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Defect Centers in Nitrogen-Enriched High-Resistivity *n*-Type Silicon Induced by High-Energy Protons

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Outline

- Nitrogen-enriched n-type high-resistivity FZ Si
- 23-MeV proton irradiations and changes of the material properties
- Radiation defect centers
  - FTIR absorption results
  - PL results
  - HRPITS results
    - 2D spectra
    - Defect centers properties
    - Defect centers concentrations and introduction rates
- Conclusions

n-Type Nitrogen-Enriched High-Resistivity Silicon (FZ Si:N)

New Topsil's product developed within the framework of the NitroSil project that will be launched into semiconductor materials' market next year.

First *p*-in-*n* pad detectors have been made by CiS. Excellent I-V characteristics; studies of radiation hardness in progress.

Fabrication of first strip detectors in progress within the framework of RD50 NitroStrip project.

Fabrication of first monolithic integrated pad detectors for studies of transactinides elements at the Institute of Electron Technology in Warsaw.

Wafers parameters of high-resistivity FZ Si:N

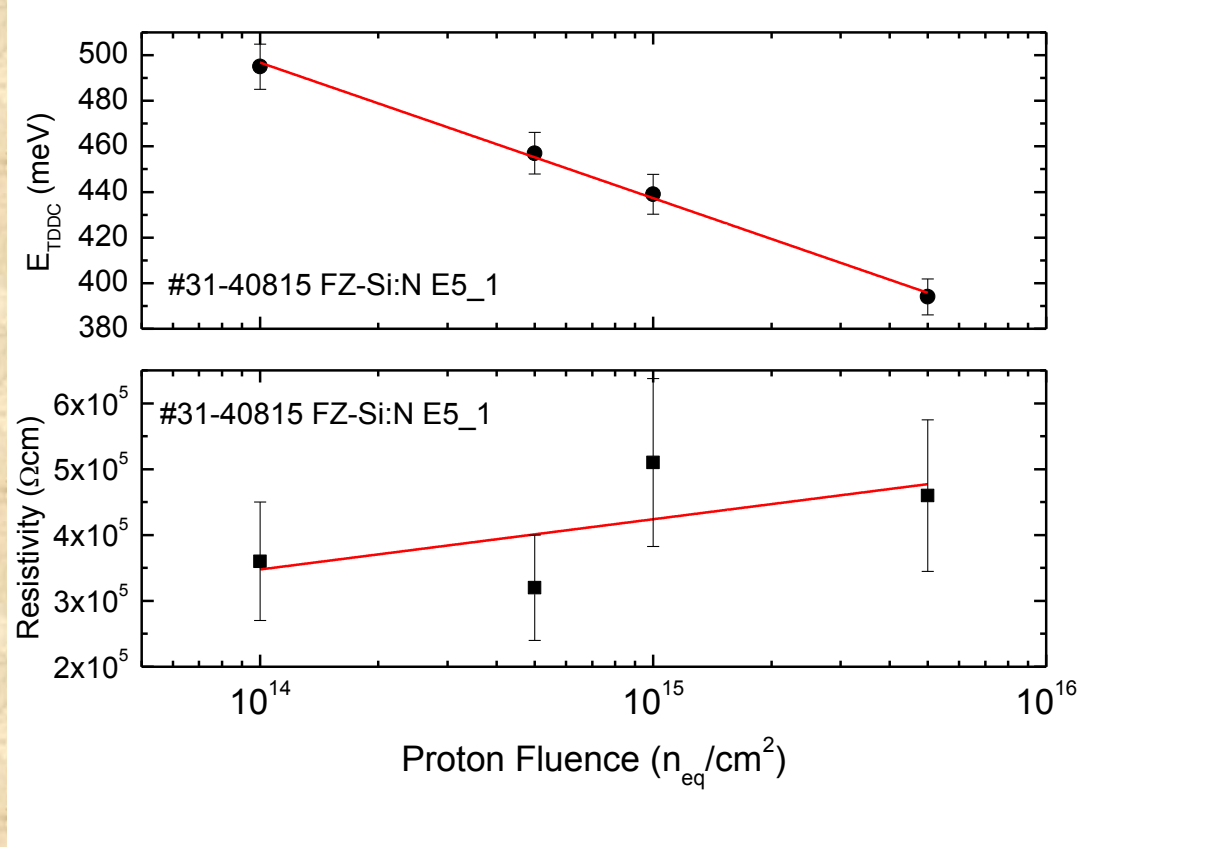
- 4” detector grade wafers, orientation: <100>, thickness: 300 µm
- NTD-doped, phosphorus concentration: ~2.5×10^{12} cm^{-3}
- Resistivity: 2200 ±200 Ωcm; exceptionally uniform radial distribution
- Nitrogen concentration: ~ 1.5×10^{15} cm^{-3}
- Residual boron concentration: < 1×10^{11} cm^{-3}
- Residual oxygen concentration: (2- 8)$\times10^{15}$ cm^{-3}
- Residual carbon concentration: < 5×10^{15} cm^{-3}
- Minority carriers lifetime and electron mobility: ~2 ms, 1600 $cm^{2/}Vs$

Proton irradiation

- Facilities: Karlsruhe Institute of Technology (KIT)
- Proton energy: 23 MeV
- Fluence: 1E14, 5E14, 1E15 and 5E15 n_{eq}/cm^2
- Proton beam current: (1.5 – 1.7) μA
- Temperature: - 20 ^{o}C

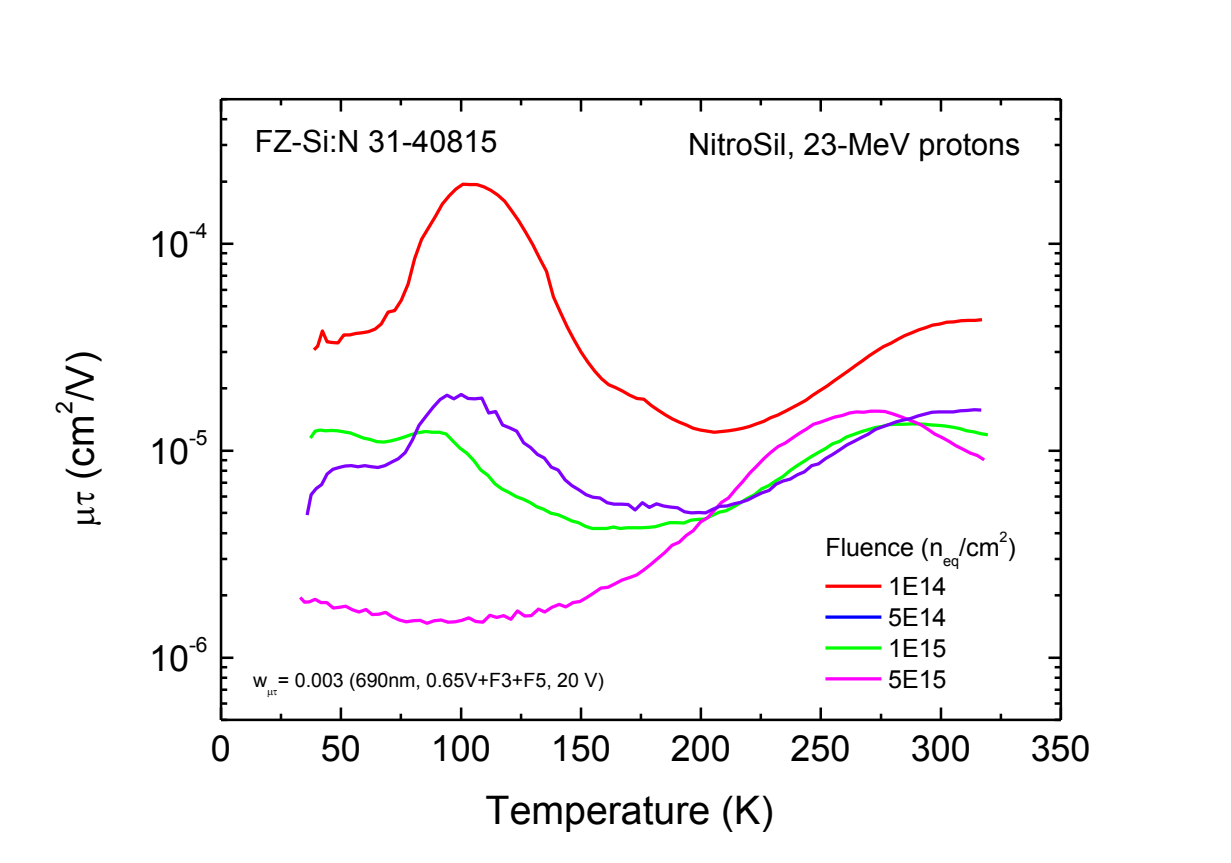
Changes of the material properties due to proton irradiation

