Radiation damage in Si-based sensors - from "microscopic" reasons to "macroscopic" consequences for detector performance

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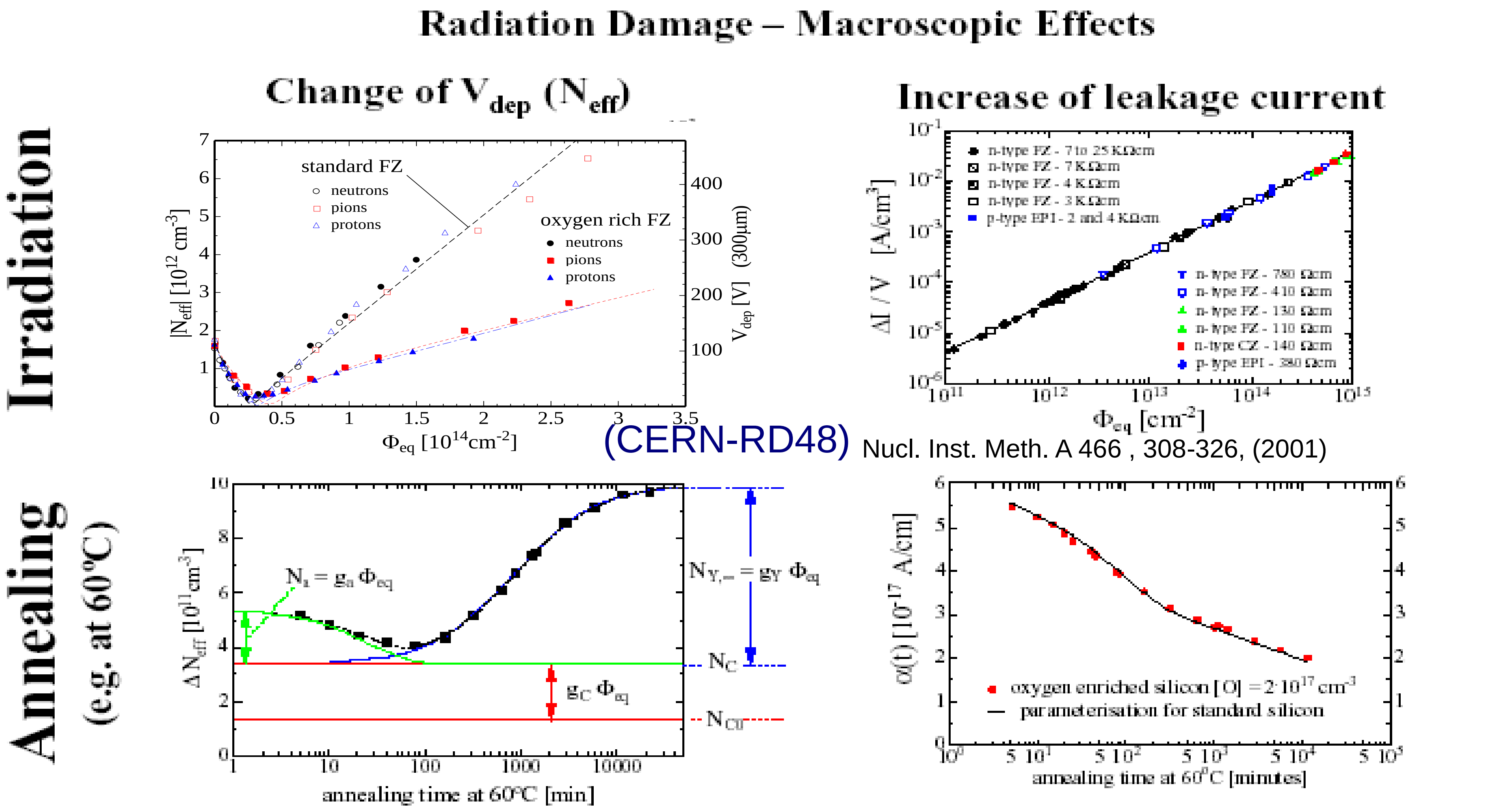
Work performed in the framework of CERN-RD50 Collaboration (http://rd50.web.cern.ch/rd50/)

