Carrier lifetime and charge extraction-collection variations during irradiation of the MCZ Si wafers and detectors by 8 MeV protons

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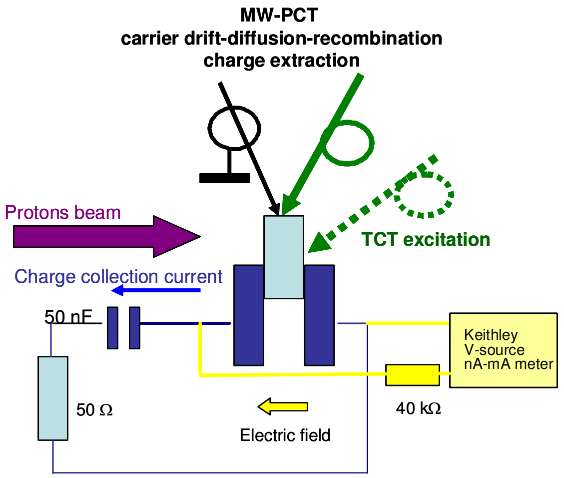
Outline

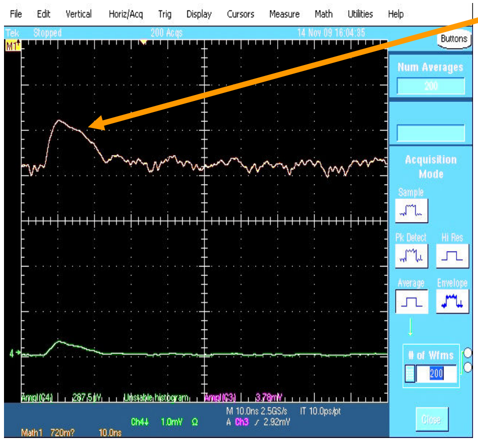
- Motivation of measurements and regimes
- Lifetime variations during irradiation with penetrative protons
- Simultaneous measurements of carrier recombination-diffusion and charge extraction-collection-TCT during irradiation by 8 MeV protons
- Summary

Motivation of measurements and regimes

To control simultaneously carrier drift, diffusion and recombination the combined MW-PCT and ChE/C-TCT measurements have been carried out



-The concerted measurements require the elevated excitation densities (relatively to a pure TCT regime), to be able to register the MW-PCT photoresponse. ChC signal increases and broadens with I_{ex}



Pure TCT – $I_{ex\text{-}TCT}$

Transient in semilog scale

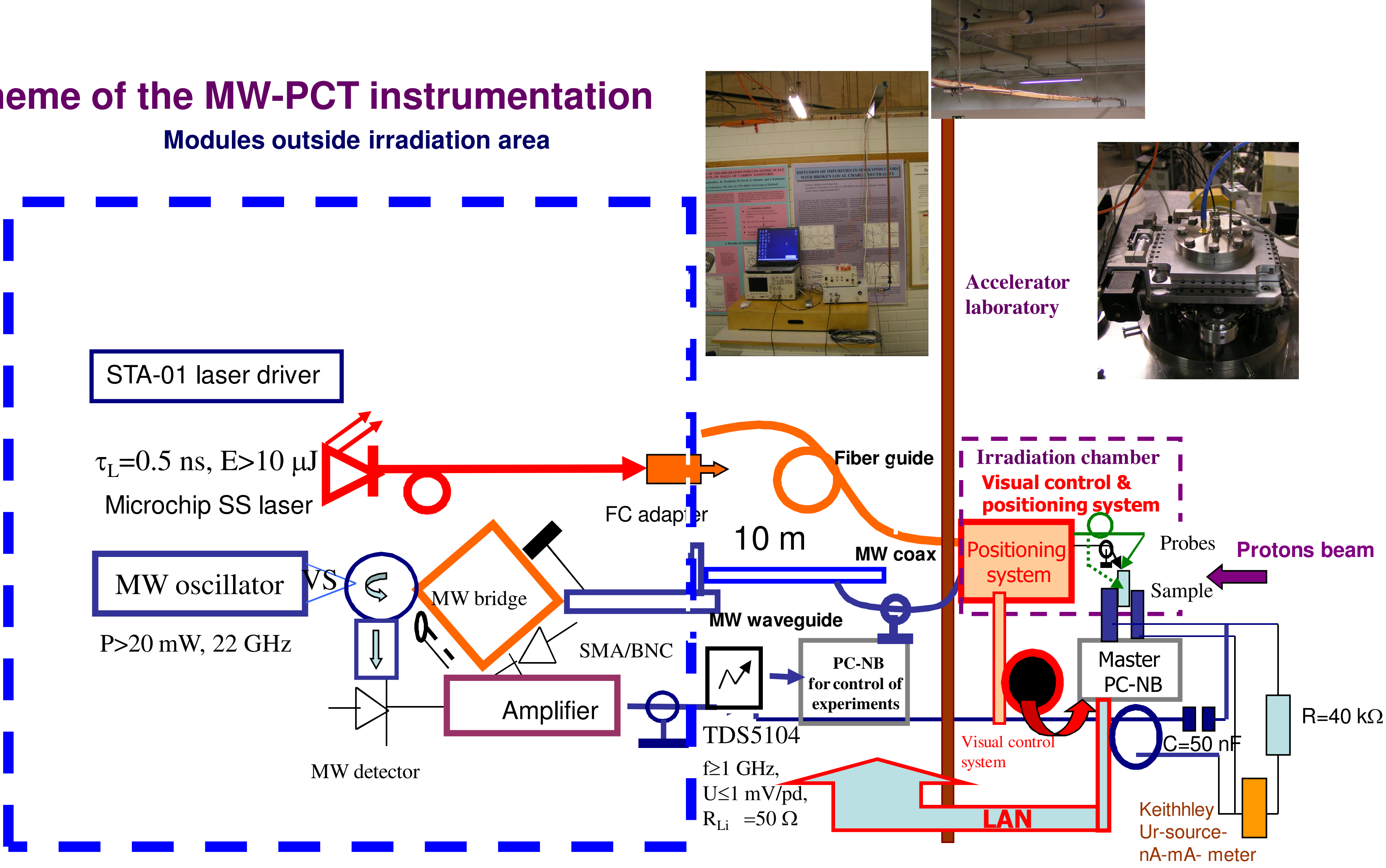
Transient in linear scale

TCT +ChC– (1.1-2)$I_{ex\text{-}TCT}$

The TCT in situ measurements have been performed with simultaneous registration of the total leakage current, to control the beam induced current and an impact of the production of radio-isotopes