The Fermi-level position and the resistivity at 300 K vs. proton fluence



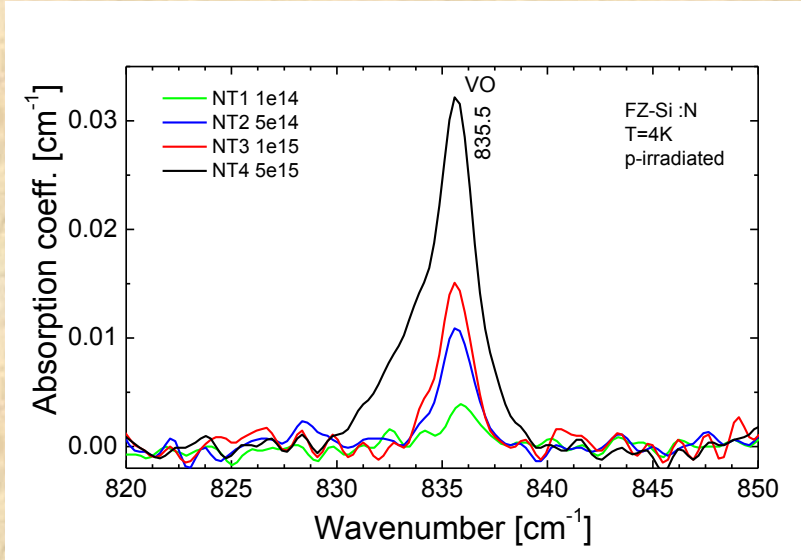
Changes of the material properties due to proton irradiation

Effect of proton fluence on the temperature dependence of the mobility-lifetime product

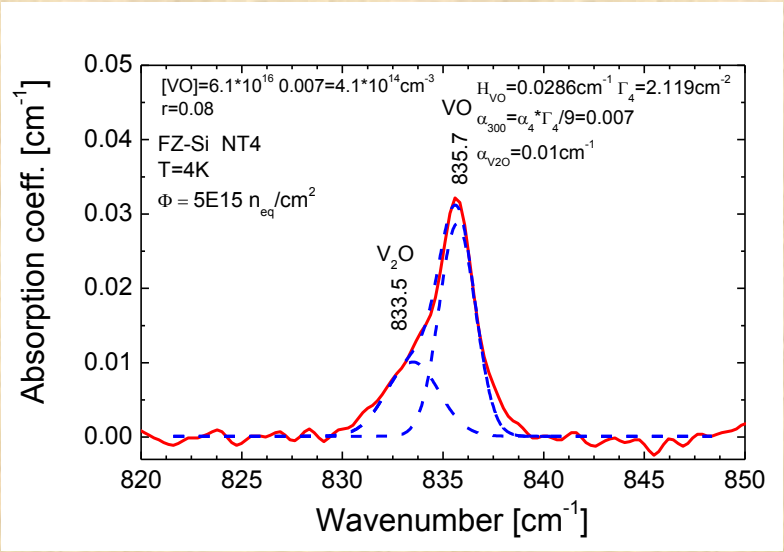


FTIR results – VO center

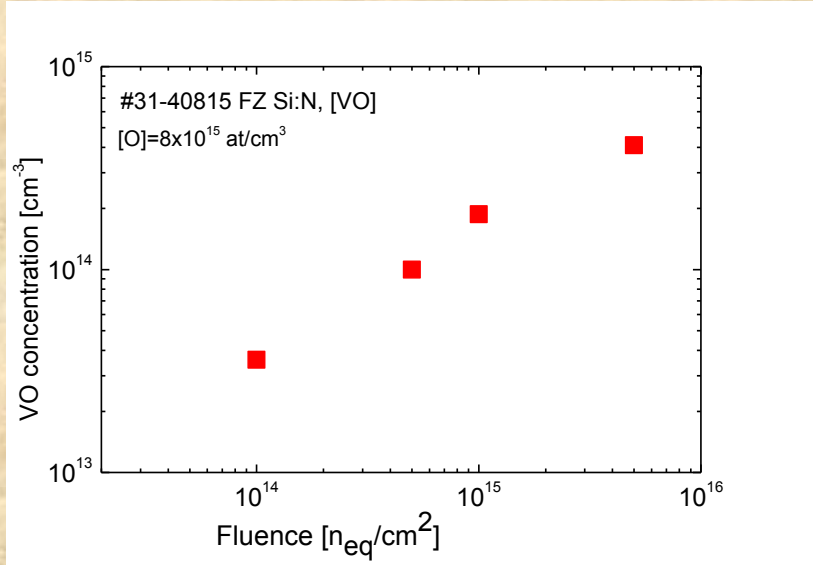
LT absorption spectra



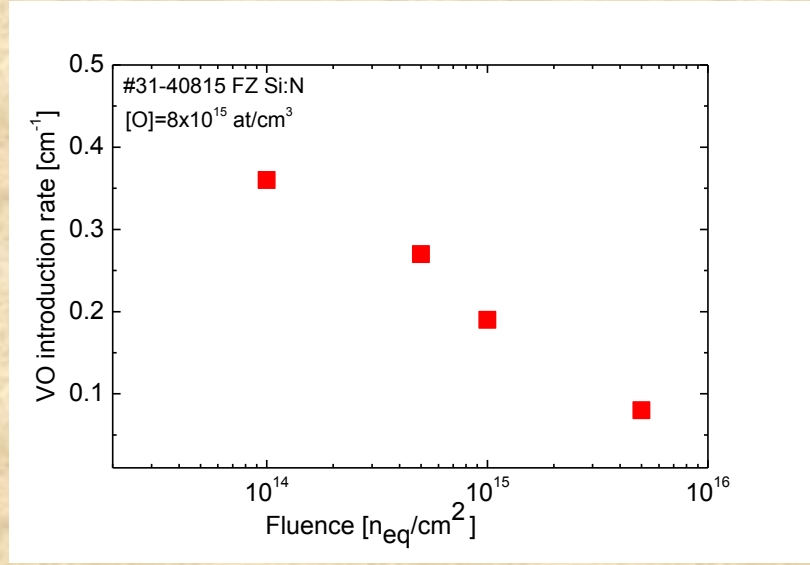
VO + V_2O for Φ = 5E15 n_{eq}/cm^2



VO concentration vs. fluence

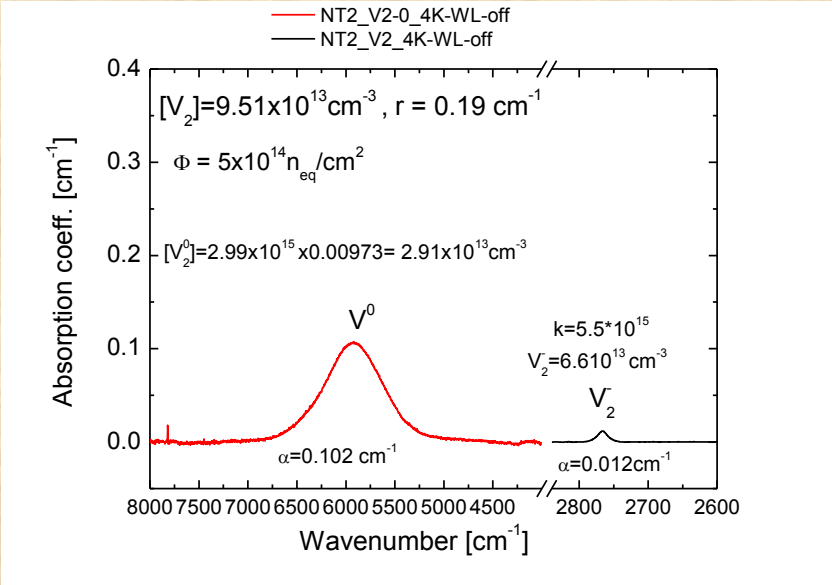


VO introduction rate vs. fluence

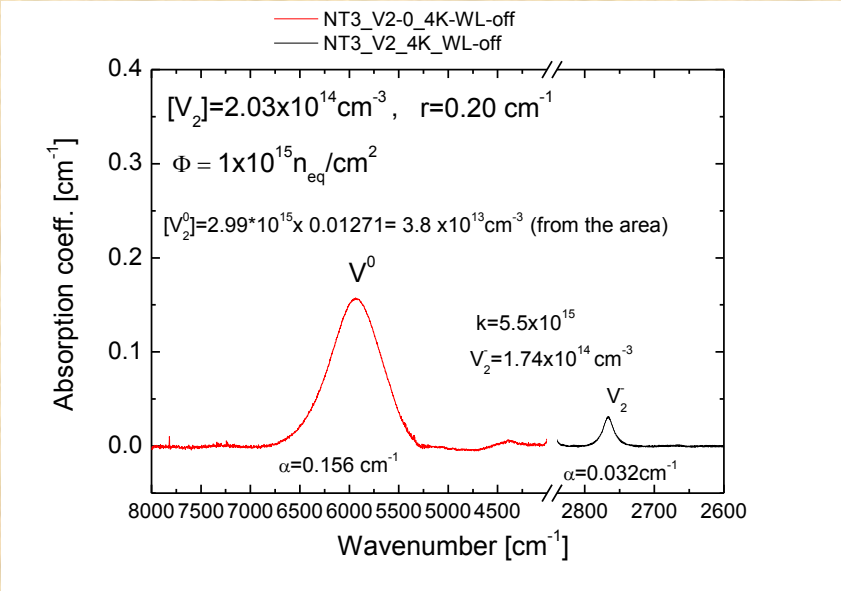


FTIR results – divacancies (V_2)

