Initial I-V and e-TCT measurements of a depleted CMOS sensor within the CERN-RD50 collaboration

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Outline

- Introduction
  - RD50-MPW1 (Motivations)
  - RD50-MPW2

- I-V measurements
  - Breakdown voltage $V_{BD}$
  - Leakage current $I_{leak}$

- E-TCT measurements
  - Experimental setup
  - Calculation of substrate resistivity

- Irradiation campaign
  - Irradiated I-Vs
  - Irradiated e-TCT

- Summary and future work
RD50-MPW1 and motivations for the new submission

- General design features
  - MPW in the 150 nm HV-CMOS process from LFoundry
  - Submitted Nov ‘17, received Apr ‘18
  - Fabricated using 2 different substrate resistivities: 500-1100 Ω·m (600 measured) and 1900 Ω·cm (1100 measured)

- Chip details
  - Large matrix of DMAPS pixels for particle physics applications
  - Test structures for e-TCT

- Measurements
  - Sensors work well but devices exhibit high leakage current $I_{\text{leak}}$ and low breakdown voltage $V_{\text{BD}}$
RD50-MPW2

- General design features
  - MPW in the 150 nm HV-CMOS process from LFoundry
  - Submitted February 2019, received February 2020
  - Fabricated in substrate resistivities 10 (standard), 500-1100, 1900, >2000 Ω·cm (nominal)

- RD50-MPW2 Aim: Optimise parameters $I_{\text{leak}}$ and $V_{\text{BD}}$
  - Both parameters were improved
  - Measurements and further studies are currently underway

**Summary**

- General design features
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  - Both parameters were improved
  - Measurements and further studies are currently underway

**Introduction**

- Initial I-V, $\Phi_{\text{eq}} = 0$
- E-TCT, $\Phi_{\text{eq}} = 0$
- I-V, $\Phi_{\text{eq}} > 0$
- E-TCT, $\Phi_{\text{eq}} > 0$

**Summary**

- General design features
  - MPW in the 150 nm HV-CMOS process from LFoundry
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RD50-MPW2: summary of changes from RD50-MPW1

- Included guard rings at the edge of the device
  - Improve $I_{\text{leak}}$
- Modified pad diodes and analog buffers
  - Chamfered corners to improve $V_{\text{BD}}$
- Four test matrices for I-V and e-TCT measurements
  - 50 $\mu$m x 50 $\mu$m pixels
  - 60 $\mu$m x 60 $\mu$m pixels to improve $V_{\text{BD}}$
- Careful placement of “blocking layers” to improve $I_{\text{leak}}$
RD50-MPW2 I-V measurements, Test matrix 1: 50 μm × 50 μm pixels

- Connections:
  - gnd! = 0 V
  - OUTER = (floating)
  - INNER = +1.8 V
  - sub! = -HV

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RD50-MPW2 comparison with RD50-MPW1

- **I-V measurements**
  - $\rho = 1100 \, \text{Ω} \cdot \text{cm}$
  - 50 μm × 50 μm pixel
  - 10 mA compliance
- **Pad connections**
  - gnd! = 0 V
  - OUTER = floating
  - INNER = +1.8 V
  - sub! = -HV
- **RD50-MPW2 $I_{\text{leak}}$**
  - Reduced by many orders of magnitude with respect to MPW1

**Summary**

- I-V measurements
  - $\rho = 1100 \, \text{Ω} \cdot \text{cm}$
  - 50 μm × 50 μm pixel
  - 10 mA compliance
- Pad connections
  - gnd! = 0 V
  - OUTER = floating
  - INNER = +1.8 V
  - sub! = -HV
- RD50-MPW2 $I_{\text{leak}}$
  - Reduced by many orders of magnitude with respect to MPW1
**Introduction**

**I-V, \( \Phi_{eq} = 0 \)**

**E-TCT, \( \Phi_{eq} = 0 \)**

**I-V, \( \Phi_{eq} > 0 \)**

**E-TCT, \( \Phi_{eq} > 0 \)**

**Summary**

RD50-MPW2 I-V measurements: Test matrices

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**above:** RD50-MPW2 floorplan. 3 × 3 test matrices for e-TCT are highlighted in red, green, blue and pink and magnified. The central pixel of each structure is then magnified to demonstrate the different corner shapes. Active matrix is highlighted with the orange dashed box.

