Optical Remote Sensing - Passive

Chap. 5. Detector-Sensor Performance (I)

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5.1. Detector-sensor architecture overview

Irradiance at the focal plane

Irradiance due to uniform radiance L of an area element dA_i in the aperture

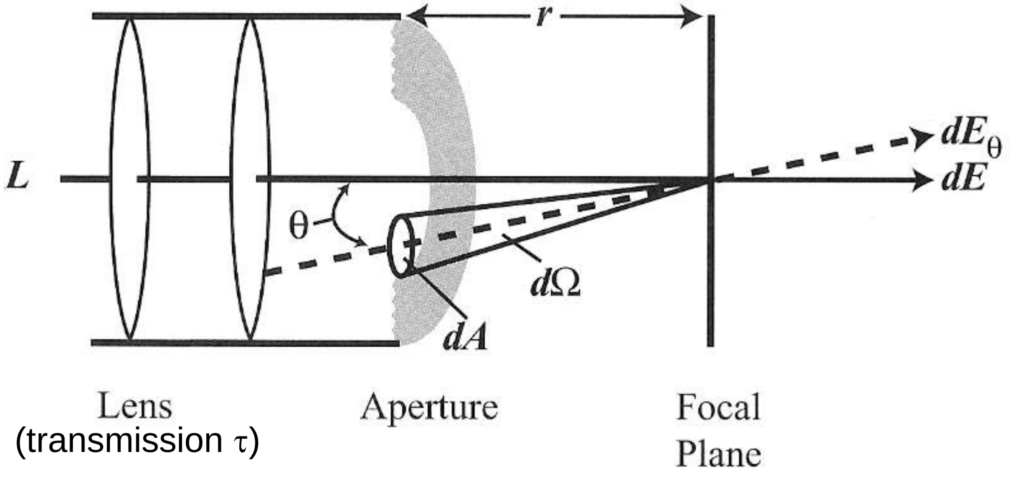
$$dE_i = \tau L d\Omega_i \cos\theta_i$$

where $d\Omega_i = \dfrac{dA_i}{r_i^2}$

1) If the aperture is small (D<<f, i.e., f# high) then $\theta_i \approx 0$, $r_i \approx r$, and

2) If system is focused at infinity, r=f

$$E = \int_A \tau L \frac{dA_i}{f^2} = \ldots = \frac{L}{\boxed{\dfrac{4(f\#)^2}{\pi\tau}}}$$



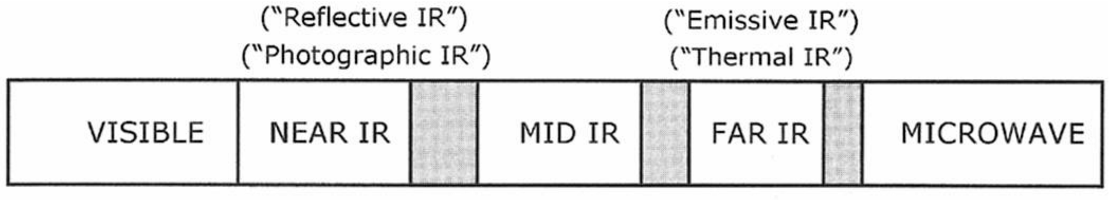
GENERAL CASE (valid for all f#)

G# (throughput of the optical system)

$$E = \frac{L}{G\#} \quad \left[\frac{W}{m^2}\right]$$

$$G\# = \frac{1 + 4(f\#)^2}{\pi\tau} \quad \left[sr^{-1}\right], \quad f\# = \frac{f}{D}$$

Cameras vs. Electro-Optical (EO) imaging systems



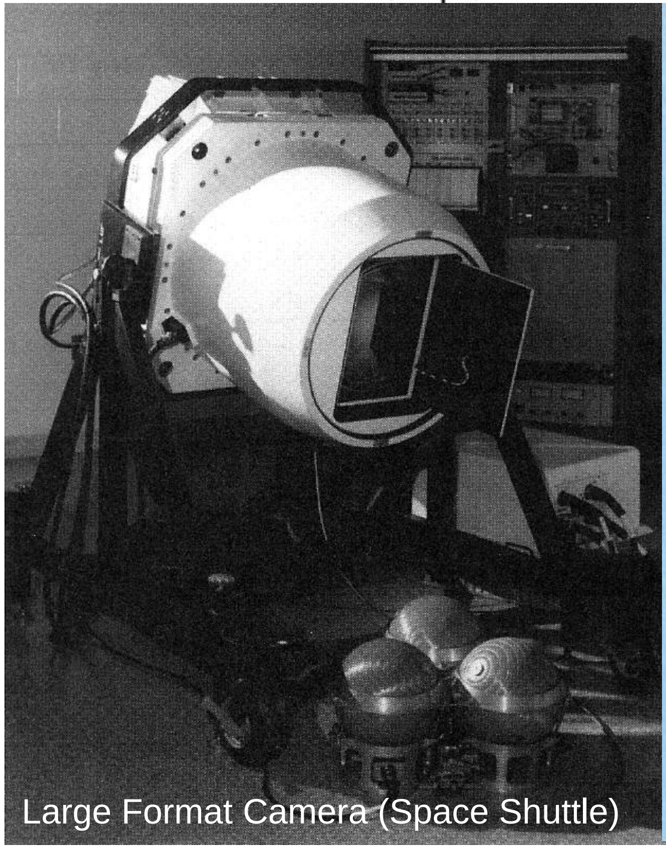
0.72 µm 1.30 µm 3.5 µm 4.5 µm 8 µm 12 µm

reflected sunlight

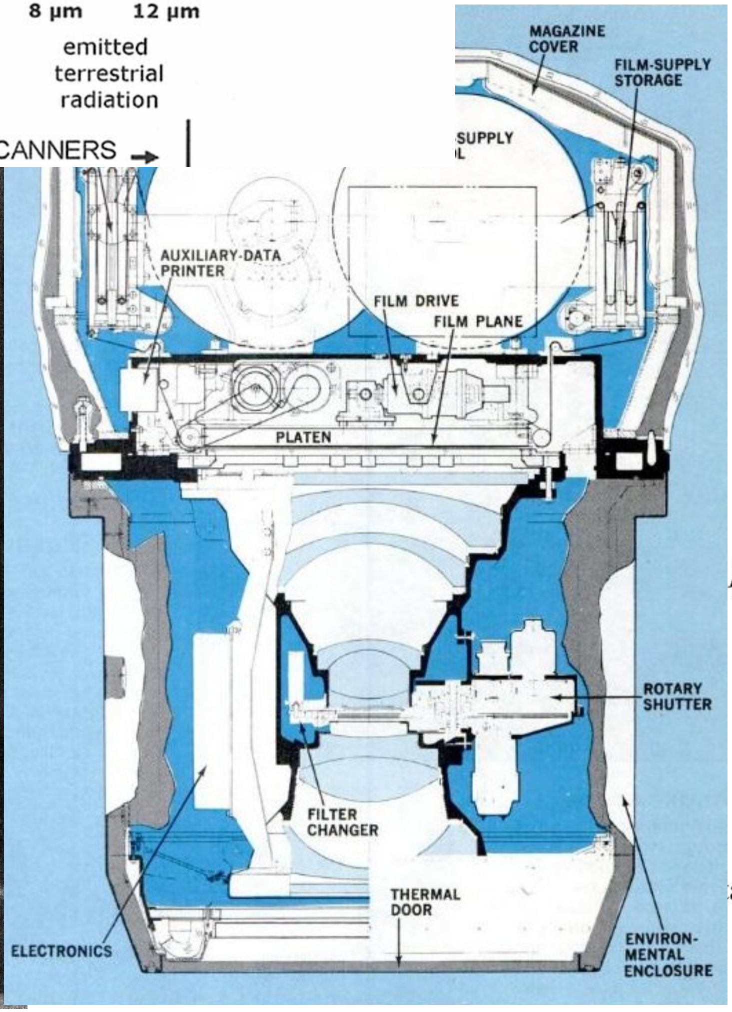
geothermal energy

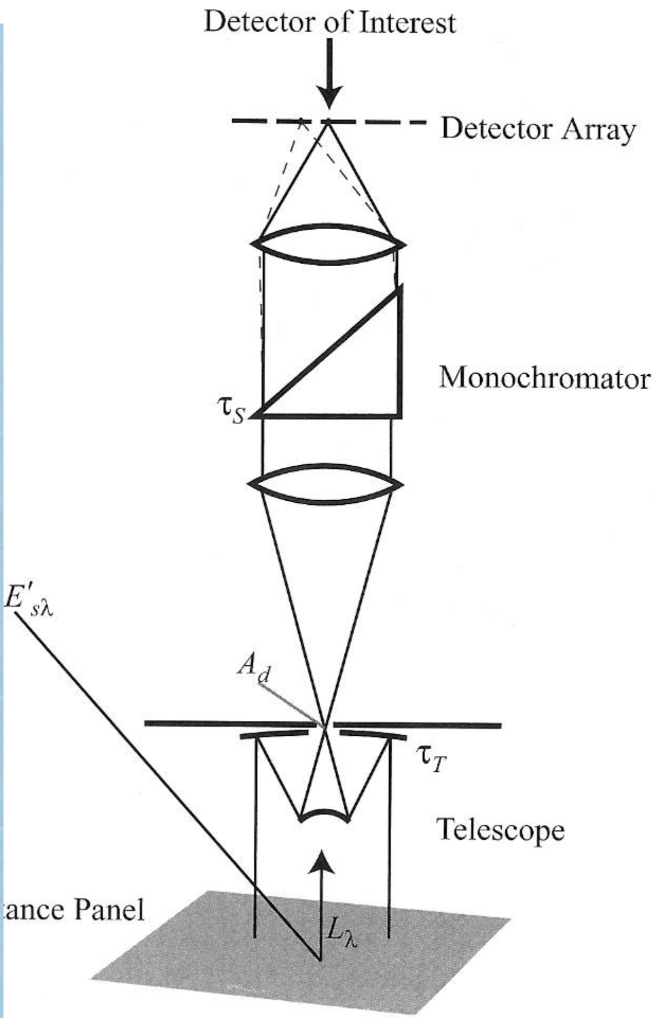
emitted terrestrial radiation

← CAMERAS → | ← THERMAL SCANNERS → |



Large Format Camera (Space Shuttle)



