Measurement of effective space charge concentration vs. neutron fluence in p-type substrates from LFoundry

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Introduction

• RD50 submitted CMOS pixel detector prototype chip *RD50-MPW1* in 150 nm LFoudnry process

• chips were produced on p-type wafers in 2 different initial resistivities:
  ~ 500 $\Omega$ cm and ~1.9 $k\Omega$ cm

• chips were irradiated in reactor in Ljubljana to several different fluences ranging from 1e13 n/cm$^2$ to 2e15 n/cm$^2$

• depletion depth at different bias voltages was measured with E-TCT

• $N_{\text{eff}}$ estimated from depletion depth and studied as a function of neutron fluence
Passive pixel arrays for E-TCT

Measurements made with:

- 3x3 pixel array of 50 µm x 50 µm pixels
- Central pixel to read out
- Outer pixels connected together

RD50-MPW1 CMOS chip

Two bond pads:
- Outer pixels
- Central pixel
RD50 CMOS chip

Scheme of a pixel
• Passive pixel: same scheme as active pixel except there is no transistors in the wells
• DNWELL connected to bias voltage and to the amplifier via bias-T
• P-substrate connected to ground

Chips are not thinned, back plane not processed, substrate biased through the implants on top
Detector current before irradiation

Current measured on outer 8 pixels of 3x3 pixel array (50x50 um² pixel)

- high current before irradiation, several reasons for this, more detail:
  ➔ talk by Matthew Lewis Franks later today
- chips were exposed to 2 Mrad TID from background radiation in the reactor
  ➔ at zero reactor power there is no neutrons, only photons
  ➔ leakage current smaller after 2 Mrad TID irradiation
Edge TCT setup

( more details: www.particulars.si )
Before irradiation

Central pixel connected to readout amplifier

Depletion depth: FWHM of the charge profile across the centre of the pixel
Charge collection profile

- all 9 pixels connected to readout amp.
- bias = 50 V (2 Mrad TID)
Before irradiation

- charge collection profile measured across the middle of central pixel
- depletion depth: FWHM of charge profile

Fit: \[ d = d_0 + \frac{2e \epsilon_0}{e_0 N_{\text{eff}}} \cdot V_{\text{sub}} \]

parameter \( d_0 \): built in voltage, finite laser beam width...

**W9:**
\[ N_{\text{eff}} = (1.8 \pm 0.3) \cdot 10^{13} \text{ cm}^{-3} \]
Resistivity: 720 \( \Omega \text{cm} \pm 150 \Omega \text{cm} \)

**W10:**
\[ N_{\text{eff}} = (1.0 \pm 0.2) \cdot 10^{13} \text{ cm}^{-3} \]
Resistivity: 1.3 k\( \Omega \text{cm} \pm 0.15 \) k\( \Omega \text{cm} \)
\[ \Rightarrow \text{somewhat lower than nominal 1.9 k}\Omega\text{cm} \]

No observable effect of 2 Mrad TID on \( N_{\text{eff}} \)
Chips irradiated in reactor in Ljubljana

- fluences: $1 \times 10^{13}$, $2 \times 10^{13}$, $5 \times 10^{13}$, $1 \times 10^{14}$, $2 \times 10^{14}$, $5 \times 10^{14}$, $1 \times 10^{15}$, $2 \times 10^{15}$,
- each fluence separate chip

\[ \text{no efficiency gaps between pixels} \]
Annealing

- Depletion depth increases by up to ~20% after annealing for 80 minutes at 60°C.

