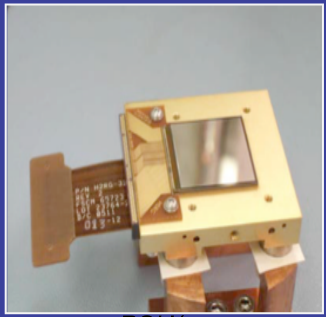
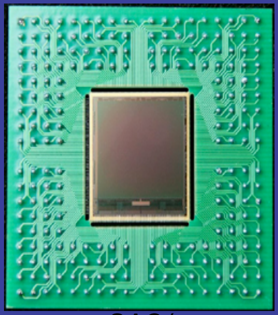
Development and Status of X-ray Detectors for X-ray Surveyor HDXI:

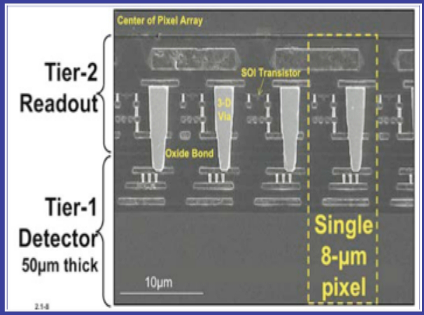
Wide FOV, Small Pixels, Fast readout, moderate energy resolution



PSU/ Teledyne



SAO/ Sarnoff



MIT/Lincoln Lab

Abe Falcone
Penn State University

With contributions from:
Ralph Kraft, Mark Bautz, Almus Kenter, & David Burrows

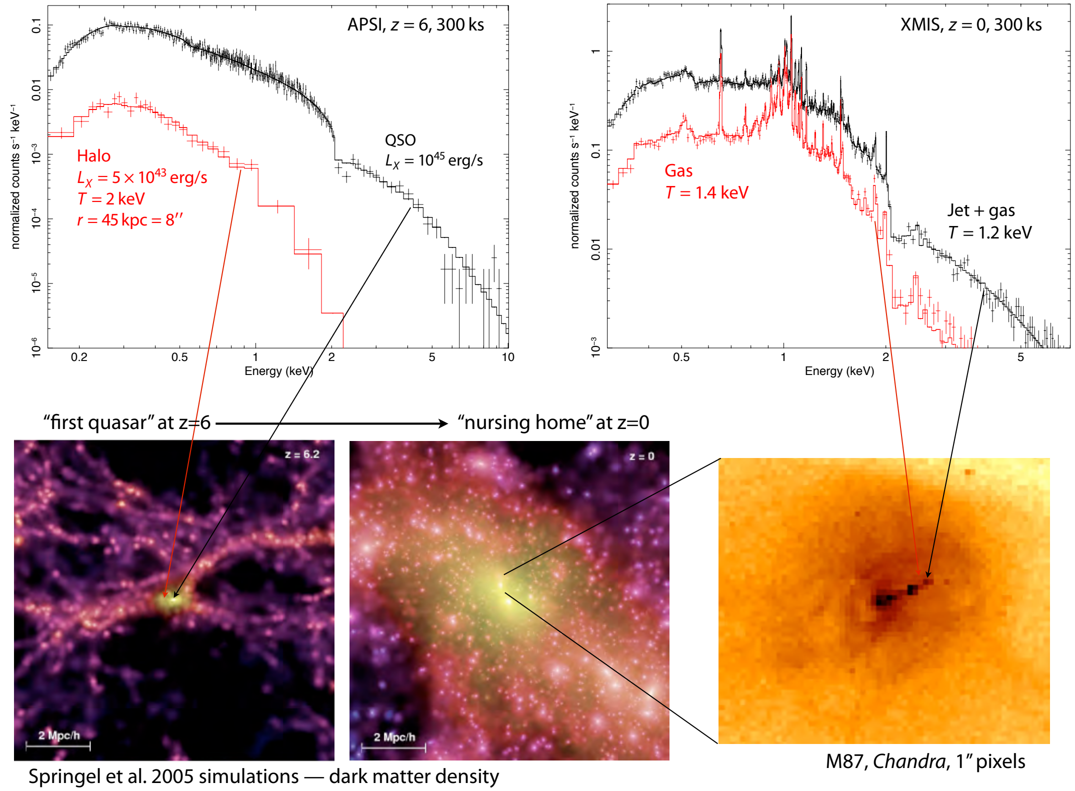
X-ray Astronomy in the future

- X-ray Surveyor is likely to be a *high throughput* mission that has effective area in excess of 10 times that of the current generation (of order several times 10^4 cm^2), while achieving *angular resolution* similar to Chandra (< arcsec HPD).

