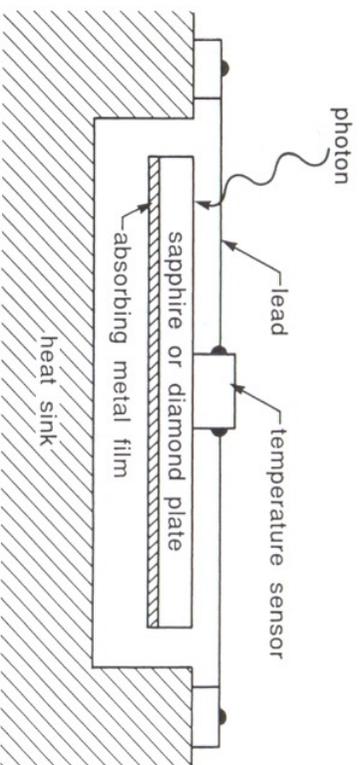


Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

7th Lecture: 26 October 2011



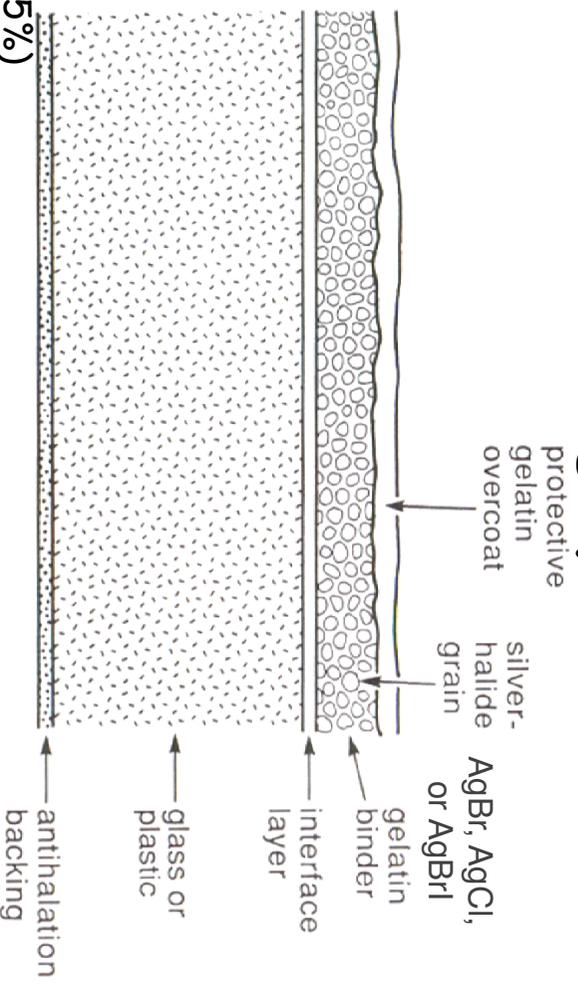
Overview

- I. PHOTOCODUCTORS
 - 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 → $\sim 10^9$ 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

PERIODIC TABLE OF THE ELEMENTS

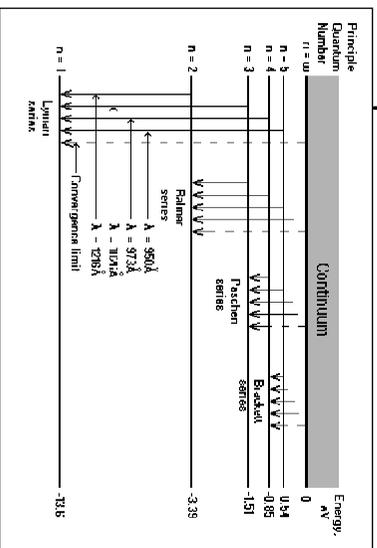
<http://www.kf-spl.it/periodic/>

GROUP	PERIOD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
		IA	IIA	GROUP IUBC										IIIA	GROUP CAS		VIA	VIIA	VIIIA
		ATOMIC NUMBER		GROUP IUBC		GROUP CAS		SYMBOL		EL. ELEMENT NAME		STANDARD STATE (25 °C, 101 kPa)		GROUP IUBC		GROUP CAS		GROUP IUBC	
1	1	1, 1.0079		1		1		H		Hydrogen		Gas		1		1		1	
2	2	2, 4.0026		2		2		He		Helium		Gas		2		2		2	
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4	4	4, 9.0122		4		4		Be		Beryllium		Solid		4		4		4	
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6	6	6, 24.305		6		6		Mg		Magnesium		Solid		6		6		6	
7	7	7, 39.098		7		7		K		Potassium		Solid		7		7		7	
8	8	8, 40.078		8		8		Ca		Calcium		Solid		8		8		8	
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93	93	93, 304		93		93		Uuq		Ununquadium		Solid		93					

