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Measuring light

ELEC-E5710 Sensors and Measurement Methods

Optical detectors are everywhere!

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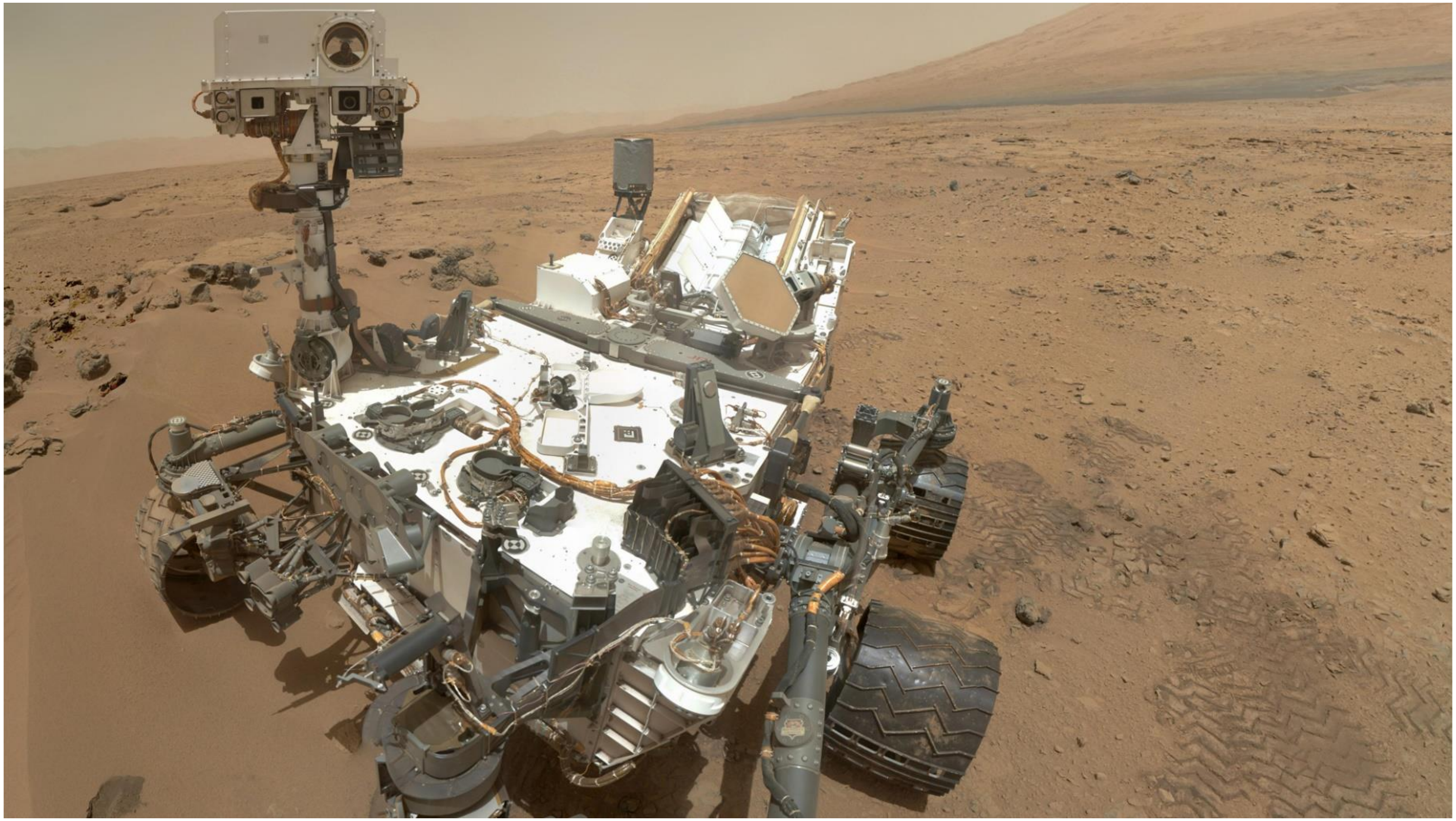

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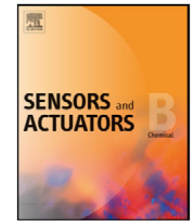

Optical measurements and pattern-recognition techniques for identifying the characteristics of beer and distinguishing Belgian beers

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A B S T R A C T

A miscellaneous assortment of 86 beers was characterized using non-destructive, rapid and reagent-free optical measurements. Diffuse-light absorption spectroscopy performed in the visible and near-infrared bands with the use of optical fiber spectrometers was tested innovatively to gather turbidity-free spectroscopic information. Furthermore, conventional turbidity and refractive index measurements were added

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Photon

- Photons behave as fields (waves) but they can be detected only as discrete particles
- Photons have no rest mass but they do have energy and momentum

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}} \Rightarrow E = hf$$

energy (E) frequency (f)

Photon

- Photons behave as fields (waves) but they can be detected only as discrete particles
- Photons have no rest mass but they do have energy and momentum

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}} \Rightarrow p = \frac{hf}{c}$$

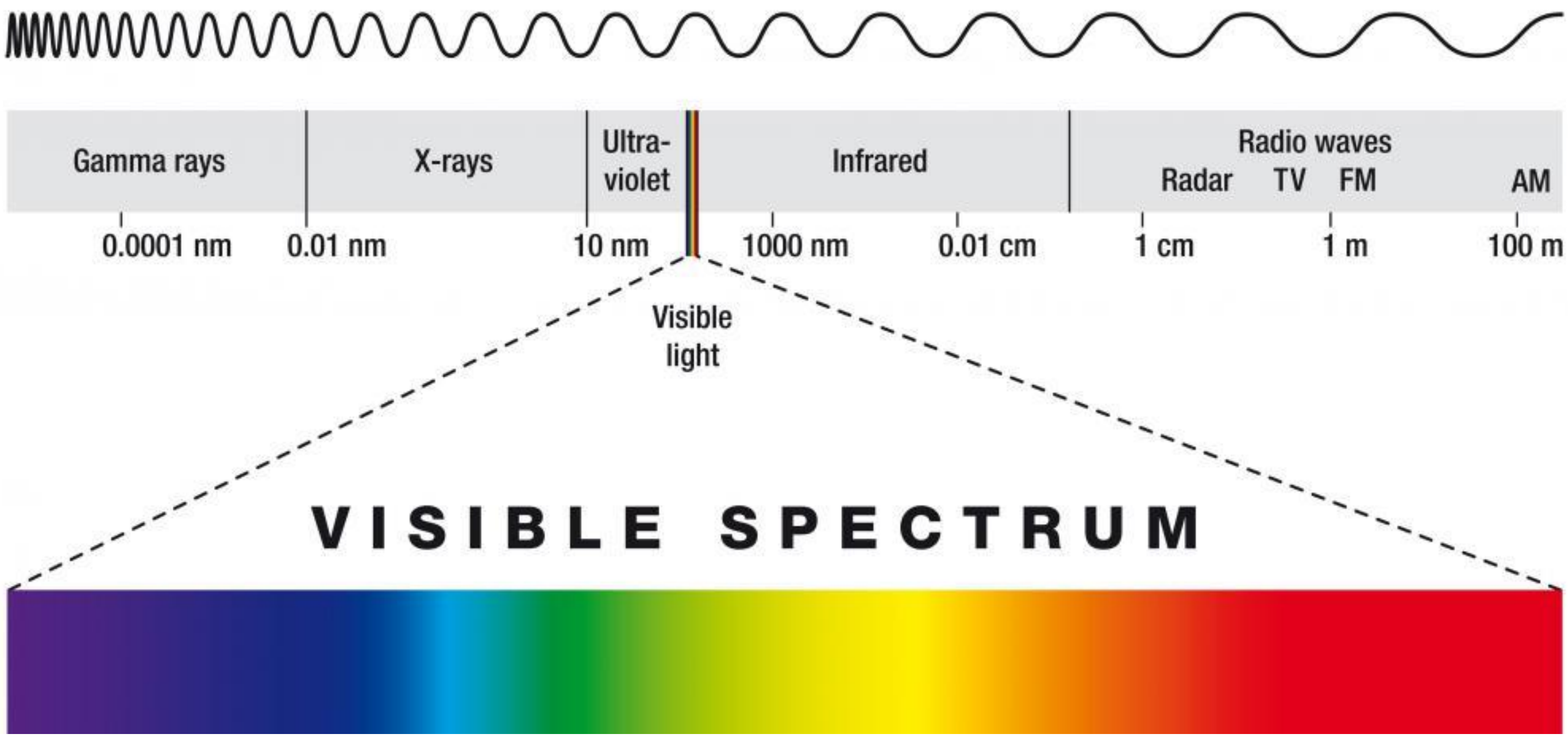
momentum

Wavelength

- The spectrum of electromagnetic radiation can be denoted equivalently in terms of energy, frequency or wavelength
- Vacuum wavelength: $\lambda_0 = \frac{c}{f}$
- Speed of light and wavelength in propagation medium having refractive index *n:*

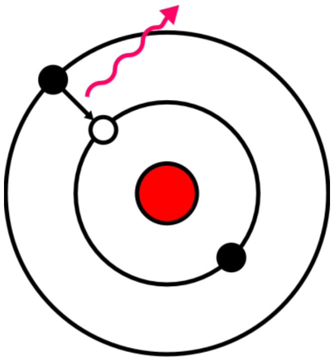
$$v = \frac{c}{n} \qquad \lambda = \frac{v}{f} = \frac{c}{nf} = \frac{\lambda_0}{n}$$

Electromagnetic spectrum



Measuring light

- In **radiometry**, electromagnetic radiation is measured
  - Photons and fields have nothing to do with eyesight
  - Measuring the power of radiation – unit is watt (W)
  - Spectral distribution of quantities
- In **photometry,** light perceived by “average” human eye is measured
  - Spectrum is weighted with the luminosity function (depends on the brightness level)
  - Measuring the luminous flux – unit is lumen (lm)

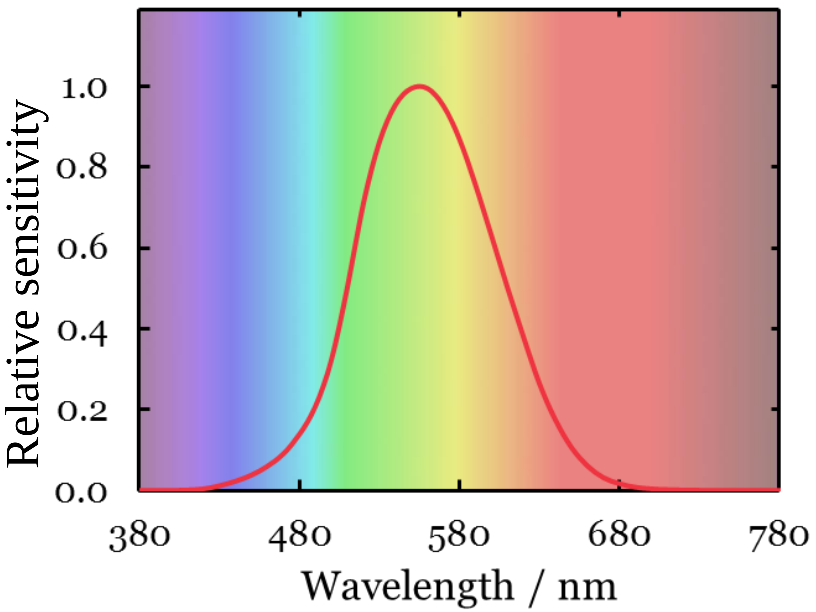


The first photometric instrument

- **Human eye!**
- Brightness of the object is compared visually when it is illuminated by standard source and test source
- Standard source may be for example precisely manufactured candle (candlepower)
- Every eye is unique
- It is difficult to compare the brightness of saturated colors
- Pupils adjust to different light levels – comparison of brightnesses is difficult
  - Early solution: measure the diameter of the pupil rather than estimate brightness