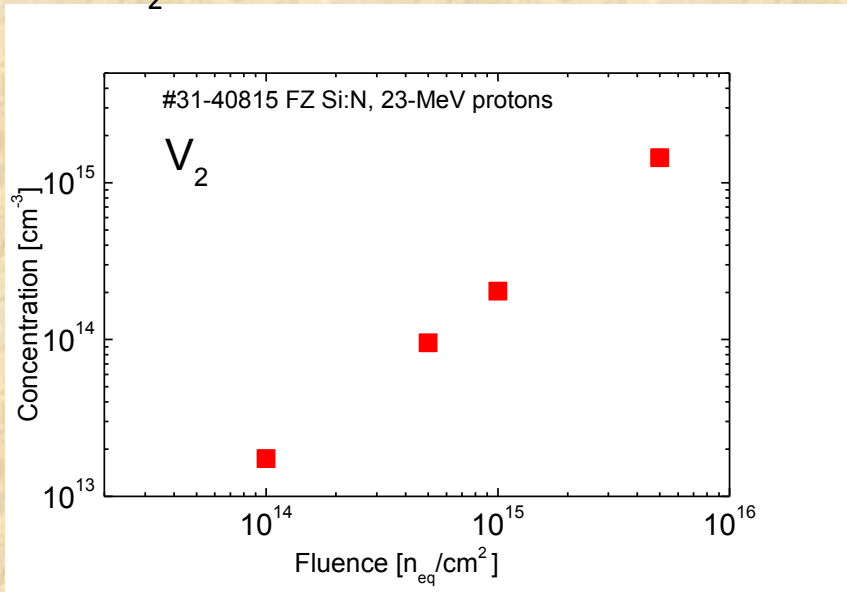
Φ = 5E14 n_{eq}/cm^2



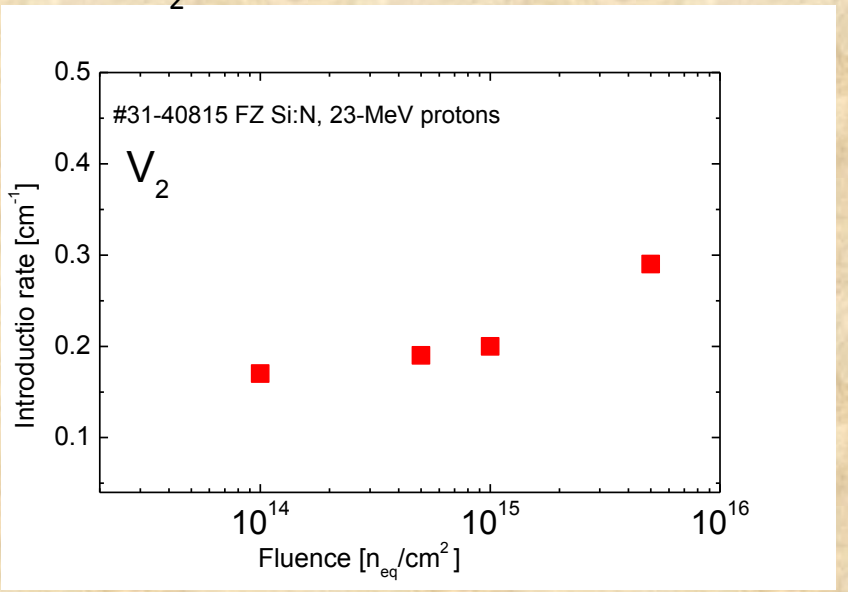
Φ = 1E15 n_{eq}/cm^2



V_2 concentration vs. fluence



V_2 introduction rate vs. fluence



$[V_2]$ - Calibration factors

V_2^- - 2767cm^{-1} intracentr transitions G.Davies at all.,PRB V73, 165202, 2006
$V_2^{0/-}$ - 5897 cm^{-1} J.H.Svenson et all.,PRB V38, 4192, 1988-II

$[V_2^-] = 5.5 * 10^{15} * \alpha$

G.Davies at all.,PRB V73, 165202, 2006

$[V_2^0] = 2.99 * 10^{15} * S$

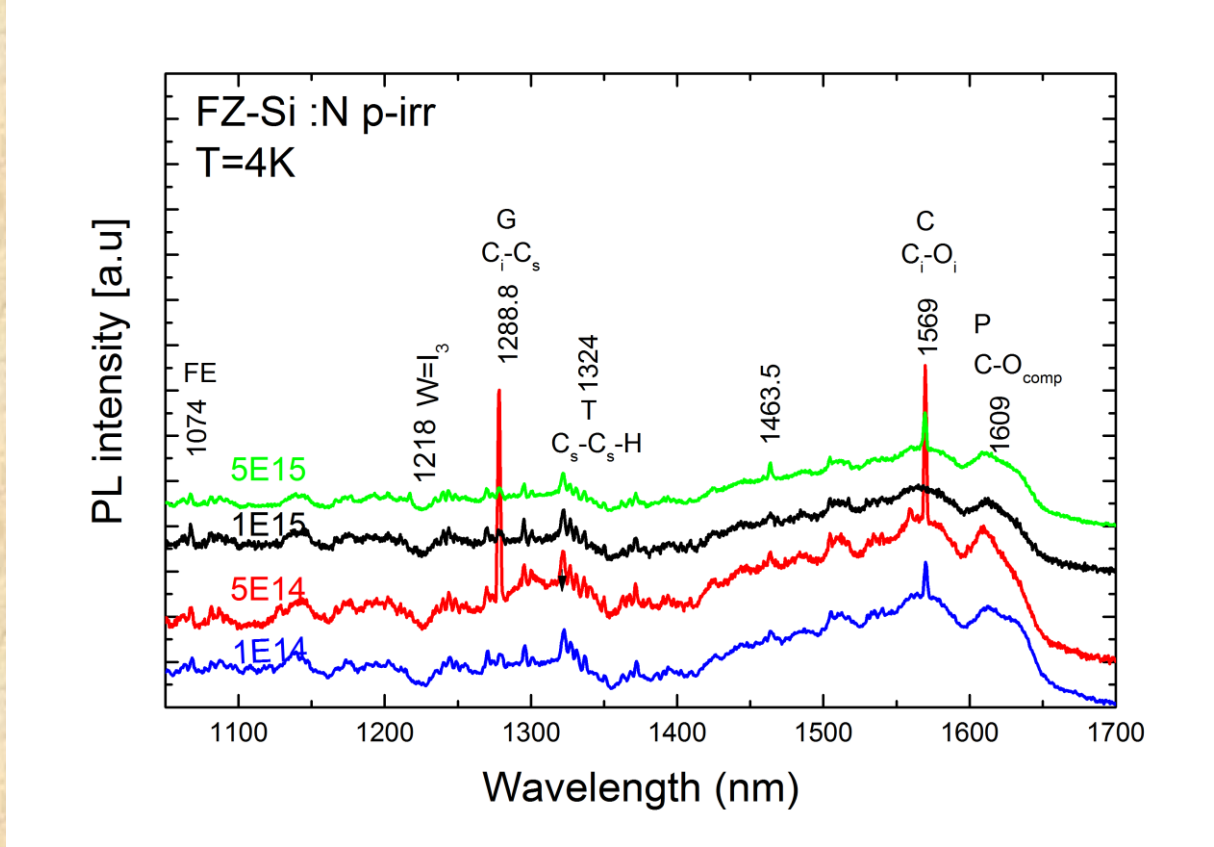
where S – integrated absorption

$$N = 1/f * 8.21 \cdot 10^{16} \frac{n}{(n^2+2)^2} \int \alpha(E_F) dE_F$$

Solid State Phys. V6 Acad.Press.London 1958, 353-411
where:
f – oscilator strength= 0.05
n – refractive index = 3.42
$\alpha(E_f)$- absorption coefficient at photon energy E_f

