Overview of the recent activities of the RD50 collaboration on radiation hardening of semiconductor detectors for the SLHC

G. Casse
OUTLINE:

• Presentation of RD50
• Silicon materials currently under investigation
• RD50 masks and detector structures
• Results with diode measurements
• Results with segmented detectors
• 3-d detector activity
• Summary and future work
RD50: Radiation hard semiconductor devices for very high luminosity colliders

See http://rd50.web.cern.ch/rd50/

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Characterization of microscopic defects
- properties of standard-, defect engineered and new materials pre- and post-irradiation

Defect engineered silicon:
- Epitaxial Silicon
- CZ, MCZ
- Other impurities H, N, Ge, ...
- Thermal donors
- Pre-irradiation
- Oxygen Dimer

Development of new radiation tolerant materials:
- SiC
- GaN
- other materials

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Common irrad.
- Standardization of measurements

Evaluation of new detector structures
- 3D detectors
- Thin detectors
- Cost effective solutions
- Semi 3D

- LHC-like tests
- Links to HEP
- Links to R&D on electronics
- Comparison: pad-mini-full detectors
- Pixel group

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Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

257 Members from 50 Institutes

41 European and Asian institutes
Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Laappeenranta), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo (2x)), Poland (Warsaw (2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool)

8 North-American institutes
Canada (Montreal), USA (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50
**RD50 approaches to develop radiation hard detectors**

- **Material Engineering - Defect Engineering of Silicon**
  - Understanding radiation damage
    - **Macroscopic effects and Microscopic defects**
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - Oxygen rich Silicon
    - DOFZ, Cz, MCZ, EPI
  - Oxygen dimer & hydrogen enriched Silicon
  - Influence of processing technology

- **Material Engineering-New Materials** *(work concluded)*
  - Silicon Carbide (SiC), Gallium Nitride (GaN)

- **Device Engineering (New Detector Designs)**
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D detectors
  - Simulation of highly irradiated detectors
  - Semi 3D detectors and Stripixels
  - Cost effective detectors

- Development of test equipment and measurement recommendations

**Related Works – Not conducted by RD50**
- “Cryogenic Tracking Detectors” (CERN RD39)
- “Diamond detectors” (CERN RD42)
- Monolithic silicon detectors
- Detector electronics

**Radiation Damage to Sensors:**

- **Bulk damage due to NIEL**
  - Change of effective doping concentration
  - Increase of leakage current
  - Increase of charge carrier trapping

- **Surface damage due to IEL**
  (accumulation of positive charge in oxide & interface charges)
Silicon Growth Processes

- **Floating Zone Silicon (FZ)**
  - Basically all silicon detectors made out of high resistivity FZ silicon

- **Czochralski Silicon (CZ)**
  - The growth method used by the IC industry
  - Difficult to produce very high resistivity

- **Epitaxial Silicon (EPI)**
  - Chemical-Vapor Deposition (CVD) of Si
  - up to 150 μm thick layers produced
  - growth rate about 1μm/min

G. Casse, Novosibirsk, 28/02 5/03 2008  
10th International Conference Instr. Colliding Beam Physics
### Silicon Materials under Investigation

