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

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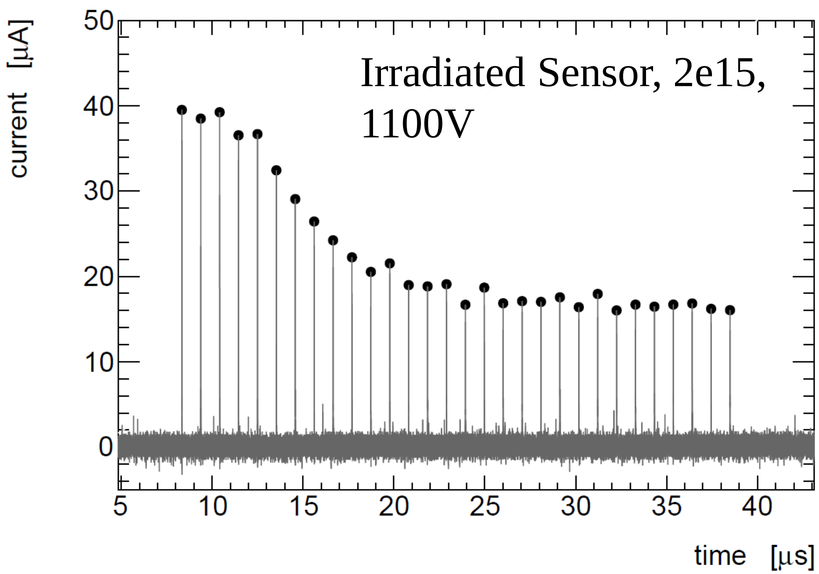
Preface:

- Observed: Subsequent pulse detection showed a significant decrease of amplitude
  - ➢ Dependence on voltage, laser intensity, temperature, pulse repetition time and fluence

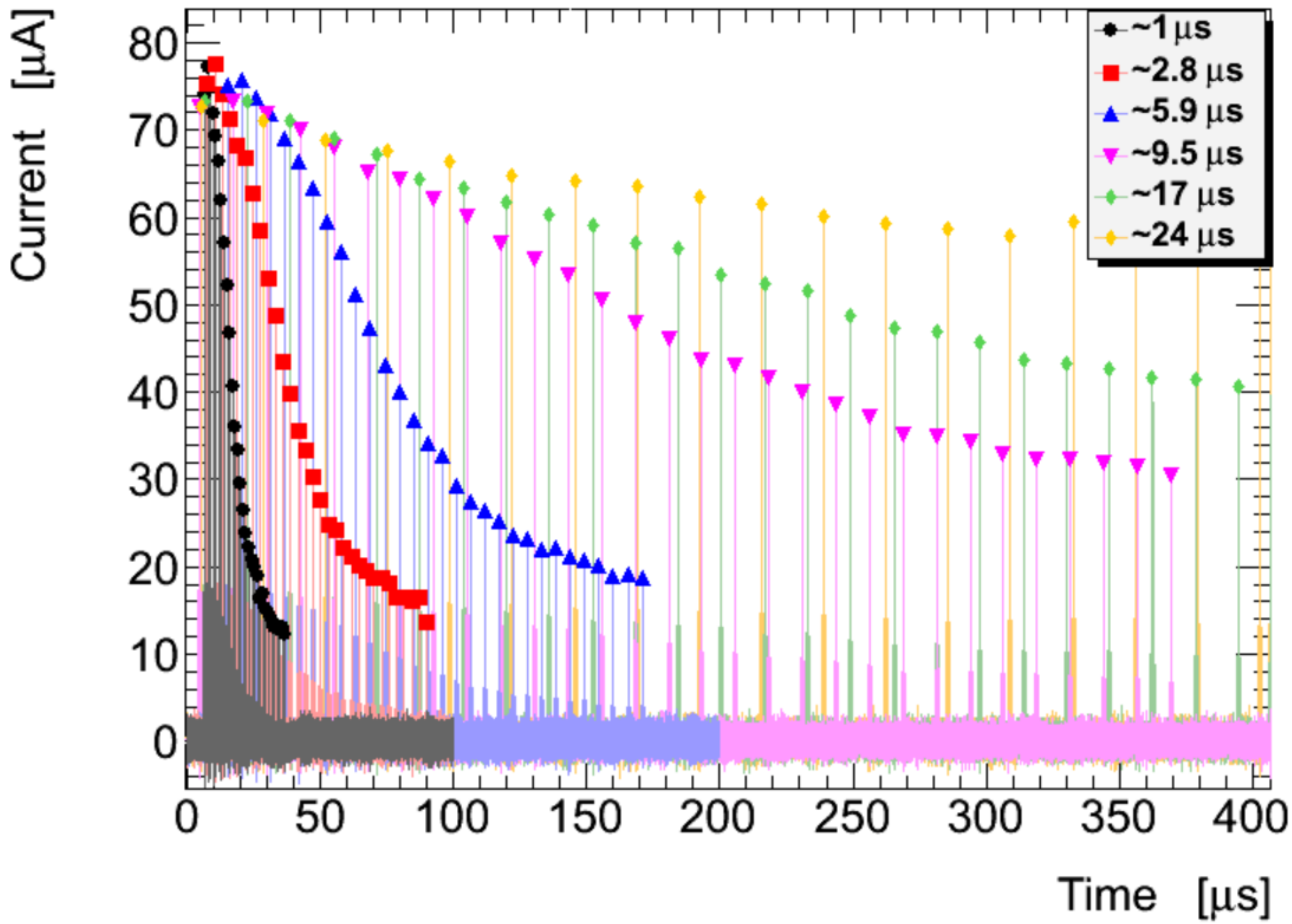
- Decrease was observed in several different measurements:
  - ➢ Edge-TCT measurements (infrared laser, strip sensors)
  - ➢ Top TCT measurements (red laser, diodes + strip sensors)

- Focus now on the „easiest“ kind of measurement
  - ➢ Top TCT measurements (one carrier type injection)
  - ➢ Fluences between 3e14 and 2e15 $\frac{n_{eq}}{cm^2}$

- Update now on the investigation of the cause, improved simulations and fit model



Reminder



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

Delay-dependent decrease of charge, Top-TCT measurement

Polarization vs Relaxation

Possible explanations:

1. Polarization:
   - Electric field change due to trapping of generated charge

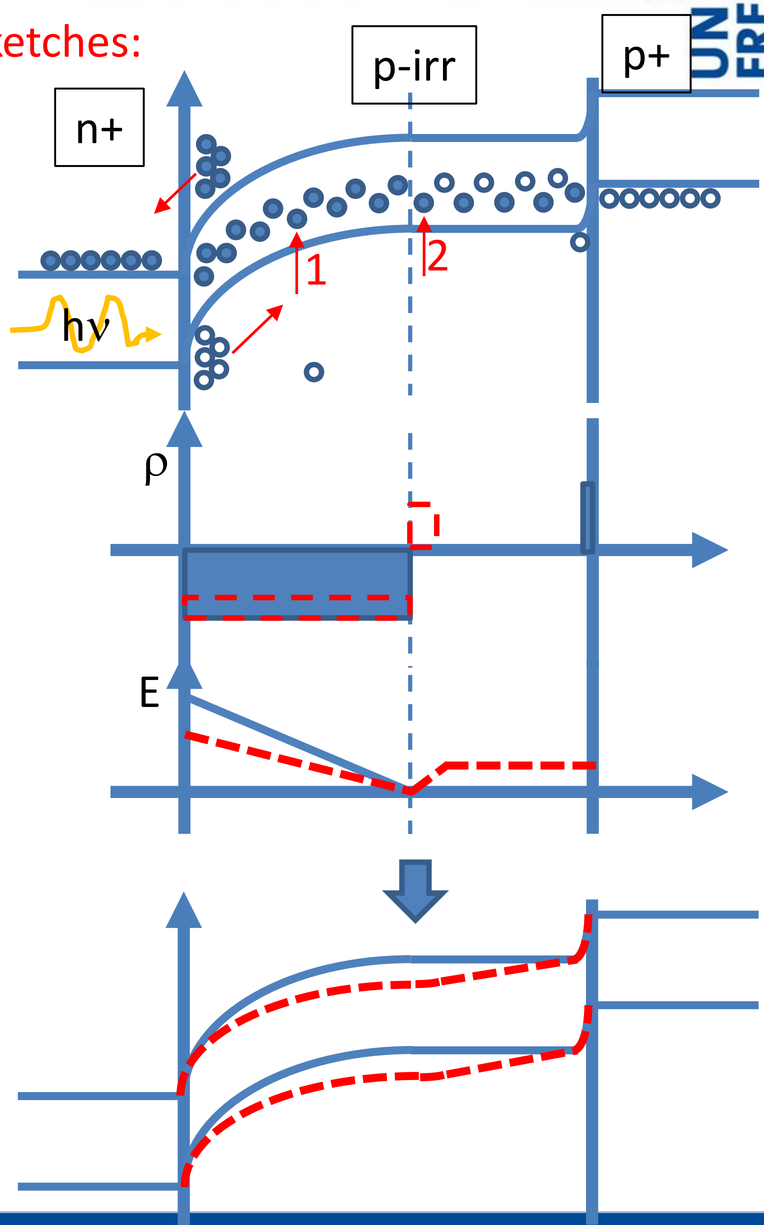
2. Relaxation:
   - Slow dielectric relaxation of the non depleted bulk after the drift of generated charge

We would like to warmly thanks Prof. Klanner for the comments about the relaxation effect and the ongoing discussion…

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

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)

