Measurements of de-trapping times in irradiated silicon detectors

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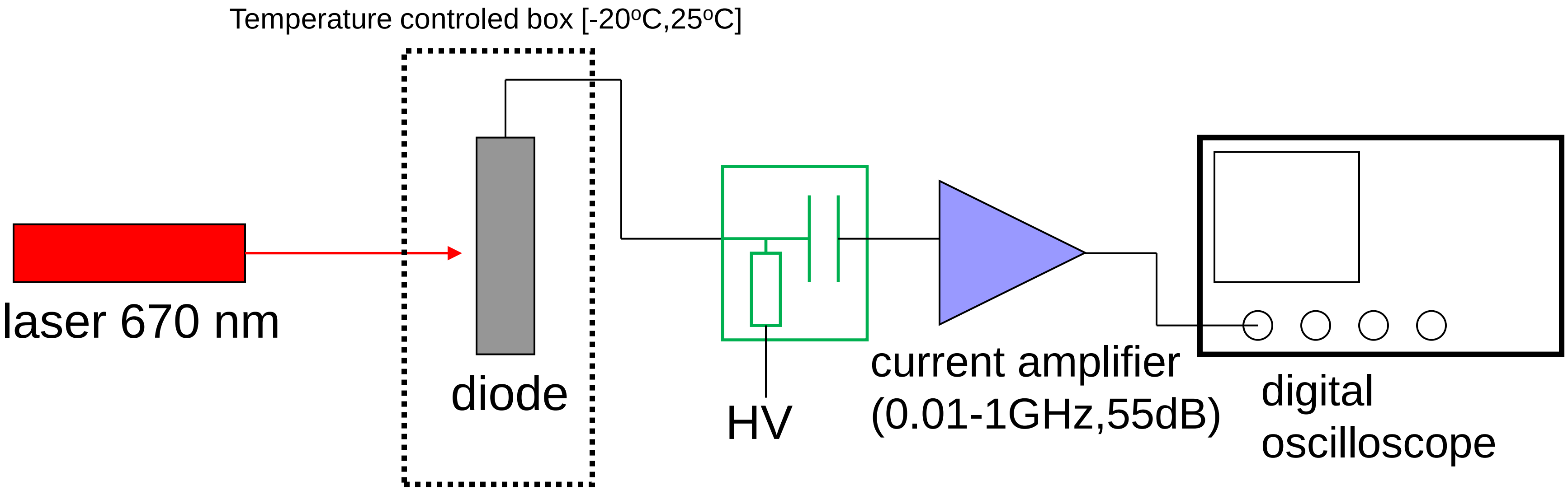
Motivation

- Emission times of carriers are crucial for defect characterization
  - at close to RT conventional methods (TSC,DLTS) are difficult to operate particularly at high fluences

- Direct observation of de-trapped charge previously trapped during the drift of carriers (prompt generation of non-equilibrium carriers)

- De-trapping can play some role in CCE for longer shaping times and low bias voltages (not really LHC case)

Experimental setup - TCT



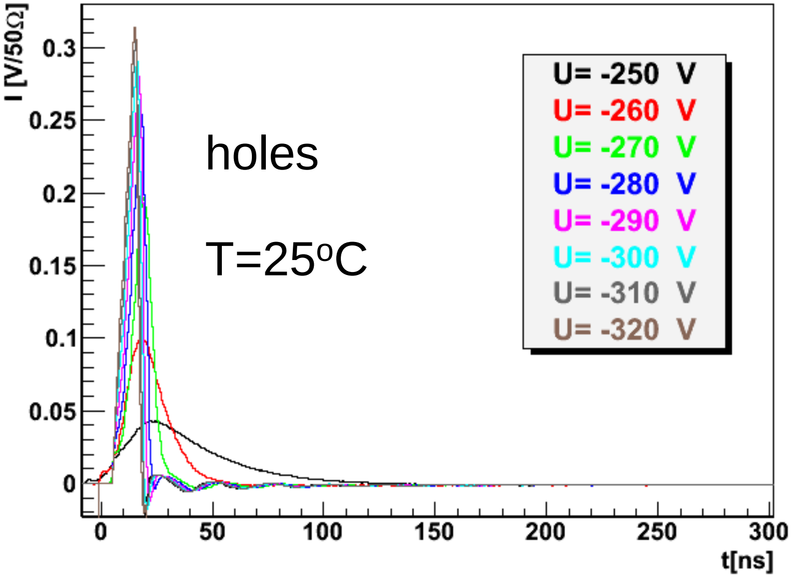
Conventional TCT was used with small modifications:

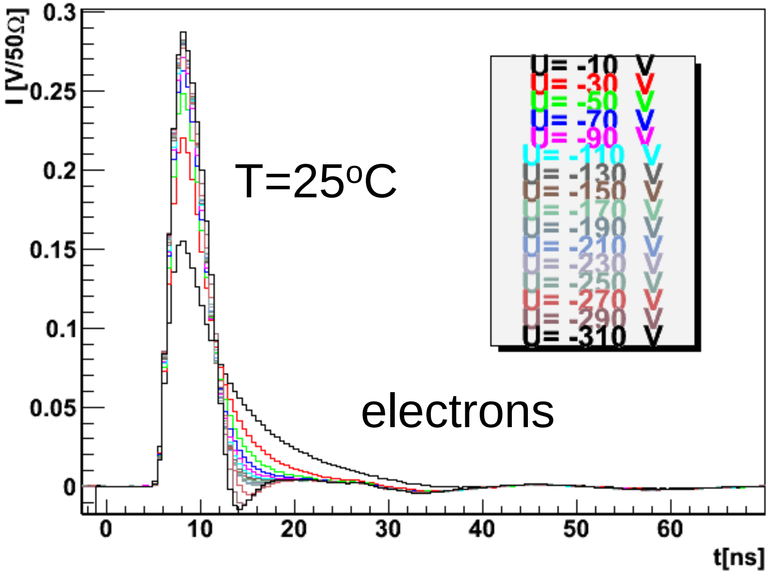
- Signals taken on the time **scale of few μs**
- Bias-T with different bandwidth was used
- Self-triggering of oscilloscope to avoid small DC offset