- This will enable:
  - Black hole spin measurements for a sample out to z~3 (and many more at lower redshift)
  - Spatially and temporally resolved high resolution spectroscopy of distant and low flux young AGN
  - Deeper surveys of black holes and active galactic nuclei (AGN).
  - Precision cosmology on the large scale structure will be addressed using spatially resolved spectra of clusters
  - Warm Hot Intergalactic Matter studies with absorption lines
  - Iron lines will be resolved in time around AGN
  - Spectra for black holes at z~10 will be obtained
  - AGN outflows and their acceleration site parameters will be mapped spatially
  - Equation of state will be probed in high density environments

To achieve this, we require a *wide-FOV*, *fine-angular-resolution* instrument with *very fast readout*, *low power*, *rad hard*, *high QE*, & *small-pixel* detectors.

X-Ray Surveyor science



- 5′×5′ microcalorimeter with 1″ pixels
- ***22'×22' CMOS imager with 0.33" pixels (HDXI)***
- gratings with R=5000

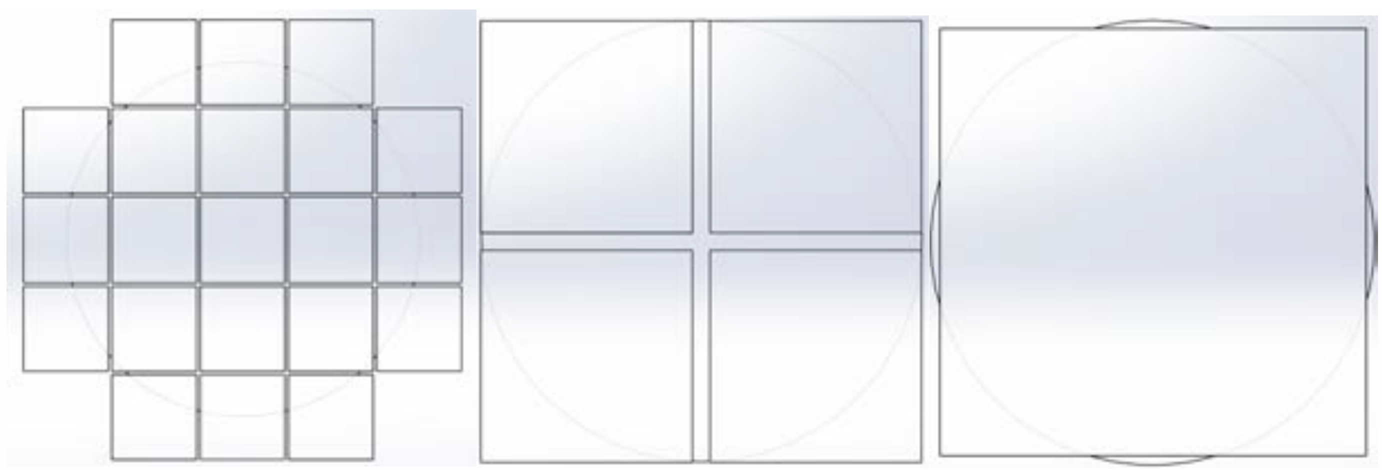
- **f = 10m, ⌀ = 3m mirrors with 0.5″ HPD resolution, A_{eff} = 2.3 m^2 at 1keV**

For HDXI, X-Ray CMOS active pixel sensors (APSs) are an excellent candidate, …
... but more development is needed

HDXI "Initial Concept" Parameters

HDXI Parameters/ Requirements	
Energy Range	0.2 – 10 keV QE > 90% (0.3-6 keV), QE > 10% (0.2-9 keV)
Field of View	22’ × 22’ (4k × 4k pixels)
Pixel size	≤ 16 × 16 micron (≤ 0.33 arcsec)
Read noise	≤ 4 e^-
Energy resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Frame rate	> 100 frame/s (full frame) > 10000 frame/s (windowed region)
Radiation tolerance	10 years at L2

