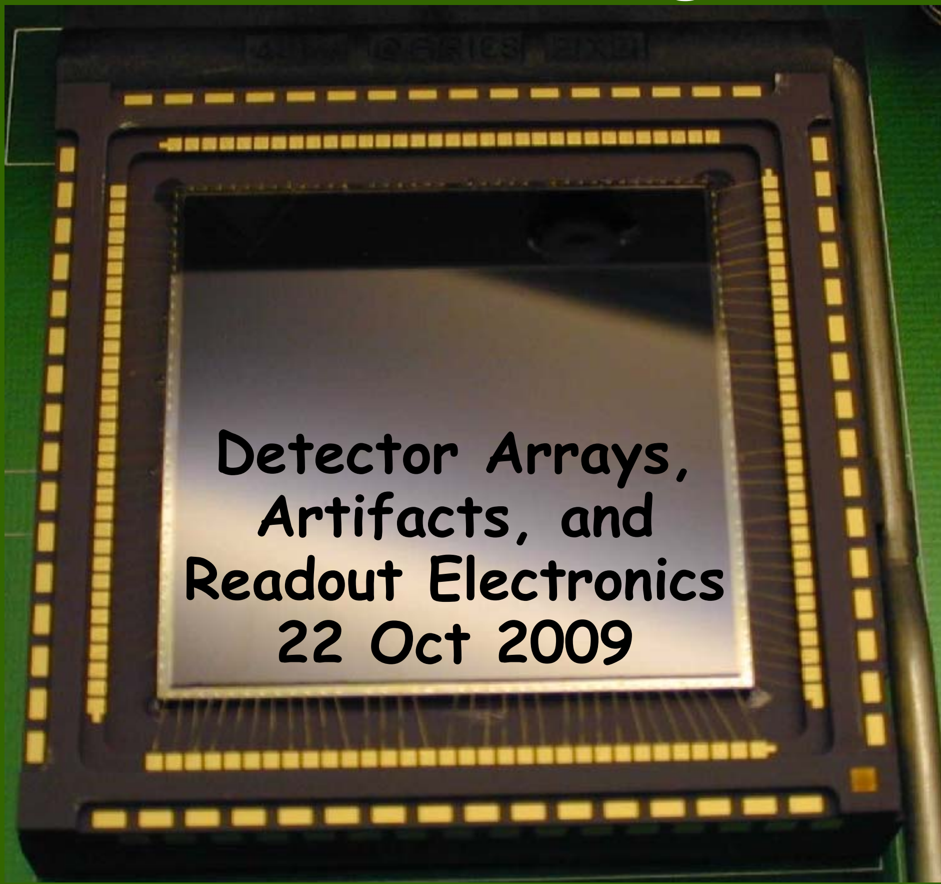
Detection of Light



See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Detector Arrays

Overview

Individual photoconductors + Readout electronics = Detector array

In the optical/IR there are two main types:

IR arrays (1μm – 40 μm)

+ direct pixel access

- complex and expensive devices (~few 10^5\$)

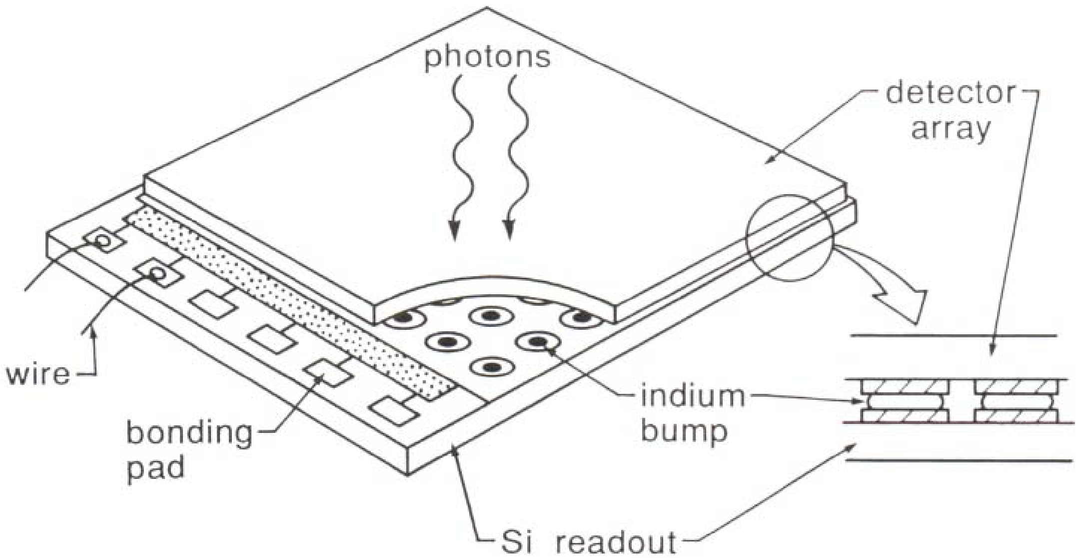
CCDs (0.1nm – 1 μm)

