

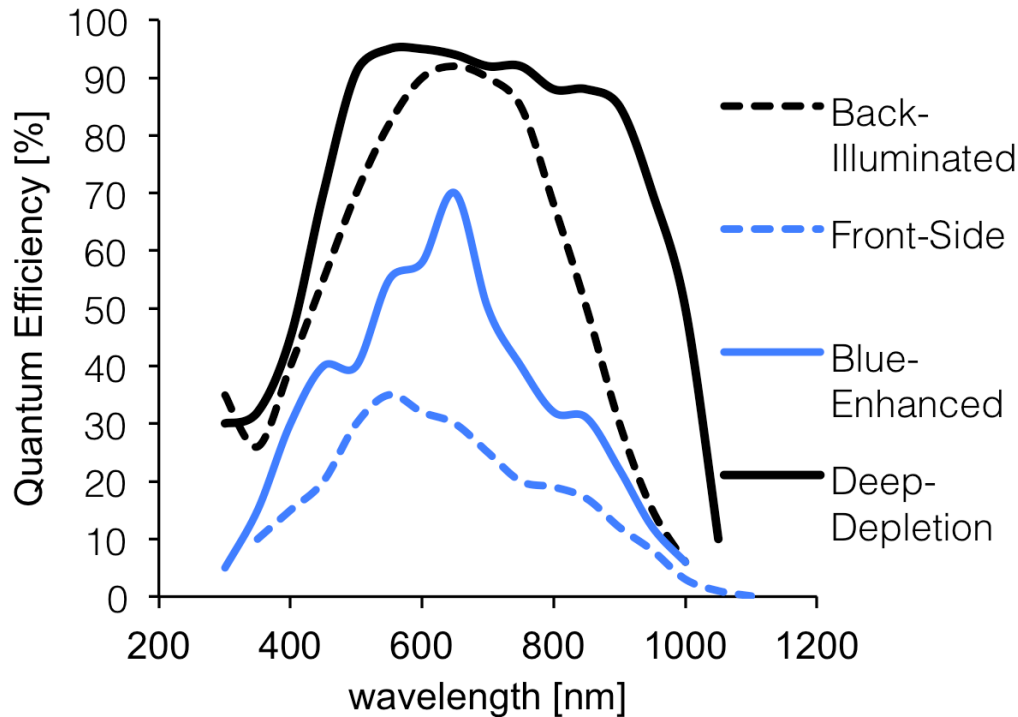
Lecture 10: Detectors 2

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Overview

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

Backside Illumination

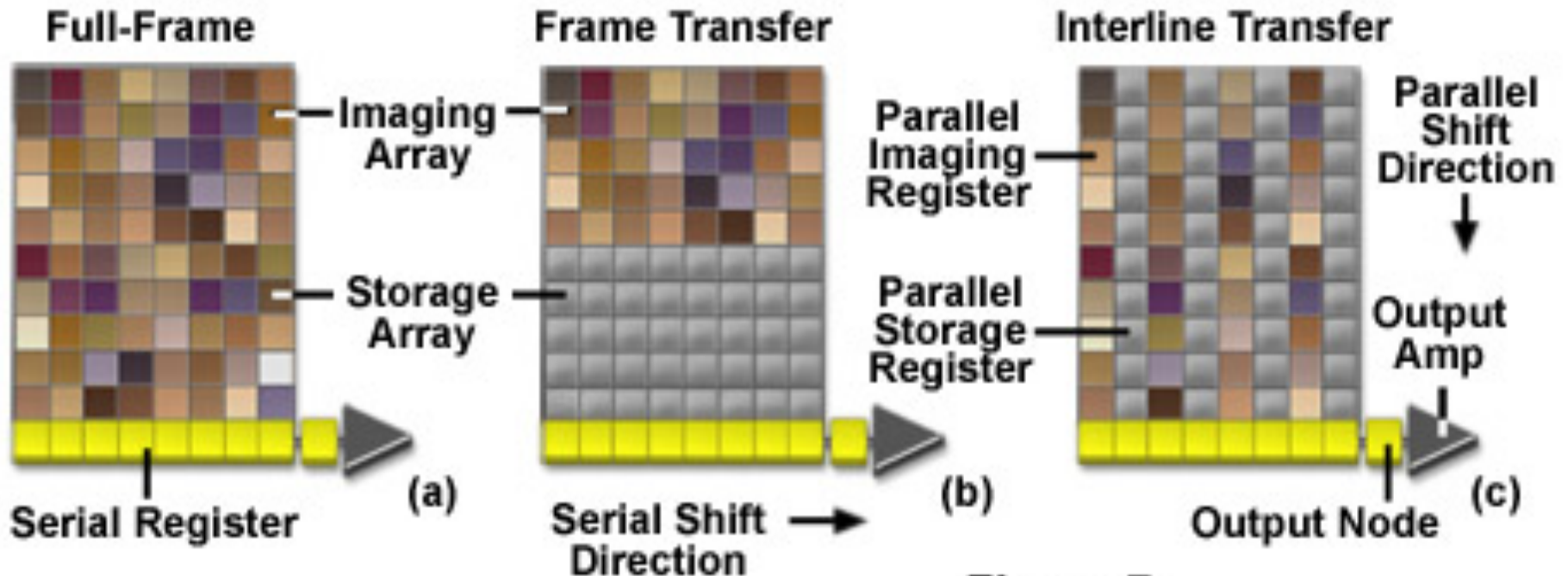


front illumination:
poly-silicon gate electrodes absorb in the blue and lead to interference effects

blue-enhanced: holes in poly-silicon gate electrodes

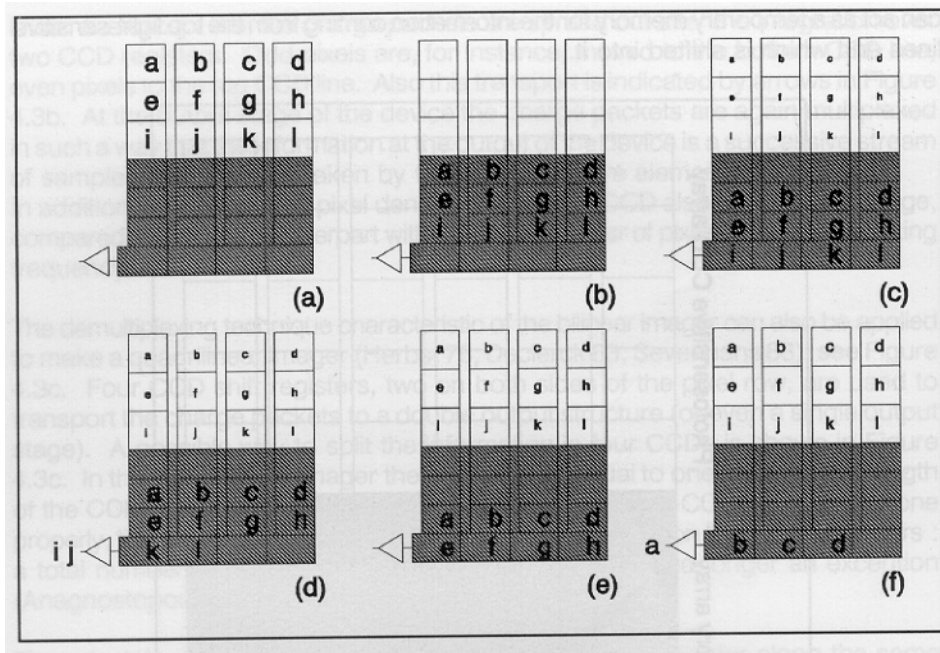
- back-illumination: thin silicon → photo-electrons reach potential wells
- electric field gradient moves charges: increase doping concentration in regions close to silicon surface
- increases sensitivity in blue where electrons are generated close to rear silicon surface
- minimize reflection of light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