Scheme of the MW-PCT instrumentation

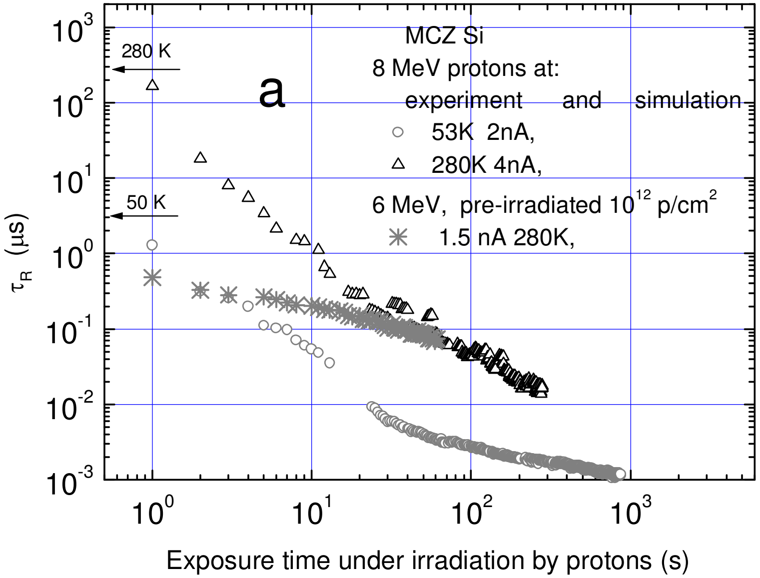
Modules outside irradiation area

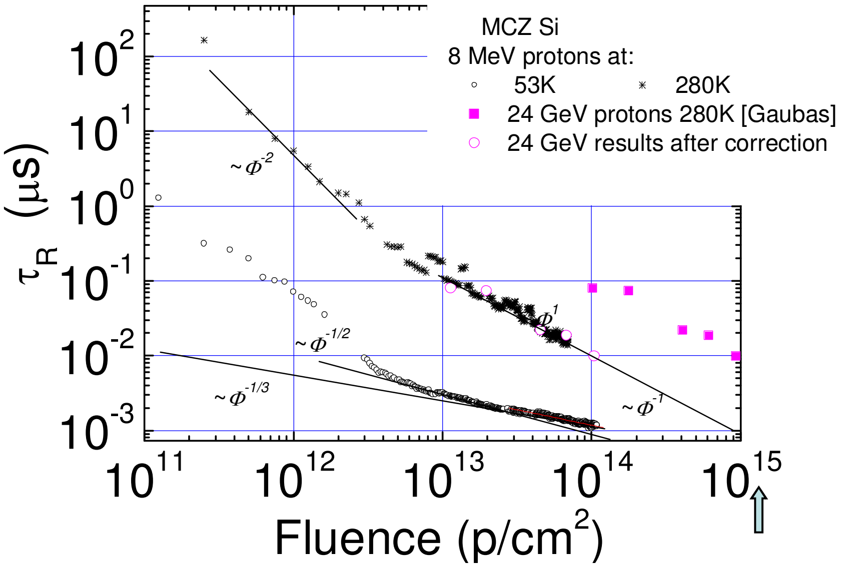


The transient microwave probed photoconductivity (MW-PCT) instrument for the direct measurements of the carrier decay transients by employing MW absorption are tested and installed. VUTEG-3HE, master PC-NB, antenna/excitation fiber modules, positioning and visual control modules are installed within irradiation chamber at accelerator laboratory. Delivering of signals to destination outside running irradiation area are implemented by using LAN. The sample holder with electrodes and wiring system are installed for simultaneous charge collection- TCT measurements within chamber during irradiations.

Lifetime variations during irradiation:

measured in wafer samples by MW-PCT at cross-sectional excitation without applied E field





At low fluence the protons irradiation influence on the lifetime is superlinear, it can be roughly approximated as a quadratic dependence, but this dependence in the pre-irradiated sample can be approximated as a square root on the fluence. This dependence can be understood as dependent on the defect generation and their modification. Pre-irradiation create new radiation centers and further irradiation induce the modification of centers.

The square root dependence on irradiation proposes the linear dependence of recombination efficiency on the average distance between the radiation induced centers. At higher fluencies the generation and modification of defects reach the equilibrium and the linear dependence of recombination efficiency was observed.

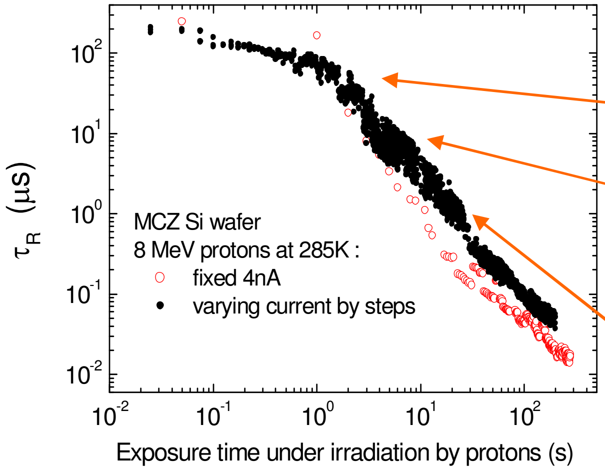
Lifetime variations during irradiation:

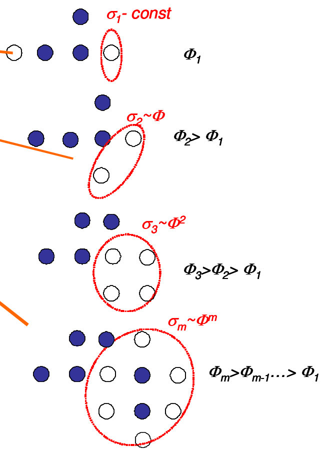
Also, it is possible to model this dependence by proposal of the vacancies migration to form the different clusters.

