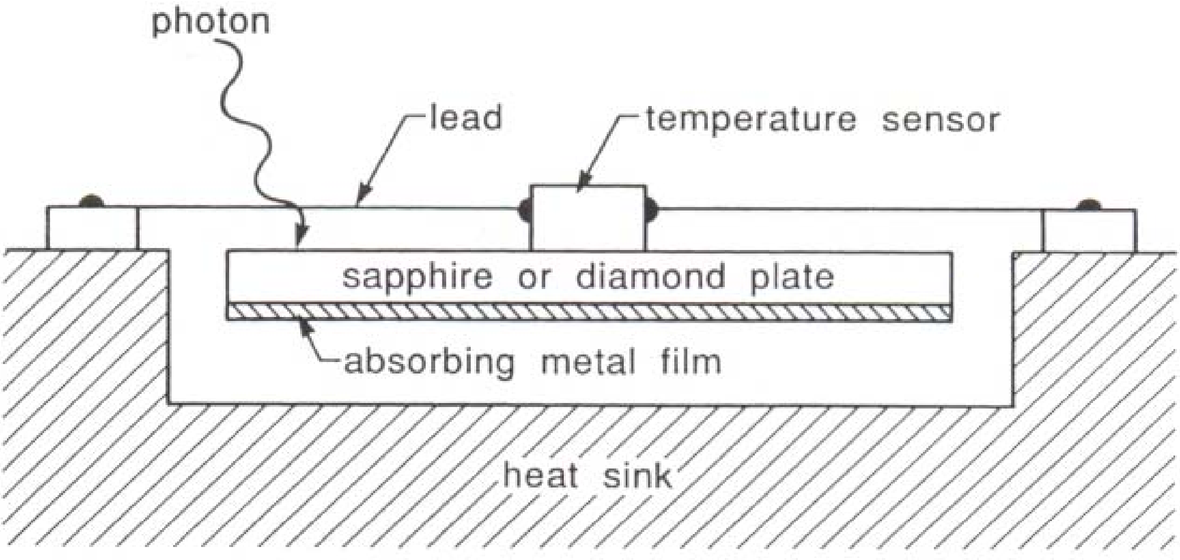
Astronomische Waarneemtechnieken
(Astronomical Observing Techniques)

9th Lecture: 19 November 2008



Based on "Detection of Light - from the Ultraviolet to the Submillimeter", by George Rieke, 2nd Edition, 2003, Cambridge University Press, ISBN 0-521-01710-6.

Outline

1. Introduction
2. Photon Detectors
    a) Photographic Plates
    b) Intrinsic Photoconductors
    c) Extrinsic Photoconductors
    d) Stressed and BIB Detectors
    e) Photodiodes
    f) Array Readout and Electronics
    g) CCDs
    h) Some Aray Artifacts
3. Thermal Detectors
    a) Bolometers
    b) Composite and etched Bolometers
4. Coherent Receivers
    a) Principle of Heterodyne Receivers
    b) Mixers and Local Oscillators
    c) Comparison: coherent ⇔ incoherent Receivers

Three Basic Types of Detectors

1. Photon detectors

   Respond directly to individual photons → releases bound charge carriers. Used from X-ray to infrared.

   Examples: photoconductors, photodiodes, photoemissive detectors, photographic plates

2. Thermal detectors

   Absorb photons and thermalize their energy → modulates electrical current. Used mainly in IR and sub-mm detectors.

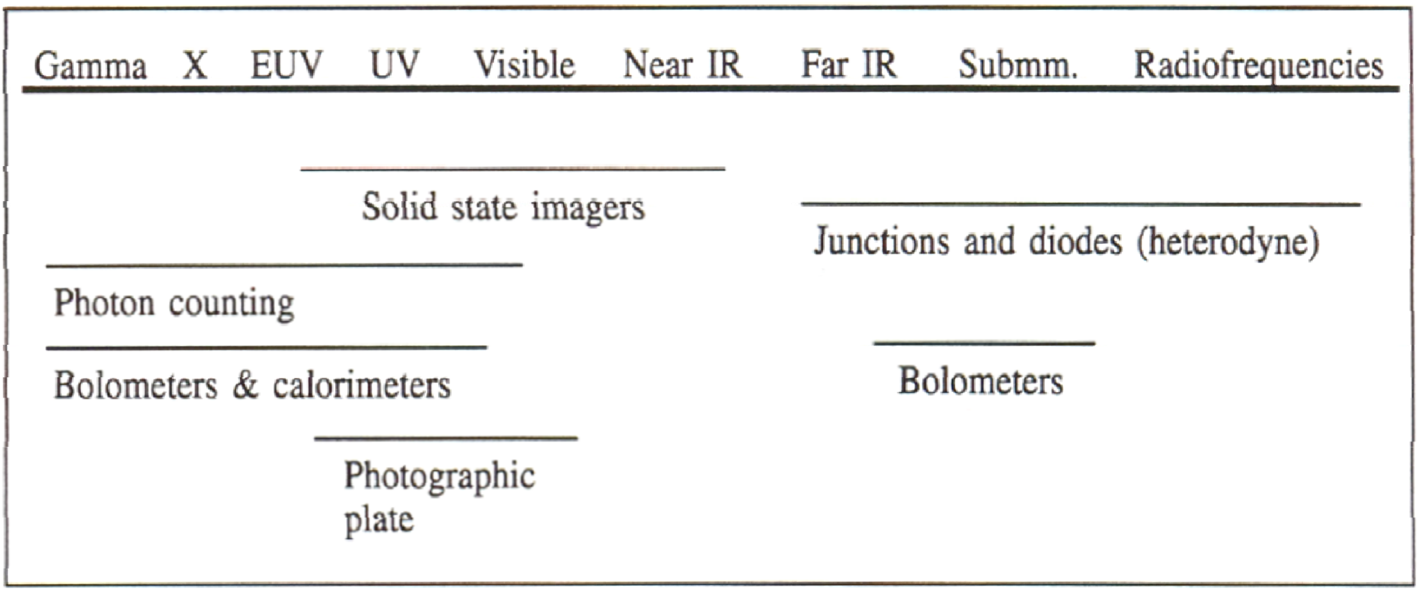
   Examples: bolometers

3. Coherent receivers

   Respond to electrical field strength and preserve phase information (but need a reference phase "local oscillator"). Mainly used in the sub-mm and radio regime.

   Examples: heterodyne receivers

Detector Types ⇔ Wavelength Range

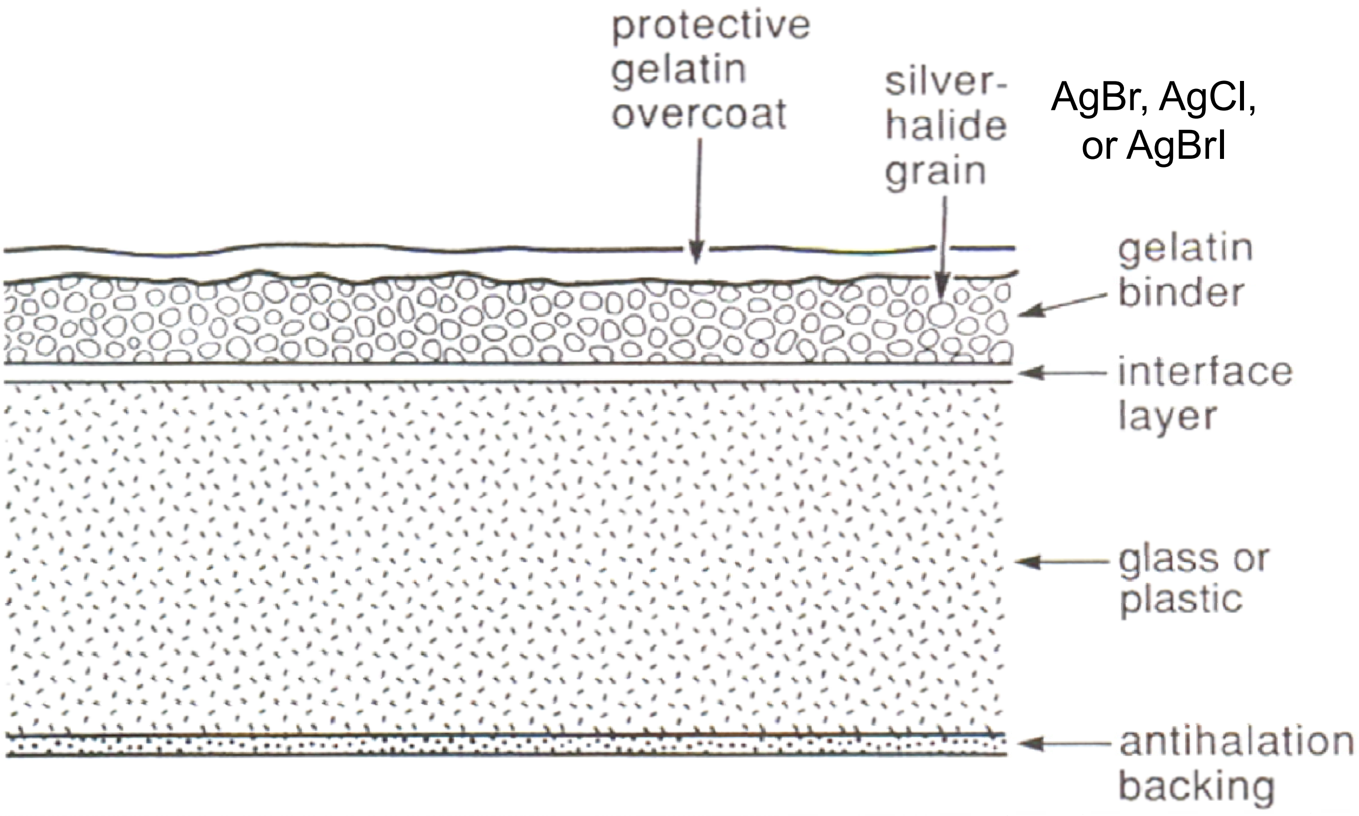


Part I
Photon Detectors

Part II
Thermal Detectors
Part III
Coherent Receivers

Photographic Plates

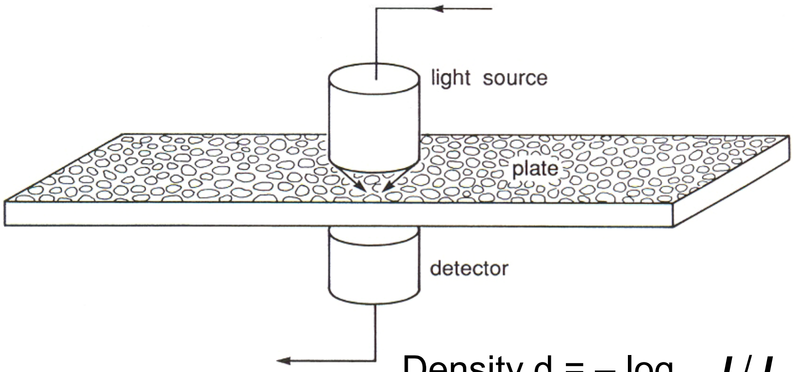
The Photographic Plate



Bandgap of AgBr is 2.8 eV ($\lambda < 440$nm for direct absorption)

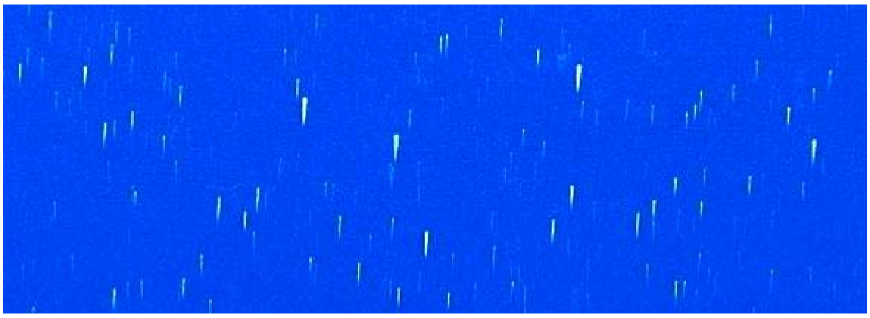
Analysis of Photoplates

- Densitometer!



Density $d = -\log_{10} I / I_0$

- and simple scanners
- (e.g. Digitized First Byurakan Survey (DFBS))



Advantages of Photographic Plates

- A 8" – 10" plate can have 10^{11} – 10^{12} grains, ~10^{9} pixels
- Inexpensive
- Include own data storage system
- Stable over very long periods of time

Disadvantages of Photographic Plates

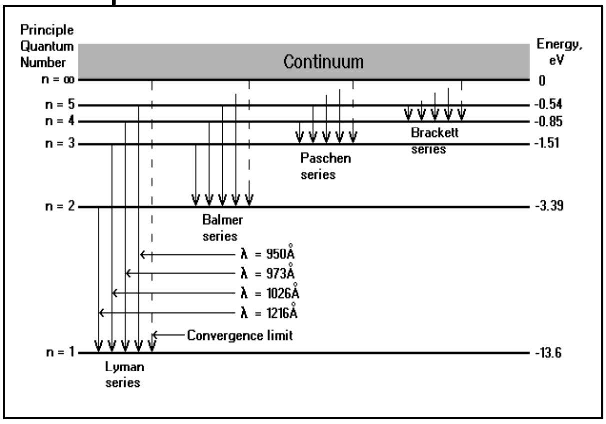
- Low DQE (~2-5%)
- Non-linearity
- Non-uniformity
- Time resolution
- Wavelength coverage
- Digitization

