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Introduction to IR detectors

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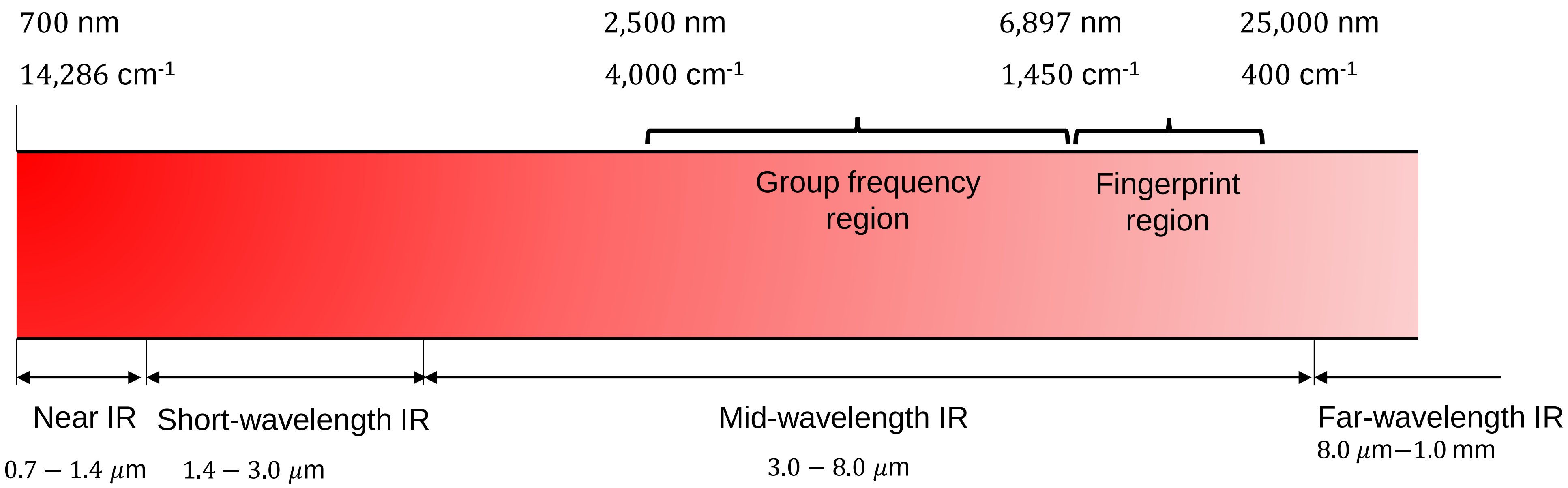
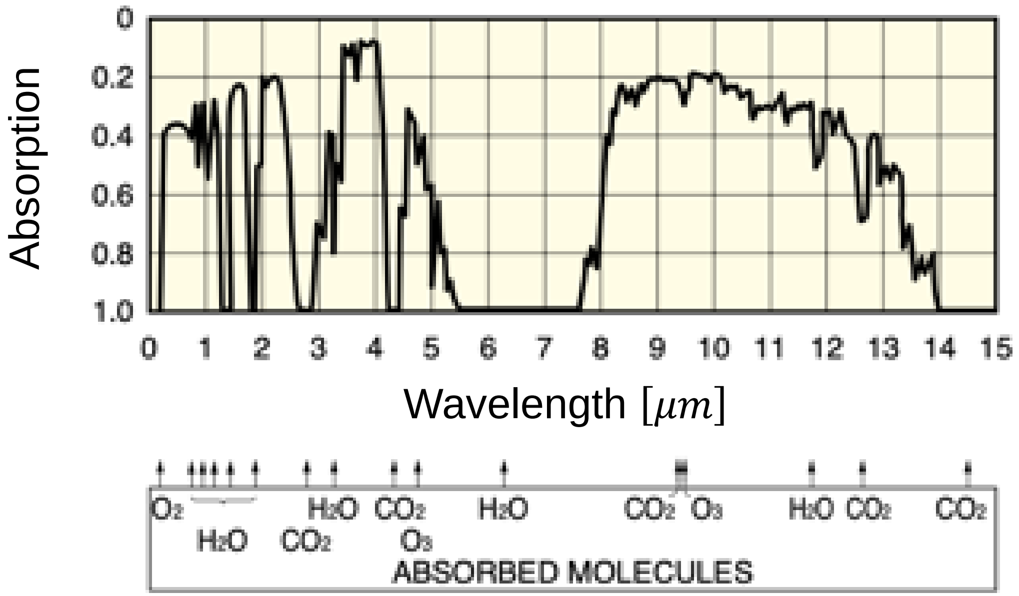
- Thermal detectors
- Photon detectors (brief overview)

