Anneal induced transforms of radiation defects in hadron and electron irradiated Si

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- Temperature dependent carrier trapping lifetime (TDTL)
- Results on n-type and p-type CZ Si irradiated by 6.6 MeV electrons
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Motivation

- The better understanding of radiation damage of particle detectors is important in order either 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.
- Knowledge of evolution of the most harmful radiation defects under heat-treatment procedures is inevitable for development of the anneal technologies.
- The radiation defects identification by applying the contact-less MW-PC measurements and TDTL analysis, when the standard contact methods (C-DLTS) become unsuitable due to the disordered structures and internal electric fields existing within heavily radiation damaged materials.

Samples and irradiations

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}
Resistivity	4.5 Ωcm	4.5 Ωcm	>3 kΩcm	10 kΩcm	>3 kΩcm	>3 kΩcm

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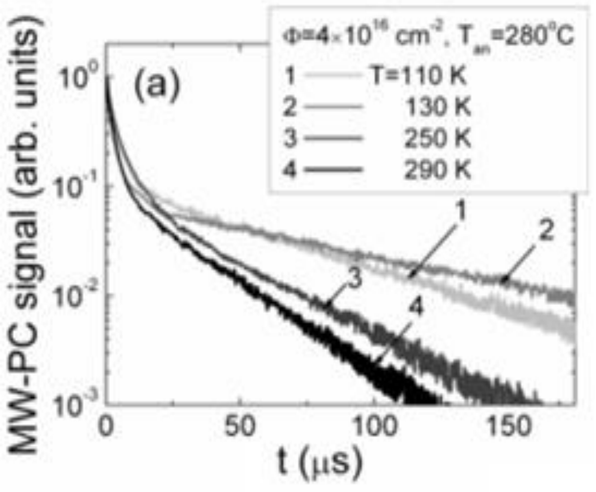
Resistivity	4.5 Ωcm	4.5 Ωcm	>3 kΩcm	10 kΩcm	>3 kΩcm	>3 kΩcm

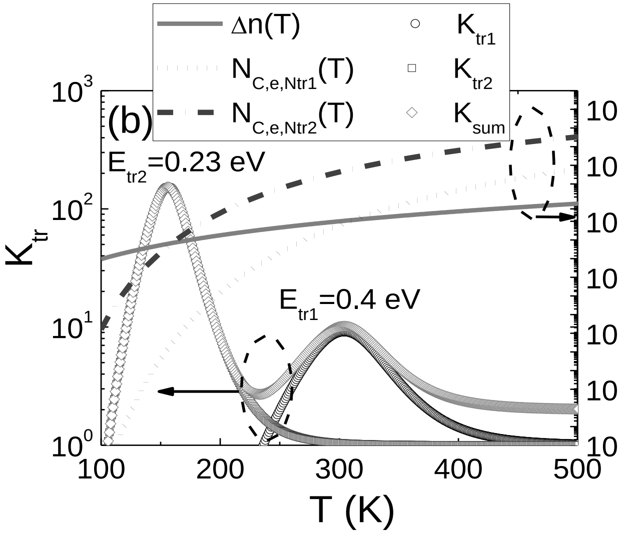
Anneals

- The isochronal anneals for 24 hours 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.

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:

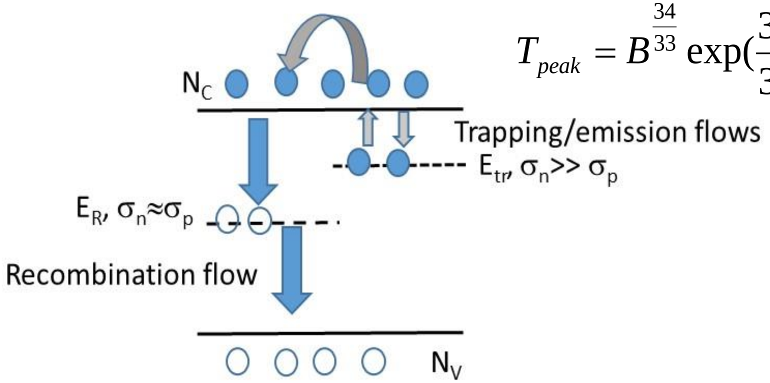
$$T_{peak} = A^{2/3}\exp\left(\frac{2}{3}\frac{E_{tr}}{kT_{peak}}\right), \quad \text{for fixed } \Delta n_C = const$$

