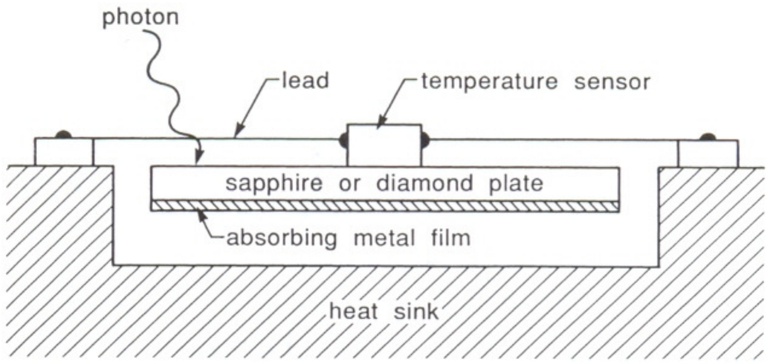
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

7th Lecture: 26 October 2011

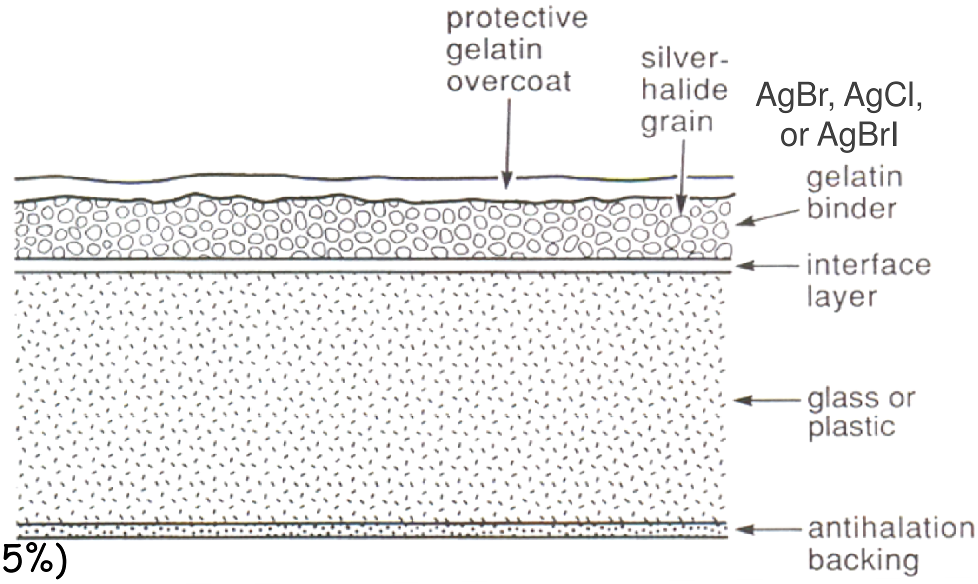


Overview
I. PHOTOCONDUCTORS
Intro: Solid State Physics
Intrinsic Photoconductors
Extrinsic Photoconductors
IR arrays ⇔ CCDs
Detector Noise
II. BOLOMETERS
III. COHERENT RECEIVERS
Basic Principle
Performance Characteristics

