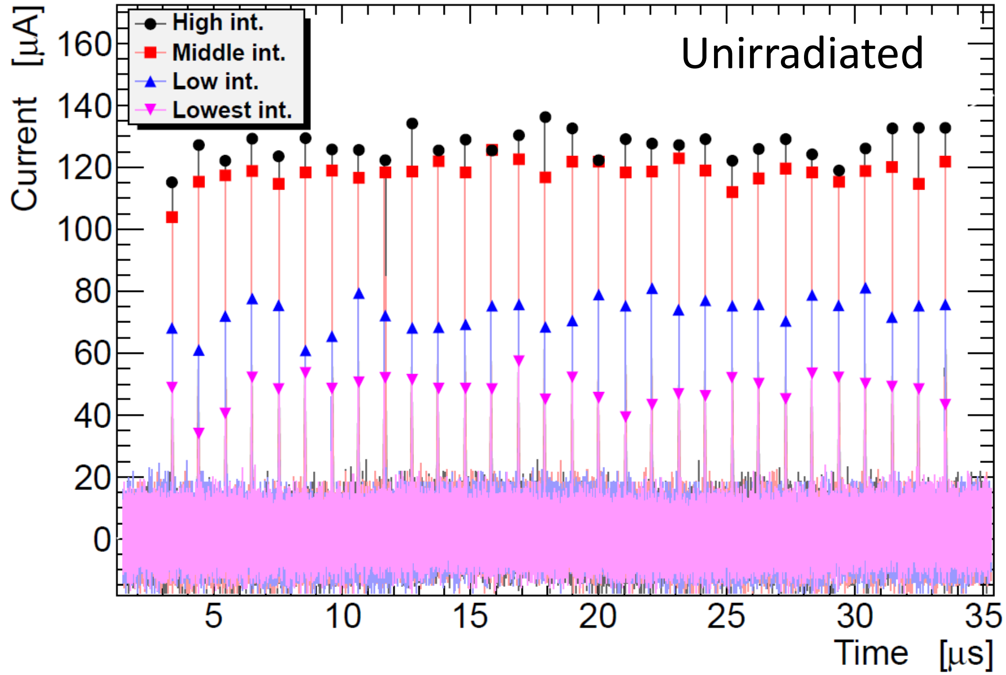
- Red laser (640nm) beam directed on the sensor top, creating charges only few μm deep
  - Signal peak amplitude mostly depending on electric field peak
  - Only holes traveling to the sensor back

- Drifting charge carriers create a signal on the readout channel, which is amplified and recorded

- Used sensors: 1x1 cm^2 p-type diodes and strip sensors , 300 µm thickness, irradiated to 5e14, 1 and 2e15 $\frac{n_{eq}}{cm^2}$ with reactor neutrons

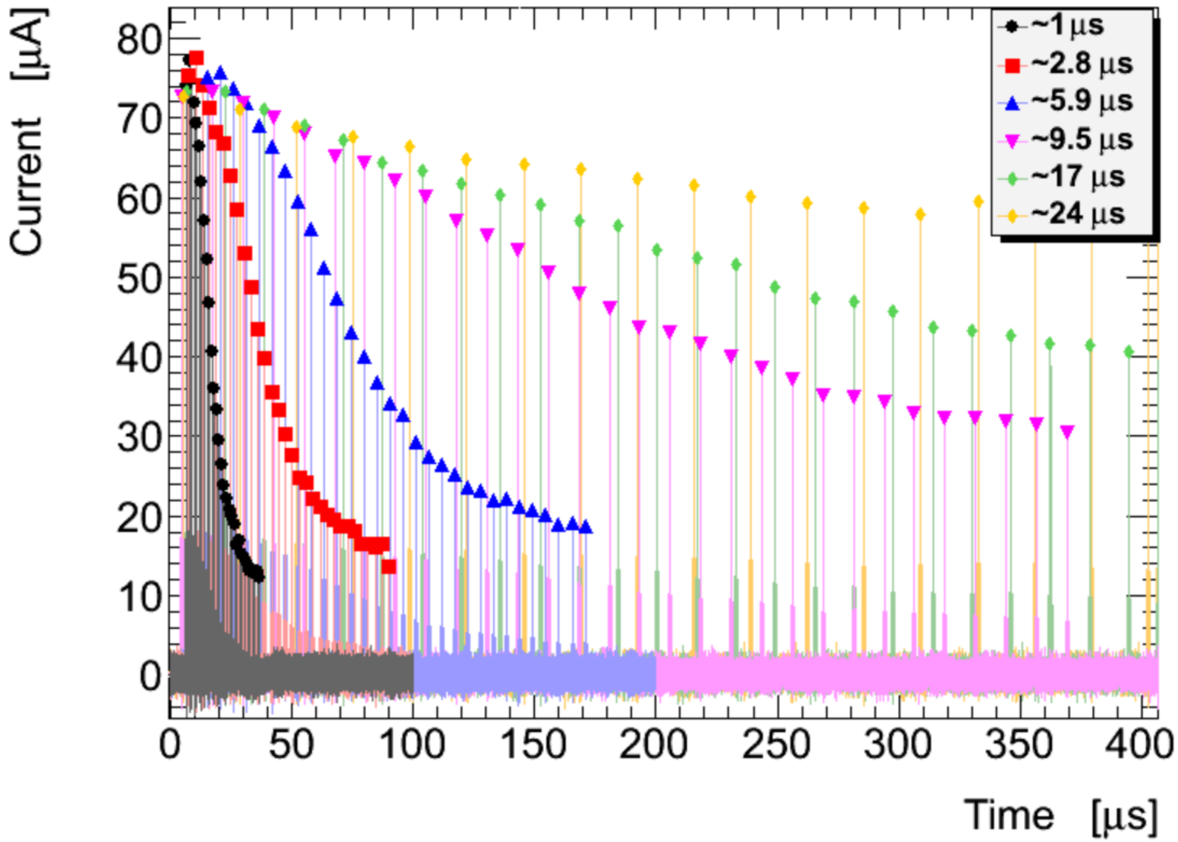


Measurements to Investigate Trapping Effects



- To investigate the effect: Send 30 individual laser pulses to the sensor
- Time delay and laser intensity are programmable
- Without trapping: Roughly same signal amplitude expected for all pulses

Dependence on delay

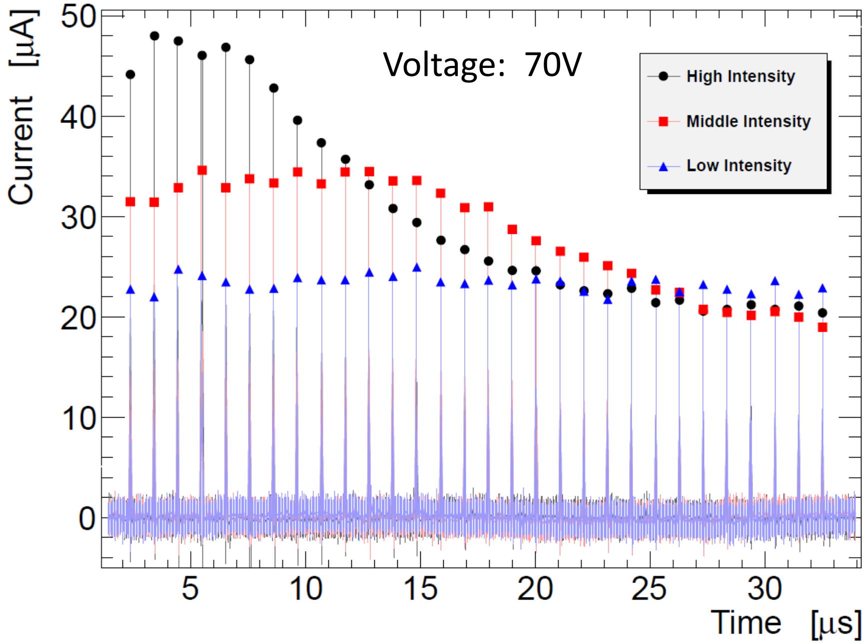


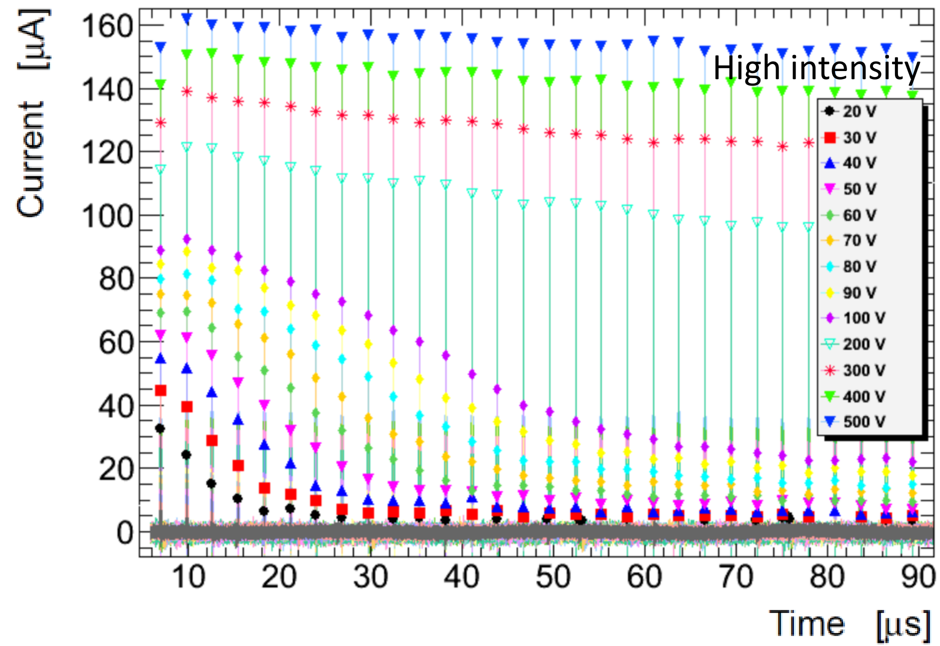
Voltage: 100V
High Intensity
Fluence: 2e15 $\frac{n_{eq}}{cm^2}$

- With irradiated sensor: Significant decrease observed
- Short delay: Little to no detrapping, field change more significant
- Longer delay: More charge already detrapped, field change already relaxing again

Experimental Results

Dependence on intensity and voltage





- Intensity dependence:
  - ➢ High intensity: More charge is created and trapped
  - ➢ Low intensy: Trapped charge not sufficient to change electric field

- Voltage dependence:
  - ➢ Low voltage: El. field vanishes fast -> flat / overturned el. field profile
  - ➢ High voltage: Velocity saturated, measurement insensitive
    - → Less trapped charge due to faster drift?

Fluence: 1e15 n_{eq}/cm^2
Delay: ~2.8 μs

Explanation: Polarization or Relaxation

Known: There has to be a change of the electric field distribution

- ➢ Previously flowing charge is the reason, but in what form?

