Carrier recombination characteristics in neutron irradiated Si at extreme fluences

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Outline

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- ☐ Principles of measurement techniques and instruments
  - ☐ Microwave probed photoconductivity (MW-PC) transients technique
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  - ☐ Light-induced transient grating (LITG) technique

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- ☐ Experimental results in Si wafers irradiated by neutrons over an extended range of fluences
  - ☐ Carrier lifetime variations
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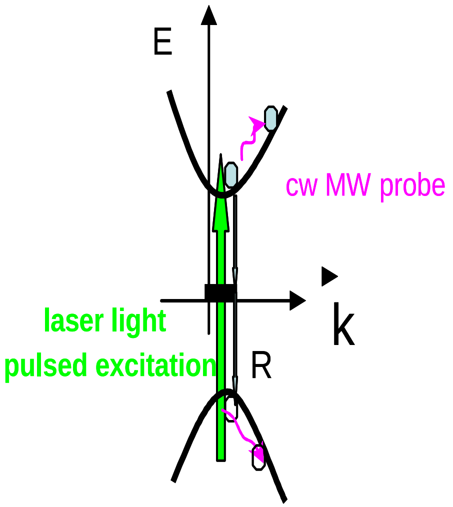
Motivation

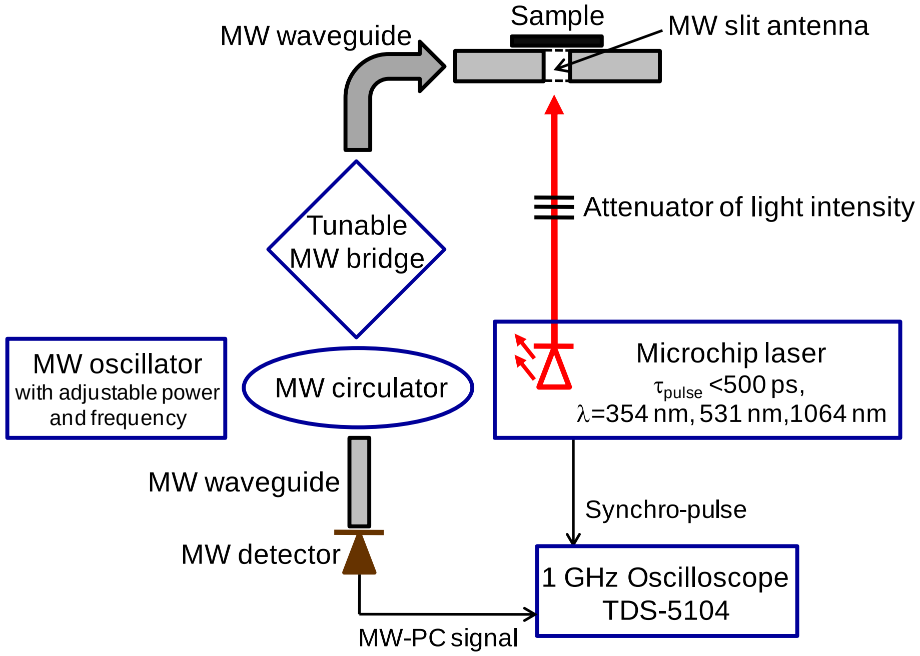
- ☐ Carrier lifetime is related to the operational characteristics of particle detectors.
- ☐ It depends on the irradiation fluence and is sensitive to the density of defects.
- ☐ Measuring of carrier lifetime in irradiated structures is important in order to predict the modification of operational characteristics of particle detectors and to evaluate the radiation damage.
- ☐ At extreme fluences, carrier lifetime values decrease to tens of ps. Therefore, measurement techniques of sufficient temporal resolution are also needed.

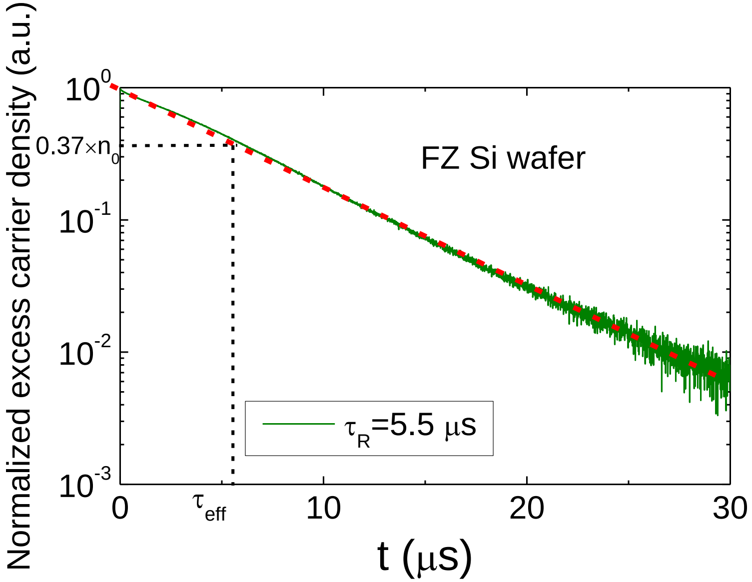
The aim of this work was to apply the transient pump-probe techniques for the characterization of fast carrier decay phenomena and to estimate the carrier lifetime, diffusion coefficient and diffusion length in Si wafer samples irradiated at extreme fluences.