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

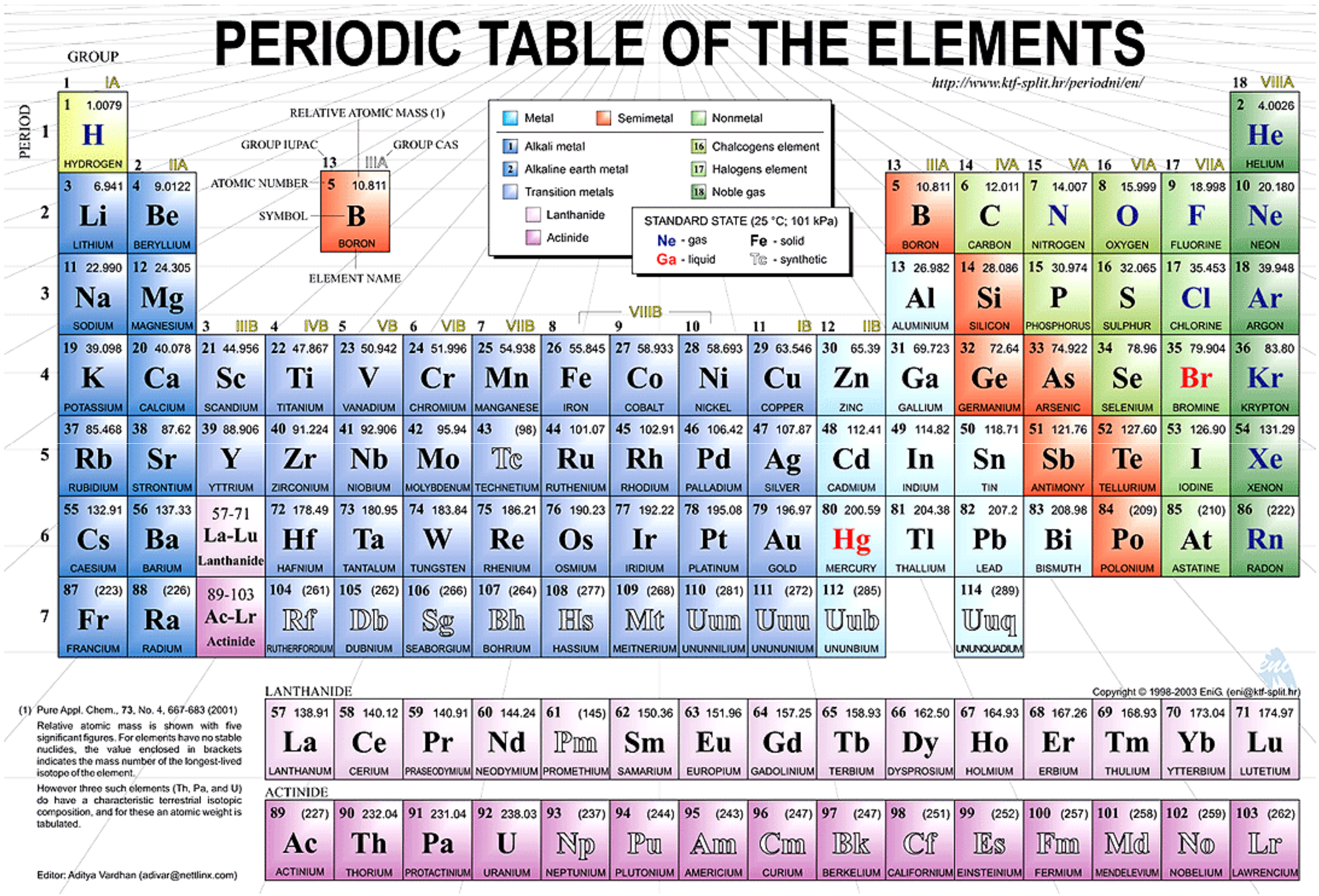
Part II

Thermal Detectors

Part III

Coherent Receivers

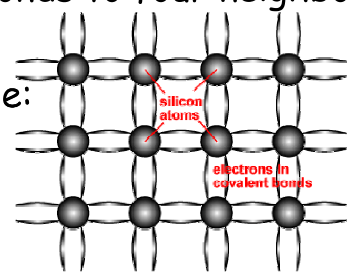
Intro to Solid State Physics



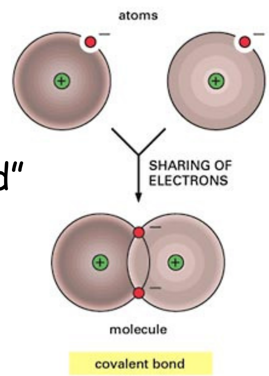
The Diamond Lattice

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

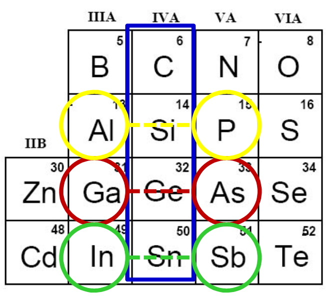
Example:

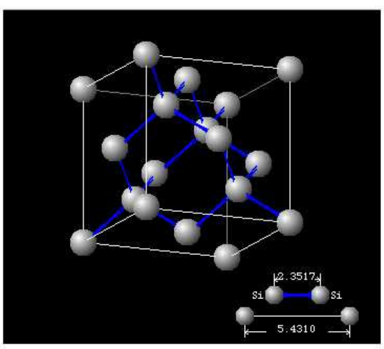


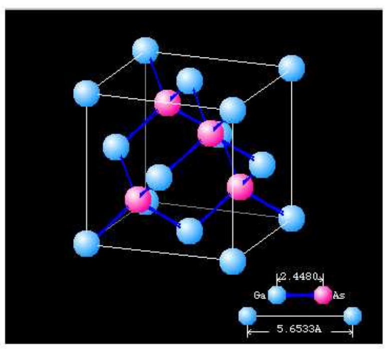
These double-bonds between neighbours are due to "shared" electrons



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



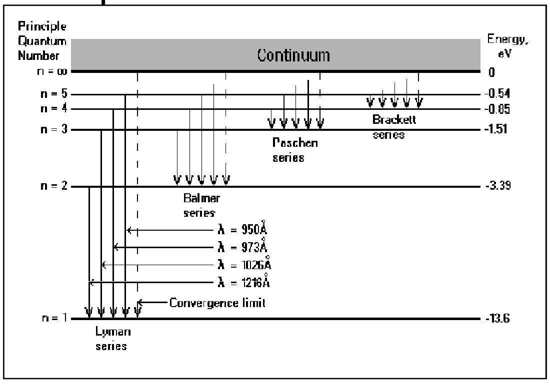


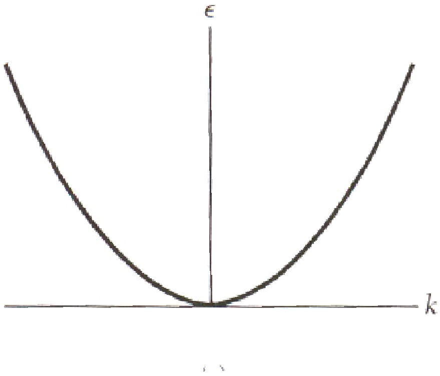


Electronic States and Bands

Single atomic system

Example: H atom



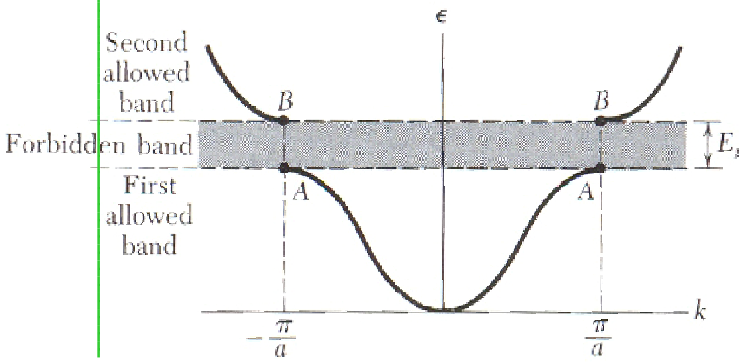


Atomic crystal

Wavefunctions Ψ overlap

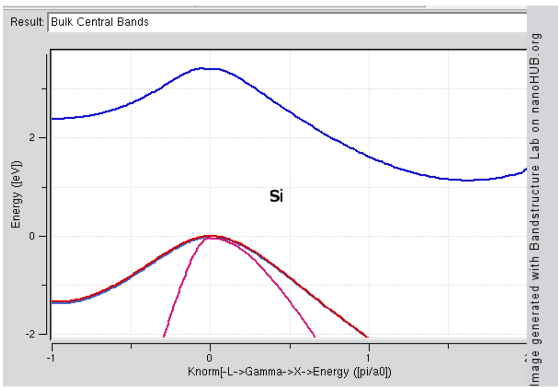
→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