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**Test matrix 1** for e-TCT
- 50 µm × 50 µm pixel
- 3 µm electrode spacing
- Rounded corners
  - (Similar to RD50-MPW1)

**Test matrix 2** for e-TCT
- 60 µm × 60 µm pixel
- 8 µm electrode spacing
- Rounded corners
  - (Geometry shared with the pixels in the active matrix)

**Test matrix 3** for e-TCT
- 60 µm × 60 µm pixel
- 8 µm electrode spacing
- Chamfered corners

**Test matrix 4** for e-TCT
- 60 µm × 60 µm pixel
- 8 µm electrode spacing
- Squared corners
RD50-MPW2 I-V measurements: Test matrices

- I-V measurements
  - $\rho = 1100 \ \Omega \cdot \text{cm}$
  - All pixel types
  - 10 $\mu$A compliance
- Pad connections
  - Same as before
- RD50-MPW2 $V_{BD}$
  - Increasing electrode spacing increases $V_{BD}$
  - Modifying corner shape can further increase $V_{BD}$

Initial I-V and e-TCT measurements of a depleted CMOS sensor within the CERN-RD50 collaboration

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RD50-MPW2 Test matrices: Breakdown voltage $V_{BD}$

### Introduction
- I-V, $\Phi_{eq} = 0$
- E-TCT, $\Phi_{eq} = 0$
- I-V, $\Phi_{eq} > 0$
- E-TCT, $\Phi_{eq} > 0$

## Summary
- **I-V measurements**
  - $\rho = 500-1100$ (W7), $1900$ (W10), $>2000$ $\Omega \cdot \text{cm}$ (W13)
  - All four test matrices
  - $V_{step} = 2$ V
- **Pad connections**
  - Same as before
- **Leakage current $I_{leak}$**
  - Generally increases with $\rho$

Measurements done at IFIC
**RD50-MPW2 Test matrices: Breakdown voltage $V_{BD}$**

- Different current compliances $I_{comp}$ used to measure $V_{BD}$
  - 100 nA, 1 μA, and 10 μA

- Two parameters calculated in order to determine breakdown voltage
  - $k = \frac{dI/dV}{I/V}$
  - $ILD = \left(\frac{d\ln[I(V)]}{dV}\right)^{-1} \equiv \left[\frac{1}{I} \cdot \frac{dI(V)}{dV}\right]^{-1}$

- $V_{BD}$ criteria
  - $V$ where $I_{comp}$ is reached (computed for comparison)
  - $V$ for maximum $k$
  - $V$ for minimum $ILD > 0$

Measurements done at IFIC
RD50-MPW2 Test matrices: Breakdown voltage $V_{BD}$

<table>
<thead>
<tr>
<th>1st matrix (round 3 mm)</th>
<th>2nd matrix (round 8 mm)</th>
<th>3rd matrix (hexagonal 8 mm)</th>
<th>4th matrix (square 8 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bd}$ (Icomp)</td>
<td>$V_{bd}$ (k)</td>
<td>$V_{bd}$ (ILD)</td>
<td>$V_{bd}$ (Icomp)</td>
</tr>
<tr>
<td>0.5-1.1 kΩ·cm</td>
<td>62 V</td>
<td>60 V</td>
<td>62 V</td>
</tr>
<tr>
<td></td>
<td>W7_1 (Icomp = 100nA)</td>
<td>W7_2 (Icomp = 100nA)</td>
<td>W7_3 (Icomp = 100nA)</td>
</tr>
<tr>
<td></td>
<td>60 V</td>
<td>56 V</td>
<td>54 V</td>
</tr>
<tr>
<td></td>
<td>W7_3 (Icomp = 100nA)</td>
<td>W7_3 (Icomp = 1µA)</td>
<td>W7_3 (Icomp = 1µA)</td>
</tr>
<tr>
<td></td>
<td>58 V</td>
<td>54 V</td>
<td>124 V</td>
</tr>
<tr>
<td>1.9 kΩ·cm</td>
<td>62 V</td>
<td>60 V</td>
<td>62 V</td>
</tr>
<tr>
<td></td>
<td>W10_1 (Icomp = 100nA)</td>
<td>W10_2 (Icomp = 100nA)</td>
<td>W10_3 (Icomp = 100nA)</td>
</tr>
<tr>
<td></td>
<td>58 V</td>
<td>54 V</td>
<td>54 V</td>
</tr>
<tr>
<td></td>
<td>W10_3 (Icomp = 100nA)</td>
<td>W10_3 (Icomp = 1µA)</td>
<td>W10_3 (Icomp = 1µA)</td>
</tr>
<tr>
<td></td>
<td>58 V</td>
<td>54 V</td>
<td>124 V</td>
</tr>
<tr>
<td>&gt;2 kΩ·cm</td>
<td>58 V</td>
<td>54 V</td>
<td>54 V</td>
</tr>
<tr>
<td></td>
<td>W13_1 (Icomp = 100nA)</td>
<td>W13_2 (Icomp = 100nA)</td>
<td>W13_2 (Icomp = 100nA)</td>
</tr>
<tr>
<td></td>
<td>58 V</td>
<td>54 V</td>
<td>54 V</td>
</tr>
<tr>
<td></td>
<td>W13_2 (Icomp = 100nA)</td>
<td>W13_2 (Icomp = 1µA)</td>
<td>W13_2 (Icomp = 1µA)</td>
</tr>
<tr>
<td></td>
<td>56 V</td>
<td>54 V</td>
<td>124 V</td>
</tr>
</tbody>
</table>