Motivation

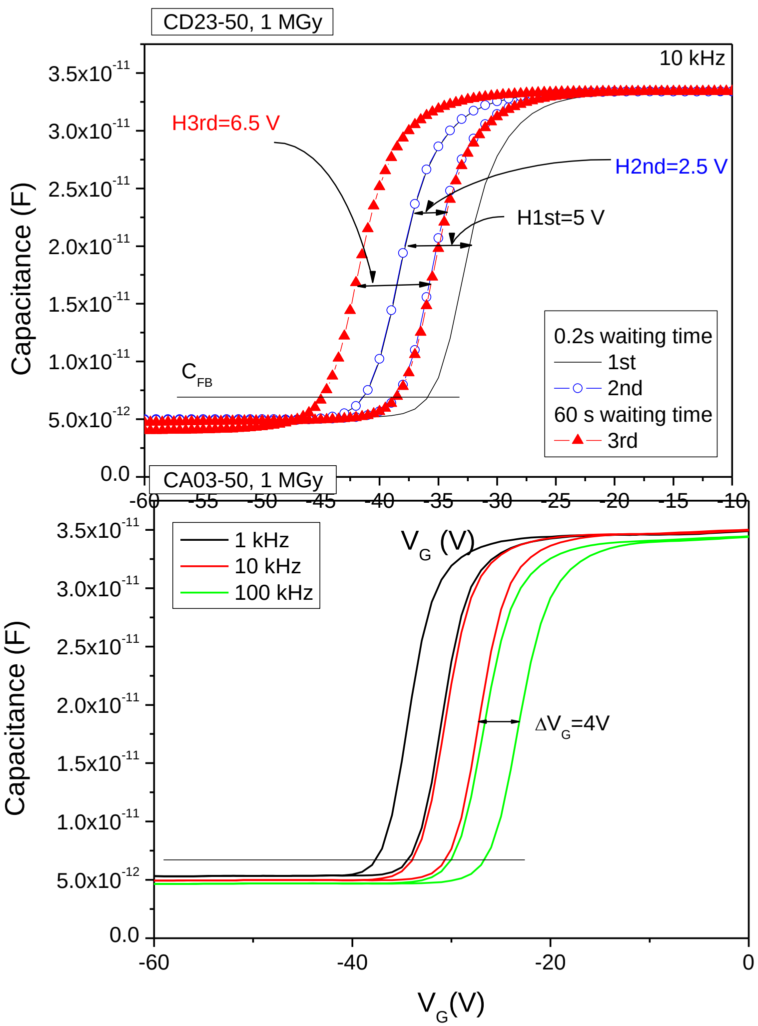
a) ***bulk radiation damage*** - resulting from the non-ionizing energy loss (as e.g. LHC and SLHC)



(CERN-RD48) Nucl. Inst. Meth. A 466 , 308-326, (2001)

"Defect engineering" needed for SLHC application in the tracking area to improve the detectors radiation tolerance

b) Surface and interface related effects - caused by ionization in environments with high X-ray doses (as e.g. in XFEL: Doses of up to 1GGy in 3 years of operation, up to 10^5 12 keV photons per pixel of 200 μm × 200 μm).



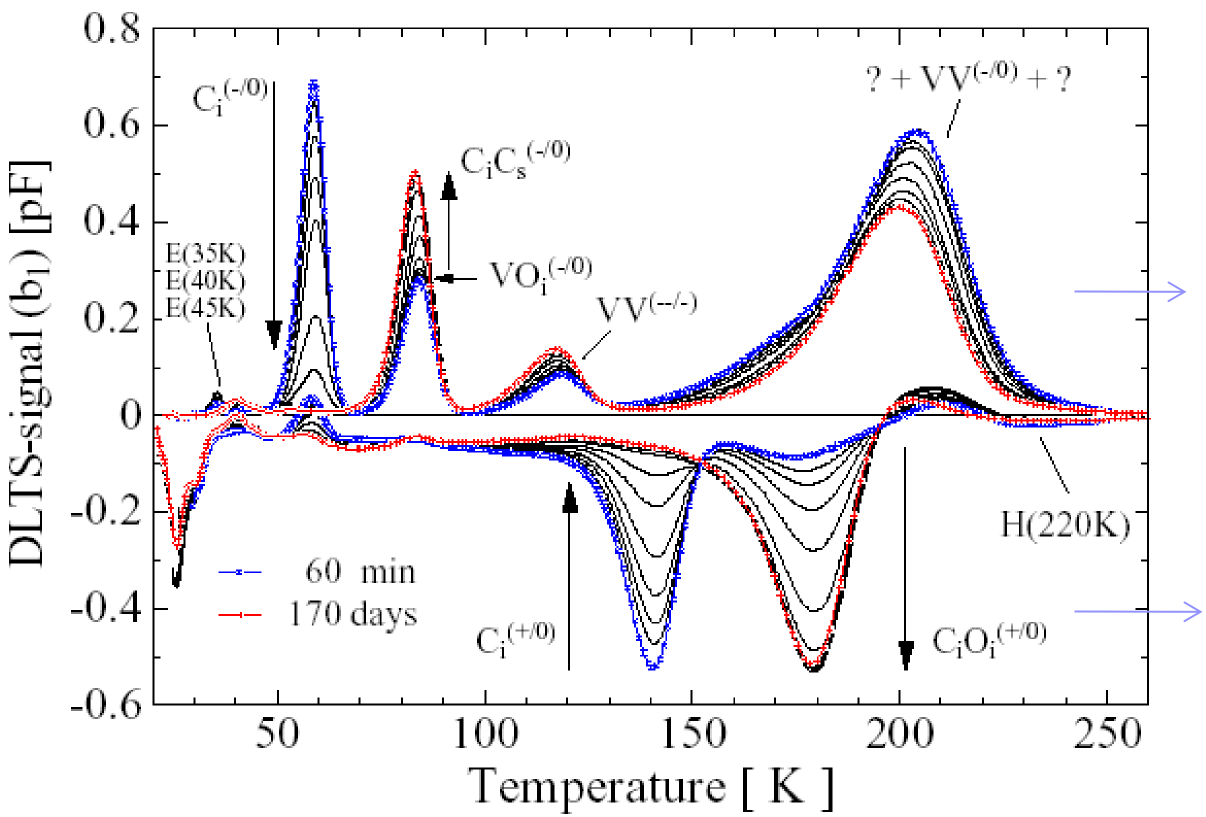
MOS with high resistivity Si (for XFEL)

