Research of carrier recombination characteristics in Si and wide-band-gap materials

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Outline

- ☐ Motivation

- ☐ Principles of measurement techniques and instruments
  - ☐ Microwave probed photoconductivity transients technique
  - ☐ Transient absorption technique in pump-probe configuration

- ☐ Recombination characteristics in Si structures
  - ☐ Carrier lifetime in Si wafers
  - ☐ Carrier lifetime variations in layered structures

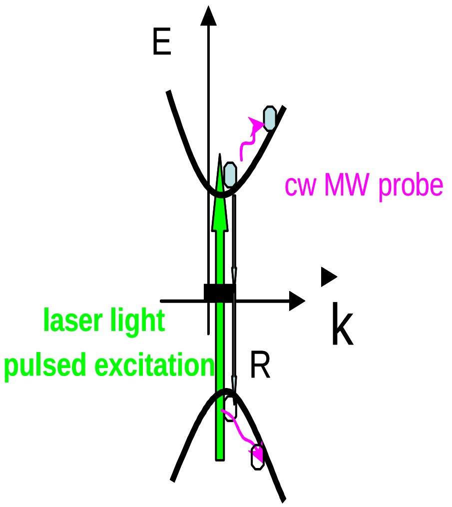
- ☐ Recombination characteristics in wide-band-gap materials
  - ☐ Carrier lifetime in nitride structures
  - ☐ Carrier lifetime in diamond structures

- ☐ Conclusions

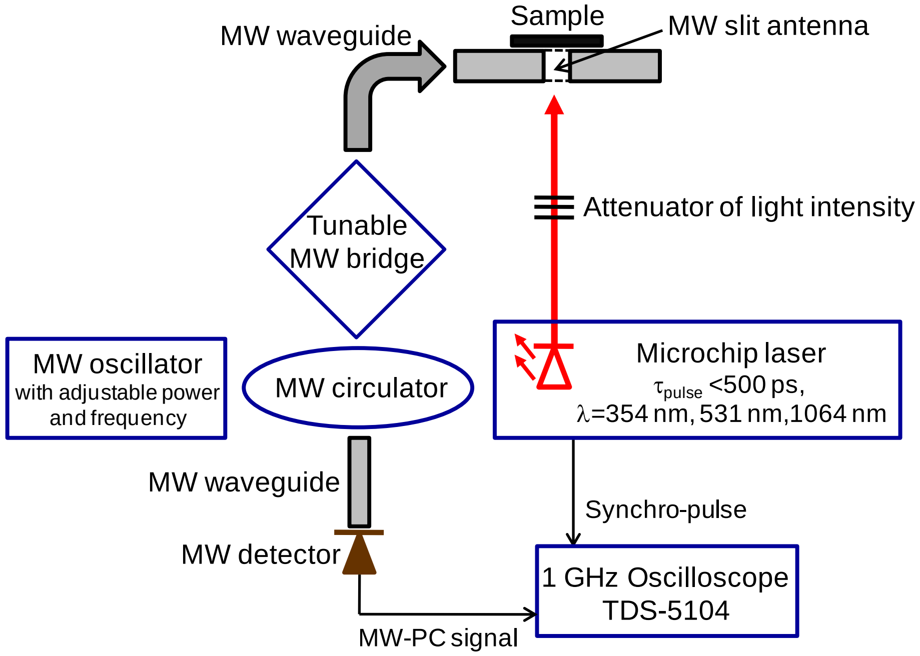
Motivation

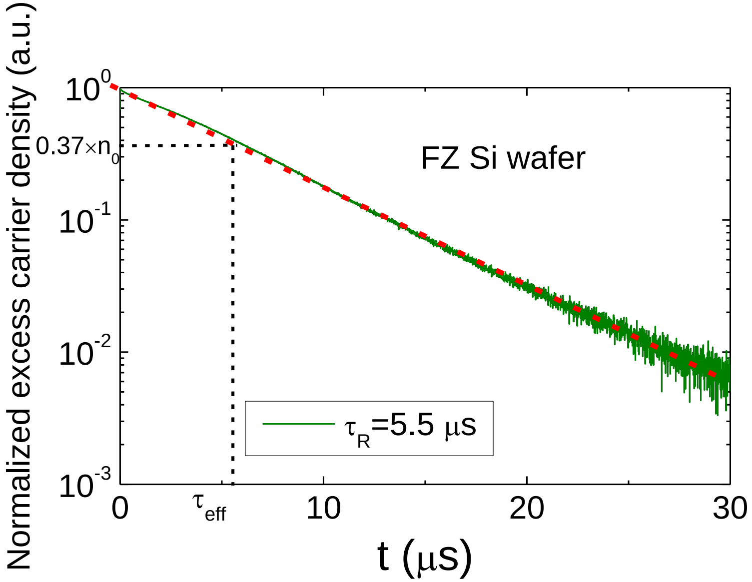
Investigation of recombination characteristics in Si and wide-band-gap sensor materials and structures as a function of material production technology and irradiation parameters.

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.



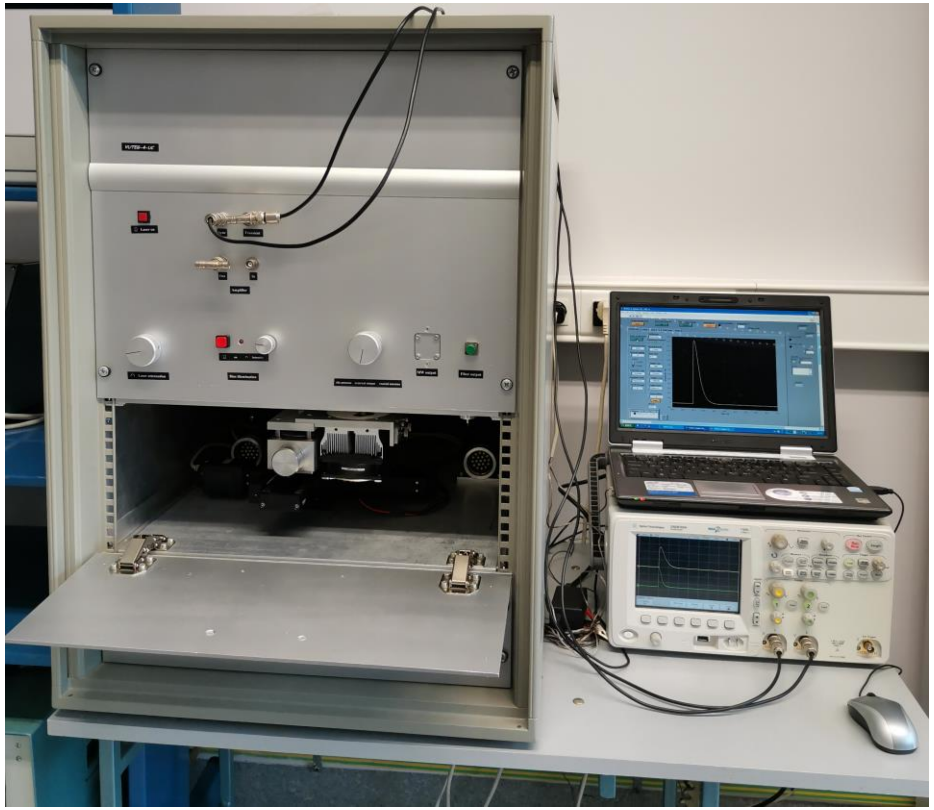


$$\tau_R = n \Big/ \left(-\frac{\partial n}{\partial t} \right)\Bigg|_{\exp(-1)}$$

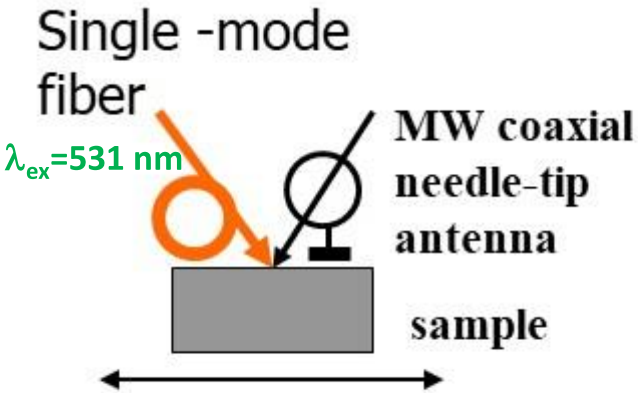
Microwave probed photoconductivity transients technique

Technical capabilities of the instrument VUTEG-4:

- 2D recombination lifetime scanning of Si wafers of dimensions up to 12 cm in diameter.
- Scan regime of wafer edge is foreseen in this instrument, which is implemented using a needle-tip MW antenna probe intersecting with a single mode fibre tip.
- Assurance of the nitrogen gas and temperature stabilized environment during measurements.