Focal Plane Architecture



- astronomy: **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

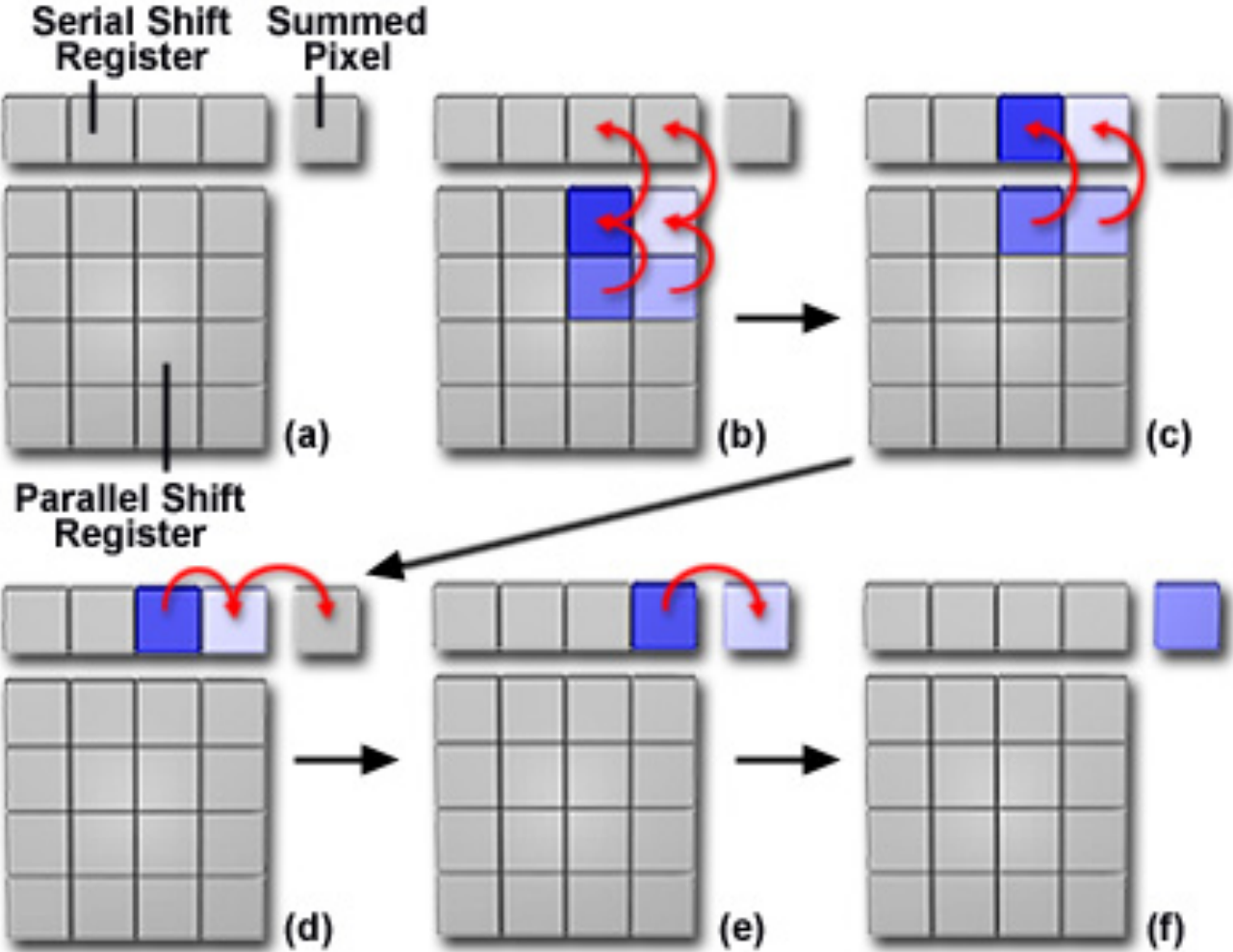
Frame Transfer Operation



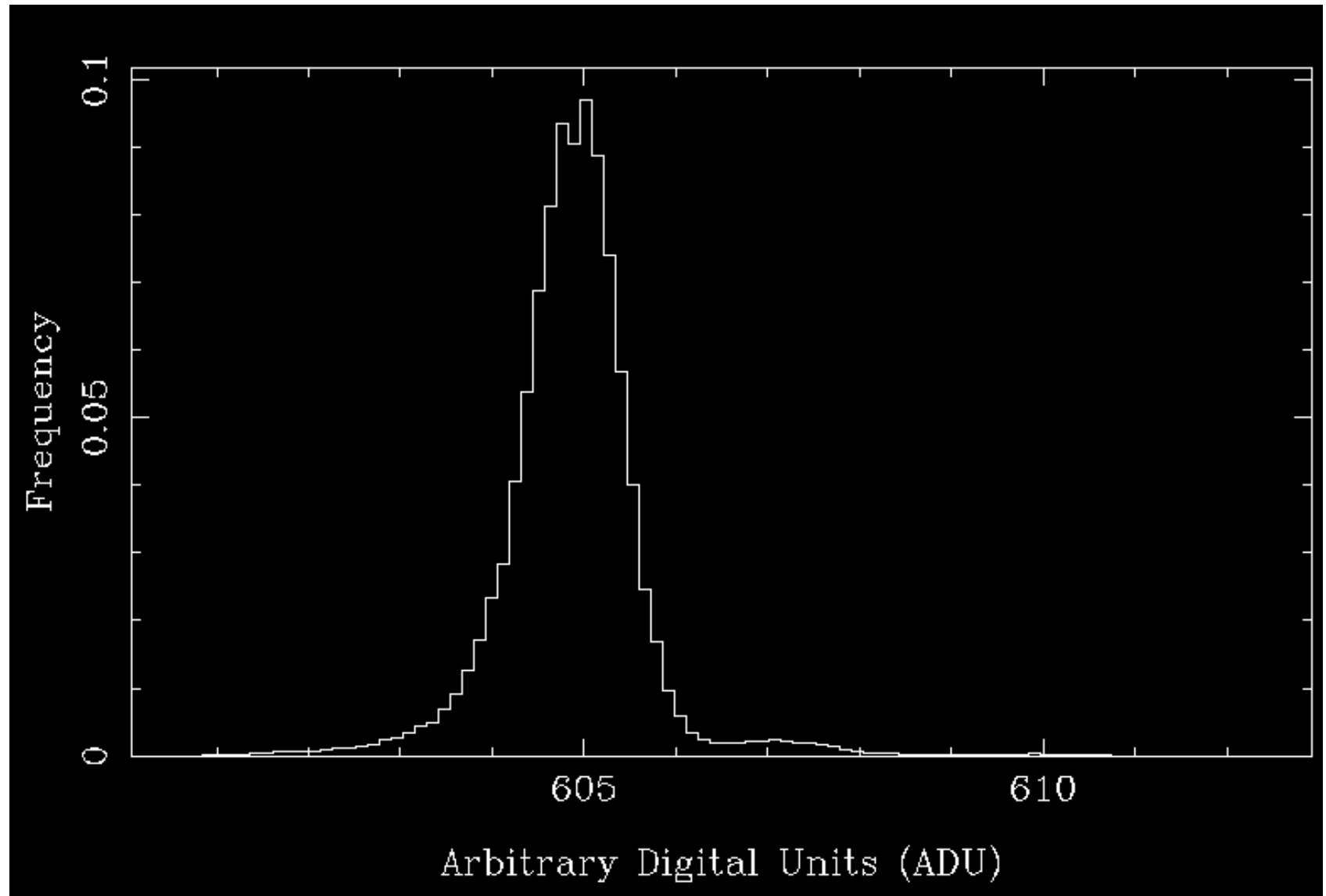
- transfer needs to be done quickly to prevent disturbance by light falling on the image section during read-out
- during readout, all CCD cells in image array are again in integration mode

