



Effect of nitrogen-doping on characteristics of pad detectors irradiated with high proton fluences

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30th RD50 Workshop 5 -7 June 2017, AGH Kraków, Poland

Outline

- Starting material: N-free and N-rich *n*-type, HR FZ Si wafers
- *p*-in-*n* pad detectors with various properties of the active region material: N-free, N-rich, and O-rich (DOFZ)
- 23-MeV proton irradiations: 5E13, 1E14, 5E14, 1E15, and 5E15 $n_{\text{eq}}/\text{cm}^2$
- Effect of nitrogen-doping on: the active region material resistivity, electron mobility-lifetime product ($\mu\tau$) and leakage current after proton irradiation
- Radiation defect centers produced in the detectors active region material by the proton irradiations – HRPITS results
- Effect of nitrogen-doping on the concentrations of irradiation induced defect centers
- Conclusions

p-in-*n* pad detectors fabricated on *n*-type high-resistivity N-free and N-rich FZ Si wafers, \varnothing 100 mm

Detectors active region materials with various properties

1

Standard high-resistivity *n* type FZ Si wafers P-doped in NTD process

Orientation	ρ (300 K) [Ωcm]	[P] [cm^{-3}]	[B] [cm^{-3}]	[N] [cm^{-3}]	[O] [cm^{-3}]	[C] [cm^{-3}]	Processing at CiS
(100)	2200	2.4×10^{12}	$< 1 \times 10^{11}$	$< 2 \times 10^{14}$	5×10^{15}	$(1-5) \times 10^{15}$	Standard

2

High-resistivity *n* type N-rich FZ Si:N wafers N-enriched during the crystal growth and P-doped in NTD process

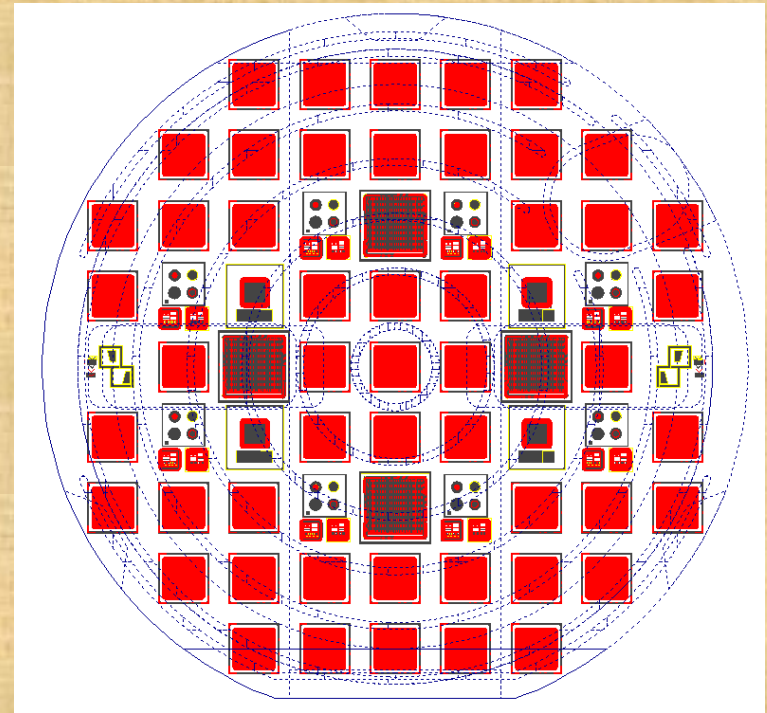
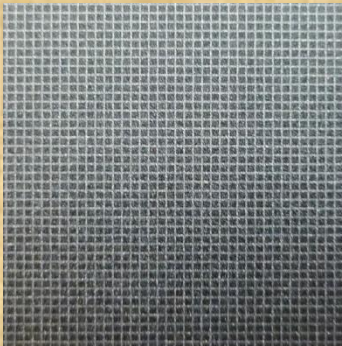
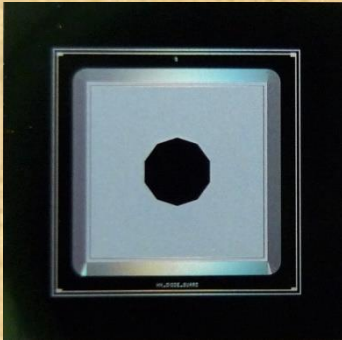
Orientation	ρ (300 K) [Ωcm]	[P] [cm^{-3}]	[B] [cm^{-3}]	[N] [cm^{-3}]	[O] [cm^{-3}]	[C] [cm^{-3}]	Processing at CiS
(100)	2000	3.9×10^{12}	$< 1 \times 10^{11}$	1.5×10^{15}	8×10^{15}	$(1-5) \times 10^{15}$	Standard

3

Standard high-resistivity *n* type FZ Si wafers P-doped in NTD process and O-enriched at CiS by oxygen in-diffusion from oxide layer (24 h, 1150 °C) – DOFZ material,
 $[O] = 3.8 \times 10^{17} \text{ cm}^{-3}$

p -in- n pad detectors with various properties of the active region material (FZ Si) : N-free, N-rich, and O-rich (DOFZ)

