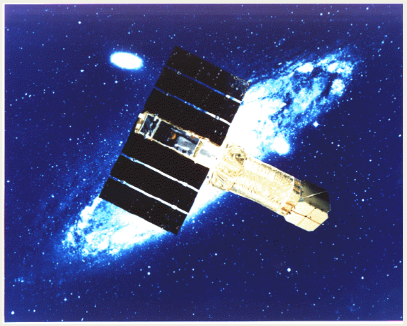
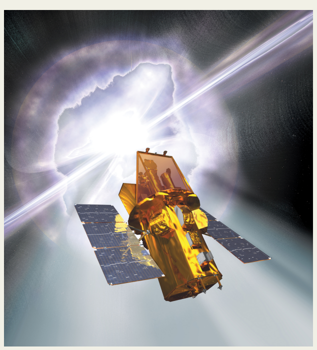
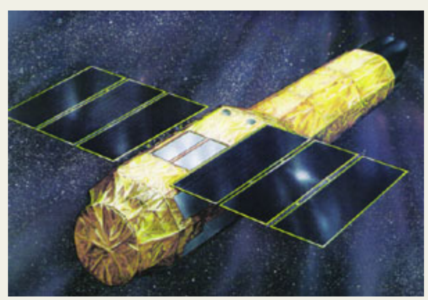
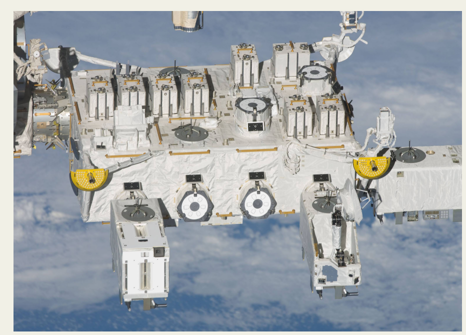



CCDs for X-ray Astronomy

Catherine Grant, MIT

X-ray Astronomy School

1 August 2011

Outline

- Basic principles and operation
- Performance: Quantum efficiency, energy resolution
- Detector features: Pileup, charge transfer inefficiency, contamination, background
- Future X-ray imaging detectors

Outline

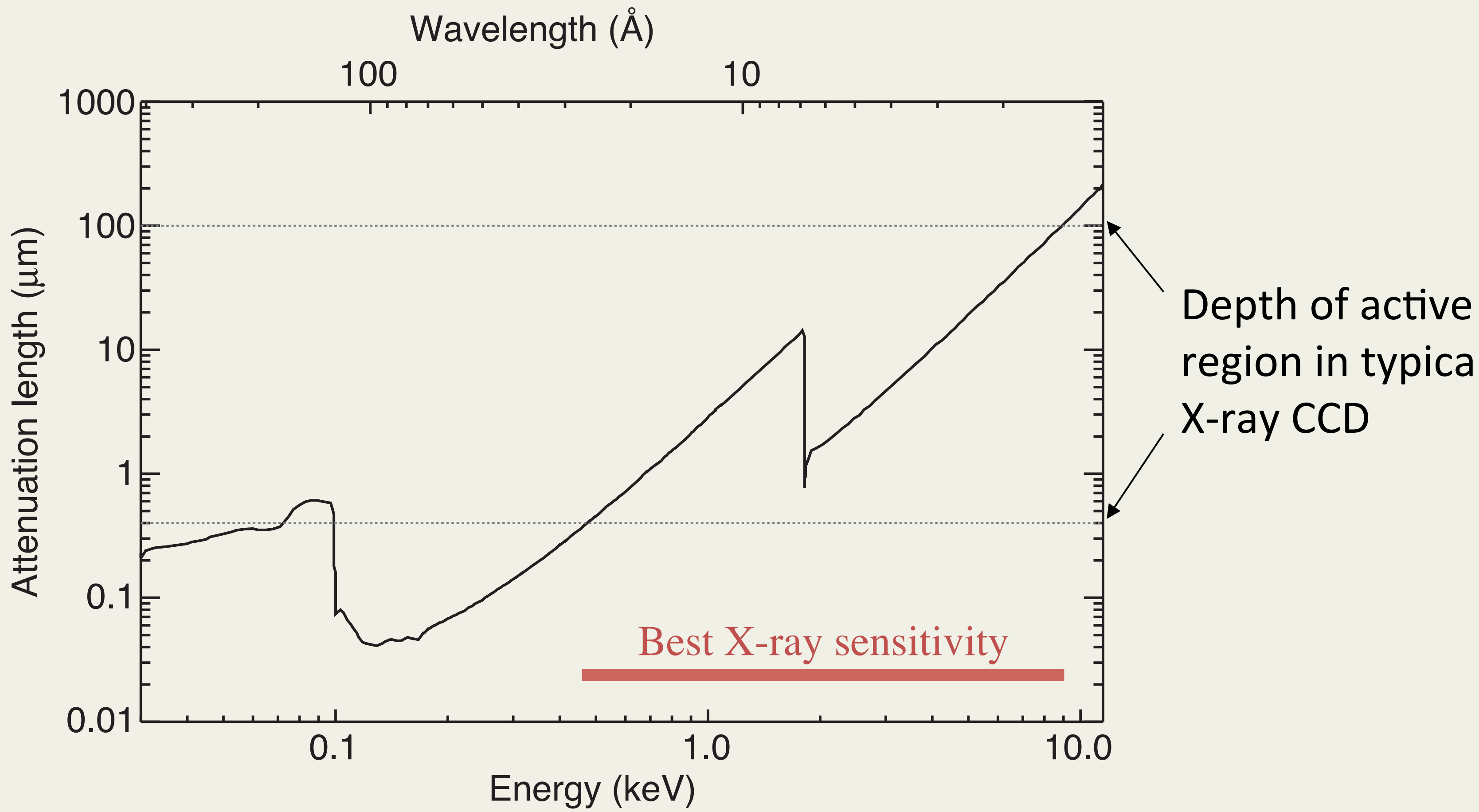
- Basic principles and operation
- Performance: Quantum efficiency, energy resolution
- Detector features: Pileup, charge transfer inefficiency, contamination, background
- Future X-ray imaging detectors

CCDs in a nutshell

- CCD = Charge-coupled device
  - An array of linked ("coupled") capacitors
  - Photons interact in a semiconductor substrate (usually silicon) and are converted into electron-hole pairs
  - Applied electric field used to collect charge carriers (usually electrons) and store them in pixels
  - Pixels are "coupled" and can transfer their stored charge to neighboring pixels
  - Stored charge is transferred to a readout amplifier
  - At readout amplifier, charge is sensed and digitized

Photoelectric Absorption in Silicon

Mean absorption depth



Photoelectric Absorption

- Photoelectric interaction of X-ray with Si atoms generates electron-hole pairs.
- On average: $N_e = E_x / w$
  - N_e = number of electrons
  - E_x = energy of X-ray photon
  - w = ionization energy to create electron-hole pair
  - w ~ 3.7 eV/e^- for Si (temperature dependent)
- X-ray creates a charge cloud which can diffuse and recombine or drift under influence of an applied electric field

Charge Collection: Doping

- Conductivity sensitive to presence of impurity atoms
- Doping: replace small number of silicon atoms by impurities
- n-type, excess e^-
  - Five valence e^- (P, As)
- p-type, excess holes
  - Three valence e^- (B, Al)
- Overall material uncharged
- Layering differently doped materials, encourages electric current in one direction depending on applied voltage polarity

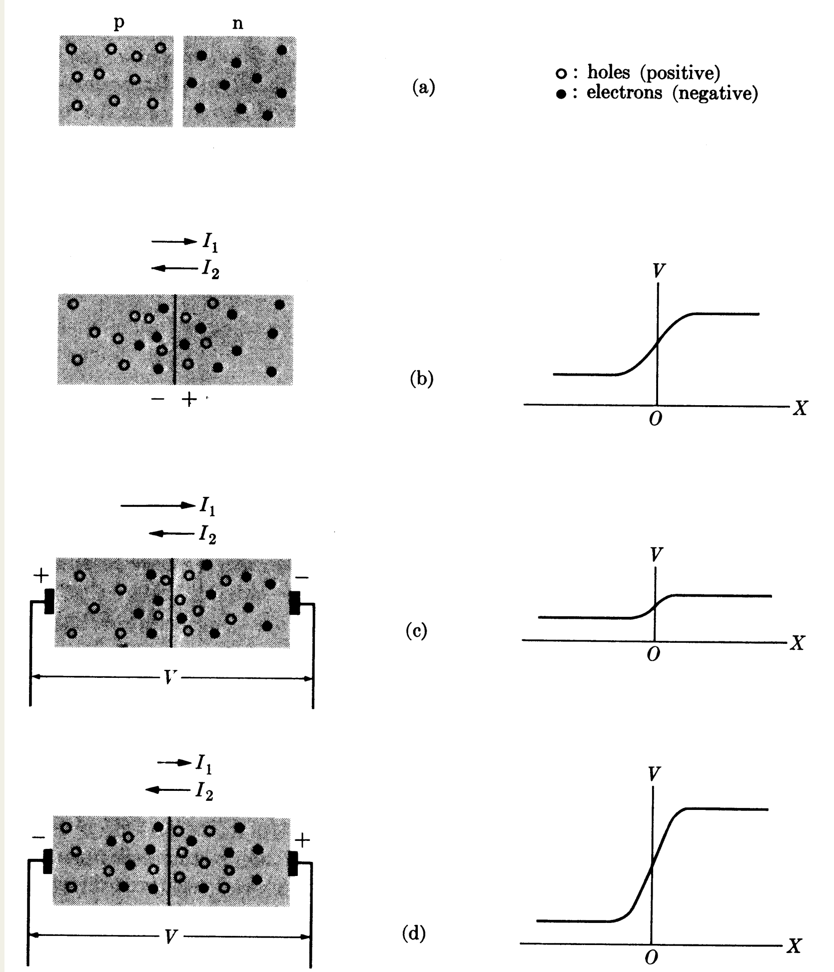


Fig. 6–41. The p-n junction.

Charge Collection

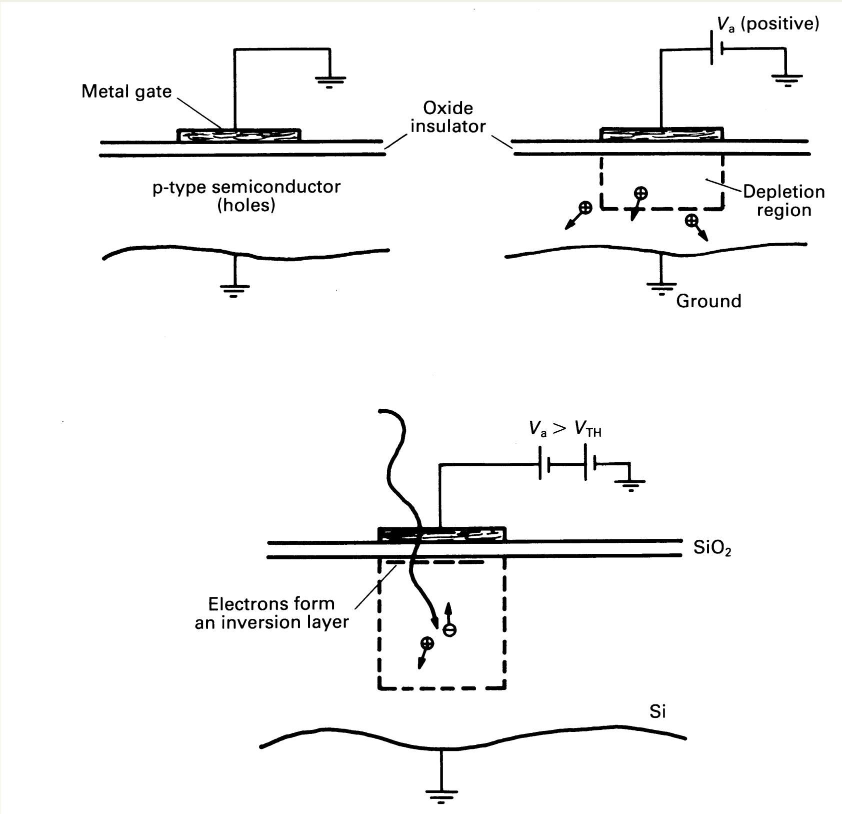


Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.