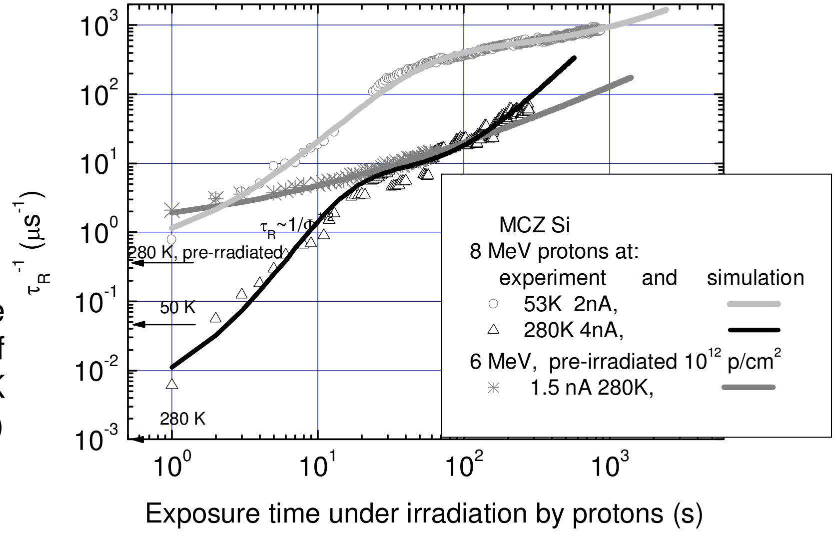
Comparison of the variations experimental (symbols) of the inverse recombination lifetime during irradiation: by 6 MeV protons at 280K of the pre-irradiated material, and by 8 MeV protons at 53 K and 280K temperatures of the initial MCZ Si and the simulated (lines) characteristics by using a modified polynomial model presented by Eq.:

$$\tau_{R-1}=c_T[(B_1+\sigma_1\Phi)+((B_2+\sigma_2\Phi^2)/(1+\sigma_2\Phi^2/(B_{2t}))+((B_3+\sigma_3\Phi^3)/(1+\sigma_3\Phi^3/B_{3t}))].$$

Here, c_T is carrier thermal velocity, $\sigma_m(\Phi)=\sigma_{mk}\Phi^k$ –cross-section of carrier capture at defects aggregated of *m* primary defects, $Bm=\sigma_{m0}\Phi_0^m$ is initial (0) value of accumulated Φ for creation of a definite type of recombination centers, and B_{mt} is a threshold value of B_m for a dominance of the excess *m* type defects.





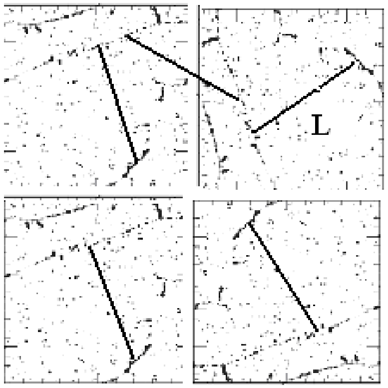


The non-linear lifetime reduction rates can be phenomenologically described by accepting a simultaneous change of the concentration of definite defects and of the cross-section dependent on fluence. The latter could be even associated with geometrical cross-section when, for instance, several vacancies join into nanometric pore.

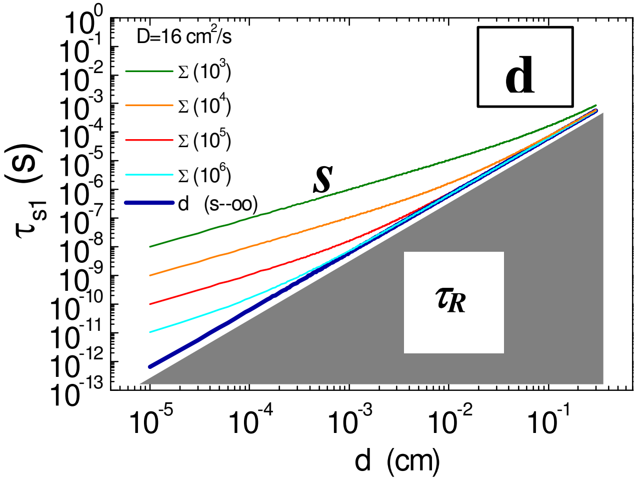
However, growth of such defects would be dependent on stability of such multivacancy aggregates, e.g. V_n, and on the instantaneous density of primary defects able to agglomerate. Therefore, aggregation of the extended defects should exhibit a saturation effect at every accumulated fluence. These assumptions can be accepted if simultaneous increase of primary defects in density

Lifetime variations during irradiation:

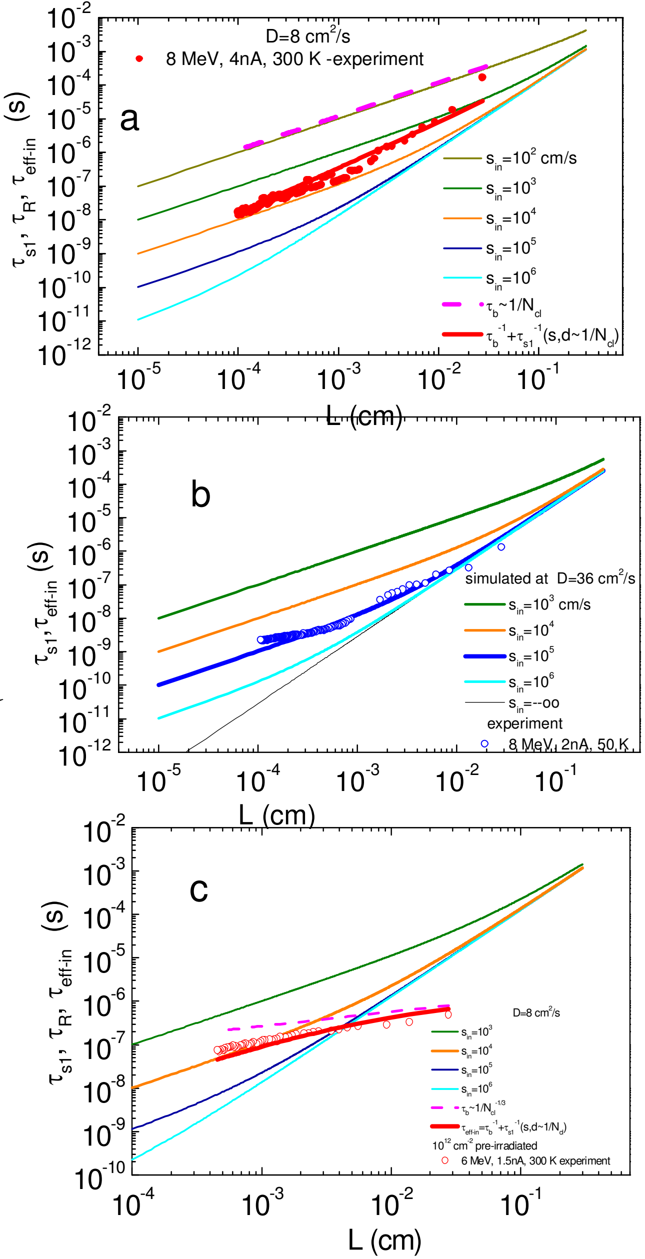
alternatively, lifetime variations can be explained by the inside surface recombination on extended defects



The extended radiation defects along the path of particle tracks (after Huhtinen) as the inside surfaces for recombination characterized by *sI*, spaced by volume averaged distances *L* shown by thick lines.



Surface recombination lifetime as a function of sample thickness for different values of *s*

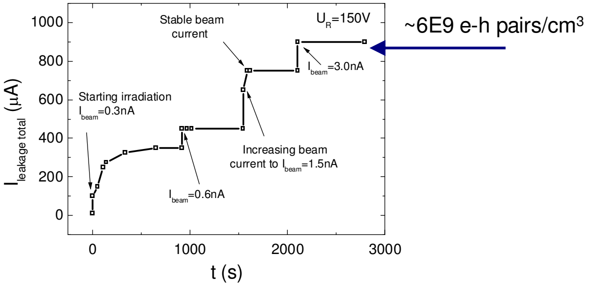


Comparison of variations of the initial carrier decay component obtained in experiments (symbols) during irradiation by 8 MeV protons (a,b) and by 6 MeV (c) protons at temperatures of 280 K (a,c) and of 50 K (b) for the initial MCZ Si (a,b) and the pre-irradiated (c) material with the simulated characteristics (lines) by using a model of simultaneous action of surface $\tau_s = d^2/\pi^2 D$ and bulk recombination Eq. :

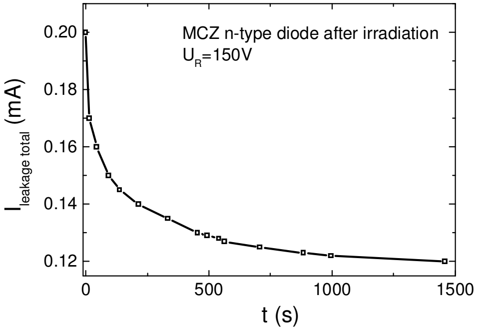
$1/\tau_{eff,\ in} = 1/\tau_{Rinitial} + \Sigma_{jp}(1/\tau_{R,jp}) + \eta_{r=1}{}^2 D$ and at assumption of $L \sim ct_{exp}{}^{-1}$.

TCT before, during and after irradiation by 8 MeV protons

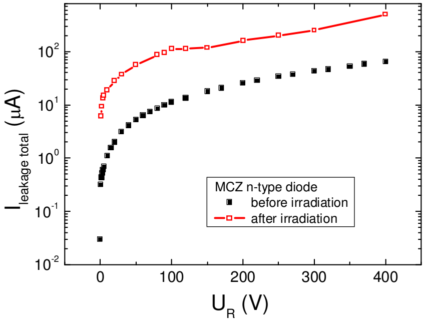
Control of the beam current changing within irradiation



Control of the decay of radio-isotopes just after beam switched of (t=0)



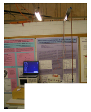
Control of the leakage current increase after irradiation

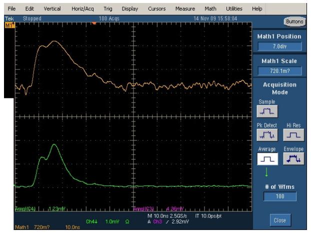


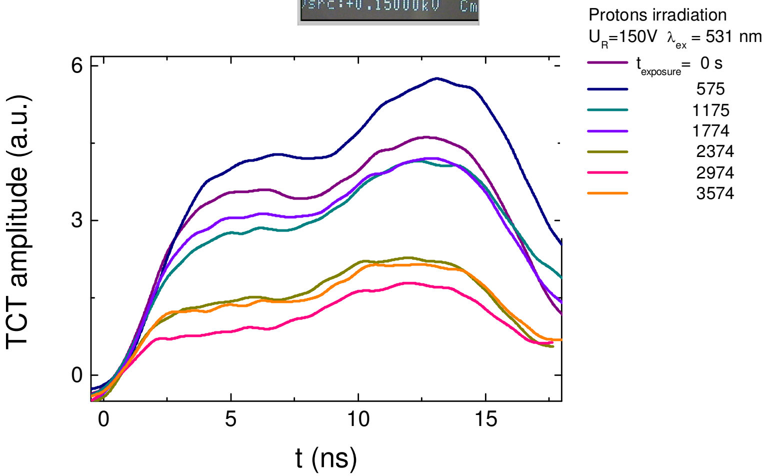
Simultaneous measurements of TCT and of total leakage current