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [µm]</th>
<th>Symbol</th>
<th>( \rho ) (Ωcm)</th>
<th>[O(_i)] (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard FZ (n- and p-type)</td>
<td>50, 100, 150, 300</td>
<td>FZ</td>
<td>1–30(\times 10^3)</td>
<td>&lt; 5(\times 10^{16})</td>
</tr>
<tr>
<td>Diffusion oxygenated FZ (n- and p-type)</td>
<td>300</td>
<td>DOFZ</td>
<td>1–7(\times 10^3)</td>
<td>~ 1–2(\times 10^{17})</td>
</tr>
<tr>
<td>Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)</td>
<td>100, 300</td>
<td>MCz</td>
<td>~ 1(\times 10^3)</td>
<td>~ 5(\times 10^{17})</td>
</tr>
<tr>
<td>Czochralski Si, Sumitomo, Japan (n-type)</td>
<td>300</td>
<td>Cz</td>
<td>~ 1(\times 10^3)</td>
<td>~ 8–9(\times 10^{17})</td>
</tr>
<tr>
<td>Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)</td>
<td>25, 50, 75, 100, 150</td>
<td>EPI</td>
<td>50 – 100</td>
<td>&lt; 1(\times 10^{17})</td>
</tr>
<tr>
<td>Diffusion oxyg. Epitaxial layers on CZ</td>
<td>75</td>
<td>EPI–DO</td>
<td>50 – 100</td>
<td>~ 7(\times 10^{17})</td>
</tr>
</tbody>
</table>

- **Standard** for particle detectors
- **Used for LHC Pixel detectors**
- **“new” silicon material**

- DOFZ silicon - Enriched with oxygen on wafer level, inhomogeneous distribution of oxygen
- CZ/MCZ silicon - high O\(_i\) (oxygen) and O\(_{2i}\) (oxygen dimer) concentration (homogeneous)
- formation of shallow Thermal Donors possible
- Epi silicon (inhomogeneous) - high O\(_i\), O\(_{2i}\) content due to out-diffusion from the CZ substrate
- thin layers: high doping possible (low starting resistivity)
- Epi-Do silicon - as EPI, however additional O\(_i\) diffused reaching homogeneous O\(_i\) content
Irradiation facilities

RD50 institutes enjoy access to several world class irradiation facilities. In particular, the irradiations of the silicon detectors here shown have been performed in the CERN/PS Irrad1 (maintained by Maurice Glaser) and in the Triga nuclear reactor of the J. Stefan Institute of Ljubljana. Many thanks for the irradiation!

- **Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):**

  - **CIS Erfurt, Germany**
    - 2005/2006/2007 (RD50): Several runs with various epi 4" wafers only pad detectors
  - **CNM Barcelona, Spain**
    - 2006 (RD50): 22 wafers (4"), (20 pad, 26 strip, 12 pixel), (p- and n-type), (MCZ, EPI, FZ)
    - 2006 (RD50/RADMON): several wafers (4"), (100 pad), (p- and n-type), (MCZ, EPI, FZ)
  - **HIP, Helsinki, Finland**
    - 2006 (RD50/RADMON): several wafers (4"), only pad devices, (n-type), (MCZ, EPI, FZ)
    - 2006 (RD50): pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation
    - 2006 (RD50): full size strip detectors with 768 channels, n-type MCz-Si wafers
  - **IRST, Trento, Italy**
    - 2004 (RD50/SMART): 20 wafers 4" (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500µm
    - 2004 (RD50/SMART): 23 wafers 4" (p-type), (MCZ, FZ), two p-spray doses 3E12 amd 5E12 cm⁻²
    - 2005 (RD50/SMART): 4" p-type EPI
    - 2006 (RD50/SMART): new SMART mask designed
  - **Micron Semiconductor L.t.d (UK)**
    - 2006 (RD50): 4", microstrip detectors on 140 and 300µm thick p-type FZ and DOFZ Si.
    - 2006/07 (RD50): 93 wafers, 6 inch wafers, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)
  - **Sintef, Oslo, Norway**
    - 2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers
  - **Hamamatsu, Japan (Not RD50 but surely influenced by RD50 results on this material)**
    - In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups

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Pad, strip and pixel sensors available for further tests …… we are open for any collaboration.
**Standard thickness diode: n-type FZ, DOFZ, Cz and MCz Silicon**

**24 GeV/c proton irradiation**

- **Standard FZ silicon**
  - type inversion at \( \sim 2 \times 10^{13} \text{ p/cm}^2 \)
  - strong \( N_{\text{eff}} \) increase at high fluence

