Charge carrier detrapping in irradiated silicon sensors after microsecond laser pulses

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Outline

1. Motivation/Aim
2. Setup and diodes
3. Photocurrent during illumination
4. TCAD simulations
5. Measurements and method
6. Conclusions

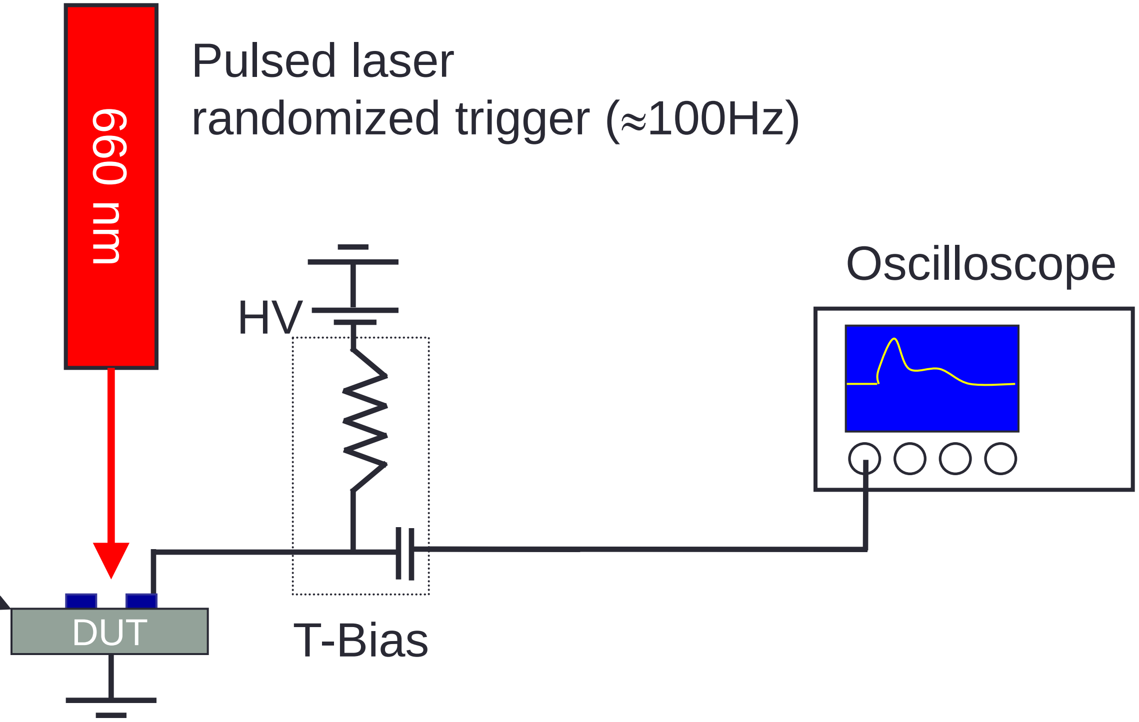
Motivation/Aim

- Knowledge of energy levels and cross-sections of de-trapping centres is crucial for defect characterization
- These parameters can be determined by investigating the temperature dependence of the time-constant τ for de-trapping
- For defects deep in the bandgap the de-trapping happens on a µs-timescale (around RT)

- Previous work: see e.g. Kramberger, Cindro, Mandic, Mikuz, Zavrtanika, “Determination of detrapping times in semiconductor detectors” (2012 JINST 7 P04006)

Setup and Diodes

CERN TCT setup for µs-pulses



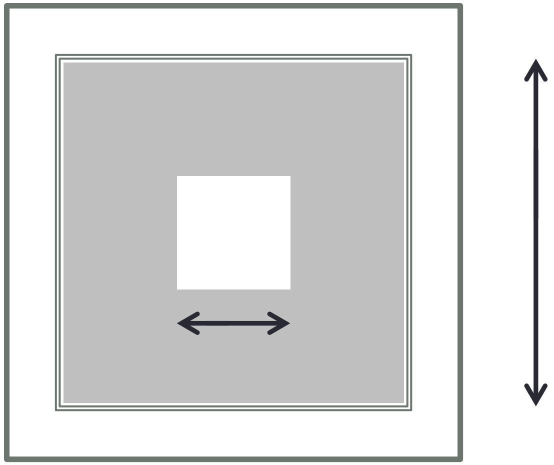
Pulsed laser
randomized trigger (≈100Hz)

Laser gets absorbed
in first 3µm

- Red laser illumination with variable pulse width (0.5 - 20µs)
- Variable bias voltage with T-Bias (20kHz-10GHz, HV < 200V)
- Amplifier was not used (to have maximal bandwidth, but: ~1mV signals)
- Temperature controlled (flushed with dry air for T < 10°C)

Investigated diodes

- Material: Micron, 300µm, FZ p- and n-type
- Irradiation: 24GeV protons with $\Phi = 5\times10^{14}, 1\times10^{14}, 5\times10^{13}, 1\times10^{13}$ p/cm^{-2}
- Annealing: 80min at 60°C
- Illumination: front (back fully metalized)

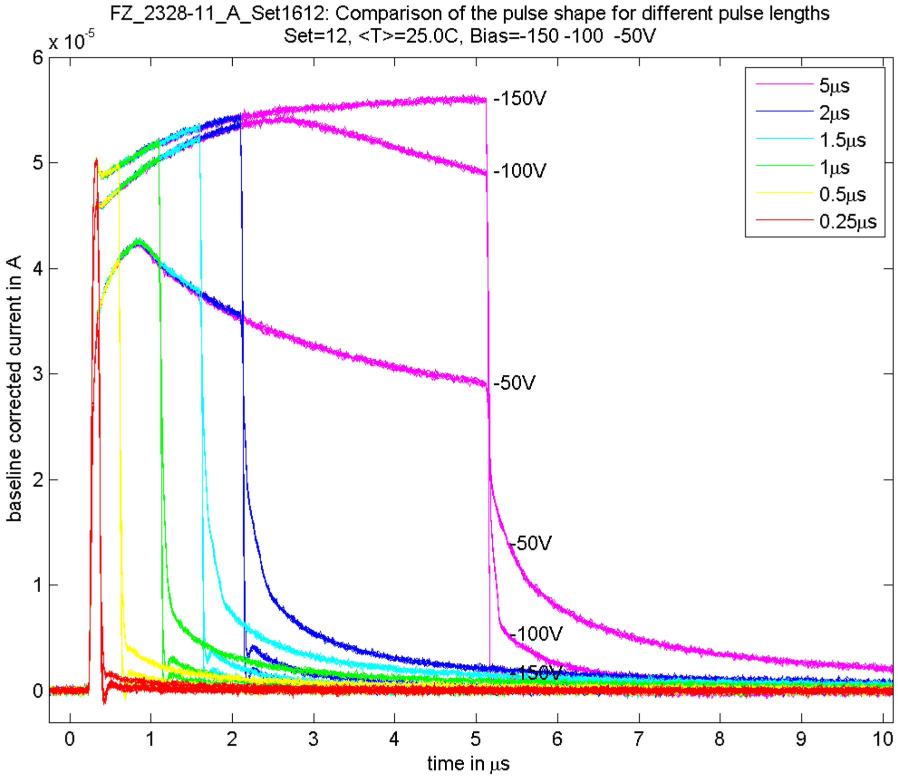


Pad: 4.5 × 4.5 mm^2

window:
1.5 × 1.5 mm^2

Example of transient current

- TCT signals have been measured (up to 50µs after illumination)
- Temperature range investigated: ca. -10 to 30°C
- Stability of signal confirmed by recording 10 times the (same) waveform which itself is an average of 1024 shots



Example:

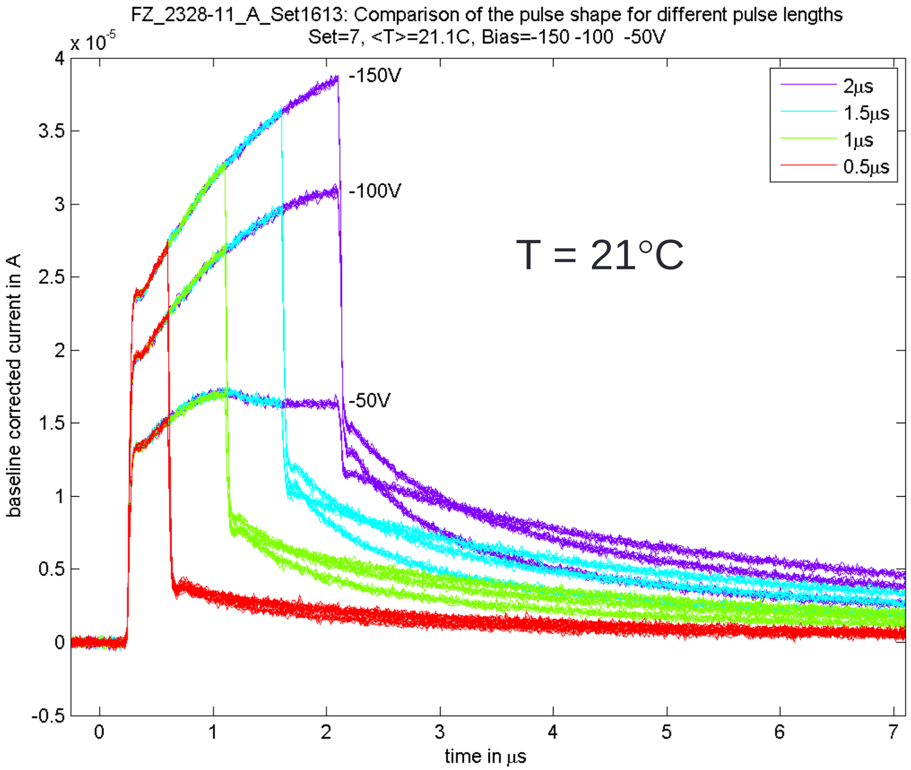
- $1e14 p/cm^2$
- n-in-p (holes transport)
- T = 21°C
- Bias: 50, 100, 150V
- Pulse length: 0.25-5µs
- 660nm, top illumination

