Defects and Materials

(many) (Si, SiC, GaN)

2002-2023

Defects and Materials

Goal: achieve a comprehensive enough understanding of the radiation induced degradation of detectors to develop suitable radiation hard sensors.

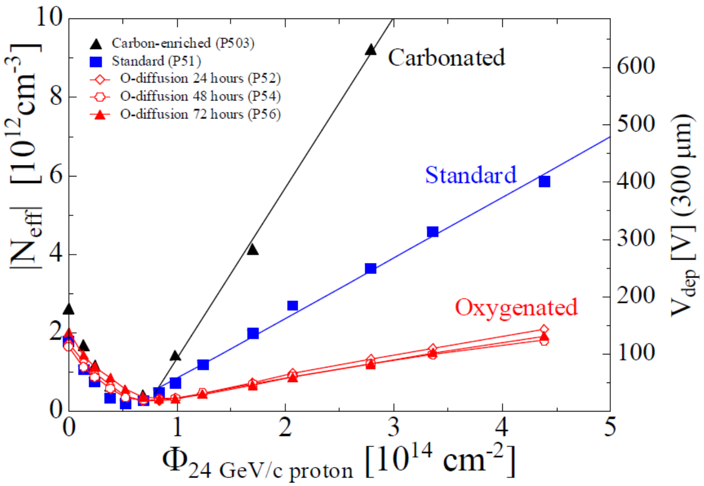
- Study of the microscopic defects, their reaction and annealing kinetics and especially their relation to the macroscopic damage parameters

- Propose defect engineering approaches

Silicon

Research started based on the knowledge acquired during the ROSE (RD48) Collaboration on **n-type Si**

Influence of C and O concentration 23 GeV protons

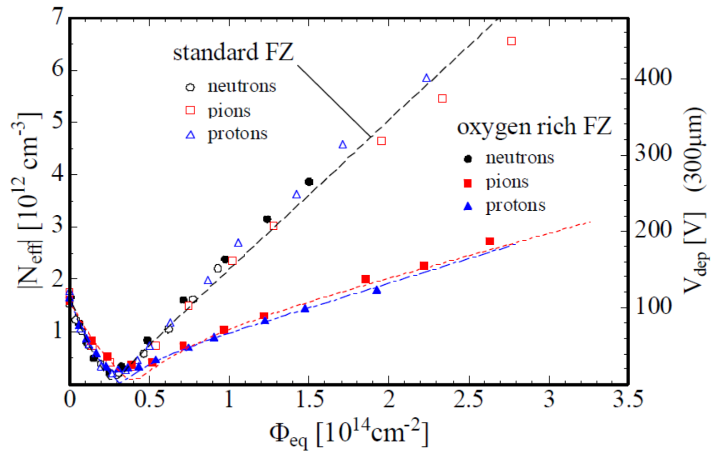


Compared to standard silicon:

- **High Carbon ⇒ less radiation tolerant**
- **High Oxygen ⇒ more radiation tolerant**

Oxygen and standard silicon - Particle dependence -

23 GeV protons - 192 MeV pions - reactor neutrons



- **Strong improvement for pions and protons**
- **Almost no improvement for neutrons ⇒ "Proton-Neutron-Puzzle"**

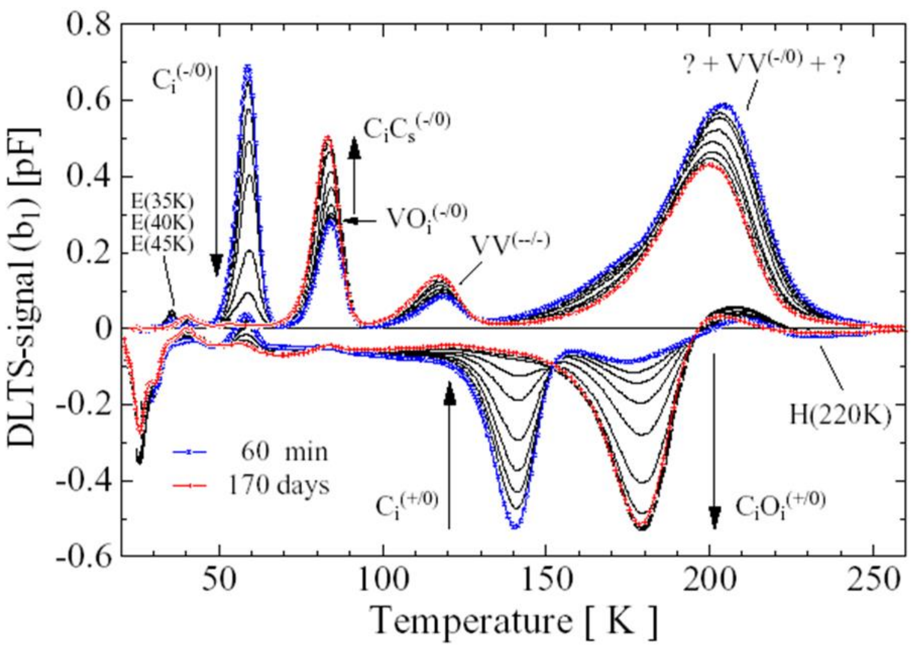
Michael Moll – VERTEX 2001, Brunnen, Switzerland 23.-28. September 2001

G. Lindstrom, et al., Nucl. Instr. and Meth. A 466 (2001) 308; Z. Li, et al., IEEE Trans. Nucl. Sci. NS-42 (1995) 219

Silicon

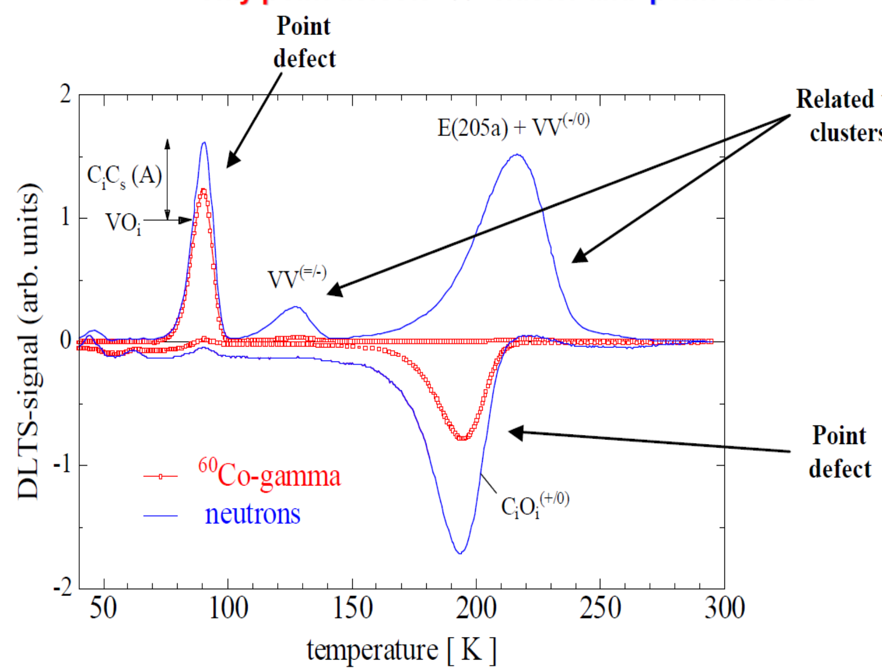
<u>Quantitative</u> microscopic investigations
– until 2001 **only by DLTS** so, only after **low irradiation fluences**

