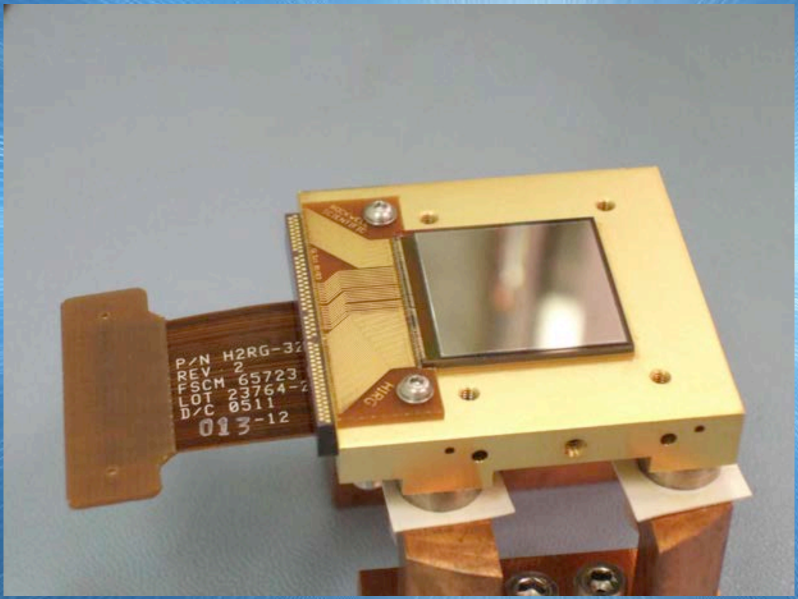
X-ray Active Pixel Sensors: Status and Development Needs for Future Missions



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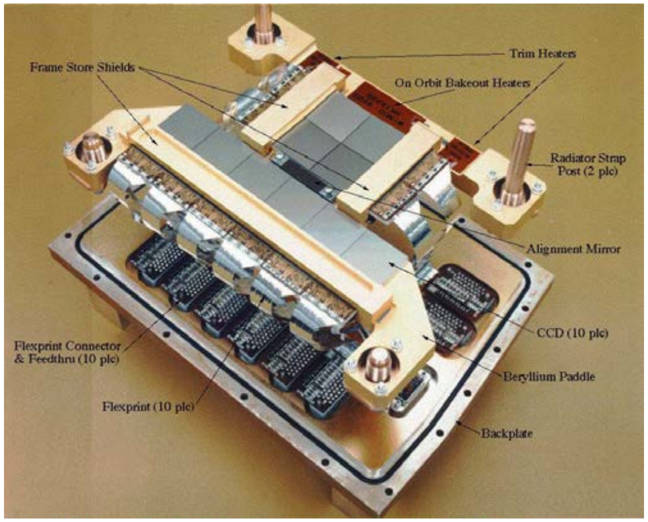
CCDs: Heritage

- 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

  while retaining large format

Wide field of view X-ray instruments requiring good spatial resolution will continue to require Silicon sensors (e.g. CCDs & active pixel sensors) in the foreseeable future



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
  - Moderate-to-poor time resolution
  - High sensitivity to **radiation damage**
  - **Photon pileup** at high count rates
  - **High power** needs

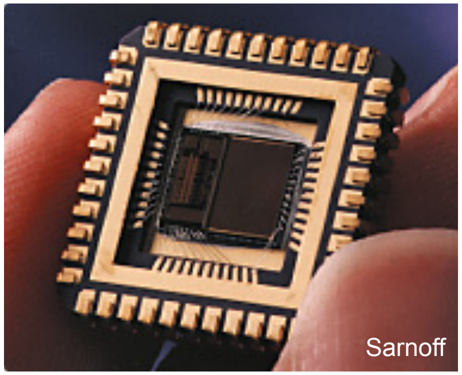
- Future missions (e.g. Smart-X) call for high throughput and a need to overcome pile-up and radiation limitations, as well as power limitations.
- Any future mission calling for a wide field X-ray imager will need to overcome some (or all) of these CCD disadvantages, and grating sensor arrays may also benefit from improvements.