Introduction

IR Electromagnetic spectrum

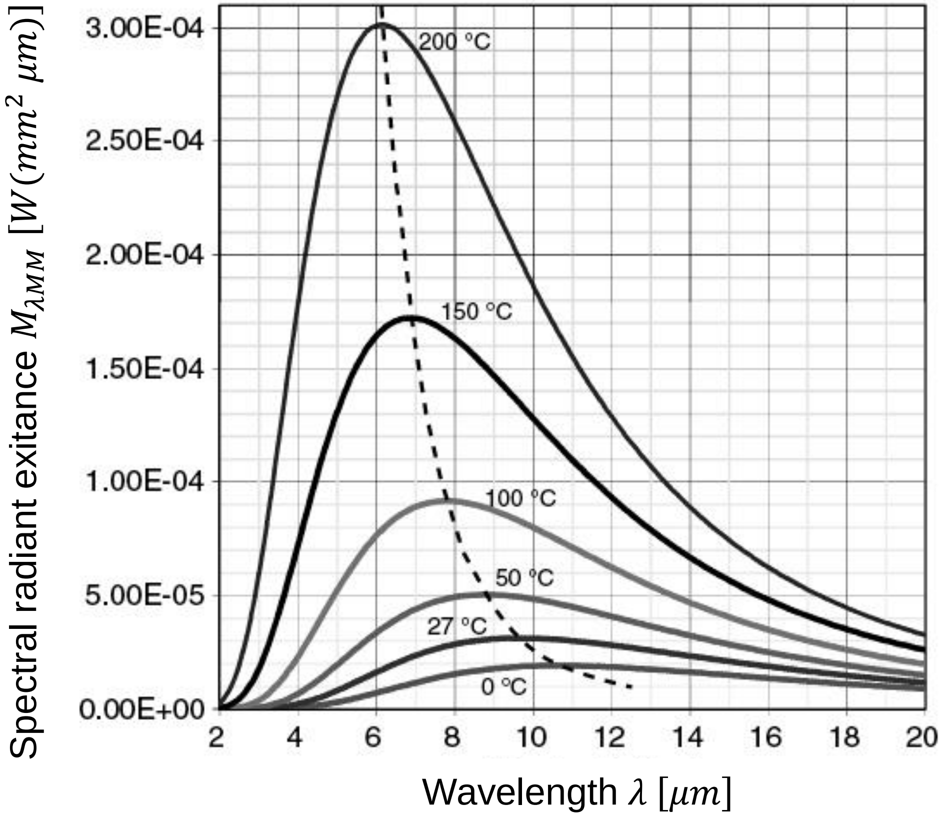


Atmospheric Absorption of IR



- Absorption and scattering affect the passage of IR through the Earth's atmosphere
- Two broadly defined atmospheric "windows" of relatively high transmittance (low absorption) are between 3 - 5 μm and 8 - 14 μm