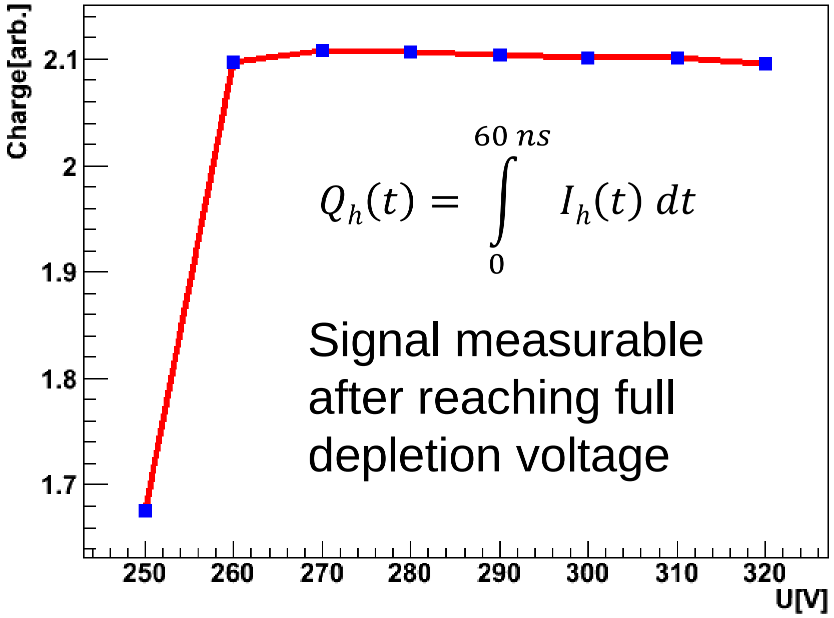
Samples

- MCz-n type samples (WODEAN), 1 kΩcm, V_{fd}~250 V
- Samples irradiated with neutrons to 10^{14} cm^{-2} and $3x10^{14}$ cm^{-2}
- Measurements shown are after annealing of 80 min at 60°C

Method (I) – non irradiated sample

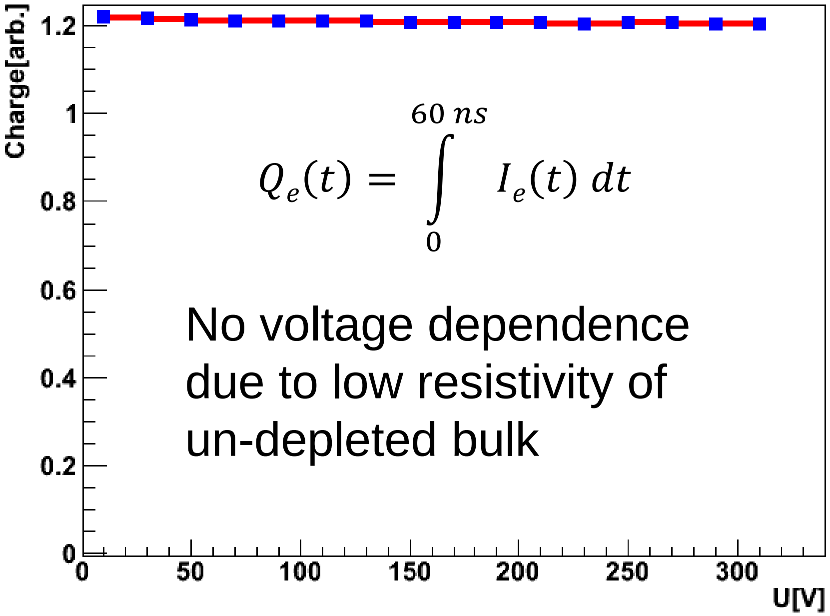






$$Q_h(t) = \int_0^{60\,ns} I_h(t)\,dt$$

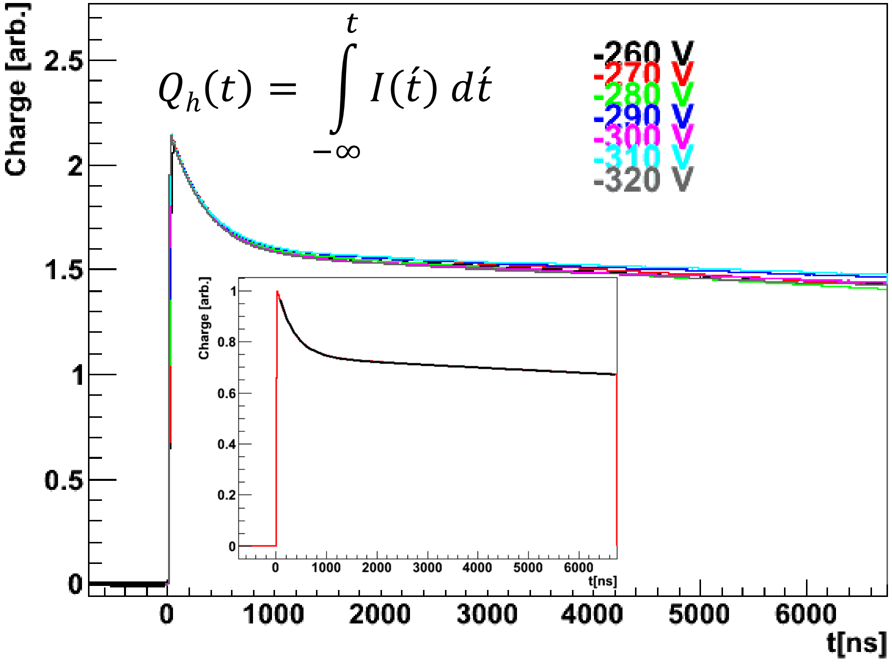
Signal measurable after reaching full depletion voltage

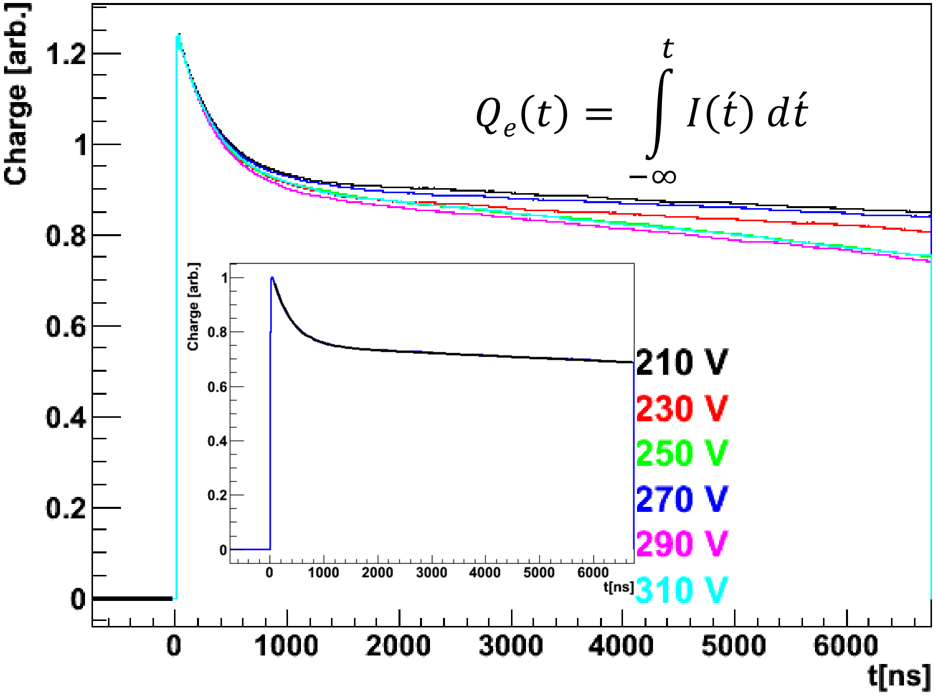


$$Q_e(t) = \int_0^{60\,ns} I_e(t)\,dt$$

No voltage dependence due to low resistivity of un-depleted bulk

Method (II) – non irradiated sample





As there is no charge trapping the evolution of the signal in time is the consequence electronics (amplifier, Bias-T):