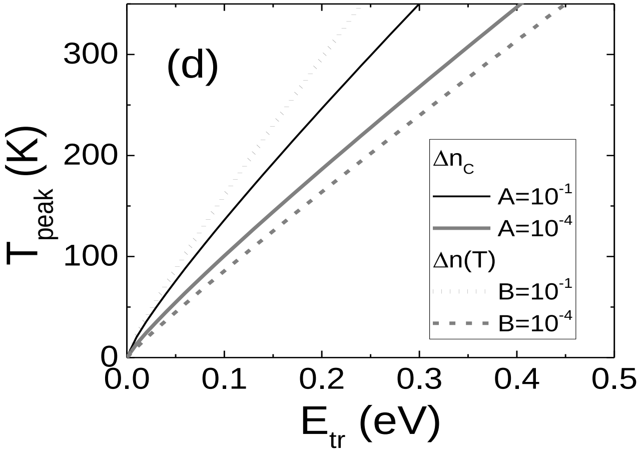
$$T_{peak} = B^{\frac{34}{33}}\exp\left(\frac{34}{33}\frac{E_{tr}}{kT_{peak}}\right), \quad \text{for } \Delta n(T)$$

$A=\Delta n_C/K$

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

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

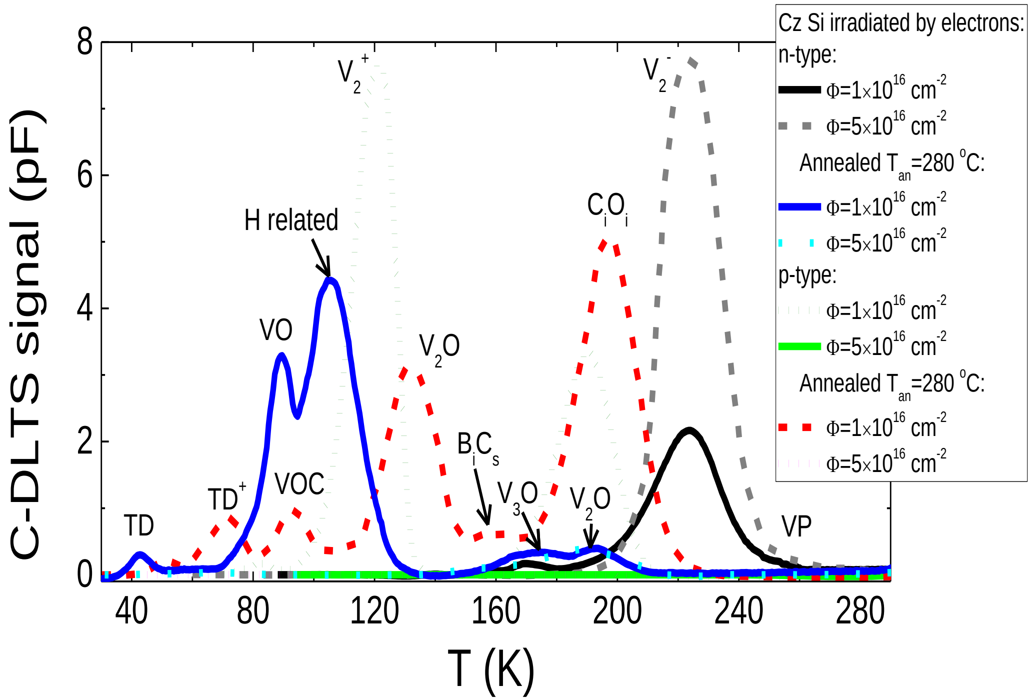




Peak temperature (within TDTL spectrum) dependence on trapping centre activation energy (E$_{tr}$) simulated for the fixed Δn$_C$=const and temperature varied *$\Delta n(T)$* excess carrier density

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.

