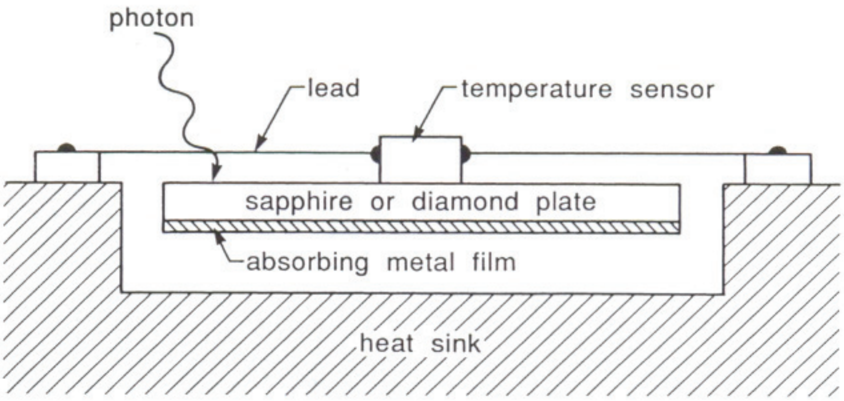
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

9th Lecture: 29 October 2012



Overview

I. PHOTOCONDUCTORS

Intro: Solid State Physics
Intrinsic Photoconductors
Extrinsic Photoconductors
Readout & Operations
Detector Noise
Flatfieding Techniques

II. BOLOMETERS

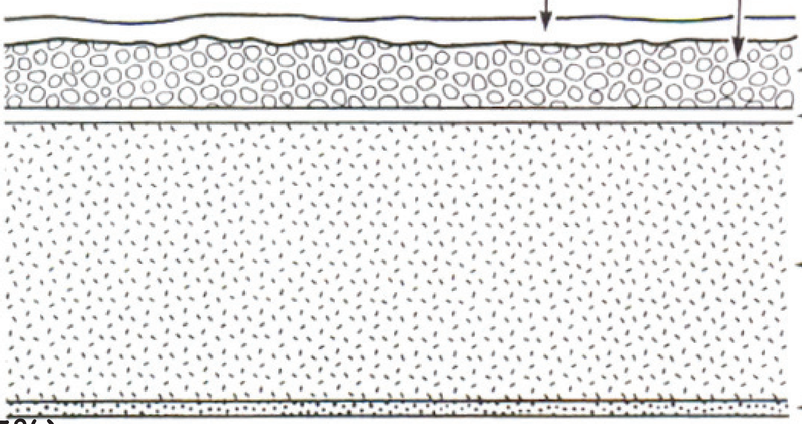
III. COHERENT RECEIVERS

Outlook: MKIDs

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.

Overview

Preface: The Photographic Plate



Disadvantages:

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

Advantages:

- 10″ plate → 10^{12} grains → ~10^9 pixels
- Inexpensive
- Include own data storage system
- Stable over very long periods of time

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

2. Thermal detectors

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

Examples: bolometers

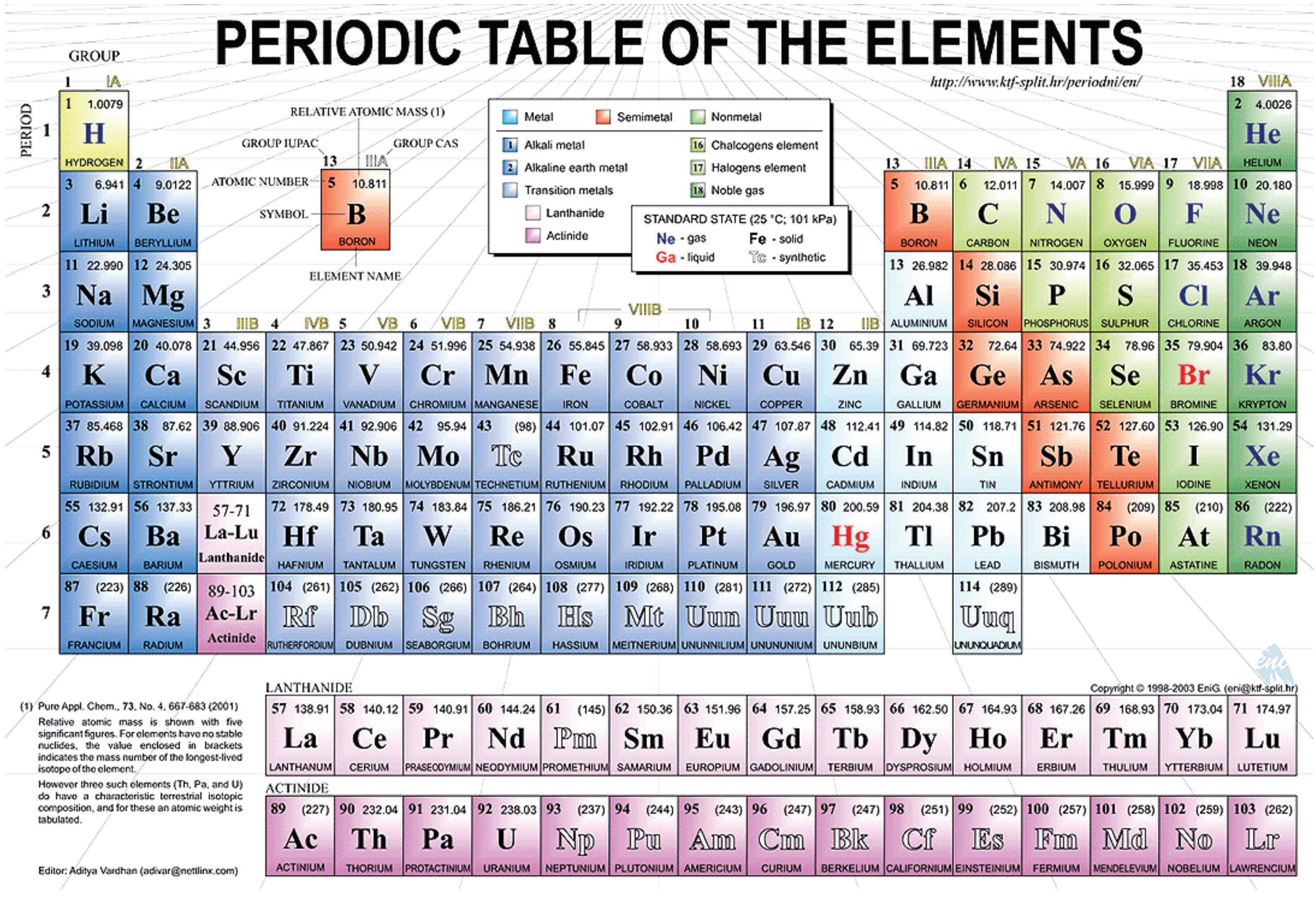
3. Coherent receivers

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

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

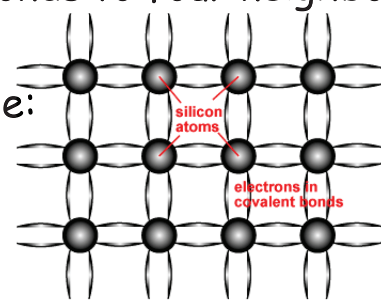
Intro to Solid State Physics



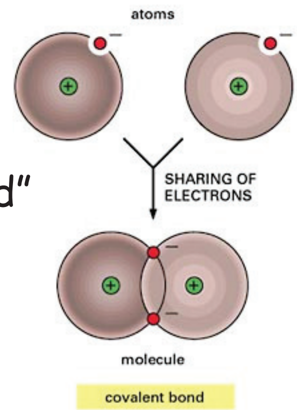
The Diamond Lattice

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

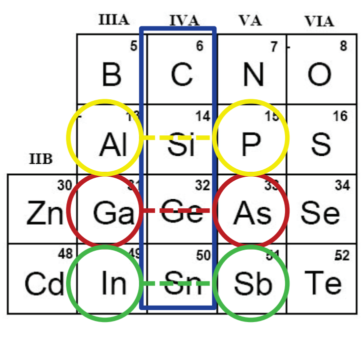
Example:

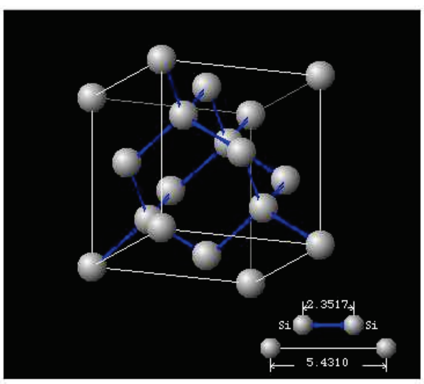


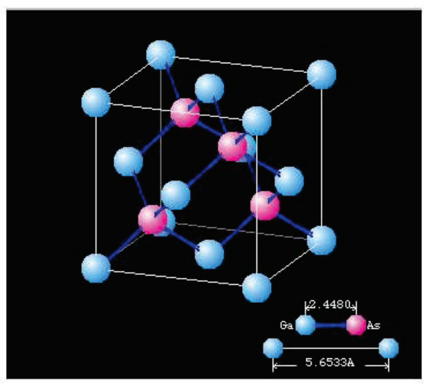
These double-bonds between neighbours are due to "shared" electrons



Note that a diamond lattice can not only be formed by IV elements [C, Si, Ge] but also by III-V semiconductors