Microwave probed photoconductivity transients technique



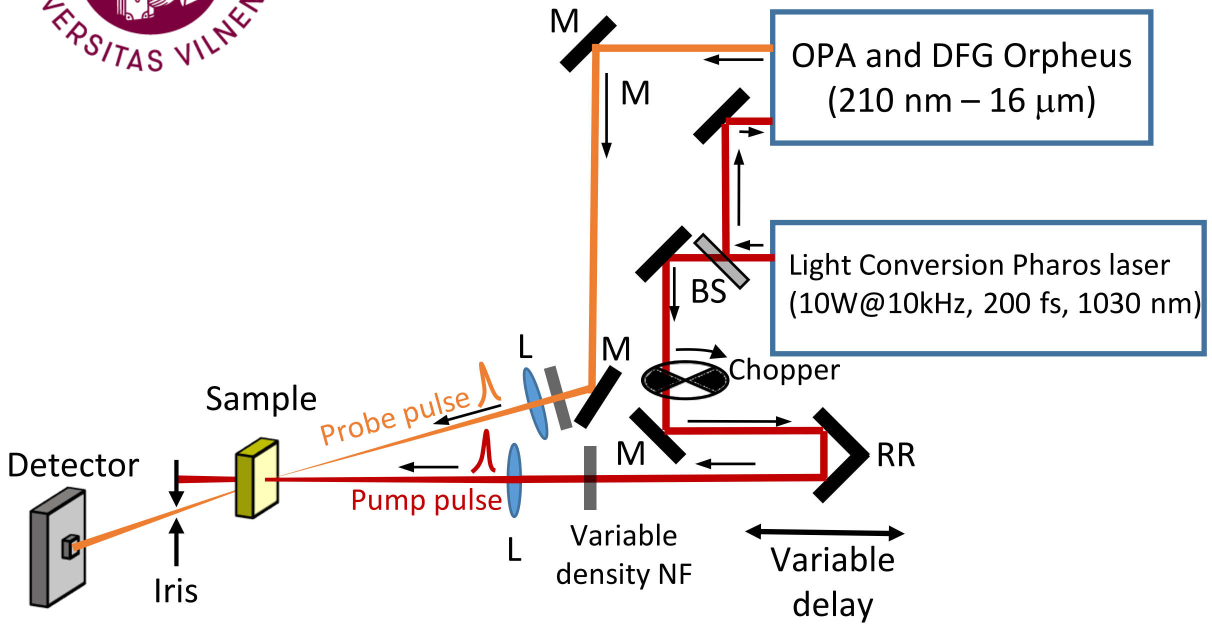
The microwave probed photoconductivity technique is based on the direct measurements of the carrier decay transients by employing MW absorption by excess free carriers.



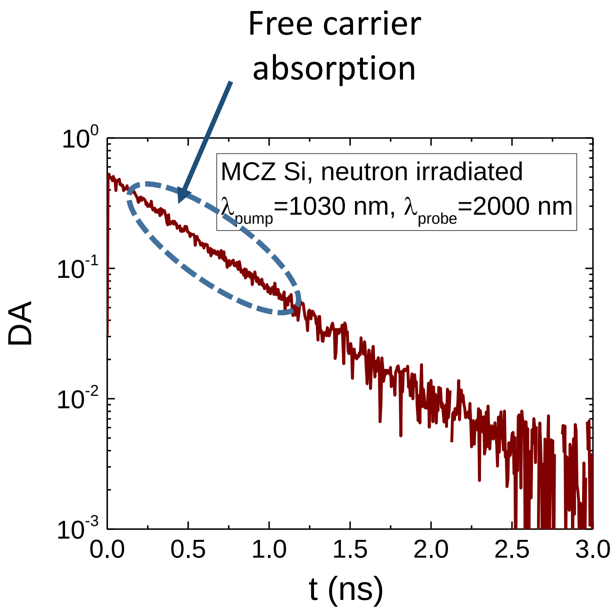


$$\tau_R = n \Big/ \left(-\frac{\partial n}{\partial t}\right)\Bigg|_{\exp(-1)}$$

Transient absorption (DA) technique in pump-probe configuration



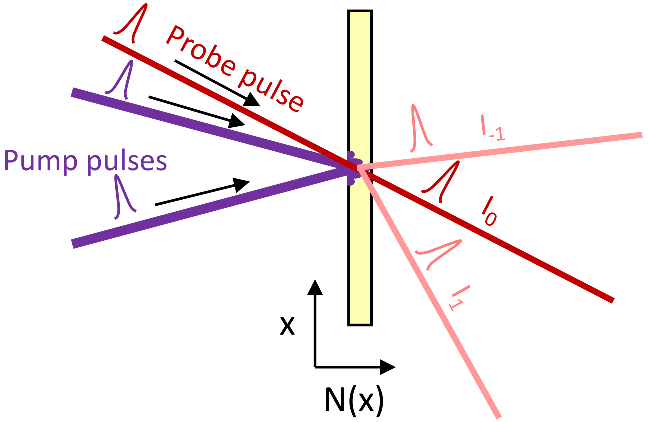
$$DA(t) = ln\frac{I_{unexc}}{I_{exc}(t)} = \Delta N \sigma_{eh} d \exp\left(-\frac{t}{\tau}\right)$$