Binning

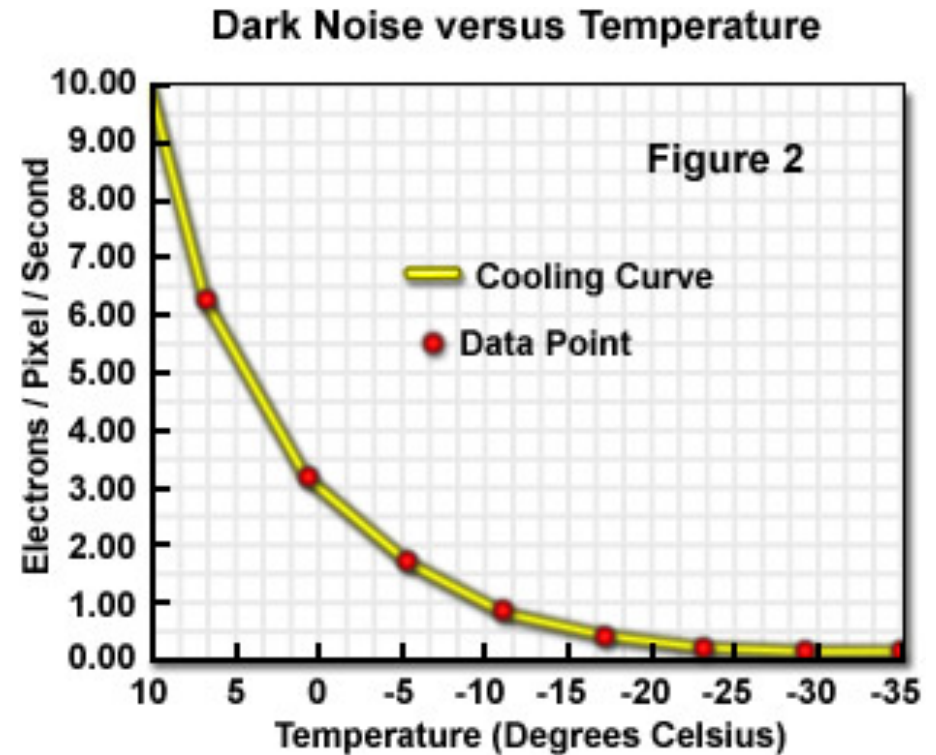
2 x 2 Pixel Binning Read-Out Stages



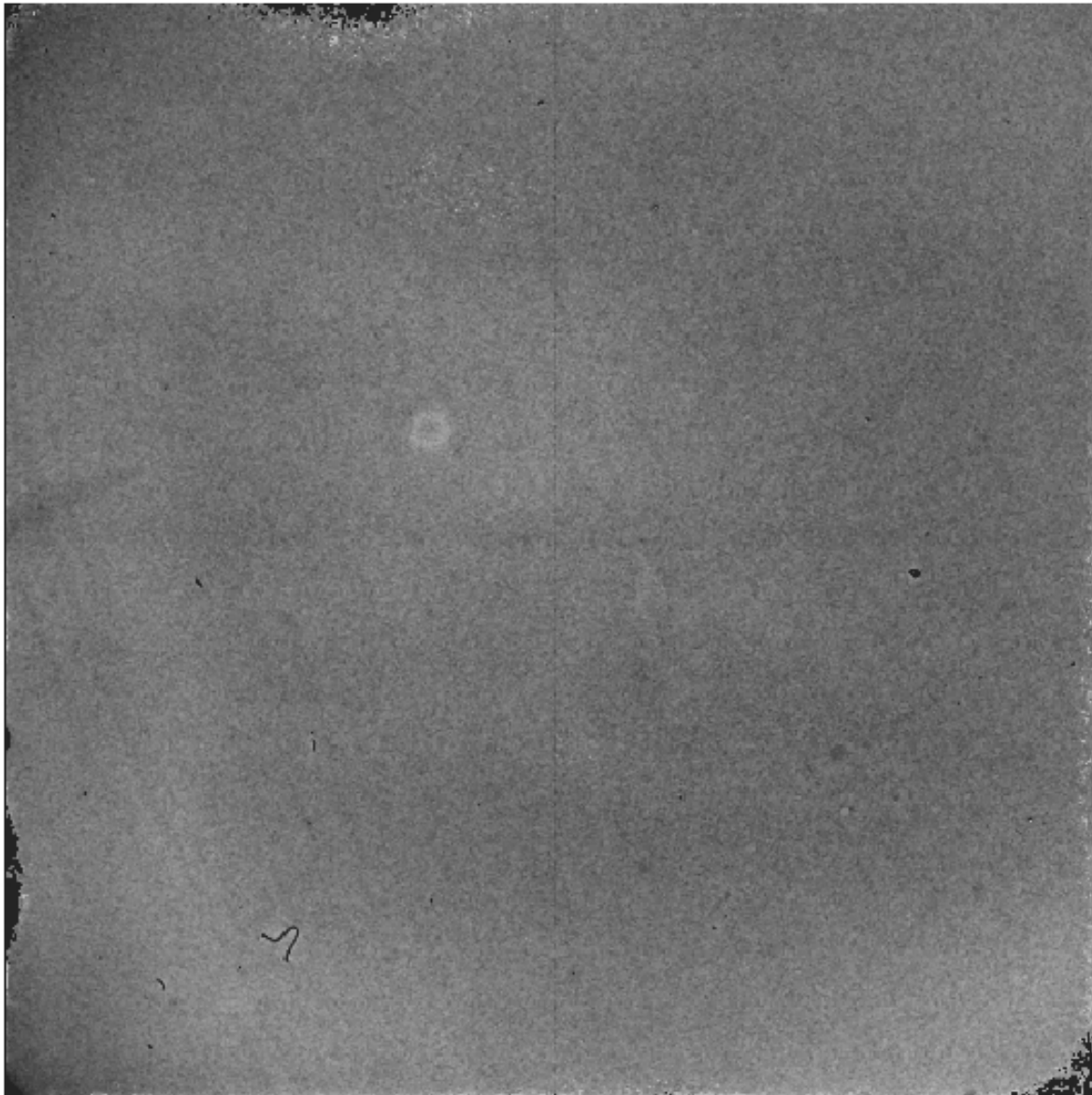
Bias



Dark Current

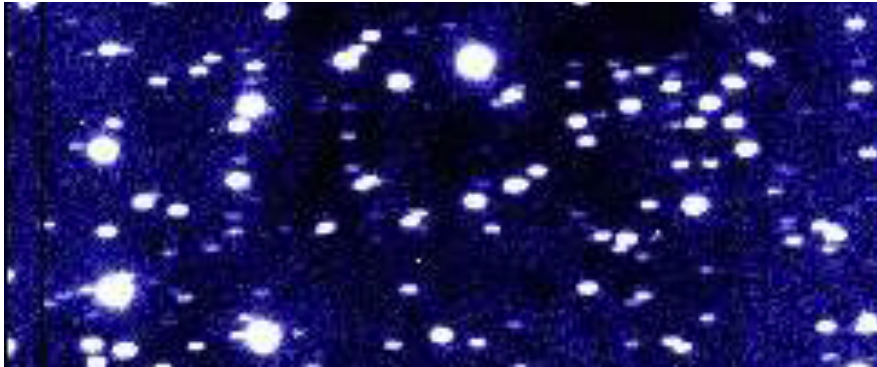


Flatfield

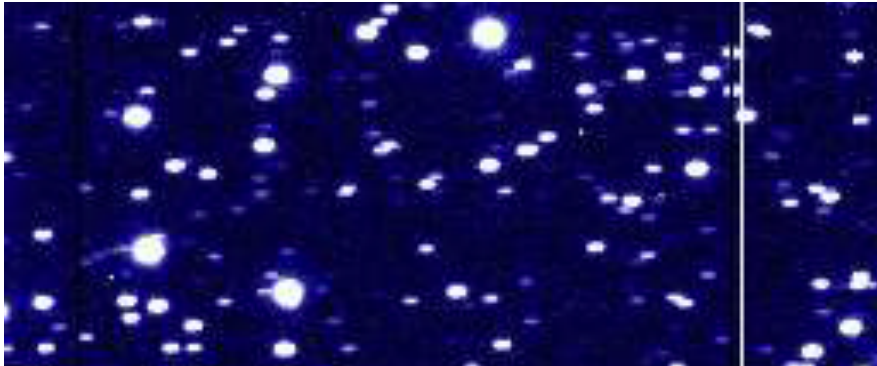
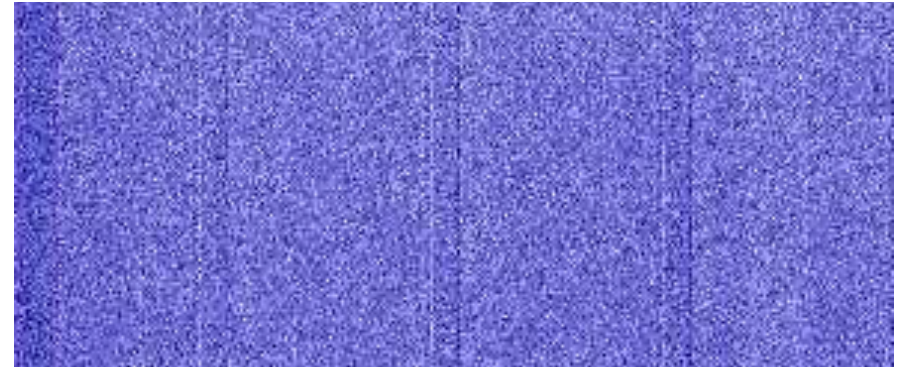


CCD Data Reduction

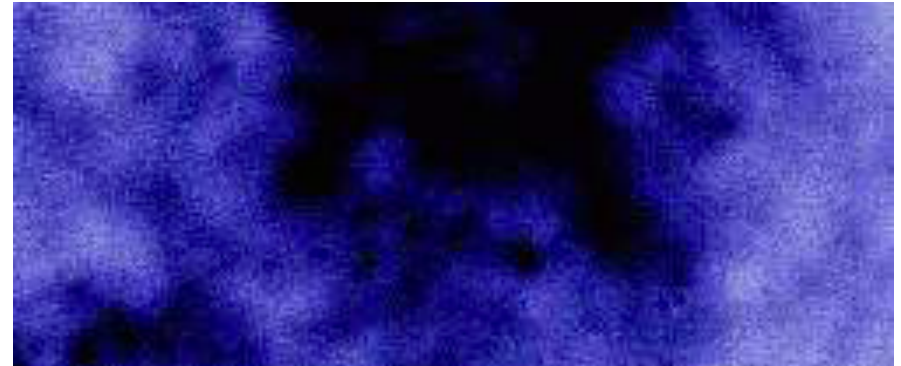
Raw



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

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

- $F - (t_f/t_d)(D - B) - B$ often normalized such that mean of $S' = \text{mean of } S$

CMOS and CCD

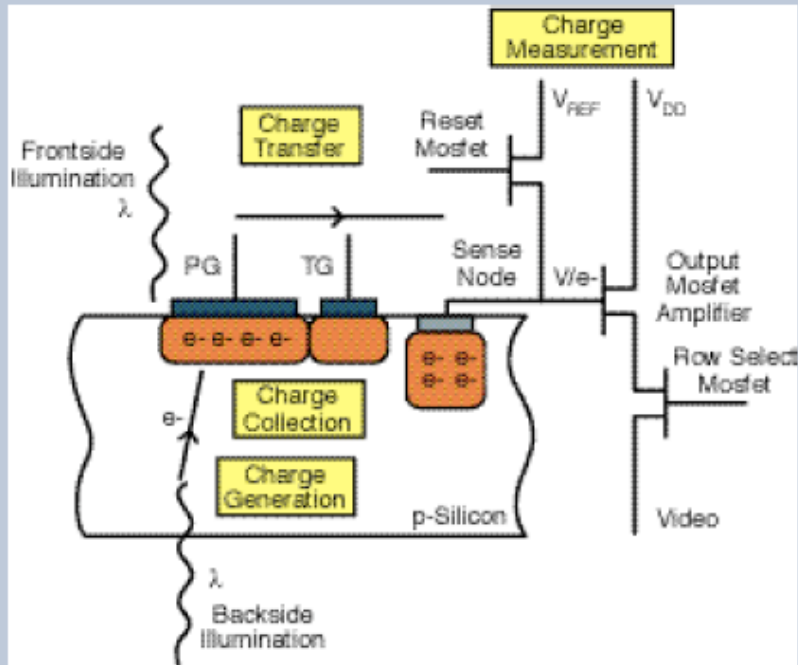


FIGURE 1 A cross-section of a CMOS pixel shows the four major functions required to generate an image.