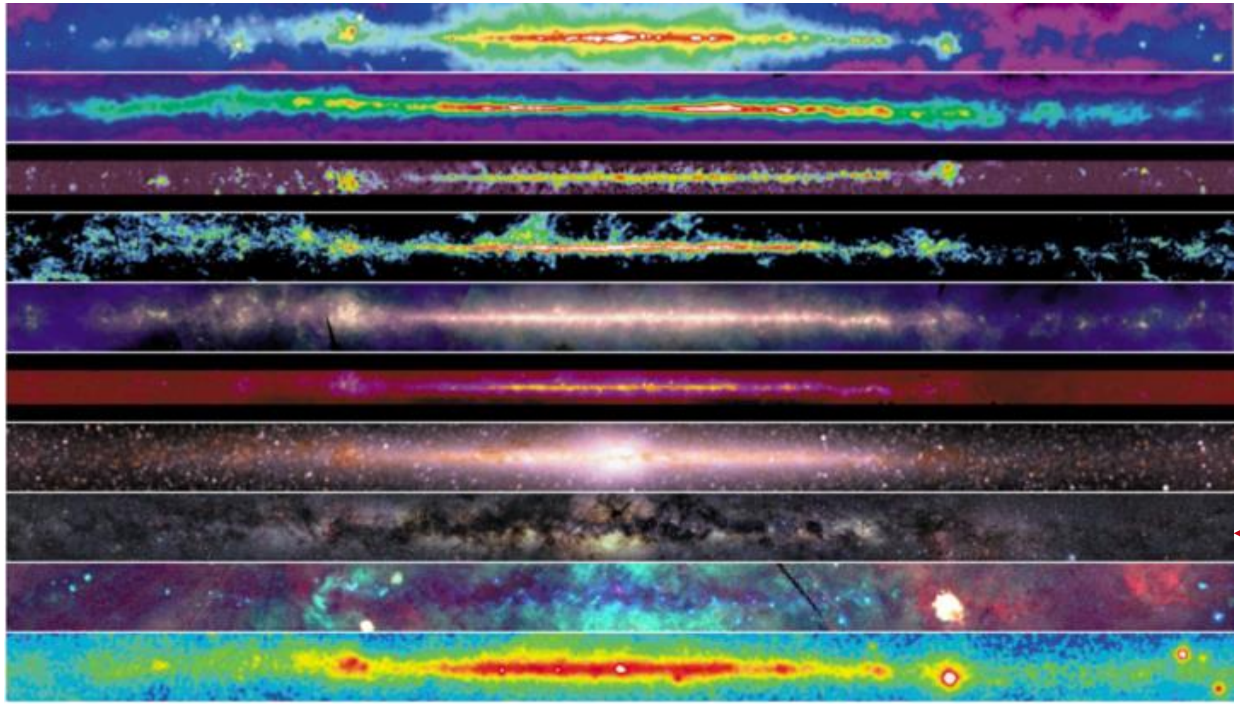
Black body



Peak emission at environmental temperatures is in the $8\ \mu m - 12\ \mu m$ range. This range is important in thermal imaging.

Why is IR important?

1. We can detect and study structures and processes that are effectively invisible in the optical range.



view of the Milky Way in various IR bands

view of the Milky Way in optical

Source: https://asd.gsfc.nasa.gov/archive/mwmw/mmw_sci.html

Why is IR important?

2. We can see and detect objects in the absence of visible light: thermal imaging.

Source: https://www.atncorp.com

Why is IR important?

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3. We can probe the human body.

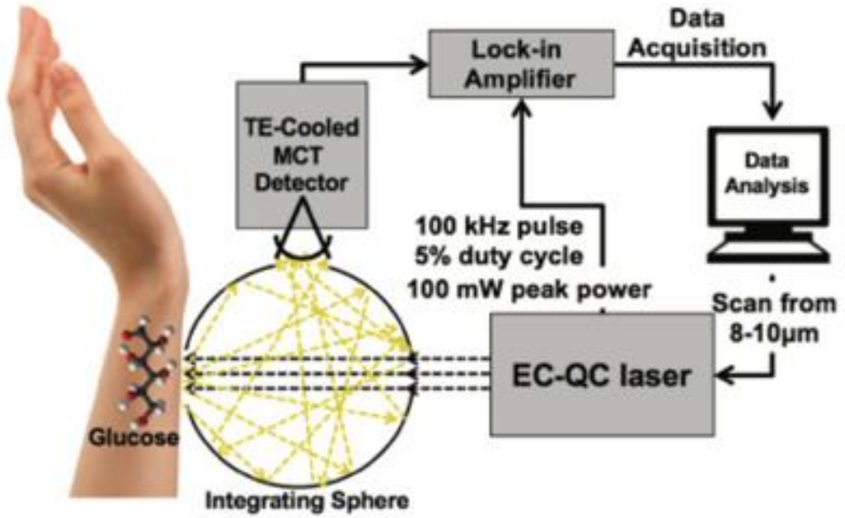
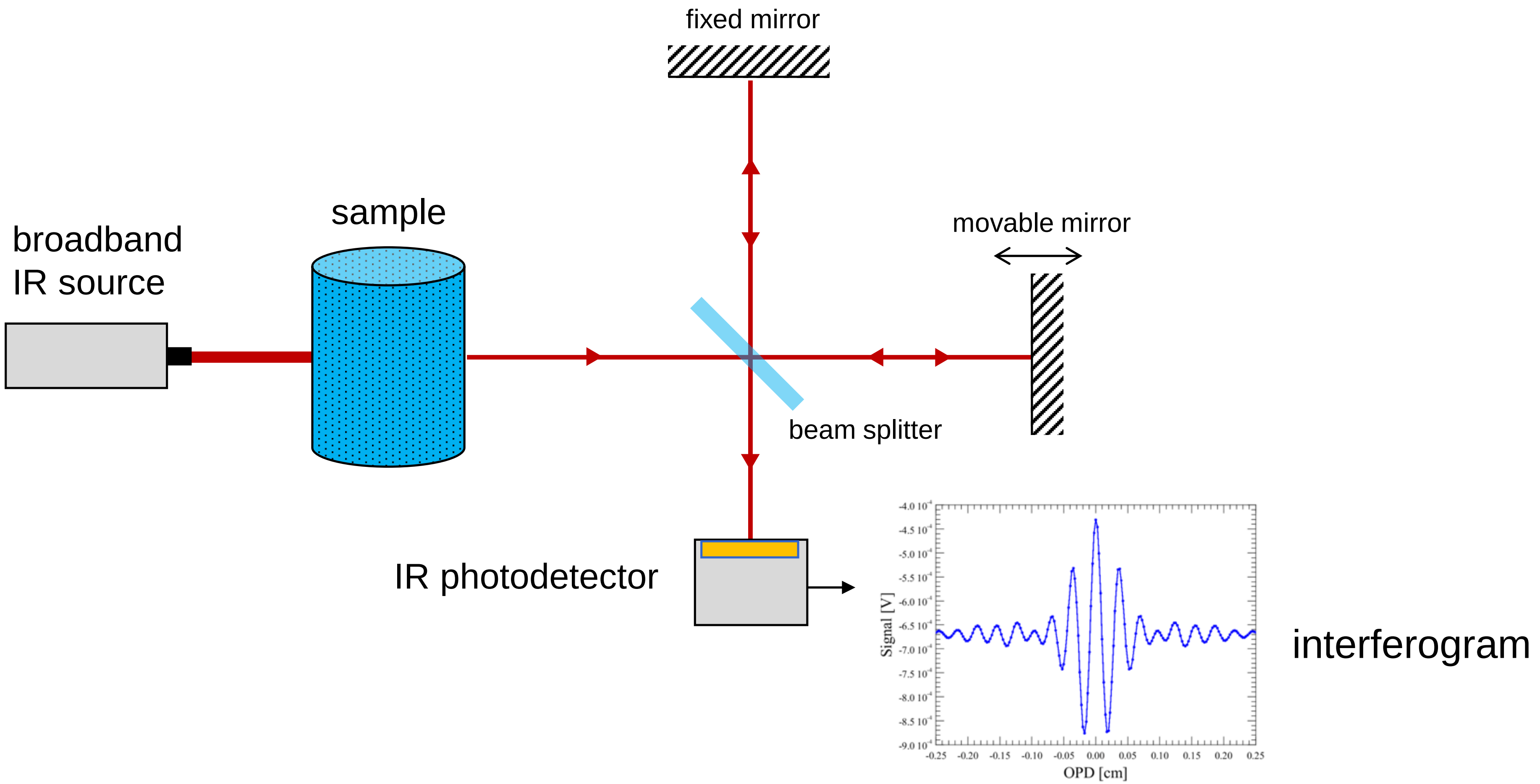