- **Oxygenated FZ (DOFZ)**
  - type inversion at \( \sim 2 \times 10^{13} \text{ p/cm}^2 \)
  - reduced \( N_{\text{eff}} \) increase at high fluence

- **CZ silicon and MCZ silicon**
  - no type inversion in the overall fluence range (verified by TCT measurements)
  - (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
  - Strong indications for a reduced reverse annealing in MCZ silicon (2006)

- **Common to all materials (after hadron irradiation):**
  - reverse current increase
  - increase of trapping (electrons and holes)

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Diode results: Standard FZ, DOFZ, Cz and MCz Silicon

C-V Measurements

Slope of $V_{fd}$ increase with fluence

- MCz (p and n type): $55 \text{ V/}10^{14} \text{ cm}^{-2}$ ($g_c \sim 0.8 \text{ cm}^{-2}$) – lower stable damage than seen before?
- Fz (p and n type): $125 \text{ V/}10^{14} \text{ cm}^{-2}$ ($g_c \sim 1.8 \text{ cm}^{-2}$) – in agreement with previous results

There is no evidence of acceptor removal (neutron irradiated samples)

It seems that MCz should perform better – do we see this performance in CCE?

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N-irradiation: Charge collection (pads)

$V_{fd}$ from CV (denoted by arrows) agrees well with the kink in CCE

- The slope of charge increase with voltage is directly related to $V_{fd}$
  - Increase of $V_{fd}$ can be measured by the change of slope and vice versa
  - Similar $V_{fd}$ = similar slope -> same E field or not very important, true for pads
- High resistive non-depleted bulk is well reflected in linear increase of charge – different from non-irr.

G. Kramberger, Measurements of CCE on different RD50 detectors, ATLAS tracker upgrade workshop, Valencia, December 2007
**Diode results: thin FZ detectors and epitaxial Si**

- **Why thin detectors?**
  - Advantage:
    - lower depletion voltage \( V_{fd} \propto d^2 \), full depletion at large \( \Phi \) possible
    - lower leakage current \( \propto d \): if yes lower noise contribution, lower power dissipation
    - smaller collection time \( t_c \propto d \), less charge carrier trapping
  - Draw back:
    - smaller signal for mips \( \propto d \)
    - larger capacitance \( C_{det} \propto 1/d \), larger electronic noise

  → **find an optimal thickness**

- **Questions:**
  - depend the damage effects on the device thickness?
  - which impurities play a major role in the damage (P, O, C, H, others)?

E. Fretwurst et al., 11th RD50 workshop
**Thinning Technology**

1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process DEPFETs on top side
5. structure resist, etch backside up to oxide/implant

- **Sensor wafer**: high resistivity d=150mm FZ wafer.
- **Bonded on low resistivity “handle” wafer**.
- *(almost) any thickness possible*

Thin (50 µm) silicon successfully produced at MPI.

- MOS structures
- diodes
- No deterioration of detector properties, keep $I_{\text{leak}} < 100\text{pA/cm}^2$
Oxygen depth profiles

- **EPI-ST, 72 µm**: [O] inhomogeneous, 
  \( <[O]> = 9.3 \times 10^{16} \text{ cm}^{-3} \)

- **EPI-DO, 72 µm**: [O] homogeneous, except surface, 
  \( <[O]> = 6.0 \times 10^{17} \text{ cm}^{-3} \)

- **MCz**: [O] homogeneous, except surface 
  \( <[O]> = 5.2 \times 10^{17} \text{ cm}^{-3} \)

E. Fretwurst et al., 11th RD50 workshop
Comparison protons versus neutrons
EPI-72 µm, MCz-100 µm

- EPI-devices (here 72 µm) reveal no SCSI after proton damage contrary to neutron damage
- Same behavior holds for thin MCz-diodes
- $\beta > 0$ (dominant donor creation) for protons (more point defects than clusters)
- $\beta < 0$ (dominant acceptor creation) for neutrons (more clusters than point defects)
Comparison protons versus neutrons
FZ-50 µm, FZ-100 µm