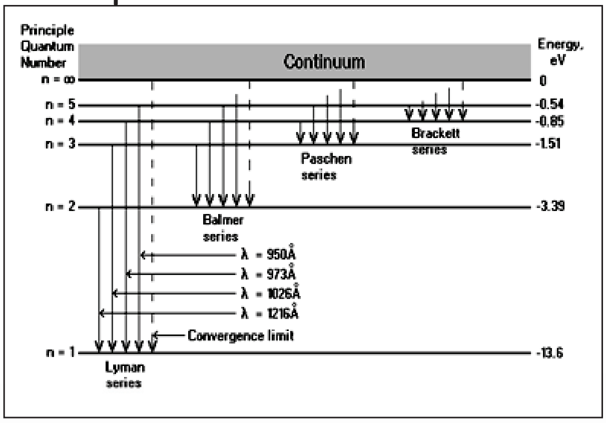


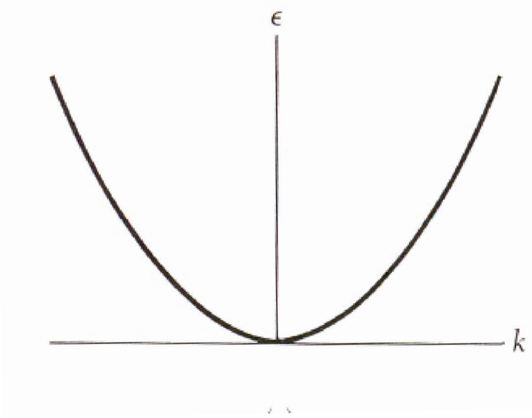


Electronic States and Bands

Single atomic system

Example: H atom



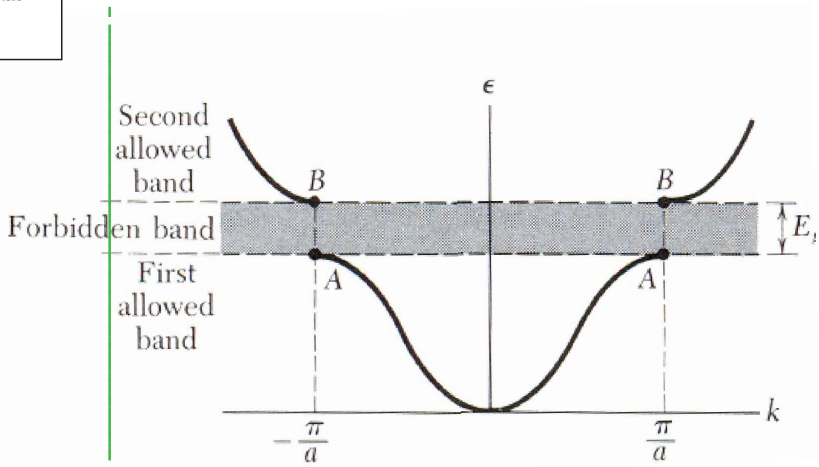


Atomic crystal

Wavefunctions Ψ overlap

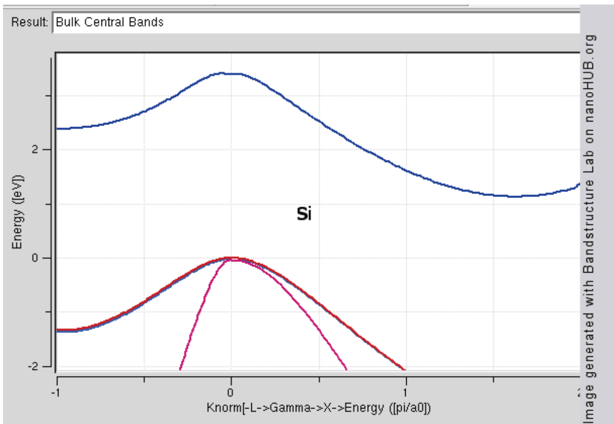
→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

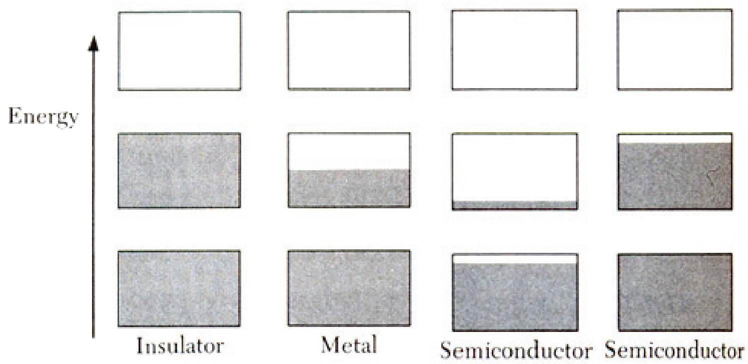
→ Multiple splitting ➔ "bands"



Electric Conductivity

Conductivity requires charge carriers in the conduction band



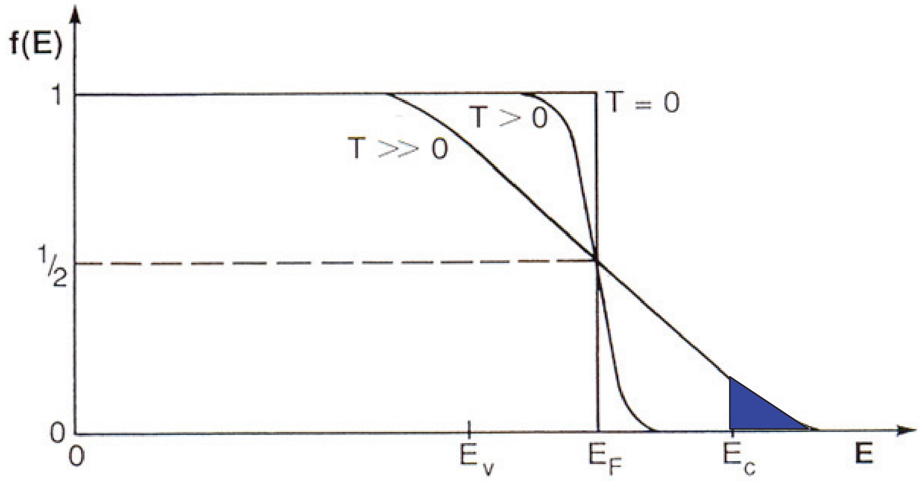


One needs to overcome the bandgap E_g to lift an e^- into the conduction band. This can be done via:

1. external excitation, e.g. via a photon ←photon detector
2. thermal excitation
3. impurities

The Fermi Energy

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



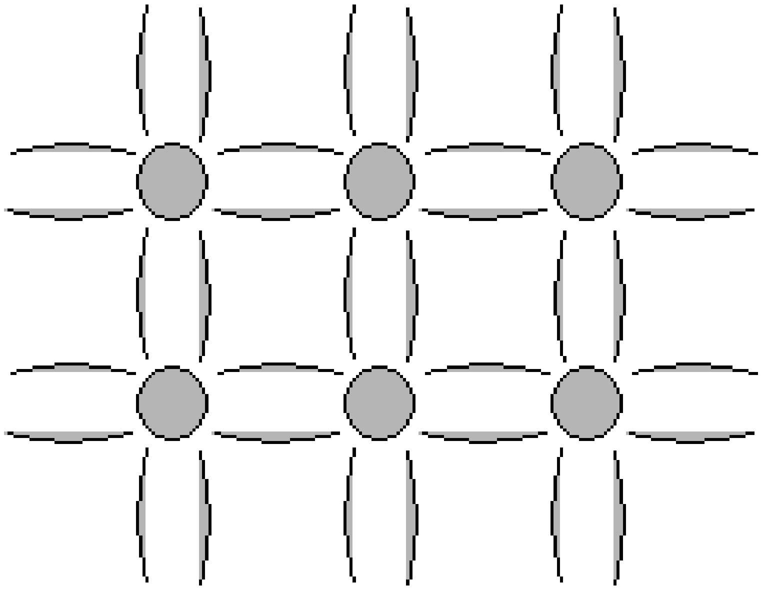
$$n_0 = N_c f(E_c) \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2}$$

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

Intrinsic Photoconductors

The Basic Principle

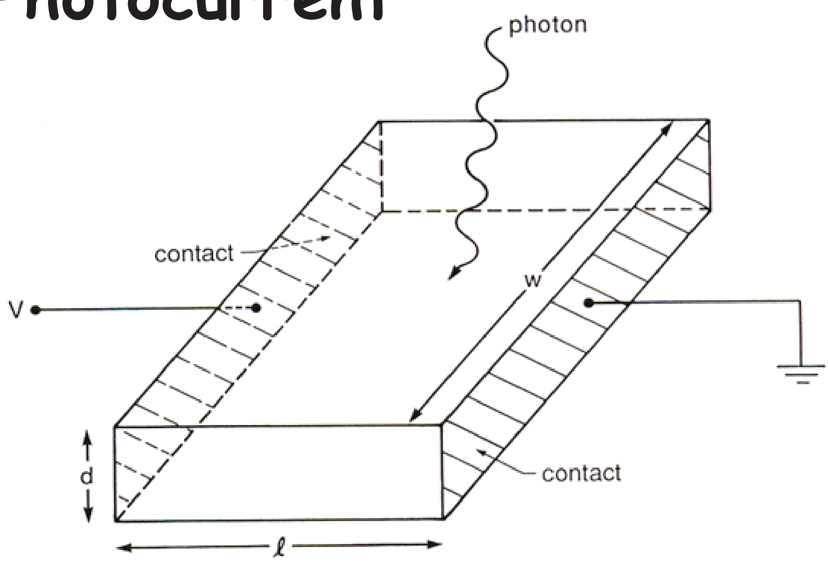
- E_γ lifts e^- into conduction band
- electric field $\bar{E}$ drives charges to electrodes
- few charge carriers → high resistance



The Photocurrent

Conductivity:

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



where:
R_d = resistance
w,d,l = geometric dimensions
q = electric charge
n_0 = number of charge carriers $\quad n = \frac{\varphi \eta \tau}{wdl}$
φ = photon flux
τ = mean lifetime before recombination
μ_n = electron mobility ~ mean time between collisions.