1) Polarization
   - ➢ Trapping of generated charge in the entire sensor area, especially at the edge of the depletion zone
   - ➢ Electric field change until the charges are detrapped

2) Relaxation
   - ➢ Highly irradiated silicon behaves like a relaxation semiconductor (relaxation time > lifetime)
   - ➢ Trapping only in the non-depleted part of the sensor

The two explanations produce similar effects, but:

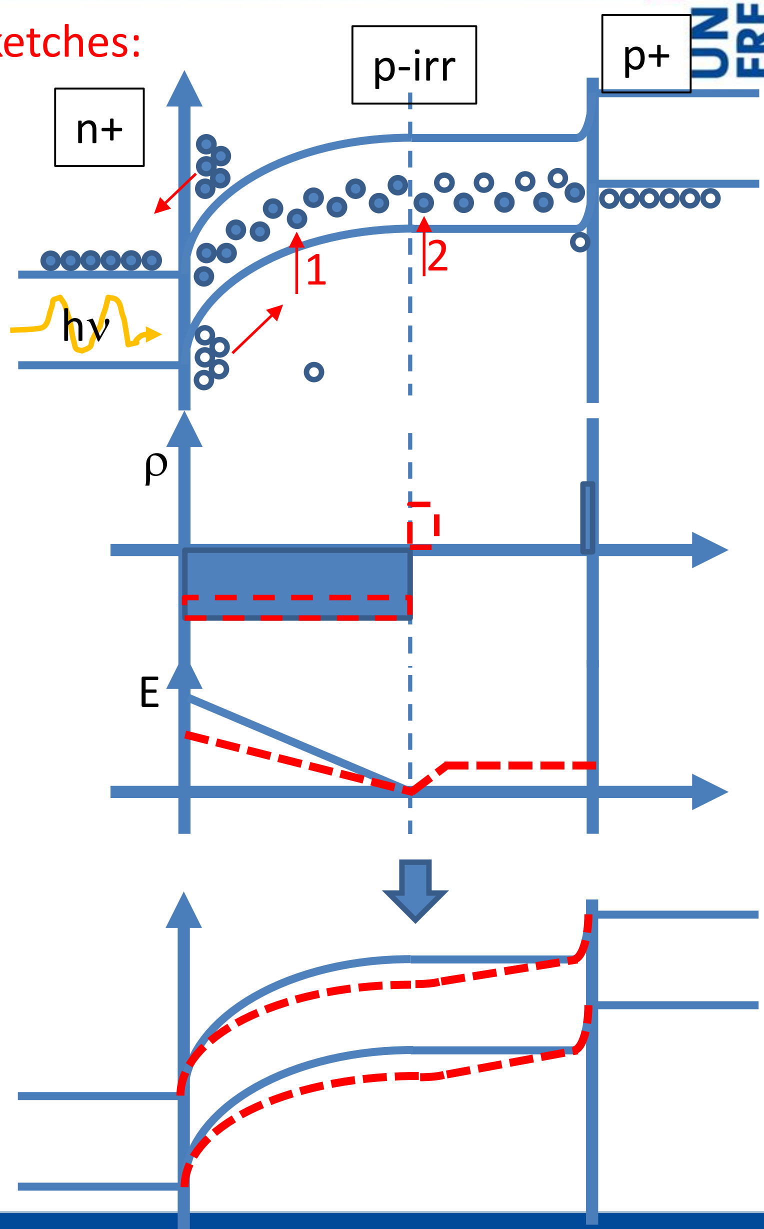
1) The phenomena should follow the defects dynamics (dependencies in temperature etc), polarization changes with carrier type (+/-)
2) Non depleted bulk is the key

Polarization: Description

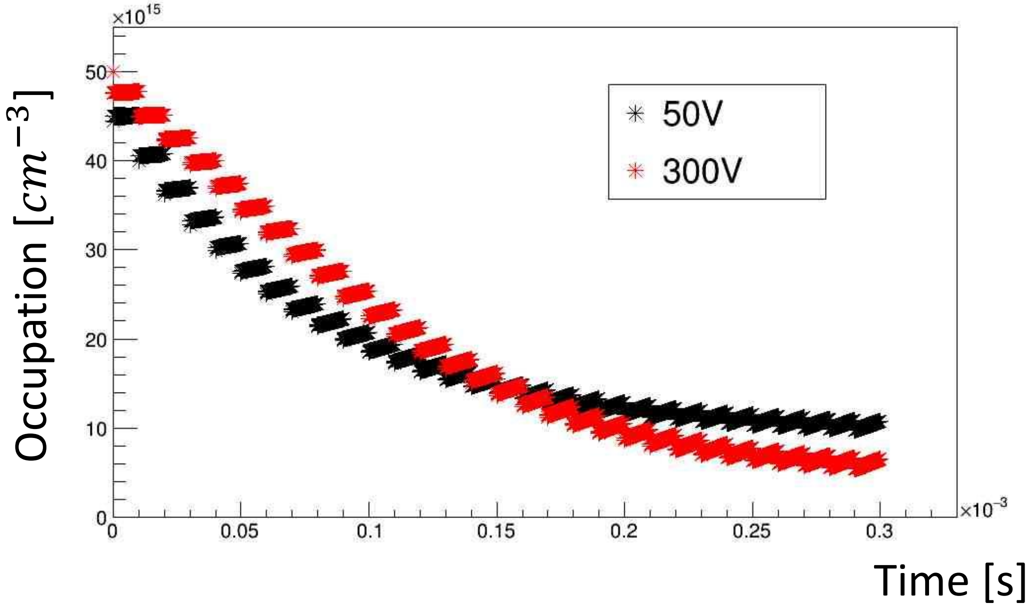
Processes:

- (1) Created holes drift, some get trapped by defect levels in depleted area
  (2) Remaining holes reach undepleted bulk, diffuse and get fully trappd or recombine
- Trapped holes change the space charge
- The electric field changes , potential drops in both regions
- The trapped charge is released and diffuses
  - ➢ Recombination with few free electrons, polarization relaxes
- The restoration of stability is an average of the full detrapping levels.
- NOTE: undepleted bulk is almost instrinsic [1].

Sketches:



[1] Mc Pherson, Phys B, 2003



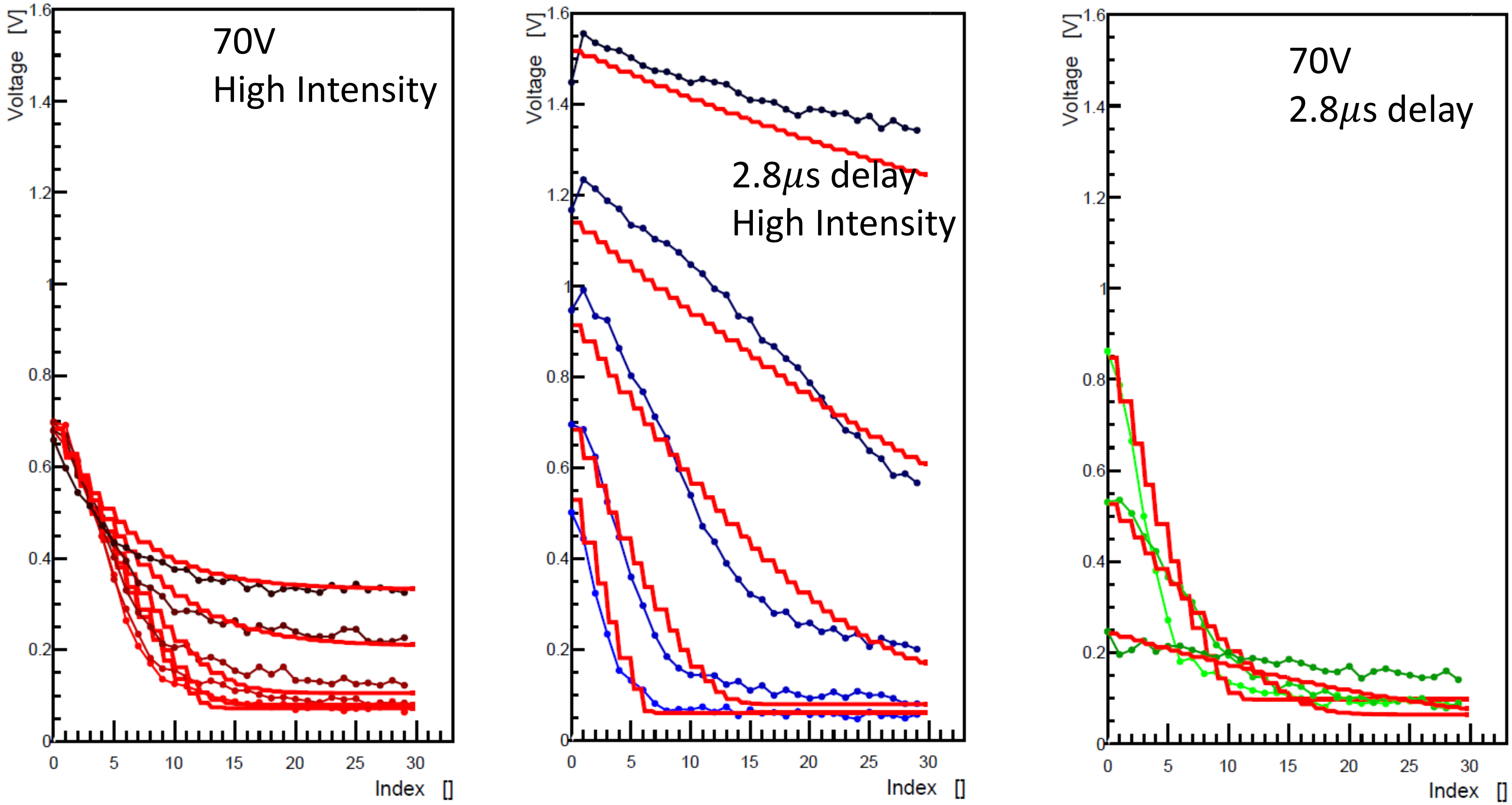
- Theoretical model to describe the trap occupation – trapping + detrapping at every pulse
  - At every pulse: certain number δn_t of carriers trapped, decreasing the signal
    $\delta n_t \propto 1/\text{bias}$ from observations!
  - Between pulses: certain number of carriers detrapped before next pulse

- Extraction of the expected current peak amplitude to fit to the data
  - Top TCT for irradiated diodes at non-depleting bias voltages
  - Only holes captured: current peak proportional to electric field peak at the top

Polarization: Fits

Sensor: $1 \cdot 10^{15} n_{eq}/cm^2$ diode, neutron irradiated

Different Delays **Different Voltages** **Different Intensities**



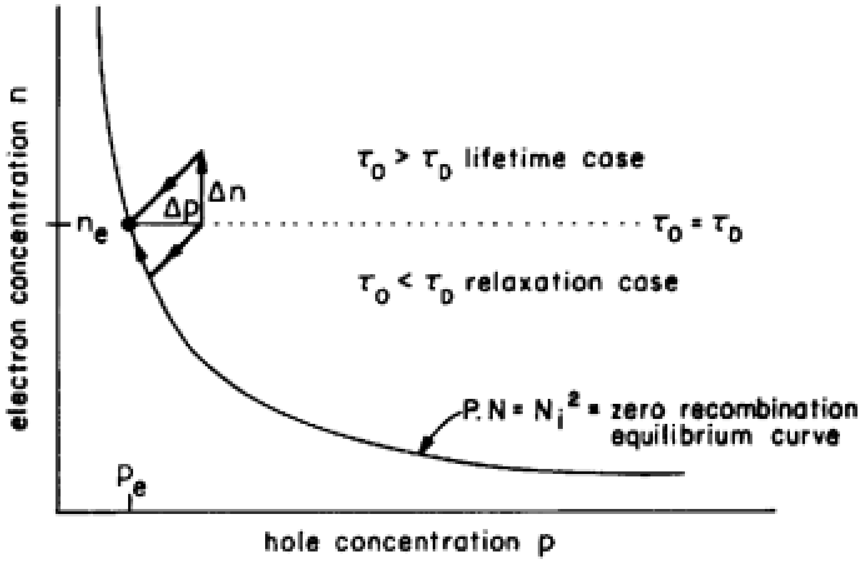
Considering only charge trapped in the depleted region: Work in progress!