FZ-50 µm:
- $\beta > 0$ for protons (dominant donor creation)
- $\beta < 0$ for neutrons (dominant acceptor creation)

FZ-100 µm:
- $\beta < 0$ for protons and neutrons (dominant acceptor creation)

E. Fretwurst et al., 11th RD50 workshop
Possible advantages of non-inverted detectors: reverse reverse-annealing

\[ V_{\text{ref}} \text{ [V]} \]

- EPI-ST, 72 \( \mu \text{m}, 3.4 \times 10^{15} \text{ cm}^2 \)
- EPI-ST, 150 \( \mu \text{m}, 2.6 \times 10^{14} \text{ cm}^2 \)

\( T_a = 80^\circ \text{C} \)

E. Fretwurst et al., 11\textsuperscript{th} RD50 workshop
Thick diodes RD50 results in short

- Leakage current – invariant on material type
- Trapping times – invariant on material type (seem to exhibit non-linear dependence at high fluences)
- Materials:

\[ \frac{\Delta I}{V} = \alpha \cdot \Phi_{eq} \]

\[ \frac{1}{\tau_{eff,e,h}} = \beta_{e,h} \cdot \Phi_{eq} \]

Reverse annealing: acceptors always introduced, \( \tau_{ra} \) depends on oxygen – the more the longer…

G. Casse, Novosibirsk, 28/02 5/03 2008  10th International Conference Instr. Colliding Beam Physics
Segmented detectors: side matters!!

Schematic changes of Electric field after irradiation

Effect of trapping on the Charge Collection Efficiency (CCE)

Collecting electrons provide a sensitive advantage with respect to holes due to a much shorter $t_c$. P-type detectors are the most natural solution for $e$ collection on the segmented side.

$$Q_{tc} \equiv Q_0 \exp(-t_c/\tau_{tr}), \quad 1/\tau_{tr} = \beta \Phi.$$
Trapping induced charge sharing (G. Kramberger)

electrode hit in the center by ionizing particle

\[ \sum Q_i \equiv Q_{\text{diode}} \]

all electrodes \((\text{pitch–implant width}) \rightarrow 0\)

\[ Q_{\text{hit}} < Q_{\text{diode}} \]

\[ Q_{\text{hit}} > Q_{\text{diode}} \]

\(p^+\) elect. \(\rightarrow\) wider clusters

\(n^+\) elect. \(\rightarrow\) larger signals
Proton irradiations

P-type miniature detectors from CNM

Extremely good performances in term of charge collection after unprecedented doses (1., 3.5., and $7.5 \times 10^{15}$ p cm$^{-2}$) were obtained with these devices!!

G. Casse et al., NIM A 568(2006)
P-type miniature detectors from CNM

For the first time the CCE was measured as a function of the accelerated annealing time with LHC speed electronics (SCT128A chip), and the results were really surprising!!

\[3.5 \times 10^{15} \text{ p cm}^{-2}\]

Initial \(V_{FD} \sim 1300\text{V}\), final \(\sim 6000\text{V}\)

\[7.5 \times 10^{15} \text{ p cm}^{-2}\]

Initial \(V_{FD} \sim 2800\text{V}\), final \(\sim 12000\text{V}\)

Predictions from RD48 parameters for Oxygen enriched devices (best scenario: after 7 RT annealing years the \(V_{FD}\) goes from \(\sim 2800\text{V}\) to \(\sim 12000\text{V}\)!
Results with neutron irradiated Micron detectors

Now µ-strip detector CCE measurements up to $1 \times 10^{16} \text{ n cm}^{-2}$!
Charge collection efficiency vs fluence for micro-strip detectors irradiated with n and p read-out at LHC speed (40MHz, SCT128 chip).
Neutron irradiation: p-type miniature detectors from Micron

Annealing characterisation.