- DLTS, room temperature annealing -
- neutron irradiated -



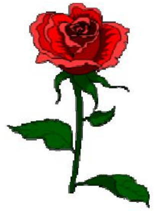
Gamma-irradiation ⇔ Neutron-irradiation

only point defects ⇔ cluster and point defects



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

The DLTS detected defects after low irradiation levels does not explain the diodes macroscopic behaviour after high irradiation fluences



Silicon

RD48 Models

I) For explaining the "type inversion" in n- type Silicon, it must exist an acceptor like defect with a close-to-midgap level

- **V_2O-model**

Higher oxygen content ⇒ less negative space charge

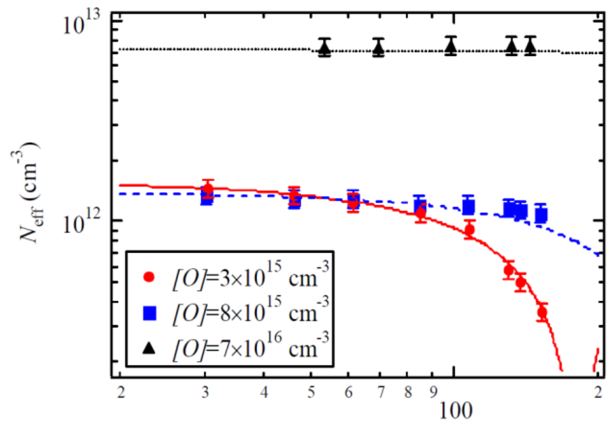
V → O → VO (not harmful at room temperature)

V → VO → V_2O (negative space charge)

K. Gill, G. Hall, and B. MacEvoy, J. Appl. Phys. ***82****, 126, 1997 B.C. MacEvoy, A. Santocchia, G. Hall, Physica B 273–274 (1999) 1045.*

^{60}Co gamma irradiation

- Model predictions and experimental data -

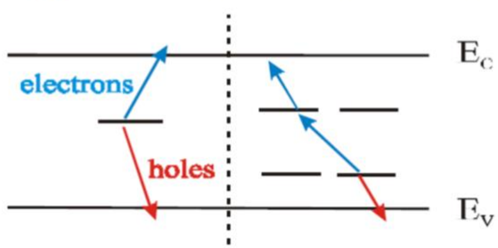


II) For explaining the high leakage currents in irradiated n- type Silicon

- **Intercenter charge transfer – model**

Enhanced charge carrier generation inside clusters
⇒ depending strongly on the defect density in the clusters

Shockley-Read-Hall statistics (standard theory)



Inter-center charge transfer model (inside clusters only)

Watts, SJ at al, 33rd Annual IEEE International Nuclear and Space Radiation Effects Conference, IEEE TRANSACTIONS ON NUCLEAR SCIENCE 43 (6), pp.2587-2594, 1996

Bridging the gap between the defect analyses and device performances

a crucial step for further Si device developments

- ***Develop proper measuring & analyzing procedures for correct evaluations of defect concentration after high irradiation levels (****when the degradation of diodes performance actually occurs)* – ***I-DLTS and TSC***

- ***Search for still undetected defects responsible for the observed macroscopic radiation damage after:***
    - ***Co^{60} gamma irradiation in-type Si (point defects)***
    - ***hadron irradiation (clusters)***

- **WODEAN group on n-type Silicon -** Involve all RD50 available tools for thorough defect analysis and possible defect engineering. (DLTS, TSC, PITS, PL, τ_{recomb}, FTIR, PC, EPR, diode C/V, I/V and TCT)

- ***Acceptor Removal working group –*** *defects in* ***p-type Silicon***

Current based measuring techniques on highly irradiated diodes: TSC and I-DLTS
(HH, NIMP, CERN, Florence)

Errors and how they can be prevented when bulk damage is investigated:

a) Variation in the depleted volume caused by the different front and back electrode areas *(usually the back area is larger than the front area). When space charge sign inversion occurs during the T scan and the electric field switches from the front to the back contact leads to an increase in the Current signal only due to the contacts geometry. An accurate determination of defect concentrations in such situation can be prevented if samples have* ***guard-rings grounded & the diodes are fully depleted*** *(the later cannot be fulfilled in I-DLTS). This way, also the contribution of surface defect states are eliminated and deeper defects can be detected by TSC measurements.*

– ***fully deplete*** *the measured diodes* ***over the full temperature scan*** *if possible*

- or, ***employ TSCap experiments*** *for determining the variation of the depleted width*

b) *When* ***filling a trap with forward injection****, to correctly calculate the fraction of filled traps,* ***both defect capture cross sections****, for electrons and for holes,* ***has to be known****.*

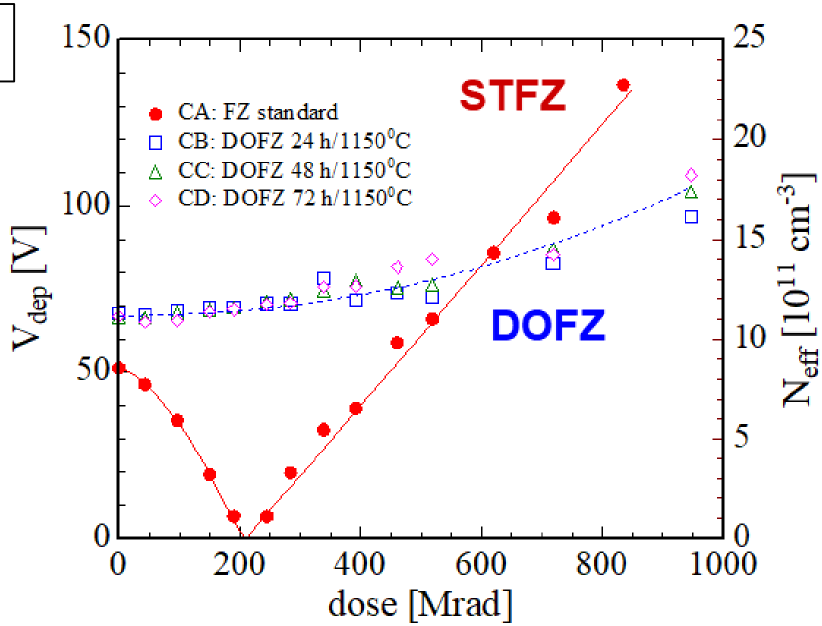
c) Account for the Poole-Frenkel effect o defect' activation energy