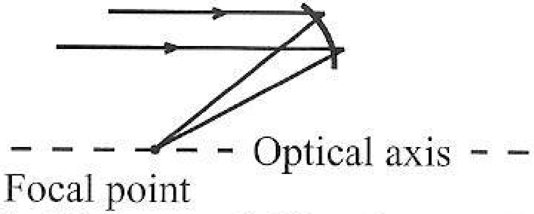


Optics: Telescope configurations

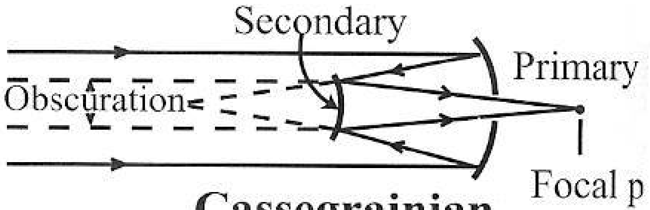
KEY PARAMETERS:

- Type
- Focal length, f
- Aperture, D
- f# = f/D
- Spectral transmission, $\tau_T(\lambda)$
- Secondary obscuration, D_{obs}
- Eff. area,

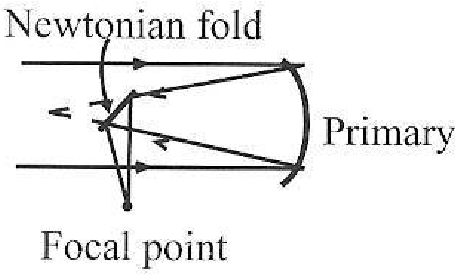
$$A_{ef} = \pi\left(\frac{D}{2}\right)^2 - \pi\left(\frac{D_{obs}}{2}\right)^2$$



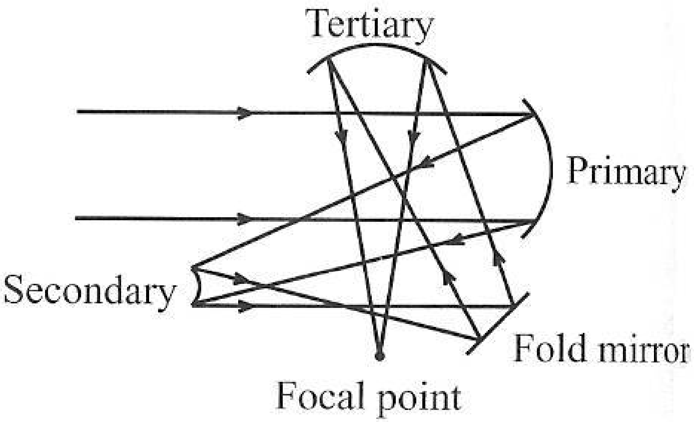
Herschel Mount (off-axis parabolic)

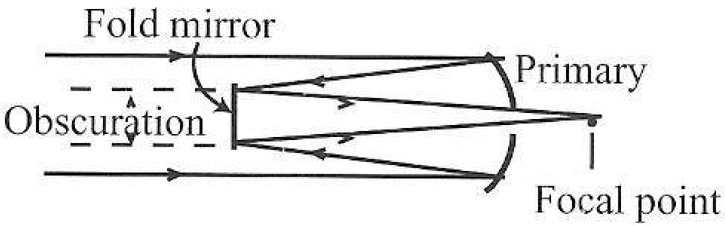


Cassegrainian



Newtonian



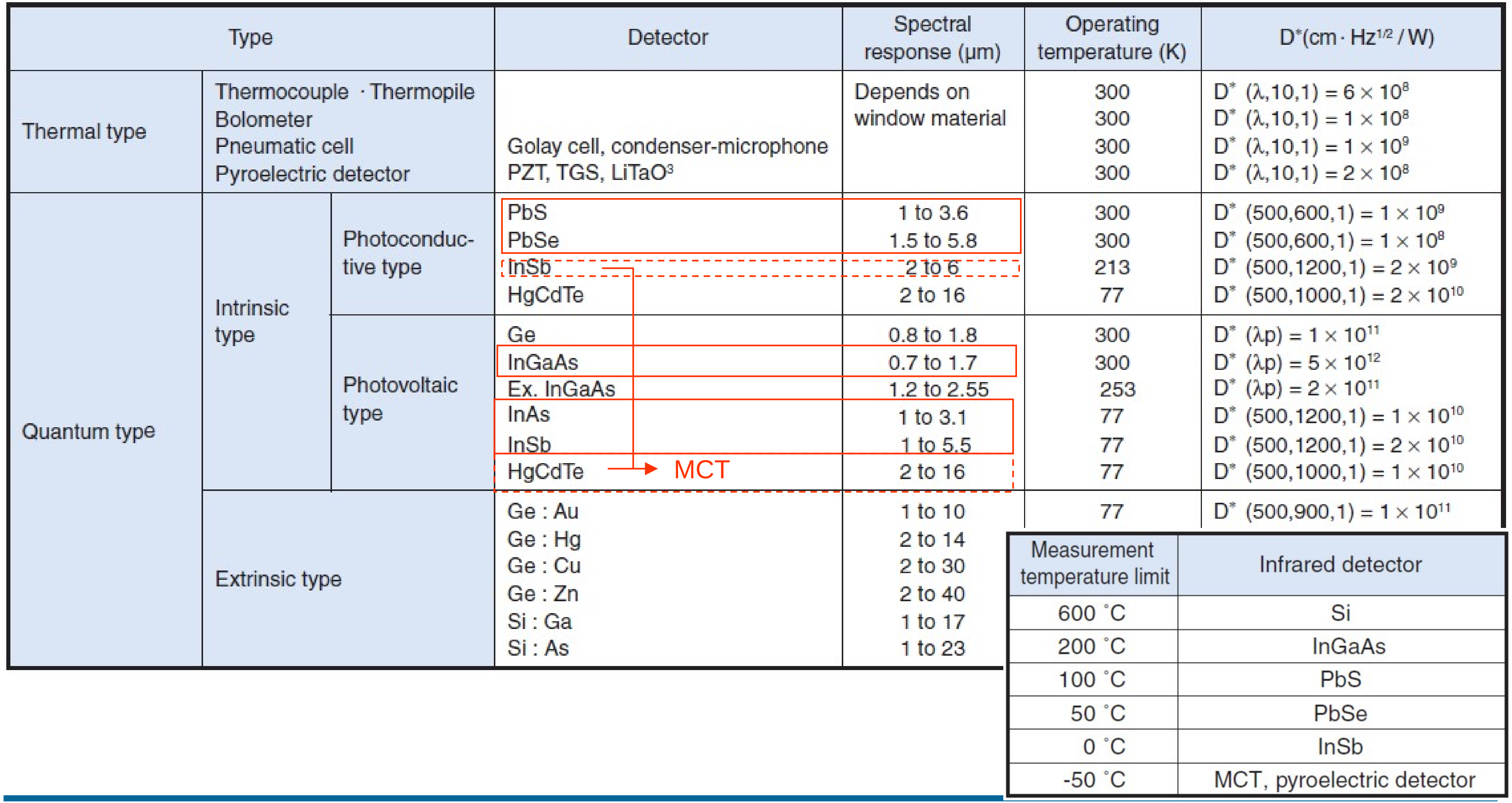


Folded Parabolic

Three-Mirror Anastigmat (TMA)

5.2 Detector types

I. OVERVIEW OF INFRARED (IR) DETECTORS



Type			Detector	Spectral response (µm)	Operating temperature (K)	D*(cm · Hz$^{1/2}$ / W)
Thermal type	Thermocouple · Thermopile			Depends on window material	300	$D^*(\lambda,10,1) = 6 \times 10^8$
	Bolometer				300	$D^*(\lambda,10,1) = 1 \times 10^8$
	Pneumatic cell		Golay cell, condenser-microphone		300	$D^*(\lambda,10,1) = 1 \times 10^9$
	Pyroelectric detector		PZT, TGS, LiTaO^3		300	$D^*(\lambda,10,1) = 2 \times 10^8$
Quantum type	Intrinsic type	Photoconductive type	PbS	1 to 3.6	300	$D^*(500,600,1) = 1 \times 10^9$
			PbSe	1.5 to 5.8	300	$D^*(500,600,1) = 1 \times 10^8$
			InSb	2 to 6	213	$D^*(500,1200,1) = 2 \times 10^9$
			HgCdTe	2 to 16	77	$D^*(500,1000,1) = 2 \times 10^{10}$
		Photovoltaic type	Ge	0.8 to 1.8	300	$D^*(\lambda p) = 1 \times 10^{11}$
			InGaAs	0.7 to 1.7	300	$D^*(\lambda p) = 5 \times 10^{12}$
			Ex. InGaAs	1.2 to 2.55	253	$D^*(\lambda p) = 2 \times 10^{11}$
			InAs	1 to 3.1	77	$D^*(500,1200,1) = 1 \times 10^{10}$
			InSb	1 to 5.5	77	$D^*(500,1200,1) = 2 \times 10^{10}$
			HgCdTe → MCT	2 to 16	77	$D^*(500,1000,1) = 1 \times 10^{10}$
	Extrinsic type		Ge : Au	1 to 10	77	$D^*(500,900,1) = 1 \times 10^{11}$
			Ge : Hg	2 to 14		
			Ge : Cu	2 to 30		
			Ge : Zn	2 to 40		
			Si : Ga	1 to 17		
			Si : As	1 to 23		