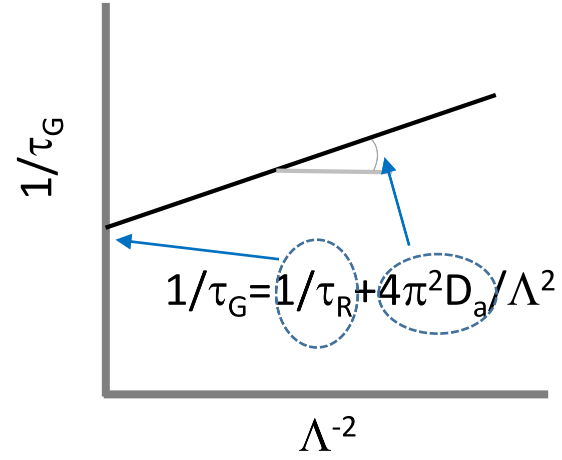
DA transient measured in neutron irradiated Si wafer sample using pump and probe laser pulses of different wavelengths.

- Light Conversion Pharos laser (10W@10kHz, 200 fs, 1030 nm).
- Optical parametric amplifier (OPA) and differential frequency generator (DFG) Orpheus (210 nm – 16 μm).
- The variable delay of the probe pulse enables step by step measurements of the time evolution of the DA.
- The time resolution of the measurement depends on the pulse duration of the laser used, i.e. it is in the range of hundreds of fs.
- Variable pump and probe wavelength.

Light-induced transient grating (LITG) technique



The light-induced transient grating (LITG) experimental setup.



Principle of extraction of D_a and τ_R parameters.

The sample is excited by a spatially modulated interference field of two coherent pump beams, which create a transient spatially modulated free carrier pattern with the grating spacing Λ

$$N(x) = N_0 + \Delta N\left(1 + cos\left[\frac{2\pi x}{\Lambda}\right]\right)$$

Diffraction efficiency $\eta_1 \sim J_1^2(\Phi) \approx (\Phi/2)^2$ $\Phi(t) = (2\pi/\lambda) n_{eh} \Delta N(t) d$

$$\frac{I_{1\,diffracted}(t)}{I_0(t)} = \eta_1(t) \propto \exp\left(\frac{-2t}{\tau_g}\right)$$

The grating decay time τ_g is related with recombination and diffusion times τ_R and τ_D

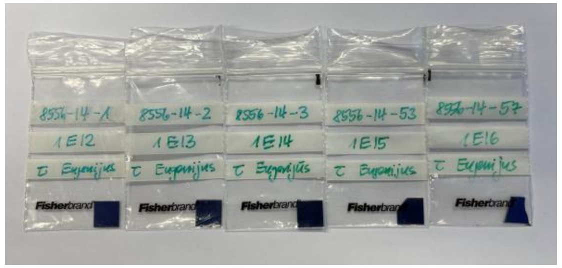
$$\frac{1}{\tau_g} = \frac{1}{\tau_R} + \frac{1}{\tau_D} = \frac{1}{\tau_R} + \frac{4\pi^2 D_a}{\Lambda^2} \qquad D_a = \frac{n + p}{n/D_h + p/D_e}$$

Measurements with different induced grating periods Λ allows evaluating D_a and τ_R by fitting

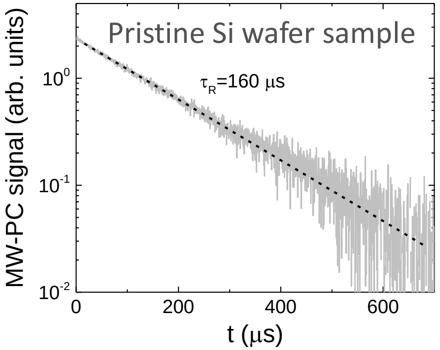
$$\boxed{\frac{1}{\tau_g} = f\left(\frac{1}{\Lambda^2}\right)}$$

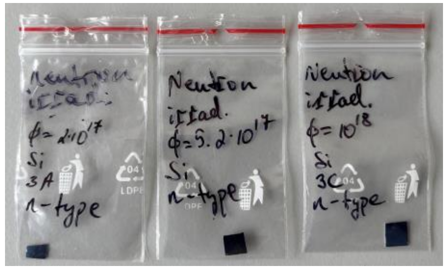
Samples investigated

MCZ Si wafer fragments
- high resistivity;
- surface passivated;
- 300 μm thick;
- irradiated with reactor neutrons in the fluence range $\Phi=10^{12}$-10^{16} cm^{-2}.

