First results from the HEPAPS4 Active Pixel Sensor

L. Eklund, L. Jones, A. Laing, D. Maneuski, R. Turchetta, F. Zakopoulos

Presented at the 10th International Conference on Instrumentation for Colliding Beam Physics

February 28 to March 5 2008

Budker Institute of Nuclear Physics, Novosibirsk, Russia
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
  \[ V_G = \frac{Q_{PD}}{C_{PD}} \]
- 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.

- 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>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>gain</td>
<td>noise</td>
<td></td>
</tr>
<tr>
<td>2 diodes in parallel</td>
<td>3x3 µm²</td>
<td>11 µV/e⁻</td>
<td>45 e⁻</td>
<td></td>
</tr>
<tr>
<td>4 diodes in parallel</td>
<td>1.7x1.7 µm²</td>
<td>10 µV/e⁻</td>
<td>47 e⁻</td>
<td></td>
</tr>
<tr>
<td>Single diode</td>
<td>1.7x1.7 µm²</td>
<td>16 µV/e⁻</td>
<td>37 e⁻</td>
<td></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
Noise components

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_{leak}
  - Shot Noise = sqrt(I_{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:
  
  \[ S_{ADC} = G \cdot n_e \]
  
  \[ \sigma^2_{ADC} = (G \cdot \sigma_e)^2 \]

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

- Hence in the region dominated by photon noise
  
  \[ \frac{\sigma^2_{ADC}}{S_{ADC}} = G \]
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 Distribution 40000 pixels

- Gain = 5.1
- Gain RMS = 0.51
- # pixels with gain:
  - < 3 e^−/ADC: 41pix
  - > 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 µm²
- $I_{\text{dark}} = 0.2$ nA/cm²
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