Electronic States and Bands

Single atomic system

Example: H atom

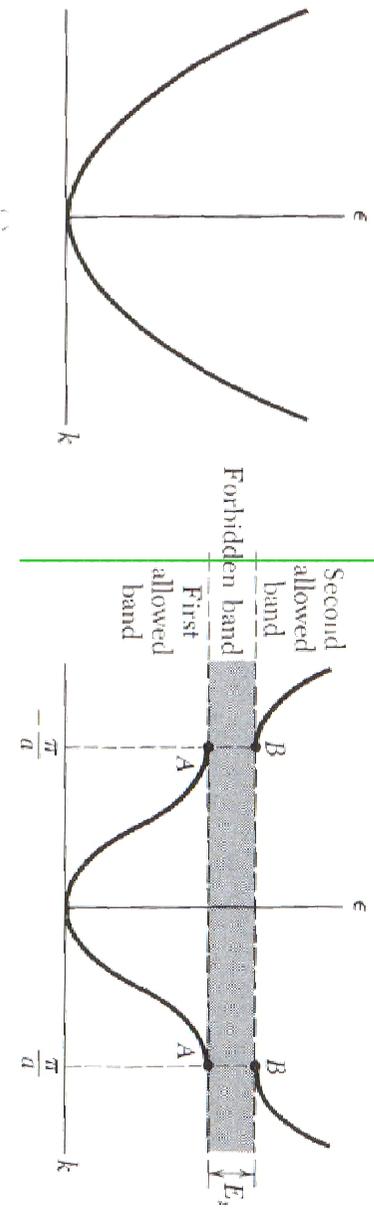


Atomic crystal

Wavefunctions Ψ overlap

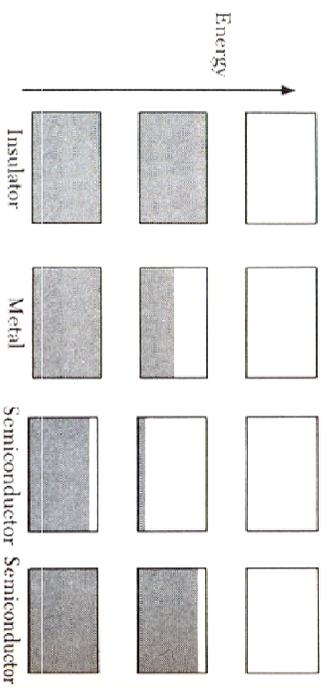
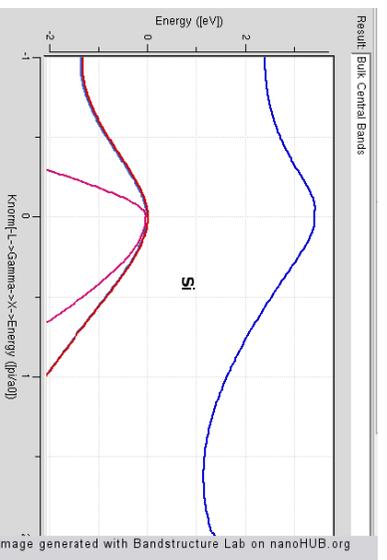
→ Energy levels of individual atoms split due to Pauli principle (avoiding the same quantum states)

→ Multiple splitting → "bands"



Electric Conductivity

Conductivity requires charge carriers in the conduction band

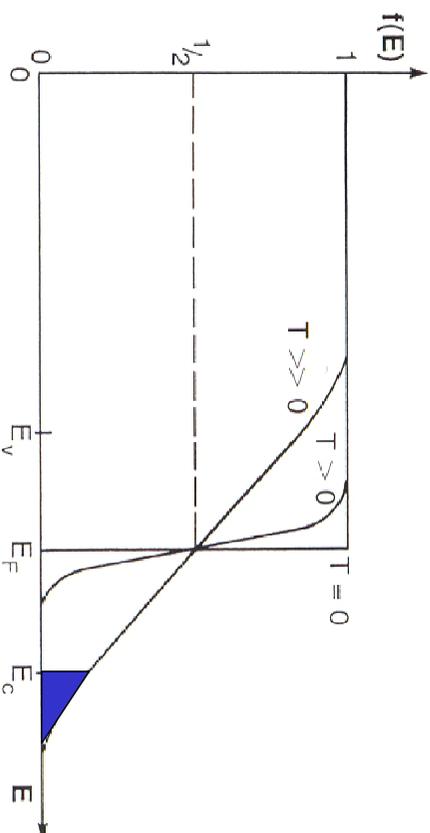


One needs to overcome the bandgap E_g to lift an e^- into the conduction band. This can be done via:

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.