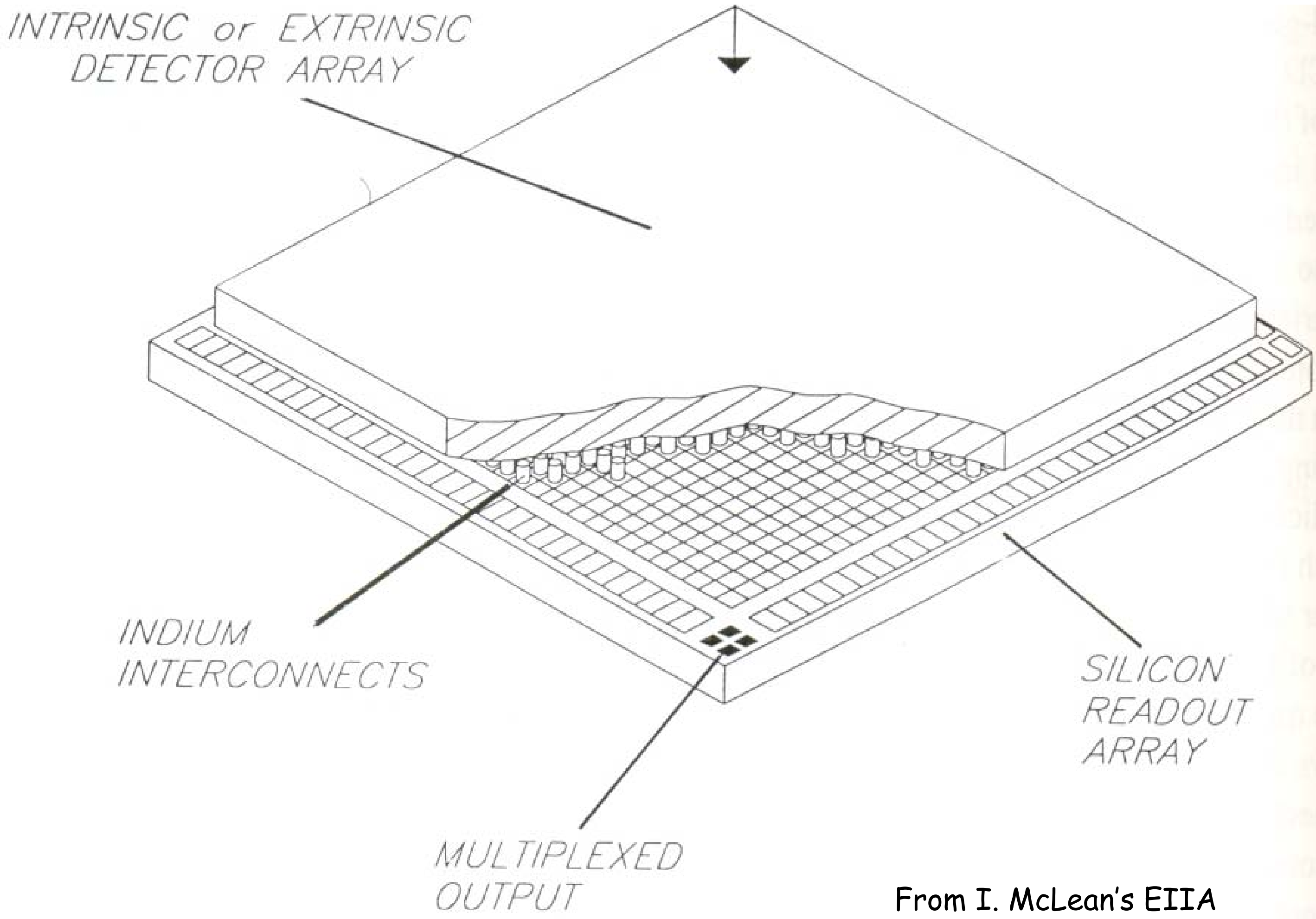
+ monolithic structures built in silicon wafers
  (incl. FETs → CMOS, which are a mixture between CCDs and arrays)

- charge transfer inefficiencies

Production of Infrared Arrays

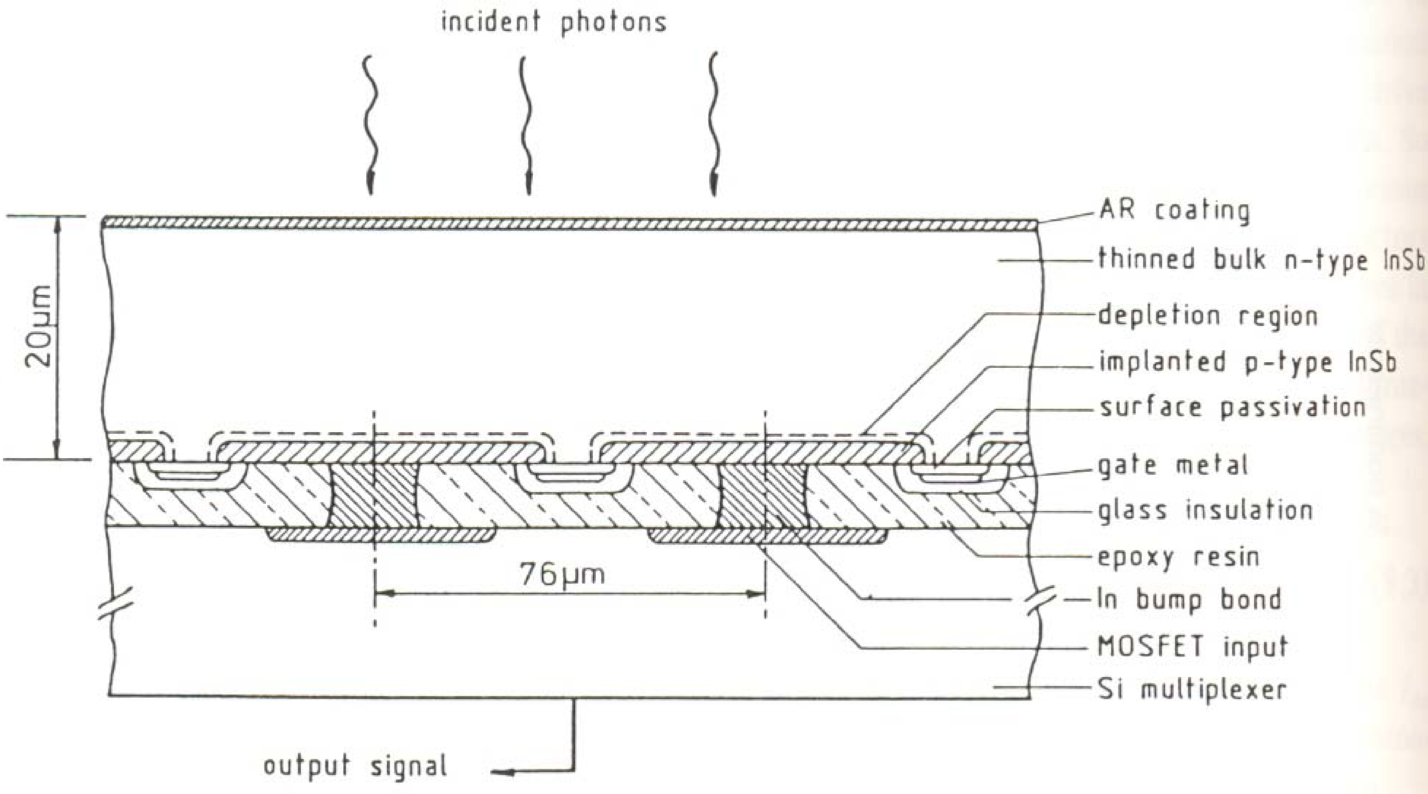
1. Produce a grid of readout amplifiers
2. Produce a (matching mirror image) of detector pixels
3. Deposit Indium bumps on both sides
4. Squeeze the two planes together ➔ hybrid arrays
5. The Indium will flow and provide electrical contact





From I. McLean's EIIA

The Bonding Structure of IR Arrays



From I. McLean's EIIA

Typical Array Artifacts

Thermal Mismatch

Thermal mismatch is a problem when cooling the hybrid array!