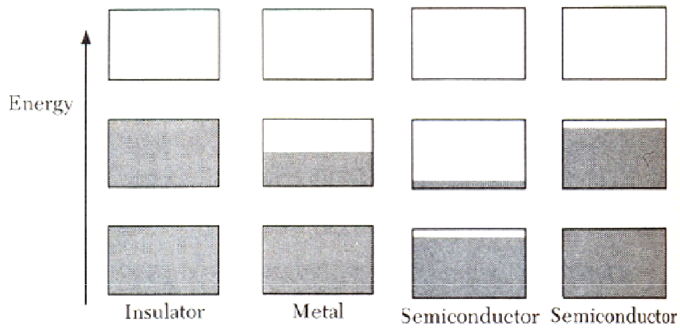
→ Multiple splitting ➔ "bands"



Electric Conductivity

Conductivity requires charge carriers in the conduction band



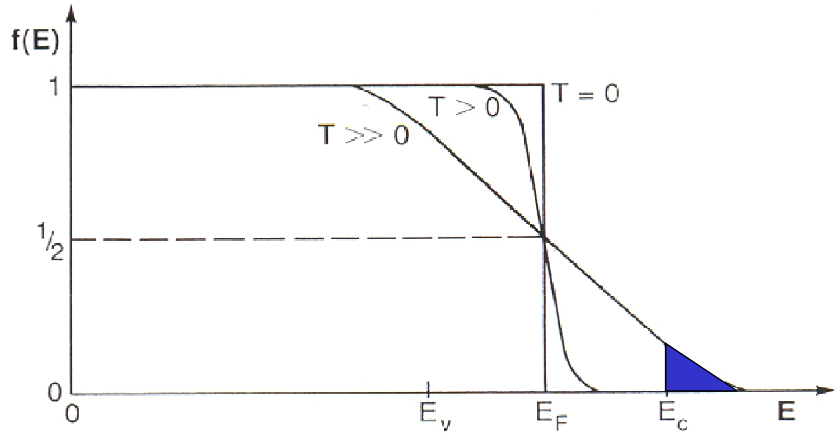


One needs to overcome the bandgap E_g to lift an e^- into the conduction band. This can be done via:

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.



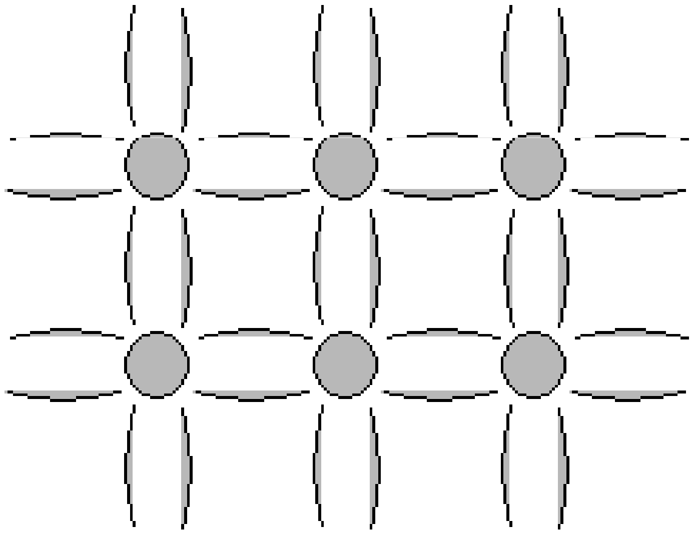
$$n_0 = N_c f(E_c) \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_{eff} kT}{h^2}\right)^{3/2}$$

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

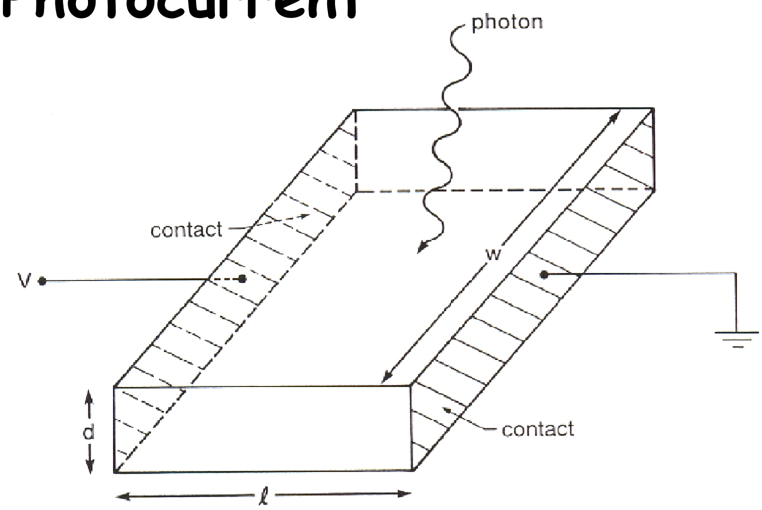
Intrinsic Photoconductors

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 $\eta \equiv \frac{\text{\# absorbed photons}}{\text{\# incoming photons}}$