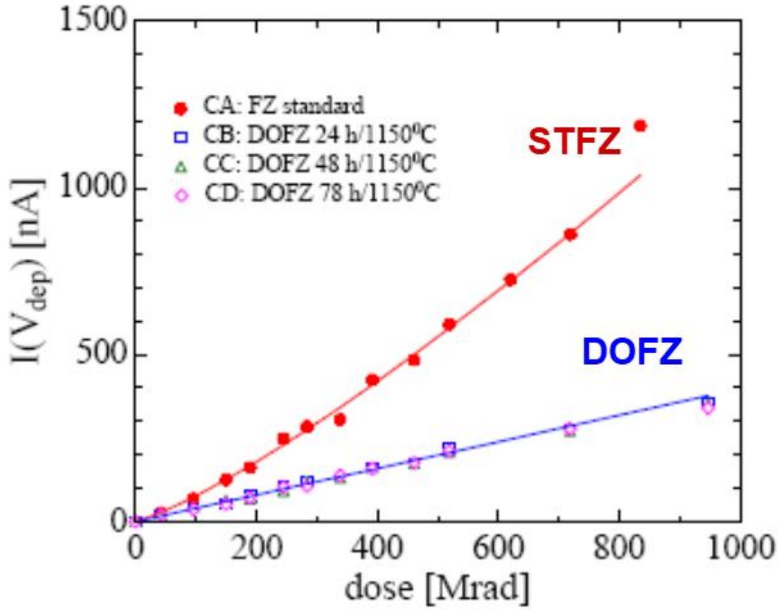
Pintilie, I.; Pintilie, L.; Moll, M.; Fretwurst, E.; Lindstroem, G. Thermally stimulated current method applied on diodes with high concentration of deep trapping levels. Appl. Phys. Lett. ***2001****, 78 (4), 550–552. DOI: /10.1063/1.1335852;* David Menichelli, Monica Scaringella, Mara Bruzzi, Ioana Pintilie, and Eckhart Fretwurst, Anomalous current transients related to defect discharge in irradiated silicon diodes, Phys. Rev. B **70**, 195209, 2004.
Pintilie, I.; Buda, M.; Fretwurst, E.; Lindström, G.; Stahl, J. Stable radiation-induced donor generation and its influence on the radiation tolerance of silicon diodes. Nucl. Instrum. Methods Phys. Res. A ***2006****, 556(1), 197-208. DOI:/10.1016/j.nima.2005.10.013 ; C. Liao et al.,"Investigation of the Boron removal effect induced by 5.5 MeV electrons on highly doped EPI- and Cz-silicon" NIMA 2023,1056, 168559, https://doi.org/10.1016/j.nima.2023.168559 .*

Search for still undetected defects responsible for the radiation damage

❑ **Point defects** (after **Co[60]- γ irradiation**)

n-type Si

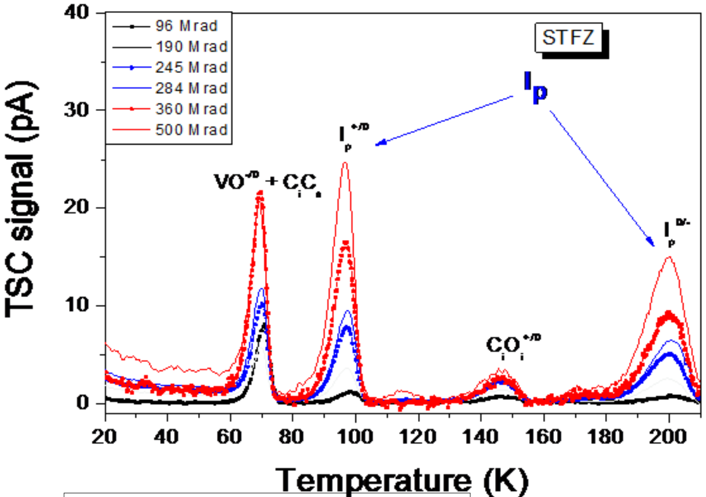




B.C. MacEvoy, A. Santocchia, G. Hall, Physica B 273–274 (1999) 1045; B. Dezillie, Z. Li, V. Eremin, W. Chen, L.J. Zhao, IEEE Trans. Nucl. Sci. NS-47 (6) (2000) 1892; G. Lindstr.om, et al., (The RD48 Collaboration), Nucl. Instr. and Meth. A 466 (2001) 308; B.C. MacEvoy, G. Hall, Mater. Sci. Semicond. Process. 3 (2000) 243; E. Fretwurst et al, Nuclear Instruments and Methods in Physics Research A 514 (2003) 1–8 7

- **Very pronounced beneficial effect of oxygen on both I and V_{dep} implying:**
- ***a close to midgap acceptor in O lean material (predicted by the V_2O model)***
- ***a shallow donor in O rich material***
- ***No annealing effects***

Search for still undetected defects responsible for the radiation damage



n-type Si

Deep acceptor (-/0)

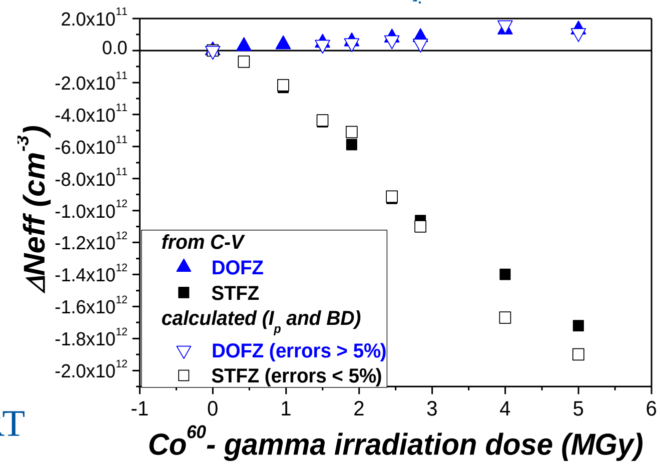
I_p center in STFZ

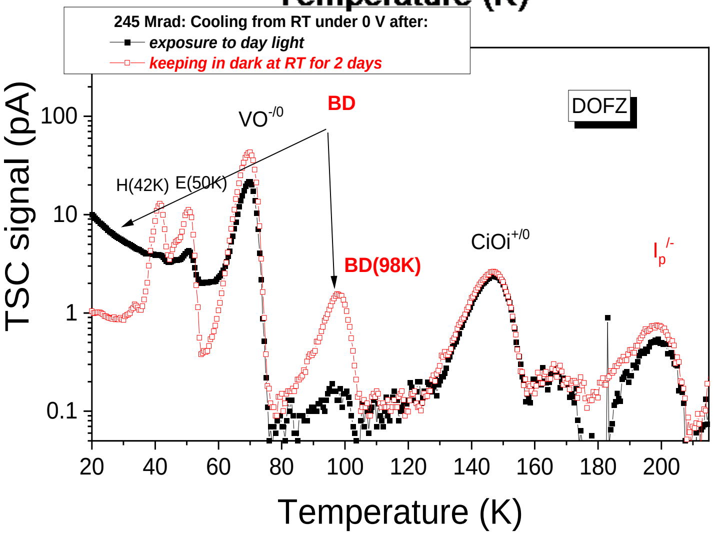
$E_a = E_c - 0.545$ eV

$\sigma_n = (1.7 \pm 0.2) \times 10^{-15}$ cm^2 ;

$\sigma_p = (9 \pm 1) \times 10^{-14}$ cm^2

~ 90% occupied with (-) at RT





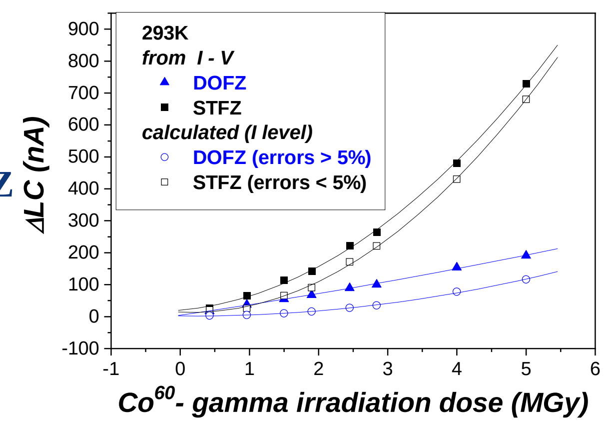
Shallow donor (+ at RT)

BD center –generated in DOFZ

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

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

Overcompensates the effect of I_p acceptors!



