Effect of proton fluence on radiation defect structure of high-purity silicon for particle detectors

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Outline

- Material: N-free, high-purity FZ Si wafers
- Neutron irradiations
- Radiation defect centers studies:
  - Photoluminescence
  - FTIR
  - HRPITS
- Conclusions

Material

Orientation	Type	ρ(300K) [Ωcm]	[P] [x10^{12}cm^{-3}]	[O] [x10^{15}cm^{-3}]	[C] [x10^{15}cm^{-3}]	[N] [x10^{14}cm^{-3}]
<100>	*n*	2200±200	~2.5	4	<5	<1

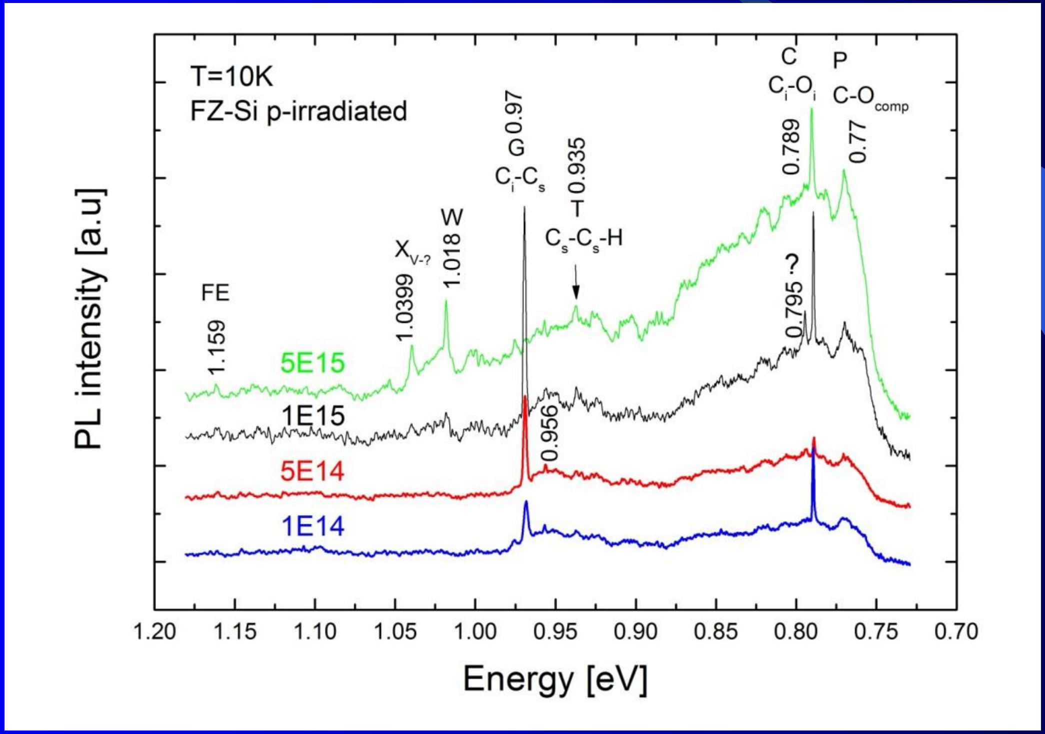
Electron mobility (300 K): ~ 1600 cm^2/Vs

High-energy proton irradiations

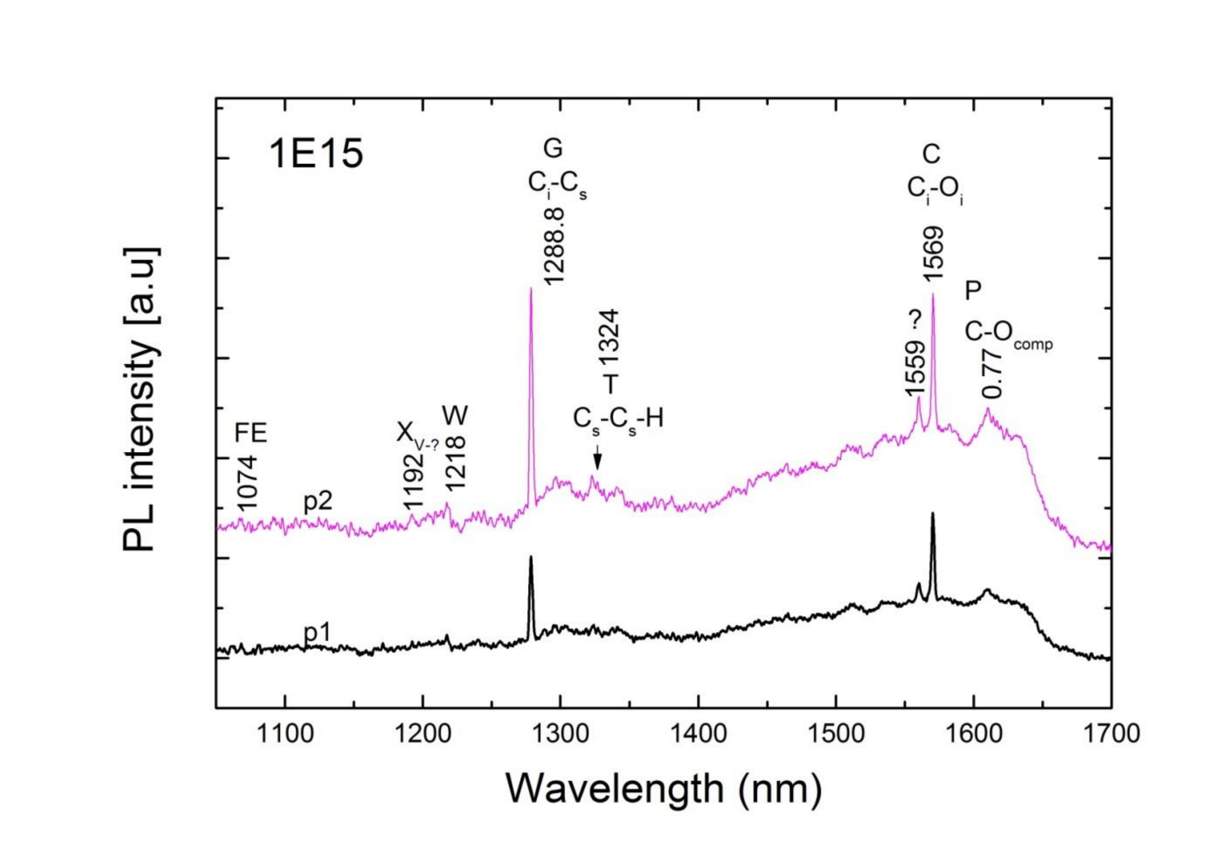
- Proton irradiation facilities at KIT.
- Protons energy: 23 MeV.
- Four proton fluences equivalent to the damage made by 1-MeV neutrons: 1×10^{14}, 5×10^{14}, 1×10^{15} , and 5×10^{15} cm^{-2}.

After irradiation with each fluence the material at 300K was semi-insulating with the resistivity of ~ 2×10^{5} Ωcm.

