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Effect of fluence on defect structure of proton-irradiated high-resistivity silicon

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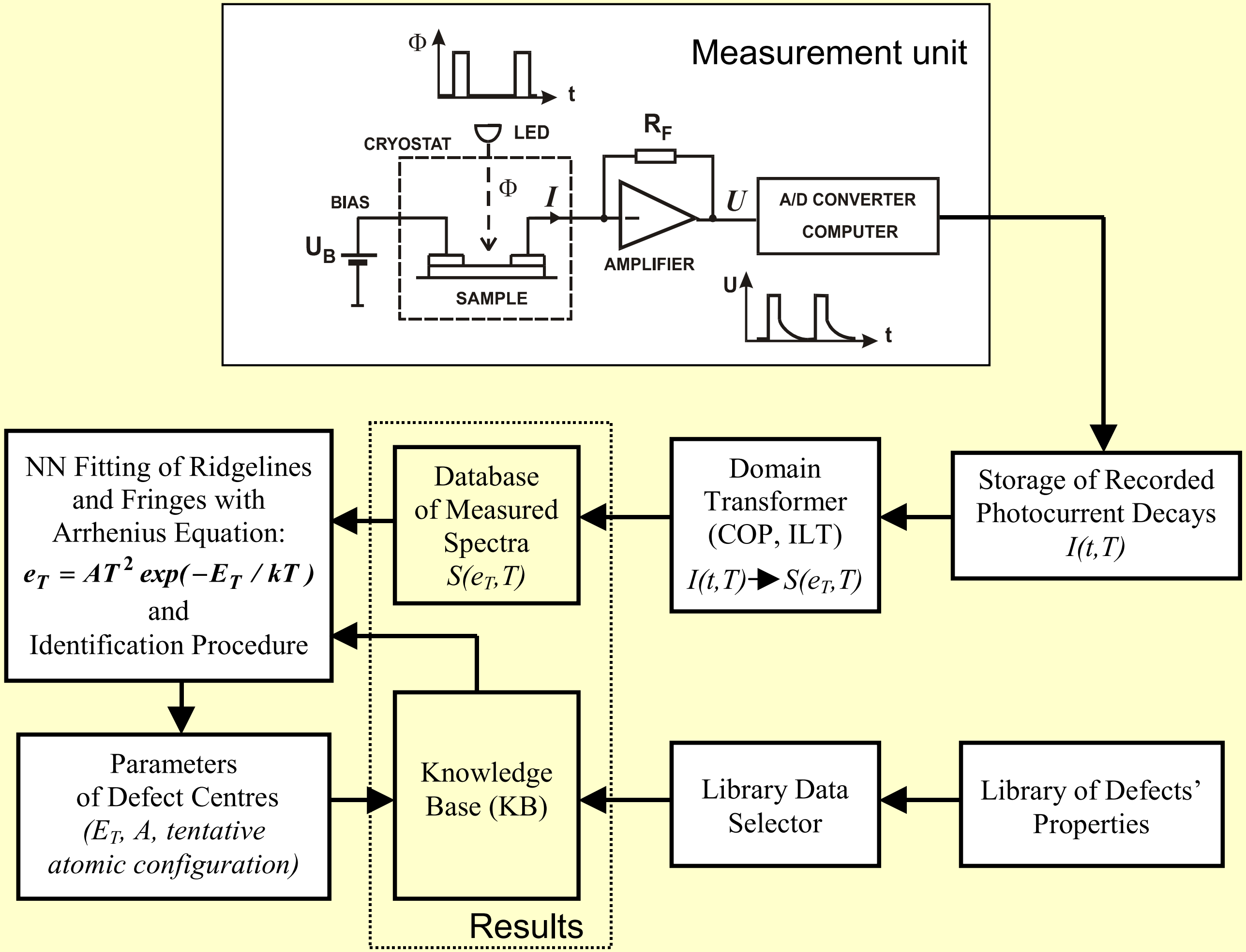
- **Motivation**
- **Intelligent experimental system for studies of defect centres by PITS technique**
- **Proton irradiated samples**
- **Effect of fluence on defect structure of high-resistivity Czochralski-grown Si**
- **Effect of fluence on defect structure of high-resistivity float-zone Si**
- **Conclusions**

Motivation

- Fast proton damage in bulk silicon is still not fully understood.
- DLTS samples: $n \geq 1\times10^{14}$ cm^{-3}, fluences ~$5\times10^{10} - 3\times10^{13}$ p/cm^2, annealed at 40 - 400 ^{o}C.
- Using a better resolution of experimental system new radiation defect centres can be observed.
- Studies of defect centres in high-resistivity Si-Cz and Si-FZ (net donor concentration below 5×10^{12} cm^{-3}) after proton irradiation with higher fluences ($1\times10^{13} - 1\times10^{15}$ p/cm^2) are of great interest.