Different thermal contraction between the layer of photo-sensitive material and the silicon readouts

Example: silicon α ~ $2.6\cdot10^{-6}$, HgCdTe α ~ $5\cdot10^{-6}$, $\frac{\Delta L}{L_0} = \alpha_L \Delta T$

→ $\Delta L_{mis} = L_0(\alpha_{HgCdTe} - \alpha_{Si})\Delta T = 36.9mm\cdot(5-2.6)\cdot10^{-6}\frac{1}{K}\cdot200K = 17.7\mu m$

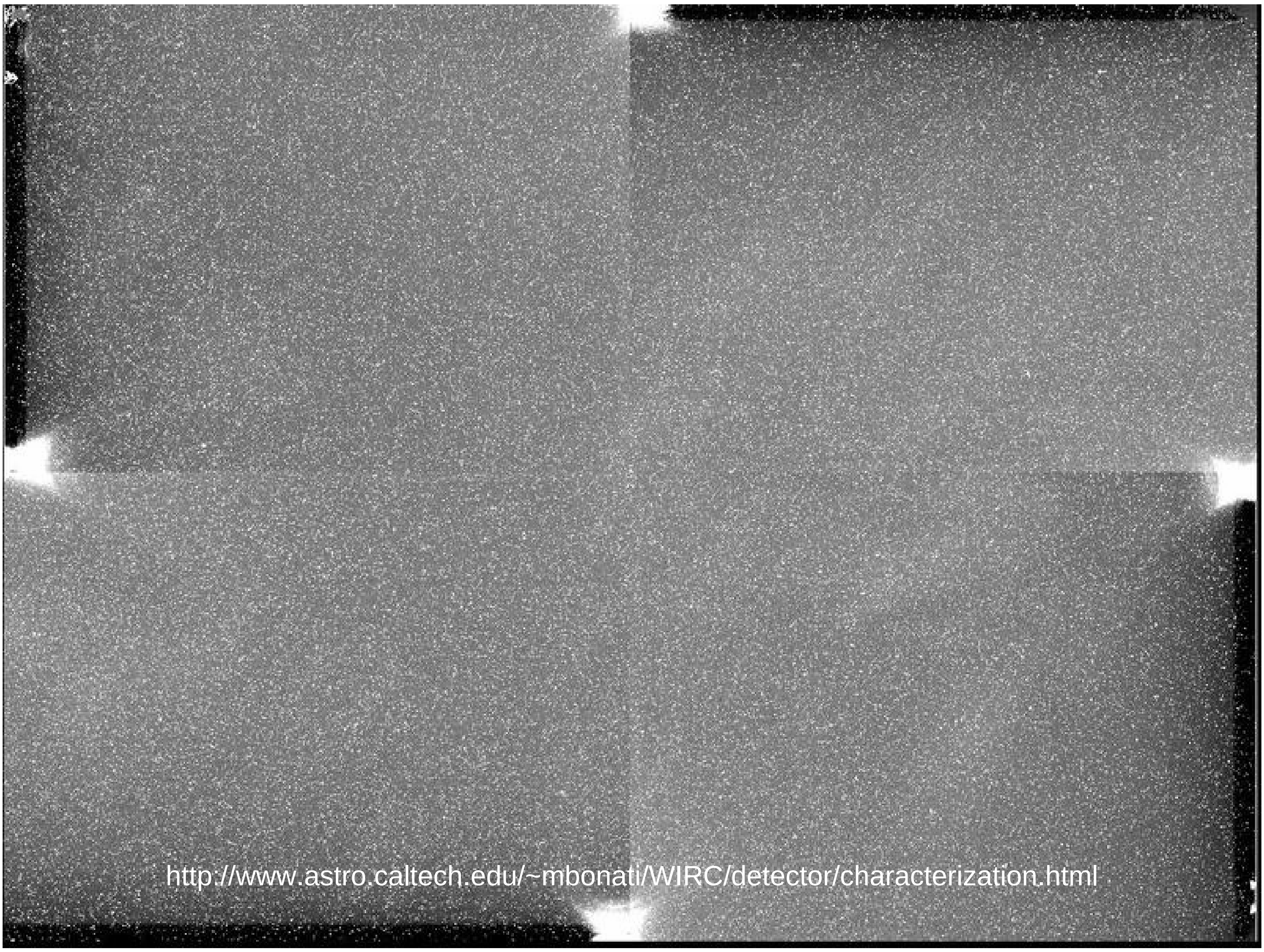
for a 2k × 2k array with 18µm pixels

→ mismatches of ~ 1 pixel → stresses → Indium bumps break → dead pixels

Thermal Pre-Amp Glow

Electroluminescense and thermal glow are a problem for active devices placed closely (to avoid signal losses and noise in long connections) to the phot-sensitive area.

Mitigation: turn MOSFETs off while integrating.
(This does not work for CTIAs where the power has to be on to balance the output continuously).



Dead / Hot / Rogue Pixels

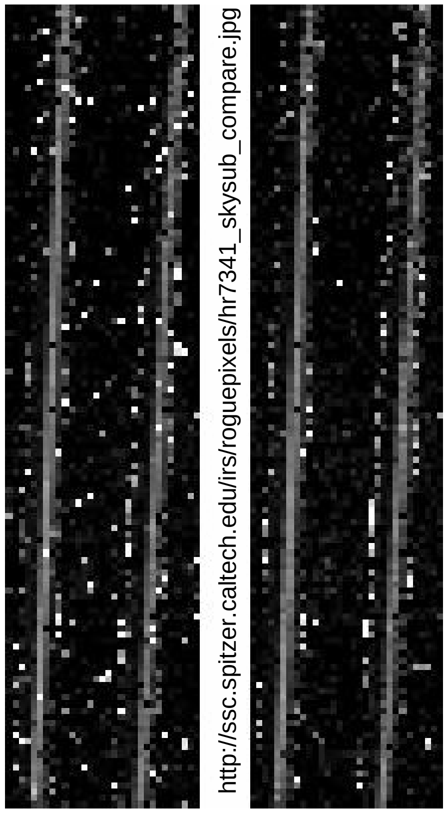
A dead pixel is a defective pixel that delivers no signal and cannot be used.

A hot pixel displays a highly elevated signal and noise level. It usually remains "hot" but may deliver limited information.

A rogue pixel* has abnormally high dark current and/or photon responsivity (similar to a hot pixel) . However, rogue pixels sometimes may be "healed" by annealing or other techniques.