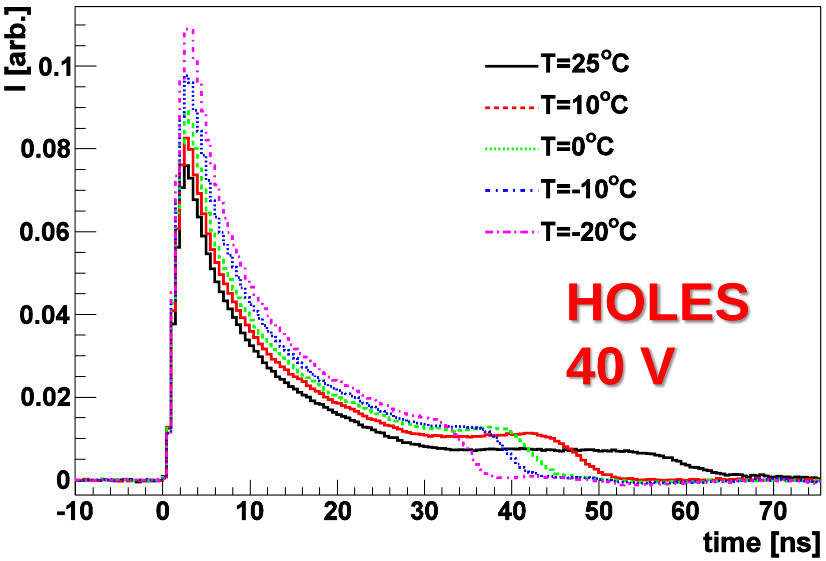
$$Q(t) = \int_0^t I(x) * h(t-x) \, dx \approx Q(t_d) \; h(t) \quad t \gg t_d$$

$$h(t) = \sum_{i=0}^{2} a_i \; \exp(-t/\tau_i)$$

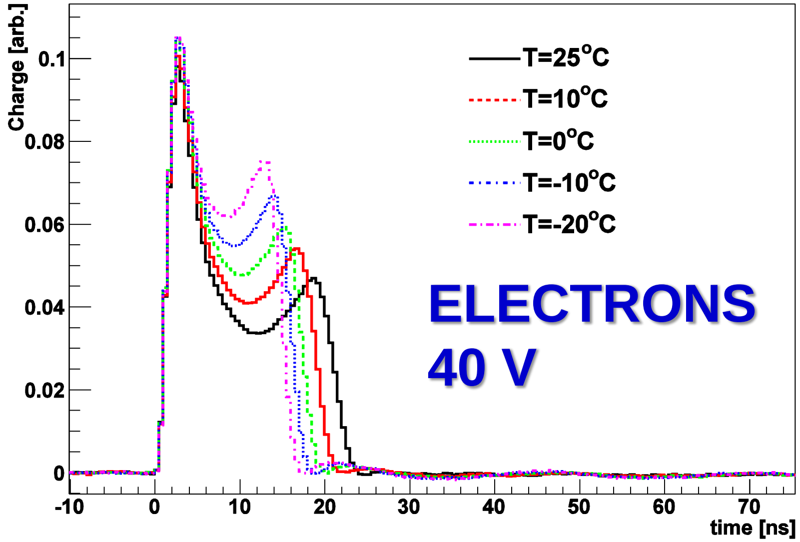
a_1=0.245, τ_1=342 ns
a_2=0.755, τ_1=68000 ns

Fit is shown in the insets!

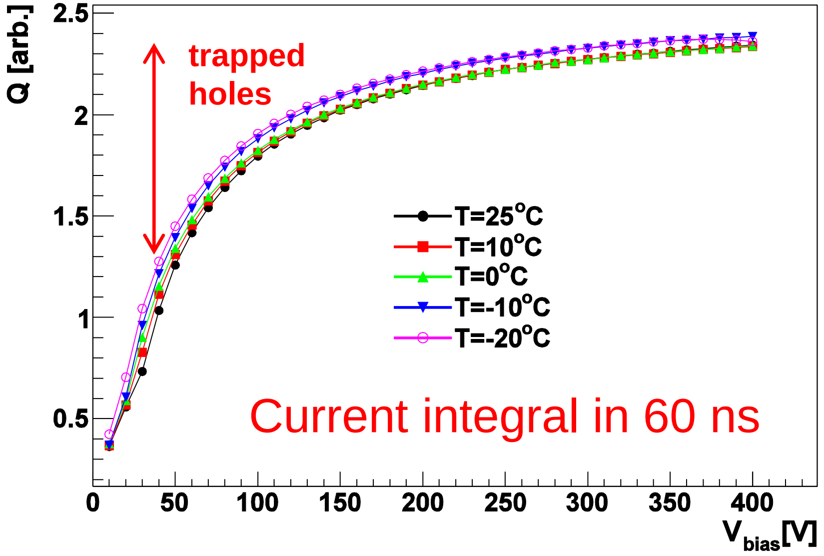
Method (III) – diode irradiated to 10^{14} cm^{-2}