Intelligent experimental system for characterisation of defect centres in high-resistivity semiconductors



Storage of Recorded Photocurrent Decays
I(t,T)

Domain Transformer (COP, ILT)
$I(t,T) \rightarrow S(e_T,T)$

Database of Measured Spectra
$S(e_T,T)$

NN Fitting of Ridgelines and Fringes with Arrhenius Equation:

$$e_T = AT^2 \exp(-E_T / kT)$$

and
Identification Procedure

Parameters of Defect Centres
(E_T, *A, tentative atomic configuration)*

Knowledge Base (KB)

Library Data Selector

Library of Defects' Properties

Schematic illustration of the intelligent experimental setup for characterisation of defect centres in high-resistivity semiconductors

10- MeV proton irradiated samples

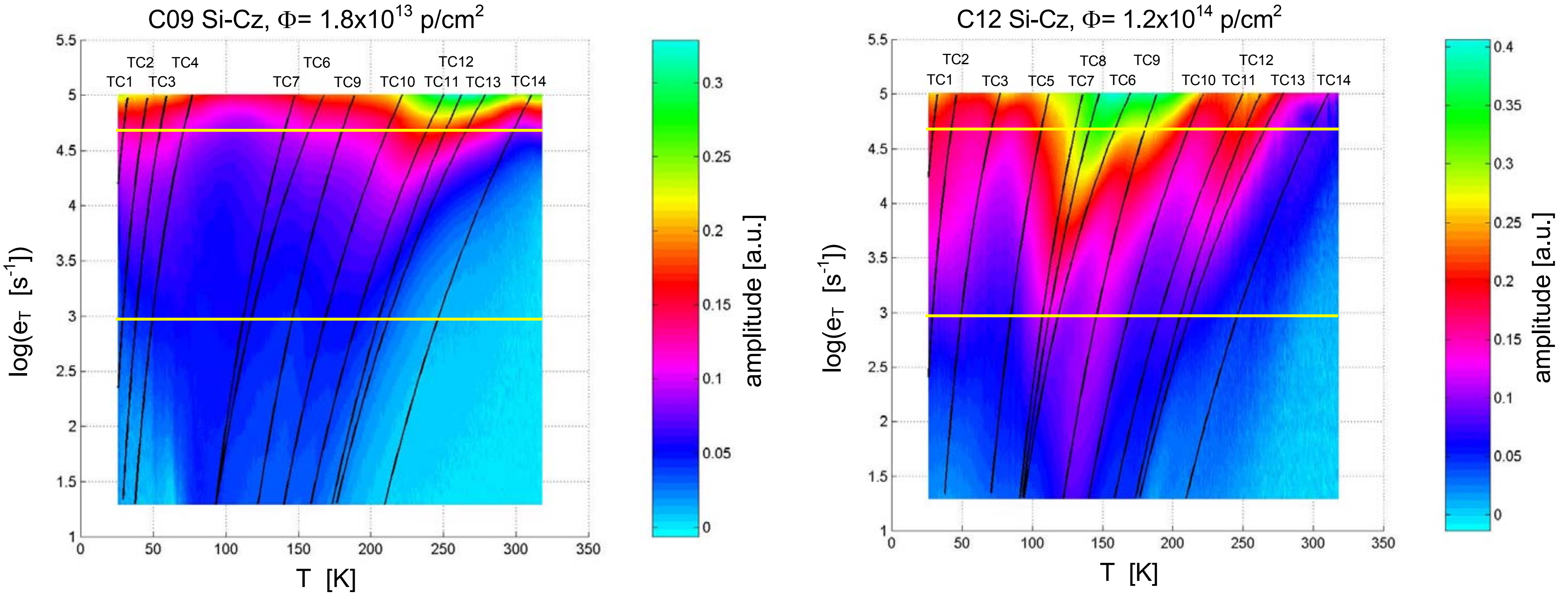
A. High-resistivity bulk Si grown by the Czochralski method in magnetic field, Okmetic