Mitigations:

- assign `NaN' (not-a-number status)
- interpolate from nearest neighbour values
- subtract off-source image
- reduce bias voltage



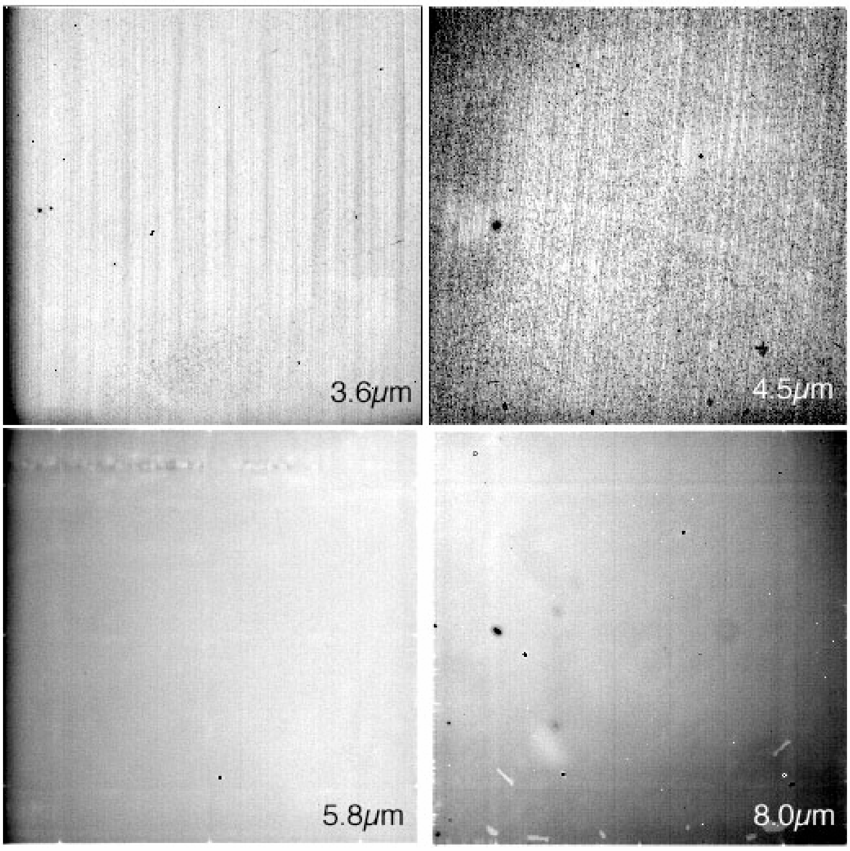
**Rogue = dishonest person, scoundrel, scamp*

Pixel-to-Pixel Variations

Also called "fixed pattern noise". It is a combination of offsets, dark current variations, and response variations.

Significant patterns can occur on small and large scales.

Example: the "super flats" for IRAC *(from the Spitzer IRAC User Manual)*



Mitigation:

Produce and apply "flat field" (= response map to uniform illumination)

→ accurate up to 10^{-5}.

Latent Images

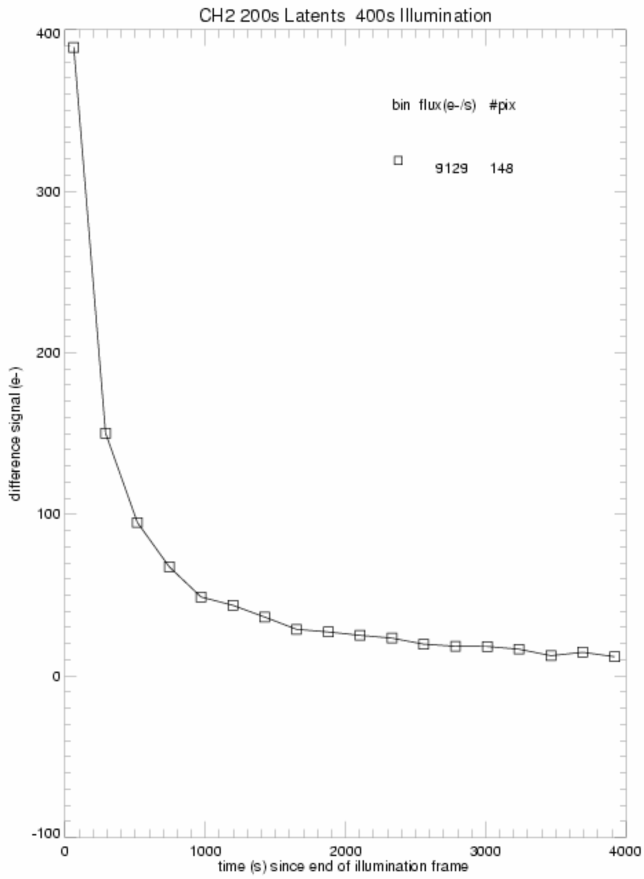
(or "Residual images" or "Memory effect")

After strong illumination a small fraction of the photoelectrons is *trapped*. The traps may release a hole or electron long after the illumination.

Typically, residual images are < 1% but can still create severe problems (remember, 1% is only 5 magnitudes).

Mitigations:

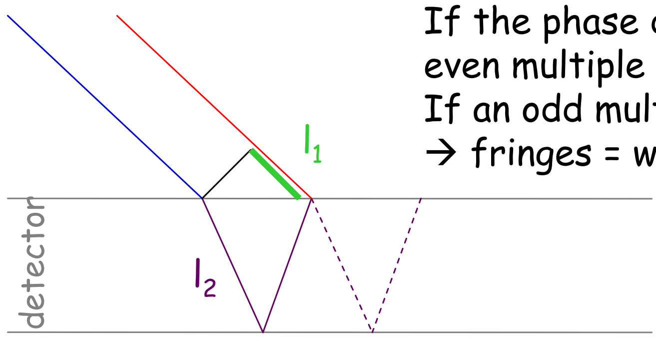
- just wait (decay time)
- apply frequent resets (clean the trap)
- annealing (heat array, e.g. 6K → 20K)
- use ND filters or shutter during target acquisition.



from Spitzer-IRAC User Manual (section 6.1.3.2.3)

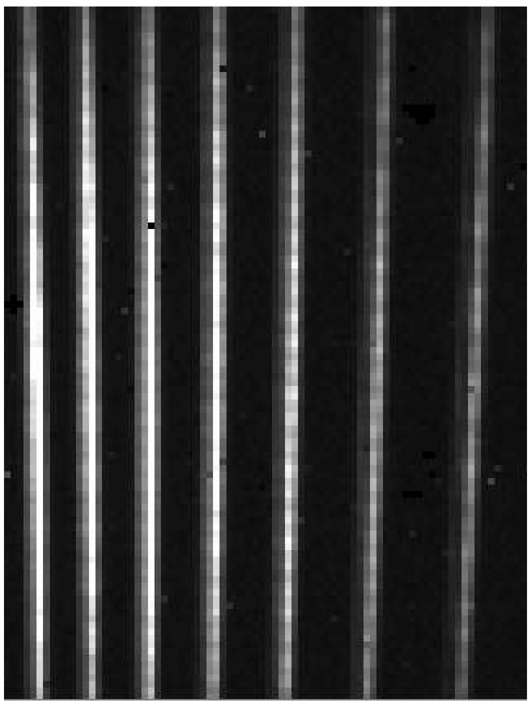
Fringing

Photons may reflect off the back of the detector and interfere with the incoming light.