Photometry – eye sensitivity

- CIE (International Commission on Illumination) has determined the luminosity function of a human eye
- *V*(*λ*) – the backbone of photometry!
- Devices are manufactured to imitate human eye



The quantities of radiometry and photometry

Radiometry (X_e)	Photometry (X_v)
Radiant intensity I_e ($W \cdot sr^{-1}$)	Luminous intensity I_v (cd)
Irradiance E_e ($W \cdot m^{-2}$)	Illuminance E_v (lx = lm/m^2)
Radiation power F_e (W)	Luminous flux F_v (lm = cd$\cdot$sr)
Radiance L_e ($W \cdot sr^{-1} \cdot m^{-2}$)	Luminance L_v ($cd \cdot m^{-2}$)
Radiant energy Q_e (J)	Luminous energy Q_v (lm$\cdot$s)

$$X_v = K_m \int X_{e,\lambda}(\lambda) V(\lambda) d\lambda$$

$$K_m = 683.002 \text{ lm W}^{-1}$$

Photometric measurement devices: Illuminance

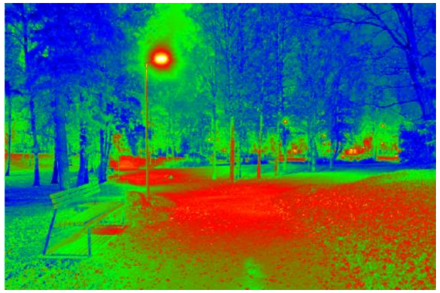
”How much light arrives to a surface”

- Diffusers are needed to collect light from every angle (cosine response)
- Collected light can be transmitted to a spectroradiometer with an optical fiber or it can be directly measured with a filtered detector (luxmeter)

Photometric measurement devices: Luminance

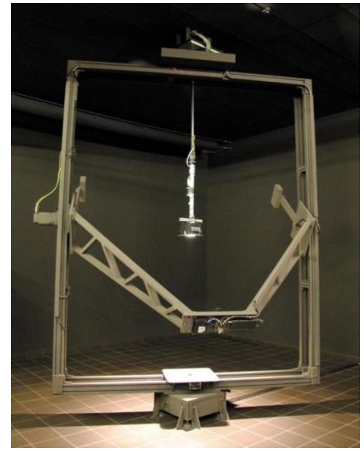
“How bright is a surface?”

- Typically focusing optics is used
- Measuring either on one point or imaging luminance
- In practice all photographic cameras are luminance meters
  - Channels can be weighted and summed to resemble $V(\lambda)$



Photometric measurement devices: Luminous flux

“How much light is emitted by a source?”

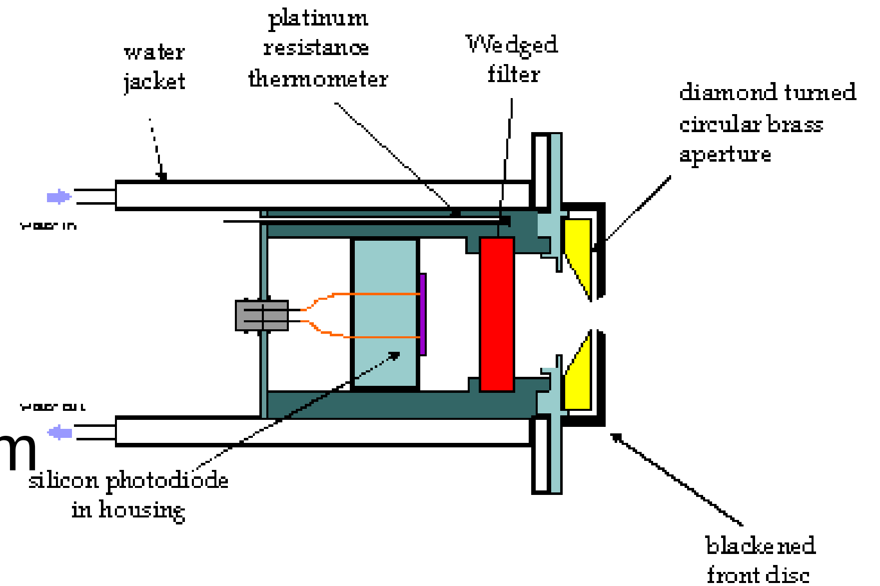


- Goniometric → detector circulates the source from every direction
- Integrating sphere → inner surface of the sphere is diffusing with the reflectance of ~98% → the intensity on the inner surface is even

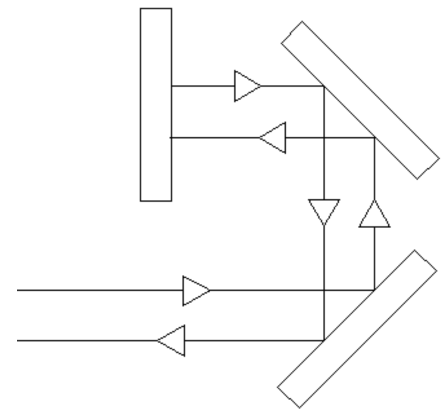
Spectral measurements

- Wavelength band
  - Filter radiometers, photometers
  - Color filters (bandwidth >100 nm)
  - Thin film filters (bandwidth 10–60 nm)
- Monochromatic wavelength band
  - Extremely narrow bandwidth is measured (0.1–5 nm) at every required wavelength of the spectrum
  - Wavelength is selected by
    - Controlling the optics of a monochromator (scanning across the spectrum) or
    - Using array detectors where spectrum is dispersed to pixel array and all channels are measured simultaneously
    - Electronically tunable optical filters (Piezo or MEMS element)

Filter radiometers

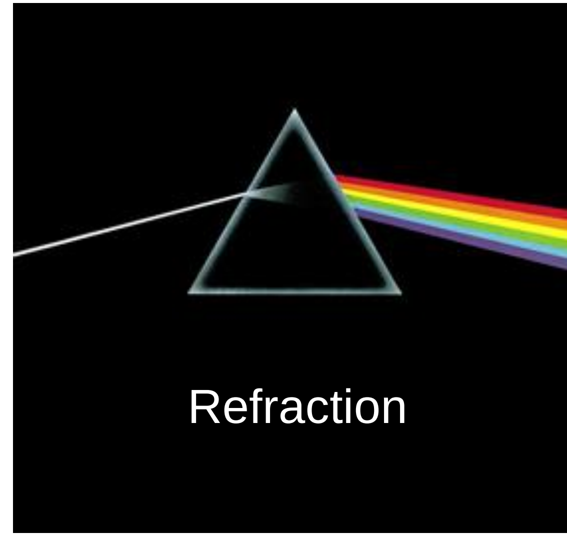


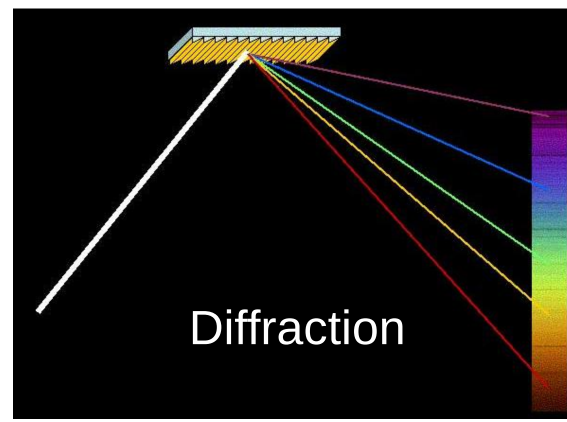
- Consists of a detector, a filter and an aperture
- Often temperature stabilized
- Significant back reflection from the detector and filter
- Back reflection minimized by using, e.g., a group of 3 photodiodes oriented at angles (***trap detector***)
  - Beam hits the detector 5 times, the reflection is 2 orders of magnitude lower (3% → 0.03%)



Monochromatic measurements

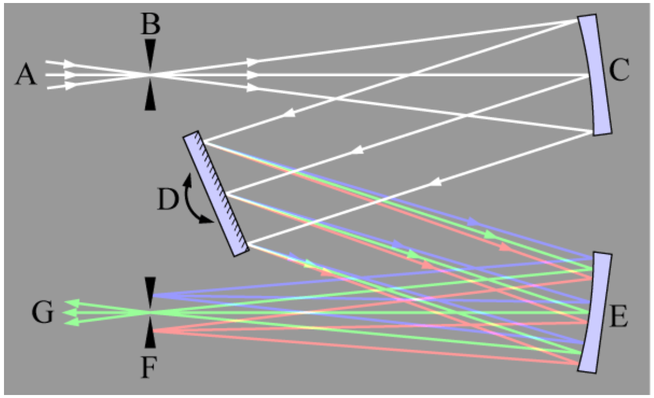
- Light is measured by dispersing it to wavelength components
- In a prism, dispersion since the refractive index is wavelength dependent
- In a diffraction grating, dispersion and interference
- Usually a reflective diffraction grating is used
  - Grating has ridges patterned in-line and manufactured mechanically or holographically





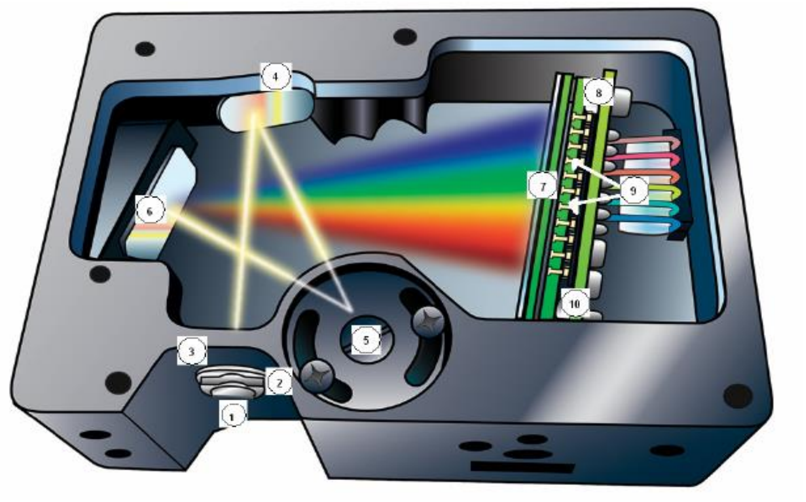
Monochromator

- Czerny-Turner is the most common configuration for a monochromator
- Image of the entrance slit (B) is imaged to the exit slit (F) at the selected wavelength
- Wavelength is selected by turning the grating (D)
- A spectroradiometer is obtained by placing a detector to the exit slit