Sample	Fluence (p/cm^2)	n at 300 K (cm^{-3})	Resistivity at 300 K (Ωcm)	Hall mobility at 300 K (cm^2/Vs)	Type
C00	non-irradiated	$3.6x10^{12}$	$1.08x10^3$	1585	n
C09	$1.8x10^{13}$	$5.8X10^{10}$	$1.1x10^5$	959	n
C12	$1.2x10^{14}$	$6.0x10^{10}$	$9.6x10^4$	1094	n

B. High-resistivity FZ Si, Topsil

Sample	Fluence (p/cm^2)	n at 300 K (cm^{-3})	Resistivity at 300 K (Ωcm)	Hall mobility at 300 K (cm^2/Vs)	Type
T00	non-irradiated	$1.5x10^{12}$	$2.8x10^3$	1600	n
T09	$1.8x10^{13}$	$5.8X10^{10}$	$1.1x10^5$	967	n
T12	$1.2x10^{14}$	$4.4x10^{10}$	$1.7x10^5$	848	n

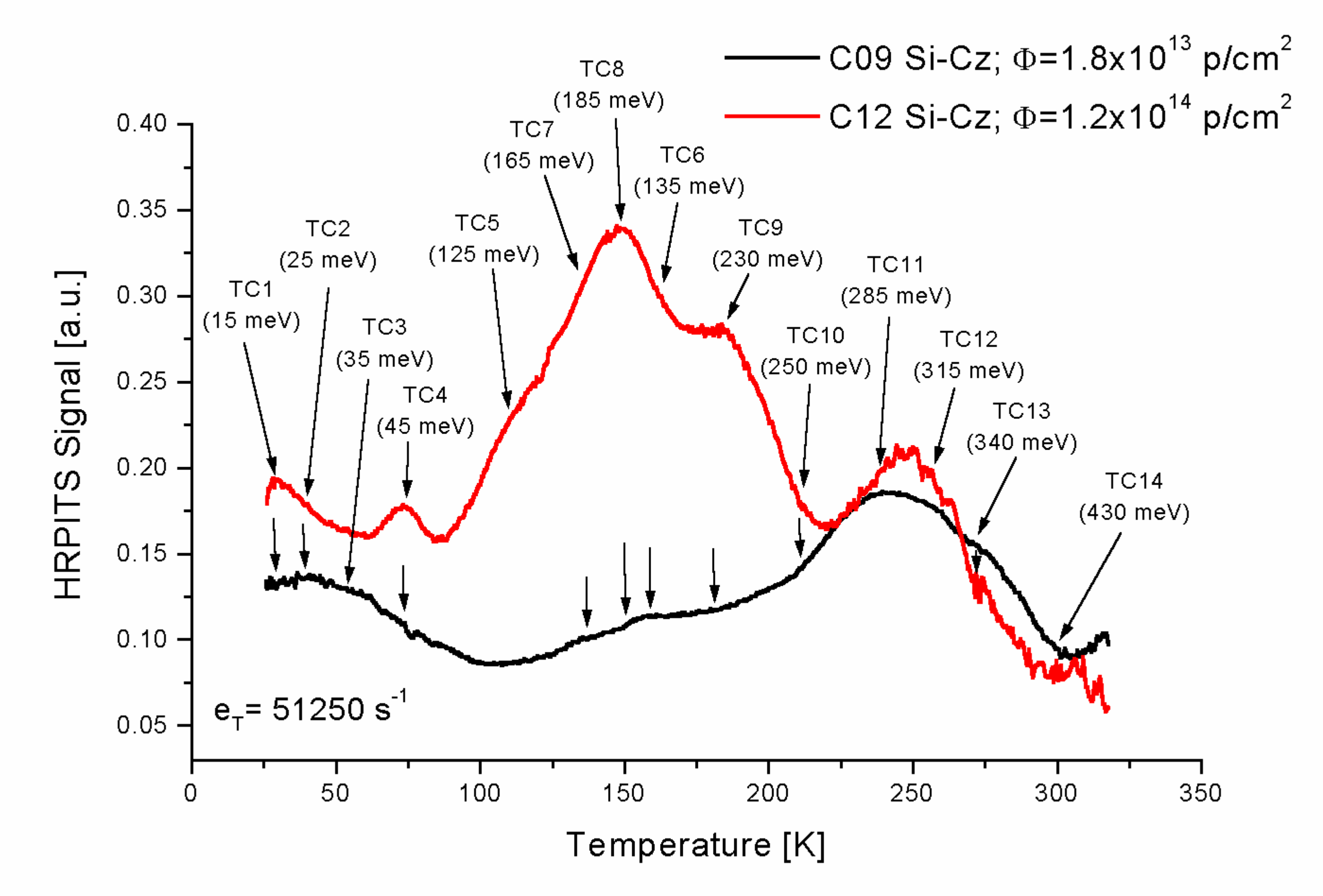
Effect of proton fluence on defect structure of Czochralski-grown Si