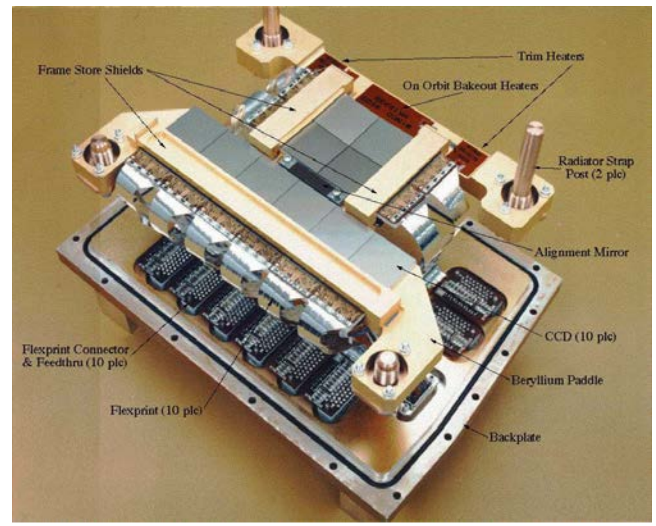
Schematic Detector Layout



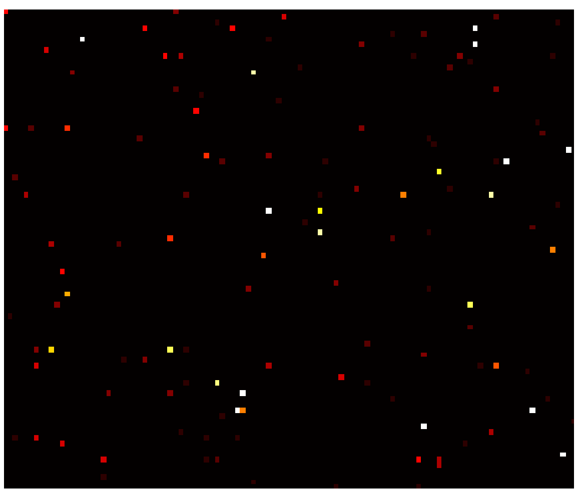
Schematic layout of detector focal plane with 3 options: (a) 21 detectors with 1024x1024 pixels, (b) 4 detectors with 2048x2048 pixels, and (c) 1 detector with 4096x4096 pixels. The multiple detector options can be tilted to accommodate a curved focal plane surface.

CCDs for past/current missions

- CCDs have been demonstrated on several existing missions (e.g. Chandra, XMM, Swift,...)
- State of the art for:
  - low noise
  - high QE
  - moderate spectral resolution
  - excellent spatial resolution