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

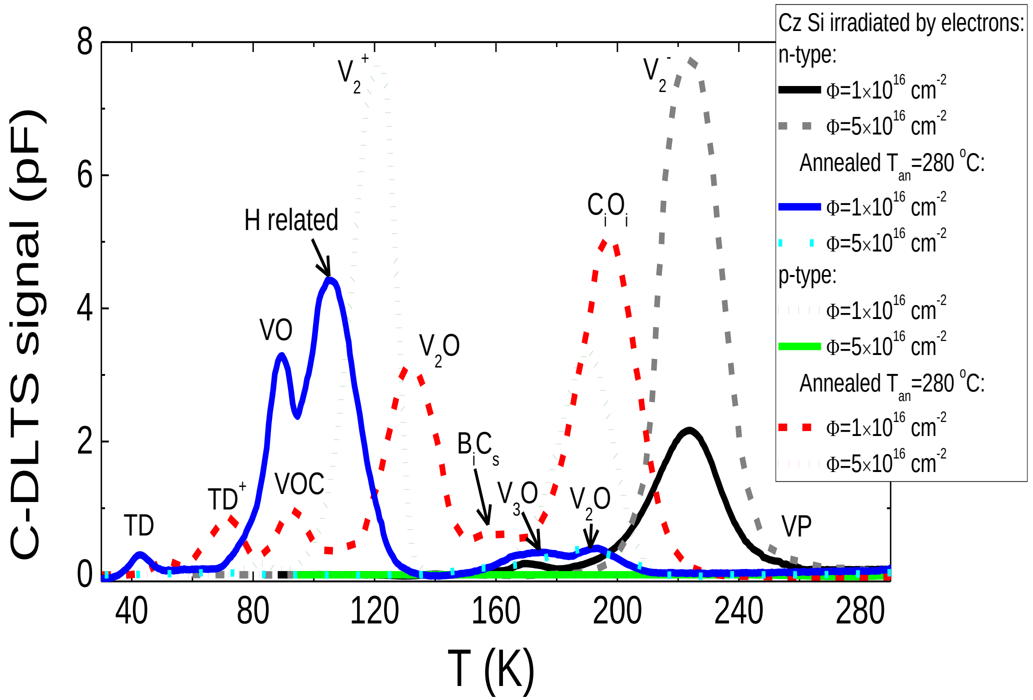


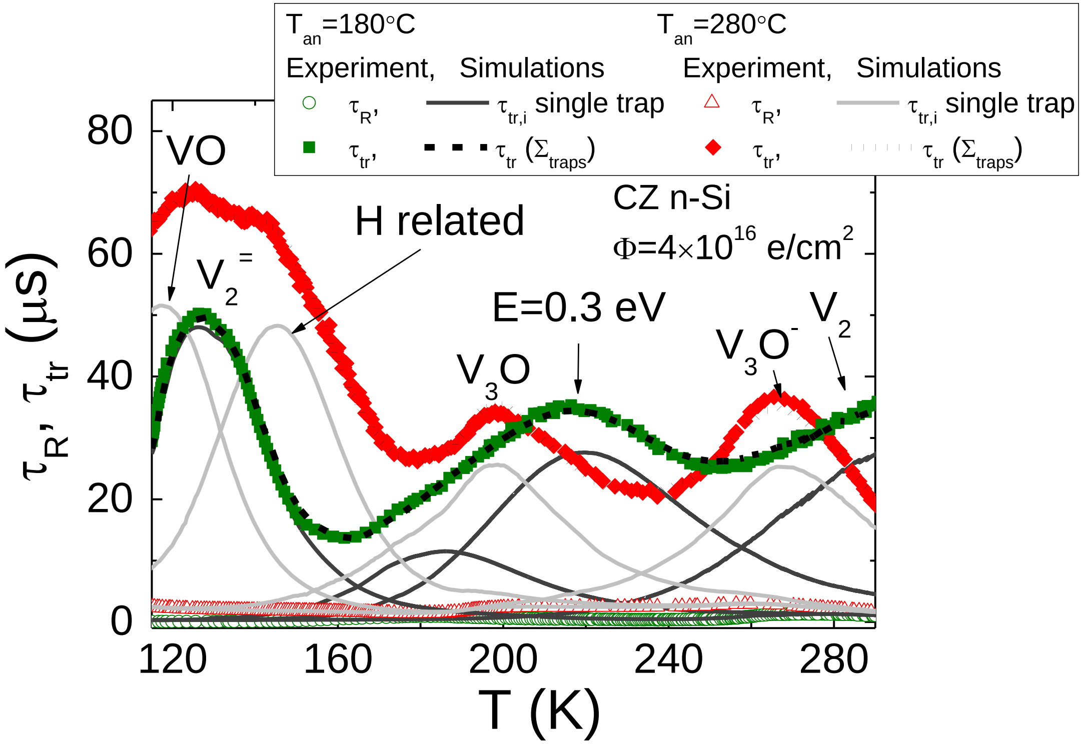
- No peaks in low temperature wing were observed in heavily irradiated n- and p-type CZ samples. This result can be explained by the low effective doping concentration in heavily irradiated material.