HOLES
40 V

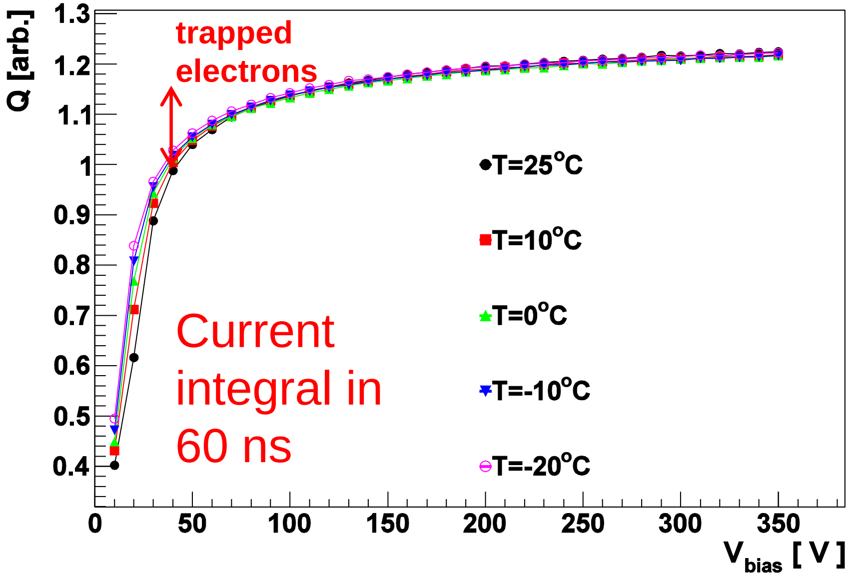


ELECTRONS
40 V



trapped holes

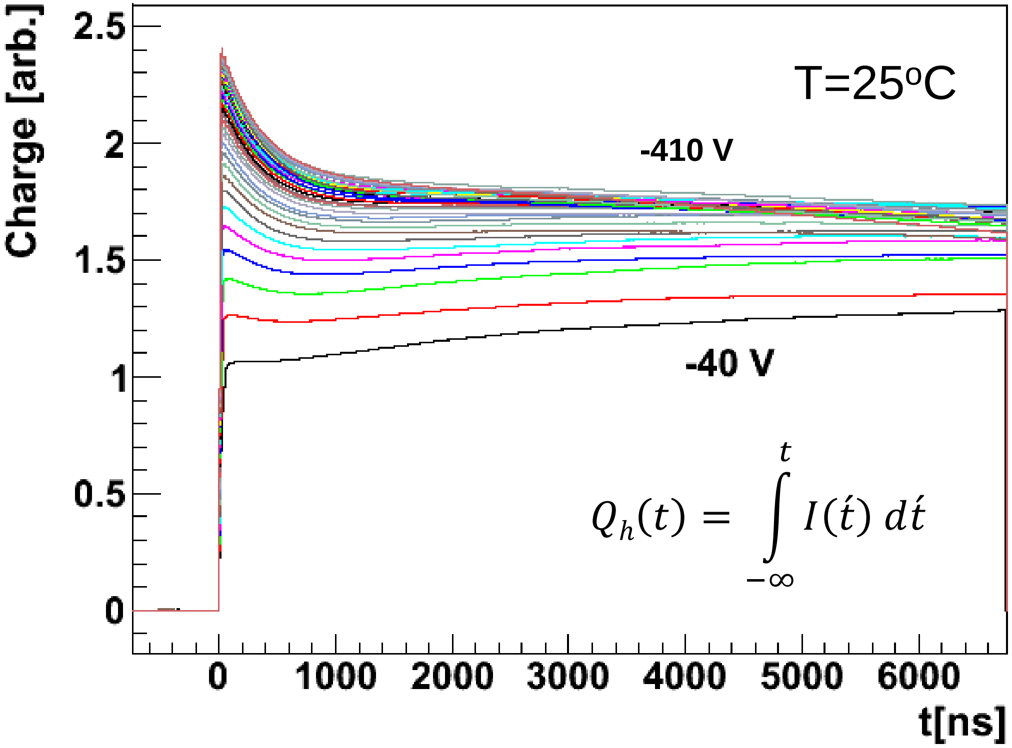
Current integral in 60 ns



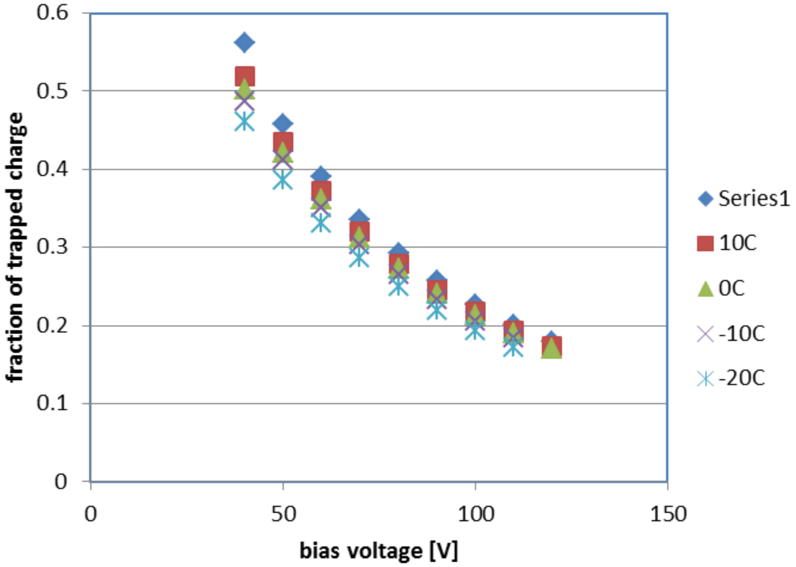
trapped electrons

Current integral in 60 ns

Method (IV) – diode irradiated to 10^{14} cm^{-2}



$$Q_h(t) = \int_{-\infty}^{t} I(t')\, dt'$$



Charge trapped by many traps

$$Q_0(1-CCE)=\sum_i Q_{t_i}$$

The shape of the Q(t) changes with voltage:

- ☐ It increases with time for lower voltages
- ☐ It has the shape similar as non-irradiated sample for very high voltages

The reason for the increase is the de-trapping of the charge trapped during the drift (note that at low voltages a lot of charge is trapped)

Method (V) – diode irradiated to 10^{14} cm^{-2}

The difference between two plots can be expressed:

$$Q_2(t) - Q_1(t) = \int_0^t [I_2(x) - I_1(x)] * h(t-x)\,dx =$$

$$= \int_0^{t_d} [I_2(x) - I_1(x)] * h(t-x)\,dx + \int_{t_d}^{t} [I_2(x) - I_1(x)] * h(t-x)\,dx$$

exponential emission of the trapped charge:

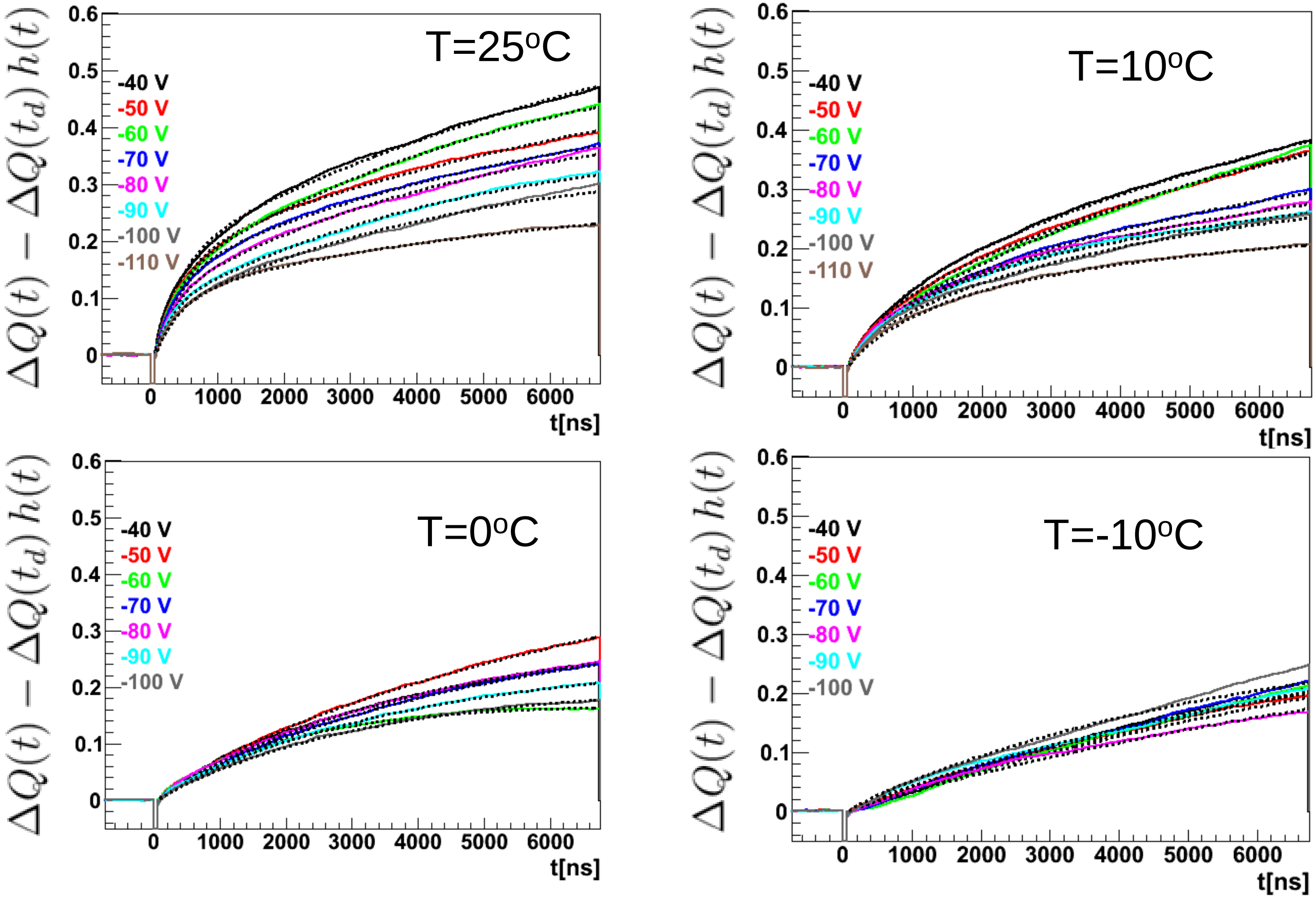
$$I(t > t_d) = \sum_i \frac{Q_{t_i}}{\tau_{d_i}} \exp(-t/\tau_{d_i})$$

$$\Delta Q(t) - \Delta Q(t_d)\,h(t) = \sum_{j=1}^{2} \sum_{i=1}^{2} \Delta Q_{ti} \left[\frac{a_j \tau_j}{\tau_{d_i} - \tau_j} \left(\exp\left(-\frac{t}{\tau_{d_i}}\right) - \exp\left(-\frac{t}{\tau_j}\right)\right)\right]$$

This equation is fit to the measured data!
Two traps were assumed (index *i*).

- Unknowns: τ_{d1}, τ_{d2}, $\Delta Q_{t1}/\Delta Q_{t2}$
- Constrain: $\sum_{i=1}^{2} \Delta Q_{ti} = Q_2(t_d) - Q_1(t_d)$

Measurements – holes (10^{14} cm^{-2})

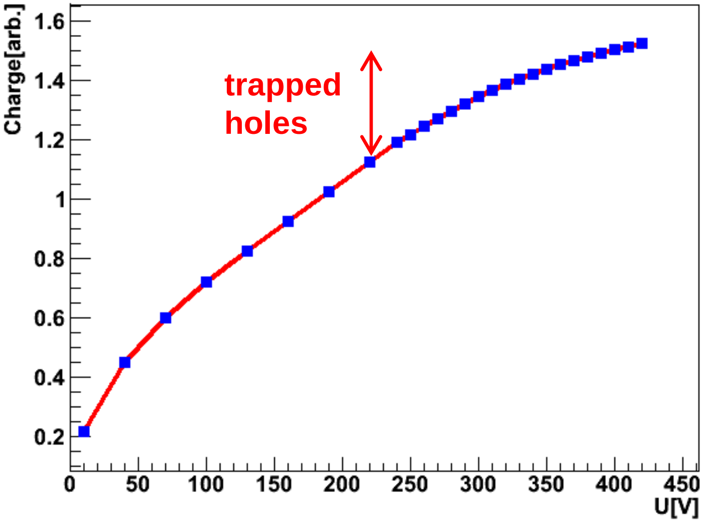


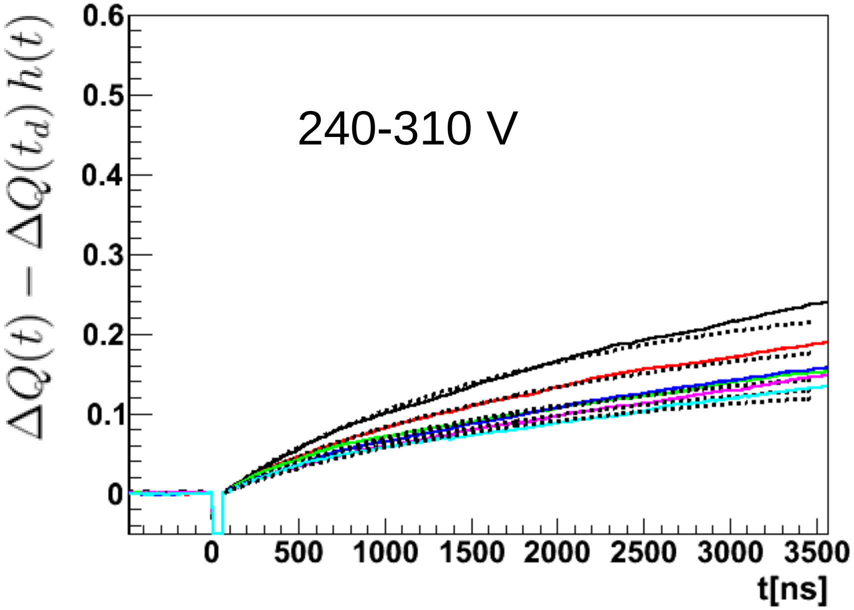
De-trapping times are longer at lower T, but amplitudes are similar