If the phase difference between l_1 and $n \cdot l_2$ is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs → fringes = wave pattern.

Fringing is most prominent in spectrographs where the monochromatic wavelength varies across the array and the conditions for constructive/destructive interference are locally met.



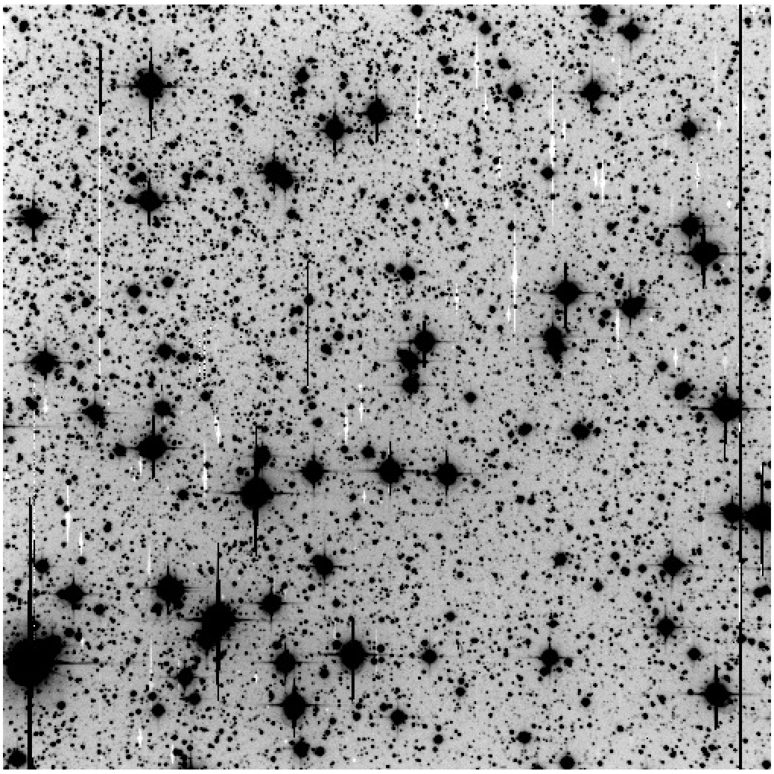
Crosstalk

When using multiple-amplifier readout, signal from one amplifier can "leak" into the signal of another.

Crosstalk ~ signal strength

The negative (white) images in the upper right quadrant correspond to the (black) star images of the lower left quadrant (flip the upper right quadrant left-right and up-down).

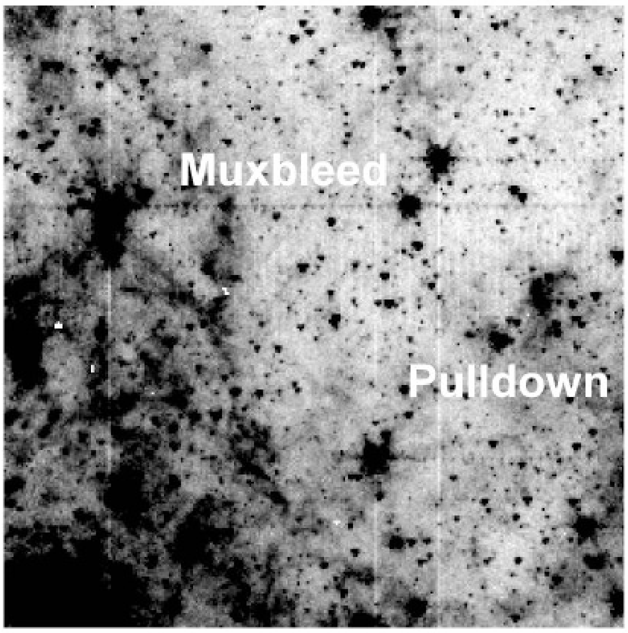
Note: there is also optical crosstalk when the nominal photon path crosses more than one pixel → problem in "thick" detectors.

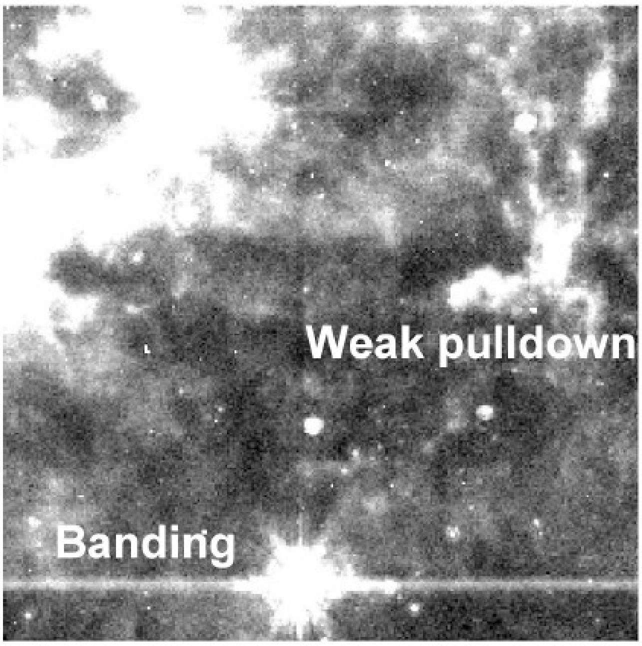


http://www.ctio.noao.edu/telescopes/36/0-9m.html

Pulldown (and other artifacts)

Pulldown occurs due to a depression of the bias voltage in columns containing very bright (sometimes also hot) pixels.





from Spitzer-IRAC User Manual (section 6.1.3.2.9)

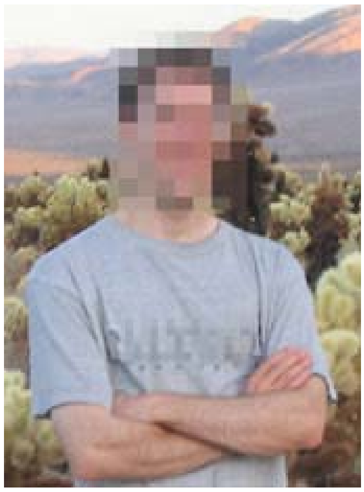
Pixelation

Pixelation is due to limited sampling with finite size pixels.