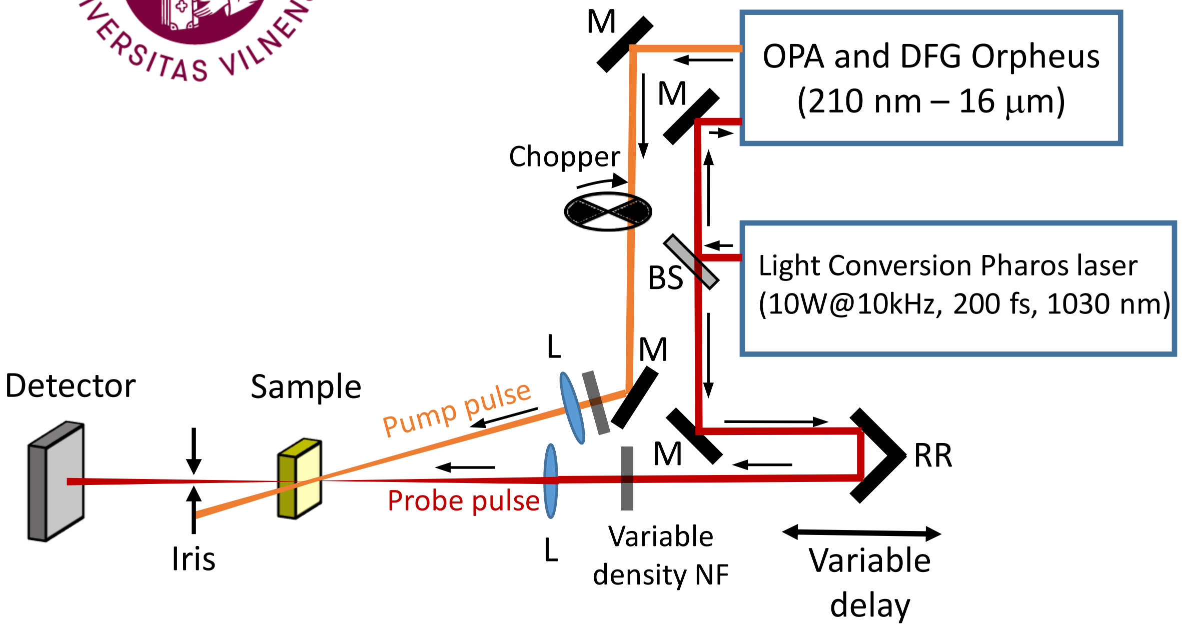


Vilnius University proprietary made instrument VUTEG-4.

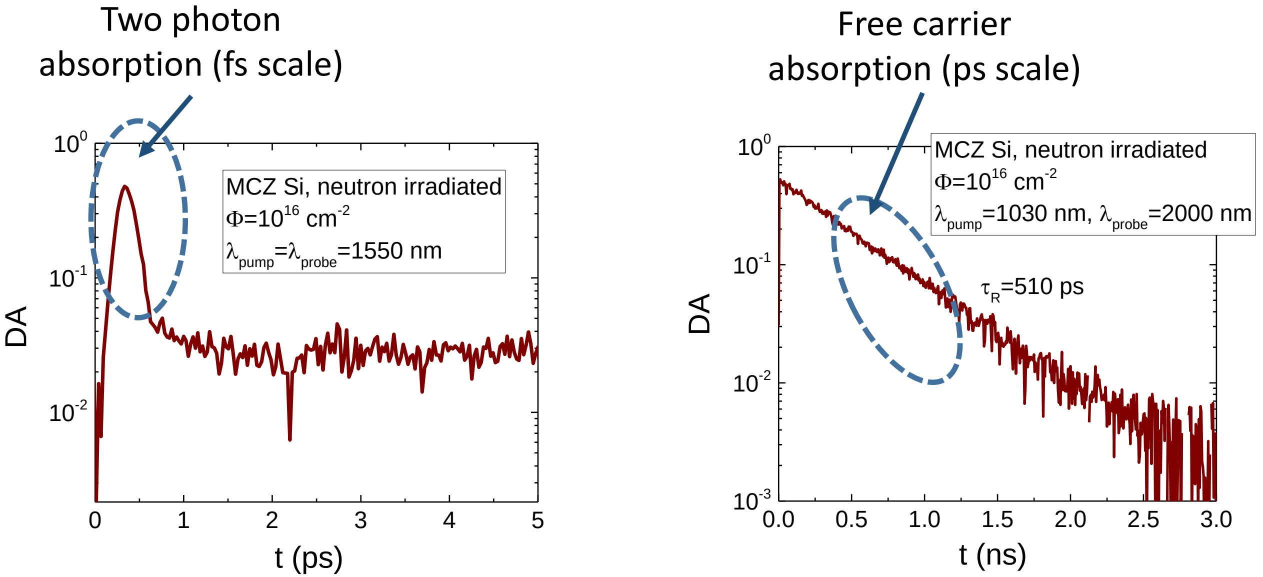


Experiment geometry for cross-sectional profiling of recombination lifetime.

Transient absorption technique in pump-probe configuration



$$DA(\lambda) = ln\frac{I_{unexc}(\lambda)}{I_{exc}(\lambda)}$$

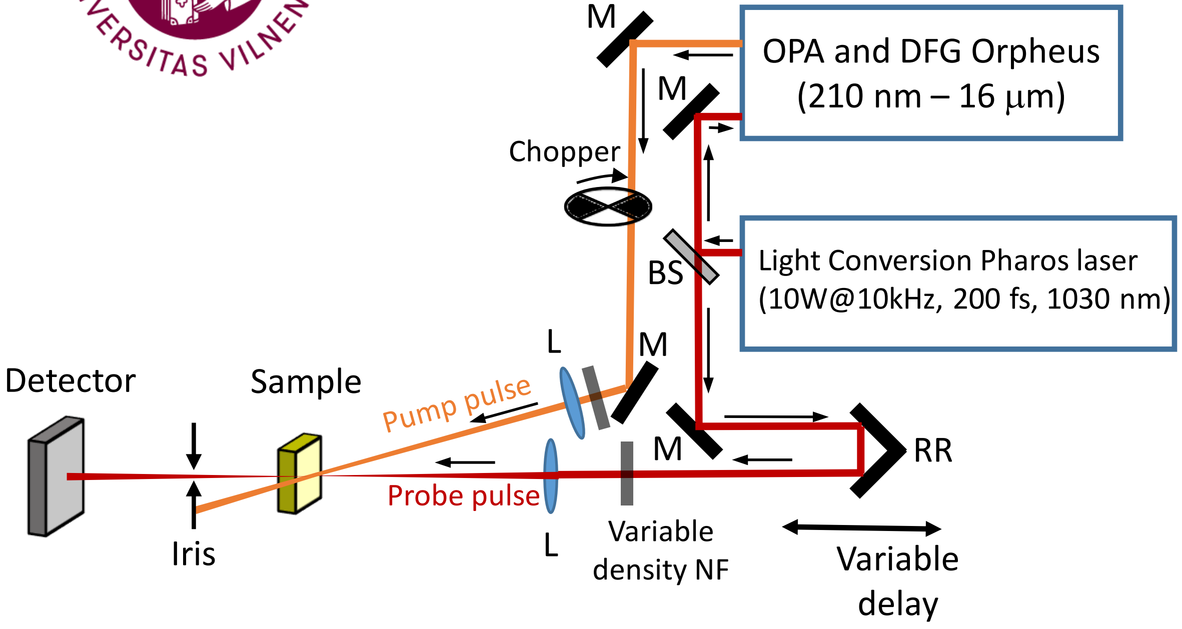

Two photon absorption (fs scale)

Free carrier absorption (ps scale)

DA transients measured in neutron irradiated with 10^{16} cm^{-2} fluence Si wafer sample using different wavelengths of pump and probe laser pulses and highlighting two photon absorption (a) and free carrier absorption (b) phenomena.

