Mixed Irradiations: Order Dependent?

Jan-Ole Gosewisch for the ETP Detector Group | November, 2018
Introduction

- Strip sensors and diodes irradiated with a total fluence of $\Phi \approx 6 \times 10^{14} \ n_{eq} \ cm^{-2}$
- Material (n-type):
  - diffusion oxygenated float zone (DOFZ), magnetic Czochralski (MCZ) and float zone (FZ) – From RD50’s NitroStrip project (as in previous talk)
- Irradiation procedure for each material set:
  - 2 sensors and 1 diode irradiated with $\Phi \approx 3 \times 10^{14} \ n_{eq} \ cm^{-2}$ protons first and $\Phi \approx 3 \times 10^{14} \ n_{eq} \ cm^{-2}$ neutrons afterwards ($p+n$)
  - 2 sensors and 1 diode irradiated with $\Phi \approx 3 \times 10^{14} \ n_{eq} \ cm^{-2}$ neutrons first and $\Phi \approx 3 \times 10^{14} \ n_{eq} \ cm^{-2}$ protons afterwards ($n+p$)
- Measurements:
  - After first irradiation: CV characteristics (-20°C, 455Hz, guard ring floating)
  - After the second irradiation: CV and signal (ALiBaVa with $^{90}$Sr source)
  - Annealing study: Seed signal
Irradiation and Annealing

- Proton irradiation:
  - At ZAG (Karlsruhe) with 23 MeV (hardness factor of 2)
  - Samples are cooled down (to roughly -30°C) while irradiating
  - Measurement of the fluence with a Ni-foil (±15%)
    - First irradiation with protons $\Phi = 2.7 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$
    - Second irradiation with protons $\Phi = 2.9 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$

- Neutron irradiation:
  - At Ljubljana inside a spallation reactor
  - Samples are not cooled inside the reactor (roughly 20h annealing)
  - Real fluences
    - First irradiation with neutrons $\Phi = 3 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$
    - Second irradiation with neutrons $\Phi = 3.3 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$
  - All equivalent fluence same ($\Phi = 3 \times 10^{14} \text{ n}_{\text{eq}} \text{ cm}^{-2}$) within 10%
CV Characteristics of MCZ Strip Sensors

- $p \rightarrow p+n$
  - First $\Phi = 2.7 \times 10^{14}$ $n_{\text{eq}}$ cm\(^{-2}\) protons
  - Then $\Phi = 3.3 \times 10^{14}$ $n_{\text{eq}}$ cm\(^{-2}\) neutrons ($p+n$)
  - Depletion voltage increased (expected)

- $n \rightarrow n+p$
  - First $\Phi = 3 \times 10^{14}$ $n_{\text{eq}}$ cm\(^{-2}\) neutrons
  - Then $\Phi = 2.9 \times 10^{14}$ $n_{\text{eq}}$ cm\(^{-2}\) protons ($n+p$)
  - Depletion voltage unchanged/reduced!

![CV Characteristics (p+n)](image1)

![CV Characteristics (n+p)](image2)
CV Characteristics of FZ Strip Sensors

- \( p \rightarrow p+n \)
  - First \( \Phi = 2.7 \times 10^{14} \text{ } n_{eq} \text{ cm}^{-2} \) protons
  - Then \( \Phi = 3.3 \times 10^{14} \text{ } n_{eq} \text{ cm}^{-2} \) neutrons \((p+n)\)
  \( \rightarrow \) Depletion voltage increased (expected)

- \( n \rightarrow n+p \)
  - First \( \Phi = 3 \times 10^{14} \text{ } n_{eq} \text{ cm}^{-2} \) neutrons
  - Then \( \Phi = 2.9 \times 10^{14} \text{ } n_{eq} \text{ cm}^{-2} \) protons \((n+p)\)
  \( \rightarrow \) Depletion voltage unchanged/reduced!
CV Characteristics of Diodes

- **p → p+n**
  - First $\Phi = 2.7 \times 10^{14} \, n_{eq} \, cm^{-2}$ protons
  - Then $\Phi = 3.3 \times 10^{14} \, n_{eq} \, cm^{-2}$ neutrons ($p+n$)
  - Depletion voltage increased (expected)