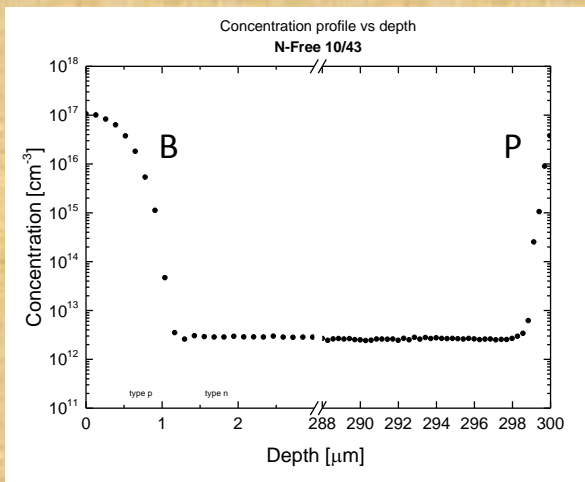
Detector type: STDW01A



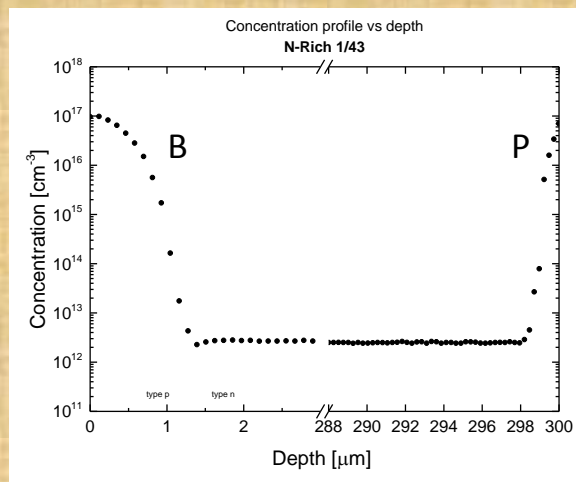
p -in- n pad detectors with various properties of the active region material (FZ Si) : N-free, N-rich, and O-rich (DOFZ)

Doping profiles for unirradiated detectors

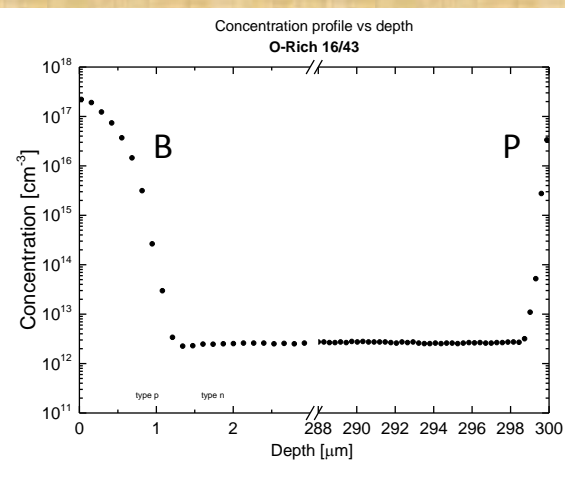
N-free material



N-rich material



N-free DOFZ material

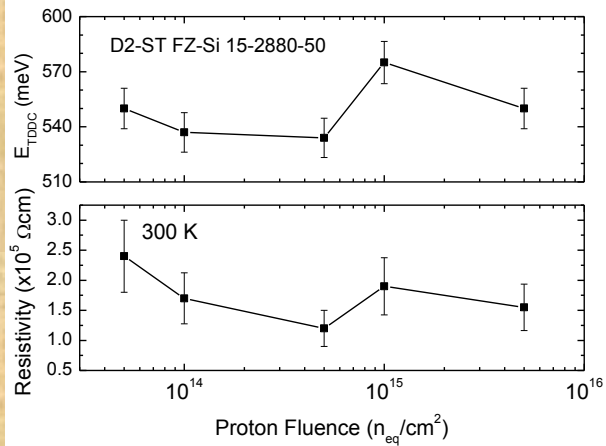


Proton irradiation

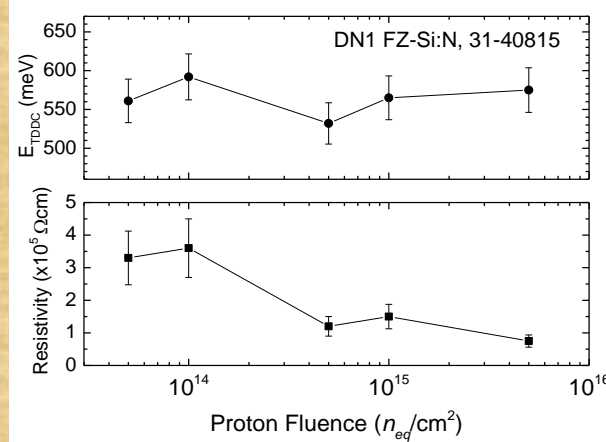
- Facilities: Karlsruhe Institute of Technology (KIT)
- Proton energy: 23 MeV
- Fluence: $5E13$, $1E14$, $5E14$, $1E15$
and $5E15$ n_{eq}/cm^2
- Proton beam current: $(1.5 - 1.7) \mu A$
- Temperature: $- 20 \text{ }^\circ C$

Effect of nitrogen-doping on the active region material resistivity at 300 K after proton irradiation