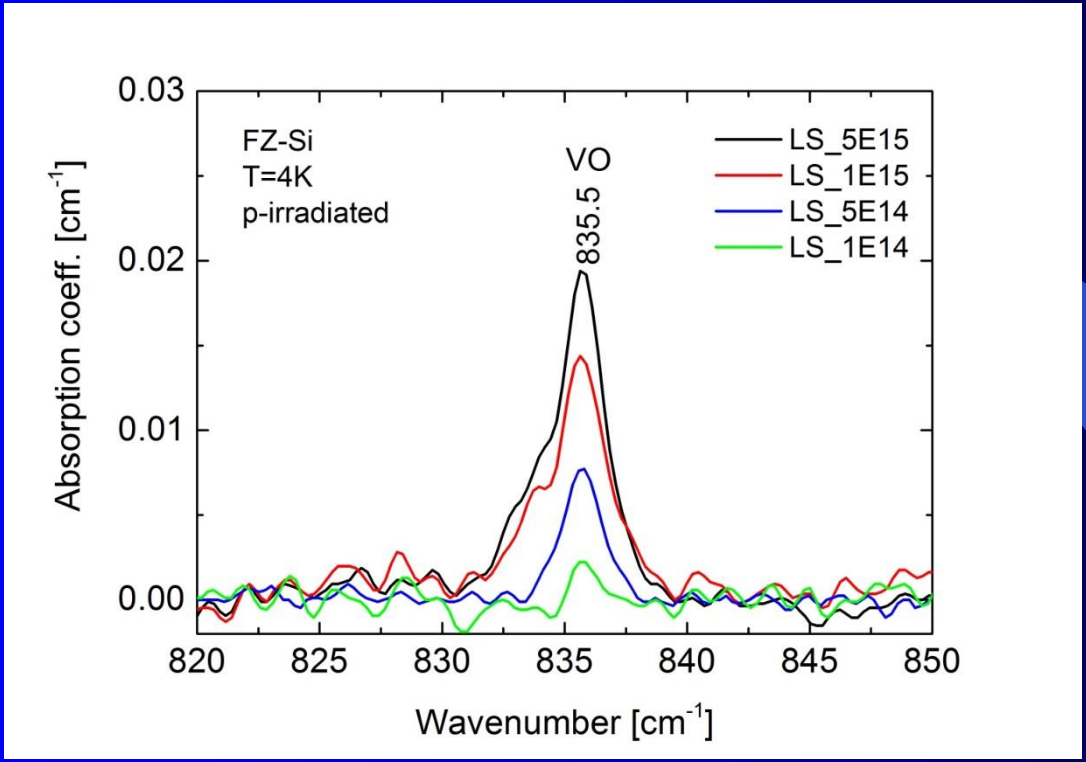
Effect of proton fluence on photoluminescence spectra



Photoluminescence spectra for two regions on the wafer Φ_e = 1E15 cm^{-2}

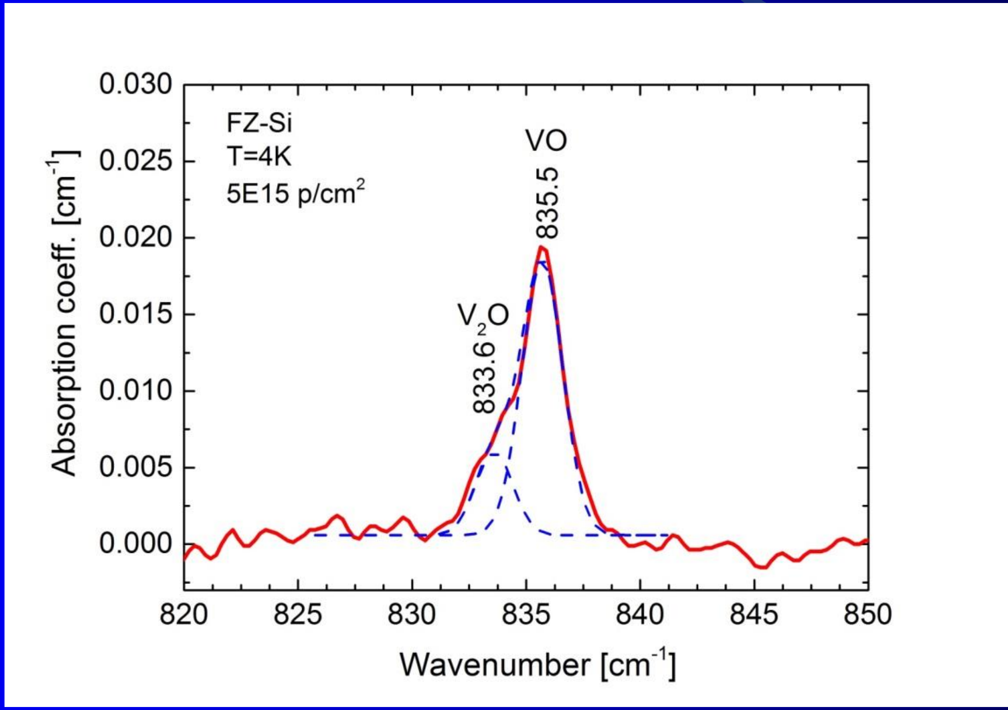


FTIR, V-O related absorption vs proton fluence



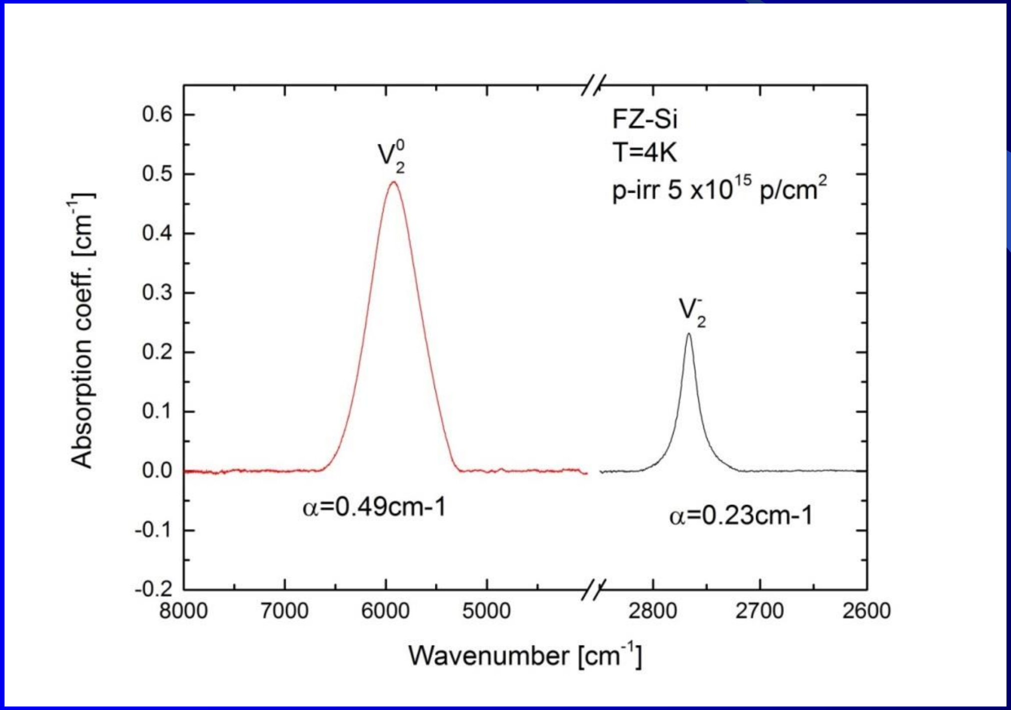
FTIR, Deconvolution of V-O related absorption