- The radiation induced defects, ascribed to VO, V_2O. V_3O and VP complexes, TD and to H related defects have been observed in the electron irradiated n-type Cz-Si samples.

- The hydrogen, oxygen and carbon related complexes of V_2O, VOC, V_3O, B_iC_s , C_iO_i, divacancy V_2^+ and TD defects have been observed in the electron irradiated p-type Cz-Si samples.

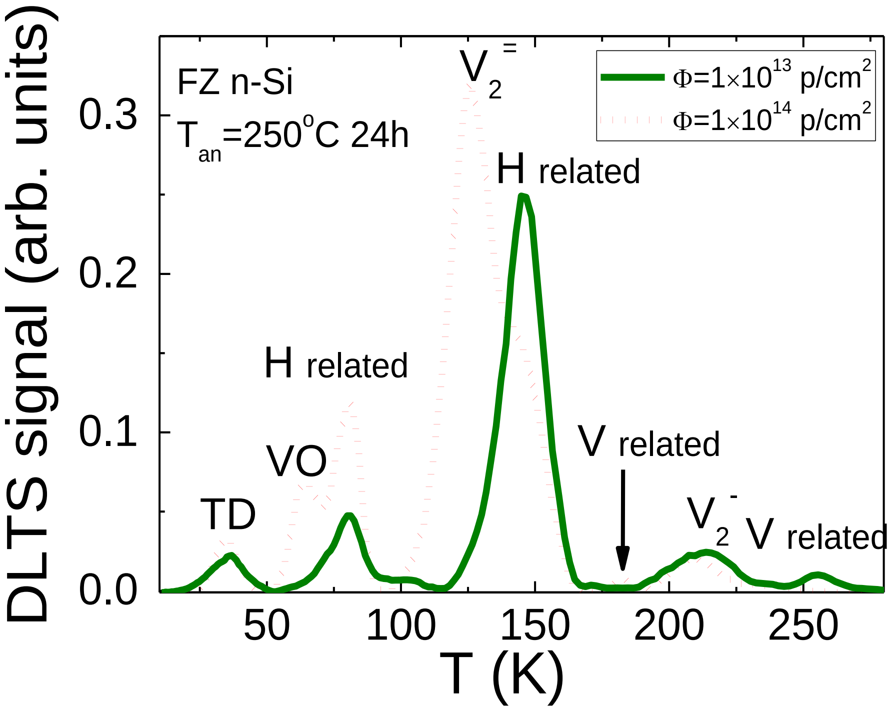
Results on n-type and p-type CZ Si irradiated by 6.6 MeV electrons





- No peaks in low temperature wing were observed in heavily irradiated n- and p-type CZ samples. This result can be explained by the low effective doping concentration in heavily irradiated material.
- 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.

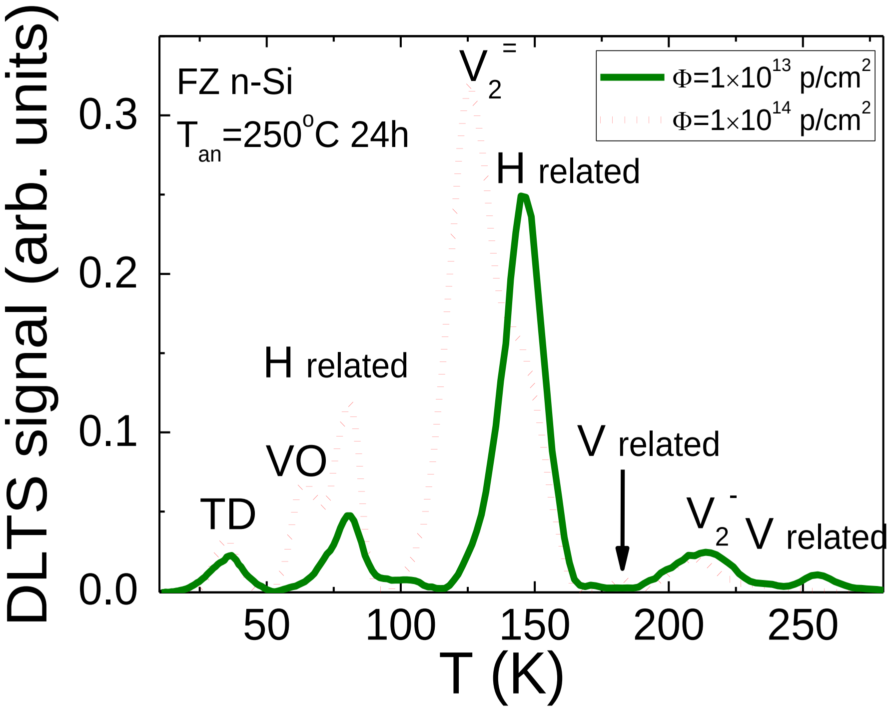
Results on n-type FZ and p-type CZ Si irradiated by 26 GeV/c protons