Relaxation: Description

Introduction:

- Electrical relaxation time τ_d larger than lifetime τ_0 defines relaxation semiconductors

  - When there is an excess of free charge, fast recombination, minority and majority carriers are reduced
  - Local potential is relaxed following the zero-recombination line thanks to diffusion of the charge excess



- Our case: Excess holes reduces the el. field in the depleted region and reach the undepleted region, where there is a near-zero recombination and generation
- The excess is spread through diffusion and decay with the dielectric relaxation time τ_d .

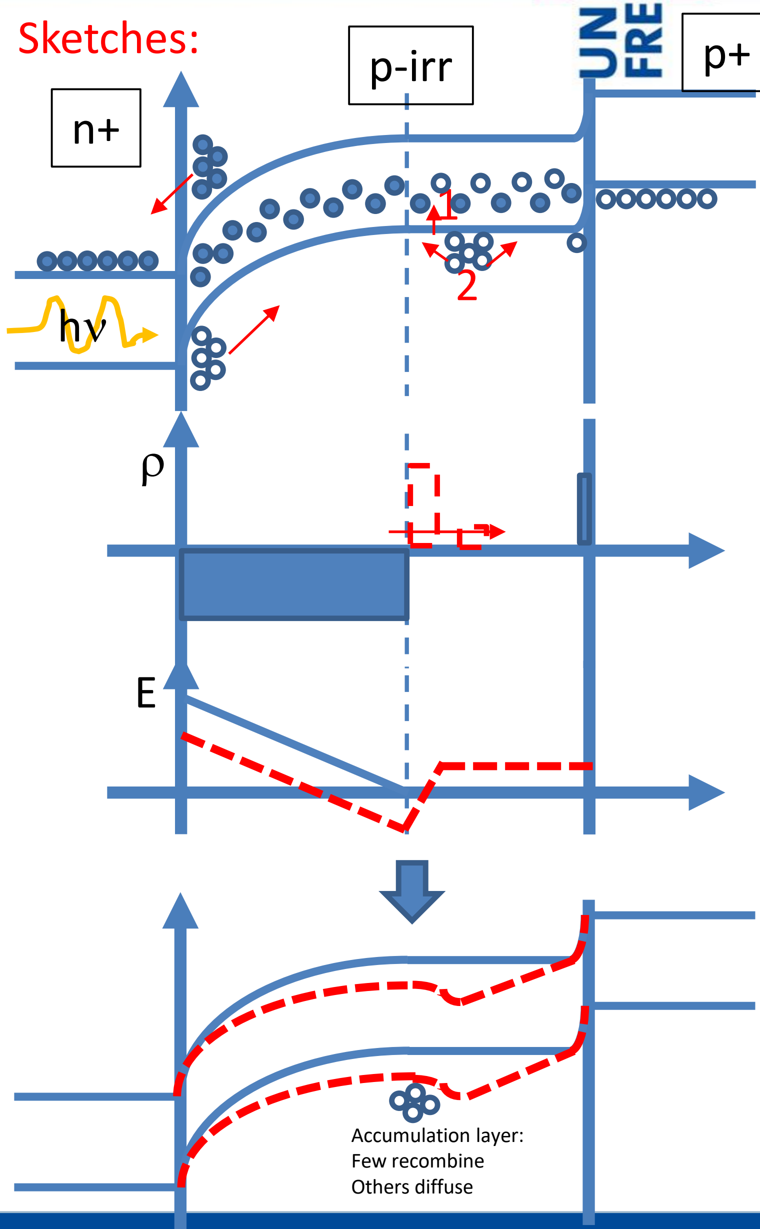
[2] Quissier, Solid State Devices, 1973 [3] Henisch, Phys Mag B, 1985

Relaxation: Description

Description:

- Dielectric relaxation can be described by time varying weighting potential
- Externally impressed charge is balanced by a potential readjusting itself
- Initially induced potential decays due to redistribution of free charges
- Induced holes drift to undepleted bulk
  - That acts as a relaxation semiconductor
- Additional positive space charge, neutralization occours with
  (1) a (small) partial immediate recombination
  (2) a slow diffusion of majority carrier relaxing to the equilibrium

Sketches:

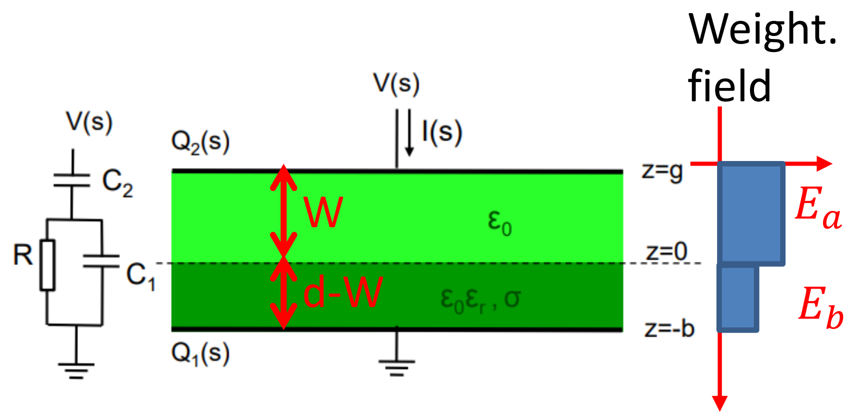


Relaxation: Model

- Trying to model the relaxation using the changing weighting field:
  - Undepleted bulk as a complex media with permittivity having a component from conductibility [4]
  - Weighting field from applying a Dirac-delta pulse train

Weighting fields in Laplace domain:

$$\begin{cases} E_a\, W + E_b\,(d - W) = V_0(s) \\ \varepsilon\, E_a = E_b\,(\varepsilon + \sigma/s) \end{cases} \xrightarrow{Laplace^{-1}}$$



Two pulses: $v_0(t) = C_0[\delta(t + \Delta T) + \delta(t)]$

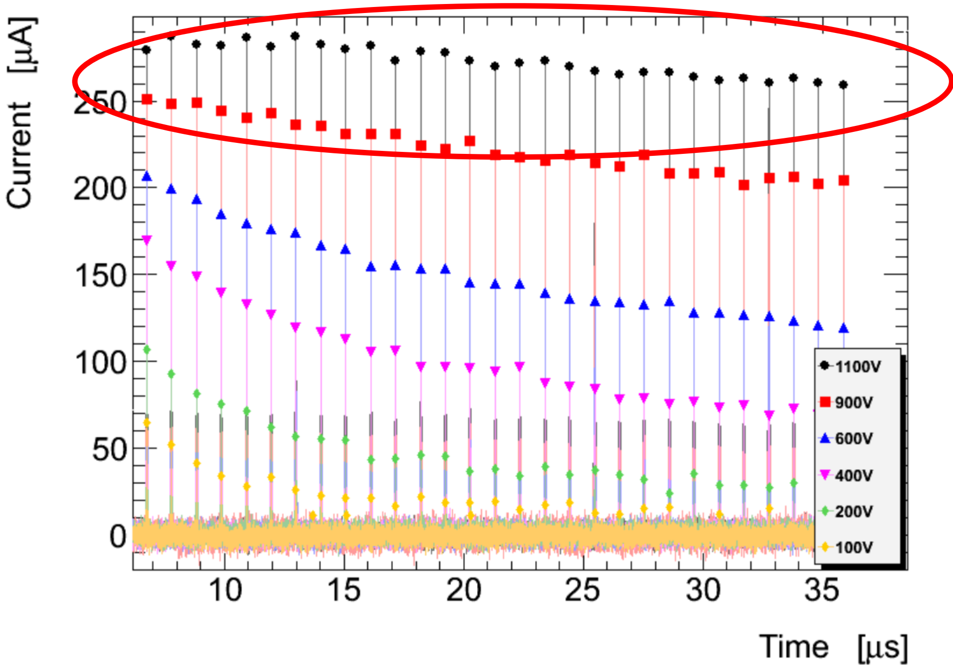
$$\mathrm{E}_a(t) = \frac{C_0}{d}\left(\delta(t + \Delta T) + \delta(t) + \frac{d-W}{W} e^{-\frac{t+\Delta T}{\tau}} + \frac{d-W}{W} e^{-\frac{t}{\tau}}\right)$$

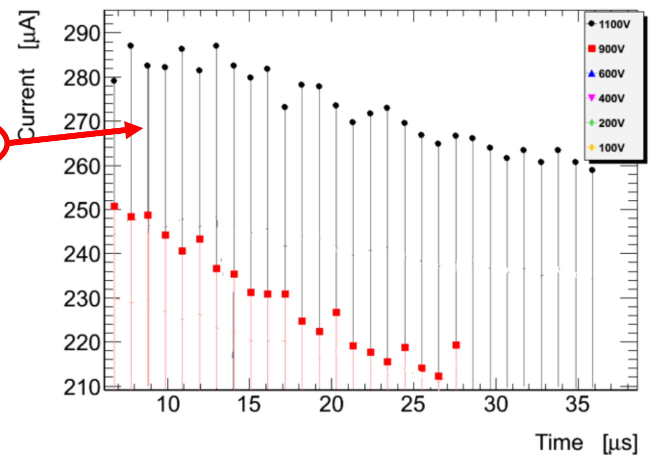
- Model shows the opposite of what we observe
  - ➢ Due to a long tail of the pulses, the following pulses are added on top and an increase should be observed
  - ➢ No current between pulses observed – exponential relaxation of free charge should lead to a detector bulk current residual