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

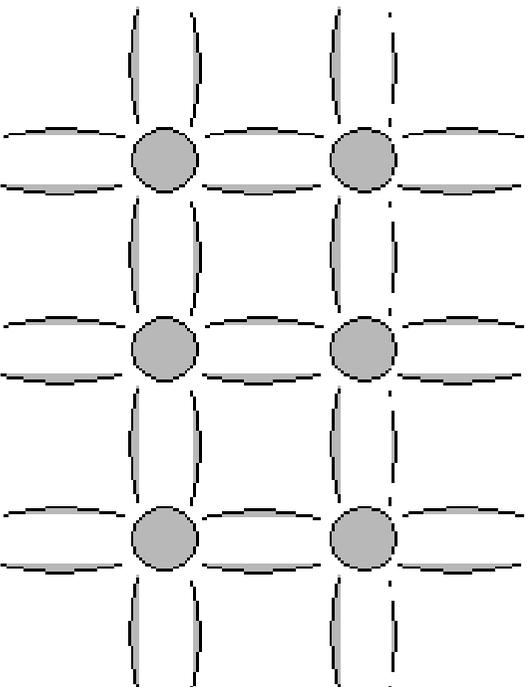
$$\text{and} \quad f(E_c) = \frac{1}{1 + e^{(E_c - E_F)/kT}} \approx e^{-(E_c - E_F)/kT}$$

Intrinsic

Photoconductors

The Basic Principle

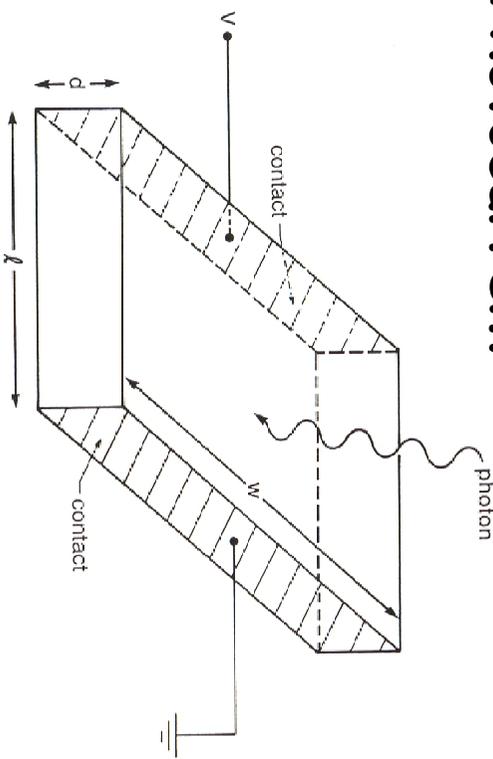
- E_y lifts e^- into conduction band
- electric field \vec{E} drives charges to electrodes
- few charge carriers \rightarrow high resistance



The Photocurrent

Conductivity:

$$\sigma = \frac{1}{R_d} \frac{l}{wd} = qn_0\mu_n$$



where:

R_d = resistance

w, d, l = geometric dimensions

q = electric charge

n_0 = number of charge carriers

ϕ = photon flux

τ = mean lifetime before recombination

μ_n = electron mobility \sim mean time between collisions.