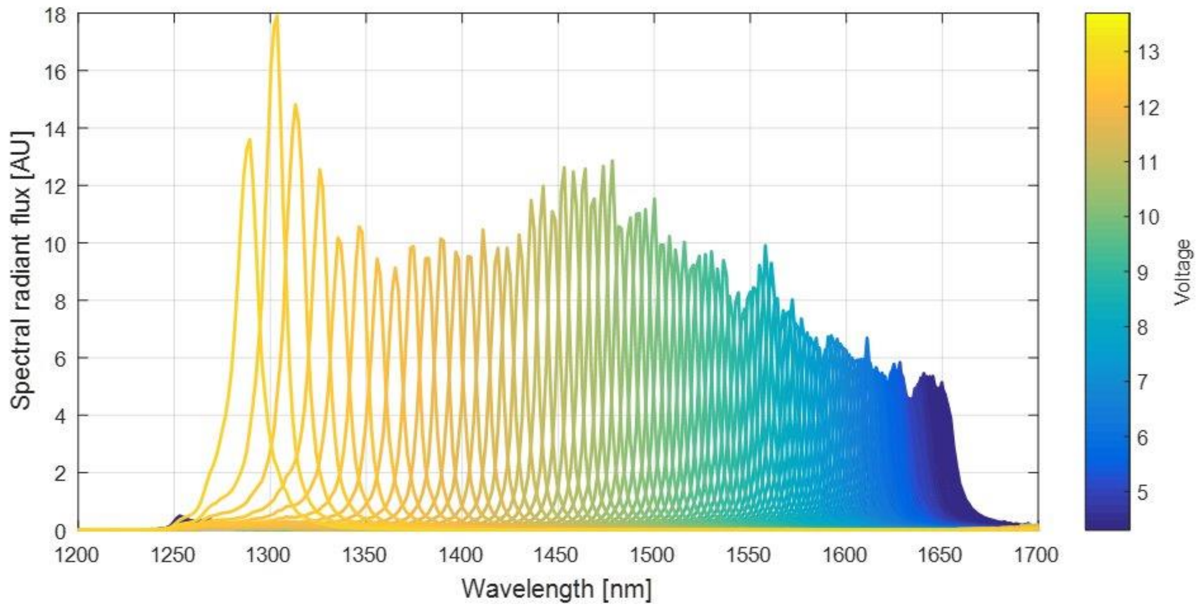
Array spectroradiometer

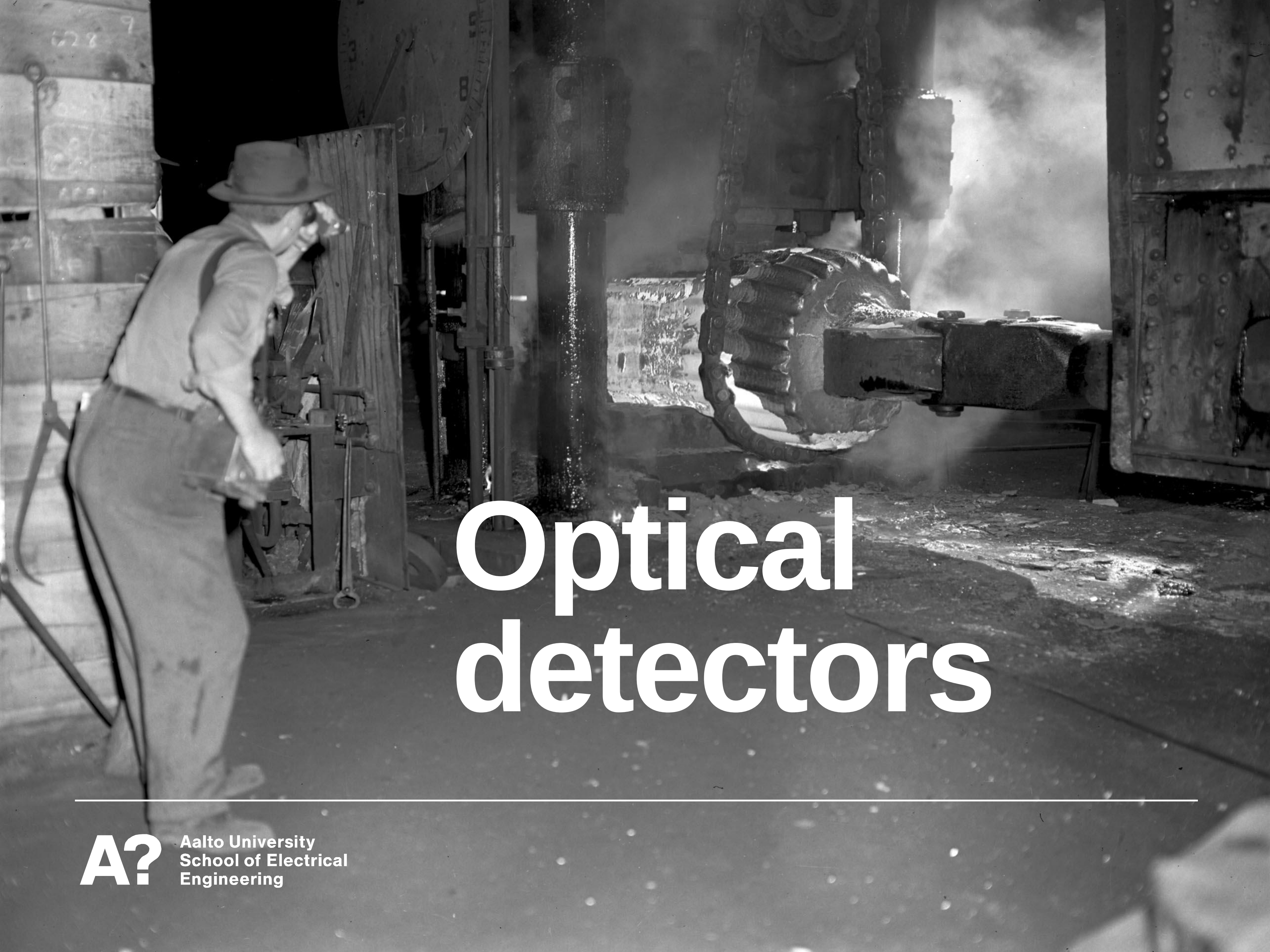
- Stationary grating, dispersed spectrum is detected with an array detector
- Pixel size defines the spectral bandwidth
- Smaller, cheaper and much faster than a monochromator with turning grating
- Not as accurate, limited wavelength range and resolution



Electrically tunable optical filters

- Thin film structure utilizing interference for wavelength selection
- Thin film thickness changed with voltage (piezo or MEMS)





Optical detectors

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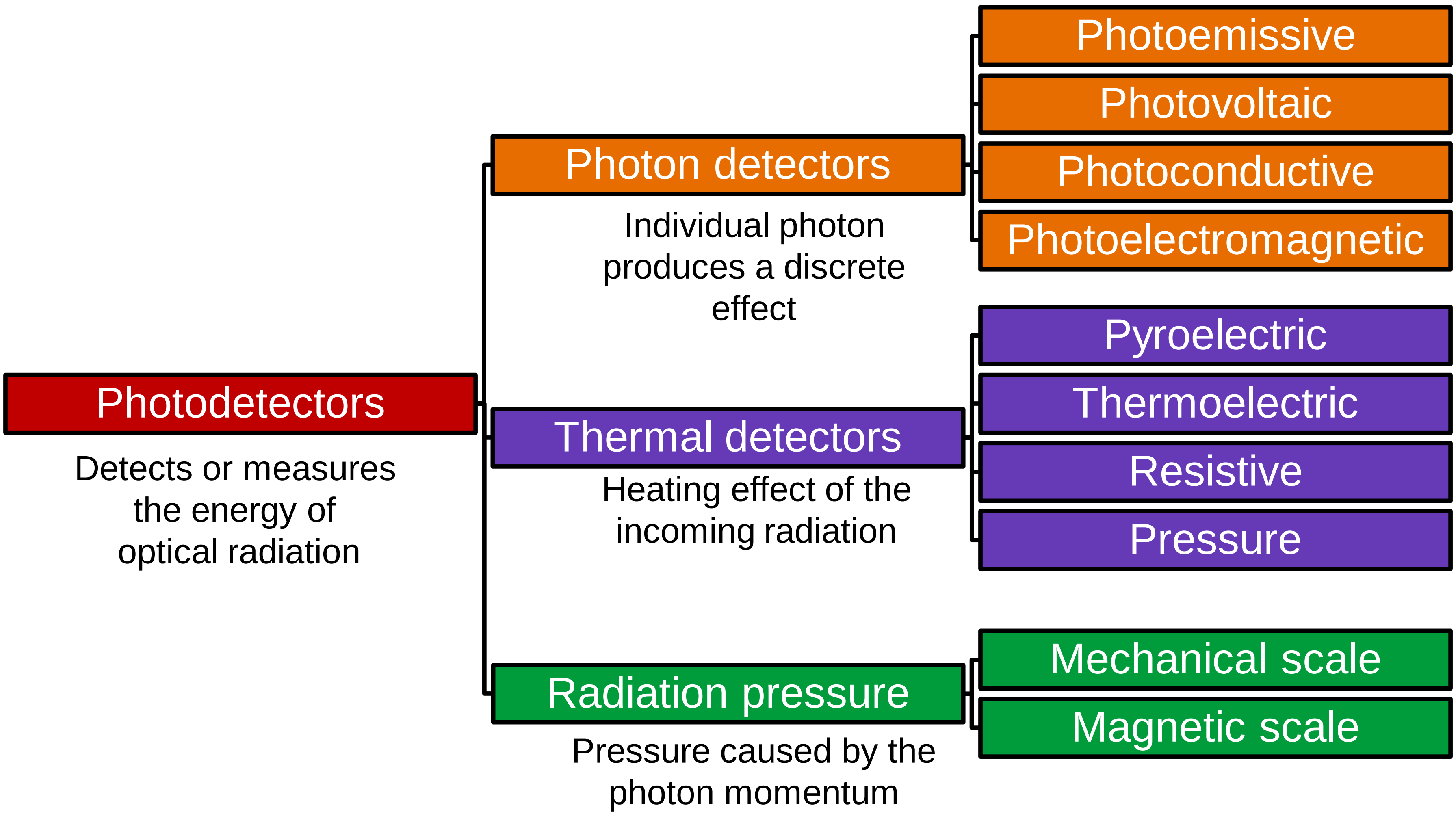
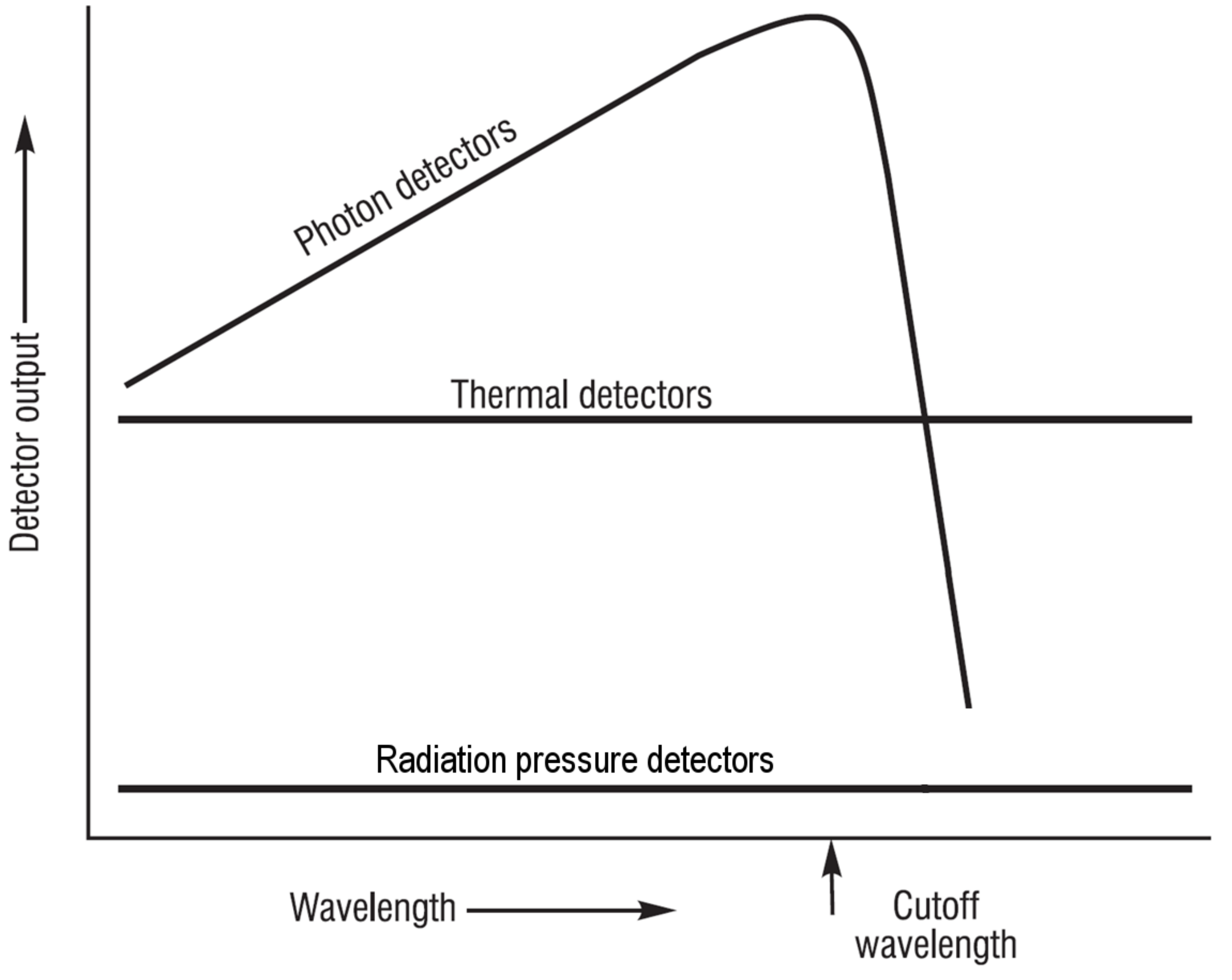
The Big Picture



