X-ray CCD Detectors and CMOS Imagers for Astronomy and Space Science

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The CEI at the OU

• Moved in 2008 to the Open University
• Sited at Walton Hall, Milton Keynes
• CEI to be housed in Planetary and Space Science Research Institute (PSSRI)
• PSSRI is the UK’s leading Planetary science institute – Beagle2, Huygens, Rosetta ExoMars
• e2v provides sponsorship to the CEI using both cash & non-cash contributions
  – PhD Student training
  – RA support
  – Visiting professor – David Burt
  – Detector samples etc…
• A press release detailing the £3M investment package is imminent
Typical Detectors & Applications

• X-ray CCDs
  – X-ray Astronomy (with focussing telescopes and collimators)
  – Remote sensing of planetary surfaces (elemental mapping)
  – **Key Requirement - <5e- rms. e.n.c to give the required spectroscopy**
  – **Virtually no degradation required with space radiation damage .....**

• CMOS Imagers (although CCDs can also do the tasks)
  – Planetary Exploration (rovers – panoramic cameras, instrument augmentation)
  – Imaging
  – UV/VIS spectrometers
  – Earth Observation Science

• **Issues for use in space**
  – Radiation Damage - impact on performance, latch up,
  – X-ray background
  – TRL
  – Speed, power, mass etc.
The TRL

- TRL = Technical Readiness Level
- Space agencies are ultra cautious
- It is becoming increasingly important at instrument proposal stage to demonstrate high TRL (e.g. >5)
- Unknowns are avoided, e.g. EMCCDs are not currently adopted for space

<table>
<thead>
<tr>
<th>TRL</th>
<th>Level description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated</td>
</tr>
<tr>
<td>3</td>
<td>Analytical &amp; experimental critical function and/or characteristic proof-of-concept</td>
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<tr>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in relevant environment</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in a relevant environment (ground or space)</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in a space environment</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and &quot;Flight qualified&quot; through test and demonstration (ground or space)</td>
</tr>
<tr>
<td>9</td>
<td>Actual system &quot;Flight proven&quot; through successful mission operations</td>
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</tbody>
</table>
Focussed X-ray Imaging

The ESA XMM/Newton Spacecraft

3 co-aligned optics, each comprising 58 nested Ni shells

Focal plane detector arrays providing imaging and spectroscopy
XMM EPIC MOS Cameras

- 2 UK MOS cameras, having focal plane arrays of 7 CCDs
- Share their telescopes with the 2 RGS instruments
- Broad-band from 0.3-10 keV, ~35 μm depletion
- Increase in throughput, high energy QE and sub-keV resolution possible
- **Redundancy** comes from multiple detectors (and cameras)
Future X-ray Astronomy Missions

- **HXMT (China) ~2012**
  - China’s first X-ray astronomy mission
  - Collimated
- **NeXT (Japan) ~2013**
  - X-ray telescope
- **IXO (ESA/NASA/Jaxa) ~2018**
  - Merger of XEUS and Con-X
### Key MOS CCD Developments Required

<table>
<thead>
<tr>
<th>Development Item</th>
<th>Current Position</th>
<th>Goal</th>
<th>Funding Source</th>
</tr>
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<tbody>
<tr>
<td><strong>Increased Efficiency</strong></td>
<td>300 µm</td>
<td>300 µm (achieved)</td>
<td>e2v PV</td>
</tr>
<tr>
<td>Deep depletion for higher &gt;5 keV QE</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>High speed readout ASIC</strong></td>
<td>RAL design, 4 chan, 7 e- rms., ~10 µs/row</td>
<td>&lt;5 e- rms., ~100ns/row</td>
<td>STFC + e2v PV, Test current examples</td>
</tr>
<tr>
<td><strong>Charge Transfer Speed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Radiation Hardness</strong></td>
<td>~10 e- rms. injection noise 2kx4k samples</td>
<td>3 e- rms., ~3x improvement over n-channel</td>
<td>e2v PV + RG case</td>
</tr>
<tr>
<td><strong>Low energy resolution</strong></td>
<td>80 eV at 500eV</td>
<td>40 eV</td>
<td>Already have first test devices</td>
</tr>
</tbody>
</table>
Increased Transfer Speed