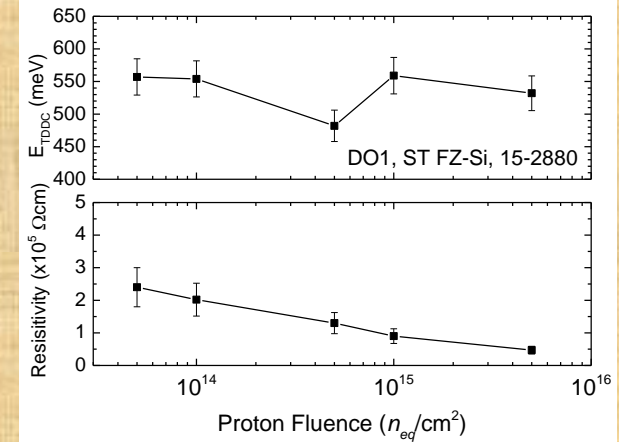
N-free material



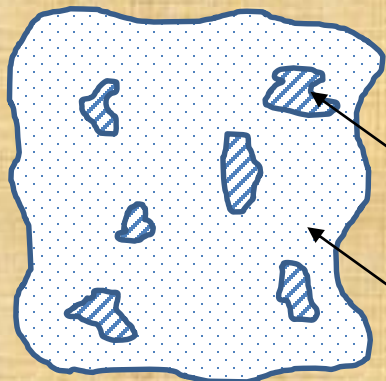
N-rich material



N-free DOFZ material



Model



Disordered regions
(high density defects clusters)
with resistivity ρ_d

Point defects regions with
resistivity ρ_p

$$\text{Total resistivity: } \rho_t = \rho_p \rho_d / (\rho_p + \rho_d)$$

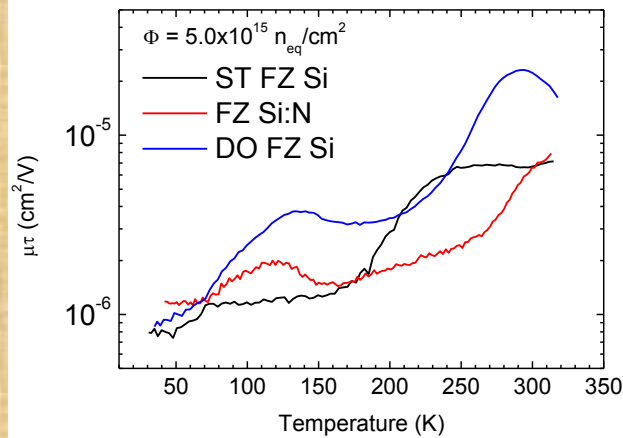
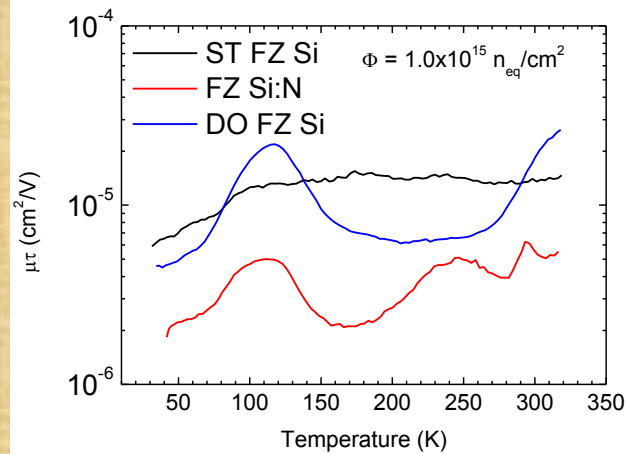
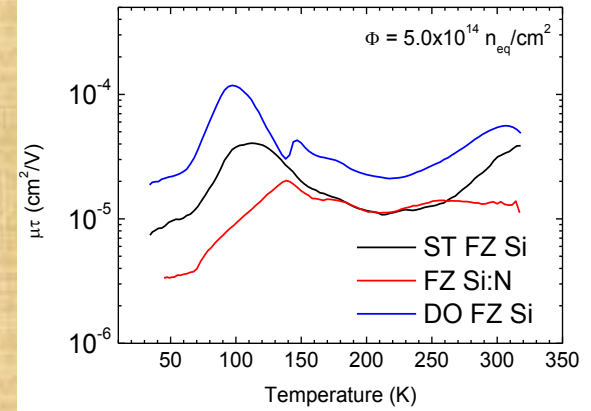
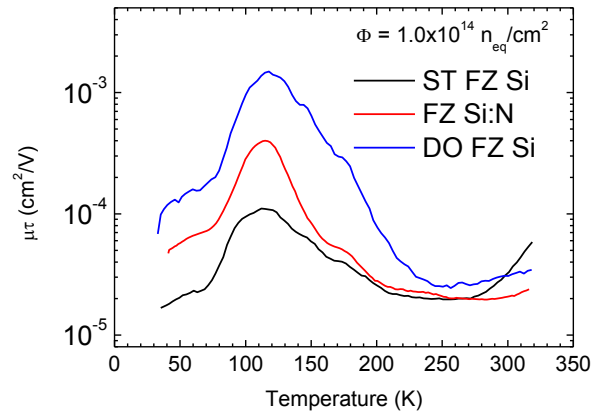
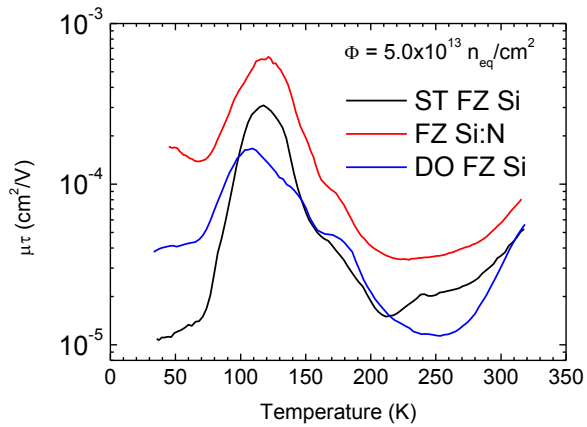
$$\text{Total conductivity: } \sigma_t = \sigma_p + \sigma_d$$

