First results from the HEPAPS4 Active Pixel Sensor

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Outline of the talk

• Active Pixel Sensors – an introduction
• The HEPAPS4 sensor
• Basic characterisation
  – Noise components and reset behaviour
  – Photon Transfer Curve
  – Linearity
  – Dark current
  – First test beam plots (very preliminary)
• Summary
Active Pixel Sensors – Introduction

- Silicon sensor technology based on industry standard CMOS processes
- Monolithic: Sensing volume and amplification implemented in the same silicon substrate
- Similar ‘use case’ as CCDs
- Photonic applications:
  - Biological/medical applications, HPDs, digital cameras, …
- Envisaged HEP applications
  - Linear collider vertex detector (~10^9 channels)
  - Linear collider calorimeter (Si/W, ~10^{12} channels)
Active Pixel Sensors - Principle of Operation

Simplest design of APS: 3MOS pixel
- Photo diode
- Reset MOS (switch)
- Select MOS (switch)
- Source follower MOS

Functional description
- Photo diode: n-well in the p-type epilayer of the silicon
- Charge collection:
  - e-h pairs from ionising radiation
  - Diffusion of charge in epi-layer
  - Collected by the diode by the built-in field in the pn-junction
- In-pixel circuitry built in p-well.
- Collected charge changes the potential on the source follower gate $V_G = Q_{PD}/C_{PD}$
- Gate voltage changes the transconductance
- Pixel selected by the select MOS
- Output voltage = $V_{DD} - g_{ds}I_{Bias}$
Active Pixel Sensor - Cartoon

- **Silicon bulk (10-700 µm)**
  - Can be thinned as much as mechanical stability allows

- **Photo diode (n-well)**
  - pn-junction with p-epi
  - 1-several diodes of varying sizes in different designs.

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- **Epi-layer (5-25 µm)**
  - Active volume of the device
  - Expected MIP: 400-2000 e⁻

- **p-well**
  - For in-pixel circuitry

- **In-pixel circuitry**
  - NMOS transistors

- **Silicon bulk (10-700 µm)**
  - Can be thinned as much as mechanical stability allows

* Typical values found in different designs
Cartoon – array of active pixels
(non-judgemental) pros and cons

• Only uses the epi-layer as active volume
  – Quite small signal (compared to hybrid pixel devices)
  – Can be thinned to minimise material
• But S/N is what counts
  – Intrinsically very low noise
  – Fight other noise components
• Radiation hardness
  – Relies on diffusion for charge collection (no bias voltage)
  – No charge shifting (as in e.g. CCDs)
• Compared to LHC style sensors
  – Relatively slow read-out speed
  – Very low power consumption (saves services!)
• Cost
  – Si sensors relatively expensive per m²
  – Standard CMOS process
  – Saves integration costs
The HEPAPS4 – large area sensor for HEP applications

- Fourth in series designed at RAL
- Selected most promising design in HEPAPS2
- Basic parameters
  - 15x15 µm² pixel size
  - 384x1024 pixels
  - 20 µm epi-layer
  - 1 MIP = 1600 e⁻ spread over several pixels
- Three different design variants:

<table>
<thead>
<tr>
<th>Design</th>
<th>Diode size</th>
<th>From simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>gain</td>
</tr>
<tr>
<td>2 diodes in parallel</td>
<td>3x3 µm²</td>
<td>11 µV/e⁻</td>
</tr>
<tr>
<td>4 diodes in parallel</td>
<td>1.7x1.7 µm²</td>
<td>10 µV/e⁻</td>
</tr>
<tr>
<td>Single diode</td>
<td>1.7x1.7 µm²</td>
<td>16 µV/e⁻</td>
</tr>
</tbody>
</table>

Results presented here are from the single diode design
HEPAPS4 operating principle

- 3MOS APS pixel as described previously
- Loop over all rows, select one at a time.
- Sample the signal on to a capacitor for each column
- Loop over columns, read out the value through four independent output drivers
- Reset the row
- Rolling shutter: Continuously cycle through pixels to read-out and reset
Fixed Pattern Noise
- Gain Variation
- Pedestal variation
  - 280 ADC or ~1400e⁻ for HEPAPS4
- Removed by subtracting:
  - Pedestal frame from dark measurement
  - Two adjacent frames