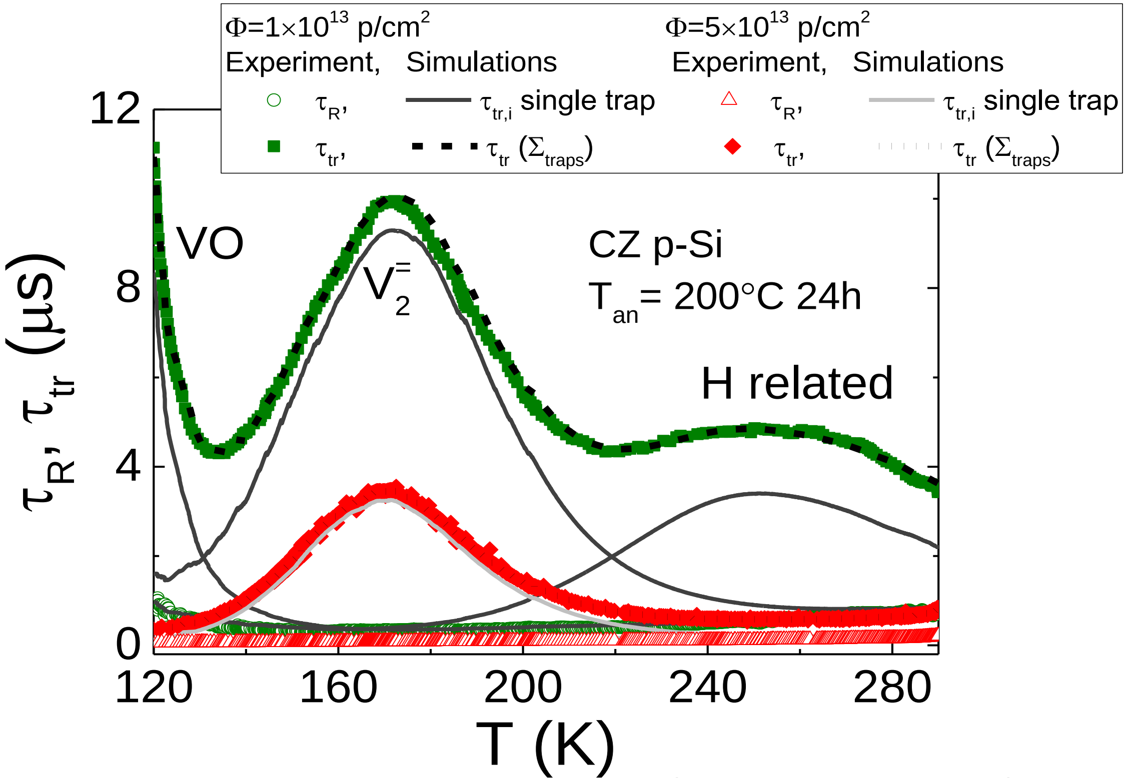


- The predominant peaks for the n-type FZ Si samples are attributed to V- and H-related defects.
- The application of DLTS technique for the p-type CZ Si samples is limited due to low effective doping concentration.

- 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.

