Note Title 3/6/2007

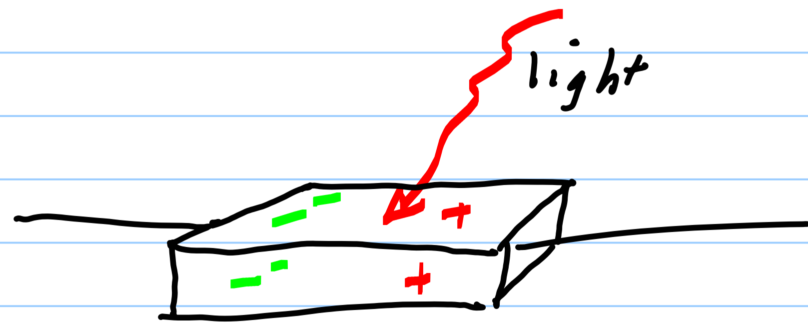
Photo Detectors

1) Chemical Detector

- Photographic plates
- historically one of the most widely used technique for spectroscopy

Photographic spectrum for Alpha Lyrae, an A0 V star

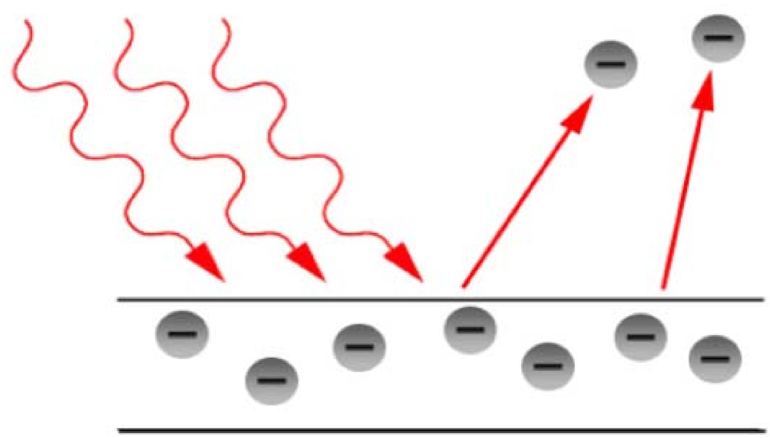
2) Photoconductor



Resistance
Changes with
Light

Photo Tube

Photo electric effect



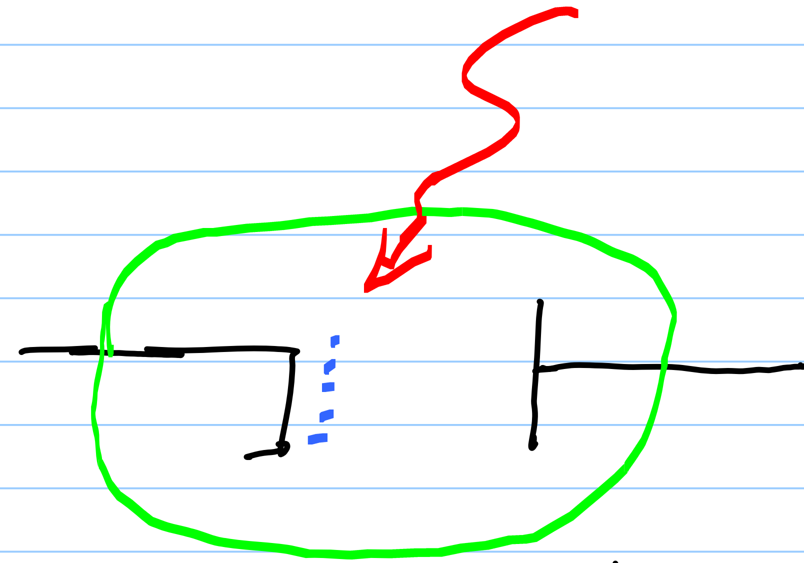
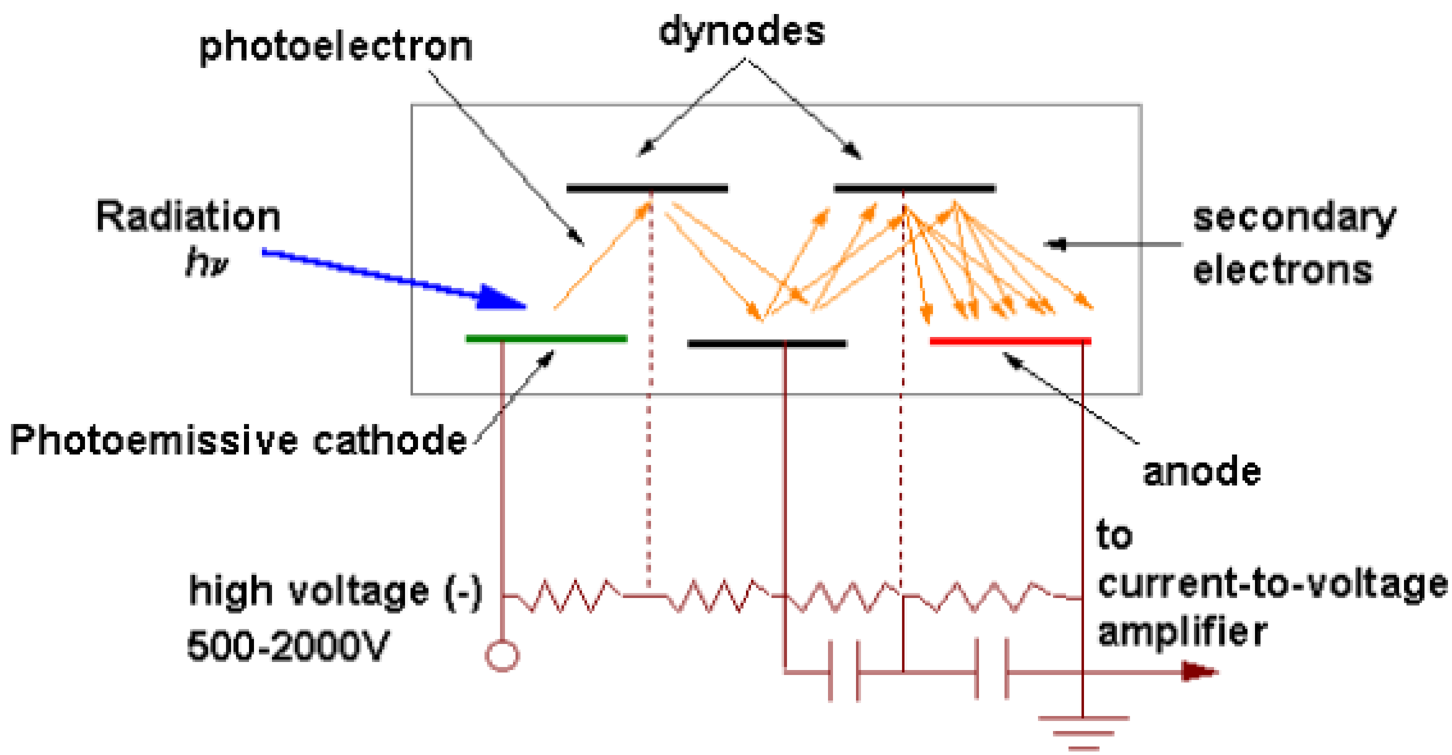