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

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

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

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

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

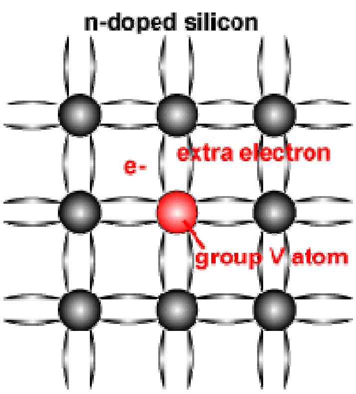
Limitations of Intrinsic Semiconductors

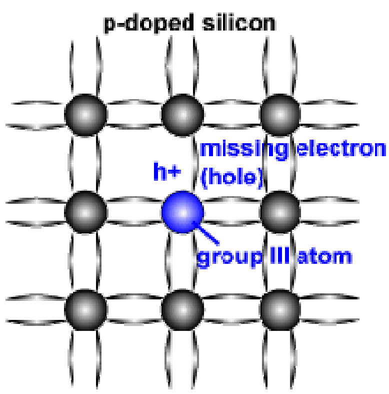
- short wavelength cutoffs $\lambda_c = \frac{hc}{E_g}$
  - → Germanium: 1.85µm
  - → Silicon: 1.12µm
  - → GaAs: 0.87µm
- non-uniformity of material
- problems to make good electrical contacts to pure Si
- difficult to "keep clean" and minimize Johnson noise

Extrinsic Photoconductors

Extrinsic Semiconductors

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





		Ge	Si
Impurity	Type	Cutoff wavelength λ_c (μm)	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

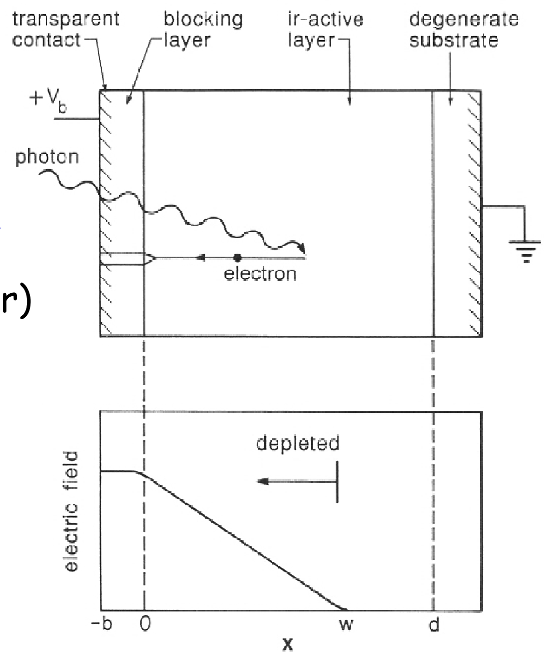
Blocked Impurity Band (BIB) Detectors

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

IR-active layer: heavily doped

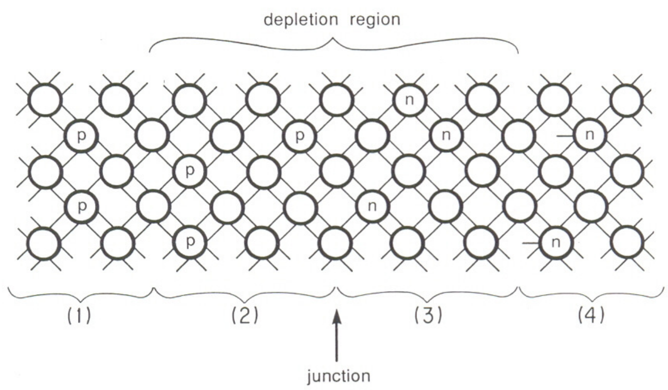
Blocking layer: thin layer of high purity (intrinsic photoconductor)

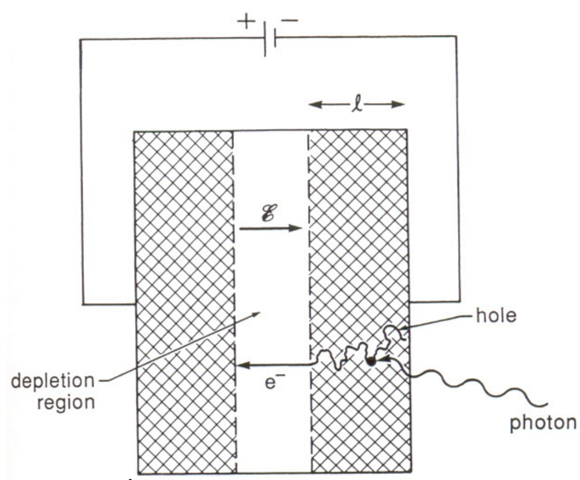
Typical species are Si:As or Si:Sb BIBs



Photodiodes

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



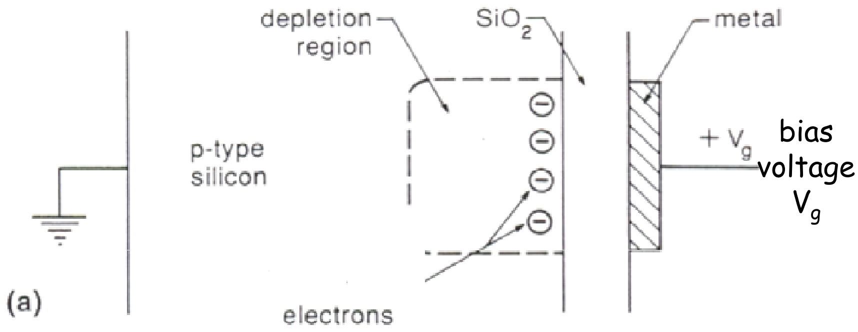


1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^--hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region → photo-current

Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

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

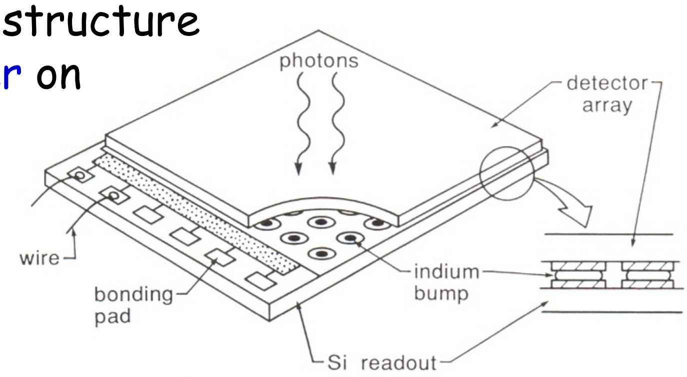


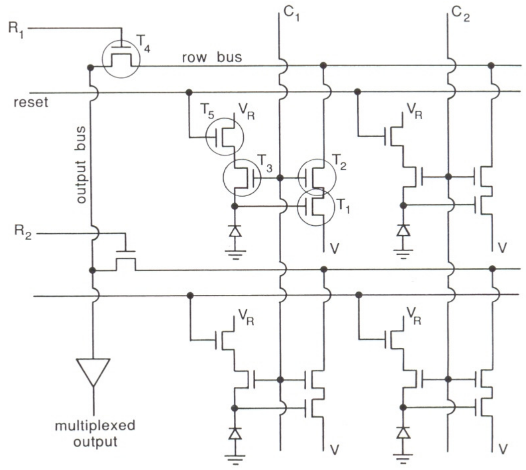
1. photons create free e^- in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO_2 layer
3. e^- accumulate at the Si—SiO_2 interface
4. the total charge collected at the interface is a measure of the number of photons during the exposure
5. → read out the number of e^-

Differences between IR Arrays and CCDs

Infrared Arrays – Construction

IR arrays have a sandwich structure with a photo-sensitive layer on one side ...



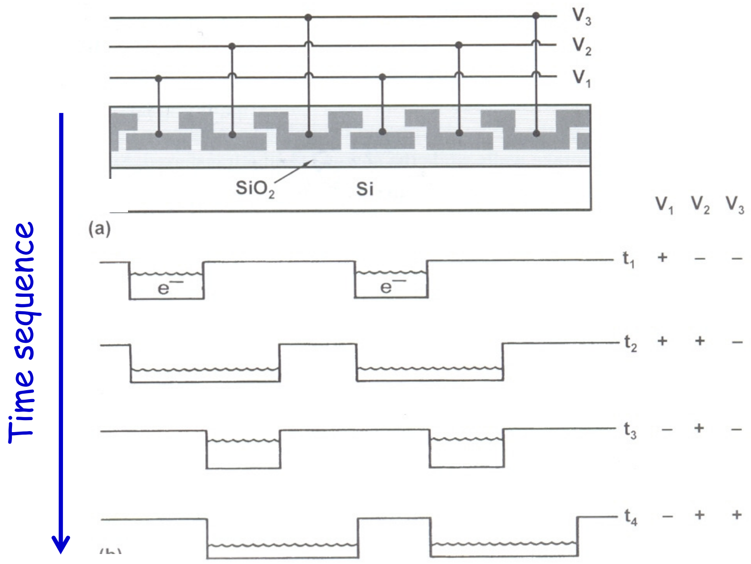


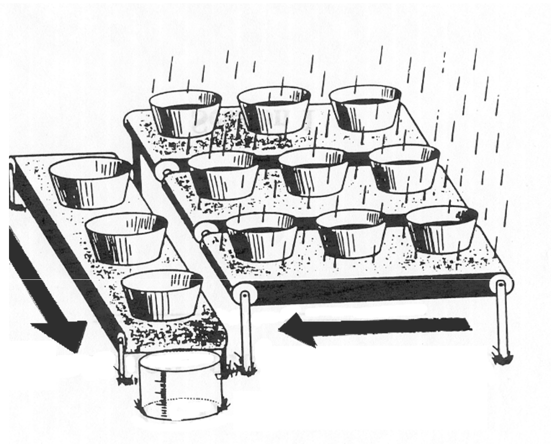
... and a multiplexer circuit on the other side.

The multiplexer allows to directly address and read individual pixels.

CCD Readouts

The collected charges are physically moved along the columns to the edge of the array to the output amplifier.





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

here: 3 sets of electrodes → 3-phase CCD

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

Detector Noise

The 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 photon arrival → transferred into the statistics of the **g**enerated and **r**ecombined holes and electrons.

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

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

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

BLIP and NEP

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

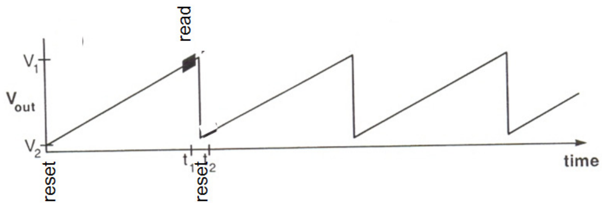
The noise equivalent power (NEP) is the signal power that yields an RMS S/N of unity in a system of Δf = 1 Hz:

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

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

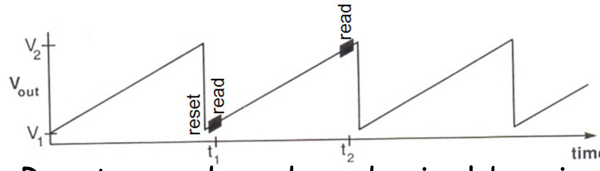
IR Array Read Out Modes

Single Sampling



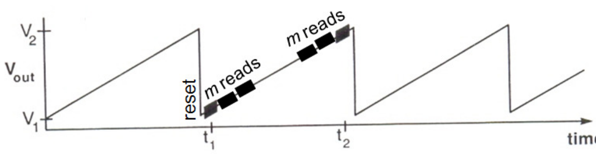
- most simple approach
- does not remove kTC noise
- measures the absolute signal level