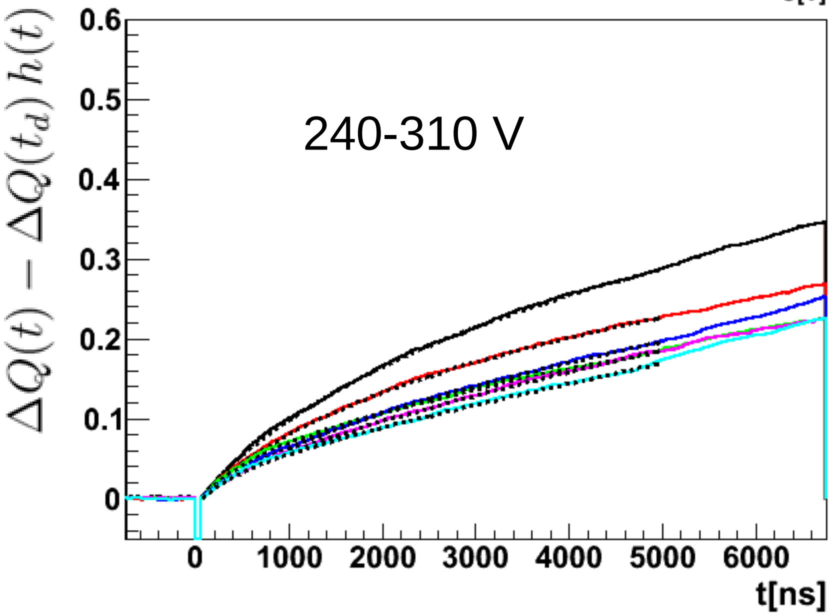
- Fits are reasonably good, however at T<=-10ºC the measurements can be fit with single exponential (only one free parameter)
- De-trapping times are in the range from 1-10 μs, the long term dominates (~80% of the de-trapping amplitude)

Measurements – holes (3×10^{14} cm^{-2})

- High Vfd~240 V results in faster drift ($V>V_{fd}$) and smaller trapped charge even though trapping times are shorter
- The fit of the mode to the data with constrain of **de-trapped charge=trapped charge** does not fit the data well at long times??

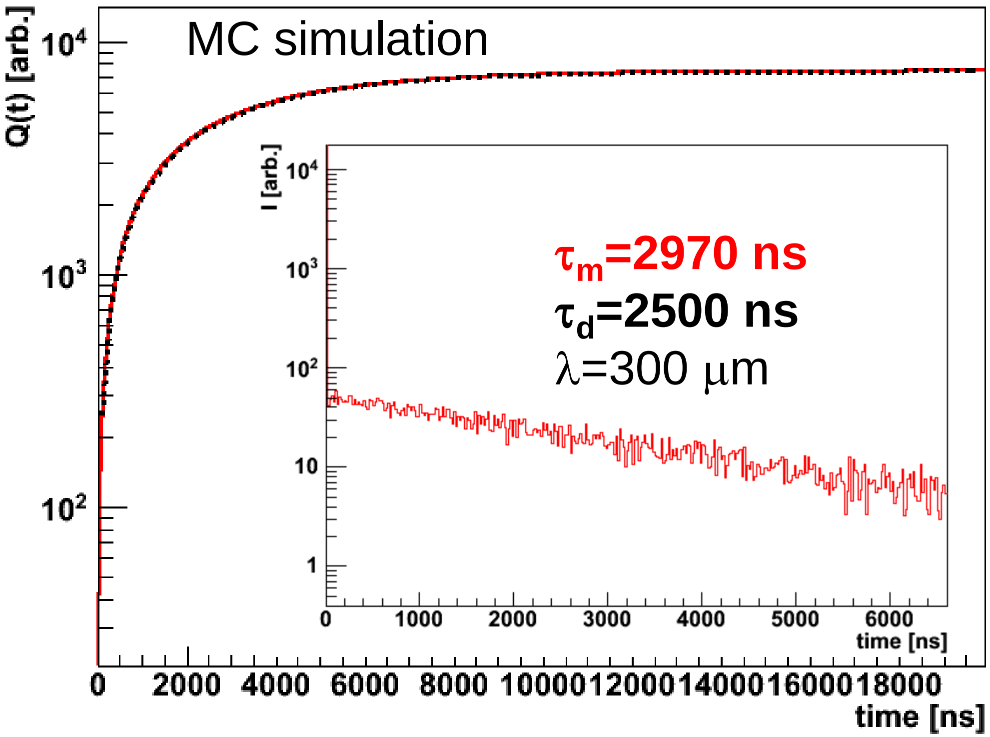


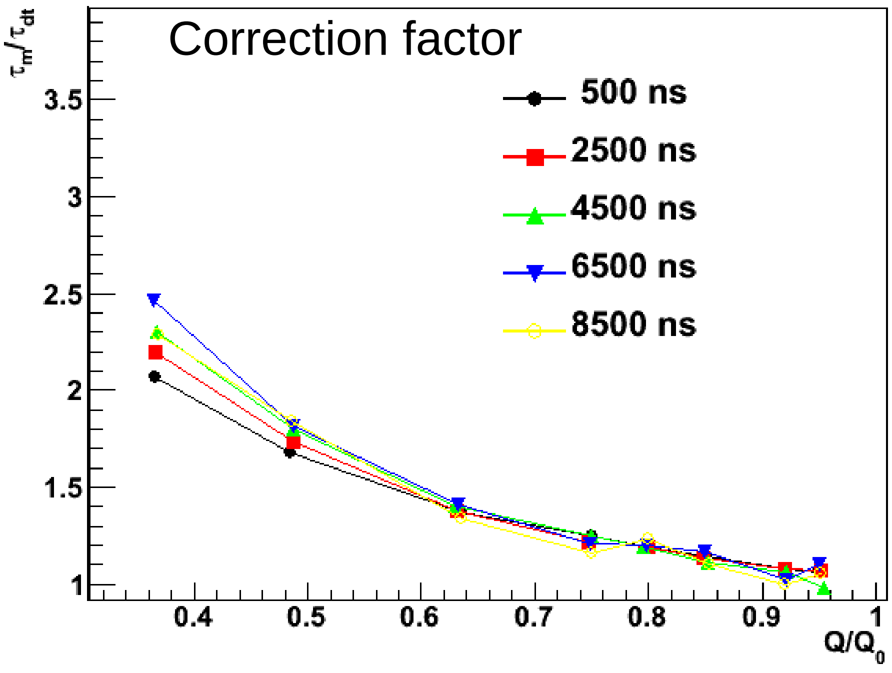




Interpretation of the measured time constants

- Trapped charge can be trapped again which influences measurements, hence **measured de-trapping times τ_d should be corrected – scaled to get proper de-trapping times.**
- **MC-simulation** was used assuming constant trapping distance over the entire volume of the detector (determines CCE=Q/Q_0). The Q(t) obtained from fit to the simulated values was compared to input values.
- The correction factor depends only on trapping times (probability of being re-trapped).