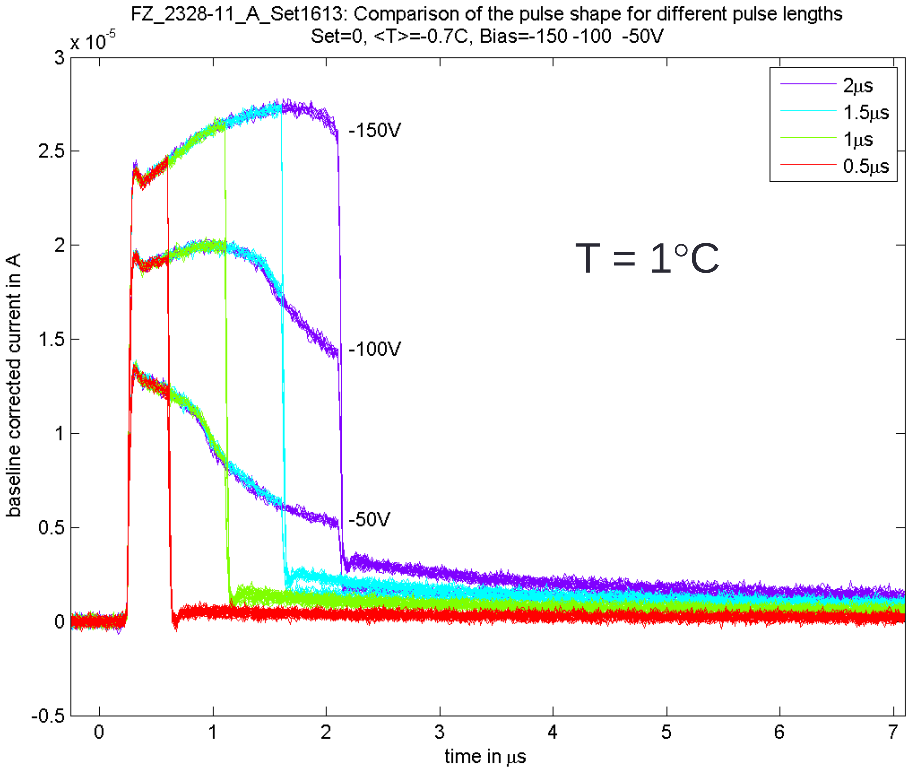
Photocurrent during illumination

Photocurrent during illumination

- Current can drop during illumination
- Happens mostly for lower bias voltage and lower temperature

Example: 5e14p/cm^2, n-in-p (holes transport)





Photocurrent during illumination

- Current can drop during illumination
- Happens mostly for lower bias voltage and lower temperature

➢ This effect is also visible in TCAD simulations
and can be explained by a reduction of the active volume due to trapped charges

TCAD Simulations
(Synopsis)

Synopsis TCAD Simulation of TCT signal of irradiated diode

Device

- silicon: p-type; 5e11cm^{-3} boron (V$_{dep}$(300µm)=35V; 25kΩcm)
- bulk dimensions: 300×10×1 µm^3 (x-y-z)
- diode: n-p-p
- 1 defect: D01 – CiOi (donor): E = 0.36eV, σ_e= 2.1e-18 cm^2, σ_h = 2.5e-15 cm^2
  generation rate : g = 0.7 cm^{-1} (24GeV/c protons) such that $N_{defect} = g \times \Phi$

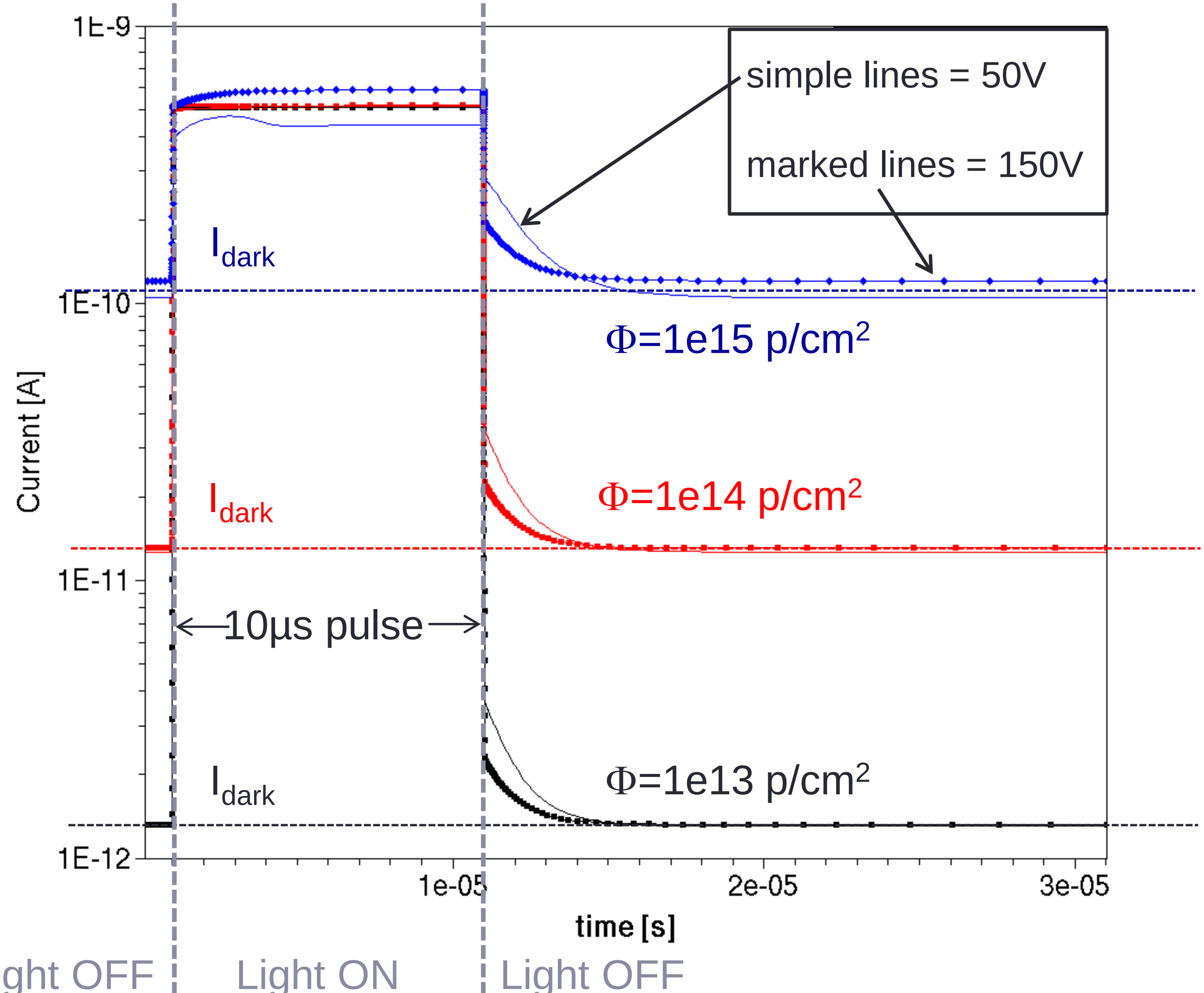
Light pulse

- 660 nm, 10mW/cm^2
- linear rise and linear fall in intensity from 0 to 100% in 1ns
- pulse length (variable, µs-order)

Physics

- Simulation: Synopsys TCAD F-2011.09
- Temperature: 300K
- Leakage current via SRH lifetime “generated” (more details in M.Moll’s talk tomorrow)

