UK Activities on Tracking and Vertexing for Linear Collider

Fergus Wilson

Particle Physics Department, Rutherford Appleton Laboratory/STFC

28-May-2013

Outline

Introduction

- The UK has concentrated on Monolithic Active Pixel Sensors (MAPS) as a potential technology for LC and CLIC vertexing, tracking and digital calorimetry.
- The main driver in recent years has not been particle physics.
- LC work has piggy-backed on other developments.
- In addition, there is of course extensive work going on with LHC and LHC upgrades (see other talks).
- I will mention silicon for digital calorimetry but will not cover other aspects e.g. particle flow algorithms.

Recent R&D Collaborations

- CALICE-UK (ILC calorimetry): Birmingham, Cambridge, Manchester, RAL/STFC, Imperial College (IC), University College, Royal Holloway.
- SPiDer (vertexing/tracking at LC): Bristol, Birmingham, IC, Oxford, Queen Mary, RAL/STFC.
- Arachnid (generic vertexing/tracking/calorimetry + ALICE ITS): Bristol, Birmingham, Queen Mary, RAL/STFC, Daresbury/STFC.
- Low-Mass and Plume (low-mass structures): RAL/STFC, Bristol, Oxford with DESY, IPHC/Strasbourg, IK-Frankfurt. Also work related to ATLAS and flavour factories.

Monolithic Active Pixel Sensors (MAPS)

Useful Features

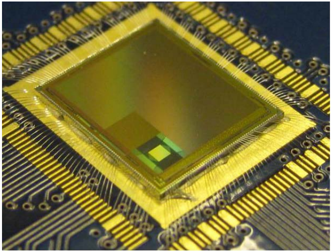
- Medium cost: 0.18 μm CMOS, mature industrial process.
- Low power: low voltage and absence of standing currents.
- Low Material: very thin overall (30-50 μm).
- Radiation Tolerant: at least 3 Mrad.
- High Granularity: pixel sizes down to $\sim$1 μm.

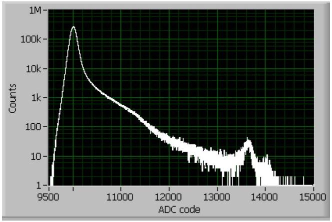
Additional Features developed

- Deep p-well/InMAPS: improved charge collection.
- High resistivity epitaxial layers: radiation hardness, improved charge collection.
- 4T structures: in-pixel structures, correlated double sampling (CDS), improved S/N, low power (10μW/pixel).
- Stitching: large structures (12 cm $\times$ 12 cm have been achieved).

FORTIS - 4T Test Image Sensor

- Test 4T and high resistivity epitaxial layer.
- 0.18 μm process, deep p-well, CDS.
- 6-45 μm pixels
- 13 variants + low/high res. epitaxial layer.
- Analogue readout.
- Noise 5.9 e^- rms, gain 61.3$\mu V/e^-$.
- Quantum efficiency 30%, full well 19,100.
- Hit resolution 3.3 μm.
- S/N > 100.

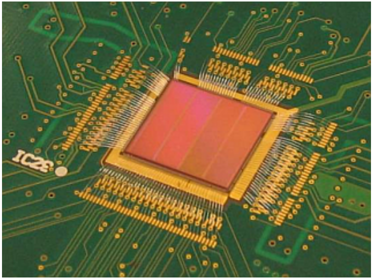




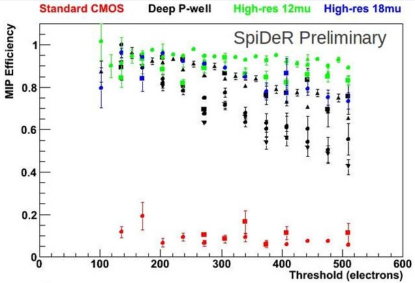
Tera-Pixel Active Calorimeter Sensor (TPAC)

CMOS sensor designed with LC digital calorimeter in mind.

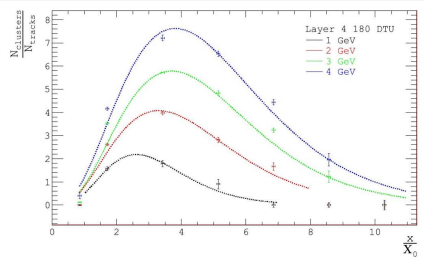
- 168×168 50 $\mu\mathrm{m}$ pixels, $1 \times 1\,\mathrm{cm}^2$.
- 0.18 $\mu\mathrm{m}$ process, deep p-well, 3T structures only.
- 4 test structures designed + 5 or 12 $\mu\mathrm{m}$ epitaxial layer.
- Per pixel trim (4 bits), mask (1-bit) and comparator.
- Only hits above threshold stored (zero-suppression).
- 400 ns timestamp with readout every 8192 timestamps (bunch train).



TPAC Characteristics - Preliminary



Improved efficiency compared to standard CMOS (red).



Shows correct behaviour as function of energy: $dE/dt = E_0 b(bt)^{a-1} e^{-bt}/\Gamma(a)$.