LT PL spectra vs. proton fluence

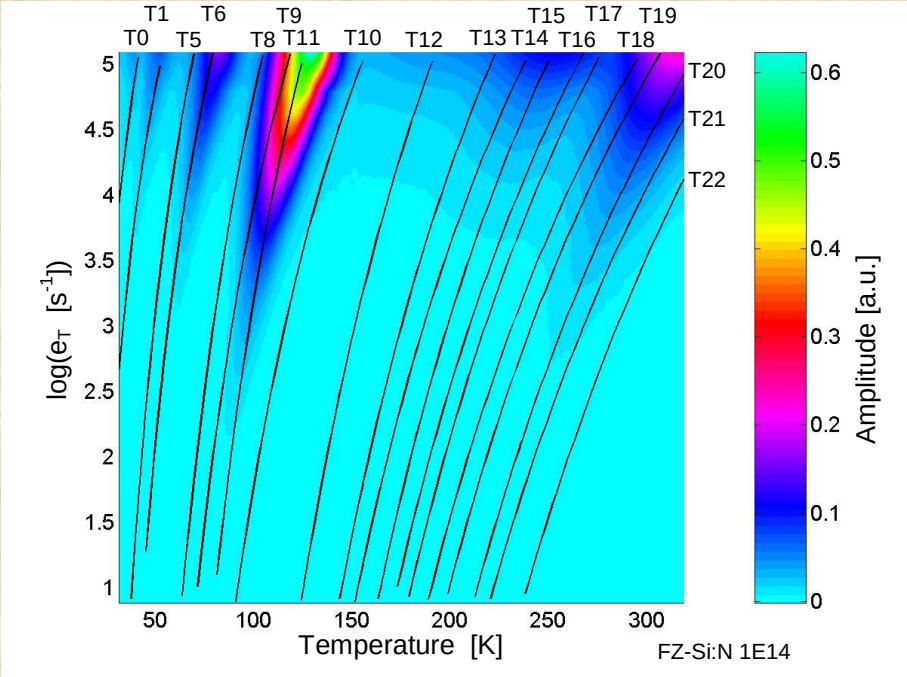
Recombination of excitons bound to radiation point defects



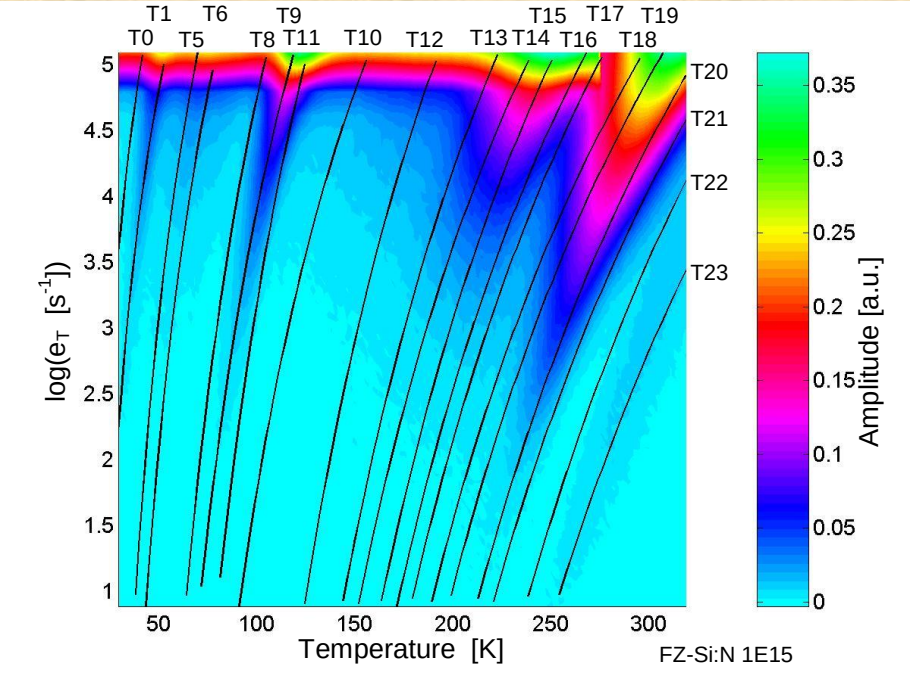
Radiation defect centers – HRPITS results

2D correlation spectra derived from the photocurrent relaxation waveforms produced by the thermal emission of charge carriers from defect centers. 20 traps with activation energies ranging from 24 to 565 meV are detected.

Proton fluence: 1E14 n_{eq}/cm^2



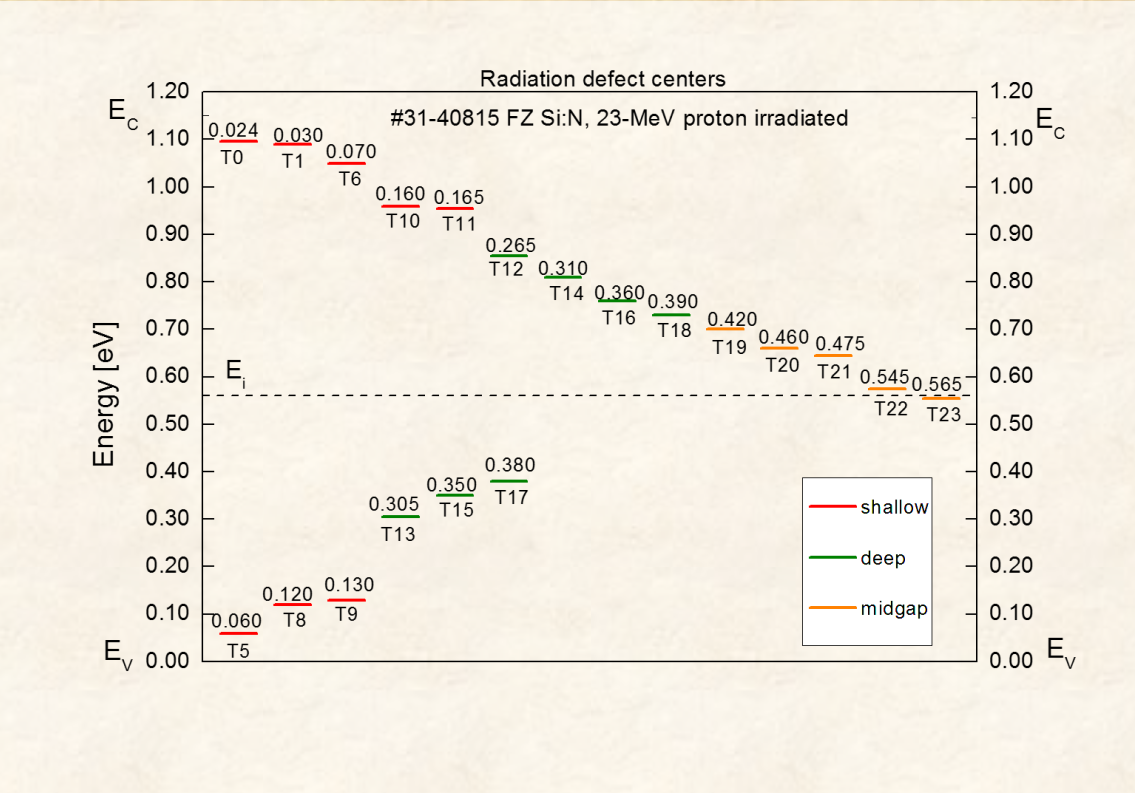
Proton fluence: 1E145 n_{eq}/cm^2



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 results – Radiation defect centers

Positions of detected defect levels in the Si bangap



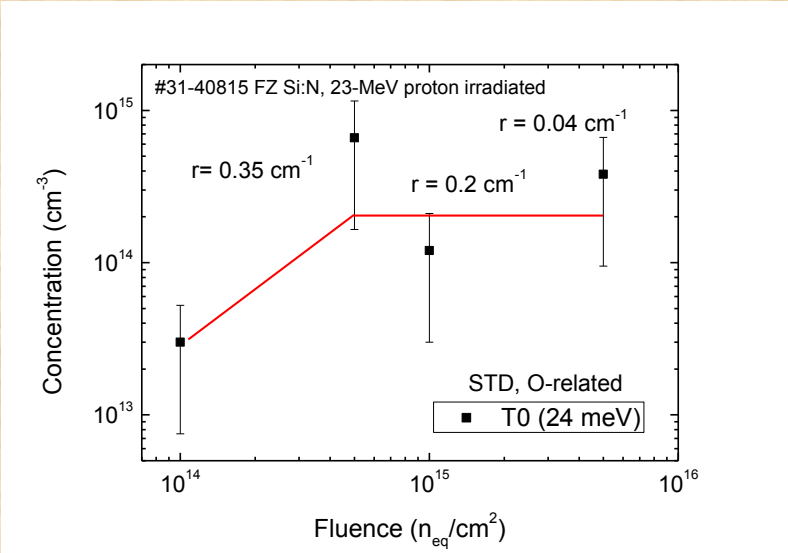
HRPITS results – Radiation defect centers properties