Mitigation:

- use more pixels per image resolution element
- dither images on sub-pixel scales
- interpolate between pixels

Pixelization is used intentionally to blur images:

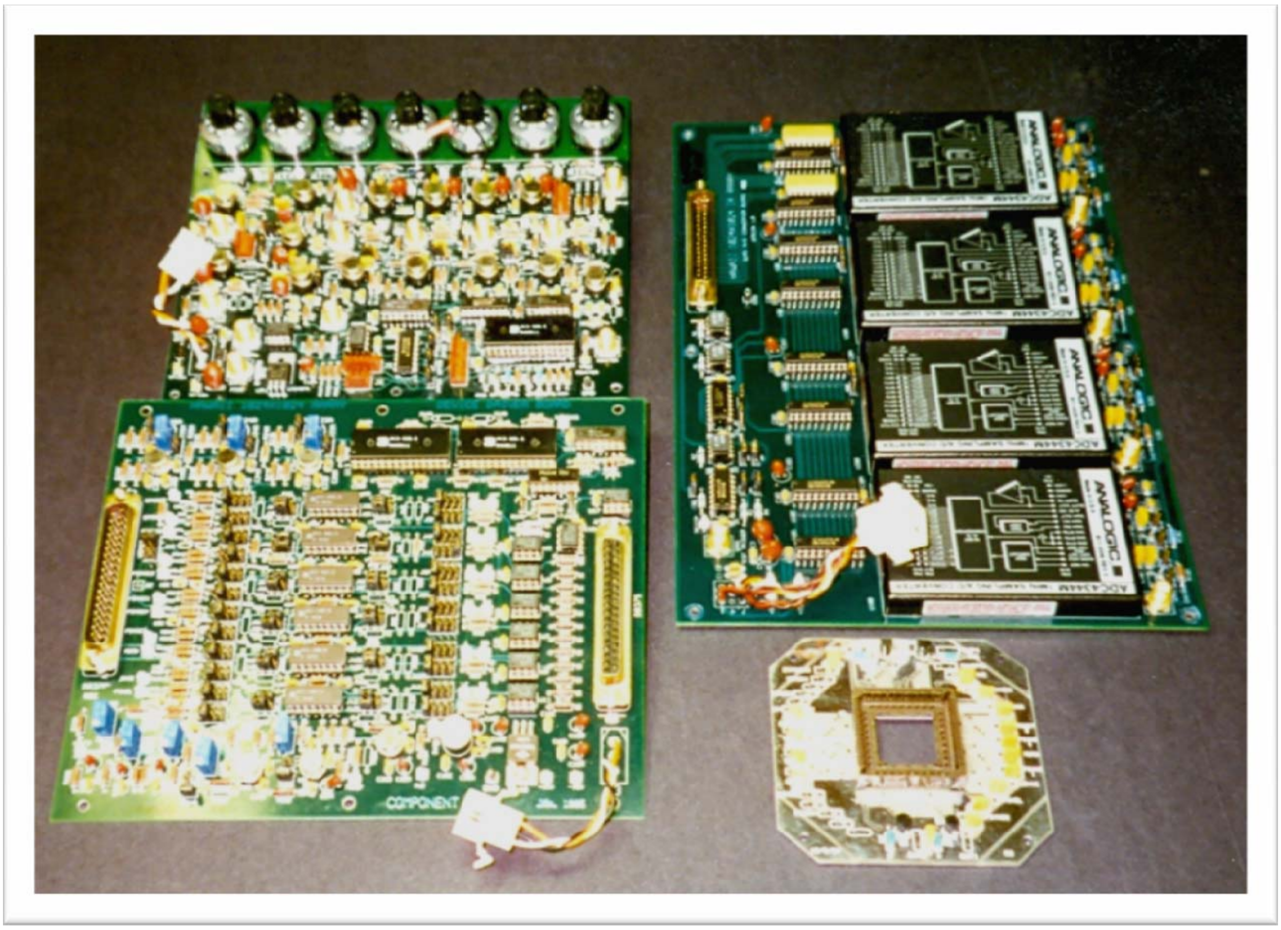


From Wikipedia:

Readout Electronics

Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)

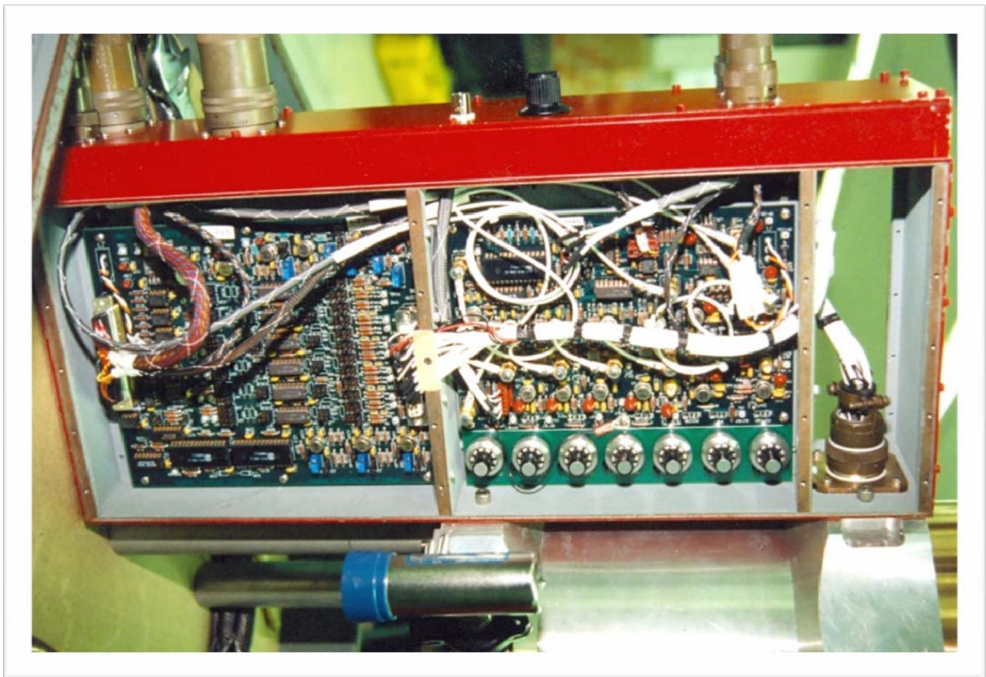


The Problem of Amplification

Typical signals per event are small and must be amplified by external electronics.