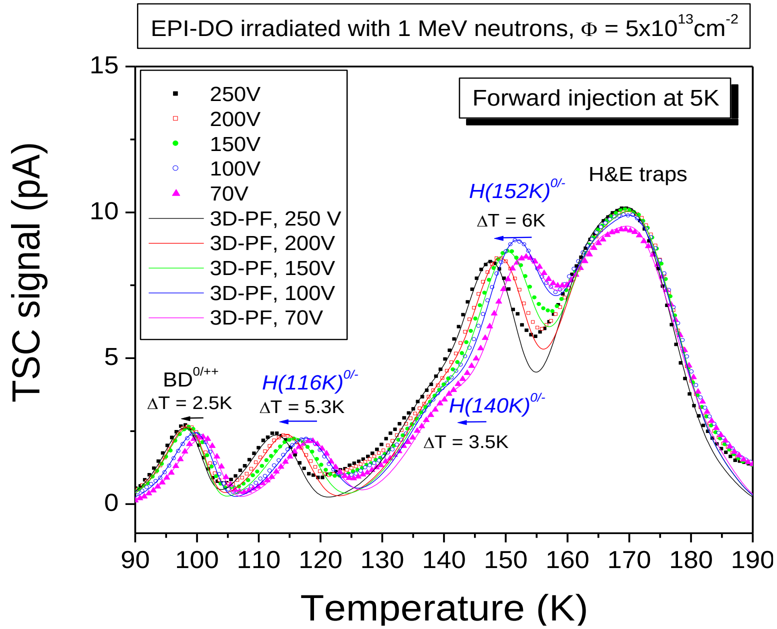
change of N_{eff} and leakage current well described

⇒ first breakthrough in understanding the damage effects

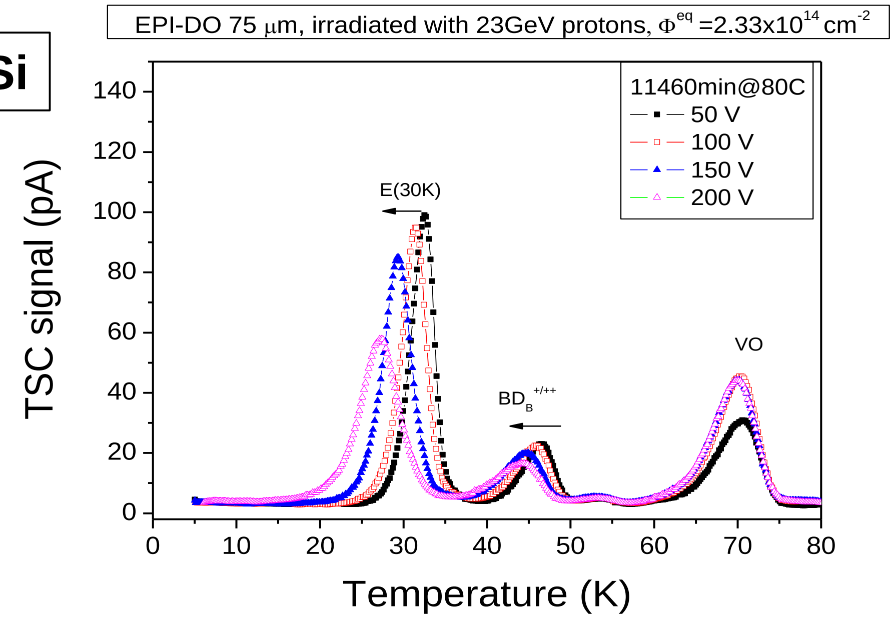
I. Pintilie, E. Fretwurst, G. Lindstroem, J. Stahl, Appl. Phys. Lett. 81 (1) (2002) 165; I. Pintilie, E. Fretwurst, G. Lindstroem, J. Stahl Appl. Phys. Lett. 82, 2169 (2003); I. Pintilie, E. Fretwurst, G. Lindstroem, J. Stahl Nucl. Inst. Meth. A 514, 18-24, (2003); I. Pintilie, G. Lindstroem, A. Junkes, E. Fretwurst, Nucl. Inst. Meth. A 611 (2009) 52–68

Search for still undetected defects responsible for the radiation damage

❑ Extended Defects (clusters) – after hadron irradiation



n-type Si



H(116K), H(140K),H(152K) & E(30K) – extended defects with enhanced field emission

$E_i^{116K} = E_v + 0.33eV,\ \sigma_p^{116K} = 4\cdot10^{-14}\ cm^2$

$E_i^{140K} = E_v + 0.36eV,\ \sigma_p^{140K} = 2.5\cdot10^{-15}\ cm^2$

$E_i^{152K} = E_v + 0.42eV,\ \sigma_p^{152K} = 2.3\cdot10^{-14}\ cm^2$

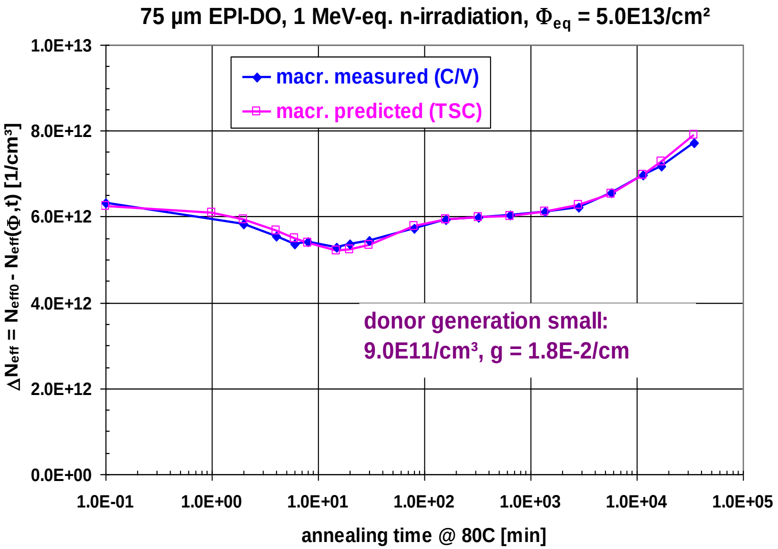
$E_i^{30K} = E_c - 0.1eV,\ \sigma_n^{30K} = 2.3\cdot10^{-14}\ cm^2$