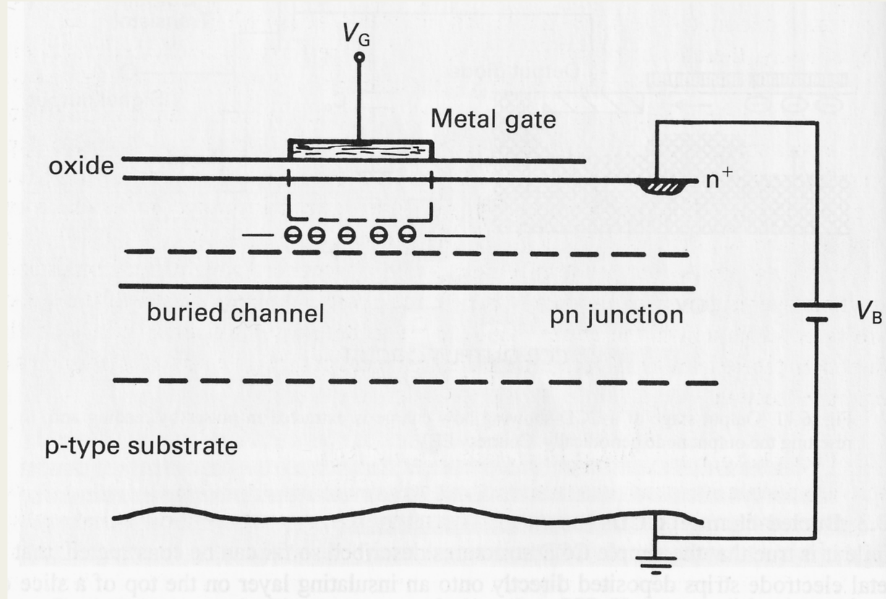
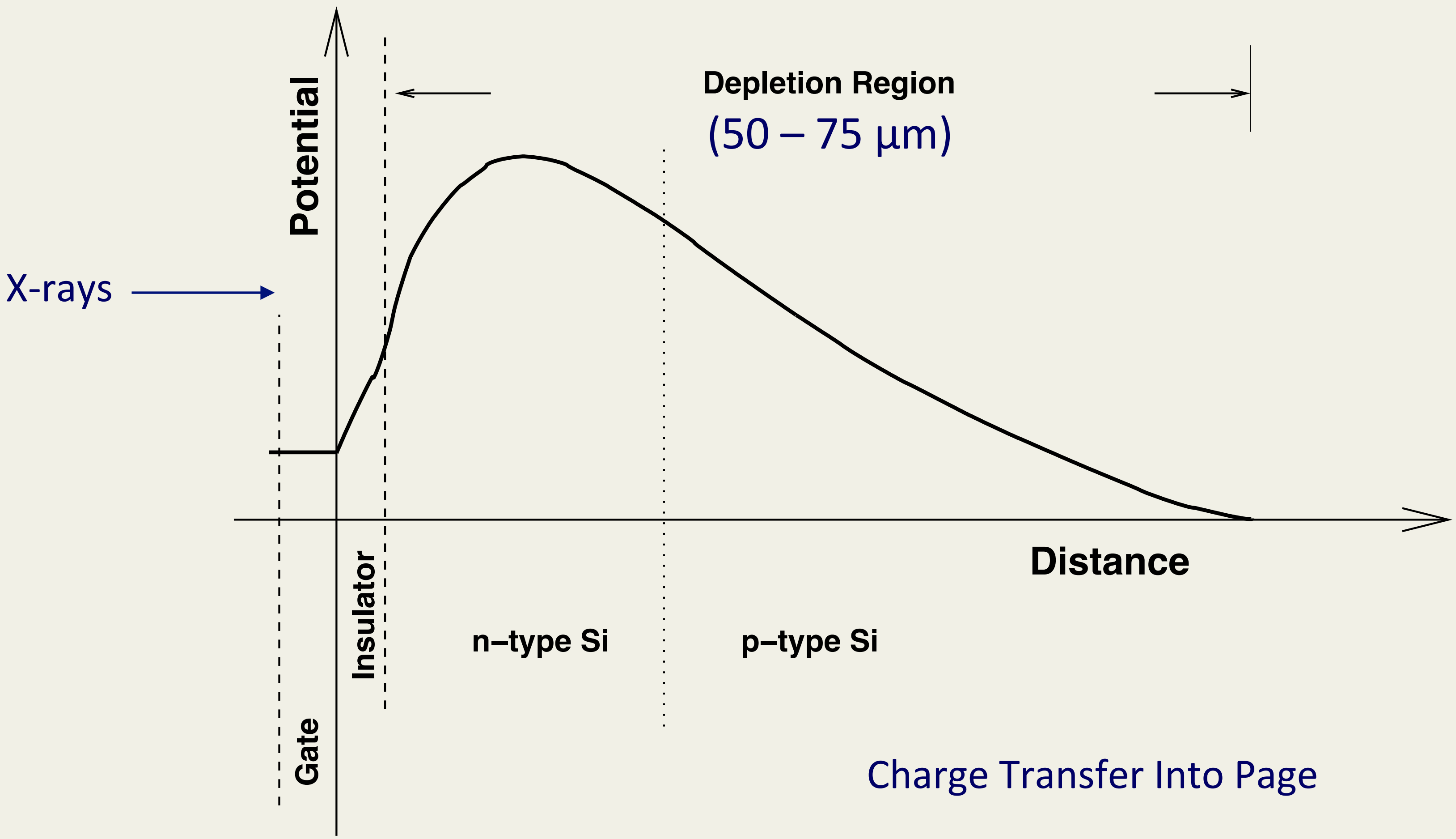


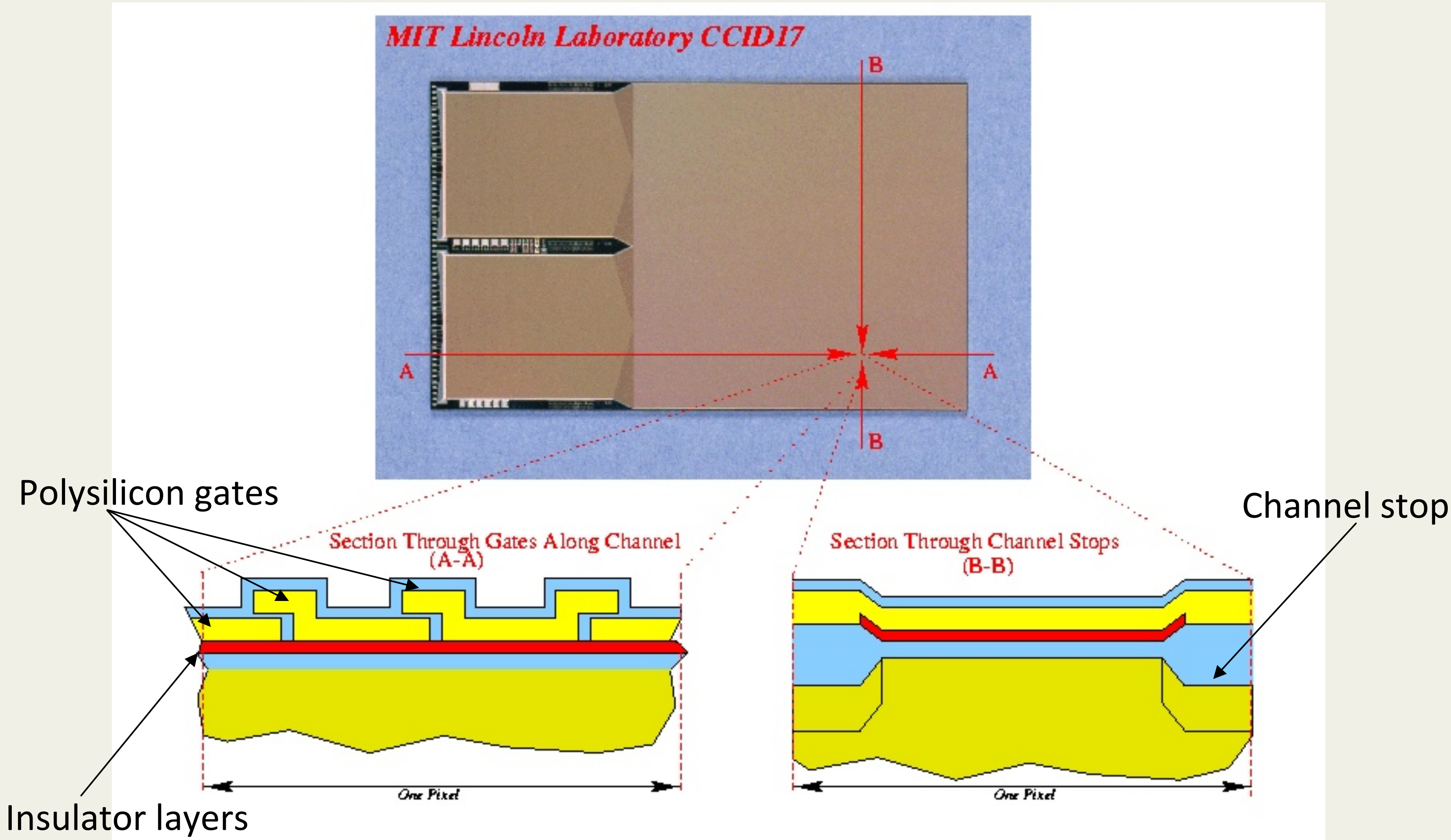
Fig. 6.12. (a) A single storage site in the buried-channel type of CCD. As the gate voltage increases the depleted zones finally meet.