Problem: infinitesimal current from device with virtually infinite impedance.

→ Requires optimized, low-noise electronics



Active Electronics Components – An Overview

Two main types of components:

- Field-Effect Transistors (FETs) – the 1st stage
- Operational Amplifiers (Op Amps) – the 2nd stage

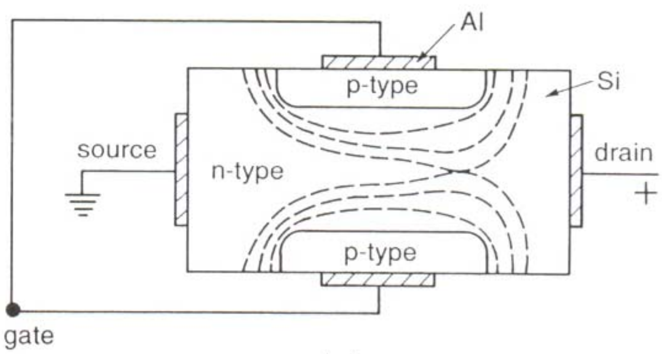
Two main types of amplifiers (circuits):

- Transimpedance Amplifier (TIA)
- Integrating Amplifiers:
    - simple integrators
    - capacitive transimpedance amplifiers (CTIA)

Field-Effect Transistors

In both FETs the current flows from the `Source' to the 'Drain' controlled by an electric field via the `Gate'.

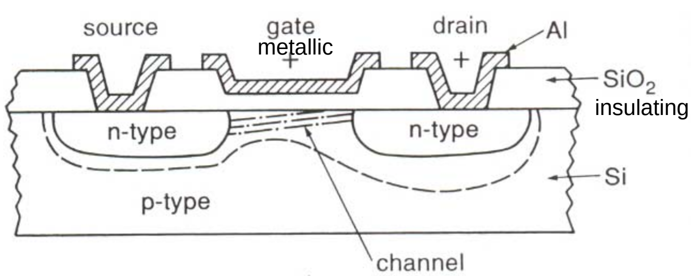
Junction FETs (JFETs)



Operation depends on high impedance obtained in he depletion region (which grows with the gate voltage).

When depletion regions join, no current flows. Beyond that point, small charges at the gate produce large changes in the drain-source current.

Metal-Oxide Semiconductor FETs (MOSFETs)



Two n-type dopants are implanted into p-type substrate, isolated from each other → no current.

If a positive voltage is applied to `gate' electrons gather below insulator → n-type channel → current flows from `source' to `drain'.

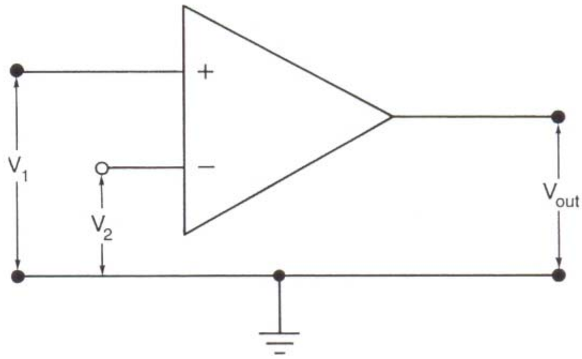
OP AMPs

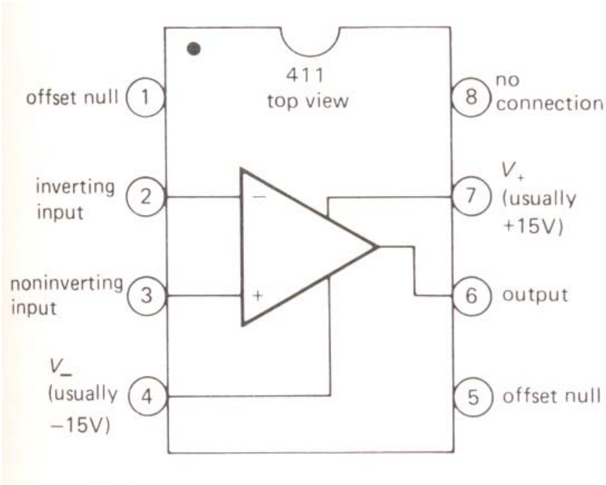
FETs are usually the first stage of amplification (often on the detector board)

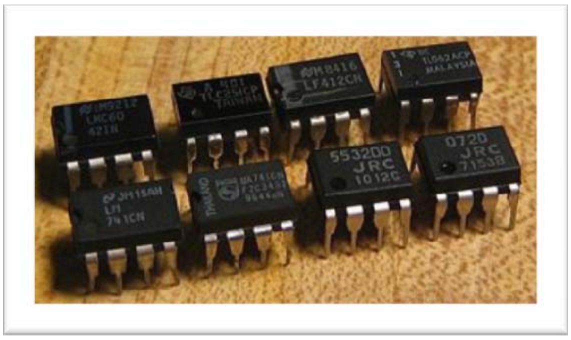
Second stage are often Operational Amplifiers (Op Amps)

Op Amps are complex integrated circuits, which can be understood as a single element:

$V_{out} \propto |V_1 - V_2|$



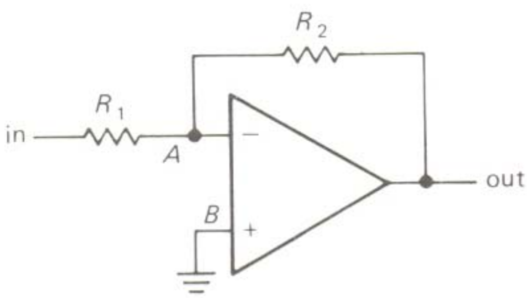




OP AMPs (2)

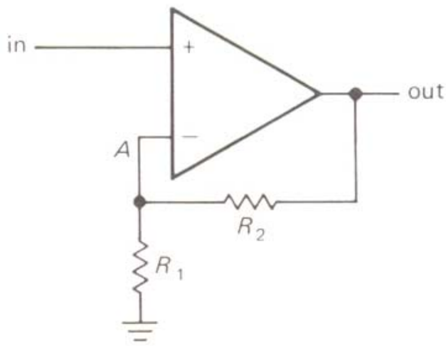
`+' and `-' refer to the non-inverting and inverting modes, i.e., changes in the output voltage relative to the polarity of the input voltage.