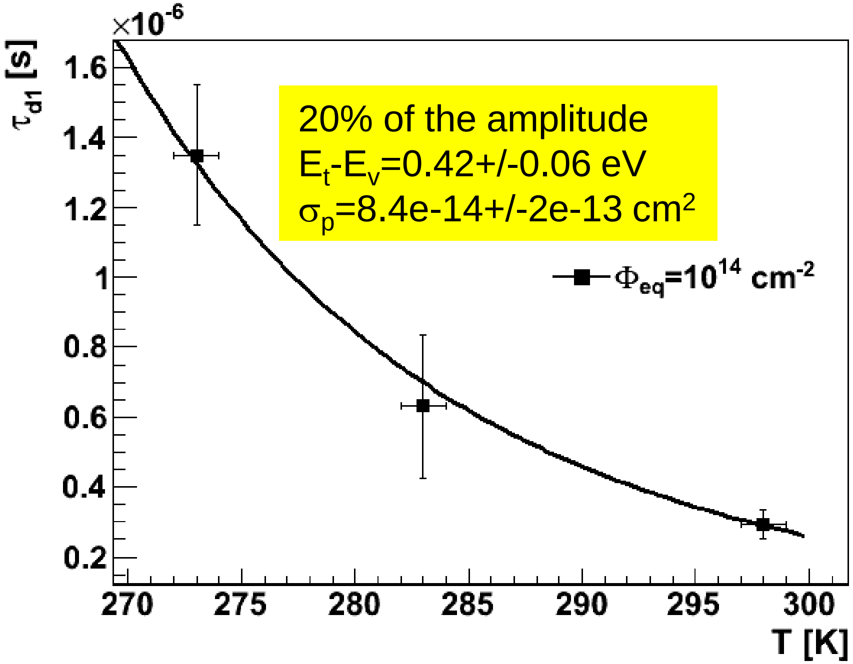




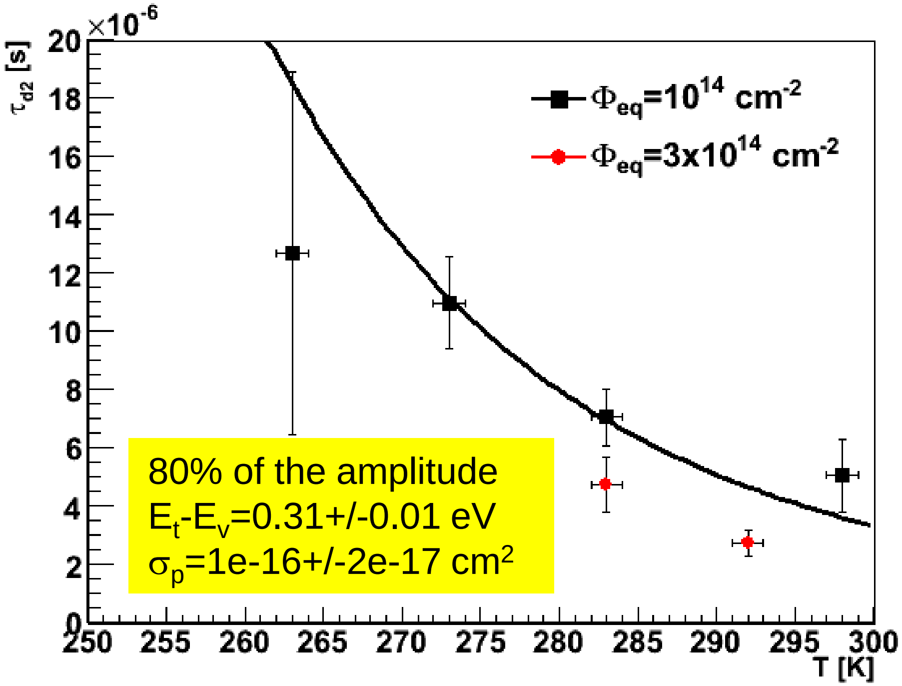
Determination of the traps

$$\frac{1}{\tau_d} = n_i \cdot v_{th,h} \cdot \sigma_p \cdot \exp\left(\frac{E_t - E_i}{k_B T}\right) \longleftarrow$$

fit to the data – free parameter σ_p and E_t



20% of the amplitude
E_t-E_v=0.42+/-0.06 eV
σ_p=8.4e-14+/-2e-13 cm^2



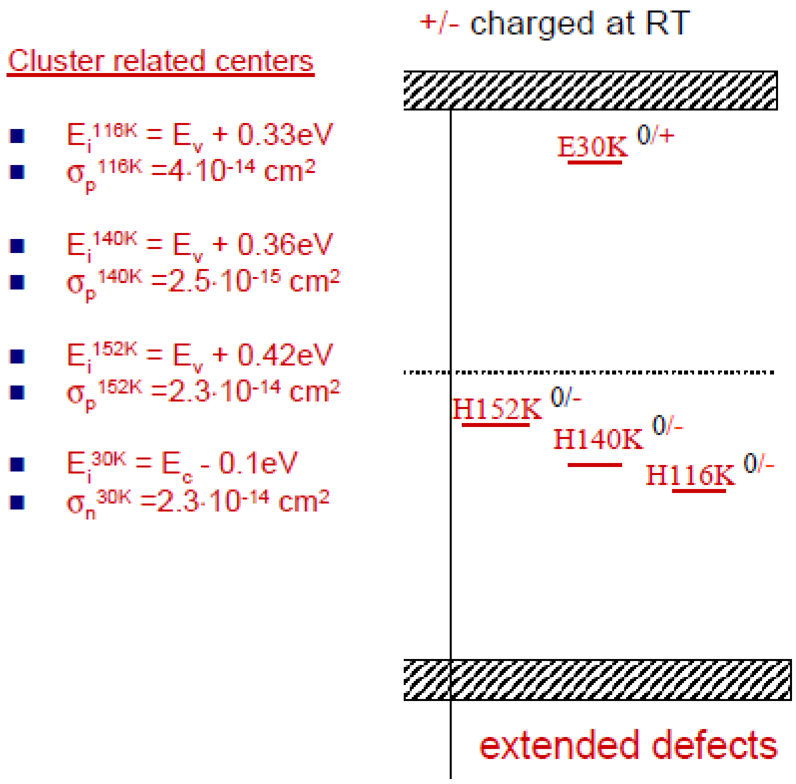
80% of the amplitude
E_t-E_v=0.31+/-0.01 eV
σ_p=1e-16+/-2e-17 cm^2

- Short component can only be established reliably up to 0°C:
  - 20% of the de-trapping amplitude (trapped charge)
  - longer time constants and smaller amount of trapped charge make determination very unreliable
- The introduction rate for the defect responsible for short component should be around 0.1 cm^{-1} (to explain trapping times/amount of trapped charge)
- Contrary introduction rates should be very high ~100 cm^{-1} for the defect responsible for long component?