Synopsis TCAD Simulation of TCT signal of irradiated diodes



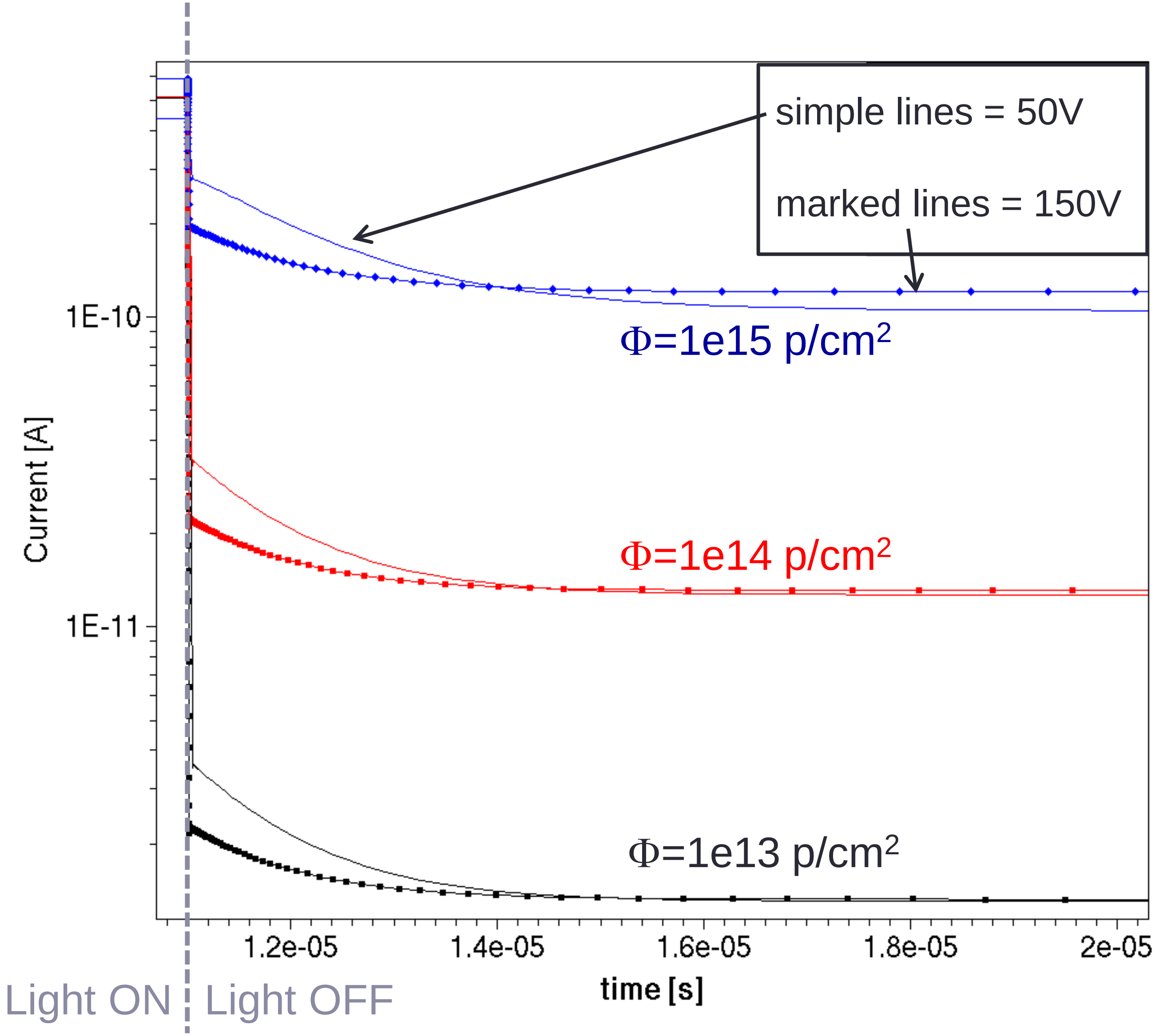
All data for 300K

Note:

- All currents for the simulated volume of 300×10×1 µm^3
- In experiment we have diodes with 300×5000×5000 µm^3

➢ we need a scaling factor of ≈2.5e6 such that, e.g., I_{dark} for 1e14p/cm^2 is ≈30µA (but in exp.: ≈100µA)

Why do we have higher transients for lower bias voltage?



Light OFF transient

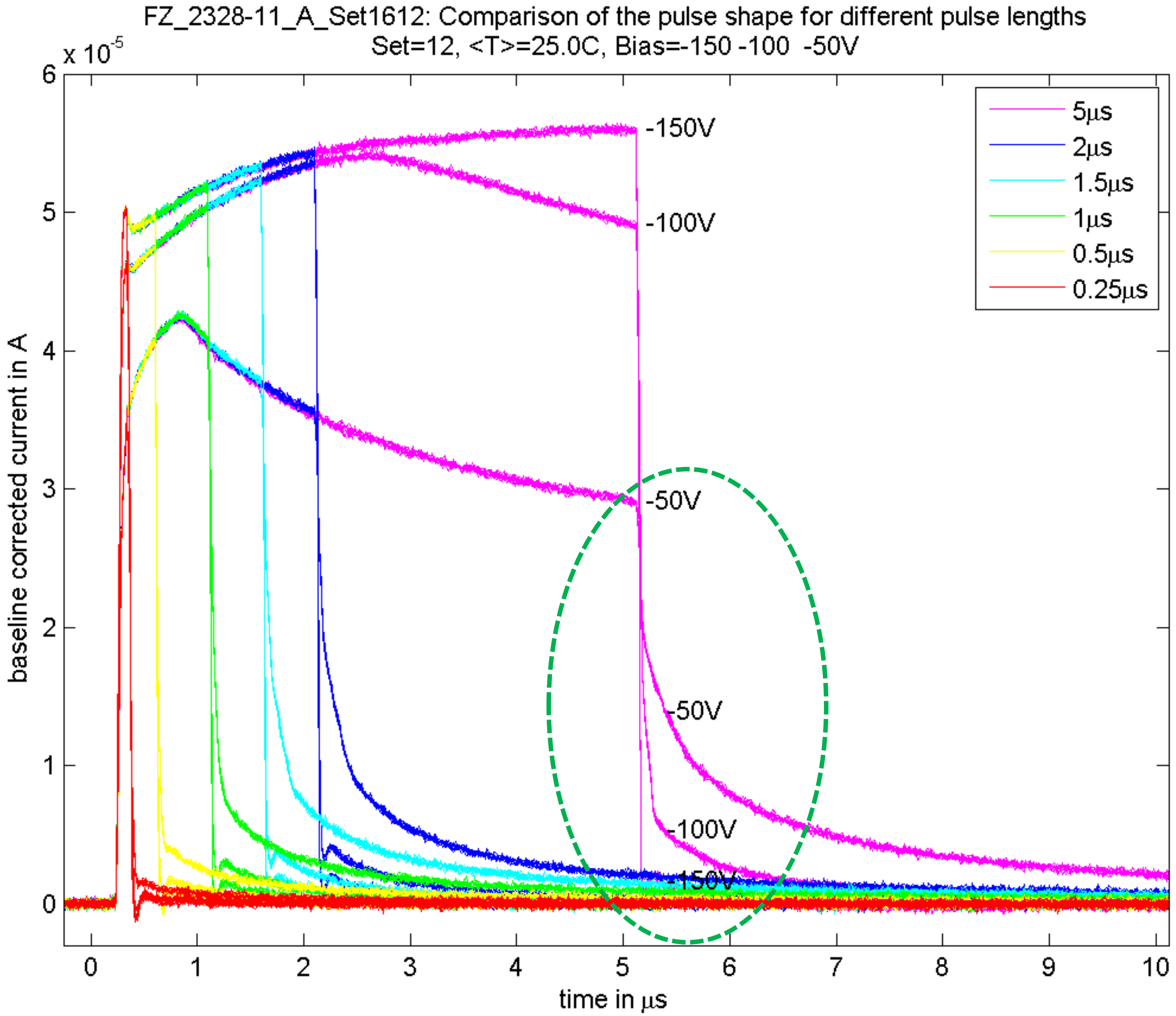
Observations:

- High transient amplitude after light pulse for lower voltage

➢ We have a better trap filling for lower voltage

➢ This can be seen in the defect occupancy plot on next slide

Example from slide 7



Example:

- 1e14p/cm^2
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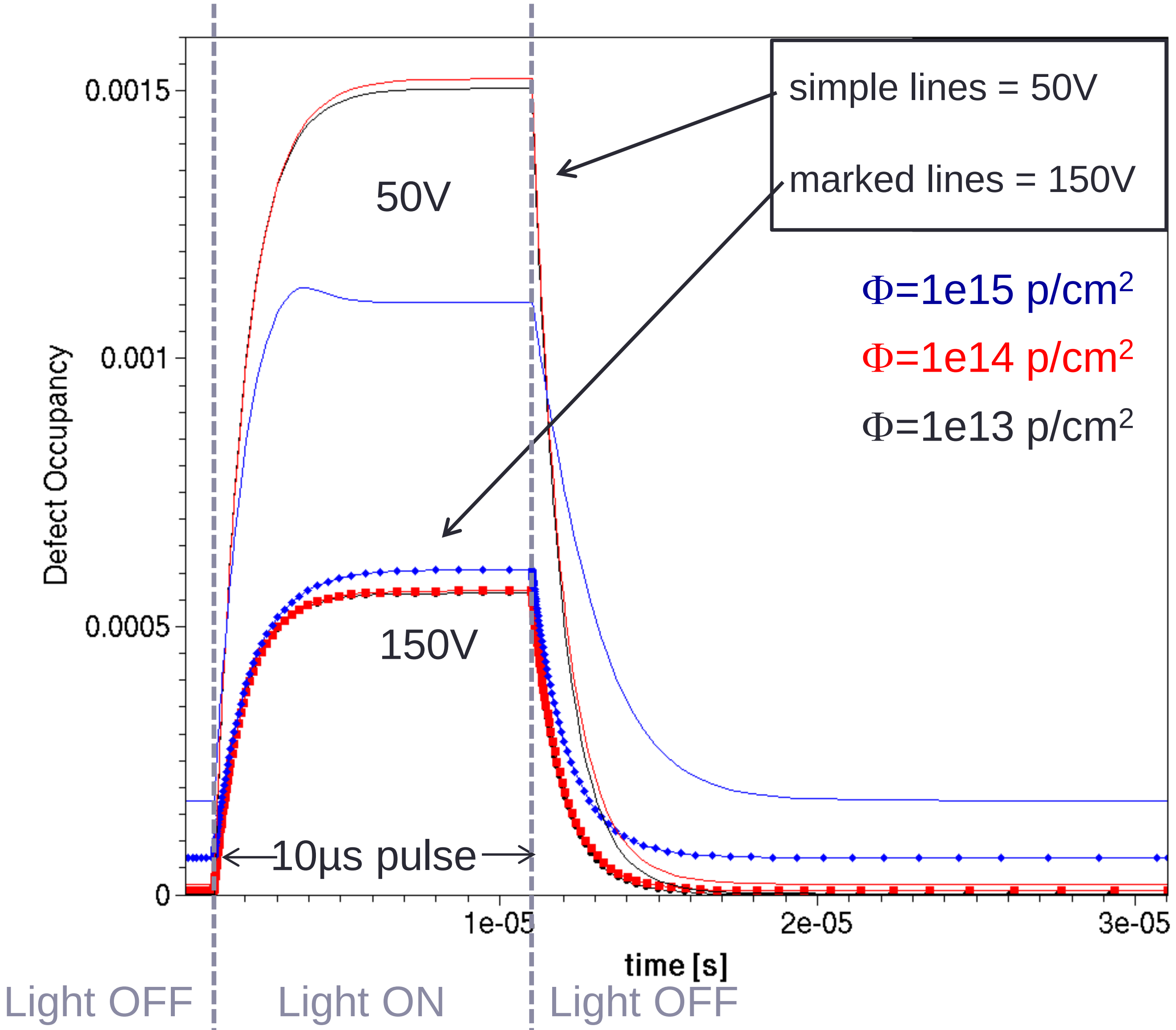
Defect Occupancy at x=150µm

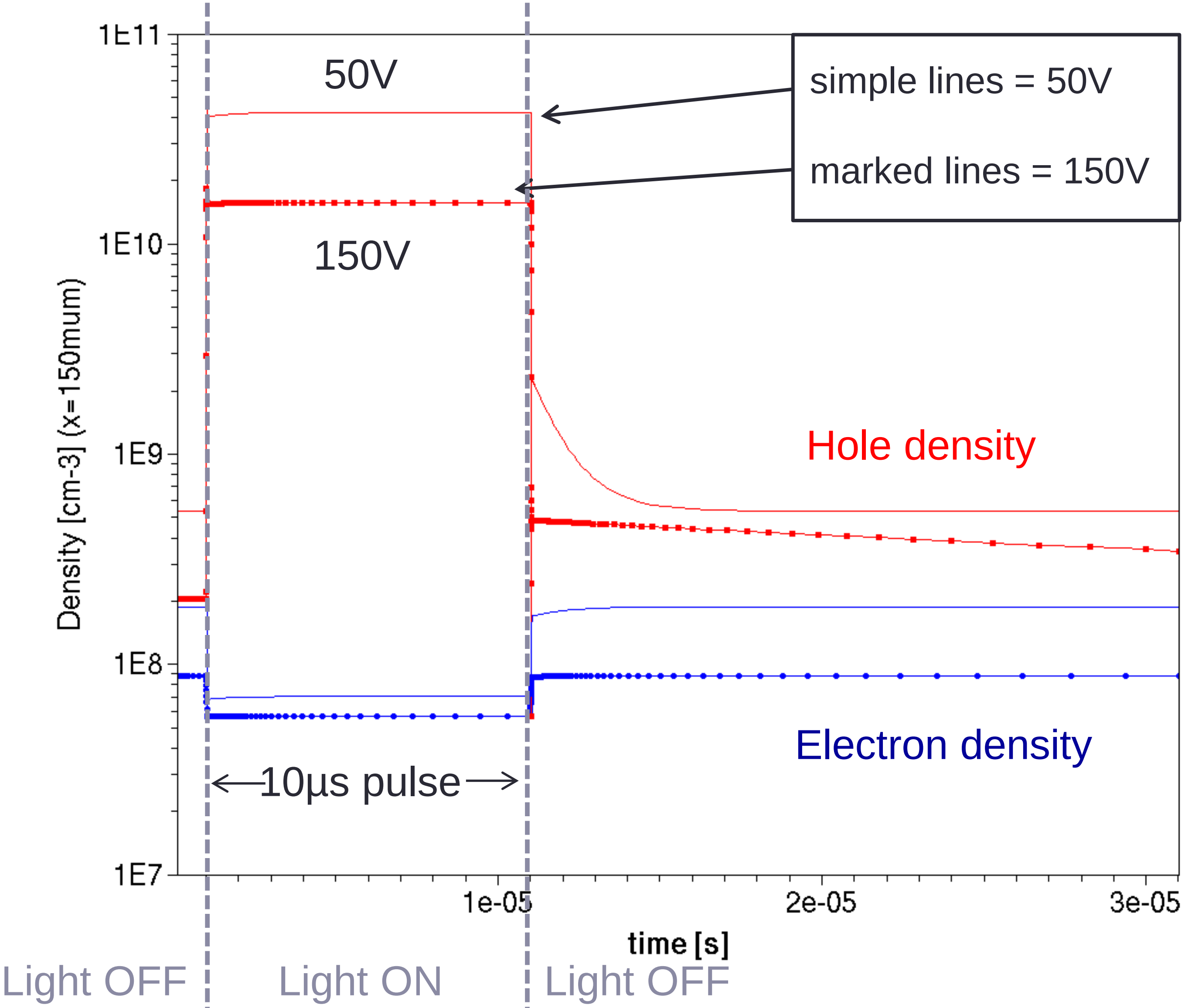


Observations:

- Higher defect occupancy for lower voltage

➢ This is a result of higher hole density for lower voltage

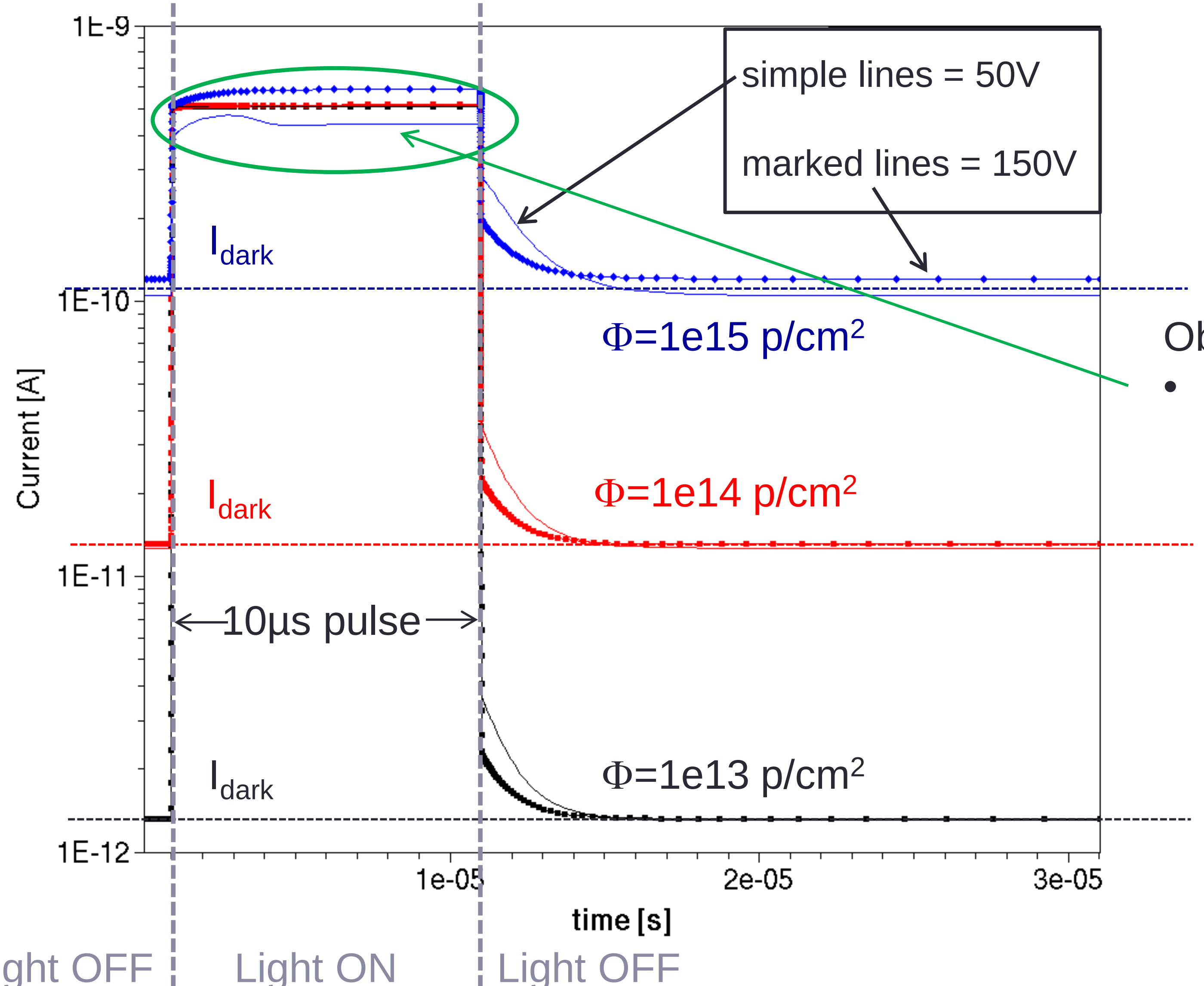
Electron and Hole Densities at x=150µm for Φ=1e14 p/cm^2



Explanation:

- Higher hole density for lower voltage
  → higher occupancy
  → larger transient
- Note: the transient currents for 50 and 100V in the case of 1e14p/cm^2 were the same. Since v_{drift} is lower for 50V we need higher carrier density to obtain the same current.