Measurement temperature limit	Infrared detector
600 ˚C	Si
200 ˚C	InGaAs
100 ˚C	PbS
50 ˚C	PbSe
0 ˚C	InSb
-50 ˚C	MCT, pyroelectric detector

I. OVERVIEW OF INFRARED DETECTORS

IR radiation has low energy (e.g., 1.24 eV at 1μm),

$$E = \frac{hc}{q\lambda} = \frac{1.24}{\eta\lambda[\mu m]} \quad [eV]$$

THERMAL DETECTORS (TD):

- Absorb incident flux and undergo a temperature change, which produces a high rate of change in electrical resistance, R(T).
- Photosensitivity is nearly independent of wavelength
- Slow response time (typ. 1 ms)
- Low detection capability
- Do not require cooling
- Used in the MWIR, LWIR

QUANTUM DETECTORS (QD):

- Photon-matter (photocathode or semiconductor) interaction
  - *quantum efficiency,* η*=[e$^-$]/[photon]*
- Photosensitivity is dependent on wavelength
- Faster response speed
- Higher detection performance
- Must be cooled (except in the NIR)
- The noise caused by background fluctuation determines the theoretical limit of D* (D star)

I. OVERVIEW OF INFRARED DETECTORS

(QD) *EXTRINSIC or "external photo-effect" detectors:*

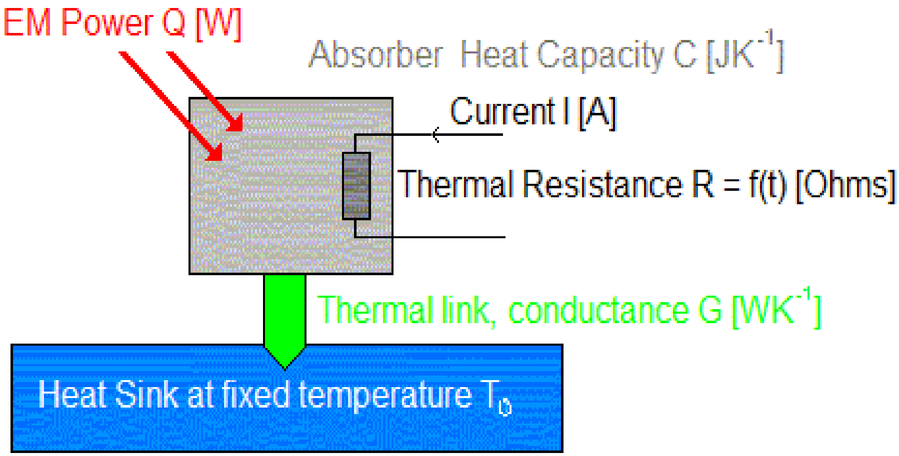
- Photo-sensitive materials (photo-cathodes) with low work functions produce a *current* in an external circuit.
- Limited to VIS-NIR, E.g., PMT (Photo Multiplier Tube)

(QD) *INTRINSIC or "internal photo-effect" detectors or PHOTON DETECTORS:*

- Semiconductors in which the electrons undergo internal energy level transitions when they absorb a photon. Most popular covering 0.2-20 μm.
- PHOTOCONDUCTIVE (PC) mode:
  - *A reverse bias is applied across the photodiode.*
  - *Wider depletion region, lower junction capacitance, shorter rise time, wider range of light intensities, improved dynamic range*
  - *Shot noise increases due to increased dark current (PIN, APD photodiodes)*
- PHOTOVOLTAIC (PV) mode:
  - *No external bias applied*
  - *Lower dark current → increased sensitivity to low light levels (PIN photodiodes)*

II. THERMAL DETECTORS: Bolometer

- (S.P. Langley, 1880)
- Device that undergoes changes of resistance as changes in dissipated power occur.
- Consists of an absorptive element (blackened thin layer of metal) connected to a heat sink (a body of constant temperature).
- Types:
  - – *The BARRETTER (R↑ as dissipated power rises) (metal)*
  - – *The THERMISTOR (R↓) (SC)*
- Metal bolometers work without cooling.
- 1-μm to 2-mm wavelengths



EM Power Q [W]

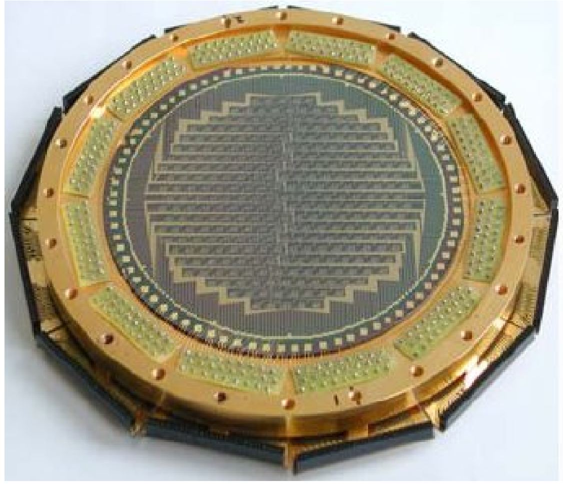
Absorber Heat Capacity C [JK^{-1}]

Current I [A]

Thermal Resistance R = f(t) [Ohms]

Thermal link, conductance G [WK^{-1}]

Heat Sink at fixed temperature T_0



http://www.apex-telescope.org/bolometer/laboca/technical/

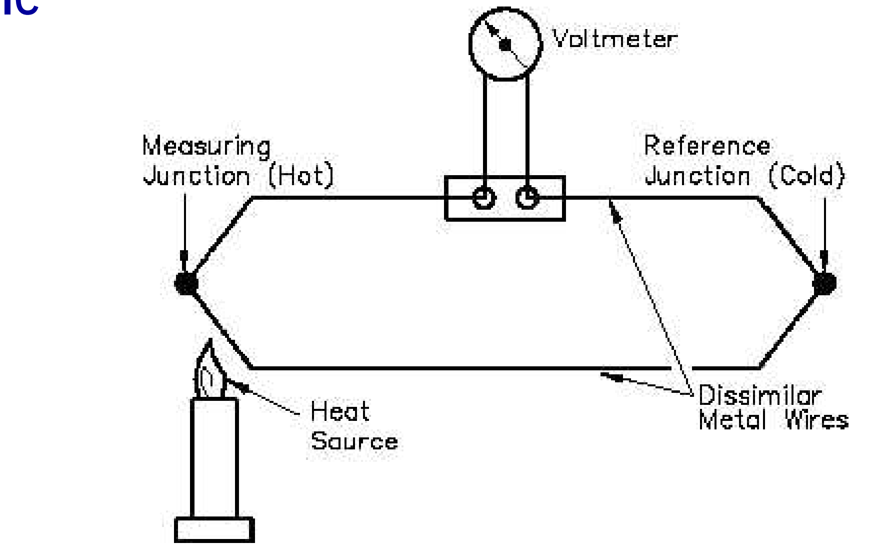
II. THERMAL DETECTORS: Termocouple/pile

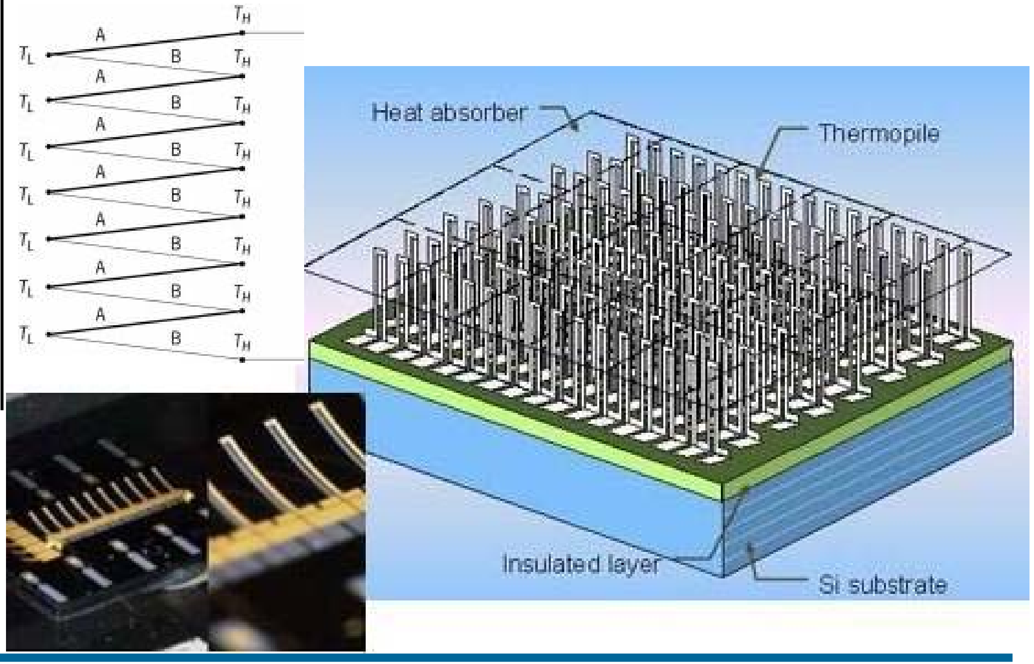
TERMOCOUPLE

- Any junction of dissimilar metals produces an electric potential related to temperature.
  - *Measures Temperature difference (typ. 1-70 μV/ºC)*
  - *A reference (cold) junction is needed*
- (Seebeck's effect, 1821) "any conductor subjected to a thermal gradient generates a voltage".