Reset-Read-Read



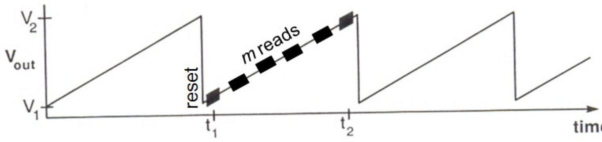
- Resets, reads and reads pixel-by-pixel
- Signal = Read(2) – Read(1)
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

(Multiple) Fowler Sampling



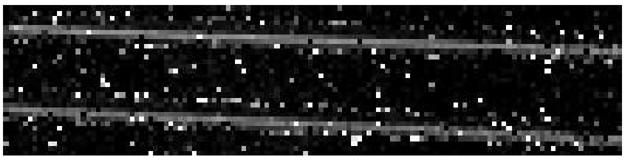
- similar to reset-read-read ...
- ... but each read is repeated *m* times
- Signal = mean(read2) – mean(read1)
- Reduces readout noise by √m over RRR

Sample-up-the-ramp Fitting

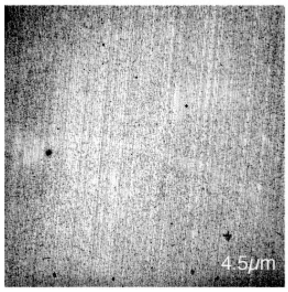


- *m* equidistant reads during integration
- linear fit → "slope"
- reduces readout noise by √m
- particularly useful in space (cosmics!)

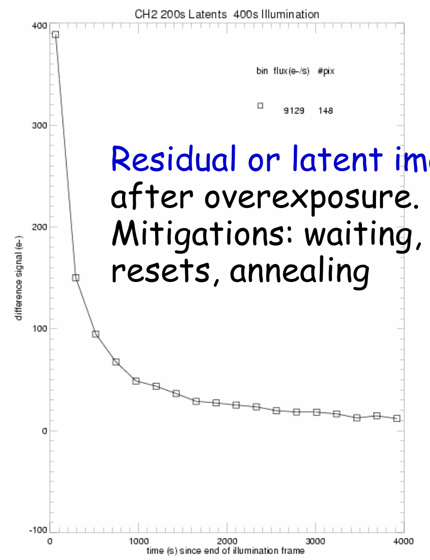
Some Detector Artefacts



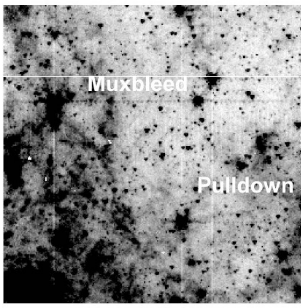
Dead, hot and rogue pixels.
Mitigation: subtract off-source image and/or reduce bias voltage



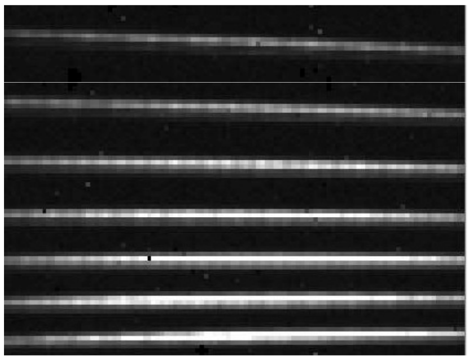
Fixed pattern noise.
Mitigation: "flat-fielding"



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



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



Fringing (in spectrographs)
Interference between planparallel surfaces.
Mitigation: thinning, removal in software.

Part I

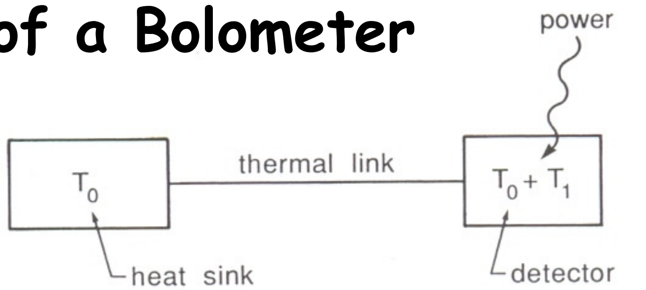
Photon Detectors

Part II
Thermal Detectors

Part III

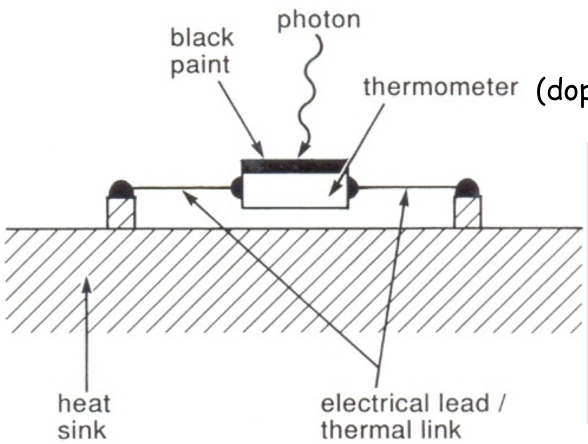
Coherent Receivers

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)