(a) **(b)**

Experimental spectral fringes obtained as a result of the correlation procedure for defect centres detected in Cz-Si irradiated with fluences of 1.8x10^{13} p/cm^2 (a) and 1.2x10^{14} p/cm^2 (b). The solid lines illustrate the temperature dependencies of emission rate determined by means of advanced computational analysis for detected defect centres.

Effect of proton fluence on defect structure of Czochralski-grown Si

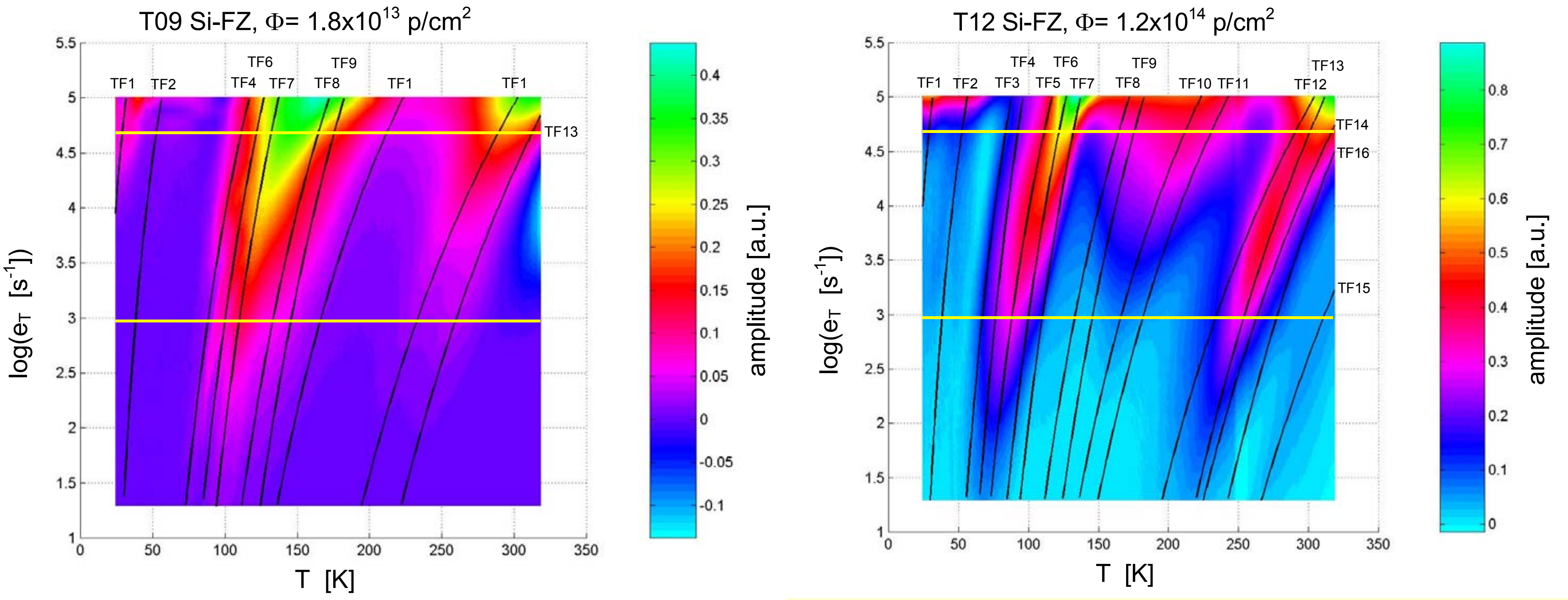


Comparison of 1-D HRPITS spectra obtained as a result of the correlation procedure for high-resistivity Cz-Si samples after 10-MeV proton irradiation with fluences of 1.8×10^{13} and 1.2×10^{14} p/cm^2.