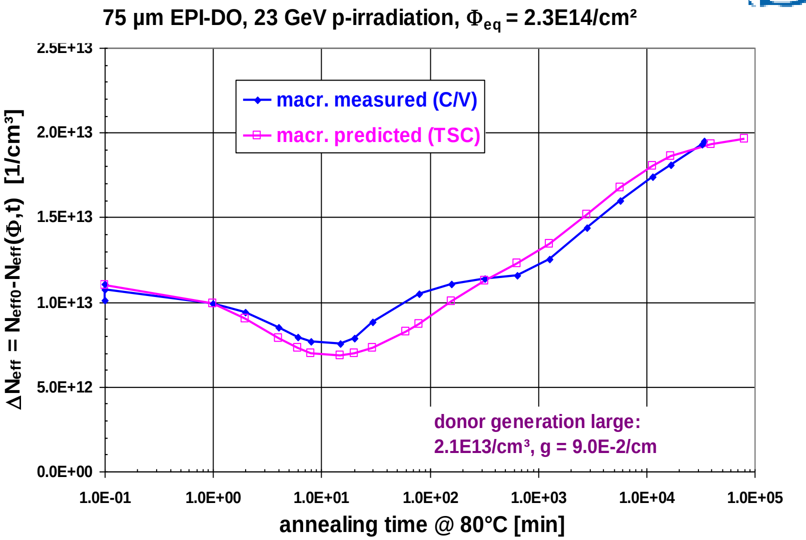
- 3 acceptors in the lower part of the gap and contribute with (-) space charge at RT

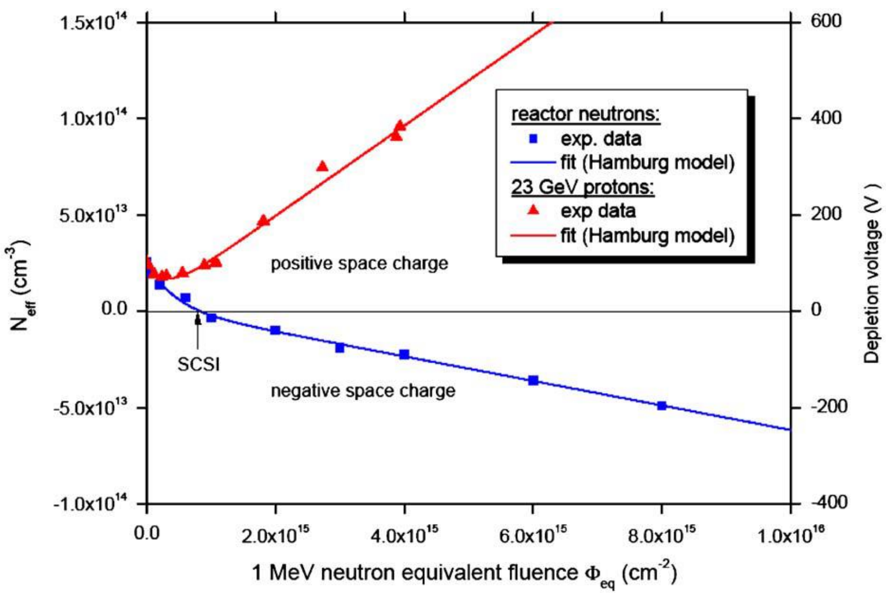
- a donor in the upper part of the gap and contribute with (+) charge at RT, enhanced generation after irradiation with charged hadrons

I. Pintilie, E. Fretwurst, G. Lindstroem, Cluster related hole traps with enhanced-field-emission--the source for long term annealing in hadron irradiated Si diodes, *APPL. PHYS. LETT. 92, 024101 2008*

Bridge the gap between the defect analyses and device performances







- **H(116K), H(140K), H(152K) & E(30K)** describe **quantitatively** the measured N_{eff}

- **generation of E(30 K) donor is strongly enhanced after proton irradiation**
  → for proton irradiation the N_{eff} remains positive while after neutron damage the type inversion occurs

I. Pintilie, G. Lindstroem, A. Junkes, E. Fretwurst, Nucl. Inst. Meth. A 611 (2009) 52–68 n-type Si

(WOrkshop on DEfect ANalysis) – WODEAN group
idea triggered by Gordon Davies' talk at RD50, CERN, Nov. 2005

Hamburg, 23-25 August 2006

Vilnius, 2-3 June 2007

Bucharest, May 2010

C-DLTS: NIMP Bucharest and Hamburg University: I. Pintilie, E. Fretwurst, G. Lindstroem
Minsk University: L. Makarenko
Oslo University: B. Svensson

I-DLTS: INFN and Florence University: D. Menichelli

TSC: NIMP Bucharest and Hamburg University: I. Pintilie, E. Fretwurst, G. Lindstroem

PITS: ITME Warsaw: P. Kaminski, R. Kozlowski

PL: Kings College London: G. Davies
ITME Warsaw: B. Surma

Recombination lifetime: Vilnius University: E. Gaubas, J. Vaitkus

FTIR: Oslo University and Minsk Joint Institute of Solid State and Semicond. Pysics: L. Murin, B. Svensson

PC: Vilnius University: J. Vaitkus, E. Gaubas

EPR: NIMP Bucharest: S. Nistor
ITME Warsaw: M. Pawlowski

Diode characteristics (C/V, I/V, TCT): CERN-PH, Hamburg University, JSI Ljubljana: M. Moll, E. Fretwurst, G. Lindstroem, G. Kramberger

E. V. Monakhov, B. S. Avset, A. Hallén, and B. G. Svensson,Phys. Rev. B 65, 233207, 2002; Gordon Davies, Shusaku Hayama, Leonid Murin, Reinhard Krause-Rehberg, Vladimir Bondarenko, Asmita Sengupta, Cinzia Davia, and Anna Karpenko, Phys. Rev. B 73, 165202, 2006; E. Gaubas, A. Uleckas, J. Vaitkus, Spectroscopy of neutron irradiation induced deep levels in silicon by microwave probed photoconductivity transients, NIMA 607, Issue 1, 2009, Pages 92-94, https://doi.org/10.1016/j.nima.2009.03.136; E. Gaubas, T. Ceponis, A. Jasiunas, A. Uleckas, J. Vaitkus, E. Cortina, O. Militaru; Correlated evolution of barrier capacitance charging, generation, and drift currents and of carrier lifetime in Si structures during 25 MeV neutrons irradiation. *Appl. Phys. Lett.* 3 December 2012; 101 (23): 232104. https://doi.org/10.1063/1.4769370;