Fluence (n_{eq}/cm^2): 1E14, 5E14, 1E15, 5E15

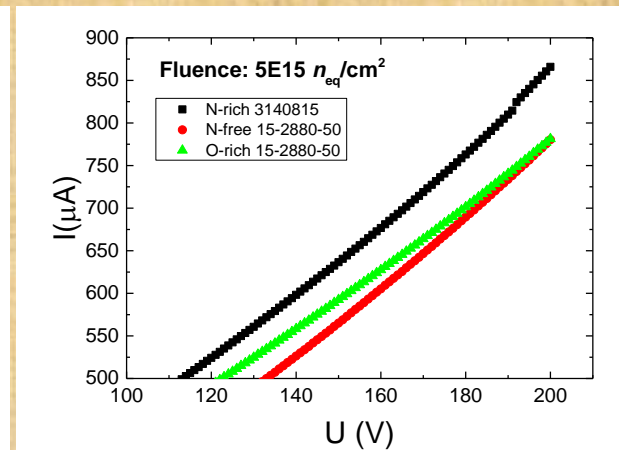
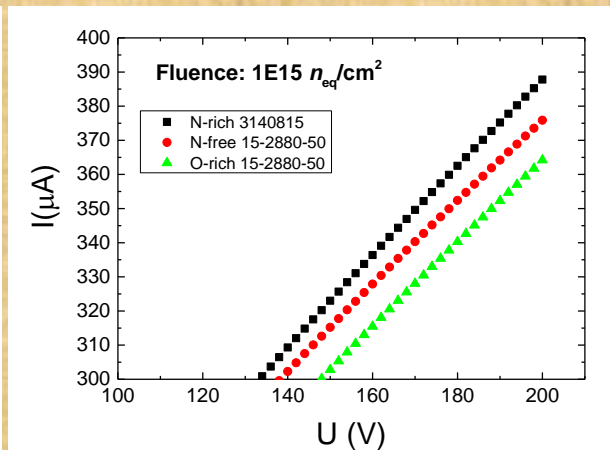
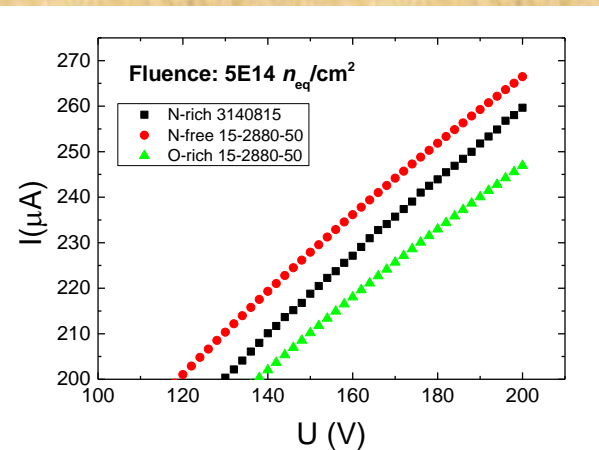
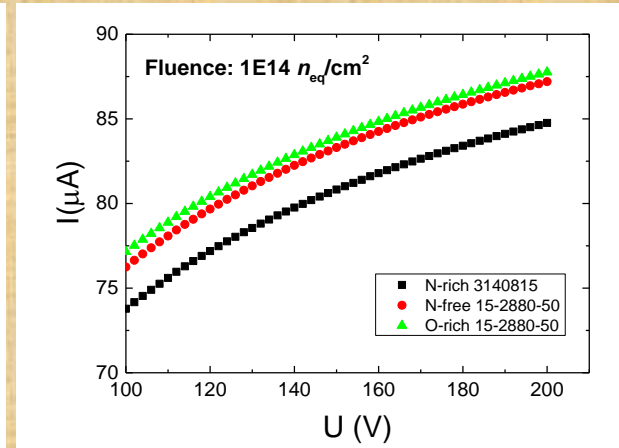
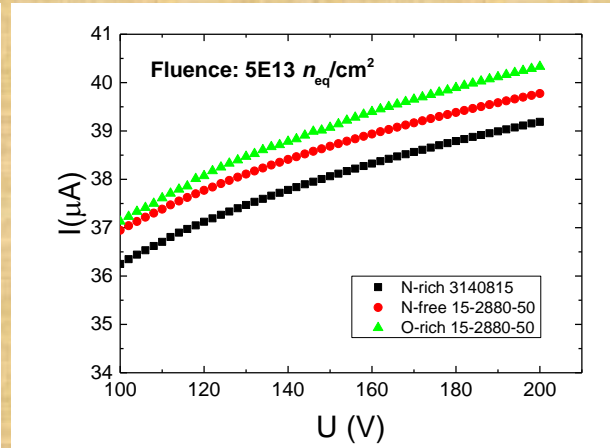
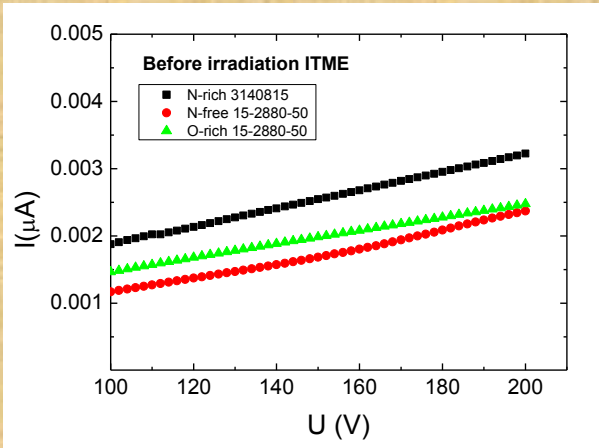
N-free σ_d/σ_t : 0.70, 0.75, 0.81, 0.91

N-rich σ_d/σ_t : 0.04, 0.12, 0.59, 0.70

Effect of nitrogen-doping on the electron mobility-lifetime product ($\mu\tau$)