TERMOPILE

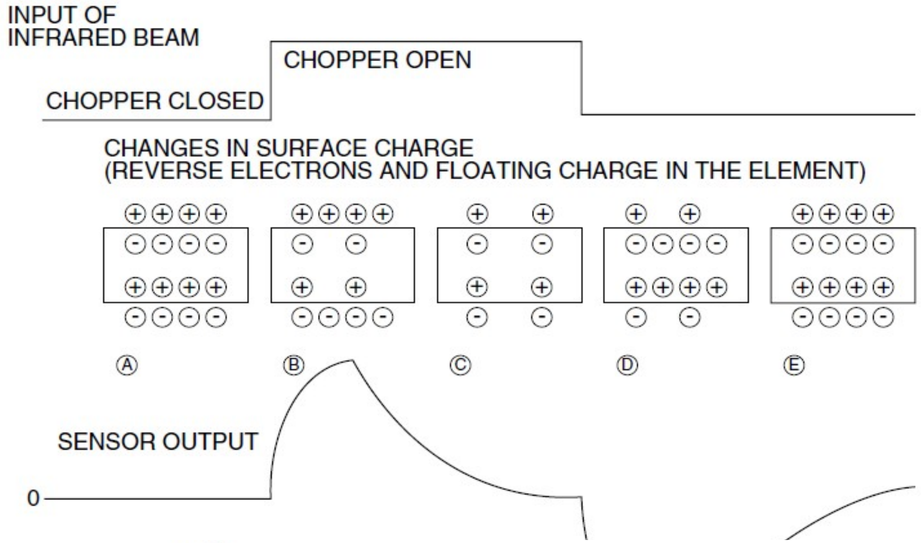
- Converts thermal into electrical energy
- Composed of thermocouples connected usually in series.

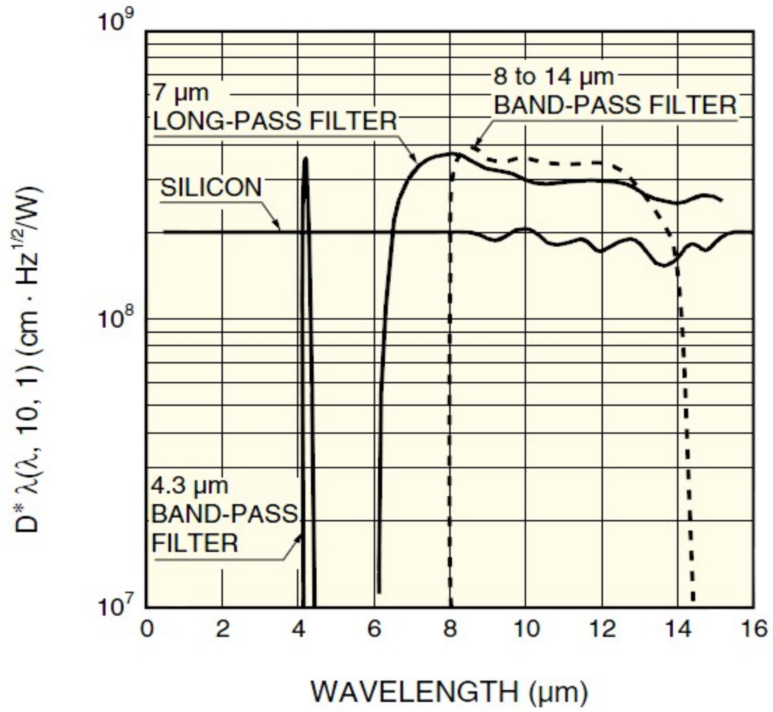




II. THERMAL DETECTORS: Pyroelectric

- Consists of a piezoelectric transducer (PZT) having the pyroelectric effect, a high resistor and a low-noise FET.
- When light is absorbed by the PZT, its temperature increases, resulting in a change in the spontaneous polarization state. These changes are output as a voltage *change*.
  - *An optical chopper is needed for measurement of still objects*
  - *No wavelength dependency. Spectral range determined only by the window material used.*

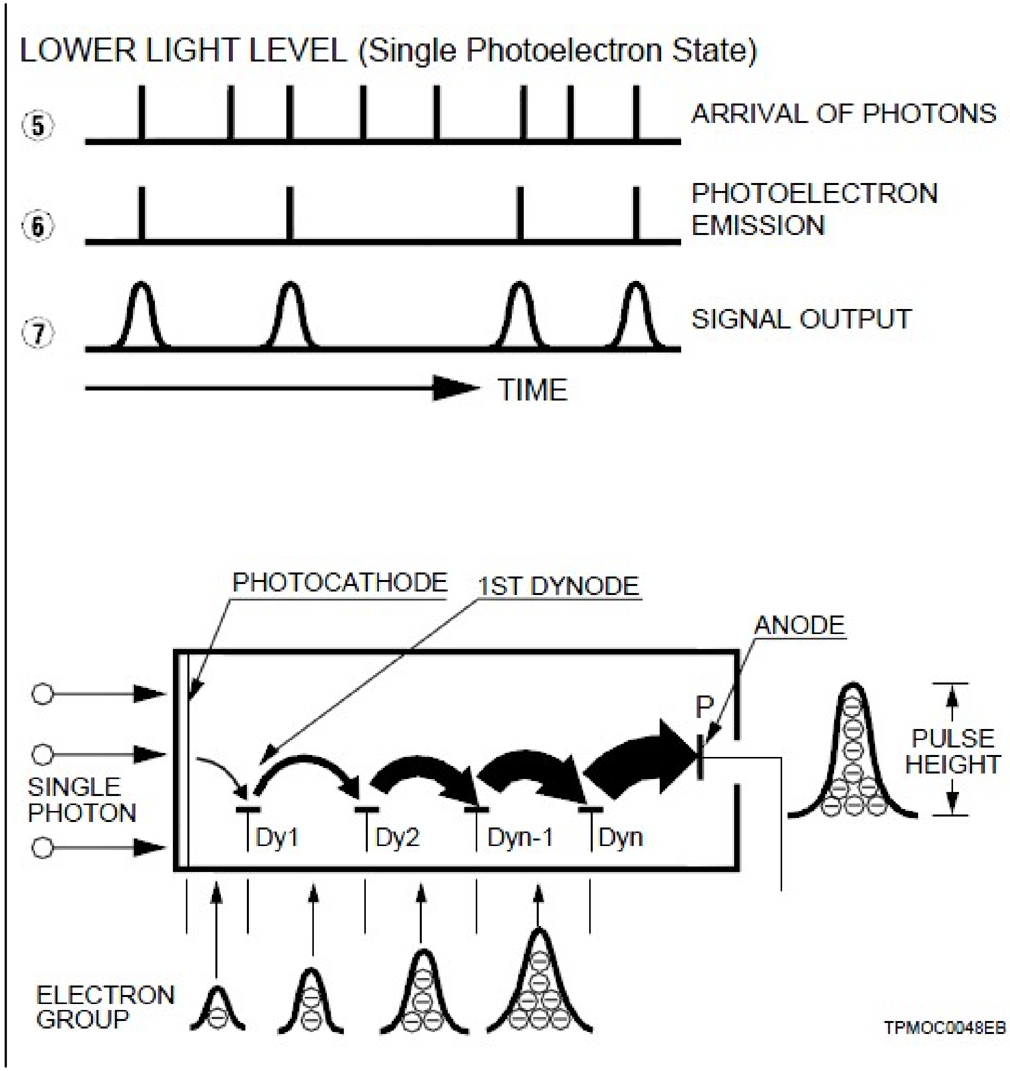




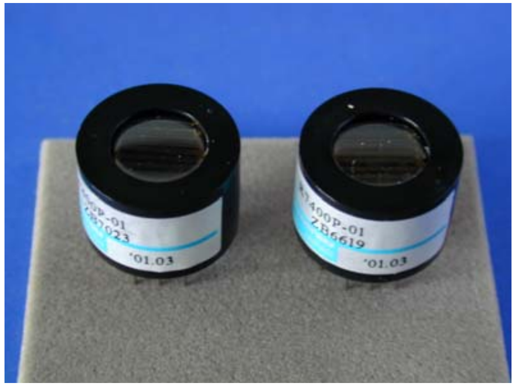
III. QUANTUM DETECTORS (QD) – EXTRINSIC: Photo Multiplier Tube (PMT)

