Si and GaN for large fluence irradiation monitoring

D.Meskauskaite[1], E.Gaubas[1], T.Ceponis[1], J.Pavlov[1], V.Rumbauskas[1], J.Vaitkus[1]

M.Moll[2], F.Ravotti[2]

[1] Vilnius University, Institute of Photonics and Nanotechnology

[2] CERN

Outline:

- Motivation
- Samples and irradiations, anneals
- Measurement Techniques: Temperature dependent carrier trapping lifetime (TDTL), Pulsed photoionization spectroscopy (PPIS), Deep-level transient spectroscopy (DLTS)
- Results on Fz and Cz Si irradiated by electrons and hadrons
- Results on multicrystaline Si irradiated by 8 MeV protons
- Results on GaN irradiated by 1MeV neutrons
- Summary

Motivation

- The better understanding of radiation damage of Si particle detectors is important in order to extend sensor lifetime and their radiation hardness or to restore their functionality after degradation caused by irradiations – one of the ways to recover detector operational features is heat treatment at technically acceptable temperatures.
- Multicrystalline silicon (mc-Si) use for the detection of charged particles – inexpensive material for mass production.
- Semi-insulating GaN is a promising material for particle tracking detectors and for imaging detectors – there still remains a lack of detailed studies of the defects in the as-grown material and their interaction with radiation induced defects, particularly in heavily irradiated samples.

Si samples and irradiations

c-Si

Type of irradiation	Electrons		Protons		Pions	
Energy	6.6 MeV		24 GeV/c		300 MeV/c	
Fluence range	10^{16}-5×10^{16} e/cm^2		10^{12}-10^{16} p/cm^2		10^{11}-3×10^{15} π^+/cm^2	
Si material	CZ n-Si	CZ p-Si	FZ n-Si	CZ p-Si	CZ n-Si	FZ n-Si
Dopant concentration	10^{15} cm^{-3}	3×10^{15}cm^{-3}	10^{12} cm^{-3}	10^{12} cm^{-3}	10^{12} cm^{-3}	10^{12} cm^{-3}

Anneals:

- The isochronal anneals have been performed at the temperatures in the range of 80˚-280˚C.
- The hadron irradiated samples were isothermally (at 80 ˚C) annealed up to 5 hours before isochronal (24 h) anneals.

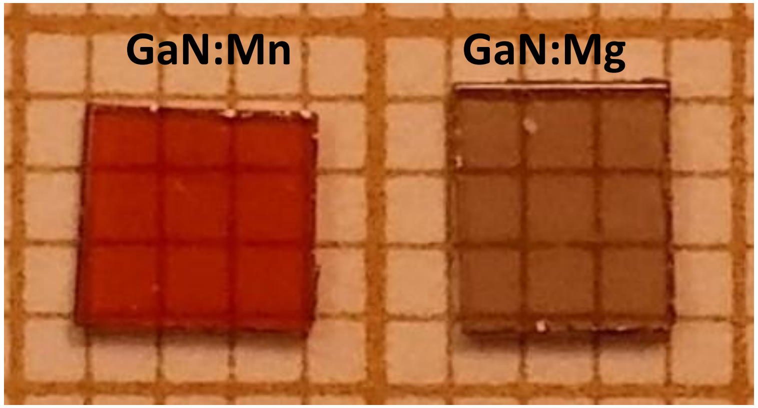
mc-Si substrates for commercial solar-cell production

Type of irradiation	Protons
Energy	8 MeV
Fluence range	10^{12}-10^{16} p/cm^2
Si material	p-Si
Dopant concentration	10^{15} cm^{-3}

Anneals:
1st annealing step: 80° C, 30 min
2st annealing step: 1st + 200° C, 60 min
3st annealing step: 2st + 300° C, 60 min
4st annealing step: 3st + 400° C, 60 min