Summary of the properties and concentrations of defect centres detected by the HRPITS method in high-resistivity Cz-Si after 10-MeV proton irradiation with fluences of 1.8×10^{13} and 1.2×10^{14} p/cm^2

Trap label	E_a [meV]	A [$s^{-1}K^{-2}$]	σ_e or σ_h [cm^2]	Trap concentration N_T [cm^{-3}]		Identification/ Remarks
				Φ=1.8x10^{13} [p/cm^2]	**Φ=1.2x10^{14} [p/cm^2]**	
TC1	**15**	2.0×10^4	1.9×10^{-17}	1.9×10^{14}	2.3×10^{14}	shallow donor ; *e*
TC2	**25**	2.5×10^4	2.4×10^{-17}	3.2×10^{14}	4.0×10^{14}	shallow donor ; *e*
TC3	**35**	2.7×10^4	2.5×10^{-17}	4.5×10^{14}	not observed	shallow donor ; *e*
TC4	**45**	1.5×10^4	1.4×10^{-17}	7.4×10^{14}	1.0×10^{15}	shallow donor ; *e*
TC5	**125**	3.5×10^6	3.3×10^{-15}	not observed	2.1×10^{15}	$C_i^{-/0}$; *e*
TC6	**135**	3.8×10^4	-	1.2×10^{15}	2.2×10^{15}	TX3, H-related ?
TC7	**165**	2.0×10^6	1.2×10^{-15}	1.0×10^{15}	2.1×10^{15}	$VO_i^{-/0} + C_iC_s(A)^{-/0}$; *e*
TC8	**185**	4.0×10^7	1.5×10^{-14}	not observed	2.6×10^{15}	$V_2^{+/0}$; *h*
TC9	**230**	4.0×10^6	3.8×10^{-15}	1.4×10^{15}	2.9×10^{15}	$V_2^{2-/-}$; *e*
TC10	**250**	1.0×10^6	3.8×10^{-16}	1.6×10^{15}	1.8×10^{15}	$VOH^{+/0}$; *h*
TC11	**285**	9.0×10^5	3.4×10^{-16}	1.9×10^{15}	1.9×10^{15}	H-related; *h*
TC12	**315**	6.0×10^5	6.1×10^{-16}	1.2×10^{15}	1.6×10^{15}	E3 (H-related), $VOH^{-/0}$; *e*
TC13	**340**	5.0×10^6	1.9×10^{-15}	1.8×10^{15}	1.4×10^{15}	$C_iO_i^{+/0}$ or C_iO_iV ; *h*
TC14	**430**	1.0×10^7	9.4×10^{-15}	1.2×10^{15}	9.6×10^{14}	$V_2^{-/0}$; *e*

Effect of proton fluence on defect structure of FZ Si



(a) **(b)**

Experimental spectral fringes obtained as a result of the correlation procedure for defect centres detected in FZ-Si irradiated with fluences of 1.8x10^{13} p/cm^{2} (a) and 1.2x10^{14} p/cm^{2} (b). The solid lines illustrate the temperature dependencies of emission rate determined by means of advanced computational analysis for detected defect centres.