Side note: Solid State Physics Basics

Electronic States and Bands

Single atomic system

Example: H atom

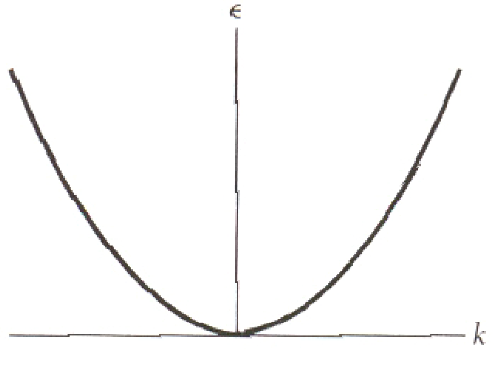


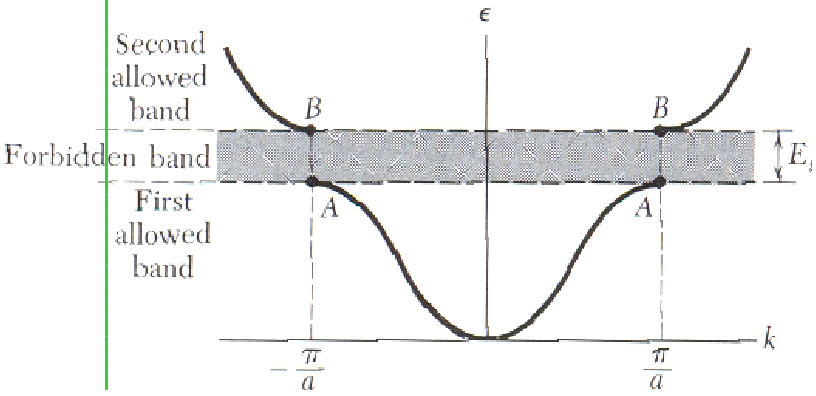
Atomic crystal

Wavefunctions Ψ overlap

→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

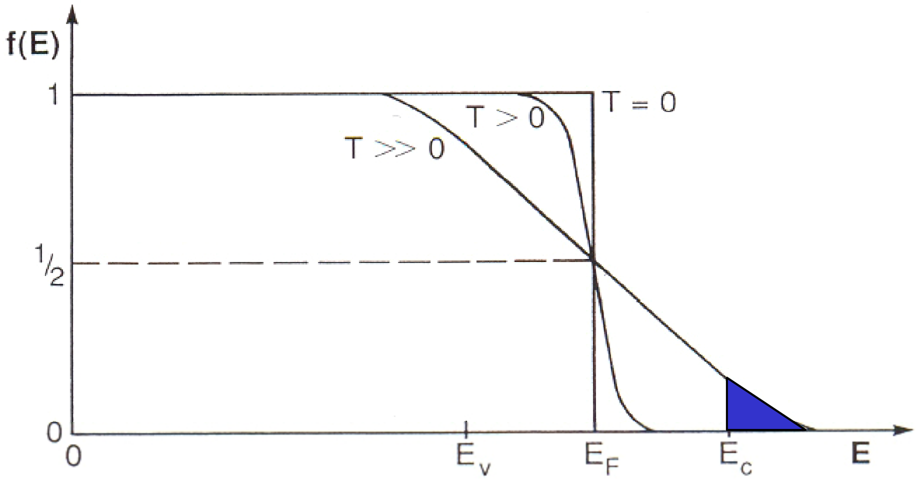
→ Multiple splitting ➔ "bands"





The Fermi Energy

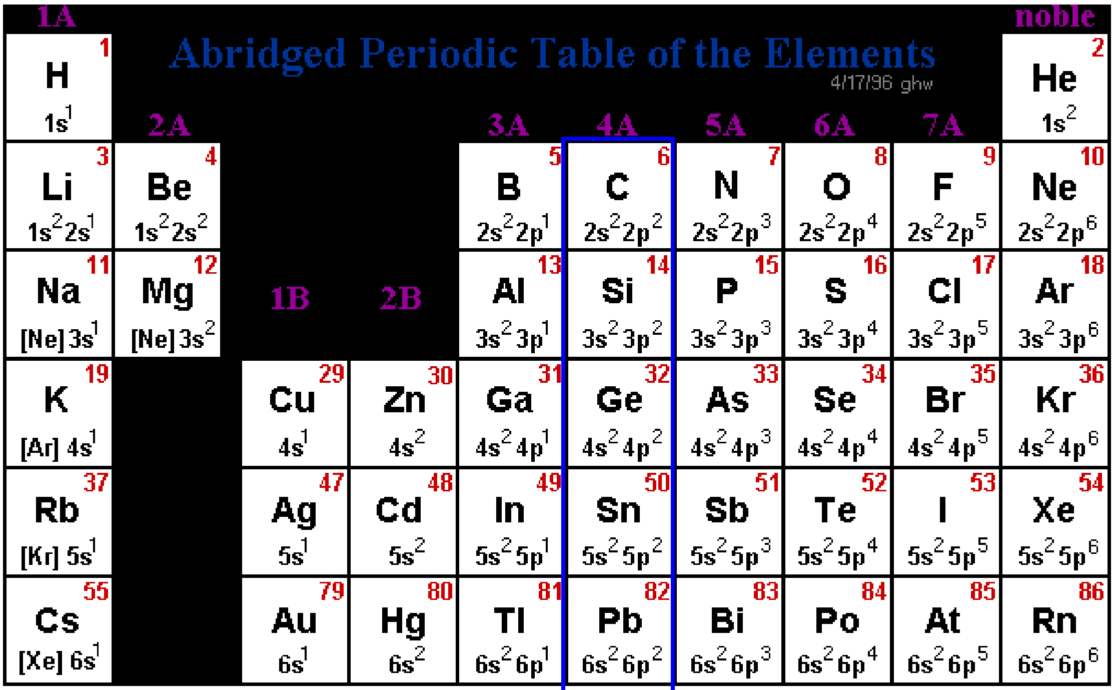
The Fermi energy E_F determines the concentration of electrons in the conduction band.



$$n_0 = N_c f\left(E_c\right) \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2}$$

$$\text{and} \quad f\left(E_c\right) = \frac{1}{1+e^{\left(E_c-E_F\right)/kT}} \overset{E_c-E_F>>kT}{\approx} e^{-\left(E_c-E_F\right)/kT}$$

The Periodic System of the Elements



Abridged Periodic Table of the Elements

4/17/96 ghw

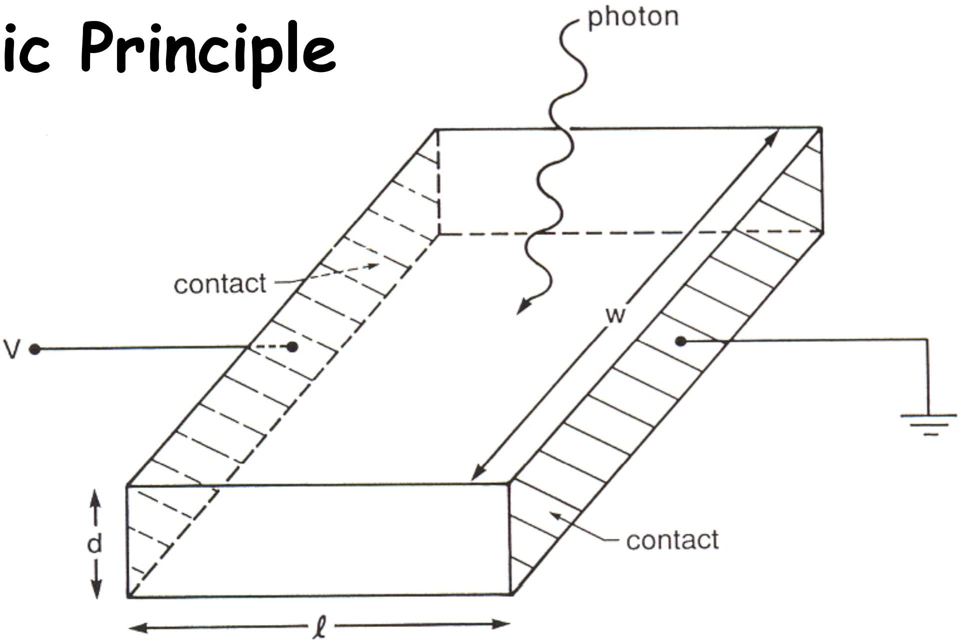
1A	2A	1B	2B	3A	4A	5A	6A	7A	noble
H 1 $1s^1$									**He** 2 $1s^2$
Li 3 $1s^2 2s^1$	**Be** 4 $1s^2 2s^2$			**B** 5 $2s^2 2p^1$	**C** 6 $2s^2 2p^2$	**N** 7 $2s^2 2p^3$	**O** 8 $2s^2 2p^4$	**F** 9 $2s^2 2p^5$	**Ne** 10 $2s^2 2p^6$
Na 11 $[Ne] 3s^1$	**Mg** 12 $[Ne] 3s^2$			**Al** 13 $3s^2 3p^1$	**Si** 14 $3s^2 3p^2$	**P** 15 $3s^2 3p^3$	**S** 16 $3s^2 3p^4$	**Cl** 17 $3s^2 3p^5$	**Ar** 18 $3s^2 3p^6$
K 19 $[Ar]\ 4s^1$		**Cu** 29 $4s^1$	**Zn** 30 $4s^2$	**Ga** 31 $4s^2 4p^1$	**Ge** 32 $4s^2 4p^2$	**As** 33 $4s^2 4p^3$	**Se** 34 $4s^2 4p^4$	**Br** 35 $4s^2 4p^5$	**Kr** 36 $4s^2 4p^6$
Rb 37 $[Kr]\ 5s^1$		**Ag** 47 $5s^1$	**Cd** 48 $5s^2$	**In** 49 $5s^2 5p^1$	**Sn** 50 $5s^2 5p^2$	**Sb** 51 $5s^2 5p^3$	**Te** 52 $5s^2 5p^4$	**I** 53 $5s^2 5p^5$	**Xe** 54 $5s^2 5p^6$
Cs 55 $[Xe]\ 6s^1$		**Au** 79 $6s^1$	**Hg** 80 $6s^2$	**Tl** 81 $6s^2 6p^1$	**Pb** 82 $6s^2 6p^2$	**Bi** 83 $6s^2 6p^3$	**Po** 84 $6s^2 6p^4$	**At** 85 $6s^2 6p^5$	**Rn** 86 $6s^2 6p^6$

"classical" semiconductors: 4 e^- in valence state (outer shell)

Elements with 4 e^- form crystals with diamond lattice structure (each atom bonds to four neighbors)

Basic Principle of (Intrinsic) Photoconductors

The Basic Principle



- Principle: $E_\gamma > E_g$
  - Lifts e^- into conduction band
  - e^- / hole pair migrate through the material
- Operation:
  - few charge carriers → high resistance
  - electric field applied → Ē drives charge carriers to electrodes

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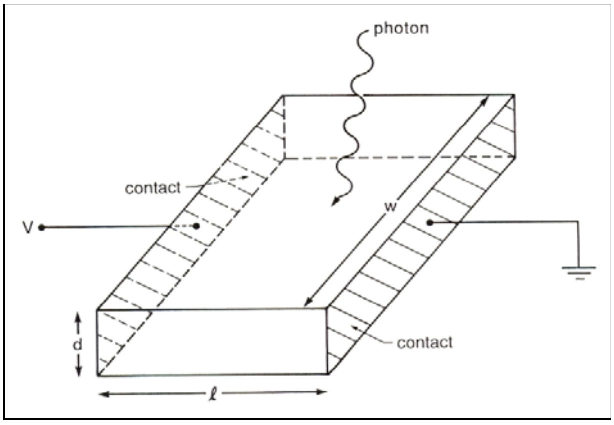
Electric Conductivity



Conductivity: $$\sigma = \frac{1}{R_d}\frac{l}{wd} = q n_0 \mu_n$$

with:

R_d = resistance

w,d,l = geometric dimensions

$$n = \frac{\varphi \eta \tau}{wdl}$$

q = electric charge

n_0 = number of charge carriers

φ = photon flux

τ = mean lifetime before recombination

μ_n = electron mobility ~ mean time between collisions.

Some Essential Definitions

Quantum efficiency η $\equiv \dfrac{\text{\# absorbed photons}}{\text{\# incoming photons}}$

Responsivity S $\equiv \dfrac{\text{electrical output signal}}{\text{input photon power}}$

Wavelength cutoff: $\lambda_c = \dfrac{hc}{E_g} = \dfrac{1.24\mu m}{E_g[eV]}$

→ Germanium: 1.85µm

→ GaAs: 0.87µm

Photo-current: $I_{ph} = \eta q \varphi G$

Photoconductive gain G: $G = \dfrac{I_{ph}}{q\varphi\eta} = \dfrac{\tau}{\tau_t} = \dfrac{\text{lifetime}}{\text{transit time}}$

Optimizing G:
- make detector as thin (τ_t) and as thick (η) as possible
- increase the bias voltage (E_x)
- eliminate defects and impurities

The product ηG describes the probability that an incoming photon will produce an electric charge that will penetrate to an electrode.

The three Main Noise Components

G-R noise

$$\langle I_{G-R}^2 \rangle = 4q^2 \varphi \eta G^2 \Delta f$$

fundamental statistical noise due to the Poisson statistics of the incoming photon stream → transferred into the statistics of the **g**enerated and **r**ecombined holes and electrons → two independent statistical processes $(2N)^{1/2}$.

Johnson or kTC noise

$$\langle I_J^2 \rangle = \frac{4kT}{R}\Delta f$$

fundamental thermodynamic noise due to the thermal motion of the charge carriers. Consider a photoconductor as an RC circuit: fluctuations in $E_{storage}$ are associated with a noise current I_J. Since $\langle Q^2 \rangle = kTC$, the charge noise is also called kTC noise or reset noise.

1/f noise

$$\langle I_{1/f}^2 \rangle \propto \frac{I^2}{f}\Delta f$$

increased noise at low frequencies, due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, and JFETs. Physical origin mostly unclear.

The total noise in the system is $\langle I_N^2 \rangle = \langle I_{G-R}^2 \rangle + \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle$

Note: bandwidth $\Delta f = \dfrac{1}{2\Delta t_{\text{int}}}$

If Poisson-distributed in time → relative error ~ 1/√t .

Background limit (BLIP) ⇔ Johnson noise limit

limited by the statistics of the incoming photon stream:

$$\langle I_{G-R}^2 \rangle >> \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle$$

limited by internal thermodynamic noise:

$$\langle I_J^2 \rangle >> \langle I_{G-R}^2 \rangle + \langle I_{1/f}^2 \rangle$$

The noise equivalent power (NEP) is the signal power that yields an RMS S/N of unity in a system of $\Delta f = 1$ Hz

$$NEP_{G-R} = \frac{2hc}{\lambda}\left(\frac{\varphi}{\eta}\right)^{1/2}$$

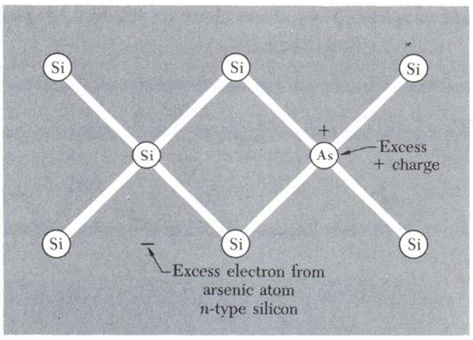
- the NEP can only be improved by increasing the quantum efficiency η.
- this is the best observing case (the limit given by nature).