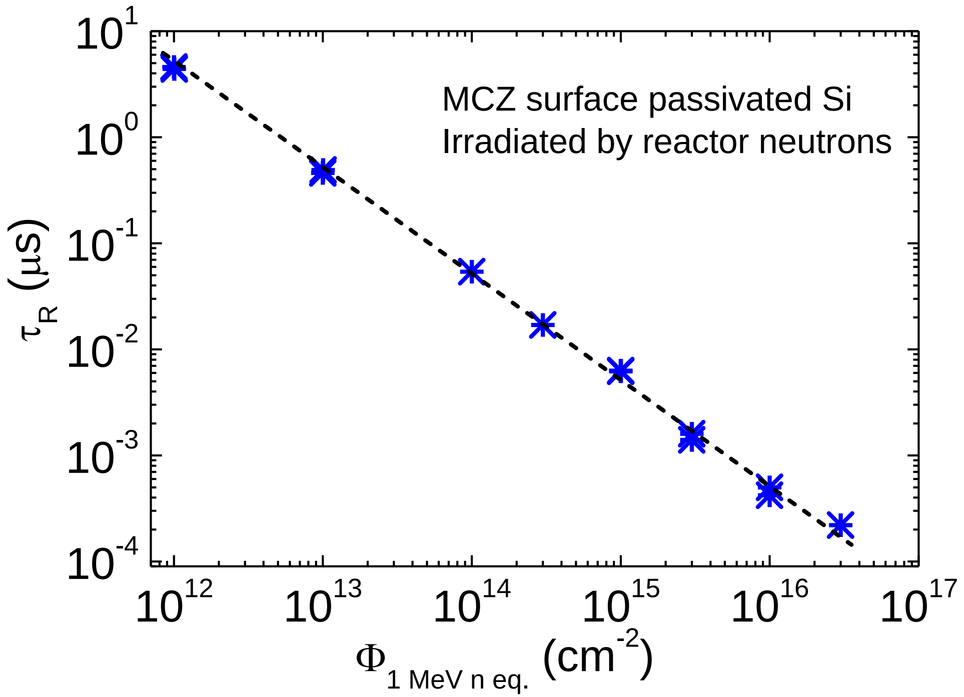


Si wafer fragments
- high resistivity (HR);
- surface passivated;
- 300 μm thick;
- lifetime in pristine samples ≥160 μs;
- irradiated with reactor neutrons in the fluence range $\Phi=2\times10^{17}$-10^{18} cm^{-2}.





Carrier recombination lifetime variations obtained by MW-PC technique



Carrier recombination lifetime as a function of reactor neutrons irradiation fluence in MCZ Si wafers.

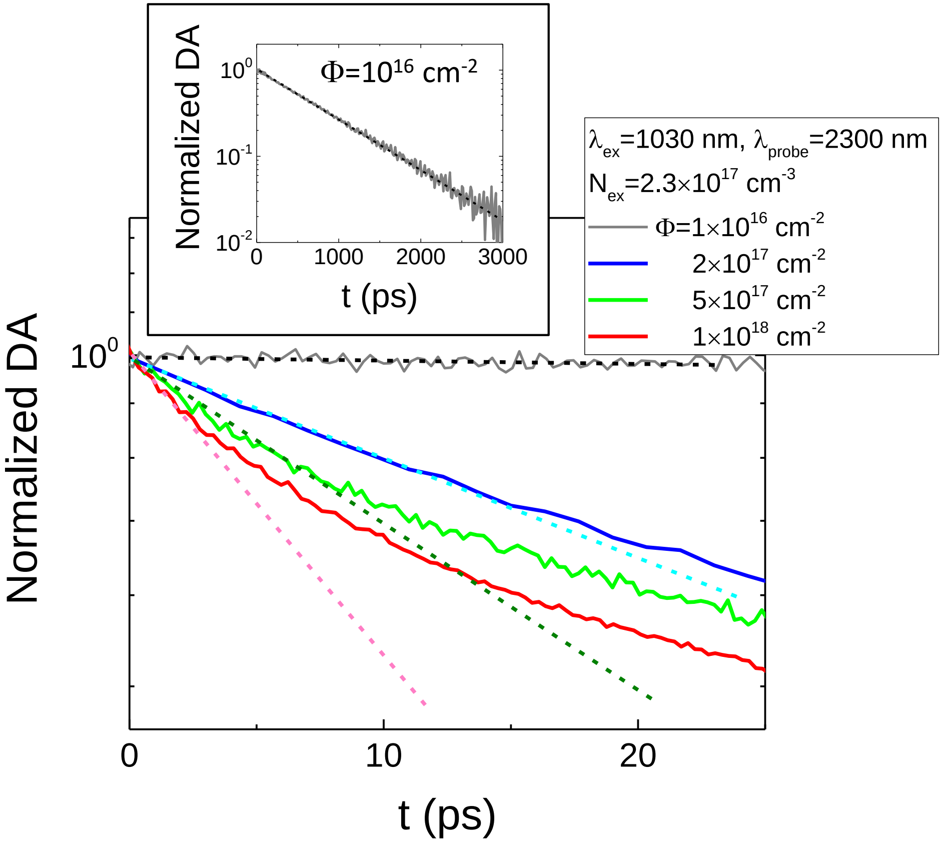
- Reciprocal τ_R dependence vs Φ within a double logarithmic scale.