- Basic element in CCD is a capacitor
  - Metal-oxide-semiconductor (MOS), or *p-n* junction

Electrostatic Potential Well
Buried-channel CCD



Pixel Structure



Charge Transfer

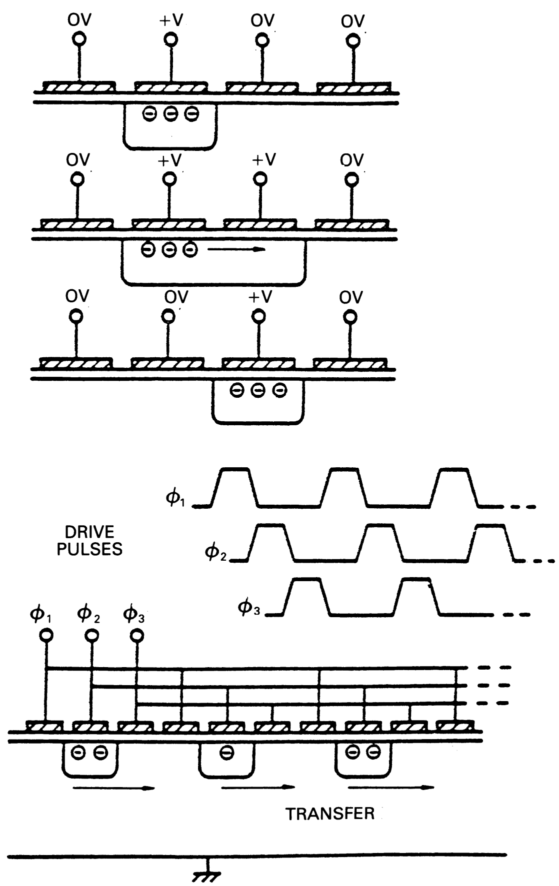
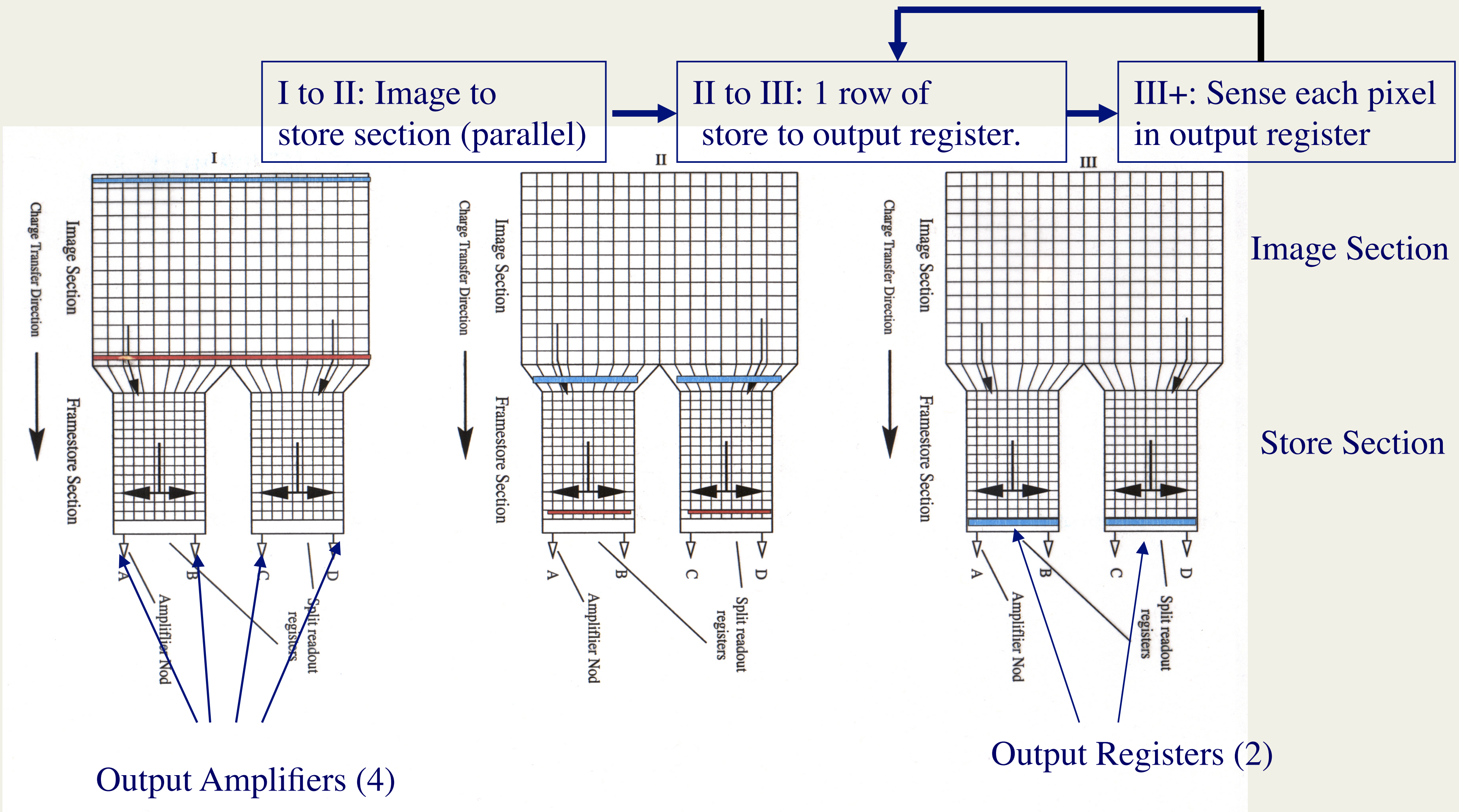


Fig. 6.9. Charge-coupling in a three-phase CCD and the associated timing waveform or clock pattern. In practice the degree of overlap between one electrode and the next depends on the CCD design.

- Charge collected under a gate
- Adjoining gates are "coupled", charge is transferred
- Repeat to continue transferring charge
- Three-phase CCD: three gates define one pixel dimension

CCD Readout Sequence

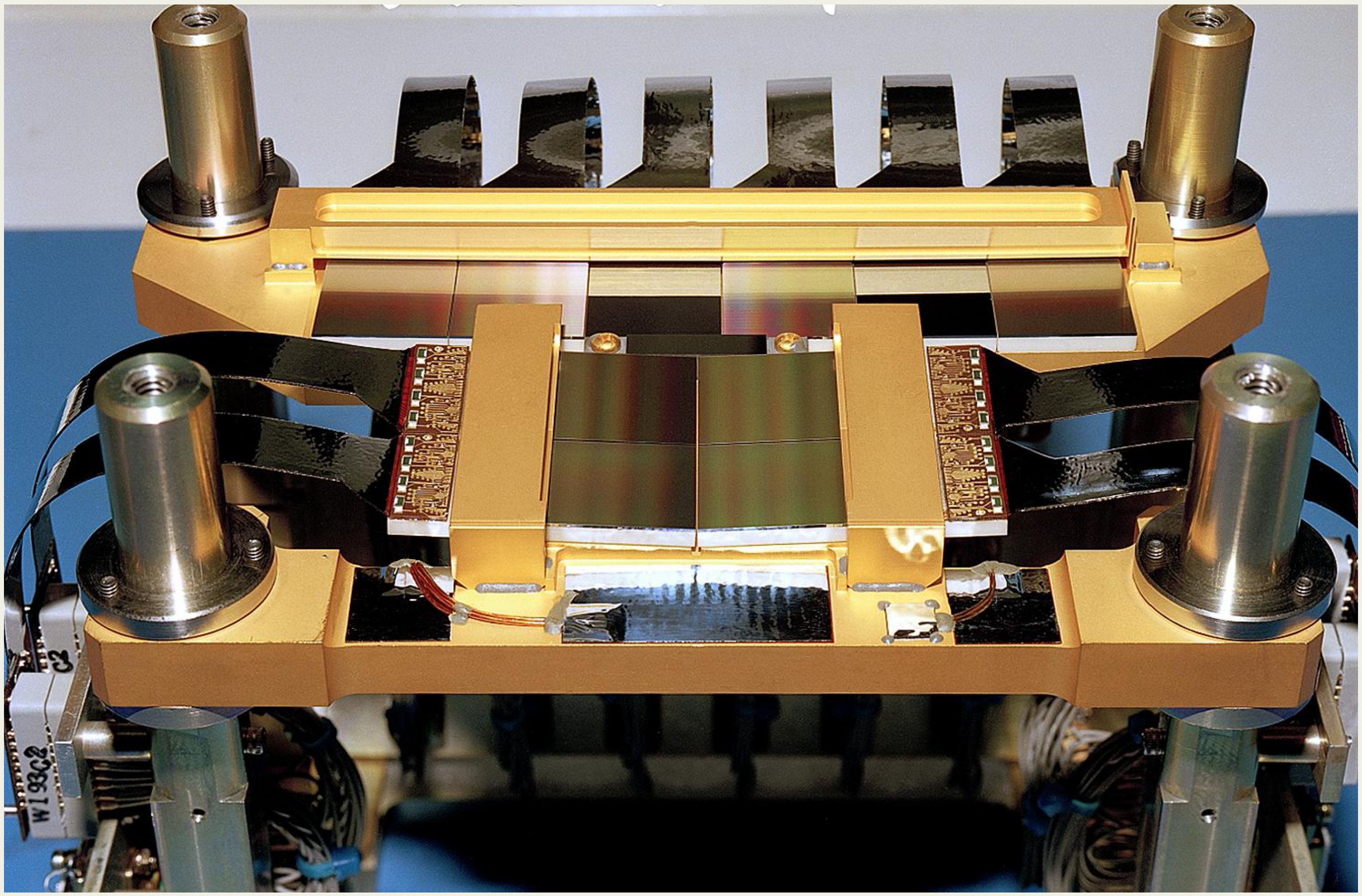


Frame transfer CCD

CCD Focal Planes

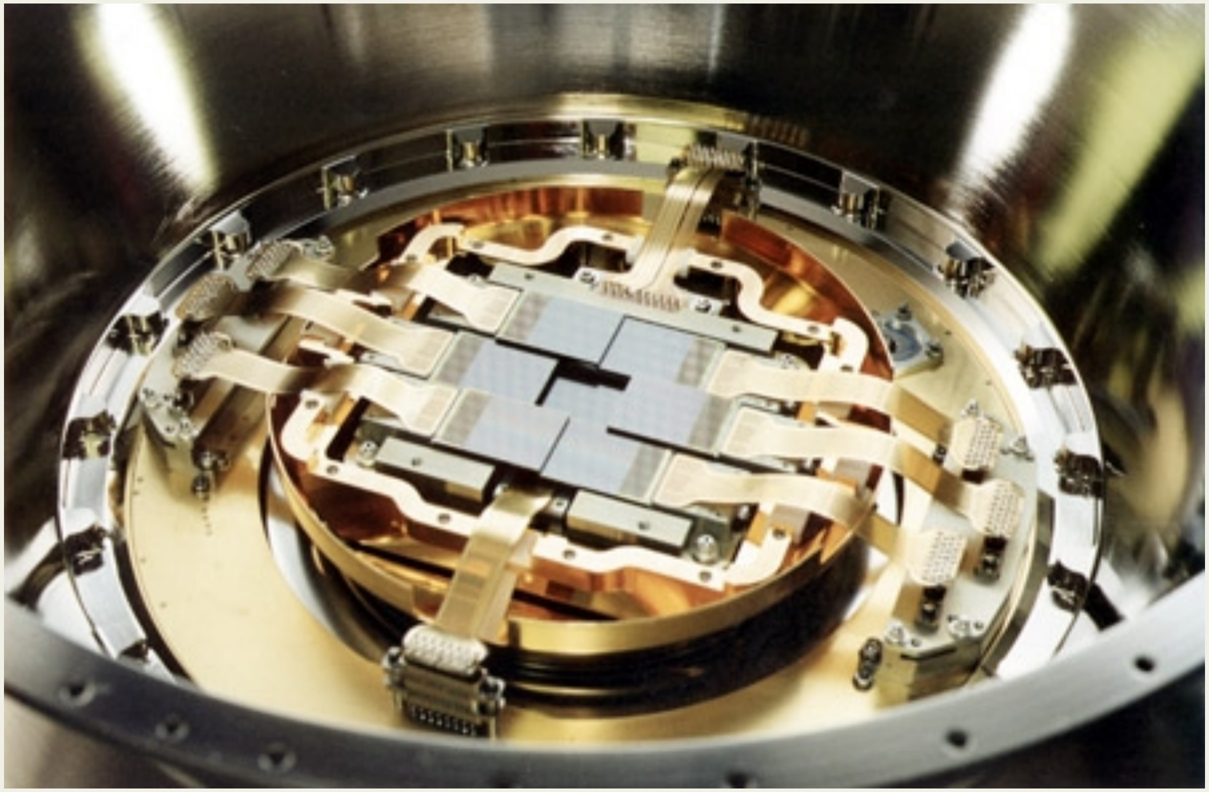
- Typical X-ray CCD is at most a few cm square
- Depending on plate scale of optics, single CCD may be insufficient for desired FOV
- Multiple CCDs can be tiled for larger focal planes
- Multi-CCD focal planes
  - Chandra ACIS, XMM EPIC & RGS, MAXI SSC
- Single CCD focal planes
  - Swift XRT, Suzaku XIS

Chandra ACIS



The Advanced CCD Imaging Spectrometer (ACIS) contains 10 planar, 1024 x 1024 pixel CCDs; four arranged in a 2 x 2 array (ACIS-I) used for imaging, and six arranged in a 1 x 6 array (ACIS-S) used either for imaging or as a grating readout. Each CCD is ~25 mm on a side. The CCDs are tilted to best approximate the telescope focal surface (ACIS-I) or the Rowland Circle of the gratings (ACIS-S).