GaN samples and irradiations

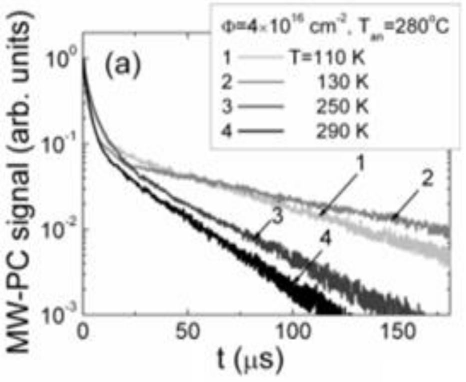
- semi-insulating (SI) bulk GaN
- grown by the ammonothermal method
- 450 μm thick
- doped with Mg (GaN:Mg) and Mn (GaN:Mn)



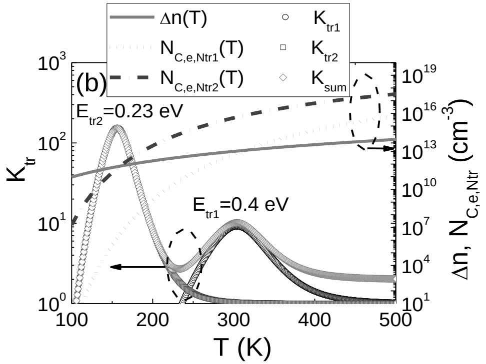
	Neutrons	
Energy	1 MeV	
Fluence range	10^{12}-5×10^{16} e/cm^2	
GaN material	GaN:Mg	GaN:Mn
Dopant concentration	~10^{19} cm^{-3}	~10^{18} cm^{-3}

Measurement Technique:

Temperature dependent carrier trapping lifetime (TDTL)



The as-recorded MW-PC transients in CZ Si sample irradiated with fluence 4×10^{16} e/cm^2 after heat treatment 280˚C at different scan temperatures.

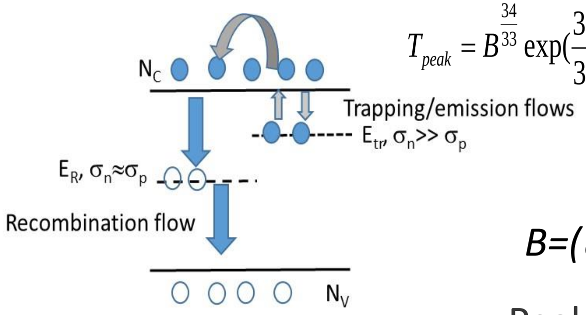


Simulated trapping coefficients (K_{tr}) as a function of temperature for trapping level with activation energy of 0.4eV and 0.23eV in Si. *$N_{C,e,Ntr}(T)$* - the effective density of band states for trapped carriers, *$\Delta n(T)$* - the excess carrier density.

T_{peak} for which the largest K_{tr}, ascribed to a single type trapping centres, is obtained, can be found by solving the transcendental equations:

$$T_{peak} = A^{2/3}\exp\left(\frac{2}{3}\frac{E_{tr}}{kT_{peak}}\right),\quad \text{for fixed } \Delta n_C = const$$

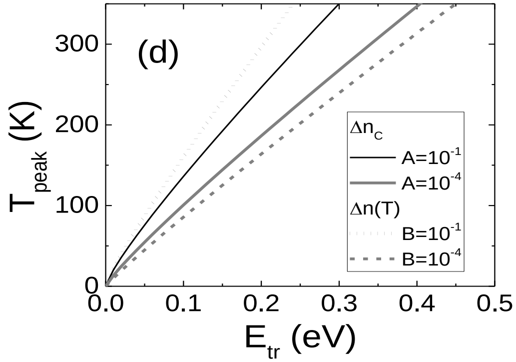
$$T_{peak} = B^{\frac{34}{33}}\exp\left(\frac{34}{33}\frac{E_{tr}}{kT_{peak}}\right),\quad \text{for } \Delta n(T)$$