$$\tau_R = \frac{1}{\sigma v_{th} N_R}$$

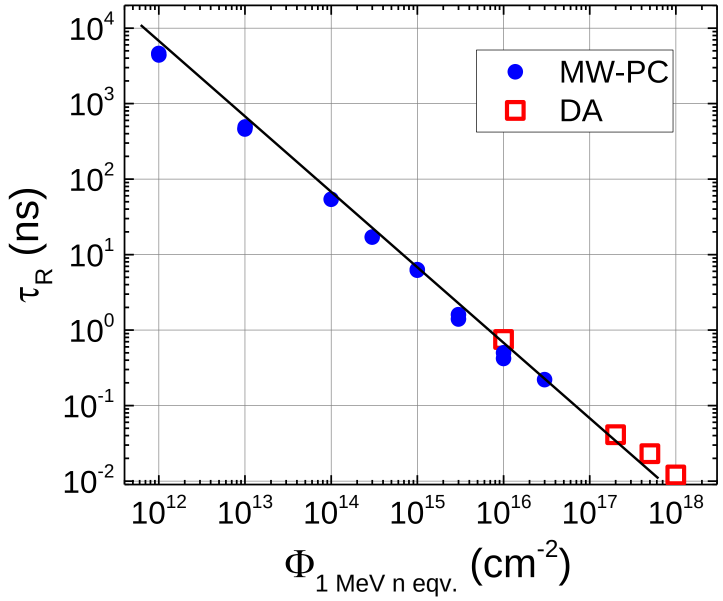
- The linear relation between the defect concentration N_R and recombination rate $R=1/\tau_R$ exists.

T. Ceponis et al, Profiling of carrier lifetime and electrical characteristics in PIN and LGAD structures, Presentation at RD50 workshop, Seville 2022-11.

Carrier recombination lifetime variations obtained by DA technique



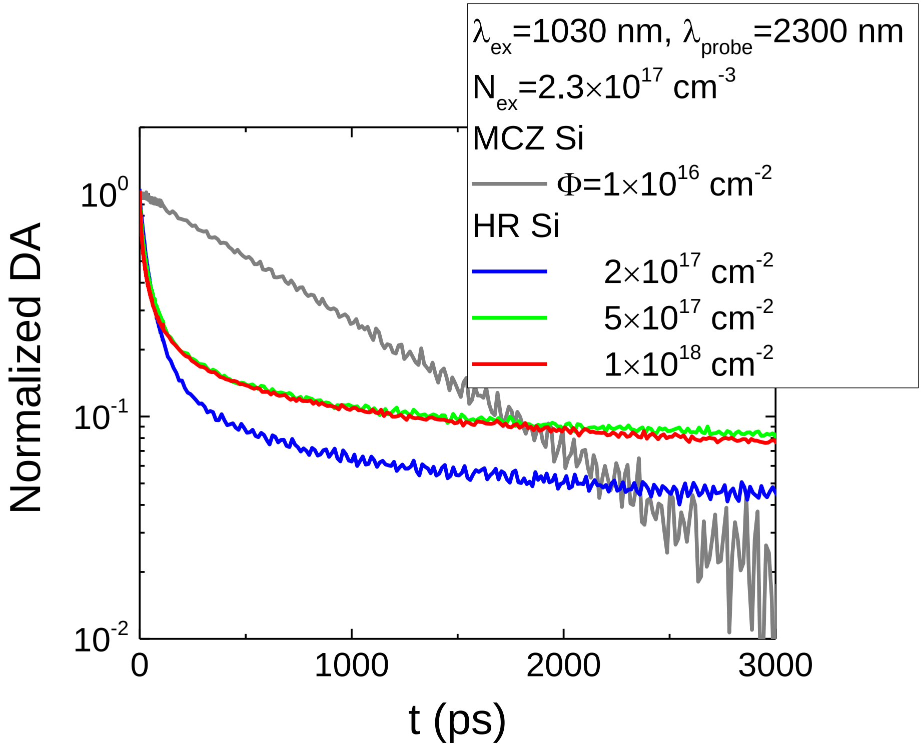
Normalized DA transients at different irradiation fluences.



Carrier recombination lifetime variations as a function of neutron irradiation fluence.

- Recombination lifetime is evaluated from the initial part of the transient.
- Recombination lifetime is inversely proportional to irradiation fluence up to $\Phi = 10^{18}$ cm^{-2}.

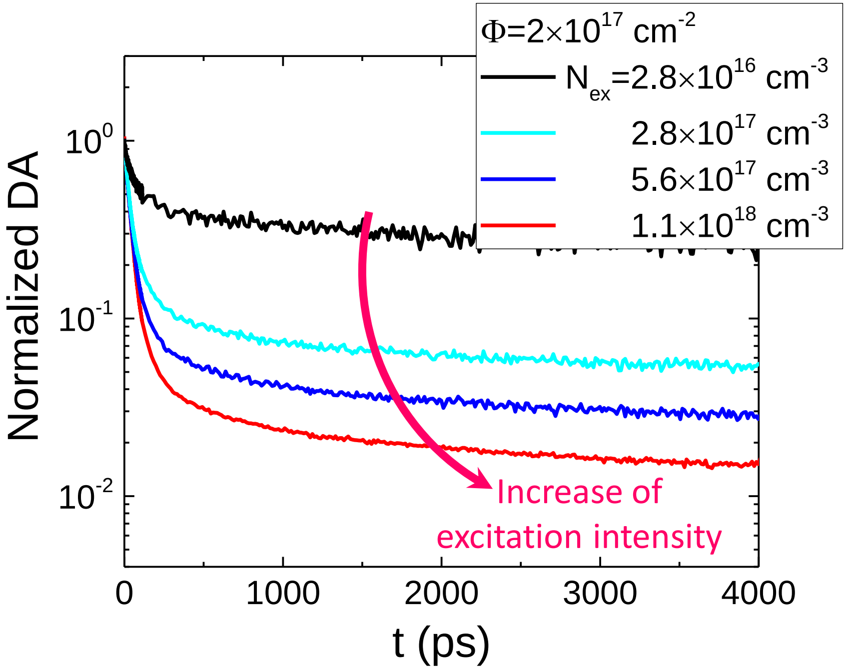
DA transients as a function of different materials and irradiation fluence



Normalized DA transients measured in different technology Si materials irradiated with different fluences.