Measurements done at IFIC
RD50-MPW2 Test matrix 2: Leakage current \( I_{\text{leak}} \)

- I-V measurements
  - \( \rho = 500-1100 \) (W7), 1900 (W10), >2000 \( \Omega \cdot \text{cm} \) (W13)
  - Only test matrix 2

- Pad connections
  - gnd! = GND
  - OUTER = GND ("guard-ring")
  - INNER = GND (through ammeter)
  - sub! = -HV

- Leakage current \( I_{\text{leak}} \)
  - Current of central DNWELL/p-substrate junction is measured using the additional ammeter
  - Below 1 pA (\( \approx 0.1 \) pA)

Measurements done at HEPHY
RD50-MPW2 e-TCT experimental setup

- **E-TCT measurements**
  - Beam diameter in the silicon FWHM $\approx 5$ $\mu$m
  - Width of light pulses $\approx 300$ ps, repetition rate 500 Hz

- **Connection scheme**:
  - INNER = +HV
  - sub! = GND
RD50-MPW2 e-TCT: Charge collection profiles

- **E-TCT measurements**
  - Wafers 5, 7, 11, 14 (10, 500-1100, 1900, >2000 Ω·cm nominal ρ, respectively)
  - Bias up to 120 V
  - (W5 up to 100 V, breakdown at ≈ 105 V)

- **Charge collection profiles**
  - Scan across centre of central pixel
  - Profiles normalised to same maximum

Measurements done at JSI
RD50-MPW2 e-TCT

Measurements done at JSI

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Introduction

I-V, $\Phi_{eq} = 0$  
E-TCT, $\Phi_{eq} = 0$

I-V, $\Phi_{eq} > 0$  
E-TCT, $\Phi_{eq} > 0$

Summary

Fit:

$$W_D = W_{D_0} + \frac{2\varepsilon_0\varepsilon_0}{\varepsilon_0 N_{eff}} \cdot V$$

Free parameters:

$W_{D_0}$ = width of charge collection profile at 0 V bias voltage

$N_{eff}$ = effective doping concentration

Constants:

$\varepsilon_0$ = permittivity of free space

$\varepsilon_{Si}$ = relative permittivity of silicon

$e_0$ = elementary charge

<table>
<thead>
<tr>
<th>Wafer</th>
<th>$N_{eff}$ [cm$^{-3}$] (0 &lt; $V$ &lt; 60)</th>
<th>$\rho$ [\Omega\cdot\text{cm}]</th>
<th>Nominal $\rho$ [\Omega\cdot\text{cm}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W5</td>
<td>$3.2\cdot10^{15}$</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>W7</td>
<td>$2.4\cdot10^{13}$</td>
<td>500</td>
<td>500-1100</td>
</tr>
<tr>
<td>W11</td>
<td>$1.2\cdot10^{13}$</td>
<td>1100</td>
<td>1900</td>
</tr>
<tr>
<td>W14</td>
<td>$5.9\cdot10^{12}$</td>
<td>2200</td>
<td>&gt;2000</td>
</tr>
</tbody>
</table>
RD50-MPW2 irradiated I-V