+0.11990mA

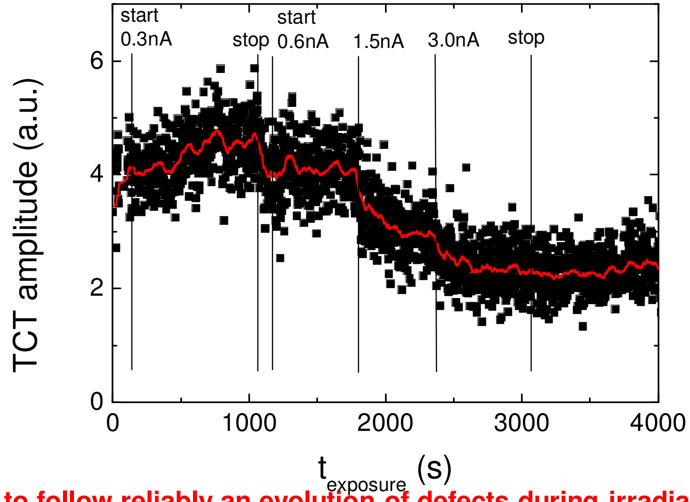
Vsrc:+0.15000kV Cm





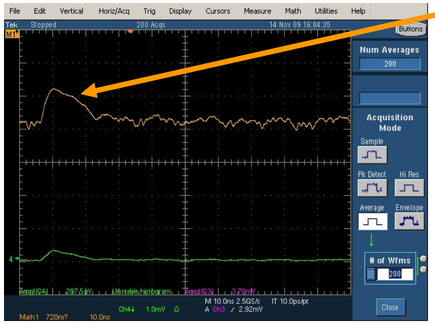


MCZ n- type Si base



It is difficult to follow reliably an evolution of defects during irradiation by measurements of the TCT amplitude while shape and duration of a TCT pulse are nearly invariable at fixed U_r=150 V

Carrier recombination-diffusion and charge extraction-collection-TCT in the non-irradiated diodes



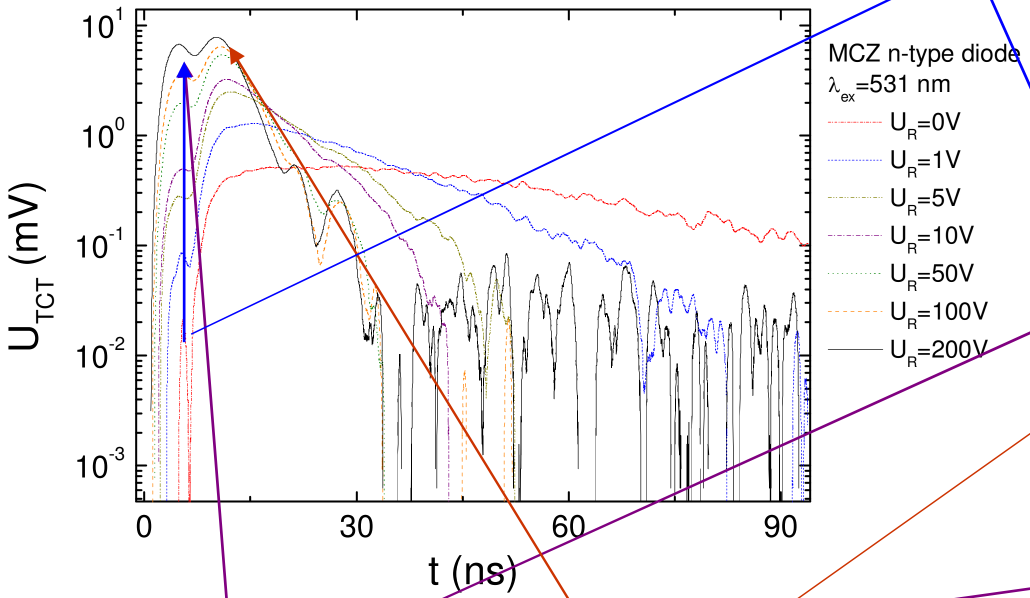
Pure TCT – $I_{ex\text{-}TCT}$

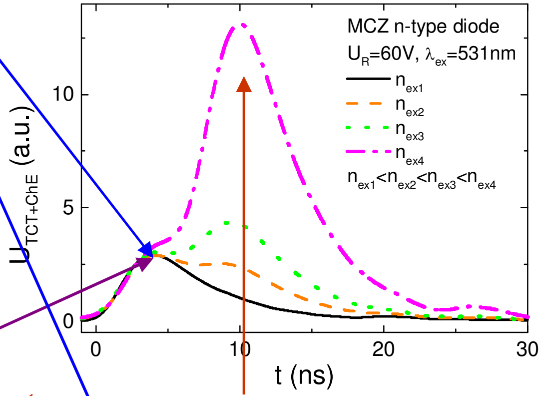
Transient in semilog scale

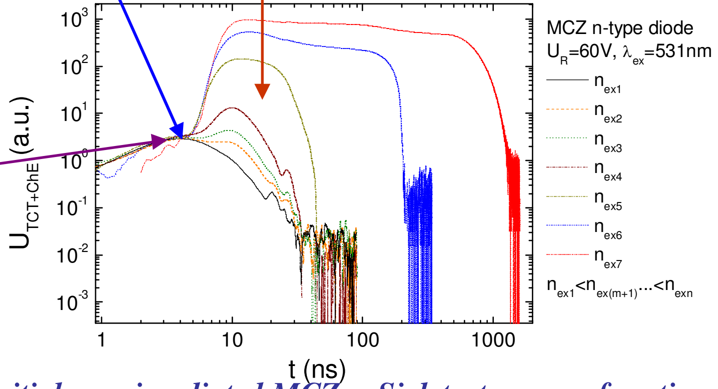
Transient in linear scale

TCT +CnC– (1.1-2)$I_{ex\text{-}TCT}$

TCT







Drift-TCT

Charge diffusion-extraction/ collection

Carrier drift (TCT), diffusion (ChE/C) and recombination components in the initial non-irradiated MCZ n-Si detectors as a function of voltage at fixed excitation density (left) and of excitation density (right) at fixed voltage. Recombination is significantly longer.