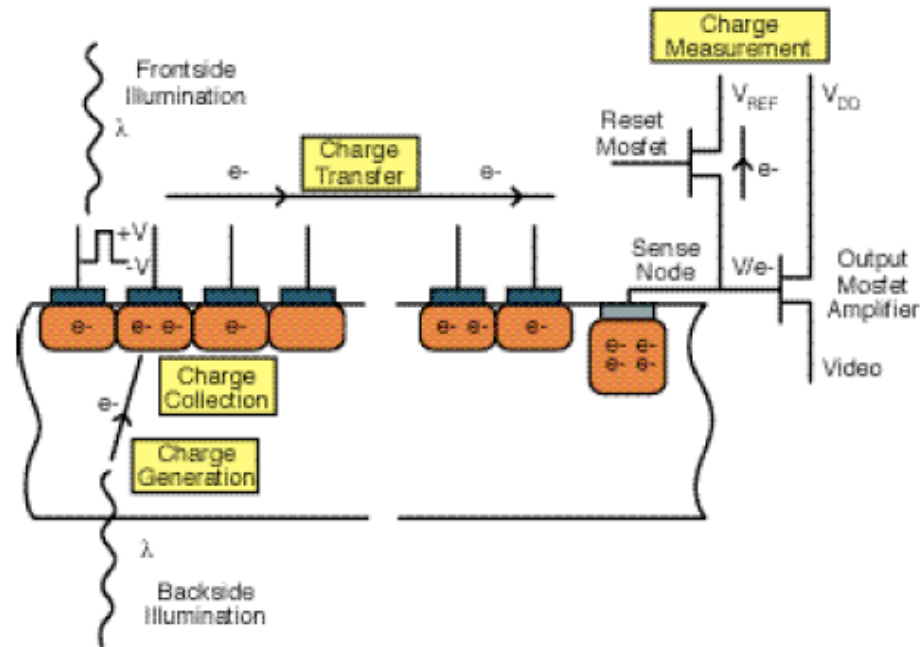
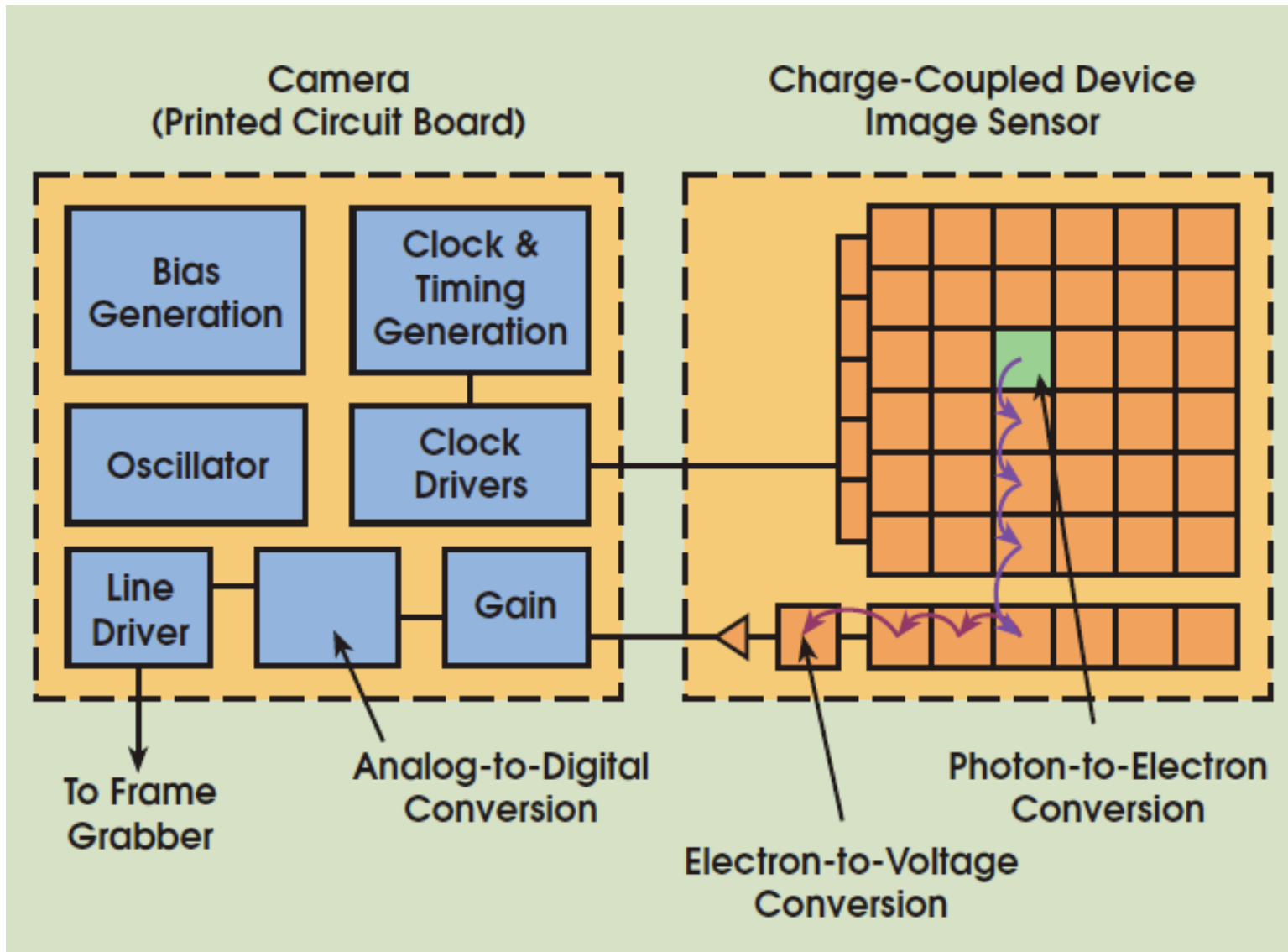


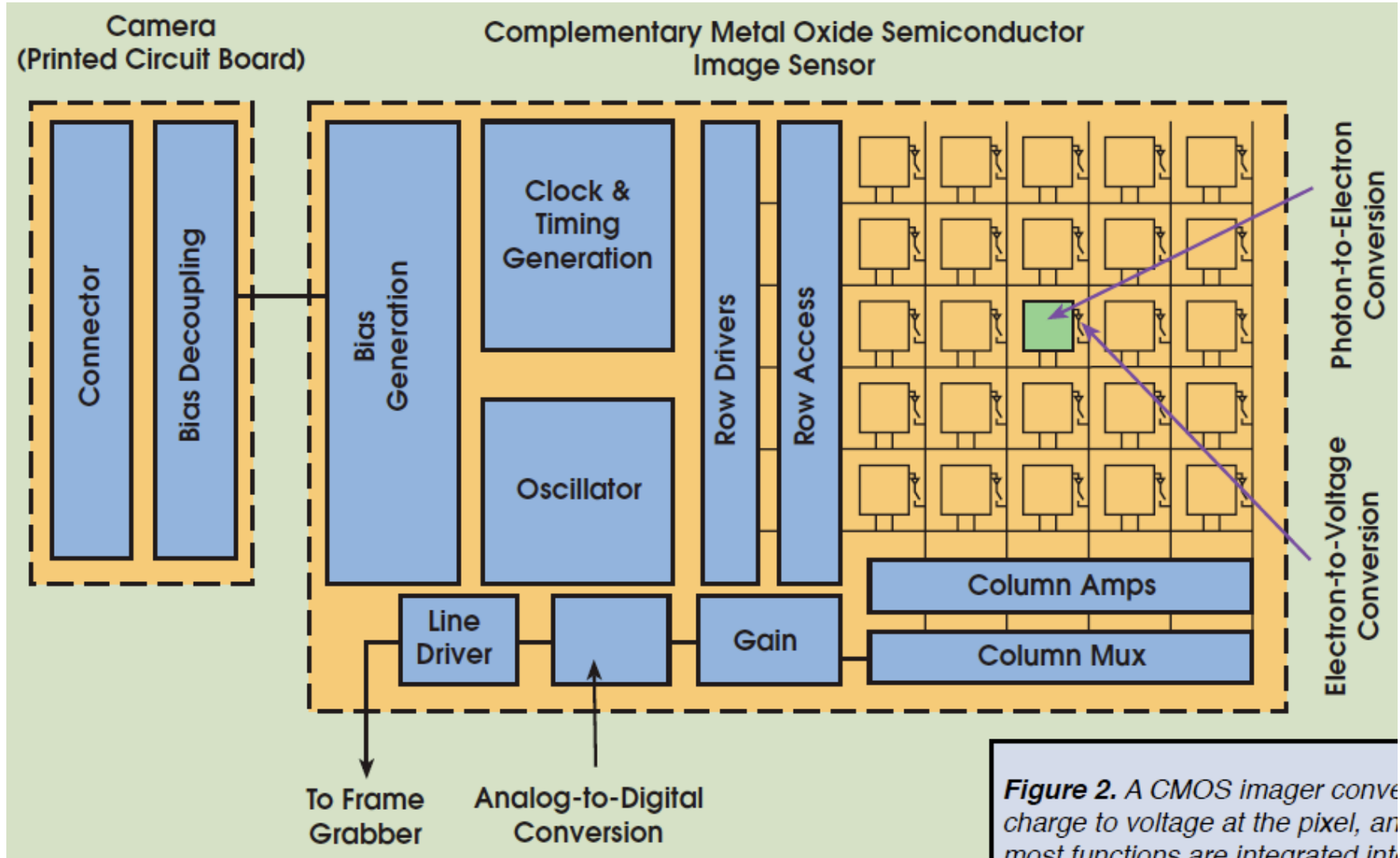
FIGURE 2 A cross-section of a CCD pixel shows the four major functions required to generate an image.