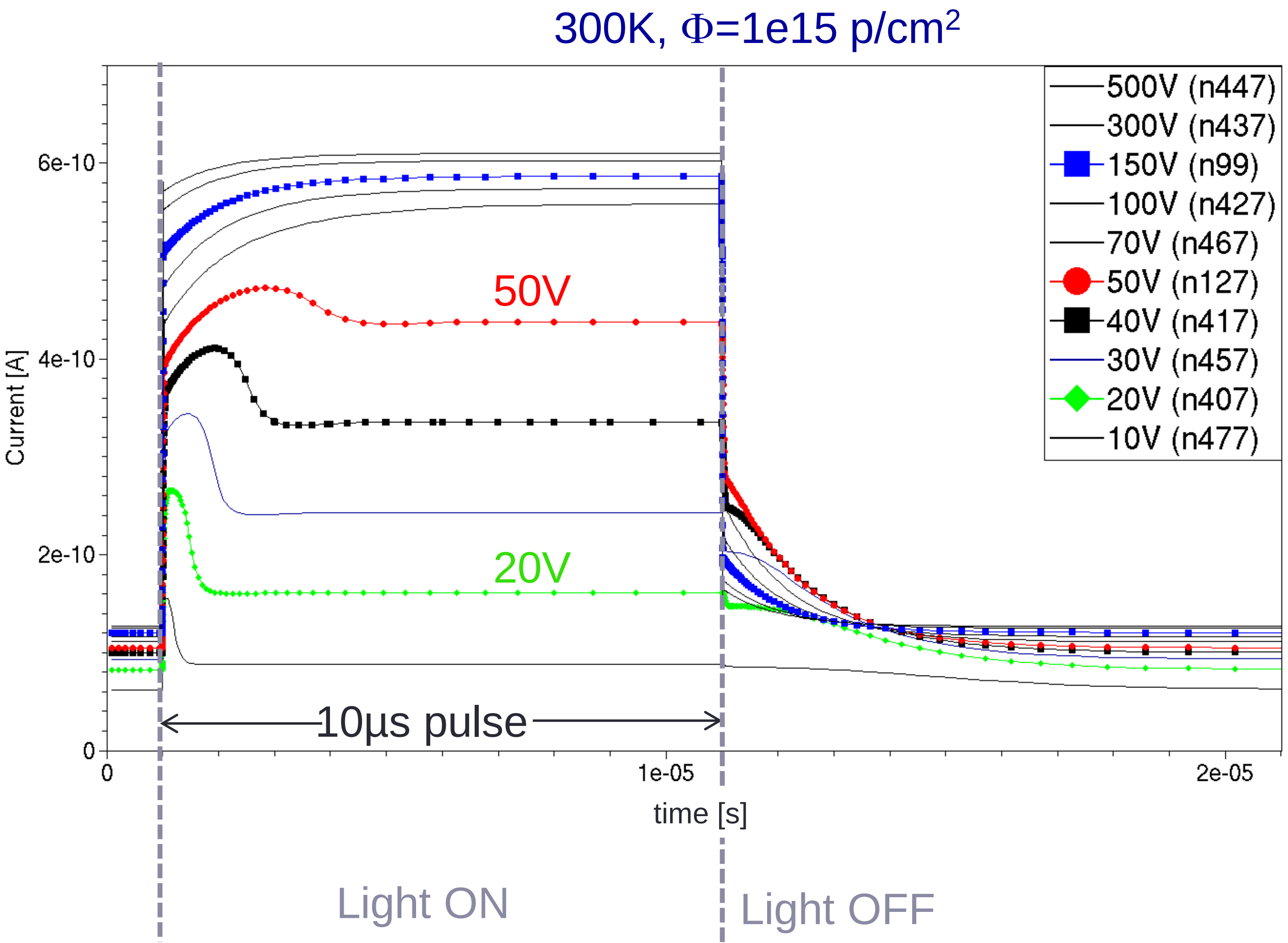
Why do we see a current drop for high fluence and low bias?



Observations:

- Current drops during illumination for 50V and Φ= 1e15 p/cm^2

Current drop for high fluence and low voltage (Voltage scan)



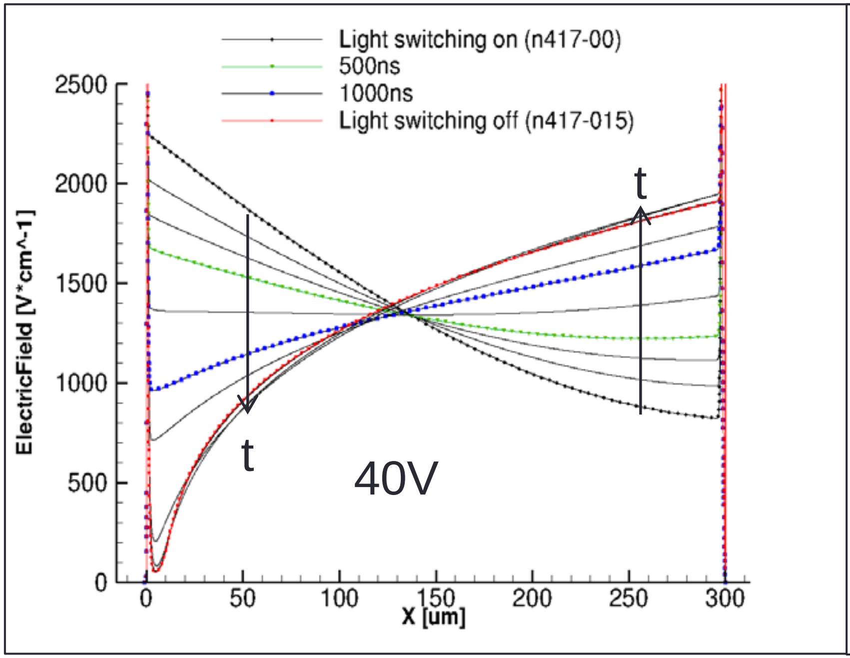
Observation:

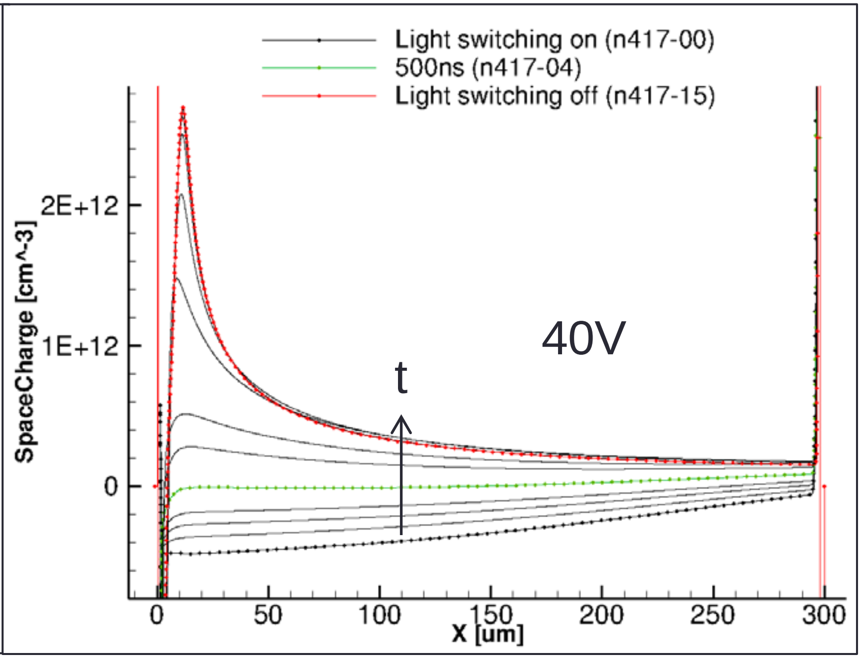
- Decrease in current for ≤50V for highest fluence Φ= 1e15 p/cm^2

➢ This is a result of a reduction of the active volume due to the opposing field from occupied defects

➢ The leakage current drops and gives a negative contribution to transient photocurrent