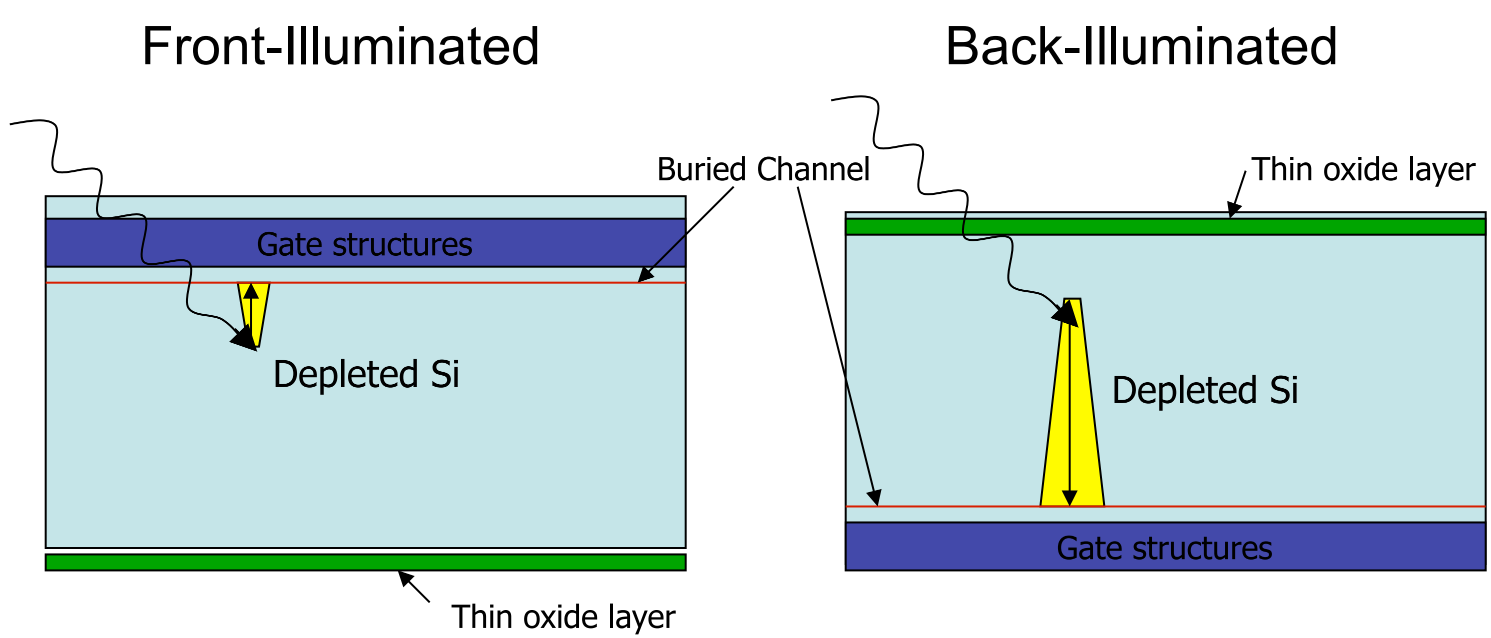
Chandra ACIS



Swift-XRT CCD Image of individual X-rays

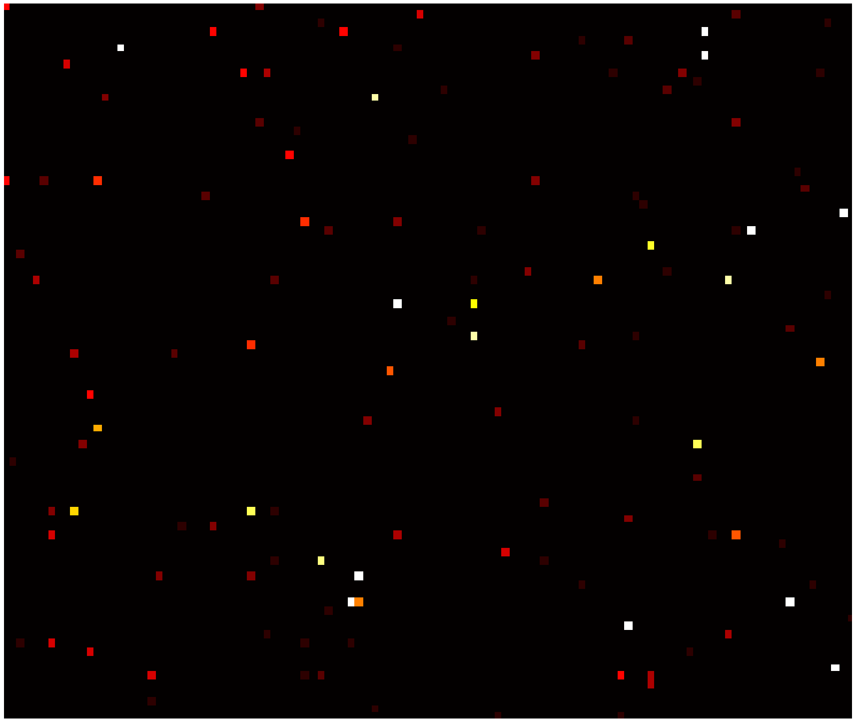
X-ray CCDs

- Photon detection
  - Photoelectric absorption in silicon, N ≅ E/3.68 eV
  - Photo-charge drifts in electric field to buried channel
  - Gates are clocked to move charge packets to readout



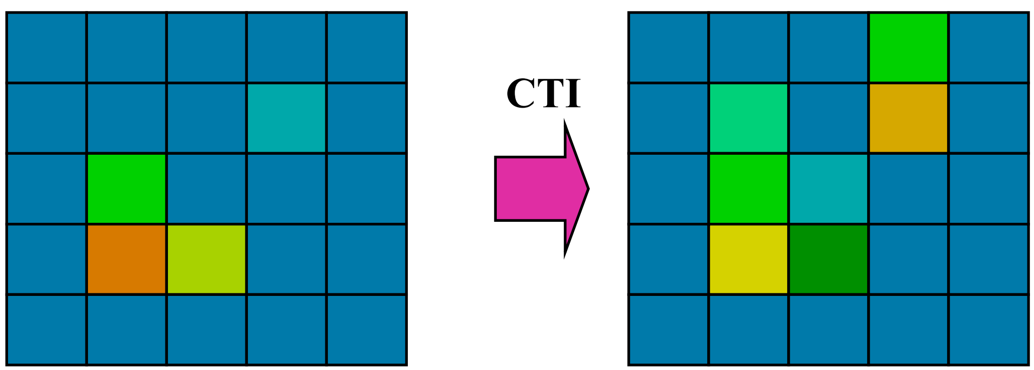
X-ray CCDs

- X-ray CCDs are photon-counting detectors
- Individual "events" must be extracted from bias level of CCD using short exposures



X-ray CCDs

- Photon detection
  - Charge splits between adjacent pixels due to spreading of charge cloud
  - Charge transferred in “bucket brigade” fashion
  - During transfer across CCD surface, some charge is lost in defects (traps), resulting in further spreading of charge into trailing pixels
  - Radiation damage can increase these traps over time



X-ray CCDs

- CCD advantages:
  - “Fano-limited” energy resolution
  - Large-format devices with good spatial resolution
  - High quantum efficiency
  - Very linear behavior

- CCD Disadvantages:
  - Energy resolution is only moderate (vs. microcalorimeter)
  - High sensitivity to **radiation damage**
  - **Photon pileup** at high count rates
  - **High power** needs

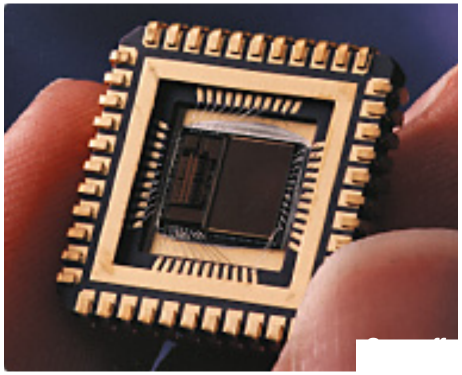
- Future missions (e.g. X-Ray Surveyor) call for high throughput and a need to overcome pile-up. All future missions, including small near-term options, need to overcome radiation limitations and power limitations.