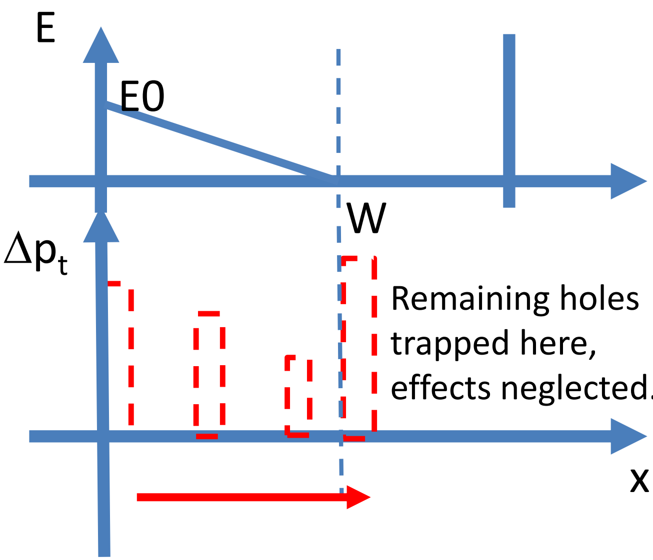
- Capture distribution: *(a bit naive but… please correct!)*

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

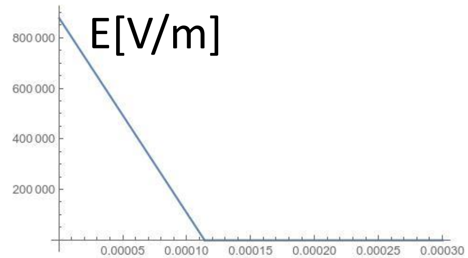
$$d\,\Delta p_t(x) = c_p(x)\, n_t\, \frac{dx}{v_h\,(x)}$$

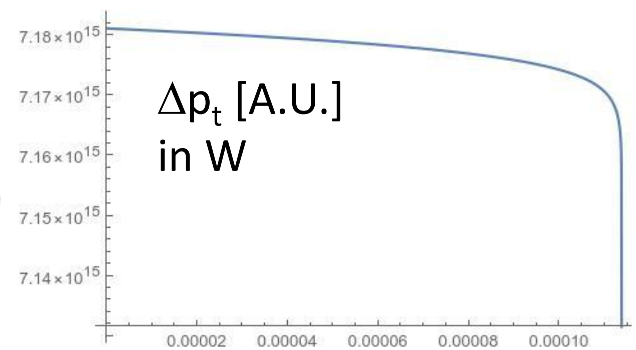
$$\frac{d\,\Delta p_t(x)}{\Delta p_t} = \frac{\sigma < v_{th} > n_t}{v_h(x)} dx$$

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



- 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





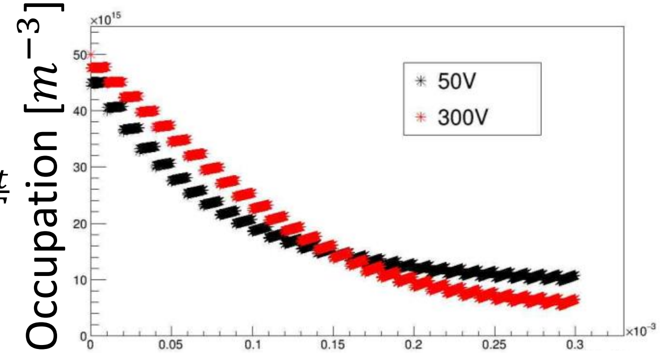
- Approximation: uniform capture
- Empirical Assumption: inversely proportional to hole velocity at x=0, and extra inverse proportionality to bias voltage (from observations)

Detrapping:

- Between pulses:

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

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



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

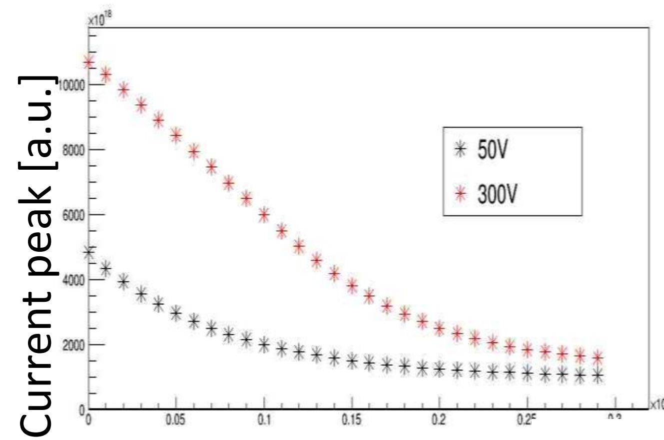
$$\Delta p_t(i\Delta T) = K(i\Delta T)\,n_t(i\Delta T), \qquad K = \frac{C * Int}{V * v_{h(x=0:E=E0(i\Delta T))}} = \frac{C * Int}{V * \mu_h E0(i\Delta T)}$$

  - Evolution:

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

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

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

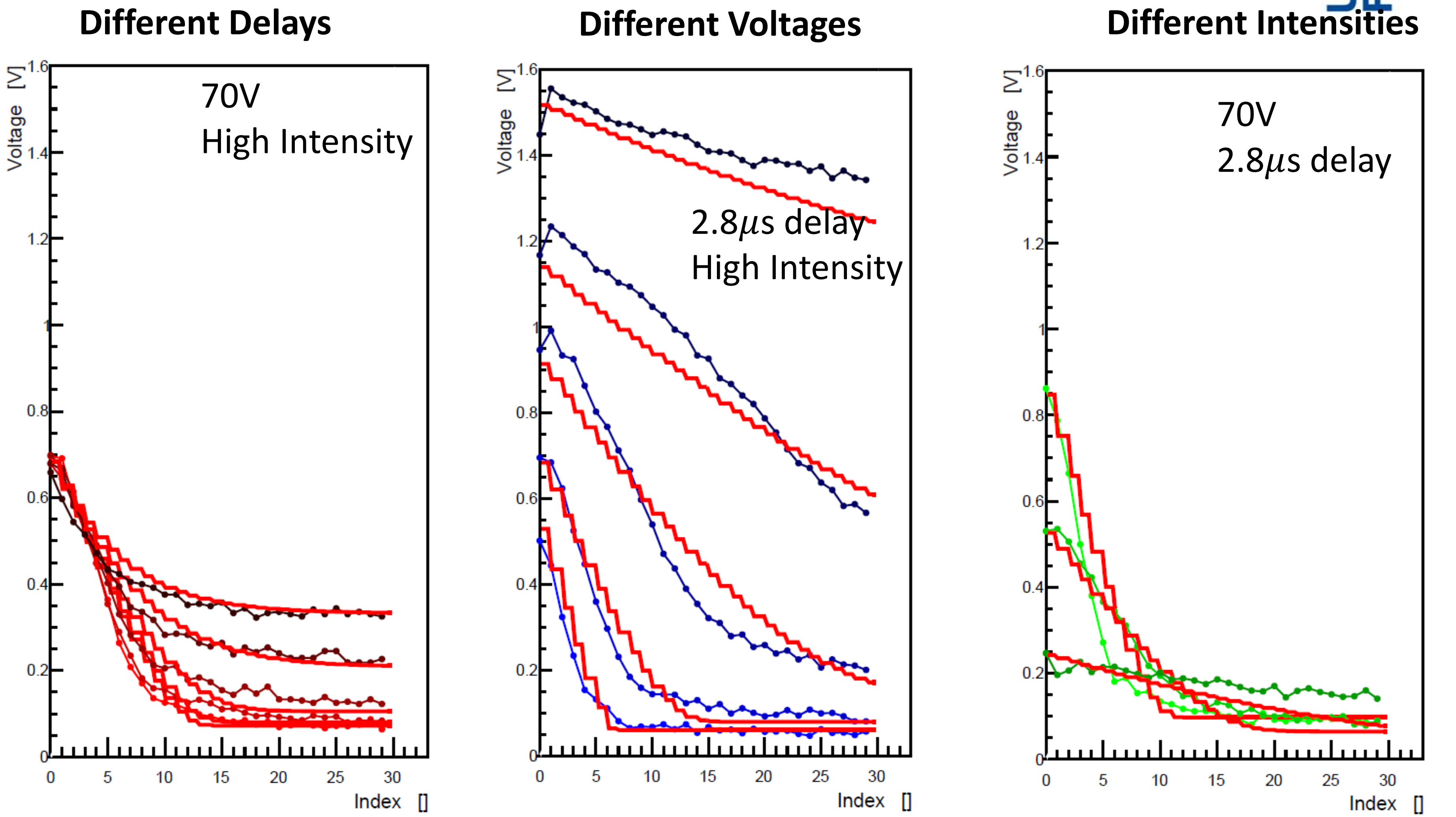


  - Current peak:

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

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

Polarization: Fits

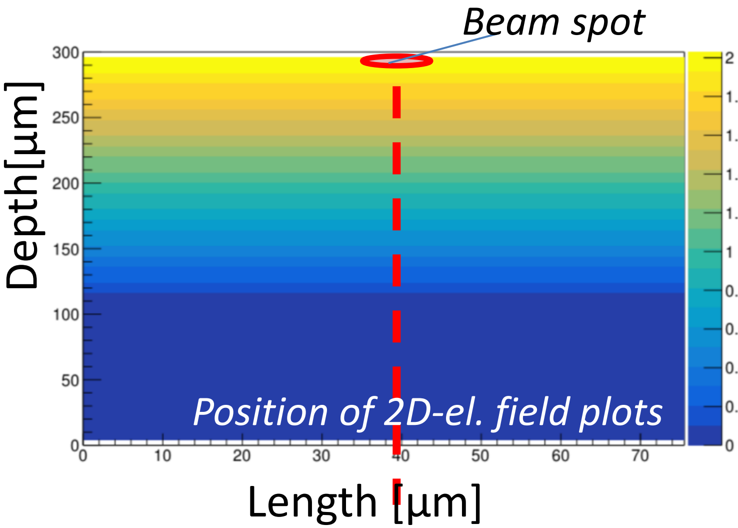


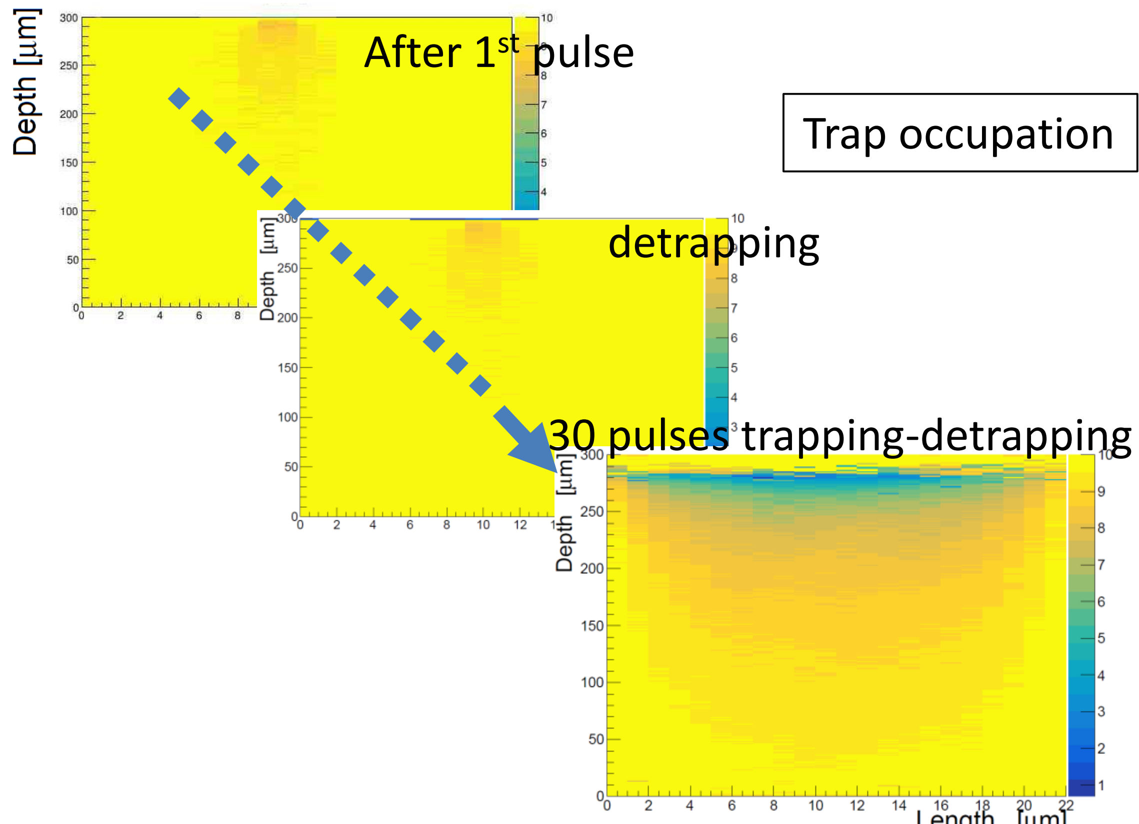
Sensor: $1 \cdot 10^{15} n_{eq}/cm^2$ diode, neutron irradiated

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



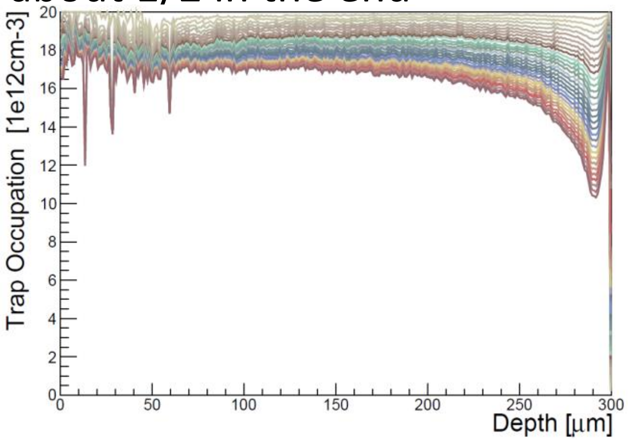


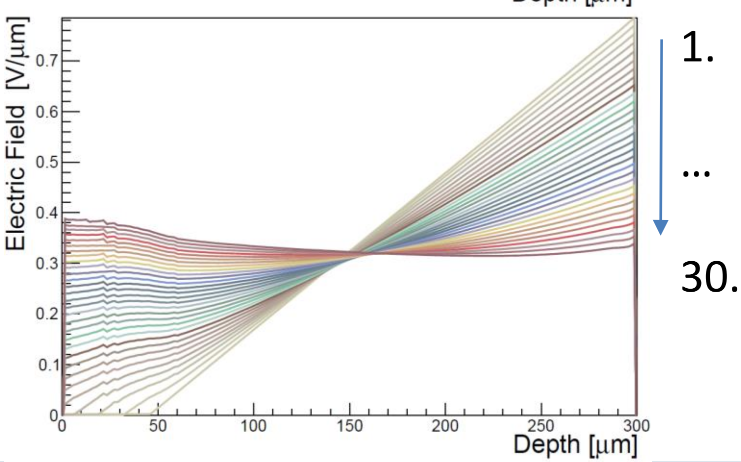
Polarization: Simulations

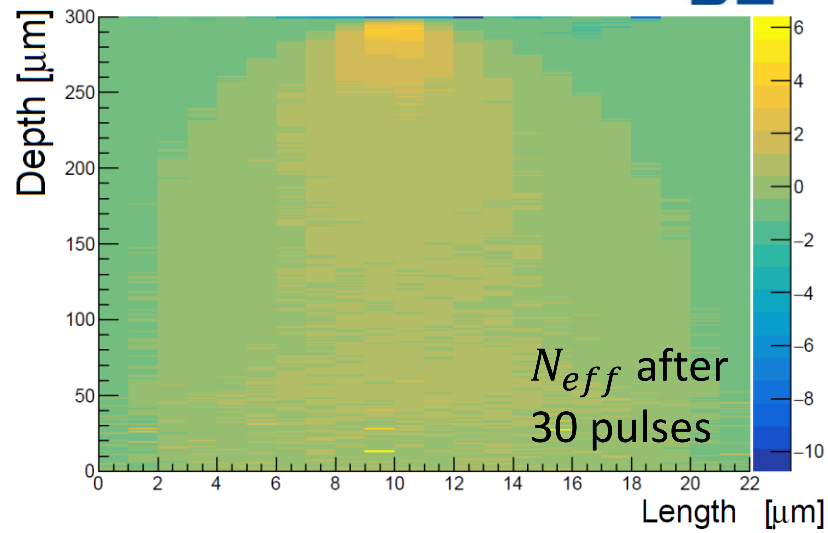
Example: low capture cross section

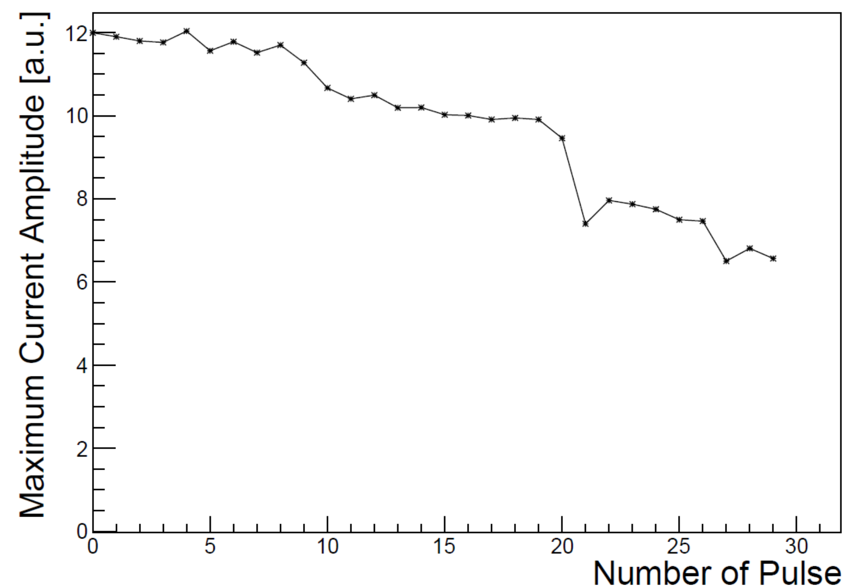
- Doping and trap concentration $1e12\ 1/cm^3$
- 50 V; S=0.4e-13 cm2
- 300 # buckets, 10 carriers/ bucket

