Acceptor removal in silicon pad diodes with different resistivities

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Acceptor removal

- **Apparent** dopant removal due to the irradiation

- Parameterization as

\[ N_{eff}(\Phi) = N_{eff0} e^{-c \cdot \Phi} + g_c \Phi \]

- For neutron irradiation, incomplete acceptor removal is also considered \((N_c < N_{eff0})\)

\[ N_{eff}(\Phi) = N_{eff0} - N_c \left( 1 - e^{-c \Phi} \right) + g_c \Phi \]

Simulation can qualitatively reproduce this behaviour **without** Boron removal
Motivation

Example: Low Gain Avalanche Detectors (LGADs)

- LGADs have a highly doped layer to achieve gain
- Interesting for their timing capabilities
- However, the gain decreases when exposed to radiation due to ‘acceptor removal’

G. Kramberger et al, JINST (2015)
Motivation

Example #2: HVCMOS
- HVCMOS is an interesting technology for monolithic pixel sensors
- However, its charge collection varies with fluence
- Increase of CCE with fluence due to ‘acceptor removal’ observed

A. Affolder et al, J. Instrumentation (2016)
Motivation

No systematic study, hard to compare results from literature:

- Different devices
- Different oxygen content
- Different material types
- Different measurement techniques

**Solution:** dedicated characterization experiment
A large number of sensors with the same structure with varying thicknesses, resistivities and material types
Materials and Devices

Simple p-type pad diodes

Epitaxial (50 μm)
- 10 Ω·cm
- 50 Ω·cm
- 250 Ω·cm
- 1000 Ω·cm

Float zone (>10 000 Ω·cm)
- 100 μm
- 150 μm
- 200 μm
- 285 μm
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Irradiation

Proton and neutron irradiation
From $\sim 7 \times 10^{13}$ to $7 \times 10^{15}$ n$_{eq}$ cm$^{-2}$
Acceptor Removal Used Methods

From CV curves, two methods were used to measure $N_{eff}$:

- **Depletion Voltage***:
  \[ N_{eff} = \left( \frac{C}{A} \right)^2 \frac{2V_{dep}}{\varepsilon \varepsilon_0 q_0} \]

- **1/C^2 Slope**:
  \[ N_{eff} = \frac{2}{A^2 \varepsilon \varepsilon_0 q_0} \frac{1}{d \left( 1/C^2 \right) / dV} \]

*This method was also applied to IV curves*
Acceptor Removal Previous Results

P. Almeida et al, 30th RD50 (2017)

Epitaxial

Floatzone

from CV/IV kink:

$$N_{eff} = \left( \frac{C}{A} \right) \frac{2V_{dep}}{\varepsilon \varepsilon_0 q_0}$$

from CV slope:

$$N_{eff} = \frac{2}{A^2 \varepsilon \varepsilon_0 q_0 d \left(1/C^2\right)} /dV$$
Annealing Study

Annealing curves show evidence of type inverted detectors — later confirmed by TCT. For more details, see dedicated presentation in the 31st RD50 workshop.

**Equations:**

- from CV/IV kink: 
  \[ N_{eff} = \left( \frac{C}{A} \right)^2 \frac{2V_{dep}}{\varepsilon \varepsilon_0 q_0} \]

- from CV slope: 
  \[ N_{eff} = \frac{2}{A^2 \varepsilon \varepsilon_0 q_0} \frac{1}{d \left(1/C^2\right)/dV} \]
Acceptor Removal  Type Inversion

Every detector was measured in TCT (top, bottom and infrared) and checked for type inversion — at higher fluences half of the plot was found to be type inverted.
Acceptor Removal by Proton Irradiation

Annealing: 10 min @ 60°C

Fitted function:

\[ N_{eff}(\Phi) = N_{eff0} \cdot e^{-c \cdot \Phi} + g_c \cdot \Phi \]
Acceptor Removal by Neutron Irradiation

Fitted function:

\[ N_{\text{eff}}(\Phi) = N_{\text{eff}0} - N_c \left( 1 - e^{-c\Phi} \right) + g_c \Phi \]

Annealing: 10 min @ 60\(^{\circ}\)C

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<thead>
<tr>
<th>( \rho ) [( \Omega \cdot \text{cm} )]</th>
<th>( -N_{\text{eff}} ) [( \text{cm}^{-3} )]</th>
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Acceptor Removal by Neutron Irradiation

Fitted function:

\[ N_{eff}(\Phi) = N_{eff0} - N_c \left( 1 - e^{-c\Phi} \right) + g_c \Phi \]

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Annealing: 10 min @ 60°C

No Type Inversion
Acceptor Removal

G. Kramberger, 11th Hiroshima Symposium

Taking type inversion into account doesn’t change the acceptor removal rate $c$ in a significant way, keeping the trend previously seen.

This parametrization is important by itself, but we would like to understand the defect dynamics of acceptor removal.
Thermally Stimulated Current (TSC)

- Gives a spectrum of the defects in the detector by measuring the leakage current while ramping up the temperature.
- Allows for the estimation of defect concentration by measuring released charge by the defect’s peak.

There is a clear dependence of the $B_iO_i$ peak with the initial Boron concentration. Suggesting that the main mechanism for acceptor removal is:

$$ I + B_s \rightarrow B_i $$
$$ B_i + O_i \rightarrow B_iO_i $$

![TSC diagram](image)
Macro vs Micro

Is there a match between defects observed through TSC and the measured $N_{\text{eff}}$ from CV?

Assumptions:
- $E(30)$ are donor like defects and contribute positive space charge
- $H(116)$-$H(140)$-$H(152)$ are acceptor like defects and contribute negative space charge
- $B_{i}O_{i}$ contributes twice its concentration
Macro vs Micro

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Macro vs Micro

Is there a match between defects observed through TSC and the measured $N_{\text{eff}}$ from CV?

There is a clear correlation between the concentration of the defects observed through TSC, and the $N_{\text{eff}}$ change measured by CV.
Summary and Outlook

Work in progress to study acceptor removal:

• CV, IV, TCT and TSC was used to investigate the evolution of Neff vs fluence of detectors of different resistivities irradiated by protons and neutrons

• An annealing study and TCT measurements confirmed type inversion in some of the proton irradiated detectors

• After correction for type inversion, Neff vs fluence plots were fitted to extract the acceptor removal parameter $c$

• Strong dependence between $B_iO_i$ production and resistivity was detected by TSC measurements

• We want to perform SIMS measurements, as we don’t know the Oxygen concentration at the moment

• We’re improving our TSC setup to study the $B_iO_i$ defect in more detail
Spare Slides
Annealing Study Interpretation of Neff

- Annealing at 60ºC
- Up to 20480 min or ~14 days of accumulated annealing
- Neff calculated from CV measurements
Annealing Study TCT confirmation

![Graph showing normalized charge collection and annealing time](image)

- **$N_{eff}$ (cm$^{-3}$)** vs. **$t_{anneal}$ (min)**
- **Normalized Charge Collection** vs. **Bias Voltage [V]**

- **50 Ω.cm**
Acceptor Removal

\[ \Delta \text{ Depletes from the top} \]

\[ \nabla \text{ Depletes from the bottom} \]