Photo tube

Photomultiplier



Photomultiplier Gain

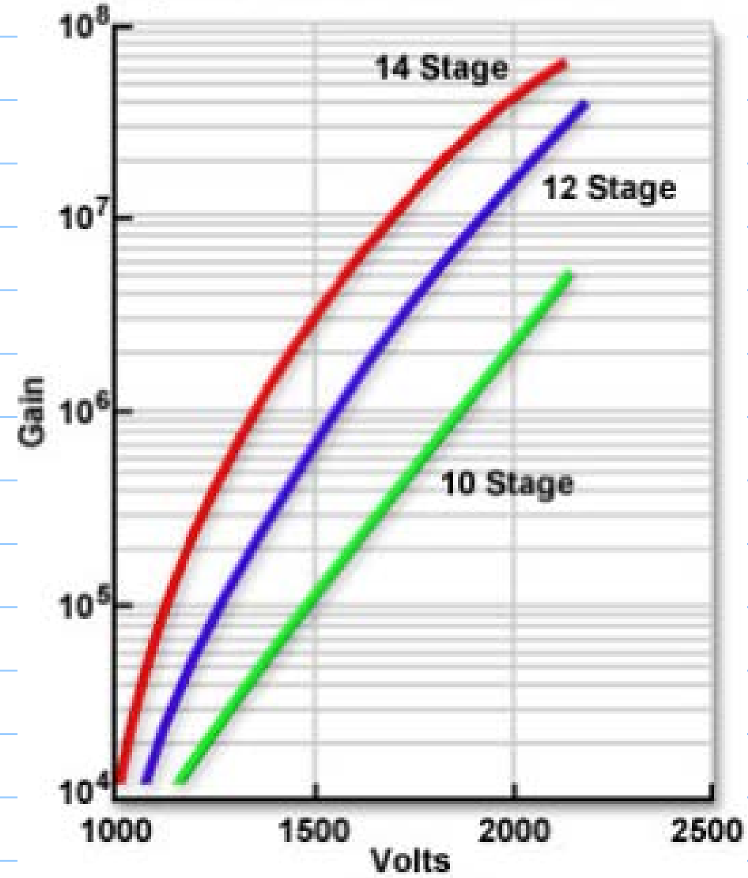


Figure 1

Photomultipliers

Quantum Efficiency in g

- depends on cathode

Luminous sensitivity S

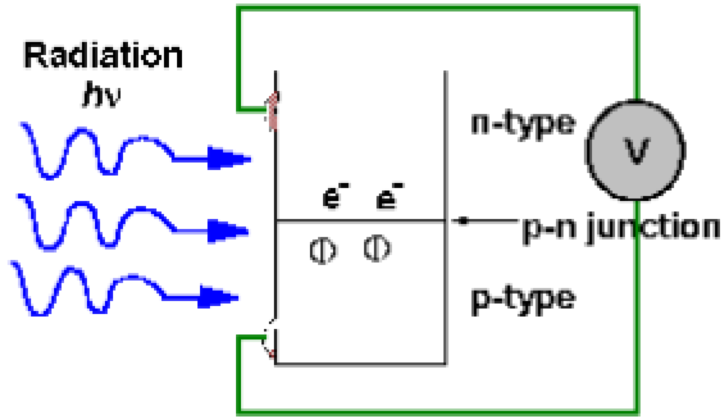
typical values of S

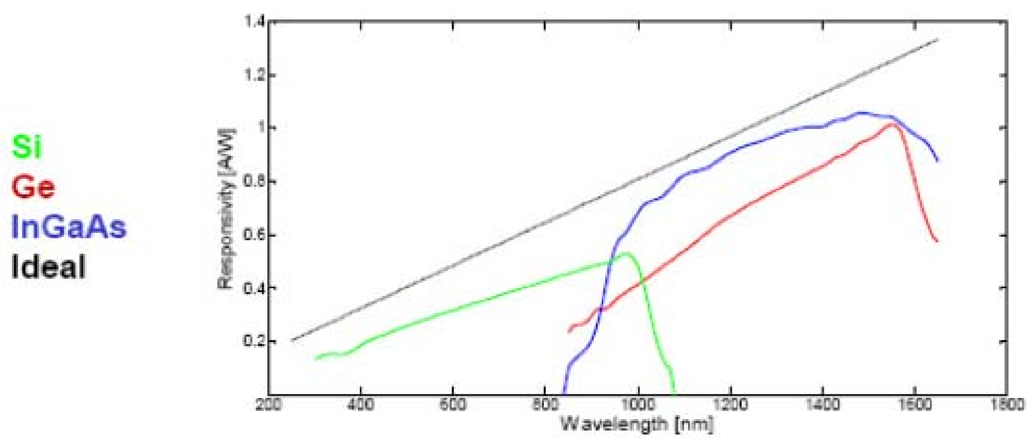
$$S \sim 20 - 400 \, mA/W$$

Noise

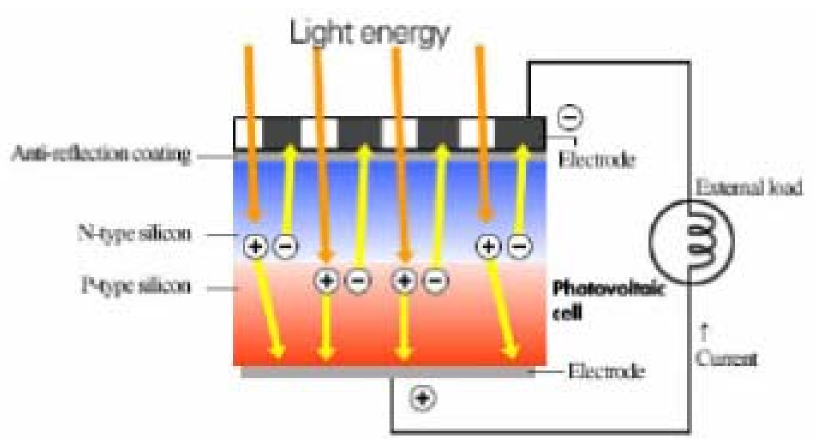
- dark current
- Noise equivalent power

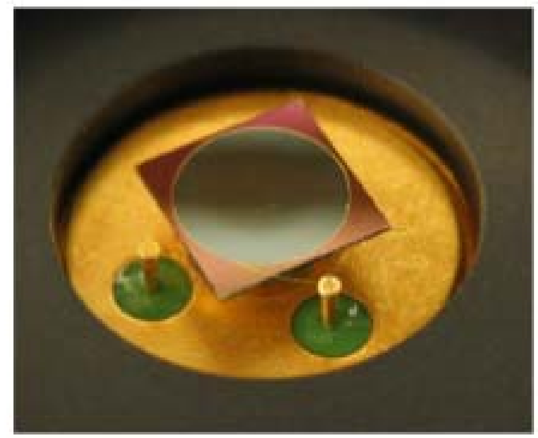
Semiconductor Photodiode

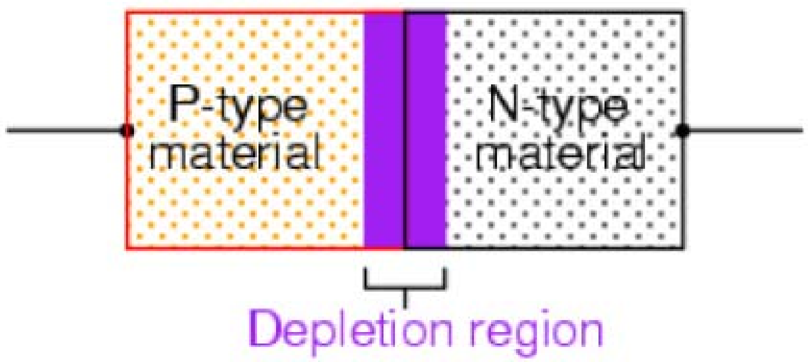




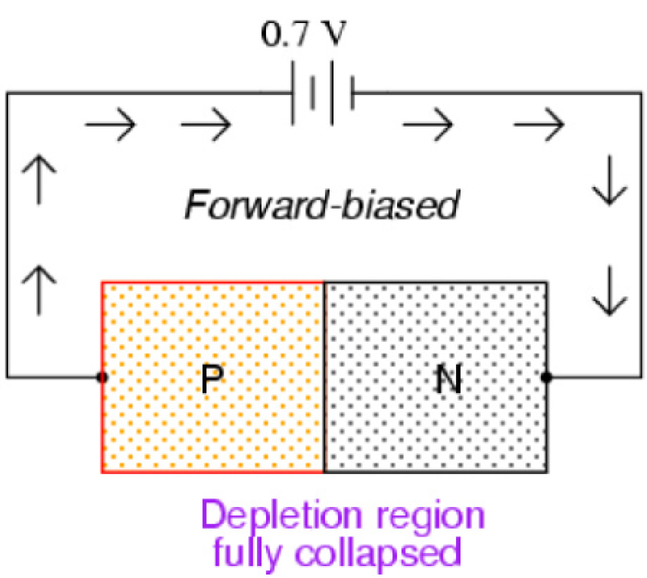
Photovoltaic or Solar Cell

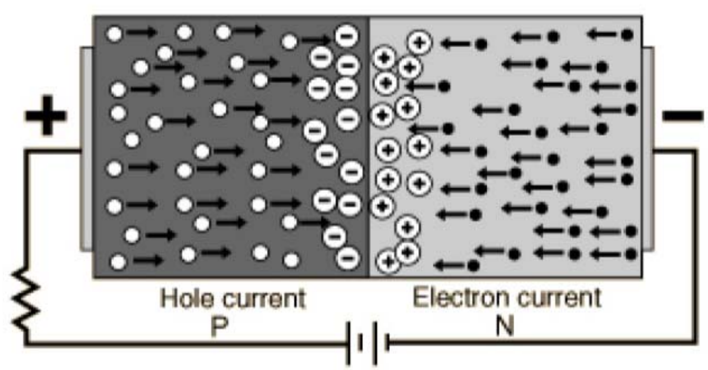




