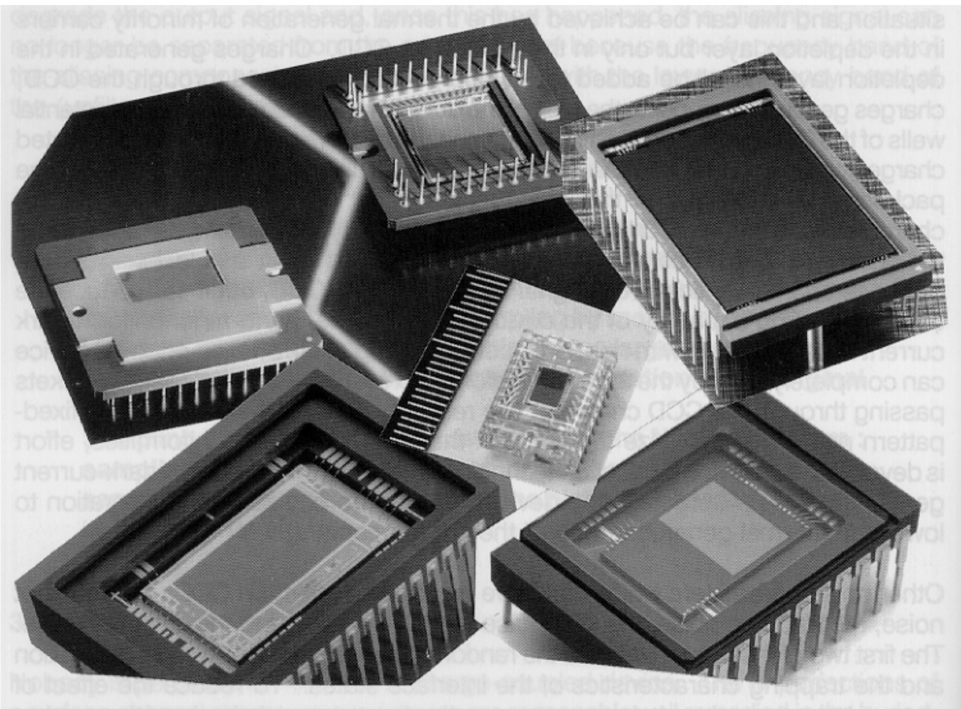
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

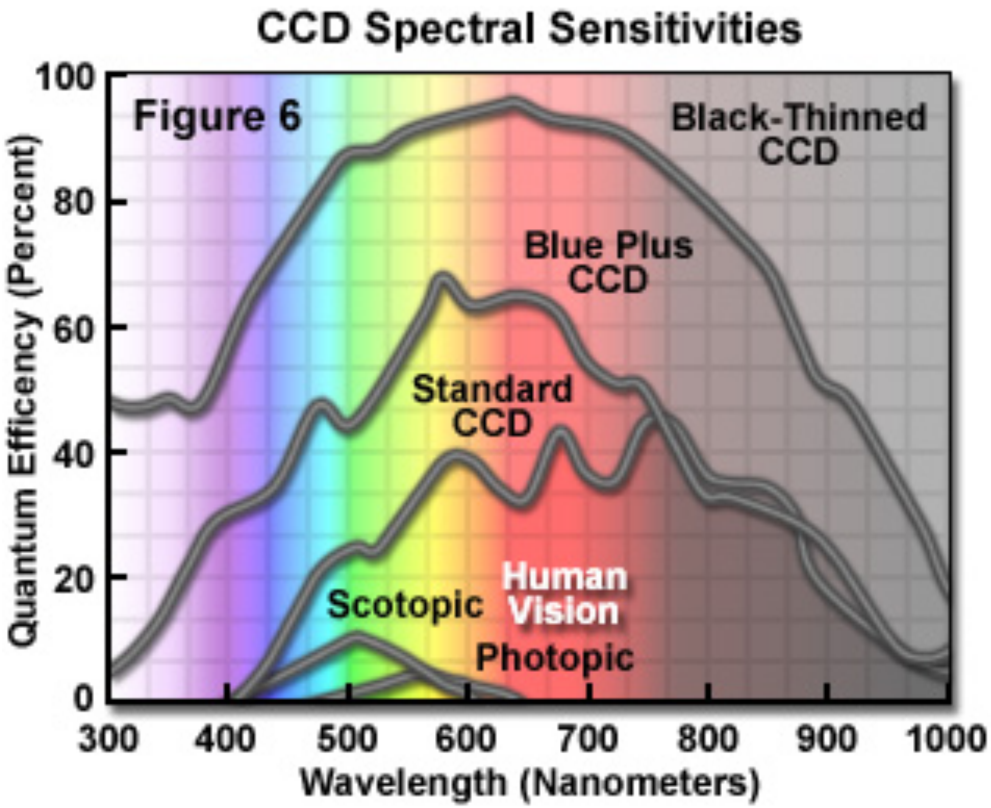
Based on lectures by Bernhard Brandl



Lecture 10: Detectors 2

1. CCD Operation
2. CCD Data Reduction
3. CMOS devices
4. IR Arrays
5. Bolometers
6. MKIDS

Backside Illumination

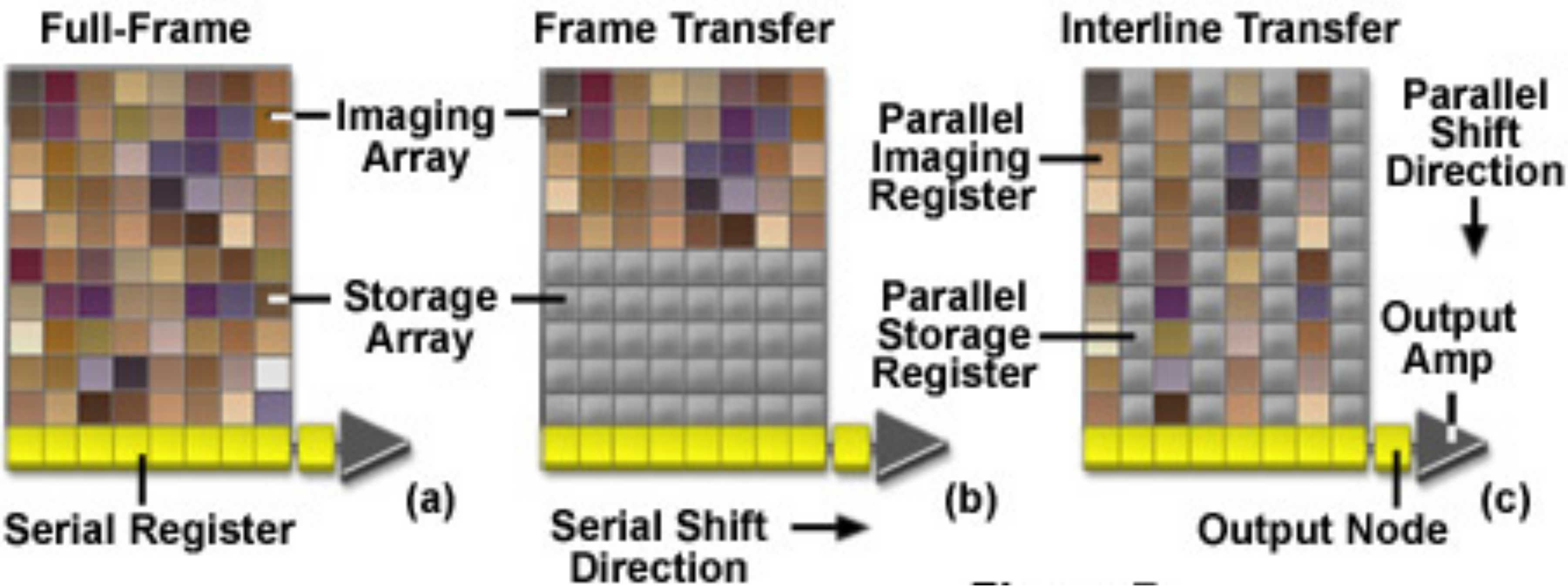


<u>front illumination</u>: poly-silicon gate electrodes absorb in the blue and lead to interference effects

<u>blue-enhanced</u>: holes in poly-silicon gate electrodes

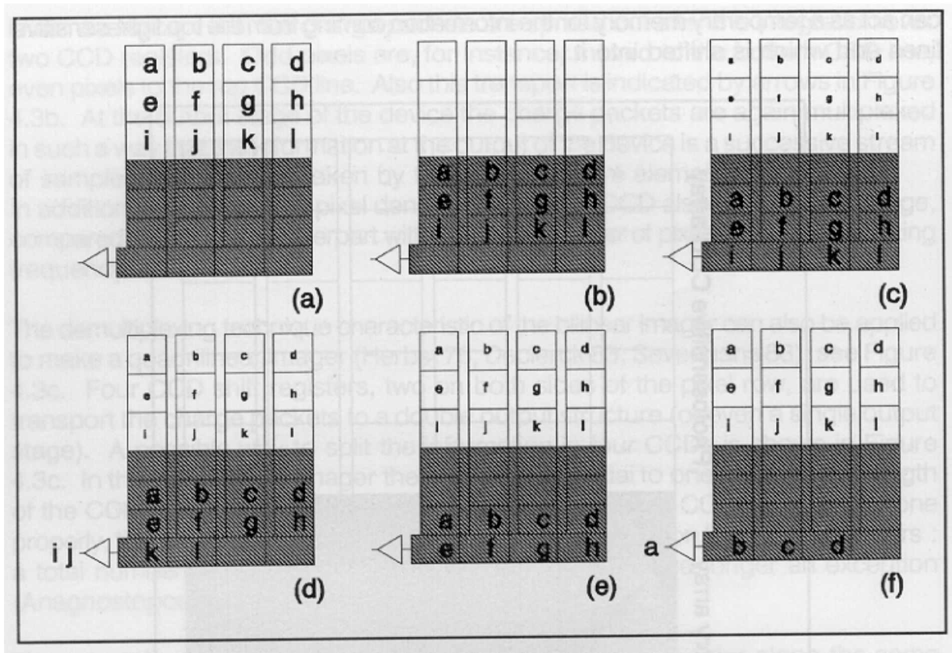
- back-illumination: thin silicon➔photo-electrons reach potential wells
- electric field gradient moves charges: increase doping concentration in regions close to silicon surface
- increases sensitivity in blue where electrons are generated close to rear silicon surface
- minimize reflection of light from back surface with SiO layer