Noise : $22e^-$, Gain 160 $\mu V/e^-$.
Tests with X-rays show S/N reduced by only 15% for a 5Mrad dose.

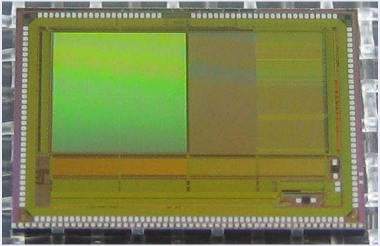
Cherwell 1 - Calorimetry/Tracking/Vertexing

4 test structures on 3 different epitaxial layers

1. DECAL 25: 48 × 96 25 μm pixels with 2 × 2 summing.
2. DECAL 50: 24 × 48 50 μm pixels.
3. Reference: 48 × 96 25 μm pixels with ADC at column base.
4. Strixel: 48 × 96 25 μm pixels with ADC embedded in pixel.

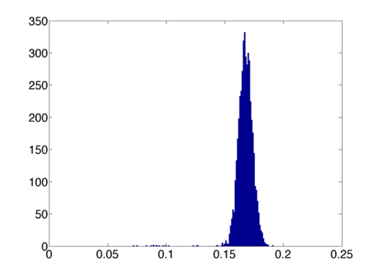
Additional features (in most variants)

- 0.5 × 0.5 cm^2, digital readout.
- 0.18 μm process, 4T structures, CDS.
- 12-bit ADC, rolling shutter, stores 10 time slices.
- Global shutter for DECAL.
- Supports power pulsing.

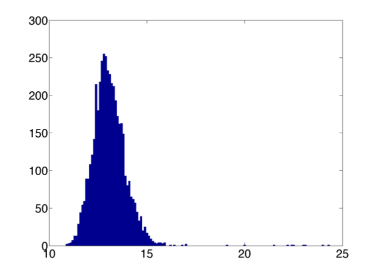


Cherwell 1 - Recent characterization work

Gain (ADC counts/e^-)



Noise (ADC counts)

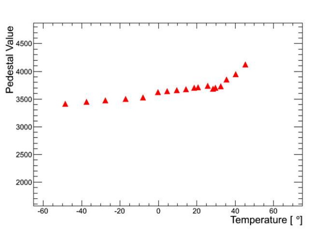


Preliminary results (May 2013)

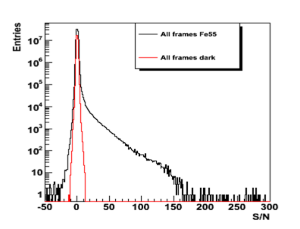
- Noise 8-12 e^- rms depending on epitaxial layer.
- Gain 0.17 ADCs/e^- or $51\mu V/e^-$.
- Full well 14700 e^-.

Cherwell 1 - Recent characterization work

Temperature Stability



Fe55 Signal-to-Noise

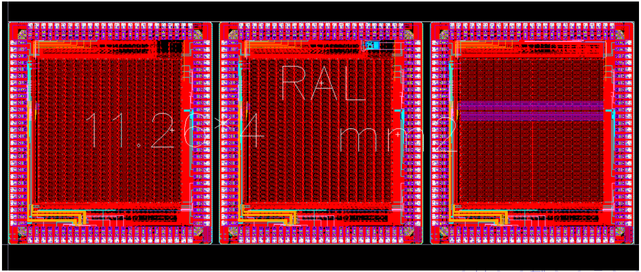


Preliminary results (May 2013)

- Temperature Stability $<$ 2 ADC counts/^{o}C between -50 to 50 ^{o}C.
- Signal-to-Noise $>$ 130.
- Hit efficiency $\gtrsim$ 99.7%.
- Hit resolution results to appear soon.
- So far Cherwell 1 is matching or exceeding design specifications.

Cherwell 2 - ALICE Inner Tracker System prototype

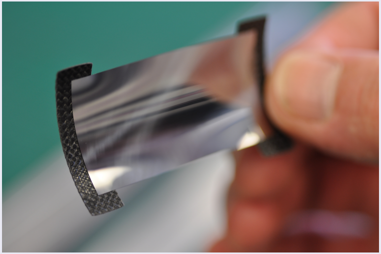
- Based on Cherwell 1 experience.
- 3 variants, (2 x all digital, 1 x analogue FE).
- In-pixel circuitry, 128×128 pixels.
- Gain $38\mu V/e^{-}$, full well 18,000 e^{-}, dynamic range 2,900.
- Power 11 mW/ cm^2.
- Rolling Shutter, Frame rate 21.76 $\mu\mathrm{s}$.
- Readout speed $\gtrsim$ 500 Mbit/sec.
- In fabrication, due in next few weeks.
- Will test at DESY in July.



Light Structures, Cryogenics and Bending

- Working with Silicon Foam and Carbide (SiC).
- Low mass carbon fibre support frames.
- Work starting on bending and forming silicon wafers.
- Work beginning on use of MAPS at low and cryogenic temperatures.