$A=\Delta n_C/K$

$K=N_{C,V}\times T^{-3/2}$

$B=(\alpha_{300}\times 300^{-4.25}\times F/K)$

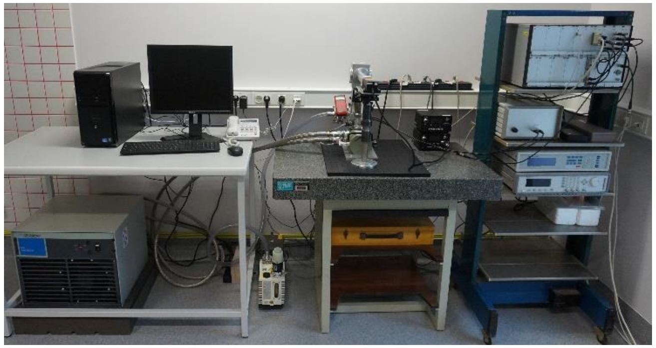


Peak temperature (within TDTL spectrum) dependence on trapping centre activation energy (E_{tr}) simulated for the fixed Δn_C=const and temperature varied *$\Delta n(T)$* excess carrier density

E. Gaubas, E. Simoen and J. Vanhellemont, Review-Carrier lifetime spectroscopy for defect characterization in semiconductor materials and devices, ECS J. Solid State Sci. Technol. 5, (2016) P3108.

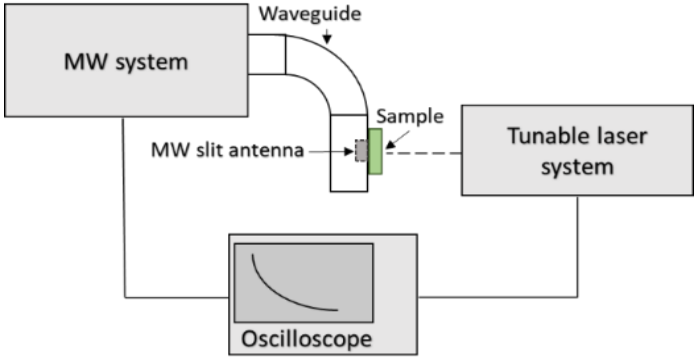
Measurement Technique:

- Deep-level transient spectroscopy (DLTS)



- Capacitance (C-DLTS) and current (I-DLTS) spectra over temperature range of 10-300K were recorded by using a HERA-DLTS System 1030 spectrometer.
- The PhysTech software installed within HERA-DLTS spectrometer was employed for analysing of the measured DLTS spectra.

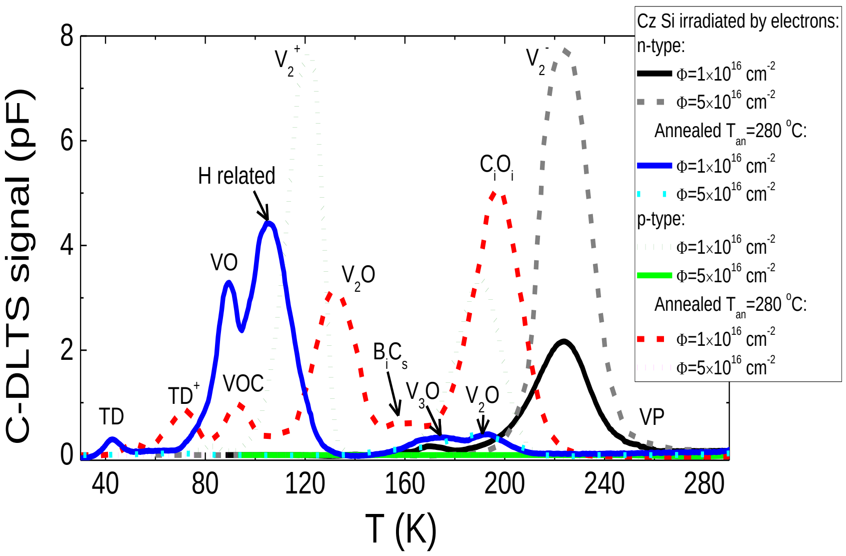
- Pulsed photoionization spectroscopy (PPIS)