Focal Plane Architecture



- astronomical CCDs: full-frame and frame-transfer arrays
- (interline-transfer arrays in commercial CCD cameras)
- frame-transfer CCD has photosensitive array and a memory array coupled to a linear output register
- full-frame device lacks storage section
- shutter interrupts illumination during readout

Frame Transfer Operation



- transfer needs to be done quickly to prevent disturbance by light falling on the image section during read-out
- during readout, all CCD cells in image array are again in integration mode

Binning

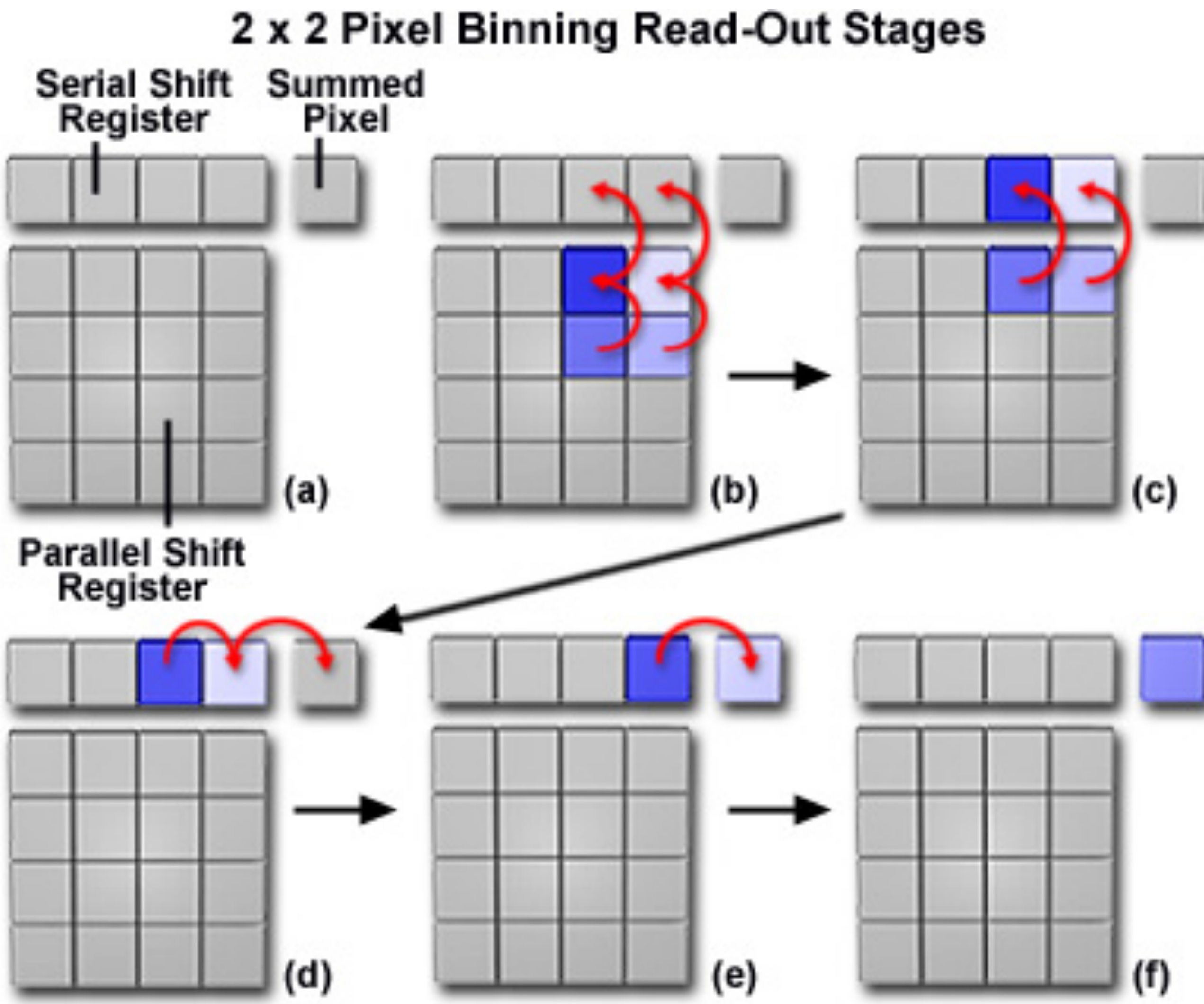
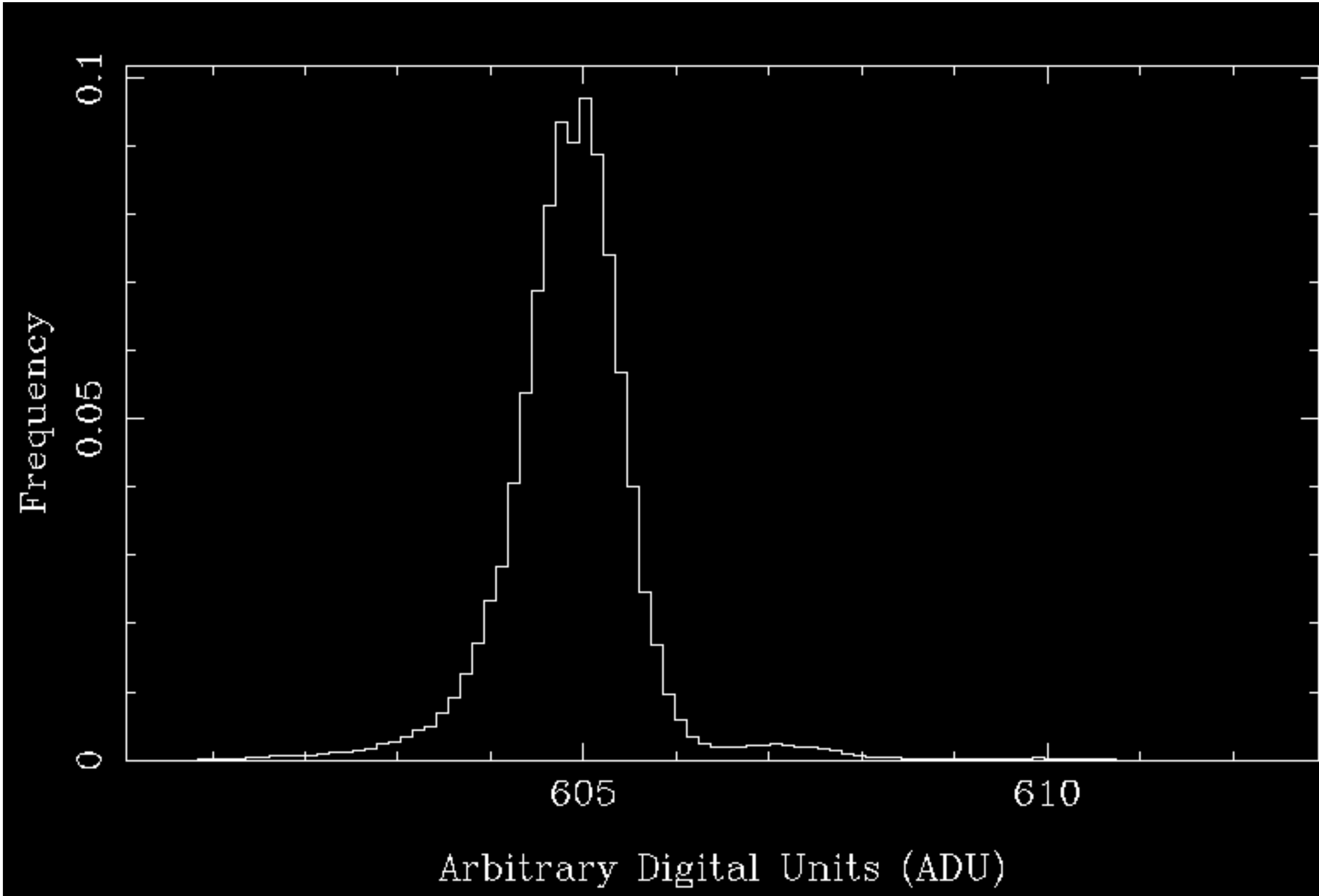
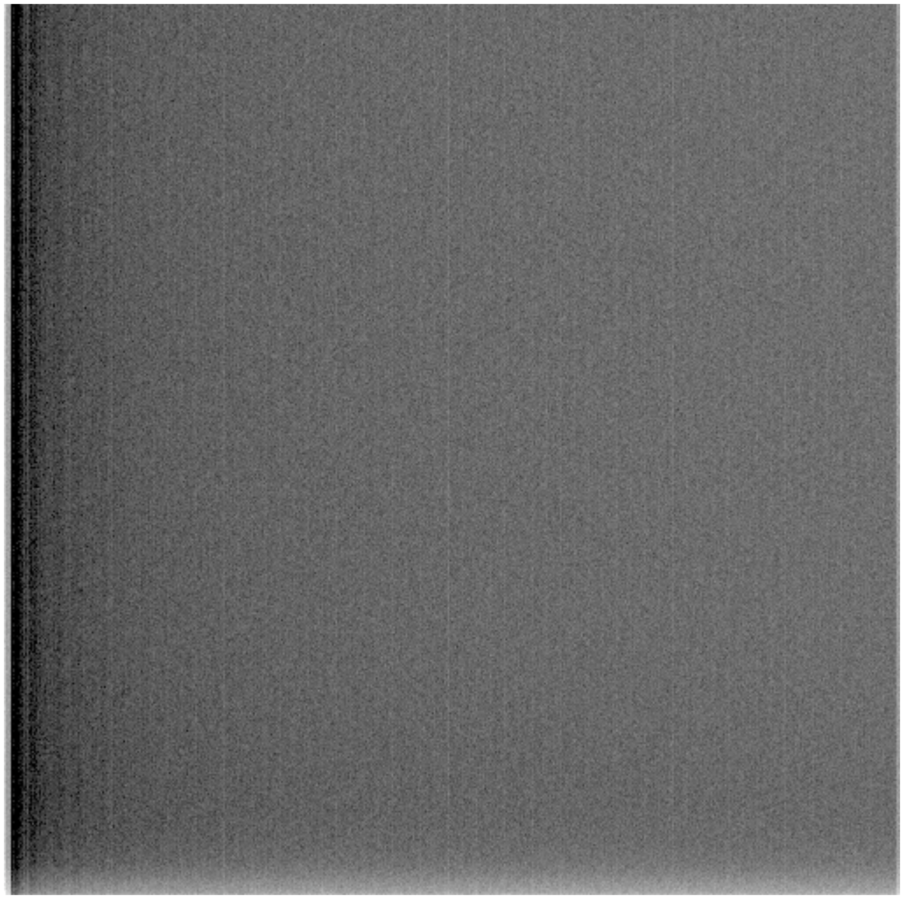