- DA transient is single exponential for MCZ sample irradiated with $\Phi=10^{16}$ cm^{-2}.
- At $\Phi \geq 2\times10^{17}$ cm^{-2}, DA transients measured in HR Si are characterized by short initial component (<100 ps) and long (>10 ns) asymptotic part.
- The amplitude of the asymptotic part increases at higher ($\geq 5\times10^{17}$ cm^{-2}) fluences.

DA transients as a function of excitation intensity



Normalized DA transients measured in neutron irradiated Si wafer sample at different excitation intensities.

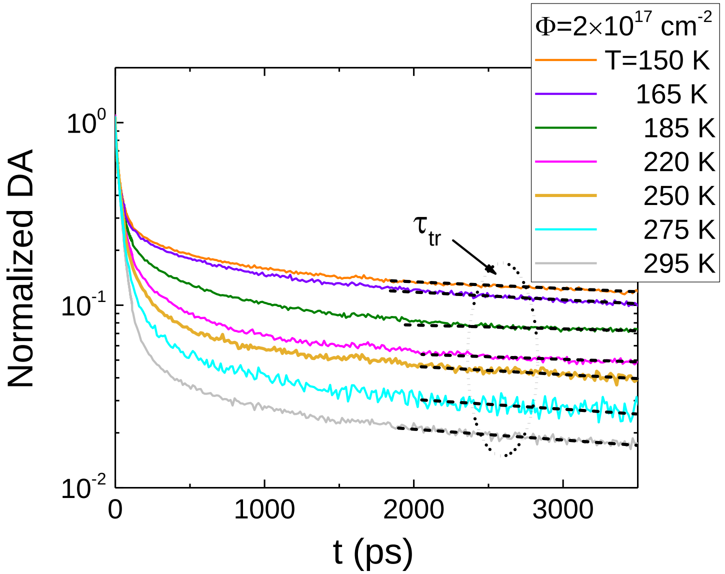
- The amplitude of the asymptotic part decreases with an increase of excitation intensity.
- Indication of trapping.
- Trapping might appear due to the formation of complexes of radiation defects with initial imperfections or radiation-induced defect clusters.

$$\tau_{tr}(T) = \tau_R\left(1 + \frac{N_{tr}N_C(T)e^{-\frac{E_{tr}}{kT}}}{\left(N_C(T)e^{-\frac{E_{tr}}{kT}} + n(T)\right)^2}\right)$$

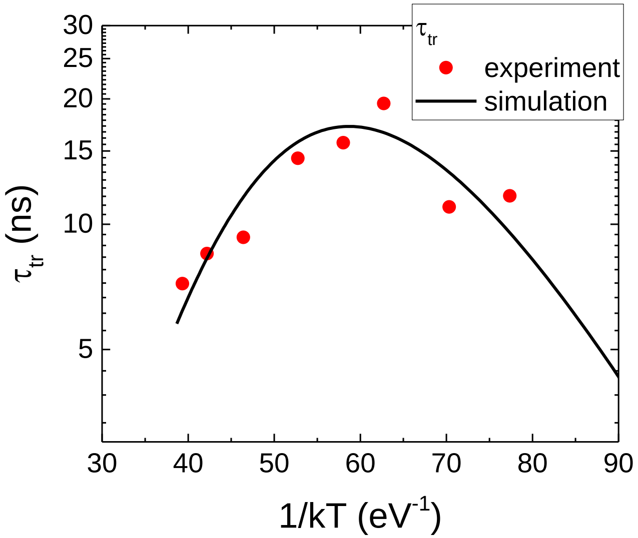
$$n(T) \sim \alpha(300K)\left(\frac{T}{300K}\right)^{4.25} \times F$$

E. Gaubas, T. Ceponis, L. Deveikis, D. Meskauskaite, J. Pavlov, V. Rumbauskas, J. Vaitkus, M. Moll, F. Ravotti, *Anneal induced transformations of defects in hadron irradiated Si wafers and Schottky diodes*, Mat. Sc. Sem. Proc. **75** (2018) 157–165.

Trapping transients as a function of temperature



DA transients measured at different temperatures.



Experimental and simulated variations of carrier trapping lifetime.