- Irreproducibility of C/G-V curves (V_{FB} depending on frequency and on bias history)
- Strong annealing effects at room temperature
- No existing data related to electrical parameters of interface states

Defect investigations needed to understand and to predict the performance of segmented Si sensors as a function of the X-ray dose

a) ***bulk radiation damage***

starting point in our investigations on p^+-n Si diodes – *typical DLTS spectra*



Electron traps

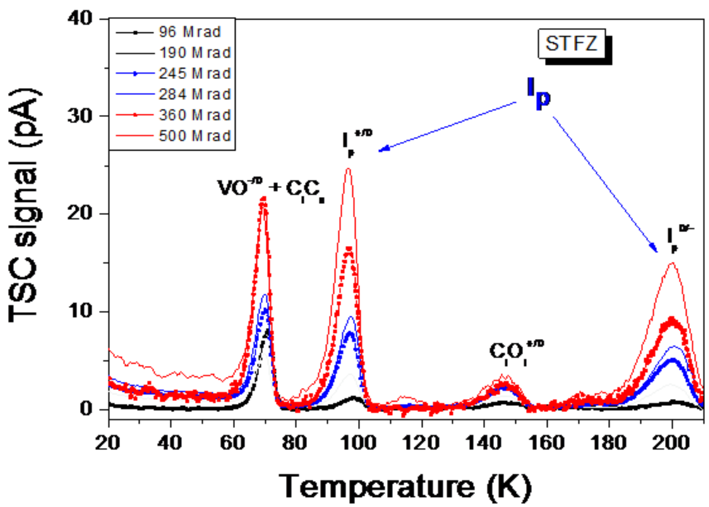
Hole traps

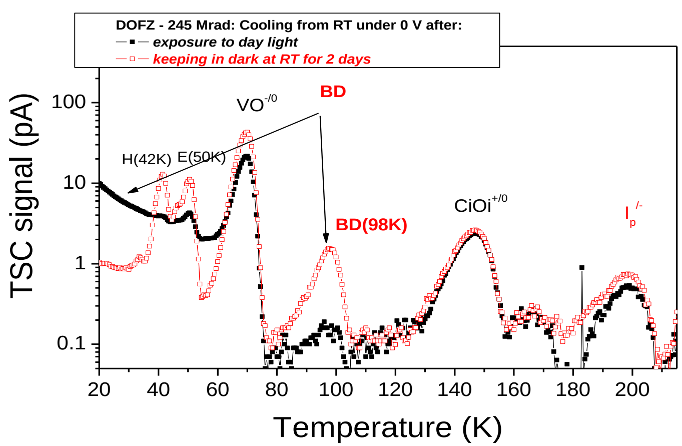
Phys. Rev. B **13, 2653 , (1976);** Radiat. Eff. **29, 7, (1976);** J. Appl. Phys. **79, 3906, (**1996); Nucl.Instrum. Methods Phys. Res. A **388, 335 , (1997);** M. Moll, Ph.D. thesis, DESY thesis 1999-040, ISSN 1435-8085, 1999

None of these defects explain the macroscopic behaviour of the irradiated diodes

I) Search for still undetected defects responsible for the radiation damage, as seen at operating temperatures

- Point defects (after gamma and low energy electron irradiation)





I_p center in STFZ (O lean material)

- ***deep acceptor*** (-/0)
- Ea = Ec – 0.545 eV
- $\sigma_n = (1.7\pm0.2)\text{x}10^{-15}$ cm^2 ;
- $\sigma_p = (9\pm1)\text{x}10^{-14}$ cm^2

~ 90% occupied with (-) at RT

<u>BD center</u> –generated in DOFZ (O rich material)

- ***shallow donor (+ at RT)***

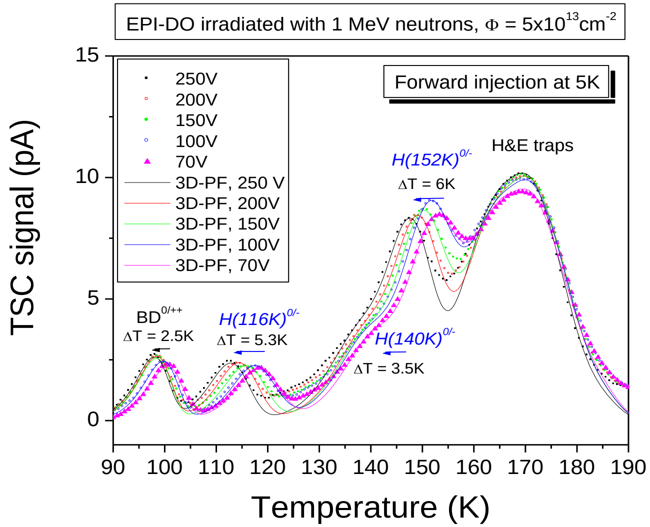
$E_i^{BD(98K)} = E_c - 0.225\ eV$ (0/++) ;