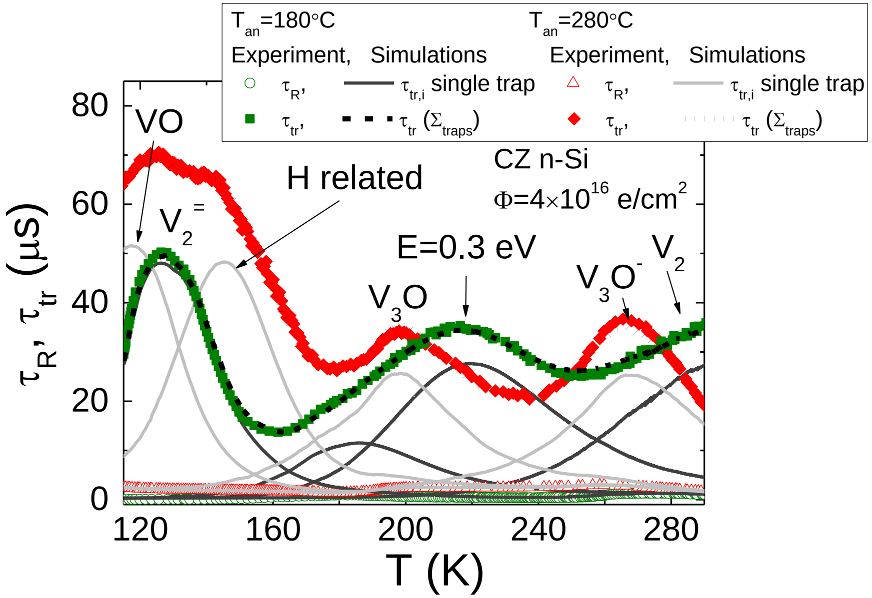


- The PPIS were implemented using excitation by a tuneable wavelength laser and measurements of the photo-response by applying microwave probed photoconductivity transient (MW-PC) technique.
- Here tunable wavelength nanosecond laser Ekspla NT342B (pulse duration 4 ns, wavelength tuning from 210 to 2300 nm) were employed.