Important Quantities and Definitions

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

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

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

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

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

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

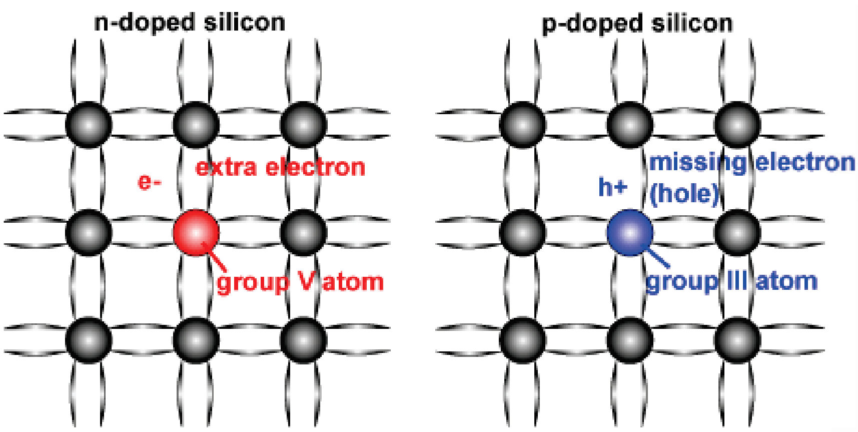
Limitations of Intrinsic Semiconductors

- short wavelength cutoffs $\lambda_c = \dfrac{hc}{E_g}$
  - → Germanium: 1.85µm
  - → Silicon: 1.12µm
  - → GaAs: 0.87µm
- non-uniformity of material
- problems to make good electrical contacts to pure Si
- difficult to "keep clean" and minimize Johnson noise

Extrinsic Photoconductors

Extrinsic Semiconductors

Solution: add impurities at low concentration to provide excess electrons → much reduced bandgap → longer wavelength cutoff



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]

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

Problems: absorption coefficients much less than for intrinsic photoconductors → low QE → active volumes (pixels) must be large

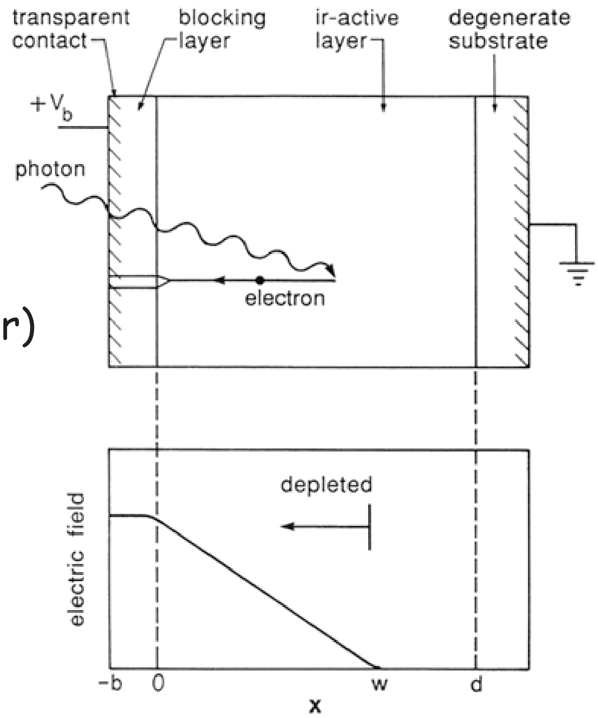
Blocked Impurity Band (BIB) Detectors

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

IR-active layer: heavily doped

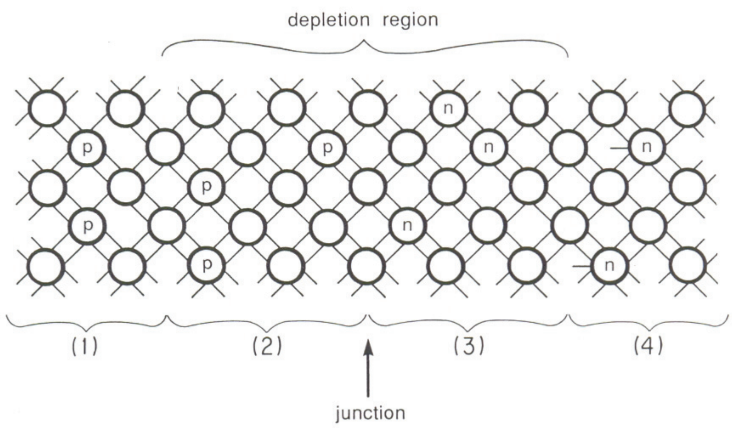
Blocking layer: thin layer of high purity (intrinsic photoconductor)

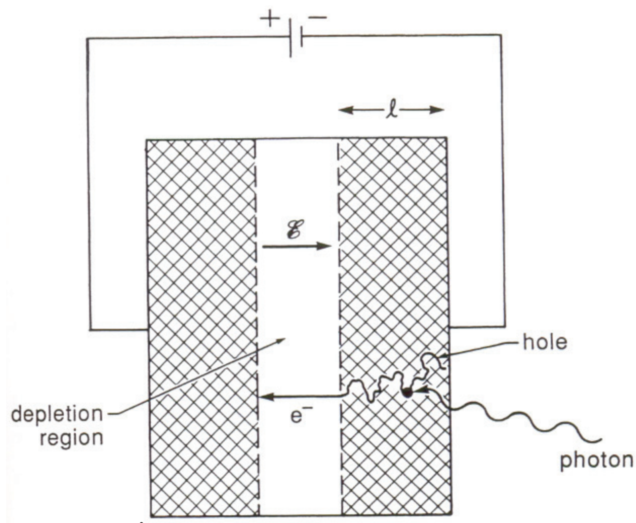
Typical species are Si:As or Si:Sb BIBs



Photodiodes

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





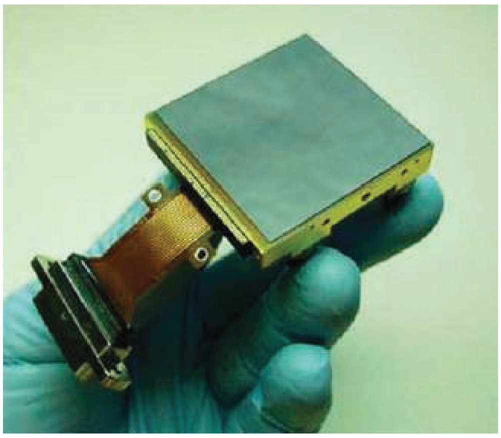
1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^--hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region → photo-current

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	≥ 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

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

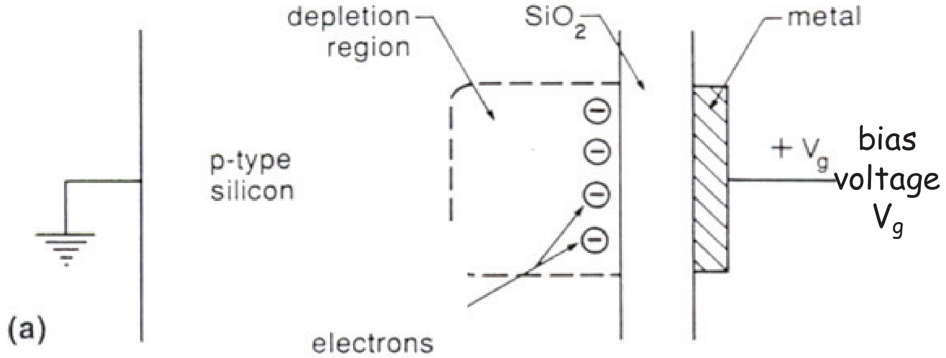
Can also be combined to a 2x2 mosaic



Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

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



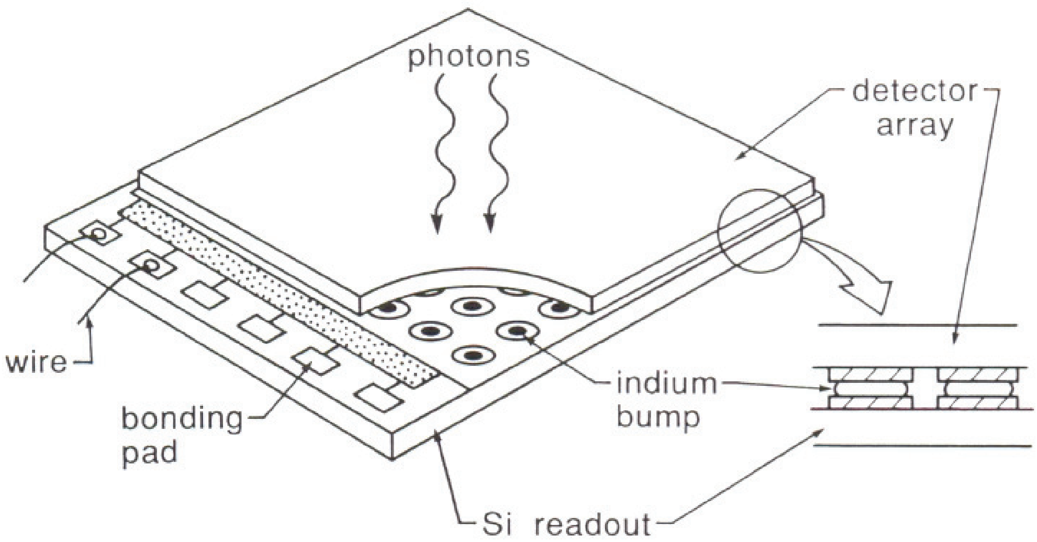
1. photons create free e$^-$ in the photoconductor
2. e$^-$ drift toward the electrode but cannot penetrate the SiO_2 layer
3. e$^-$ accumulate at the Si—SiO_2 interface
4. the total charge collected at the interface is a measure of the number of photons during the exposure
5. → read out the number of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