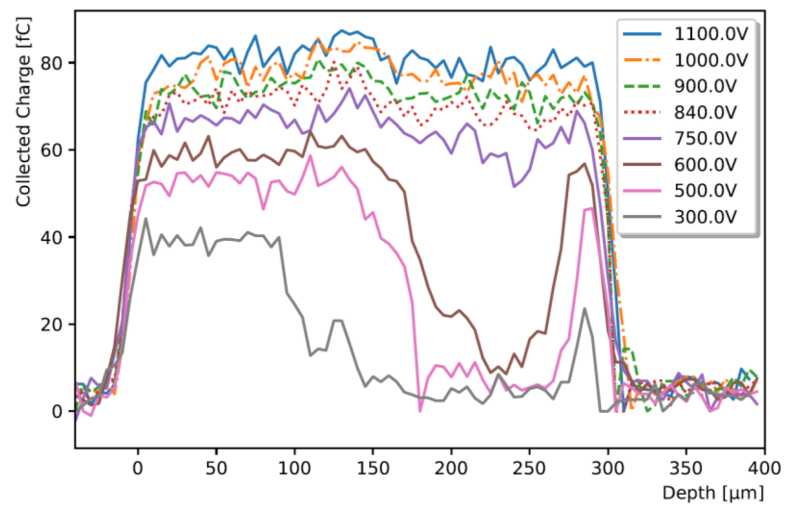
But still work in progress…

[4] Riegler, Signals in particle detectors, CERN Lecture 2019

Fluence: 5· $10^{14}\ n_{eq}/cm^2$, p-type strip sensor







- High intensity, ~1μs between pulses
- Decrease visible up to 1100V
- Sensor depleting around 900V
    - Amplitude slightly decreasing in a fully depleted sensor

Conclusion

- Signal amplitude decreases during subsequent pulse detection
- Possible explanations: Polarization effect (trapping) or relaxation
  - Key effect is the change of electric field
- Assumption of trapping/ polarization:
  - Fit model reproduces the decrease observed in measurements
  - Simulations also agree with the decrease (not shown)
- Assumption of relaxation:
  - Time varying weighting field approach is not able to explain the observations
- New measurements show a decrease in a fully depleted sensor, also supporting the polarization theory
- Current work: Finalizing the model to describe and explain everything we observe

Conclusion

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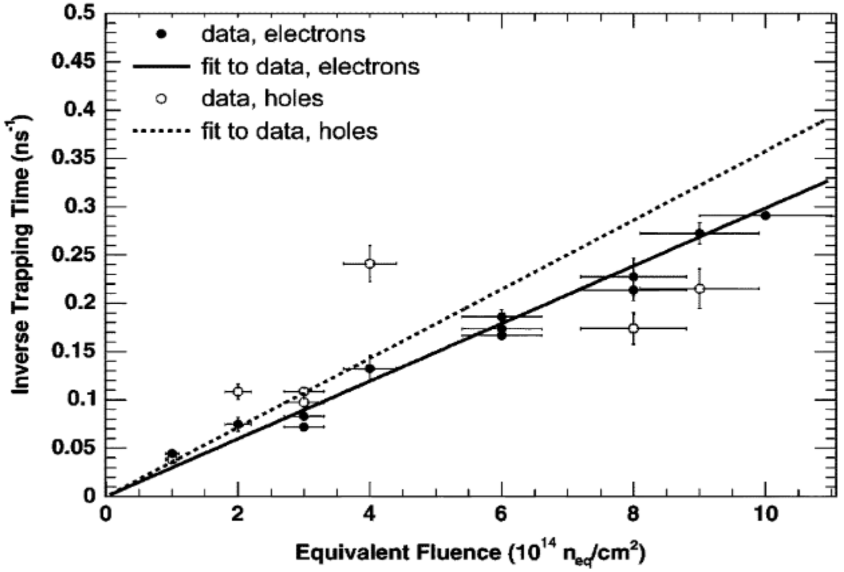
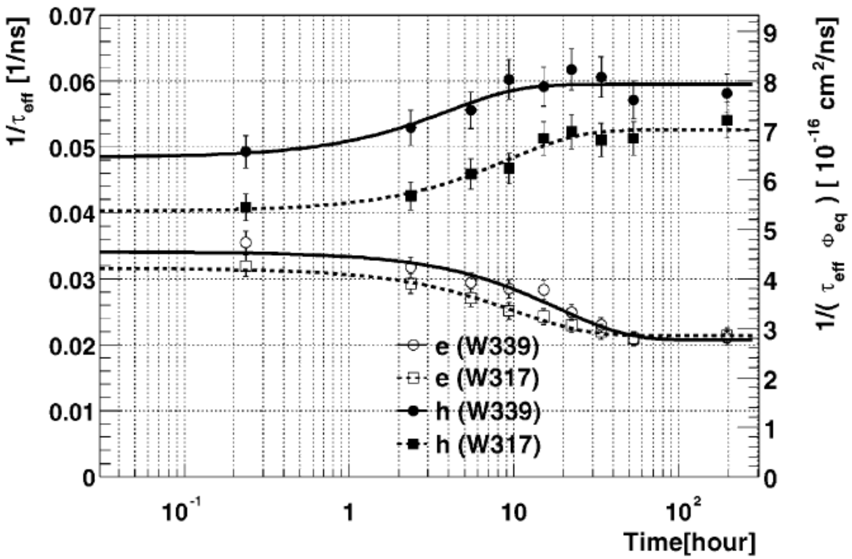
Thanks for your attention!

- Notation:
  - Pt: concentration of empty trap levels (hole occupied)
  - Nt: concentration of occupied trap level
  - Cp: capture coefficient
  - σ: capture cross section for holes
  - <vth>: thermal velocity holes
  - Vh: hole velocity
  - E: electric field
  - E0: electric field peak at x=0
  - X: depth
  - DT: pulse repetition time
  - τ: trap evolution time constant
  - i: pulse index
  - ρ: charge distribution
  - Neff:effective doping concentration
  - ε:permittivity
  - V: voltage
  - e: unit charge
  - μe, μh: electron mobility, hole mobility
  - Int: laser intensity
  - Eact: activation energy
  - Kb: Boltzmann constant
  - T: temperature

Trapping

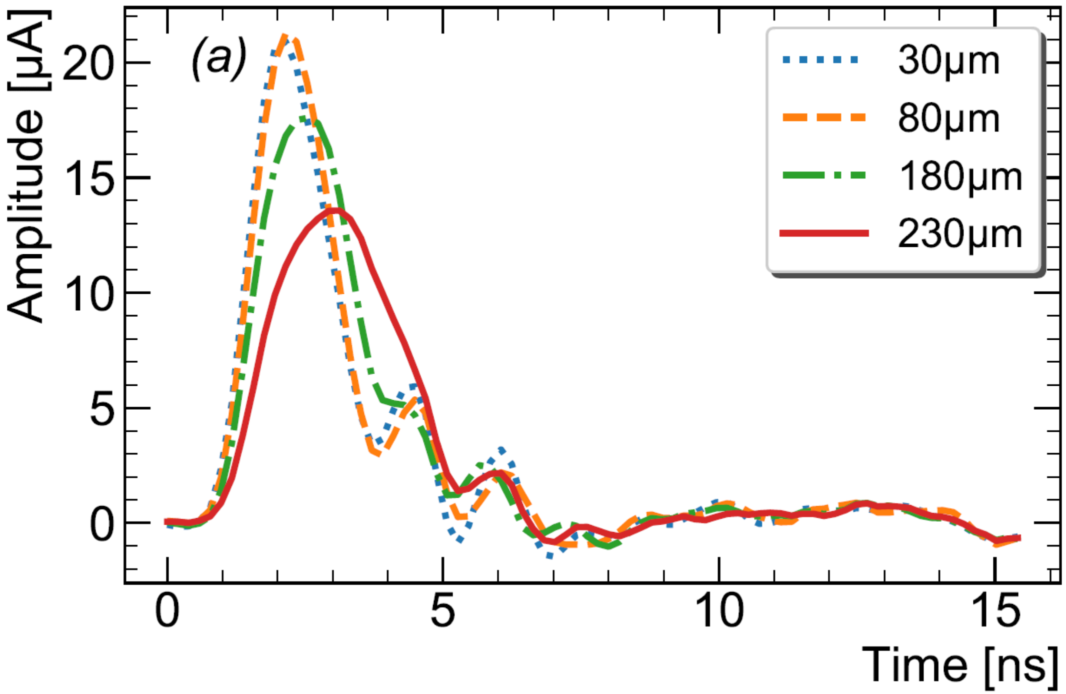
- Trapping and recombination in and through defect centers is the reason for reduced charge collection
- Irradiation introduces defects and annealing moves them, changing the relative trapping times
- Different defects have different trapping and de-trapping times





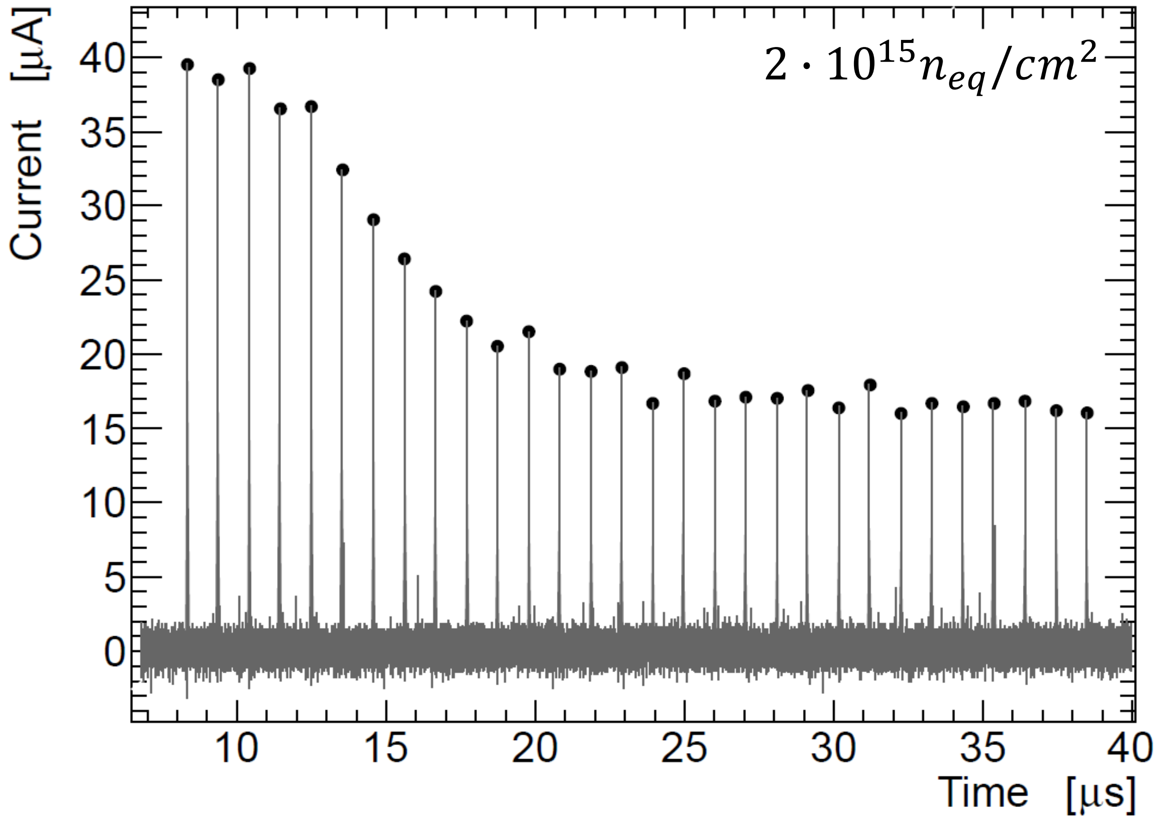
Edge-TCT Signal pulses

$1 \cdot 10^{15}\ n_{eq}/cm^2$, annealed 70min at 70°C, 1100 V



- IR laser creates signals, they get amplified and then recorded with an oscilloscope
- Shape changes slightly depending on depths (different drift times holes/ electrons)
- Signal duration almost constant, few ns signals

