Percival soft X-ray imager

Pixellated Energy Resolving CMOS Imager, Versatile and Large

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Percival

In a nutshell

Unprecedented combination:
- 1408 × 1484 pixels
- 300 Hz frame rate
- Below 15 e⁻ noise
- Sensitive to single photons
- Handle 5·10⁴ ph/pix/frame

... BSI processed for good soft X-ray performance
Science Motivation

Watching biomolecules in action … and more

- Making optimal use of the brilliance of today’s photon sources requires
  - Single-shot imagers with suitable frame rates
  - Very large dynamic range - single-photon discrimination to \(10^4\) photons/pixel/frame and more
  - Millions of pixels with little/no dead area

- In the soft X-ray regime
  - Scientific interest e.g. biosystems, weakly scattering samples
  - Particular challenge: small signal requires very low noise
  - Particular challenge: sensor surface
P2M Sensor

Designed by partner Rutherford Appleton Lab / STFC

- CMOS imager (180nm technology)
- On-chip digitization (11520 ADCs)
- 3 auto-adjusting gain levels (per pixel, per frame, overflow)
- $1408 \times 1484$ pixels, $27\mu m \times 27\mu m$
- $4 \times 4$ cm$^2$ continuous imaging area (stitched sensor)
- Data rate at 300Hz frame rate is 20 Gbit/s, streamed out over 45 LVDS lines (240 MHz, double data rate)
P2M – a stitched sensor

Designed by partner Rutherford Appleton Lab / STFC

1408 x 1484 pixel P2M

3520 x 3710 pixel variant, P13M ~ 10x10cm²

stitching blocks

704x742
P2M Sensor – Multiple Gains

Designed by partner Rutherford Appleton Lab / STFC

- 3 auto-adjusting gain levels (per pixel, per frame, overflow)
- Readout sequentially tests all three overflow configurations for each pixel against threshold
- Only best candidate digitized & sent to DAQ
Backside Illumination

How to enable soft X-rays to interact in the sensitive volume

\[
\begin{align*}
\text{Wafer Substrate} & \quad \sim 700 \mu m \text{ low-resistivity Si} \\
\text{sensitive volume} & \quad \sim 10 \mu m \text{ SiO}_2 & \text{metals} \\
& \quad \sim 10 \mu m \text{ epi Si}
\end{align*}
\]
Backside Illumination

Carrier Wafer

sensitive volume

SiO$_2$

diode

high-purity Si epilayer

Wafer Substrate

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Entrance window post-processing

High sensitivity to low-energy radiation requires:

- Absence of passive material
- Absence of traps
- Optimized field geometry at sensor surface

High-quality backside processing is crucial!

e.g. 50 nm of SiO$_2$: loss of 25% of 250 eV photons
Post-Processing for Percival

• Prototype Sensor post-processed by NASA’s JPL “delta-doping”
  • Pioneered ultra-thin entrance windows (few nm)
  • Bureaucratic difficulties mainly make access difficult & time-consuming
  • TS sensors processed by JPL give nice soft X-ray performance
  • Unfortunately – due to said bureaucratic difficulties –
    e.g. not possible to BSI-process 2nd generation test devices in reasonable time

• P2M sensor post-processing
  • JPL remains a key partner and will process wafers
  • Exploring alternate routes to “good” post-processing
    (for some applications 10s of nm are acceptable)
  • EMFT currently a partner in tests (bonding, thinning, pad exposure)
  • Some routes to thicker dopant layers (10s to 100s of nm) exist, not tried yet
  • Easier-to-access MBE-based post-processing capable of processing both wafers and
    single (prototype) sensors direly needed
P2M System

Currently undergoing benchtop tests in front-illuminated configuration

- In-vacuum detector head
  - sensor
  - Includes sensor biasing board
  - Several hundred LVDS control & data lines, are (re)distributed here
  - Sensor will be cooled to ~ -30°C
  - 2-side buttable
  - movable
**P2M System**

Currently undergoing benchtop tests in front-illuminated configuration

- Carrier board hosts
  - FPGA running finite state machine
  - Mezzanine board (also AGIPD, Lambda) reordering data for easier processing streaming out 20 Gbit/s data
- Interface to slow control, facility information, trigger

Mezzanine for data streamout shared by AGIPD, LAMDBDA, and Percival
P2M System
Currently undergoing benchtop tests in front-illuminated configuration

- Control & DAQ
  - 20 Gbit/s from one sensor
    (reading full images: 300 Hz, 2M pixels, 30 bit/pixel incl. CDS)
  - Virtual hdf5 developed in part for this project
  - Python interface & Odin GUI interface
  - API for link to Tango, DOOCs, EPICS, etc.

- Software Framework for Characterization
  - Data validation
  - Calibration constants
  - Sensor characterization

- Testing
Prototype Performance – Noise

Dispersion of pixel noise in one chip

- reasonably low parameter dispersion between different samples (also from different wafers)

Dispersion of mean pixel noise over several chips

- Noise below Poisson limit

- preliminary tests indicate ~10e- rms reachable by multiple sampling
Prototype Performance – Gains

- Automatic gain adjustment works
- 3 gains accessible via overflow switch architecture
- Dynamic range to 3.5 Me- i.e. 50k photons at 250eV
Prototype Performance – soft X-rays

backside-illuminated (BSI)

• Imaging at 92 eV, single-shot at FLASH

  left: Airy ring pattern

  right: fine diffraction rings from liquid sample

• Airy rings match expectation

• Charge Collection Efficiency (lower limit to Quantum Efficiency) measured at ~70% above 400 eV
Prototype – Charge sharing

Charge from a single photon’s interaction in most cases spreads over more than one pixel.

This makes detecting the photon more difficult, and more so the lower the photon’s energy.

A CCE of 80% at 400eV does NOT promise we’ll be able to find 80% of single photons at 400eV.

Different chip thicknesses, the thinner the less pronounced this effect.

E.g. single 600eV photons would be easily found (brightest pixel bright enough) in ~ 2/3 - 3/4 of cases.

Epilayer thickness aim 10µm to optimize soft X-ray response.
P2M Operation

- First light
- Visible light, room temperature
- 100Hz frame rate
  (streamout speed of full acquisition system still ramping up)
- Automatic gain switching works
Project Status & Outlook

P2M FSI undergoing benchtop testing

- P2M system operates, saw first light
- P2M sensor demonstrates auto gain switching in response to illumination
- Detailed characterization (including bias tweaking etc.) ongoing
- Circuit functionality at 300Hz frame rate demonstrated (reading partial image), full readout & system ramping up to this
- P2M backthinned sensor in hand, awaiting wirebonding
- Expect first X-ray tests in fall 2018
- First delta-doped P2M BSI ~ Xmas 2018

P2M backthinned & pads exposed by Fraunhofer EMFT Munich
Thank you for your attention!

and

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