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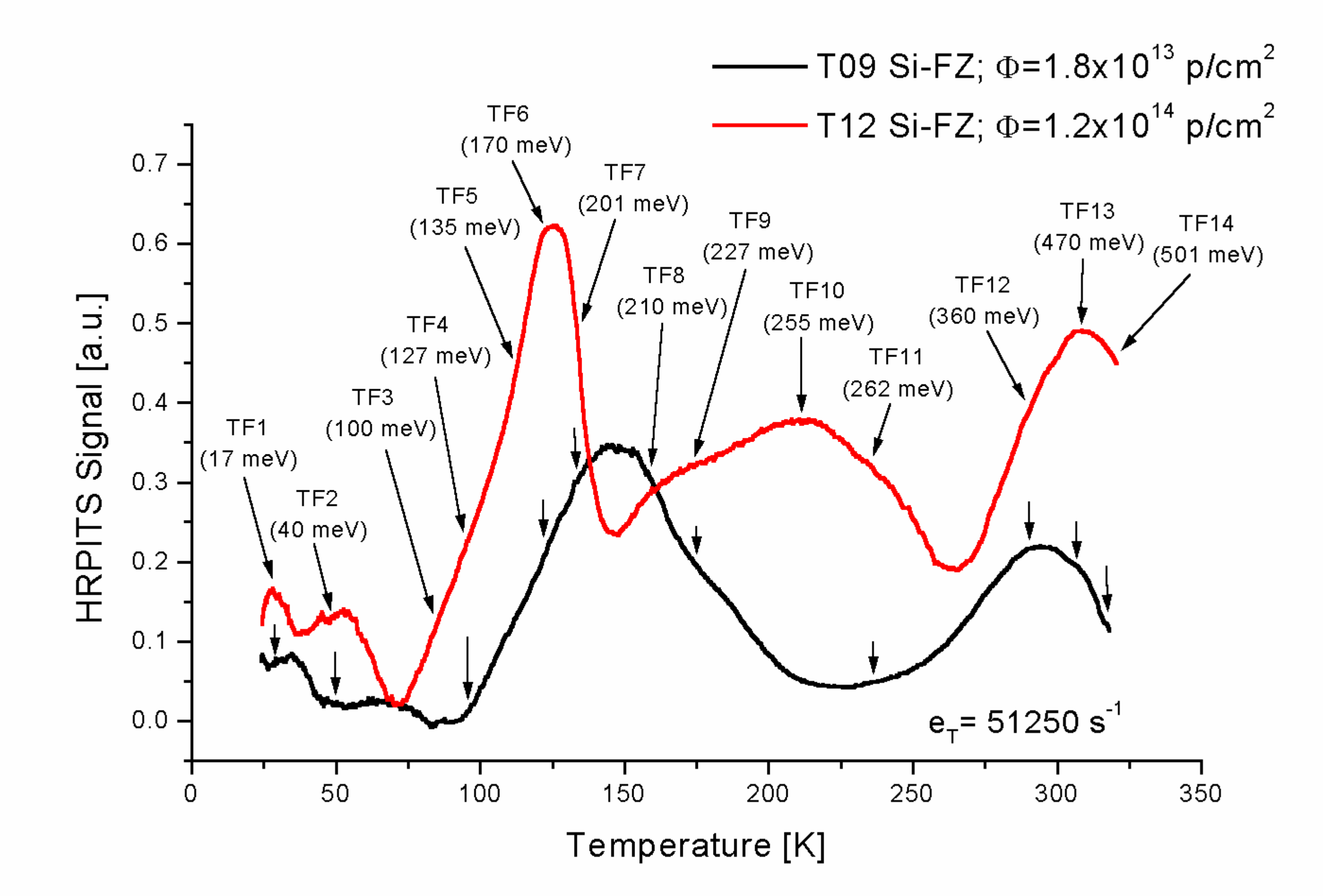

Comparison of 1-D HRPITS spectra obtained as a result of the correlation procedure for high-resistivity FZ-Si samples after 10-MeV proton irradiation with fluences of 1.8×10^{13} and 1.2×10^{14} p/cm^2.

Summary of the properties and concentrations of defect centres detected by the HRPITS method in high-resistivity FZ-Si after 10-MeV proton irradiation with fluences of 1.8×10^{13} and 1.2×10^{14} p/cm^2