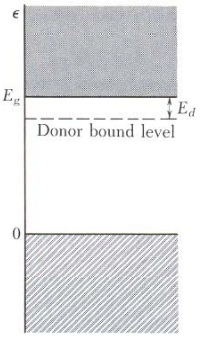
$$NEP_J = \frac{2hc}{Gq\eta\lambda}\left(\frac{kT}{R}\right)^{1/2}$$

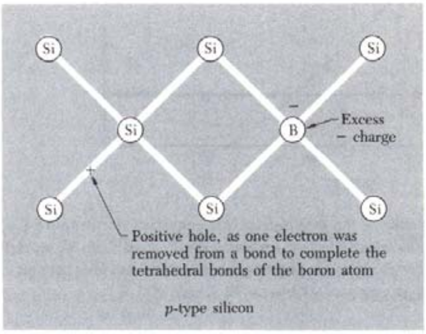
- the NEP can be improved by increasing the
  - quantum efficiency η,
  - the photoconductive gain G,
  - the detector resistance R
- or by reducing the operating temp. T

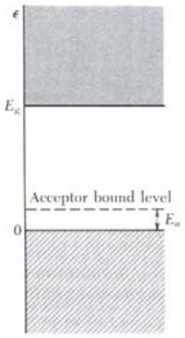
Extrinsic Photo-conductors

Extrinsic Semiconductors

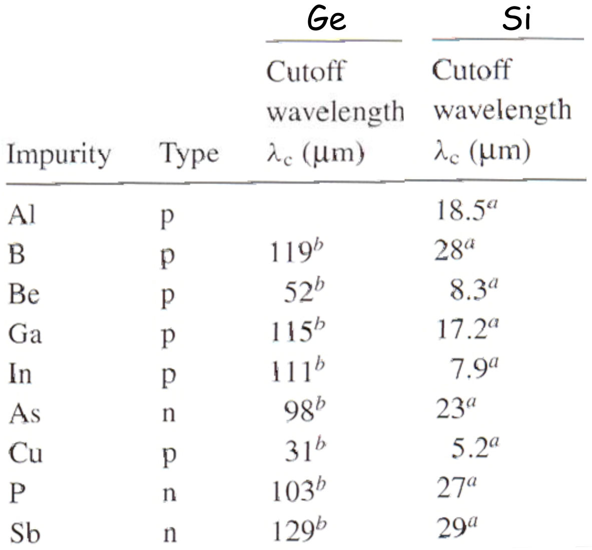








Example: addition of boron to silicon in the ratio 1:100,000 increases its conductivity by a factor 1000!



Impurity	Type	Ge Cutoff wavelength λ_c (μm)	Si Cutoff wavelength λ_c (μm)
Al	p		18.5^a
B	p	119^b	28^a
Be	p	52^b	8.3^a
Ga	p	115^b	17.2^a
In	p	111^b	7.9^a
As	n	98^b	23^a
Cu	p	31^b	5.2^a
P	n	103^b	27^a
Sb	n	129^b	29^a

Observed donor E_d and acceptor E_a ionization energies:

Donor	**Si** [meV]	**Ge** [meV]
P	45	12
As	49	13
Sb	39	10
B	45	10
Ga	65	11
In	157	11

Note that kT ≈ 26 meV at room temperature

Intrinsic versus Extrinsic Photoconductors

Intrinsic Photoconductors Extrinsic

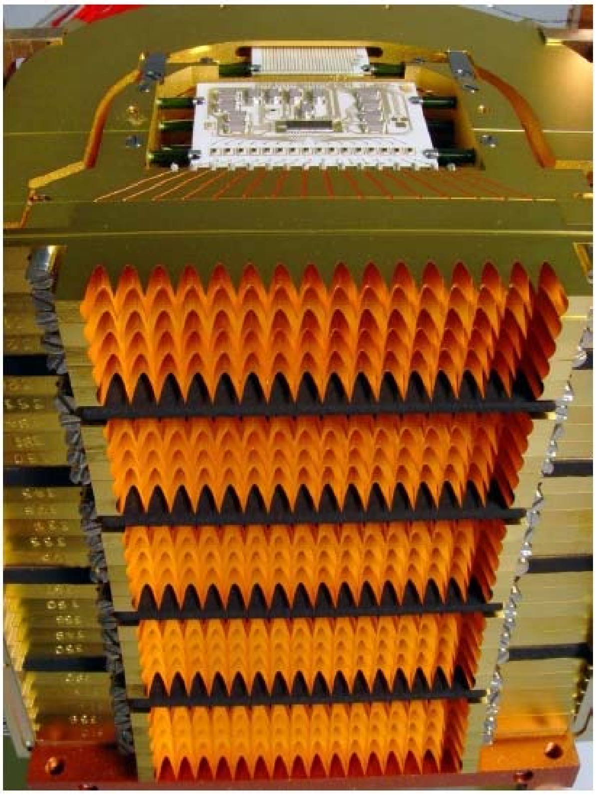
+ allows large voltage → large signals → minimizes other noise sources
- short wavelength cutoffs
- poor stability of material → non-uniformity
- problems to make good electrical contacts
- although intrinsically high resistance materials difficult to "keep clean" and obtain the high impedances to minimize Johnson noise at low light levels.

- absorption coefficients are 2 – 3 orders of magnitude less than those for direct absorption in intrinsic photoconductors → low QE → active volumes must be large → "bulk photoconductors"

Stressed Detectors and BIB Detectors

Stressed Detectors

Long λ cut-off of a p-type photoconductor can be modified by applying physical stress on the crystal.



Principle: p-type → conduction via migrating holes → external stress "helps" the inter-atomic bonds to break

Most effective: the [100] axis of the diamond lattice:

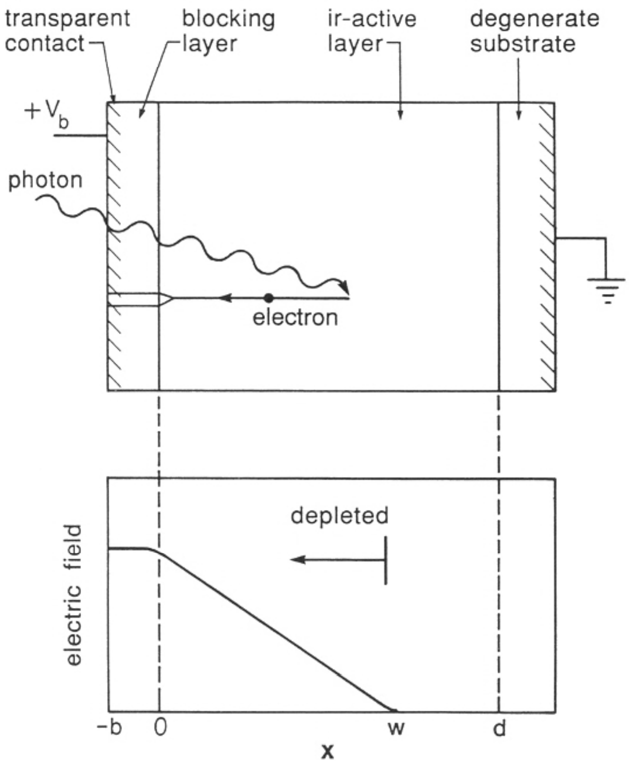
GeGa 115µm → >200µm

the practical yield stress of Ge:Ga is ~700 N mm^{-2}!

Blocked Impurity Band (BIB) Detectors

Conflicting requirements in extrinsic semiconductors:
- Efficient absorption [$\alpha(\lambda) = \sigma(\lambda) N_I$] requires large N_I → high conductivity
- Noise requirements: high resistance = low conductivity

Solution: use separate layers to optimize the optical and electrical properties independently:



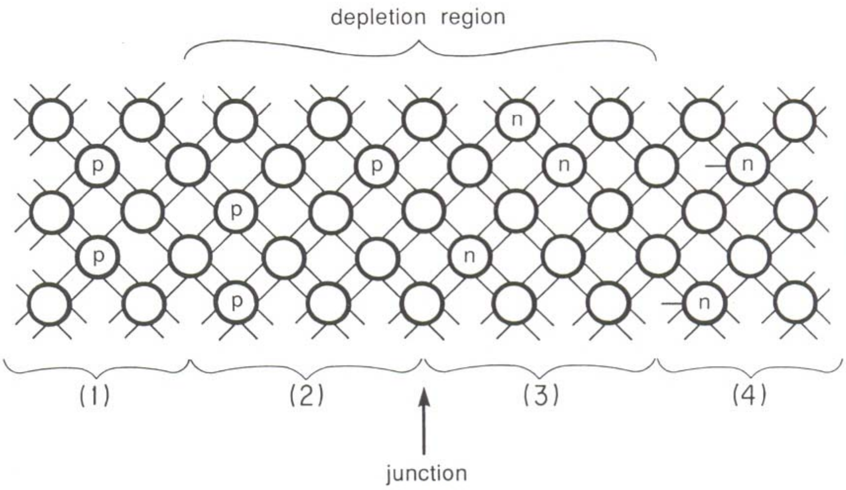
Typical species: Si:As, Si:Sb

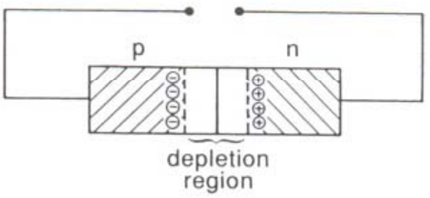
IR-active layer: heavily doped
Blocking layer: thin layer of high purity
(intrinsic photoconductor)

Photodiodes

Photodiodes

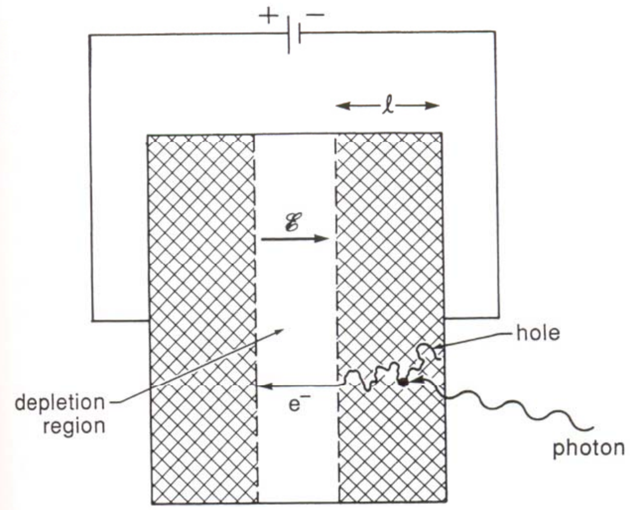
1. Based on junction between *two* oppositely doped zones
2. The two adjacent zones create a depletion region with high impedance





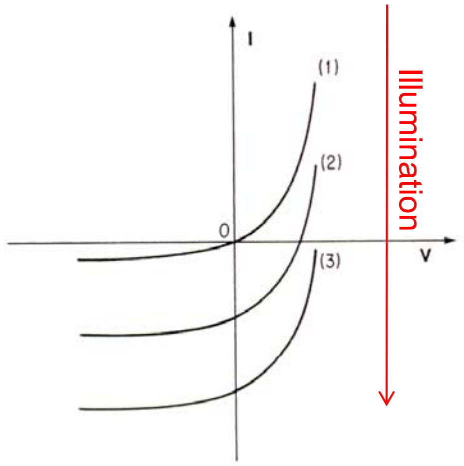
- Can operate at high sensitivity at room temperature
- intrinsic absorption → high quantum efficiency in small volumes
- Limited to λ < 15μm
- Can be constructed in arrays of millions of pixels
- Detectors of choice for 1 – 6 μm, visible and near-UV

Photo-excitation in Photodiodes



1. Photon gets absorbed in p-type part
2. Absorption creates e^--hole pair
3. e^- diffuses through material
4. Voltage drives e^- across the depletion region → photo-current

Same if absorbed in n-type part but then the hole migrates through junction.

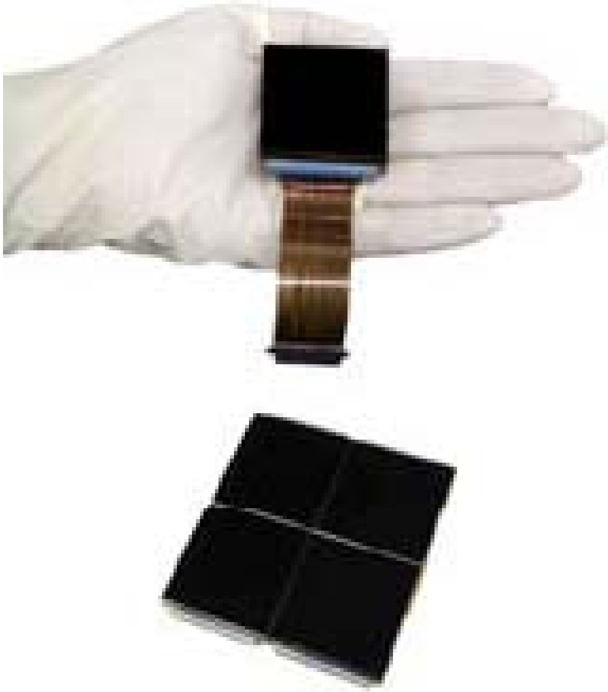


Example: State-of-the-Art Photodiodes

The Teledyne (formerly Rockwell) 2k x 2k Hawaii-2RG detector array.
See http://www.rsc.rockwell.com/imaging/hawaii2rg.html for more info

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	≥ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3µm
Operating temperature	≥ 30K
Quantum efficiency (array mean)	≥ 65%
Charge storage capacity	≥ 100,000e^-
Pixel operability	≥ 95%
Dark current (array mean)	≤ 0.1 e^-/sec (77K, 2.5 µm)
Read noise (array mean)	≤ 15 e^- CDS @ 100 kHz
Power dissipation	≤ 4 mW @ 100 kHz