$\Phi_e = 5E15\ cm^{-2}$

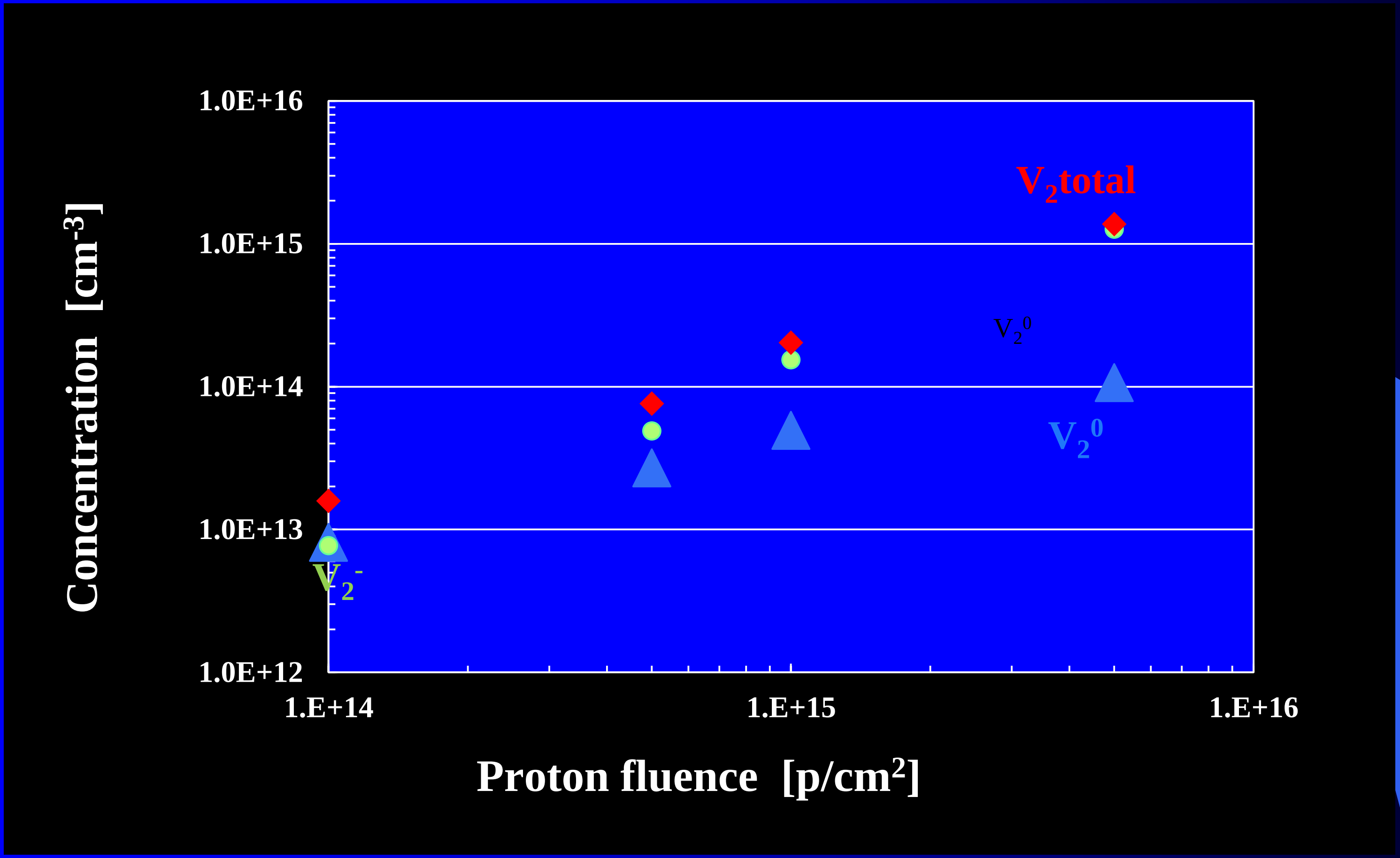


FTIR, V_2 – related absorption

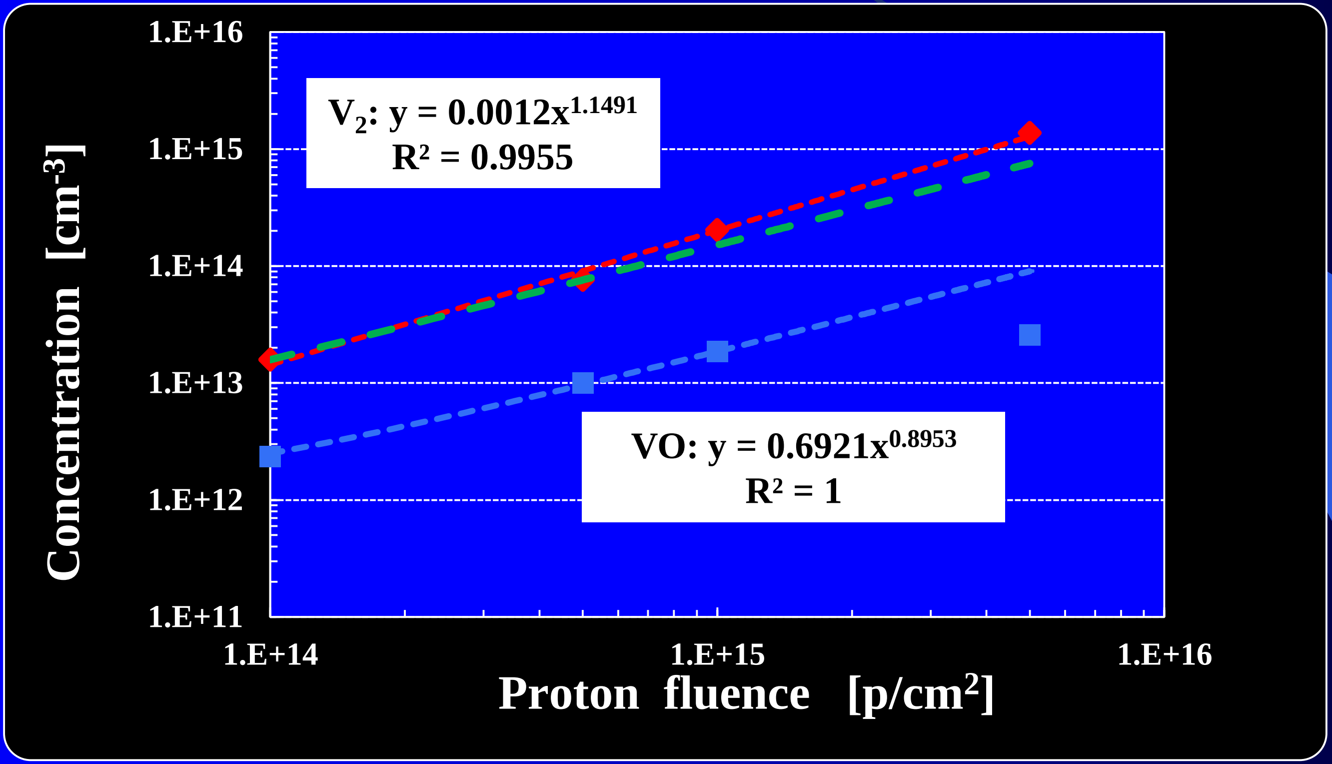
$\Phi_e = 5E15\ cm^{-2}$



FTIR, V_2 – concentration vs proton fluence

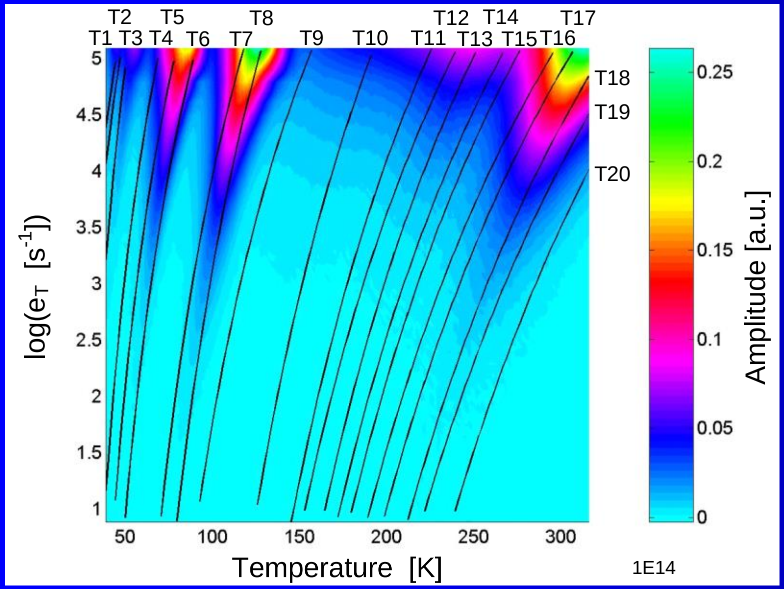


FTIR, VO and V_2 concentrations vs proton fluence



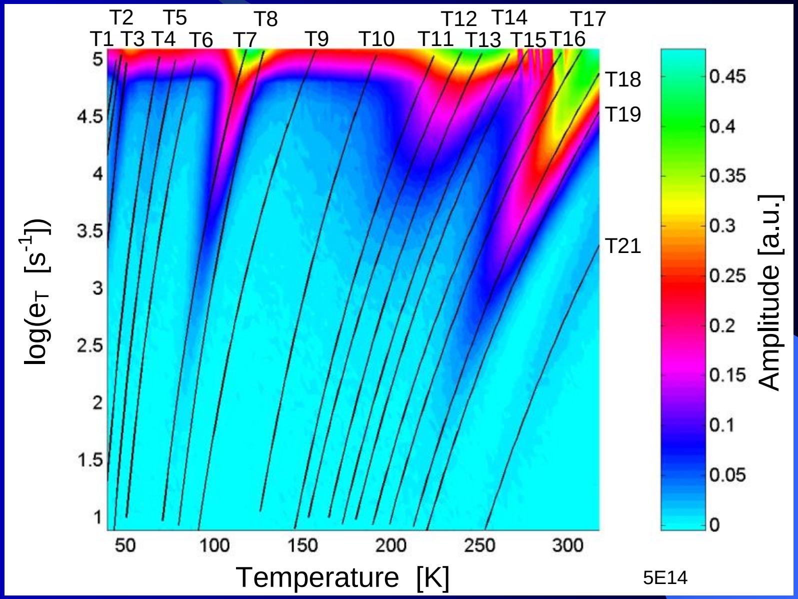
HRPITS, images of two-dimensional correlation spectra derived from the photocurrent relaxation waveforms

$\Phi_e = 1 \times 10^{14}$ cm^{-3}



E_{DC} = 482 meV

$\Phi_e = 5 \times 10^{14}$ cm^{-3}



E_{DC} = 456 meV

The solid lines illustrate the temperature dependences of thermal emission rate of charge carriers from detected defect centers according to Arrhenius formula: $e_T = AT^2 \exp(-E_a/kT)$.