Readout and Operation

I. Infrared Arrays

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"

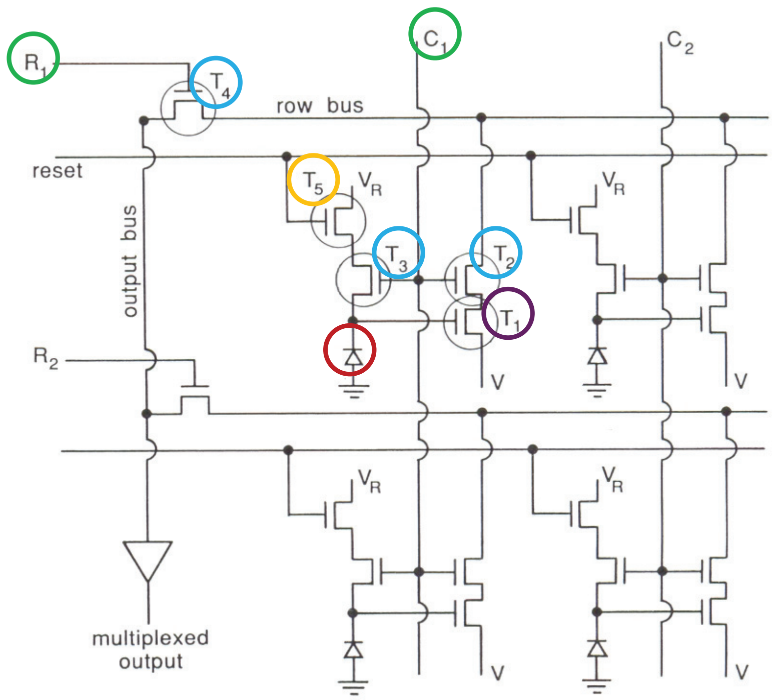
MUX Tasks:
- address a column of pixels by turning on their amplifiers
- pixels in other columns with power off will not contribute a signal

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.

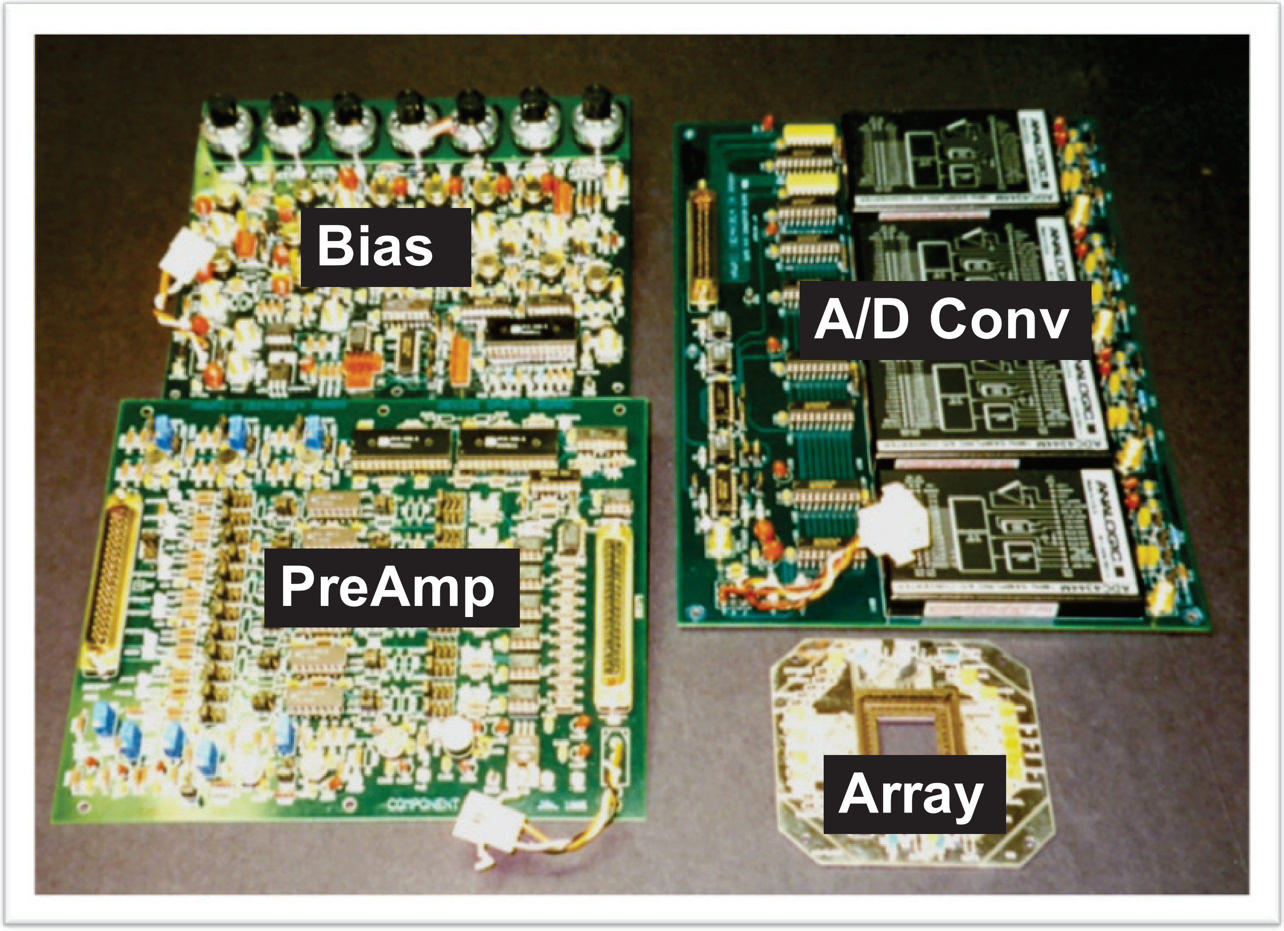
→ Power to T_1 → signal to the output bus

Reset: connect V_R via T_5 and T_3.



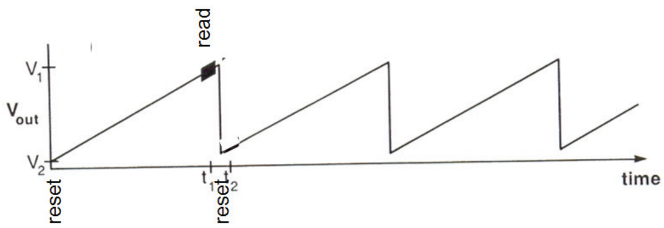
Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)



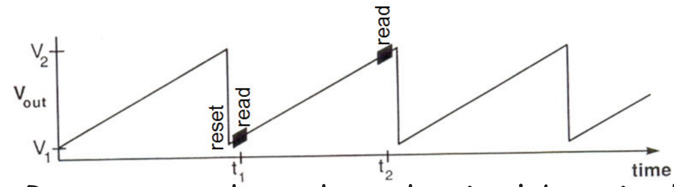
IR Array Read Out Modes

Single Sampling



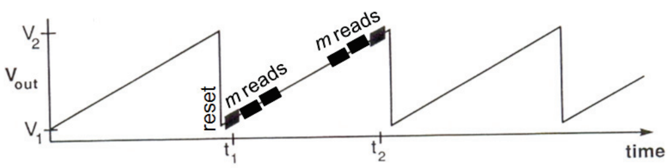
- most simple approach
- does not remove kTC noise
- measures the absolute signal level

Reset-Read-Read



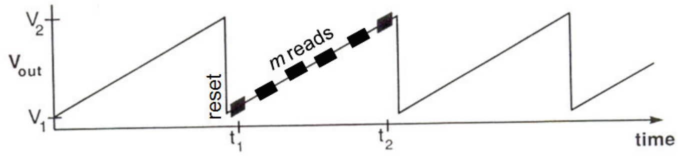
- Resets, reads and reads pixel-by-pixel
- Signal = Read(2) – Read(1)
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

(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



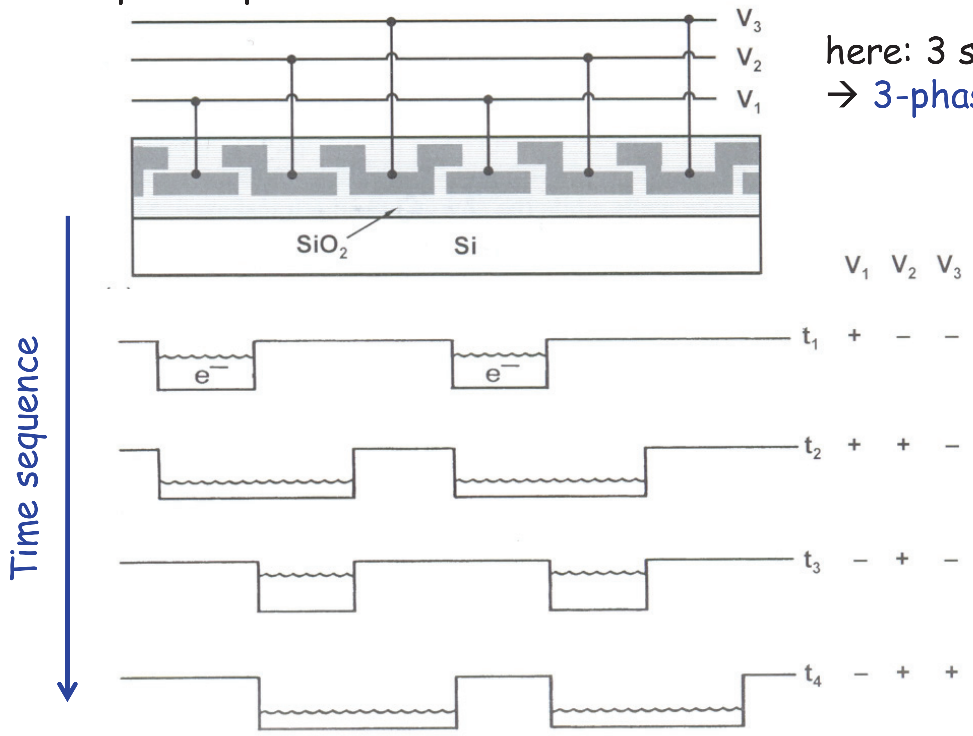
- *m* equidistant reads during integration
- linear fit → "slope"
- reduces readout noise by √m
- particularly useful in space (cosmics!)