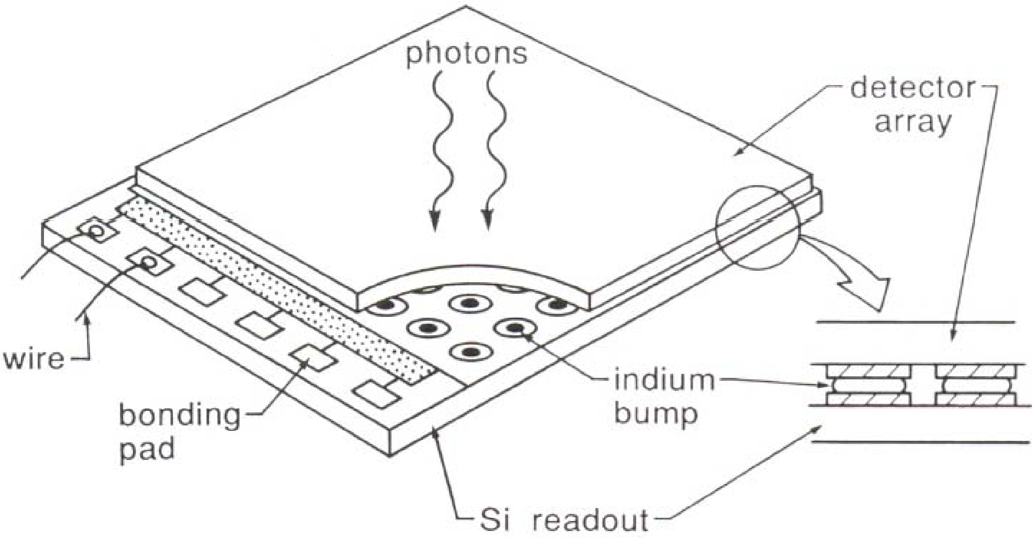
Can also be combined to a 2x2 mosaic



Array Readout and Electronics

Infrared Arrays – Construction

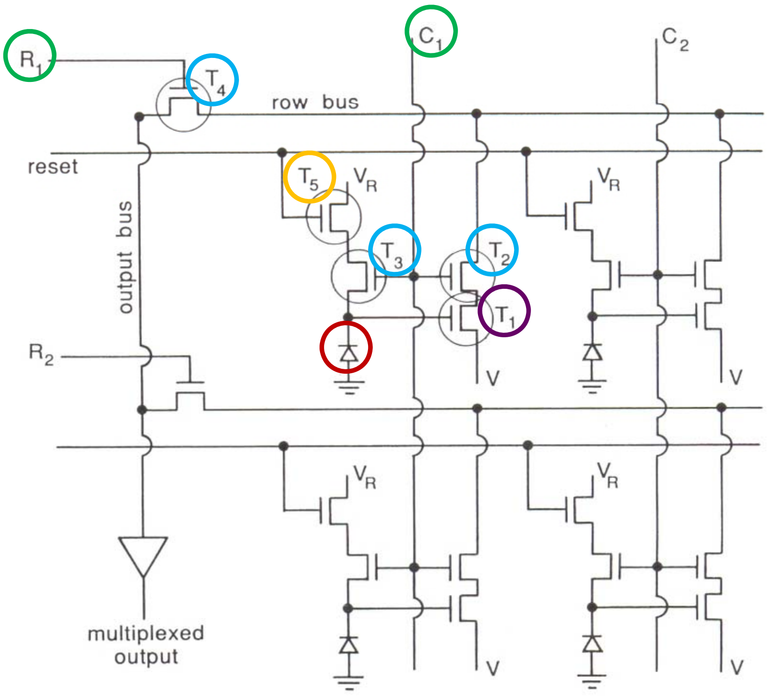
1. Produce a grid of readout amplifiers
2. Produce a (matching mirror image) of detector pixels
3. Deposit Indium bumps on both sides
4. Squeeze the two planes together ➔ hybrid arrays
5. The Indium will flow and provide electrical contact



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

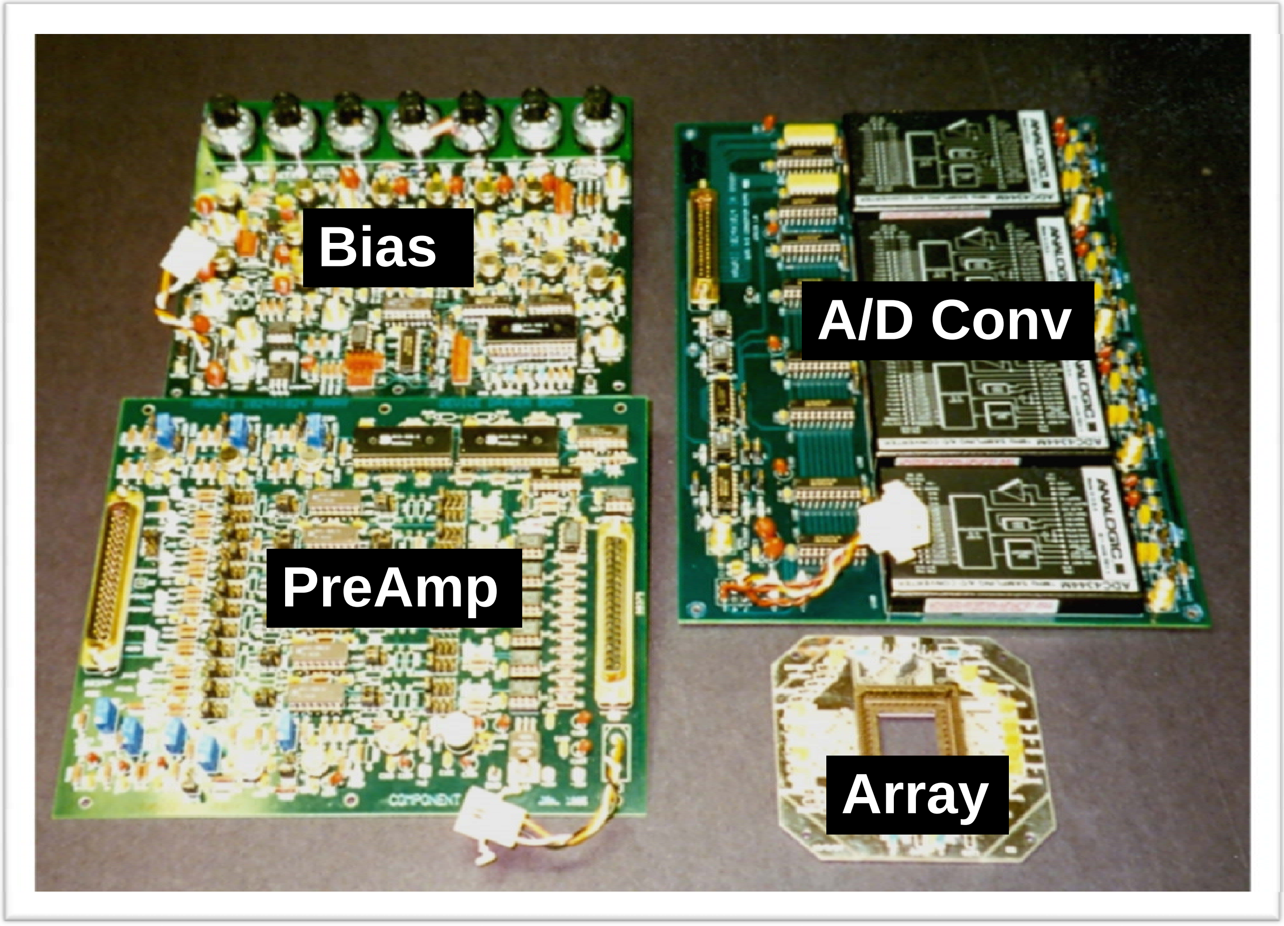
Readout uses row driver R_1 and column driver C_1 to close the switching transistors T_2, T_3, T_4.

→ Power to T_1 → signal to the output bus

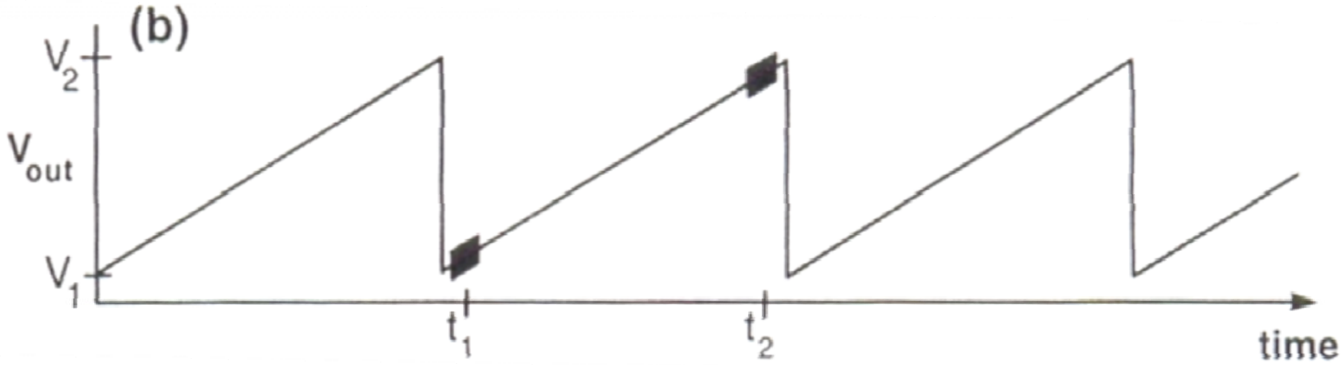
Reset: connect V_R via T_5 and T_3.

Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)



IR Array Read Out Modes



Often used Modes:

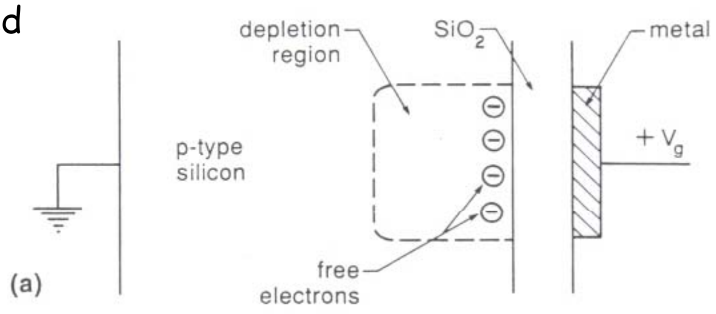
- Read-Reset – the most simple mode, directly measures the signal level
- Double-correlated sampling – good for offsets, drifts, fast reads
- Reset-Read-Read – best correlation, no reset noise
- Fowler sampling – reduces readnoise by √m (times) over reset-read-read
- SUR – linear fits, reduces RN by √m, good for cosmic ray detection

Charge Coupled Devices (CCDs)

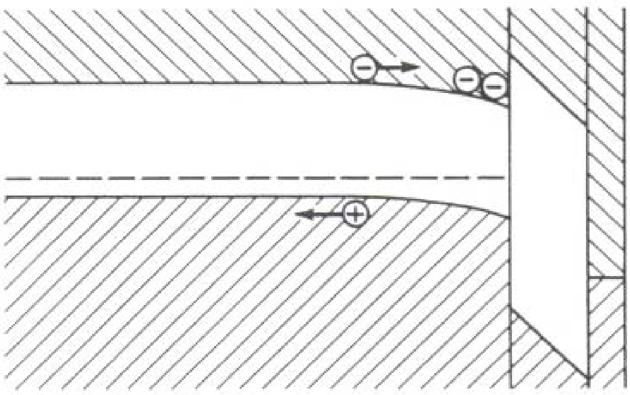
CCDs = array of integrating capacitors

Pixel structure: metal “gate” evaporated onto SiO_2 (isolator) on silicon = MOS

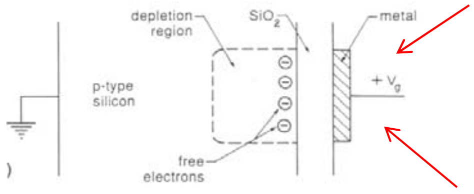
Applying a voltage V_g → bias for the intrinsic semiconductor. Charge current only due to absorbed photons.



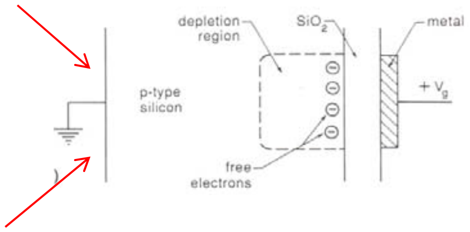
1. photons create free electrons in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO_2 layer
3. e^- accumulate at the Si—SiO_2 interface
4. the total charge collected at the interface is a measure of the number of photons during the exposure
5. → read out the number of e^-



Front and Back Illumination



Front illuminated CCDs:
The metal electrode would block the incoming photons → make electrode transparent by using heavily doped silicon instead → problems at blue/UV wavelengths (transparency of Si)



Back illuminated CCDs:
Blue/UV photons will be efficiently absorbed behind surface → long distance to depletion region → low QE.
Solution: thinning the detector (→ efficient diffusion into depletion zone)

In summary: e^- diffusion length ~ γ absorption length
Making CCDs too thin results in:

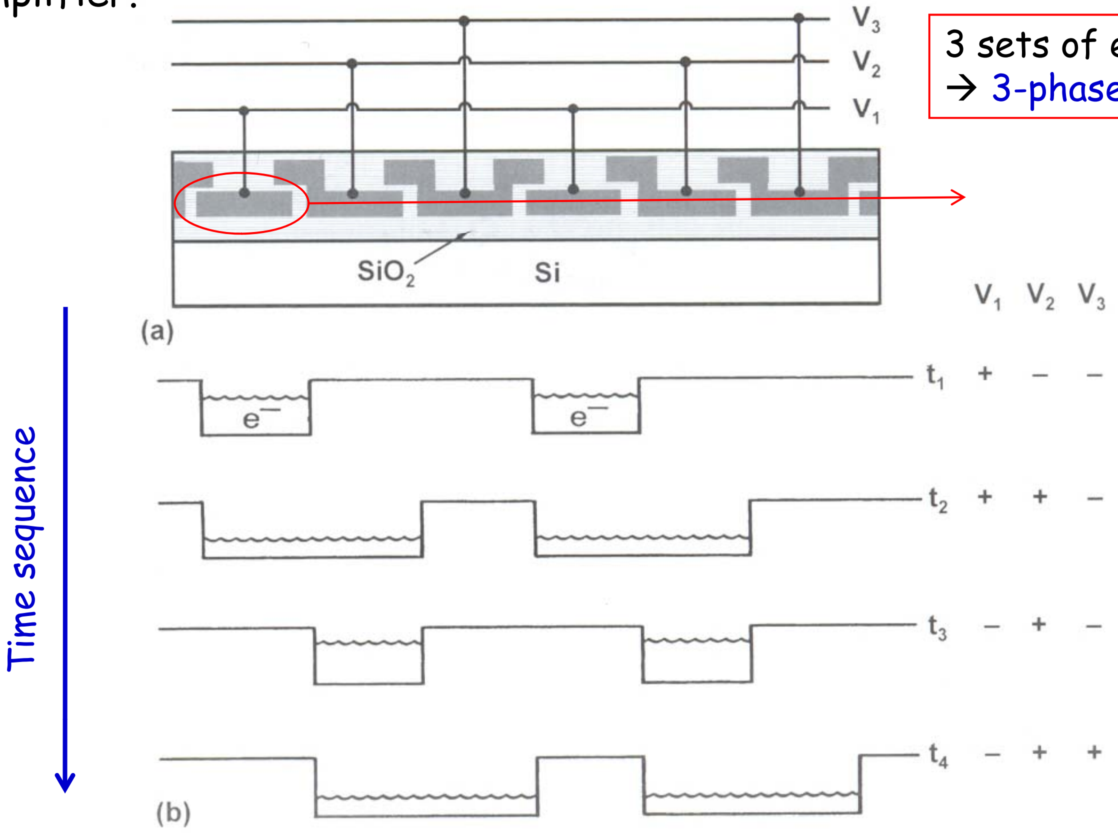
- Low QE
- Back reflection from the opposite site → fringing (see below)