- **n → n+p**
  - First $\Phi = 3 \times 10^{14} \, n_{eq} \, cm^{-2}$ neutrons
  - Then $\Phi = 2.9 \times 10^{14} \, n_{eq} \, cm^{-2}$ protons ($n+p$)
  - Depletion voltage unchanged/reduced!
Short Discussion – Frame Conditions

Result till now:

- The irradiation sequence n+p leads to a lower depletion voltage than p+n (all materials)

Annealing:

- Irradiation procedure protons + neutrons (p+n)
  - First proton irradiation → sensors are cooled down to -30°C
  - Then shipped to Ljubljana → uncontrolled annealing possible + annealing inside reactor
  - Shipped back → uncontrolled annealing could take place again

- Irradiation procedure for neutrons + protons (n+p)
  - First neutron irradiation (temperature during shipment uncritical)
  - Annealing inside the reactor - similar to p+n
  - Shipment back to KIT → same annealing time as for p+n (all sensors in the same package)
  - Irradiation with protons → should be cooled down to -30°C

Preliminary conclusion: Less depletion voltage (for n+p) due to annealing is only possible if sensors were not cooled down while irradiating with protons!
Signal measurements with an ALiBaVa setup

- Daughterboard inside a shielded box
  - 1 – Connection to motherboard
  - 2 – Beetle chip for readout
  - 3 – Pitch adapter
  - 4 – Radioactive source holder
- Copper block temperature controlled via peltier elements (-20°C to 80°C)
- Scintillator below the copper block to trigger the readout

Measurement procedure
- Pedestal run to measure the noise
- Calibration run to calibrate the gain
- Radioactive source run to measure the generated signal
Seed Signal vs Cluster Signal

- Charged particle traversing a sensor generates signal in a set of strips (cluster)
  - Seed signal: signal of the strip with the most signal (SNR ≥ 4)
  - Cluster signal: seed signal + signal of neighbouring strips (SNR ≥ 2)
- **Main difference between cluster and seed signal is an offset**
  → Comparison of both signal definitions for a proton irradiated MCZ strip sensor

![Graph showing Seed Signal at 700V (Φ_{ tot } = 6e14 p_{ eq }/cm^2)]
Seed Signal before Annealing

- **Voltage dependence of the signal (MCZ)**
  - Sensors irradiated with n+p show a significantly higher signal for all bias voltages above 300V
  - Consistent with the CV characteristics
    - Lower depletion voltage for n+p

- **Voltage dependence of the signal (FZ)**
  - One sensor with n+p clearly above the others
  - FZ5 similar signal to p+n for low voltages but higher signal at higher voltages(?)
  - Others consistent with CV characteristics
    - Lower depletion voltage for n+p
Annealing Characteristics

- **Annealing behaviour at 800V (MCZ)**
  - Dependent on the irradiation sequence!
  - Excludes annealing as an explanation for the differences after n+p and p+n irradiation

- **Annealing behaviour at 800V (FZ)**
  - Independent of the irradiation sequence
  - Before annealing: higher signal of n+p
  - Fast vanishing of the difference

- **Oxygen concentration**
  - MCZ: $4.6 \cdot 10^{17} \text{ cm}^{-3}$
  - FZ: $< 9 \cdot 10^{15} \text{ cm}^{-3}$
Conclusions

- Investigation of CV characteristics and signal dependent on the irradiation sequence
- The irradiation sequence n+p results in a lower depletion voltage than for p+n irradiated samples for all investigated materials (MCZ, FZ, DOFZ)
- In agreement with this lower depletion voltage, the signal is higher (before annealing)
- The signal difference vanishes rapidly (after some days annealing time) due to strong beneficial annealing of the p+n irradiated sensors
  - The signal annealing behaviour is similar for both irradiation sequences and FZ material
- It is ambiguous if this is also the case for DOFZ material
- Contrary, the irradiation sequence was crucial for the annealing behaviour of MCZ material
  - n+p irradiated samples showed significantly less reverse annealing
    - Finally excludes annealing as a possible explanation