- A >30x increase in the throughput for the IXO optic can be achieved by
  - Fewer pixels (1/3)
  - An increase in readout speed (3x)
  - An increase in number of output nodes (8x)
- For a 2x1” format detector, frame time is 30 ms
- To retain >100:1 integration:transfer time – Frame transfer time should be <300 μs
- Line transfer time <<0.5 μs
- This requires the new technique of metal buttressing over the polysilicon electrodes to reduce resistance
- This technique has been developed for the CPCCD for LCFI at e2v/RAL
Geant4 Background Model and Results

- XMM MOS singles
- XMM MOS all x-ray type
- XMM MOS simulated singles
- XMM MOS simulated all x-ray types

Energy (keV) vs. counts/sec/keV/cm²
Low Background Detectors for E-WFI

- Optimal sensitivity combines
  - Expected source spectrum
  - Mirror efficiency (basically <2 keV)
  - Detector QE
  - Detector background
- XMM detectors sensitive to
  - Single or double sided detection (+100%)
  - Thickness of “Entrance window” (+50%)
  - Pixel size (~10-20%)
- We are performing a study to maximise instrument sensitivity
- Dominant background for high orbit is soft electrons off the metalwork
- Full-depleted, BI, structures have a background penalty >2x
- Warning against using many elements in the baffle/camera for XRF
High Speed Readout

- High throughput required to minimise pile-up
- System noise specification of 5 e- rms.
- XMM/EPIC 1 node at 160 kHz
- XEUS minimum requirement: 8 nodes at 1 MHz
  - 30 x faster than XMM/EPIC
- Initial development with RAL (1 and 4 channel, 6-10 e- noise)
- Aim to develop a full 8 channel design

Clock timing diagram

2-channel CDS ASIC

4 Channel ASIC
Increased Detection Efficiency
(see poster by Murray)

- Use of high purity bulk (FZ) material can increase depletion depth
- De-coupling rear substrate from that local to FET can enable increased bias
- 300 µm depletion for -100V on substrate
- 2nd generation devices tested using 512x2048 format – 13.5µm pixels
- Used on-chip binning to explore FWHM resolution vs. pixel size

![Graph showing Quantum Efficiency Measurements](image)

![Graph showing Spectral Resolution Measurements](image)
The New Family of SCDs

- **The Swept Charge Device**

- **Non-imaging CCD technology for XRF**

- Developed under the UK Impact programme ~1998

- New generation of devices designed in 2007

- New design provides improvements to:
  - Radiation hardness
  - Readout speed
  - Operating temperature

<table>
<thead>
<tr>
<th>Designation</th>
<th>Pixel Area</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD235</td>
<td>20</td>
<td>5 mm²</td>
</tr>
<tr>
<td>CCD234</td>
<td>200</td>
<td>100 mm²</td>
</tr>
<tr>
<td>CCD236</td>
<td>200</td>
<td>440 mm²</td>
</tr>
</tbody>
</table>

- 2-phase operation with 100 μm pitch

“L”-shaped electrodes

Dummy output node
CCD234 and CCD235

- CCD234 – Area = 100 mm²
- CCD235 – Area = 5 mm²
Large Pixels (100 μm)

- X-ray optic PSF is ~1mm in diameter
- Fewer/larger pixels promote an increase in frame rate
- New CCDs tested with 100 μm pixel pitch for HXMT
- Large pixels demonstrating high charge collection and good CTE for X-ray spectroscopy
- Improved radiation hardness due to charge confinement – needs verification by tests
- CCD236 shown – 2 phase, 100 μm pitch

Cu-K in CCD235

X-Ray Spectrum from Cu
CCD235 Resolution at Elevated Temperatures

- Cu-K spectra in the CCD235 operated at 100 kHz above room temperature
- Is this a record for resolution vs. temperature for a full device?
- Note that the leakage contribution can be reduced by running faster
- Elemental identification at +50°C is possible
SXI on HXMT

- Working with IHEP in Beijing to use an array of CCD236 SCDs for a soft X-ray imager on HXMT
- Detector area = 320 cm²
- Approval imminent