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

CCD Camera



CMOS Camera

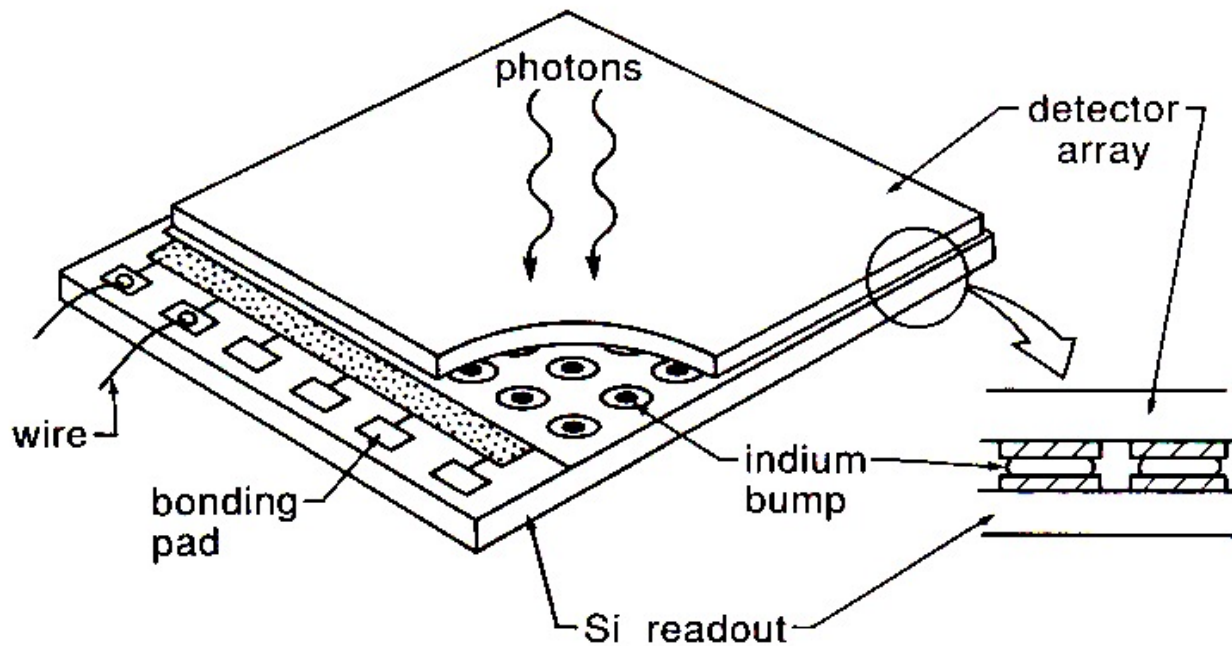


CMOS vs. CCD

- 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

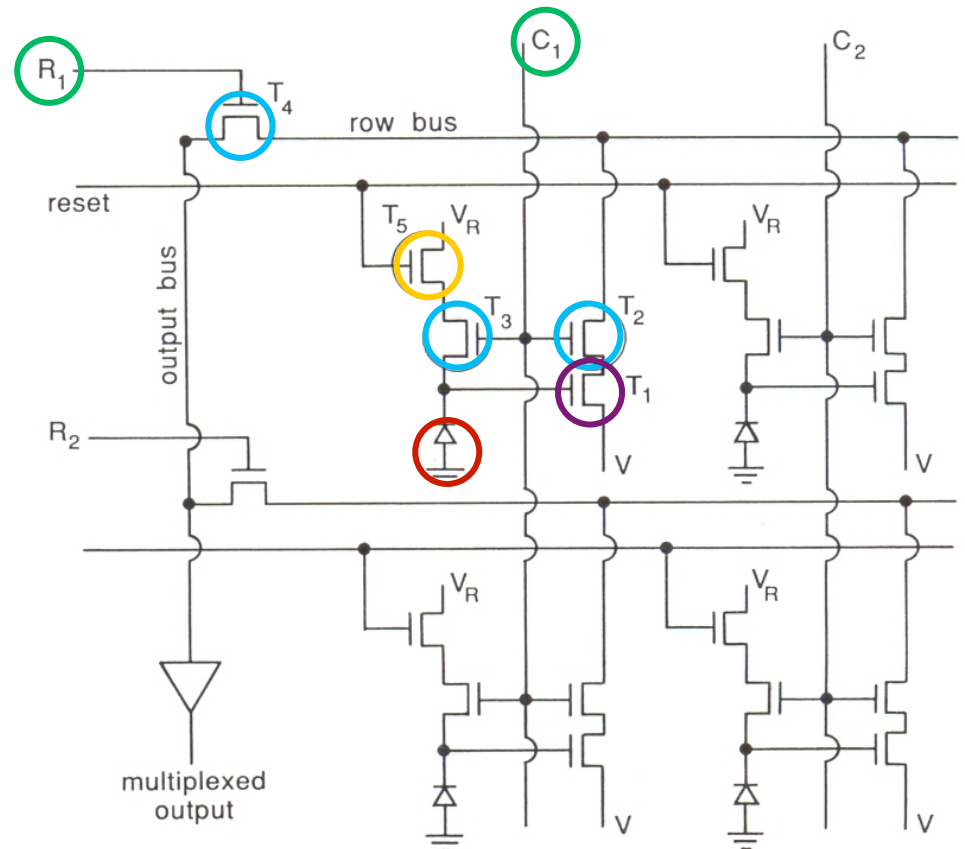


Multiplexers

Multiplexing: "Pixel signals \rightarrow Sequential output lines"

Multiplexer (MUX) Tasks:

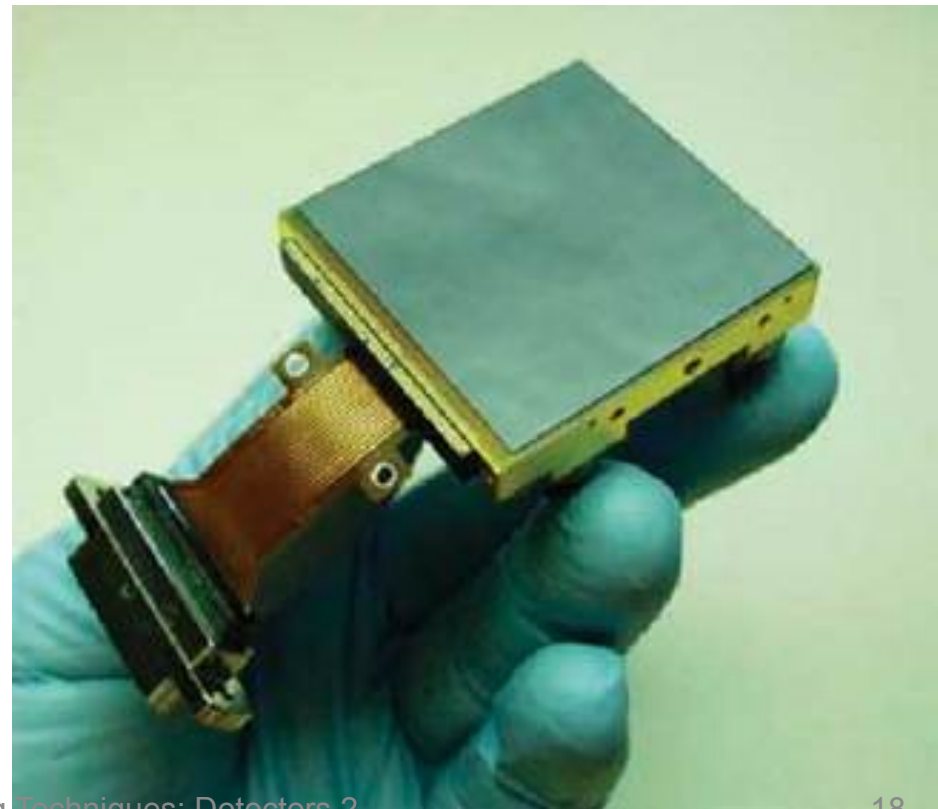
- address a column of pixels by turning on their amplifiers
 - pixels in other columns with power off will not contribute to signal
-
- Signal at **photodiode** \rightarrow gate T_1
 - Readout uses row driver R_1 and column driver C_1 to close the switching transistors T_2, T_3, T_4
 - Power to $T_1 \rightarrow$ signal to the output bus
 - Reset: connect V_R via T_5 and T_3 .



Example: The Teledyne HAWAII-2RG

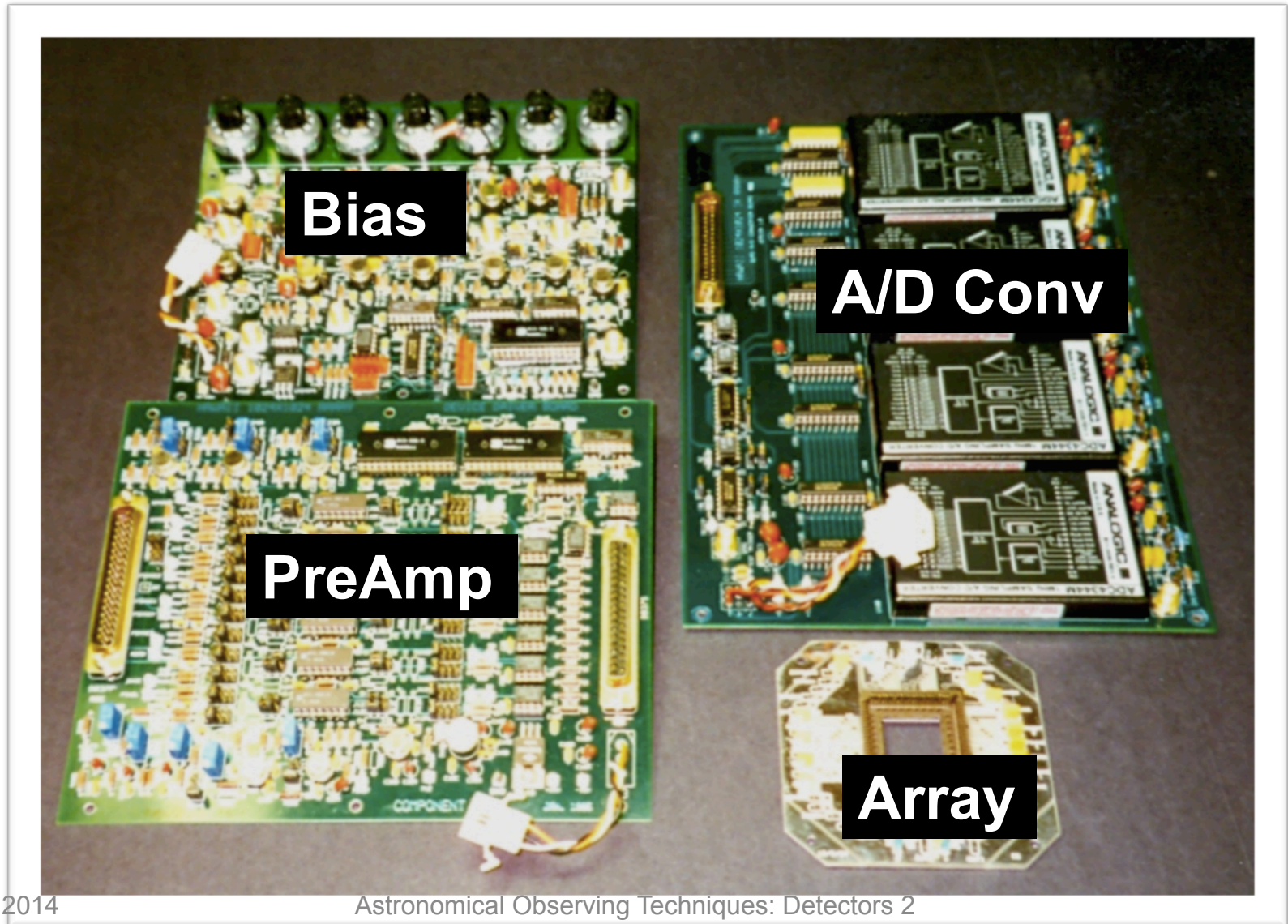
Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 μm
Fill factor	$\geq 98\%$
Output ports	Signal: 1, 4, 32 selectable guide window and reference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