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

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

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

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

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

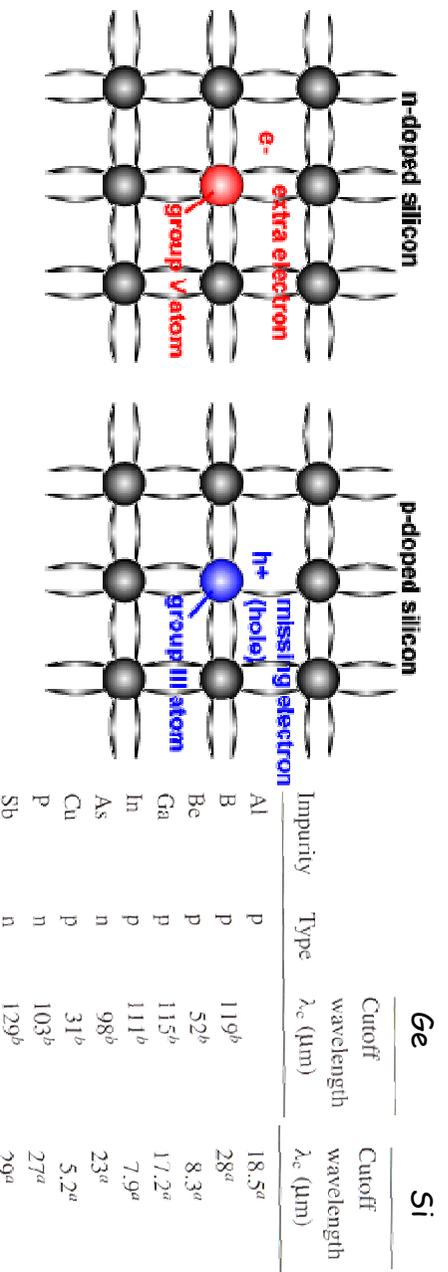
Limitations of Intrinsic Semiconductors

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

Extrinsic Photocconductors

Extrinsic Semiconductors

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



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

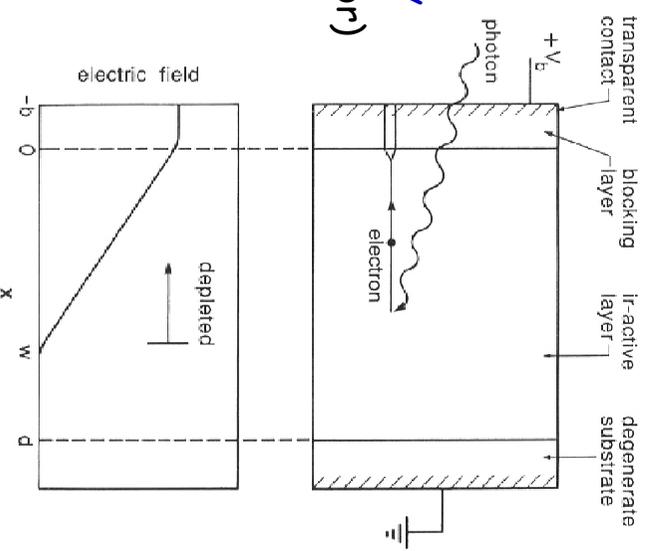
Problems: absorption coefficients much less than for intrinsic photoconductors → low QE → active volumes (pixels) must be large

Blocked Impurity Band (BIB) Detectors

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

IR-active layer: heavily doped

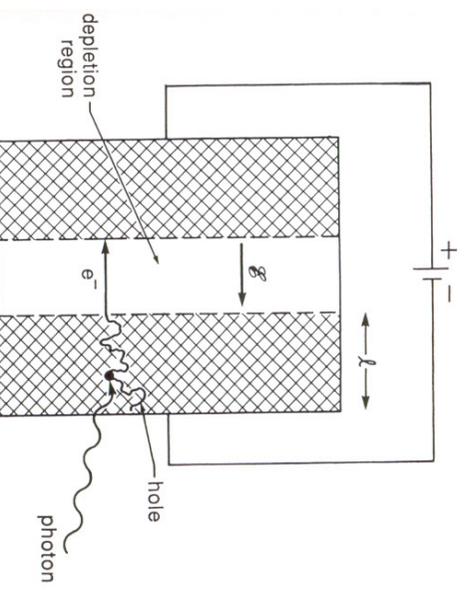
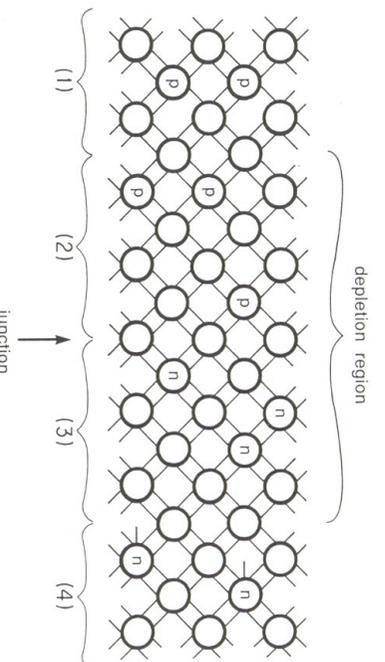
Blocking layer: thin layer of high purity
(intrinsic photoconductor)



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

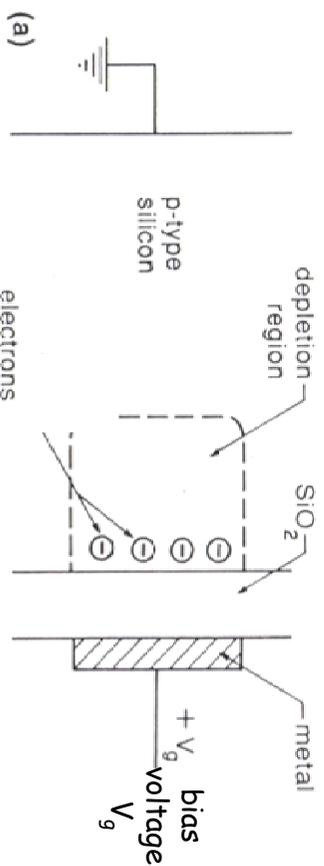


1. Photon gets absorbed e.g. in the p-type part
2. Absorption creates an e^- -hole pair
3. The e^- diffuses through the material
4. Voltage drives the e^- across the depletion region \rightarrow photo-current

Charge Coupled Devices (CCDs)

CCDs = array of integrating capacitors.

Pixel structure: metal "gate" evaporated onto SiO₂ (isolator) on silicon = MOS

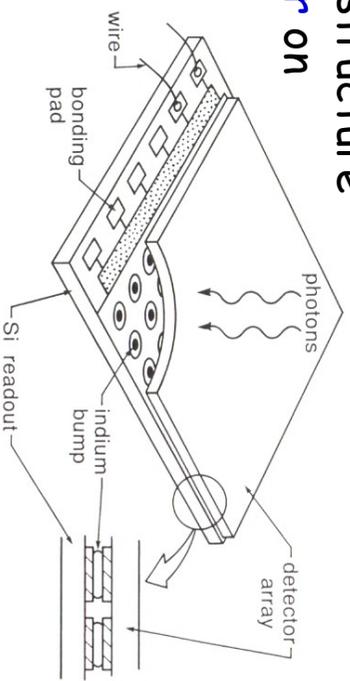


1. photons create free e^- in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO₂ layer
3. e^- accumulate at the Si—SiO₂ interface
4. the total charge collected at the interface is a measure of the number of photons during the exposure
5. → read out the number of e^-