Readout and Operation

II. CCDs

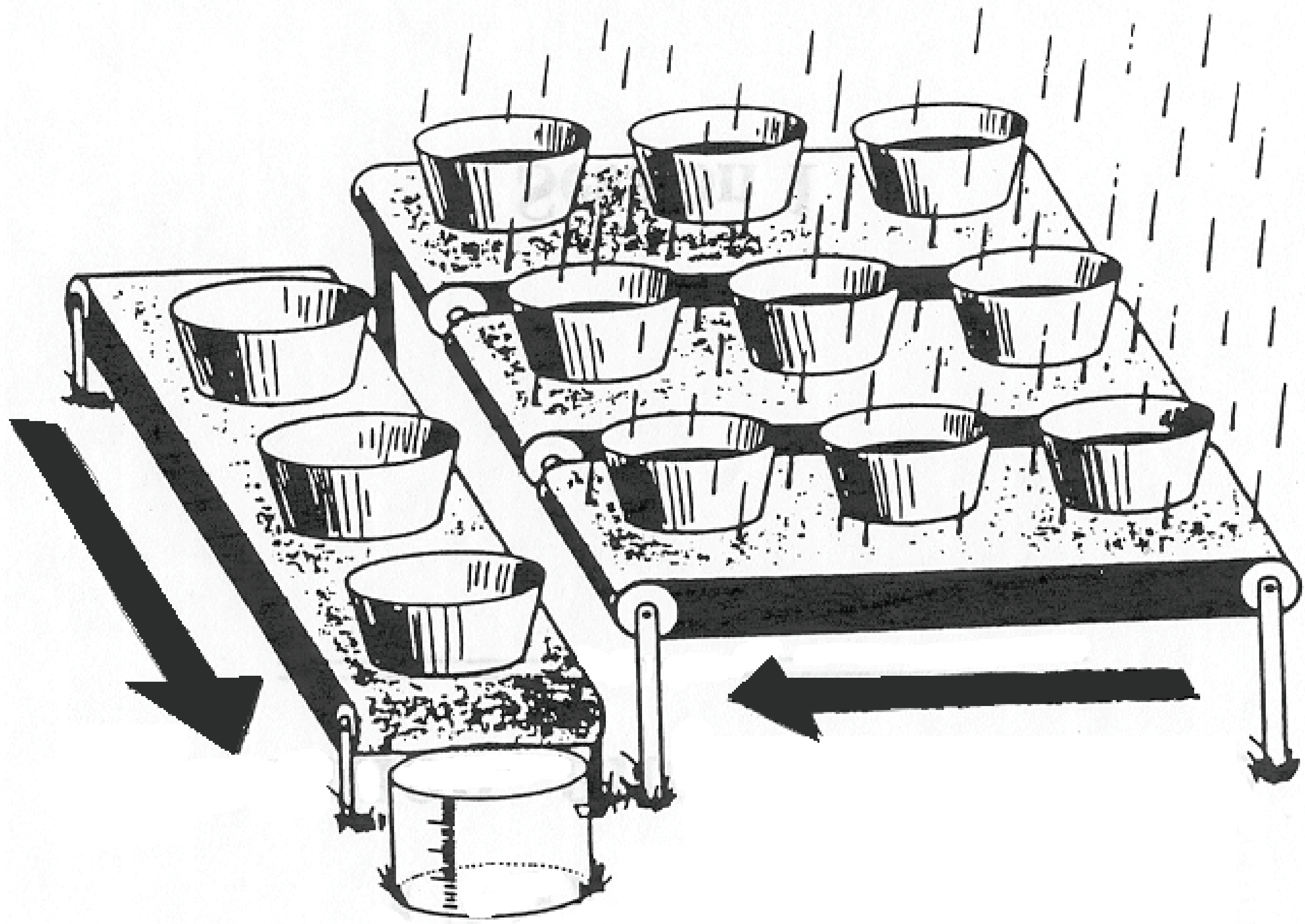
Charge Coupled Readouts

Collected charges are passed along the columns to the edge of the array to the output amplifier.



here: 3 sets of electrodes
→ 3-phase CCD

Be aware of charge transfer (in-)efficiencies (CTEs) due to electrostatic repulsion, thermal diffusion and fringing fields.



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: $\varepsilon = (1\text{-}CTE)$

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

Orthogonal Transfer CCDs (OTCCD)

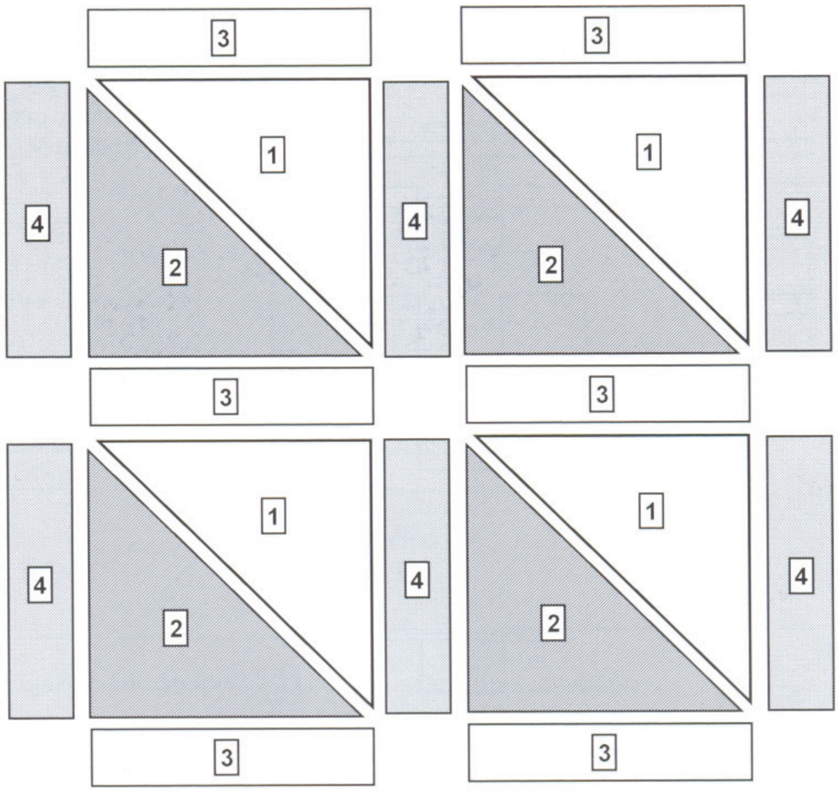
For TDI it would be desirable to move the charges in *any* direction to follow the image motion. This can be done with the OTCCD.

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.

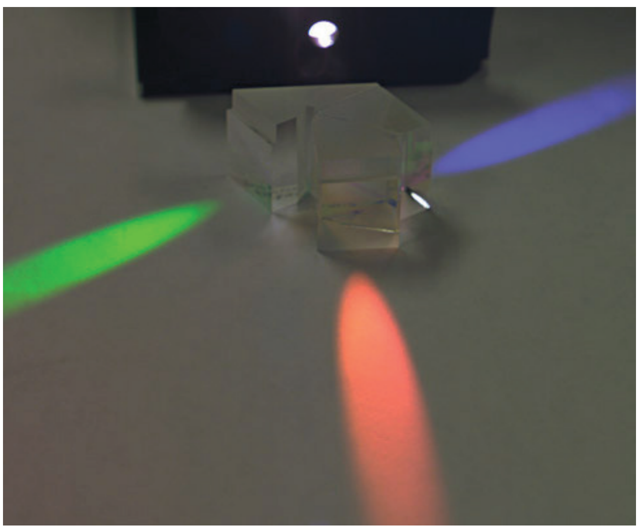
Moving to the opposite directions: reversing the clocking.

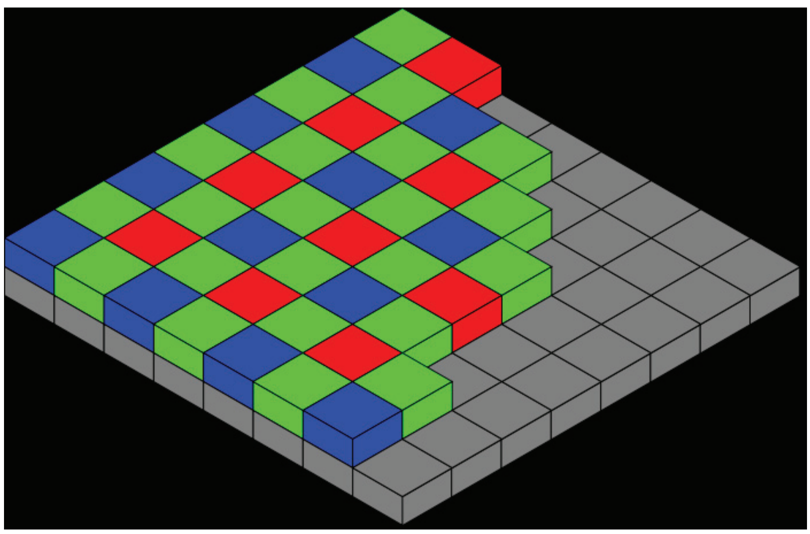


Side note: CCD Color Images

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.





Detector Noise

The main Noise Components

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

fundamental statistical noise due to the Poisson statistics of the photon arrival → transferred into the statistics of the **g**enerated and **r**ecombined holes and electrons.