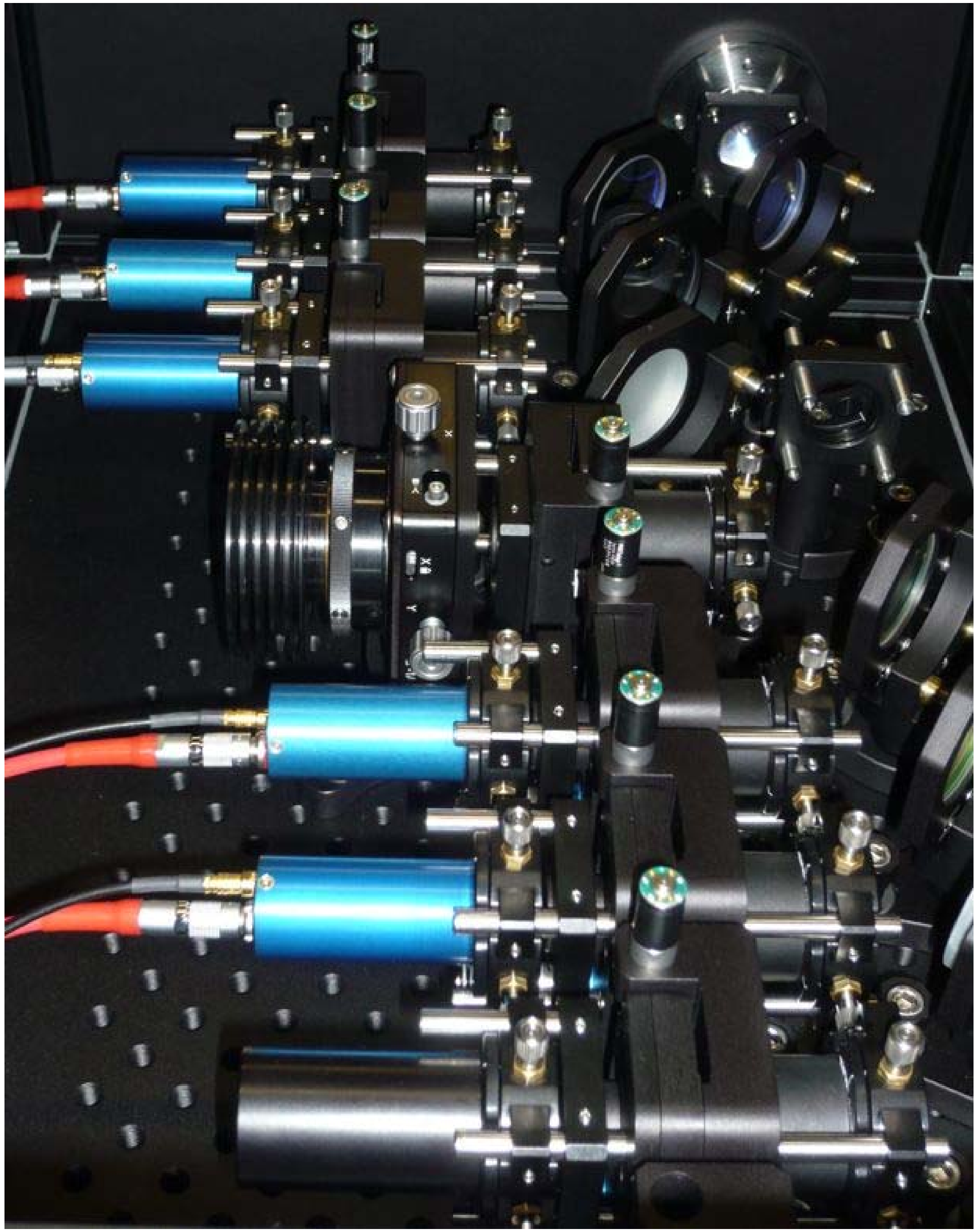
(Link) *Hamamatsu Application Note ("Photon Counting", AN1998)* ▷

- A class of vacuum tubes
- UV, VIS and NIR single-photon detection!
  - *Extremely sensitive*
- PMT structure
  - *Photocathode and dynodes*
- Top characteristics: Very high gain ($M=10^6$-10^8), low noise, high frequency response, large collection area



III: QD – EXTRINSIC:
Photo Multiplier Tube (PMT)





© Source: Wikimedia Commons (ancient PMTs, left column). Hamamatsu Photonics (today's PMTs, left column, bottom right). UPC-RSLAB (UV-VIS-NIR polychromator front end, right column)

IV. QUANTUM DETECTORS - INTRINSIC: InGaAs PIN photodiode (PV)

Voltage-current characteristics

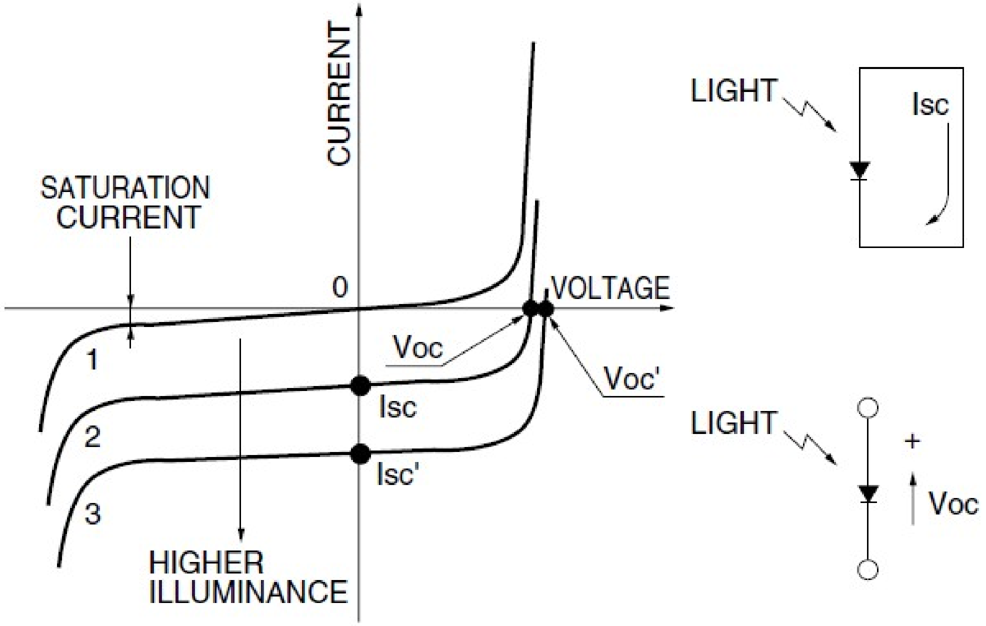
- (Darkness)

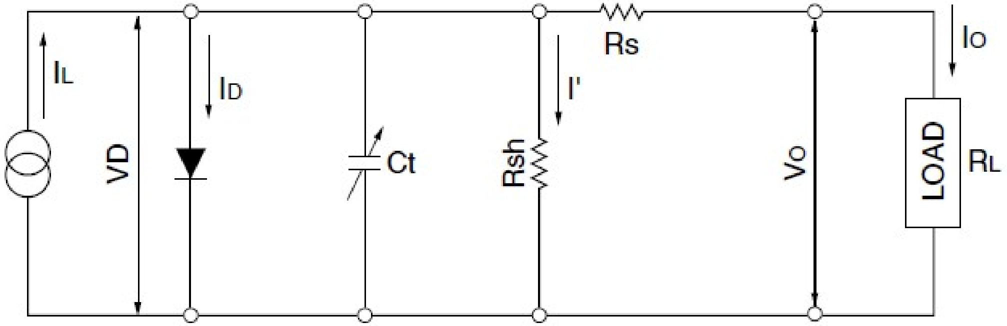
$$I_D = I_{sat}\left[\exp\left(qV_D/KT\right)-1\right]$$

- (Illuminated)

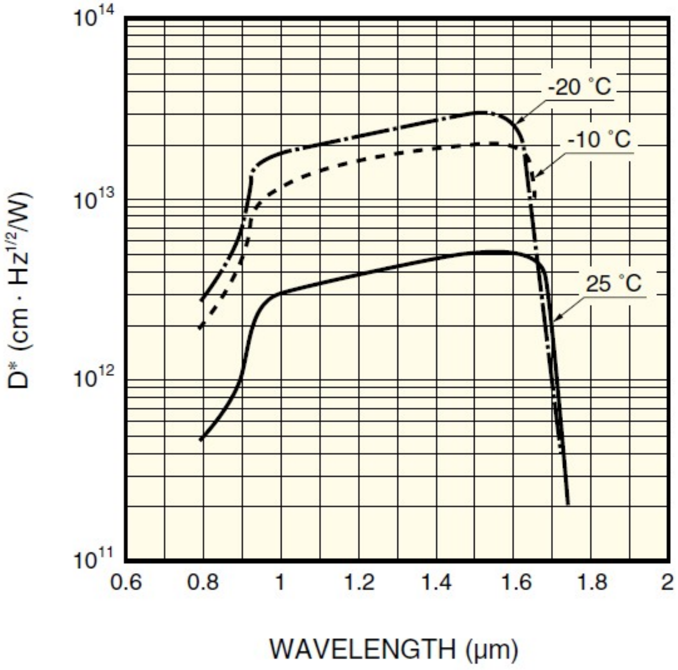
$$I = I_D - I_L, \quad I_L = R_i P$$

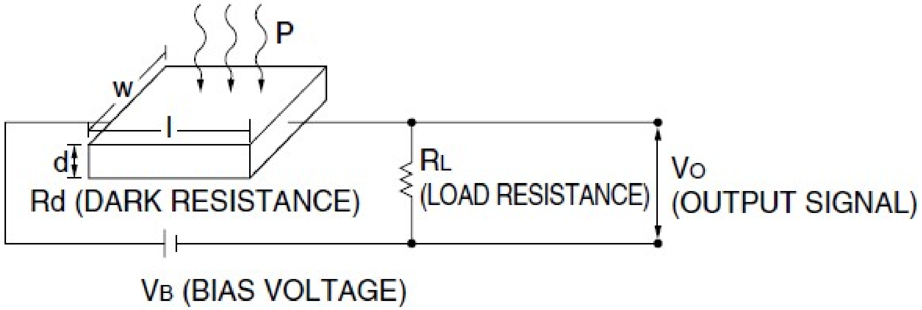
- (Illuminated) When both terminals of the photodiode are left open, a forward voltage V_{op} appears
- (Illuminated) When both terminals are shorted, a current I_{sc} flows in the reverse direction
- PC mode also possible (reverse bias applied)