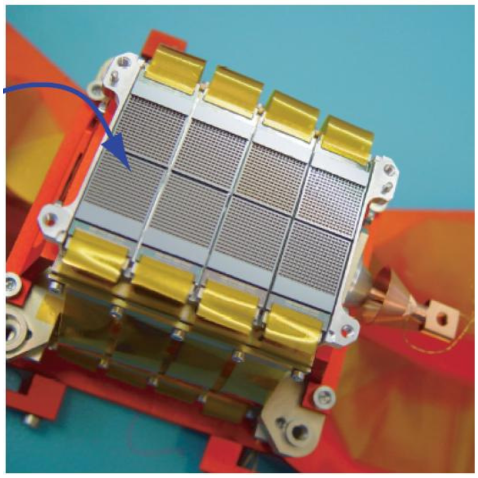
- measure the voltage across thermo.
- voltage depends on resistance
- resistance depends on temperature
- temperature depends on photon flux

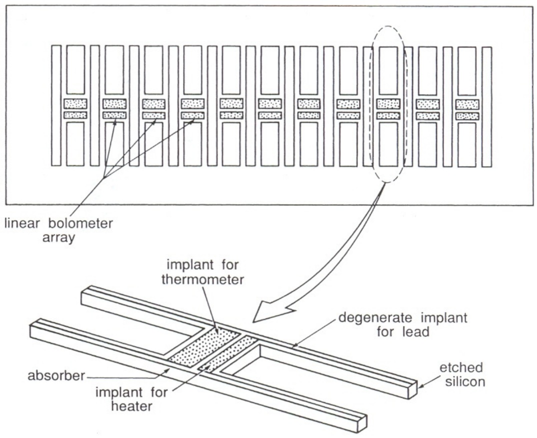
Bolometers are especially for the far-IR/sub-mm wavelength range!

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.





Precision etching techniques in Si minimize the size of the structures →

- low heat capacity C
- short thermal time response ~ C/G
- multiplexing advantage ("arrays")

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

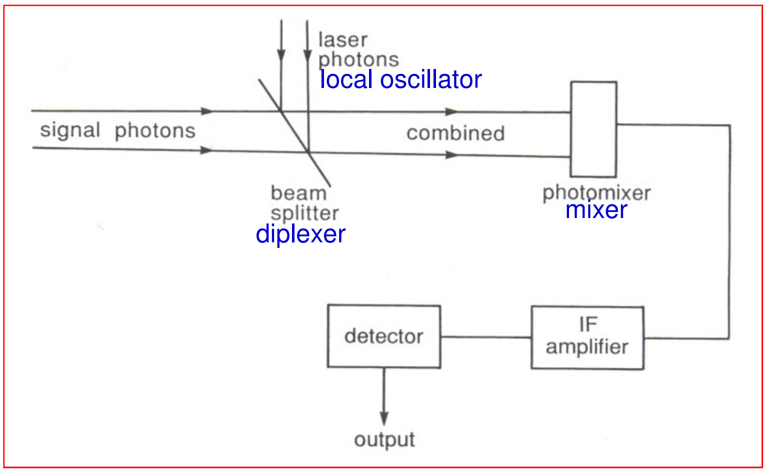
Basic Principle

Problems:

- very low photon energies → wave character of light is dominant
- often very weak signals → amplification essential

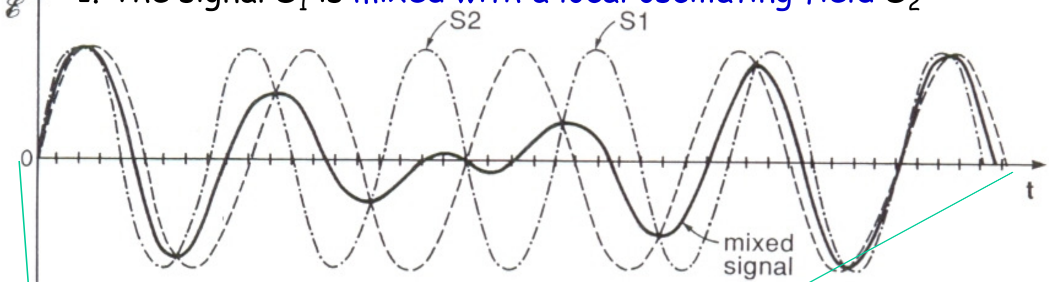
Solution:

- mix signal with reference wave

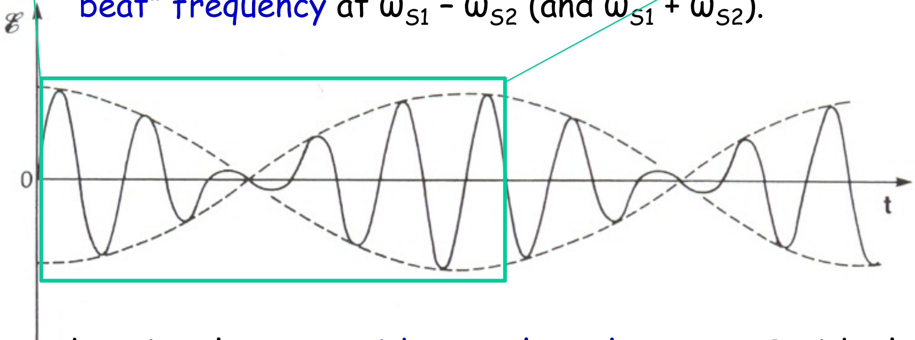


Step 1: Use a Local Oscillator

1. The signal S_1 is mixed with a local oscillating field S_2



2. The mix produces a down-converted difference, intermediate, or "beat" frequency at $\omega_{S1} - \omega_{S2}$ (and $\omega_{S1} + \omega_{S2}$).