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







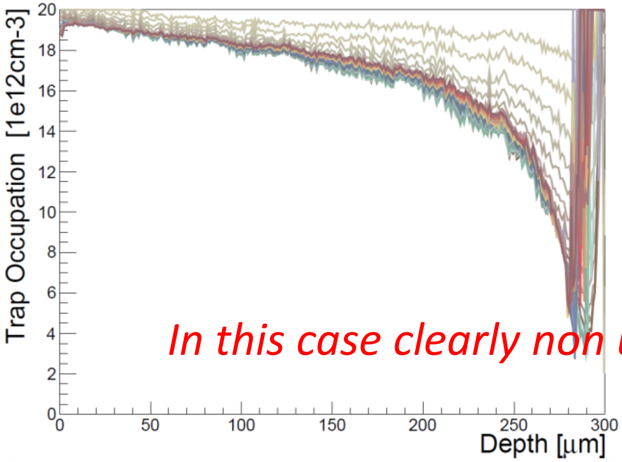


Polarization: Simulations

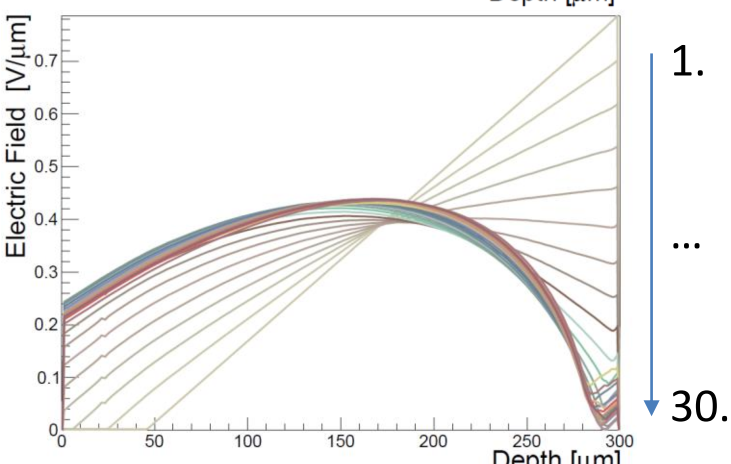
Example: large capture cross section

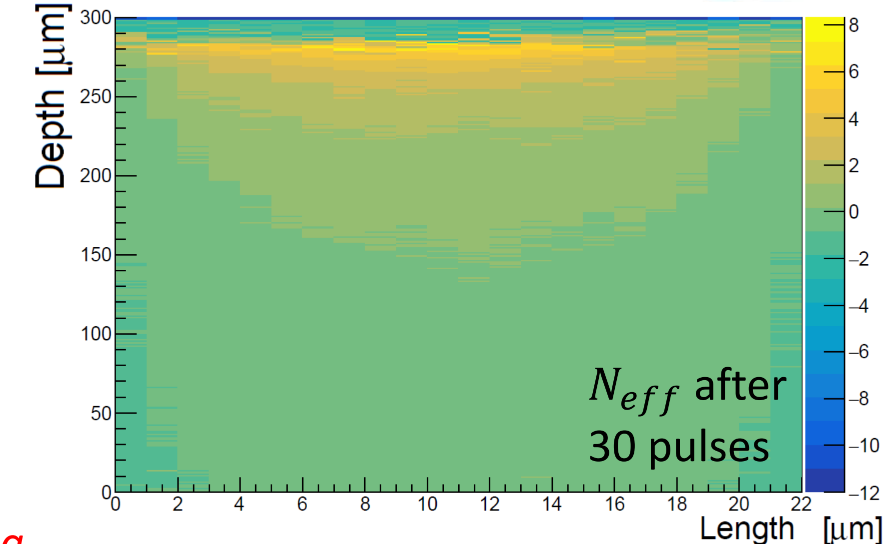
- Doping and trap concentration $1e12\ 1/cm^3$
- 50 V; S=4e-13 cm2
- 300 # buckets, 10 carriers/ bucket

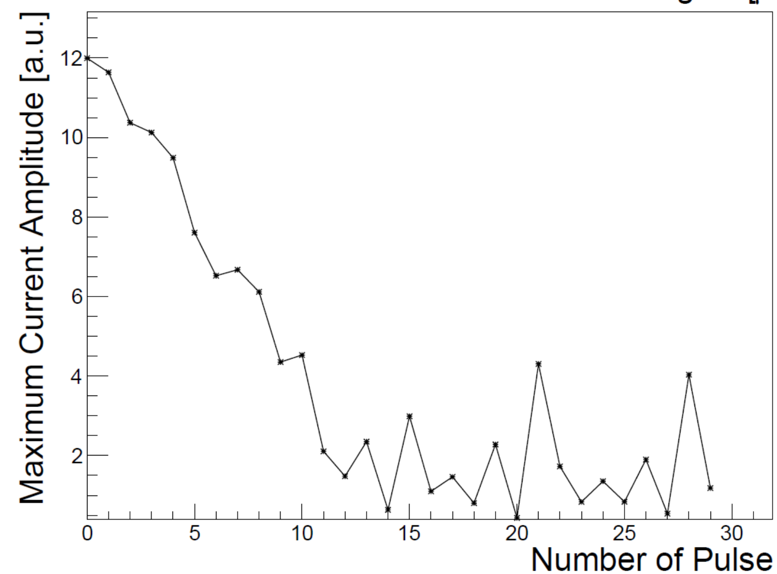
➢ Amplitude almost zero in the end



In this case clearly non uniform trapping







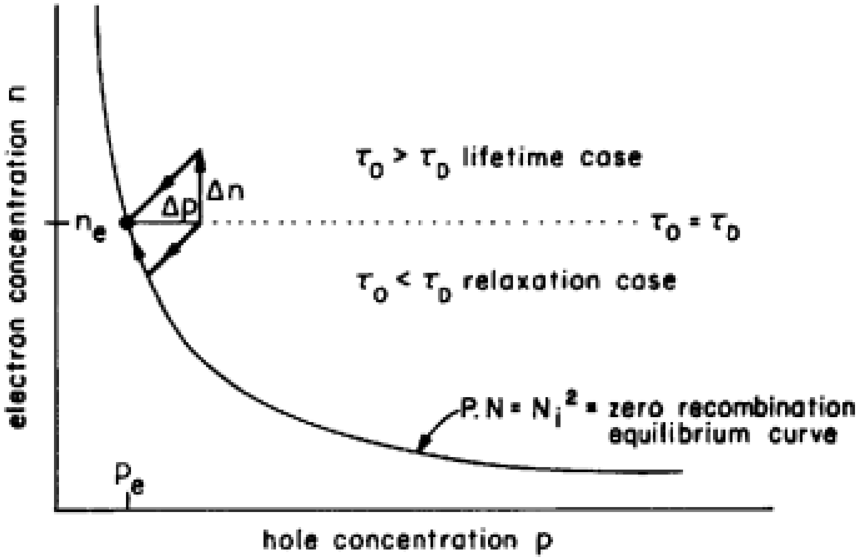
Relaxation: Description

Introduction:

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

- Highly irradiated silicon behaves like a relaxation semiconductor

  - ➢ 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 τd.

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

Relaxation: Description

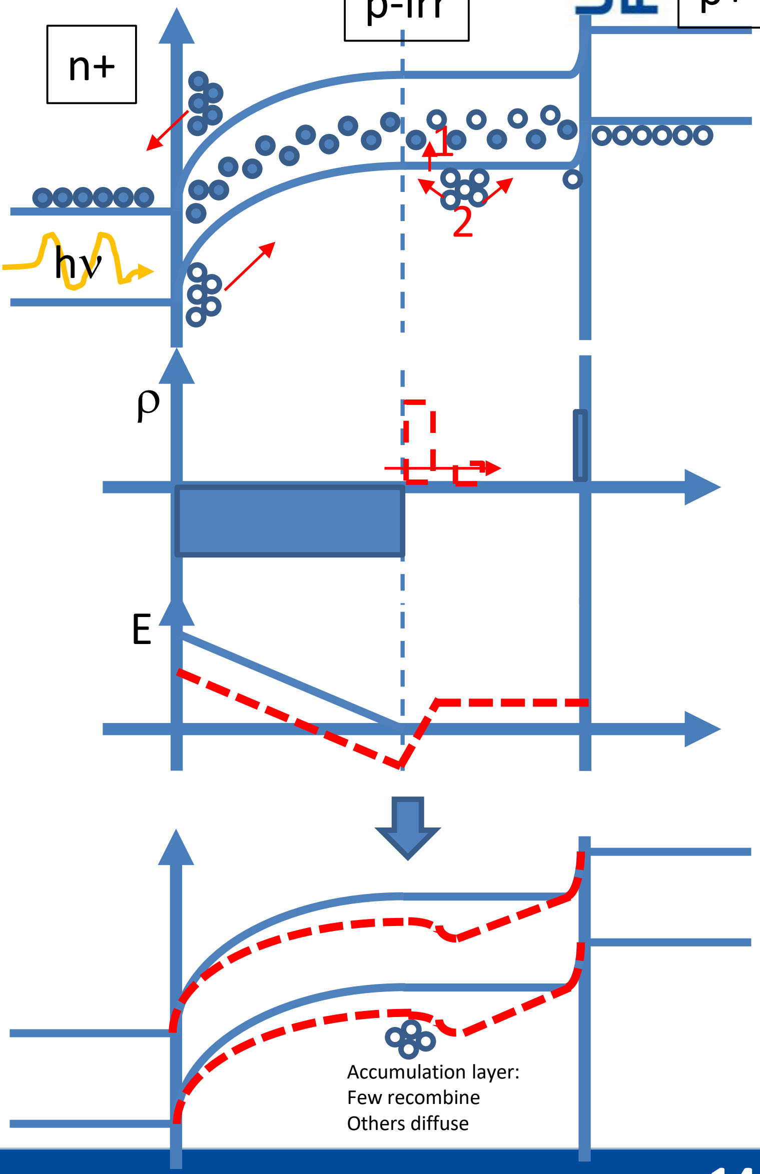
Description:

- Dielectric relaxation can be nicely described by time varying weighting potential [backup][6]
- Externally impressed charge to a medium with conductivity σ is balanced by a potential readjusting itself with an effective permittivity $\varepsilon_{eff}=\varepsilon+\sigma/s$
- Initially induced potential decays with $\tau=\varepsilon/\sigma$ due to redistribution of free charges
- Induced holes drift to undepleted bulk
  - ➢ acts as a relaxation semiconductor
- Additional positive space charge, neutralization occours with a (small) partial immediate recombination (1) and a slow diffusion (2) of majority carrier relaxing to the equilibrium

WORK IN PROGRESS: in discussion with Prof. Klanner

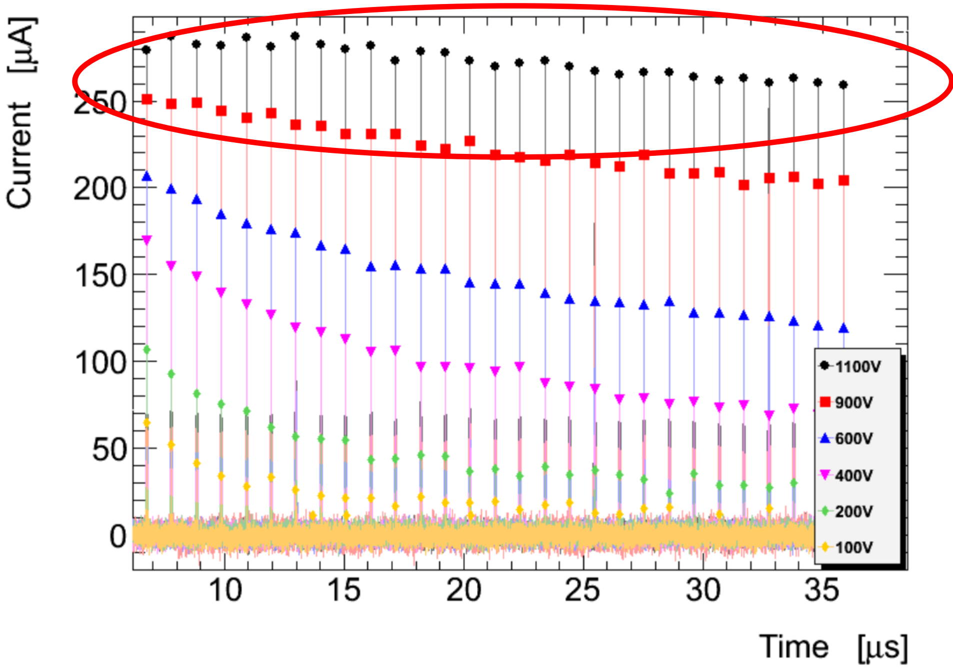
[6] Schwandt, Klanner, NIM A, 2019.

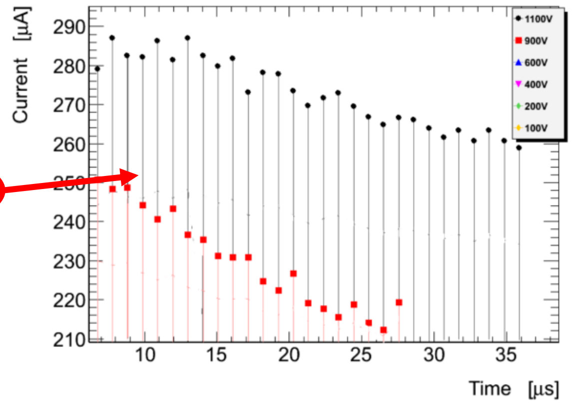
Sketches:

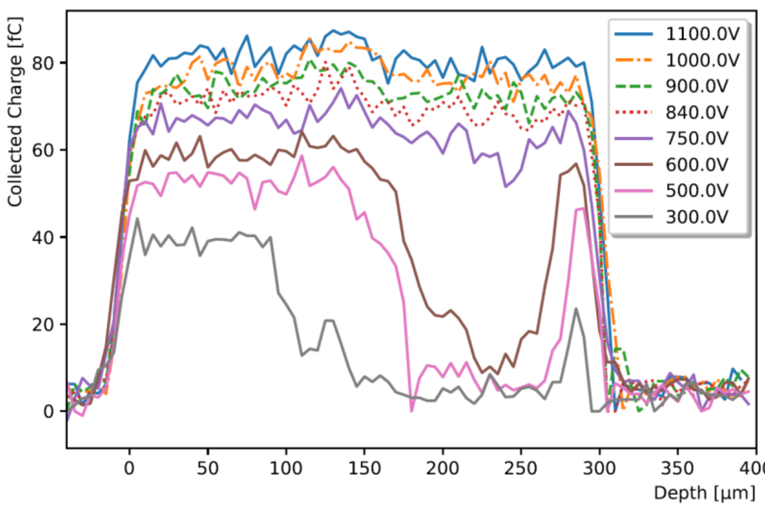


New Measurements

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







- High intensity, ~$1\mu s$ 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
  - Effects on electric field are similar

- Assumption of trapping/ polarization:
  - Simulations agree with the decrease in subsequent detection
  - Fit model reproduces the decrease observed in measurements

- Assumption of relaxation:
  - Under investigation/ discussion, simulation or model not developed yet

- New measurements show a decrease in a fully depleted sensor, hinting that trapping is definitely contributing

- More studies and simulations are necessary to differentiate between the possible explanations

Conclusion

- Signal amplitude decreases during subsequent pulse detection
- Possible explanations: Polarization effect (trapping) or relaxation
  - Effects on electric field are similar
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Thanks for your attention!

Backup

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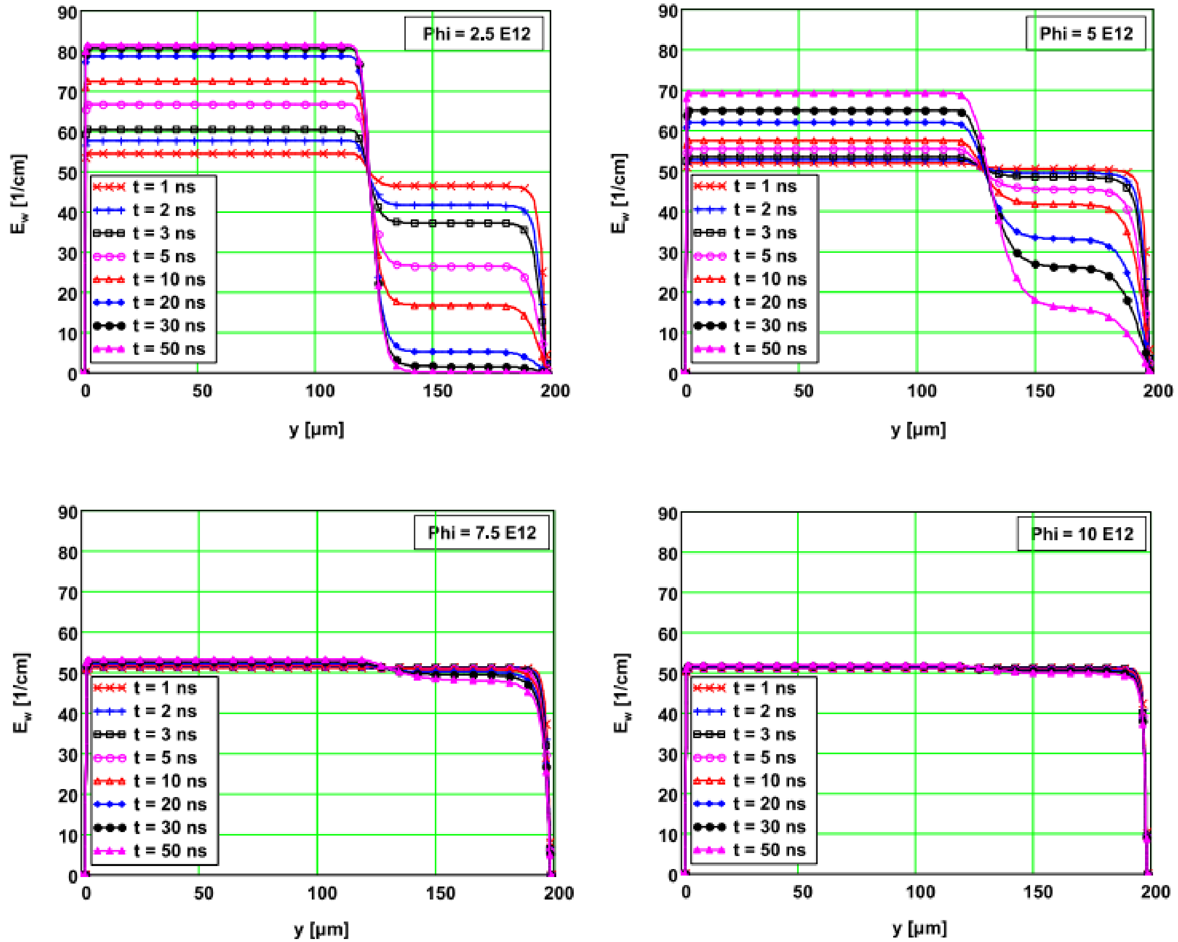
- Notation:
  - Pt: concentration of empty trap levels (hole occupied)
  - Nt: concentration of occupied trap level
  - Cp: capture coefficient
  - σ: capture cross section for holes
  - <vth>: thermal velocity holes
  - Vh: hole velocity
  - E: electric field
  - E0: electric field peak at x=0
  - X: 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

Description:

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



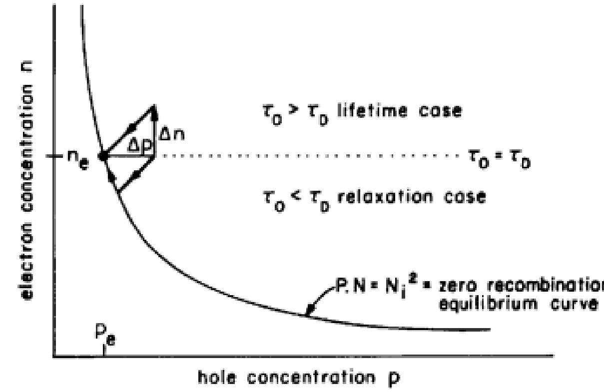
[6] Schwandt, Klanner, NIM A, 2019.