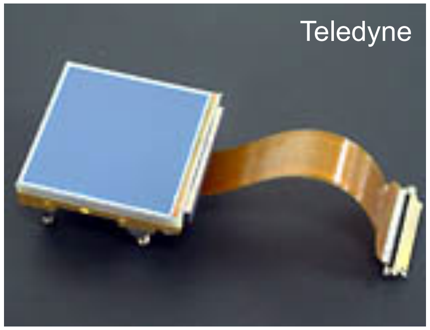
The Future: Active Pixel Sensors

- 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

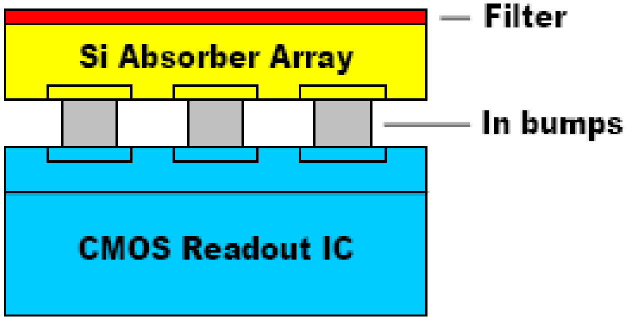
- Monolithic
  - Single Si wafer used for both photon detection and read out electronics
  - Sarnoff and MPE
- Hybrid
  - Multiple bonded layers, with detection layer optimized for photon detection and readout circuitry layer optimized independently
  - MIT/LL and Teledyne

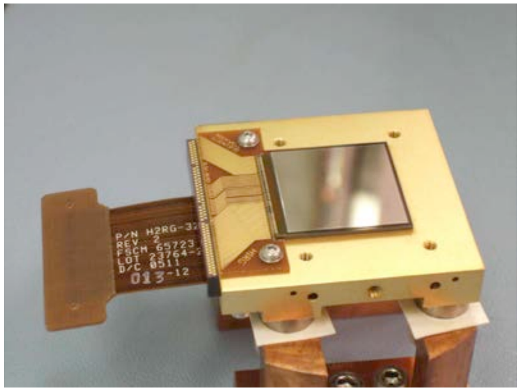


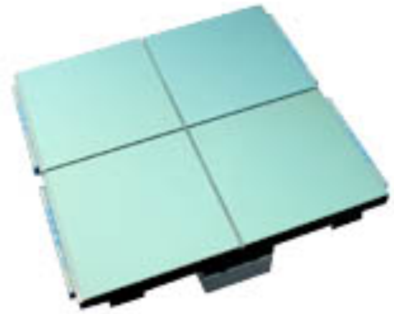


PSU/Teledyne Hybrid CMOS Detectors

- 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
- Very high speed (>10 Mpixel/sec and N outputs), low power, and radiation hard device suitable for future high-throughput X-ray missions
- However, current readnoise (~8 e^-) and inter-pixel crosstalk need improvement. Fano-limited performance with <1% crosstalk is expected, with work in progress.
- Progress is limited by funding!