Spectral sensitivities of detectors



Photon detectors

- Photons excite electrons → electron-hole pairs → detected as electrical current
- Number of electrons is proportional to the number of quanta
- Sensitivity is heavily dependent on wavelength
- Linear range up to 1 mW, fast response

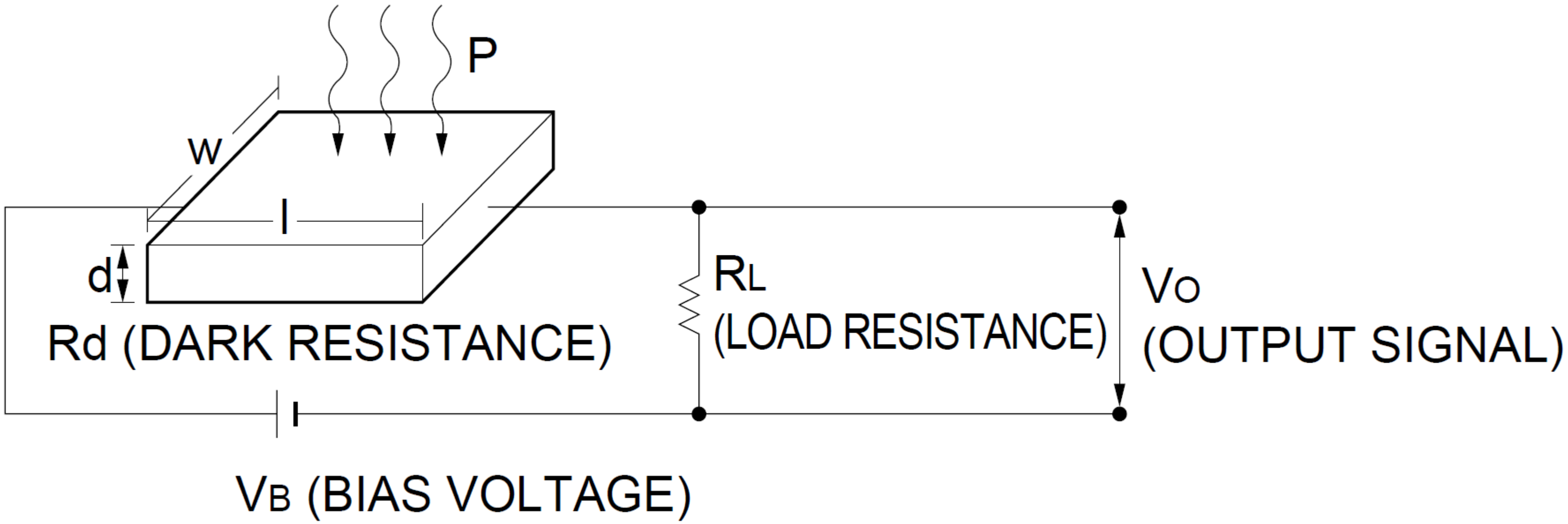
Light dependent resistor (LDR)

- **Inexpensive cadmium sulphide cell**

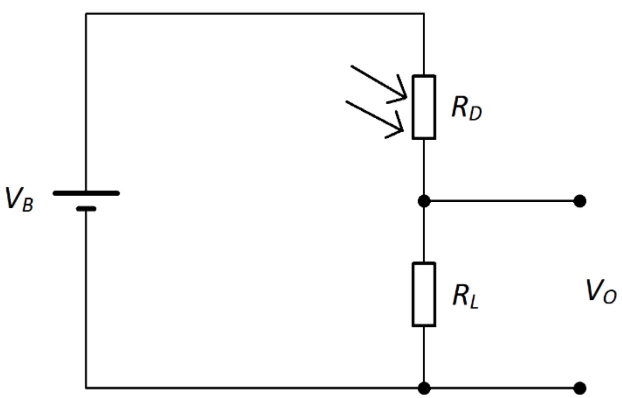
- **Slow**
- **Noisy**
- **Nonlinear**
- **etc…**