Model and simulations

TCT regime

$t := 1\cdot 10^{-10}, 2\cdot 10^{-10} .. 2\cdot 10^{-5}$

above full depletio

$nex0(Ur) := \frac{eps\cdot eps0\cdot Ur}{e\cdot d^2}$ $\quad nex0(122) = 8.998\cdot 10^{11}$ $\quad Ttr(Ur) := \frac{d^2}{miu\cdot Ur}$

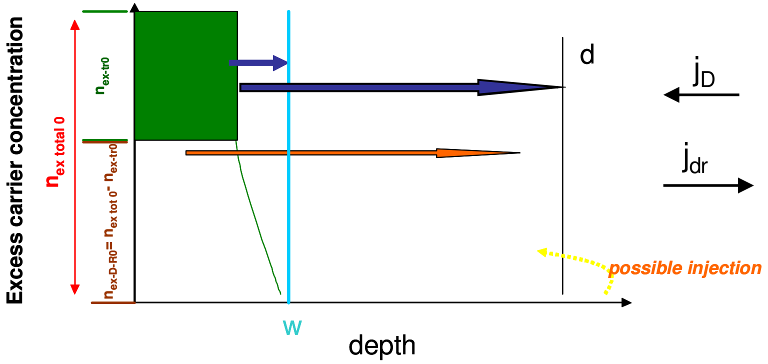
$Mex0 = 0.8998\cdot 10^{12}$ $\quad TefR = 10^{-5}$

$$MexFD(t,Ur) := nex0(Ur)\cdot\left(\exp\left(\frac{-t}{Ttr(Ur)}\right) - \exp\left(\frac{-t}{TefR}\right)\right) + Mex0\exp\left(\frac{-t}{TefR}\right)$$

$$MexF(t,Ur) := \frac{1}{tauL}\cdot\int_0^t \frac{imp(t-x)}{1}\cdot MexFD(x,Ur)\,dx$$

Drift $n_{ex\text{-}tr0} = Cu_r/eSd^* = \varepsilon\varepsilon_0 U_r/ed^{*2}$

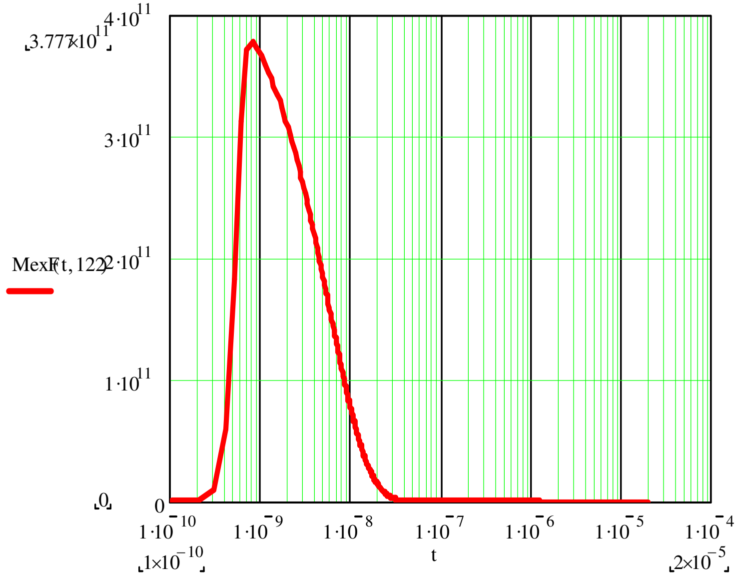
$d^{*2} \sim d^2|_{FD,\ bulk\ exc}$, $wd|_{<FD,\ bulk\ exc}$, $w/\alpha|_{<FD,\ surf\ exc}$, $d/\alpha|_{FD,\ bulk\ cr\text{-}sect\ exc}$

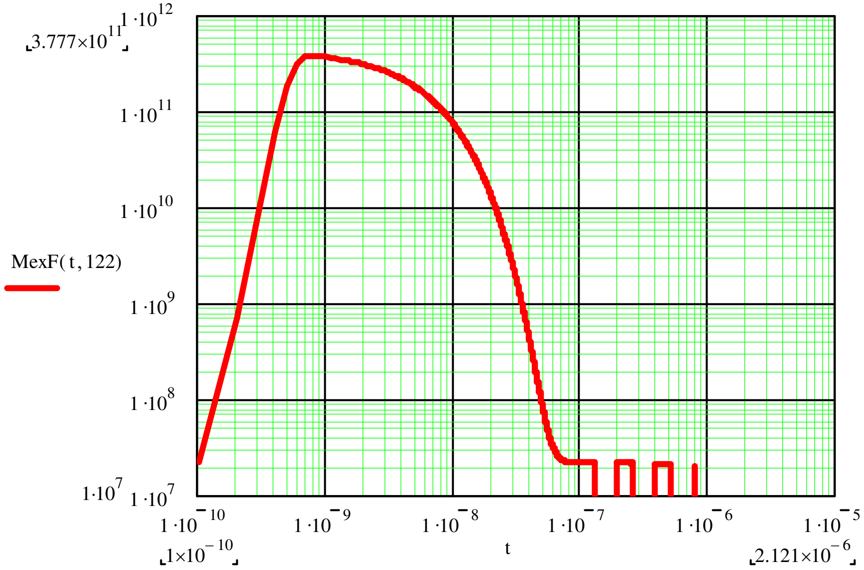


$dn_{ex\text{-}tr}/dt = -\,n_{ex\text{-}tr}/t_{tr}$, $\quad n_{ex\text{-}tr}(t) = n_{ex\text{-}tr0}\exp(-t/t_{tr}) \cong n_{ex\text{-}tr0}(1-t/t_{tr})|_{t<t\ tr}$

