Defects and Materials
(many)       (Si, SiC, GaN)

2002-2023
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 \textit{n-type Si}

\textbf{Influence of C and O concentration}

\textbf{23 GeV protons}

\textbf{Oxygen and standard silicon}

\textit{- Particle dependence -}

\textbf{23 GeV protons - 192 MeV pions - reactor neutrons}

\begin{itemize}
  \item \textbf{Compared to standard silicon:}
  \begin{itemize}
    \item High Carbon \Rightarrow \text{less radiation tolerant}
    \item High Oxygen \Rightarrow \text{more radiation tolerant}
  \end{itemize}
  \item \textbf{Strong improvement for pions and protons}
  \item \textbf{Almost no improvement for neutrons} \Rightarrow \text{“Proton-Neutron-Puzzle”}
\end{itemize}


Quantitative microscopic investigations – until 2001 only by DLTS so, only after low irradiation fluences

The DLTS detected defects after low irradiation levels does not explain the diodes macroscopic behaviour after high irradiation fluences
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\textsubscript{2}O-model**

  Higher oxygen content $\Rightarrow$ less negative space charge

  $V \xrightarrow[O]{} VO$ (not harmful at room temperature)

  $VO \xrightarrow{} V\textsubscript{2}O$ (negative space charge)


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

- **Intercenter charge transfer – model**

  Enhanced charge carrier generation inside clusters $\Rightarrow$ depending strongly on the defect density in the clusters

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, $\tau_{\text{recomb}}$, FTIR, PC, EPR, diode C/V, I/V and TCT)

- **Acceptor Removal working group** – defects in p-type Silicon
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 of defect’ activation energy

Search for still undetected defects responsible for the radiation damage

**Point defects** (after Co\(^{60}\) - γ irradiation)

- **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\(_2\)O model)*
  - a shallow donor in O rich material
- **No annealing effects**

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Search for still undetected defects responsible for the radiation damage

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} \text{ cm}^2

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

\sim 90\% \text{ occupied with (-) at RT}

Shallow donor (+ at RT)

BD center – generated in DOFZ

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

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

Overcompensates the effect of I_p acceptors!

\textbf{n-type Si}

\[
\Delta N_{\text{eff}} \left( \text{cm}^{-3} \right)
\]

\text{Co}^{60} - \text{gamma irradiation dose (MGy)}

\text{DOFZ (errors > 5\%)}

\text{STFZ (errors < 5\%)}

\text{\Delta LC (nA)}

\text{Co}^{60} - \text{gamma irradiation dose (MGy)}

\text{DOFZ (errors > 5\%)}

\text{STFZ (errors < 5\%)}

\text{first breakthrough in understanding the damage effects}

Search for still undetected defects responsible for the radiation damage

Extended Defects (clusters) – after hadron irradiation

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

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

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

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

$E_i^{30K} = E_c - 0.1eV, \sigma_n^{30K} = 2.3 \cdot 10^{-14} \text{ cm}^2$

- 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
Bridge the gap between the defect analyses and device performances

75 µm EPI-DO, 1 MeV-eq. n-irradiation, \( \Phi_{eq} = 5.0E13/cm^2 \)

- \( \Delta N_{eff} = N_{eff0} - N_{eff}(\Phi,t) \) [1/cm³]
- \( \text{macr. measured (C/V)} \)
- \( \text{macr. predicted (TSC)} \)
- donor generation small: 9.0E11/cm³, \( g = 1.8E-2/cm \)

75 µm EPI-DO, 23 GeV p-irradiation, \( \Phi_{eq} = 2.3E14/cm^2 \)

- \( \Delta N_{eff} = N_{eff0} - N_{eff}(\Phi,t) \) [1/cm³]
- \( \text{macr. measured (C/V)} \)
- \( \text{macr. predicted (TSC)} \)
- donor generation large: 2.1E13/cm³, \( g = 9.0E-2/cm \)

- \( H(116K), H(140K), H(152K) \) & \( E(30K) \) 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

(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

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

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 - $B_iO_i$, $B_sSi_i$, 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 ($N_{eff}$)

![Diagram showing defect configurations](image)

Acceptor removal in B-doped Silicon

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

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

- PAD diodes - good correlations between defect investigations and macroscopic properties
- LGADs – 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 BiOi is affecting both, defect concentration and Neff as determined from TSC and C-V measurements.

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\textsubscript{2}/4H-SiC or Al\textsubscript{2}O\textsubscript{3}/4H-SiC MOS structures provided a good correlation with the developments in MOSFET technology.
- **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

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Studies doped with various impurities 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.

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$\sigma$ (cm$^2$)</th>
<th>$N$ (cm$^{-3}$)</th>
<th>Defect type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1=1.4$</td>
<td>$5.7\times10^{-19}$</td>
<td>$5\times10^{14}$</td>
<td>$C_{l}$</td>
</tr>
<tr>
<td>$E_2=1.9$</td>
<td>$1.6\times10^{-16}$</td>
<td>$4\times10^{10}$</td>
<td>$C$ related</td>
</tr>
<tr>
<td>$E_3=2.2$</td>
<td>$9.1\times10^{-17}$</td>
<td>$3\times10^{10}$</td>
<td>Vacancy $V_{Ga}$</td>
</tr>
<tr>
<td>$E_4=2.6$</td>
<td>$6.3\times10^{-16}$</td>
<td>$8\times10^{10}$</td>
<td>Vacancy $V_{Ga}$</td>
</tr>
<tr>
<td>$E_5=2.9$</td>
<td>$9.1\times10^{-15}$</td>
<td>$1\times10^{12}$</td>
<td>$C_N$</td>
</tr>
<tr>
<td>$E_6=3.0$</td>
<td>$3.1\times10^{-14}$</td>
<td>$4\times10^{13}$</td>
<td>$C$ related</td>
</tr>
<tr>
<td>$E_7=3.3$</td>
<td>$1.6\times10^{-13}$</td>
<td>$2\times10^{16}$</td>
<td>$C_{N}O_{N}$ or $C_N$</td>
</tr>
</tbody>
</table>

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!