HRPITS, images of two-dimensional correlation spectra derived from the photocurrent relaxation waveforms

$\Phi_e = 1\times10^{15}$ cm^{-3}

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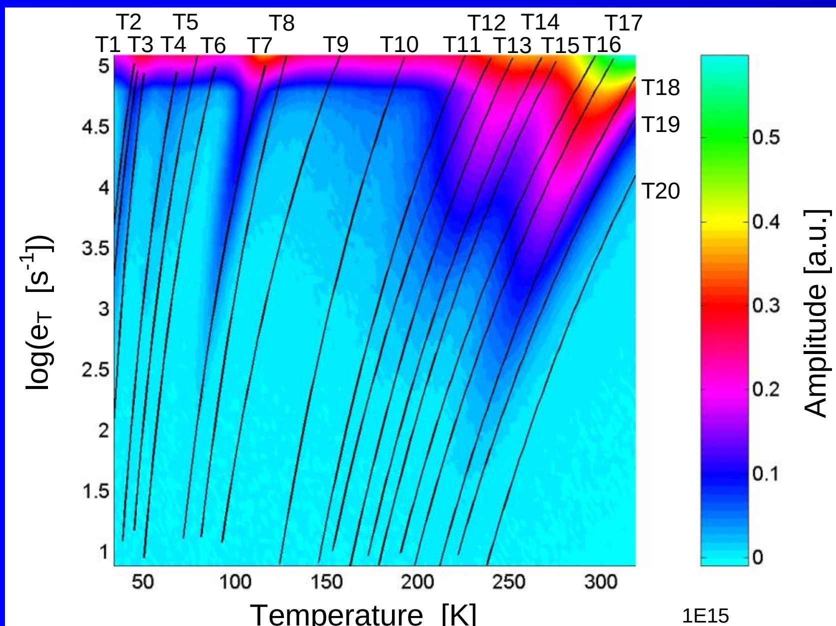
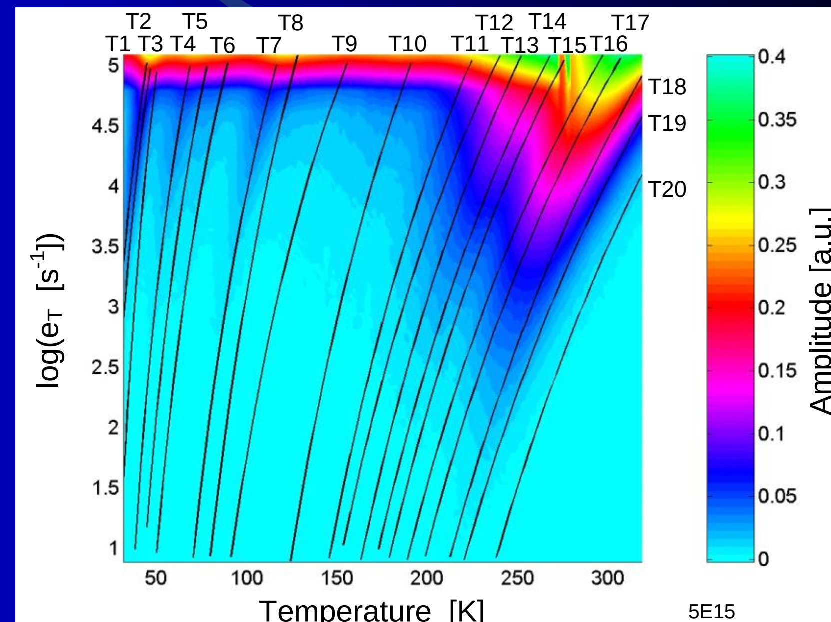