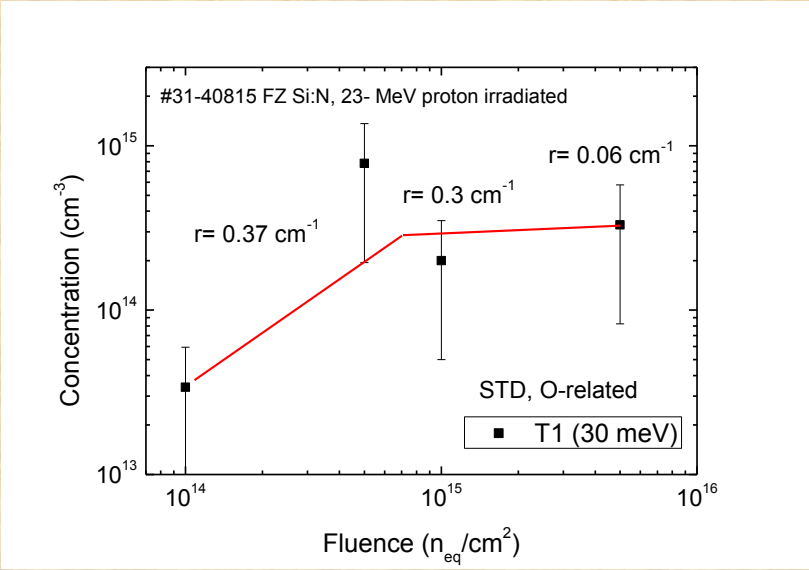
Summary of traps parameters

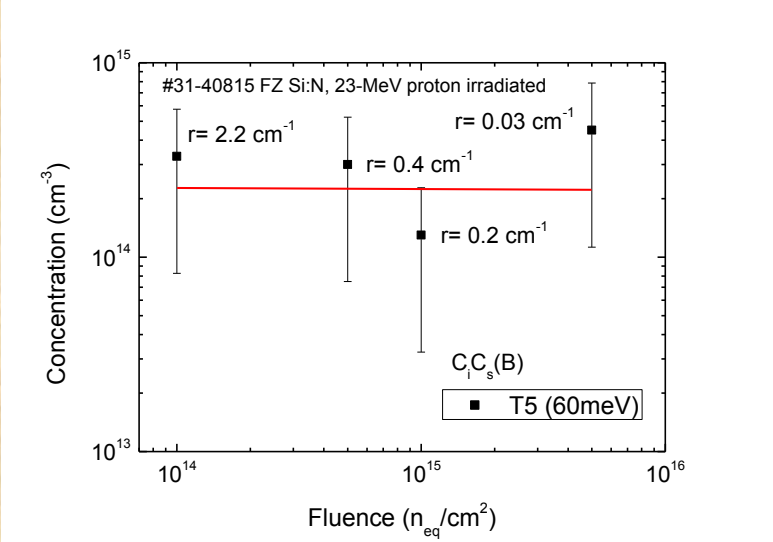
Defect label	E_a (meV)	A ($K^{-2}s^{-1}$)	Tentative identification
T0	24	5.4×10^4	*e*, STD
T1	30	2.8×10^4	*e*, STD
T5	60	5.0×10^5	*h*, C_iC_s (B) (+/0)
T6	70	5.5×10^5	*e*, OTD
T8	120	6.2×10^6	*e*, C_i (-/0)
T9	130	2.8×10^6	*h*, I_3 (+/0)
T10	160	6.6×10^5	*e*, OTD
T11	165	3.1×10^7	*e*, VO (-/0)
T12	265	2.8×10^7	*e*, E_c-270 meV, I-related
T13	305	1.9×10^7	*h*, C_i (+/0)
T14	310	6.7×10^6	*e*, VOH (-/0)
T15	350	1.9×10^7	*h*, VOC?
T16	360	1.0×10^7	*e*, V_3 (2-/-)
T17	380	1.3×10^7	*h*, C_iO_i (+/0)
T18	390	5.7×10^6	*e*, V_4 (2-/-)?
T19	420	1.5×10^7	*e*, V_2 (-/0)
T20	460	1.5×10^7	*e*, V_3 (-/0)
T21	475	1.2×10^7	*e*, V_2O (-/0)
T22	545	5.3×10^7	*e*, V_4 (-/0)?
T23	565	2.3×10^7	*e*, V_5 (-/0)?

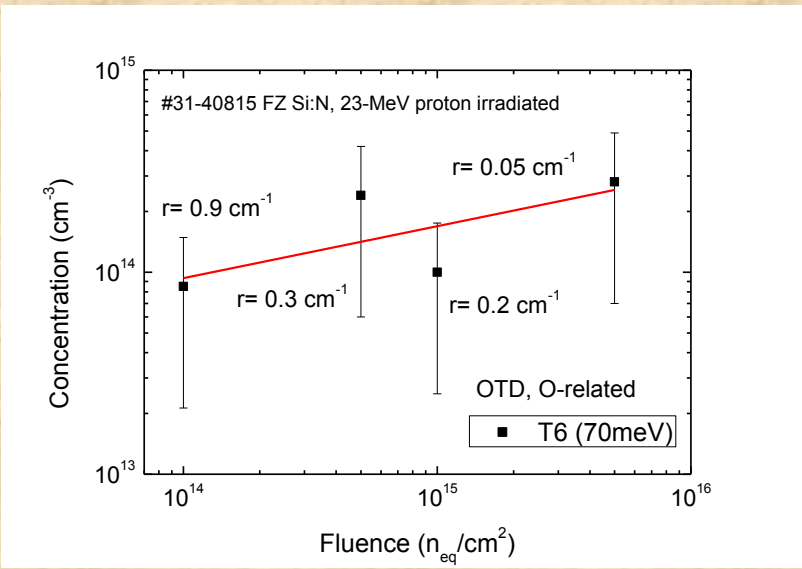
HRPITS Results – Effect of Fluence on Concentrations and Introduction Rates of Radiation Defect Centers

Shallow centers (1)