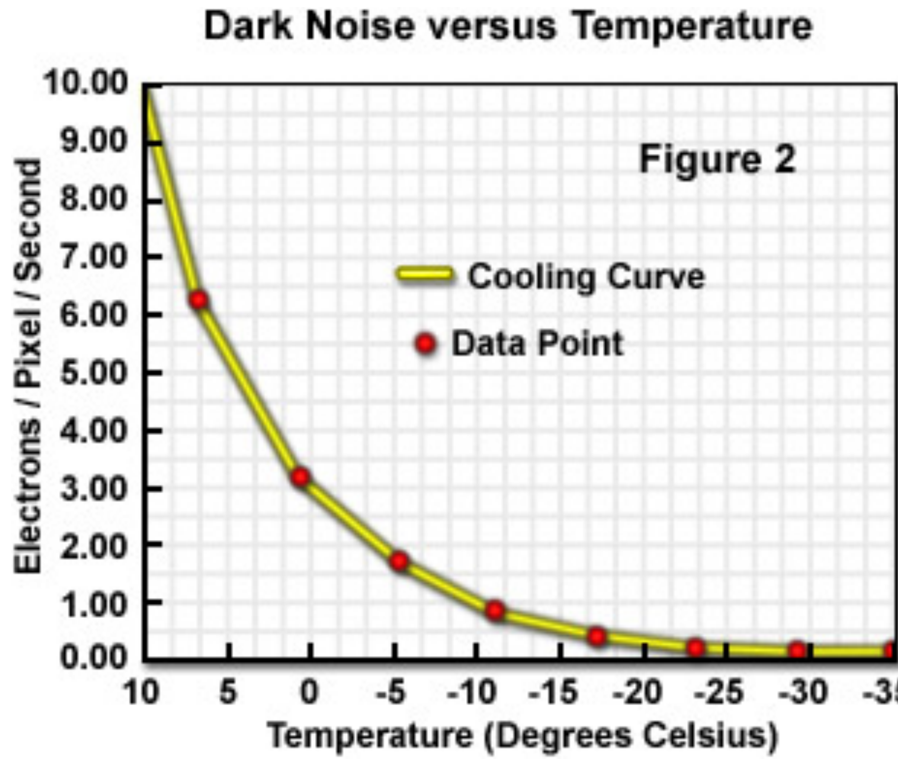
Figure 1

Bias

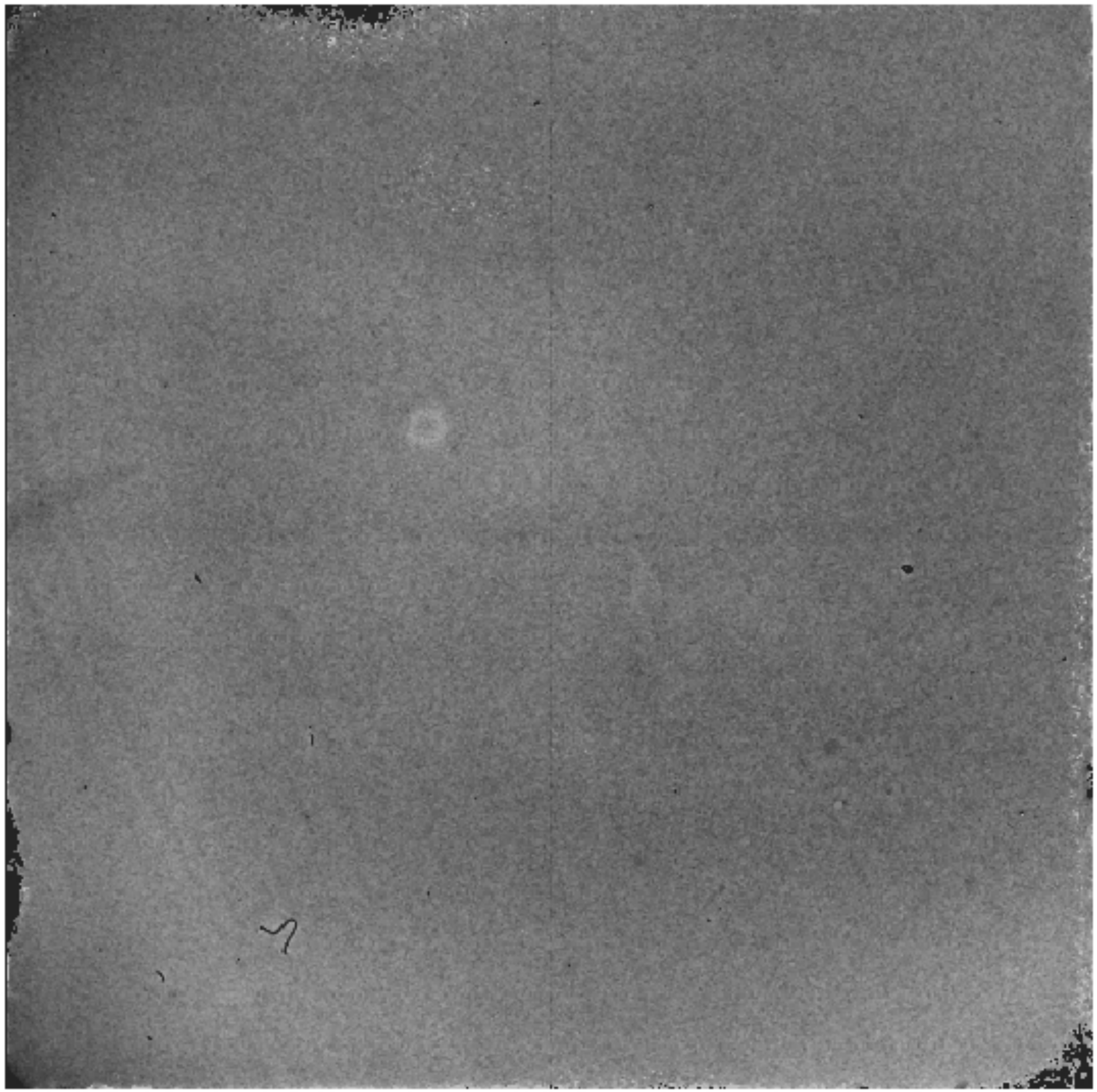


Dark Current



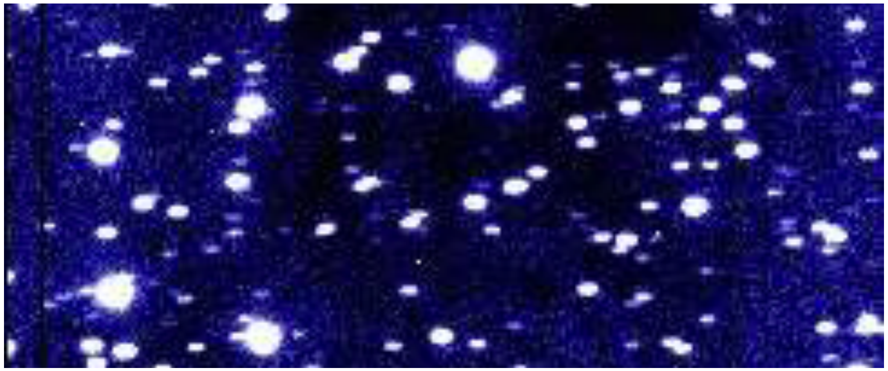


Flatfield

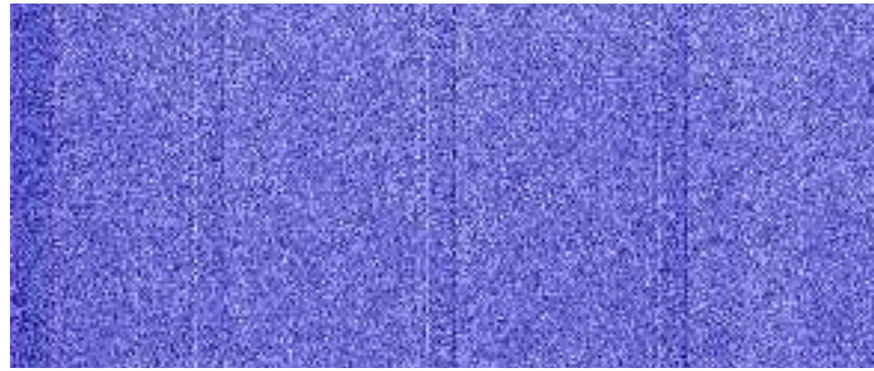


CCD Data Reduction

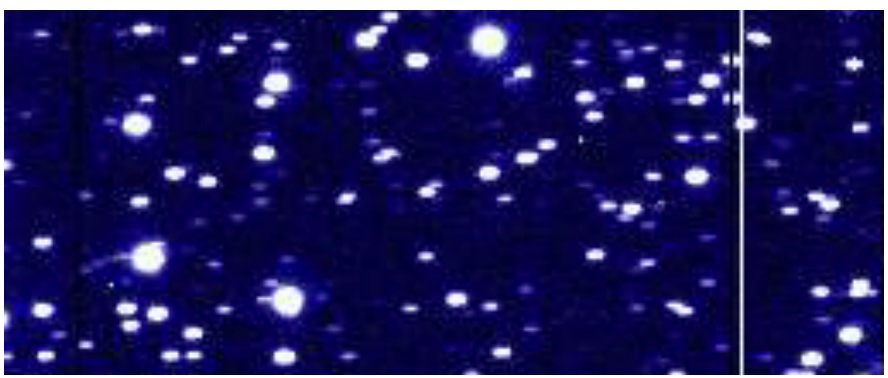
Raw



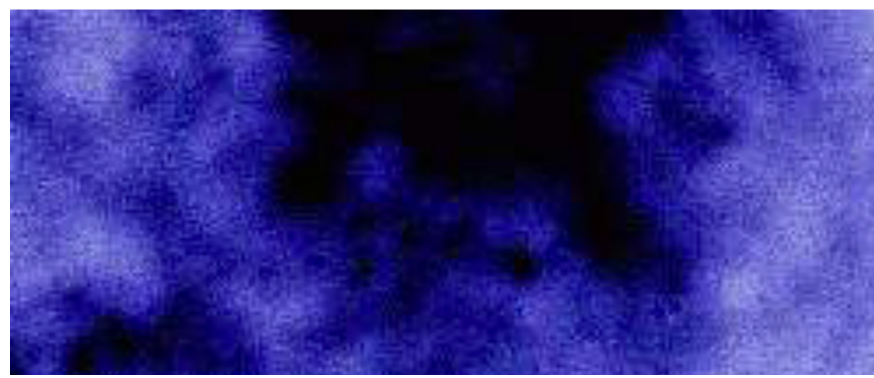
Bias + Dark Current



Reduced



Flatfield



Typical Array Detector Data Reduction

- science frame S, exposure time t_S
- dark frame D, exposure time t_D
- bias frame B, zero exposure time
- flat field frame F, exposure time t_F
- corrected (calibrated) image given by