Can also be combined to a 2x2 mosaic



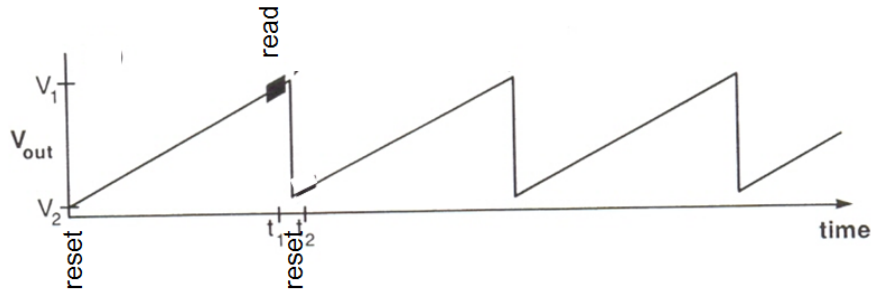
Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)



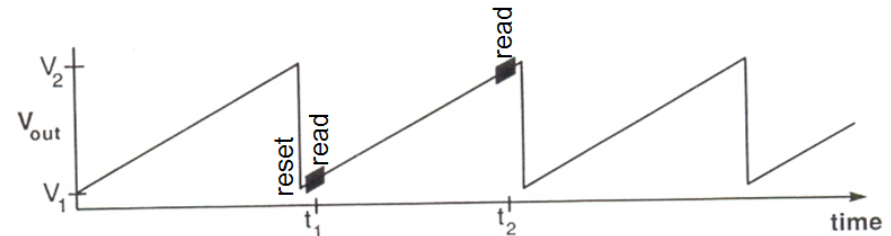
IR Array Read Out Modes

Single Sampling



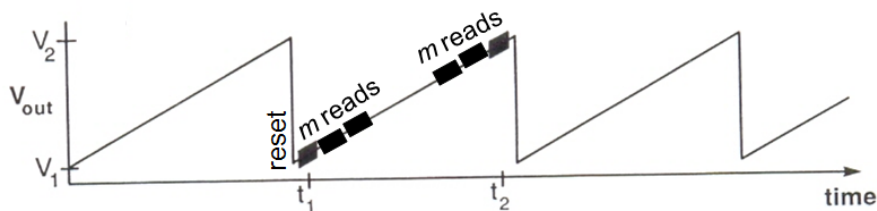
- most simple approach
- does not remove kTC noise
- measures the absolute signal level

Reset-Read-Read



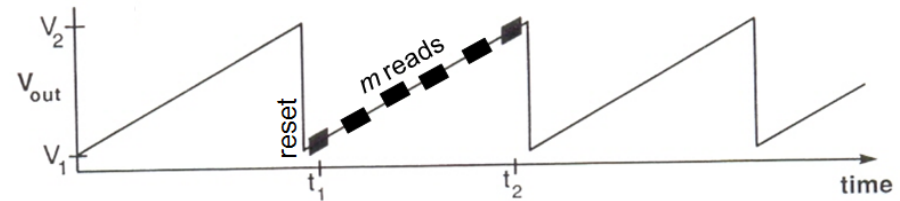
- Resets, reads and reads pixel-by-pixel
- Signal = Read(2) - Read(1)
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

(Multiple) Fowler Sampling



- similar to reset-read-read ...
- ... but each read is repeated m times
- Signal = mean(read2) - mean(read1)
- Reduces readout noise by \sqrt{m} over RRR

Sample-up-the-ramp Fitting



- m equidistant reads during integration
- linear fit \rightarrow "slope"
- reduces readout noise by \sqrt{m}
- particularly useful in space (cosmics!)

CCDs vs IR Arrays

CCDs:

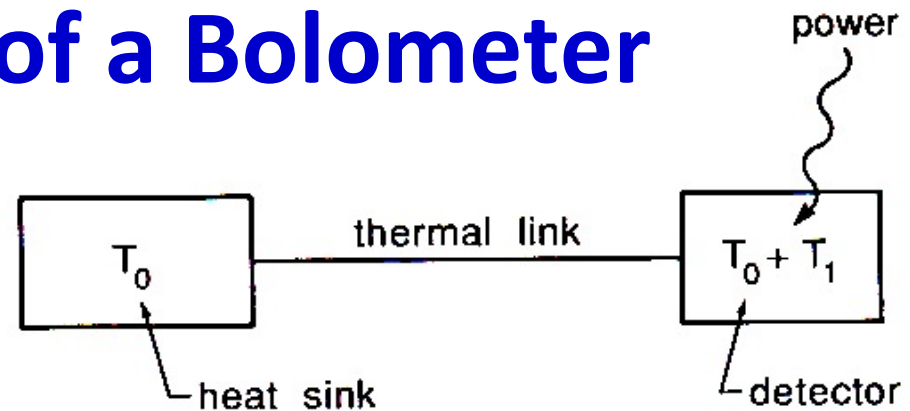
- destructive reads
- charges are physically shifted to the output line
- shutter determines exposure time

IR arrays:

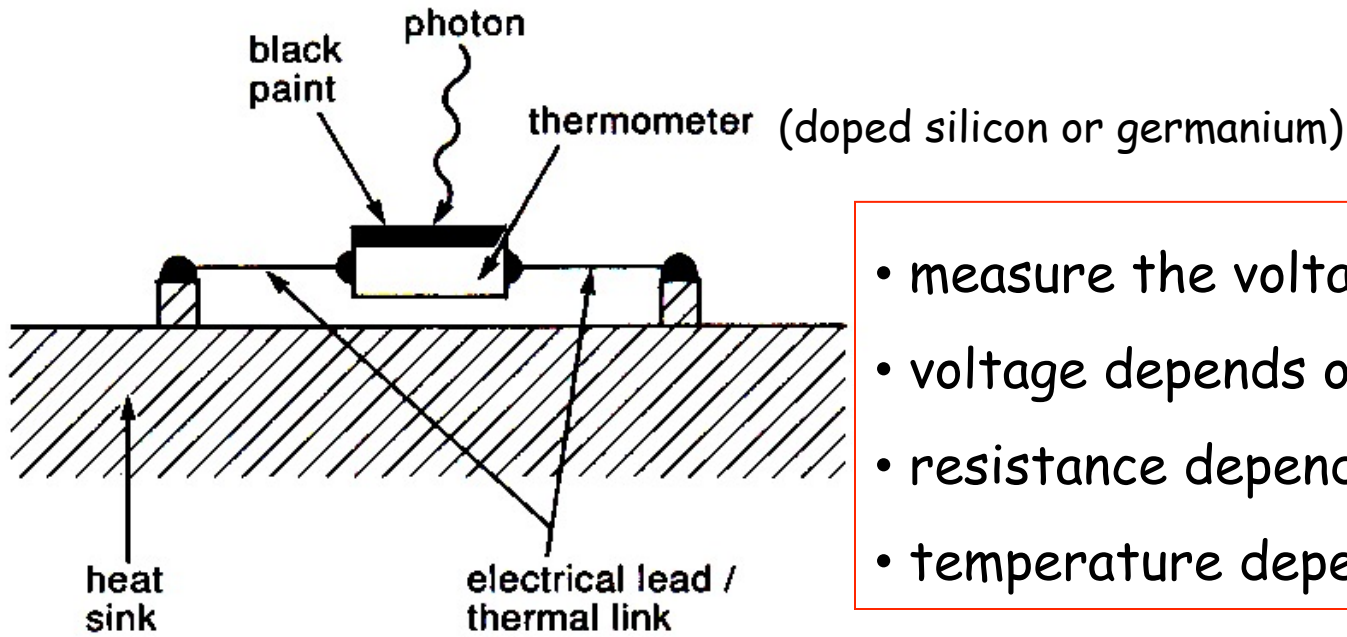
- non-destructive reads
- readout requires sophisticated multiplexer circuit
- multiplexer readout addresses individual pixels directly
- read/reset determines exposure time

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:
$$P_T(t) = GT_1 + C \frac{dT_1}{dt}$$

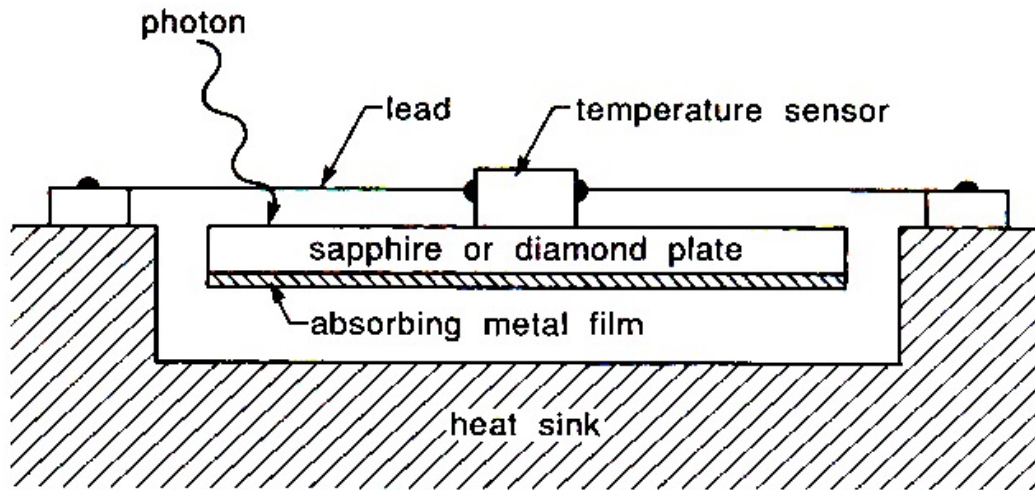


- measure the voltage across thermo.
- voltage depends on resistance
- resistance depends on temperature
- temperature depends on photon flux