- The estimated activation energy and concentration of traps:
  - $E_{tr} \cong 0.15$ eV,
  - $N_{tr} > 10^{17}$ cm^{-3}.

$$\tau_{tr}(T) = \tau_R \left(1 + \frac{N_{tr} N_C(T) e^{-\frac{E_{tr}}{kT}}}{\left(N_C(T) e^{-\frac{E_{tr}}{kT}} + n(T)\right)^2}\right)$$

$$n(T) \sim \alpha(300K)\left(\frac{T}{300K}\right)^{4.25} \times F$$

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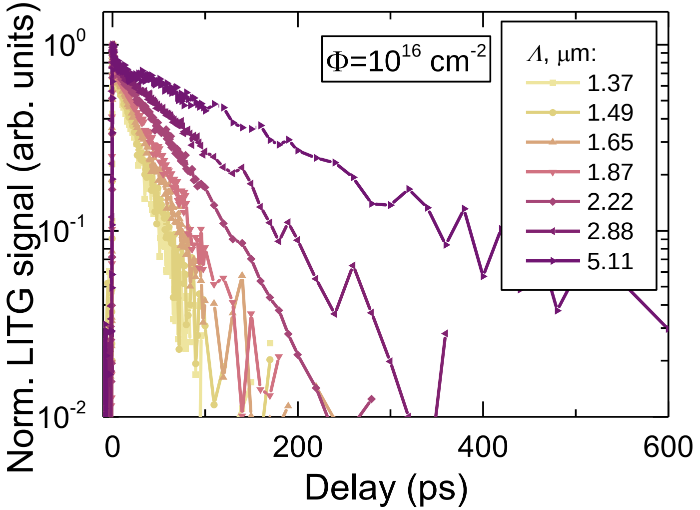
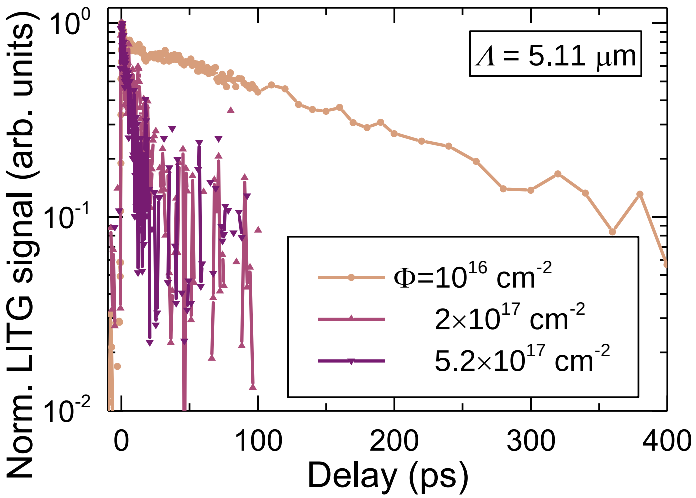
LITG transients as a function of irradiation fluence



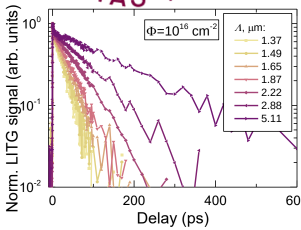
Normalized LITG transients as a function of the grating period measured in neutron irradiated Si material with $\Phi=10^{16}$ cm^{-2}.

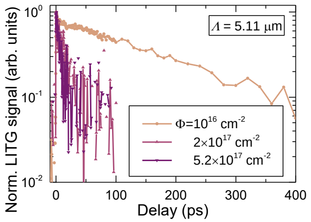


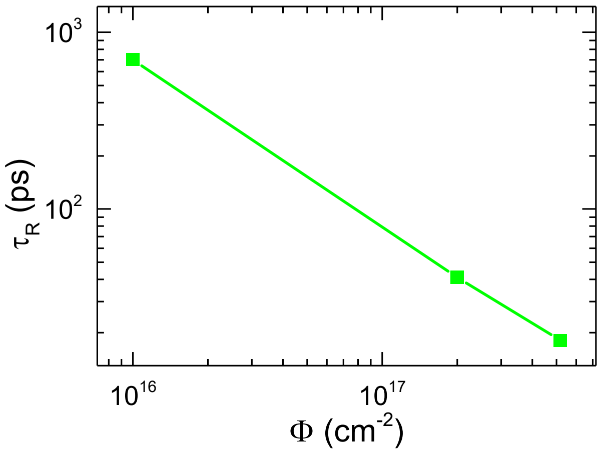
Normalized LITG transients as a function of grating period Λ at different irradiation fluences.

- LITG transients are single exponential.
- Relaxation rate increases with the enhancement of irradiation fluence.

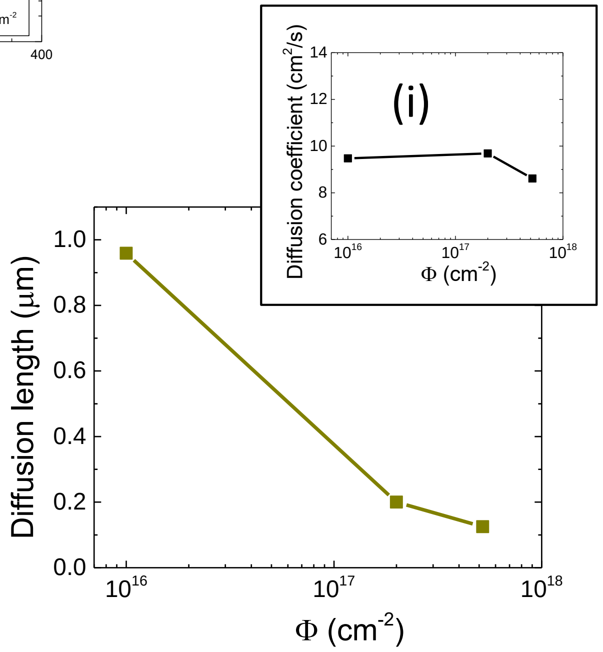
Carrier lifetime and diffusion coefficient evaluations using LITG technique







Carrier recombination lifetime variations as a function of neutron irradiation fluence.