Differences between IR Arrays and CCDs

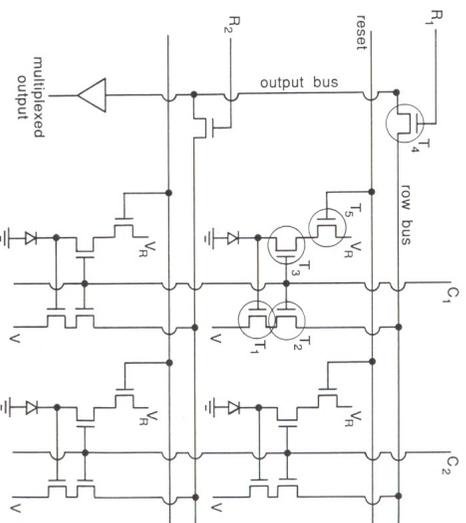
Infrared Arrays - Construction

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



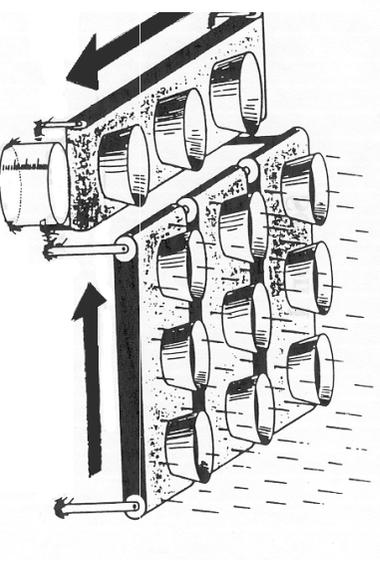
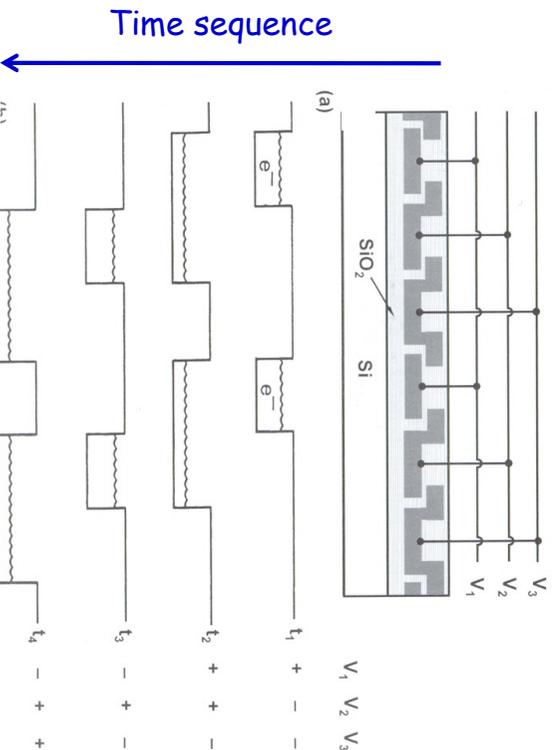
... and a **multiplexer circuit** on the other side.

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.edu/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 recombined 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:

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

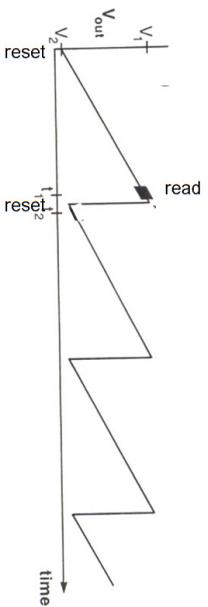
The **noise equivalent power (NEP)** is the signal power that yields an RMS S/N of unity in a system of $\Delta f = 1$ Hz:

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

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

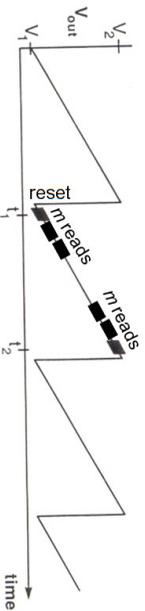
IR Array Read Out Modes

Single Sampling



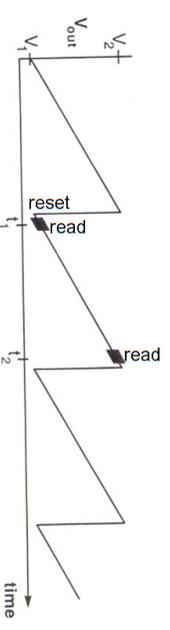
- most simple approach
- does not remove KTC noise
- measures the absolute signal level

(Multiple) Fowler Sampling



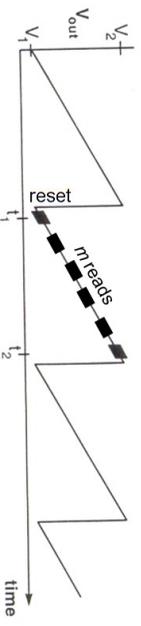
- similar to reset-read-read ...
- ... but each read is repeated m times
- Signal = $\text{mean}(\text{read}2) - \text{mean}(\text{read}1)$
- Reduces readout noise by \sqrt{m} over RRR