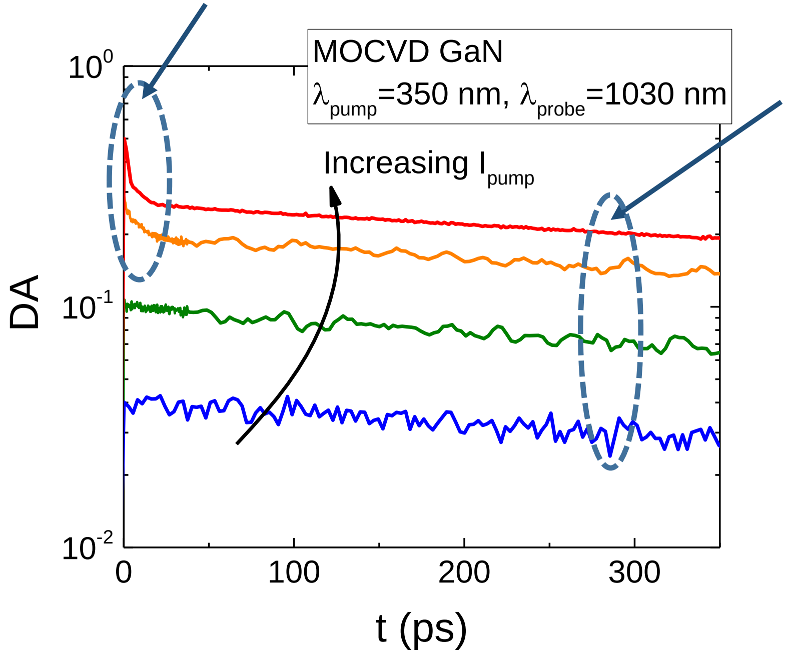
- Light Conversion Pharos laser (10W@10kHz, 200 fs, 1030 nm).
- Optical parametric amplifier (OPA) and differential frequency generator (DFG) Orpheus (210 nm – 16 μm).
- The variable delay of the probe pulse enables step by step measurements of the time evolution of the DA.
- The time resolution of the 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.

Transient absorption technique in pump-probe configuration



$$DA(\lambda) = \ln\frac{I_{unexc}(\lambda)}{I_{exc}(\lambda)}$$

Non-linear recombination at higher carrier densities

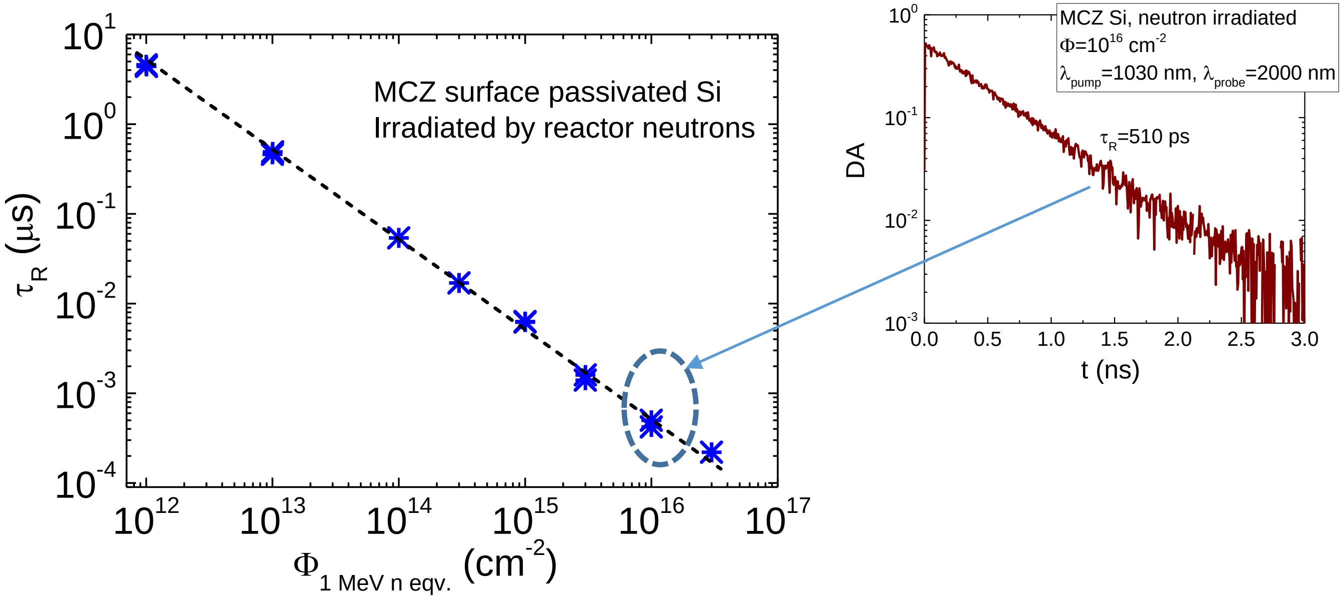


Linear recombination

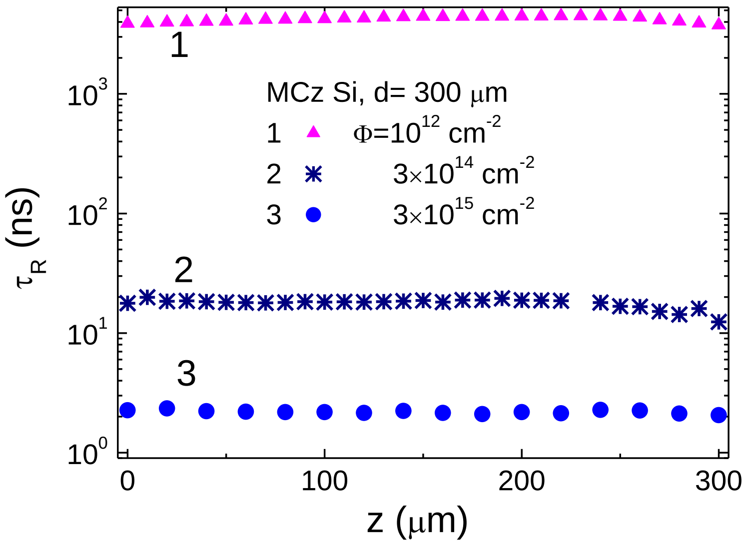
- Light Conversion Pharos laser (10W@10kHz, 200 fs, 1030 nm).
- Optical parametric amplifier (OPA) and differential frequency generator (DFG) Orpheus (210 nm – 16 μm).
- The variable delay of the probe pulse enables step by step measurements of the time evolution of the DA.
- The time resolution of the 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.

Profiling of carrier lifetime in MCZ Si wafers irradiated with reactor neutrons

MCZ Si wafer fragments
- surface passivated;
- 300 μm thick;
- irradiated with reactor neutrons.



Recombination lifetime as a function of reactor neutron irradiation fluence in MCZ Si wafers.

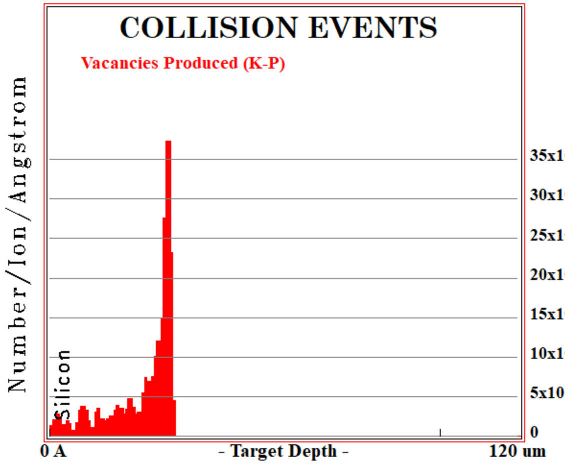


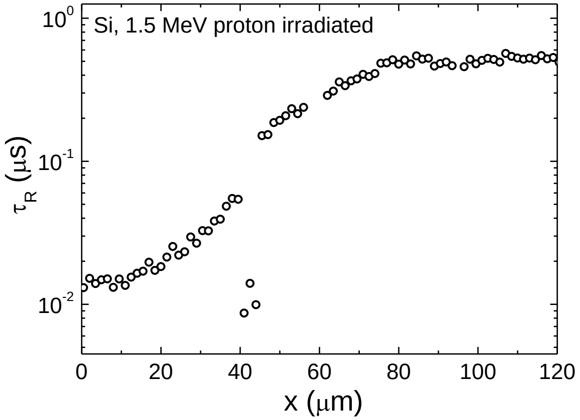
Carrier lifetime depth-distribution profiles measured in 300 μm-thick MCZ Si wafers after neutron irradiation using different fluences.