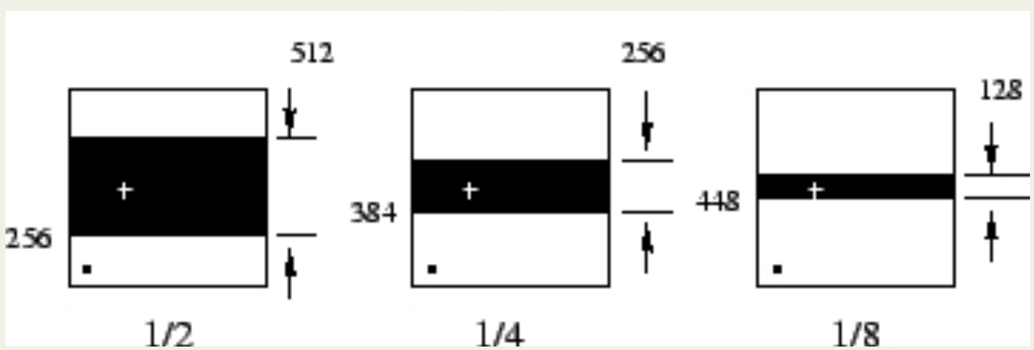
XMM-Newton EPIC-MOS



One of the three focal planes in the European Photon Imaging Camera (EPIC). The seven MOS CCDs are 600 x 600 pixels each, arranged with one in the center of the field of view and the other six surrounding it. The CCDs are offset from one another to better match the curvature of the focal plane.

CCD Operation

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires ≤ 1 photon interaction per pixel per frametime
- Minimum frame time limited by readout rate
  - Tradeoff between increasing readout rate and noise
- For ACIS, 100 kHz readout (10 μs/pix) ⇒ 3.2 s frametime
- Frame time can be reduced by reading out subarrays or by continuous parallel clocking (1D imaging)



1.5 s 0.8 s 0.4 s

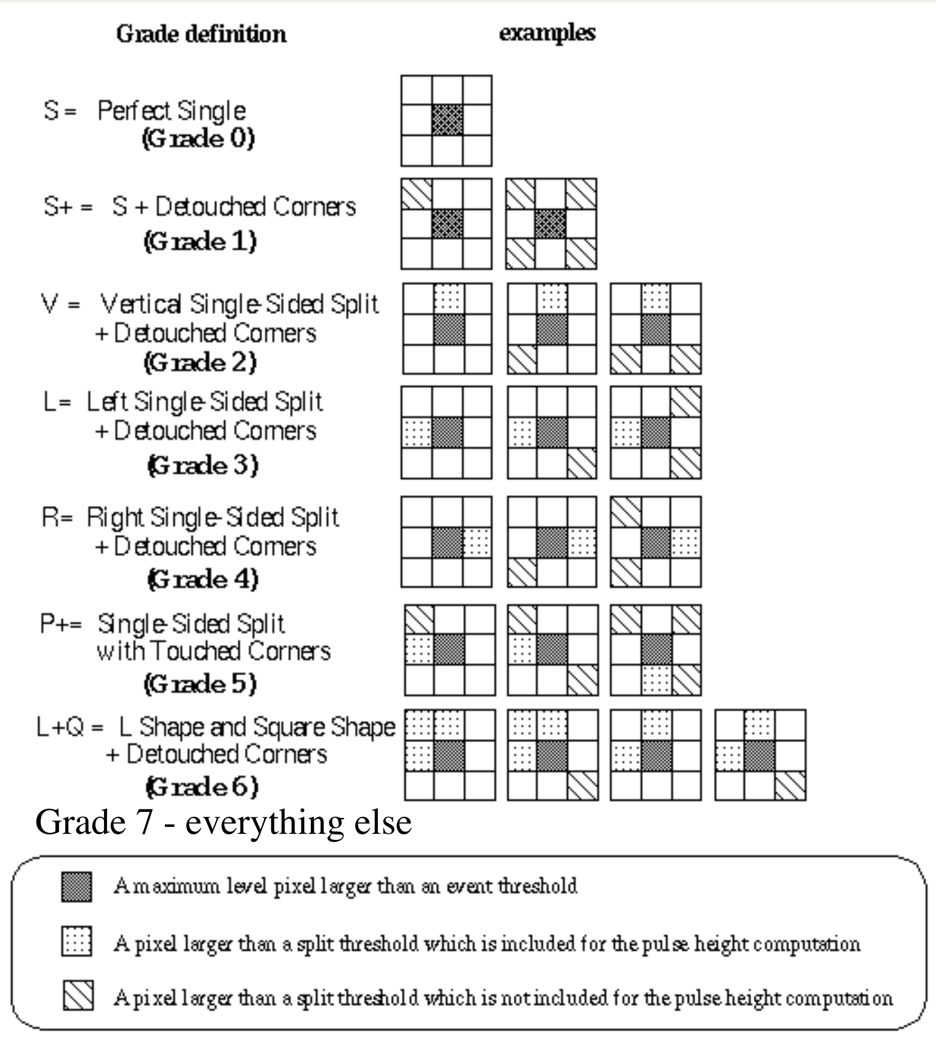
(CXC Proposer's Observatory Guide)

Event Processing

- CCD output rate (~10 Mbits/s/CCD) exceeds telemetry resources
  - Short frame time, low source count rates $\Rightarrow$ most pixels are empty
  - Raw CCD frames processed on-board to find candidate X-ray events
- Event selection:
  - CCD bias level determined and removed
  - Pixel pulse height must be greater than threshold value
  - Pixel is a local maximum (3 x 3 pixels on ACIS)
- For each event, record position, time and pulse heights of event island (3 x 3 pixels for ACIS)
- Events are assigned a grade which characterizes the morphology of the pulse heights in the event island.

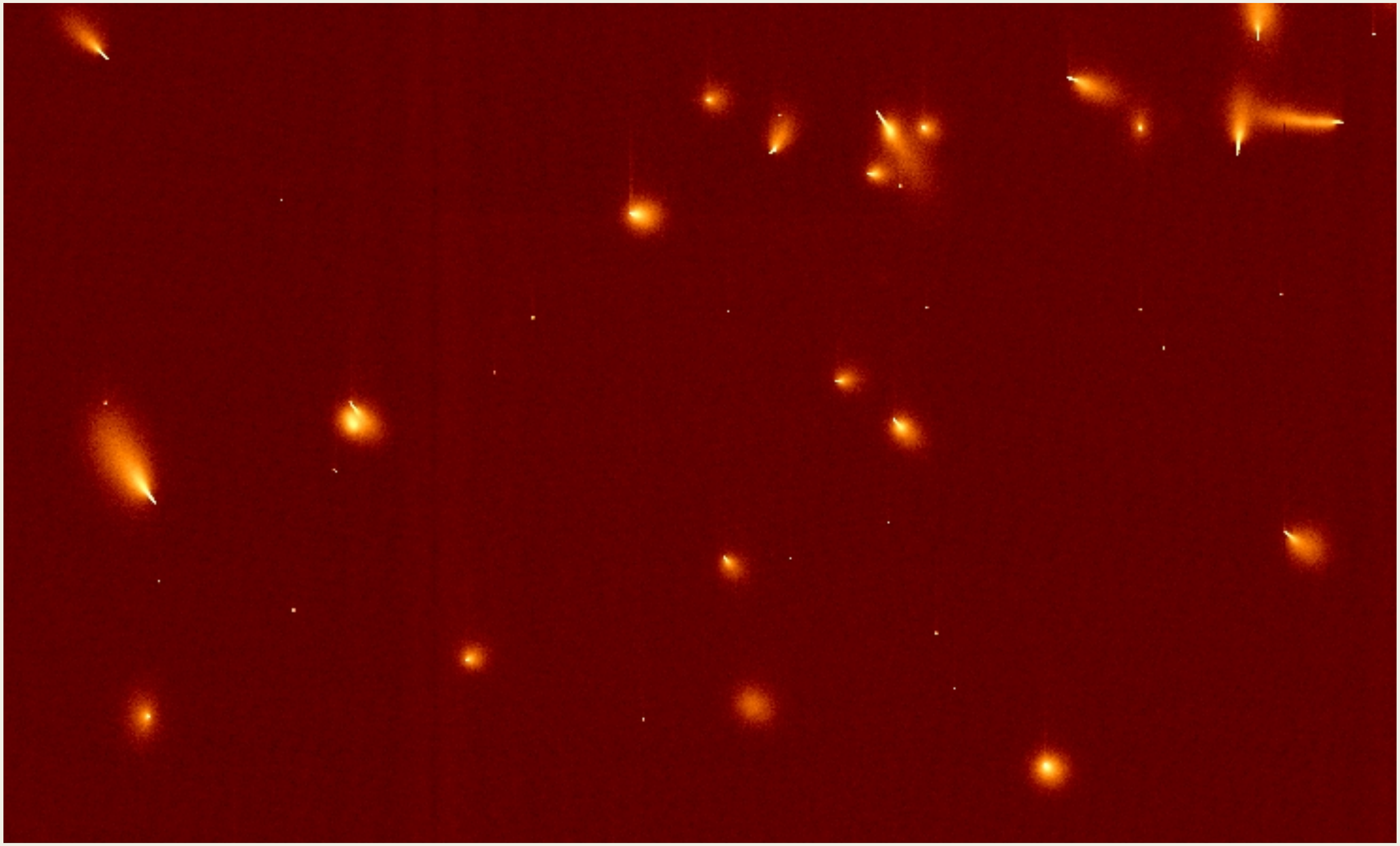
Grading events

ASCA Grade Codes



- Event grade can be used to discriminate between X-ray and cosmic ray events
- X-ray events split into simpler/ smaller shapes (single, singly-split)
- Cosmic ray events are more complex
- Onboard grade filtering can further reduce telemetry
- Grade filtering can improve spectral resolution - split events are noisier than singles