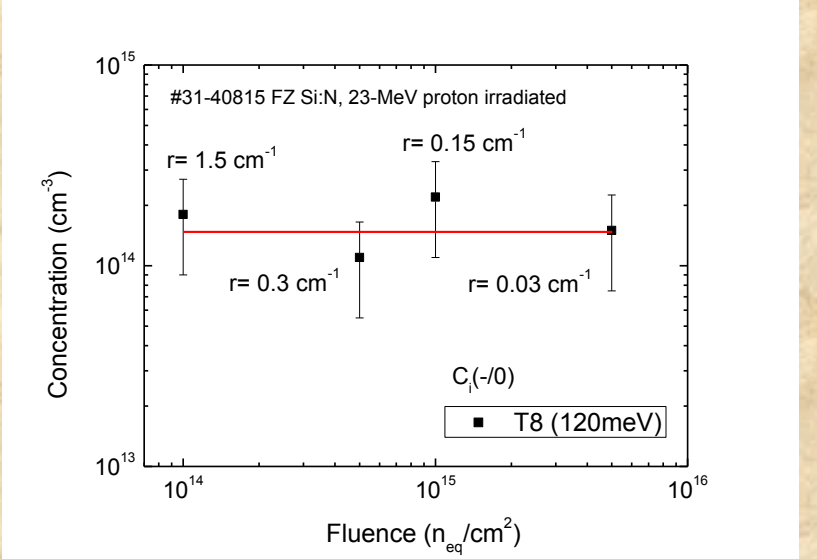


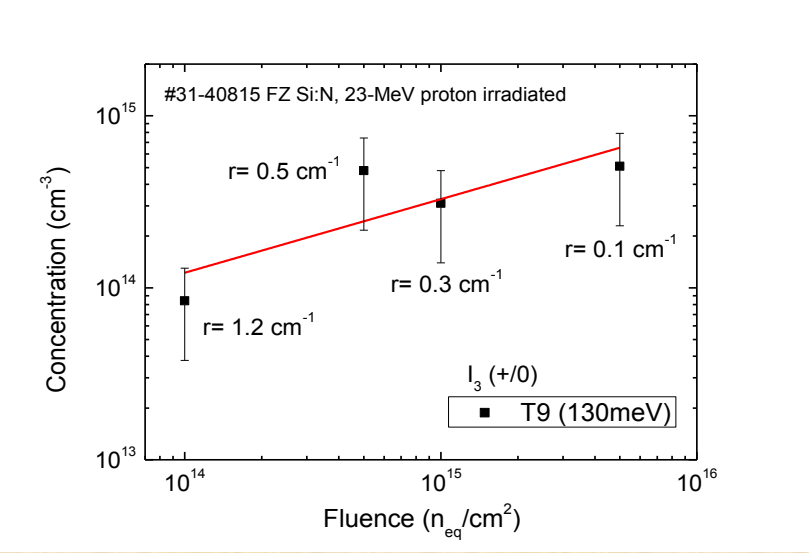


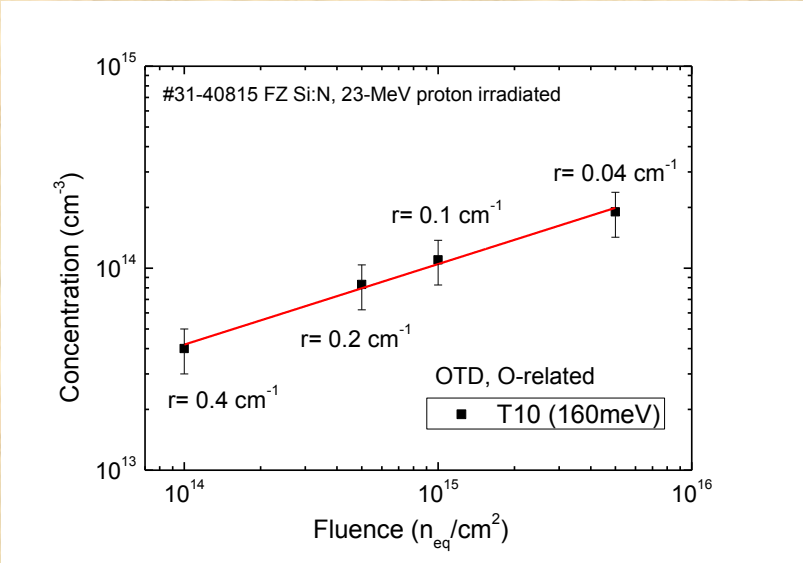


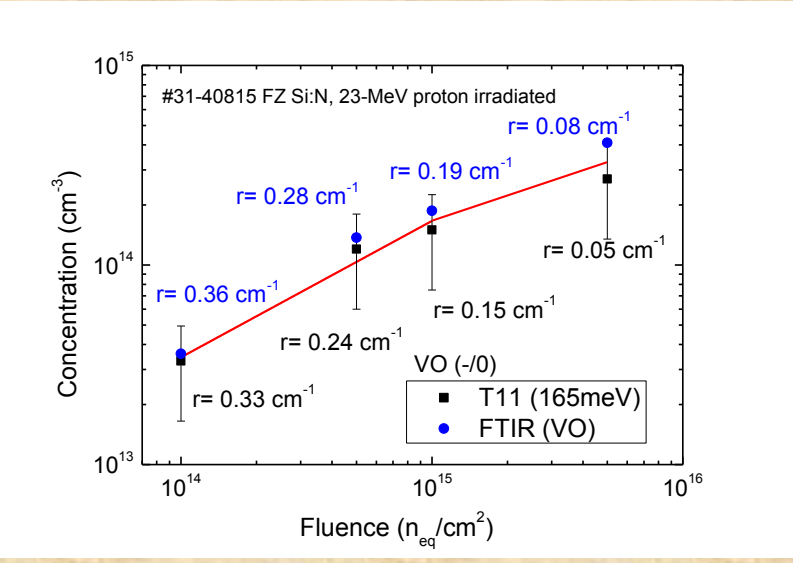
HRPITS Results – Effect of Fluence on Concentrations and Introduction Rates of Radiation Defect Centers

Shallow centers (2)