Fig. 7 Schematic of a noninvasive mid-infrared glucose sensor. Pulse-light (between 900 and 1200 cm^{-1}) is emitted from an EC-QC laser and the backscattered light from the skin is collected by a detector.[5]

Source: “Noninvasive blood glucose detection using a quantum cascade laser”, Rassel, S., Xu, C., Ban, D., *Analyst*, 2020,145, 2441-2456

Why is IR important?

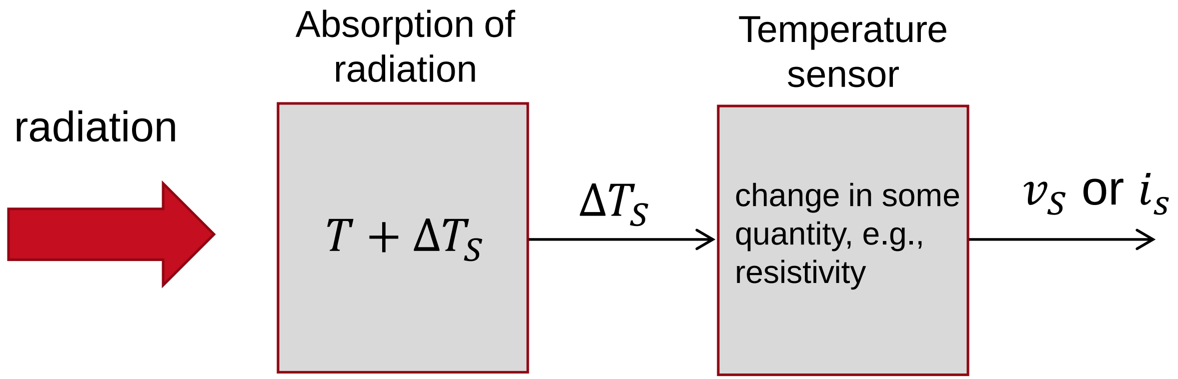
4. We can probe molecules: e.g., Fourier-transform infrared spectroscopy



IR detection and detectors

1. Detection of IR radiation is inherently more difficult than detection of visible light.
2. The challenge has spawned many innovative techniques and the development of materials.
3. IR detectors can be roughly divided into two classes: thermal and photonic.

Types of IR detectors: thermal sensors

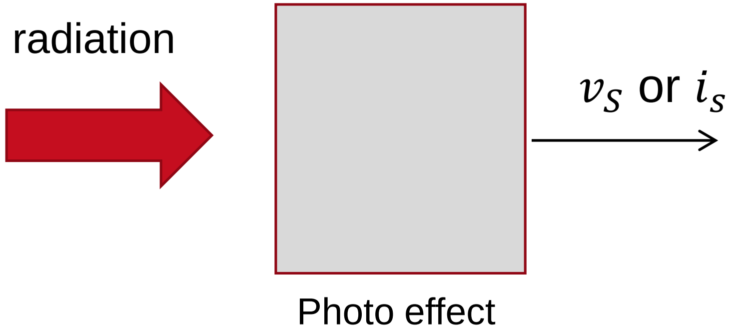


Thermal sensors experience a temperature change due to absorption of radiation. The change in temperature is converted to electrical signal.