$$S' = \frac{S - \frac{t_s}{t_D}\left(D - B\right) - B}{F - \frac{t_F}{t_D}\left(D - B\right) - B}$$

- F-(t_f/$t_{d)}$(D-B)-B often normalized such that mean of S′ = mean of S

CMOS and CCD

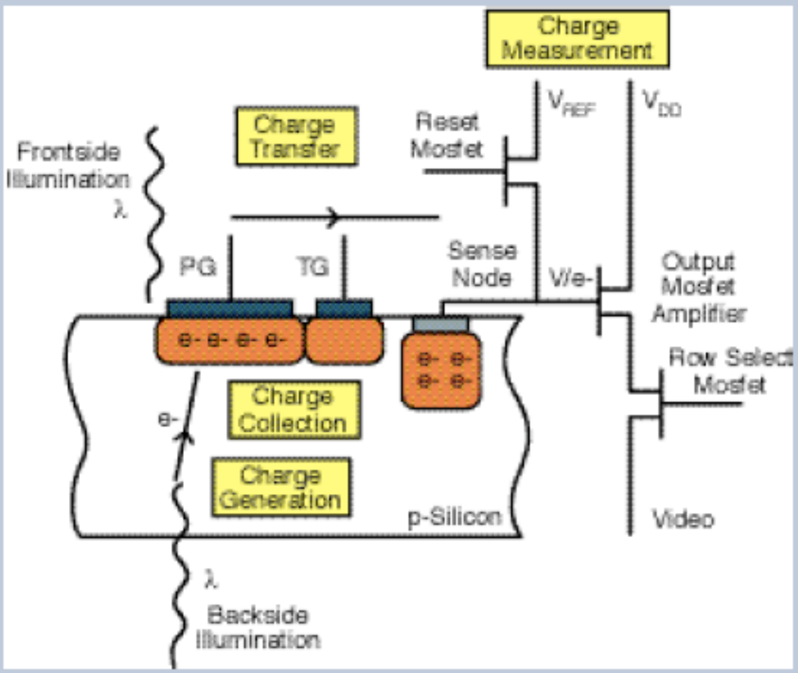


FIGURE 1 A cross-section of a CMOS pixel shows the four major functions required to generate an image.

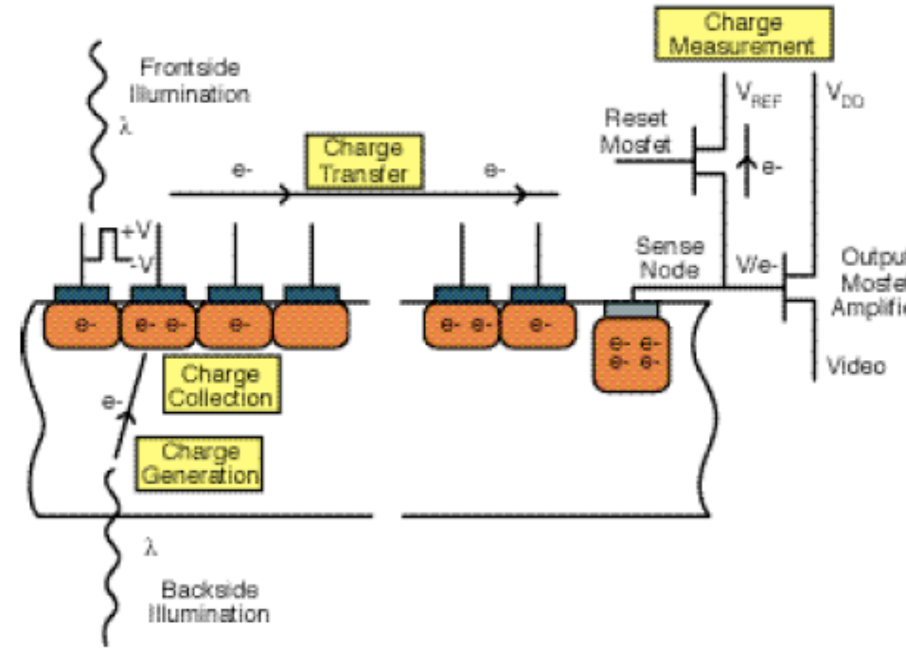
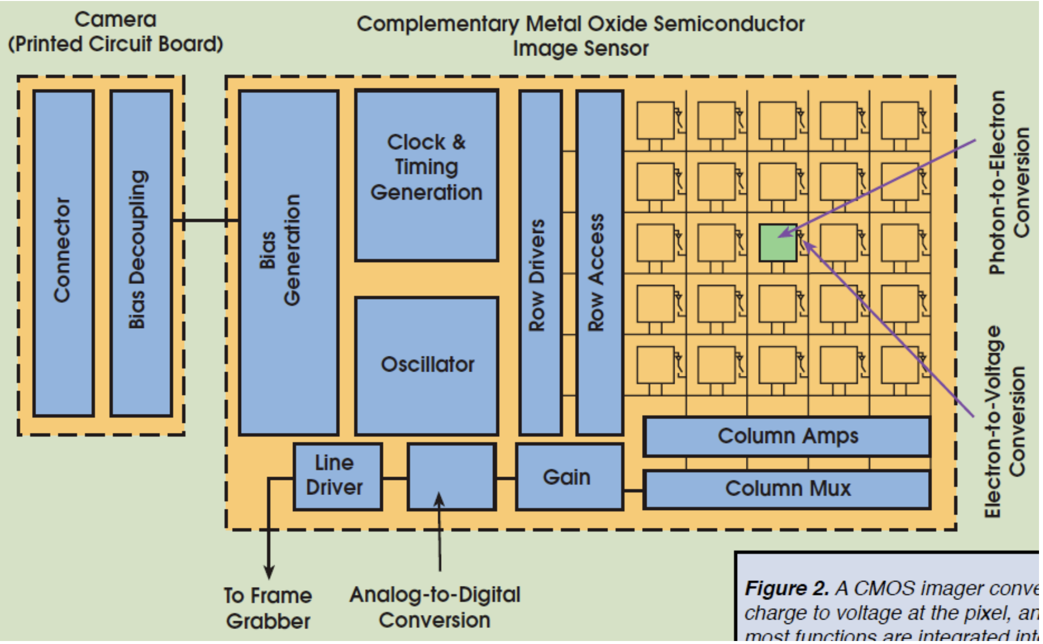
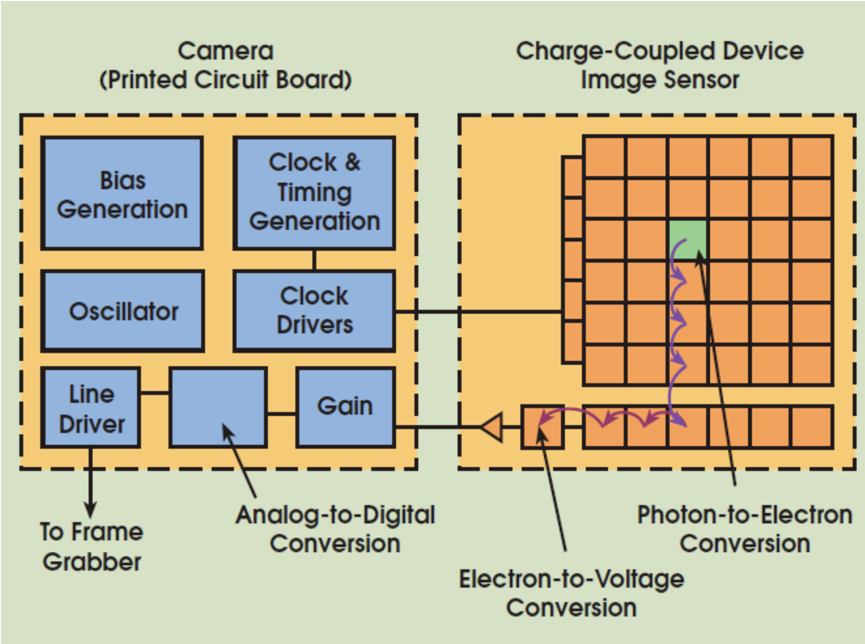


FIGURE 2 A cross-section of a CCD pixel shows the four major functions required to generate an image.