Reset noise
- As described on next slide
- Can be removed by Correlated Double Sampling
  - Sample the reset value before charge collection
  - Can be done in H/W or (partially) offline

Dark Current
- Leakage current in the photo diode
- Depends on the Average offset = $I_{\text{leak}}$
  - Shot Noise = $\sqrt{I_{\text{leak}}}$

Common mode noise
- Can be partially subtracted

Read noise
- The fundamental noise of the chip
Pixel Reset Behaviour

- Pixels are reset by asserting a signal on the Reset Switch.
- The charge collecting node is set to the reset voltage $V_{\text{RST}}$.
- Soft Reset: $V_{\text{RST}} = V_{\text{DD}}$
  - Less reset noise
- Hard Reset: $V_{\text{RST}} < V_{\text{DD}}$
  - Less image lag
  - Decreases dynamic range

- Plot shows HEPAPS4 reset from fully saturated with soft reset operation ($V_{\text{RST}}=V_{\text{DD}}$).
HEPAPS4 as imaging sensor

- APS sensor also used in digital cameras
- HEPAPS4 becomes a B/W 400 kpix camera
- Plots show visually the effects of pedestal subtraction
Photon Transfer Curve (PTC) – Basic Principle

Shine light on the sensor and increase the illumination gradually

- Plot signal variance vs. mean
- Read noise will dominate for low intensities, but:

  \[ S_{ADC} = G \cdot n_e \]

  \[ \sigma_{ADC}^2 = (G \cdot \sigma_e)^2 \]

- # of photons per pixel is a Poisson process
  \[ \sigma_e^2 = n_e \]

- Hence in the region dominated by photon noise
  \[ \frac{\sigma_{ADC}^2}{S_{ADC}} = G \]
Photon Transfer Curve - Results

- Read out a region of 200x200 pixels
- Subtract pedestal frame
  - Calculate mean signal per pixel
- Subtract two adjacent frames:
  - Removes fixed pattern noise
  - Calculate variance per pixel

Assume constant gain 1000-5000 ADC
- Slope gives gain = 5.1 e^-/ADC
- Noise floor not shown, since it is dominated by systems noise
- Saturation starts after 6000 ADC

Expected value from design: 7.8 e^-/ADC
Photon Transfer Curve - Gain Distributions

- Same analysis for 40,000 pixels
- 800 frames to calculate mean and variance
- Fit slope for each pixel

![Gain Map (200x200 pixels)](image)

- Gain = 5.1
- Gain RMS = 0.51
- # pixels with gain:
  - < 3 e^-/ADC: 41 pix
  - > 8 e^-/ADC: 90 pix
Linearity

- Non-linearity arises from
  - Change in sense node capacitance when charged
  - Non-linearity of source follower
- Measurement method:
  - Constant, low illumination
  - Continuous acquisition of frames
  - No reset between frames

Relative gain is the derivative of this curve, normalised to the gain at 0 ADC
- Relative gain > 90%
  - 0-1640 ADC
  - 0-8360 e⁻
- Relative gain > 80%
  - 0-3780 ADC
  - 0-19300 e⁻
Dark Current

- Dark current is leakage current in the photo diode
- Method:
  - Readout two consecutive frames without reset between the frames
  - Subtract the two frames to remove pedestal and fixed pattern noise
  - Vary the integration time

Linear fit to the curve
- Slope 530 ADC/s = 2700 e^-/s
- Pixel size 15x15 µm^2
- I_{dark} = 0.2 nA/cm^2
First Test Beam Plots

- Test beam at DESY: 6GeV electrons
- Combined with ISIS pixel sensor
- Configuration of sensor slightly different from photonic measurements in the lab
- Analysis in progress
- Two ‘muse-bouche’ plots:
  - Hit map: accumulation of reconstructed clusters
  - Landau: Cluster charge in ADC values
Summary

• Active Pixel Sensors are an attractive technology for certain applications in HEP
  – The principle of operation
• HEPAPS4 – a large area APS designed for HEP applications
• First results from the characterisation:
  – Gain 5.1 e-/ADC with an RMS of 0.5 e-/ADC over 40k pixels
  – 90% of gain up to 8400 e-
  – 80% of gain up to 19300 e-
  – Dark current 2700 e-/s per pixel
• Two preliminary plots from the beam test