Thermal Sensors

Sensor	What changes or what is measured?
Bolometer	Change in electrical conductivity
Thermopile	Voltage is generated at the junction of different materials
Pyroelectric	Change in electrical polarization

Types of IR detectors: photon sensors



In a photon detector, the interaction of photons with charge carriers in the detector lead directly to the formation of the electrical signal. A photodiode and avalanche photodiode are two well-known examples of photon detectors.

Absorption coefficients of select materials

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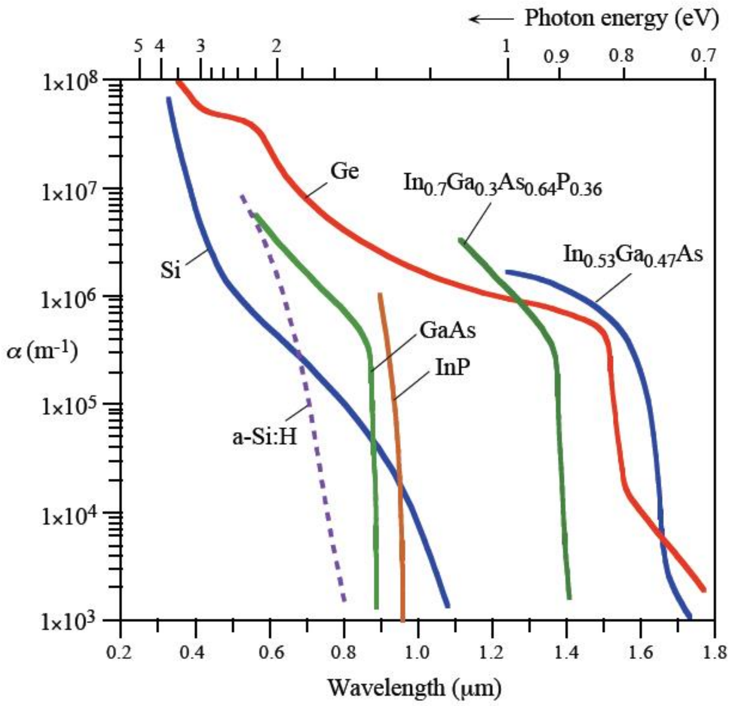

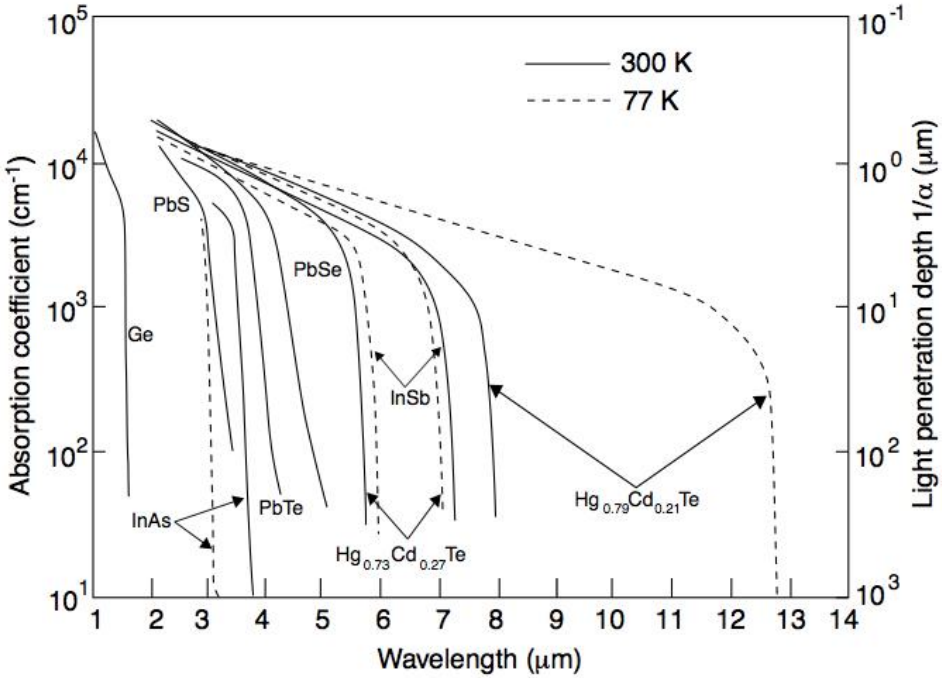

The choice of the of the material for the photon sensor will depend on the wavelength of the measured radiation.

Responsivity

$$R = \frac{i_S}{\Phi(\lambda)\Delta\lambda}$$ (nearly monochromatic)

R – Responsivity (A/W)

$\Phi(\lambda)$ – Spectral radiant incident power (W/m)

$\Phi(\lambda)\Delta\lambda$ – Incident power (W)

i_S – Output current (A)

Noise equivalent power, NEP

$$NEP = \frac{i_n}{R}$$

rms noise output

Noise equivalent power (NEP) is the incident power of the detector generating a signal output equal to the *rms* noise output. Alternatively, the NEP is the light level that produces a signal-to-noise ratio (S/N) of 1.