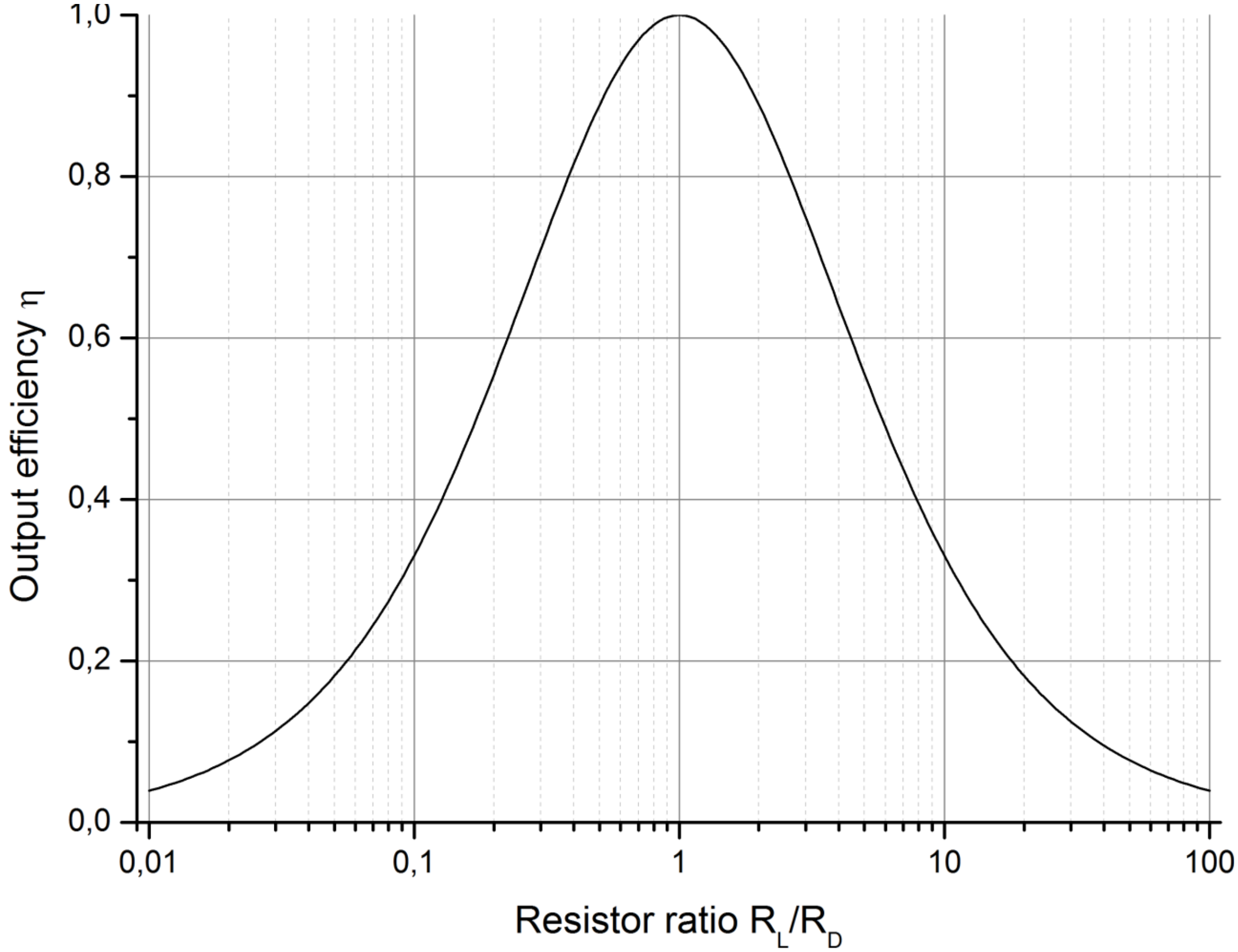
- **Very common**

Signal extraction



Signal extraction





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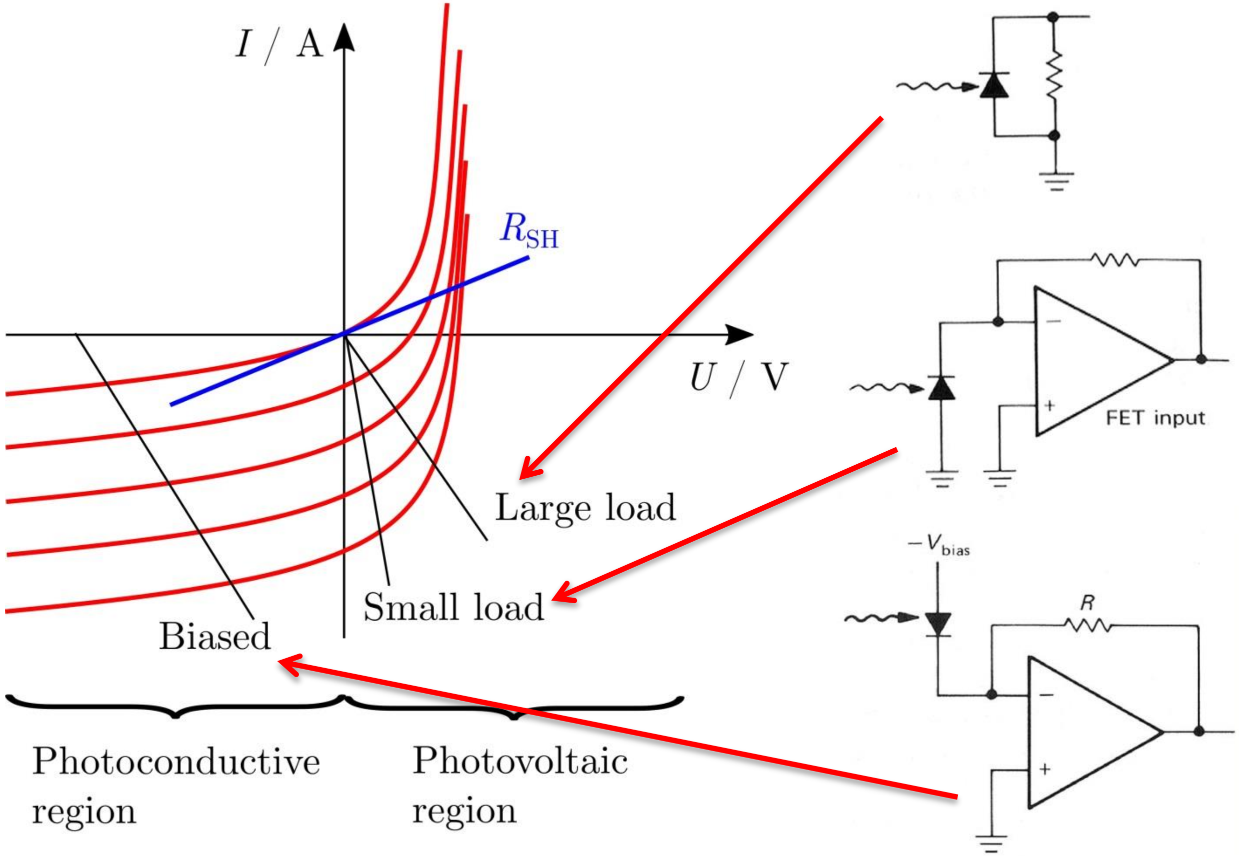
Photodiodes

- Used either in photovoltaic or photoconductive mode
  - Photovoltaic – “zero bias”, current is measured directly
  - Photoconductive – negatively biased, response time drastically decreases but noise increases
- Avalanche photodiodes (APD)
  - High (reverse bias) voltage creates electric field which accelerates and multiplies excited electrons → amplification of the signal
  - Suits measuring of the lowest light levels
- The most important parameters of photodiodes
  - Responsivity – A/W
  - Dark current
  - Noise-equivalent power (NEP) – The lowest light level creating a signal comparable to RMS noise at 1 Hz bandwidth

Photodiodes I/V curve

- Current measurement would change the internal resistance of the photodiode
- Voltage can be measured more accurately



Visible spectrum

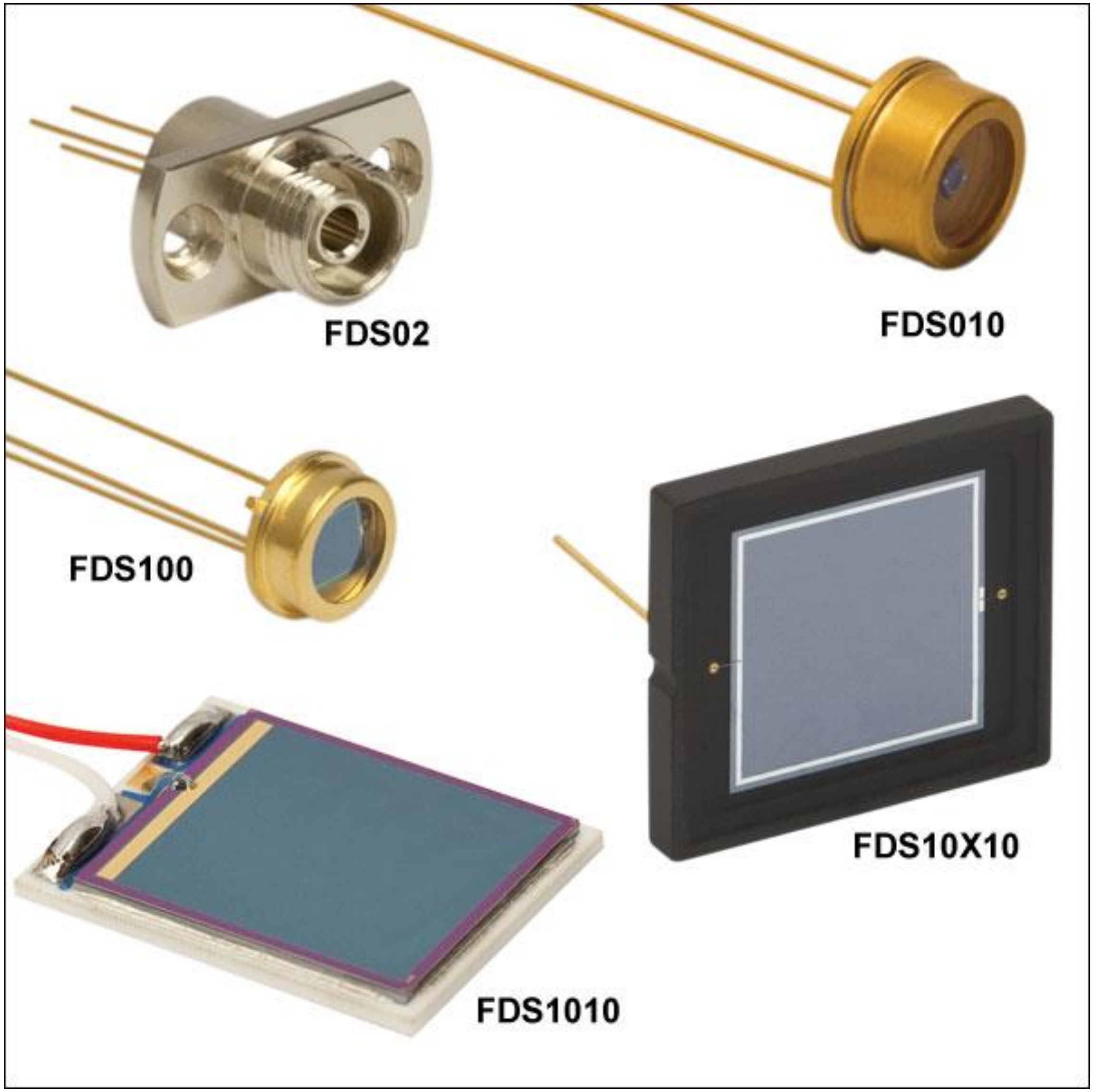
- Usually silicon detector
- Very good linearity up to 1 mW
- Stability, low noise, long life span
- Wavelength range about 300–1000 nm

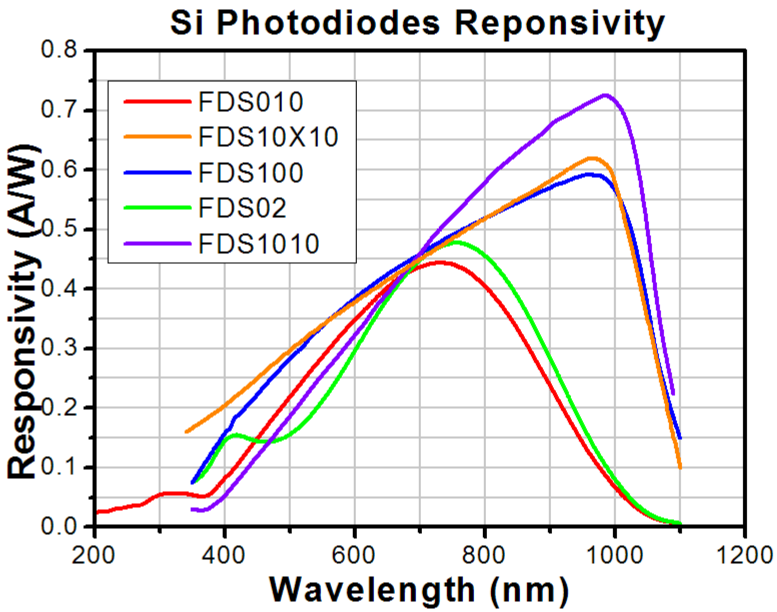
$$R(\lambda) = \frac{i(\lambda)}{P(\lambda)}$$