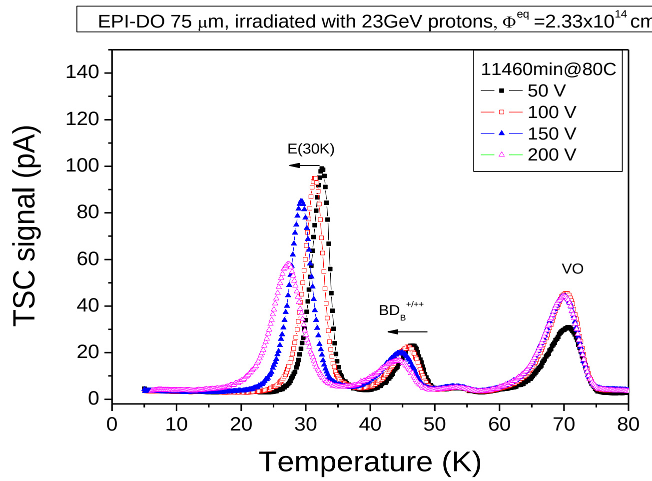
$E_i^{BD(50K)} = E_c - 0.15\ eV$ (+/++)

Overcompensates the effect of I_p acceptors!

I. Pintilie et al, APPL. PHYS. LETT. 81 , 165-167, 2002
I. Pintilie et al, APPL. PHYS. LETT 82, 2169 (2003);
I. Pintilie et al , Nucl. Inst. Meth. A 514, 18-24, (2003)

Extended defects (clusters), responsible for hadron damage





Cluster related centers

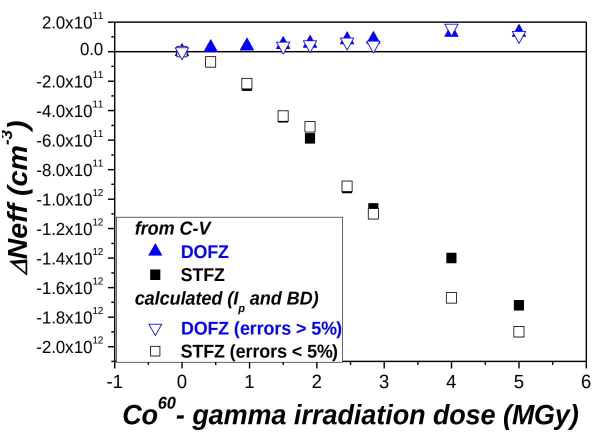
$E_i^{116K} = E_v + 0.33eV$
$\sigma_p^{116K} = 4 \cdot 10^{-14}\ cm^2$

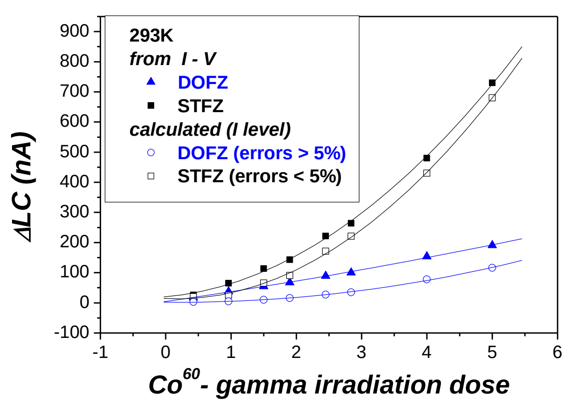
$E_i^{140K} = E_v + 0.36eV$
$\sigma_p^{140K} = 2.5 \cdot 10^{-15}\ cm^2$

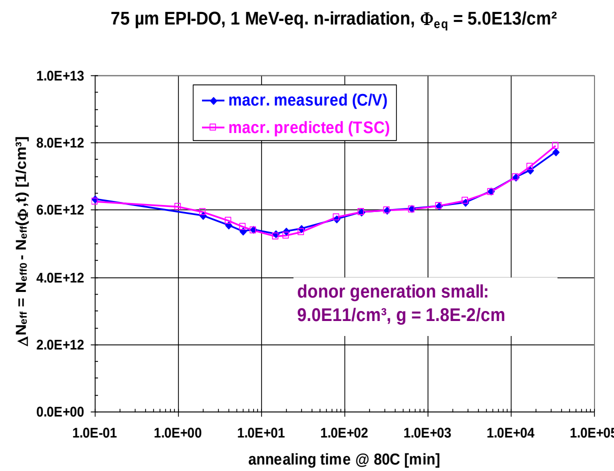
$E_i^{152K} = E_v + 0.42eV$
$\sigma_p^{152K} = 2.3 \cdot 10^{-14}\ cm^2$

$E_i^{30K} = E_c - 0.1eV$
$\sigma_n^{30K} = 2.3 \cdot 10^{-14}\ cm^2$
enhanced generation after irradiation with charged hadrons

II) Bridge the gap between the defect analyses and device performances as a crucial step for further device developments