![Graph showing charge distribution before and after annealing.](image-url)
After irradiation with neutrons

- depletion depth vs. bias voltage
- measured after annealing for 80 min at 60°C

- depletion depth changes with irradiation
- acceptor removal effects
\[ N_{\text{eff}} = N_{\text{eff}0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{\text{eq}})) + g_c \cdot \Phi_{\text{eq}} \]

<table>
<thead>
<tr>
<th></th>
<th>(N_{\text{eff}0})</th>
<th>(N_c/N_{\text{eff}0})</th>
<th>(c)</th>
<th>(g_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W9</td>
<td>2.2e13 cm(^3)</td>
<td>0.75</td>
<td>2.1e-14 cm(^2)</td>
<td>0.031 cm(^{-1})</td>
</tr>
<tr>
<td>W10</td>
<td>1.2e13 cm(^3)</td>
<td>0.41</td>
<td>14 e-14 cm(^2)</td>
<td>0.016 cm(^{-1})</td>
</tr>
</tbody>
</table>

\(N_{\text{eff}}\) vs. fluence

- Zoom to low fluences
Compare with other measurements

- this measurement consistent with other substrates with similar initial resistivity

- low resistivity 20 Ωcm (CHESS2, AMS): improves with fluence in this fluence range but large initial $N_{\text{eff}}$
- resistivity ~ 200 Ωcm, (CHESS2, AMS): smallest change of $N_{\text{eff}}$ in this fluence range

- LF (2000 Ohm-cm) from: I. Mandić et al., JINST 12 P02021 2017
Compare removal parameter $c$ with other CMOS substrates.

From B. Hiti et al., "Charge collection in irradiated HV-CMOS detectors"
https://doi.org/10.1016/j.nima.2018.07.022

This measurement
Summary for CMOS, diodes, LGAD

- LRRD50 fit into the summary plot:
  - $c$ drops with increasing $N_{\text{eff}0}$
  - $c$ higher after proton irradiation

**Epi diodes:**
- P. Dias de Almeida, 32nd RD50 Workshop, 2018
- [https://indico.cern.ch/event/719814/contributions/3022586/](https://indico.cern.ch/event/719814/contributions/3022586/)
- K. Kaska
  - [http://repositum.tuwien.ac.at/obvutwhs/content/titleinfo/1633435](http://repositum.tuwien.ac.at/obvutwhs/content/titleinfo/1633435)

**LGAD:**

**Pad diodes:**
- G. Kramberger, 26th RD50 workshop, Santander, 2015
  - [https://indico.cern.ch/event/381195/contributions/905665/](https://indico.cern.ch/event/381195/contributions/905665/)

**CMOS:**
- A. Affolder et al., JINST 11 P04007 2016
- I. Mandić et al., JINST 12 P02021 2017
- E. Cavallaro et al., JINST 12 C01074 2017
- B. Hiti et al., JINST 12 P10020 2017
- B. Hiti et al, (NIMA) [https://doi.org/10.1016/j.nima.2018.07.022](https://doi.org/10.1016/j.nima.2018.07.022)

**See also:**
  - [https://doi.org/10.1109/TNS.2018.2819506](https://doi.org/10.1109/TNS.2018.2819506)
- G. Kramberger, HSTD11, Okinawa, 2017
  - [https://indico.cern.ch/event/577879/](https://indico.cern.ch/event/577879/)
- Y. Gurimskaya, 33rd RD50 workshop
  - [https://indico.cern.ch/event/754063/contributions/3222777/](https://indico.cern.ch/event/754063/contributions/3222777/)
Summary

- measurements with irradiated pixel detector structures on *RD50-MPW1* chip by LFoundry, two initial resistivities

- TID irradiation by background radiation in the reactor (no neutrons)
  - smaller leakage current measured after 2 Mrad TID
    - may help to identify the source of the excessive detector current measured before irradiation
  - no effect of 2 Mrad TID on depletion depth

- neutron irradiation
  - uniform charge collection efficiency across pixel structure → no efficiency gaps observed
  - depletion depth increases (~ 10 %) after annealing for 80 minutes at 60°C
  
  → $N_{eff}$ measured with E-TCT and studied as the function of fluence
    - acceptor removal parameter $c$ extracted
      - results consistent with previous measurement
      → acceptor removal constant higher for substrates with lower initial resistivity
Depletion depth vs. fluence

- depletion depth at 100 V
  - calculated from function fitted to depletion vs. bias (see slide 12):