Detectivity and Specific Detectivity

$$D = \frac{1}{NEP}$$

(Detectivity)

$$D^* = D(A_d \Delta f)^{1/2} = \frac{(A_d \Delta f)^{1/2}}{NEP}$$

(Specific detectivity)

Comments on Specific Detectivity, D^*

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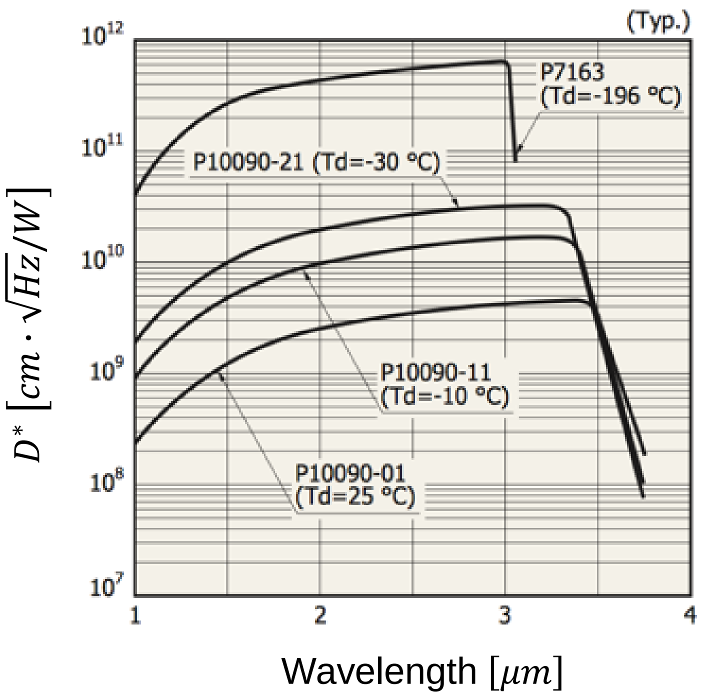
1. Specific detectivity is a figure of merit used to compare performance of photodetectors of the same class. It is defined as a reciprocal of the detector's NEP normalized to unit area and unit bandwidth.

2. The logic of the above equation: NEP is proportional to $\sqrt{i_d^2}$ but i_d is proportional to $\sqrt{A}\sqrt{\Delta f}$ (the first dependence is due to the fact that the dark current I_d is proportional to *the area* A), so NEP is proportional to $\sqrt{A}\sqrt{\Delta f}$. Therefore, multiplying the inverse of NEP by $\sqrt{A}\sqrt{\Delta f}$ removes the dependence on the area and bandwidth.