Relaxation: description

Introduction:

- Electrical relaxation time τd larger than lifetime $\tau 0$ 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 $\tau d=\rho\varepsilon$ 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.

[2] Quissier, Solid State Devices, 1973 [3] Henisch, Phys Mag B, 1985 [4] Van Roosbroeck, Phys Rev B, 1972

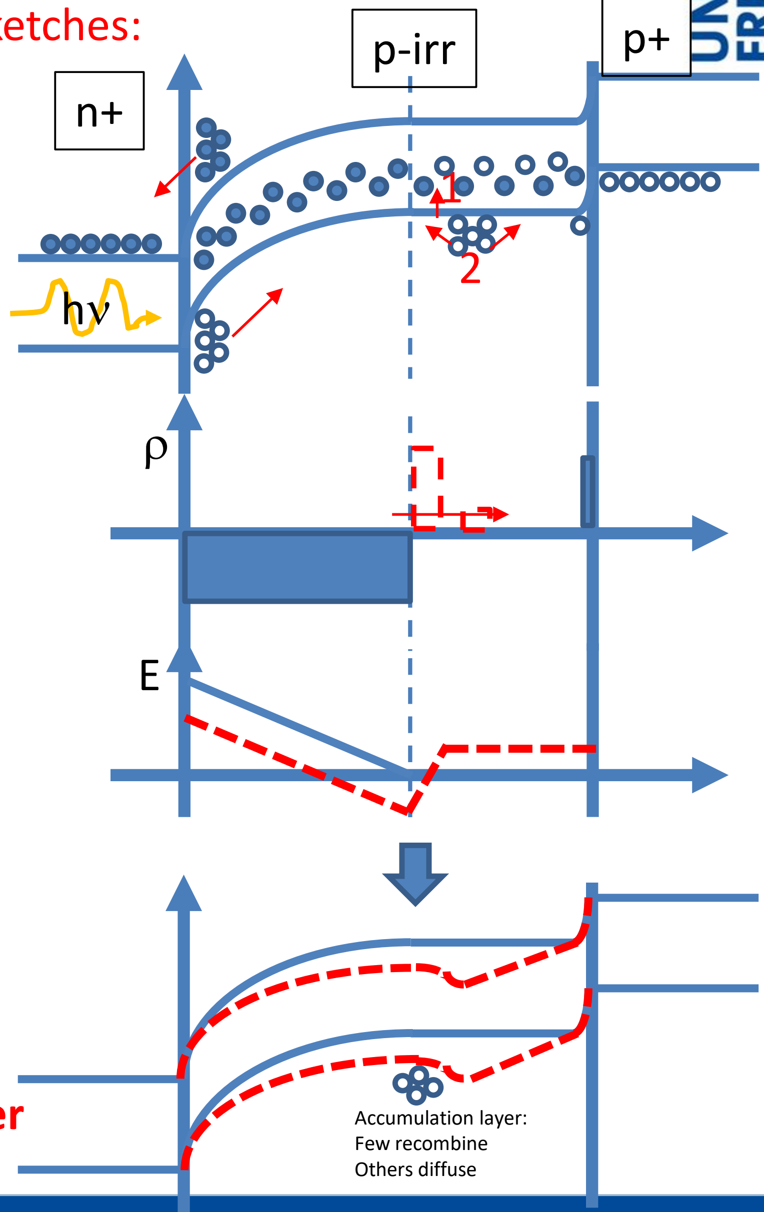
Relaxation: description

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 εeff=ε+σ/s; the potential initially induced by the external charge decays with τ=ε/σ 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 equilibrium with a time constant τ=ε/σ.

WORK IN PROGRESS: to discuss with Prof. Klanner

Sketches:



[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

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:

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

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

with $p_{MAX} = N_t$

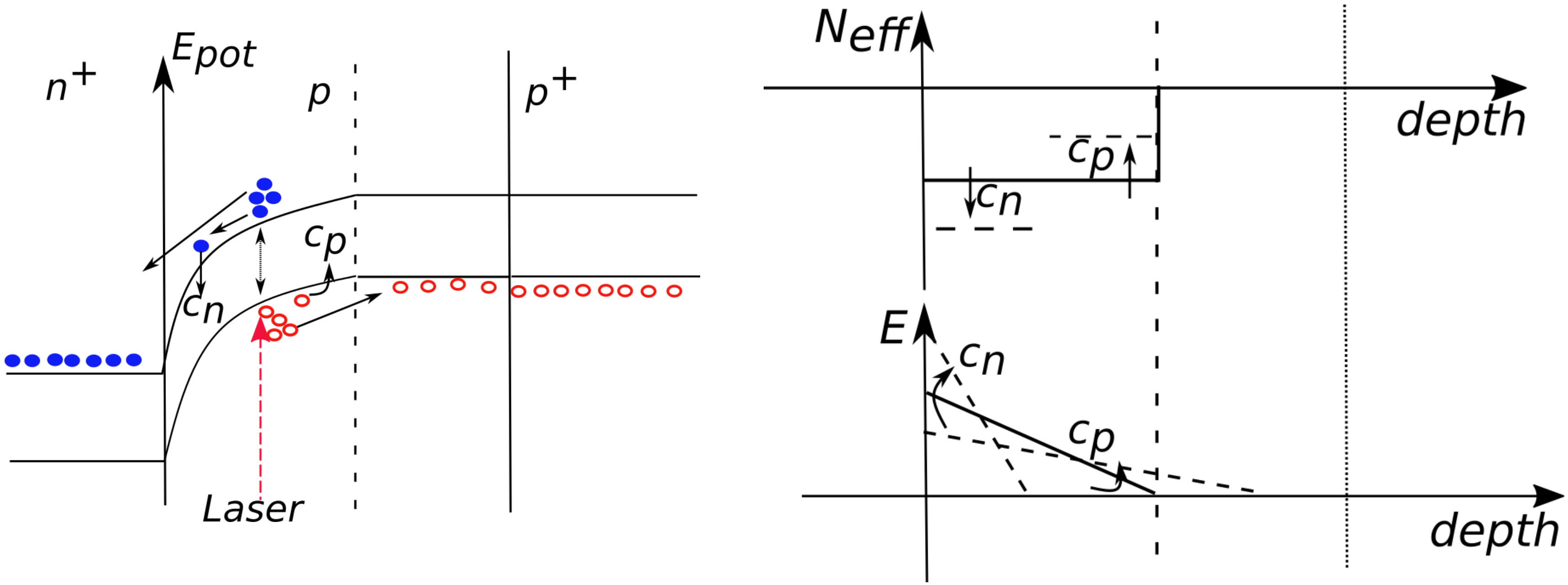
- El. Field peak (from assumption of constant W): $E_0 = \sqrt{\frac{2eV\;\; \left(N_{eff} - p_t(i)\right)^2}{\varepsilon\;\; N_{eff}}}$

- Current peak:

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

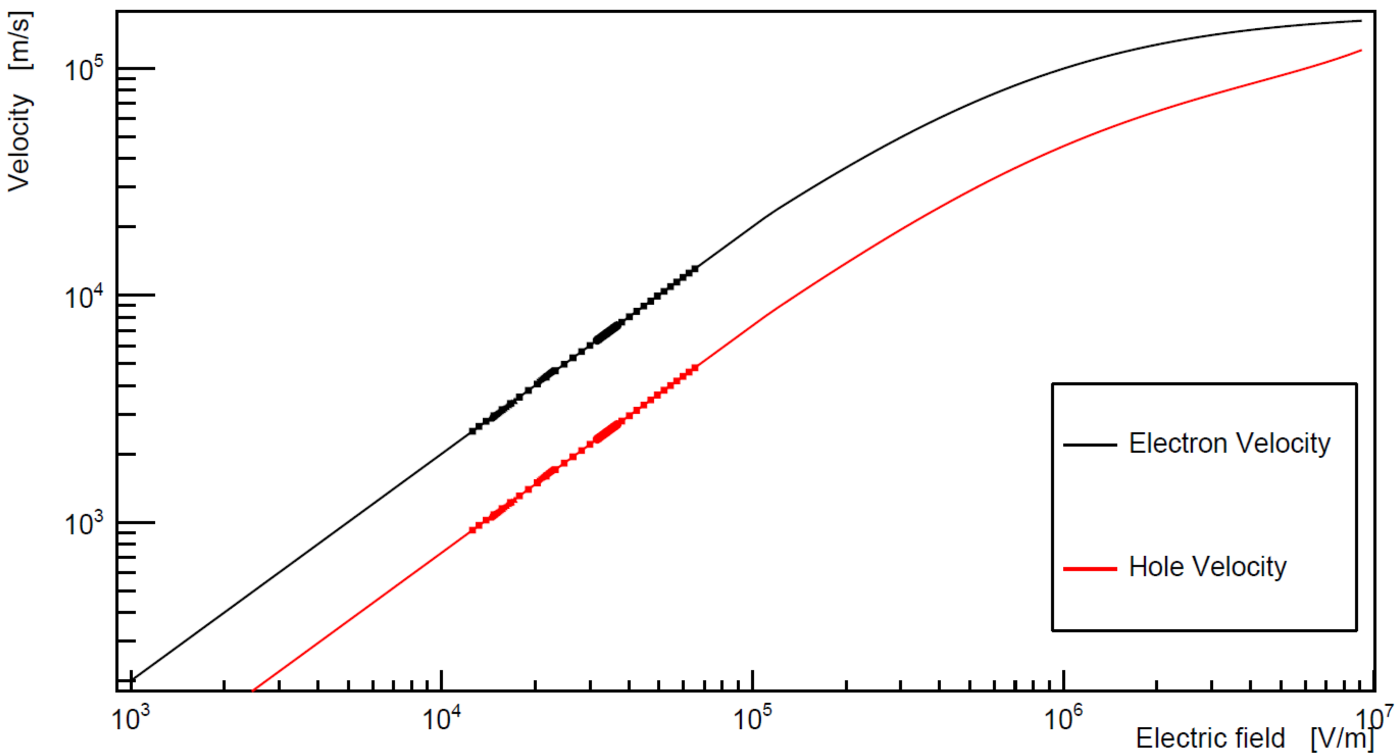
where $n_e = n_h \propto$ intensity, for μ_e, μ_h see [Scharf, Klanner, NIM A 2005]