G. Casse, 11th RD50 workshop
Partial comparison of CCE between FZ and MCz materials (p-type only).
Long term annealing (strips, binary)

Only some points measured so far:
The CCE follows the trend of the $V_{fd}$:
- initial rise (beneficial annealing) increase in collected charge by $\sim 10\%$ (@500V)
- decrease by again 20-30% (@500V) during the reverse annealing 1000 min
- Smaller effect for Fz-p detector due to larger $V_{fd}$ after irradiation (relatively smaller effect)
CCE at higher voltages shows annealing of electron trapping times $\rightarrow$ one of the reasons why long term annealing is not so damaging.

From H. Sadrozinski et al. 11th RD50 workshop

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Important parameter:

Trapping Time Constants

collected charge for different \( V_{\text{bias}} \) depends on trapping time

calculate: \( i_m(t) = i_0(t) \exp(-t/\tau_{\text{eff}}) \)

with different \( \tau \)

even measurable with thin diodes

if slope = 0, trapping time determined
Inverse Trapping Time vs. Fluence (DOFZ + epi)

\[ \beta_{n,e} = (3.01 \pm 0.09) \times 10^{-16} \text{ cm}^2/\text{ns}, \]

J. Weber, 11th RD50 Workshop 12 - 14 November 2007 CERN

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Thin and thick segmented detectors

Comparison of CCE with 140µm and 300µm thick detectors from Micron irradiated to various n fluences, up to $1 \times 10^{16}$ cm$^{-2}$!

- $5 \times 10^{14} \text{n}_{\text{eq}} \text{ cm}^{-2}$
- $1.6 \times 10^{15} \text{n}_{\text{eq}} \text{ cm}^{-2}$
Thin and thick segmented detectors

Comparison of CCE with 140µm and 300µm thick detectors from Micron irradiated to various n fluences, up to $1 \times 10^{16}$ cm$^{-2}$!

G. Casse, 11th RD50 workshop

$3 \times 10^{15} \, n_{eq} \, \text{cm}^{-2}$

$1 \times 10^{16} \, n_{eq} \, \text{cm}^{-2}$
Comparison of reverse current between 140µm and 300µm thick detectors from Micron irradiated to $1 \times 10^{16} \text{ cm}^{-2}$!

**SURPRISE:** reverse current is the same!
Alternative geometries: 3D detectors

- **“3D” electrodes:**
  - narrow columns along detector thickness,
  - diameter: 10µm, distance: 50 - 100µm
- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard

*Introduced by: S.I. Parker et al., NIMA 395 (1997) 328*
3D activities: simulations

• Simulated MIPs passing through detector at 25 positions, to roughly map the collection efficiency. 150V bias. Charge sharing not taken into account. Dose $10^{16} n_{eq}$/cm$^2$
• Low collection within n$^+$ and p$^+$ columns (seen experimentally)

D. Pennicard, 11$^{th}$ RD50 workshop
3-D strip detector measurements

- Cz p-spray, unirradiated
- 5μm step size
- 80μm x 80μm area
- y axis along the strips
- At variable bias voltage

11th RD50 Workshop, CERN, 13 November 2007  Gregor Pahn, Universität Freiburg

G. Casse, Novosibirsk, 28/02 5/03 2008  10th International Conference Instr. Colliding Beam Physics
OUTLOOK:

Investigation of n-MCz detectors with proton irradiation

Further Investigation of O and thickness effects

Systematic investigation of the effect of initial wafer resistivity

Investigate best solution for interstrip isolation

Investigation of optimal solution for diode geometry in 3D devices.