$dn_{D\text{-}R}/dt = Dd^2 n_{D\text{-}R}/dx^2 - n_{D\text{-}R}/\tau_R$, $\quad n_{D\text{-}R}(t) = n_{D\text{-}R,0}\exp(-(\tau_R^{-1} + D\eta_1^{2})t)$

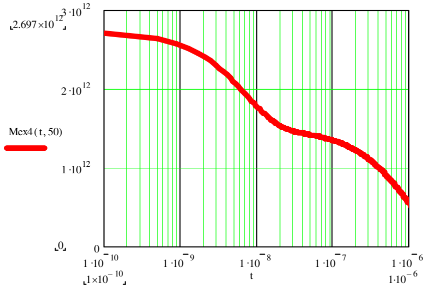
$n_{ex} = n_{D\text{-}R} + n_{ex\text{-}tr}$

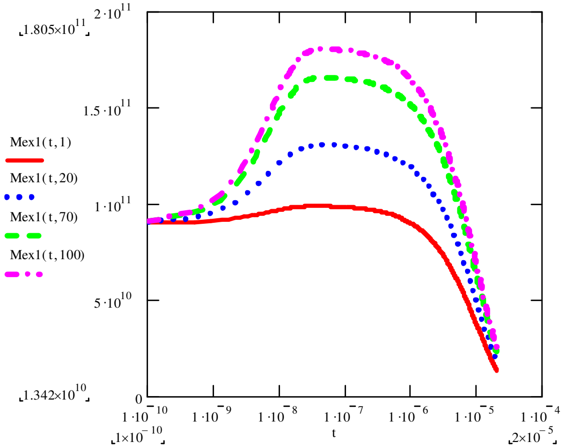




Model and simulations

TCT +charge-extraction (Ch-E) regime





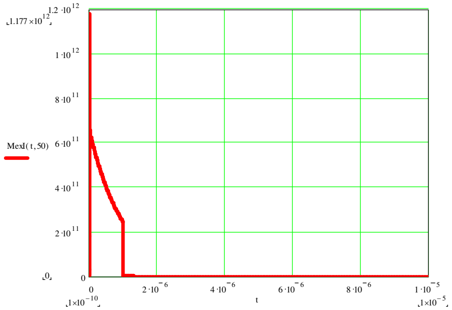
$$\mathrm{tauL} := 6 \cdot 10^{-10}$$

$$t := 1 \cdot 10^{-10}, 2 \cdot 10^{-10} .. 1 \cdot 10^{-5}$$

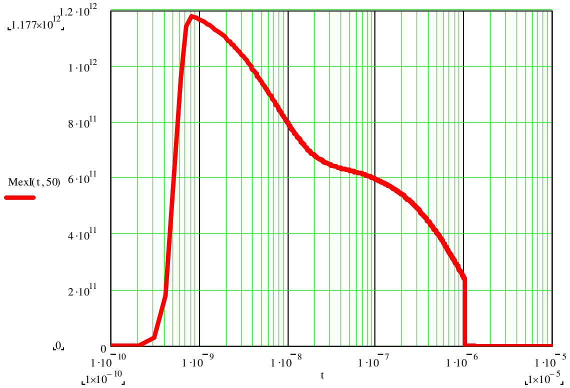
$$\mathrm{MexI}(t, \mathrm{Ur}) := \frac{1}{\mathrm{tauL}} \cdot \int_0^t \frac{\mathrm{imp}(t - x)}{1} \cdot \mathrm{Mex4}(x, \mathrm{Ur})\, dx$$