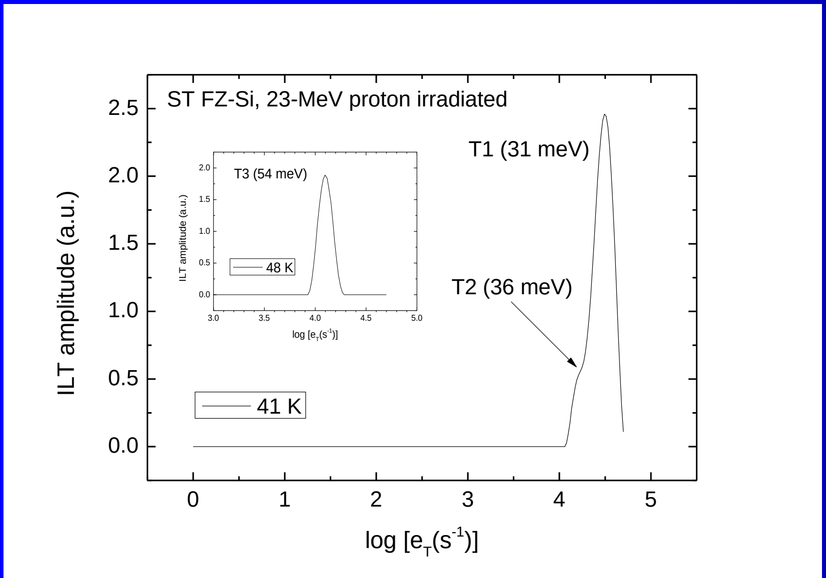


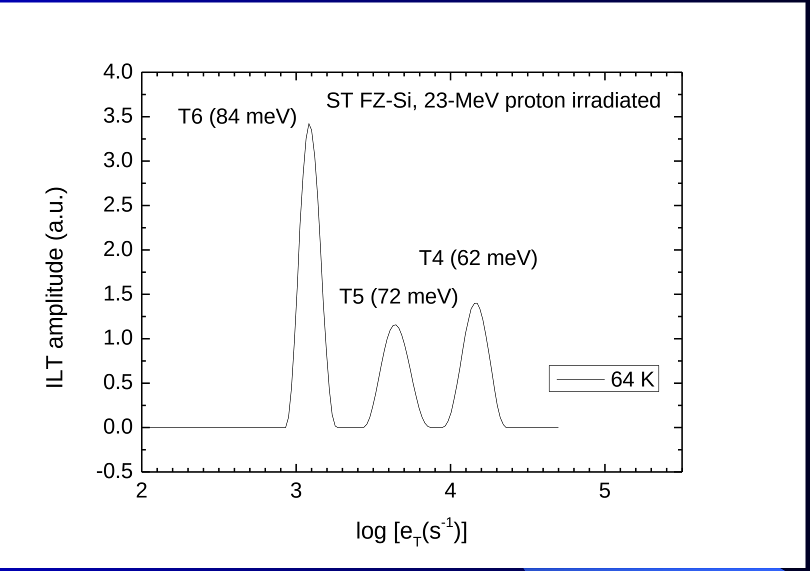
E_{DC} = 436 meV

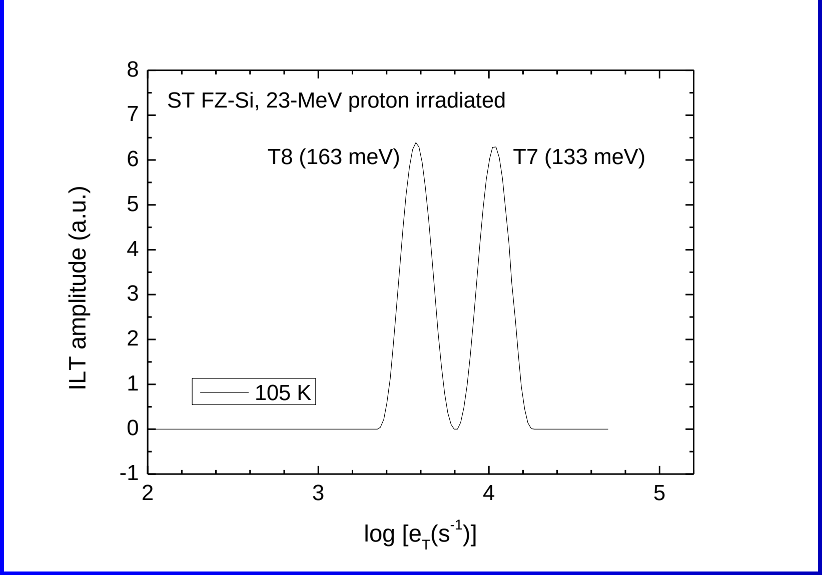
E_{DC} = 449 meV

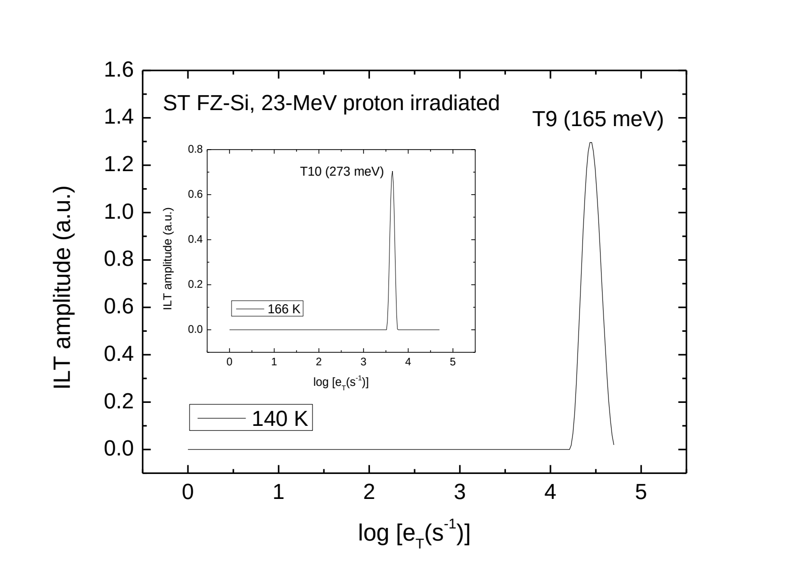
The solid lines illustrate the temperature dependences of thermal emission rate of charge carriers from detected defect centers according to Arrhenius formula: $e_T = AT^2 \exp(-E_a/kT)$.

Laplace 1D spectra (1)

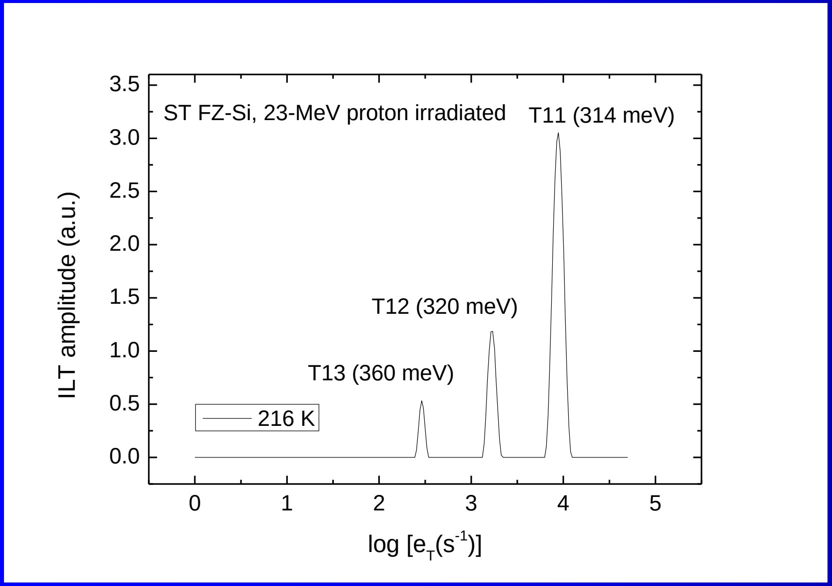


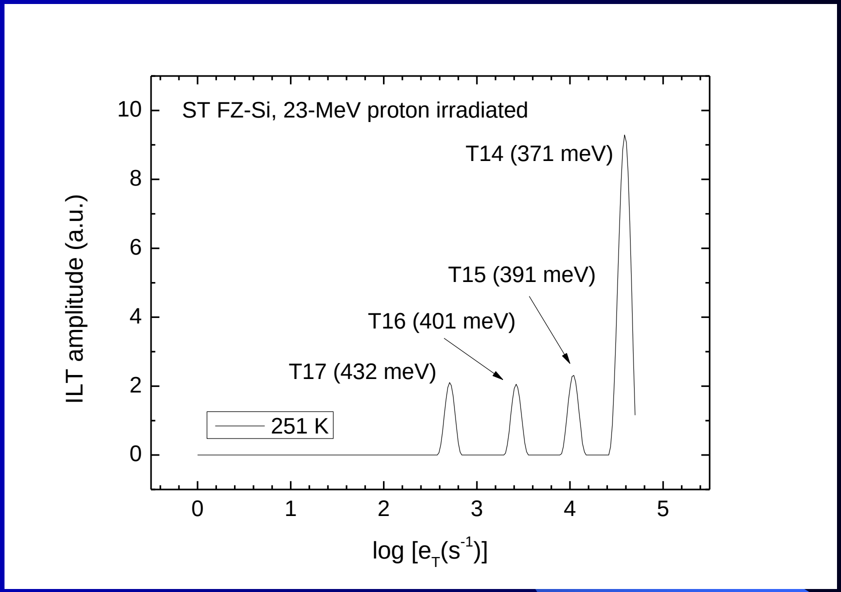


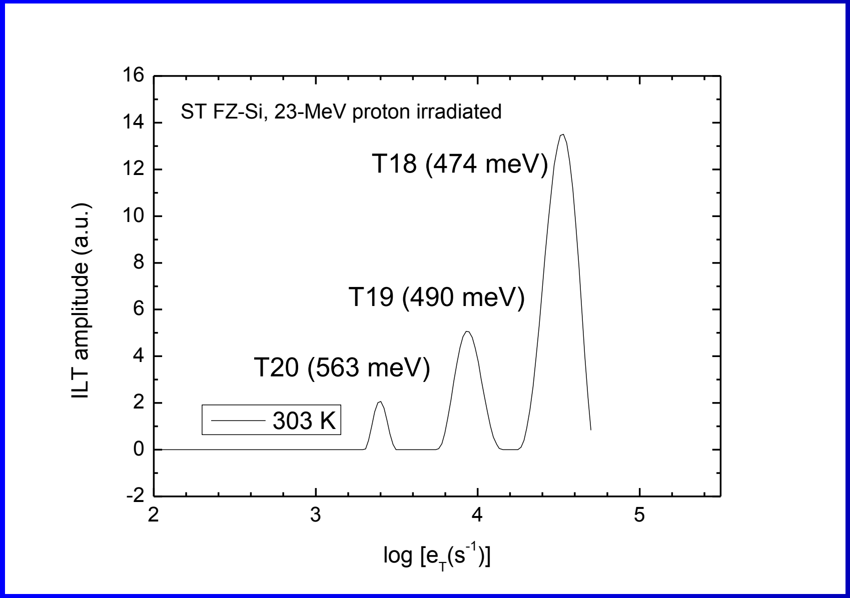


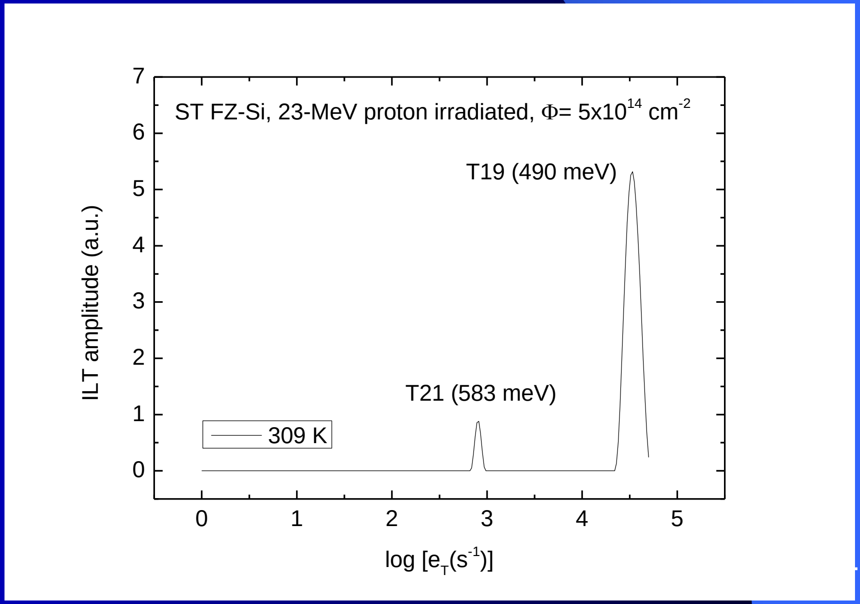


Laplace 1D spectra (2)