Making CCDs too thick results in:

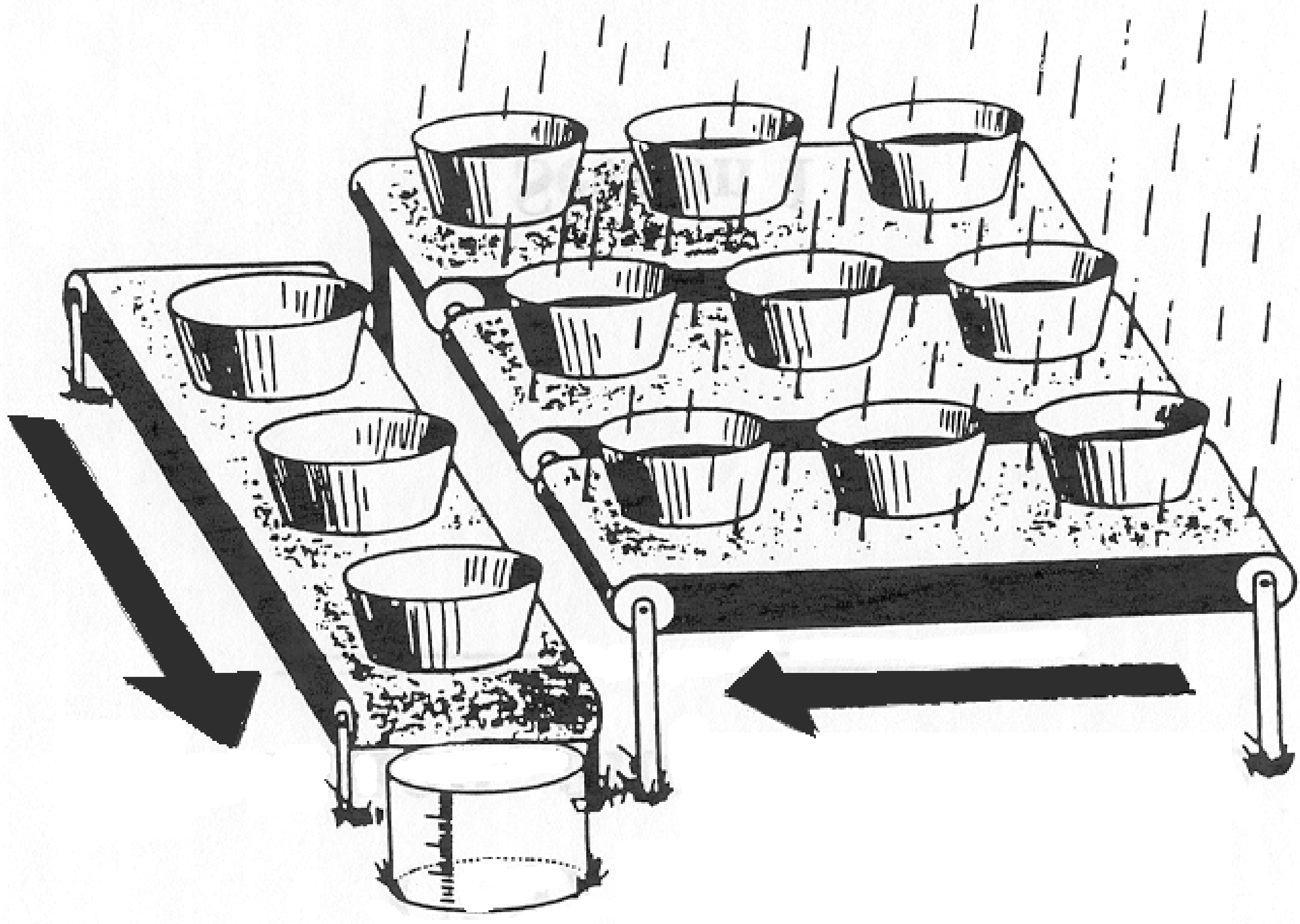
- Wandering into neighbouring depletion zones → loss in resolution

Charge Coupled Readouts

Alternative to CIDs: charge coupled readouts → collected charges are passed along the columns to the edge of the array to the output amplifier.



3 sets of electrodes
→ 3-phase CCD



http://solar.physics.montana.edu/nuggets/2000/001201/ccd.png

Charge Transfer Efficiency (CTE)

Time-dependent mechanisms that influence the CTE:

1. Electrostatic repulsion causes electrons to drift to the neighbouring electrode with time constant for charge transfer τ_{SI}.

2. Thermal diffusion drives electrons across the storage well at τ_{th}.

3. "Fringing fields" due to dependency of the well on the voltages of neighbouring electrodes (τ_{ff}).

Approximation for the CTE of a CCD with *m* phases: $CTE = \left(1 - e^{-t/\tau}\right)^m$

Noise from charge transfer inefficiency: $\varepsilon = (1\text{-}CTE)$

Orthogonal Transfer CCDs (OTCCD)

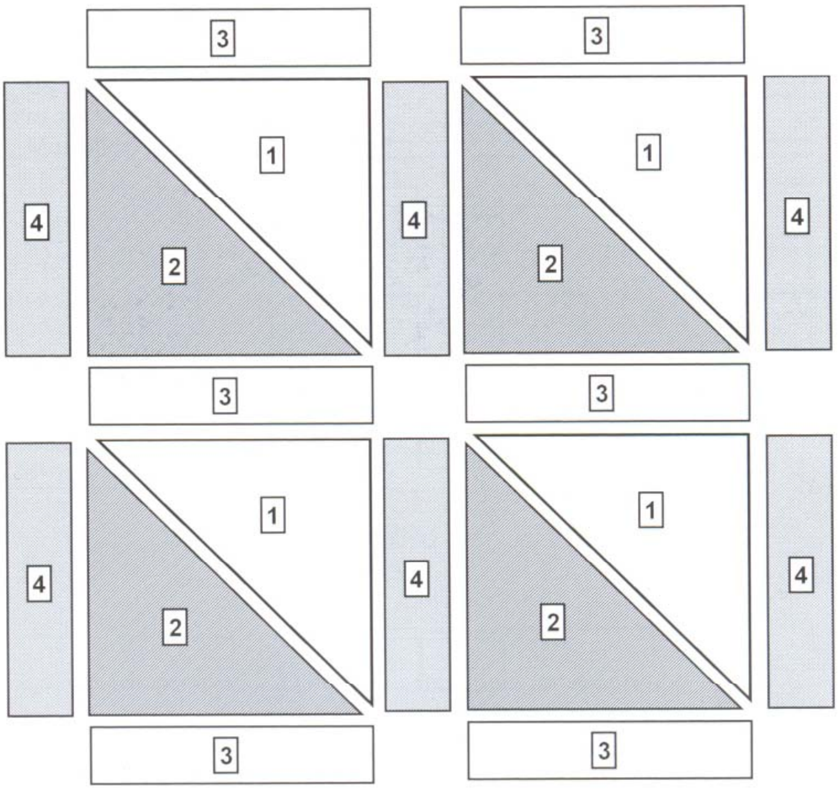
For TDI it would be desirable to move the charges in *any* direction to follow the image motion. This can be done with the OTCCD.

OTCCD operation:

To move a charge to the right, `3’ is negative to act as channel stop, `1’, `2’, and `4’ are operated as a conventional CCD.

To move a charge up, `4’ is negative to act as channel stop, `1’, `2’, and `3’ are operated as a conventional CCD.

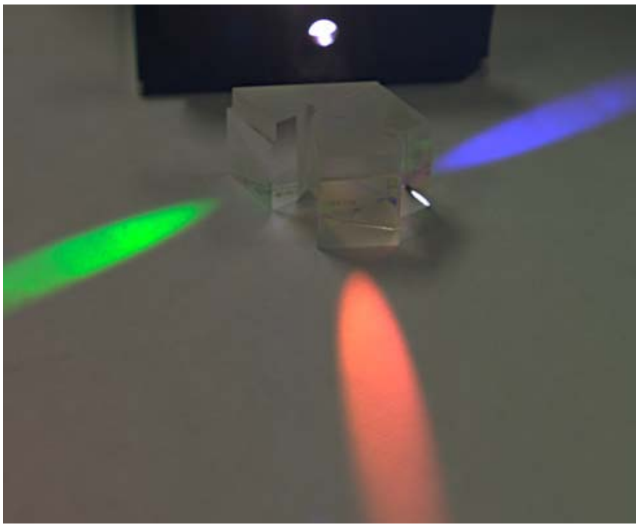
Moving to the opposite directions: reversing the clocking.

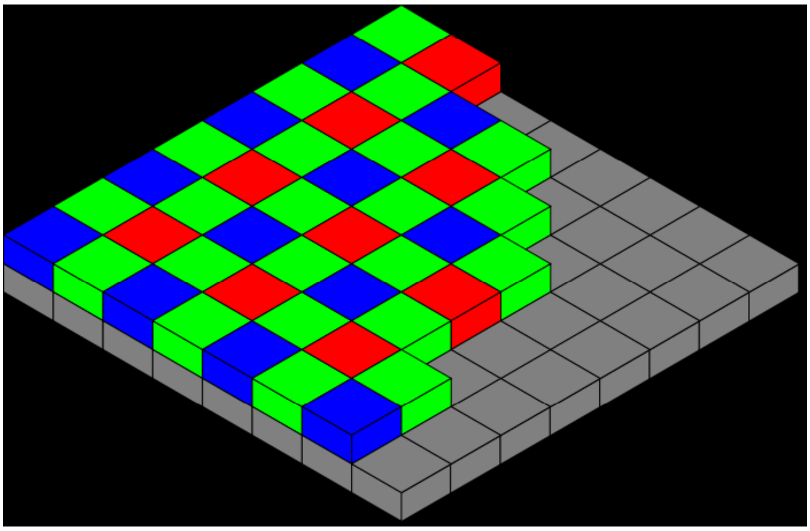


Side note: CCD Color Images

Essentially three ways to do it (from Wikipedia):

1. Take three exposures through three filters subsequently – only works for fixed targets (standard for astronomy).
2. Split the input beam in three channels, each with a separate and optimized CCD (*very* expensive cameras).
3. Use a Bayer mask over the CCD – each subset of 4 pixels has one filtered red, one blue, and two green.





Some Array Artifacts

Problem: Dead/Hot/Rogue Pixels

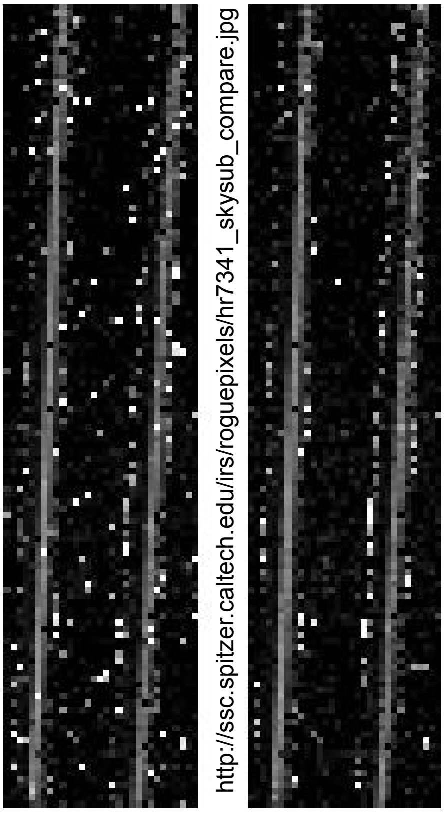
A dead pixel is a defective pixel that delivers no signal and cannot be used.

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



http://ssc.spitzer.caltech.edu/irs/roguepixels/hr7341_skysub_compare.jpg

**Rogue = dishonest person, scoundrel, scamp*

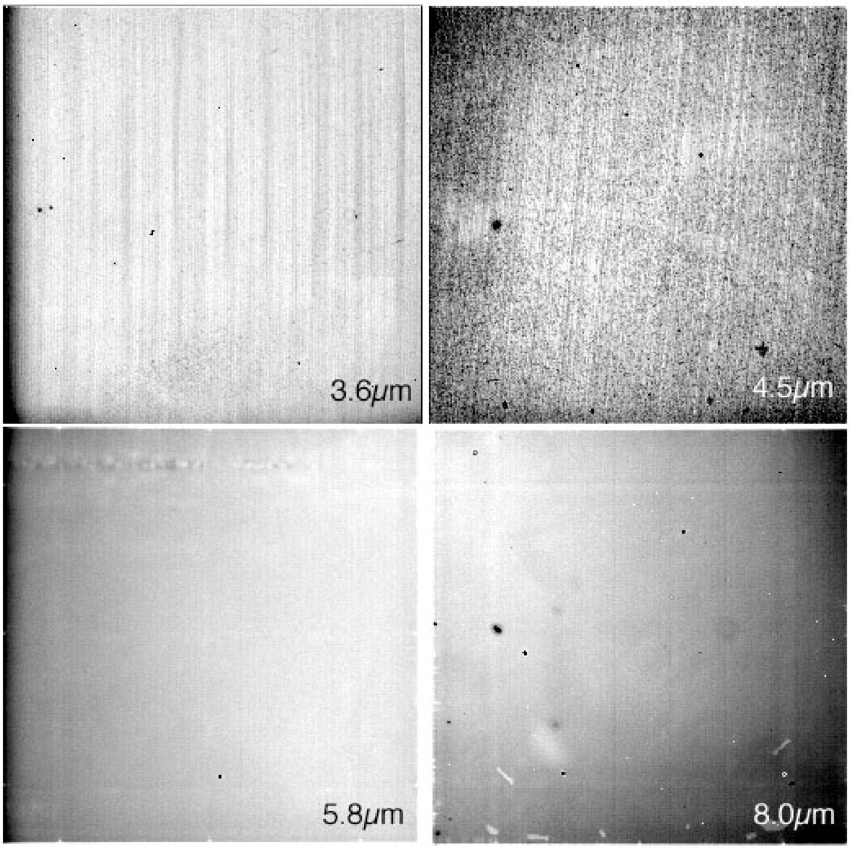
Problem: Pixel-to-Pixel Variations

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 after one year in space.