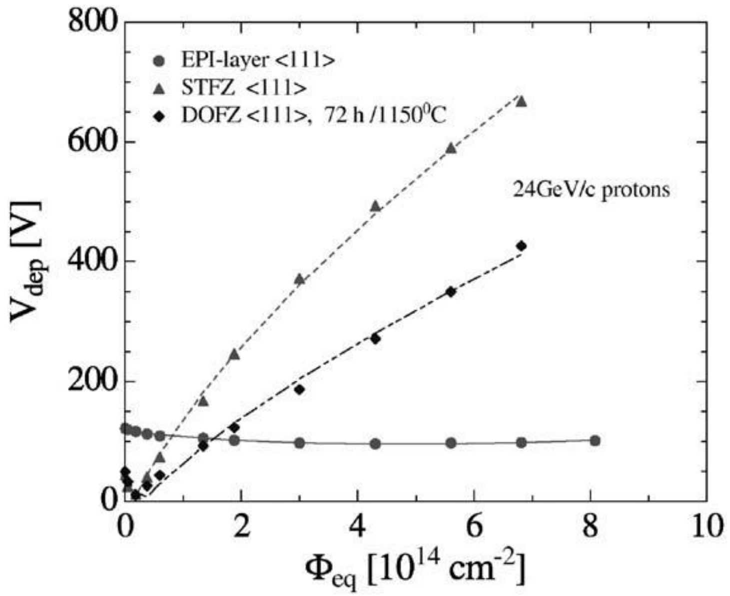




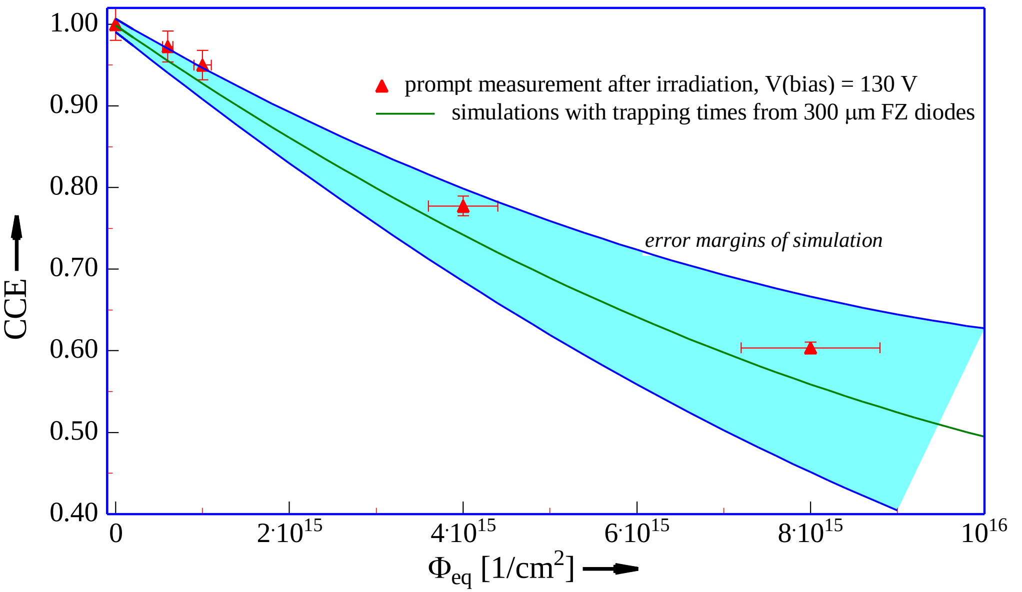


I. Pintilie et al, APPL. PHYS. LETT. 92, 024101 2008; I. Pintilie et al, Nucl. Inst. Meth. A 611 (2009) 52–68

Superior radiation tolerance of thin epi-silicon detectors



Fluence dependence of V_{dep} after 24 GeV/c proton irradiation for Epi (50 µm, 50 Ωcm), STFZ (300 µm, 2-5kΩcm) and DOFZ silicon (300 µm, 2-5kΩcm)



Charge collection efficiency after reactor-neutron irradiation in Epi/Cz-silicon (50 µm, 50 Ωcm)

Epi-Si:

- **no type inversion for protons, small increase of positive space charge**
- **Radiation hardness up to $8\cdot10^{15}$ n/cm² demonstrated**
- **CCE = 60% sufficient for requested S/N – ratio in SLHC applications**
- **N_{eff} -** Dependence on particle type (protons vs. neutrons) **-** *Violation of NIEL (Non Ionizing Energy Loss) Hypothesis!*