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

QE and Composite Bolometers

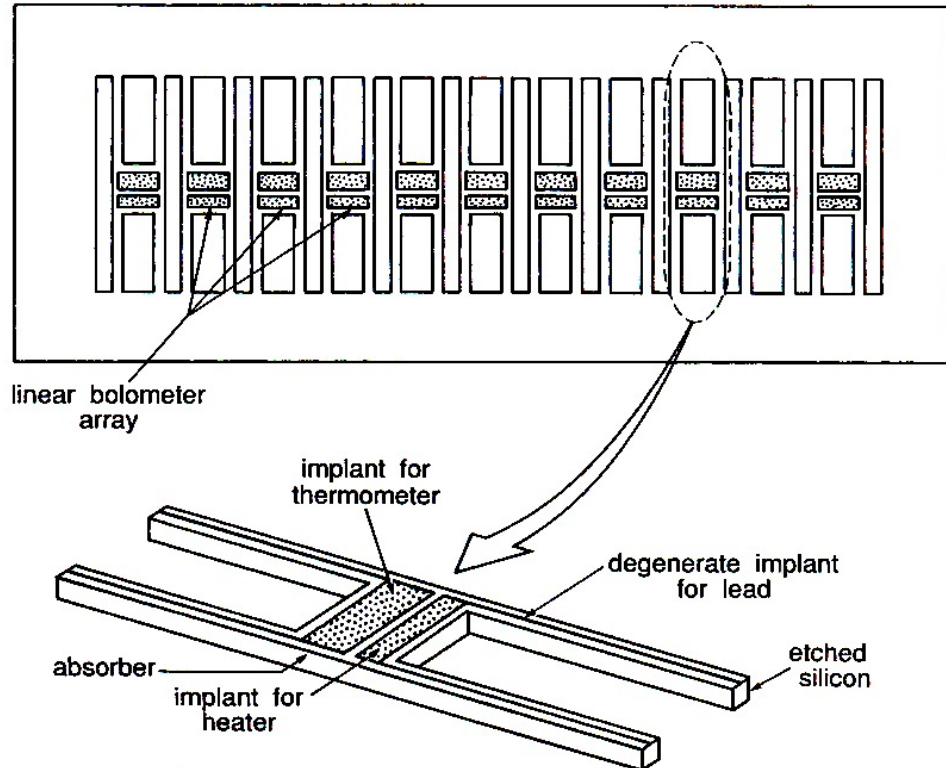
- Si bolometers with high impurity concentrations can be very efficient absorbers
- But: QE is too low. Solution: enhance absorption with black paint – but this will increase the heat capacity
- A high QE bolometer for far-IR and sub-mm would have too much heat capacity → **composite bolometers**



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 $\sim C/G \rightarrow$ small structures minimize the heat capacity C by reducing the volume of material.

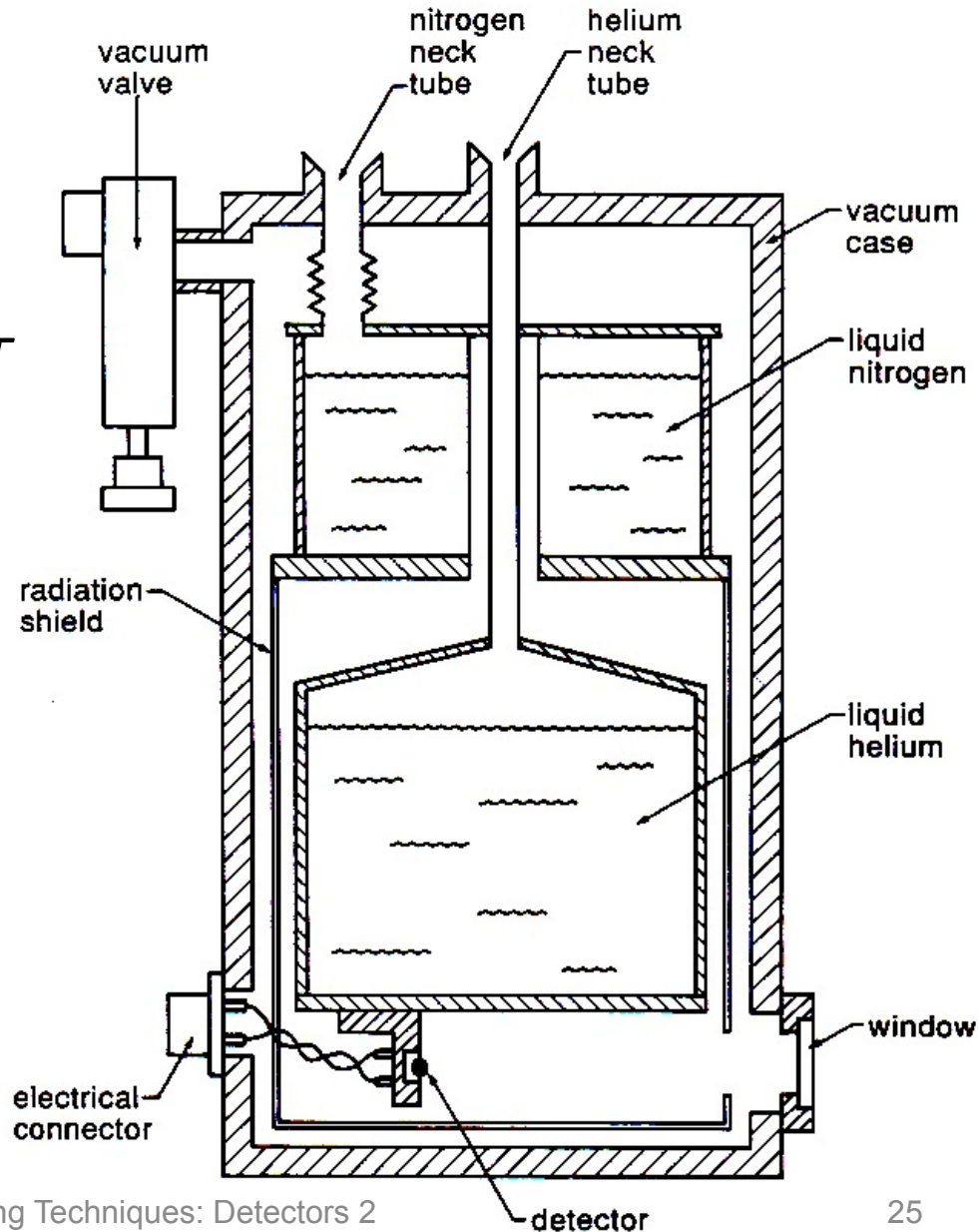


Low Operating Temperatures

Four standard cooling options:

1. ^4He dewar (air pressure) $\rightarrow T=4.2\text{K}$
2. ^4He dewar (pumped) $\rightarrow 1\text{K} < T < 2\text{K}$
3. ^3He (closed-cycle) refrigerator $\rightarrow T \sim 0.3\text{K}$
4. adiabatic demagnetization refrigerator $\rightarrow T \sim 0.1\text{K}$

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

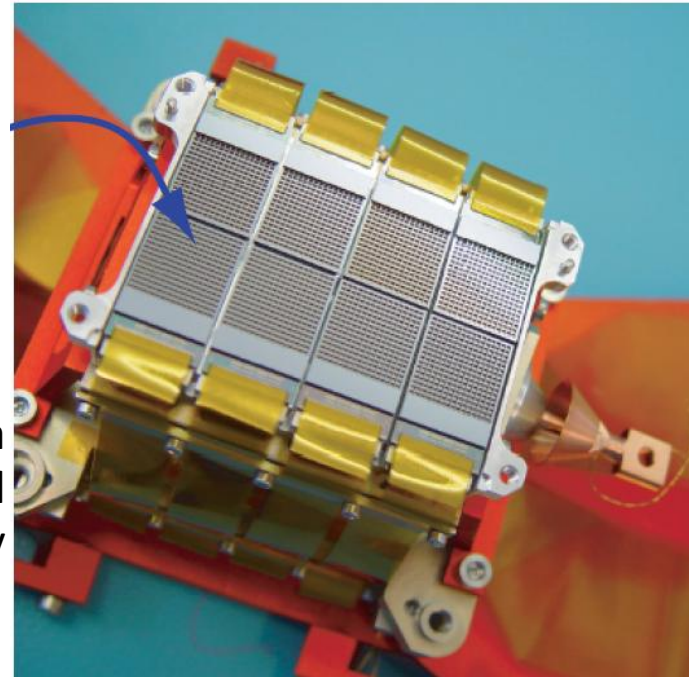


Bolometers – an Overview

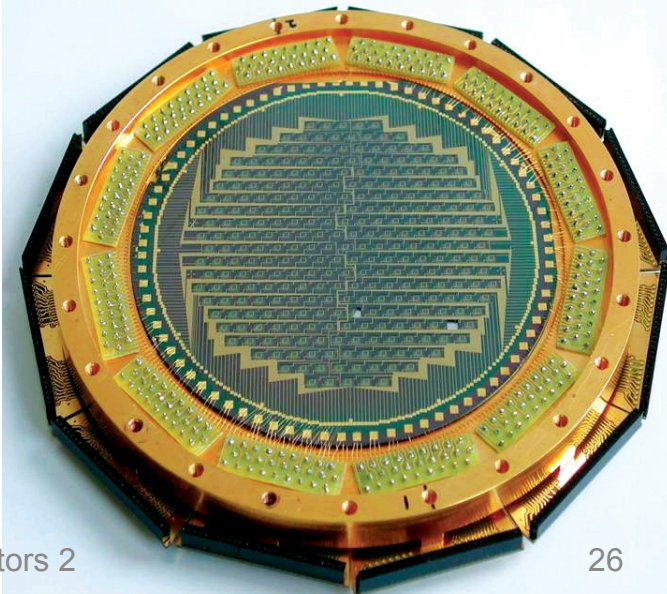


The “single pixel” Ge:Ga bolometer invented in 1961 by Frank Low

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



- LABOCA - the multi-channel bolometer array for APEX operating in the $870\ \mu\text{m}$ (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.