X-ray/Particle Discrimination

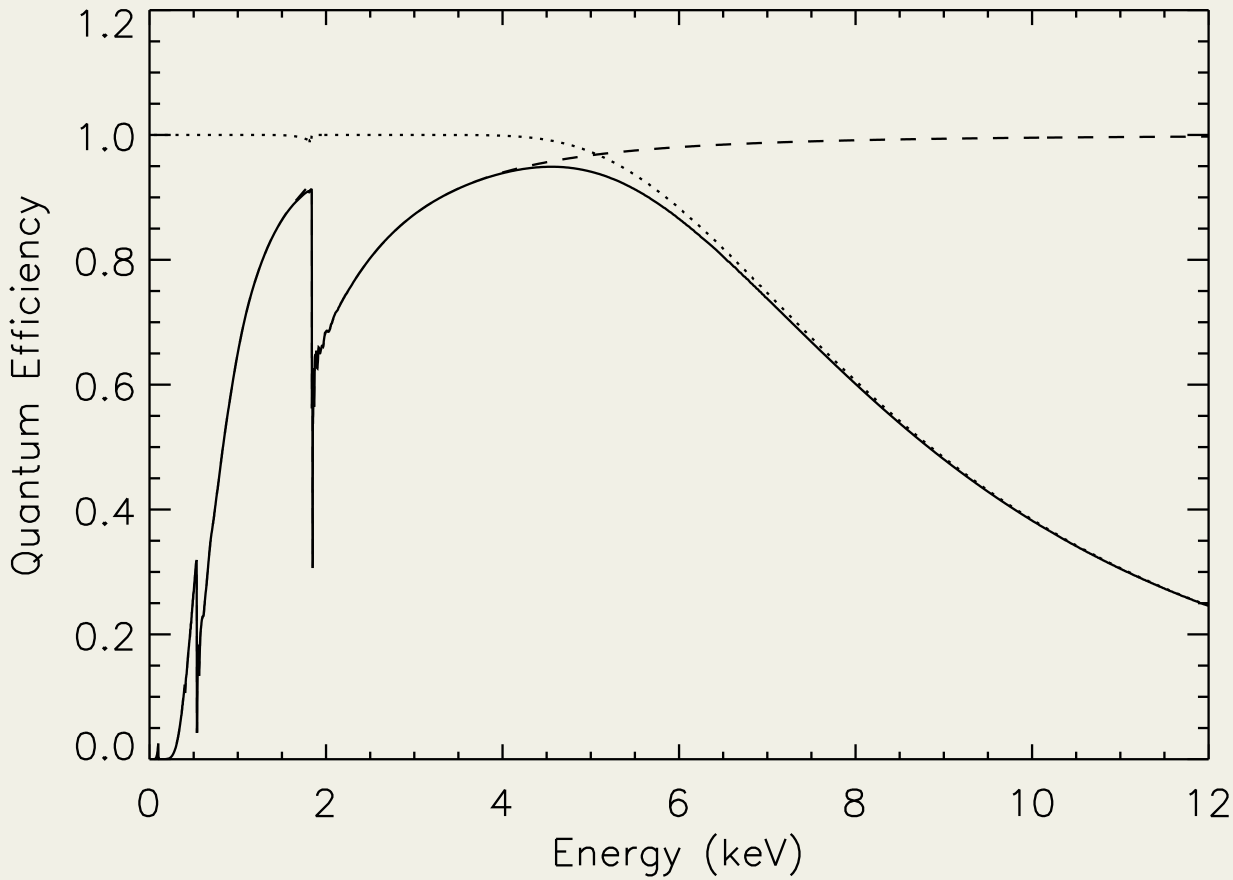


Blobs/streaks - charged particles.   Small dots - X-ray events.

Outline

- Basic principles and operation
- Performance: Quantum efficiency, energy resolution
- Detector features: Pileup, charge transfer inefficiency, contamination, background
- Future X-ray imaging detectors

CCD Quantum Efficiency



Transmission through deadlayers
(channel stops, gates, oxide layers)

$T = \prod_i e^{-\mu_i t_i}$

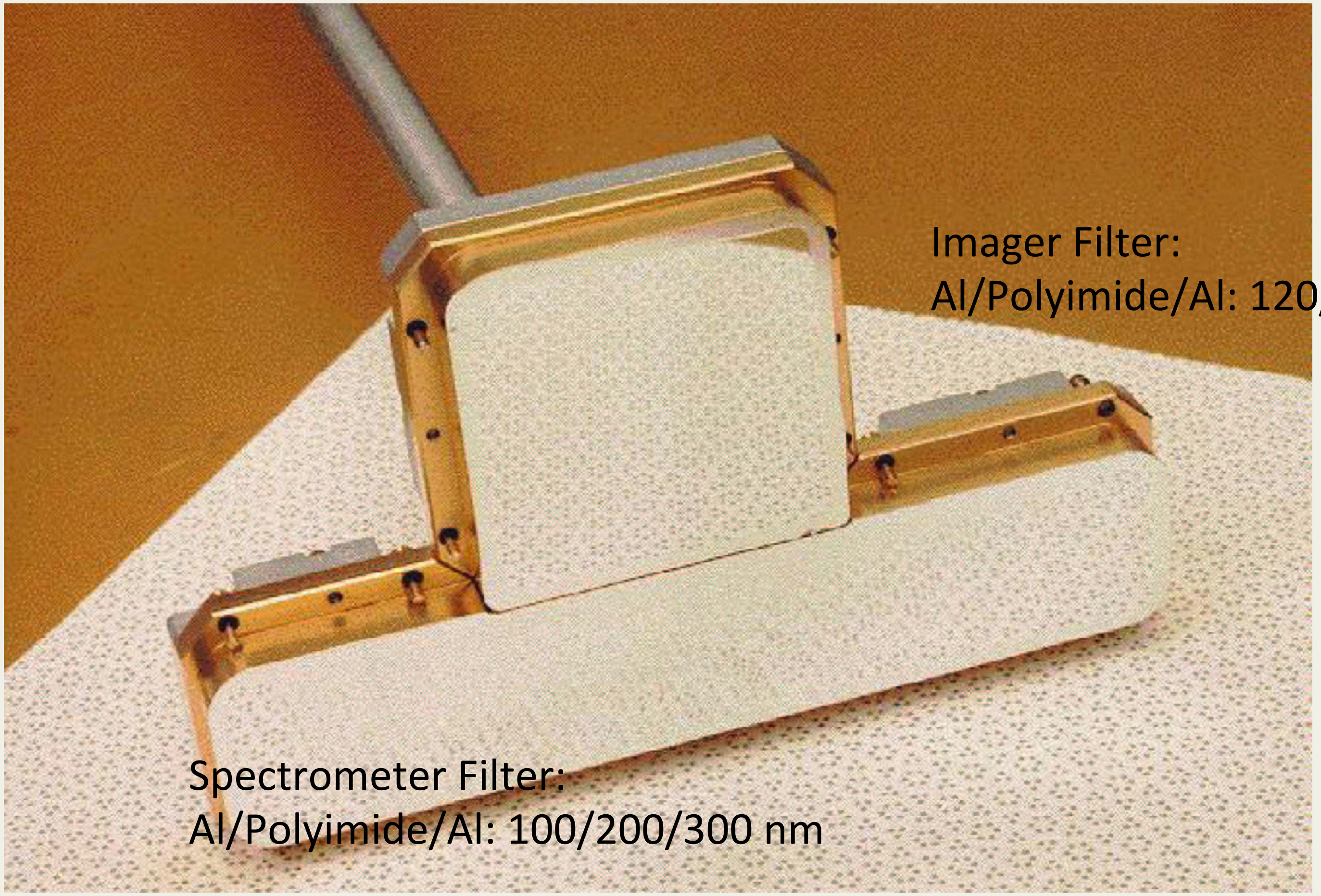
Absorption in depleted region

$A = 1 - e^{-\mu_{Si} d}$

μ = linear absorption coefficient
t = thickness of deadlayer
d = depletion depth

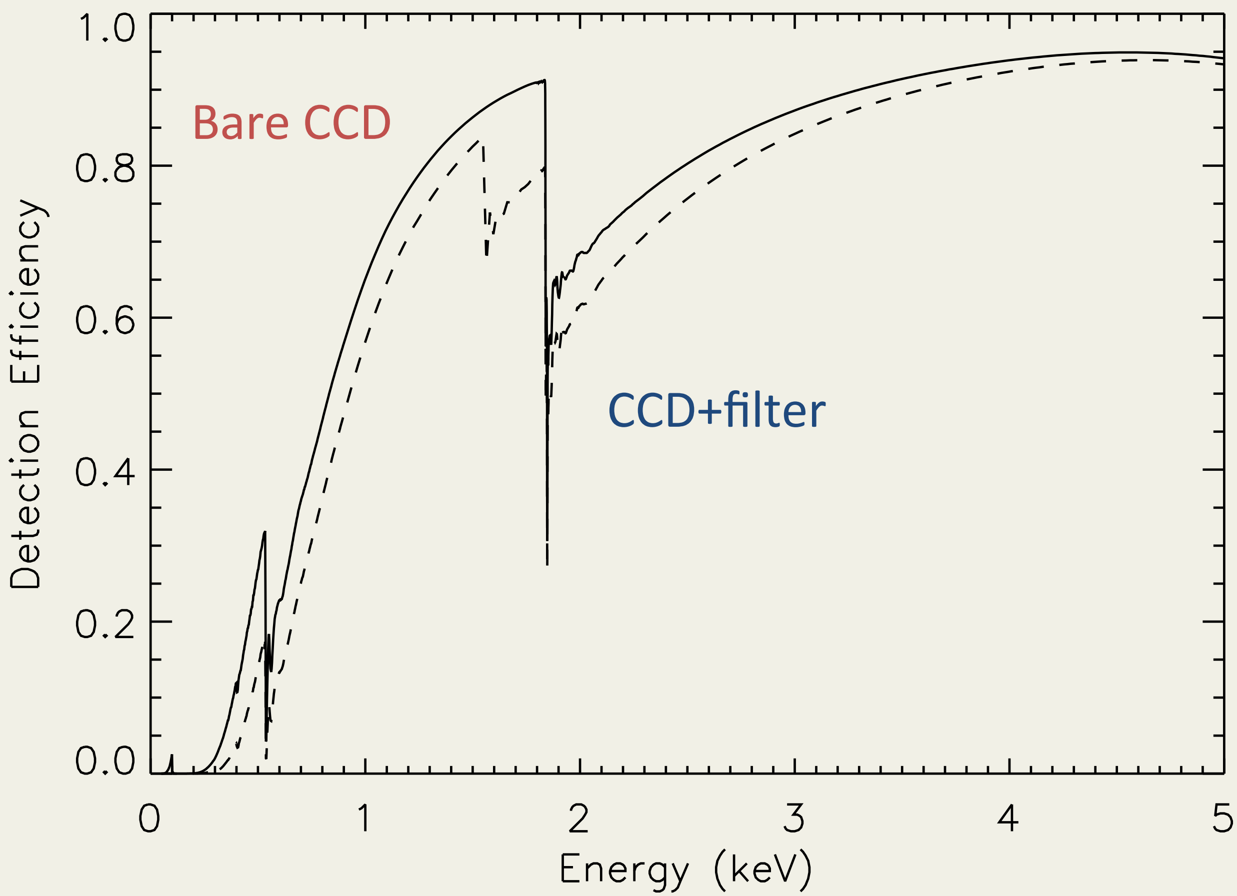
$$QE = (1 - e^{-\mu_{Si} d}) \prod_i e^{-\mu_i t_i}$$

Optical Blocking Filters



- CCDs also sensitive to optical photons
- Cause noise and pulse height calibration issues
- Filter materials usually plastic and aluminum