Electric Field change model:



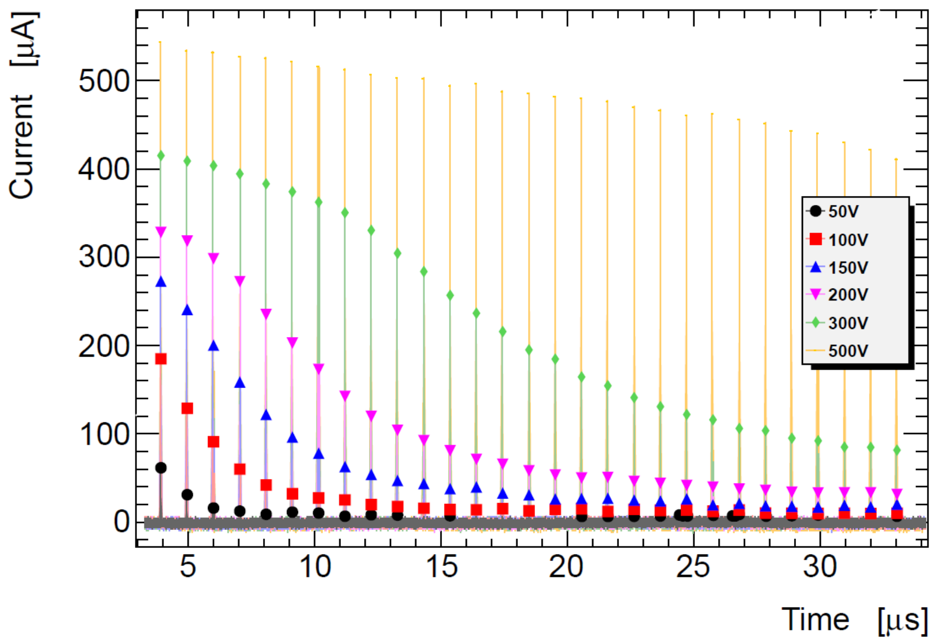
- Trapped charges change the eff. Doping concentration and thereby the el. Field
- Trapping of electrons reduces the depletion width, trapped holes increase it
- This would mean:
  - Intensity dependence: Amount of trapped charges determines speed of field change
  - Voltage dependence: Effect reduces 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)