Time evolution of E-field and space charge density





- For voltages below 60V the detector goes into underdepletion at the front junction during the pulse which leads to a reduction in photocurrent
- Figure shows space charge sign inversion (from neg. to pos. space charge)

Measurements and Method

Signal Components

- For irradiated detectors we expect the current AFTER illumination to be of the form:

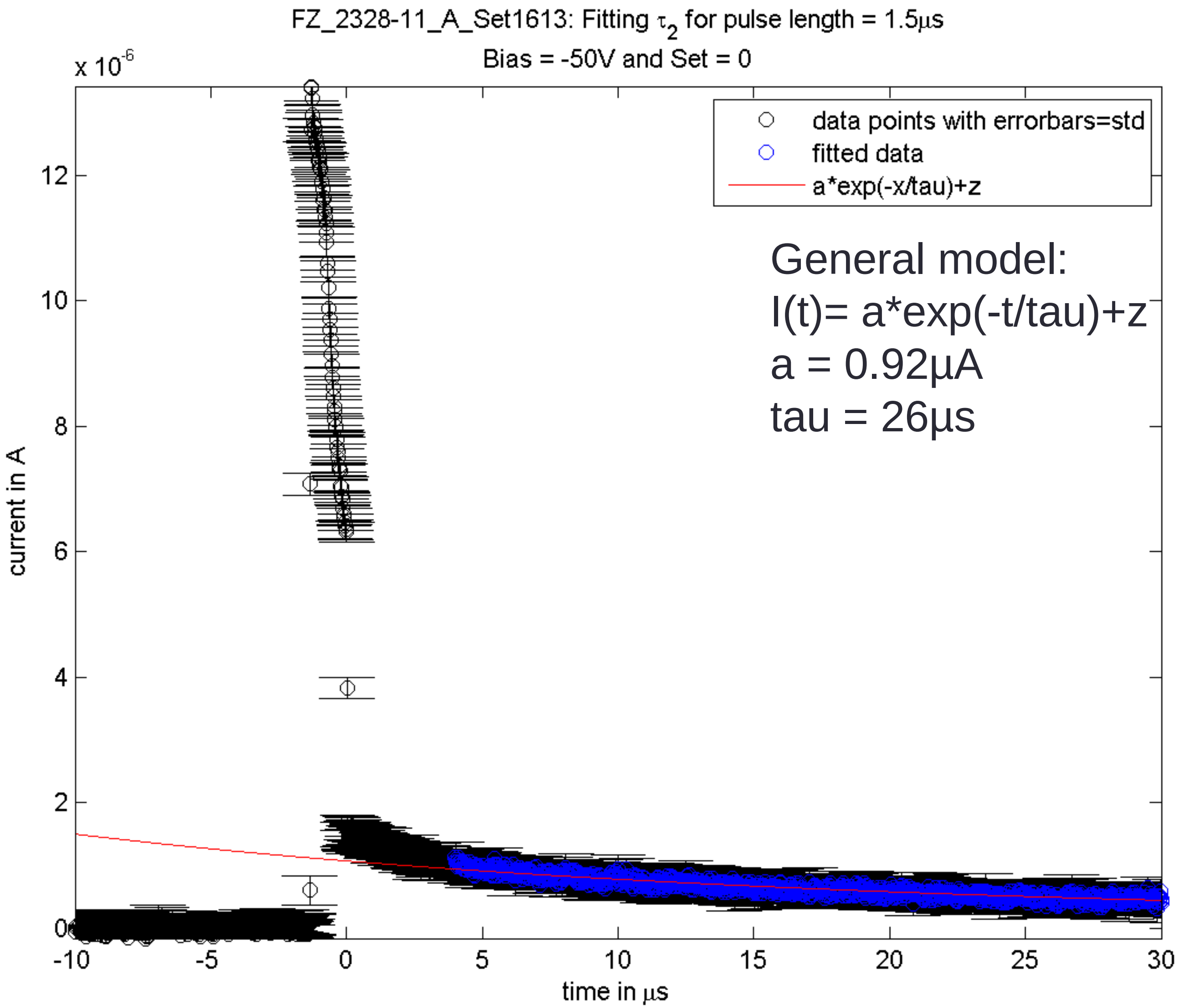
$$I(t) = \sum_i A_i \exp(-t/\tau_i)$$

- In the case of two time-constants:

$$I(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$$

with free parameters A_1, A_2, τ_1 and τ_2.

Tau extraction for "slow" transient: τ_2



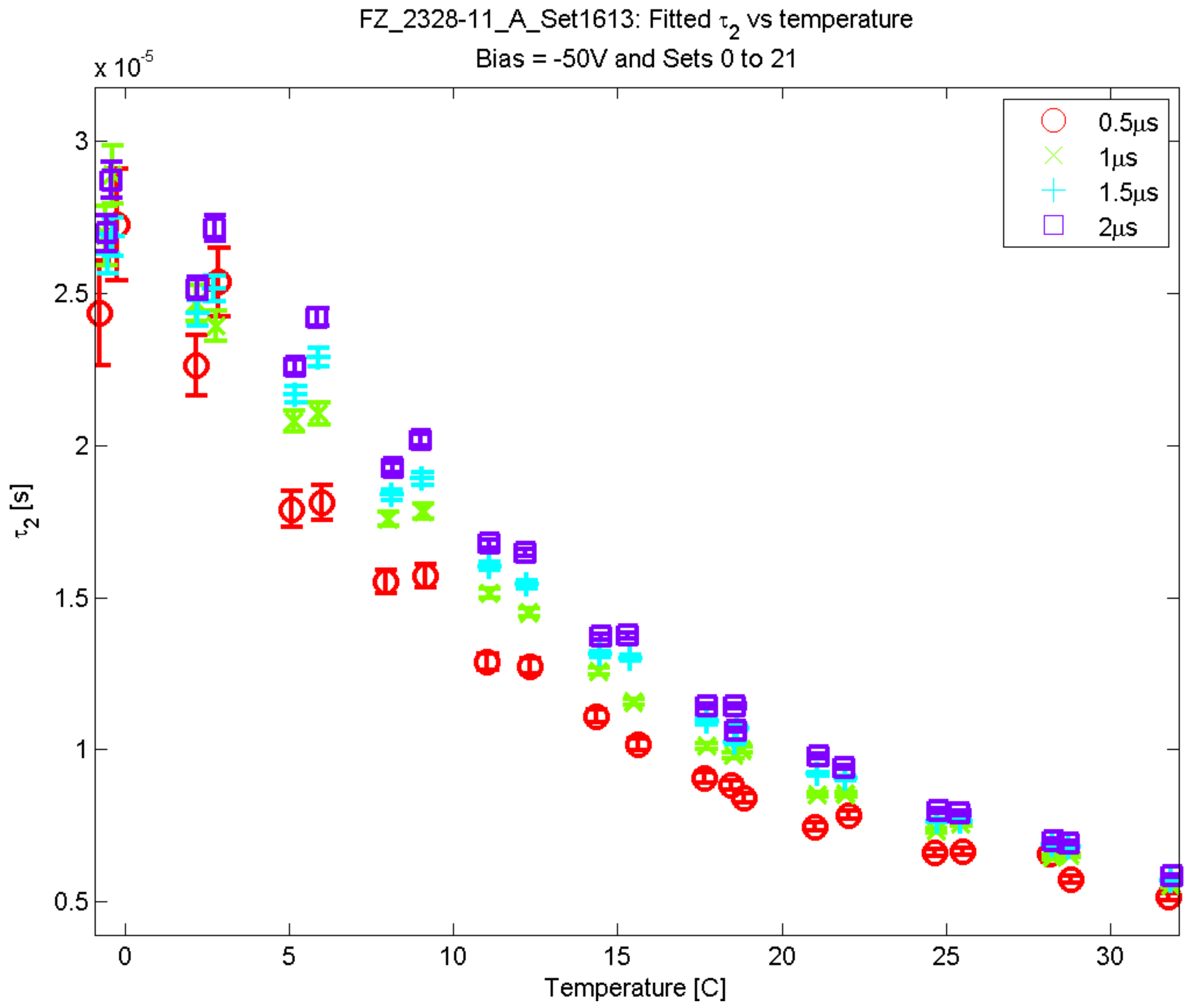
General model:
$I(t)= a*exp(-t/tau)+z$
a = 0.92μA
tau = 26μs

Φ=5e14 p/cm^2

Fitting process:

- Averaged data with errorbars = std of 10 "identical" measurements
- Only fitting to "tail" of transient: τ_2
- 95% confidence interval also obtained