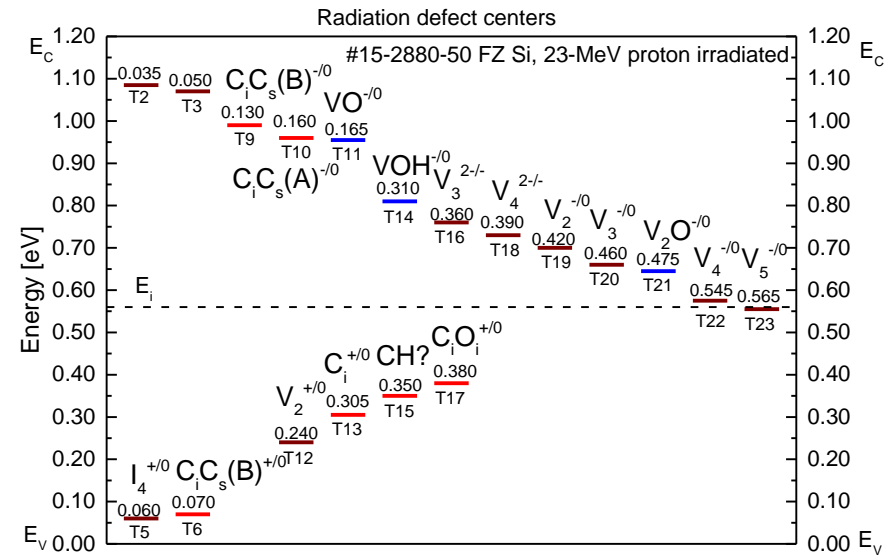
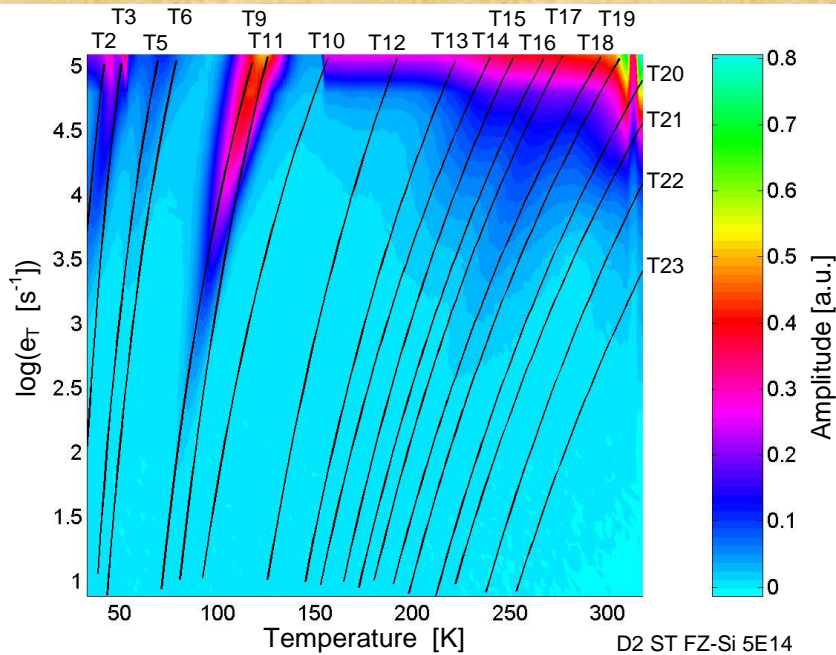
Effect of nitrogen-doping on the detectors leakage current



Radiation defect centers produced in the detectors active region N-free material

HRPITS 2D correlation spectrum
 $\Phi = 5E14 \text{ n}_{\text{eq}}/\text{cm}^2$

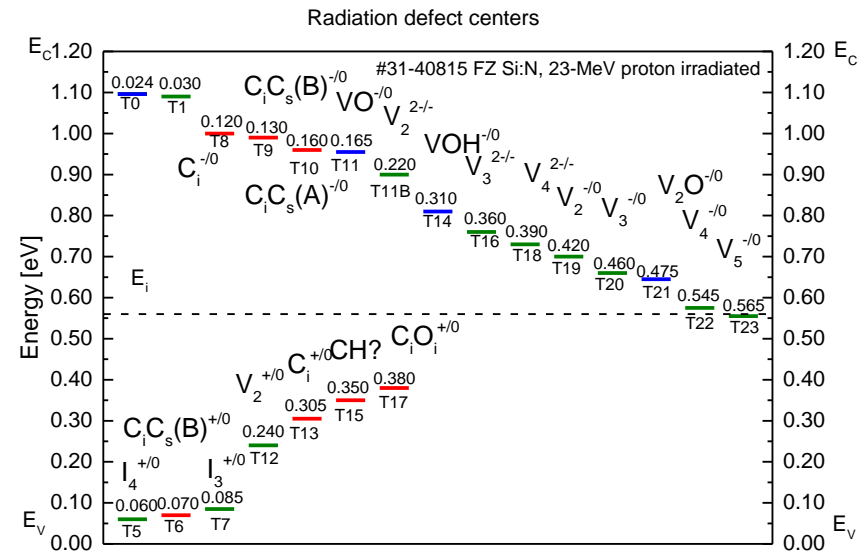
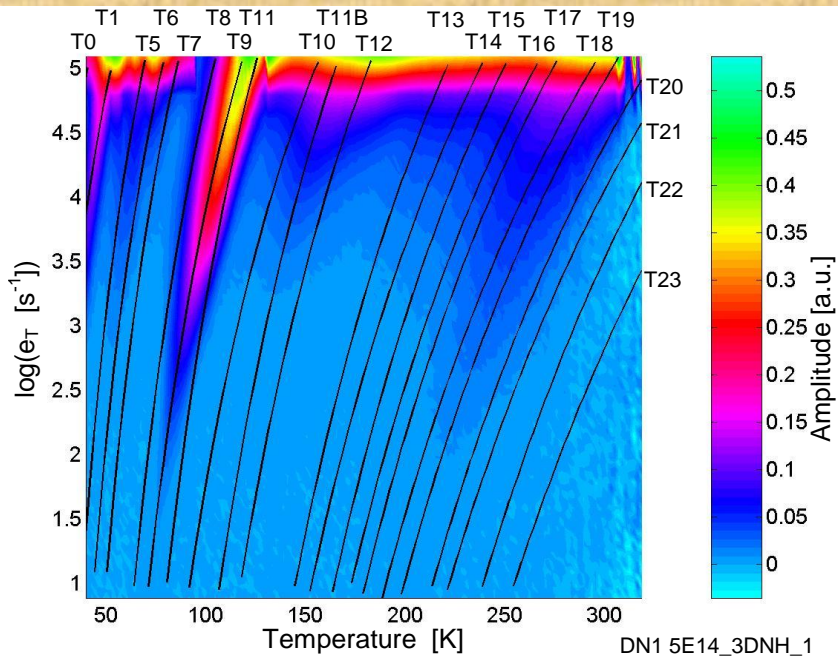
Defect levels aligned with the band edges