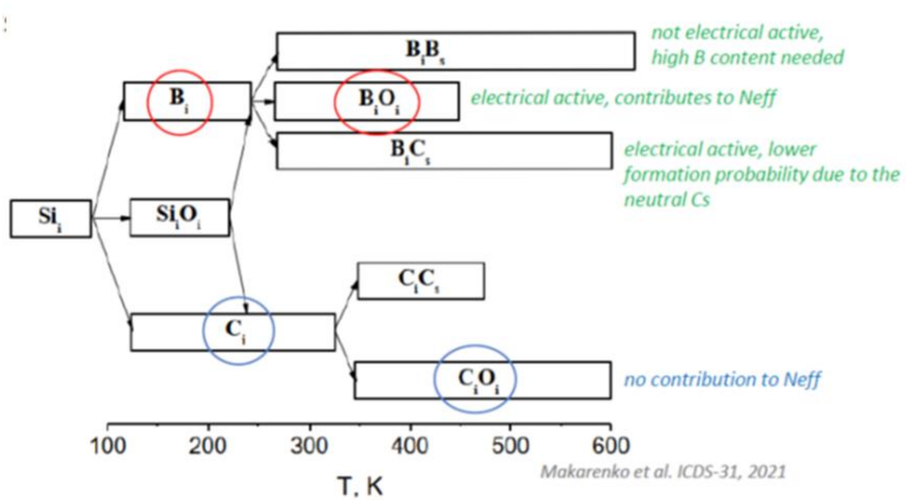
Radiation induced defects in *p-type* Silicon

same defects as in n-type Si

- **point defects** depending on the impurity content – O, C,H. ***exception*** - the VP center related to n-type doping (with P)
- **extended defects** (impurity independent clustered vacancies and interstitials)

+ **dopant related point defects** (containing B - $\mathbf{B_iO_i}$, B_sSi_i, BiCs, B_iB_s…)

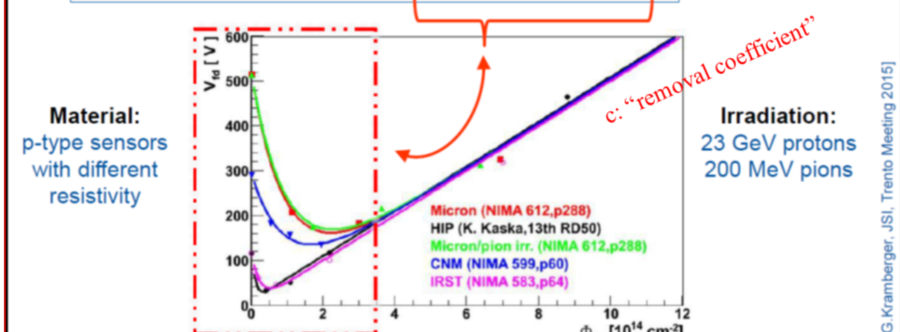
Main **detrimental effect**: **removal of the acceptors** from their substitutional lattice site (deactivation of shallow dopant) and change of the effective doping concentration (N_{eff})



- N_{eff} is usually extracted from CV measurements
  - Assuming: V_{fd} is a valid parameter to extract N_{eff}
  - Assuming: N_{eff} constant throughout the bulk
- Parameterization of N_{eff}:

$$V_{fd} = \frac{e_0 |N_{eff}| d^2}{2\epsilon\epsilon_0}$$

$$|N_{eff}| = |N_{eff,0}| + g_{eff}\Phi_{eq} - N_{C0}[1 - \exp(-c\Phi_{eq})]$$

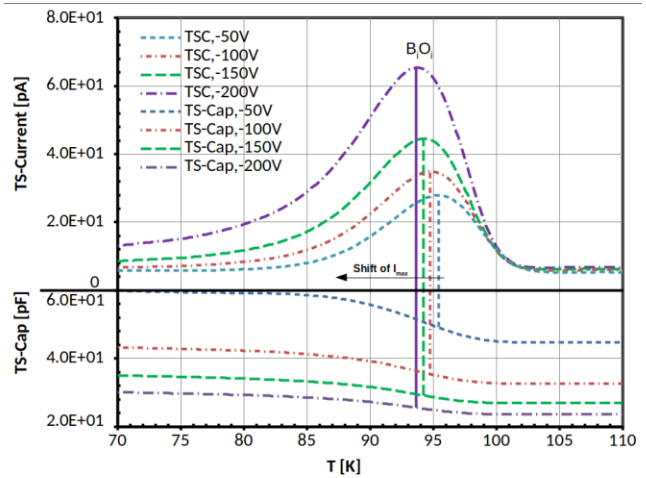


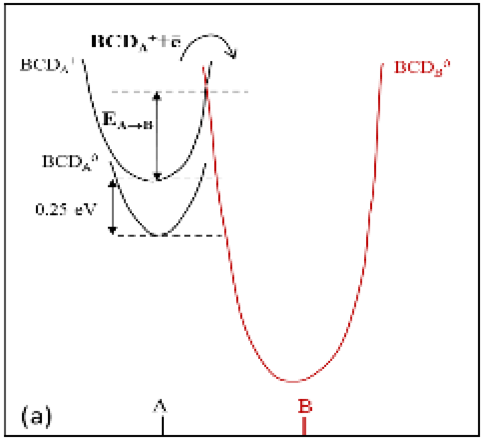
L.F. Makarenko et al, Primary defect transformations in high-resistivity p-type silicon irradiated with electrons at cryogenic temperatures, *Physica B* **2009**, 404, 4561–4564. DOI: 10.1016/S9999-9994(09)20505-8; M. Moll, Displacement Damage in Silicon Detectors for High Energy Physics, IEEE Transactions on Nuclear Science 2018, 65, pp. 1561-1582; M. Moll, Acceptor removal-Displacement damage effects involving the shallow acceptor doping of p-type silicon devices, *Proceedings of Science (Vertex2019)* **2020**, 027. DOI: 10.22323/1.373.0027

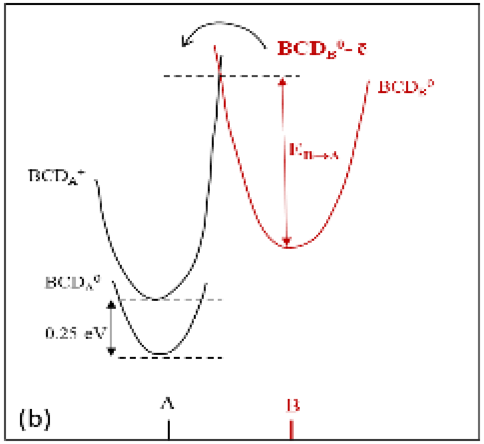
Acceptor removal in B-doped Silicon

"Acceptor removal" RD50 working group: CERN, HH, NIMP, Minsk, CiS, Torino

- **focus on B_iO_i defect (or B_sSi_i *) – trapping parameters, rates and bistable properties**







- **PAD diodes - good correlations** between defect investigations and macroscopic properties
- **LGAD**s – **problems** !

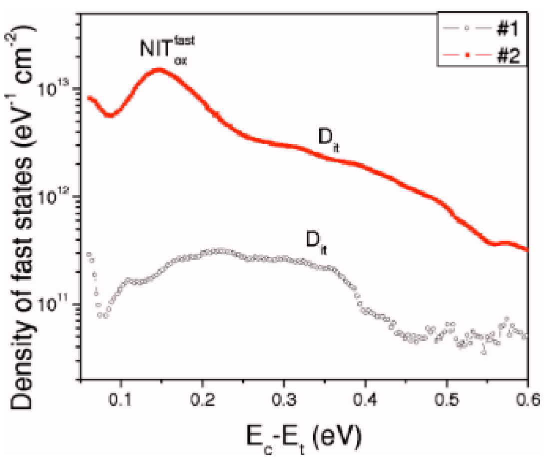
- DLTS does not work and TSC is affected by the change in the gain occurring due to the emission from traps during the temperature scan). In addition, the bistable behavior of the $\mathbf{B_iO_i}$ is affecting both, defect concentration and N_{eff} as determined from TSC and C-V measurements.