Comments on Specific Detectivity, D^*

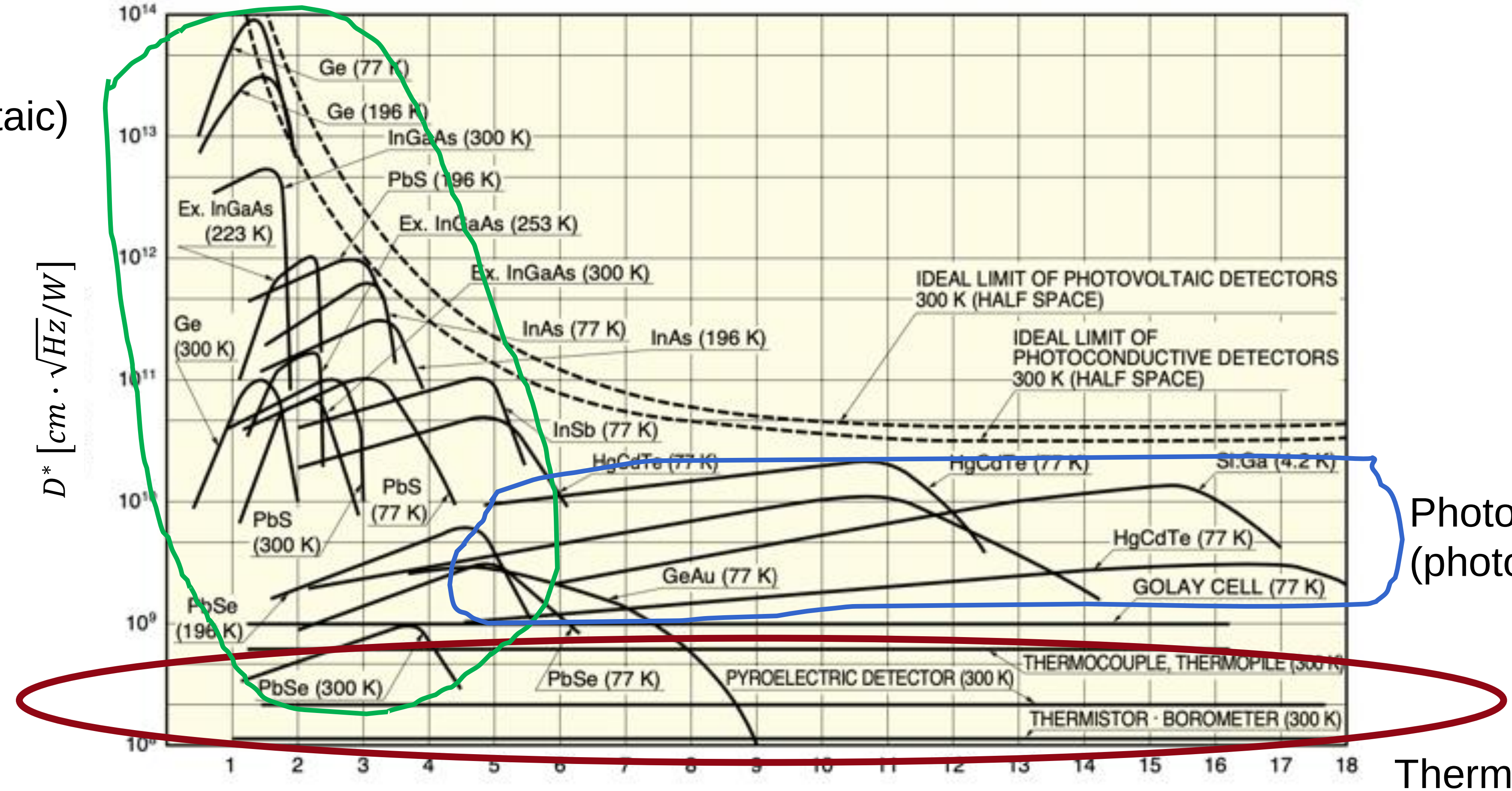
3. Specific detectivity can be a complicated function of wavelength, temperature, bias, and other parameters. There us no single equation for D^* for all of the detectors.
4. Specific detectivity is commonly given for IR detectors in the form of a plot as a function of wavelength.



Specific detectivity for different classes of detectors

Photonic
(photovoltaic)

$D^* \left[cm \cdot \sqrt{Hz}/W\right]$



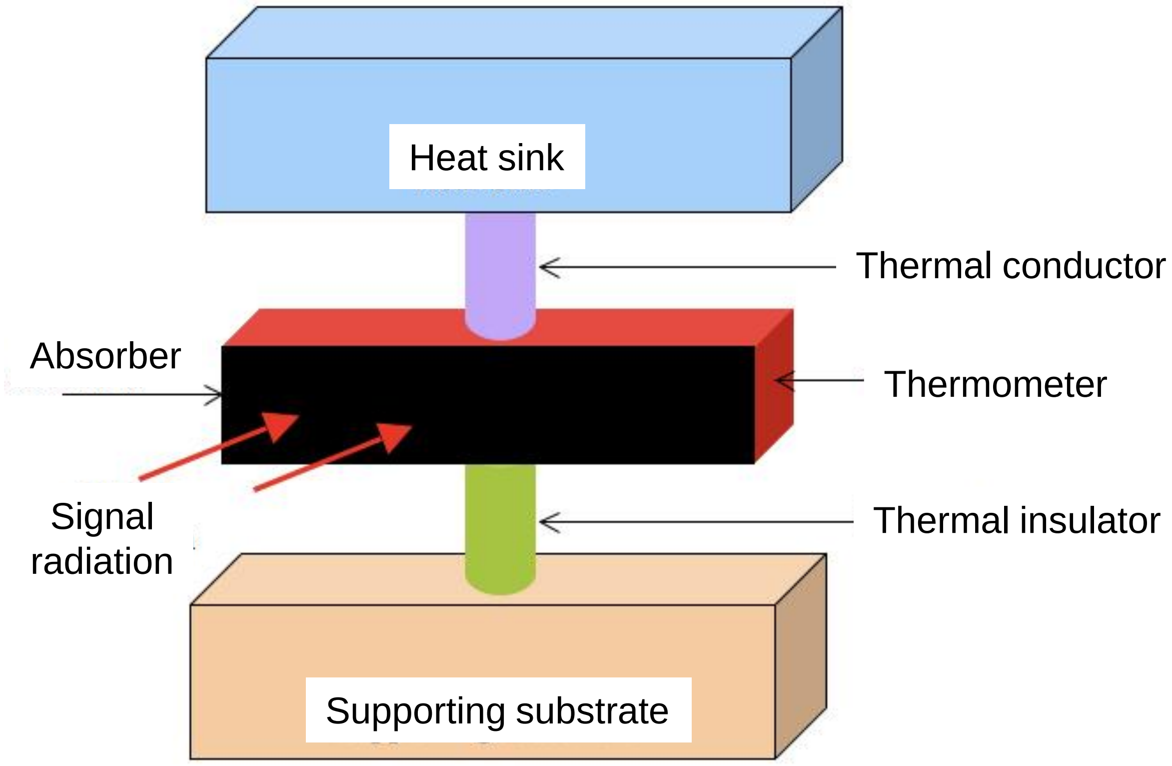
Photonic
(photoconductive)