- Similar effects were also observed for p-type material
  - But no full comparable data set (CVs of n+p irradiated sensors)
Backup
Signal Annealing of MCZ Material

Seed Signal at 800V ($\Phi_{tot} = 6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$)

![Graph showing seed signal over annealing time for different materials.](image)
Signal Annealing of MCZ Material

Seed Signal at 800V ($\Phi_{\text{tot}} = 6\times10^{14}$ n$_{\text{eq}}$/cm$^2$)

- MCZ1 p
- MCZ2 p
- MCZ3 n
- MCZ4 n
- MCZ5 n+p
- MCZ6 n+p
- MCZ7 p+n
- MCZ8 p+n

Annealing Time (Days)

Seed Signal (e)
HPK Material – CV and IV Characteristics

CV Characteristics (T= -20°C)

IV Characteristics (T= -20°C)
Signal over Fluence of n-type Sensors

From 2017 JINST 12 P06018
IV Characteristics n+p vs p+n

- After the total fluence of $\Phi \approx 6\times10^{14}$ $n_{eq}$ cm$^{-2}$
  - Neutron after proton irradiation (p+n) 
    - More leakage current
  - Proton after neutron irradiation (n+p) 
    - Less leakage current

![IV Characteristics after total Fluence](image-url)

- IV Characteristics after total Fluence
  - MCZ5 n+p
  - MCZ6 n+p
  - MCZ7 p+n
  - MCZ8 p+n
  - DOFZ5 n+p
  - DOFZ6 n+p
  - DOFZ7 p+n
  - DOFZ8 p+n

![IV Characteristics after total Fluence](image-url)
Signal after Irradiation – FZ and DOFZ 600V

- **Annealing behaviour of the seed signal (FZ)**
  - Independent of the irradiation sequence
  - Before annealing: higher signal of n+p
    → Consistent with CV measurements

- **Annealing behaviour of the seed signal (DOFZ)**
  - Dependent on the irradiation sequence?
  - Before annealing: higher signal of n+p
    → Consistent with CV measurements
Signal after Irradiation – MCZ 600V

- Annealing behaviour of the seed signal (MCZ) at 600V
  - Still stronger reverse annealing of the p+n irradiated material

![Graph showing seed signal at 600V](Image)

Seed Signal at 600V ($\Phi_{tot} = 6e14 \ n_{eq}/cm^2$)

- MCZ5 n+p
- MCZ6 n+p
- MCZ7 p+n
- MCZ8 p+n
Voltage Dependence after Annealing

Seed Signal after 14 Days Annealing ($\Phi = 6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$)

Seed Signal after 203 Days Annealing ($\Phi = 6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$)
IV Characteristics of DOFZ Material

- **Left side:**
  - First proton then neutron irradiation \((p+n)\)
  - → Leakage current increased (expected)

- **Right side:**
  - First neutron then proton irradiation \((n+p)\)
  - → Leakage current unchanged!
IV Characteristics of MCZ Material

- **Left side:**
  - First proton then neutron irradiation \((p+n)\)
  - \(\rightarrow\) Leakage current increased (expected)

- **Right side:**
  - First neutron then proton irradiation \((n+p)\)
  - \(\rightarrow\) Leakage current unchanged/reduced!

![Graphs showing IV Characteristics](image-url)
IV Characteristics of FZ Material

Left side:
- First proton then neutron irradiation (p+n)
  → Leakage current increased (expected)

Right side:
- First neutron then proton irradiation (n+p)
  → Leakage current unchanged/reduced!

![Graphs showing IV Characteristics (p+n) and (n+p)]
CV Characteristics of DOFZ Material

- **p \rightarrow p+n**
  - First $\Phi = 2.7 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$ protons
  - Then $\Phi = 3.3 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$ neutrons ($p+n$)
  - Depletion voltage increased (expected)

- **n \rightarrow n+p**
  - First $\Phi = 3 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$ neutrons
  - Then $\Phi = 2.9 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$ protons ($n+p$)
  - Depletion voltage unchanged/reduced!