- Irradiation to a range of neutron equivalent fluences $\Phi_{eq}$ up to $1 \cdot 10^{14}$ 1 MeV n$_{eq} \cdot$cm$^{-2}$
  - No annealing
- I-V measurements
  - $\rho = 500$-1100 (W7), 1900 (W10), >2000 $\Omega \cdot$cm (W13) nominal values
  - Only test matrix 2
- $V_{BD}$ and $I_{leak}$
  - $I_{leak}$ increases with $\Phi_{eq}$
  - $V_{BD}$ decreases with $\Phi_{eq}$ and similar for all $\rho$

Measurements done at HEPHY
RD50-MPW2 irradiated I-V

- Irradiation to neutron equivalent fluence $\Phi_{eq} = 2 \cdot 10^{15} \text{ 1 MeV n}_{eq} \cdot \text{cm}^{-2}$
  - No annealing
  - 80 minutes annealing at 60 °C

- I-V measurements
  - W14 ($\rho = 2200 \Omega \cdot \text{cm measured}$)
  - Only test matrix 2

- $V_{BD}$ and $I_{leak}$
  - $I_{leak}$ increases with $\Phi_{eq}$
  - $V_{BD}$ similar to before irradiation

Measurements done at JSI
RD50-MPW2 irradiated e-TCT: Charge collection profiles

- **E-TCT measurements**
  - Only irradiated Wafer 14
  - W14 ($\rho = 2200 \, \Omega \cdot \text{cm measured}$)
  - Irradiated to $\Phi_{\text{eq}} = 2 \times 10^{15} \, 1 \, \text{MeV} \, n_{\text{eq}} \cdot \text{cm}^{-2}$

- **Charge collection profiles**
  - Depletion depth shrinks due to irradiation
  - But $\approx 70 \, \mu\text{m}$ depleted at 120 V

Measurements done at JSI
RD50-MPW2 irradiated e-TCT

Measurements done at JSI

Initial I-V and e-TCT measurements of a depleted CMOS sensor within the CERN-RD50 collaboration
Summary

- RD50-MPW2 $I_{\text{leak}}$ and $V_{\text{BD}}$
  - $I_{\text{leak}}$ was reduced by many orders of magnitude with respect to RD50-MPW1
  - $V_{\text{BD}}$ was increased with respect to RD50-MPW1
  - Methods developed for RD50-MPW2 will be incorporated in future RD50 submissions

Ongoing and future work

- $I_{\text{leak}}$ and $V_{\text{BD}}$
  - Complete $I_{\text{leak}}$ measurements for other test matrices, more samples and resistivities
  - Extract $V_{\text{BD}}$ for more samples and resistivities
- C-V measurements
- Irradiation campaign
  - Annealing studies
  - E-TCT of other fluences
E-TCT charge collection profiles

More charge collected at larger $y$ (depth)
- length of laser beam inside charge collection region increases
- shape of the region

Not expected in larger pixel array
- Depletion much smaller than dimensions of the structure

[1] Plot and diagram courtesy of I. Mandić (JSI) - I. Mandić et al., 2017 JINST 12 P02021, doi.org:10.1088/1748-0221/12/02/P02021
Diagram of $I_{\text{leak}}$ measurements setup

- **Connections:**
  - HV connected to p-substrate (sub!)
  - Low side of power supply grounded and connected to DNWELL of 8 outer pixels (OUTER), GND pad (gnd!) and Ammeter
  - Ammeter connected to DNWELL of inner cell (INNER)

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$I_{\text{leak}}$ measurements full range test

- Contact test
  - 5 – 130 V bias voltage
  - 10 µA compliance
  - Second test structure used (same as active matrix pixels)
  - Full range tested to see breakdown
  - 5 V – 60 V (not 30 V) range used for leakage studies
2D cross-section of test structure pixels in RD50-MPW2

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TCAD simulations of 3D pixel corners

Squared pixel corner

Chamfered pixel corner

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