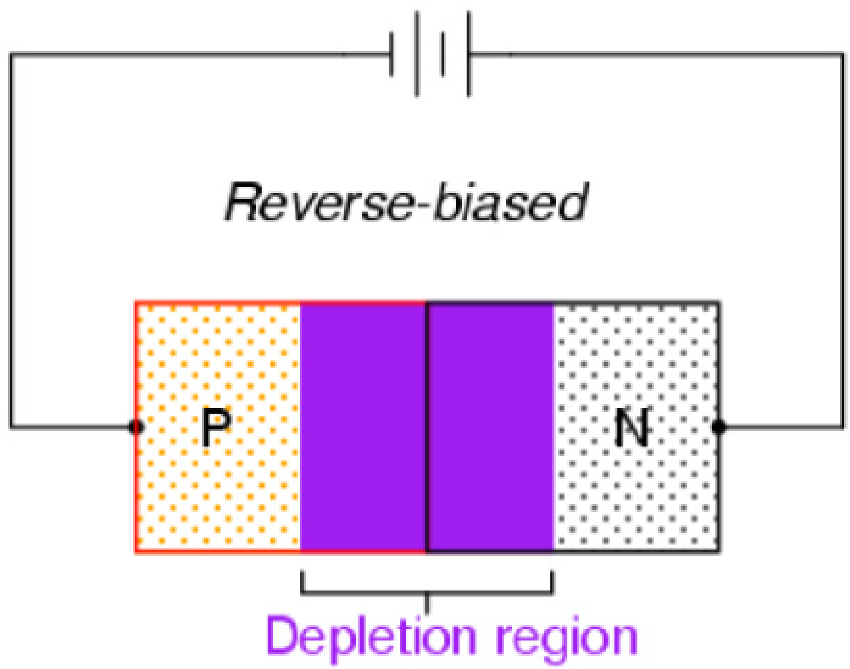


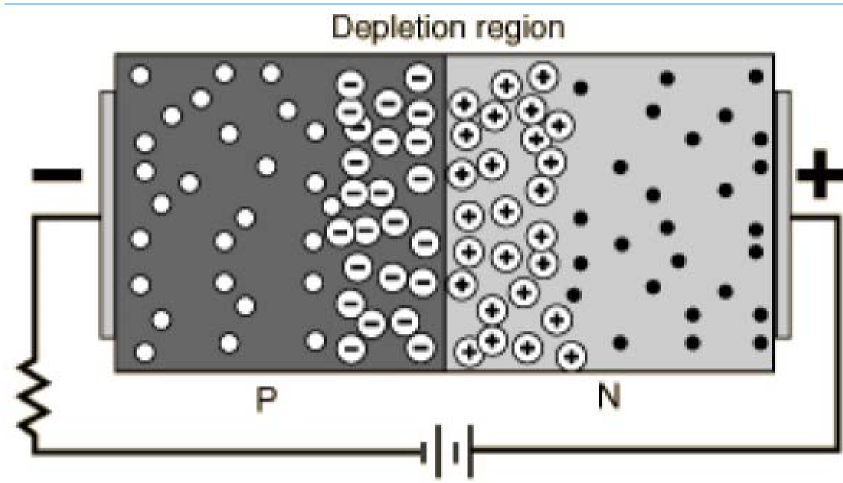
P-N junction representation

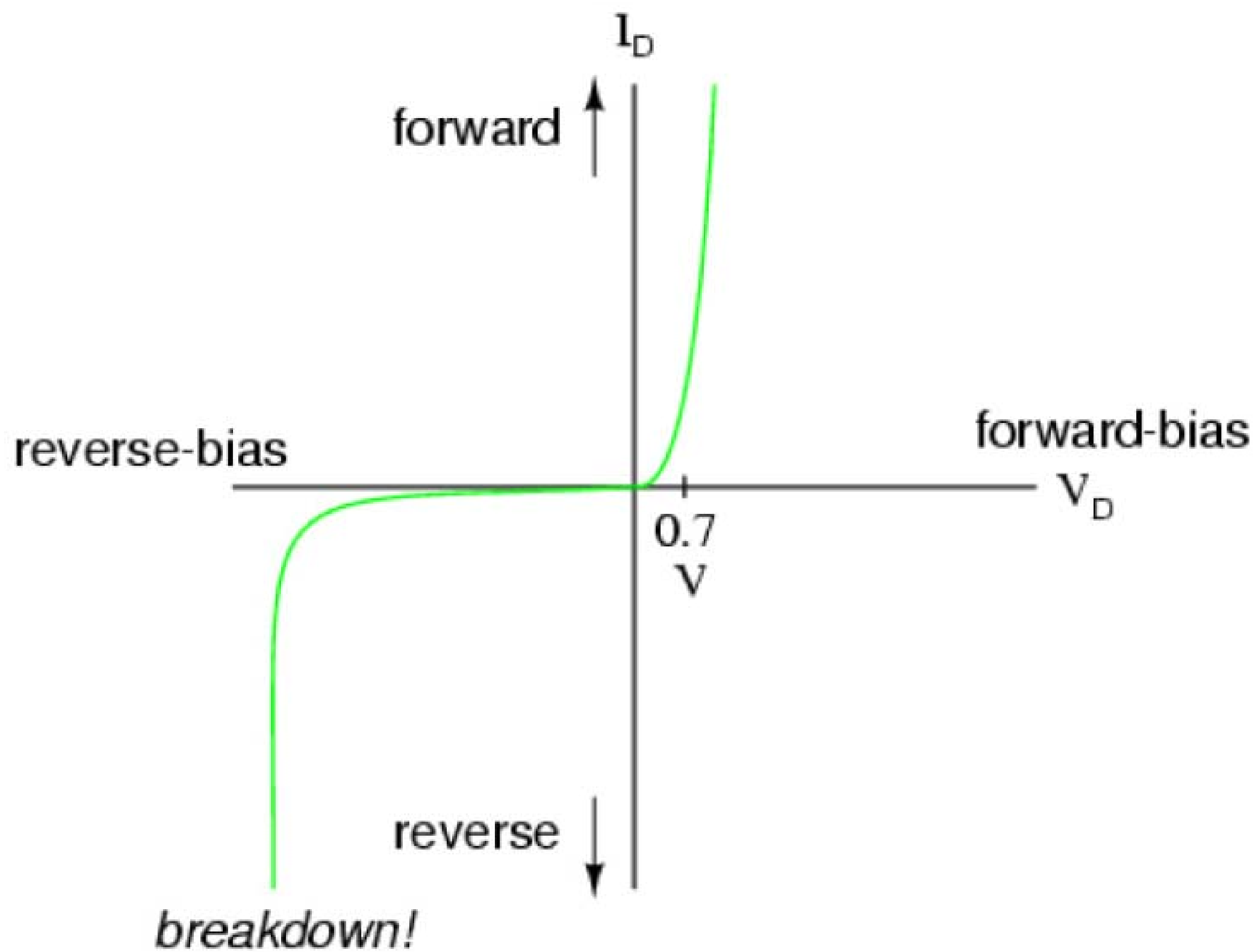




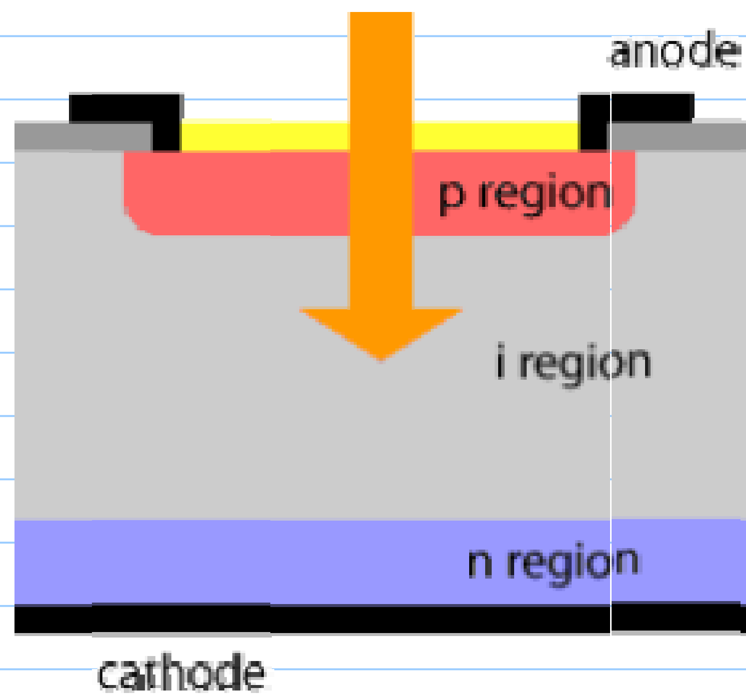
Reverse Bias PN Jcn






I_D
forward
reverse-bias
forward-bias
V_D
0.7
V
reverse
breakdown!

PIN Photodiode



Noise in PIN Detectors

Noise Equivalent Power = NEP

$$NEP(\lambda, f, \Delta f) = \frac{i_{nD}}{R(\lambda)} \quad \frac{\text{Watts}}{\sqrt{\text{Hz}}}$$

where

i_{nD} = noise current of the detector

$R(I)$ = responsivity at the detector wavelength

Sources of noise

1. Detector Noise
2. Thermal Noise
3. Amplifier Noise