Measurements to investigate trapping effects



- Irradiated sensor: Significant decrease observed
- Charge created previously must get trapped and slowly detrapped between pulses, influencing the following signal pulse

Relaxation: description

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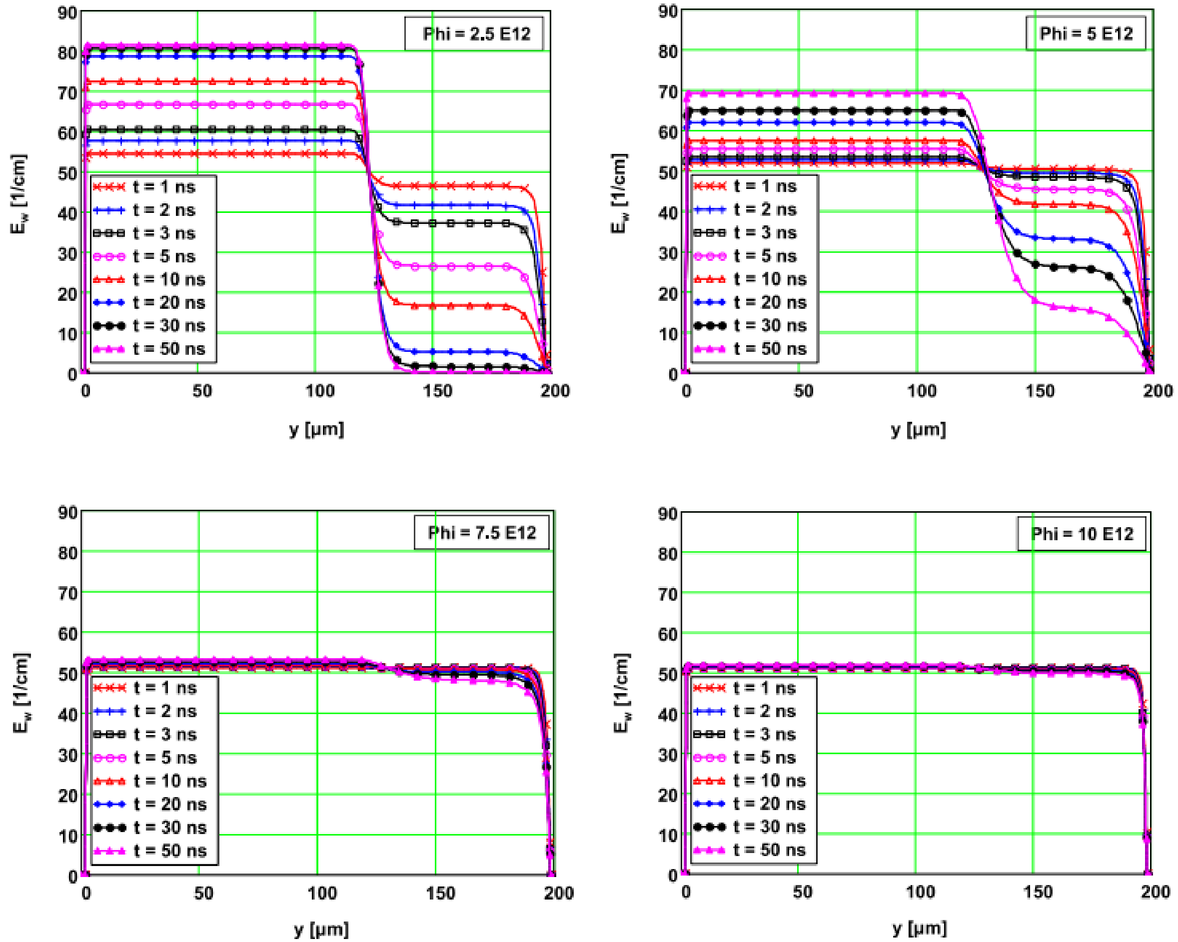
Description:

- Dielectric relaxation can be nicely described by time varying weighting potential [more in backup][6].



[6] Schwandt, Klanner, NIM A, 2019.

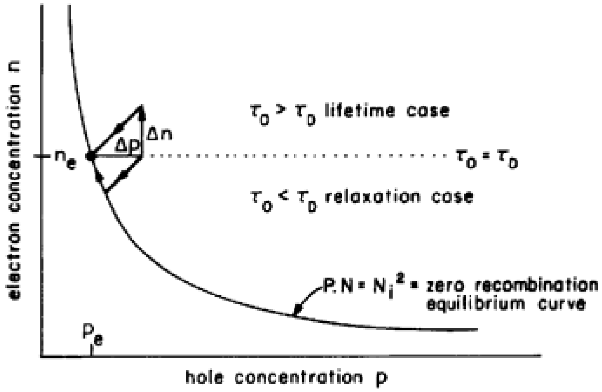
Relaxation: description

Introduction:

- Electrical relaxation time τd larger than lifetime τ0 defines relaxation semiconductors
- Highly irradiated silicon behaves like a relaxation semiconductor
  - In a neautral bulk, a perturbation of the local potential is slowly readjusted by few free carriers and neutrality holds after non negligible time [2] defined by the dielectric relaxation time τd. Space charge effects are important.
- When a free charge perturbation (Δp) occours:
  - Relaxation semiconductor:

  recombination occurs faster, minority and majority carriers reduces; relaxation occours with a slow diffusion of carrier excess with dielectric relaxation time τd=ρε along the 0-recombination curve (np=ni2) [3].
  - Lifetime semiconductor:

  the carrier excess is compensated by a compensation from free carriers of the opposite sign and relaxation occours with a slow recombination.



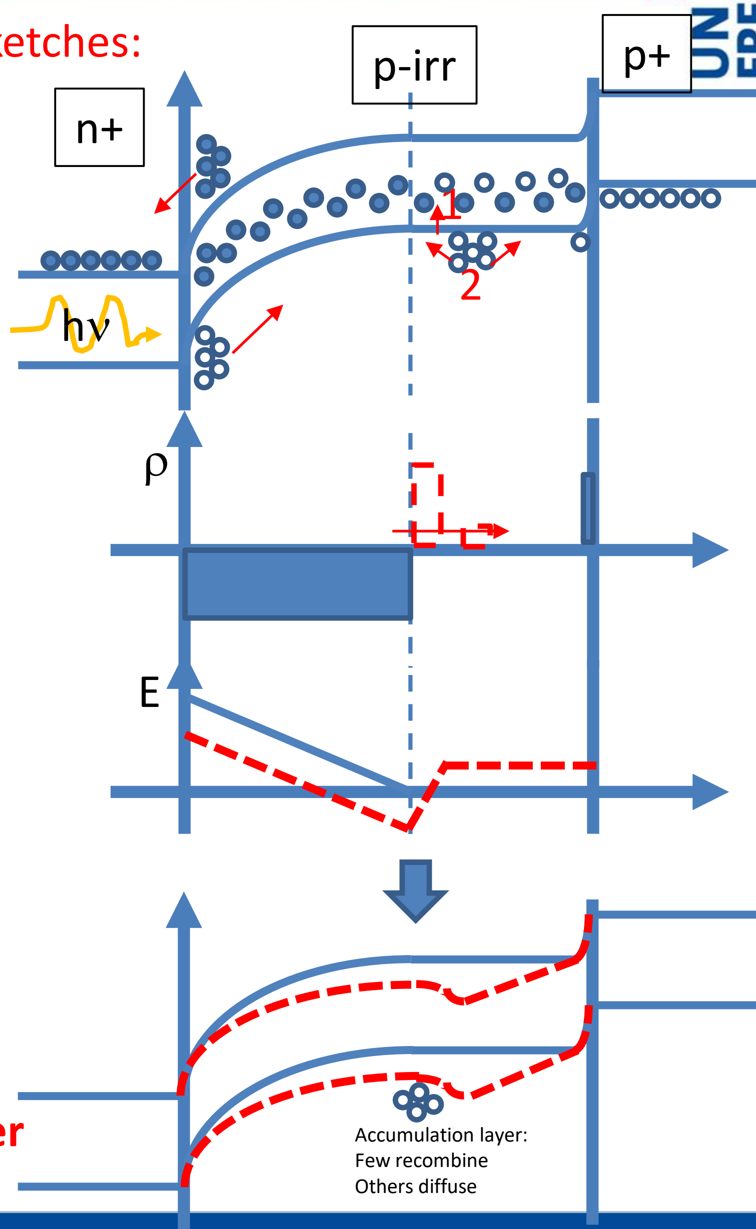
- In our case: free charge is generated and drift in a reverse potential („reverse drift“) in the majority carrier direction [4]; the holes in excess produce a locally reduced field in the depletion region and reach the undepleted region, where there is a near-zero recombination and generation and the excess is spread through trough diffusion and decay with the dielectric relaxation time τd.

Relaxation: description

Description:

- Dielectric relaxation can be nicely described by time varying weighting potential [more in backup][6].
- In words: an externally impressed charge to a medium with conductivity σ is balanced by a potential which readjust itself with an effective permittivity of $\varepsilon_{eff}=\varepsilon+\sigma/s$; the potential initially induced by the external charge decays with $\tau=\varepsilon/\sigma$ due to the redistribution of free charges.
- The induced holes drift to the nondepleted bulk, which act as a relaxation semiconductor.
- They are add a positive space charge and neutralization occours with a (small) partial immediate recombination (1) and a slow diffusion (2) of majority carrier relaxig to the equilibium with a time constant $\tau=\varepsilon/\sigma$.