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

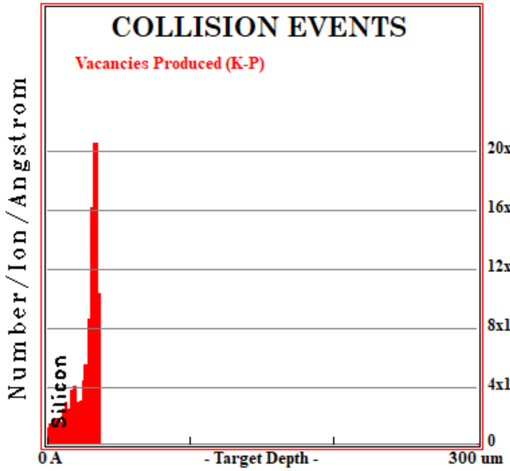
Profiling of carrier lifetime in homogeneous Si structures irradiated with stopped protons

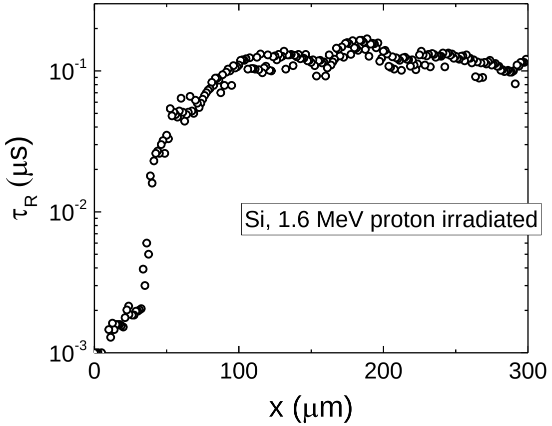
1.5 MeV protons, $\Phi=10^{14}$ cm^{-2}





1.6 MeV protons, $\Phi=10^{15}$ cm^{-2}





MCZ Si wafer fragments
- surface passivated;
- 1000 μm thick;
- irradiated with 1.5 MeV, 1.6 MeV protons.

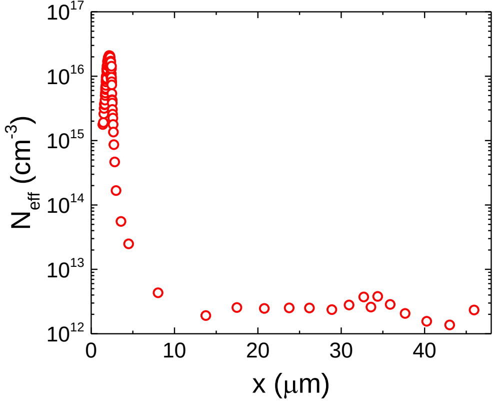
- The profile of carrier lifetime correlates with the TRIM simulated defects distribution profile.
- Small discrepancy between the simulated and measured projectile range position and the spread of measured profile can be explained by lateral diffusion of carriers and the experimental errors due to the fibre spot diameter (≈6 μm) and the defect peak dispersion (width of δ-layer at half of its peak amplitude is ≈10 μm).

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

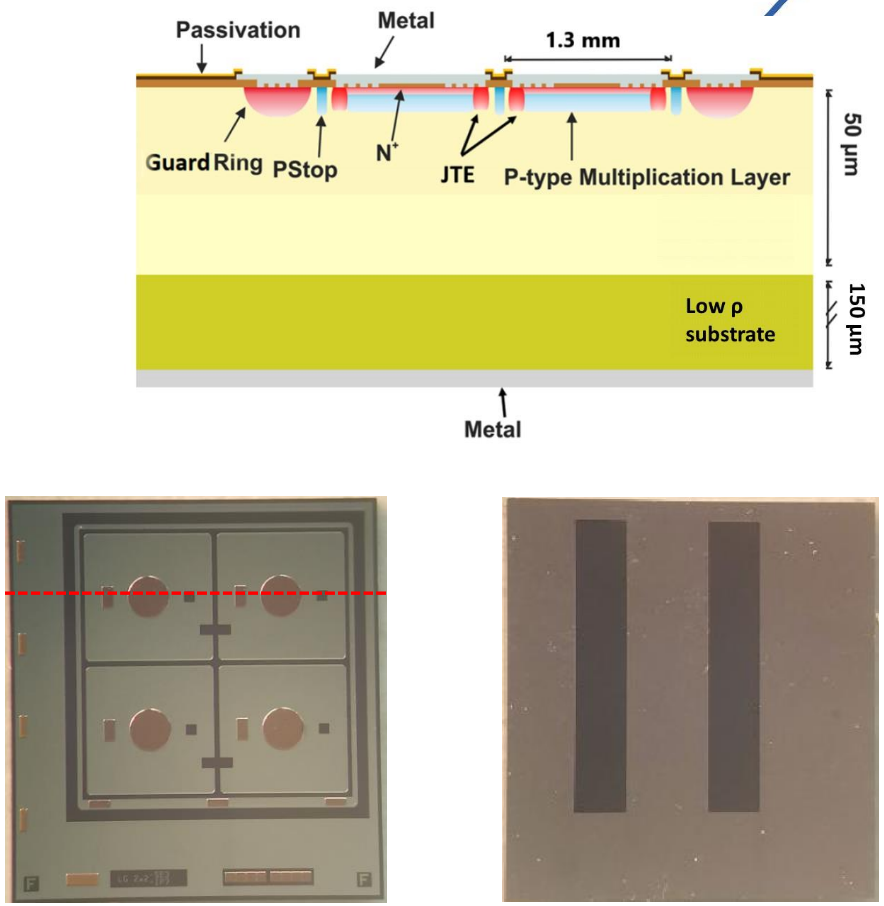
Proton irradiated LGAD structures

LGADs manufactured by Hamamatsu Photonics (HPK) – HPK2 run, wafer W31:

- $n^{++}p^{+}pp^{++}$ structure,
- 2 × 2 matrix with 1.3 × 1.3 mm^2 of area sensors,
- 50 µm thick active layer,
- 200 µm total thickness,
- single guard ring,
- irradiated with 23 GeV protons in the range of fluences Φ=10^{12}-10^{16} cm^{-2},
- cut and boundary polished for profiling of carrier lifetime.

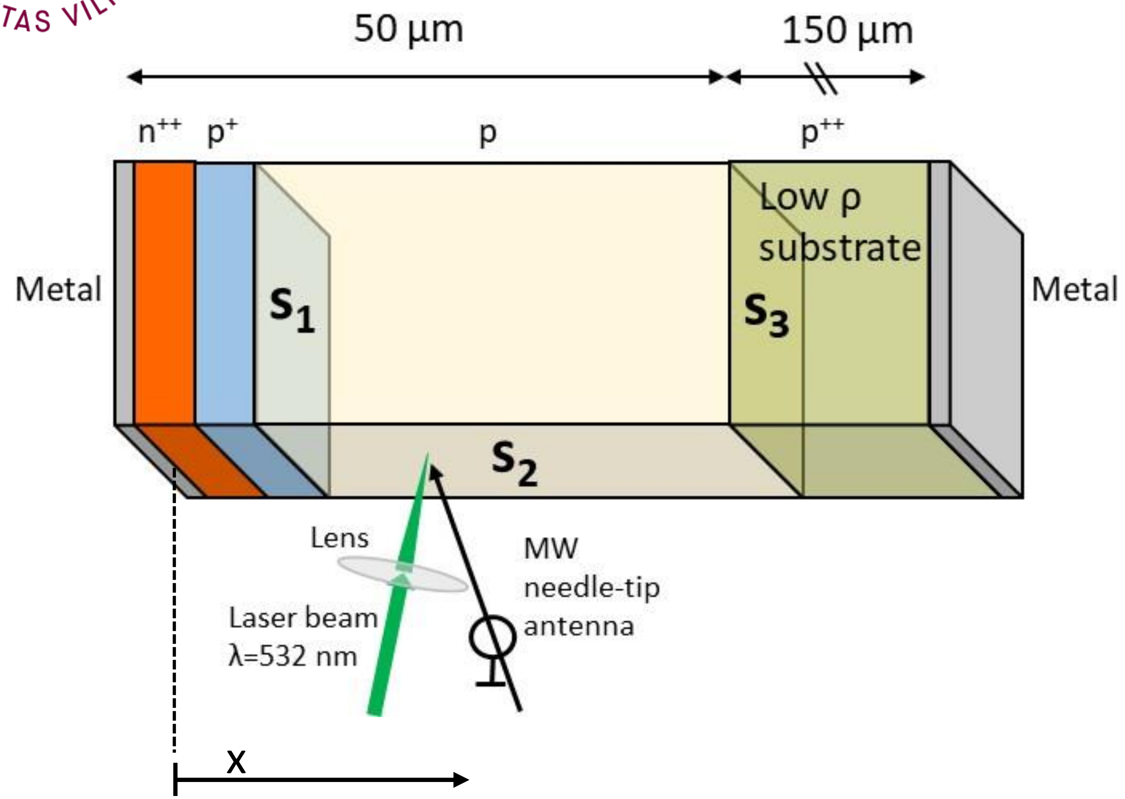


Doping profile of active layer of non-irradiated LGAD evaluated from C-V characteristic.