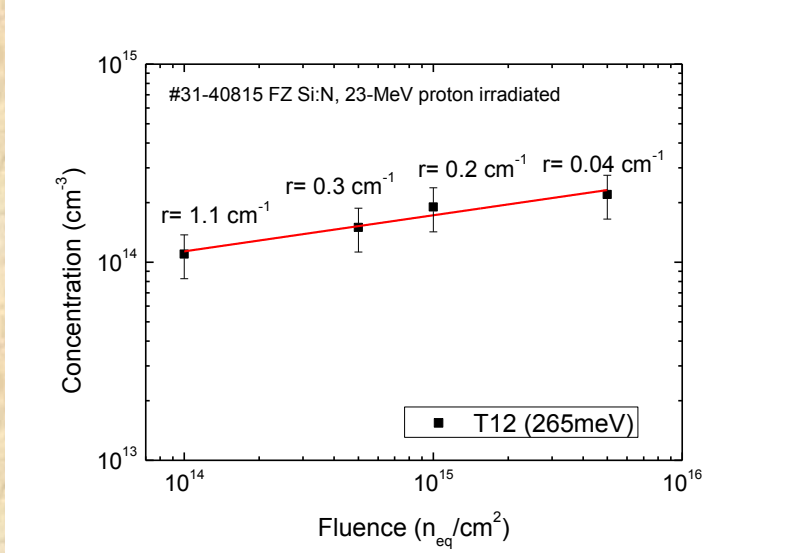


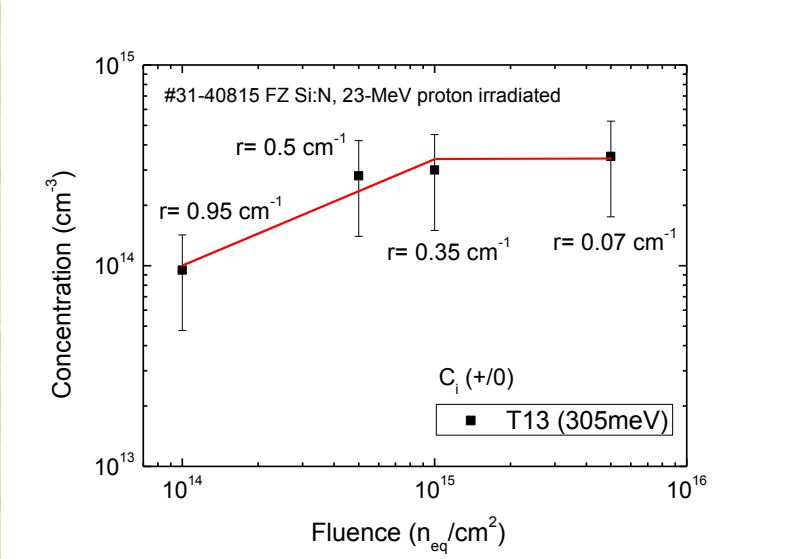


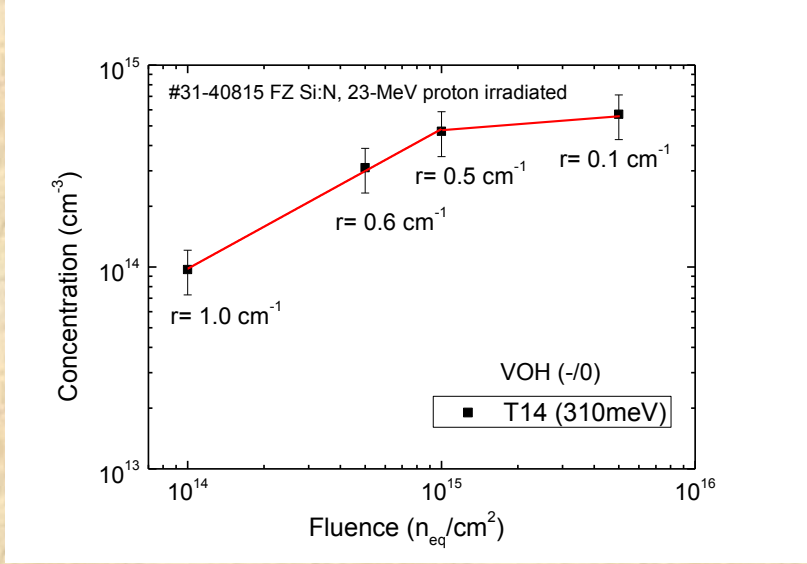


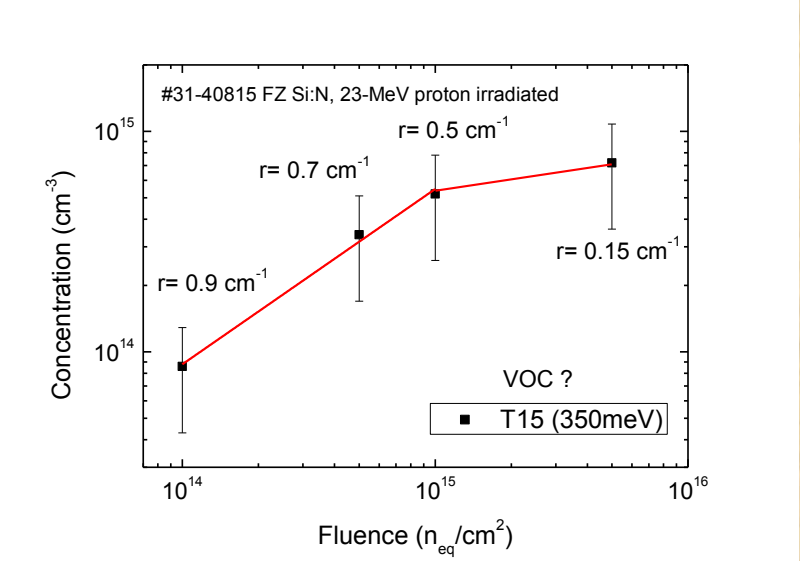
HRPITS Results – Effect of Fluence on Concentrations and Introduction Rates of Radiation Defect Centers

Deep centers (1)



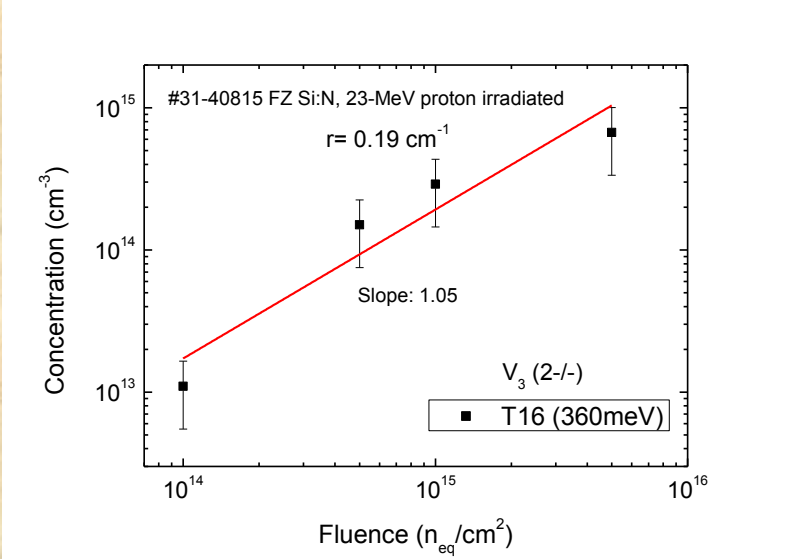


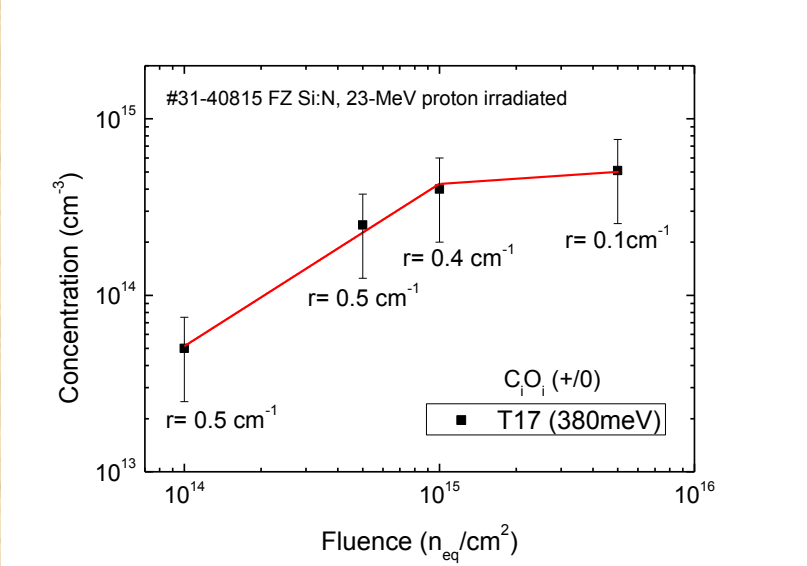


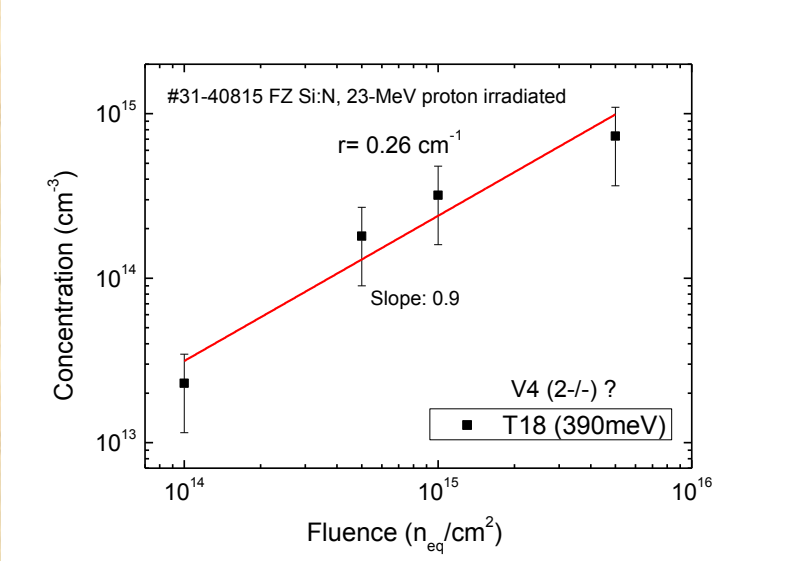


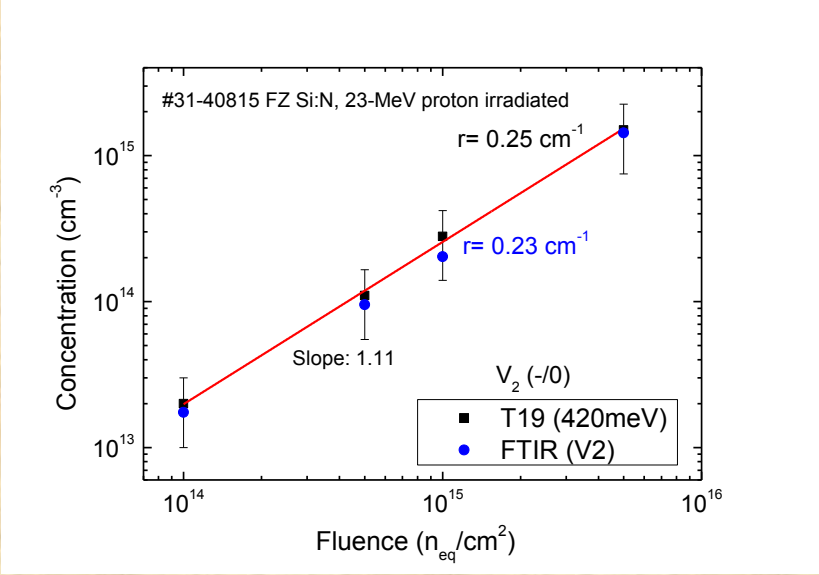
HRPITS Results – Effect of Fluence on Concentrations and Introduction Rates of Radiation Defect Centers

Deep centers (2)