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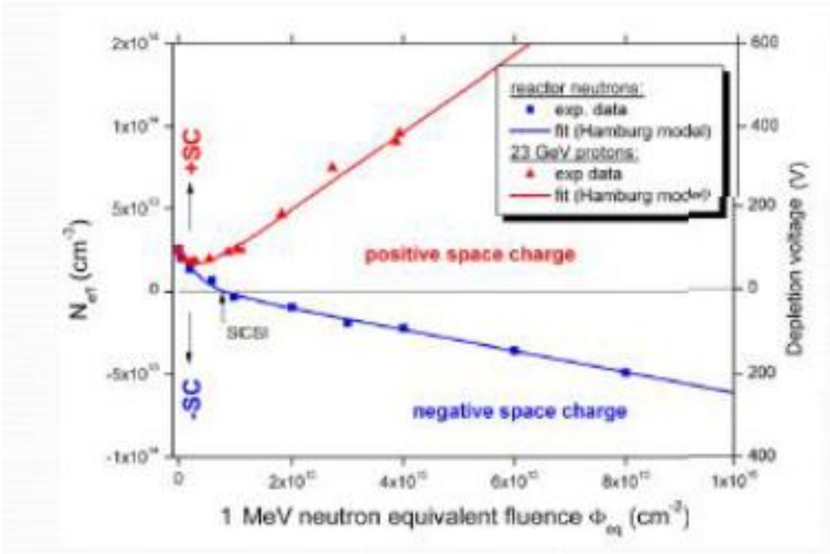
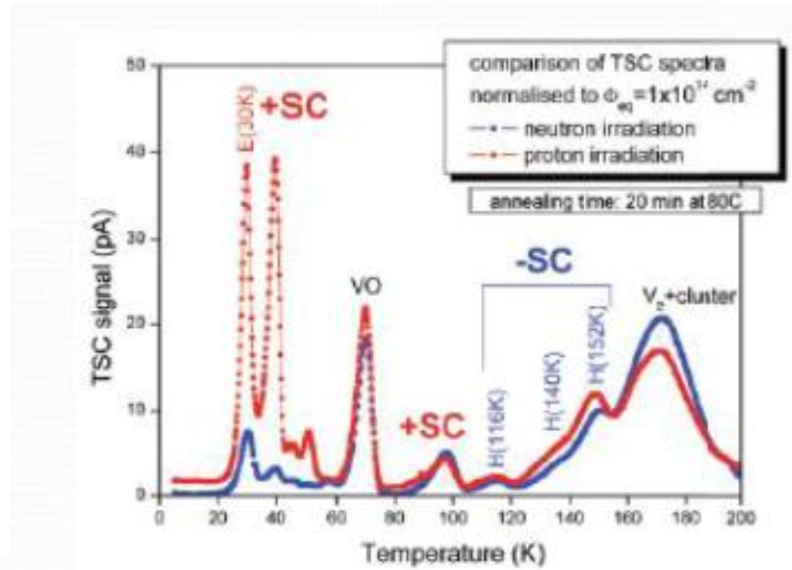
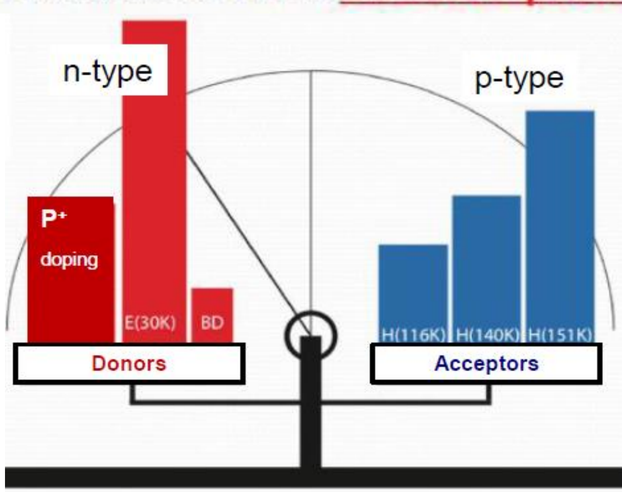