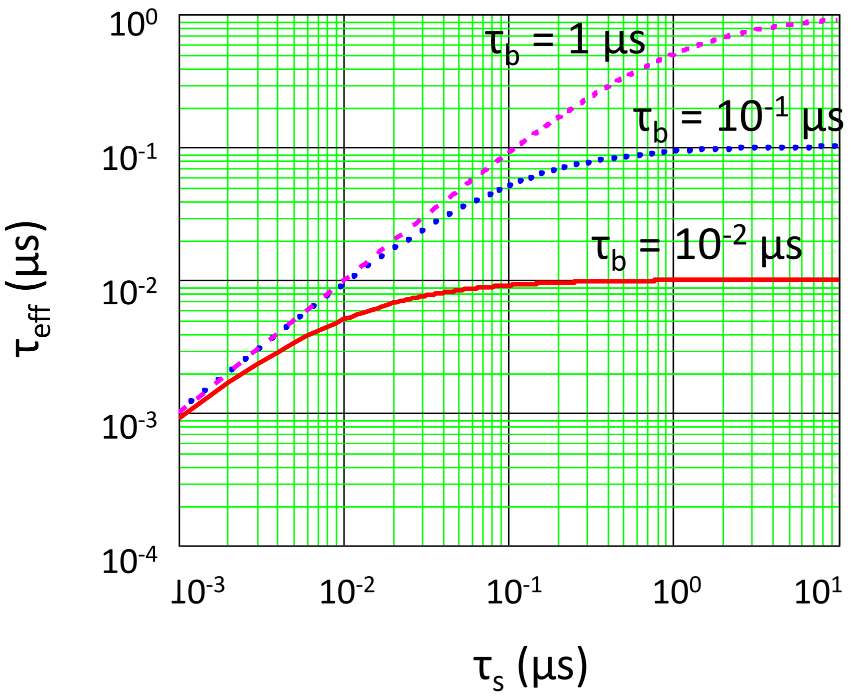
Structure (top figure) and photos of front and backside view (bottom left and right, respectively) of the investigated LGAD structures.

Influence of surface recombination

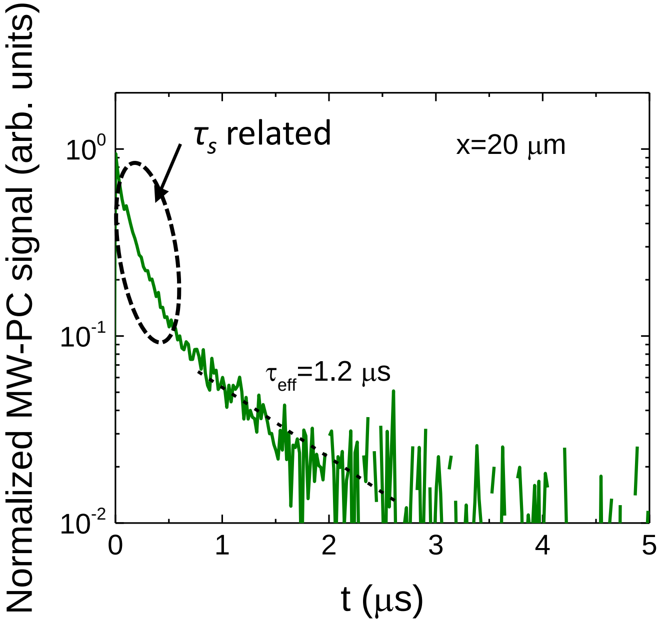


Competition of carrier recombination within bulk and at the sample surfaces **s**, affect the shape of recorded MW-PC transients and complicate the extraction of τ_b.

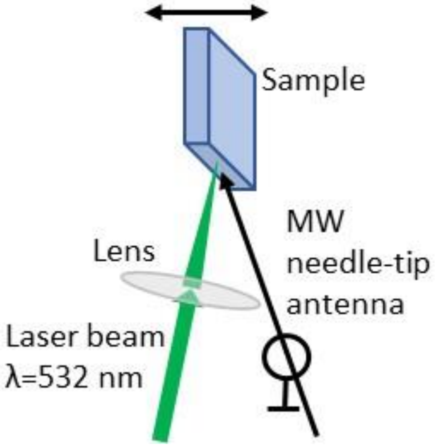
$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_s}$$



Profiling of carrier lifetime in non-irradiated LGAD structures

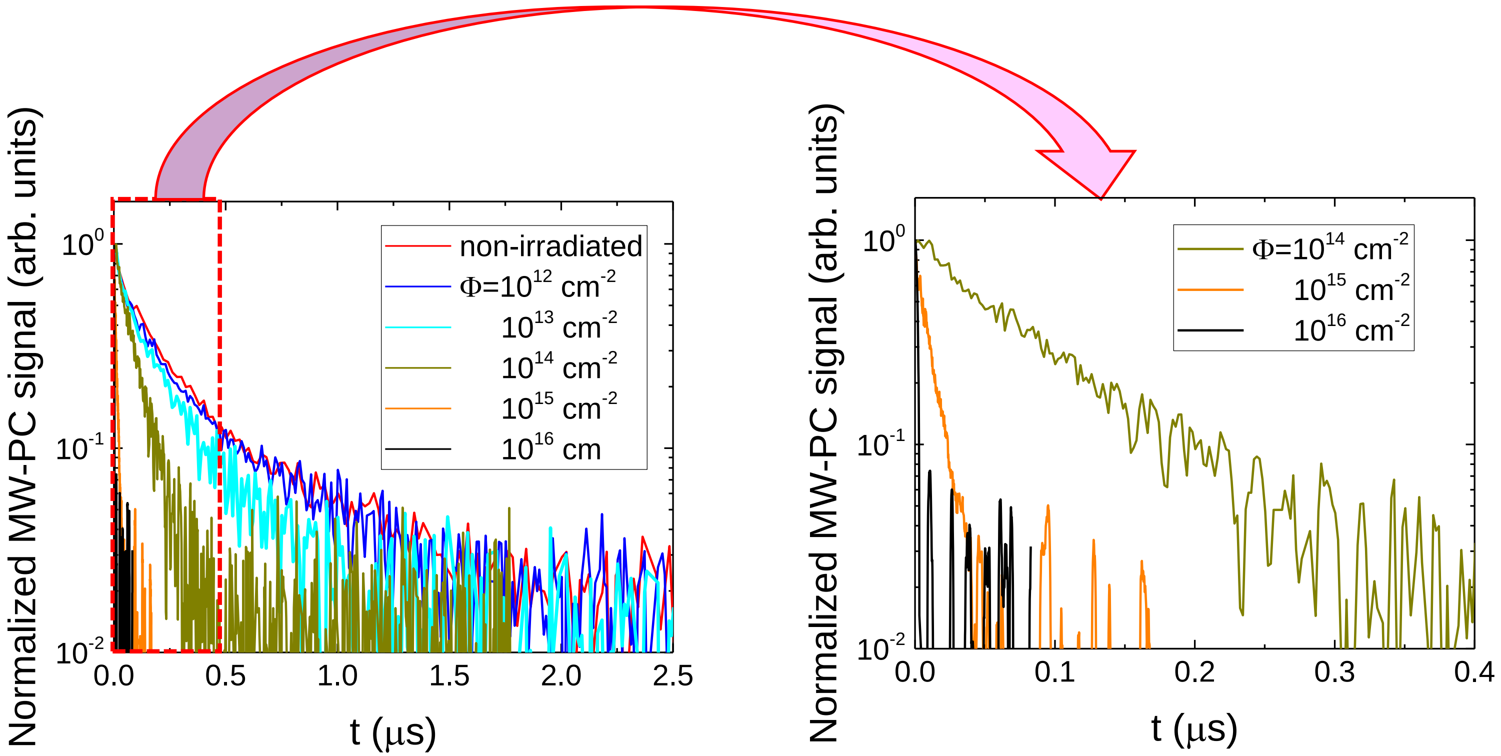


MW-PC transient obtained by edge scanning of boundary of non-irradiated LGAD structure.



T. Ceponis et al., Carrier lifetime variations in proton irradiated LGAD structures, 42nd RD50 workshop, 20-23 June 2023, Tivat.