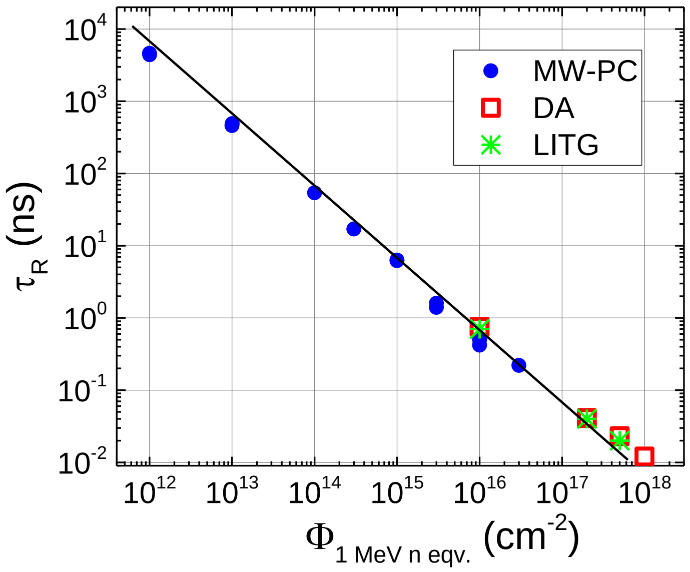


Diffusion length and ambipolar diffusion coefficient (i) as a function of neutron irradiation fluence.

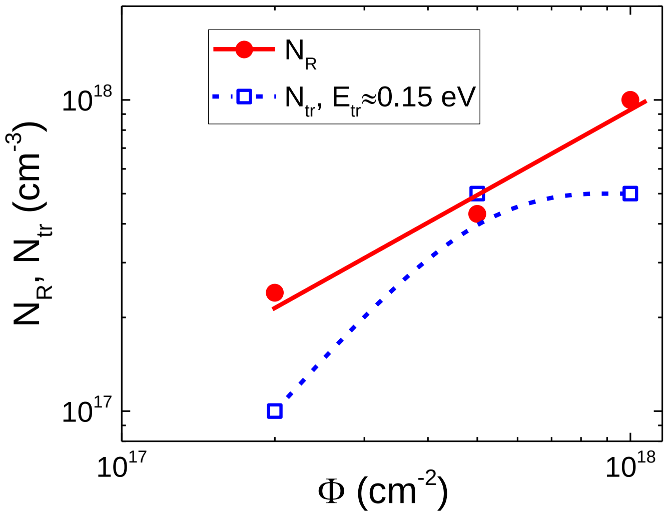
- The carrier recombination lifetime decreases from ~1 ns to ~20 ps with neutron irradiation fluence varying from 10^{16} cm^{-2} to 5×10^{17} cm^{-2}.
- The ambipolar diffusion coefficient was almost constant in all the investigated samples and was evaluated as ~9 cm^2/s.
- The diffusion length decreases from 1 μm to less than 200 nm with varying fluence from 10^{16} cm^{-2} to 5×10^{17} cm^{-2}.

Tendencies of concentration variations dependent on extreme fluences attributed to recombination and trapping centres

- Carrier recombination lifetime is inversely proportional to irradiation fluence up to $\Phi = 10^{18}$ cm^{-2}.
- The extracted τ_R values are in good agreement using different characterization techniques within their application limits.



Carrier recombination lifetime variations as a function of reactor neutrons irradiation fluence, evaluated using different characterization techniques.



Tendencies of concentration variations of recombination and trapping centres dependent on extreme fluences.

N_R estimated assuming $\sigma=10^{-14}$ cm^2, $v_{th}=10^7$ cm/s,

$$\tau_R = \frac{1}{\sigma v_{th} N_R}$$

Conclusions

- Combining the MW-PC, DA and LITG techniques allows the estimation of carrier lifetime values ranging from picoseconds to milliseconds.

- Carrier recombination lifetime decreases from ~40 ps to ~12 ps at extreme neutron irradiation fluences ranging from $\Phi = 2\times10^{17}$-10^{18} cm^{-2}, as obtained using DA and LITG techniques.

- Carrier ambipolar diffusion coefficient was evaluated as ~9 cm^{2}/s and was almost constant in all the investigated samples irradiated at elevated fluences. Whereas the diffusion length decreased from 1 μm to less than 200 nm with varying fluence from 10^{16} cm^{-2} to 5×10^{17} cm^{-2}.

- At extreme irradiation fluences DA transients were characterized by short initial component and long asymptotic part. The latter was proposed to be related with the trapping due to the formation of complexes of radiation defects with initial imperfections or radiation-induced defect clusters.

- Activation energy and concentration of traps were estimated as $E_{tr} \approx 0.15$ eV and $N_{tr} > 10^{17}$ cm^{-3}, respectively, by temperature-dependent trapping lifetime measurements.

Thank you for your attention

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