Simulated transient

Linear scale

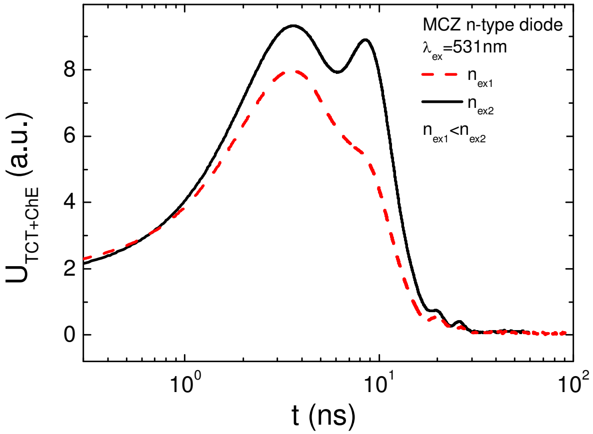


Simulated transient

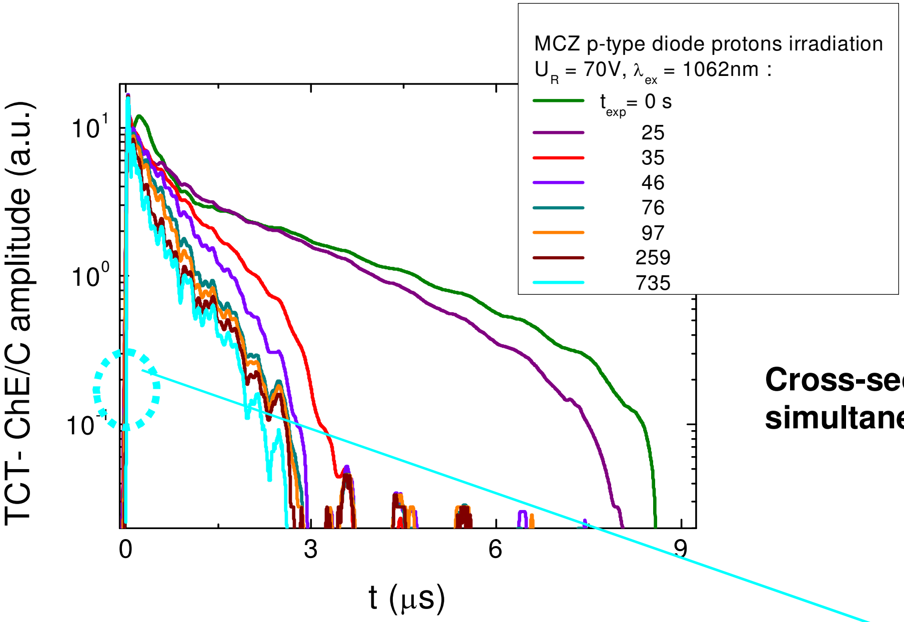


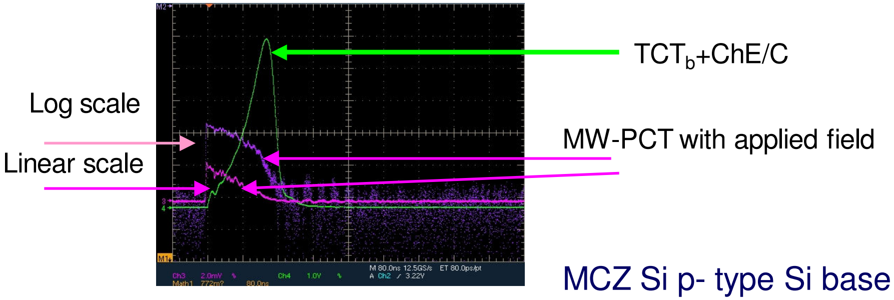
Semilog scale

Measured transients



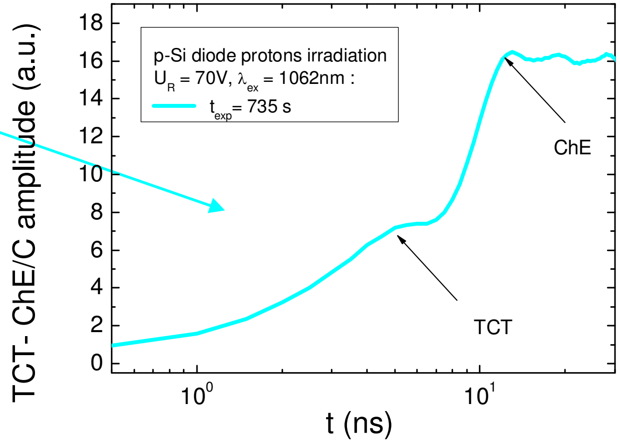
Simultaneous measurements of carrier recombination-diffusion and TCT-charge extraction/collection during irradiation by 8 MeV protons

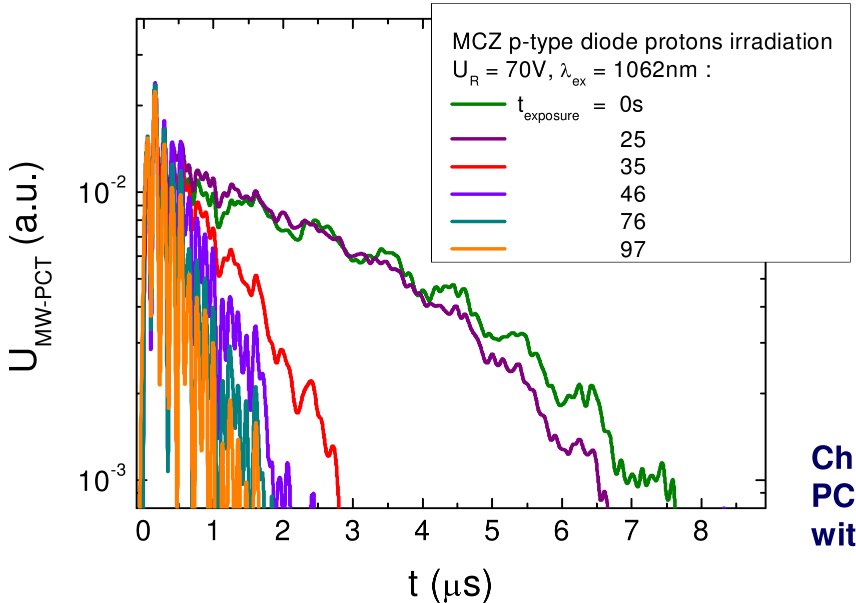




MCZ Si p- type Si base

Cross-sectional IR probing regime with applied electric field and simultaneous ChE measurements





ChE transient shortens during exposure in agreement with MW-PCT which shows continued recombination lifetime reduction with enhancement of fluence

Summary

- **Examined MW-Photoconductivity transient (PCT) exposure characteristics show defect evolution aspects in different scales: most probable processes are related to the lattice excitation and recombination induced migration of defects.**

- **The polynomial approximation would feature a formation rate for definite type of single defects averaged over densities of various species, while the inside surface recombination approach would show excess carrier decay rate in the crystal when bulk averaged distances of their free motion are shortened with enhancement of particle tracks density.**

The latter approximation fits well the lifetime variations during exposure of stopped 3 MeV protons, when only linear and square terms are adjusted in the polynomial model. Formation and competition of the point and the extended defects, which dimensions (geometrical cross-sections of clusters) are limited by a damage area and a defect stability reason, can be observed only in the limited range of exposures under irradiation by stopped 3 MeV protons.

- **Simultaneous measurements of the MW-PCT and Charge extraction transient /Collection exposure characteristics during irradiation by 8 MeV protons enable one to follow fluence dependent changes of carrier recombination – diffusion parameters. However, it is difficult to follow reliably an evolution of defects during irradiation by measurements of the TCT amplitude while shape and duration of a TCT pulse are nearly invariable at fixed Ur.**

- **Charge extraction transient shortens to TCT during exposure, while MW-PCT shows continued recombination lifetime reduction with enhancement of fluence**

THANK YOU FOR ATTENTION!