Results on Fz and Cz Si irradiated by electrons and hadrons

n-type and p-type CZ Si irradiated by 6.6 MeV electrons

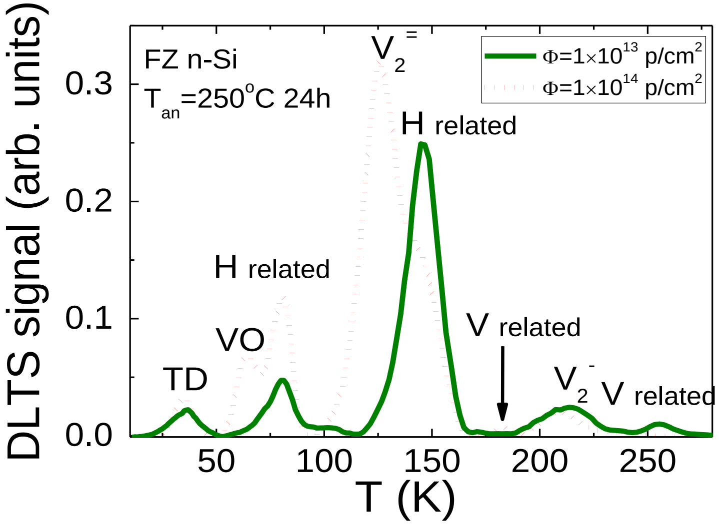




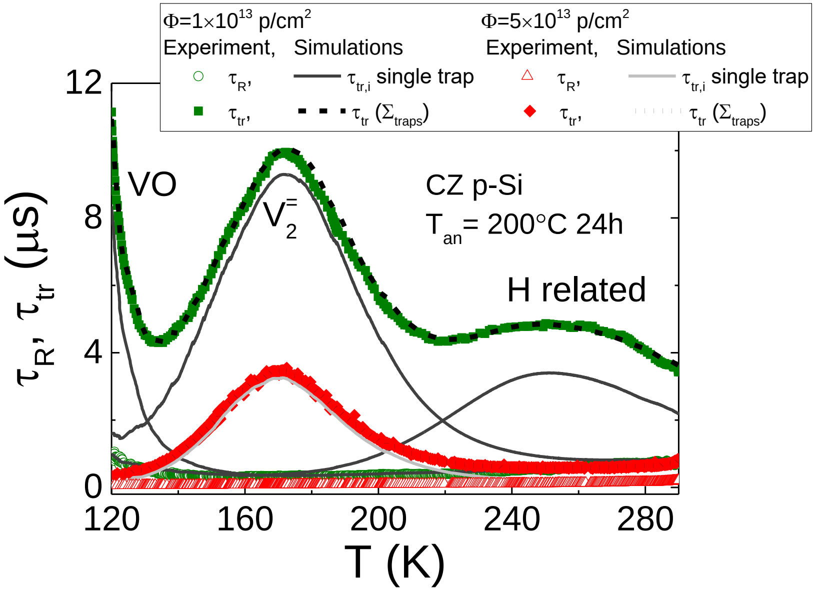
- No peaks in low temperature wing were observed in heavily irradiated n- and p-type CZ samples.
- The radiation induced defects, ascribed to vacancy related complexes, TD and to H related defects have been observed in the electron irradiated Si samples.
- Application of the TDTL technique allowed to identify the trapping centres appeared after heat treatment at $T_{an} \geq 80^\circ C$ even in heavily irradiated samples.

Results on Fz and Cz Si irradiated by electrons and hadrons

n-type FZ and p-type CZ Si irradiated by 26 GeV/c protons



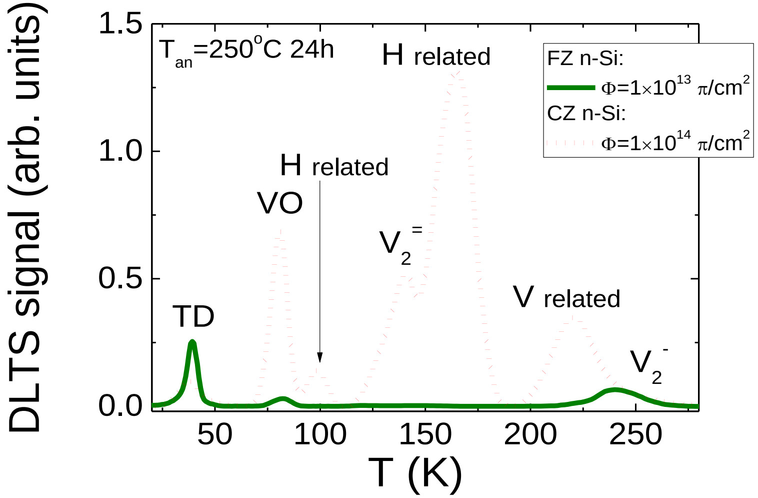
- The predominant peaks for the n-type FZ Si samples are attributed to V- and H-related defects.
- DLTS measurement are not suitable for p-type CZ Si samples irradiated by 26 GeV/c protons, due to the low concentration of the effective doping.