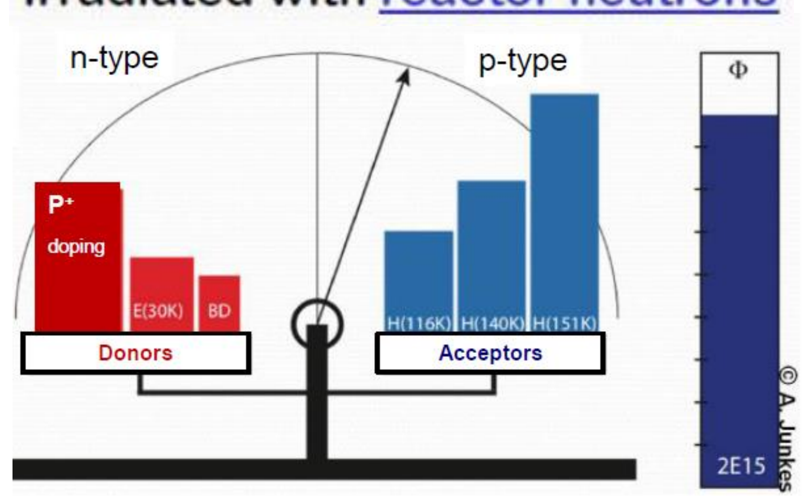


Epitaxial silicon (***EPI-DO, 72µm, 170Ωcm, diodes)***

irradiated with 23 GeV protons



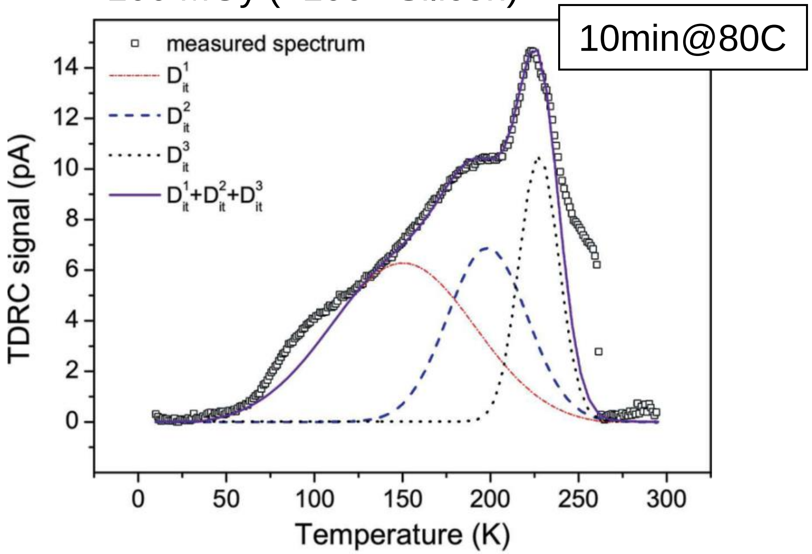
irradiated with reactor neutrons



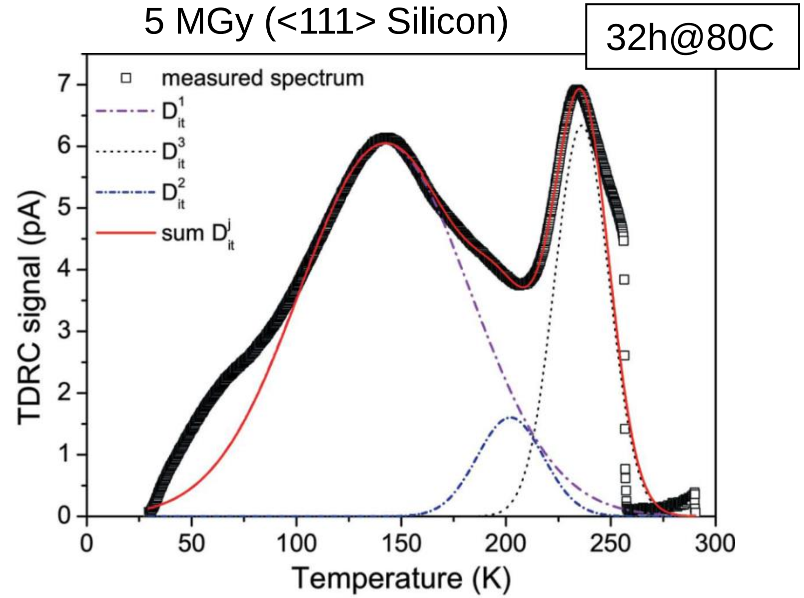
b) Surface and interface related effects

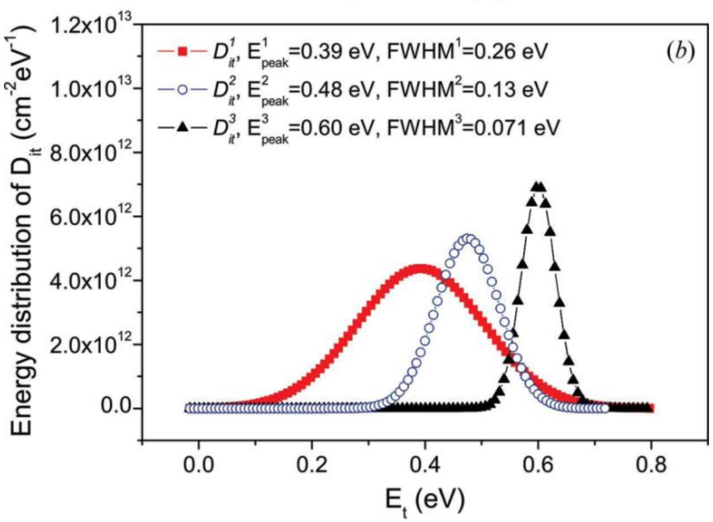
I) Detection and characterization of Interface states in MOS structures with high resistivity Si (for XFEL)