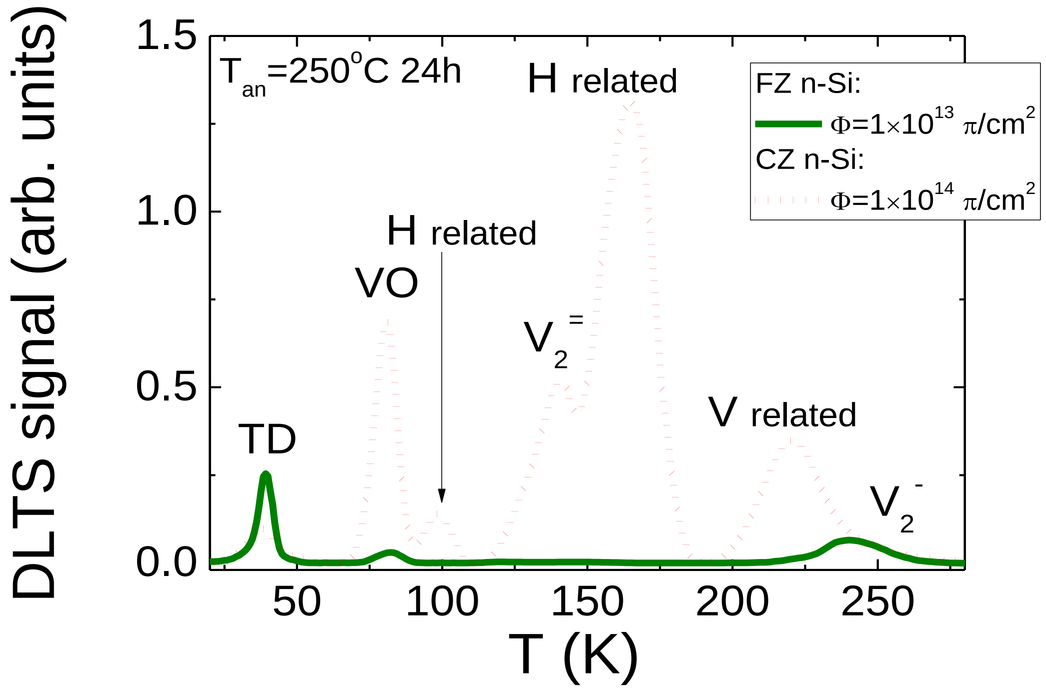
Results on n-type FZ and p-type CZ Si irradiated by 26 GeV/c protons





- The predominant peaks for the n-type FZ Si samples are attributed to V- and H-related defects.
- The application of DLTS technique for the p-type CZ Si samples is limited due to low effective doping concentration.
- 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.

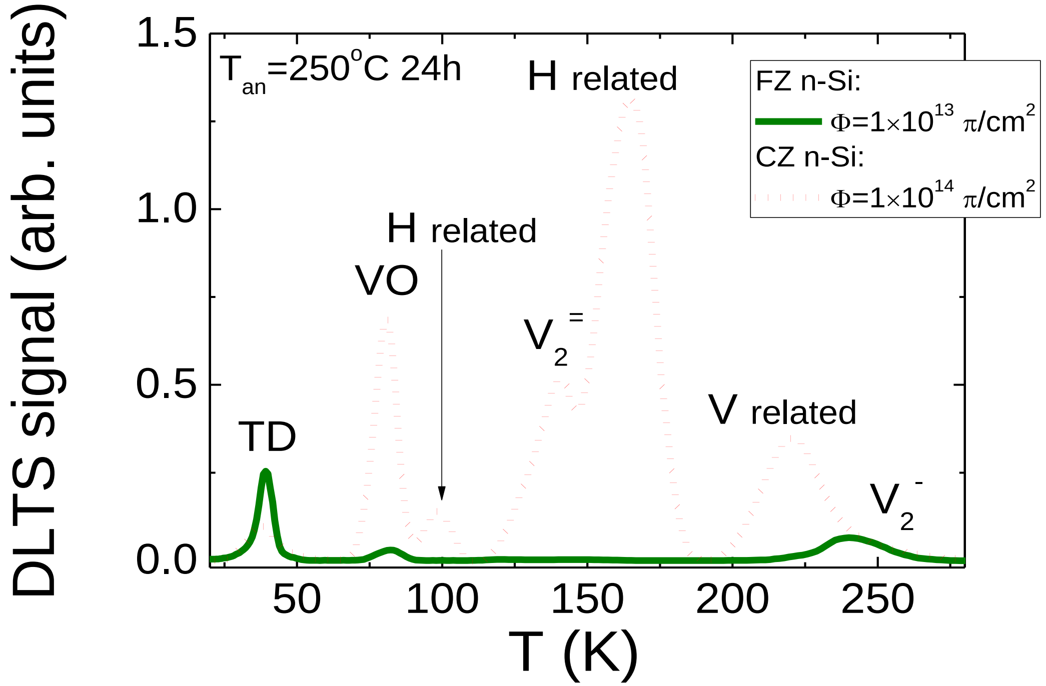
Results on n-type FZ and CZ Si irradiated by 300 MeV/c pions