Can they be correlated with DLTS/TSC measurements?

Microscopic measurements:

I. Pintilie, 3rd MC-PAD training event, Ljubljana, 2010



Cluster related centers

- $E_i^{116K} = E_v + 0.33eV$
- $\sigma_p^{116K} = 4\cdot10^{-14}\ cm^2$

- $E_i^{140K} = E_v + 0.36eV$
- $\sigma_p^{140K} = 2.5\cdot10^{-15}\ cm^2$

- $E_i^{152K} = E_v + 0.42eV$
- $\sigma_p^{152K} = 2.3\cdot10^{-14}\ cm^2$

- $E_i^{30K} = E_c - 0.1eV$
- $\sigma_n^{30K} = 2.3\cdot10^{-14}\ cm^2$

TCT measurements:

Fast (could be H(152)?):

E_{t1}-E_v=0.42 eV

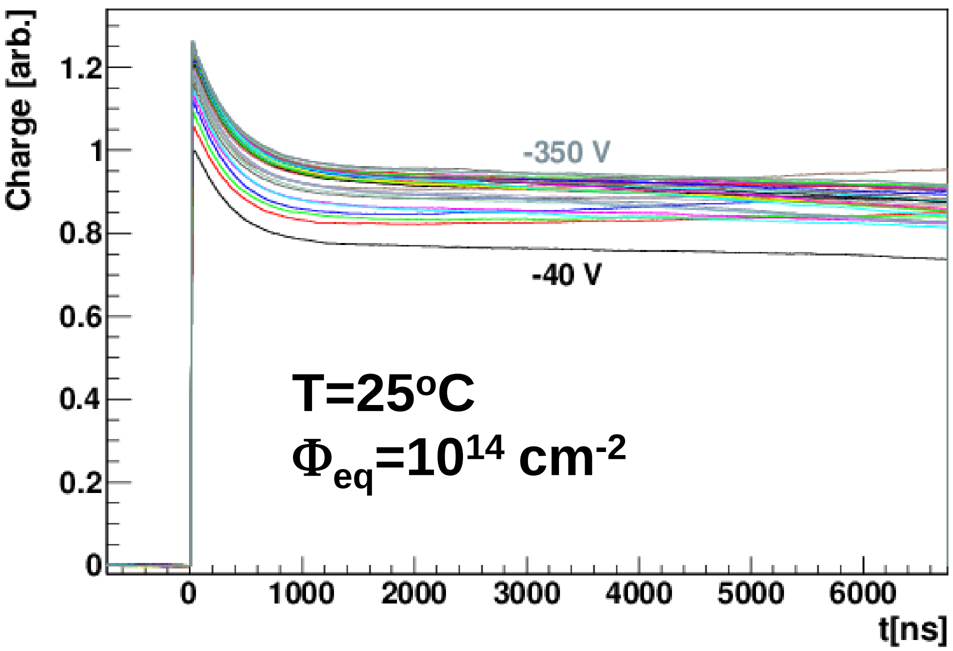
σ_p=8e-14 cm^{-2}

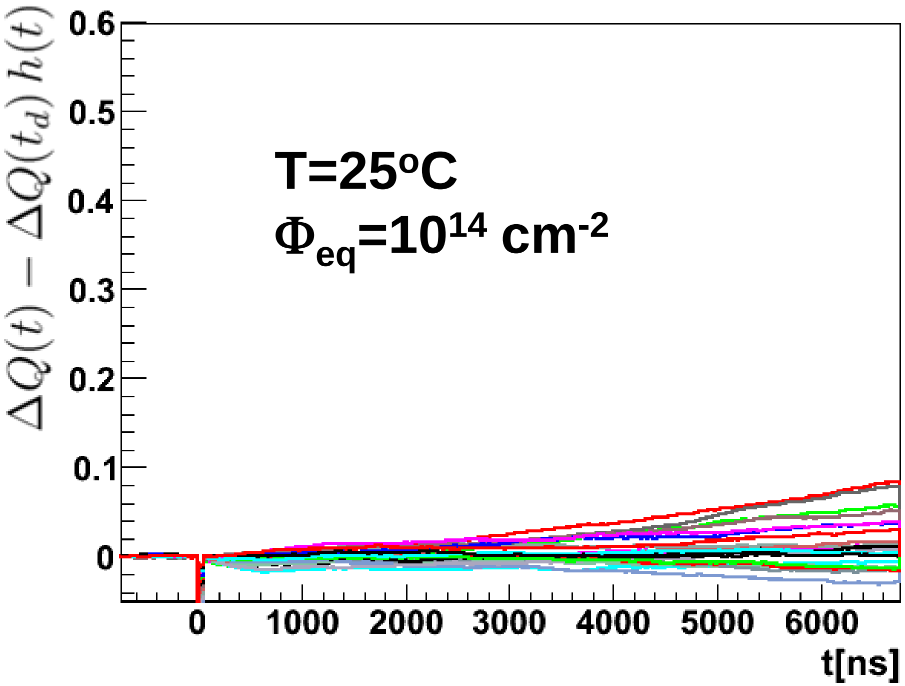
Slow (could be H(140) or/and H(116)?):

E_{t2}-E_v=0.31 eV

σ_p=1e-16 cm^{-2}

What about de-trapping times of electrons?





- Sensitivity is lower due to less charge trapped (mainly the effect of velocity)
- Emission times of electrons are larger than the time scale investigated –

  de-trapping times of electrons are larger than ~10 μs

Conclusions & outlooks

- A method for measurement of de-trapping times using TCT was developed.
- It was found that de-trapping times of holes are of order of μs
  - effective traps with E_t=0.31 eV, σ_h=1e-16 cm^{-2} (20% of the trapped charge) and E_t=0.42 eV, σ_h=8e-14 cm^{-2} (80% of the trapped charge) result in good fit to the data
- Electron de-trapping times are longer that few tens μs
- Future work
  - annealing studies
  - more temperature points
  - improved modeling (bias dependent de-trapping?)
  - material dependence?

But as usually there is a lack of manpower ….