Shot noise – source Poisson statistics

$$i_{nshot} = \sqrt{2q(I_d + I_{ph})\Delta f} \quad \frac{\text{Amps}}{\sqrt{\text{Hz}}}$$

where

q = electron charge

I_d = Dark current

I_{ph} = Photo current

Δf = noise bandwidth

Thermal noise

$$i_{thermal} = \sqrt{\frac{4KT\Delta f}{R_{shunt}}} \quad \frac{\text{Amps}}{\sqrt{\text{Hz}}}$$

where

K = Boltzmans constant

T = Temp K

Δf = Noise bandwidth

R_{shunt} = shunt resistance (Function of temp)

Temp Dependence of Shunt Resistance

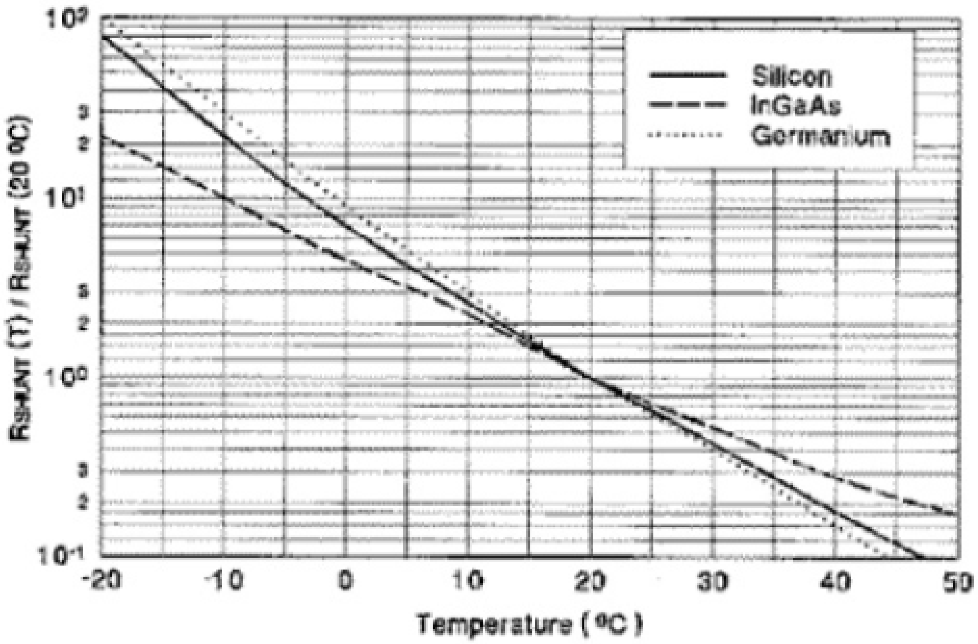


Figure 2. Shunt resistance vs. temperature for Silicon, InGaAs and Germanium PIN detectors.