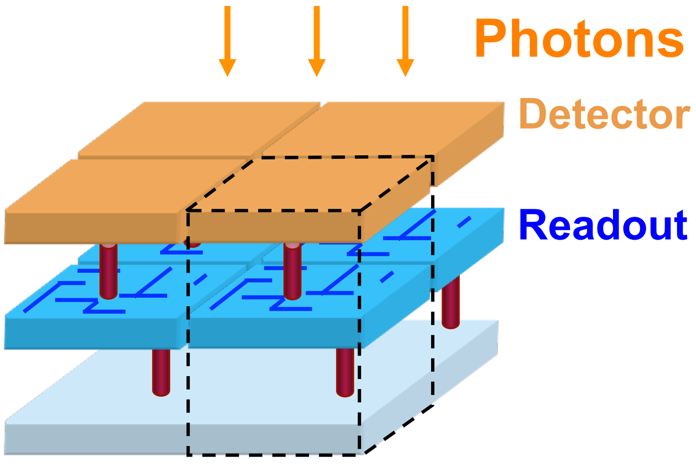


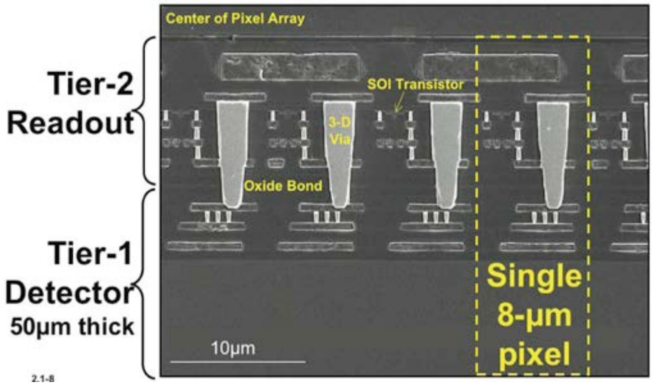




Active Pixel Sensors at MIT/LL

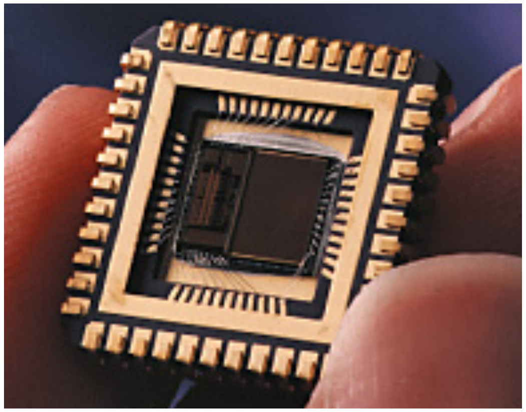
- Multilayer electronics
- 100% fill factor
- Scalable to large focal planes
- Optimize material and fabrication by layer
- Potential for pixel-level intelligence
- Detector layer is high resistivity Si
- achieved 256×256, 8 μm pixels with in-pixel CDS
- Back illuminated 50 μm thick
- < 13 e^- read noise,
<190 eV FWHM @ 5.9 keV
- Progress is limited by funding!

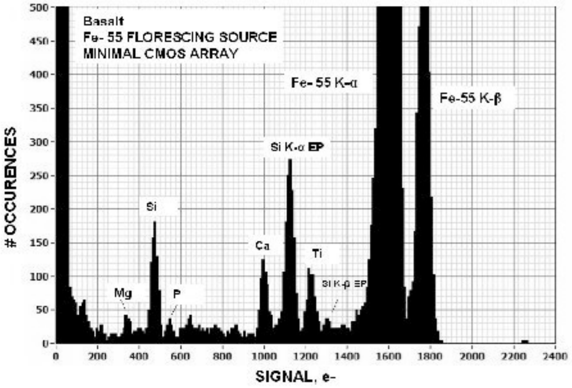




JHU/SAO/Sarnoff Monolithic CMOS

- Single layer of Si for both X-ray detection layer and read out circuitry
- Fano limited (< 2 e^-) noise
- 8 µm pixel 3T devices tested
- 1k × 1k device with 5T readout fabricated
- On chip analog CDS possible
- High resistivity Si used for a test device (but this led to high dark current)
- Depletion depth currently limited to <20 µm
- Progress is limited by funding!