Johnson or kTC noise $\left\langle I_{J}^{2}\right\rangle = \frac{4kT}{R}\Delta f$

fundamental thermodynamic noise due to the thermal motion of the charge carriers. Consider a photo-conductor as an RC circuit. Since $\langle Q^2\rangle = kTC$, the charge noise is also called kTC noise or reset noise.

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

increased noise at low frequencies, due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, and JFETs, …

The total noise in the system is: $\left\langle I_{N}^{2}\right\rangle = \left\langle I_{G-R}^{2}\right\rangle + \left\langle I_{J}^{2}\right\rangle + \left\langle I_{1/f}^{2}\right\rangle$

BLIP and NEP

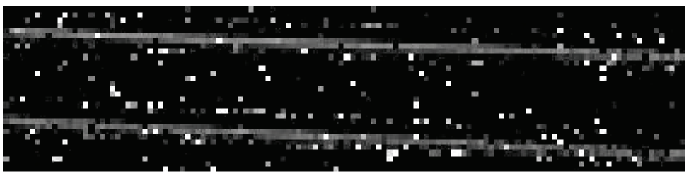
Operationally, background-limited performance (BLIP) is always preferred: $\langle I_{G-R}^2 \rangle >> \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle$

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

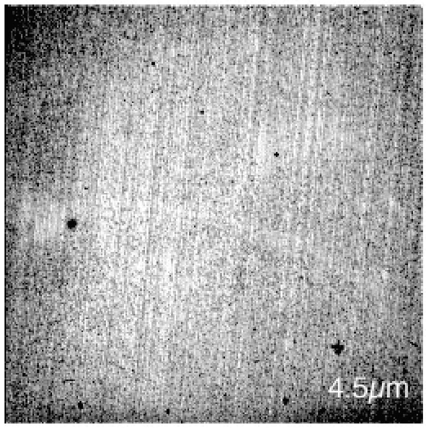
$$NEP_{G-R} = \frac{2hc}{\lambda}\left(\frac{\varphi}{\eta}\right)^{1/2}$$

In BLIP the NEP can only be improved by increasing the quantum efficiency η.

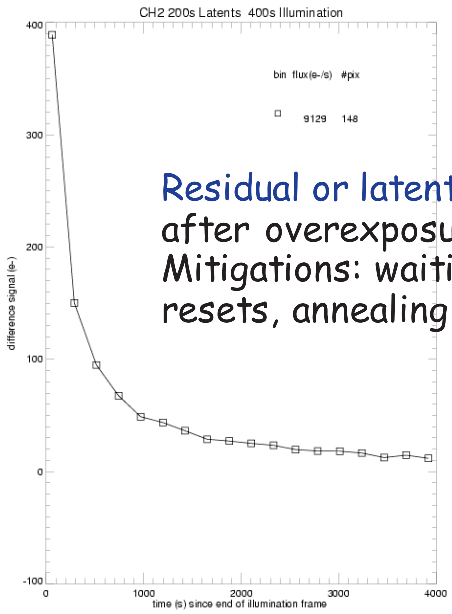
Detector Artefacts (1)



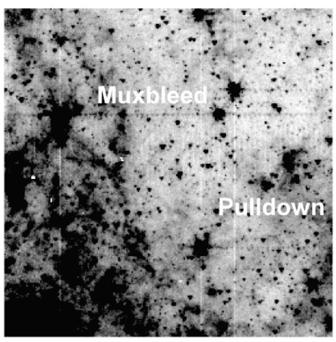
Dead, hot and rogue pixels.
Mitigation: subtract off-source image and/or reduce bias voltage

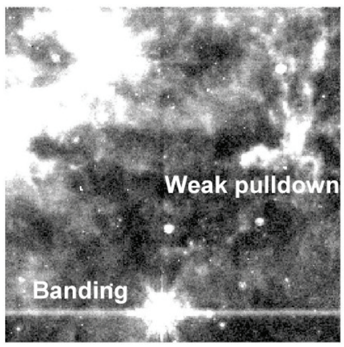


Fixed pattern noise.
Mitigation: "flat-fielding"



Residual or latent images after overexposure.
Mitigations: waiting, frequent resets, annealing

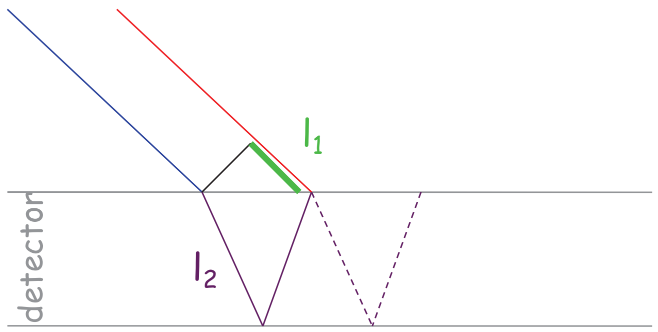


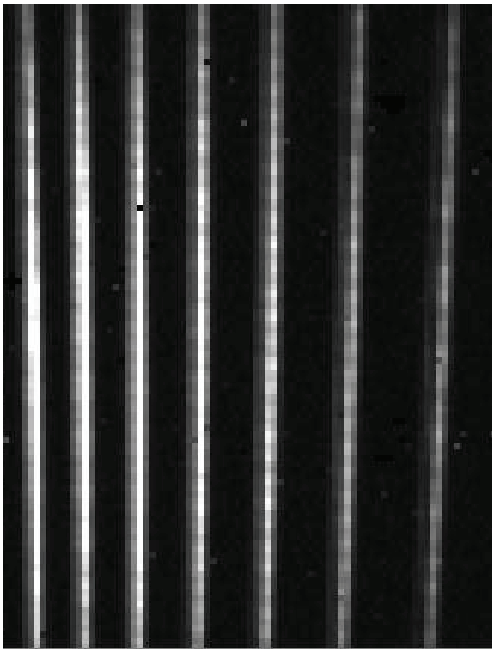


Muxbleed, pulldown and banding.
Mitigation: avoid bright sources, short exposures.

Detector Artefacts (2): Fringing

In spectrographs: photons 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.

Flatfielding Techniques

General Flatfielding

Detector response (QE, bias) varies slightly from pixel to pixel → image has "structure", even with flat illumination
→ flat-fielding; common methods are:

1. Dome flats: illuminate a white screen within the dome (can be done during the day, but may introduce spectral artifacts)

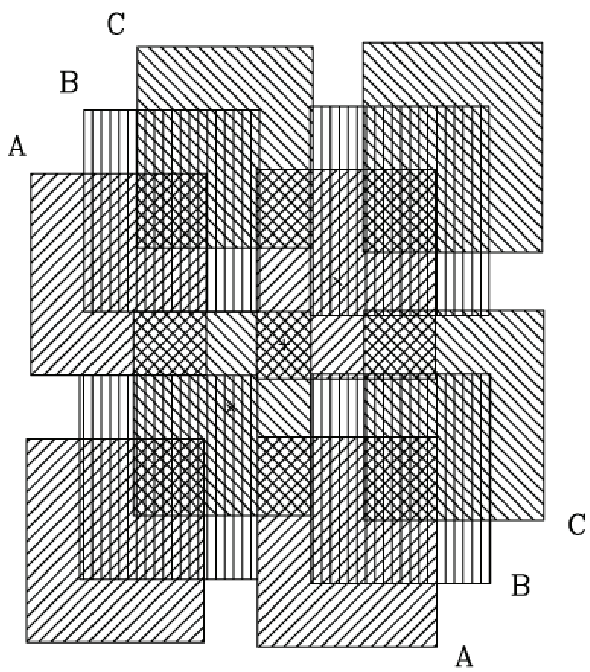
2. Twilight flats: observe the twilight sky at two times during sunrise or sunset (high S/N but time is often too short to get FFs for all filters)

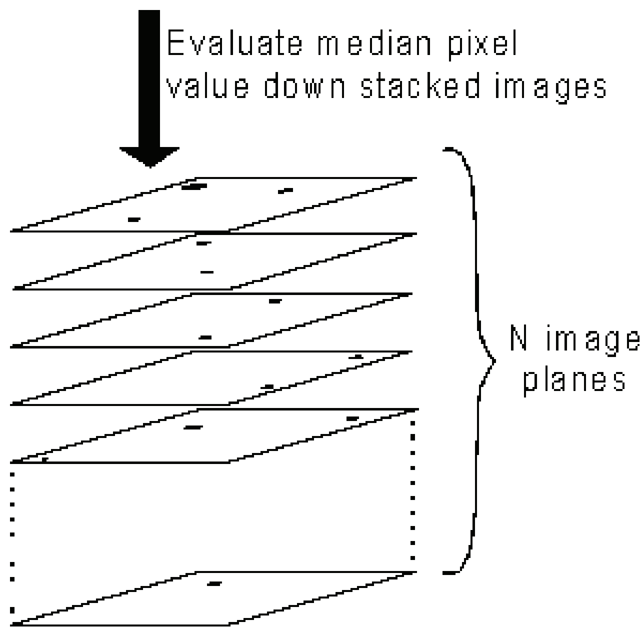
3. Sky flats: use the observations themselves (spectrally best, but often low S/N)

In all cases: use the difference between two flux levels F_1, F_2 to compute the flatfield $FF = \left(\frac{F_1 - F_2}{\text{median}(F_1 - F_2)} \right)^{-1}$ with which all images have to be multiplied.