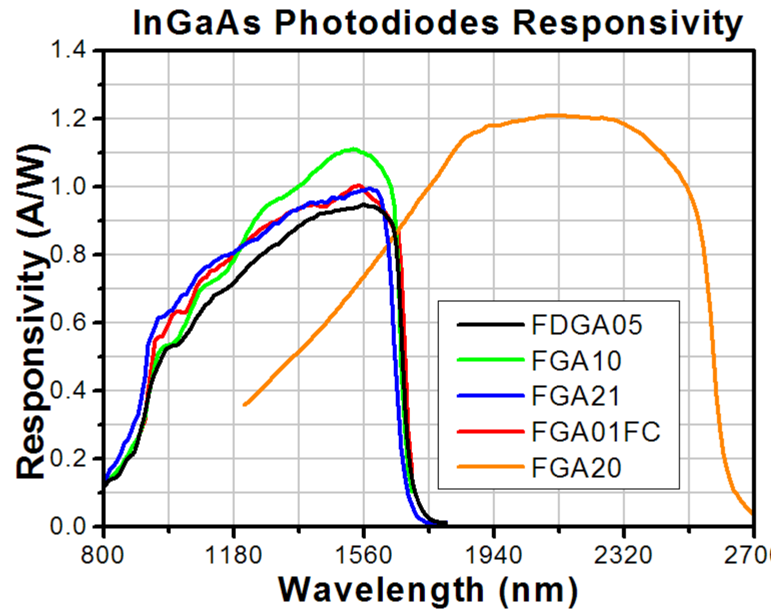
Carrier losses and gains

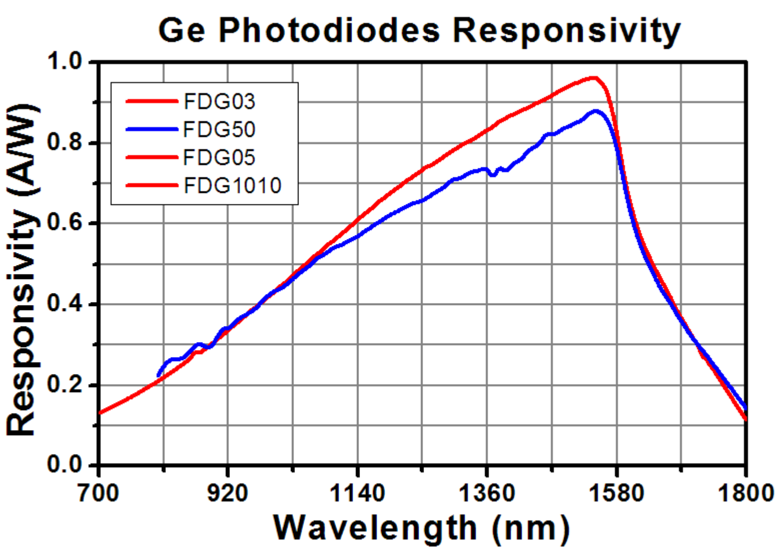
Reflectance losses

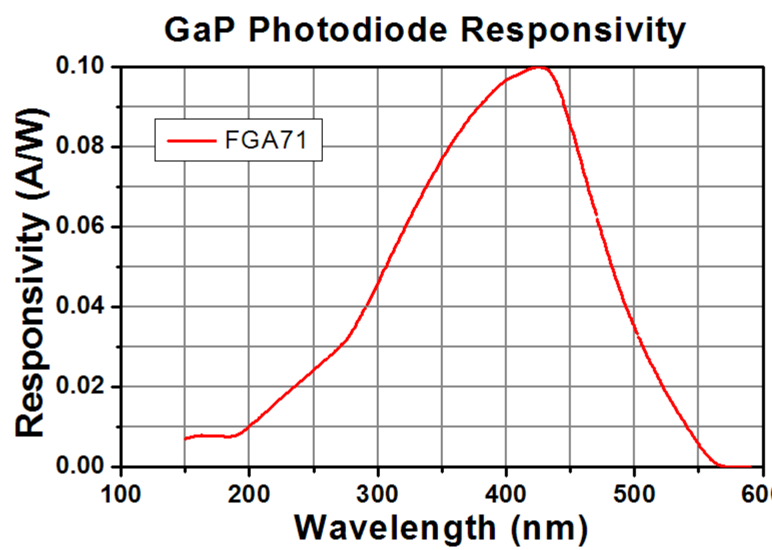
$$R(\lambda) = \frac{e\lambda}{hc}\left(1 - \delta(\lambda)\right)\left(1 - \rho(\lambda)\right)$$


FDS02
FDS010
FDS100
FDS10X10
FDS1010

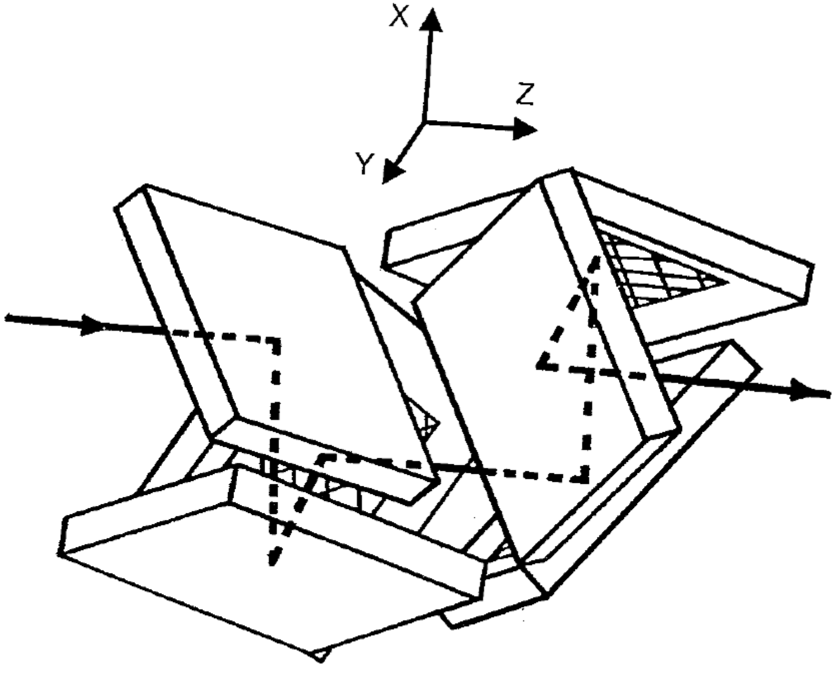

Si Photodiodes Reponsivity
Responsivity (A/W)
Wavelength (nm)
FDS010
FDS10X10
FDS100
FDS02
FDS1010
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
200
400
600
800
1000
1200

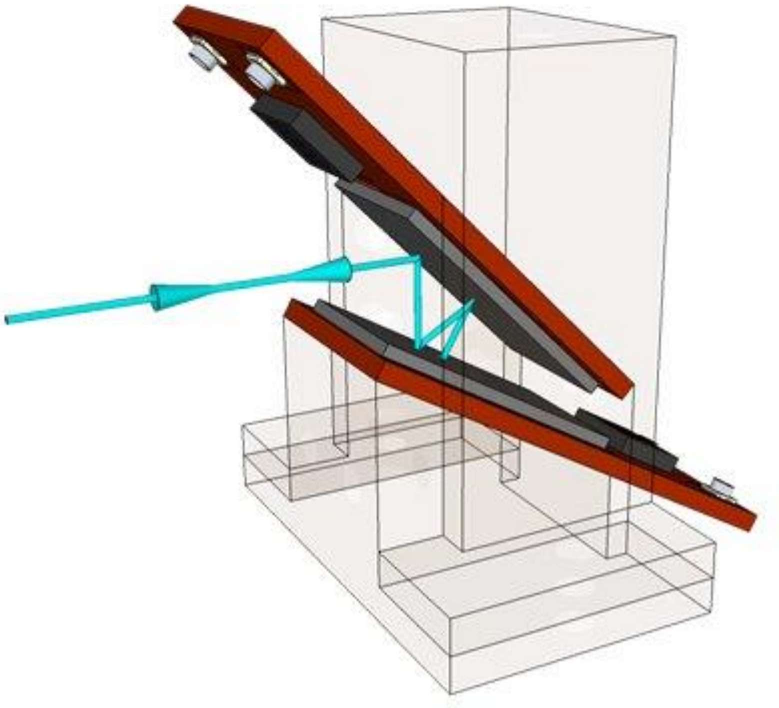

InGaAs Photodiodes Responsivity
Responsivity (A/W)
Wavelength (nm)
FDGA05
FGA10
FGA21
FGA01FC
FGA20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
800
1180
1560
1940
2320
2700


Ge Photodiodes Responsivity
Responsivity (A/W)
Wavelength (nm)
FDG03
FDG50
FDG05
FDG1010
0.0
0.2
0.4
0.6
0.8
1.0
700
920
1140
1360
1580
1800


GaP Photodiode Responsivity
Responsivity (A/W)
Wavelength (nm)
FGA71
0.00
0.02
0.04
0.06
0.08
0.10
100
200
300
400
500
600

Trap configuration





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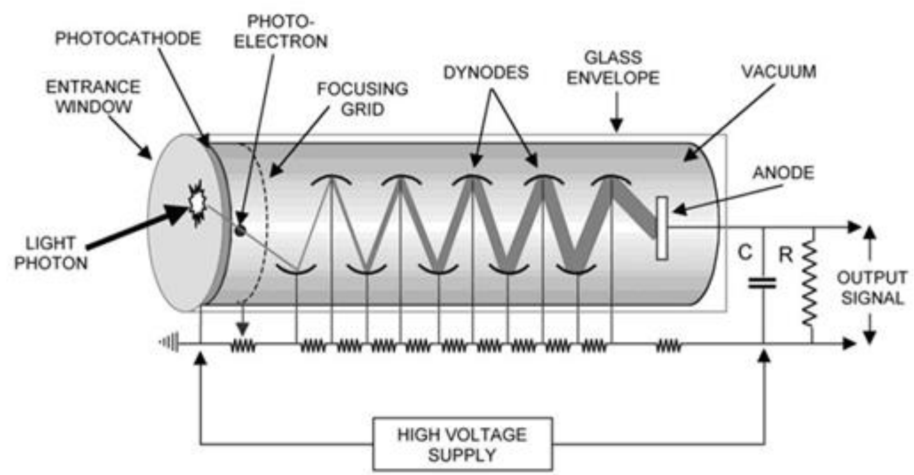
Photomultiplier tube (PMT)

- Photon released electrons are accelerated to a dynode
- Electrons hitting the dynode surface release electrons from the surface
- Every dynode connected in series is in higher voltage than the previous one

- Amplification even 10^8
- The most common application is accurate UV measurement

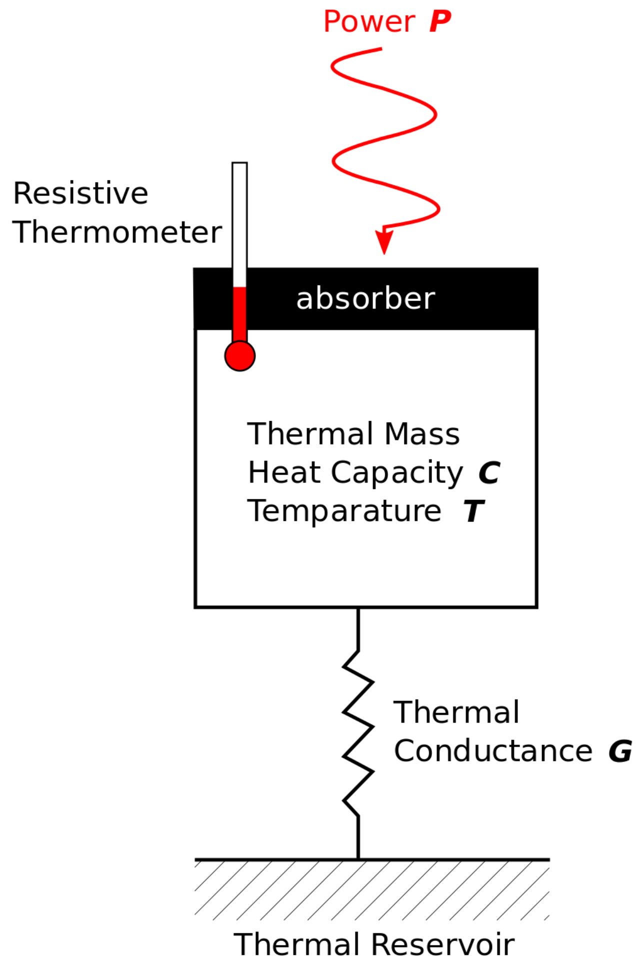


Thermal detectors

- Heating caused by incident radiation is measured
- Painted black → better absorption
- Spectrally flat across the wavelength range from UV to IR
- Linear range up to tens of kilowatts, slow response