- Complementary Metal Oxide Semiconductor (CMOS)
- Charge Coupled Device (CCD)

CMOS and CCD Cameras



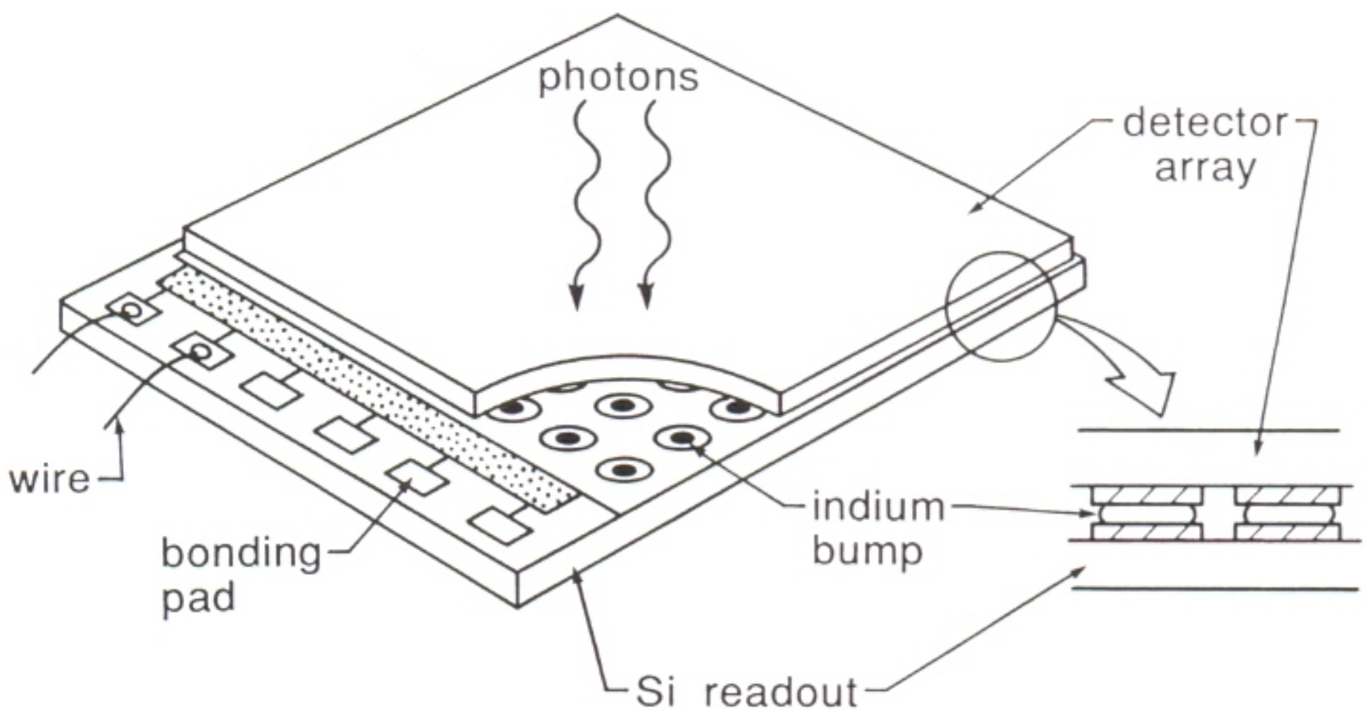


CMOS vs. CCD

- CMOS advantages over CCD:
  - standard semiconductor processing
  - low power consumption (1% of CCD)
  - random access to regions of interest
  - blooming and streaking much reduced compared to CCDs
  - additional electronics can be integrated on chip and in pixel (smart sensor)
  - non-destructive readout
- CMOS disadvantages:
  - small geometric fill factor (microlenses can help)
  - typically larger read noise

Infrared Arrays – Construction

1. Produce a grid of readout amplifiers
2. Produce a (matching mirror image) of detector pixels
3. Deposit Indium bumps on both sides
4. Squeeze the two planes together ➔ hybrid arrays
5. The Indium will flow and provide electrical contact



Multiplexers

Multiplexing: "Pixel signals → Sequential output lines"

MUX Tasks:

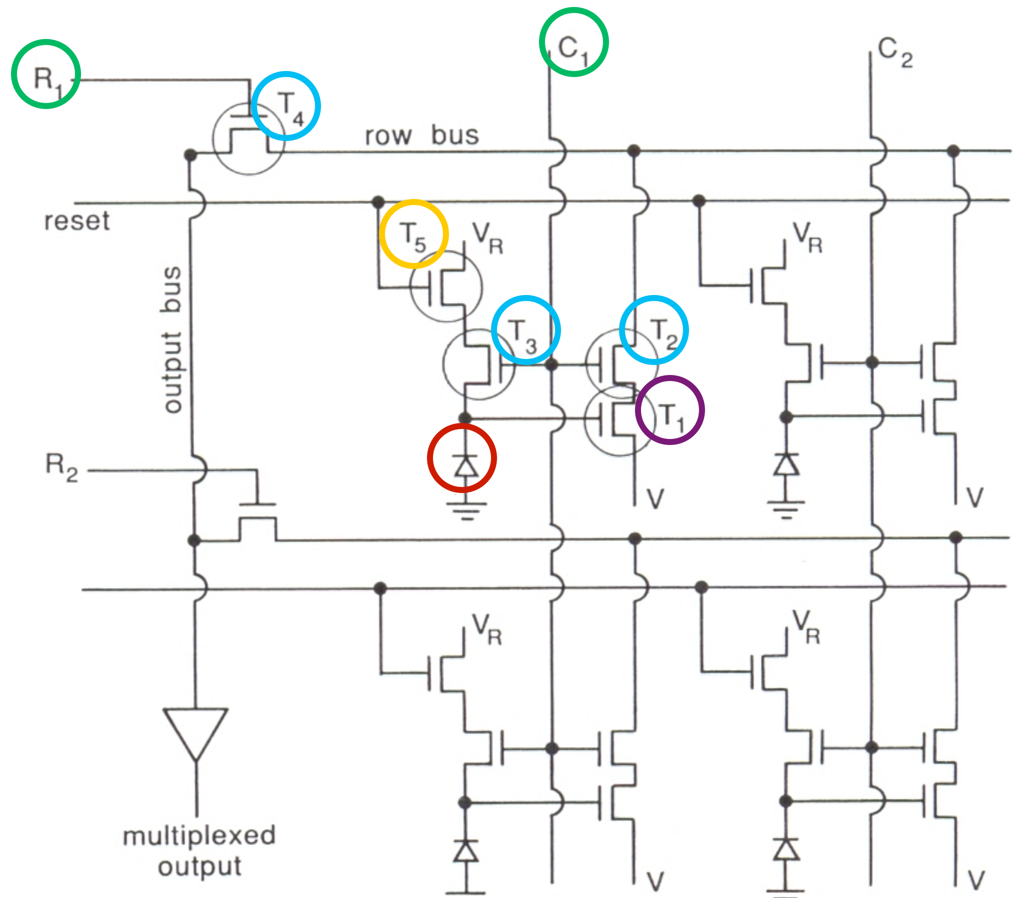
- address a column of pixels by turning on their amplifiers
- pixels in other columns with power off will not contribute a signal

Signal at photodiode → gate T_1

Readout uses row driver R_1 and column driver C_1 to close the switching transistors T_2, T_3, T_4.

→ Power to T_1 → signal to the output bus

Reset: connect V_R via T_5 and T_3.

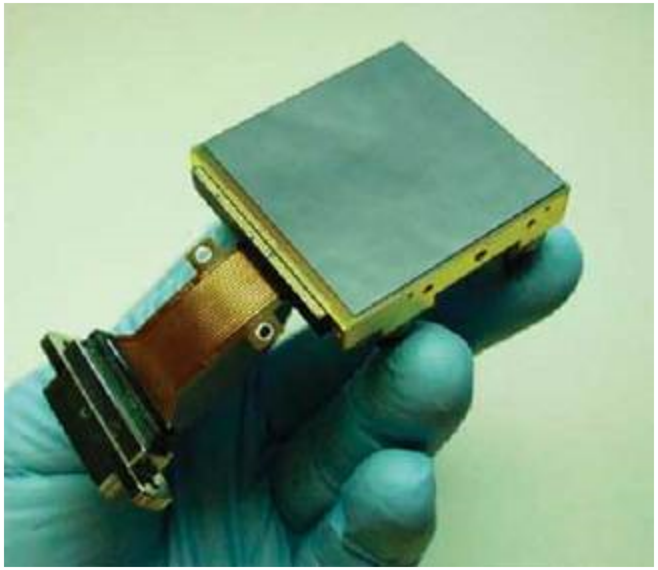


Example: The Teledyne HAWAII-2RG

Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 µm
Fill factor	$\geq$ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3µm
Operating temperature	$\geq$ 30K
Quantum efficiency (array mean)	$\geq$ 65%
Charge storage capacity	$\geq$ 100,000e^-
Pixel operability	$\geq$ 95%
Dark current (array mean)	$\leq$ 0.1 e^-/sec (77K, 2.5 µm)
Read noise (array mean)	$\leq$ 15 e^- CDS @ 100 kHz
Power dissipation	$\leq$ 4 mW @ 100 kHz