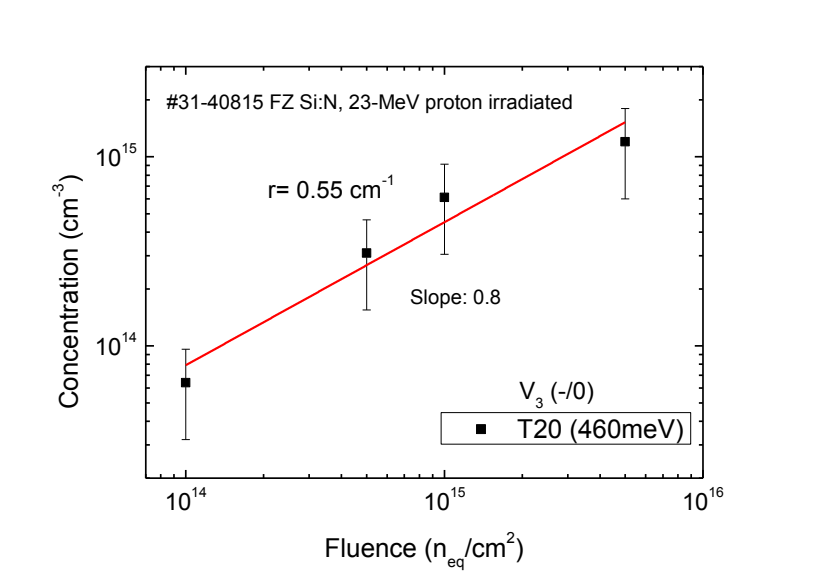


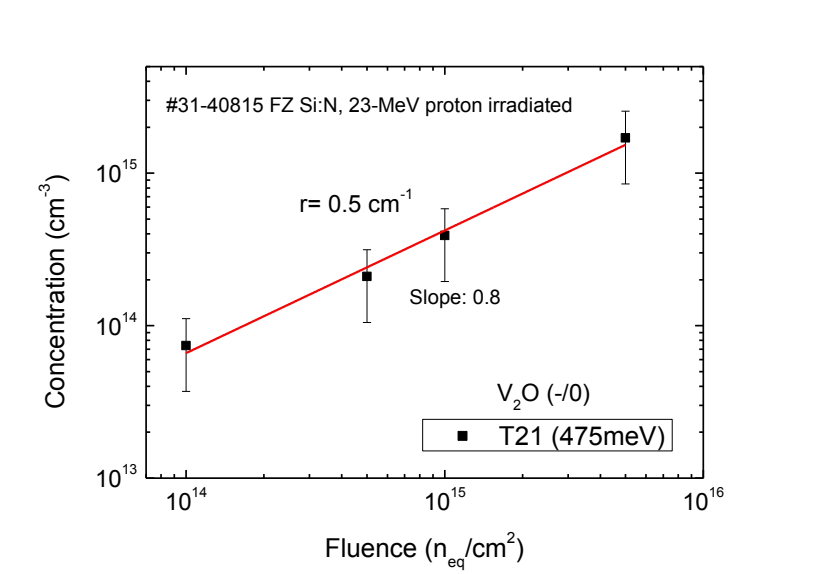


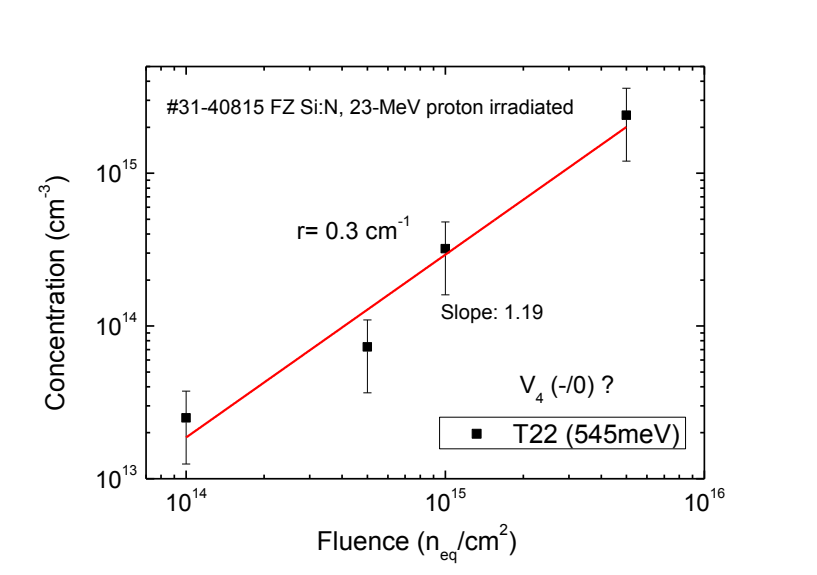


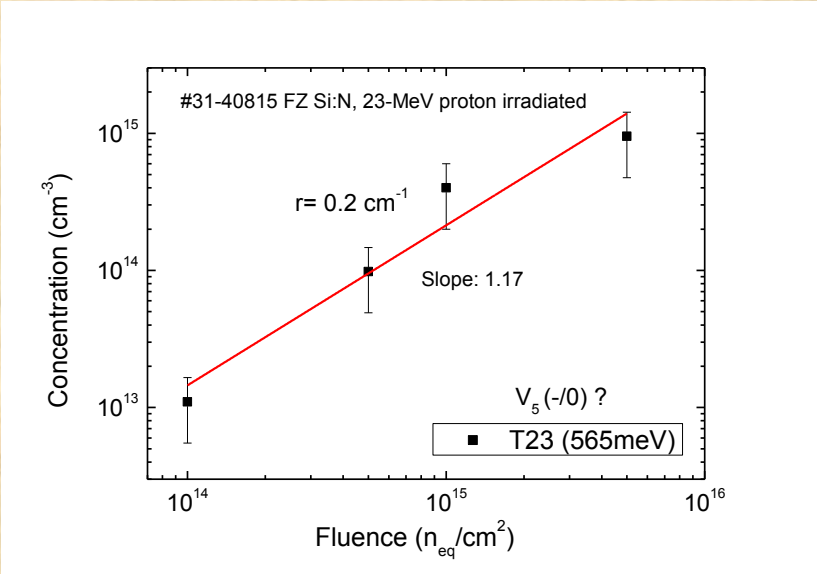
HRPITS Results – Effect of Fluence on Concentrations and Introduction Rates of Radiation Defect Centers

Midgap centers

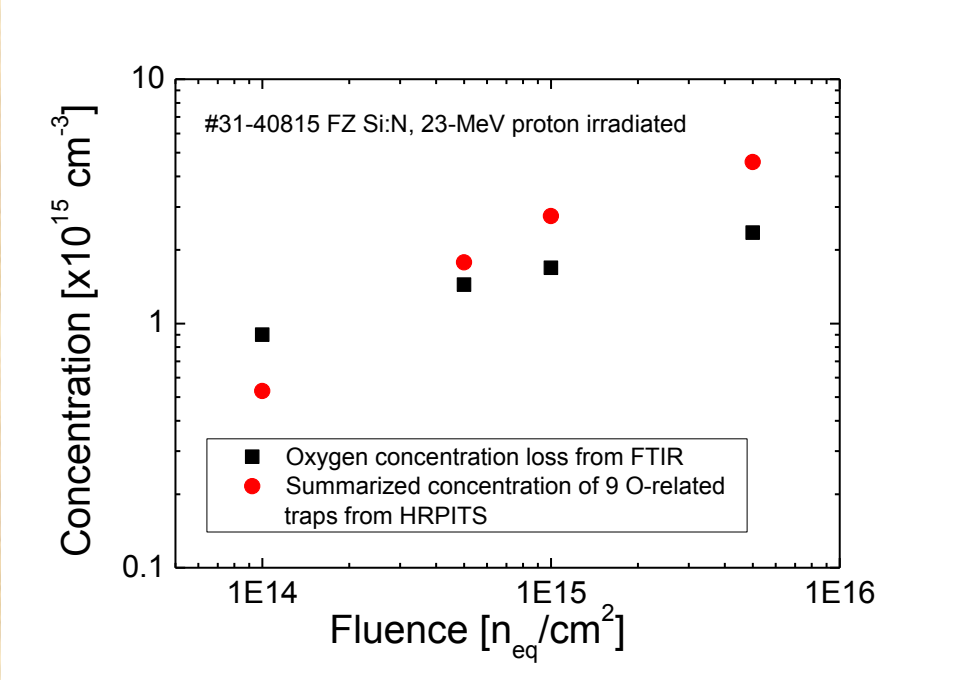








Comparison of the loss in the interstitial oxygen concentration induced by the proton irradiation and the total concentration of the oxygen related defect centers vs. proton fluence



Conclusions

- We have studied the effect of 23-MeV proton fluence, ranging from 1E14 to 5E15 n_{eq}/cm^2, on the properties and concentrations of irradiation-induced point defects in *n*-type high-resistivity FZ silicon enriched with nitrogen.
- Twenty radiation defect centers with activation energies ranging from 24 to 565 meV have been revealed. These centers can be attributed to three categories: residual oxygen related, residual carbon related and small aggregates of vacancies.
- For the defect centers related to the residual impurities, except for the V_2O, the introduction rate significantly decreases with increasing the proton fluence. For the centers related to the small vacancy clusters, the introduction rate is nearly constant with the fluence rise. The highest introduction rate, equal to 0.55 cm^{-1}, is for trivacancies V_3 (-/0).

Acknowledgements

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Thank you for your attention