Quest for satisfactory microscopy model with accurate prediction of the electrical properties of the devices
SPARES
**EPI Devices – Irradiation experiments**

- Epitaxial silicon
  - Layer thickness: 25, 50, 75 μm (resistivity: ~ 50 Ω·cm); 150 μm (resistivity: ~ 400 Ω·cm)
  - Oxygen: [O] ≈ 9×10^{16} cm^{-3}; Oxygen dimers (detected via IO_2-defect formation)

- Only little change in depletion voltage

- No type inversion up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2  
  ⇒ high electric field will stay at front electrode!

- Explanation: introduction of shallow donors is bigger than generation of deep acceptors

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Epitaxial silicon – Thin silicon - Annealing

- 50 µm thick silicon can be fully depleted up to $10^{16}$ cm$^{-2}$
  - Epitaxial silicon (50Ω cm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KΩ cm, MPI Munich, wafer bonding technique)

- Thin FZ silicon: **Type inverted**, increase of depletion voltage with time
- Epitaxial silicon: **No type inversion**, decrease of depletion voltage with time
  $\Rightarrow$ No need for low temperature during maintenance of experiments!

[MPI Munich project: Thin sensor interconnected to thinned ATLAS readout chip (ICV-SLID technique)]

[E.Fretwurst et al., NIMA 552, 2005, 124]

G. Casse, Novosibirsk, 28/02 5/03 2008 10th International Conference Instr. Colliding Beam Physics
Proton irradiation: $N_{\text{eff}} (V_{fd})$ normalized to 100 $\mu$m EPI

- **Low fluence range:**
  Donor removal, depends on $N_{\text{eff,0}}$
  Minimum in $N_{\text{eff}}(\Phi)$ shifts to larger $\Phi$ for higher doping

- **High fluence range:**
  EPI-DO and -ST:
  $\beta(72) > \beta(100) \approx \beta(150) \rightarrow$ initial doping?
  and
  $\beta(\text{EPI-DO}) > \beta(\text{EPI-ST}) \rightarrow$ oxygen effect?

- NO TYPE INVERSION, $\beta > 0$

\[
N_{\text{eff}} (\Phi) = N_{\text{eff,0}} \cdot \exp(-c \cdot \Phi) + \beta \cdot \Phi
\]

$\beta > 0$, dominant donor generation

$\beta < 0$, dominant acceptor generation

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Proton irradiation: annealing of $V_{fd}$ at 80 °C

EPI diodes

- Typical annealing behavior of non-inverted diodes:
  - $V_{fd}$ increase, short term annealing
  - $V_{fd,\text{max}}$ (at $t_a \approx 8$ min), stable damage
  - $V_{fd}$ decrease, long term annealing

$$V_{fd}(\Phi,t) = V_C(\Phi) \pm V_a(\Phi,t) \pm V_Y(\Phi,t)$$

- stable damage ± short term ± long term annealing
- + sign if inverted
- − sign if not inverted

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Development of $N_{\text{eff}}$ resp. $V_{\text{fd}}$ normalized to 100 $\mu$m
FZ and MCz

- **Low fluence range:**
  Donor removal, depends on $N_{\text{eff},0}$
  Minimum in $N_{\text{eff}}(\Phi)$ shifts to larger $\Phi$ for higher doping

- **High fluence range:**
  $\beta(\text{FZ-50}) \approx \beta(\text{MCz-100}) > \beta(\text{FZ-100})$

- $\beta > 0$ or $< 0$?

  Expected:

  FZ-50, FZ-100 $\rightarrow \beta < 0$, inversion, low [O]

  MCz-100 $\rightarrow \beta > 0$, no inversion, high [O]
Annealing of $V_{fd}$ at 80 °C
FZ diodes

- Annealing behavior of FZ-100 μm:
  - Inverted diode
  - $V_{fd}$ decrease (short term component)
  - $V_{fd,min}$ (stable component)
  - $V_{fd}$ increase (long term component)

  for protons and neutrons

- Annealing behavior of FZ-50 μm:
  - Surprise??
  - €after proton damage no inversion
  - after neutron damage inversion

Thickness effect?

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