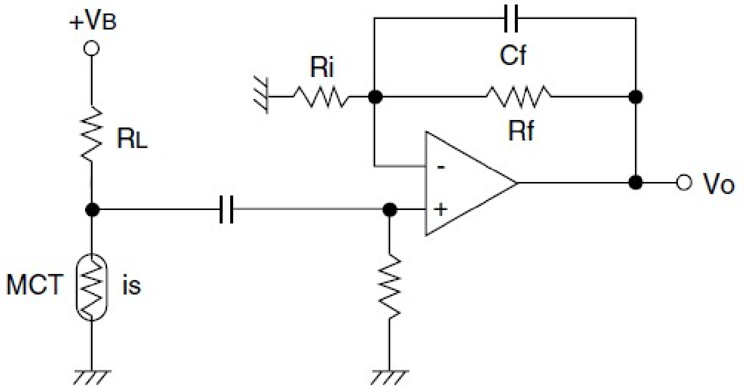




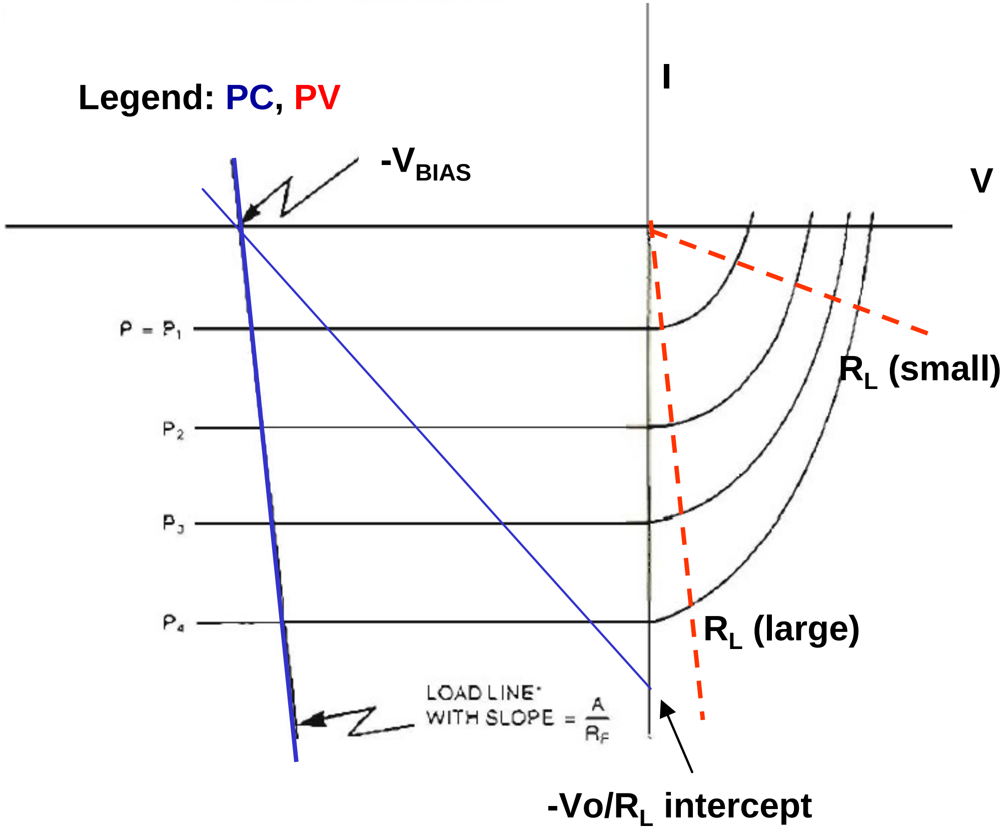
Photovoltaic (PV) vs. Photoconductive (PC) modes for PIN photodiodes







$$V_o = -\, i_s \cdot R_d \cdot \left(1 + \frac{R_f}{R_i}\right) \quad \left(\begin{array}{l} i_s\text{: SIGNAL CURRENT} \\ R_d\text{: DARK RESISTANCE} \end{array}\right)$$

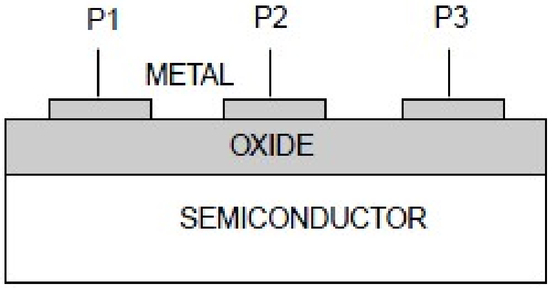


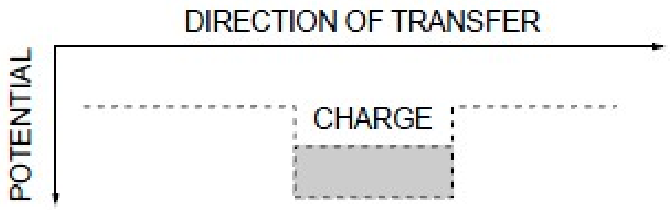
IV. QD – INTRINSIC: InGaAs CCD arrays

CCD (*Charge-Coupled Device;* Boyle-Smith, AT&T Lab., 1970)

Charge that is stored in one area of the CCD is transferred (coupled) to an adjacent area.

- *Charge-storage areas are referred to as "potential wells"*
- *Based upon a MOS (Metal Oxide Semiconductor) capacitor (Fig.)*
- *Gate electrodes (P1, P2, P3)*
- *Pixels are groups of gate electrodes*
- *The CCD is comparable to an "analog" shift register*

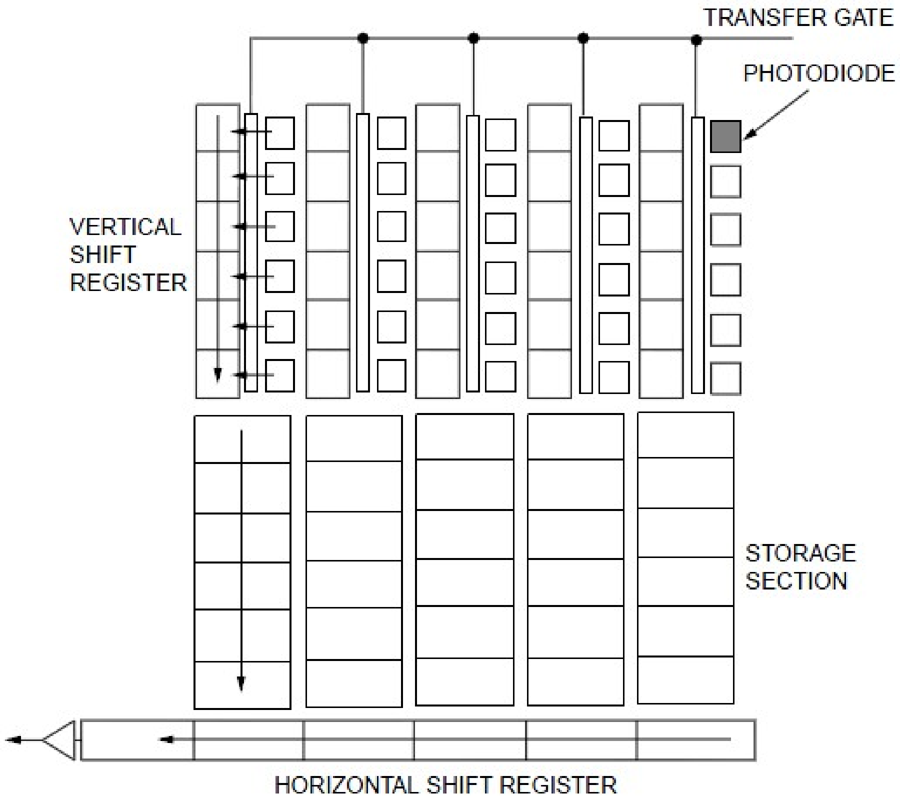


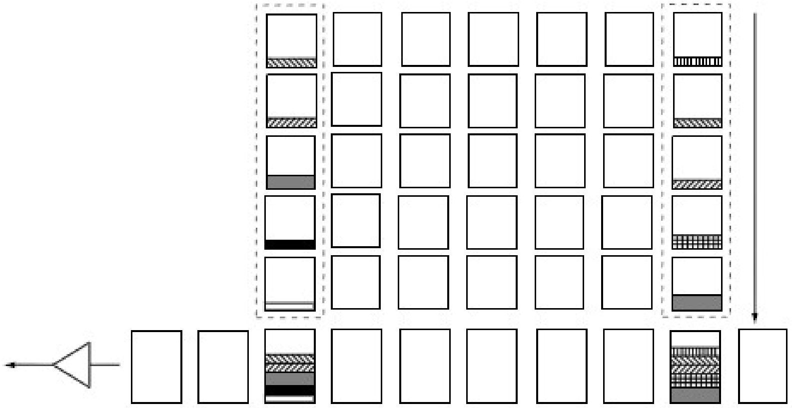


- When light comes through transparent electrode into the CCD semiconductor, *photoelectric conversion generates a signal charge that is collected into the potential well beneath the electrode.*

