Time resolution of the RD50-MPW2 HV CMOS

Uwe Krämer, Jory Sonneveld
Depleted MAPS: small and large collection electrodes

- High field almost everywhere
- Short drift distances
- Higher radiation tolerance

- Very small sensor capacitance $\sim 5$ fF
- Reduced noise & power
- Readout outside charge collection well: less cross talk

RD50-MPW2

- Stronger electric field results in less trapping and higher radiation tolerance
- Larger electric field comes at a cost: more capacitance, power and more noise

ALICE MAPS prototypes

From E. Vilella, *Vertex2018*
RD50 CMOS development

See also overview talk by Eva Vilella

2017
RD50-MPW1

2019
RD50-MPW2

2021
RD50-MPW3

2023
RD50-MPW4

Coming soon!
Four submissions of RD50 HV CMOS monolithic sensors

RD50-MPW1
5 x 5 mm²
50 x 50 μm²
Matrix of 26 x 52 pixels with 16-bits counter
Matrix of 40 x 78 pixels FEI3style readout
Low breakdown $V_{bd} = 60$ V
High leakage current $I_{leak} \approx \mu A$

RD50-MPW2
3.2 x 2.1 mm²
High breakdown $V_{bd} = 120$ V
Low leakage current $I_{leak} \approx nA$
Analog readout only

RD50-MPW3
6.6 x 5.1 mm²
Small 8x8 matrix 60 x 60 μm² pixels
64x64 pixel matrix 62 x 62 μm² pixels
In-pixel digital readout
Advanced peripheral readout

RD50-MPW4
64 x 64 PIXEL MATRIX
6.3 mm
5.4 mm
Next talk by Bernhard Pilsl
Matrix of 40 x 78 pixels
FEI3style readout

Low breakdown $V_{bd} = 60$ V
High leakage current $I_{leak} \approx \mu A$
Continuous reset ToT scales with signal size
Switched reset much faster reset

Two pixel flavors
4-bit trim DAC
Large variety of test structures
Depletion depths of ~190 μm
Produced in 1.9 kΩ·cm and 3.0 kΩ·cm resistivities
Data acquisition of RD50-MPW2

- **Caribou** used for powering
- **ZYNQ-ZC706 with Yocto based linux**
Back-TCT measurements at Nikhef
Back-TCT measurements at Nikhef

- 980 nm laser driven with pulse generator
  - Pulse width 10 ns
  - Rise and fall time 2 ns
- Amplitude 2.4 V
- Optical attenuator for varying laser intensity
- DSO3000 oscilloscope
  - 500 MHz bandwidth
  - 4 GSa/s sampling rate
Time resolution

Laser pulse injected with various intensities

The spread in the time difference between the pulse sent to the laser and the comparator output from the chip gives the time resolution.
Time resolution measurement

- All measurement points are at 50% constant fraction
- \( \text{ToT} = t_{\text{fall hit 50\%}} - t_{\text{rise hit 50\%}} \)

First point of signal is relevant value for time measurement:

Laser measurements
- \( \Delta t = t_{\text{rise hit 50\%}} - t_{\text{rise pulse 50\%}} \)

Test pulse measurements
- \( \Delta t = t_{\text{rise hit 50\%}} - t_{\text{fall pulse 50\%}} \)
Threshold and calibration

**Threshold:**
- Threshold 1000 mV with a baseline of 900 mV
- Performed threshold equalization (trimming)
- Switched reset pixels: 1460 e⁻
- Continuous reset pixels: 2980 e⁻

**Charge calibration:**
- For continuous pixels time over threshold $\propto$ charge
- Charge calibrated with time over threshold from charge injection at different voltages

$V_{\text{bias}} = 100$ V
Electronics circuit contribution to time resolution

- Charge of 12100 e⁻ injected through injection capacitance bypassing the pixel sensor
- Time resolution from electronics only is 200 ps
Time resolution for RD50-MPW2 pixel matrix

- $V_{\text{bias}} = 100$ V
- MIP-like charge of 12100 e$^-$ equivalent charge injection via laser centered on each pixel:
  
  $\sigma_t, \text{switched} = 211 \pm 45$ ps
  $\sigma_t, \text{continuous} = 227 \pm 27$ ps

- Switched reset pixels have a slightly better time resolution
In-pixel time resolution

- Scan in 3 µm steps
- Continuous pixel (3,2)

- Better time resolution under collection well:
  \[ \sigma_{t, \text{well}} = 250 \pm 42 \text{ ps} \]
  \[ \sigma_{t, \text{pixel}} = 267 \pm 56 \text{ ps} \]

- Charge sharing up to \(~10\) µm beyond pixel boundary
In-pixel vs pixel center ToA and time resolution

- **In-pixel scan over entire pixel**
- **Scan at center of pixel varying charge by attenuating laser signal**
- **Overlap at high ToT values: in-pixel scan over center**
- **Below ToT = 150 ns: fluctuations from inhomogeneous charge collection times**

![Graph showing overlap and time resolution comparison](image)