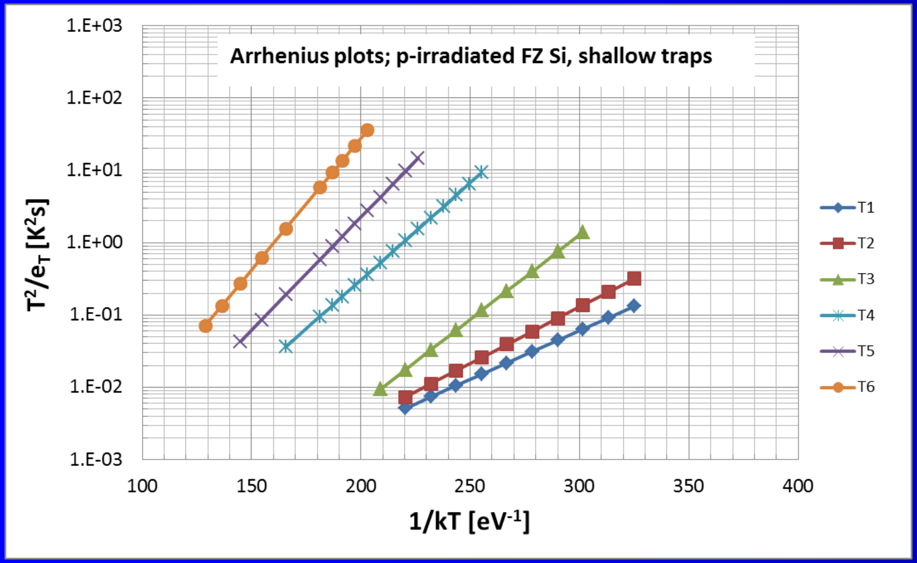


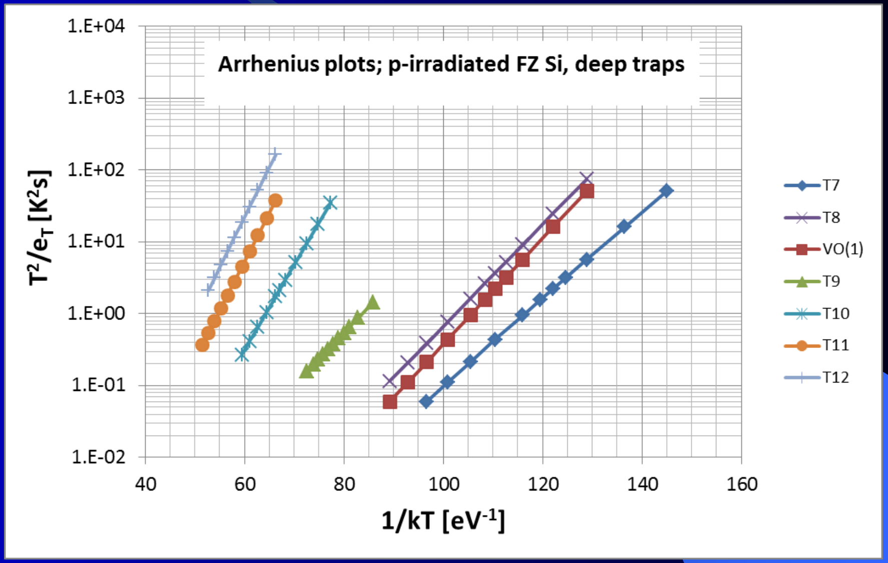




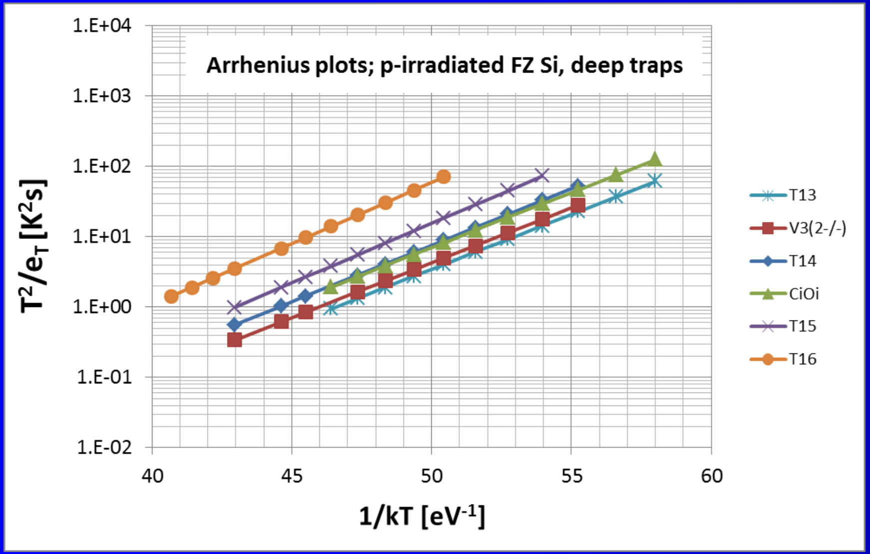


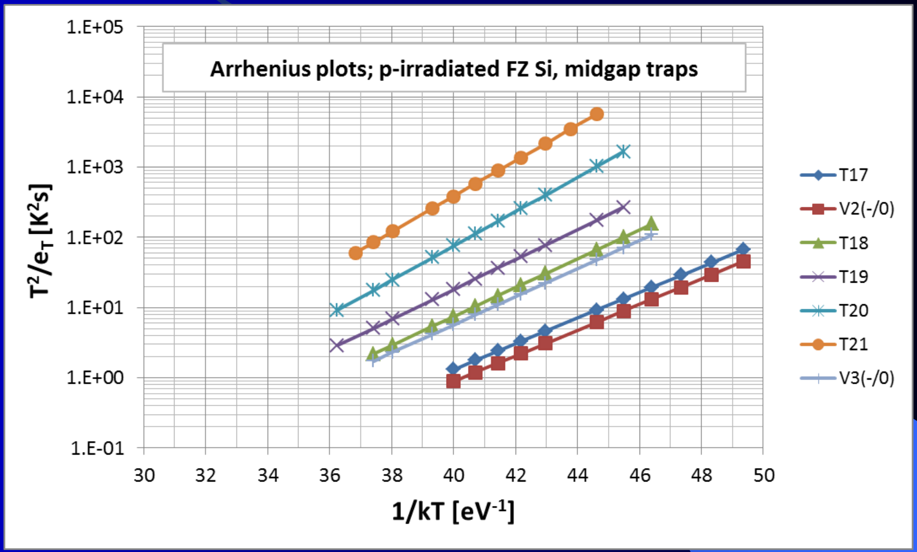
Arrhenius plots for the resolved defect centers (1)





Arrhenius plots for the resolved defect centers (2)