Tau extraction for “slow” transient: τ_2



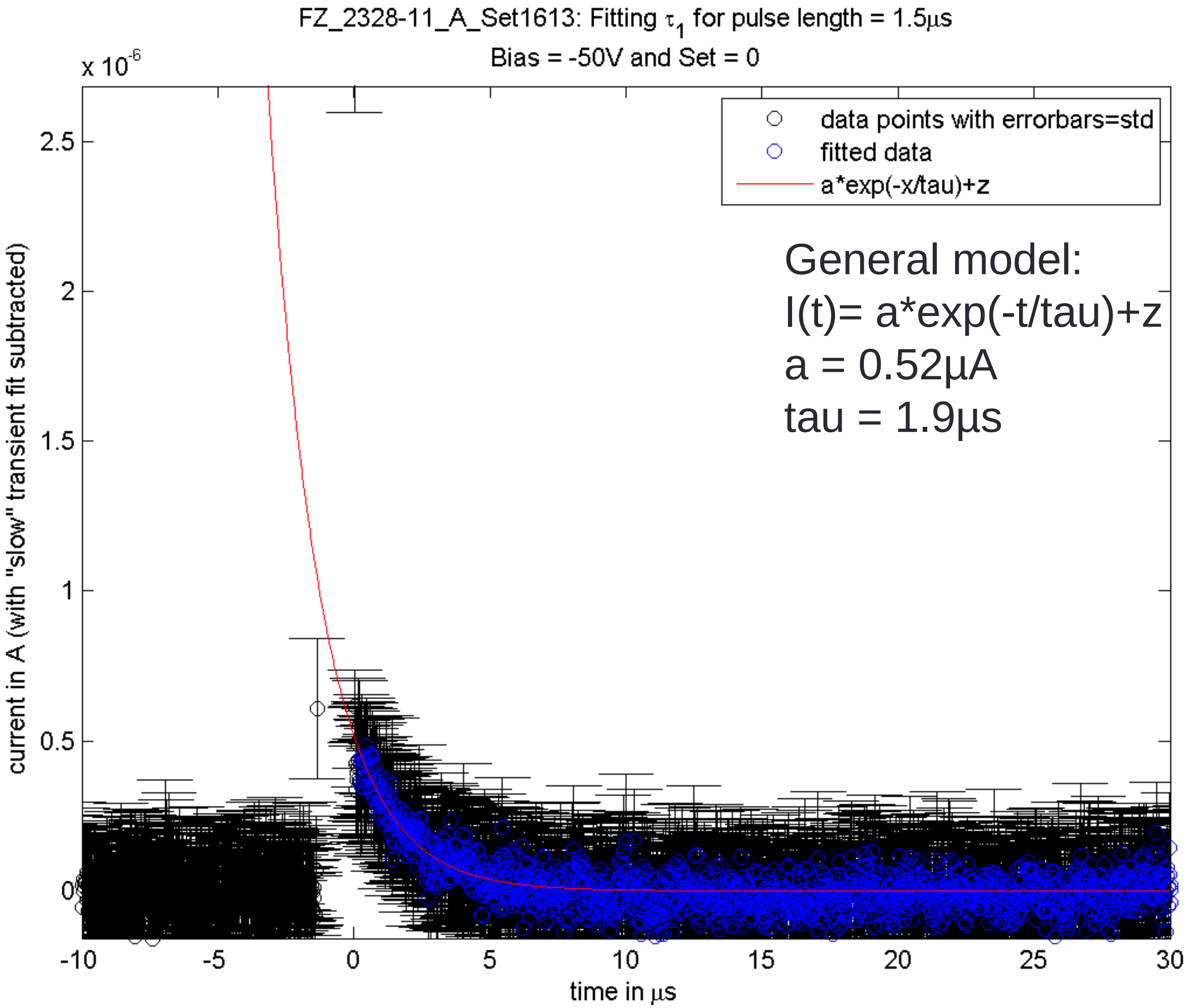
Φ=5e14 p/cm^2

- Each temperature was measured twice (0 to 30°C and down to 0°C)

➢ Data shows correct trend and is reproducible

➢ Tau extraction seems to work for “slow” transient

Tau extraction for “fast” transient: τ_1



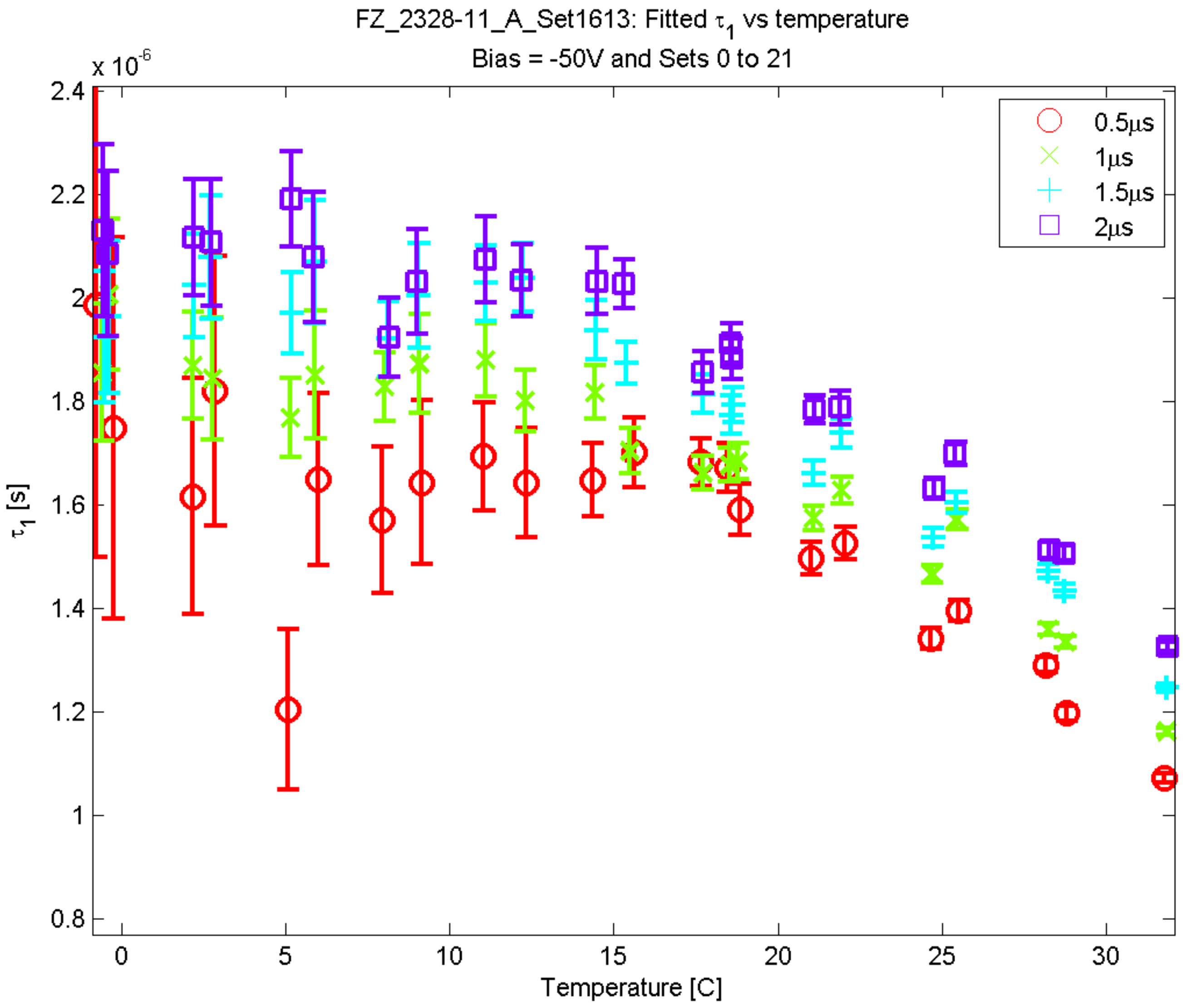
General model:
I(t)= a*exp(-t/tau)+z
a = 0.52µA
tau = 1.9µs

Φ=5e14 p/cm^2

Fitting process:

- “Slow” transient subtracted before fitting to averaged data with errorbars = std of 10 “identical” measurements
- Nearly all points after illumination are taken

Tau extraction for “fast” transient: τ_1



Φ=5e14 p/cm^2

- Each temperature was measured twice (0 to 30°C and down to 0°C)
- ➢ Data shows big spread for low temperature
- ➢ Tau extraction seems to fail for “fast” transient

Parameter extraction: τ-fitting & Arrhenius plot

- The detrapping time constant is linked to defect parameters by:

$$\tau_h = \frac{1}{\sigma_h v_h N_V}\exp\left(\frac{E_t}{k_B T}\right)$$

absolute value of the energy level calculated from valence band maximum

σ_h … hole detrapping cross-section
v_h … thermal hole velocity
N_V … effective density of states in valence band maximum

- Looking explicitly on T-dependence:

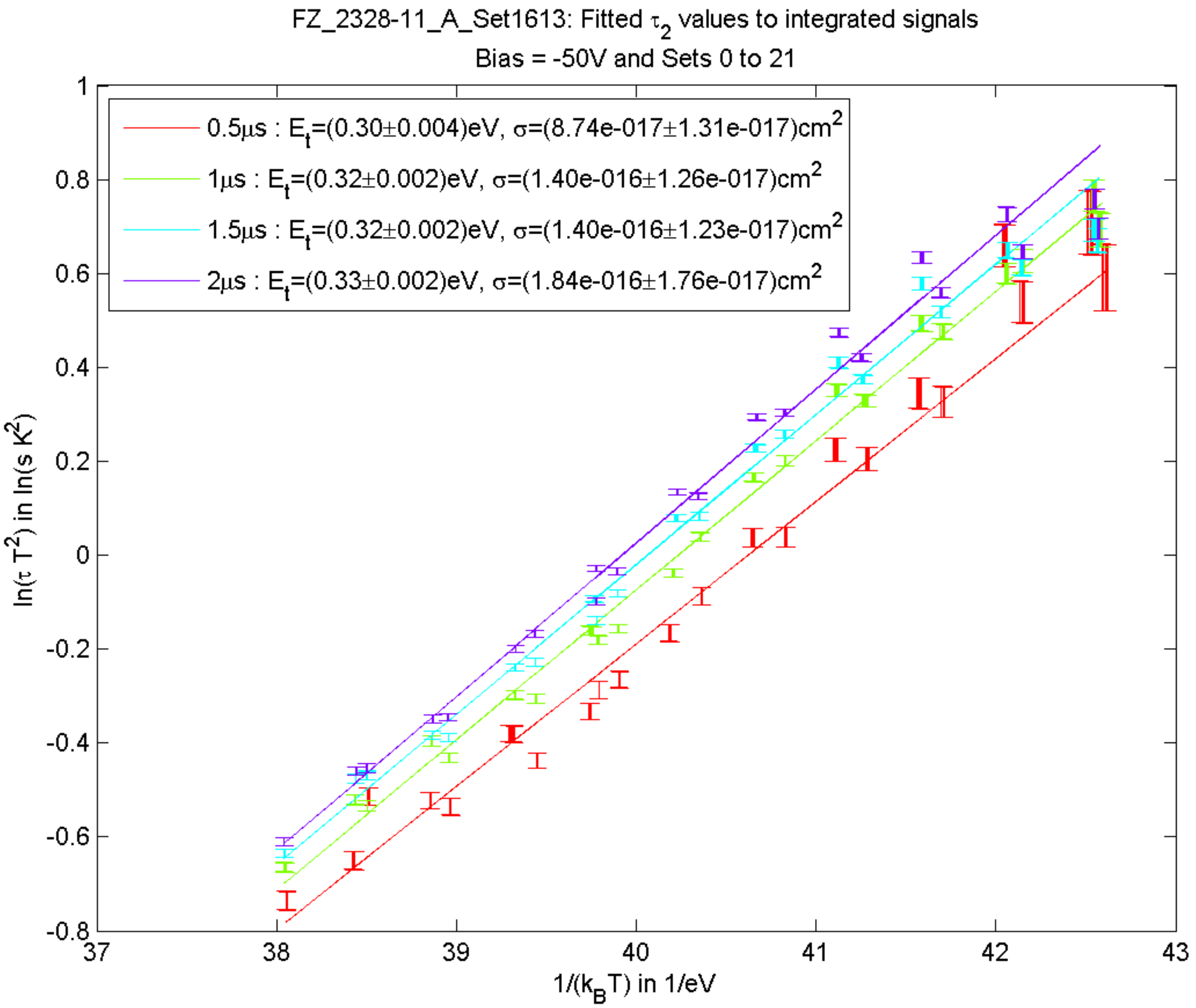
$$v_h\, N_V = \sqrt{\frac{3k_B T}{m_h}}\;\frac{1}{4}\left(\frac{2m_h k_B T}{\pi\hbar^2}\right)^{3/2} \equiv \gamma_h T^2$$

- And we can analyse data in an Arrhenius plot:

$$\ln(\tau_h T^2) = \frac{E_t}{k_B T} - \ln(\sigma_h \gamma_h) \qquad \Rightarrow \text{ read off } E_t \text{ and } \sigma_h \text{ from slope and intersect}$$

PRELIMINARY

Arrhenius plot for “slow” transient: τ_2



Φ=5e14 p/cm^2

from slope:

E_{th} = 0.32eV

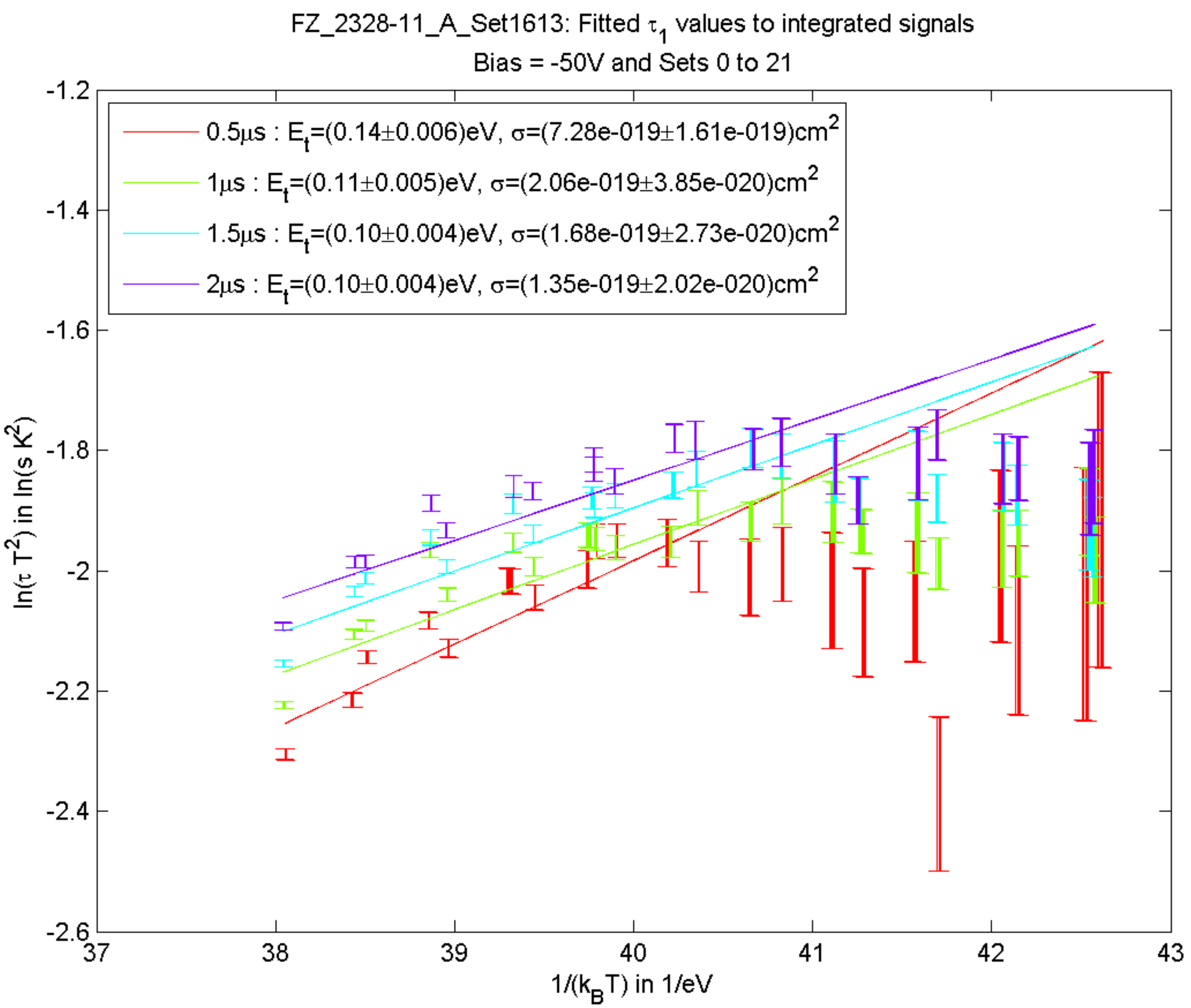
from Intercept &

γ_h = 1.8x10^{25} s^{-1}(mK)$^{-2}$

σ_h = 1.4x10^{-16} cm^2

PRELIMINARY

Arrhenius plot for “fast” transient: τ_1



FZ_2328-11_A_Set1613: Fitted τ_1 values to integrated signals

Bias = -50V and Sets 0 to 21

Φ=5e14 p/cm^2

from fit:

$E_{th} \approx 0.1$eV

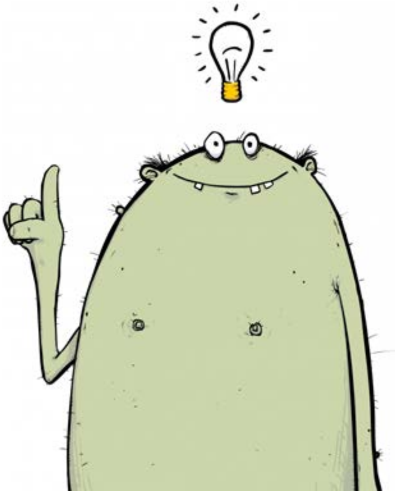
$\sigma_h \approx 1\text{x}10^{-19}$ cm^2

- Not physically reasonable

→ maybe effect from electronics?

Conclusions

- Varying both pulse length and bias voltage together with TCAD simulations gave better understanding of the current transient formation
- But we need to …
  - improve the extraction of the time constants τ_i from $I(t)$ or $\int I(t)dt$ (fitting to exp+exp is numerically very ill-conditioned)
  - increase the detrapping signal by choosing the “optimal” pulse length (for given temperature and bias voltage)
  - Study behaviour with IR laser (1060nm, instead of 660nm) which has much higher penetration depth
  - …



Thanks for your attention!