Sketches:



WORK IN PROGRESS: to discuss with Prof. Klanner

[6] Schwandt, Klanner, NIM A, 2019.

Description with time dependent weighting field [5]:

- Equations for an externally impressed charge in a dielectric media with finite conductivity (like undepleted bulk):
  - Poisson:

$$\nabla[\varepsilon\nabla\varphi] = -\rho$$

    - Time derivative: $\nabla\left[\varepsilon\nabla\frac{\partial}{\partial t}\varphi\right] = -\frac{\partial}{\partial t}\rho = \nabla J$
  - Currents: ohmic due to finite conductivity σ plus externally induced *Je*

$$\mathrm{J} = -\sigma\nabla\varphi + J_e \;\Rightarrow\; \nabla J = -\sigma\nabla(\nabla\varphi) - \frac{\partial}{\partial t}\rho_e$$

  - Poisson with externally impressed current:

$$\nabla\left[\varepsilon\nabla\frac{\partial}{\partial t}\varphi + \sigma\nabla\varphi\right] = -\frac{\partial}{\partial t}\rho_e \quad \xrightarrow{Laplace} \quad \nabla[\varepsilon\nabla s\varphi + \sigma\nabla\varphi] = -s\rho_e$$

$$\nabla\left[\varepsilon_{eff}\nabla\varphi\right] = -\rho_e \quad , \quad \varepsilon_{eff} = \varepsilon + \sigma/s$$

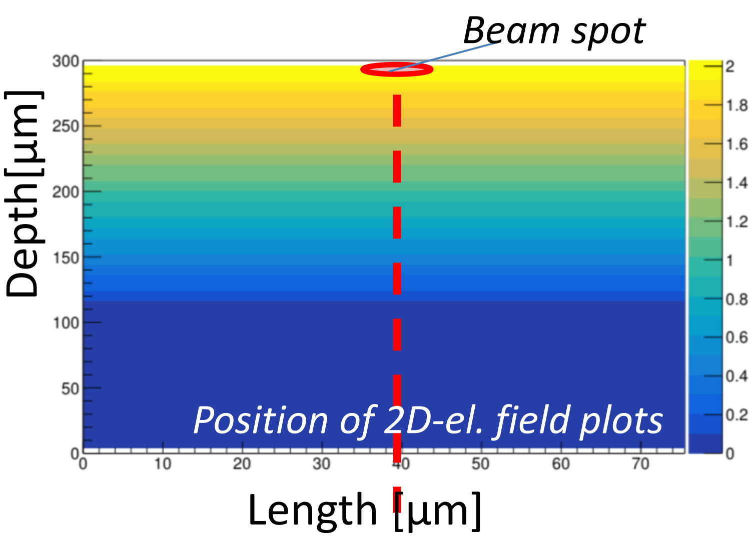
- The relaxation of the dielectric media can be then described by the time varying weighting field [6], which can be calculated applying an Heaviside-step reference voltage at the readout electrode.

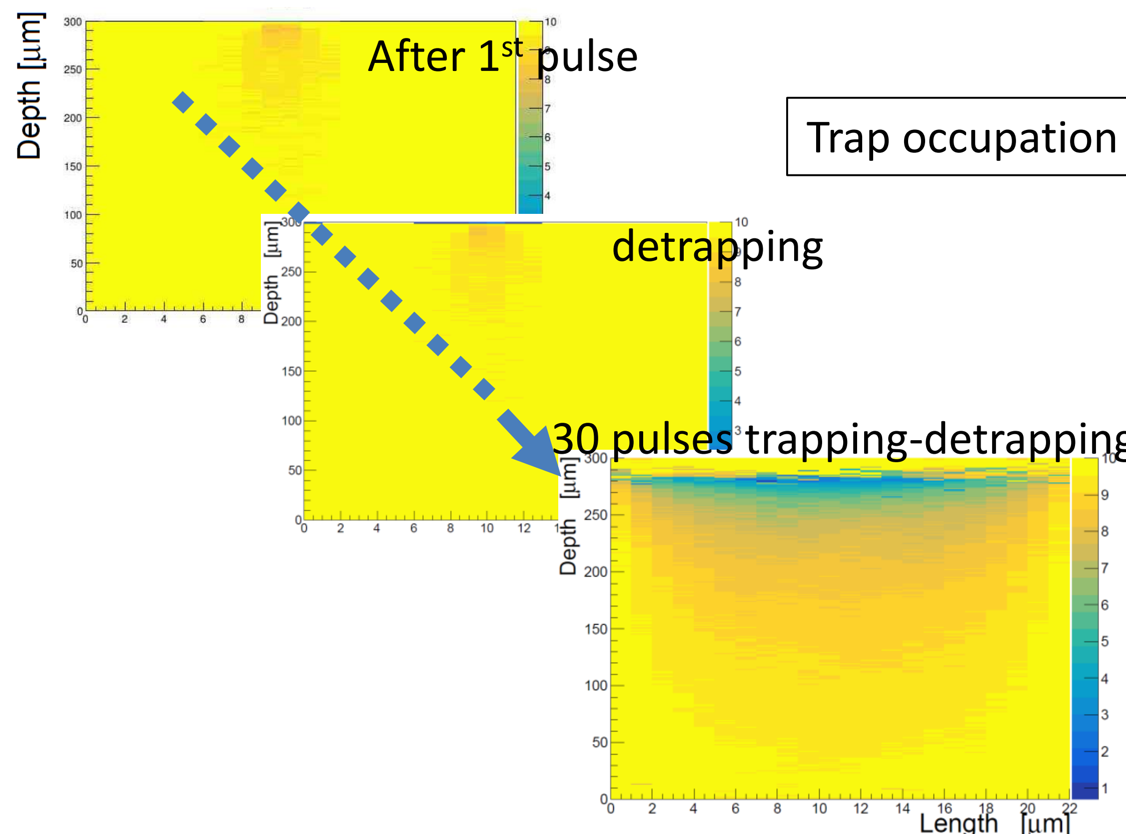
[5] Riegler, Detector seminar at CERN, 12/2019. [6] Riegler, 10.1016/j.nima.2019.06.056, 2019

Polarization: Simulations

- Buckets with created charge are followed bin by bin towards junctions, recalculating the amount of trapped charge according to the trapping probabilities
- El. field, N_{eff}, and trapped charges are recalculated after each pulse, and after the delay time between pulses has passed
- Variable: Voltage, $N_{eff}(0)$ (~fluence), laser intensity, number of defects, time delay, capture cross section

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



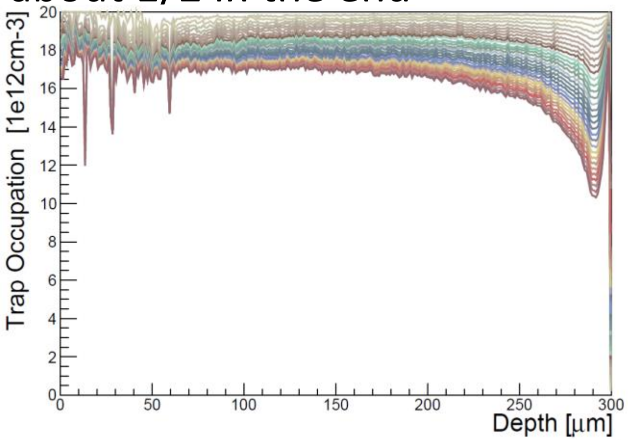


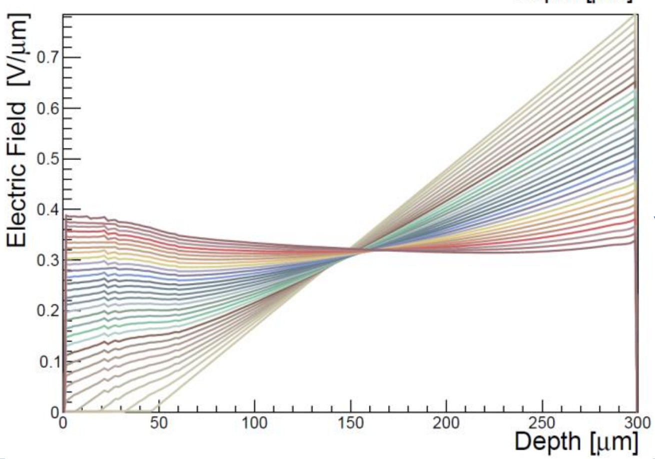
Polarization: Simulations

Example: low capture cross section

- Doping and trap concentration $1e12\ 1/cm^3$
- 50 V; S=0.4e-13 cm2
- 300 # buckets, 10 carriers/ bucket

➢ Faster decrease, max. amplitude only about 1/2 in the end

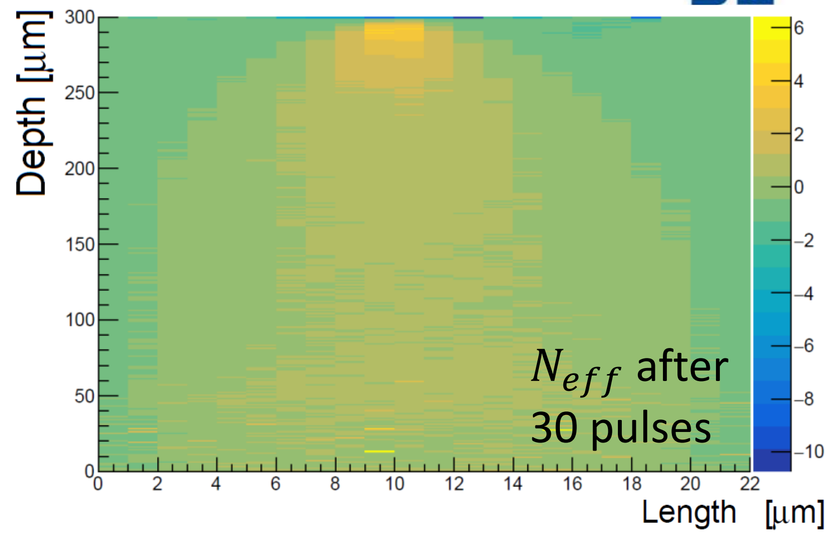


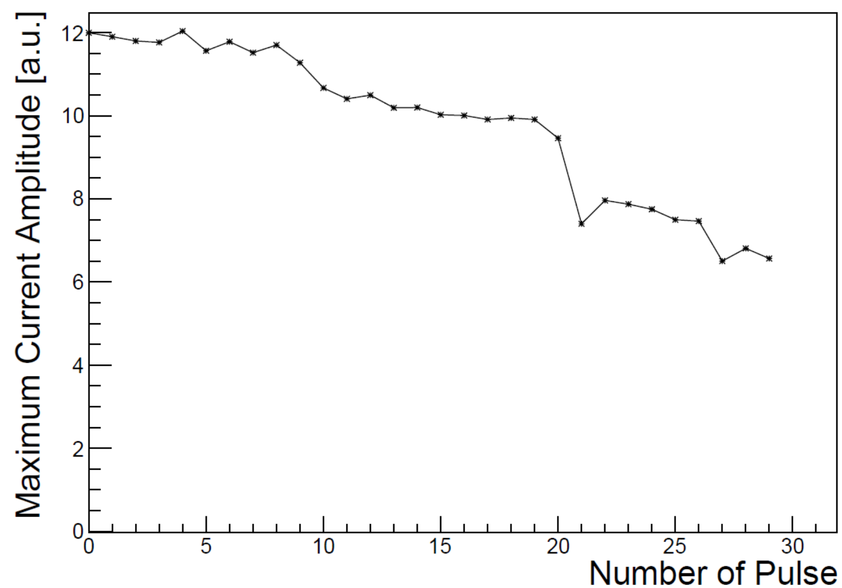


1.