Soft X-ray Detector (SCD, 400 cm²)
SCDs for Lunar Mapping

• SCDs used in the D-CIXS instrument on ESA’s Smart-1 lunar orbiter
  – Detectors heavily radiation damaged during the long transit to the moon
• Also to be flown on the C1XS spectrometer on ISRO’s Chandrayaan-1 lunar orbiter
  – Improved instrument design to meet science goals over 2 year mission duration
• Both instruments use an array of SCDs in a 4x1 array package
• 6 such packages used per instrument, providing 24 sensors

• D-CIXS package shown below with 4 SCDs driven in parallel requiring only 12 connections

Clementine Iron Map of the Moon
Etna Basalt
(Polished, 10 minute data collection)

Tail of noise peak, as a result of image processing
Device Simulation is becoming important -
Modelling the Gaia CCD pixels with Silvaco software

George Seabroke

e2v Centre for Electronic Imaging
Planetary & Space Sciences Research Institute
Open University, Milton Keynes, UK
Gaia 3D model: doping

ATLAS
Data from gaia3d_drain_sbc.str
Radiation Damage becomes Important with the larger CCDs

- CCDs developed for SDO
- Now considered for Euclid

- CCD203
  - 4 node
- CCD204
  - 2 node, charge injection
- e2v has a number CCD processes with different degrees of radiation tolerance – for the dual dielectric process.

- Low voltage process is space qualified and available as standard. Rad hard devices will be available end 2008. This should also reduce radiation induced dark signal. Rad hard devices have been shown to operate at up to 1MRad.

- The low voltage and rad hard processes have the further advantage of lower clock voltage (~7V) and hence much reduced power consumption.
Dosplacement Damage in XMM

1 revolution = 2 days

\( T_{\text{MOS}} = -90 \, ^\circ\text{C} \)

\( T_{\text{MOS}} = -120 \, ^\circ\text{C} \)
FWHM of Mn-Kα as a function of temperature for a CCD54 over the expected mission 10 MeV equivalent fluence, and the resulting degradation to the Mg, Al and Si spectra for 2 year operation.
Charge Injection to Improve CTE

- First implemented in 1993 in the XMM EPIC CCD
- Gaia to use periodic charge injection
- WFC3 results indicate continuous charge injection provides a dramatic (20x) improvement
- However, noise on injected signal 13-15 e- rms.
- Large variability in inter-column injection for low injection levels (see our results for CCD22)

![Charge Injection in CCD22 Across the Row](image)

![Graph of σ(e⁻) vs Row # (pixel)](image)
Injection Uniformity Analysis

- Standard deviation vs. mean injection level
- Injection noise can be as low as 5 e- rms. but is uncontrollable and highly variable
- Goal to develop a low-noise injection system

Continuous injection CCD frame
(ID = 16.5 v, IG = 10.2 v)
Mission-Specific Time-Temperature Diagram
- Euclid mission shown

Temperature (K):
- Injection 100:1
- Injection 1000:1

Problem Area

Integrating Mode

TDI Period

Temperature Range

Emissio Time Constant (s)

Problem

Area

Injection 1000:1

Injection 100:1

P-V (E=0.46eV, s=4±2mm)
P-V (E=0.42eV, s=2mm)
V-V-V (E=0.24eV, s=2mm)
V-V (E=0.42eV, s=2mm)
P-Ci (E~0.38eV, s=4mm?, metastable)
P-Ci (E~0.30eV, s=4mm?)
P-Ci (E~0.26eV, s=4mm?, metastable)
P-Ci (E~0.20eV, s=4mm?)
O-V (E=0.16±0.01eV, s=6±2mm)
p-channel CCDs

- Avoid the admixture of known traps by using n-type float zone material with p-channel implant
- Devices manufactured in $1024^2$, $1024 \times 512$ and $2048 \times 4096$ formats
- Preliminary testing on $1024^2$ CCDs shows between 3x improvement (e2v)
- Further batches need fabricating and evaluation

- Further testing underway to characterise the residual traps in detail
Characterisation of e2v CMOS Active Pixel Sensors
CMOS Imager R&D