Developed with PLUME collaboration

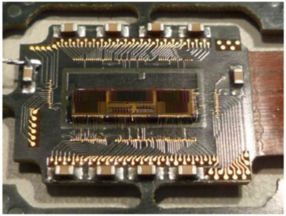


Mechanical tests of bent silicon (Arachnid)

HMRM and Sophia

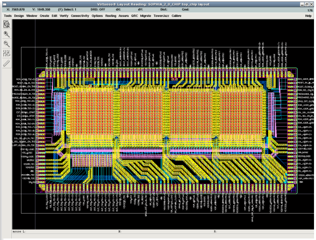
Highly Miniaturised Radiation Monitor

- Sensor size : 50x50 μm, 250 μm thick, 10.3 mm by 2.4 mm.
- Low noise, rad tolerant, designed for ESA.
- To be launched on Tech Demo Satellite.



Single Photon Avalanche Detectors

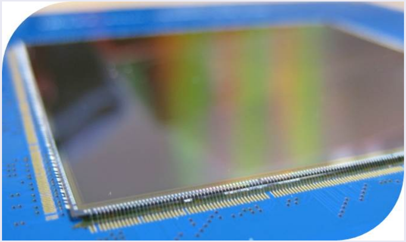
- 0.18 μm CMOS, alternative to APDs and CCDs.
- Targetting FLIM, 3D imaging, astronomy, PET and mass spectroscopy.
- Photon Detection Probability up to 27%
- Timing resolution: 0.5 ns FWHM.



Achilles for TEM and Lassena for X-ray imaging

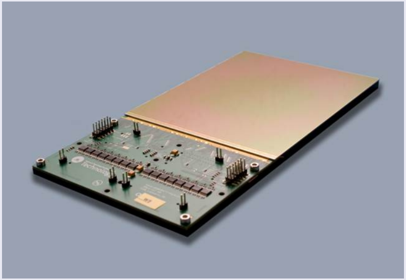
Transmission Electron Microscope

- 4096 x 4096 14 μm pixels
- Sensor Size: 61 mm x 63 mm
- Analogue output, 40 fps.
- Commercialised FEI (www.fei.com).



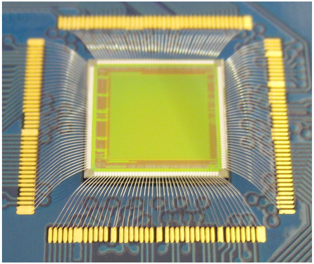
X-ray Imaging

- 2800 x 2400 50 μm pixels.
- 139.2 mm $\times$ 120 mm.
- Analogue output, 30 fps.
- 3-side buttable with minimal dead space.



PImMS 1 & 2 - Pixel Imaging Mass Spectroscopy

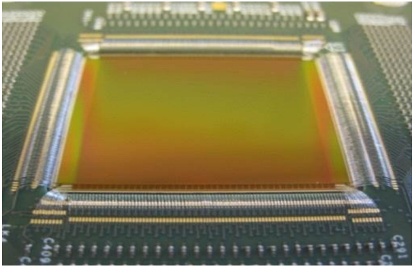
- Based on TPAC.
- Event-based time-stamping pixel sensor.
- 382 $\times$ 382 70 μm pixels.
- 80MHz, 12.5 ns time resolution.
- 12 bit timestamp storage.
- 4 registers per pixel for multiple event detection.
- Per pixel trim, mask and comparator.
- Analogue readout for focusing and event size measurement.
- Gadolinium thin film coating used in neutron imaging.



PiMMS 1 camera

Kirana - Ultra High Speed Imaging Sensor

- 924 × 768, 30 μm pixels.
- Die size: 32.5 × 25.5 mm.
- CDS, in-pixel storage.
- Continuous readout at 1,180 fps.
- Burst mode: 180 frames at 2 MHz (but sensor will work at 5 MHz).
- Gain: $80\mu V/e^-$.
- Full well: $11{,}700e^-$.
- Commercialised (Specialised Imaging).



University and National Laboratory Capabilities

- Complete set of characterisation facilities: high strength magnets (up to 7T), radiation sources, X-rays, lasers, visible light sources, metrology, environmental chambers, etc...
- CMOS Sensor Design Group certified to ISO9001-2008.
- Active in-house sensor and ASIC design team.
- Birmingham Cyclotron available for testing.
- VHDL/FPGA and DAQ expertise both for commercial and CERN systems (e.g. ATCA and GLIB).
- Extensive simulation capabilities for electronics, cooling, finite element analysis, etc...
- Facilities and clean rooms available at Universities and National Laboratories.

Conclusion

- UK heavily involved in LHC silicon.
- The UK has continued to develop MAPS as a viable technology for particle physics.
- MAPS prototypes have been designed, fabricated and tested.
- Production MAPS sensors have been commercialised for medicine, neutron facilities, space, and remote sensing.
- Results from Cherwell 1 and Cherwell 2 will appear this year.
- There has been extensive progress in MAPS capabilities relevant to LC : charge collection, efficiency, speed, signal-to-noise, power, material thickness, large areas and radiation hardness.
- Now just have to bring them all together for the LC.