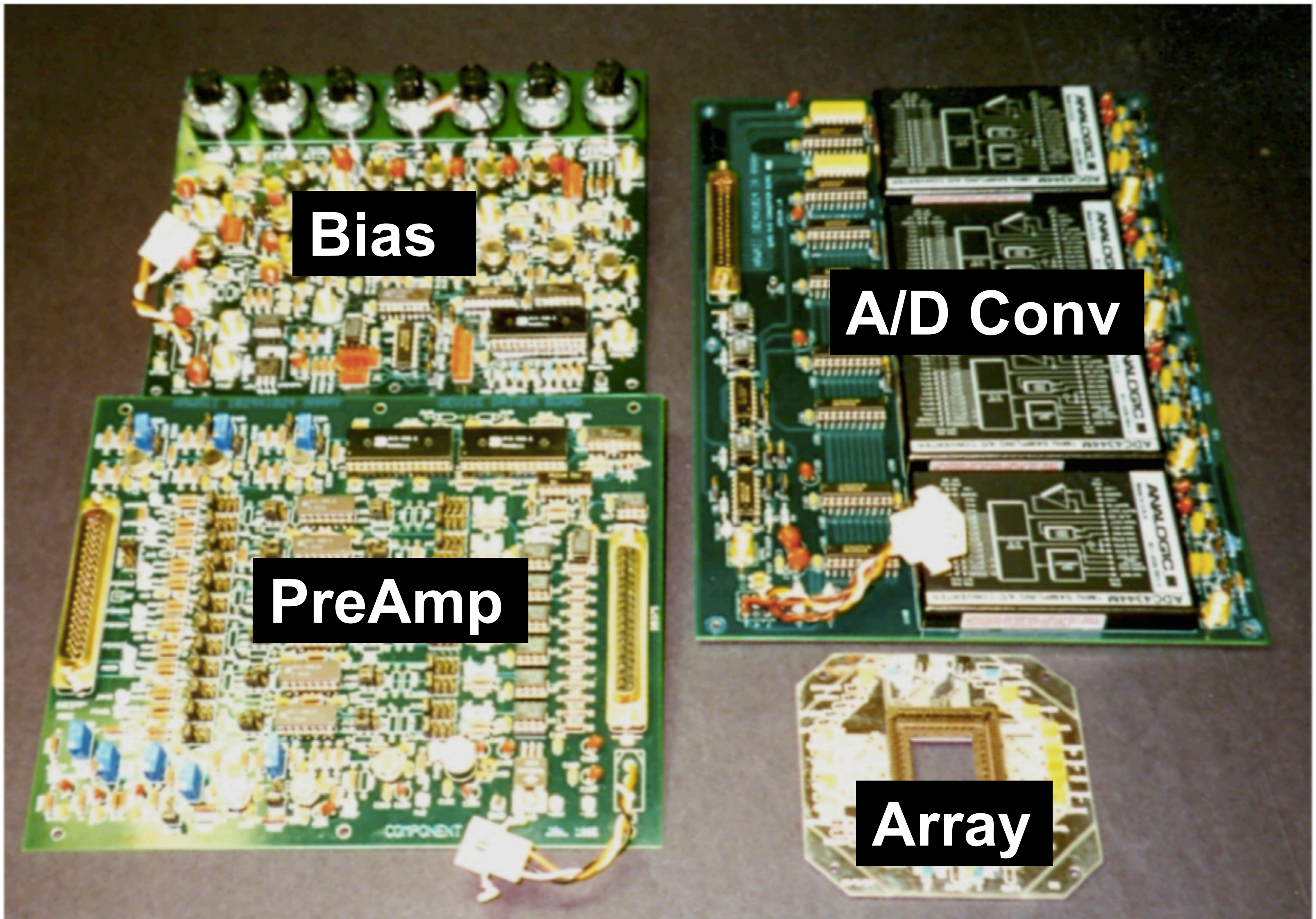
See http://www.rsc.rockwell.com/imaging/hawaii2rg.html for more info

Can also be combined to a 2x2 mosaic



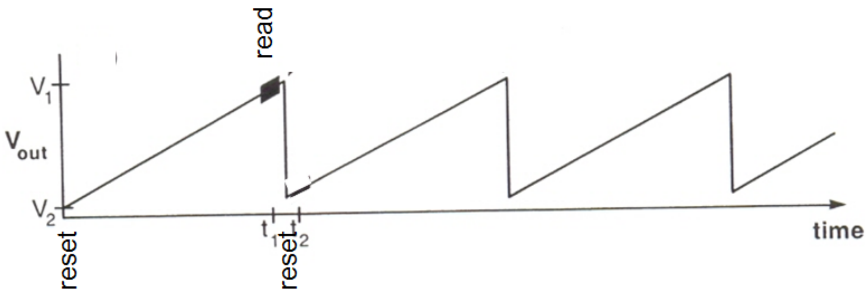
Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)



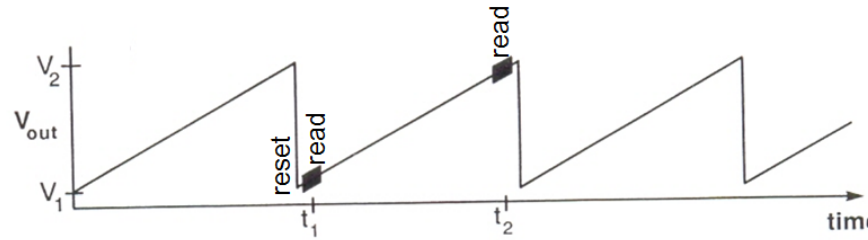
IR Array Read Out Modes

Single Sampling



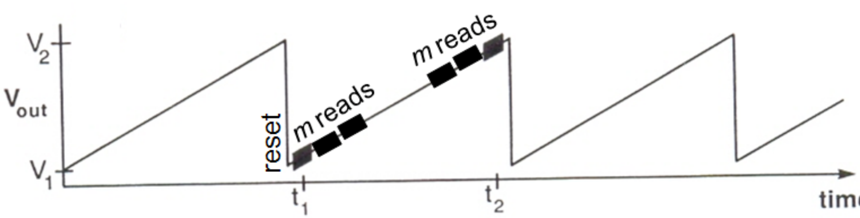
- most simple approach
- does not remove kTC noise
- measures the absolute signal level

Reset-Read-Read



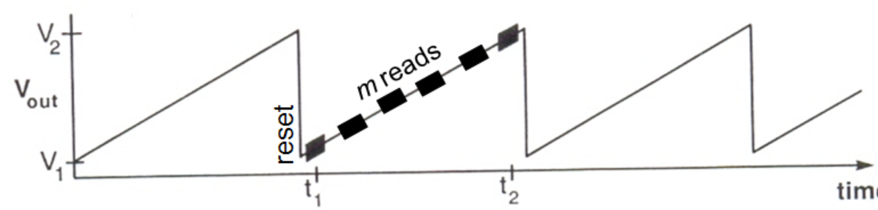
- Resets, reads and reads pixel-by-pixel
- Signal = Read(2) – Read(1)
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

(Multiple) Fowler Sampling



- similar to reset-read-read ...
- ... but each read is repeated *m* times
- Signal = mean(read2) – mean(read1)
- Reduces readout noise by √m over RRR

Sample-up-the-ramp Fitting



- *m* equidistant reads during integration
- linear fit → "slope"
- reduces readout noise by √m
- particularly useful in space (cosmics!)

CCDs and IR Arrays are fundamentally different!

CCDs:

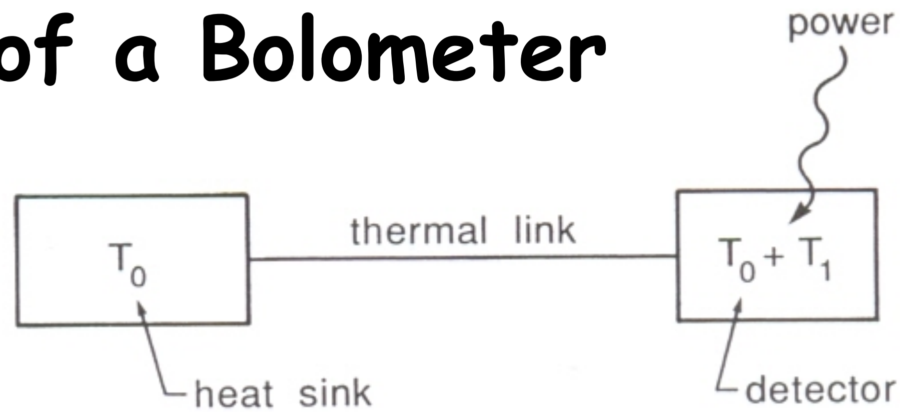
- destructive reads
- charges are physically shifted to the output line
- shutter determines exposure time

IR arrays:

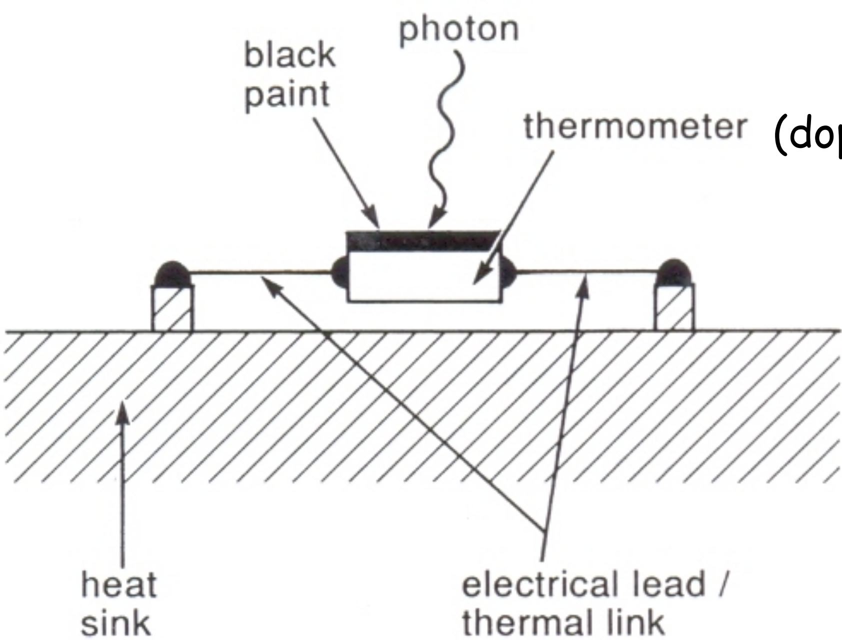
- non-destructive reads
- readout requires sophisticated multiplexer circuit
- multiplexer readout addresses individual pixels directly
- read/reset determines exposure time

Basic Principle of a Bolometer

A detector with thermal heat capacity C is connected via a thermal link of thermal conductance G to a heat sink of temperature T_0.