• In the past we have worked with e2v on development of prototype test imagers as part of their dental programme
  – $128^2$ test imagers; CMOS001 and CMOS002
  – $10^2$ test structures to evaluate pixel designs
• In future e2v aims to be a provider of quality CMOS imagers for space and science applications
• Current developments are targeted toward high performance imagers for space
• Low noise, high dynamic range
• Back-illumination for high sensitivity
### Early Results from test devices

#### Photon transfer characterisation

- CMOS002 Photon Transfer Curve
- Reset Noise = 77 e- (r.m.s)
- Full well 350k e-

<table>
<thead>
<tr>
<th>Mean Signal (DN)</th>
<th>Standard Deviation (DN)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>10000</td>
<td>10000</td>
</tr>
</tbody>
</table>

#### Leakage current (room Temp and low T)

- Log (ID) vs 1/Temperature (K⁻¹)

#### Hot carrier effects (electro-luminescence)

- CMOS001 n+/pwell Diode
- CMOS002 nwell/psub Diode

#### Quantum efficiency measurement

- Wavelength (nm) vs QE (%)
- n+/p-well Pixel
- n-well/p-sub Pixel
- n+/p-well Diode
- n-well/p-sub Diode
CMOS development

- e2v is well established as the leading supplier of CCDs for space and scientific applications.
- Most of the main process steps are identical for space CMOS and CCD manufacture.

**Diagram:**
- Design → Wafer fab
- Backthin → Package → Test → Qual
- Uses existing processes
CMOS development

- e2v has very extensive IP already developed in CMOS imaging

- Expertise includes
  - 3T: rolling shutter
  - 4T: low noise-rolling shutter
  - 5T: global shutter (99.7% efficiency) with ROI capability
  - from 2.2 µm (Telecom) to 19 µm (Medical)

- Initial focus has been on dental and industrial now moving to Space

- Devices from 3 foundries have been backthinned results all look good

- Significant benefit from the volume requirements for dental and industrial imaging

- Second space CMOS programme in progress
A programme was run last year for a geostationary ocean imager using a 2M pixel CMOS sensor for Astrium. These devices are now available both as demonstrators and fully qualified FM devices.

- Number of pixels: 1415(H) x 1430(V)
- Pixel Size: 14.81 µm x 11.53 µm
- Image area: 20.96 mm x 16.49 mm
- Optical Fill factor: 65%
- Conversion gain: 4.75 µV/e
- Dynamic range: 0.98V
- Data rate: 10 MHz
- Connectors: Pin Grid Array (PGA)
- Power consumption: 50mW
• Wafers have been thinned from Tower, UMC and IBM. All behave much as expected. The only issue has been the epi starting thickness which has meant that we have been very cautious about the thinning process and hence QE obtained has not yet matched that available from CCDs.

• Further work is in progress using epi of different starting thickness (12µm)

• Backthinned demonstrators are available of the 838x640 pixel sensor

• Next step is to space qualify a backthinned CMOS sensor
Existing e2v CMOS devices

- Devices are currently available with the following performance:
  - 0.5Mpixes sensor
  - 5.8µm square pixels with microlens
  - Global shutter
  - 60 frames per second at full resolution (838 x 640)
  - Good responsivity
  - 8 bit parallel output
- Commercial devices but potentially could be qualified for space use
Proton Radiation Testing of 838x640 pixel imager

- Preliminary testing conducted to look at leakage current effects after proton irradiation
- Devices exposed to 5E9 and 1E10 cm⁻² (10 MeVp)
- Characterisation underway
Spin-Off into other areas

• Utilising the X-ray photon-counting mode of CCDs

• X-ray Fluorescence
  – Analysis of contaminants
  – unnamed company

• X-ray diffraction
  – Portable in-situ XRF/XRD for geology
  – www.inXitu.com

• Beta Autoradiography
  – Thin tissue imaging using 3H, 14C
  – www.xcam.co.uk
Conclusions

• MOS CCDs continue to be developed for future X-ray instruments in space science for both X-ray astronomy plus lunar and planetary science

• SCD technology is being applied to XRF for elemental mapping for Lunar science, with future instrument opportunities for lunar and planetary science

• CMOS imagers are already in design/production for space Earth Observation

• Development of critical technology components is being addressed
  – CMOS imager technology developments
  – Readout support ASICs
  – Transfer time (CCD)
  – Increased QE (CCD & CMOS)