Radiation defect centers produced in the detectors active region N-rich material

HRPITS 2D correlation spectrum
 $\Phi=5E14 n_{eq}/cm^2$

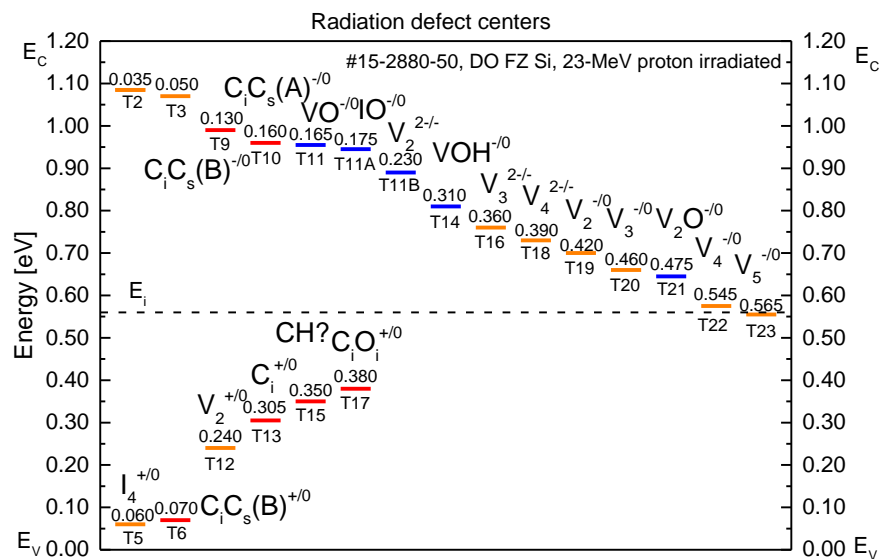
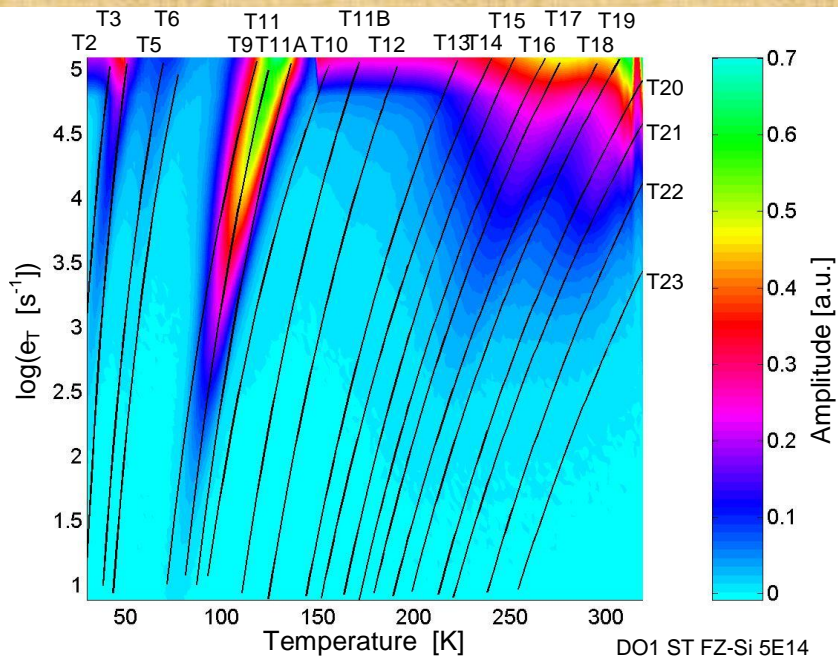
Defect levels aligned with the band edges



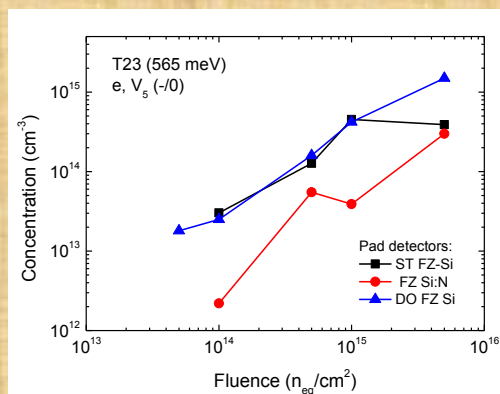
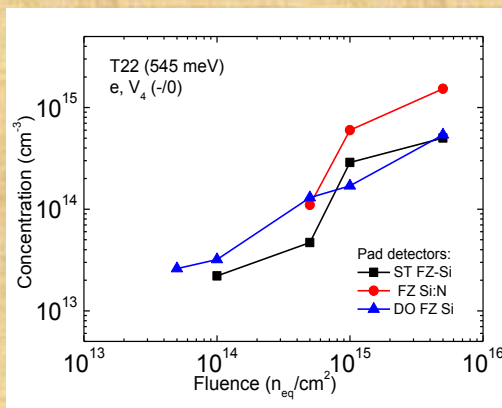
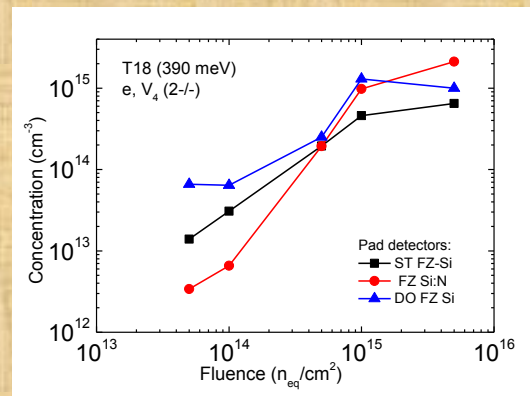
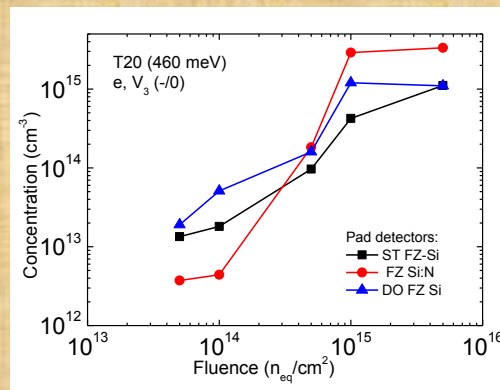
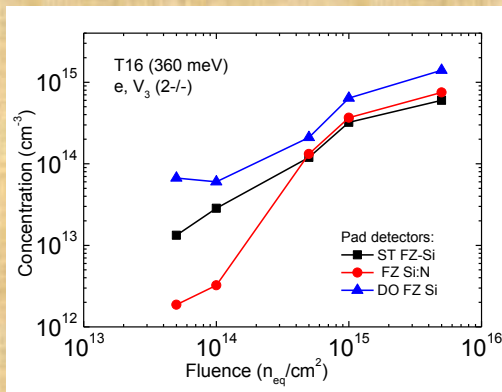
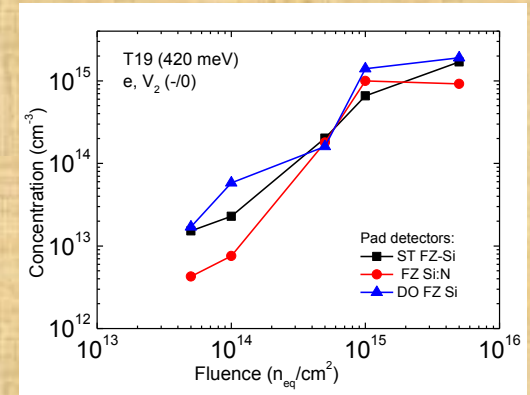
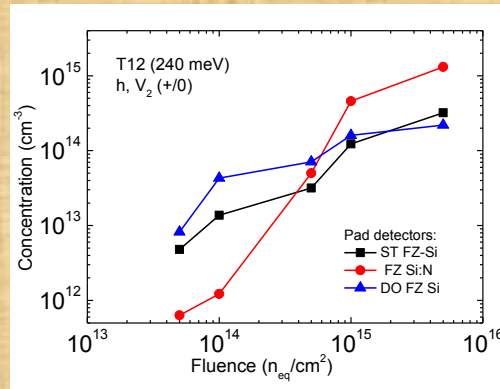
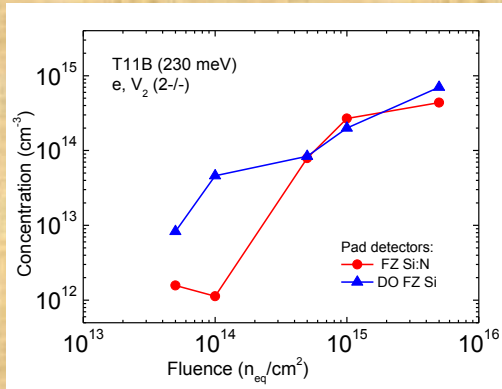
Radiation defect centers produced in the detectors active region N-free DOFZ material