The total power absorbed by the detector is: $$P_T(t) = GT_1 + C\frac{dT_1}{dt}$$



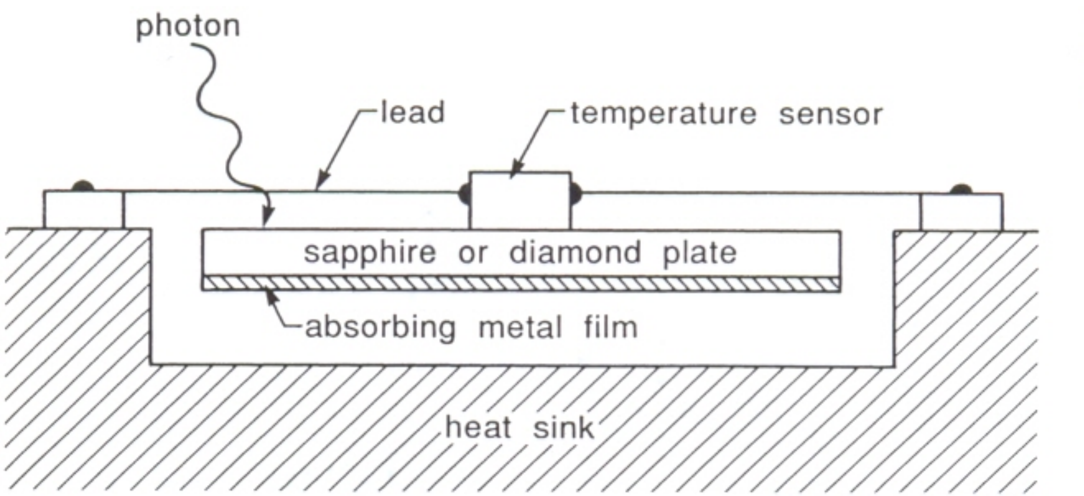
(doped silicon or germanium)

- measure the voltage across thermo.
- voltage depends on resistance
- resistance depends on temperature
- temperature depends on photon flux

Bolometers are especially for the far-IR/sub-mm wavelength range!

QE and Composite Bolometers

- In some cases Si bolometers with high impurity concentrations can be very efficient absorbers.
- In many cases, however, the QE is too low. Solution: enhance absorption with black paint – but this will increase the heat capacity.
- A high QE bolometer for far-IR and sub-mm would have too much heat capacity → composite bolometers.

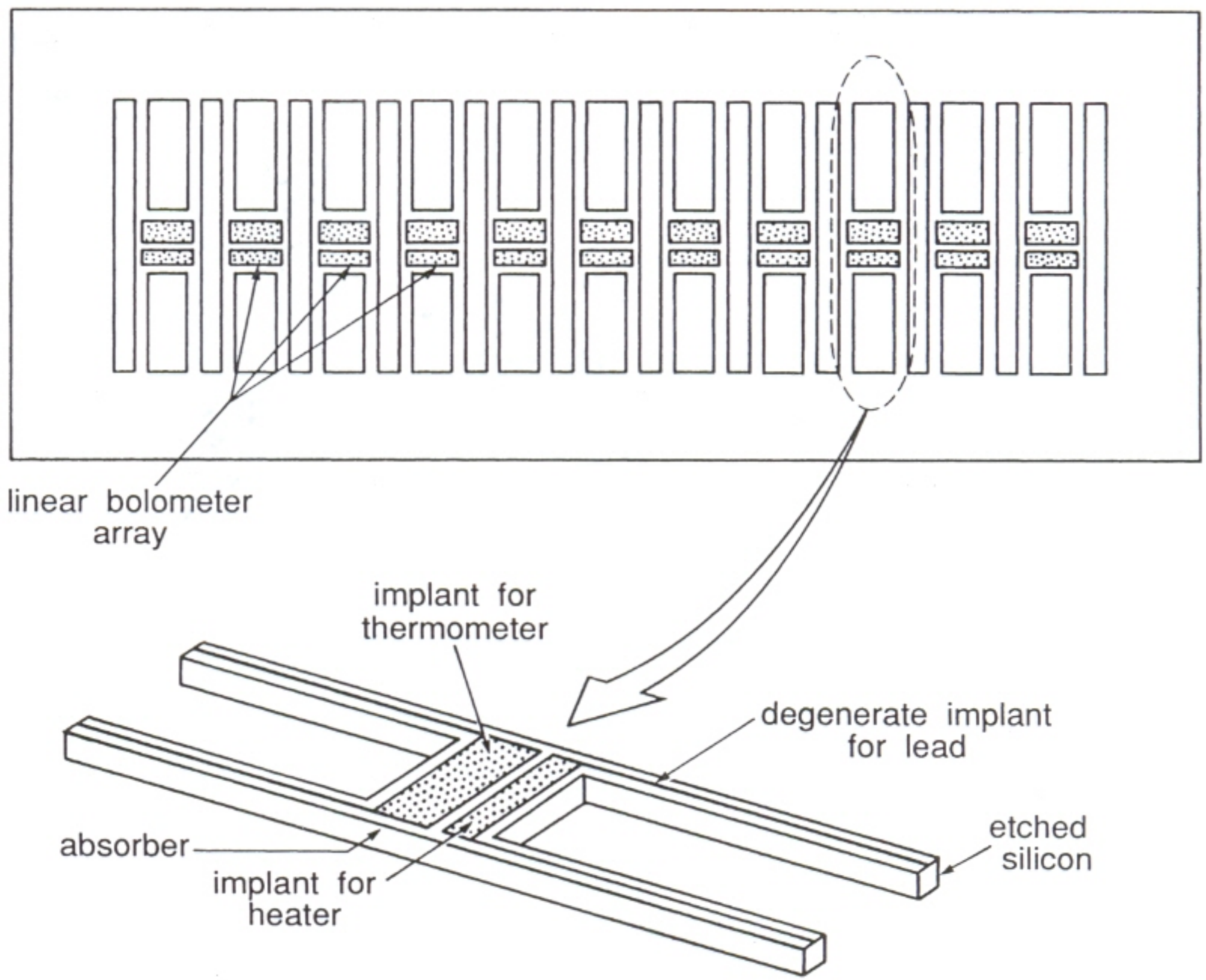


The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Etched Bolometers

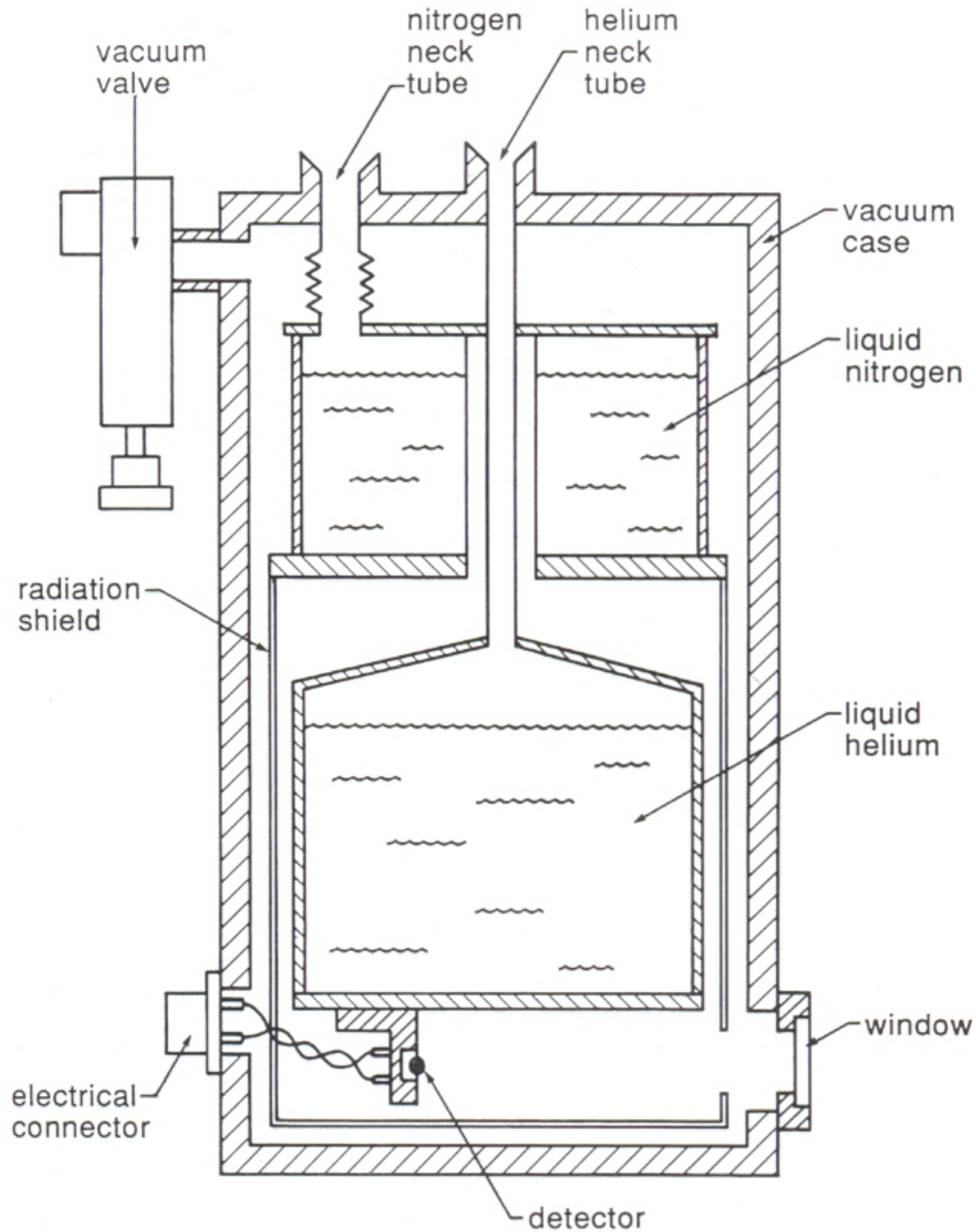
The bolometer design has been revolutionized by precision etching techniques in Si

Thermal time response ~ C/G → small structures minimize the heat capacity C by reducing the volume of material.



Low Operating Temperatures

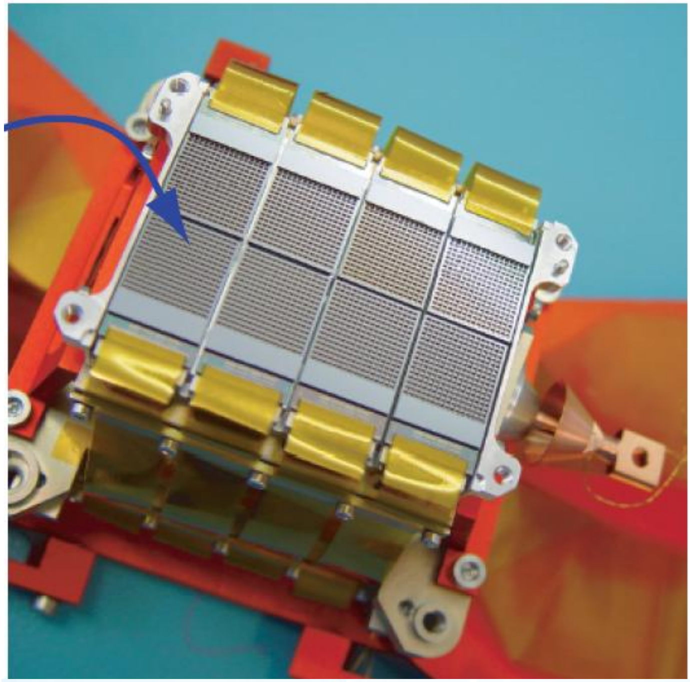
1. Four standard options to cool:
2. ^{4}He dewar (air pressure) → T=4.2K
3. ^{4}He dewar (pumped) → 1K< T <2K
4. ^{3}He (closed-cycle) refrigerator → T~0.3K
5. adiabatic demagnetization refrigerator → T ~ 0.1K



Simplest solution is to use a two-stage helium dewar (here: model from Infrared Laboratories, Inc.)