100 MGy (<100> Silicon)



5 MGy (<111> Silicon)



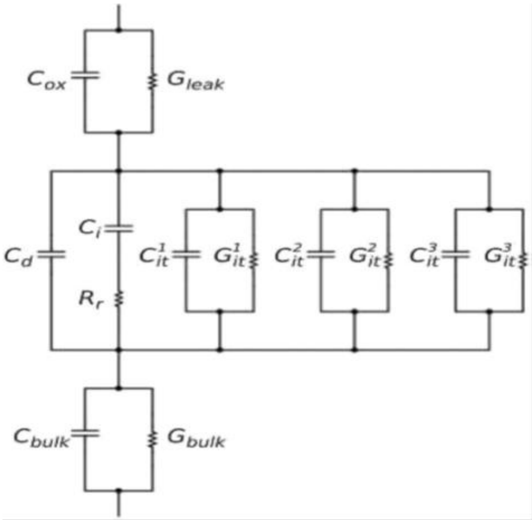


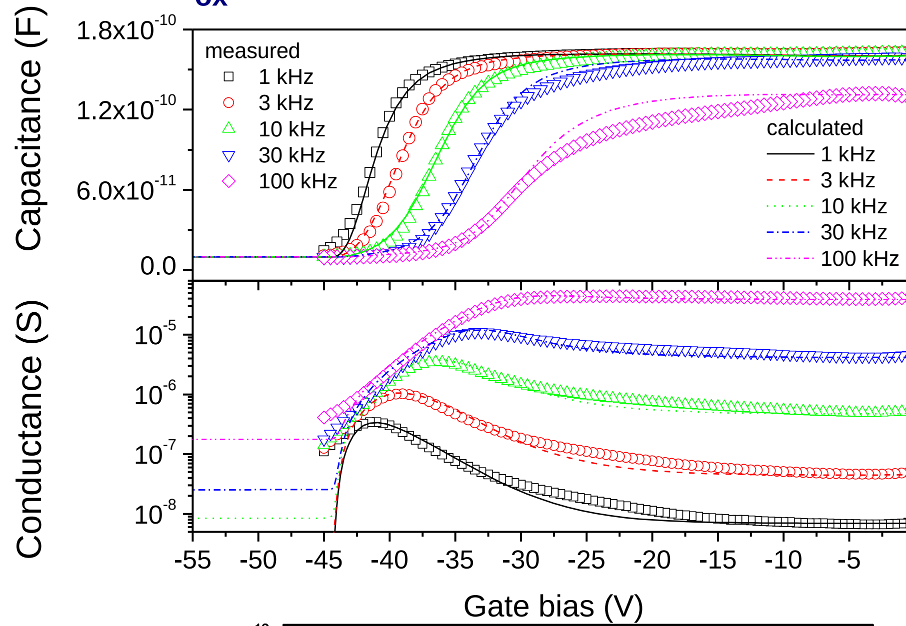
J. Synchrotron Rad. (2012). 19, 340–346

	D_{it}^1	D_{it}^2	D_{it}^3
σ [cm^2]	1.2×10^{-15}	5×10^{-17}	1.0×10^{-15}
peak energy [eV]	0.39	0.48	0.60
FWHM [eV]	0.26	0.13	0.071

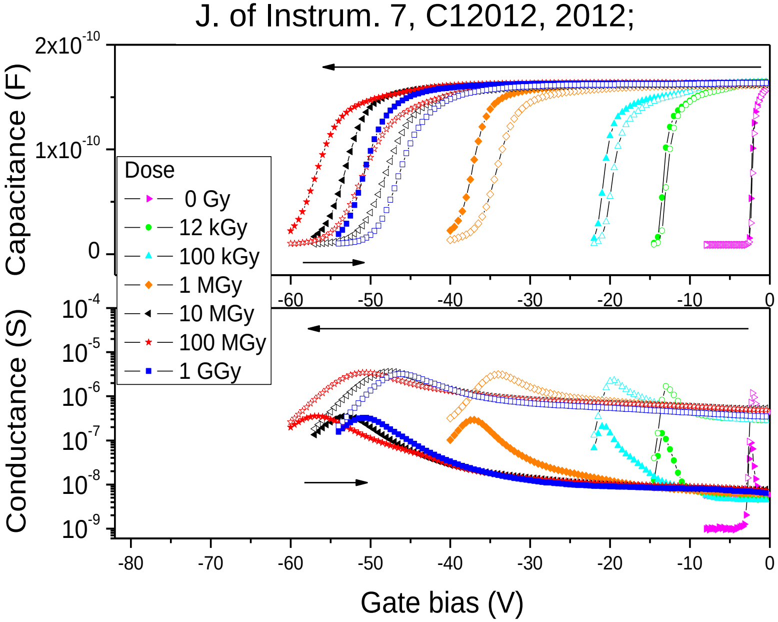
II) Bridge the gap between the defect analyses and device characteristics

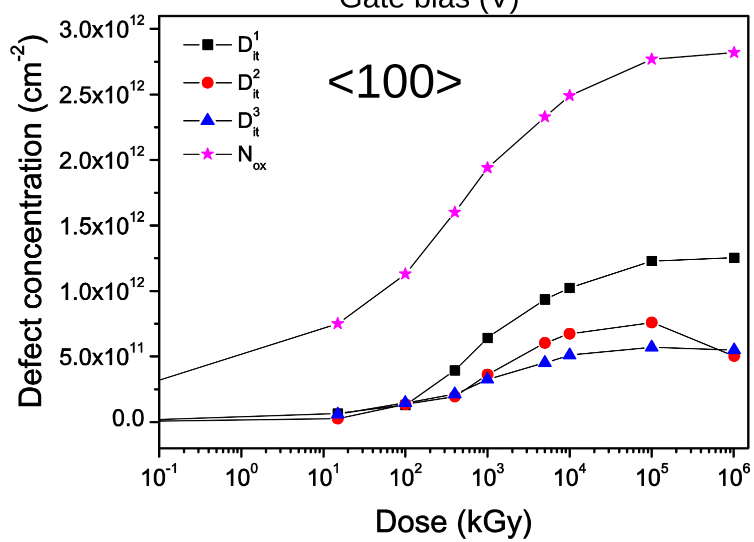
Calculation of C/G-V curves and determination of N_{ox}





J. Synchrotron Rad. (2012). 19, 340–346;
J. of Instrum. 7, C12012, 2012;





For <111> material the D_{it} and N_{ox} are ~ 20-30 % higher

Conclusions

- **Direct correlation between defect investigations and device properties can be achieved! Moreover, when electrical characteristics of the defects are known then models predicting the device performance in different operational scenarious can be developed**
- **Atomic and electronic point defects – dependent on the material ⇒ defect engineering does work**
- **Cluster related defects – independent on the material ⇒ Possibility of compensation with point defects via defect engineering**
- **Still missing the identification of the chemical nature of the defects that deteriorates the device characteristics**

Acknowledgements: Members of CERN-RD50 Collaboration;

PNII-ID-PCE-2011-3 Nr. 72/5.10.2011