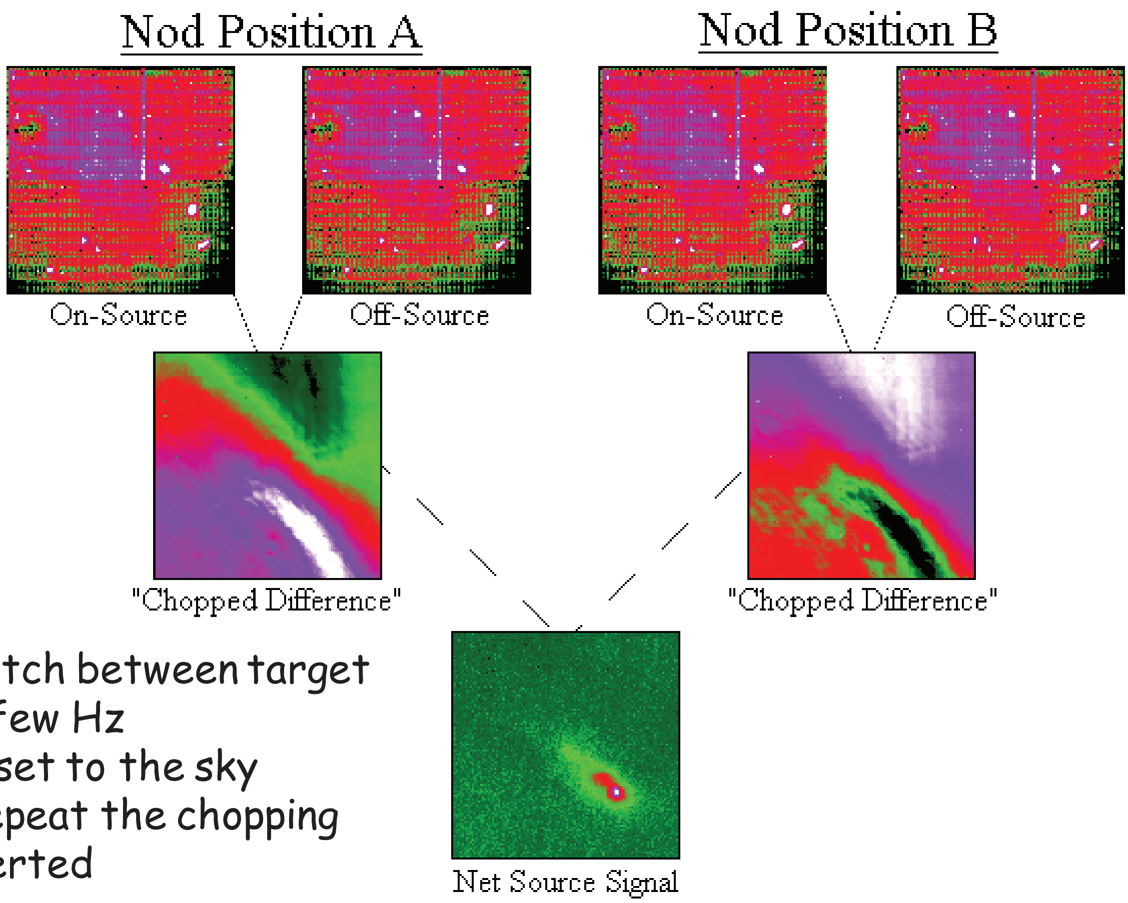
Dithering / Jittering

1. Observe the same field with many exposures, each offset by a small amount
2. Combine the image e.g., via median filerting





Chopping / Nodding



Chopping: switch between target and sky at a few Hz
Nodding: offset to the sky position to repeat the chopping sequence inverted

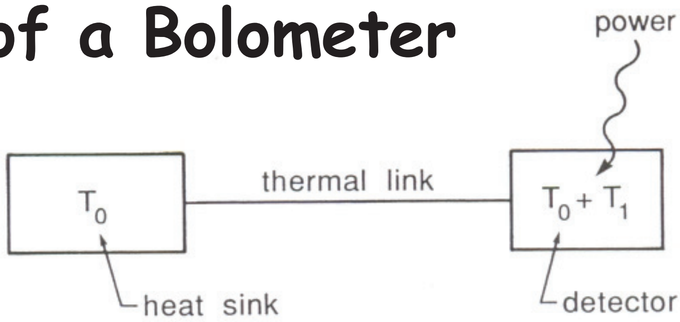
Part I
Photon Detectors

Part II
Thermal Detectors

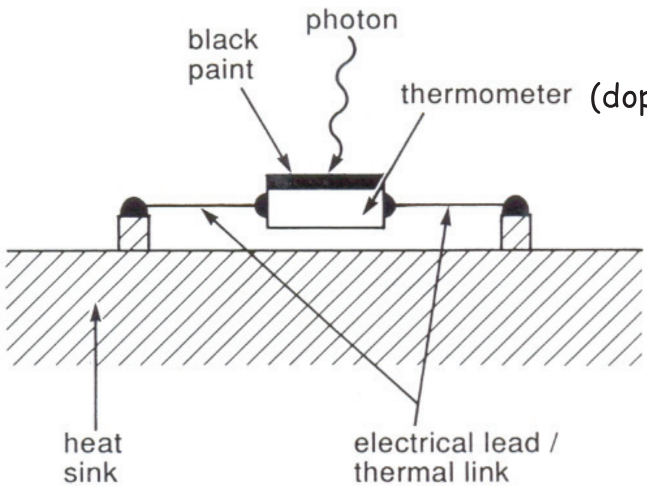
Part III
Coherent Receivers

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

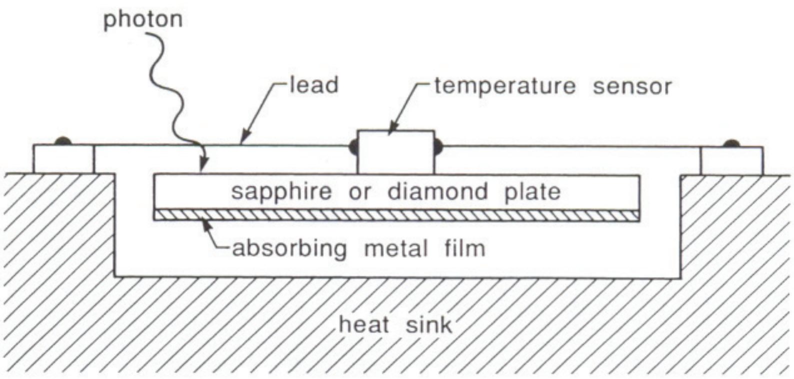
Bolometers are especially for the far-IR/sub-mm wavelength range!

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.

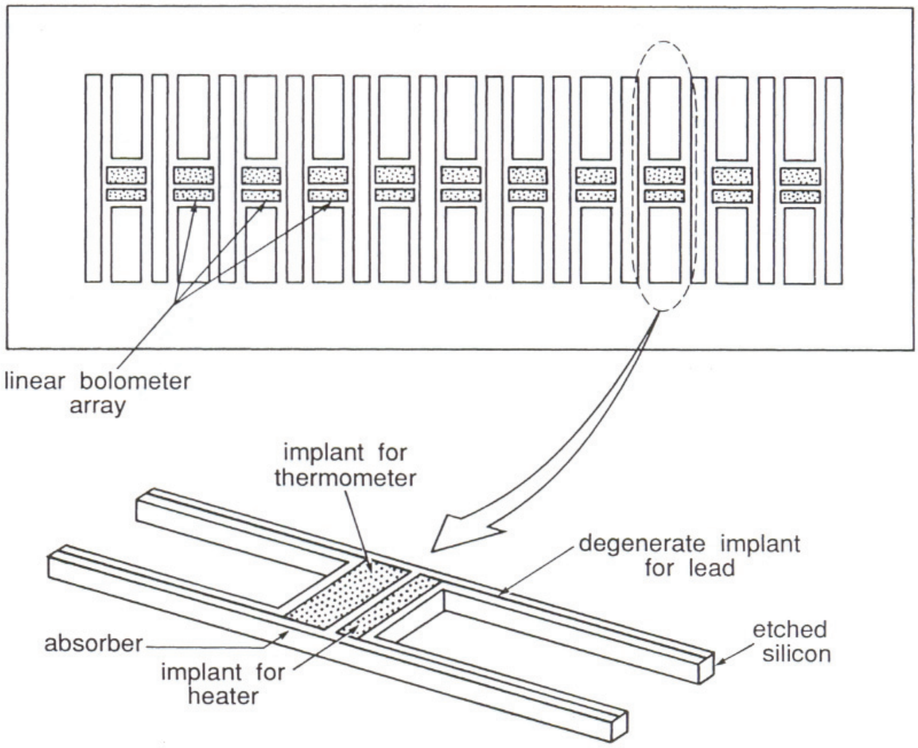


The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Etched Bolometers

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

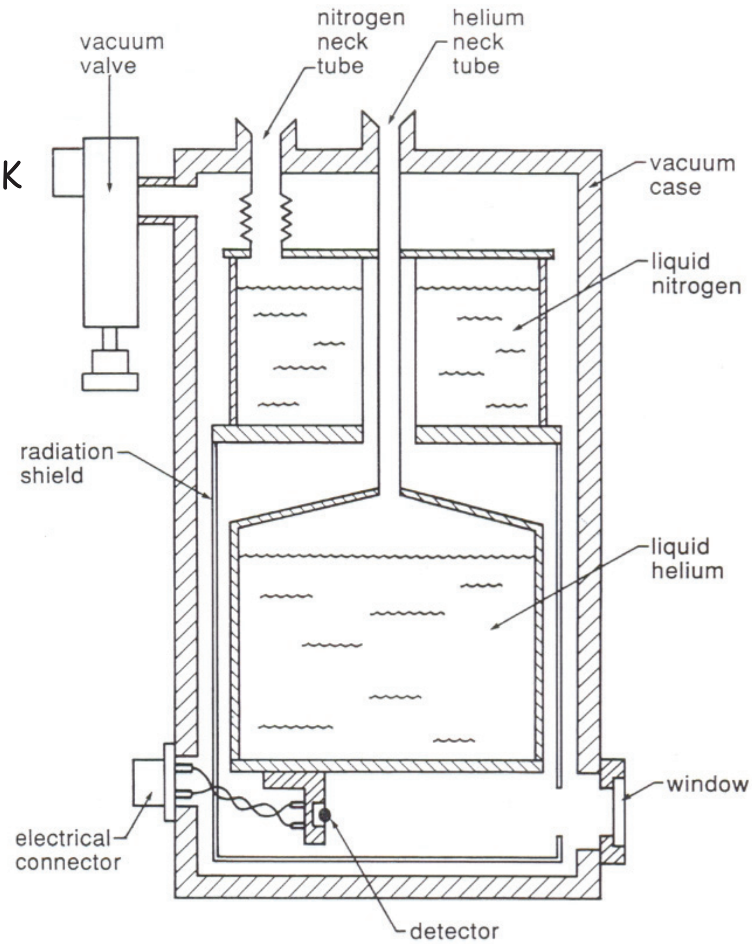
Thermal time response ~ C/G → small structures minimize the heat capacity C by reducing the volume of material.