Bolometer

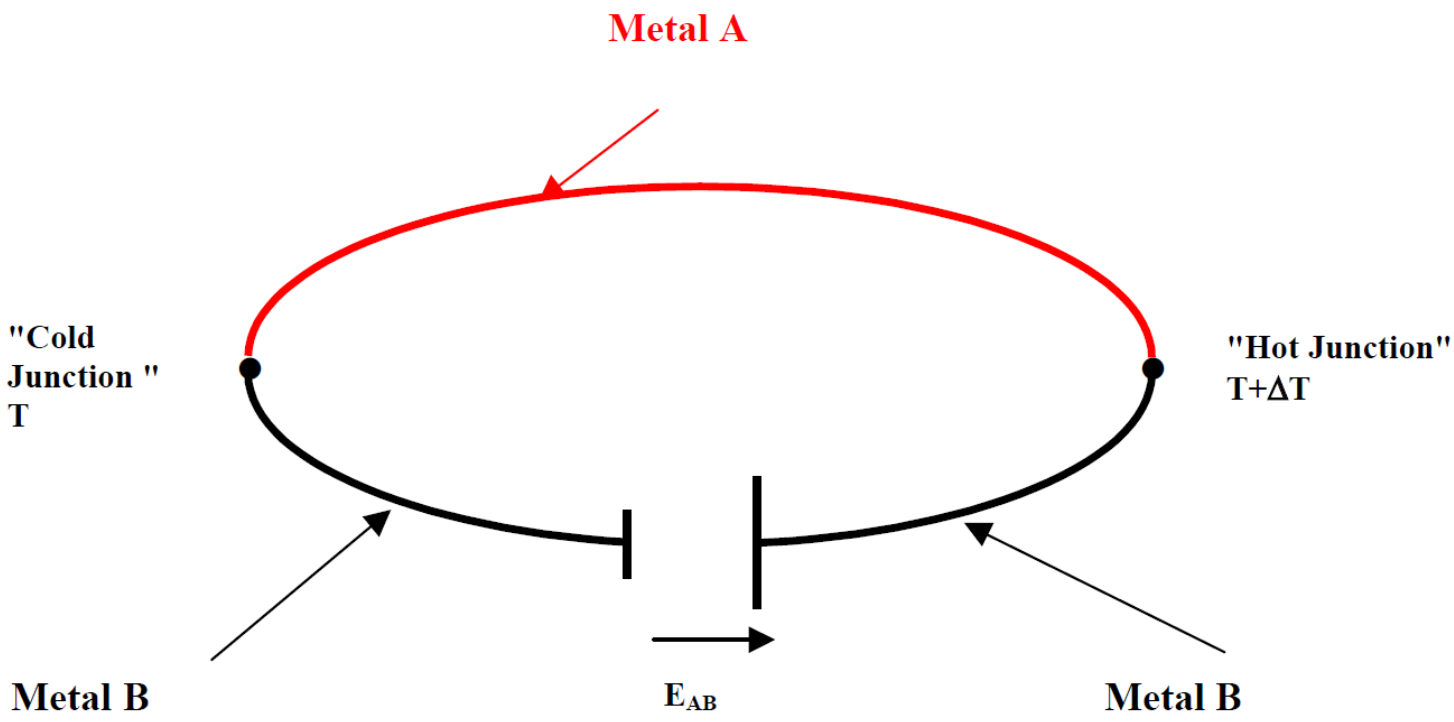
- Measurement of absorbed power via heating effect
- Metal, semiconductor or superconductor as thermometer
- Optional unilluminated reference
- Cooling improves sensitivity
- Sensitive to every form of energy



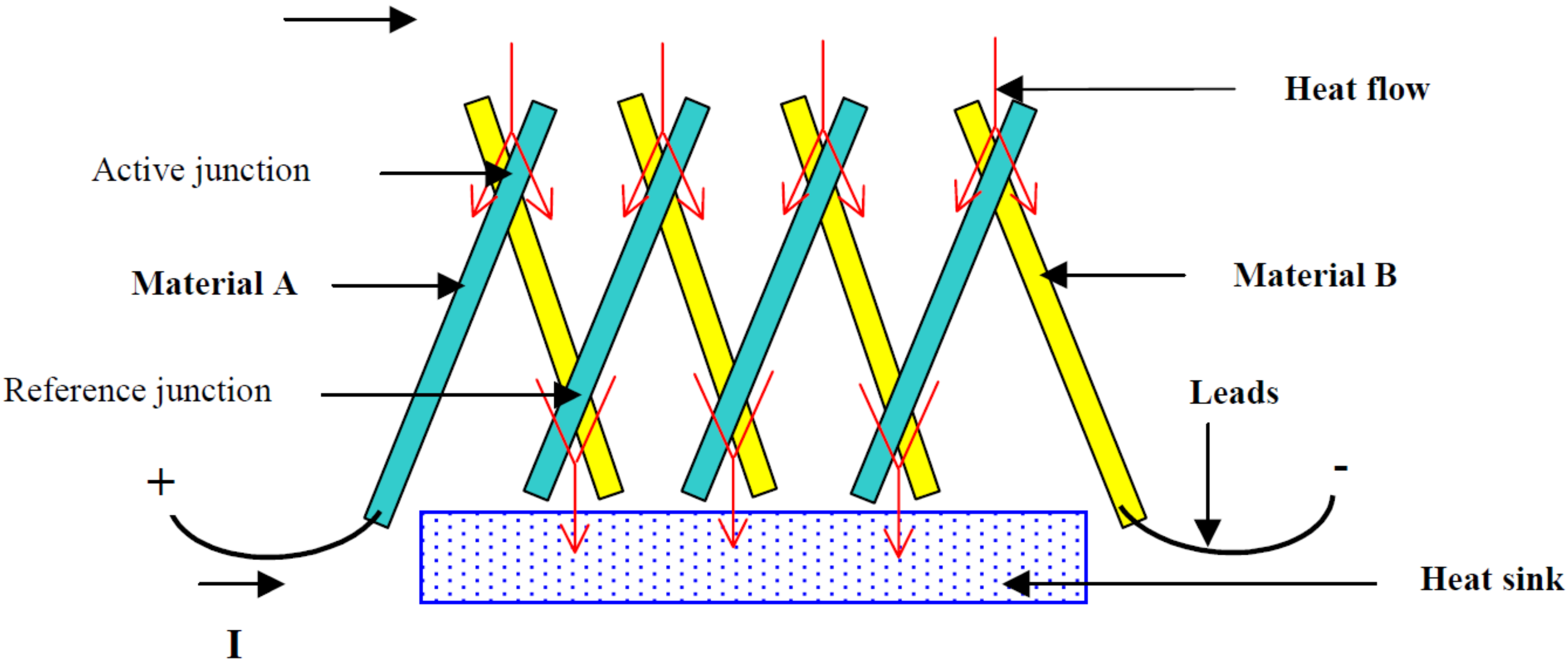
Thermoelectricity

(Seebeck effect + Peltier effect + Thomson effect)

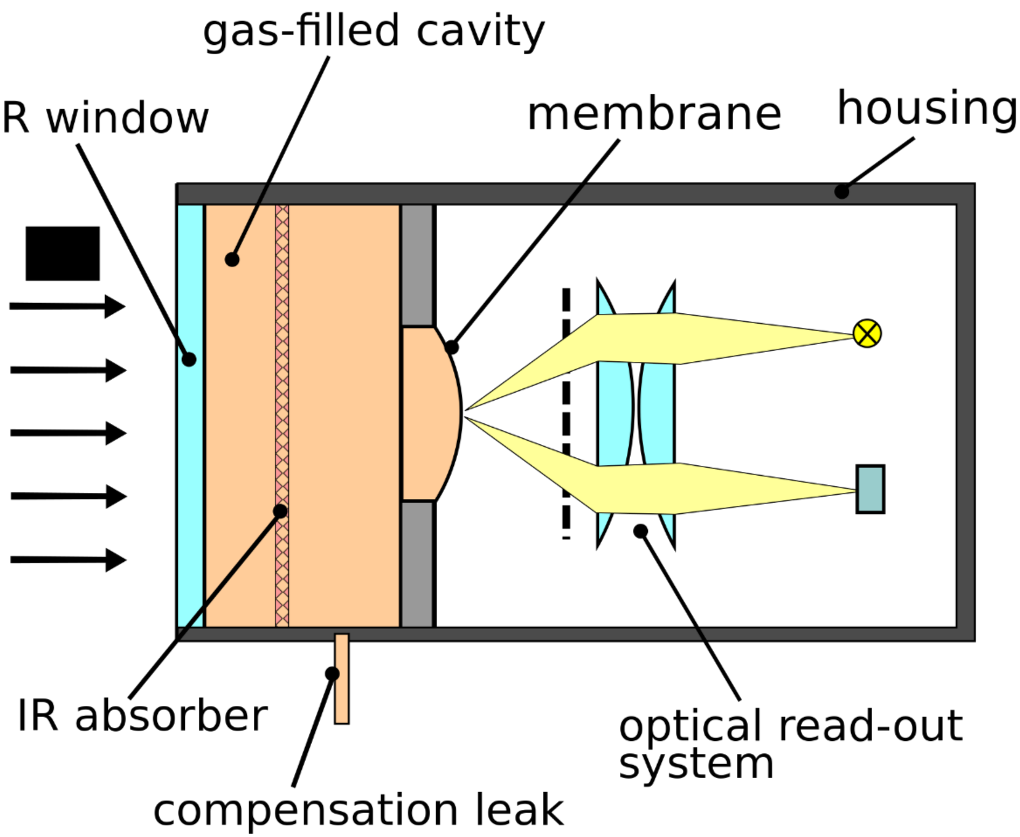
= Direct conversion of temperature differences to electric voltage and vice-versa



Thermopile


Heat flow
Active junction
Material A
Material B
Reference junction
Leads
+
-
Heat sink
I