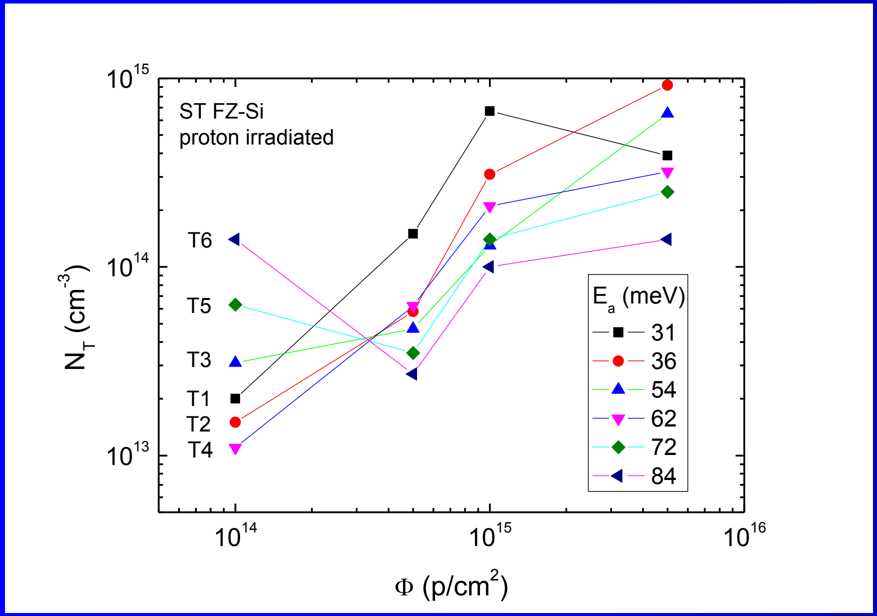


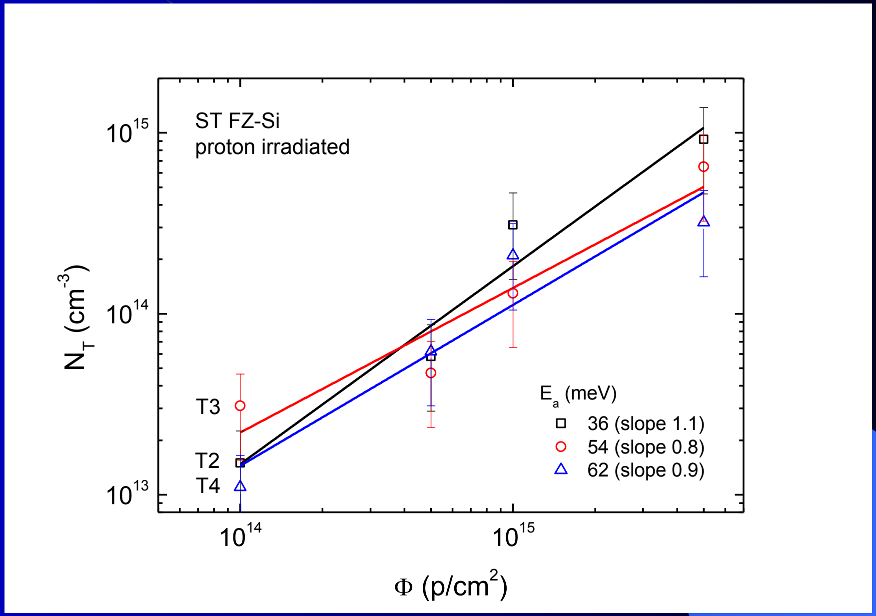


Properties and identification of radiation defect centers

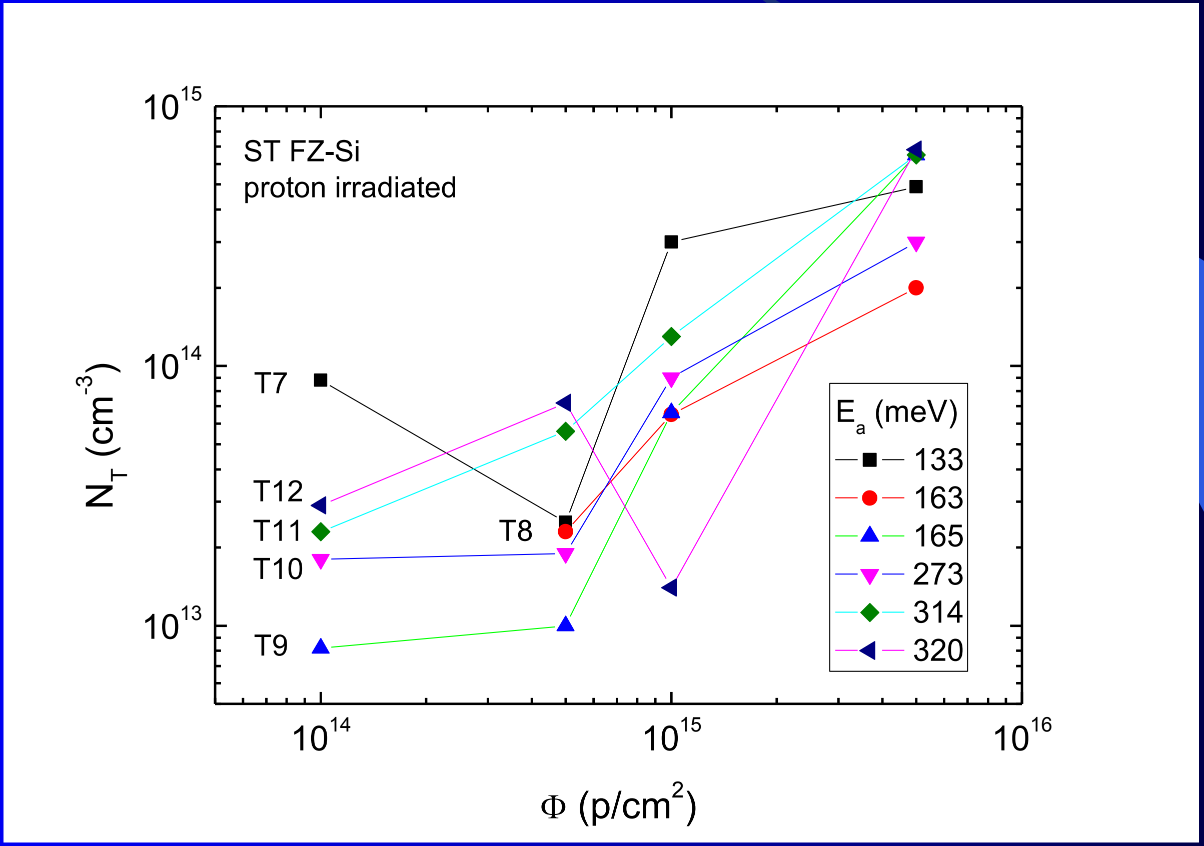
Trap label	E_a (meV)	A ($s^{-1}K^{-2}$)	Comment
T1	31±1	(1.8±0.6)E+5	
T2	36±1	(3.8±1.3)E+5	
T3	54±2	(8.4±2.8)E+6	
T4	62±2	(8.0±2.6)E+5	
T5	72±2	(8.0±2.6)E+5	
T6	84±3	(7.1±2.3)E+5	
T7	133±4	(4.2±1.4)E+6	I_3(+/0) ?
T8	163±5	(1.8±0.6)E+7	VO_i(-/0)
T9	165±5	(9.9±3.3)E+5	
T10	273±8	(4.2±1.4)E+7	
T11	314±9	(2.9±0.9)E+7	
T12	320±10	(1.0±0.33)E+7	
T13	360±11	(2.9±1.0)E+7	V_3(2-/-)
T14	371±11	(1.5±0.5)E+7	C_iO_i (+/0)
T15	391±12	(2.0±0.7)E+7	
T16	401±12	(8.6±2.9)E+6	
T17	432±13	(2.3±0.8)E+7	V_2(-/0)
T18	474±14	(2.3±0.8)E+7	V_3(-/0) or V_2O(-/0) ?
T19	490±15	(1.8±0.6)E+7	
T20	563±17	(8.0±2.7)E+7	
T21	583±17	(3.5±1.2)E+7	