The Future: Active Pixel Sensors

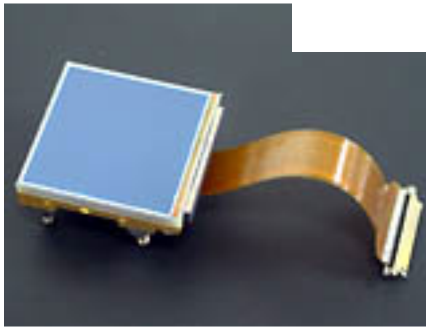
- Random-access pixel readouts
- Silicon-based devices:
  - Similarities to CCDs:
    - Photoelectric absorption in silicon
    - Energy resolution should be comparable to CCDs
    - Large arrays like CCDs
  - Radiation hard (charge is not transferred across the device)
  - High count rate capability with low pile-up (arbitrary window readout vs entire device readout for CCD, and multiple output lines boosts full frame rate)
  - Low power (<100 mW for some devices)
  - On-chip integration of signal processing electronics
  - Some devices have >200 μm depletion depths → full soft X-ray energy range
  - Large formats (up to 4k × 4k abuttable devices)
  - Pixel sizes from 8 μm to 100 μm

Different Active Pixel Sensors

- Monolithic
  - Single Si wafer used for both photon detection and read out electronics
  - Sarnoff/SAO and MPE



- Hybrid
  - Multiple bonded layers, with detection layer optimized for photon detection and readout circuitry layer optimized independently
  - LL/MIT and Teledyne/PSU



SAO/Sarnoff Monolithic CMOS

Monolithic CMOS (SAO/Sarnoff-SRI)

Moore's law comes to (X-Ray) imagers

A. Kenter, T. Gauron, R. Kraft @ SAO
Support: Moore Foundation, NASA APRA , Smithsonian IR&D
Collaboration with Sarnoff/SRI. Fabrication at JAZZ-Tower Semiconductor

- **Single piece of Si.**
- **Benefits of CMOS industry:**

<u>Very rapid</u> development:

1. **Design/specification --(Sarnoff,SAO)**
2. **Layout/"tape-out" ----------(Chronicle)**
3. **Fabrication------------------(JAZZ Semi.)**
4. **Thinning--------------------(Mike Lesser)**
5. **Testing/evaluation------(SAO/Sarnoff)**

Devices can be tailored for particular mission/ application or they can be made versatile with real-time selectable features.
Versatile devices with broad applications and larger potential market appeal to manufacturers.

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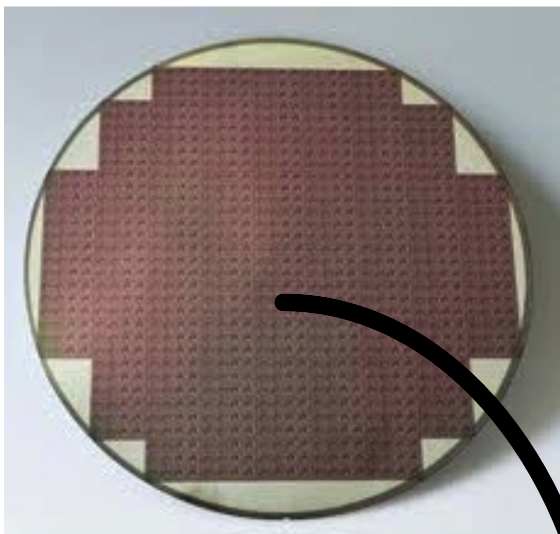
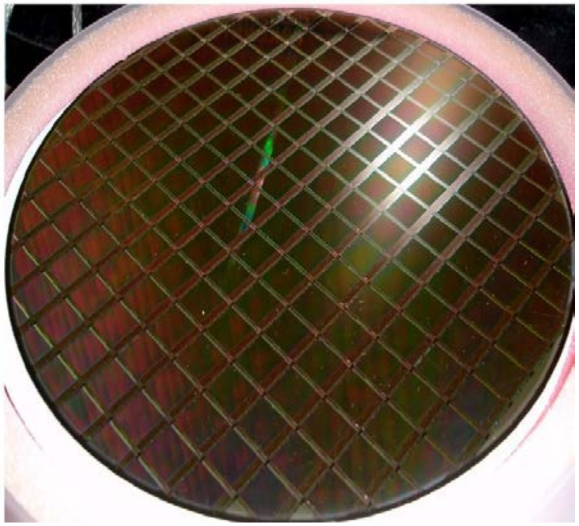


8" Si wafer

22mm reticle

Monolithic CMOS X-ray @SAO



2016 Photo: Sarnoff-SRI 8" wafer,
Stitch-able imager reticle, M=N=1.

"Standard/Custom" CMOS IC processes and controls:

- Very high yield, Low final per-item cost.
- (Presently) limited thickness (<50μm)

- Available stitch-able "Mk by Nk" formats production:
  → any rectangular size can be fabricated.

- High On-chip integration (e.g. fast, parallel row-at-a-time
- clamp and sample CDS).
- Entire row is CDS processed in ~ 20μsec

- Many read modes: SNAP, Rolling Shutter with AC coupled
- on-chip analog CDS or DC coupled for digital CDS.
- Very high cadence window read rate.