Reset-Read-Read



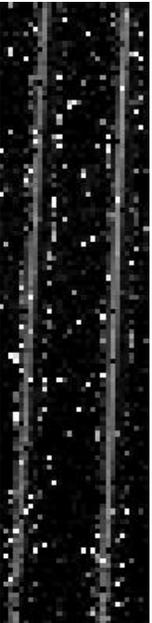
- Resets, reads and reads pixel-by-pixel
- Signal = $\text{Read}(2) - \text{Read}(1)$
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

Sample-up-the-ramp Fitting



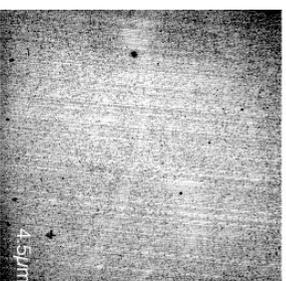
- m equidistant reads during integration
- linear fit \rightarrow "slope"
- reduces readout noise by \sqrt{m}
- particularly useful in space (cosmics!)

Some Detector Artefacts

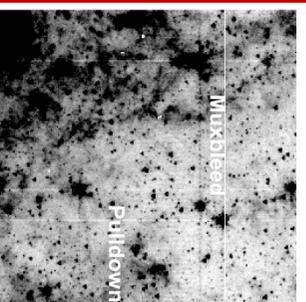
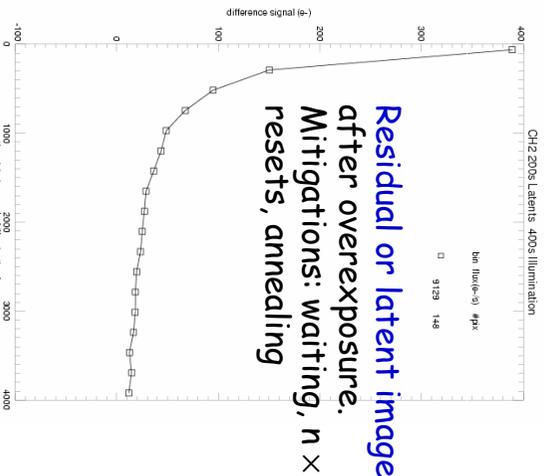


Dead, hot and rogue pixels.

Mitigation: subtract off-source image and/or reduce bias voltage

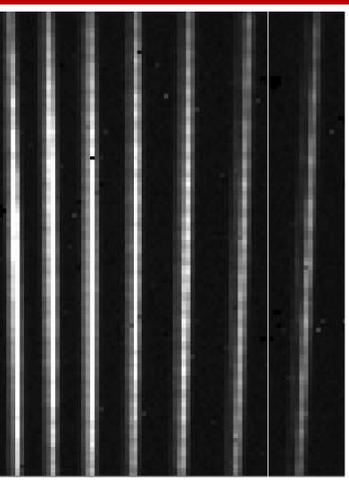


Fixed pattern noise.
Mitigation: "flat-fielding"