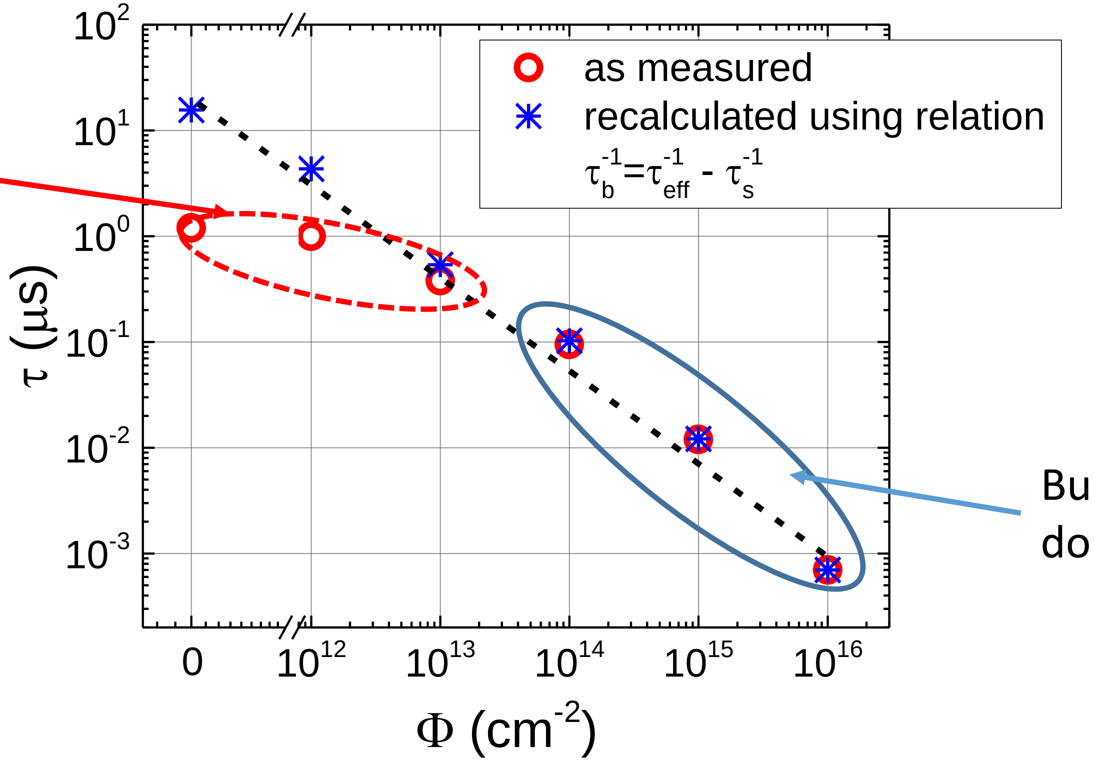
Profiling of carrier lifetime in proton irradiated LGAD structures



MW-PC transients obtained by edge scanning of the boundary LGAD structures as a function of proton irradiation fluence.

T. Ceponis et al., Carrier lifetime variations in proton irradiated LGAD structures, 42nd RD50 workshop, 20-23 June 2023, Tivat.

Carrier lifetime variations in proton irradiated LGAD structures



Affected by surface recombination

Bulk recombination dominates

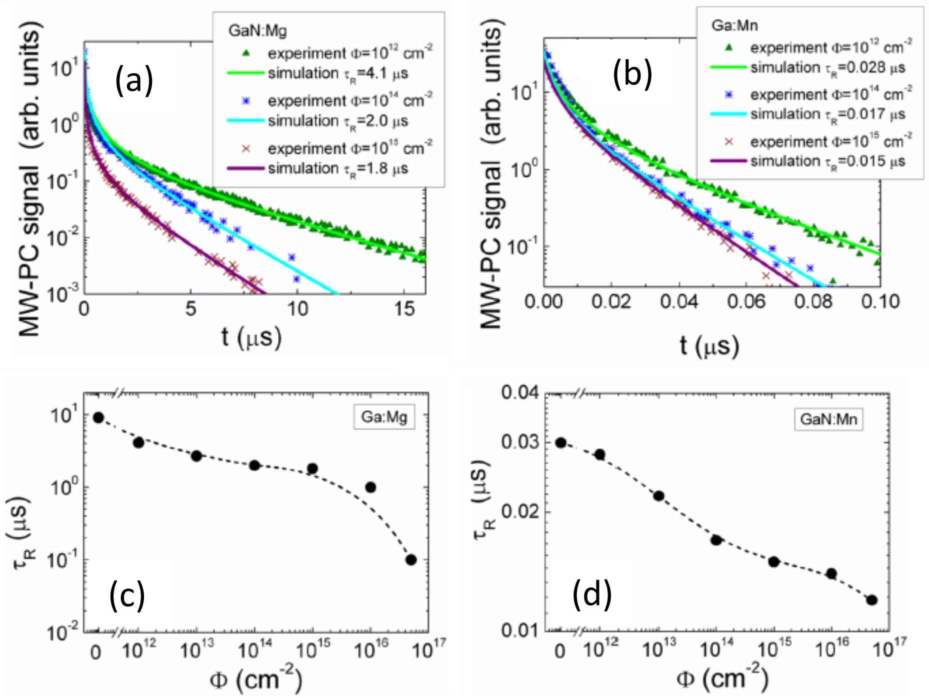
Recombination lifetime as a function of proton irradiation fluence in LGAD structures.

T. Ceponis et al., Carrier lifetime variations in proton irradiated LGAD structures, 42nd RD50 workshop, 20-23 June 2023, Tivat.

Recombination characteristics in ammonothermal GaN

GaN:Mg

GaN:Mn



Neutron fluence dependent MW-PC transients measured in AT GaN:Mg (a) and GaN:Mn (b) material. Variations of non-radiative recombination lifetimes as a function of fluence for GaN:Mg (c) and GaN:Mg samples.

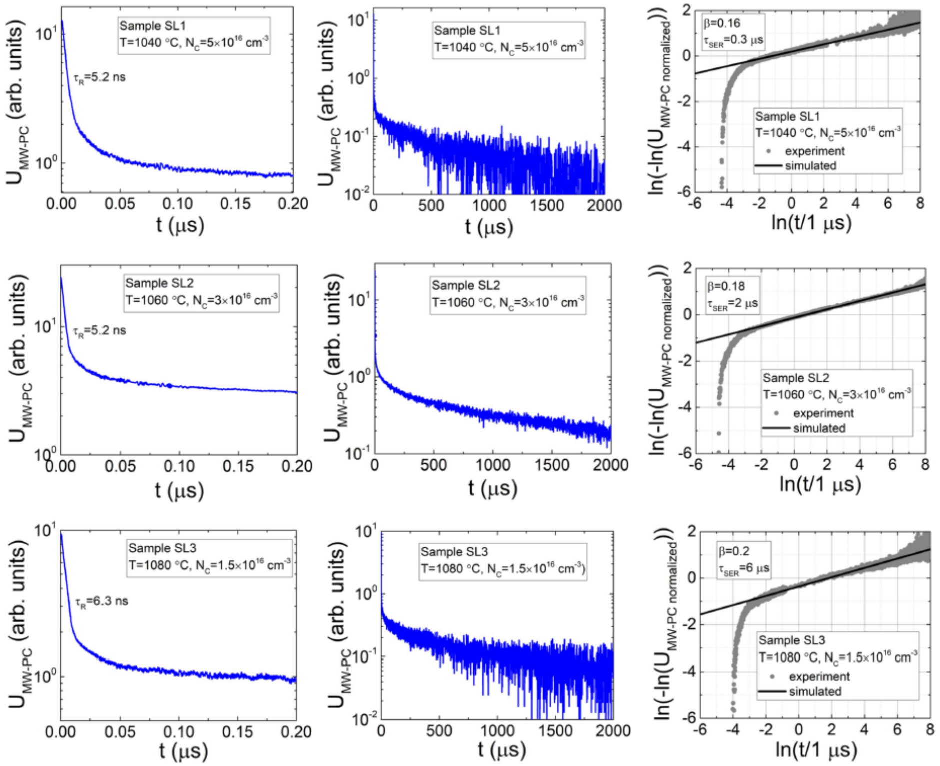
- Sample thickness – 400 μm
- Low dislocation density material- 7×10^4 cm^{-2}
- $N_{Mg}=10^{19}$ cm^{-3}, $N_{Mn}=10^{18}$ cm^{-3}
- Decay is two componential affected by radiative and non-radiative (through deep levels) recombination

$$n_{\mathrm{ex}}(t) = \frac{n_{\mathrm{ex},0}\exp\left(-\frac{t}{\tau_{\mathrm{R}}}\right)}{1 + Bn_{\mathrm{ex},0}\tau_{\mathrm{R}}\left[1 - \exp\left(-\frac{t}{\tau_{\mathrm{R}}}\right)\right]}$$

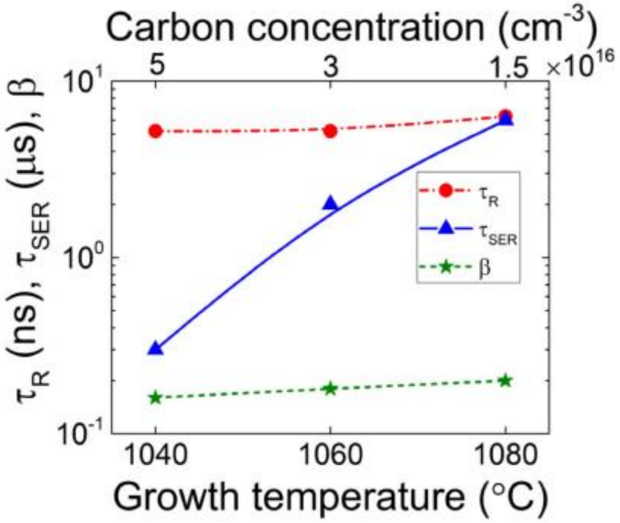
- Carrier lifetime is sensitive on existing impurities (Mn, Mg) and on irradiation fluence.