(from Spitzer IRAC User Manual)



Mitigation:
Produce and apply "flat field" (= response map to uniform illumination) → accuracies up to 10^{-5}.

Problem: Latent Images

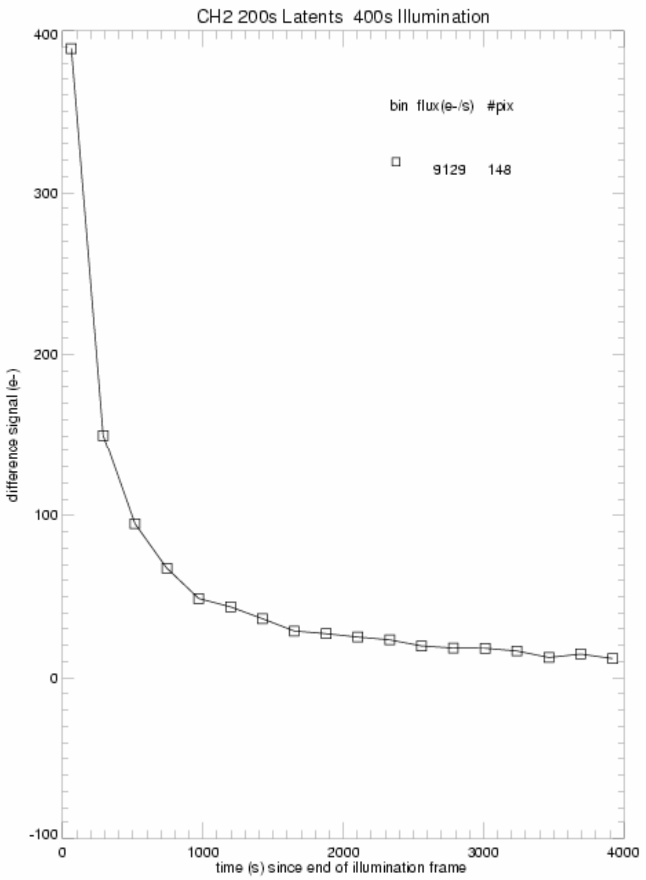
(or "Residual images" or "Memory effect")

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:

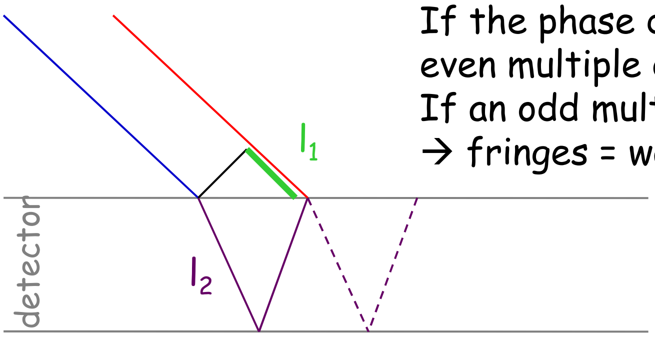
- just wait (decay time)
- apply frequent resets (clean the trap)
- annealing (heat array, e.g. 6K → 20K)
- use ND filters or shutter for target acquisition)



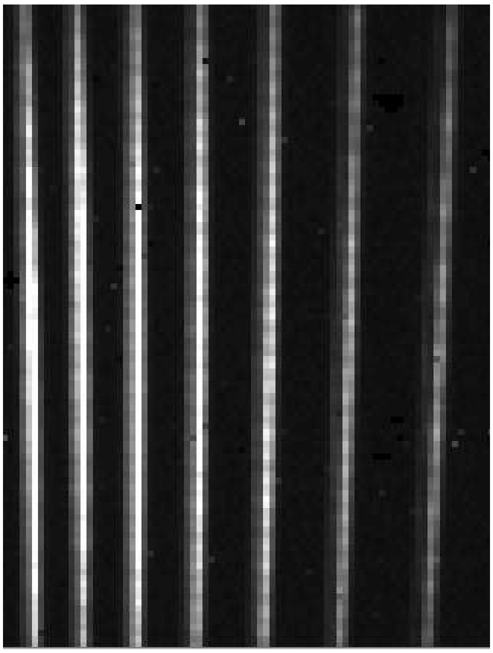
from Spitzer-IRAC User Manual (section 6.1.3.2.3)

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.

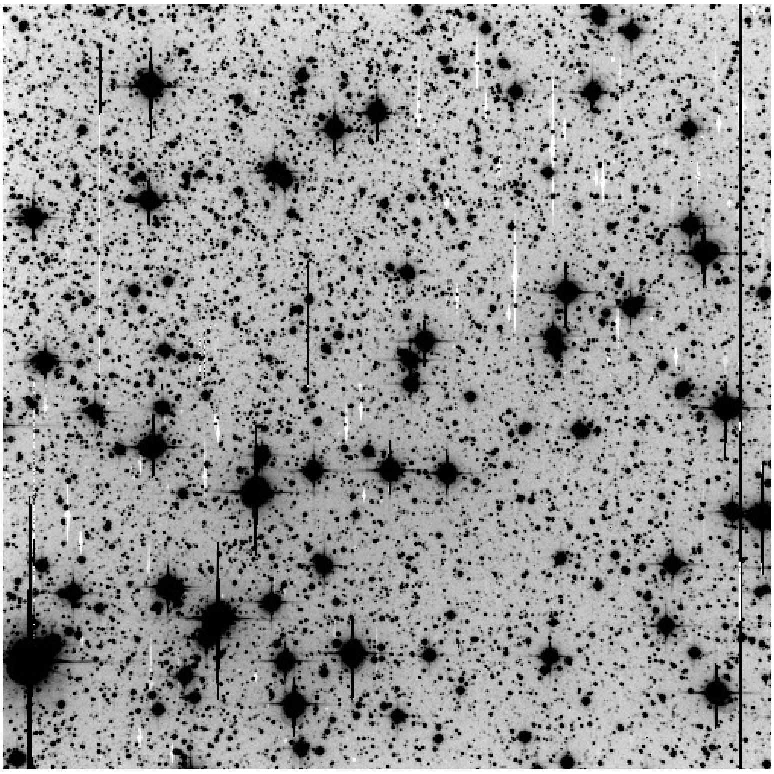


Fringing is most prominent in spectrographs where the monochromatic wavelength varies across the array and the conditions for constructive/destructive interference are locally met.

Crosstalk

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

Here: 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).

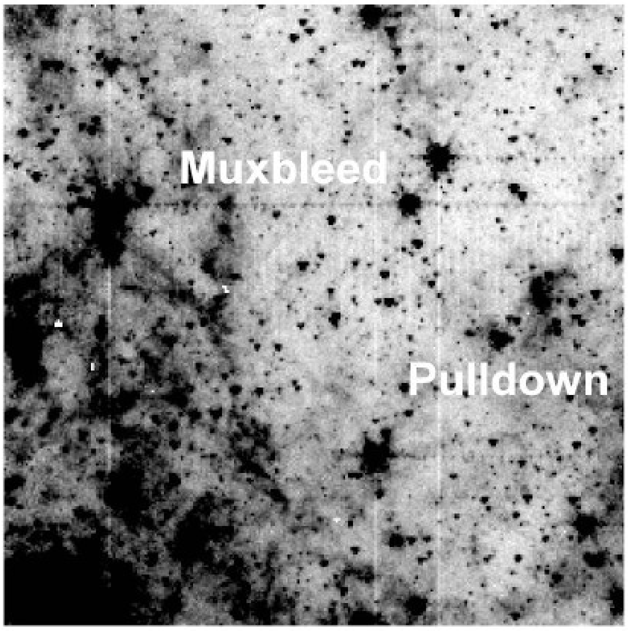


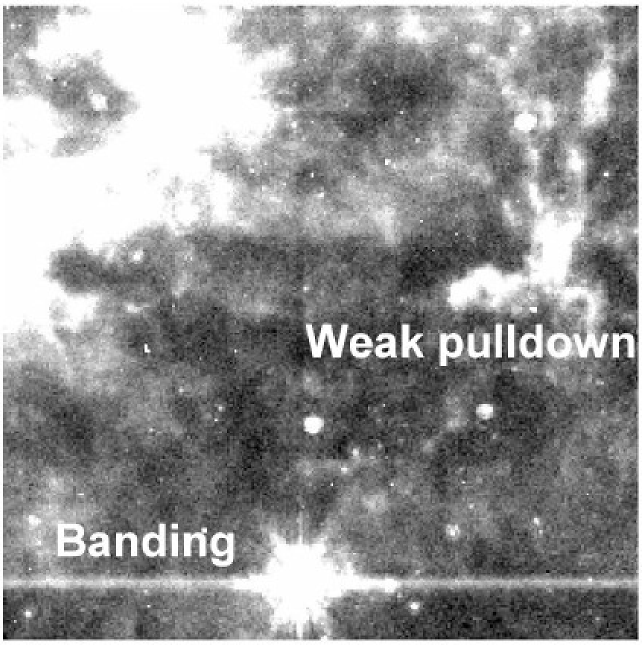
http://www.ctio.noao.edu/telescopes/36/0-9m.html

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

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.

Mitigations:

- 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:

Part I
Photon Detectors
Part II
Thermal Detectors
Part III
Coherent Receivers

Bolometers

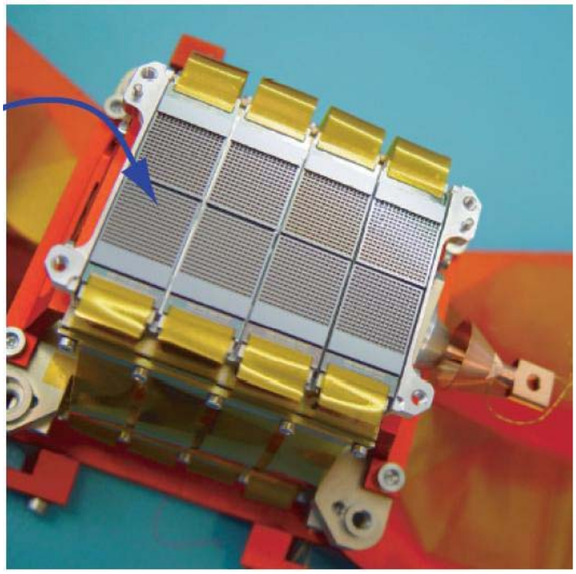
Bolometers

So far: photon detection via direct excitation of charge carriers

Now: photon absorption and conversion into energy (heat)

- Absorber is decoupled from the detection process
- Especially for low light levels
- Especially for the far-IR & sub-millimeter wavelength range

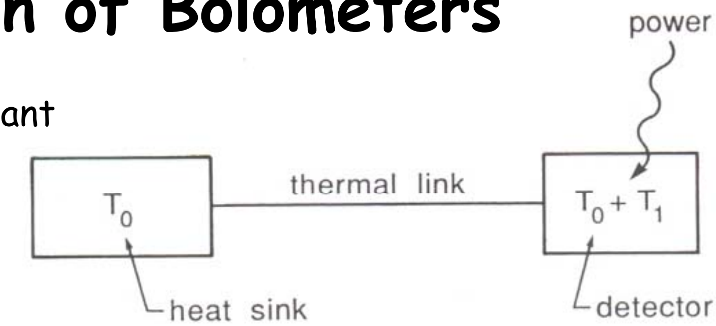
Invention of the Ge:Ga bolometer in 1961 by Frank Low



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

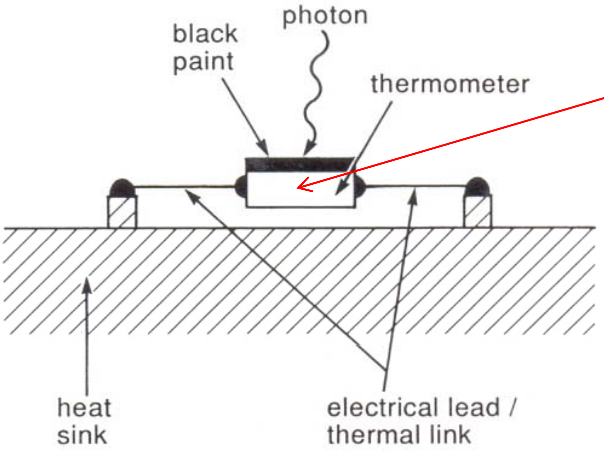
Basic Operation of Bolometers

Principle: detector absorbs the constant power P_0 and is connected via thermal link with thermal conductance G to a heat sink of temperature T_0.



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

The electrical time constant is shorter than the thermal time constant!



Chip of doped silicon or germanium

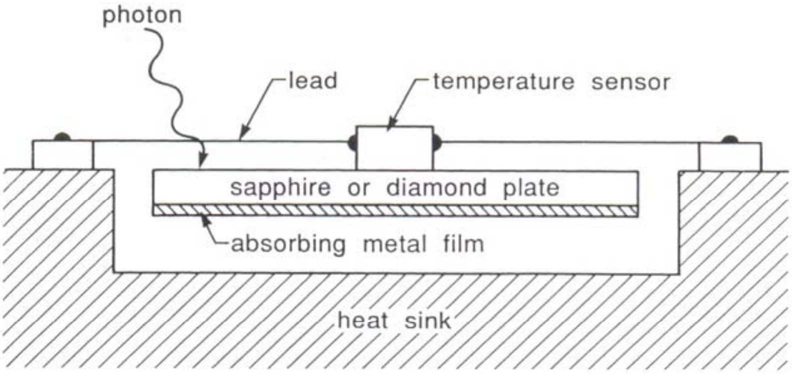
- High input impedance amplifier measures the voltage
- Voltage depends on resistance
- Resistance depends on temperature

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.