<table>
<thead>
<tr>
<th>Pixel center</th>
<th>In-Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>78</td>
</tr>
<tr>
<td>Mean</td>
<td>8.69e+01</td>
</tr>
<tr>
<td>Mean σ</td>
<td>1.03e+02</td>
</tr>
<tr>
<td>Std Dev</td>
<td>4.05e+01</td>
</tr>
<tr>
<td>Std Dev σ</td>
<td>4.53e+00</td>
</tr>
</tbody>
</table>

4 ns later ToA

<table>
<thead>
<tr>
<th>Pixel center</th>
<th>In-Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>541</td>
</tr>
<tr>
<td>Mean</td>
<td>1.06e+02</td>
</tr>
<tr>
<td>Mean σ</td>
<td>1.01e+02</td>
</tr>
<tr>
<td>Std Dev</td>
<td>4.13e+01</td>
</tr>
<tr>
<td>Std Dev σ</td>
<td>5.54e+00</td>
</tr>
</tbody>
</table>

250 ps worse time resolution

![Graph showing overlap and time resolution comparison](image)
Time resolution for RD50-MPW2 pixel matrix

- Effect in row 0 and column 7 was also seen in other chips
- In-pixel scan of continuous pixel at border to investigate worse time resolution
- This effect is no longer seen in RD50-MPW3 and is not expected in RD50-MPW4.
In-pixel measurement (0,0)

- Pixel shape is skewed
- Electric field not symmetric: uncontained only in one direction

Time over threshold

Time delay

Time resolution
RD50-MPW2 chip structure

- Lines are top level metal lines
- Structure not symmetric for each edge of the pixel matrix
Summary and outlook

- RD50 HV CMOS not optimized for fast timing can achieve 227 ps time resolution for a MIP-like charge.
- The electronics contribution to the time resolution is 220 ps.
- A first in-pixel scan of RD50-MPW2 shows quite homogeneous time resolution over entire pixel.
- MPW3 results shown last meeting.
- Expect improved results in RD50-MPW4 that will arrive soon.
Additional material
Time resolution for switched vs continuous reset pixels

- 12100 e$^-$ equivalent charge injection via laser centered on each pixel
- Charge calibrated with time over threshold from charge injection at different voltages
Time resolution for electronics only

- Charge of 12100 e\(^-\) injected through injection capacitance bypassing the pixel sensor
- Time resolution from electronics only is 200 ps
Time resolution measurement

- All measurement points are at 50% constant fraction
- $\text{ToT} = t_{\text{fall_hit}_{50\%}} - t_{\text{rise_hit}_{50\%}}$

First point of signal is relevant value for time measurement:

Laser measurements
- $\Delta t = t_{\text{rise_hit}_{50\%}} - t_{\text{rise_pulse}_{50\%}}$

Test pulse measurements
- $\Delta t = t_{\text{rise_hit}_{50\%}} - t_{\text{fall_pulse}_{50\%}}$
Charge calibration

- Voltage step function with amplitude $U_{\text{inj}}$
- Connected to injection capacitance $C_{\text{inj}} = 2.8 \text{ fF}$
- Injected charge: $Q_{\text{inj}} = C_{\text{inj}} U_{\text{inj}}$

Time over threshold to charge conversion from fit to measured ToT by varying $U_{\text{inj}}$

\[
ToT(Q) = a \cdot Q + b - \frac{c}{Q - t}
\]
In-pixel measurement: (5,2)

- Charge sharing appears to be reduced relative to continuous pixel
- ToT appears to increase halfway through the pixel, possibly resulting from laser fluctuations
In-pixel measurement: (3,2)

- Continuous pixel gathers charge \(\sim 10 \, \mu m\) beyond pixel “boundary”
I. 8 × 8 Analog pixel matrix with pixel size of 60 μm × 60 μm, two flavors:
I.A. Continuous-reset pixels (column 0 to 3)
I.B. Switched-reset pixels (column 4 to 7)
I.C. Bias block
I.D. Row configuration registers
I.E. Column configuration registers
II. Analog buffer
III. Test structures
IV. SEU tolerant memory
V. Bandgap
RD50-MPW2 frontend

Switched reset

Continuous reset
Measured performance of RD50-MPW2

Measured in previous MPW2:
● ENC < 50 e-
● Time-walk < 10 ns
● Leakage 120 pA/pixel
● ToT 30 ns
● Breakdown 120 V

Collection electrode size:
40 μm in MPW2
42 μm in MPW3

From simulation for current MPW3:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>62 μm × 62 μm</td>
</tr>
<tr>
<td>Cd</td>
<td>~ 250 fF</td>
</tr>
<tr>
<td>Power</td>
<td>22 μW/pixel (VDD = 1.8 V)</td>
</tr>
<tr>
<td>Gain</td>
<td>230 mV (for 5 ke−)</td>
</tr>
<tr>
<td>ToT</td>
<td>55 ns (for 5 ke−)</td>
</tr>
<tr>
<td>ENC</td>
<td>120 e−</td>
</tr>
<tr>
<td>Time walk</td>
<td>9 ns</td>
</tr>
</tbody>
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