E. Gaubas et al., J. Phys. D: Appl. Phys. **50** (2017) 135102

Recombination characteristics in MOCVD GaN grown on Si



MW-PC transients, recorded in GaN structures with different carbon concentration grown on AlN/AlGaN superlattile at different time scales.

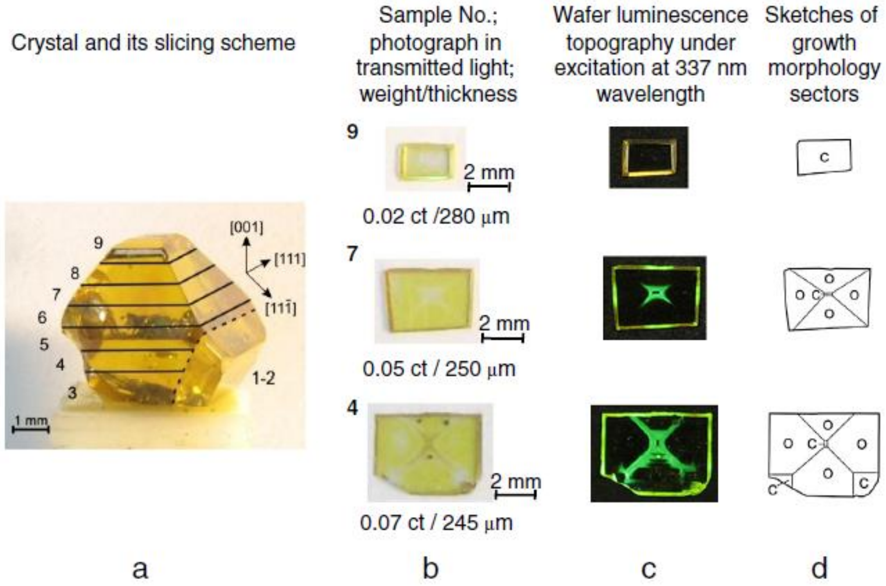


$$n(t) \cong n_0 \left\{ \frac{A_{\mathrm{cryst}}}{A_{\mathrm{exc-spot}}} \exp\left(-\frac{t}{\tau_{\mathrm{R}}}\right) + \frac{A_{\mathrm{TD}}}{A_{\mathrm{exc-spot}}} \exp\left(-\left(\frac{t}{\tau_{\mathrm{SER}}}\right)^{\beta_{\mathrm{SER}}}\right) \right\}$$

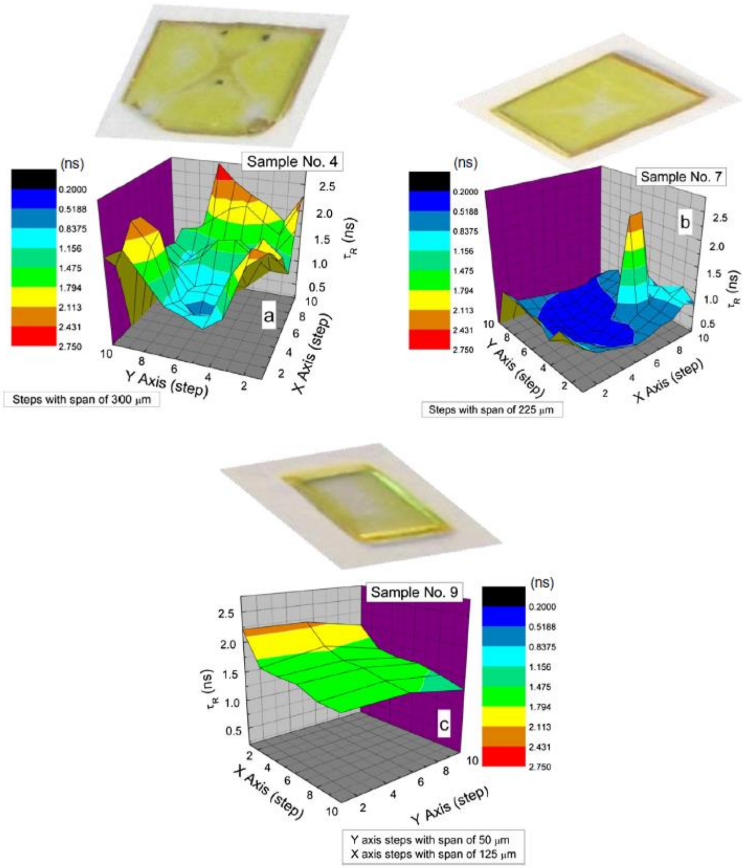
- d_{GaN} = 1 μm
- Dislocation density - 10^9 cm^{-2}
- MW-PC transients can be described by exponential initial decay phase, which indicates carrier decay in perfect crystal areas and stretched exponential relaxation due to dispersive carrier transport within dislocation networks with carrier trapping in the dislocation-rich areas.

E.Gaubas et al., Semicond. Sci. Technol. 33 (2018) 075015

Recombination characteristics in HPHT diamond



(a) - The as-grown crystal and a scheme of slicing of the wafer samples; (b) — weight and dimension parameters and photographs of the as-polished diamond wafers taken in transmitted light; (c) — the fluorescence topographs registered under excitation by ultraviolet light; d — the idealized sketches of the growth-morphology sectors. Here, "C" denotes cube sectors, "O" indicates the octahedral sectors.



Carrier lifetime lateral distribution profiles in different wafers of No. 4 (a), No. 7 (b) and No. 9 (c), respectively, mapped by the MW-PC transient scans

Carrier lifetime profiles correlate with the distribution of impurities within the HPHT diamond samples.

E. Gaubas et al. Diamond & Related Materials 47 (2014) 15–26.

Conclusions

- MW-PC technique is suitable for characterization of recombination characteristics in pristine and irradiated Si and wide-band-gap materials for time scales ≥ 1 ns.
- Transient absorption technique in pump-probe configuration using femtosecond laser coupled with OPA-DFG can be employed for characterization of carrier dynamics processes in sub picosecond time scales for pristine and irradiated Si and wide-band-gap materials.
- The carrier lifetime profiles obtained by edge scanning of the microwave probed photoconductivity transients correlate with the simulated stopping ranges of incident particles.
- The edge scanning of microwave probed photoconductivity transients can be employed for profiling of carrier lifetime within junction structures (active region of LGADs), although the extraction of carrier lifetime values is complicated due to significant impact of surface recombination at $\Phi \leq 10^{13}$ cm^{-2}. At higher irradiation fluences $\Phi \geq 10^{14}$ cm^{-2} the bulk recombination dominates.
- For accurate evaluation of bulk lifetime in Si, surface passivated wafer samples are necessary.
- Recombination characteristics in wide-band-gap materials are sensitive to present impurities and defects, therefore depend on material growth method and technological regimes.

Thank you for your attention

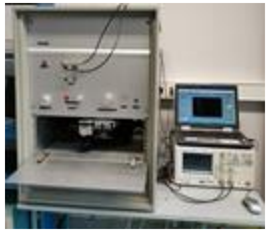
Vilnius University group is open for new collaborations and willing to contribute in investigation of recombination and electrical characteristics in pristine as well as heavily irradiated Si and wide-band-gap material based structures.

This research was funded by the Research Council of Lithuania.

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

Facilities and instrumentation at Photoelectric Phenomena Research Group

Instrumentation for testing of the electric characteristics of radiation detectors.



Instrument for measurements of carrier recombination characteristics VUTEG-04

Instrumentation for profiling of carrier drift current transients and sensor timing measurements

DLTS spectrometer HERA-DLTS System FT 1030.

Optical stand for spectroscopy and ultra-fast phenomena research.