IV. QD – INTRINSIC: InGaAs CCD arrays

- H/V registers
  - *The vertical register is series of photosensitive columns (64, 128 or 256 pixels, etc.) which transports charge to the horizontal register.*
  - *The horizontal register transports charge to an (on-chip) charge-to-voltage amplifier.*
  - *Two sections: Photosensitive section and the storage section (the latter can be removed)*
- BINNING of signal charge
  - *Line and pixel binning are synonyms or charge accumulation (i.e., integration = summation) in potential wells.*





IV. QD – INTRINSIC: InGaAs CCD arrays

Characteristics

1. *Node sensitivity:* Charge-to-voltage conversion gain,

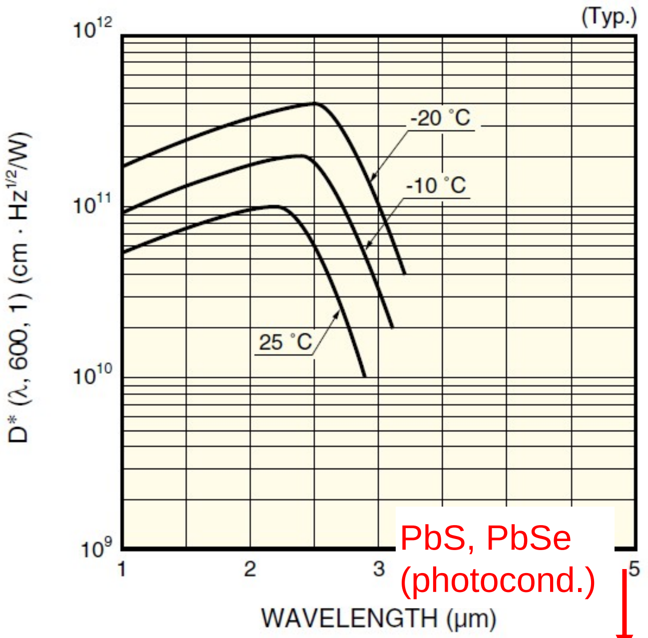
$$S_v = q\frac{\Delta V_{out}}{C_{node}} \quad \left[\frac{V}{e^-}\right]; \quad with\ C_{node} = 44fF, S_v = 2.0\,\mu V/e^-$$

2. *Spectral response:* Determined by the wafer/sensor structure (VIS-NIR)
3. *Photo-Response Non-Uniformity* (PRNU): Spatial variations in the QE.
4. *Full-well capacity:* Saturation charge for a well.
5. *Charge transfer efficiency* (“bucket brigade fashion”): Typ. $1\text{-}10^{-5}$.
6. *Dark current:* Expressed as A/cm^2 or [e-]/pixel/s
7. *Noise:*
   - Fixed pattern noise (spatial variation in photo-response between neighbouring pixels)
   - Usual noise sources: Photo-induced shot noise, dark-shot noise, and thermal noise.
   - Thermal noise is associated to MOSFET “readout” noise

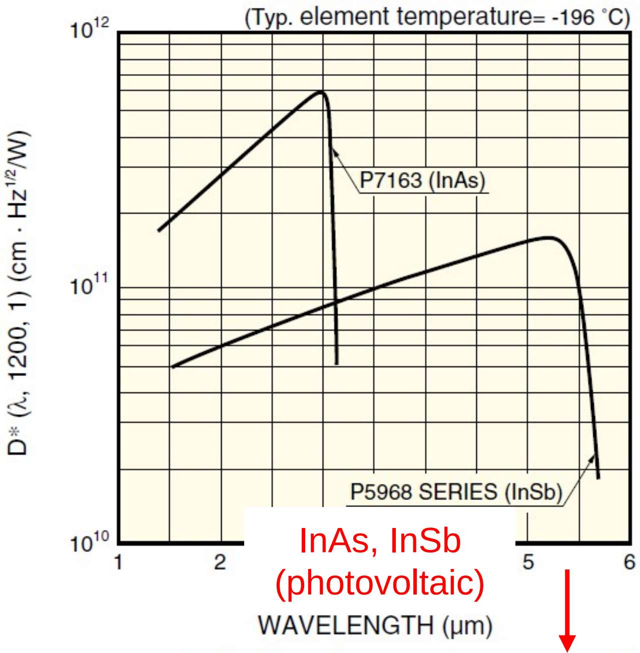
IV. QD – Intrinsic Families

FAMILIES: InGaAs (PV) // PbS, PbSe (PC) // InAs, InSb (PV) // MCT, InSb (PC)

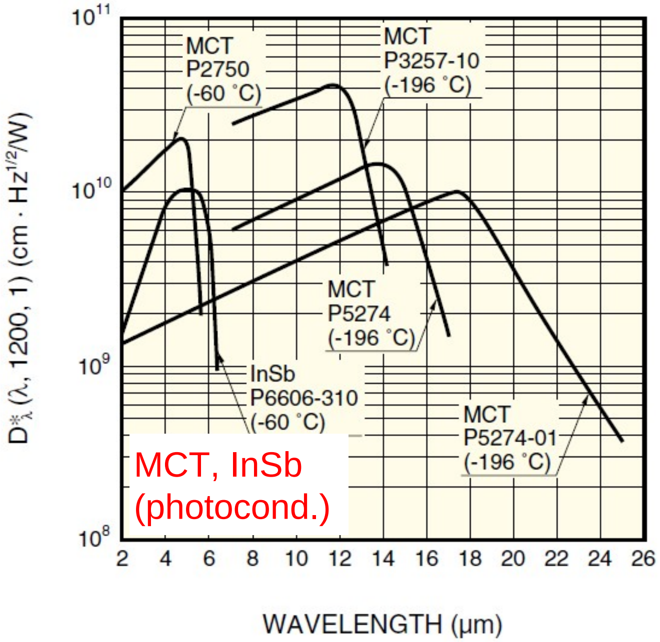
Follow ORSP_IR_detectors_summary_v1.pdf ▷



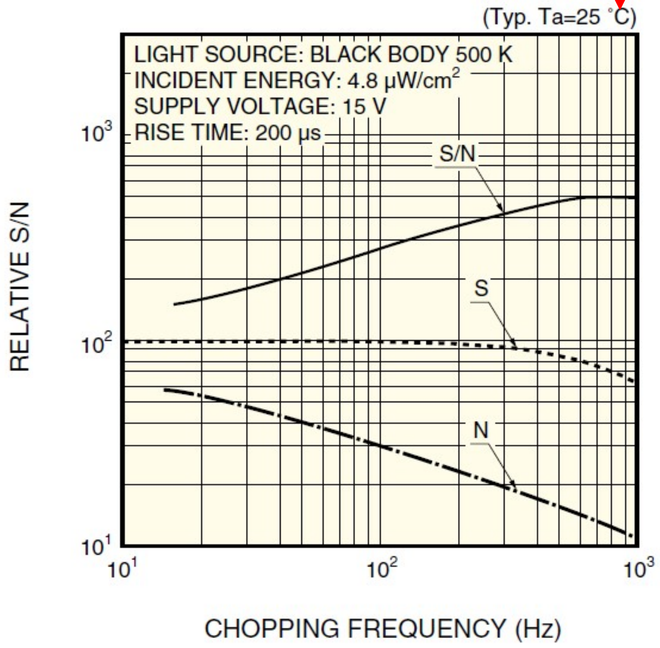
PbS, PbSe (photocond.)

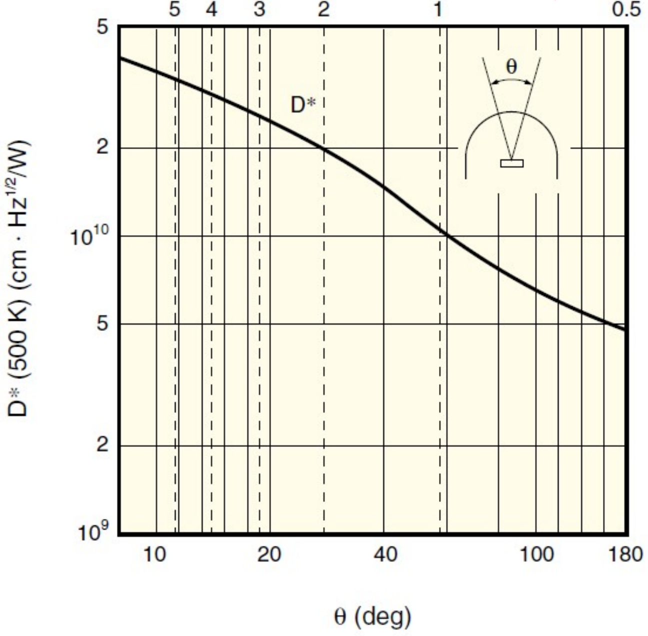


InAs, InSb (photovoltaic)



MCT, InSb (photocond.)