Low Operating Temperatures

Four standard options to cool:

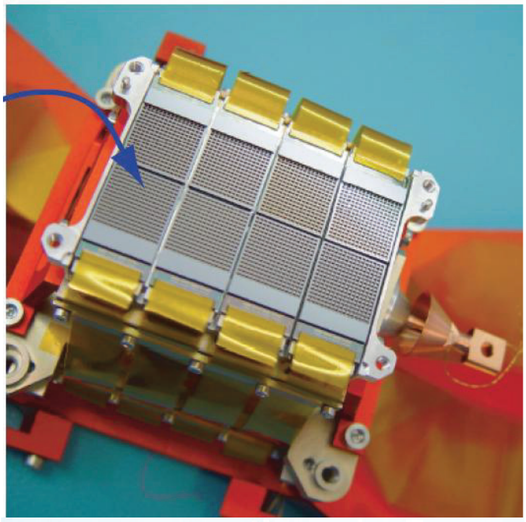
1. ^{4}He dewar (air pressure) → T=4.2K
2. ^{4}He dewar (pumped) → 1K< T<2K
3. ^{3}He (closed-cycle) refrigerator → T~0.3K
4. adiabatic demagnetization refrigerator → T ~ 0.1K



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

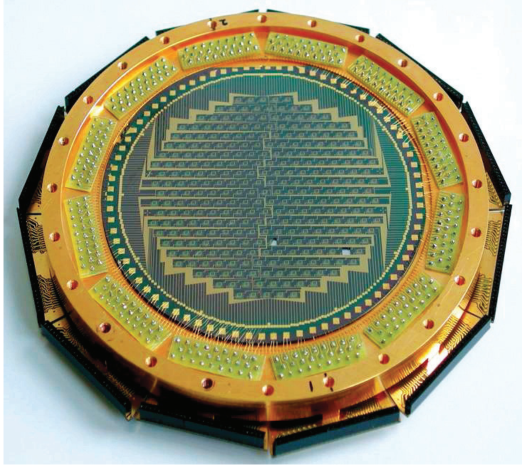
Bolometers – an Overview

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.

Part I
Photon Detectors
Part II
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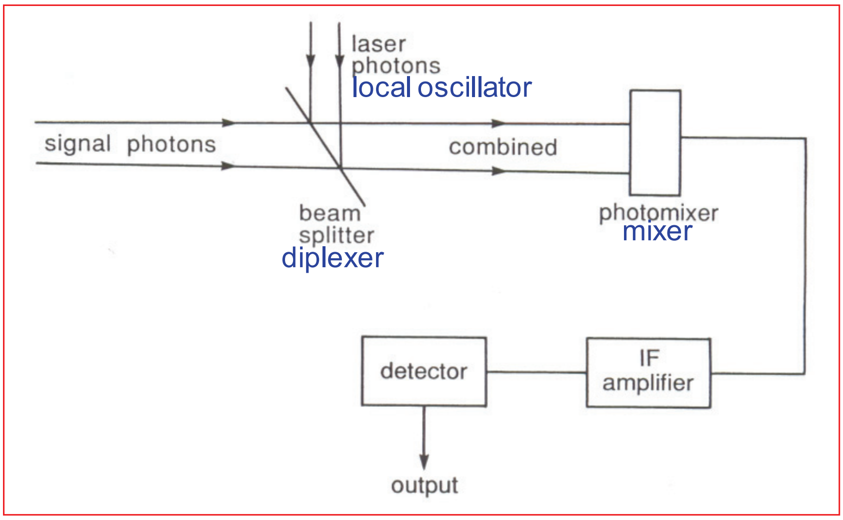
Coherent Receivers

Basic Principle

Already introduced previously → **see Radio Techniques lecture**



Performance Characteristics

Performance Comparison Bolometer ⇔ Heterodyne Receiver

Case 1: Bolometer operating at BLIP and heterodyne receiver operating in the thermal limit (hν«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 (hν»kT).

➔ the heterodyne receiver will outperform the bolometer.

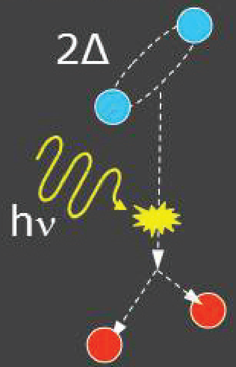
In the case of narrow bandwidth and high spectral resolution the heterodyne system will always win.

Outlook: The next Generation of Detectors

(courtesy: Jochem Baselmans/SRON)

MKIDS – Physical Principle

Superconductor has 2 types of charge carriers



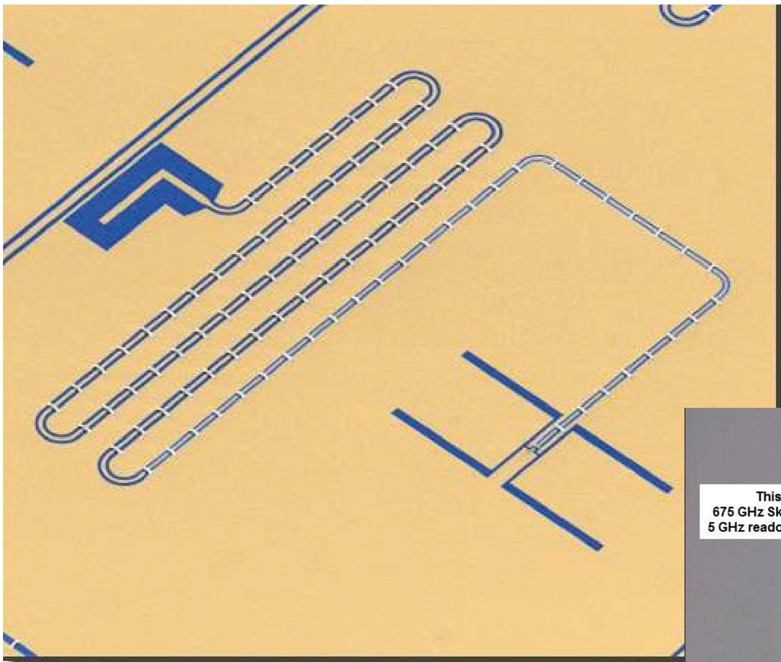
Cooper Pairs	Supercurrent	Inductance $i\omega L(P_{sky})$
Quasiparticles	Normal current	Resistance $R(P_{sky})$

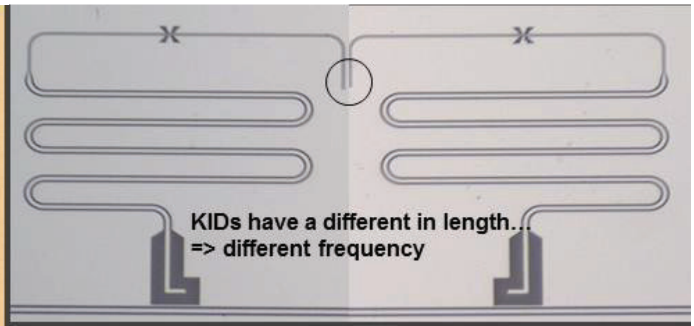
KID

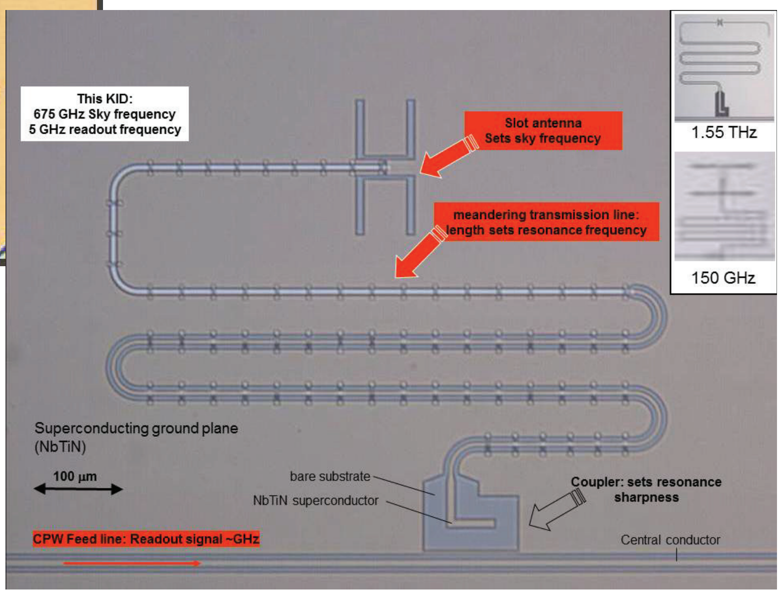
Resonator measures changes in complex surface impedance due to sky signal

KID = Kinetic Inductance Detector

MKIDS – Construction







MKIDS – Operating Principle