…

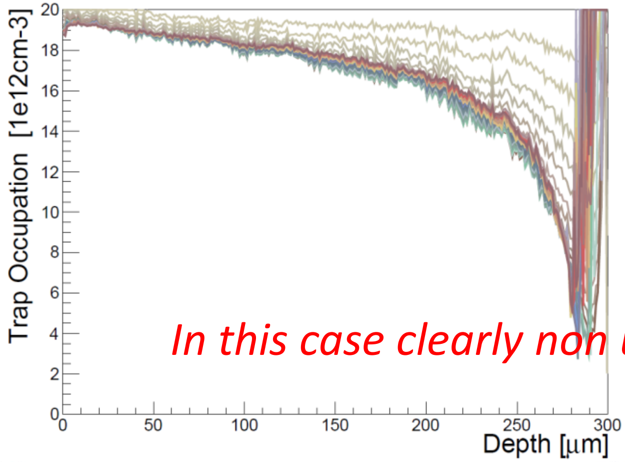
30.



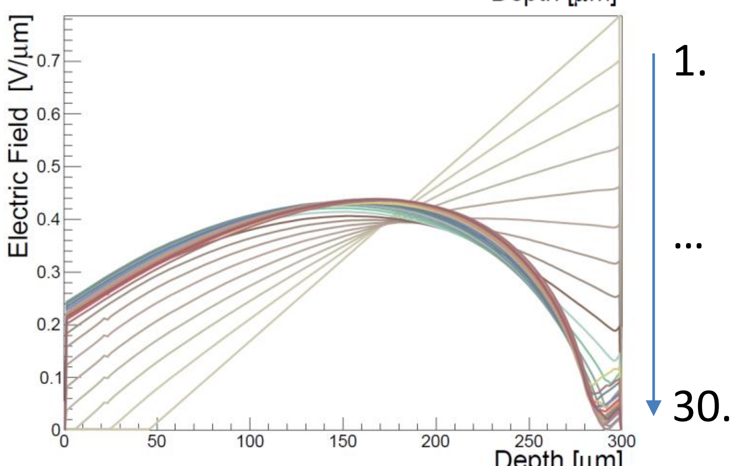


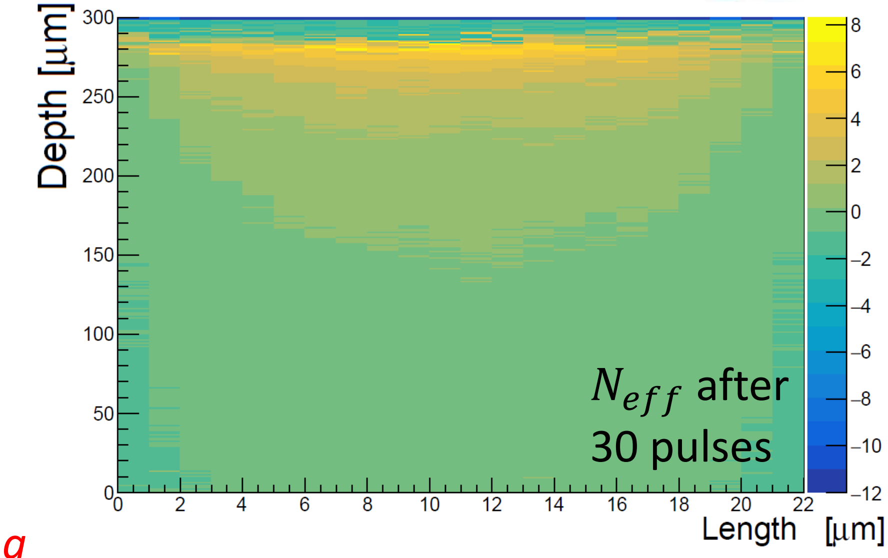
Example: large capture cross section

- Doping and trap concentration $1e12\ 1/cm^3$
- 50 V; S=4e-13 cm2
- 300 # buckets, 10 carriers/ bucket
- ➢ Amplitude almost zero in the end



In this case clearly non uniform trapping





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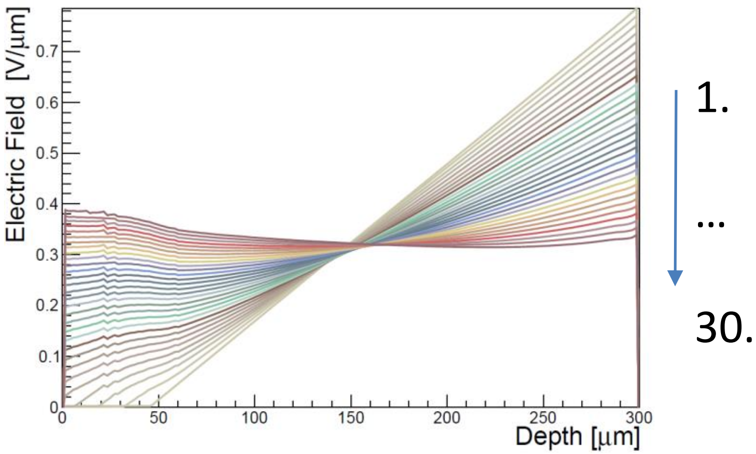
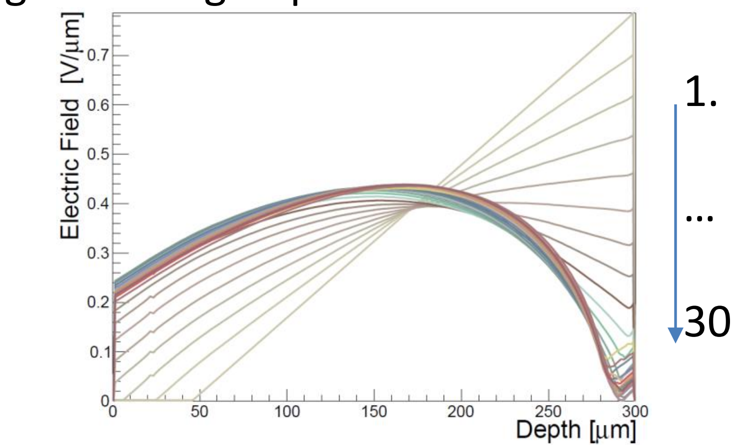
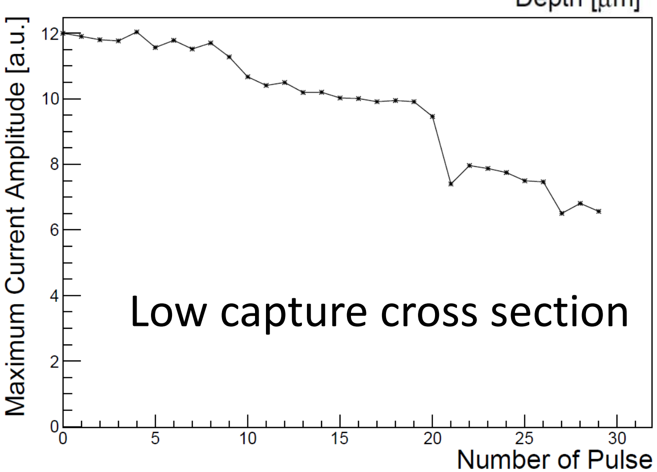
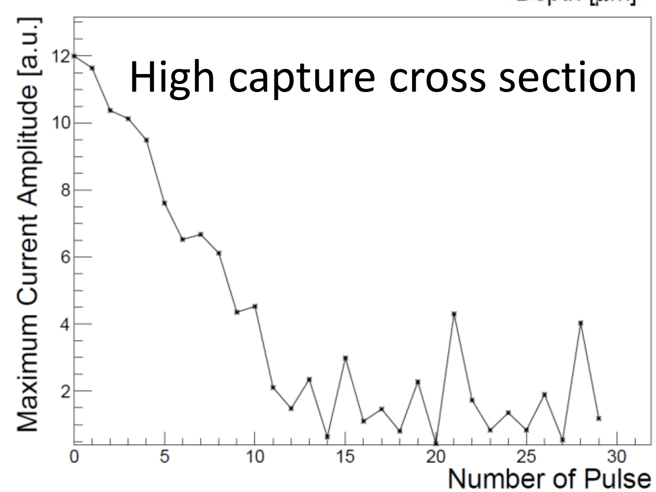
Polarization: Simulations

- Input: Voltage, , $N_{eff}(0)$ (~fluence), laser intensity, time delay, defect properties (capture cross section, concentration, activation energy)
- Electric field recalculated after trapping & de-trapping according to probabilities









Polarization: Model

- Goal: very approximated model in order to show polarization is what is really happening from the dependencies on the measurement variables (intensity, voltage, pulse repetition time)

Assumptions:

- Constant Neff => triangular field

- Capture of holes only, decreasing the negative
space charge in the depletion region (remaining holes then fully trapped at the edge)
- Trap fully occupied at equilibrium
- Uniform capture per depth
(the strongest approximation)

- Neglecting the holes trapped after the edge; fixed depletion depth
(work in progress)

- Current peak proportional to el. field peak

(In the following we use standard notation, in case see Backup)

Polarization: Model

Trapping: (Approximation of uniform capture)