Filter Transmission



At low energies (< 0.5 keV), > 50% reduction in efficiency

CCD X-ray Spectroscopy: The Basic Idea

- Photoelectric interaction of a single X-ray photon with a Si atom produces free electrons:

$$N_e = E_X / w \;\; (w \approx 3.7 \text{ eV}/e^-)$$

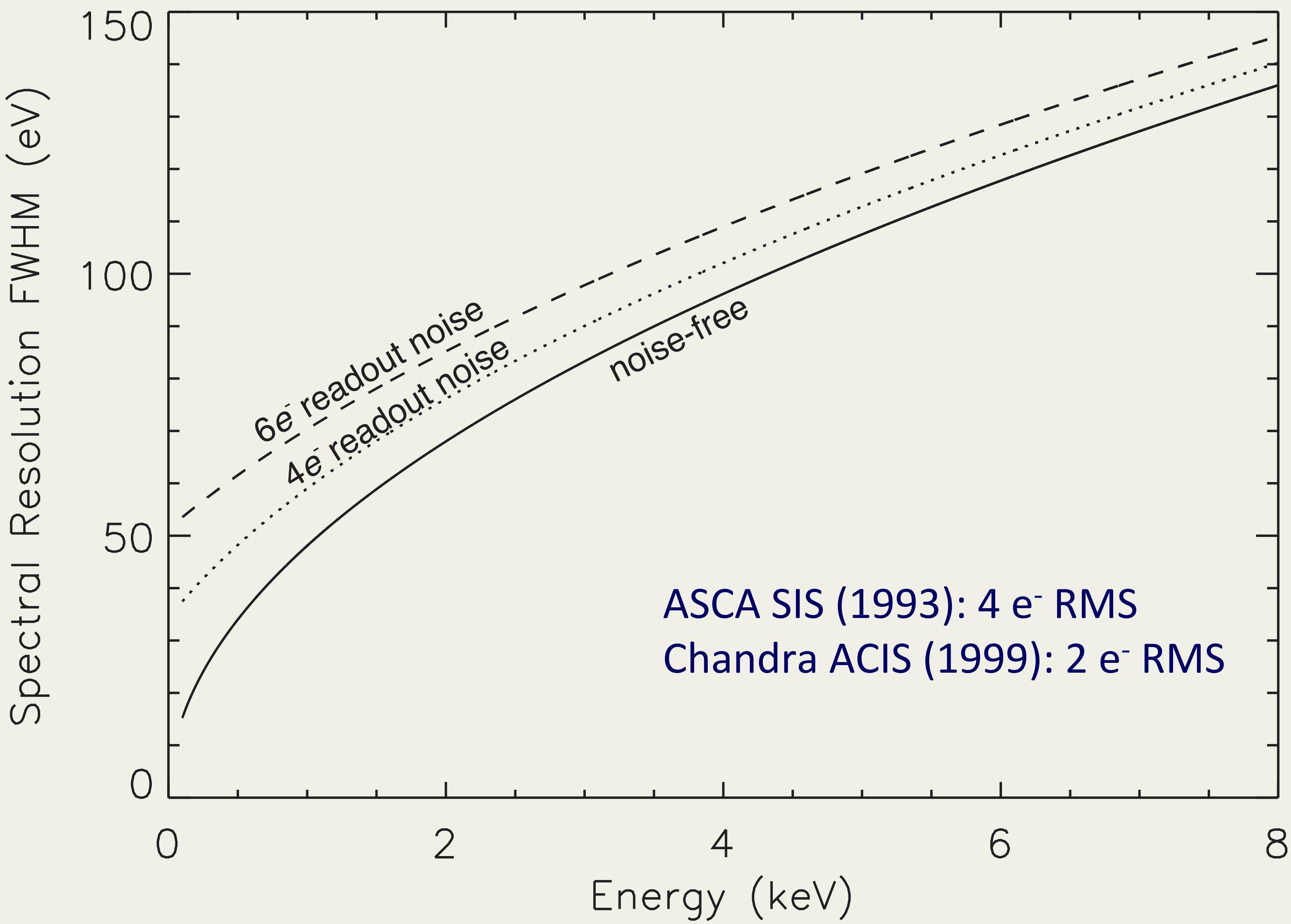
$$\sigma_\mathrm{e}^2 = F \times N_e \;\; (F \approx 0.12; \text{ not a Poisson process})$$

- Spectral resolution depends on CCD readout noise and physics of secondary ionization:

$$\text{FWHM (eV)} = 2.35 \times w \times \sqrt{\sigma_e^2 + \sigma_{read}^2}$$

- CCD characteristics that maximize spectral resolution:
  - Good charge collection and transfer efficiencies at very low signal levels
  - Low readout and dark-current noise (low operating temperature)
  - High readout rate (requires tradeoff vs. noise)

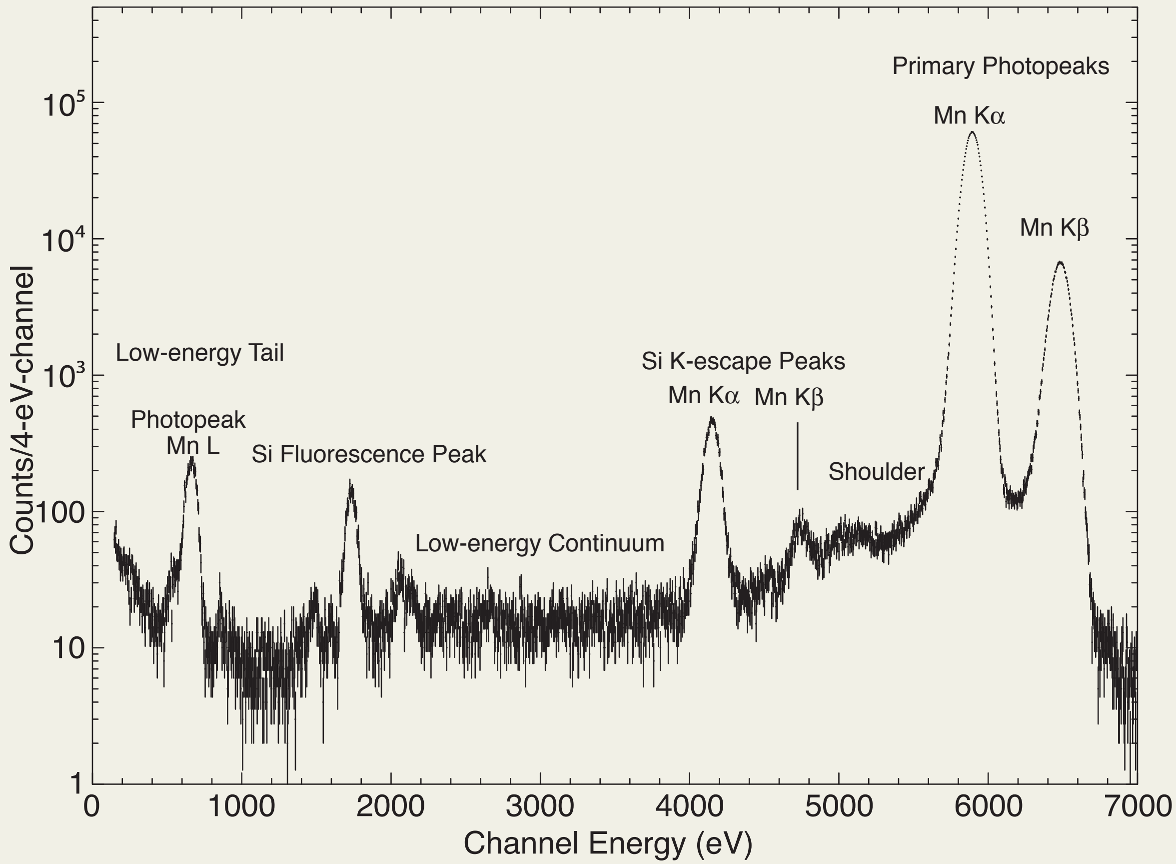
Spectral Resolution



ASCA SIS (1993): 4 e- RMS

Chandra ACIS (1999): 2 e- RMS

Spectral Redistribution Function

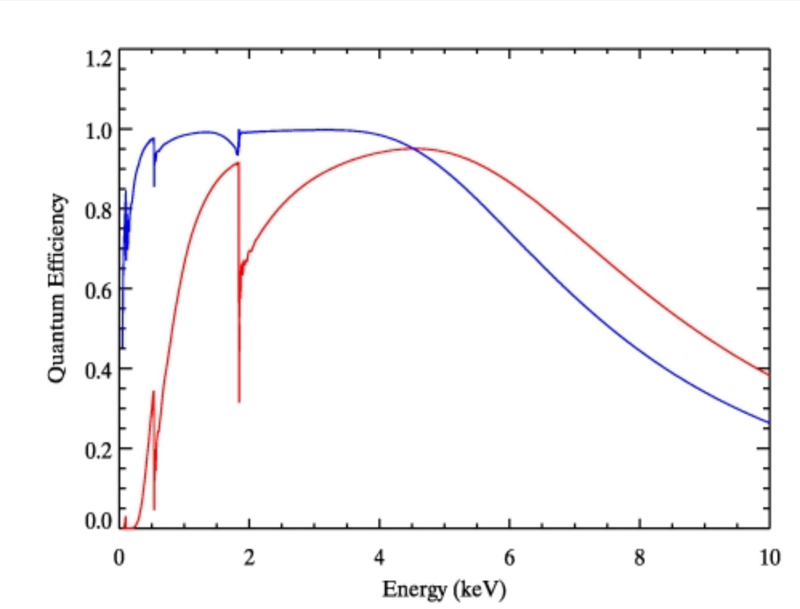


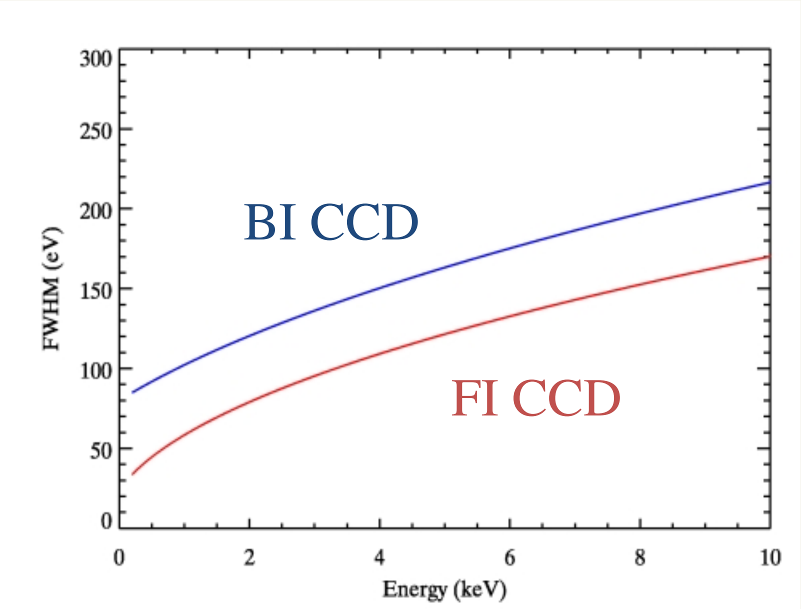
- X-ray source has three spectral lines: Mn-Kα (5.9 keV), Mn-Kβ (6.4 keV), Mn-L (0.67 keV)
- Instrument produces Si-K fluorescence and escape peaks, low-energy features
- Off nominal features ~2% of total

Low-energy Detection Efficiency

- Many astrophysically interesting problems require good low-energy (< 1 keV) efficiency (pulsars, ISM absorption, SNR, …)
- Low energy X-rays are lost to absorption in gate structures and filter
- Solutions:
  - Thinned gates, open gates (XMM EPIC-MOS, Swift XRT)
  - Back-illumination (Chandra ACIS, XMM EPIC-PN, Suzaku XIS)