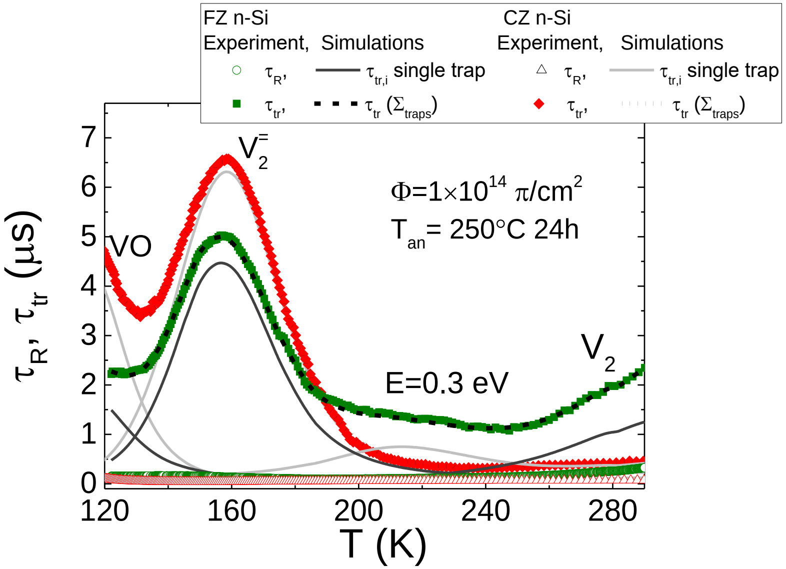


- As deduced using TDTL, the $V_2^{=}$, H-related and VO complexes are predominant radiation defects in the p-type CZ Si.
- The TDTL spectroscopy is a reliable tool for tracing of the radiation defect evolution for the range of elevated fluences.

Results on Fz and Cz Si irradiated by electrons and hadrons

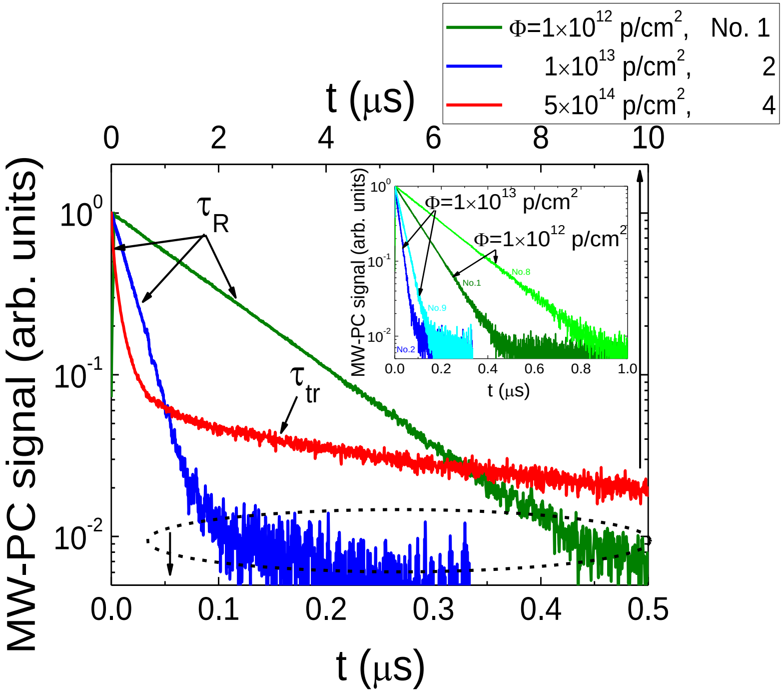
n-type FZ and CZ Si irradiated by 300 MeV/c pions