Bolometers – an Overview

The "single pixel" Ge:Ga bolometer invented in 1961 by Frank Low

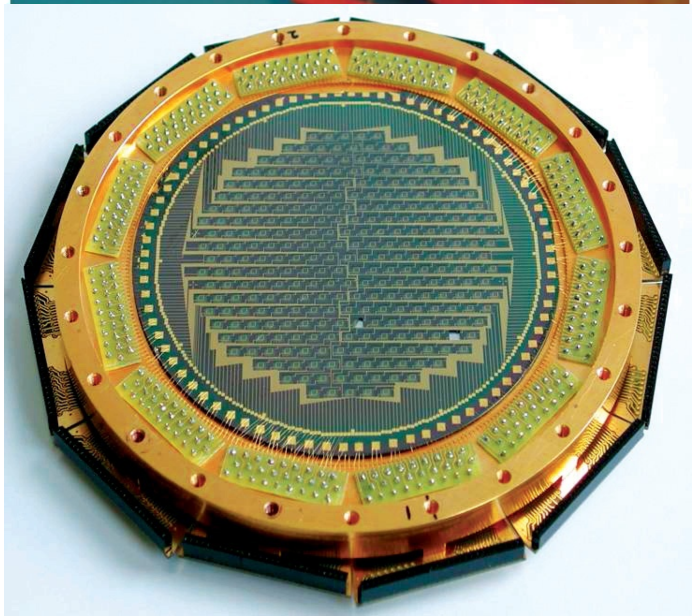


Herschel / PACS bolometer: a cut-out of the 64x32 pixel bolometer array assembly.

LABOCA – the multi-channel bolometer array for APEX operating in the 870 µm (345 GHz) atmospheric window.

The signal photons are absorbed by a thin metal film cooled to about 280 mK.

The array consists of 295 channels in 9 concentric hexagons.
The array is under-sampled, thus special mapping techniques must be used.



Performance Comparison Bolometer ⇔ Heterodyne Receiver

Case 1: Bolometer operating at BLIP and heterodyne receiver operating in the thermal limit ($h\nu \ll kT$)

➔ the bolometer will perform better

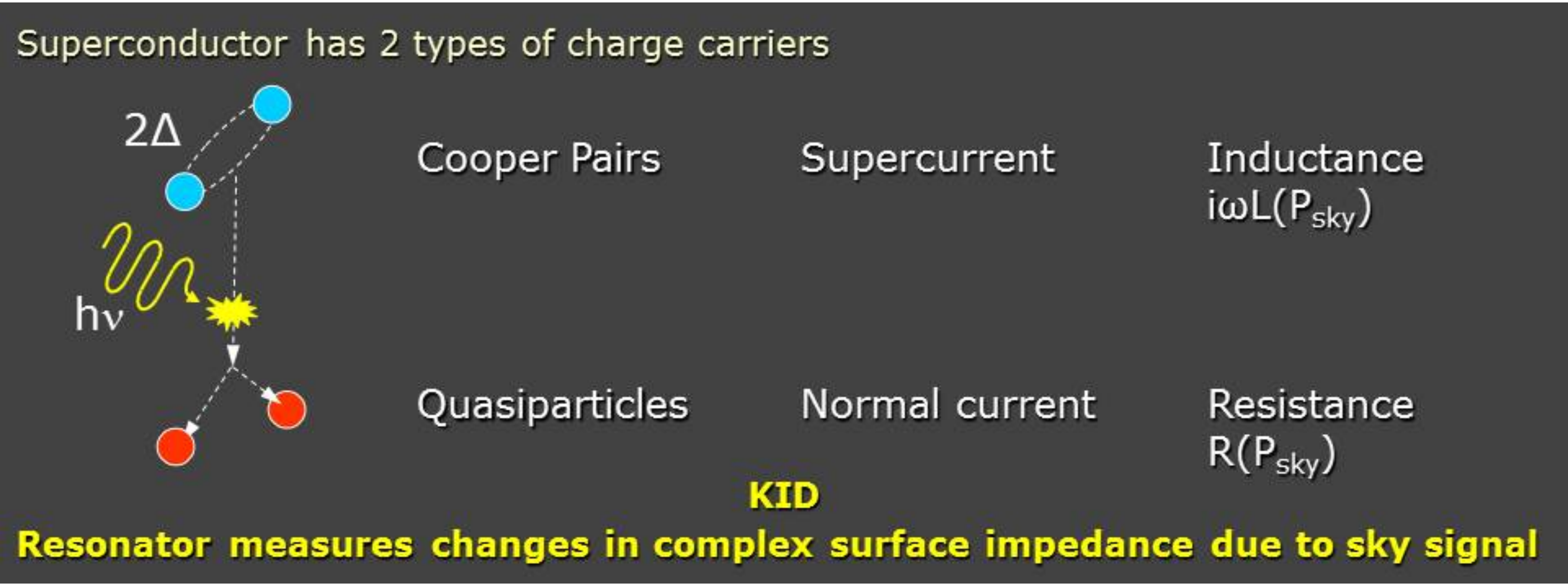
This is always true, except for measurements at high spectral resolution, much higher than the IF bandwidth.

Case 2: detector noise-limited bolometer and a heterodyne receiver operating at the quantum limit ($h\nu \gg kT$).

➔ the heterodyne receiver will outperform the bolometer.

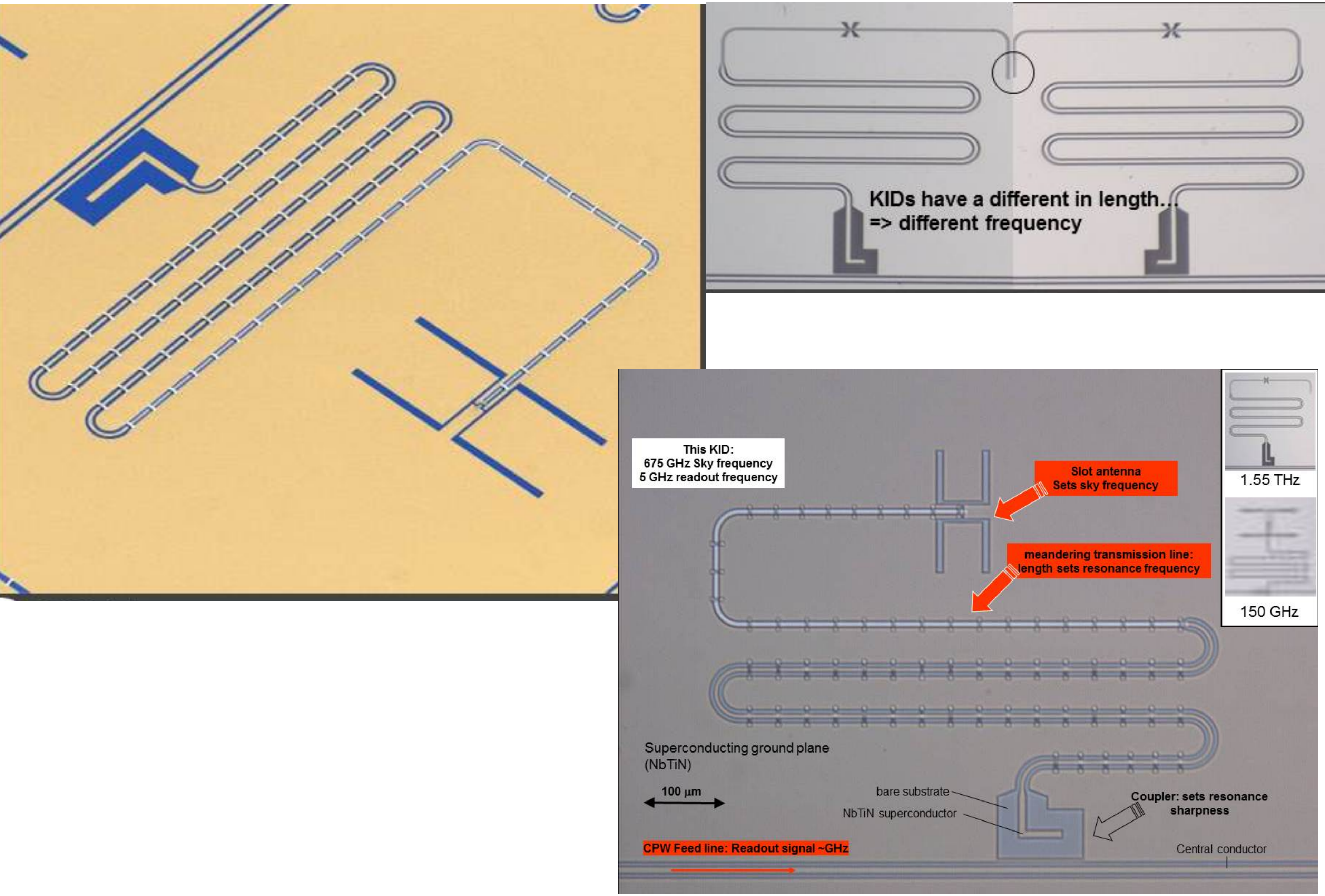
In the case of narrow bandwidth and high spectral resolution the heterodyne system will always win.

MKIDS – Physical Principle



KID = Kinetic Inductance Detector
MKID = Microwave KID

MKIDS – Construction



MKIDS – Operating Principle