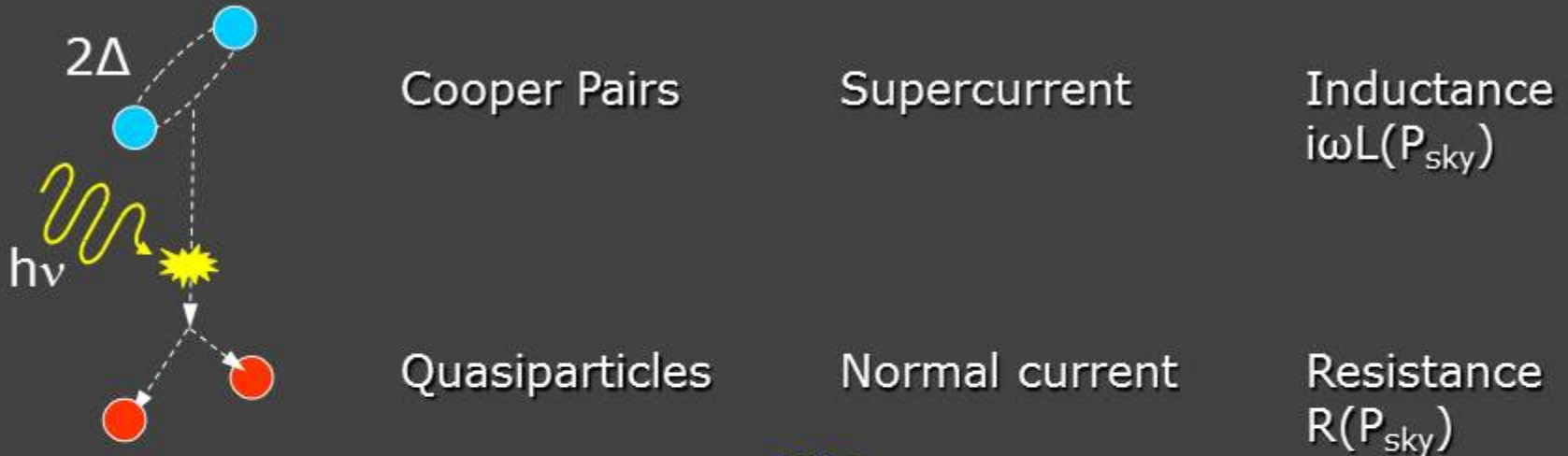
Case 2: detector noise-limited bolometer and a heterodyne receiver operating at the quantum limit ($h\nu \gg kT$).

→ 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

Superconductor has 2 types of charge carriers



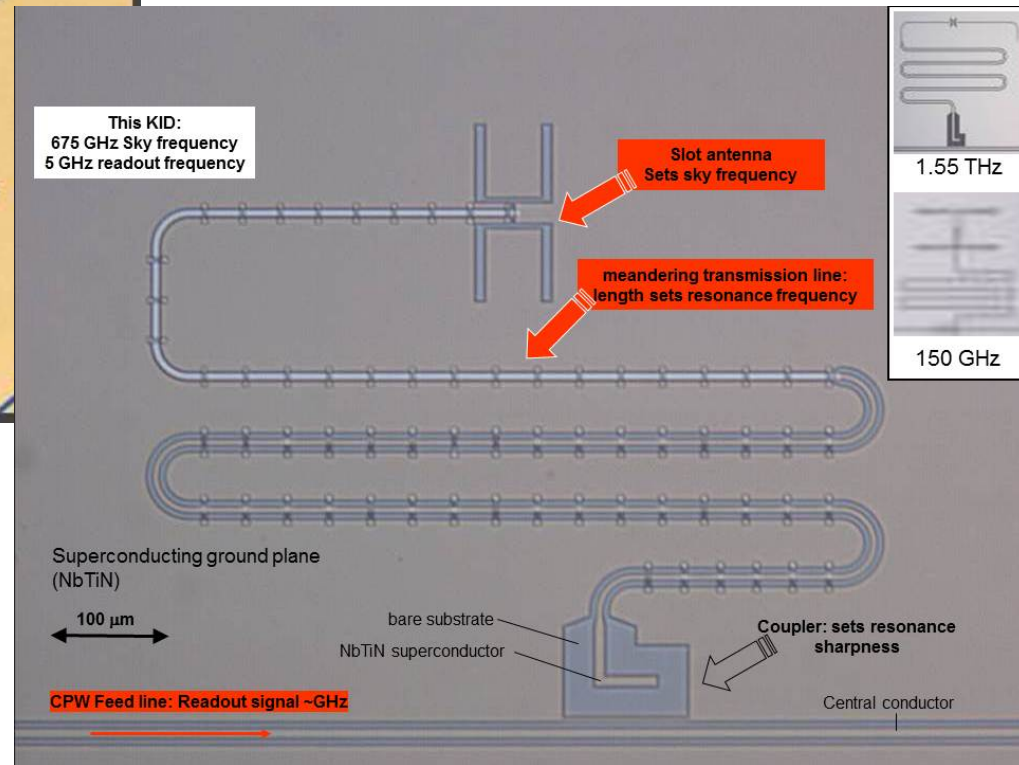
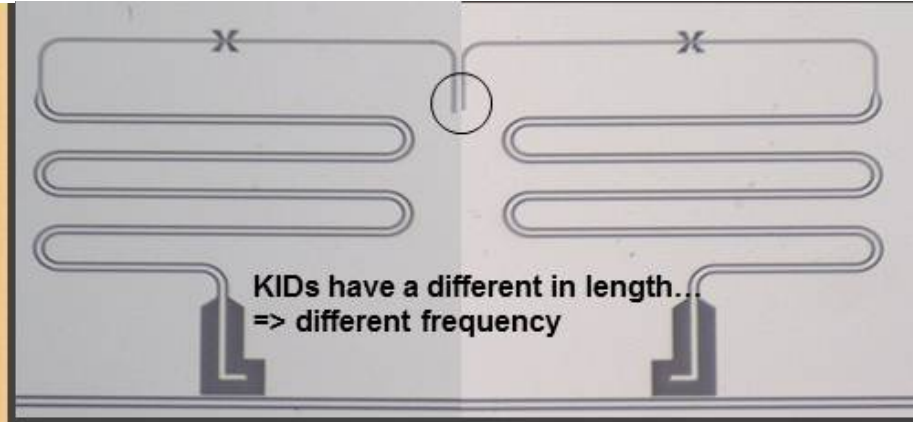
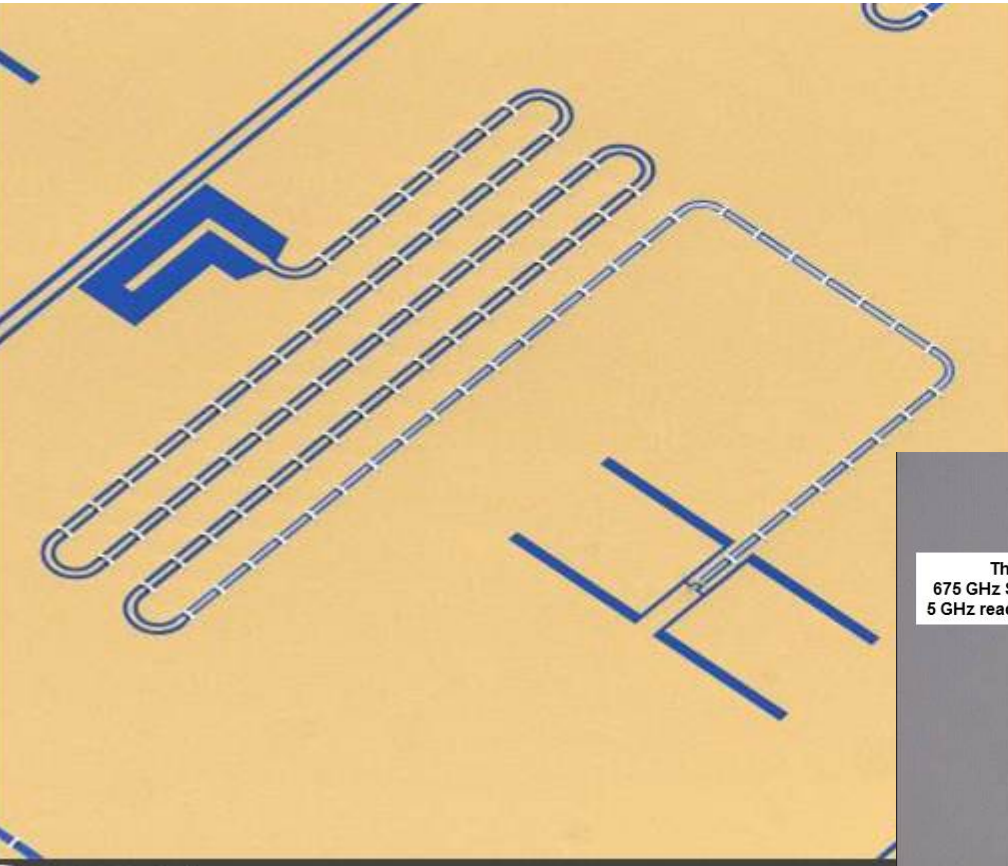
KID

Resonator measures changes in complex surface impedance due to sky signal

KID = Kinetic Inductance Detector

MKID = Microwave KID

MKIDS – Construction



MKIDS – Operating Principle