inverting amplifier
(small input impedance)



Voltage gain = $V_{out} / V_{in} = - R_2 / R_1$

non-inverting amplifier
(infinite input impedance)



Voltage gain = $V_{out} / V_{in} = 1 + R_2 / R_1$

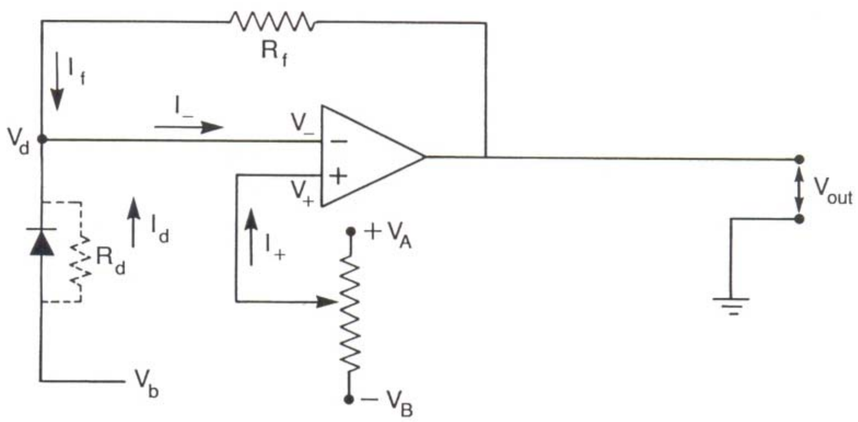
Golden rule I: the output attempts whatever necessary to make the voltage difference between the inputs zero.

Golden rule II: the inputs draw no current.

Transimpedance Amplifier (TIA)

Basic operation:

- Detector signal is connected to the inverting (-) input of the op amp.
- R_f provides negative feedback → amplifier tries to minimize the voltage difference $|V_+ - V_-| \sim 0$.
- The resulting V_{out} is a measure of the detector current
- The non-inverting input is just used to adjust the "dark level".



$$V_{out} = -V_b \frac{R_f}{R_d} = -I_d R_f$$

Advantage: V_{out} depends only on R_f and *not* on the impedance of the detector.
→ If I_d is linear with photon flux so is V_{out}.

TIA – Frequency Response

(see Rieke book, p.123 for details)

Noise voltage from amplifier:

$$\left| \left\langle \left(V^N_{out,A}\right)^2 \right\rangle^{1/2} \right| = \left\langle \left[V^N_A(f)\right]^2 \right\rangle^{1/2} \left(\frac{R_f}{R_d}\right) \left(\frac{1+\omega^2\tau_d^2}{1+\omega^2\tau_f^2}\right)^{1/2}$$

Noise voltage from detector:

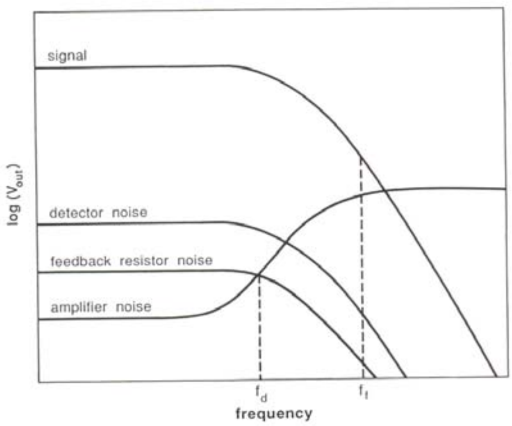
$$\left| \left\langle \left(V^N_{out,d}\right)^2 \right\rangle^{1/2} \right| = \left\langle \left[I^N_d(f)\right]^2 \right\rangle^{1/2} \frac{R_f}{\left(1+\omega^2\tau_f^2\right)^{1/2}}$$

Noise voltage from feedback resistor (ideally only kTC noise):

$$\left\langle \left(V^N_f\right)^2 \right\rangle^{1/2} = \frac{\left\langle \left(I^N_f\right)^2 \right\rangle^{1/2} R_f}{\left(1+\omega^2\tau_f^2\right)^{1/2}} = \left(\frac{4kTR_f\Delta f}{1+\omega^2\tau_f^2}\right)$$

The total output noise:

$$\left\langle \left(V^N_{out}\right)^2 \right\rangle^{1/2} = \left[\left\langle \left(V^N_{out,A}\right)^2 \right\rangle + \left\langle \left(V^N_{out,d}\right)^2 \right\rangle + \left\langle \left(V^N_f\right)^2 \right\rangle\right]^{1/2}$$

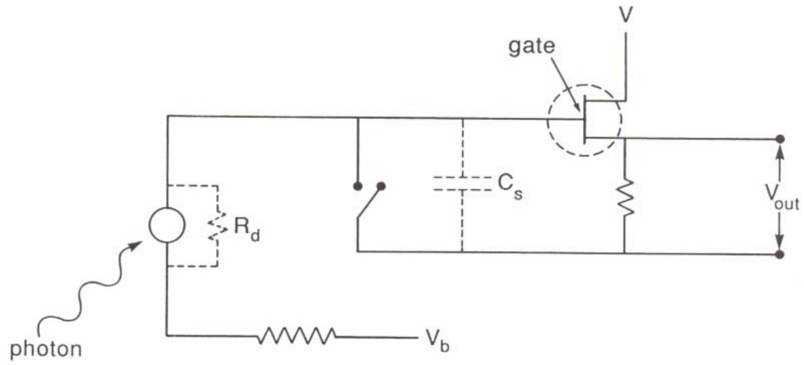


The frequency response of the circuit has to be limited to the region where high S/N is achieved (or high frequency noise will be added and can even dominate the signal) → electronic filters.

Integrating Amplifiers – Simple Integrators

FETs in "classical" thinking: a small charge flowing into the gate enables a large source-drain current.

FETs as integrating amplifiers: a small charge deposited on the capacitance at the gate creates a voltage $V=Q/C_g$. That charge can be read out by monitoring the source-drain current.



Advantage: better S/N than TIAs for long time constants
Disadvantage: bias voltage is not kept constant

Integrating Amplifiers: CTIA
(Capacitive transimpedance amplifiers)

Current can be generated from the feedback capacitor to the input of the amplifier by varying the output voltage of the amplifier.

Keeps bias voltage constant; the amplifier will balance itself: $I_f \sim I_d$

The voltage gain is:

$$V_{out} = -V_{in}\frac{C_d}{C_f}$$

Important to keep C_f small!