Amplifier noise

$$\bar{i}_{amplifier} = \sqrt{\langle \bar{i}_{amp} \rangle^2 + \langle V_{amp}\,\omega\, C_T \rangle} \;\; \frac{\text{Amps}}{\sqrt{\text{Hz}}}$$

$\bar{i}_{amp}$ = Amplifier leakage current

V_{amp} = amplifier input noise voltage

$\omega = 2\pi f$

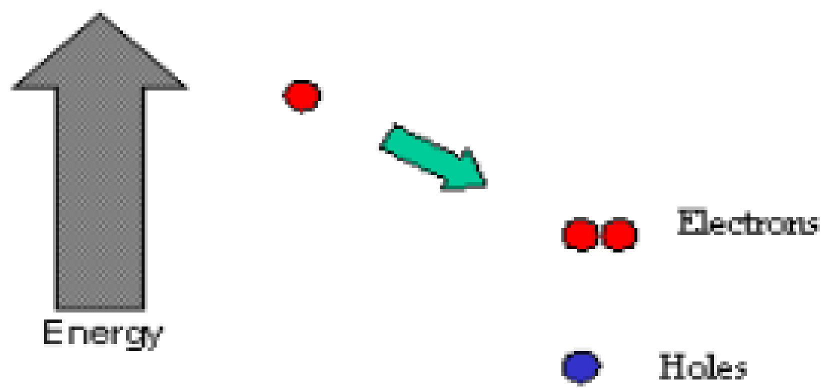
C_T = Total input capacitance

Total Noise

$$i_{n\,total} = \sqrt{\langle i_{shot} \rangle^2 + \langle i_{thermal} \rangle^2 + \langle i_{amp} \rangle^2} \quad \frac{\text{Amps}}{\sqrt{\text{Hz}}}$$

- At high light levels shot noise dominates
- At low light levels thermal noise is important so cooling is often useful

Impact Ionization



gain

100 – 1000

$$M = \frac{1}{1 - \int_0^L \alpha(x)\, dx}$$

L = space charge boundary

α = multiplication coefficient

Avalanche Photodiode

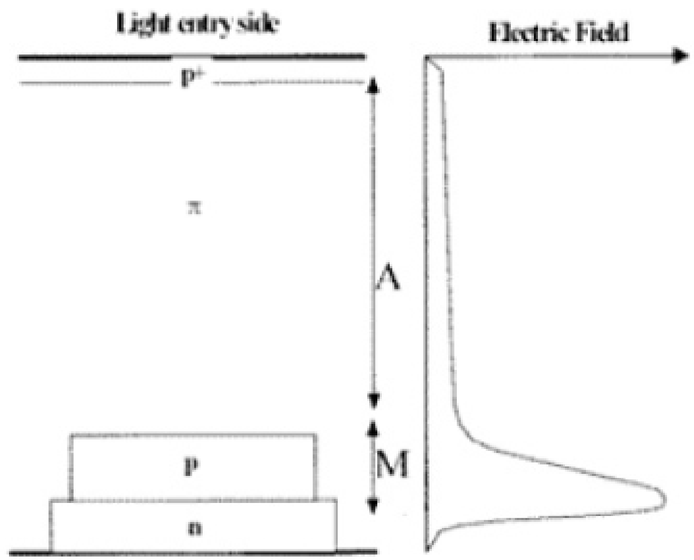


Figure 1: Reach-through APD Structure (Not to Scale)