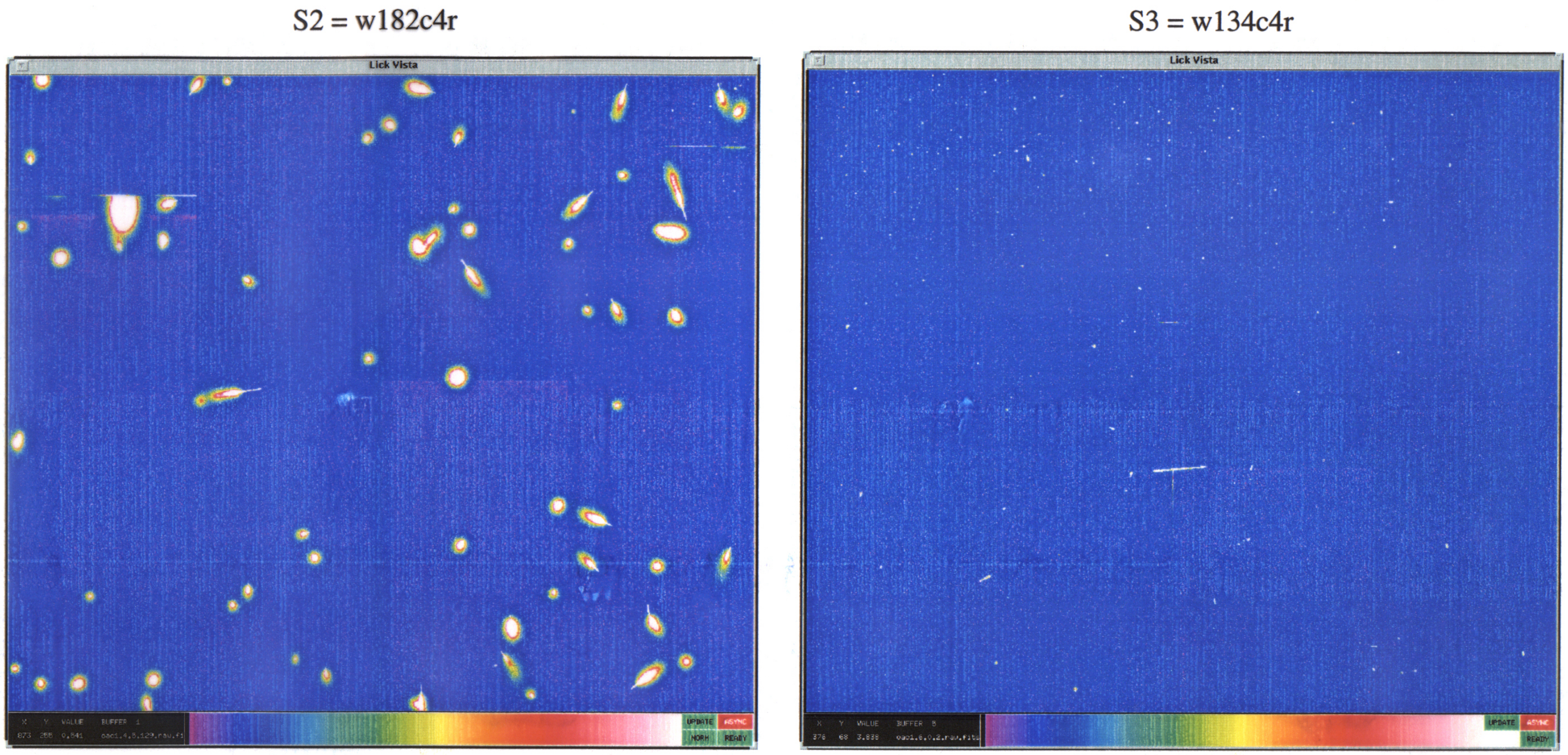
Back-illuminated CCDs





- Front-illuminated CCD, reversed and thinned
- Gate structures and channel stops are not dead layers
- Thinner dead layers ⇒ higher low-E QE
- Thinner active region ⇒ lower high-E QE
  - Not always true, XMM EPIC-pn has excellent high-E QE
- Increased noise, charge transfer inefficiency ⇒ higher FWHM
  - Technology is maturing, Suzaku XIS BI quite good FWHM

First Readout of ACIS CCDs



Front-illuminated CCD | Back-illuminated CCD

- Particle events produce large blooms on FI CCD, not on fully-depleted BI CCD
- Background rejection efficiency much higher for FI CCD

Outline

- Basic principles and operation
- Performance: Quantum efficiency, energy resolution
- Detector features: Pileup, charge transfer inefficiency, contamination, background
- Future X-ray imaging detectors

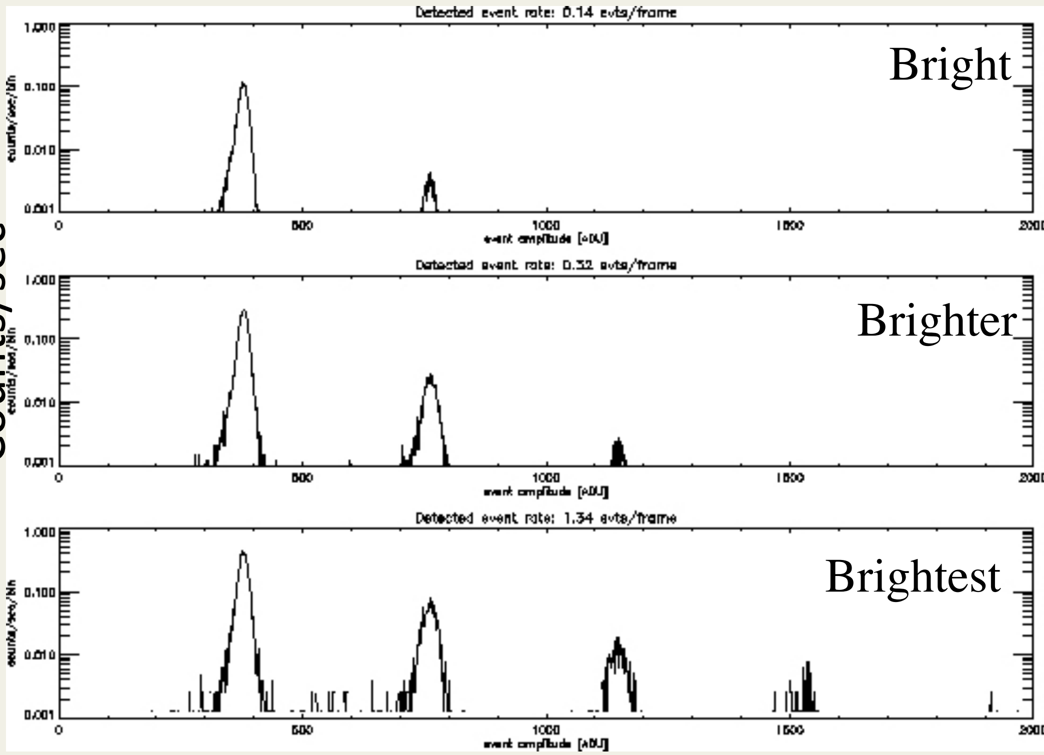
Photon Pileup

- If two or more photons interact within a few pixels of each other before the image is readout, the event finding algorithm may regard them as a single event
  - Higher inferred energy
  - Reduction of total detected events
  - Spectral hardening of continuum sources
  - Distortion of point spread function
- Correcting data for pile-up is possible but complicated
- Best to set up observation to minimize pileup
- Related affect is readout streak
  - Out-of-time events, photons interact while image is transferred

Photon Pileup

Monochromatic Source

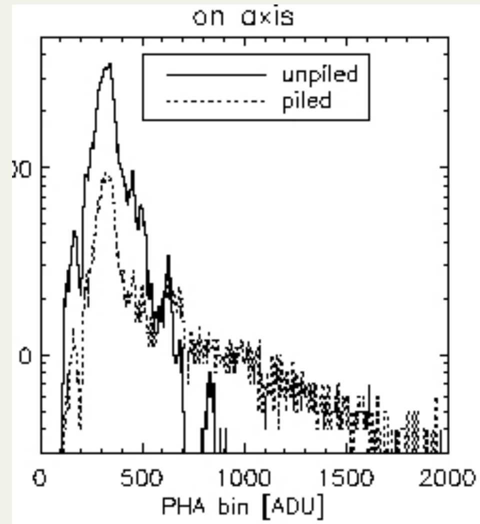
Counts/sec



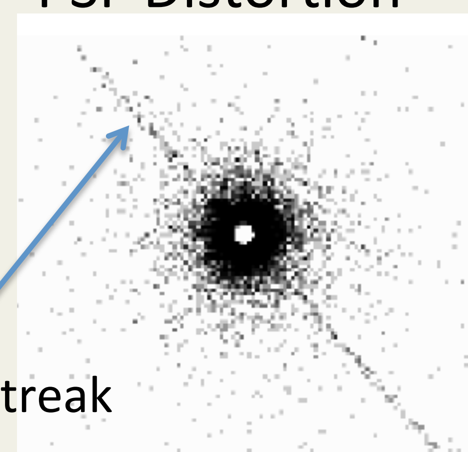
Energy

(From Chandra Proposer's Observatory Guide)

Thermal Spectrum



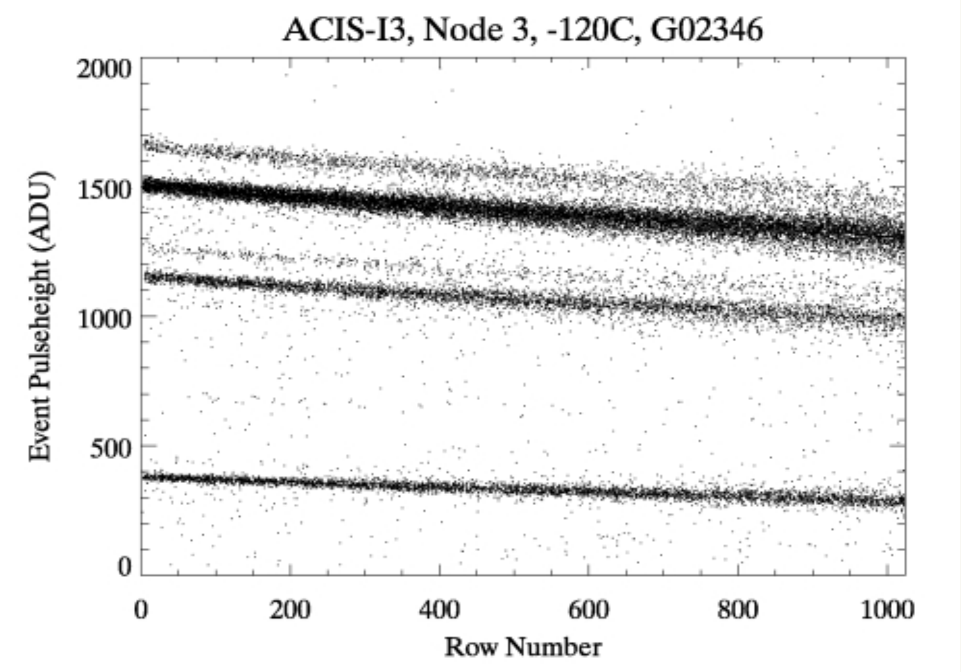
PSF Distortion



Readout Streak

Charge Transfer Inefficiency

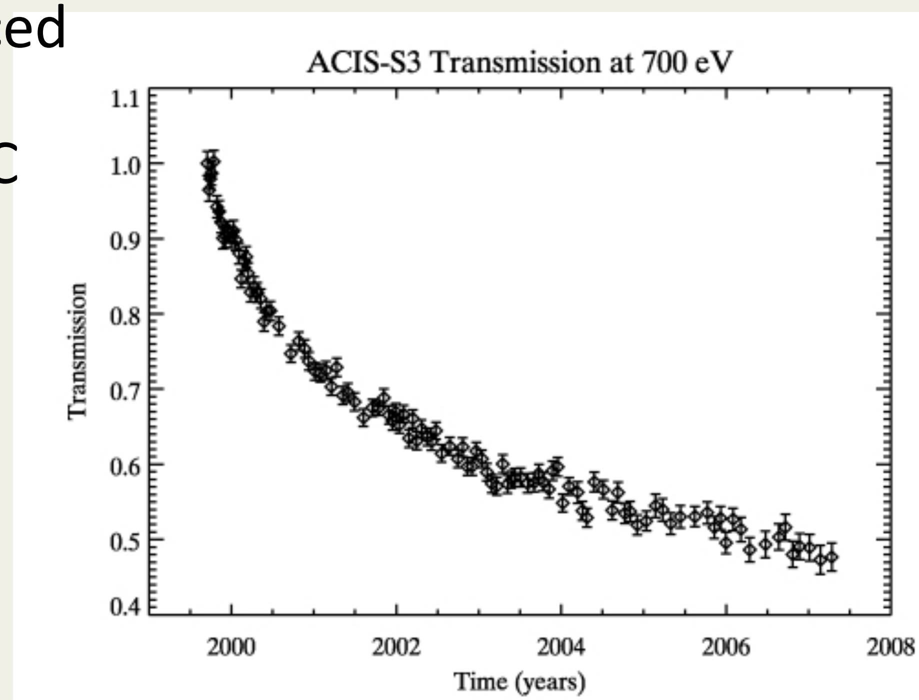
- During transfer, X-ray events lose charge to charge trapping sites
- Leads to:
  - Position dependent gain
  - Spectral resolution degradation
  - Position dependent QE
- Caused by radiation damage or manufacturing defects
- Depends on:
  - Density of charge trapping sites
  - Charge trap capture and re-emission properties (temperature)
  - Occupancy of charge traps (particle background)
- Mitigation techniques
  - Lower temperature
  - Move target closer to readout
  - Controlled charge injection (Suzaku XIS)
  - Specialized software tools