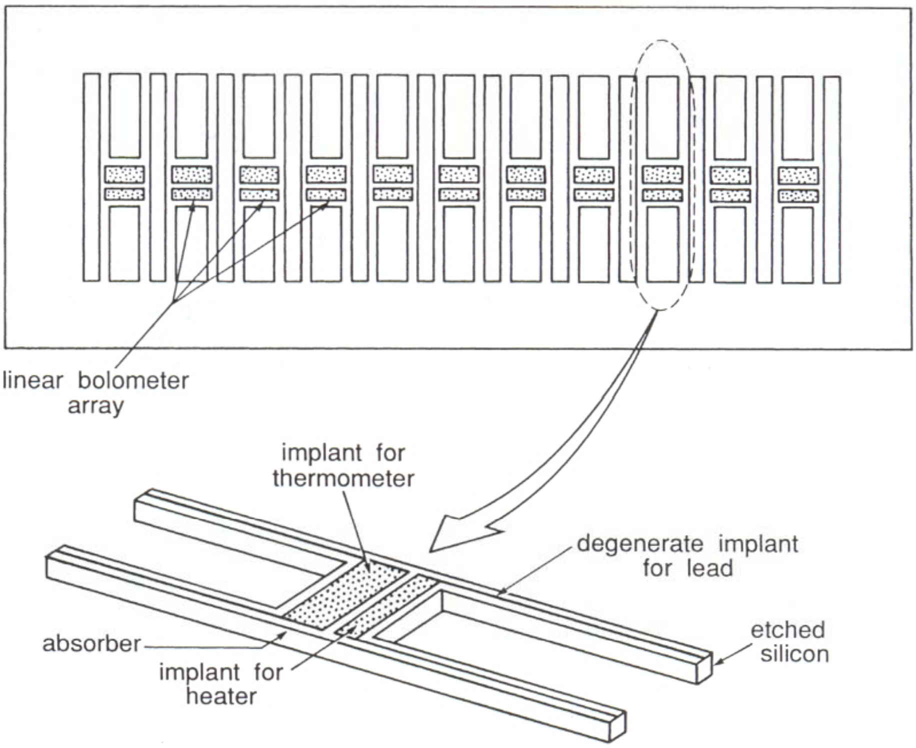


The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Etched Bolometers

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

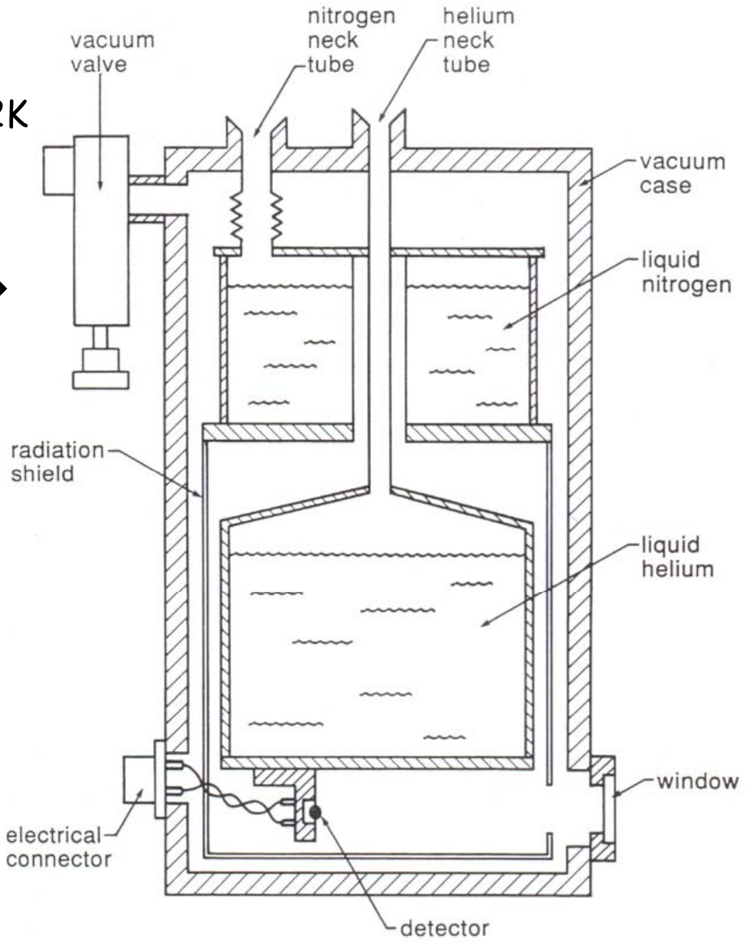
Thermal time response $\sim C/G$ → small structures minimize the heat capacity C by reducing the volume of material.



Requirement: Low Operating Temperatures

Four standard options to cool:

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



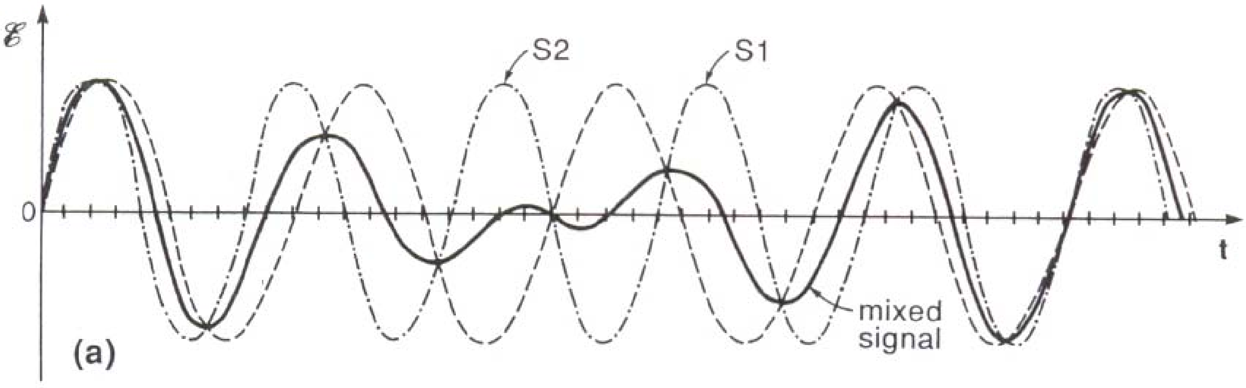
Simplest solution is to use a two-stage helium dewar (here: model from Infrared Laboratories, Inc.)

Part I
Photon Detectors
Part II
Thermal Detectors
Part III
Coherent Receivers

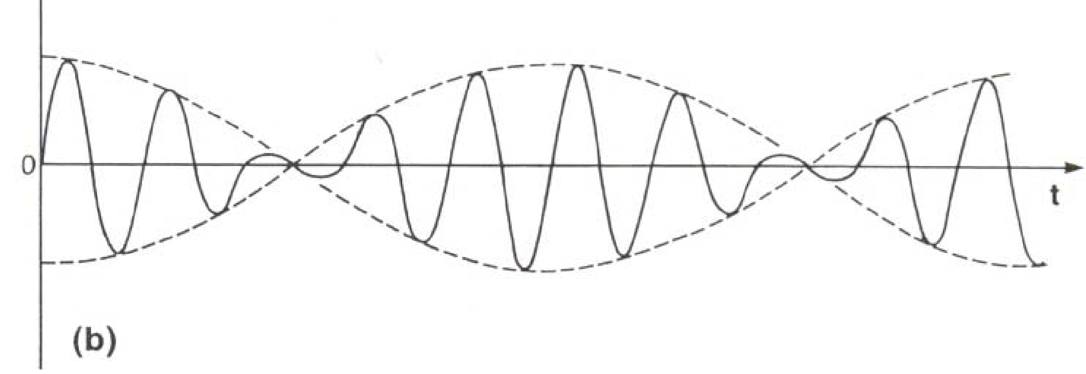
Basic Principle of Heterodyne Receivers

Basic Principle

The signal is mixed with a local oscillating field

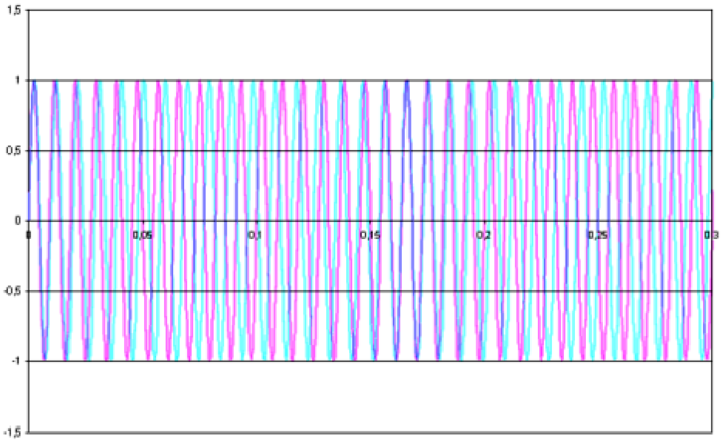


→ produces a down-converted difference or “beat” frequency at $\omega_{S1} - \omega_{S2}$ the intermediate (IF) or “beat frequency”.

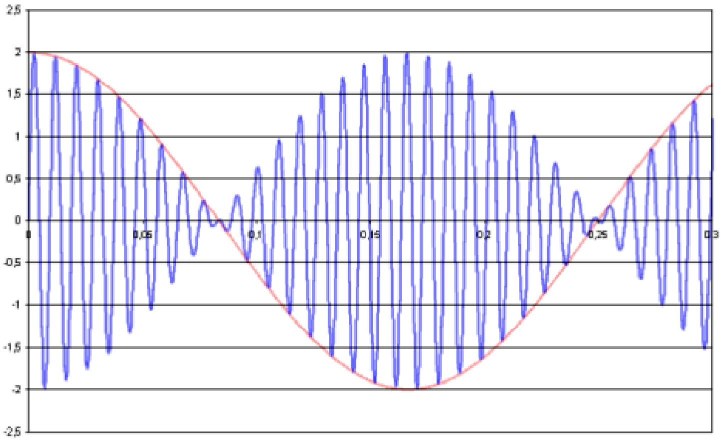


The Intermediate Frequency (IF)

The IF is the "beat frequency", the difference frequency between local oscillator and signal frequency.



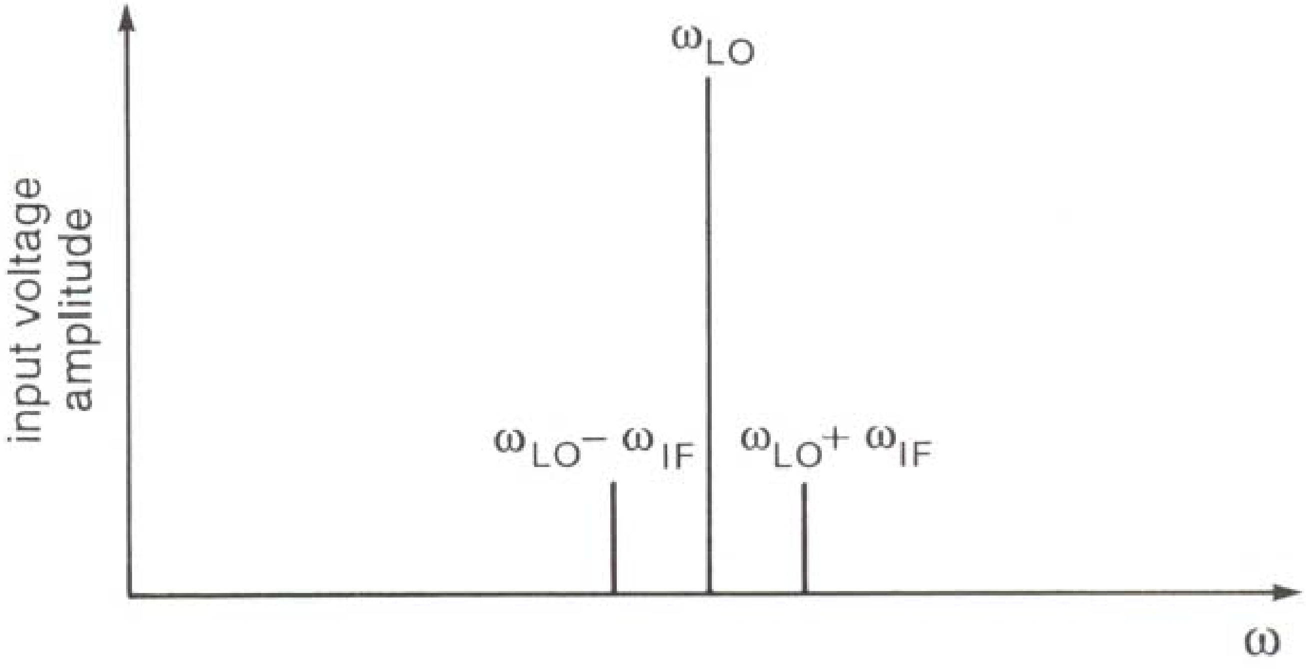
Example: To measure a signal at 1.5 GHz one could use an oscillator at 1.55 GHz, which would down-convert the signal to a 50 MHz carrier.



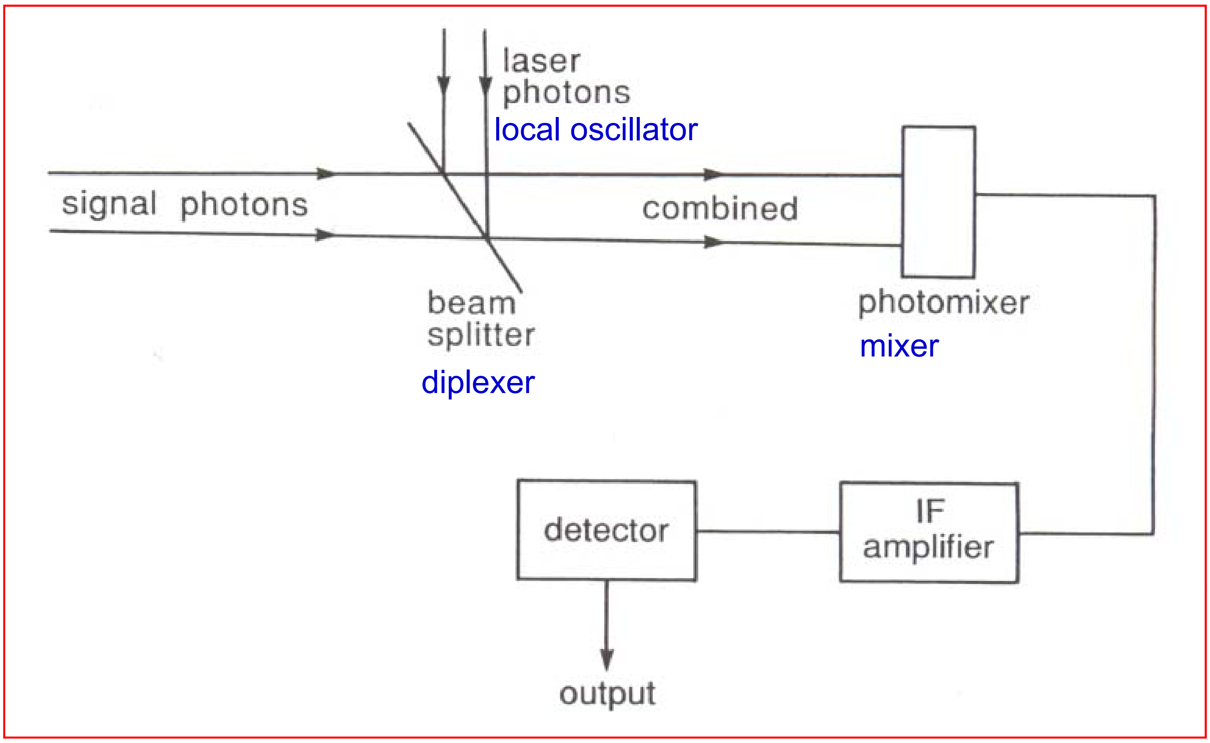
The Sidebands

Unfortunately, from the measured IF signal one cannot tell whether the signal frequency ω_S is slightly lower or higher than ω_{LO}.