ADD Gain

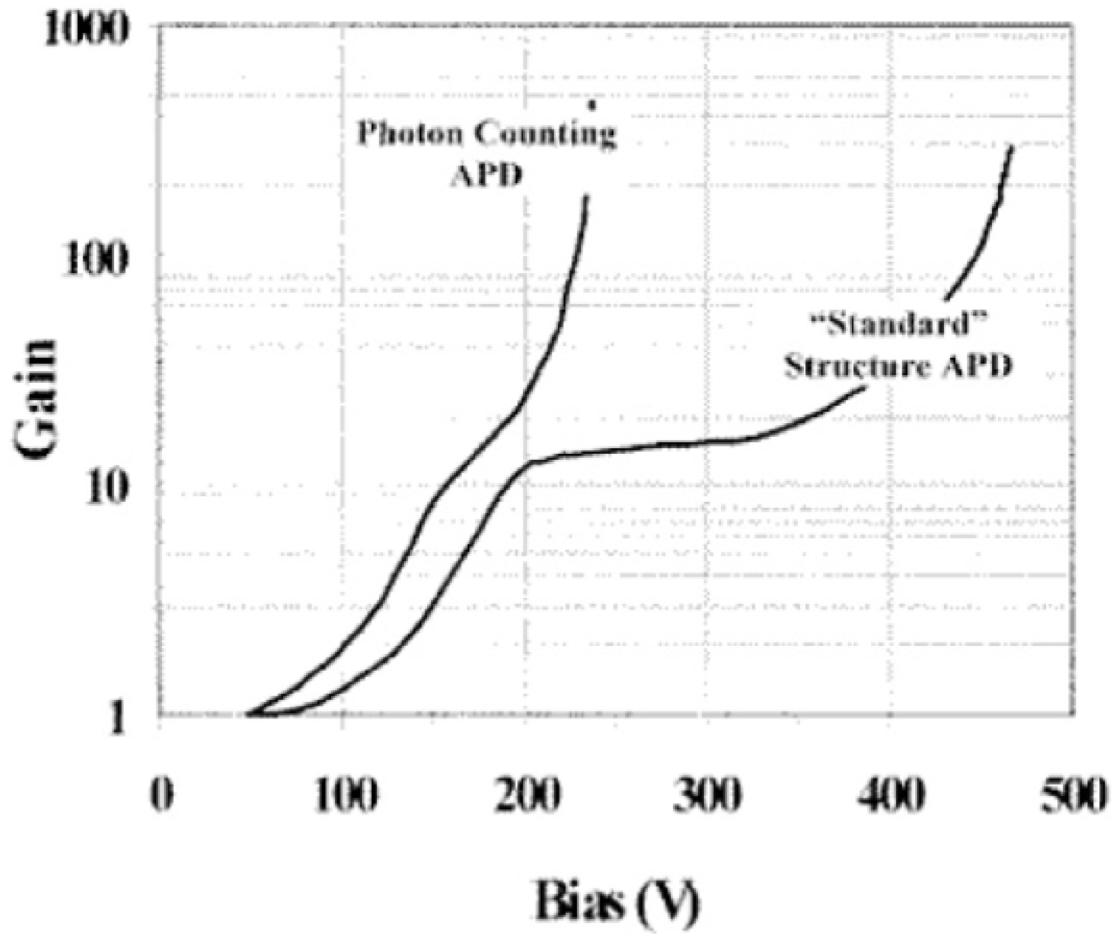


Figure 2: Typical gain-voltage curve for Si APDs

APD's operate in two regimes

- detector noise limit at low powers
- shot noise limit at high powers

Shot noise Poissonian fluctuations

$$I_{N\,shot} = (2q\Delta f I_D)^{1/2}$$

where I_D = dark current

$$I_D = I_{D_{surface}} + M I_{D_{Bulk}}$$

Total Noise in dark condition

$$i_N = \left[2q\left(I_{D_s} + I_{D_B} M^2 F\right) B\right]^{1/2}$$

where

F = excess noise factor

B = bandwidth

M = multiplication

It higher light levels

$I_{N\,total}$ = detector noise + signal shot noise

$$\overline{I}_{N\,total} = \left[2q \left[I_{DS} + \left(I_{DB} M^2 + R_o(I) M^2 P_s \right) F \right) B \right]^{1/2}$$