Muxbleed, pull-down 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

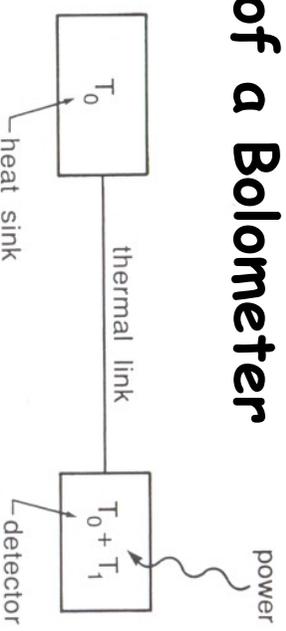
Thermal Detectors

Part III

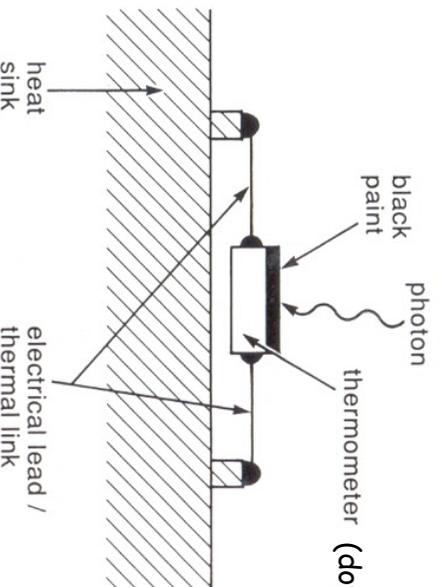
Coherent Receivers

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



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

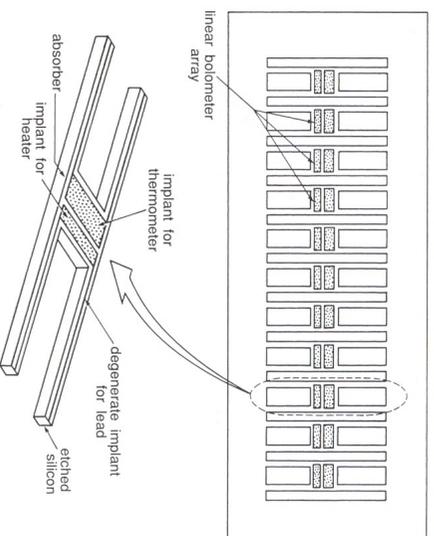
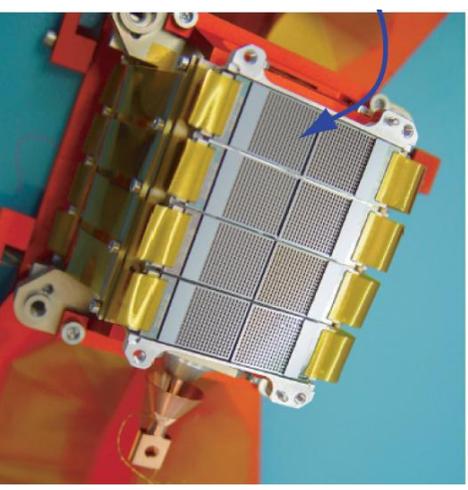
Bolometers are especially for the far-IR/sub-mm wavelength range!

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 $\sim C/G$
- multiplexing advantage ("**arrays**")

Part I

Photon Detectors

Part II

Thermal Detectors

Part III

Coherent Receivers

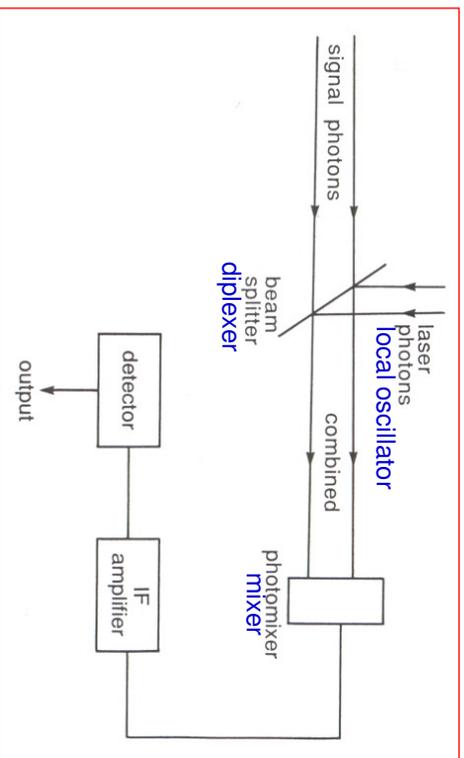
Basic Principle

Problems:

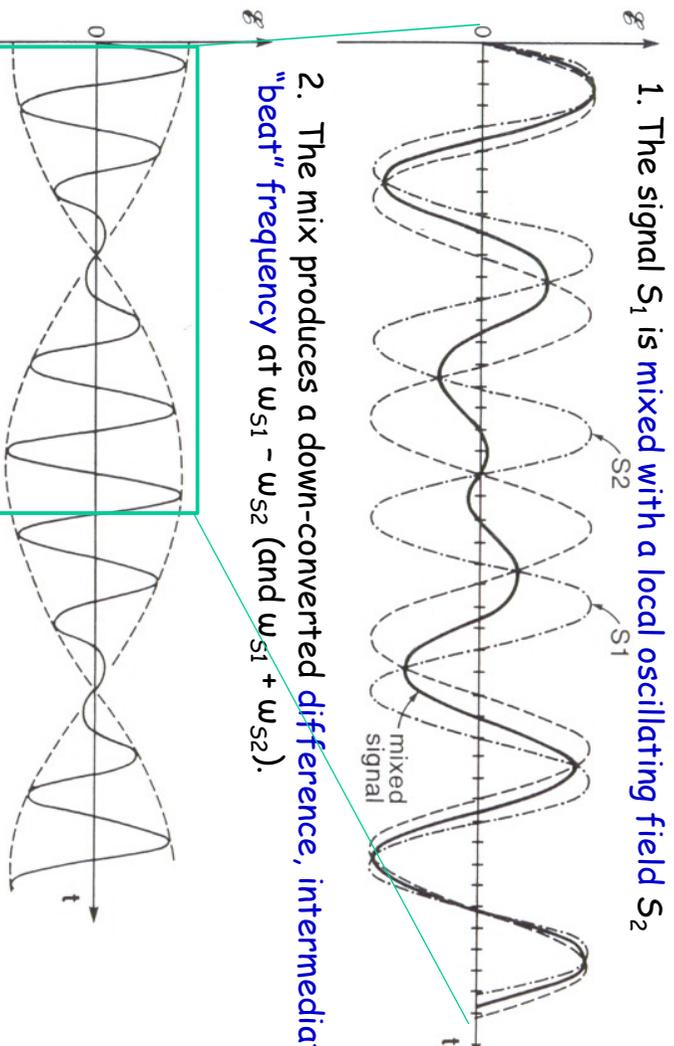
- very low photon energies → wave character of light is dominant
- often very weak signals → amplification essential