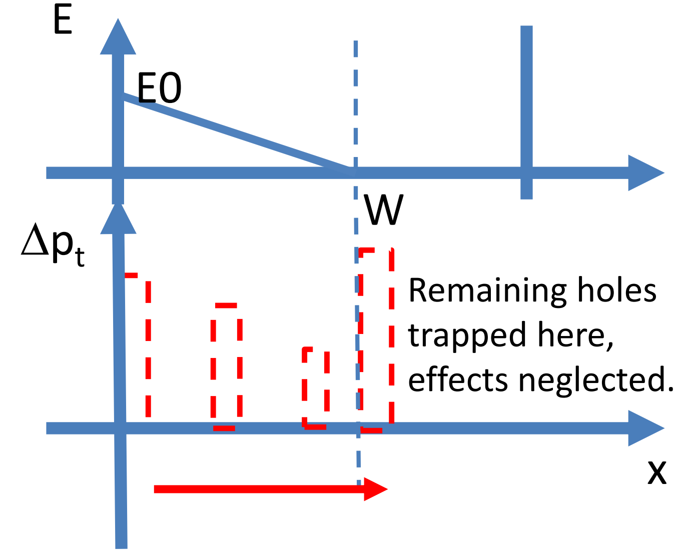
- Capture distribution: *(a bit naive but… please correct!)*

$$\frac{d\,\Delta p_t(x)}{dt} = c_p(x)\,n_t \quad , \quad c_p = \sigma < v_{th} > \Delta p_t(x)$$

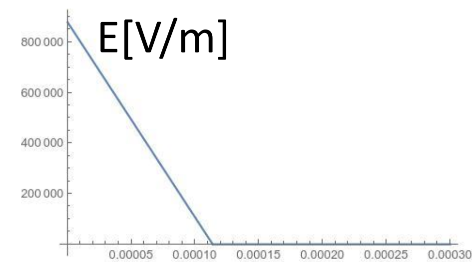
$$d\,\Delta p_t(x) = c_p(x)\,n_t\,\frac{dx}{v_h\,(x)}$$

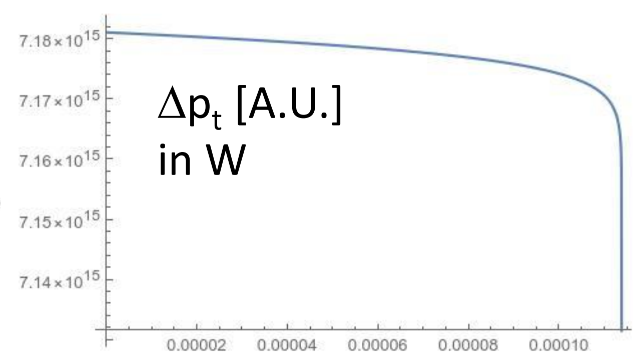
$$\frac{d\,\Delta p_t(x)}{\Delta p_t} = \frac{\sigma < v_{th} > n_t}{v_h(x)}dx$$

$$\Delta p_t(x) = \Delta p_t(x=0)e^{-\sigma<v_{th}>n_t \int_0^x \frac{1}{v_h(x')}dx'}$$



- Example:
  - $\sigma = 4\,10^{-14}$cm2
  - $< v_{th} >$=1.4 10^7cm/s
  - n_t= 5 10^{-11}cm-3
  - $v_h = \frac{v_{sh}*E/E_{ch}}{1+E/E_{ch}}$, v_{sh}= 9.5 10^6cm/s , E_{ch}=1.95 10^4V/cm





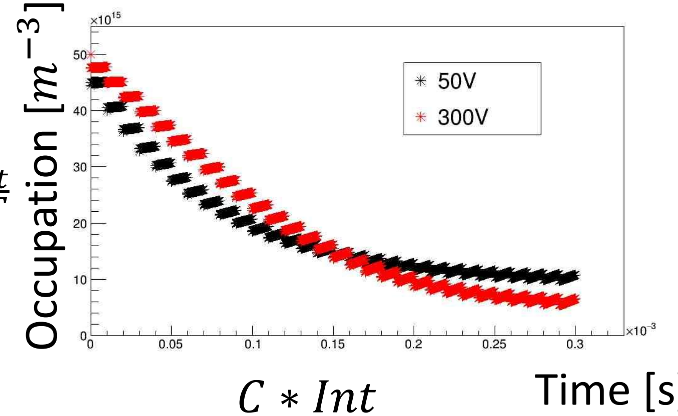
- Approximation: uniform capture
- Empirical Assumption: inversely proportional to hole velocity at x=0, and extra inverse proportionality to bias voltage (from observations)

Detrapping:

- Between pulses:

$$\frac{d\,p_t}{dt} = -e_p\,p_t \quad, p_t(\infty) = 0$$

$$\Rightarrow p_t(t - i\Delta T) = p_t\,(i\Delta T)\,e^{-\frac{t-i\Delta T}{\tau}}, \qquad 1/\tau = e_p \propto T^2 e^{\frac{E_{act}}{K_b T}}$$



- Pulses evolution:
  - Assuming uniform capture per pulse of:

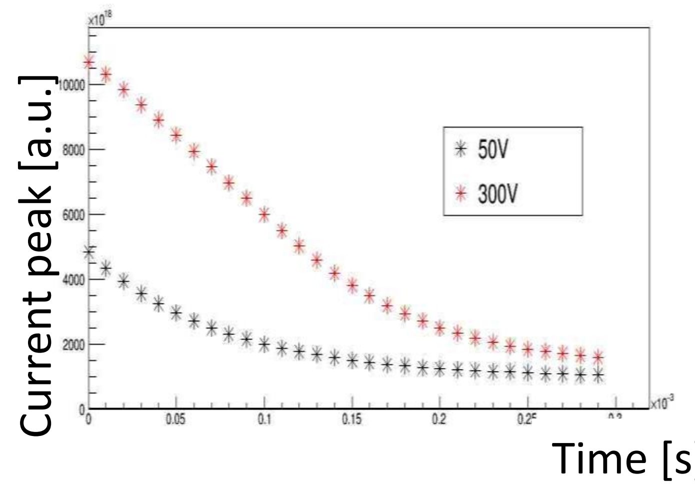
$$\Delta p_t(i\Delta T) = K(i\Delta T)\,n_t(i\Delta T), \qquad K = \frac{C * Int}{V * v_{h(x=0:E=E0(i\Delta T))}} = \frac{C * Int}{V * \mu_h E0(i\Delta T)}$$

  - Evolution:

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

$$= \left[\,p_t(i-1) + K(i-1)\left(\,N_t - p_t(i-i)\right)\right]e^{-\frac{\Delta T}{\tau}}$$

$$K(i) = \frac{C}{V\mu_h E0(i)} \quad , E0(i) = \sqrt{\frac{2eV}{\varepsilon}\frac{\left(N_{eff} - p_t(i)\right)^2}{N_{eff}}}$$



  - Current peak:

$$I_{PK} \propto [n_e\mu_e + n_h\mu_h]E_0(i)$$

  - μ_e, μ_h see [Scharf, Klanner, NIM A 2005]

Fit Model (Work in progress)

- From the assumptions: $p_t(\infty) = 0 \;\rightarrow p_t(t) = p_t(t_{pulse})e^{-\frac{t}{\tau}}$
- At every pulse i, after pulse repetition time ΔT:

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

where: $\delta n_t = \frac{\sigma<v>const}{\mu_h E(t=(i-1)\Delta T, x=0)\;\;V}\Big(Nt - p_t\big((i-1)\Delta T\big)\Big)$ (1/V empirical obs.)

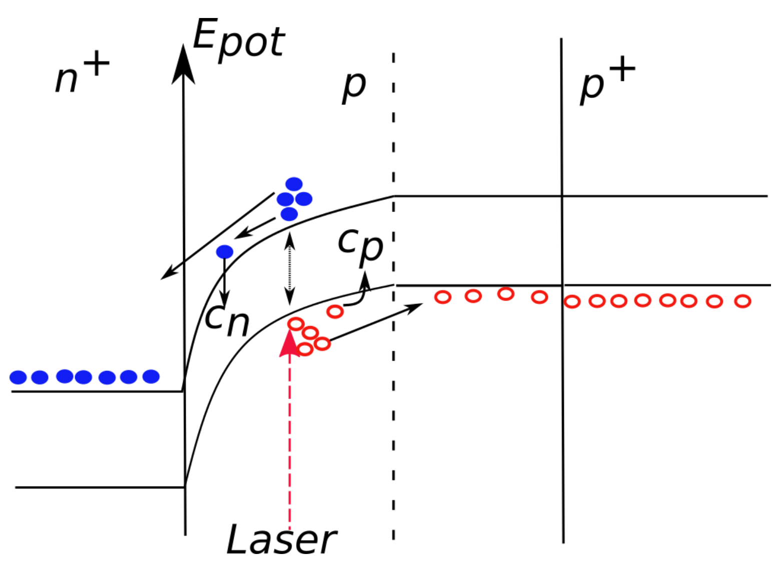
with $p_{MAX} = N_t$

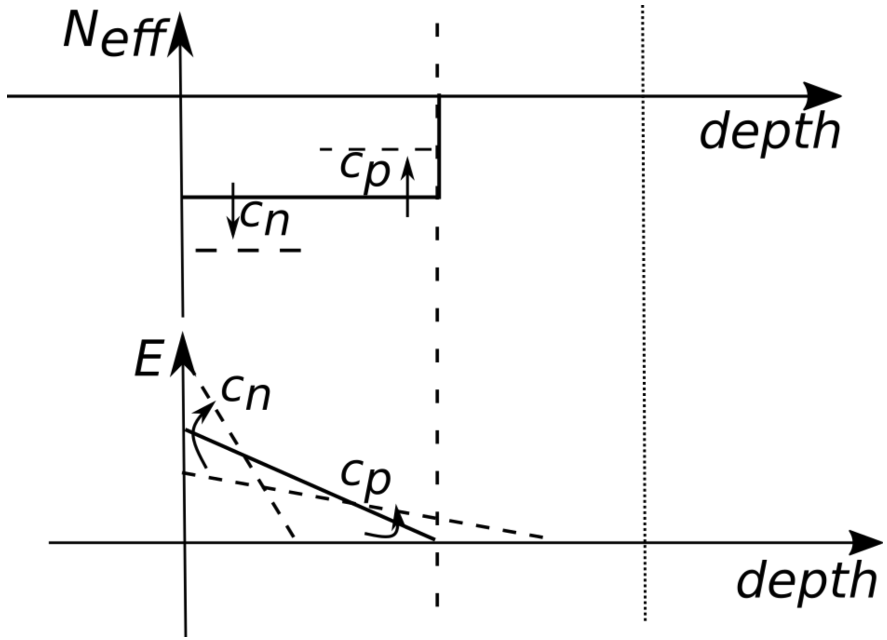
- El. Field peak (from assumption of constant W): $E_0 = \sqrt{\frac{2eV\;\;\left(N_{eff}-p_t(i)\right)^2}{\varepsilon\;\,N_{eff}}}$
- Current peak:

$$I_{PK} \propto -[n_e\mu_e + n_h\mu_h]E_0(i)$$

where $n_e = n_h \propto$ intensity, for μ_e, μ_h see [Scharf, Klanner, NIM A 2005]

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

Fit Model (Work in progress)