←Transfer Direction

Contamination

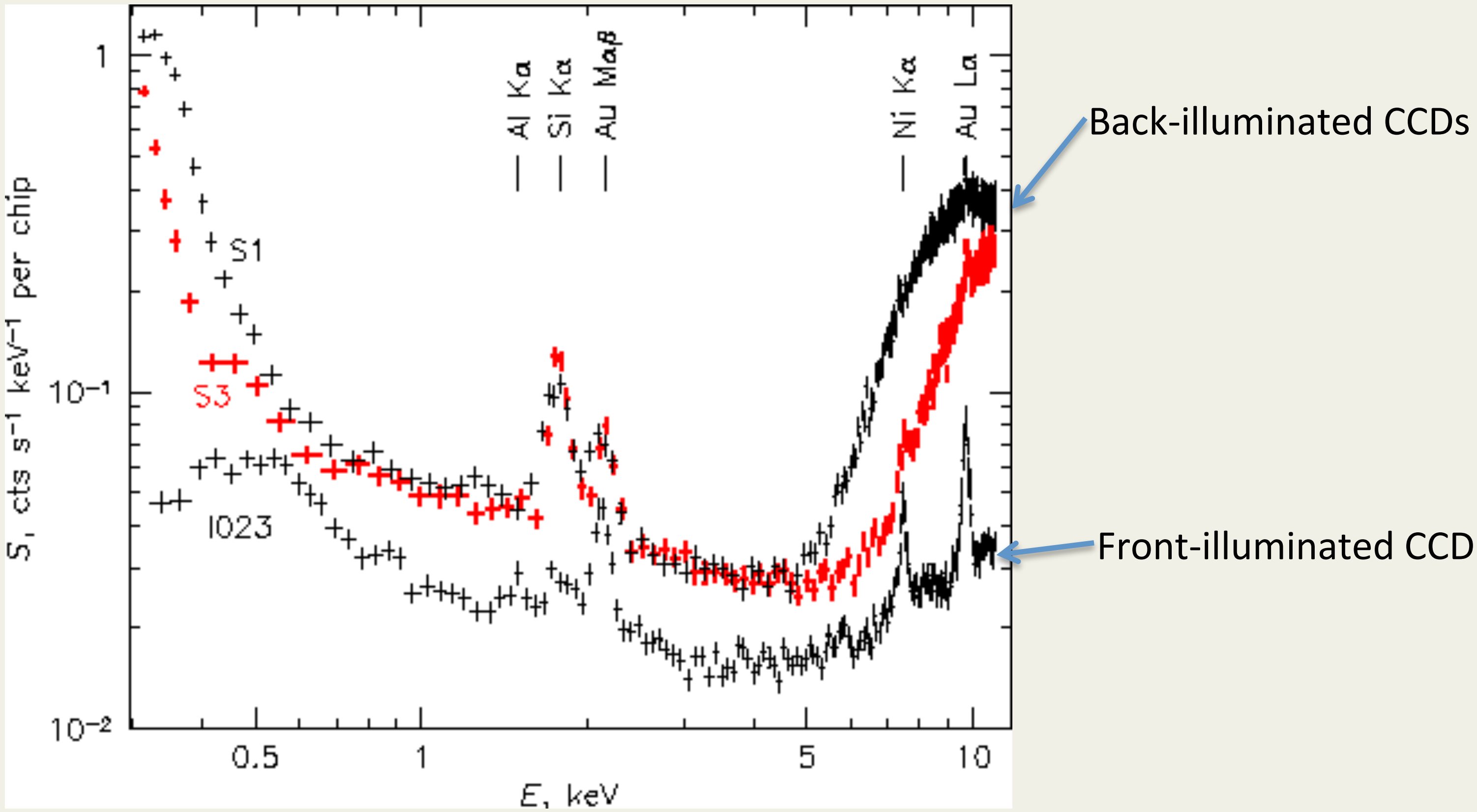
- For best performance (reduced dark current and CTI), CCDs must be operated cold (-60°C to -120°C)
- Coldest surface, danger of accumulating contamination
- Contamination acts as an additional absorbing layer
- Can be important at low energies (< 1 keV)
- Important for Chandra ACIS, XMM RGS, Suzaku XIS, others?



Background

- Cosmic X-ray background (unresolved AGN)
- Diffuse Galactic emission
- Heliospheric & geocoronal emission
- Particle background
  - Spectrum and variability depend on orbit
  - Low-earth orbit, lower bkg rates, stable long-term, orbital variability
  - High orbit (XMM & Chandra), higher bkg rates, solar cycle dependent
- Background can be reduced by filtering event grades, removing flaring times, using specialized modes
- Otherwise, background can be modeled or estimated and subtracted

Particle Background Spectrum

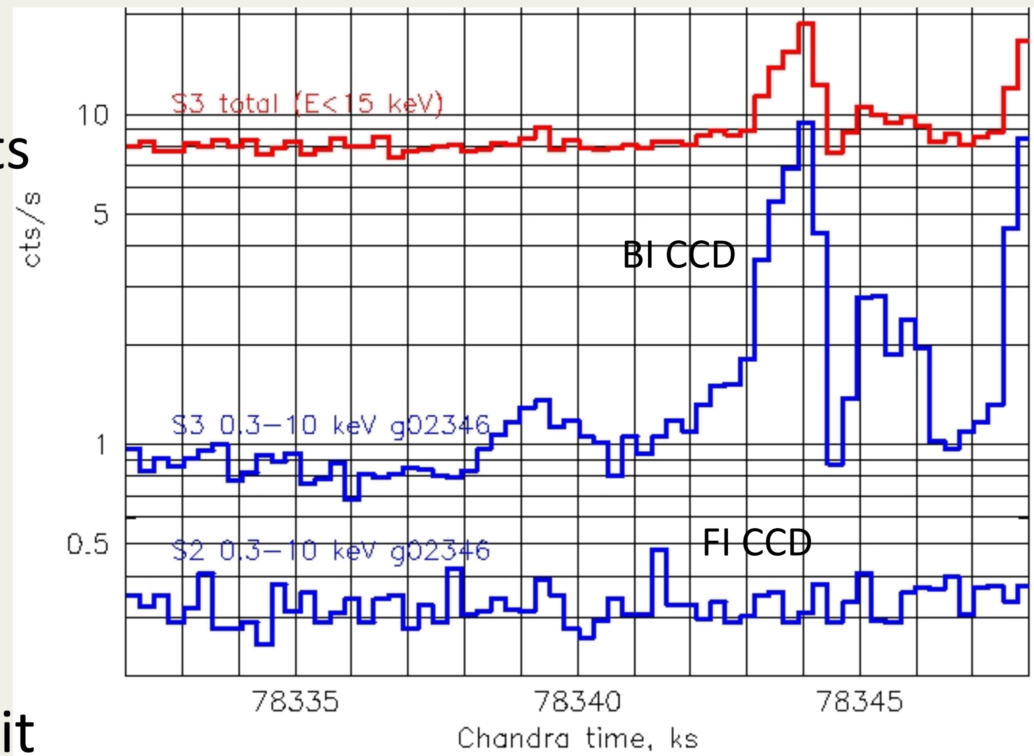


- ACIS in stowed position, no sky photons, standard grade filter
- Fluorescent lines from spacecraft materials plus continuum
- Grade filter less effective for back-illuminated CCDs, higher background rates

(From Chandra Proposer's Observatory Guide)

Background Flaring

- Short-lived increases in background rate
- Usually low energy, affects BI more than FI
- Some correlation with solar flares and geomagnetic conditions
- Believed to be ~100 keV protons
- Not seen in low earth orbit



(Markevitch, CXC Calibration)

Pixel Defects

- Radiation damage or manufacturing defects can cause pixels to have anomalously high dark current
- Can regularly exceed event threshold and cause spurious events
- Extreme cases may be removed onboard, otherwise filtered in data analysis
- Hot pixels strongly correlated with temperature
  - More important for ASCA (-60C) and Suzaku (-90C) than Chandra/XMM (-120C)
- Unstable defects cause flickering pixels (primarily ASCA)
  - Lower frequency, more difficult to detect and remove
- Related problem – micrometeoroid(!) damage
  - Hot or dead pixels, pin-holes in optical blocking filter
- Related problem #2 – cosmic ray afterglows
  - Bright cosmic ray, pixels continue to emit charge minutes later

Outline

- Basic principles and operation
- Performance: Quantum efficiency, energy resolution
- Detector features: Pileup, charge transfer inefficiency, contamination, background
- Future X-ray imaging detectors

Future X-ray Imaging Detectors

- X-ray CCDs in operation on five observatories (Chandra, XMM-Newton, Swift, Suzaku, MAXI)
- Microcalorimeter detectors provide 10-20x improvement in spectral resolution but not megapixel imaging or good low energy QE (at least not yet)
- Megapixel imaging detectors will be required for future grating spectrometers, and probably also for wide-field imaging
- Technologies being explored to provide improvements
  - Better low-energy response
  - Better radiation tolerance
  - Better time resolution/faster readout rates

Future X-ray Imaging Detectors: Faster is Better

- Current CCDs have readout times of order secs/frame.
- Faster readout (msec or less) offers many advantages:
  - * Reduced photon pileup
  - * Less dark current per readout, so can operate at higher temperature
  - * Less optical contamination per readout, so thinner optical blocking filters (better low-energy efficiency)
  - * Possibly better background rejection through temporal anticoincidence:

  (99.9% rejection for ROSAT gas counter vs 99% for CXO/XMM CCDs)
- Highly parallel readout (e.g., active pixel sensors) may yield orders of magnitude increase in frame readout rate & integrated signal processing

Want to know more?

- Observatory web pages & analysis guides often review detector basics and highlight mission-specific issues and tools
  - e.g. Chandra Proposers' Observatory Guide
- Many textbooks cover CCD physics, including:
  - Janesick, 2001. *Scientific Charge-Coupled Devices*
  - Lutz, 2007. *Semiconductor Radiation Detectors: Device Physics*
  - Sze, 2002. *Semiconductor Devices: Physics and Technology*
- Ask me! cgrant@space.mit.edu