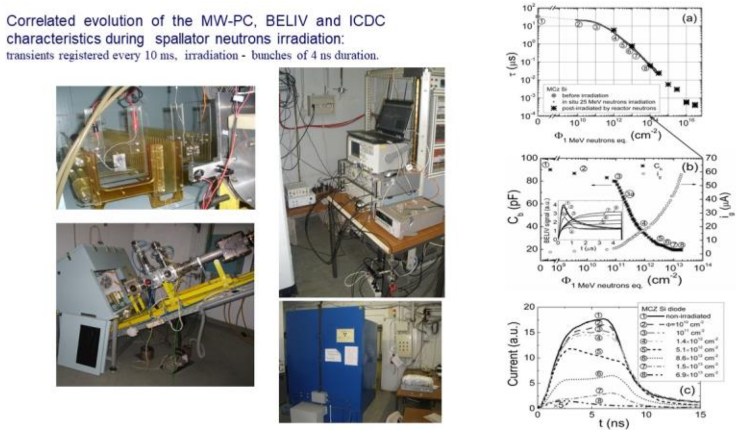
- **Instrumentation for testing of the electric characteristics of radiation detectors:**
  - Summit 11000 probe station (triax wafer chuck, $U_{br} \geq 500$ V, $I_L \leq 1$ fA, $C_{res} \leq 0.4$ pF.
  - Keysight B2912B SMU (10 fA, 210 V, 3 A DC/10.5 A pulse).
  - Keysight E4980A LRC meter (f = 20 Hz - 2 MHz, U_{ac} = 0 - 2.0 V_{rms}, U_{DC} = 0-40 V).
  - N1260A high voltage external bias tee ($U_{DC} \leq 3$ kV, f = 10 kHz – 1 MHz).
- **Instrumentation for profiling of carrier drift current transients and sensor timing measurements:**
  - Home made system (2 GHz Lecroy oscilloscope, PicoQant (1060 nm), Standa (1062 nm, 531 nm, 354 nm) ps lasers, Cividec signal amplifiers).
  - Particulars (Slovenia) Large scanning TCT setup (ps lasers, signal amplifiers, Lecroy 2.5 GHz oscilloscope, carrier two-photon injector setup implemented using Light Conversion Pharos fs laser system equipped with Orpheus OPA-DFG (210 nm – 16 μm)).
- **Instrumentation for measurements of pulsed barrier capacitance transients (BELIV):**
  - Pulsed barrier evaluation (BELIV) technique for spectroscopy of junction structures.
  - Edge scanning of BELIV transients.
  - Discretely variable excitation wavelengths in the range of 1062 –354 nm.
  - temperature range 90 – 350 K.
- **Instrument for measurements of carrier recombination characteristics VUTEG-04:**
  - Carrier lifetime scanner over 120x120 mm^2 area.
  - Scanner of the carrier lifetime and depth-distribution of defects with precision of 2 μm.
  - The range of the stabilized temperature 4°– 25° C.
  - Suppression of carrier trapping component by cw IR illumination.
  - Imaging of the distribution of radiation defects and irradiation fluences.

- **EPR scanner BRUKER-E-SCAN:**
  - Dosimetry in the range of 1Gy -200 kGy.
- **Instrument for pulsed spectroscopy of thermal and photo-ionization VUTEG-6:**
  - Contactless measurements of carrier emission lifetime.
  - For research of the evolution of radiation defects.
  - Separation of the carrier trapping component by cw IR illumination.
  - Temperature range 80 – 400° K.
- **Instrument for steady-state photo-ionization spectroscopy:**
  - Monochromator MDR4 equipped with photometric light source (0.5 – 2.35 eV).
  - SMU Keithley 2635B.
  - Liquid nitrogen cryostat.
- **Instrumentation for simultaneous spectroscopy of time-resolved luminescence and microwave-probed photoconductivity**
- **DLTS spectrometer HERA-DLTS System FT 1030:**
  - Recording of the C-I-O-DLTS spectra.
  - Temperature range 10 – 450 K.
  - Pulsed lasers for carrier injection using 1062 and 351 nm wavelengths.
  - Advanced instruments for spectra analysis.
- **Optical stand for spectroscopy and ultra-fast (hundreds of femtoseconds) phenomena research:**
  - Light Conversion Pharos laser (10W@10kHz, 200 fs, 1030 nm).
  - Optical parametric amplifier (OPA) and differential frequency generator (DFG) Orpheus (210 nm – 16 μm).
  - Techniques for pulsed photoionization spectroscopy.
  - Techniques for optical pump-probe measurements.
  - Avantes AvaSpec-ULS2048XL-EVO StarLine spectrophotometer.
  - Liquid nitrogen cryostat (78–800 K).

Major research interests of Photoelectric Phenomena Research Group

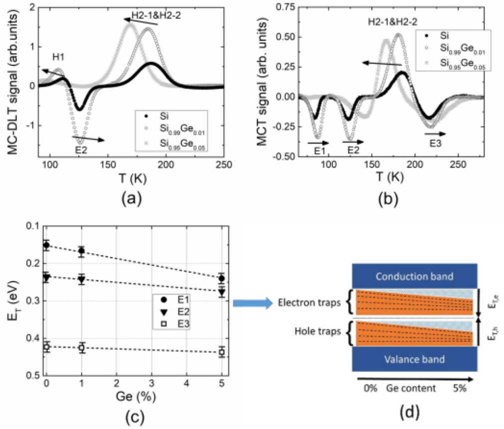
- Study of the recombination processes in modern electronic devices.
- Study of carrier transport phenomena.
- Spectroscopy of defects and creation of spectroscopy techniques based on photoelectrical phenomena.
- Search of radiation hard materials and development of radiation tolerant structures.
- Engineering of radiation defects and radiation technologies for production of electronic devices.
- Creation of new measurement technologies.
- Technologies and instruments for the remote in situ measurements in harsh irradiation environments.
- Technologies and instrumentation for spectroscopy and contactless-remote dosimetry of the large fluences of high energy radiations.
- Modelling and simulations of the modern device structures.

Technologies for the in situ monitoring of evolution of radiation defects


Correlated evolution of the MW-PC, BELIV and ICDC characteristics during spallator neutrons irradiation:
transients registered every 10 ms, irradiation - bunches of 4 ns duration.

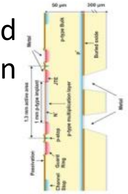
E. Gaubas, T. Ceponis, A. Jasiunas, A. Uleckas, J. Vaitkus, E. Cortina, and O. Militaru, *Correlated evolution of barrier capacitance charging, generation, and drift currents and of carrier lifetime in Si structures during 25 MeV neutrons irradiation*, Appl. Phys. Lett. **101** (2012) 232104.

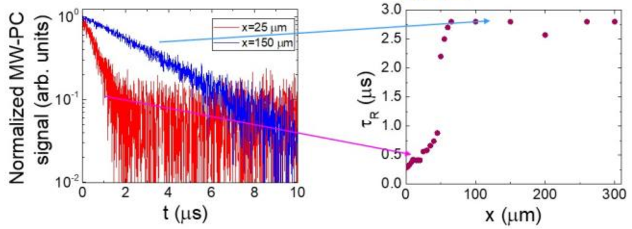
Spectroscopy of defects in irradiated semiconductors



- T. Ceponis, S. Lastovskii, L. Makarenko, J. Pavlov, K. Pukas, E. Gaubas, *Study of radiation-induced defects in p-type $Si_{1-x}Ge_x$ diodes before and after annealing*, Materials **13** (2020) 5684.
- J. Pavlov, T. Ceponis, K. Pukas, L. Makarenko, E. Gaubas, *5.5 MeV electron irradiation-induced transformation of minority carrier traps in p-type Si and $Si_{1-x}Ge_x$ alloys*, Materials **15** (2022) 1861.

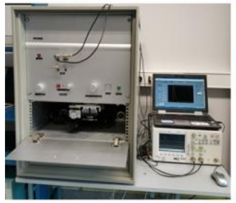
Profiling of carrier lifetime and electrical characteristics in modern sensor structures

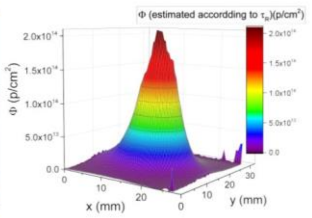




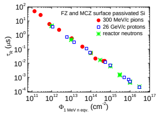
T. Ceponis, L. Deveikis, E. Gaubas, R. Markevicius, J. Pavlov, G. Pellegrini, V. Rumbauskas, Profiling of carrier lifetime and electrical characteristics in PIN and LGAD structures, Presentation at RD50 workshop, Seville 2022-11.

Technologies and instruments for particle beam profiling





Recorded profile of 26 GeV/c proton beam.



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