HRPITS 2D correlation spectrum
 $\Phi=5E14 n_{eq}/cm^2$

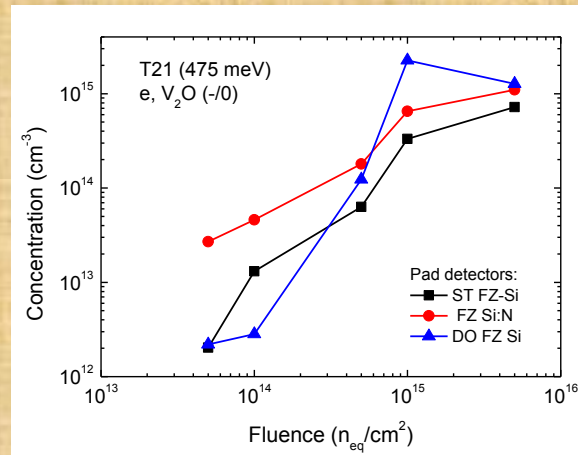
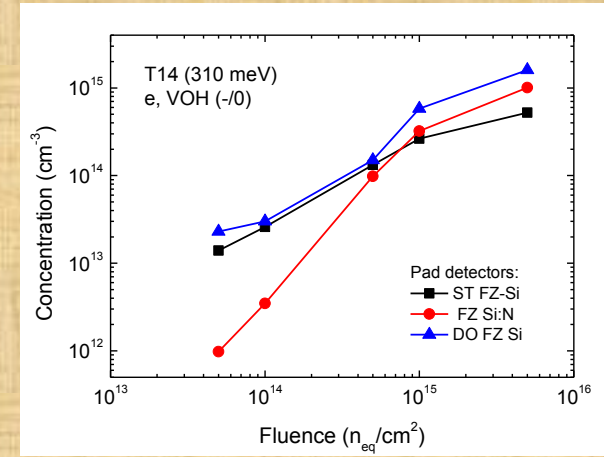
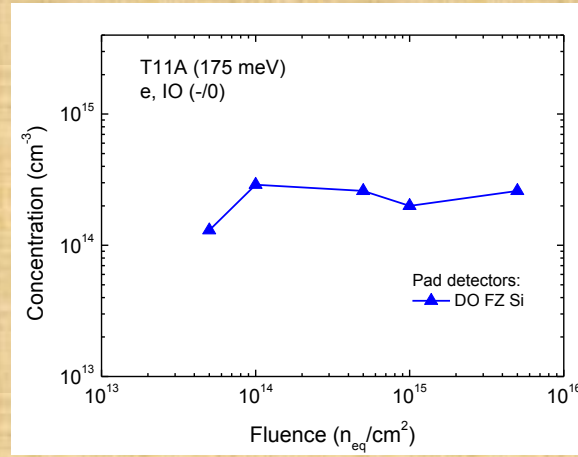
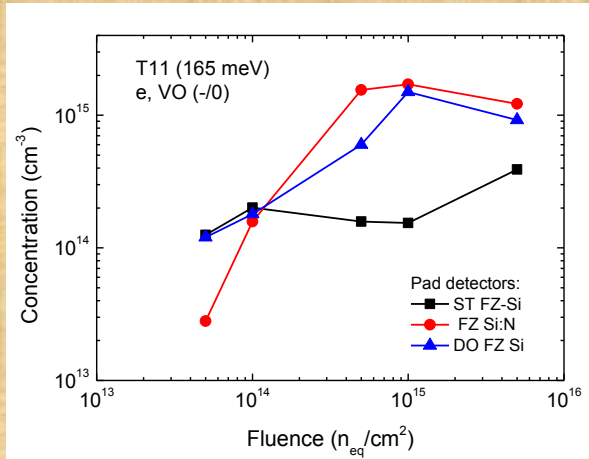
Defect levels aligned with the band edges