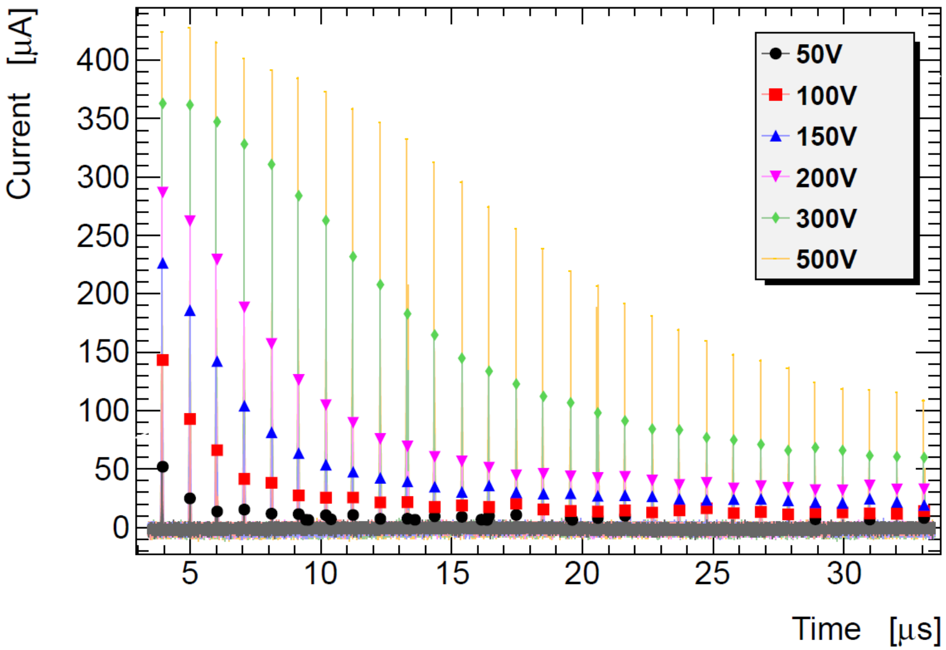


n-type diodes, type inverted, back illumination

$6 \cdot 10^{14} n_{eq}/cm^2$

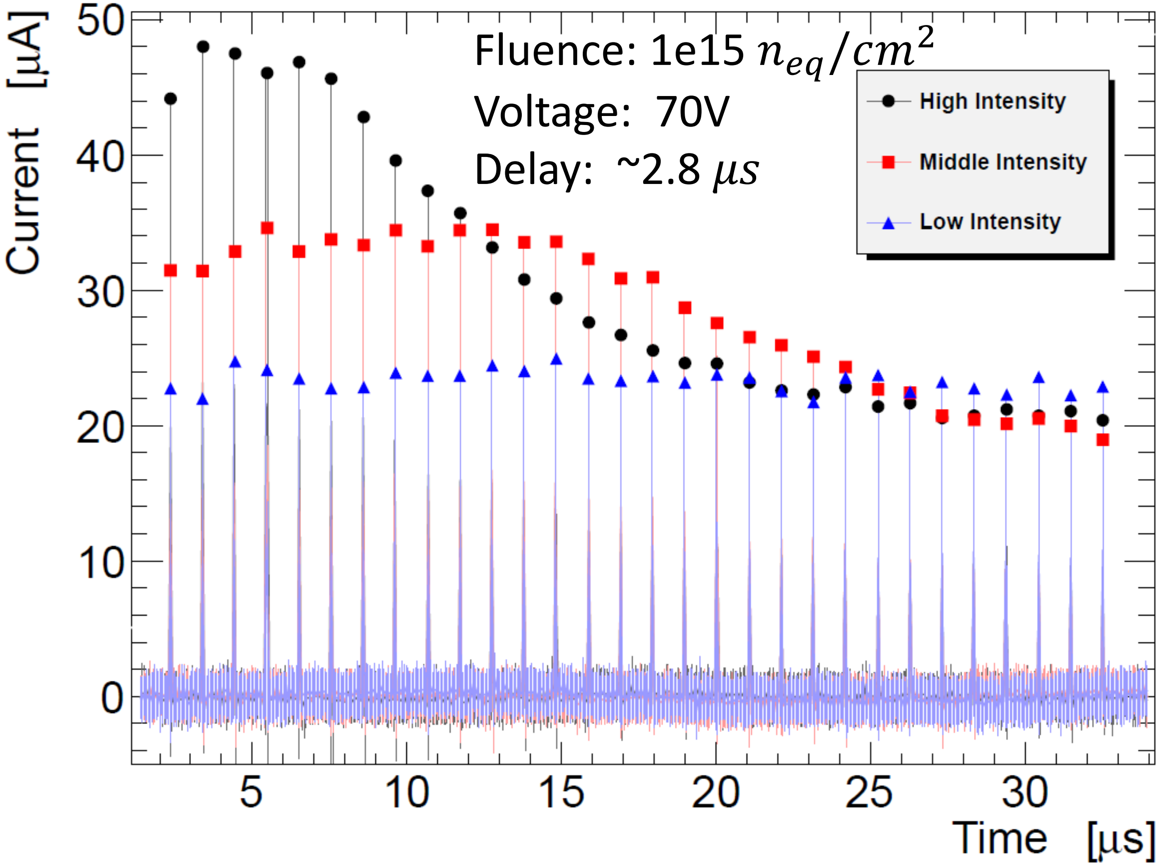


$1 \cdot 10^{15} n_{eq}/cm^2$



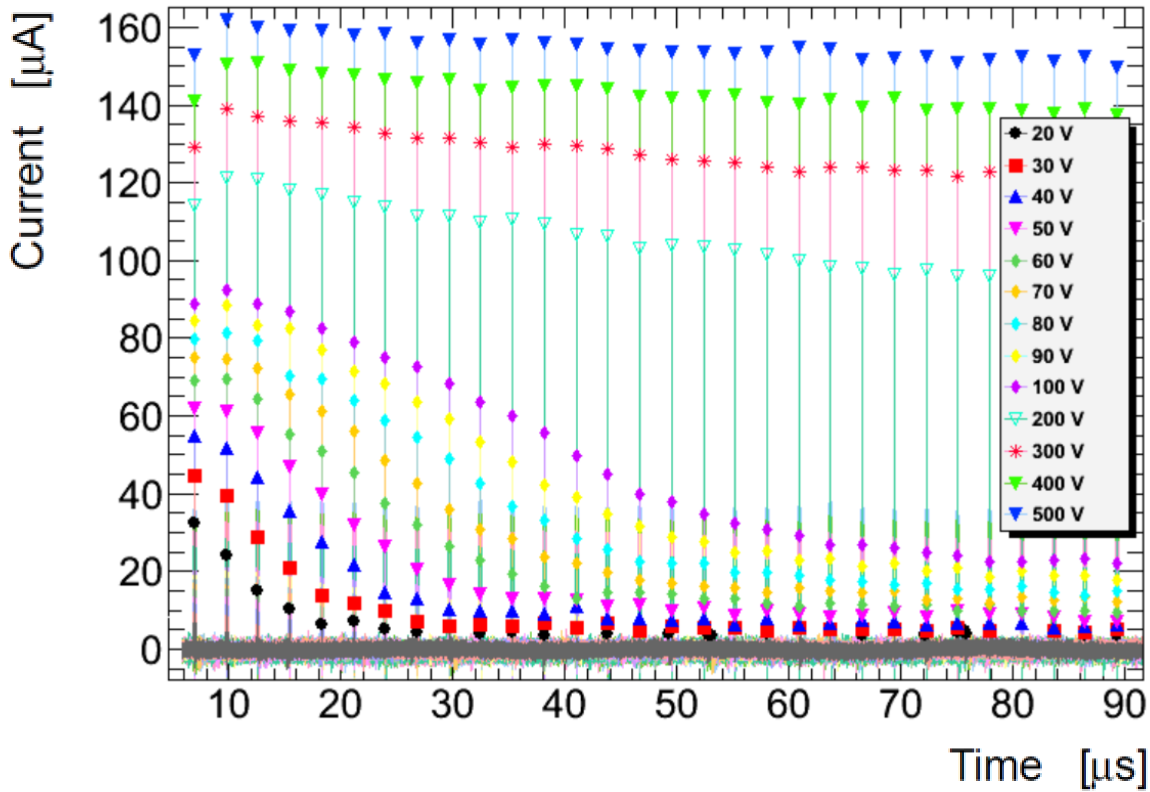
- Decrease is visible for ntype sensors as well
- Same dependencies measured: Fluence, Delay, Voltage, Intensity

Dependence on intensity



- 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

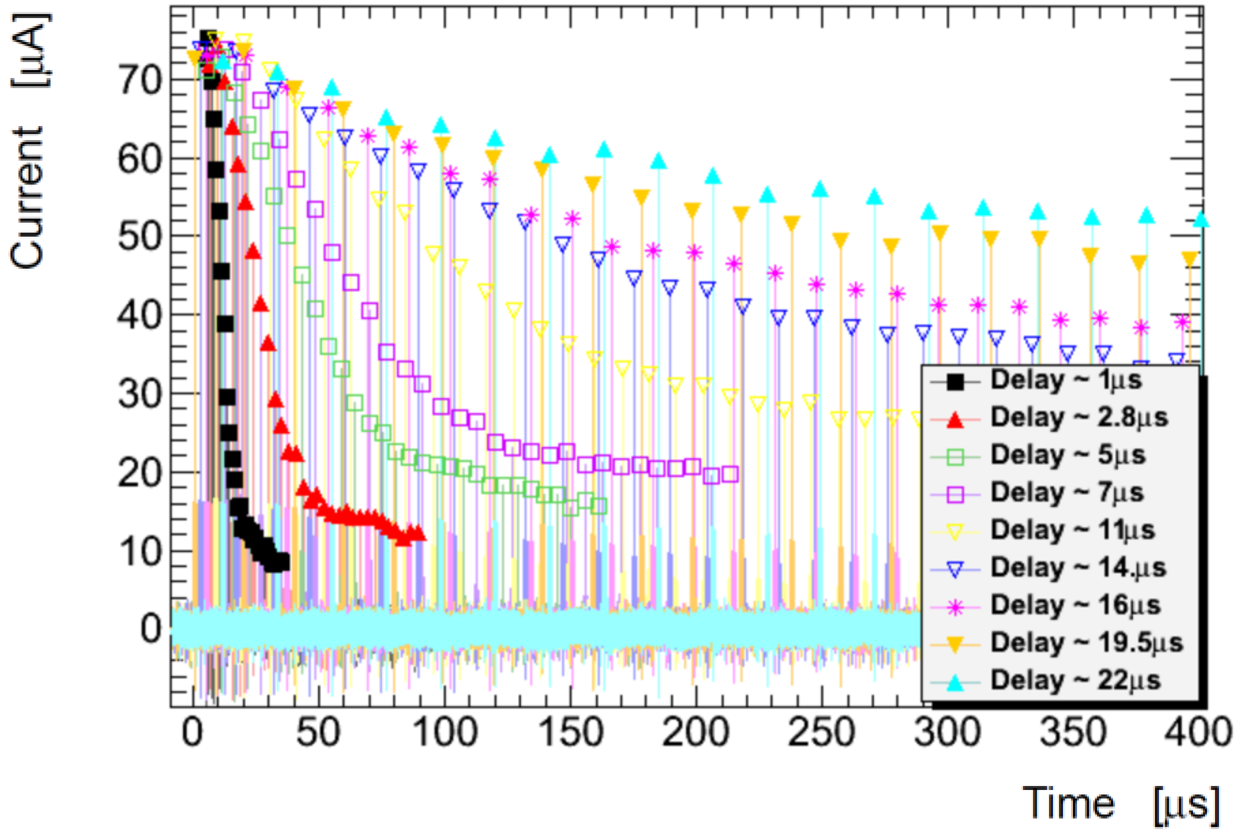
Dependence on voltage



Fluence: 1e15 n_{eq}/cm
High Intensity
Delay: ~2.8 μs

- 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

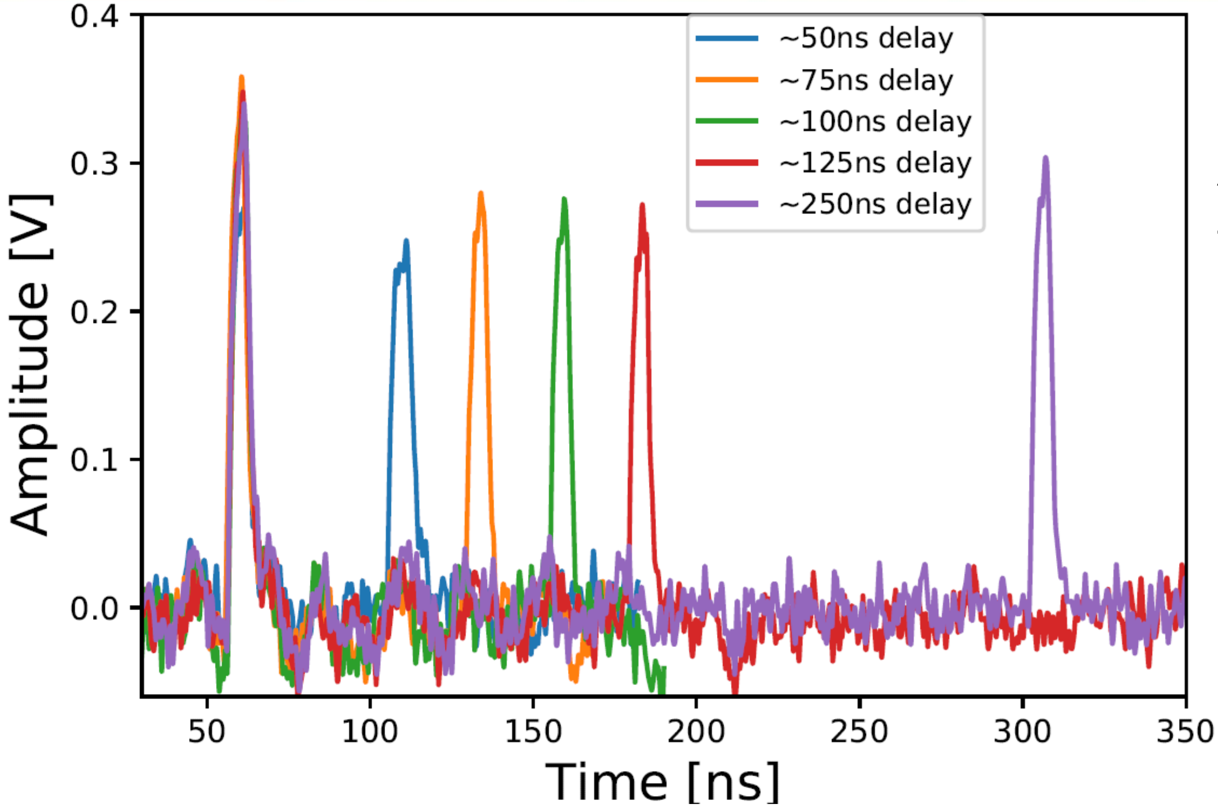
Dependence on pulse delay



Voltage: 70V
High Intensity
Fluence: 1e15 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

Irradiated Sensor, 2e15



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

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