- In the absence of other noise sources $F^{1/2}$ worse than a PIN
- However overall system can be better

Excess Noise Factor

$$F = kM + (1-k)\left\{2 - \frac{1}{M}\right\}$$

Comes from statistical nature of the multiplication process

k = ratio of electron to hole ionization processes

$k < 1$

Summary of APD's

- NEP $< 10^{-15}$ for a .5mm APD
- Photon Counting efficiency > 70%
- low light detection
  200 – 1150 nm range
- overall performance unmatched by photomultiplies

Photodiode Arrays

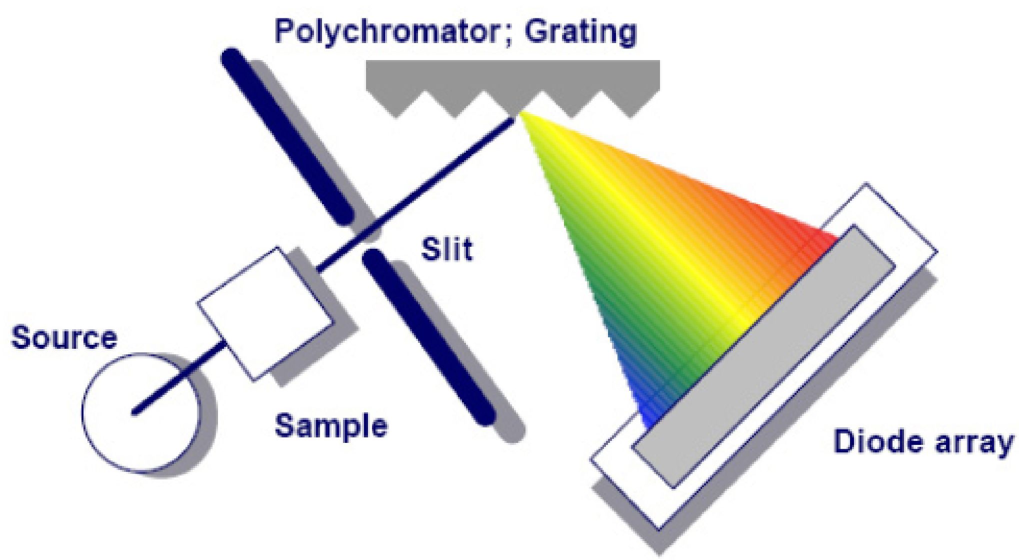
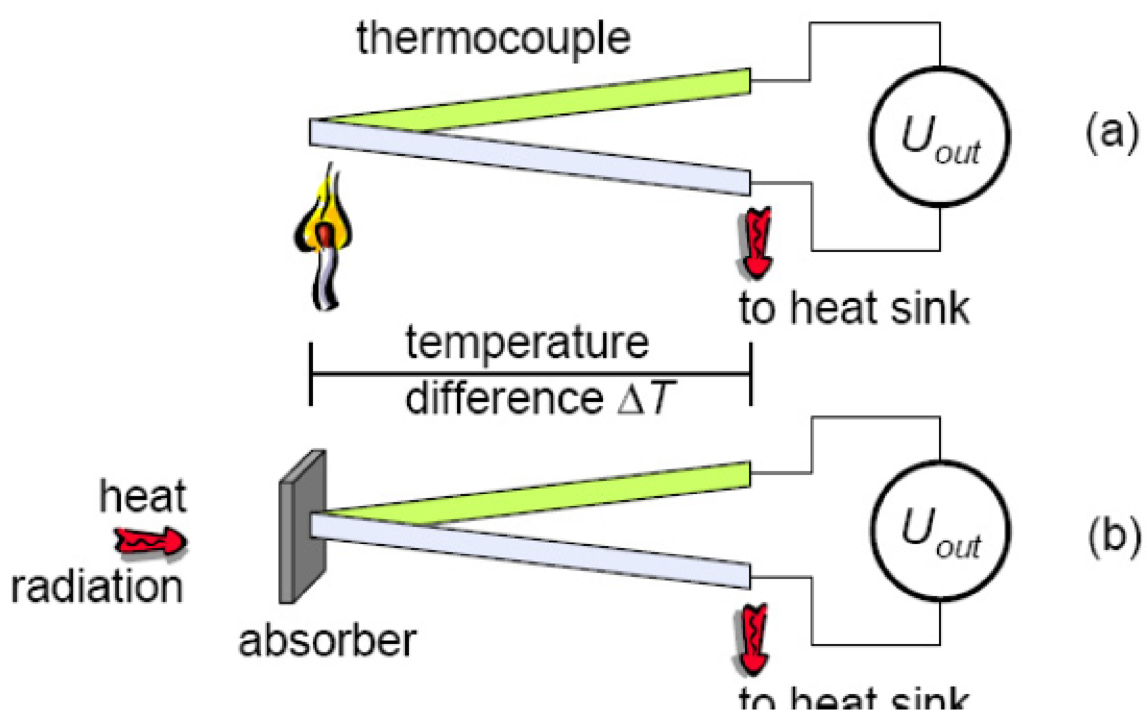
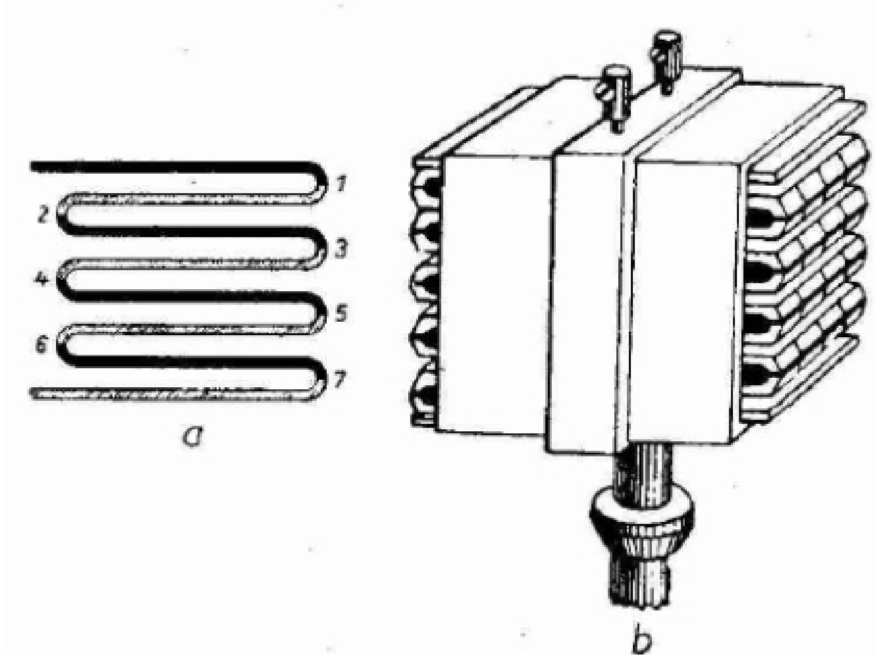