Solution:

- mix signal with reference wave



Step 1: Use a Local Oscillator



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

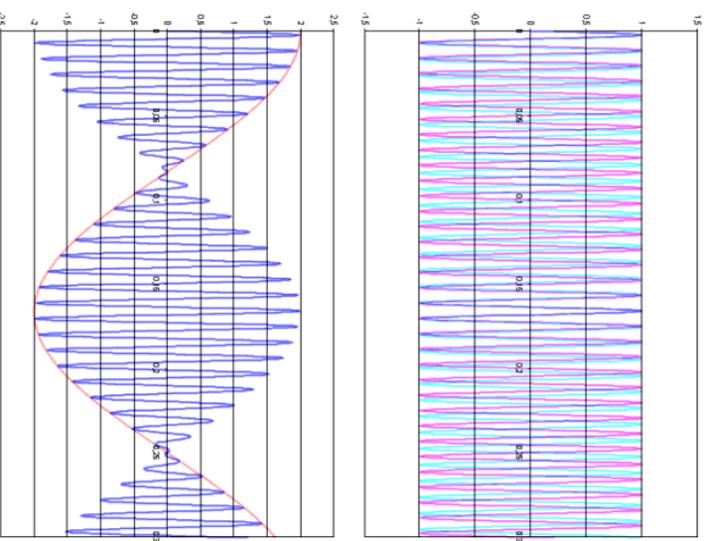
The Intermediate Frequency (IF)

The IF is the “beat frequency”, the difference frequency between **local oscillator** and **signal frequency**.

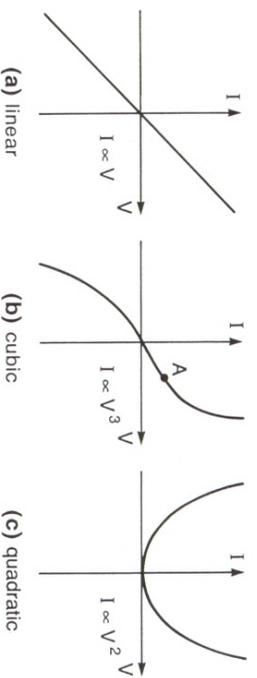
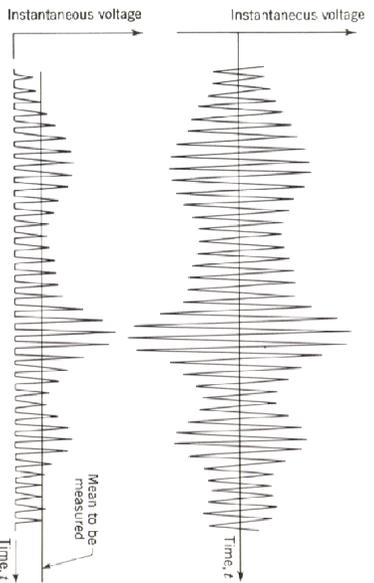
Example: Measure a signal at 1.5 GHz → use an oscillator at 1.55 GHz → down-convert the signal to a 50 MHz carrier.

$$\begin{array}{llll} \lambda = 1 \mu\text{m} & \Leftrightarrow & v = 300 \text{ THz} & \Leftrightarrow & \Delta t = 3.3 \cdot 10^{-15} \text{ s} \\ \lambda = 100 \mu\text{m} & \Leftrightarrow & v = 3 \text{ THz} & \Leftrightarrow & \Delta t = 3.3 \cdot 10^{-13} \text{ s} \\ \lambda = 1 \text{ cm} & \Leftrightarrow & v = 30 \text{ GHz} & \Leftrightarrow & \Delta t = 33 \text{ ps} \end{array}$$

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 \sim (field strength)² \sim power, which is exactly what we want to measure!

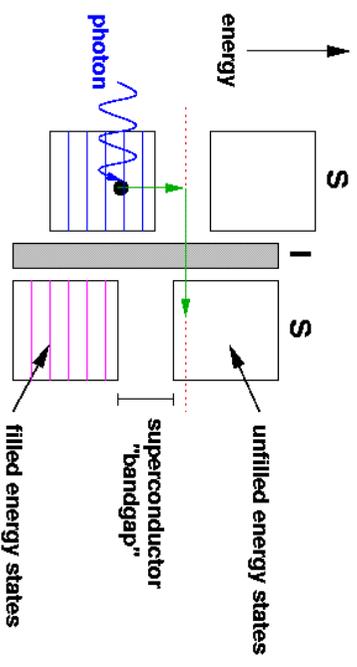
Mixer Technology

Problem: good & fast
(**recombination times!**)
“traditional” photo-conductors
do not exist for $\lambda > 40\mu\text{m}$.



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 ($h\nu \ll kT$)

→ the bolometer will perform better

This is always true, except for measurements at high spectral resolution, much higher than the IF bandwidth.

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

→ the heterodyne receiver will outperform the bolometer.

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

**Interested
to hear more?**

**→ Masters course
on**

“Detection of Light”