5.3 Detector figures of merit

RESPONSIVITY (or Photo Sensitivity), R

Wavelength dependent,

$$R(\lambda)=\frac{dS}{d\Phi(\lambda)}\quad\left[\frac{V\ or\ A}{W}\right]$$

Effective responsivity,

$$R=\frac{\int_0^\infty R(\lambda)\Phi(\lambda)d\lambda}{\int_0^\infty \Phi(\lambda)d\lambda}\quad\left[\frac{V\ or\ A}{W}\right]$$

Notation:

- R_{io} *[A/W] (intrinsic current resp.)*
- R_i *[A/W] (current responsivity)*
- R_v *[V/W] (voltage responsivity)*

QUANTUM-TYPE DETECTORS

Intrinsic responsivity (PIN, APD, PMT)

$$\Phi[W]\rightarrow\Phi[W]\frac{1}{\frac{hc}{\lambda}}\left[\frac{\frac{phot}{s}}{\frac{J}{s}}\right]\eta\left[\frac{e^-}{phot}\right]q\left[\frac{C}{e^-}\right]=\Phi\frac{\eta q\lambda}{hc}[A];\qquad R_{io}=\frac{\eta q\lambda}{hc}\quad\left[\frac{A}{W}\right]$$

- Therefore, $R_i=R_{io}M\,;\quad M=1(PIN),\quad M>>1(APD);\quad R_v=R_iG_T,\quad G_T\left[\frac{V}{A}\right]$

5.3 Detector figures of merit

SIGNAL, S

- As a rhythm: [V], [A] or [e^-/s]
- Over an integration (or "binning") time, τ_{int}, [counts] (1 [e^-] is 1 [count])

NOISE sources

Shot noise:

- Signal-shot photo-induced ($\sigma_{sh,s}$), dark noise ($\sigma_{sh,d}$), *background* ($\sigma_{sh,back}$)
  - *POISSON statistics (mean=variance)*

Thermal (Johnson) noise (σ_{th}):

- E.g., preamplifier, load/shunt resistor

Important to distinguish between the "detector" side and "system-scene" side

NOISE, N

- [V], [A], [e^-/s], [e^-]
- σ_{tot} (noise density) [V·Hz$^{-1/2}$], [A·Hz$^{-1/2}$]
- Noise eq. Bandwidth, B [Hz]

$$S = \int R(\lambda)\Phi(\lambda)d\lambda \quad [V \text{ or } A]$$

$$S = \Phi\,\tau_{int}\,\eta \quad \left[\frac{phot}{s}\right][s]\left[\frac{e^-}{phot}\right] = [e^-]$$

System Noise example computation:

(1) As a rhythm (rms current, voltage)

$$\sigma_{sh,x} = \sqrt{2qI_x} \quad \left[\frac{A}{\sqrt{Hz}}\right]$$

$$\sigma_{tot} = \left(\sigma_{sh,s}^2 + \underbrace{\sigma_{sh,d}^2 + \sigma_{sh,back}^2 + \sigma_{th}^2}_{non\text{-}scene}\right)^{\frac{1}{2}} \quad \left[\frac{A}{\sqrt{Hz}}\right]$$

$$N = \sigma_{tot}\sqrt{B} \quad [A]$$

(2) Over an integration time [e^-]

$$N_{sh,s} = \sqrt{S} \quad [e^-],$$

$$N = \left(N_{sh,s}^2 + N_{non-scene}^2\right)^{\frac{1}{2}} \quad [e^-]$$

5.3 Detector figures of merit

SNR (Signal to Noise Ratio)

$$SNR = \frac{S}{N} \quad [\;]$$

NEP (Noise Equivalent Power)

Convenience to express the noise in radiometric input units [W] rather than in output signal units ([V] or [A]).

$$NEP(\lambda) = \frac{N}{R(\lambda)} \quad \left[\frac{V \text{ or } A}{\frac{V}{W} \text{ or } \frac{A}{W}}\right] = [W] \quad or \left[\frac{W}{\sqrt{Hz}}\right]$$

SPECIFIC DETECTIVITY (“D star”), D*

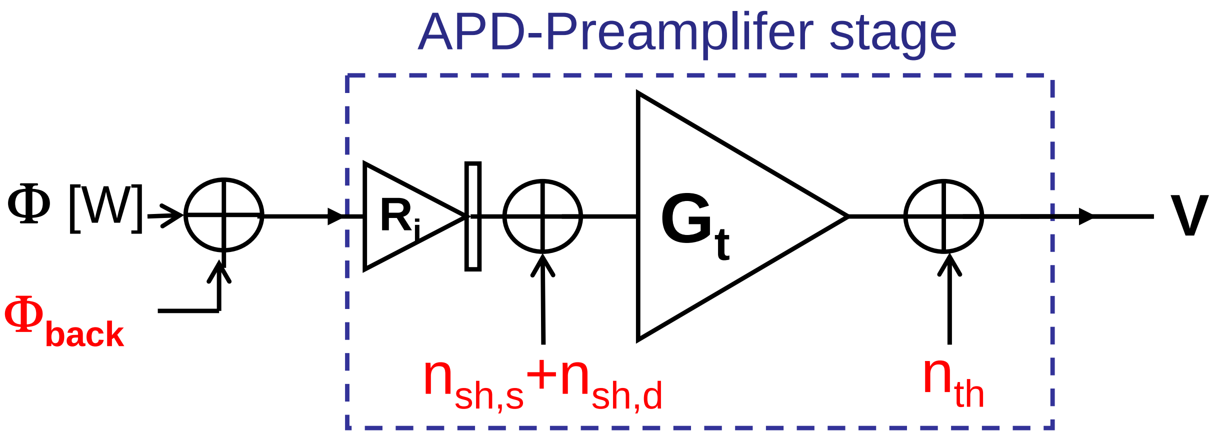
- Spectral Detectivity, D(λ)

$$D(\lambda) = \frac{1}{NEP(\lambda)} \quad \left[W^{-1}\right]$$

- D* is the spectral detectivity corrected by the area-bandwidth product of the detector
    - *The better the detector the higher D**
    - *A_d (detector area), B (bandwidth)*

$$D^*(\lambda) = \frac{\sqrt{A_d B}}{NEP(\lambda)} \quad \left[W^{-1} cm \cdot Hz^{1/2}\right]$$

Case example: SNR and NEP computation for a NIR reception channel using and APD-preamplifier combination



Φ [W] Scene flux

Φ_{back} [W] Background related flux

NOISE SOURCES

$$\sigma_V^2 = \sigma_{sh,s}^2 + \underbrace{\sigma_{sh,d}^2 + \sigma_{sh,back}^2 + \sigma_{th}^2}_{non-scene\,(BLIP)} \quad \left[\frac{V^2}{Hz}\right]$$

$$\sigma_{sh,x}^2 = 2qG_T^2 FM^2 R_{io}\Phi_x, \quad x = "s", "back"$$

photo-induced shot noise

$$\sigma_{sh,d}^2 = 2qG_T^2\left(I_{ds} + FM^2 I_{db}\right)$$

dark-shot noise

$$\sigma_{th}^2 = \sigma_{th,i}^2 G_T^2$$

thermal noise

Case example (CONT.): SNR and NEP computation for a NIR reception channel using and APD-preamplifier combination

$$SNR_V = \frac{S}{N} = \frac{useful\ voltage}{noise\ voltage} = \frac{R_V \Phi}{\sigma_V B^{1/2}}$$

APD PARAMETERS

- Surface + bulk dark current (I_{ds}, I_{db})
- Multiplication gain, M [no units]
- Excess-noise factor, $F \cong M^x$
- NEP_{APD} (manufacturer spec.)

$$\boxed{\begin{aligned} NEP_{APD} &= \frac{\sigma_{sh,d}^{APD}\sqrt{B}}{R_i^{APD}} = \\ &= \frac{\left[2q\left(I_{ds} + FM^2 I_{db}\right)B\right]^{1/2}}{\frac{\eta q \lambda}{hc} M} \qquad [W] \end{aligned}}$$

PREAMP. PARAMETERS

- Transimpedance gain, G_T [V/A]
- Thermal noise (equivalent input-referred noise density), $\sigma_{th,i}$ [$A \cdot Hz^{-1/2}$]

SYSTEM NEP ("sensor NEP")

Requires a noise reference: E.g., Noise associated with viewing a 300K blackbody or a 5% reflector at the TOA.

$$NEP = \frac{\sigma_v \sqrt{B}}{R_v} \qquad [W]$$

5.4 Radiometer relevant parameters (I): Radiometric Sensitivity

Specify SYSTEM (i.e., “sensor”) performance characteristics

NOISE-EQUIVALENT RADIANCE

Change in radiance on the front of the sensor required to produce a change in the sensor output equal to the sensor’s noise level

- Note: NEP is the “system” NEP

$$NER(\lambda)=\frac{NEP(\lambda)}{A_d}G\# \quad \left[\frac{W}{m^2 sr}\right]$$

NOISE-EQ. REFLECTIVITY

ΔL/$\Delta\rho$: Rate of change in radiance at the sensor corresponding to a unit change in reflectance

$$NE\Delta\rho(\lambda)=NER(\lambda)\left(\frac{\Delta L}{\Delta\rho}\right)^{-1} \quad [\%]$$

NOISE-EQ. TEMPERATURE

$$NE\Delta T(\lambda)=NER(\lambda)\left(\frac{\Delta L}{\Delta T}\right)^{-1} \quad [K]$$

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