Figure 1. Schematic of photodiode array spectrophotometer

Thermocouple

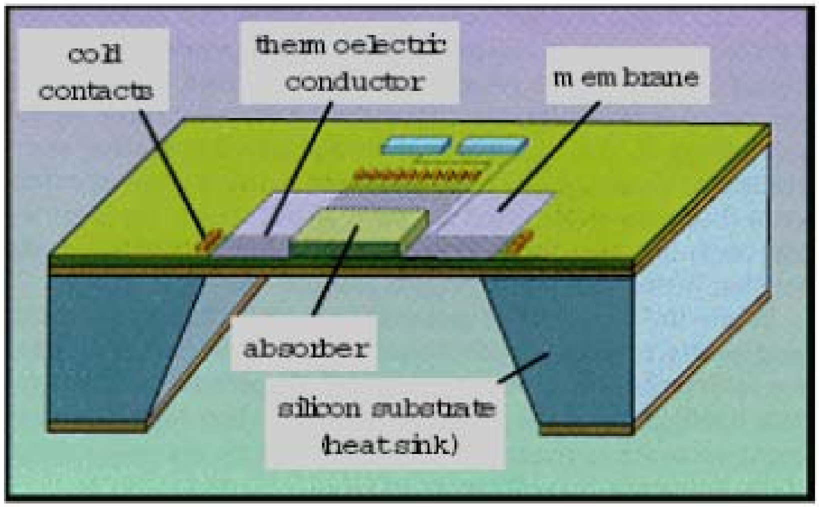


Thermopile

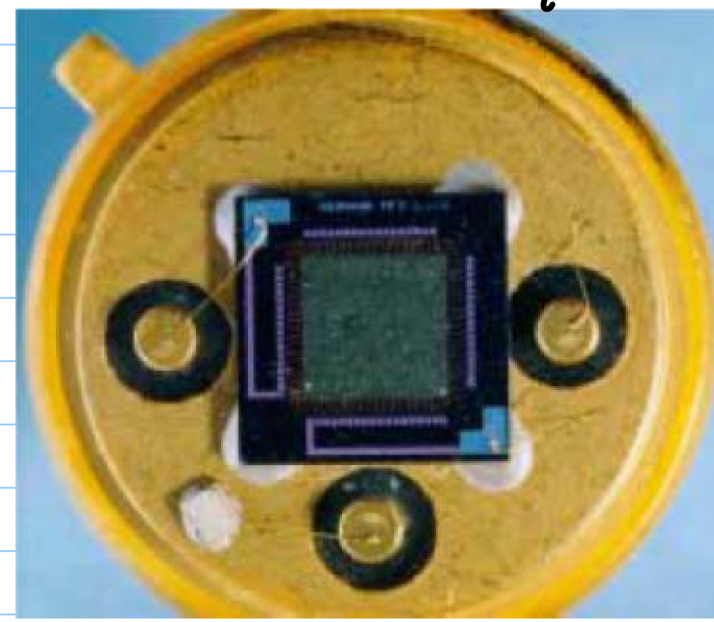


Nobili 1835

Micromachined Thermopile



Modern Thermopile



Sensitivity

$$S = \frac{U_{out}}{P_{rad}}$$

U_{out} ← voltage

P_{rad} ← radiated power

S typically 10 to 100 $\frac{\text{Volts}}{\text{Watt}}$

Total thermopower

$$\alpha = \frac{U_{out}}{\Delta T} \qquad \frac{\text{Volts}}{T(K^\circ)}$$

Typical Numbers

$$250 \ \frac{\mu V}{K}$$

with 50 elements

$$12.5 \ mV/K$$