Technical Challenges

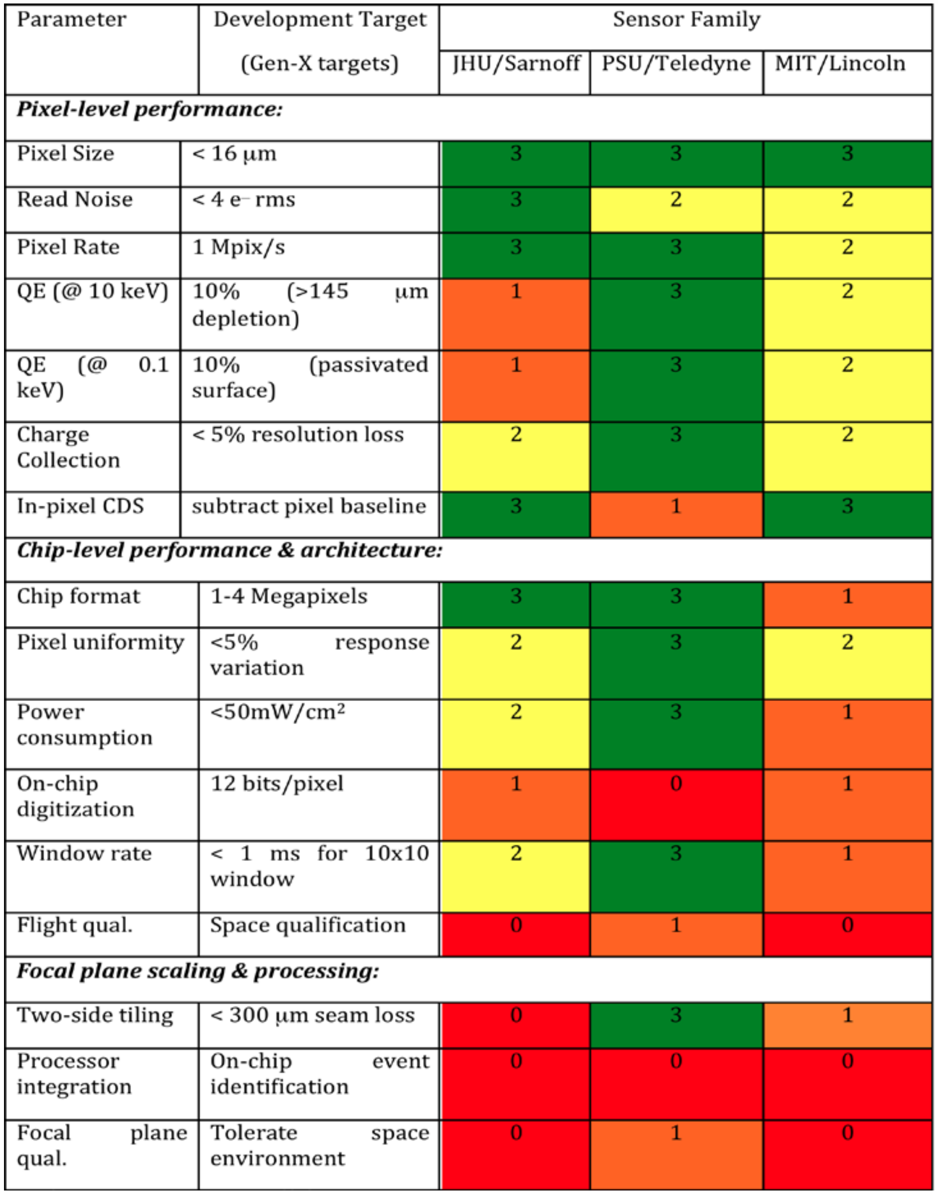
- **Quantum Efficiency**: Hybrids have achieved the depletion depths required for high quantum efficiency across the X-ray band, but the monolithic devices still need to make further developments to achieve these depletion depths
- **Read Noise**: Monolithic architectures have achieved low read noise, but hybrids still need to progress further to achieve $< 4\ e^-$
- **Small Pixels/Aspect Ratio**: 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
- **Rate**: 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 achiving 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.

Active Pixel Sensor Development Status



Parameter	Development Target (Gen-X targets)	Sensor Family		
		JHU/Sarnoff	PSU/Teledyne	MIT/Lincoln
Pixel-level performance:				
Pixel Size	< 16 μm	3	3	3
Read Noise	< 4 e^- rms	3	2	2
Pixel Rate	1 Mpix/s	3	3	2
QE (@ 10 keV)	10% (>145 μm depletion)	1	3	2
QE (@ 0.1 keV)	10% (passivated surface)	1	3	2
Charge Collection	< 5% resolution loss	2	3	2
In-pixel CDS	subtract pixel baseline	3	1	3
Chip-level performance & architecture:				
Chip format	1-4 Megapixels	3	3	1
Pixel uniformity	<5% response variation	2	3	2
Power consumption	<50mW/cm²	2	3	1
On-chip digitization	12 bits/pixel	1	0	1
Window rate	< 1 ms for 10x10 window	2	3	1
Flight qual.	Space qualification	0	1	0
Focal plane scaling & processing:				
Two-side tiling	< 300 μm seam loss	0	3	1
Processor integration	On-chip event identification	0	0	0
Focal plane qual.	Tolerate space environment	0	1	0

KEY

0 = no progress to date

1=some work

2=may be met 1-2 years

3=already demonstrated

Development Needs & Funding Profile

- While APSs are clearly the future of wide field of view high angular resolution X-ray astronomy, more developments are needed to make them ready for a large future mission.
- At this time, all 3 US-based APS technologies offer promise, but each of them has technical hurdles to overcome.
- Currently those hurdles are being approached and overcome, but the rate of progress is slow due to limited funding.
- The following funding profile would allow us to have flight-ready APSs by 2021. It assumes parallel iterations of the 3 techniques, for the next few years, followed by concentration on one detector architecture. For more details on the funding profile, see the Murray et al. response to the PCOS XraySAG RFI.

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	**Total**
$2.25M	$2.25M	$2.5M	$4.0M	$4M	$4.5M	$1.5M	$3.0M	$1.5M	$1.5M	**$27M**

Quote from Dave Burrows:
"Note that the success of the ACIS CCDs was built on >10 years of dedicated CCD development efforts"