Golay cell



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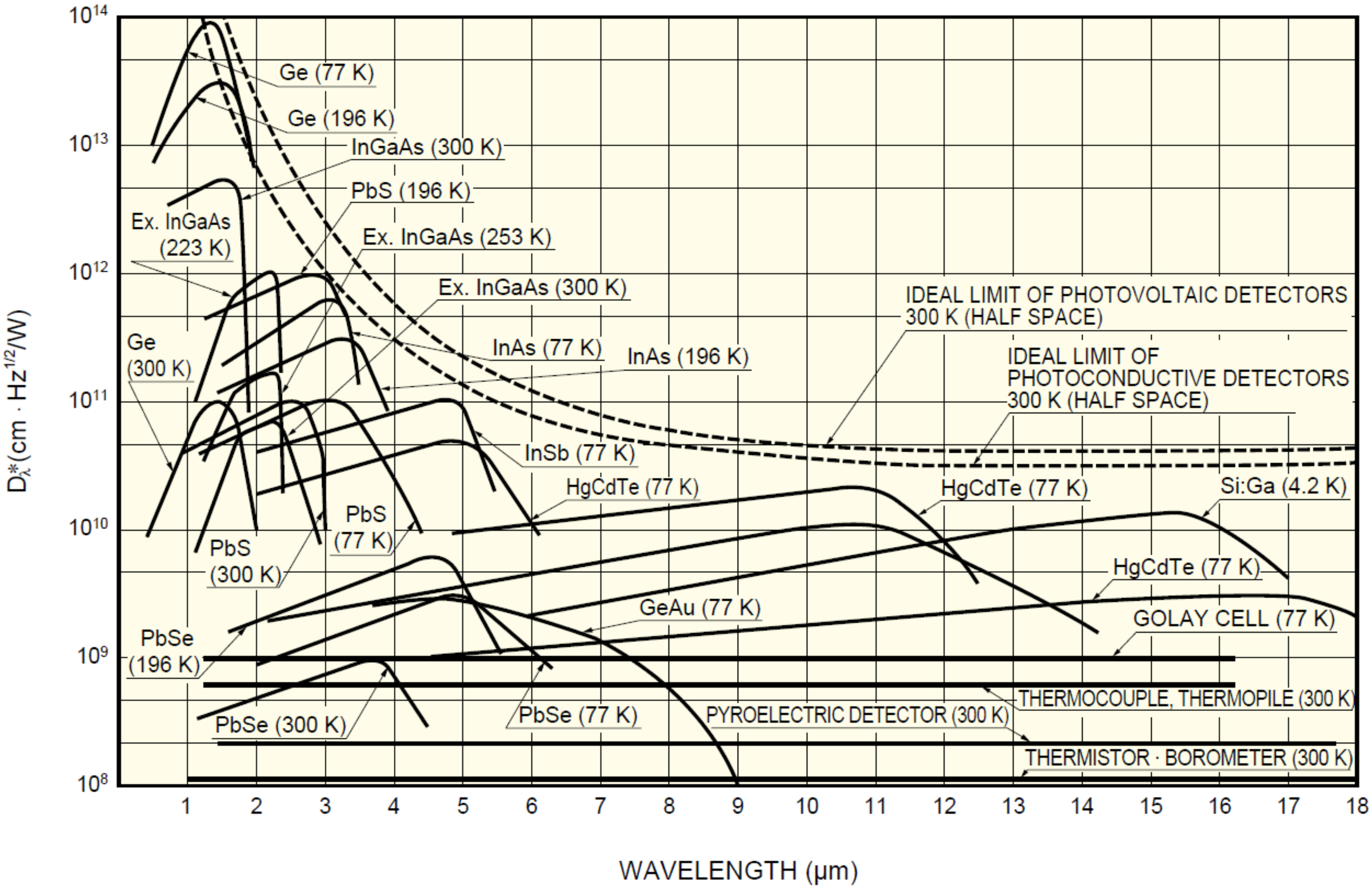
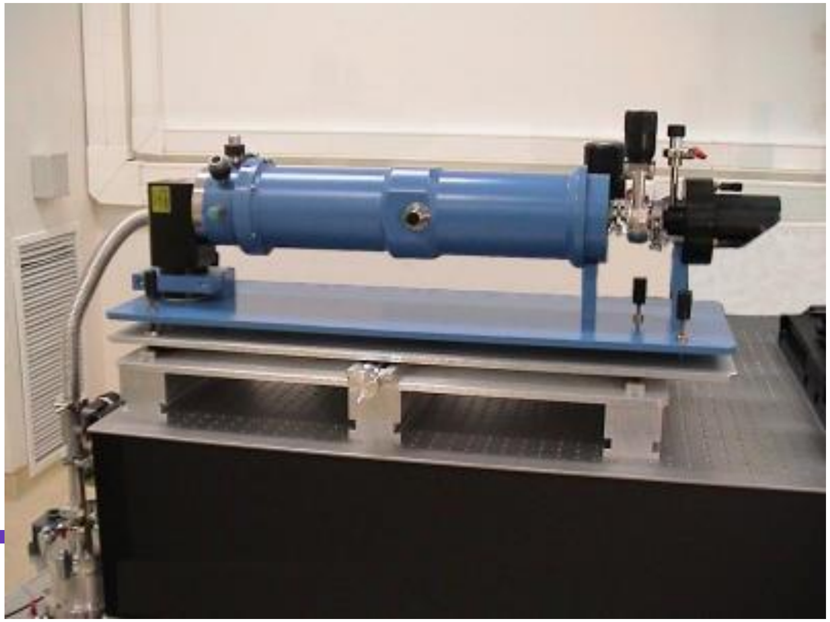
Infrared region



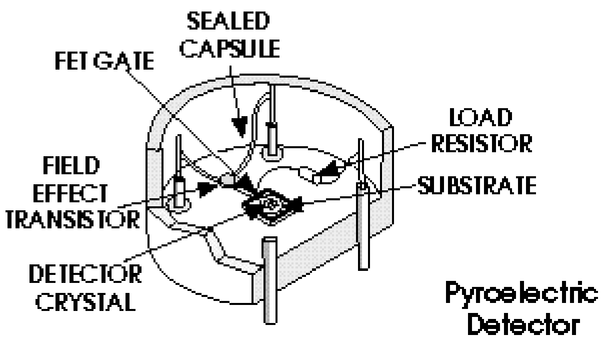
Absolute cryogenic radiometer

- "Electrical substitution radiometer"
  - Absorber is electrically heated to a specific temperature
  - Incident (laser) radiation raises the absorber temperature
  - Temperature is kept constant by reducing electrical heating power → reducing corresponds to the optical power
- The most accurate method to measure radiation power
- Operating temperature about 4 K (liquid helium) to achieve the best sensitivity and accuracy



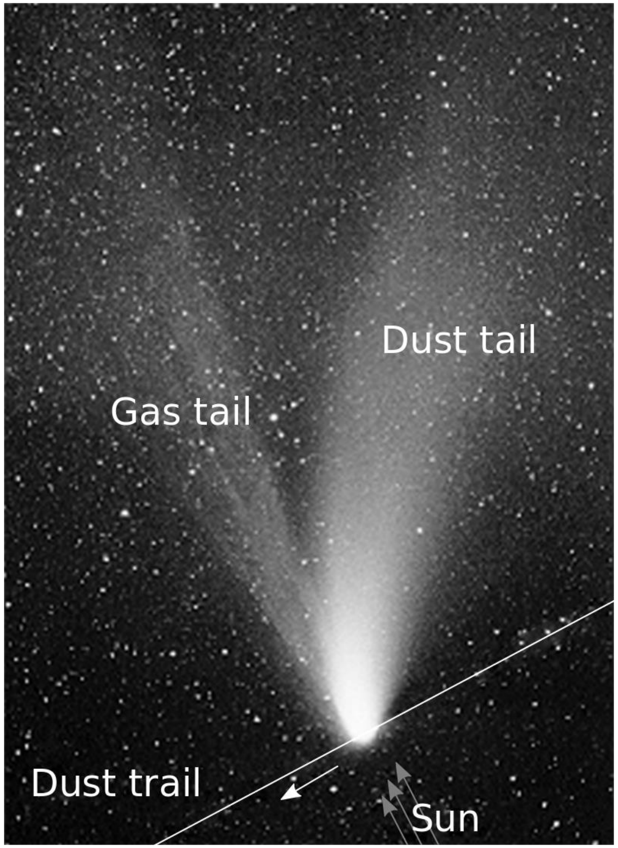
Pyroelectric detector

- Pyroelectric detector absorbs radiation and its temperature induced voltage change is measured
- Pyroelectric crystal often as an active element
- Linear response as a function of absorbed power
- More temperature sensitive and noisier than photodiodes



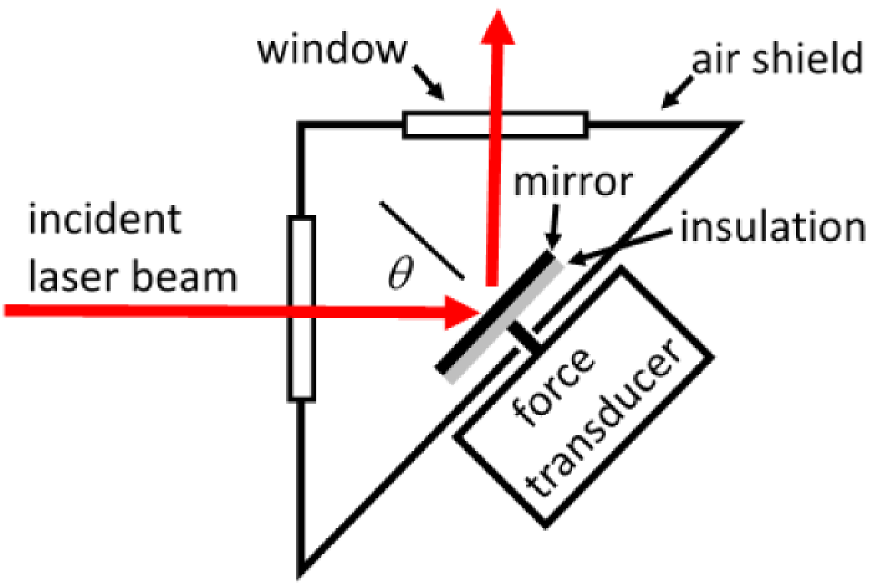
Radiation pressure detector

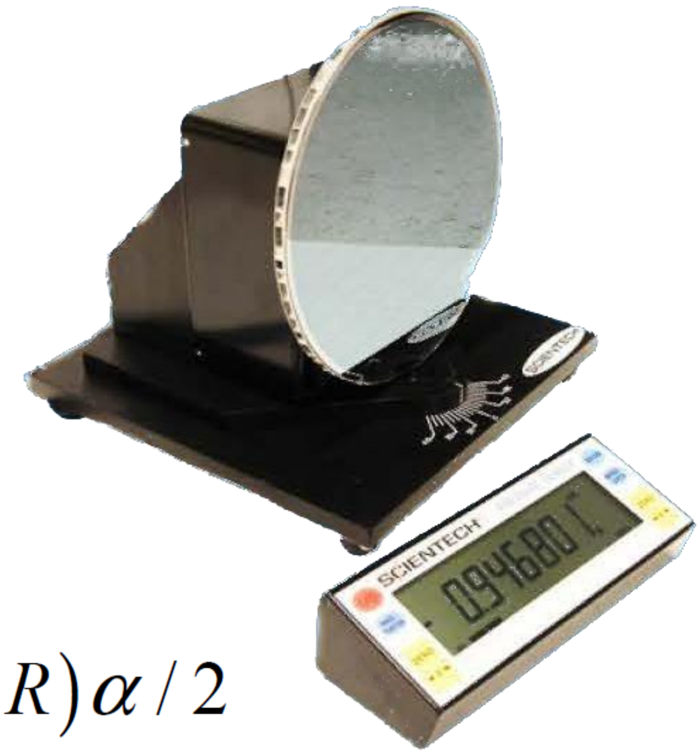
- Photons have momentum
- Energy for object movement comes from shift in wavelength



Radiation pressure detector

- Mainly high power applications (>1kW lasers)
  - Laser cutting and welding, scientific research, military applications





$$F = \left(2P/c\right) r \cos(\theta) \qquad r = R + (1-R)\alpha/2$$