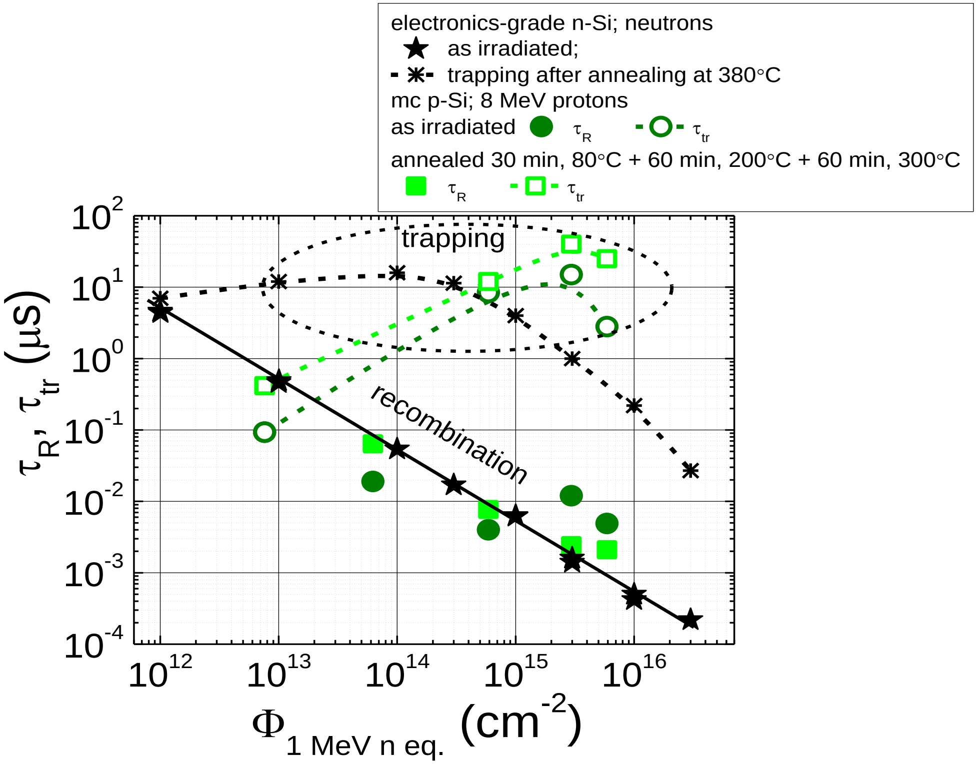




- V-related and H-related defects are dominant defects in CZ n-Si samples after heat treatment at 250˚C.
- The similarity between DLTS spectra, obtained for rather low fluence irradiations by protons and pions, indicate that the irradiation with various type penetrative hadrons induce the same defects.
- TDTL results are in qualitative agreement with DLTS results: after subsequent heat treatment using 250˚C temperature anneals, the $V_2^=$ and VO defects become predominant in FZ and CZ Si.

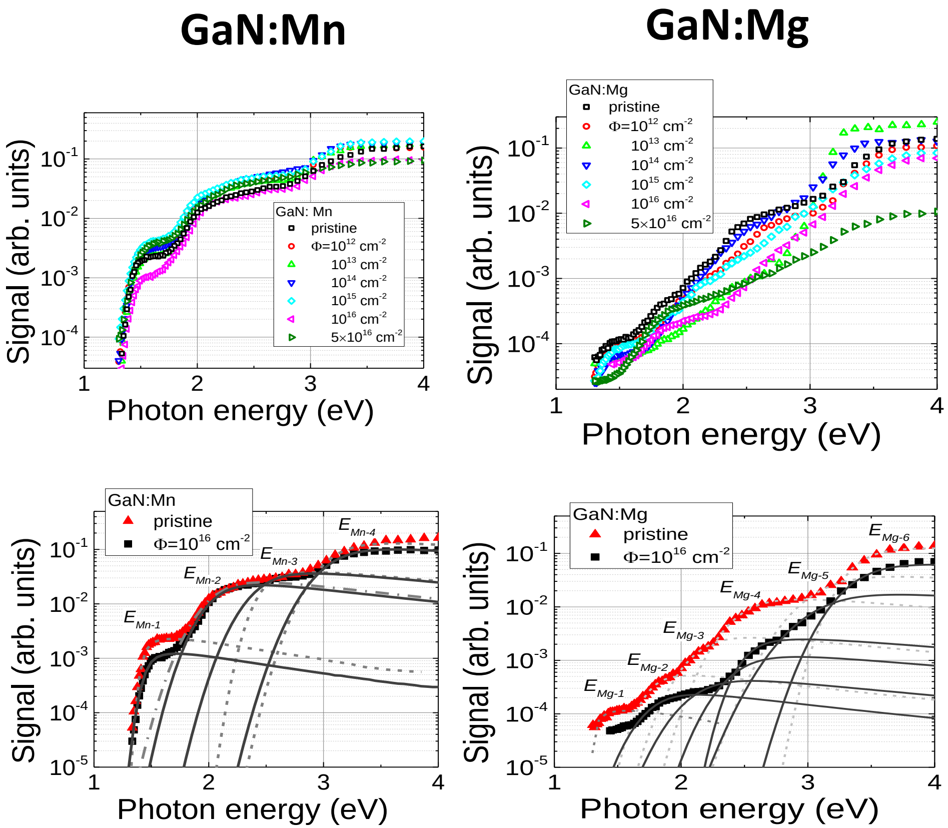
Results on mc-Si irradiated by 8 MeV protons