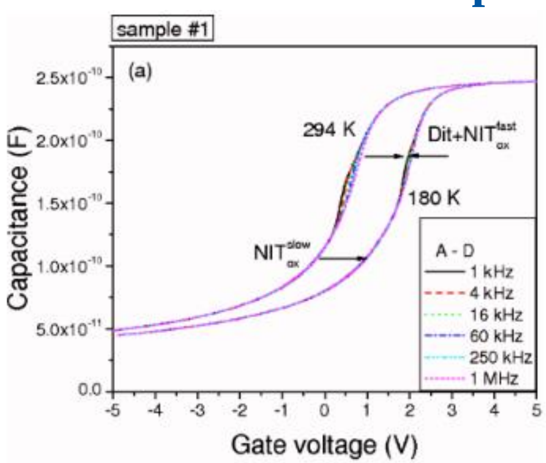
C. Besleaga et al, Bistability of the BiOi complex and its implications on evaluating the "acceptor removal" process in p type silicon , NIMA 1017, 2021, 165809; C. Liao et al., "The Boron–Oxygen (B_iO_i) Defect Complex Induced by Irradiation With 23 GeV Protons in p-Type Epitaxial Silicon Diodes," in IEEE Transactions on Nuclear Science, vol. 69, no. 3, pp. 576-586, March 2022, doi: 10.1109/TNS.2022.3148030. A. Himmerlich et al, Defect characterization studies on irradiated boron-doped silicon pad diodes and Low Gain Avalanche Detectors, NIMA 1048, 2023, 167977, https://doi.org/10.1016/j.nima.2022.167977 ; C. Liao et al.,"Investigation of the Boron removal effect induced by 5.5 MeV electrons on highly doped EPI- and Cz-silicon" NIMA 2023,1056, 168559, https://doi.org/10.1016/j.nima.2023.168559; A. Nitescu et al, Bistable Boron-Related Defect Associated with the Acceptor Removal Process in Irradiated *p*-Type Silicon—Electronic Properties of Configurational Transformations. *Sensors* **2023**, *23*, 5725. https://doi.org/10.3390/s23125725

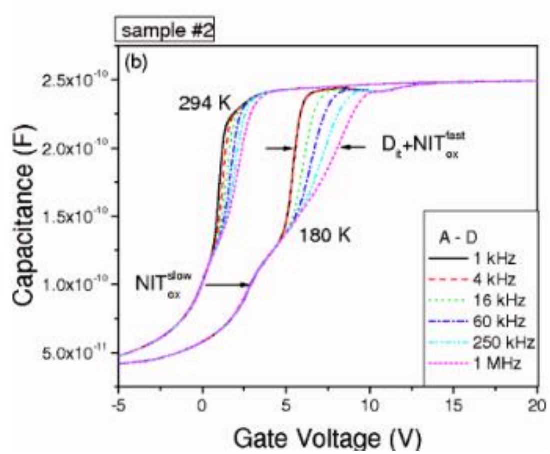
Silicon Carbide

2003 – 2006 (New Materials research line

- ***Study of native and radiation-induced defects***: Exeter University, Glasgow University, Vilnius University, NIMP – Bucharest, University of Oslo, IKZ – Berlin, University of Hamburg, University of Florence, Tel Aviv University, IOFFE PTI St. Petersburg.
- **DLTS studies of defects induced by irradiation** showed the formation of both, deep donors and acceptors however, **no correlation with the device performance** was established**.** Because also the macroscopic studies of radiation damage in SiC did not provided promising results, the research on this topic stopped in 2006.
- **Study of native bulk and interface defects** in SiO_2/4H-SiC or Al_2O_3/4H-SiC MOS structures provided a **good correlation with the developments in MOSFET technology**





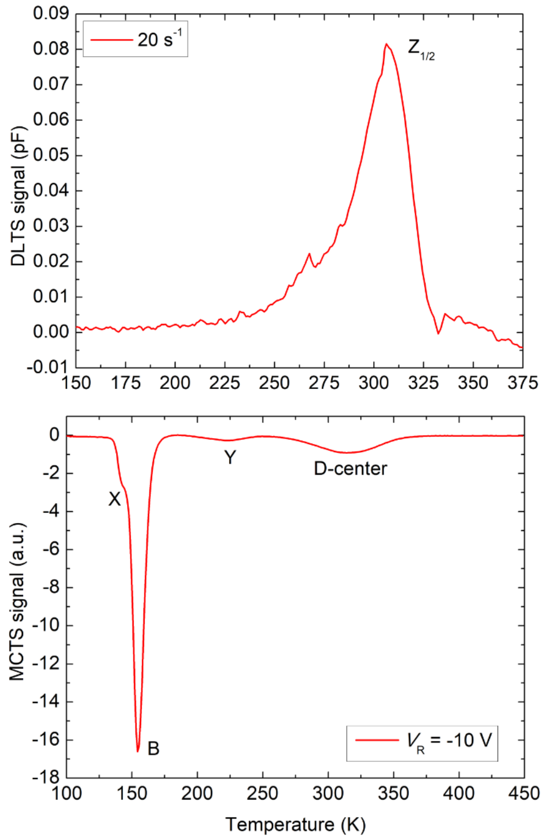


T. A. G. Eberlein et al, Z1/Z2 Defects in 4H−SiC, Phys. Rev. Lett. 90, 225502, 2003; H.Kortegaard Nielsen et al, Annealing study of a bistable defect in proton-implanted n-type 4H-SiC,Physica B: Condensed Matter 340–342, 2003, 743-747, https://doi.org/10.1016/j.physb.2003.09.151. A.Castaldini et al, Low temperature annealing of electron irradiation induced defects in . *Appl. Phys. Lett.* 25 October 2004; 85 (17): 3780–3782 https://doi.org/10.1063/1.1810627; H. K. Nielsen, et al, Capacitance transient study of the metastable M center in n-type 4H−SiC**,** Phys. Rev. B 72, 085208, 2005; I. Pintilie et al; Influence of growth conditions on irradiation induced defects in low doped epitaxial layers. *Appl. Phys. Lett.* 5 2007; 90 (6): 062113. https://doi.org/10.1063/1.2472173; M. Avice et al, Comparison of near-interface traps in and structures. *Appl. Phys. Lett.* 27, 2006; 89 (22): 222103. https://doi.org/10.1063/1.2387978; F. Moscatelli, Nitrogen implantation to improve electron channel mobility in 4H-SiC MOSFET, IEEE Transactions on Electron Devices 55, Issue 4, Pages 961 – 967,2008; I. Pintilie, et al, Analysis of electron traps at the interface; influence by nitrogen implantation prior to wet oxidation. *J. Appl. Phys.* 15 July 2010; 108 (2): 024503. https://doi.org/10.1063/1.3457906