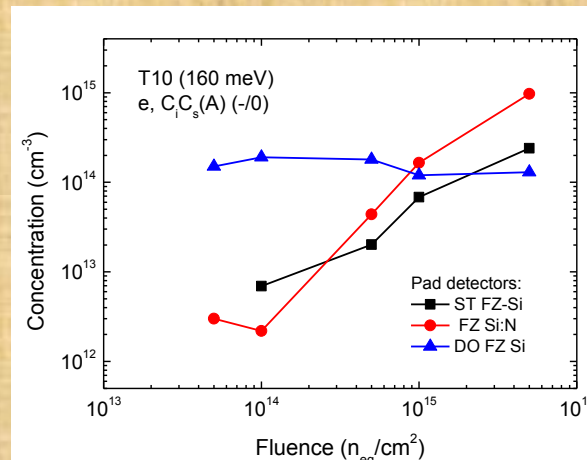
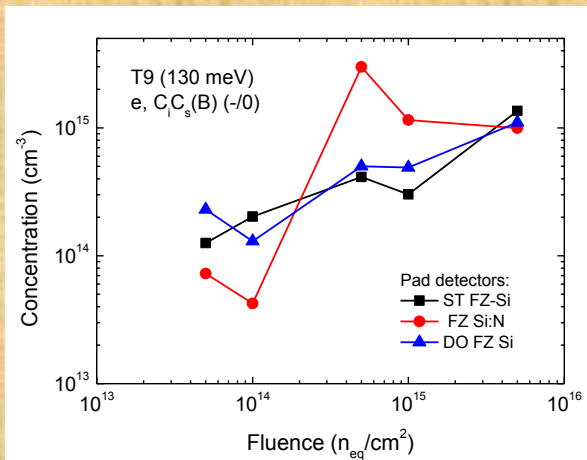
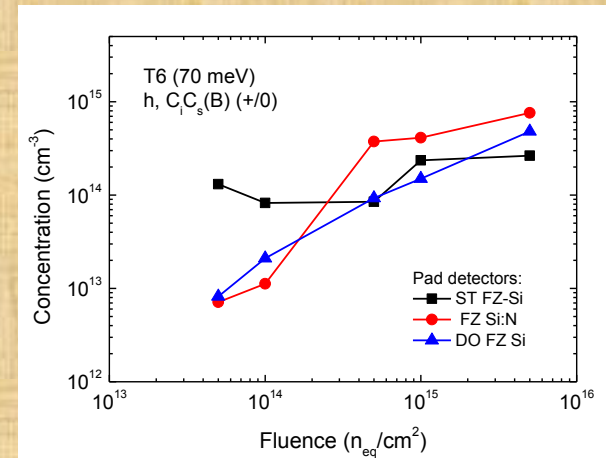
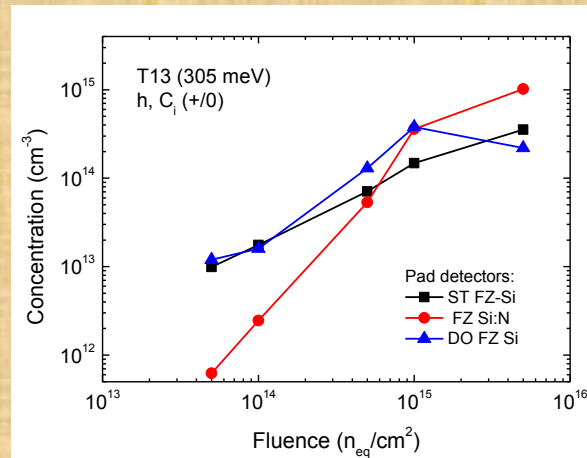
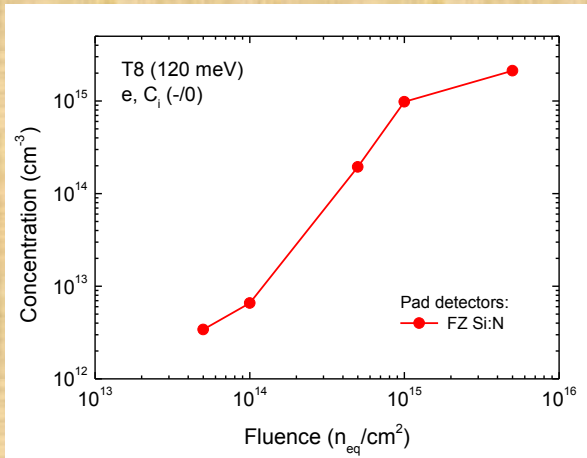
Effect of nitrogen-doping on the concentrations of irradiation induced small vacancy aggregates



Effect of nitrogen-doping on the concentrations of irradiation induced oxygen-related complexes



Effect of nitrogen-doping on the concentrations of irradiation induced carbon-related point defects



Conclusions

- ❑ Radiation hardness of *n*-type high-resistivity N-rich silicon wafers has been tested by 23-MeV proton irradiation of pad detectors and measurements of the irradiated devices characteristics and the properties of the material of their active regions.
- ❑ The results indicate that nitrogen-doping may have beneficial effect on the radiation hardness of detector grade FZ Si wafers for the fluences up to $1E14 n_{eq}/cm^2$.
- ❑ Currently, additional application tests including NitroStrip, Hamamatsu, Institute of Electron Technology in Warsaw, and University of Wollongong in Australia are in progress.
- ❑ Further application tests are needed and welcome. A limited amount of one-side or double side polished, high-resistivity, N-enriched <100> wafers is available on the collaboration basis. If interested please contact: pawel.kaminski@itme.edu.pl , see also www.nitrosil.com .

Acknowledgements

This work has been 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