- Variations of τ_R appear for ms-Si samples irradiated (synchronously) with the same fluence.
- Variations within fluence dependent τ_R in mc-Si due to initial material quality (trapping indicates intrinsic defects).

Results on GaN irradiated by 1 MeV neutrons



	Non-irradiated		Irradiated with Φ=10^{16} cm^{-2}		
	Photo-activation energy (eV)	Γ	Photo-activation energy (eV)	Γ	Defect type
GaN:Mn	E_{Mn-1}=1.40	0.05	E_{Mn-1}^{irr}=1.42	0.08	Mn related
	E_{Mn-2}=1.98	0.25	E_{Mn-2}^{irr}=1.98	0.22	Might be oxygen related
	E_{Mn-3}=2.40	0.15	E_{Mn-3}^{irr}=2.37	0.25	Ga_I or N_I
	E_{Mn-4}=2.97	0.25	E_{Mn-4}^{irr}=2.96	0.28	Unidentified
GaN:Mg	E_{Mg-1}=1.30	0.02	–	–	Donor/accept or state
	E_{Mg-2}=1.70	0.15	E_{Mg-1}^{irr}=1.71	0.22	V_NMg_{Ga}
	E_{Mg-3}=2.07	0.23	E_{Mg-2}^{irr}=2.05	0.27	V_{Ga}
	E_{Mg-4}=2.39	0.15	E_{Mn-3}^{irr}=2.37	0.25	Ga_I or N_I
	–	–	E_{Mg-4}^{irr}=2.45	0.16	Unidentified or N_I
	E_{Mg-5}=3.00	0.32	E_{Mg-5}^{irr}=3.00	0.35	Unidentified
	E_{Mg-6}=3.30	0.2	E_{Mg-6}^{irr}=3.30	0.27	Mg_I

$$\sigma \propto \frac{e^{-(E+E_d-h\nu/\Gamma^2}\sqrt{E}dE}{h\nu(E+E_d)^2}$$

Γ - the broadening parameter

$$\Gamma_0 = \frac{\nu_g}{\nu_e}\sqrt{2d_{FC}\nu_g}\ (\mathrm{T} = 0\ \mathrm{K})$$

$$\Gamma = \Gamma_0\sqrt{2\coth(h\nu_0/k_BT)}$$

Summary

- The non-monotonous variations of trap densities after different anneal steps have been identified in heavily electrons and hadrons irradiated silicon by combining the DLTS and TDTL spectroscopy.
- The similarity between DLTS spectra, obtained for rather low fluence irradiations by protons and pions, indicate that the irradiation with various type penetrative hadrons induce the same defects (the oxygen, vacancy and hydrogen related complexes and TD).
- Contactless TDTL technique allows simultaneous control of interactions among several radiation defects within large fluences irradiated Si structures.
- The AT-GaN material performance showed insignificant changes after neutron irradiation with large fluences (up to 5×10^{16} e/cm^2).

Thank you for your attention!

Acknowledgments

- This research was implemented according to AIDA-2020 grant. This study was partially supported by Lithuanian Academy of Sciences, grants LMA-CERN-2017/2018. The work was partly performed in the framework of the CERN RD50 collaboration.
- Authors are also indebted for pion irradiations performed at the proton accelerator, Paul Scherrer Institute, Villigen, Switzerland and for electron irradiations performed at the Institute of Solid State and Semiconductor Physics, Minsk, Belarus.