- Inherently "rad hard".
- Available in NMOS or PMOS (collect photo electrons or holes)

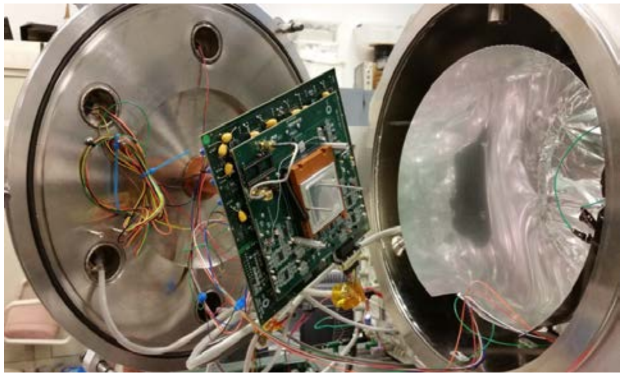
Applications:
NASA SOLO-HI, Europa Multi Fly-by, LLNL fusion diagnostics camera.

X-Ray Surveyor?

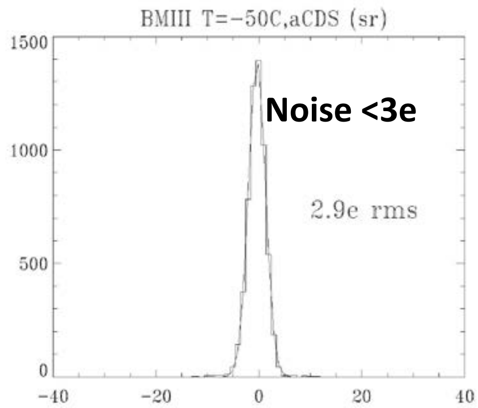
Monolithic CMOS X-ray testing @SAO

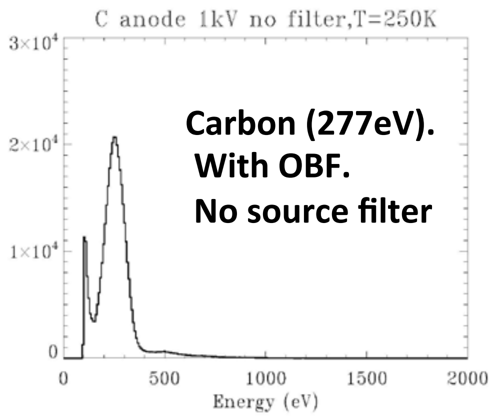
Results:

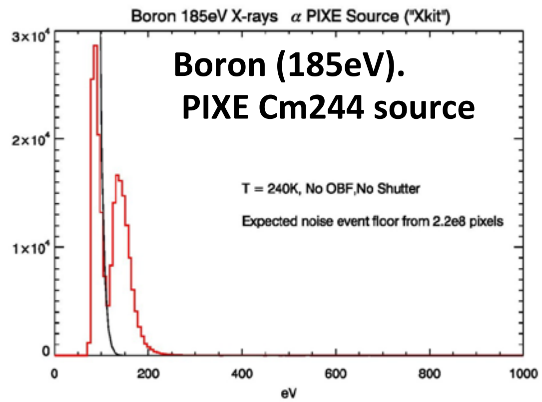
- Performance of 1k by 1k, 16μm pitch devices.
- High sensitivity ~135μV/e pixel (<Carbon x-ray> produces ~10mV @ pixel!)
- Row-at-a-time on chip CDS (1k by 1k device can CDS processes 1k pixels in ~20μ sec)
- Modest cooling requirements. Back thinned by Mike Lesser @U. of Arizona
- High through-put mitigates dark current and out-of-band optical light



BI Monolithic device with Optical Blocking Filter in SAO Detector lab X-ray test chamber .







Pixel size and soft response well matched to X-Ray Surveyor type optic PSF and EA

Almus Kenter 2016

Monolithic CMOS X-ray @SAO

Future work:

PMOS versions of devices (photo holes vs photo electrons) which have:

- Lower read noise (~1h rms)
- No Random Telegraph Signal (RTS) noise
- Lower recombination of photo charge

More output channels per Row Multiplexer for higher throughput.

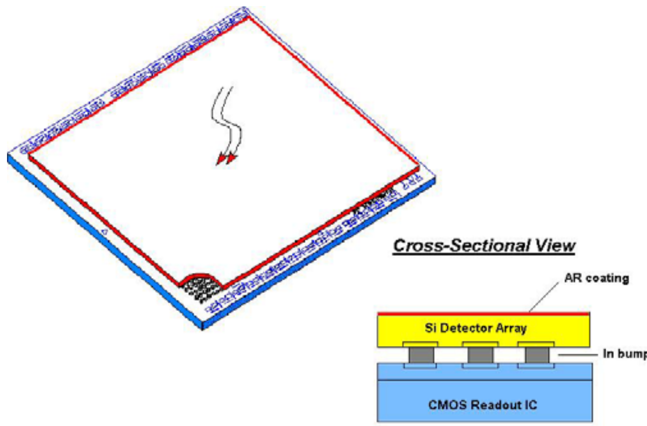
Thicker, custom high ρ Si for enhanced HE QE

Improved in-pixel charge collection efficiency for better spectral resolution.