Trap label	E_a [meV]	A [s^{-1}K^{-2}]	σ_e or σ_h [cm^2]	Trap concentration N_T [cm^{-3}]		Identification/ Remarks
				Φ=1.8x10^{13} [p/cm^2]	**Φ=1.2x10^{14} [p/cm^2]**	
TF1	**17**	5.2x10^4	4.9x10^{-17}	1.4x10^{14}	2.1x10^{14}	shallow donor ; *e*
TF2	**40**	1.2x10^5	1.1x10^{-16}	1.7x10^{14}	4.6x10^{14}	shallow donor ; *e*
TF3	**100**	7.2x10^6	2.7x10^{-15}	not observed	5.3x10^{14}	$C_iC_s(A)^{+/0}$; *h*
TF4	**127**	2.2x10^6	2.1x10^{-15}	1.1x10^{14}	9.0x10^{14}	$C_i^{-/0}$; *e*
TF5	**135**	1.3x10^8	-	not observed	2.3x10^{15}	self-interstitial agglomerate (*I*)
TF6	**170**	3.5x10^7	3.3x10^{-14}	1.1x10^{15}	3.4x10^{15}	$VO_i^{-/0} + C_iC_s(A)^{-/0}$; *e*
TF7	**201**	1.3x10^8	4.9x10^{-14}	3.8x10^{15}	3.1x10^{15}	$V_2^{+/0}$; *h*
TF8	**210**	4.8x10^6	4.5x10^{-15}	2.9x10^{15}	2.5x10^{15}	*E (115)* ; *e*
TF9	**227**	2.7x10^5	2.5x10^{-16}	1.2x10^{15}	2.7x10^{15}	$V_2^{2-/-}$; *e*
TF10	**255**	3.4x10^5	1.3x10^{-16}	not observed	3.6x10^{15}	$VOH^{+/0}$; *h*
TF11	**262**	5.2x10^7	2.0x10^{-14}	8.6x10^{14}	2.9x10^{15}	$C_iH^{+/0}$; *h*
TF12	**360**	1.0x10^6	3.8x10^{-16}	3.3x10^{15}	2.6x10^{15}	$C_iO_i^{+/0}$ or C_iO_iV ; *h*
TF13	**470**	1.9x10^7	1.8x10^{-14}	3.5x10^{14}	5.6x10^{15}	$V_2^{-/0}$; *e*
TF14	**501**	1.3x10^8	4.9x10^{-14}	not observed	3.2x10^{15}	H-related complex; *h*
TF15	**574**	2.0x10^7	7.6x10^{-15}	not observed	1.8x10^{15}	I-centre $(V_2O)^{0/-}$; *h*
TF16	**597**	8.7x10^8	8.2x10^{-13}	not observed	1.5x10^{15}	*E (325),* multivacancy, N, or H - related ; *e*

Conclusions (I)

- HRPITS technique with implementation of computational intelligence has been employed to studying the effect of fluence on defect structure of 10-MeV proton irradiated FZ and Cz silicon with starting net donor concentrations of $1.5\text{x}10^{12}$ and $3.6\text{x}10^{12}$ cm^{-3}, respectively.
- The irradiation of Cz-Si with fluences of $1.8\text{x}10^{13}$ and $1.2\text{x}10^{14}$ p/cm^2 resulted in the formation of 12 and 14 defect centres , respectively, with activation energies ranging from 15 to 430 meV.
- For the lower fluence the predominant defects in Cz-Si were found to be an H-related complex (285 meV) and $C_iO_i^{+/0}$ (340 meV).
- For the higher fluence the predominant defects in Cz-Si were found to be divacancies $V_2^{2-/-}$ (230 meV) and $V_2^{+/0}$ (185 meV).

Conclusions (II)

- The irradiation of FZ-Si with fluences of 1.8×10^{13} and 1.2×10^{14} p/cm^2 resulted in the formation of 10 radiation defects with activation energies ranging from 17 to 470 meV and 16 defects with activation energies in the range of 17-597 meV, respectively.
- For the lower fluence the predominant defects in FZ-Si were found to be the divacancy $V_2^{+/0}$ (185 meV) and $C_iO_i^{+/0}$ (340 meV).
- For the higher fluence the predominant defects in FZ-Si were found to be the divacancy $V_2^{-/0}$ (470 meV) and $VOH^{+/0}$ complex (255 meV).
- Comparison of the defect structure of Cz-Si and FZ-Si indicates that the defects occurring in the both materials after the irradiation with the lower fluence are: $VO_i^{-/0}+C_iC_s(A)^{-/0}$, $V_2^{2-/-}$, $C_iO_i^{+/0}$ and $V_2^{-/0}$. For the higher fluence apart from these defects the common defects are: $C_i^{-/0}$, $V_2^{+/0}$, $VOH^{+/0}$.
- The irradiation of high-resistivity FZ-Si with a fluence of 1.2×10^{14} p/cm^2 results in the formation of midgap centres with activation energies 501, 574 and 597 meV attributed to an H-related complex, $V_2O^{0/-}$ and an unidentified defect, respectively.

Acknowledgement

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