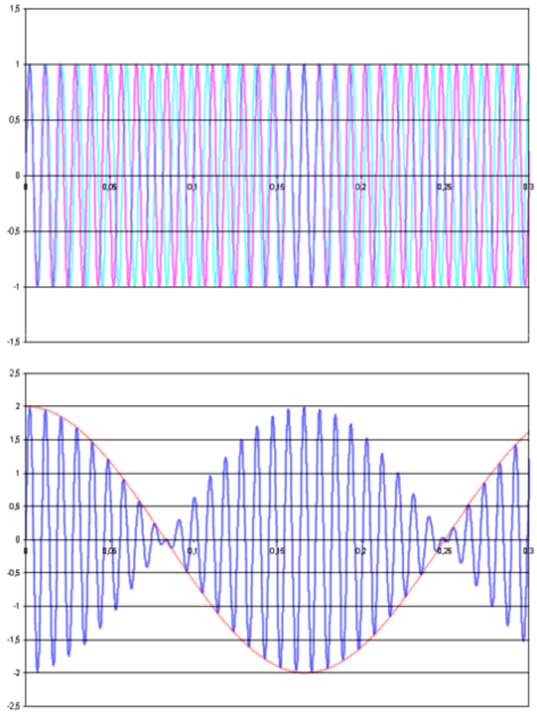


- encodes signal over a wide wavelength range → ideal for spectroscopy
- typically, power(ω_{LO}) » power(ω_S) → amplification by oscillator signal
- down-conversion to frequencies where low-noise electronics exist.

The Intermediate Frequency (IF)

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

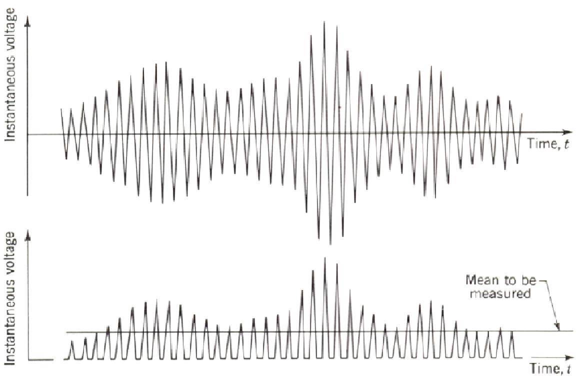
Example: Measure a signal at 1.5 GHz → use an oscillator at 1.55 GHz → down-convert the signal to a 50 MHz carrier.

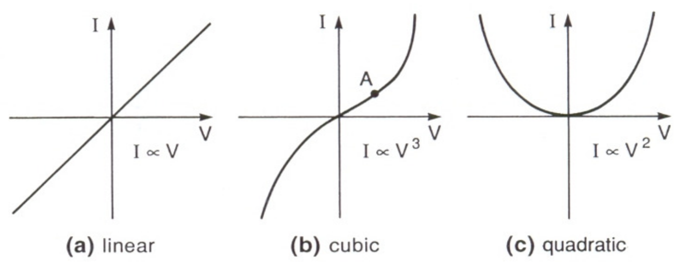


λ = 1 μm	⇔ ν = 300 THz	⇔ $\Delta t = 3.3 \cdot 10^{-15}$ s
λ = 100 μm	⇔ ν = 3 THz	⇔ $\Delta t = 3.3 \cdot 10^{-13}$ s
λ = 1 cm	⇔ ν = 30 GHz	⇔ Δt = 33 ps

At low frequencies (radio/sub-mm) one uses an electronic LO.
At high frequencies (IR) the LO may be a continuous wave (CW) laser.

Step 2: Use a non-linear Mixer



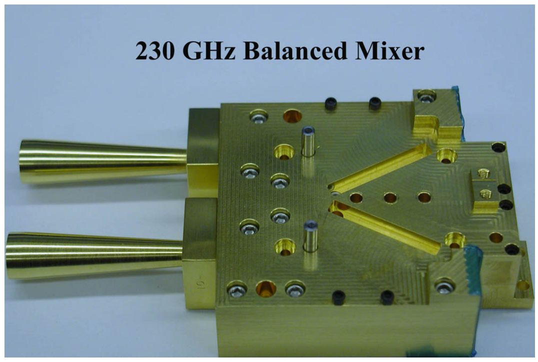


- A linear device (a) yields no output power at any frequency.
- a non-linear device (b,c) can convert power from the original frequencies to the beat frequency
- even if the mixer has an odd function of voltage around the origin (b) the conversion efficiency is zero.
- but if biased above zero (A) the average change in current is larger for positive than for negative voltage peaks.

If $I \sim V^2$ (as in a diode) then output ~ (field strength)^2 ~ power, which is exactly what we want to measure!

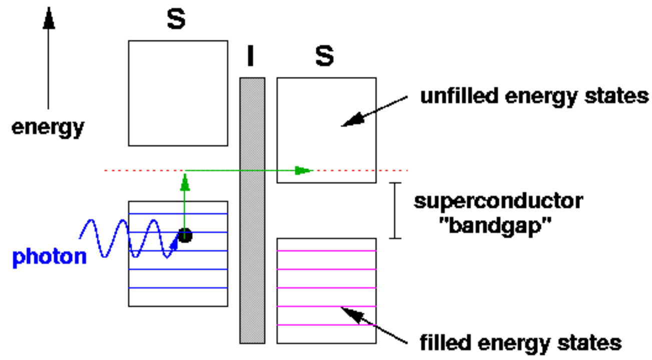
Mixer Technology

Problem: good & fast (recombination times!) "traditional" photo-conductors do not exist for $\lambda > 40\mu m$.



Common sub-mm mixers:

- Schottky diodes
- SIS junctions
- Hot electron bolometers



Performance Characteristics

Performance Estimators

To characterize the performance of heterodyne detectors we use:

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

   Obviously, the lower T_N the better the S/N.

2. The antenna temperature T_S:
   It is defined, analogous to the noise temperature, as the strength of the source flux (S/N=1) .

   In the Rayleigh-Jeans approximation, the antenna temperature is linearly related to the input flux density: $P_S \sim T_S$

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.

Interested to hear more?

→Masters course on "Detection of Light"