PSU/Teledyne Hybrid CMOS Detectors

Hybrid CMOS Detectors from Teledyne/PSU

- Based on JWST technology, IR detectors; High TRL with flight heritage from OCO
- Back illuminated (>200 micron fully depleted depth)
- random access readout
- Up to 4kx4k pixels, with abuttable designs
- Detector array and readout array built separately, bump-bonded together
  - Allows separate optimization of detector and readout
  - Readout electronics for each pixel
  - Optical blocking filter on detector



- Very high speed (>10 Mpixel/sec and 16/32/64 outputs), low power, and radiation hard device suitable for future high-throughput X-ray missions

Hybrid CMOS Detectors

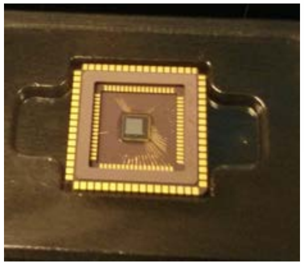
- Silicon-based devices:

  Similarities to CCDs:

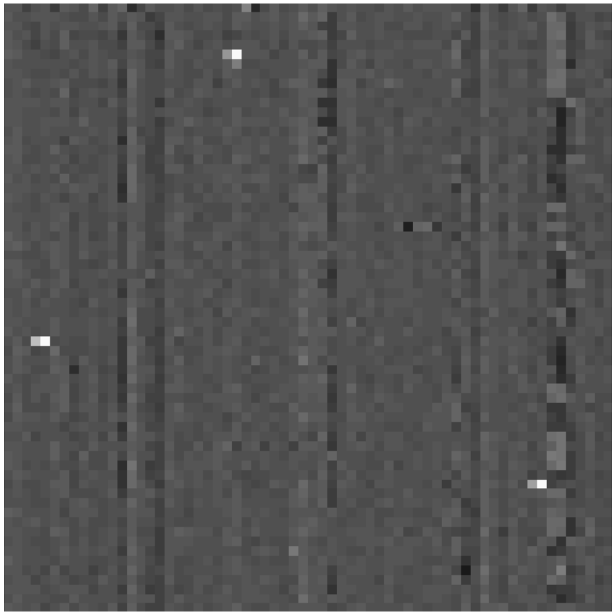
  - Photoelectric absorption in silicon with similar QE

    (see Prieskorn et al. 2013)
  - Energy resolution should be comparable to CCDs
  - Large arrays like CCDs
- Low sensitivity to radiation damage (because charge is not transferred across the device
- High count rate capability (windowed readout, and multiple output lines boosts full frame rate)
- Low power (~100-200 mW for H2RG + SIDECAR)
- On-chip integration of signal processing electronics
- >200 μm depletion depths → full soft X-ray energy range

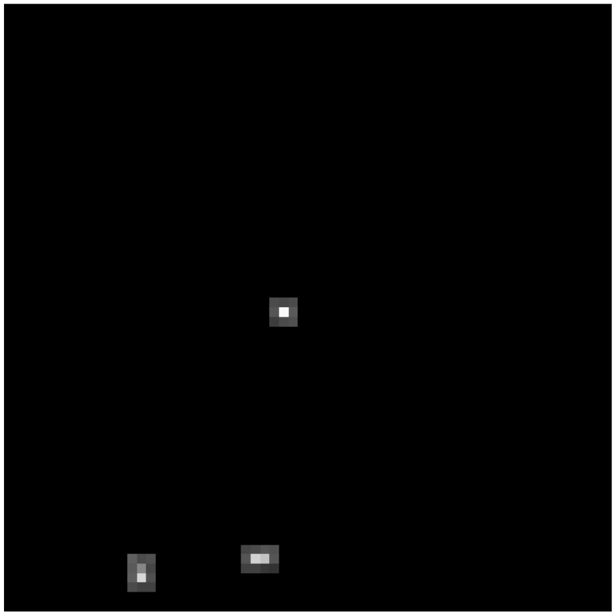
Sparse Read Out :
The Speedster Event Driven X-ray Detector



By reading only the pixels with x-ray events, effective frame rates can be faster by orders of magnitude!



Full Frame Read Out Mode:
Comparator threshold set below the noise floor



3x3 Sparse Read Out Mode:
Comparator threshold set above the noise floor

The Speedster also has in-pixel CDS, no measurable interpixel crosstalk, and selectable gain (up to ~200 μV/e).

We have achieved sparse readout with this new hybrid CMOS detector in our lab. However, this detector currently requires large (40 um) pixels and has not demonstrated read noise as low as X-ray Surveyor requirements.
(Griffith et al. 2016)

PSU/Teledyne Hybrid CMOS Small-pixel Detectors

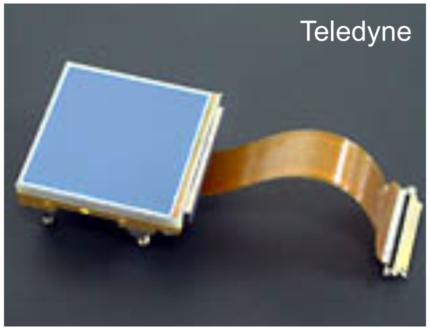
- Small pixels (<15 um) are needed for a high spatial resolution camera such as HDXI on X-Ray Surveyor.