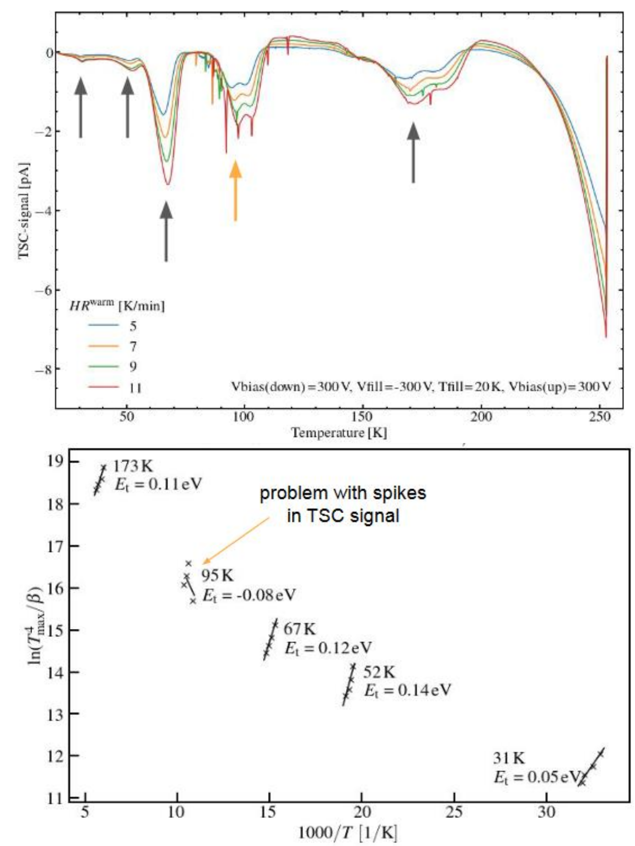
Silicon Carbide

- **2019 – the study of SiC revived** due to advances in fabrication technology leading to better and more promising performance in radiation detection
- **2022 -** start defect investigations by DLTS and TSC

T. Knezevic, E. Jelavić, Y. Yamazaki, T. Ohshima, T. Makino, and I. Capan, Materials, Apr. 2023, doi: 10.3390/ma16093347.



10^{14} p/cm^2

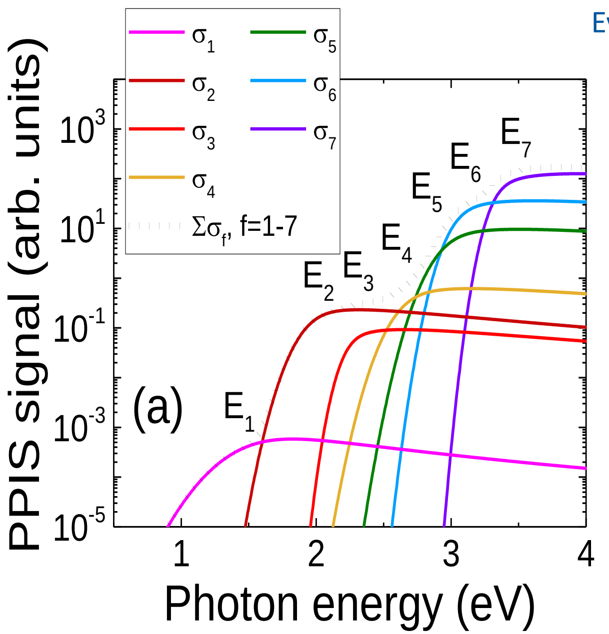


Moritz Wiehe, start of TSC experiments

J. M. Rafí *et al*., "Electron, Neutron, and Proton Irradiation Effects on SiC Radiation Detectors," in *IEEE Transactions on Nuclear Science*, vol. 67, no. 12, pp. 2481-2489, Dec. 2020, doi: 10.1109/TNS.2020.3029730; Tao Yang et al, in 2021, https://indico.cern.ch/event/1074989/contributions/4601968/; Cristian Quintana San Emeterio et al, in 2022, https://indico.cern.ch/event/1157463/contributions/4922793/ ; Rui Fan and Xinbo Zou in 2022, https://indico.cern.ch/event/1157463/contributions/4922771/; Ivan Lopez et al, in 2022, https://indico.cern.ch/event/1132520/contributions/5148174/

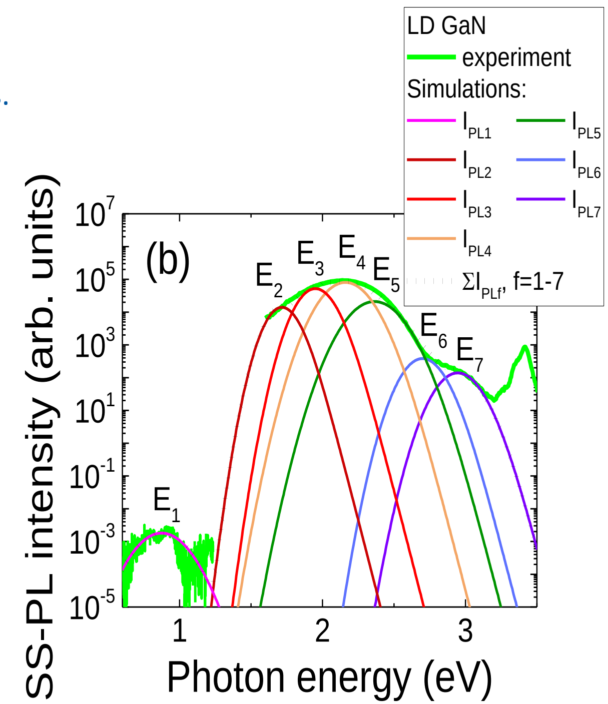
GaN

- **Studies started in 2003 by few groups in RD50 (Vilnius, Glasgow, Surrey Universities)**
- **no DLTS/TSC defect investigations because of the difficulties to form junctions**
- Characterization of defects in GaN bulk materials by Pulsed photo-ionization spectroscopy (PPIS) – technique developed by Vilnius University group



Evaluated trap parameters and identified defects.

E (eV)	σ (cm²)	N (cm⁻³)	Defect type
E_1=1.4	5.7×10^{-19}	5×10^{14}	C_I
E_2=1.9	1.6×10^{-16}	4×10^{10}	C related
E_3=2.2	9.1×10^{-17}	3×10^{10}	Vacancy V_{Ga}
E_4=2.6	6.3×10^{-16}	8×10^{10}	Vacancy V_{Ga}
E_5=2.9	9.1×10^{-15}	1×10^{12}	C_N^-
E_6=3.0	3.1×10^{-14}	4×10^{13}	C related
E_7=3.3	1.6×10^{-13}	2×10^{16}	C_NO_N or C_N



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Defects and Materials

RD50 Collaboration :

- **lead to remarkable achievements and progress in understanding the radiation damage from microscopic point of view**

- **allowed building up a strong expertise in investigating defects induced by irradiation in Si and WBG materials - *ready for addressing the DRD3 challenges***

Congratulation to all of you for the very pleasant, efficient and collaborative work in RD50!