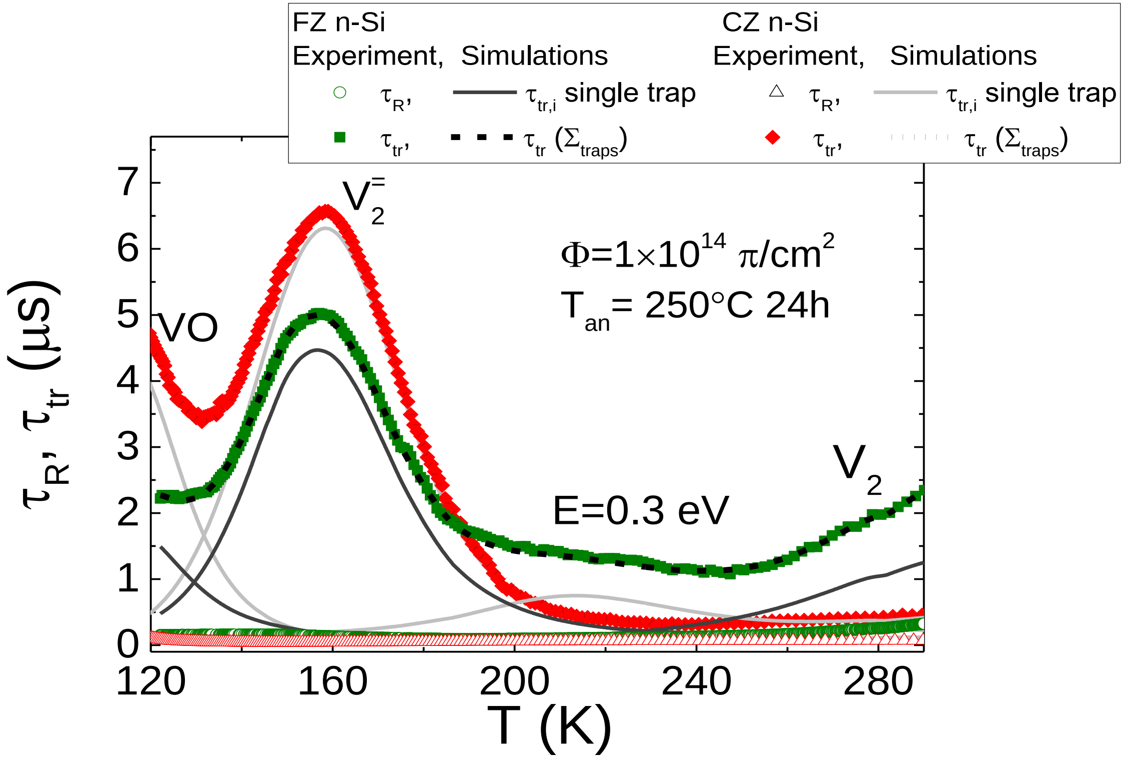


- The similarity between DLTS spectra, obtained for rather low fluence irradiations by protons and pions, indicate that the irradiation with various type penetrative hadrons induce the same defects.

- VO, double charged di-vacancy ($V_2^=$), H-related and V-related defects are dominant defects in CZ n-Si samples after heat treatment at 250˚C.
- TD and V_2^- defects are dominant defects in the FZ n-Si samples after heat treatment at 250˚C.

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





- VO, double charged di-vacancy ($V_2^=$), H-related and V-related defects are dominant defects in CZ n-Si samples after heat treatment at 250˚C.
- TD and V_2^- defects are dominant defects in the FZ n-Si samples after heat treatment at 250˚C.
- 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.
- The unidentified defect with activation energy *E*=0.3 eV might be the H-related defect.

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.
- TDTL technique allowed to identify the trapping centres after heat treatment at $T_{an}\geq 80°C$ in electron irradiated Si (C_iO_i, VO, V_3O and non-identified defects, also observed in DLTS spectra).
- 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).
- The TDTL spectra showed the spectral changes dependent on irradiation type (either protons or pions). The peaks related to the dominant traps have there been ascribed to V related complexes. The additional peak obtained for samples irradiated by pions is attributed to the non-identified defect with activation energy E=0.3 eV. This defect is also observed for electron irradiated CZ Si.
- Contactless TDTL technique allows simultaneous control of interactions among several radiation defects within large fluences irradiated Si structures.

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-2016/2017. 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.