- Recent work has shown that crosstalk (IPC) becomes negligible when using CTIA amplifiers.

- "Standard" high-TRL hybrid CMOS detectors have been measured to have read noise as low as ~7.1 e^- (RMS) *(see Prieskorn et al. 2013)*, but we need to get closer to the Fano limit.

- Teledyne and Penn State have completed an initial design and fabrication of a Si hybrid CMOS detector with *12.5 um pitch pixels, CTIA amplifiers, and in-pixel CDS*.
  - ***Initial testing of these detectors shows that we are achieving ~5 e- read noise.***

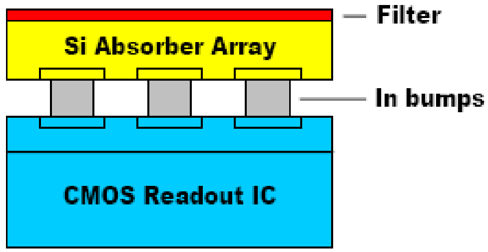
- Future work will involve: (1) scaling this test design up to large format detector, (2) attempting to reduce read noise further with improved component tolerance and attempting to maintain this low read noise at high read out rates, (3) attempting to implement event-driven readout in smaller pixels

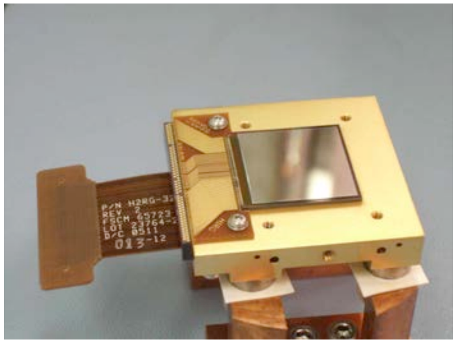


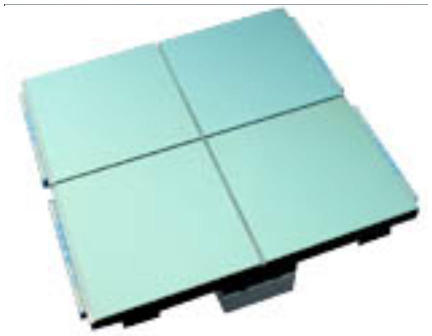
PSU/Teledyne Hybrid CMOS Detectors

- Detector array and readout array built separately, bump-bonded together
  - Allows separate optimization of detector and readout
  - Readout electronics for each pixel
  - Optical blocking filter on detector
- Based on IR detector technology with heritage from JWST and high TRL/flight-heritage from OCO
- Back illuminated with >200 micron fully depleted depth

  → excellent QE across 0.2-15 keV band
- random access readout
- Up to 4k×4k pixels, with abuttable designs
- High speed (10 Mpix/sec × N outputs), low power, and rad hard device suitable for future high-throughput X-ray missions
- Read noise (~5-10 e^-) needs improvement. Fano-limited performance is expected, with work in progress.
- Recently, inter-pixel crosstalk has been eliminated.
- Event-driven readout has been achieved on 40 μm pixels
- New test devices with 12.5 μm pixels, in-pixel CDS, and ~5 e- readnoise have been fabricated, but gain variation must be mitigated (and these devices need to be scaled to large format).
- Progress is limited by funding!







Hybrid CMOS X-ray detectors, Falcone et al.

Technical Challenges

- **<u>Quantum Efficiency</u>**: Hybrids have achieved the depletion depths required for high quantum efficiency across the X-ray band, but the monolithic devices still need to make further developments to achieve these depletion depths
- **<u>Read Noise</u>**: Monolithic architectures have achieved low read noise, but hybrids still need to progress further to achieve $< 4\ e^-$
- **<u>Small Pixels/Aspect Ratio</u>**: All devices have achieved small pixel sizes, but further development is needed to do this while retaining other advantages and while limiting impacts of increased charge diffusion due to the increase in the aspect ratio of pixel depth-to-width
- **<u>Rate</u>**: While higher frame rates are already possible with APSs, relative to CCDs, significantly more development is needed to handle the data from these increased frame rates at the focal plane level for short/medium term missions and to achieve the required read noise while simultaneously achieving fast frame rates for the long-term mission requirements (>100 frame/sec for >16 Mpix cameras)

Technical Challenges

- The PhysPAG Technology Study Analysis Group Roadmap called for a near-term push on developments of Si X-ray imagers that can operate at high rates with low power, as well as a long-term push on developing these in larger formats with small pixels.

- To achieve these goals and overcome technical challenges, the development schedule must be accelerated with additional funding.