Shallow traps concentrations vs fluence

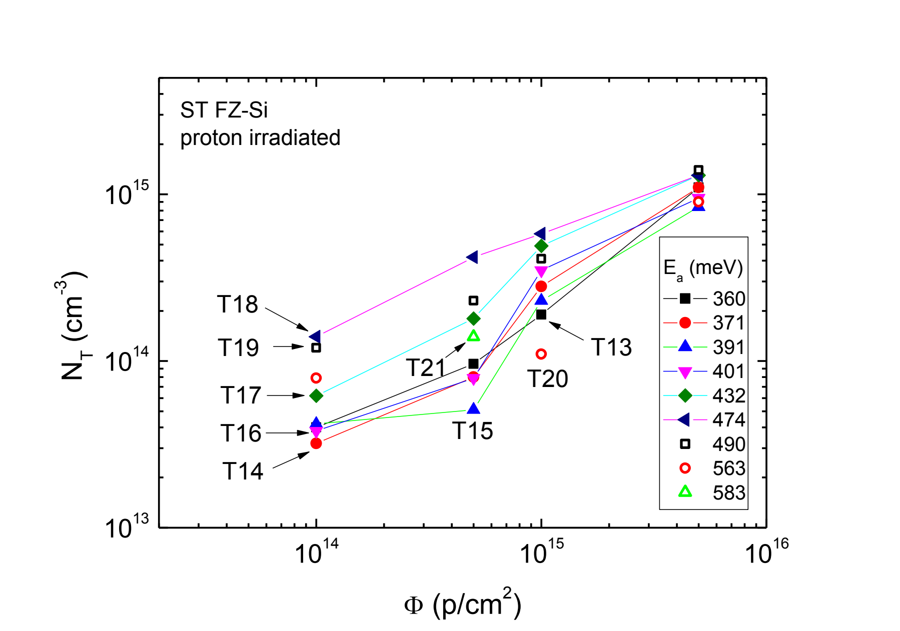


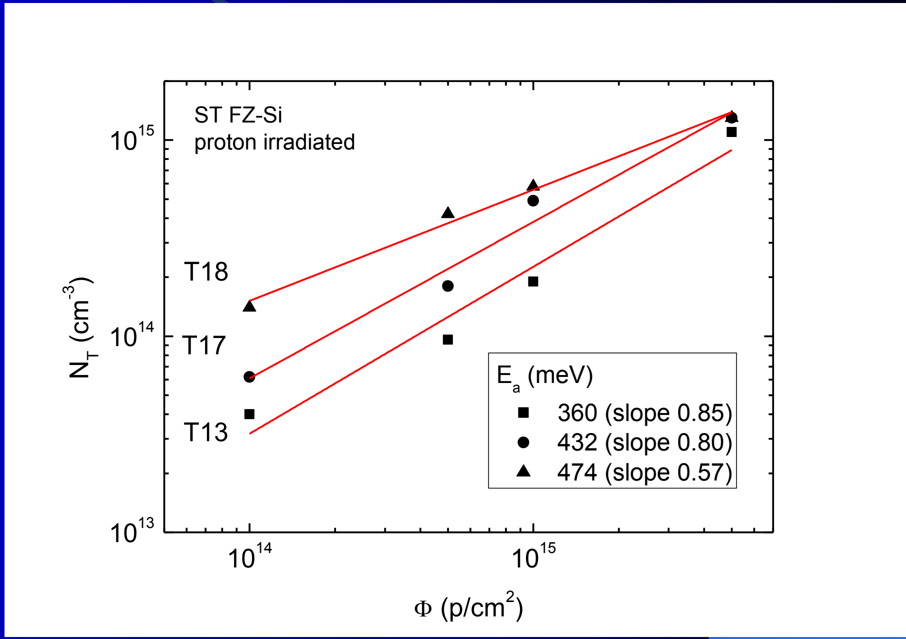


Deep traps concentrations vs fluence

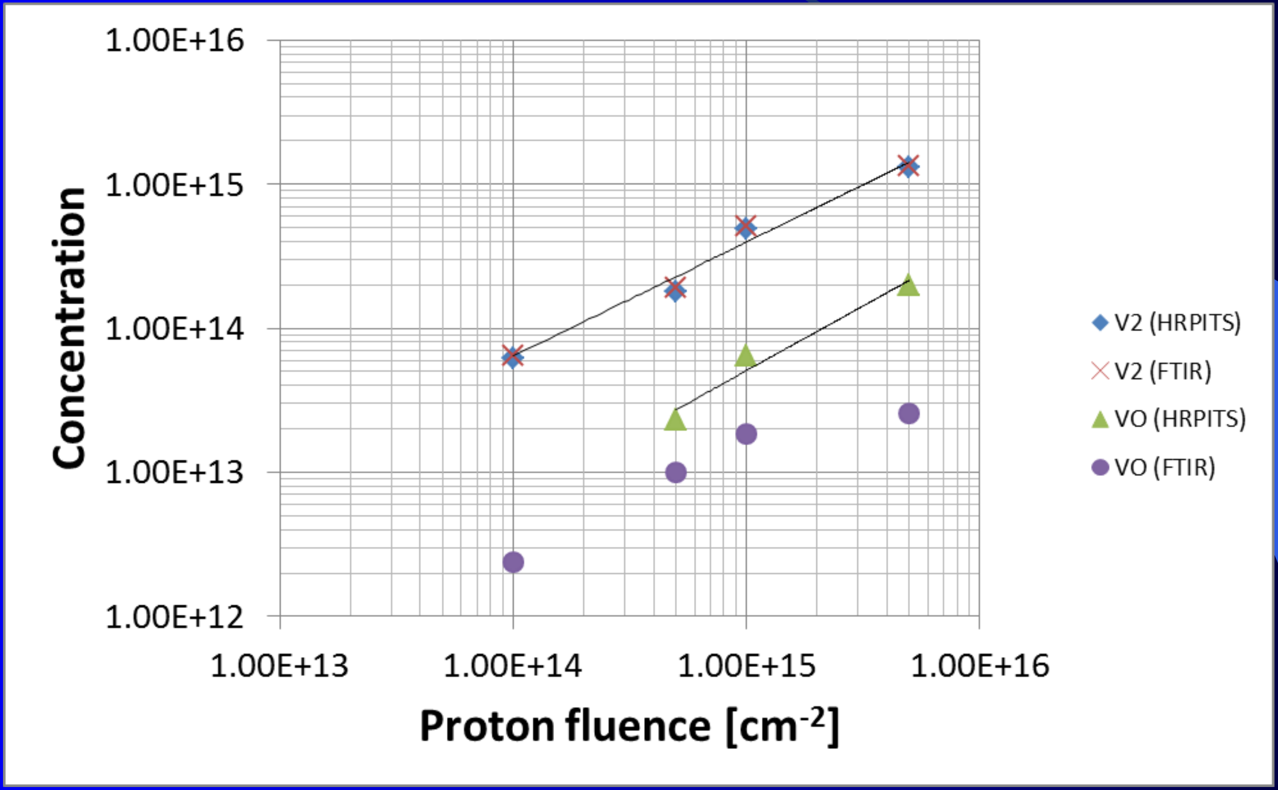


Midgap traps concentrations vs fluence





Comparison of V2 and VO concentrations



Conclusions

- We have demonstrated the effect of 23-MeV proton fluence on the properties and concentrations of electrically active radiation defect centers in detector grade, N-free, FZ Si with the resistivity of ~ 2000 Ωcm and low oxygen and carbon concentrations.
- After the irradiation with the proton fluence equal or higher than 1E14 cm^{-2} the material becomes semi-insulating with the nearly intrinsic charge carriers concentrations.
- The defect structure of the irradiated material is found to be complex. 21 irradiation-induced defect centers with activation energies of 30 – 590 meV were detected. For the majority of centers there is nearly linear increase in the concentration with the fluence.
- The divacancy concentration is found to be significantly higher than that of VO centers.

Acknowledgements

This work has been partially supported by the National Centre for Research and Development within the framework of the NitroSil project (ID: 208346) financed by the Program for Applied Research (Contract No. PBS2 / A9 / 26/2014).

Thank you for your attention

Concentration of VO defects

Calibration factor

$[VO]^* = 6.1 \times 10^{16} \times \alpha_{300K}$
$T = 300K \quad FWHM = 9 cm^{-1}$

↓

$\alpha_{4K} \times FWHM_{4K} = \alpha_{300K} \times FWHM_{300K}$

↓

α_{300K} was calculated

**A.S.Oates & R.C. Newman Appl.Phys.Latt V49 262s (1986)*

Calibration factors

$[V_2^-]^* = 5.5 \times 10^{15} cm^{-3} \times \alpha$ (2766 cm^{-1})

**G. Davies et all. Phys Rev B V73, 165202, 2006*

$V_2^0 = 2.99 \times 10^{15} \times S$ (5955 cm^{-1})

s – integrated absorption

$$N \cdot f = 8.21 \cdot 10^{16} \frac{n}{(n^2+2)^2} \int \alpha(E_F) dE_F$$

where:
N – concentration of defect (cm^{-3})
f – oscillator strength = 0.5
n – refraction index =3.42
α - absorption coefficient (cm^{-1})
E_F – photon energy (eV)