Hence, we assume that the signal contains two components of equal strength, one at if $\omega_{LO} + \omega_{IF}$ and one at $\omega_{LO} - \omega_{IF}$



Basic Operating Scheme



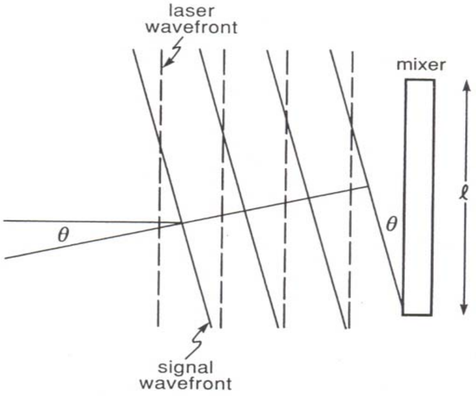
Note the order:

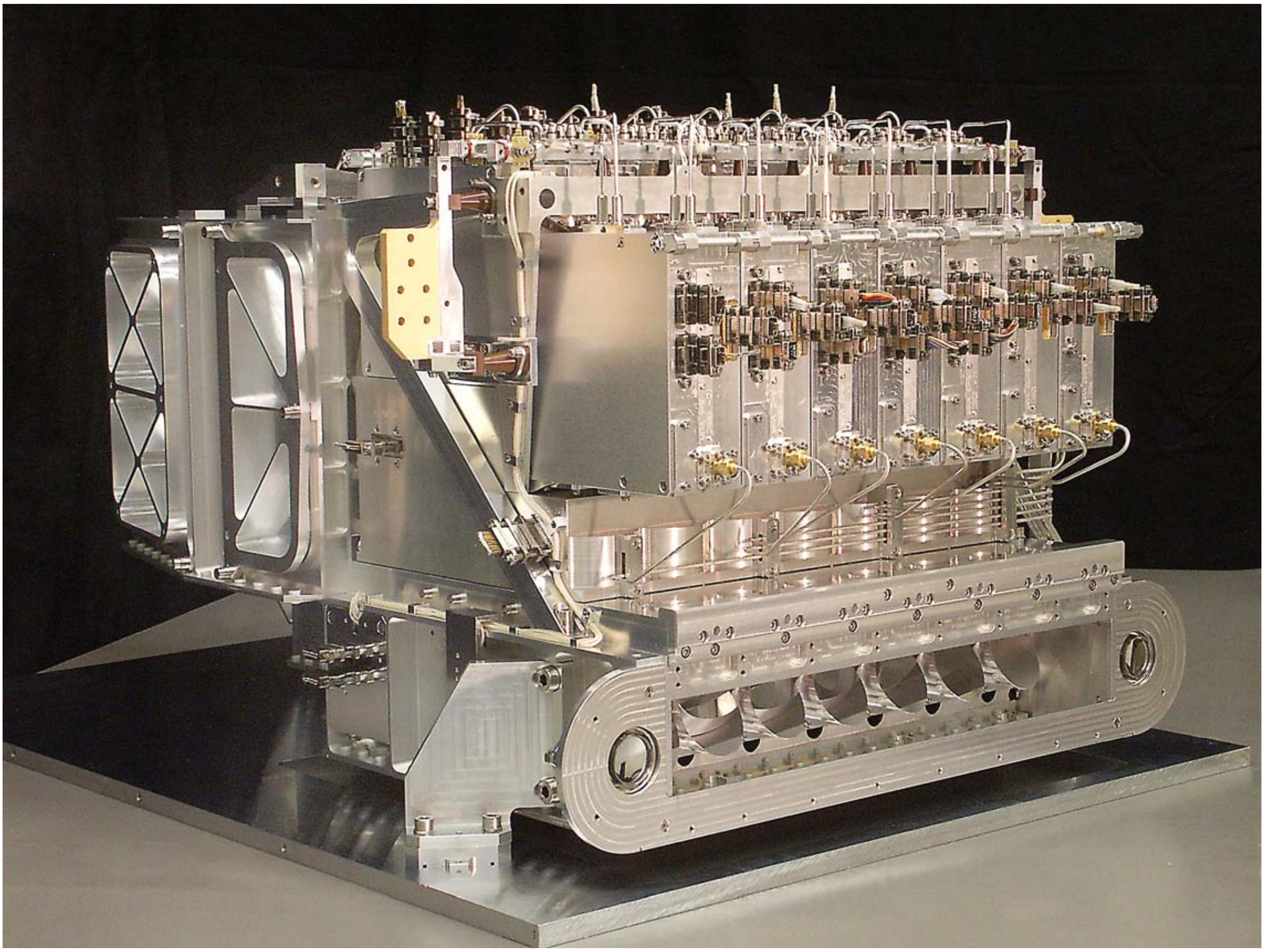
Photomixer → IF amplifier → Detector → Output

Throughput

Several factors limit the throughput of the system:

1. Only components of the signal electric field vector parallel to the laser field can interfere (incl. polarization!). Full cancellation occurs when offset ~ λ $l \sin\theta_{\max} = \lambda \approx l\theta_{\max}$
2. The Etendue $A\Omega \sim \lambda^2$ sets a constraint on the coherent beam that can be accepted by a telescope of diameter D ➔ A coherent receiver should operate at the diffraction limit of the telescope.
3. Since the laser field is polarized only one polarization component of the source can interfere and produce a signal → heterodyne receivers = single-mode detectors





Mixers and Local Oscillators

Local Oscillators (LO)

At high frequencies the LO may be a continuous wave (CW) laser

+ high power

- discrete set of frequencies

At lower frequencies one uses an electronic LO (in combination with wire antenna or waveguide)

+ easily tuneable in frequency

- low power at high frequencies (sub-mm)

Mixer Technology

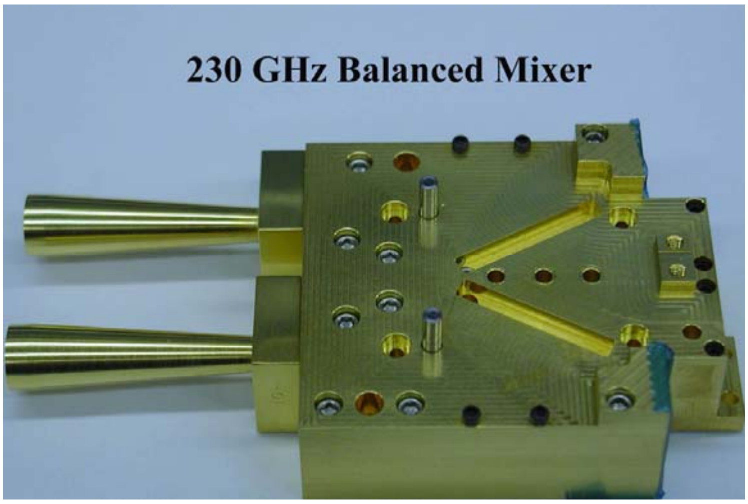
1. Good & fast photon detectors for the submm do not exist for $\lambda >$ 40μm.
2. "pixel" size ~ λ (for efficient absorption). But frequency response $\propto$ 1/size

Material	Recombination time	
Si	100 μs	
Ge	10000 μs	←
PbS	20 μs	
InSb	0.1 μs	
GaAs	1 μs	
InP	~1 μs	

➔ SIS Junctions

➔ Hot electron bolometers

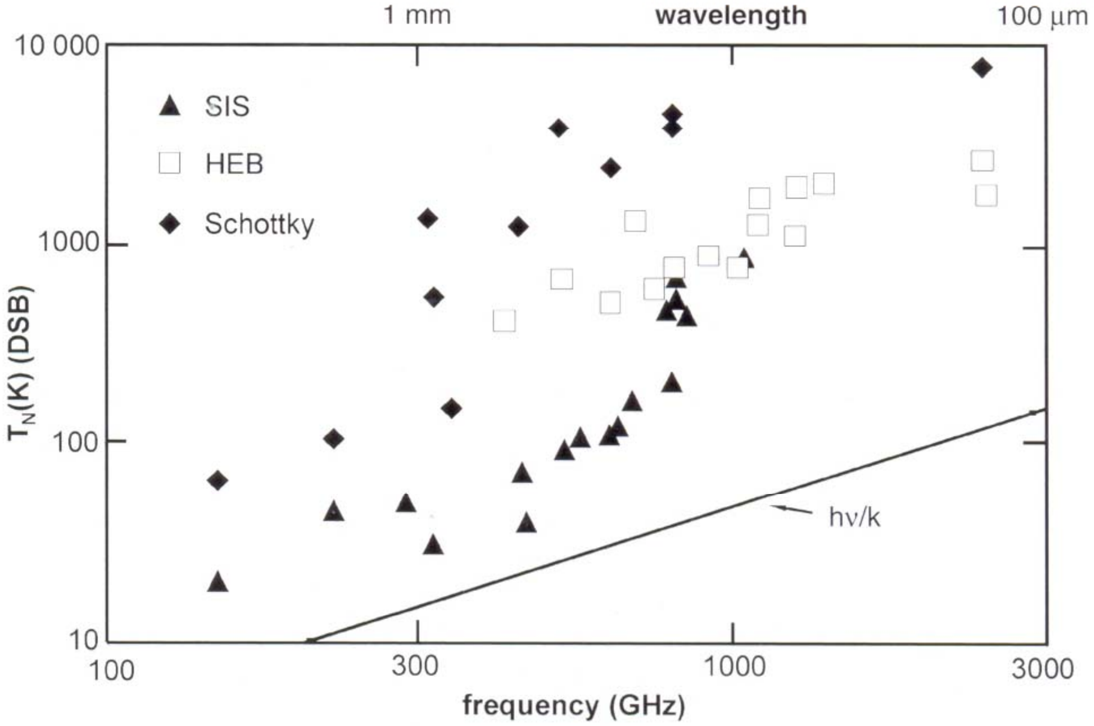
➔ Schottky diodes



Noise Temperatures

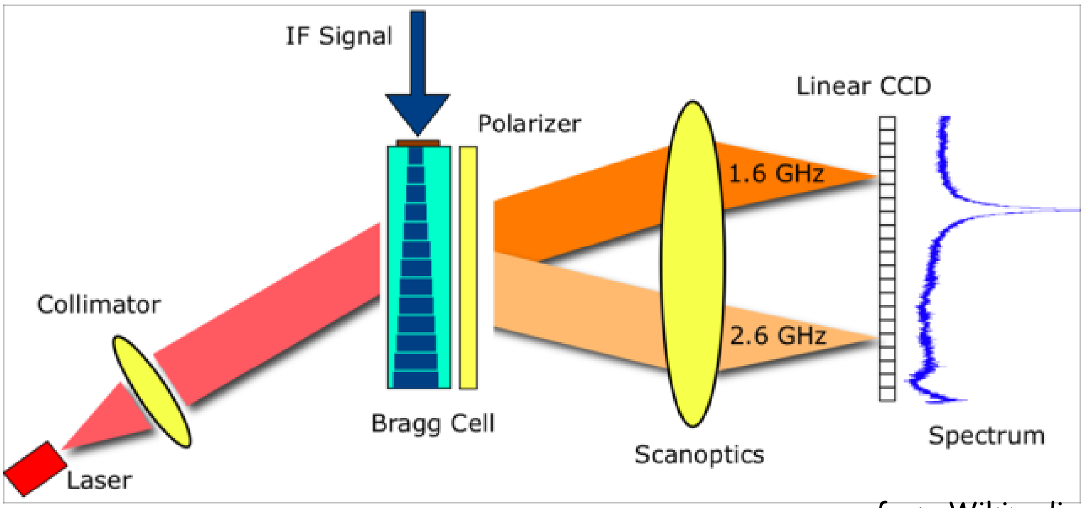
Noise temperature T_N is defined such that a matched blackbody at the receiver input at a temperature T_N produces a S/N=1.

Achieved performances of high frequency heterodyne receivers. The quantum limit is shown as solid line.



Side note: Acousto-Optical Spectrometer

An AOS converts the frequencies to ultrasonic waves that disperse a monochromatic light beam onto an array of visible light detectors.



from Wikipedia

The acoustic wave can be created in a crystal ("Bragg-cell") and modulates the refractive index → induces a phase grating. The angular dispersion is a measure of the IF-spectrum.

Comparison: Coherent ⇔ Incoherent Receivers

S/N Comparison

The achievable S/N for a coherent receiver in terms of antenna and system noise temperatures is given by the Dicke radiometer equation:

$$\left(\frac{S}{N}\right)_{coh} \approx \frac{T_S}{T_N^{sys}}\left(\Delta f_{IF}\Delta t\right)^{1/2}$$

The achievable S/N for an incoherent receiver operating at the diffraction limit is:

$$\left(\frac{S}{N}\right)_{incoh} = \frac{2kT_S\Delta\nu\left(\Delta t\right)^{1/2}}{NEP}$$

Hence, the performance ratio between these two types of receivers is:

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \frac{NEP\left(\Delta f_{IF}\right)^{1/2}}{2kT_N^{sys}\Delta\nu}$$

The Better Choice: Bolometer or Heterodyne?

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

Both receivers view the source through an etendue $A\Omega = \lambda^2$ and a background of unity emissivity at T_B. Then:

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \left[\left(\frac{1}{\eta}\right)\left(\frac{\Delta f_{IF}}{\Delta\nu}\right)\left(\frac{h\nu}{kT_B}\right)\right]^{1/2}$$

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

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \frac{NEP(\Delta f_{IF})^{1/2}}{2h\nu\Delta\nu}$$