Thermal detectors

Wavelength $[\mu m]$

Thermal detectors

Thermal Detectors: Principle



$$\Phi = \Phi_0 e^{i\omega t}$$ (Assumed form of radiant power)

$$\Delta T = \frac{\varepsilon \Phi_0}{\sqrt{G_{th}^2 + \omega^2 C_{th}^2}}$$ (Change in temperature due to incident radiant power)

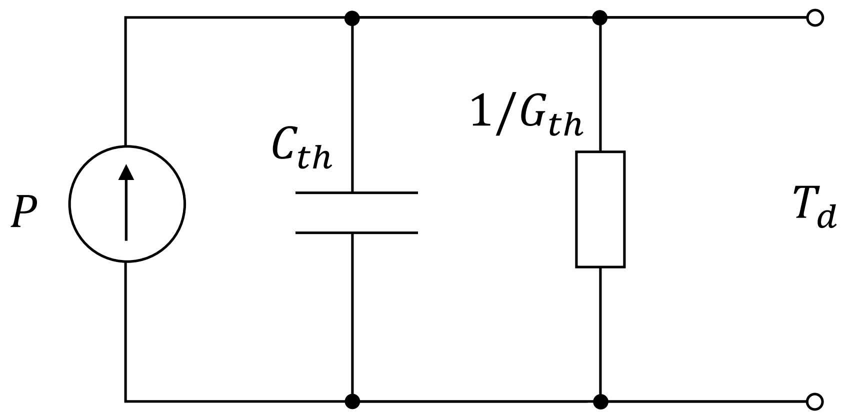
$$\tau_{th} = \frac{C_{th}}{G_{th}}$$ (Characteristic response time)

C_{th} – Heat capacity of the detector

G_{th} – Thermal conductance to the heat sink

Source: ”Infrared Detectors”, 2nd edition, Antoni Rogalski

Thermal detector: equivalent thermal circuit



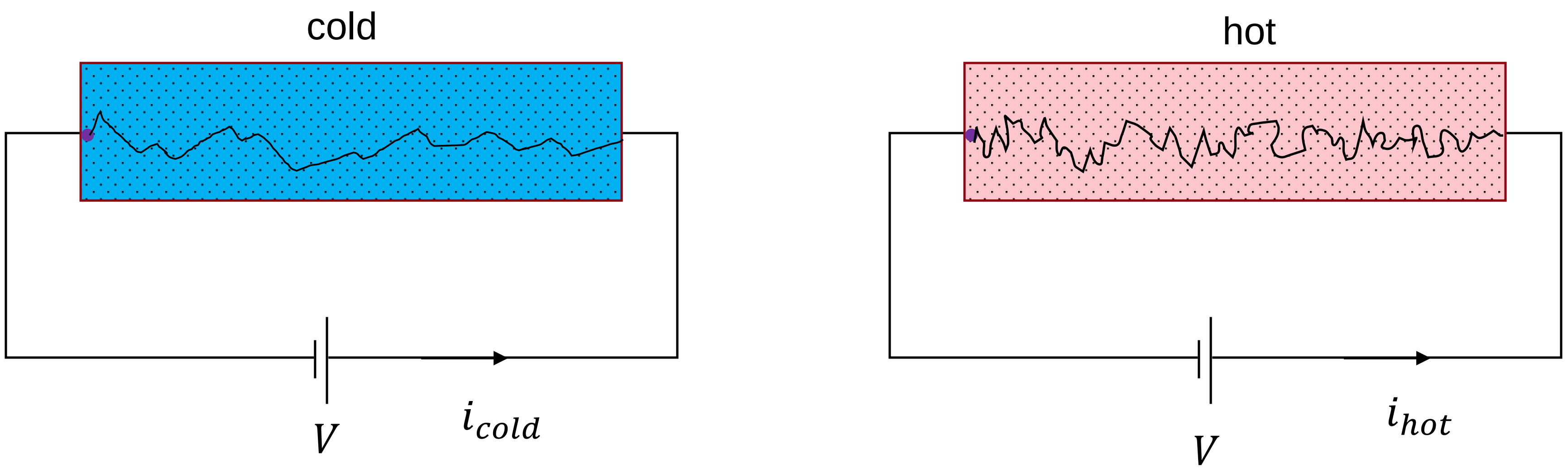
P – dissipated power (heat)

T_d – temperature increase of the detector

$\frac{1}{G_{th}}$ – thermal resistance

Thermal detectors: bolometer (thermistor)

Bolometer: thermo-resistance in a metal



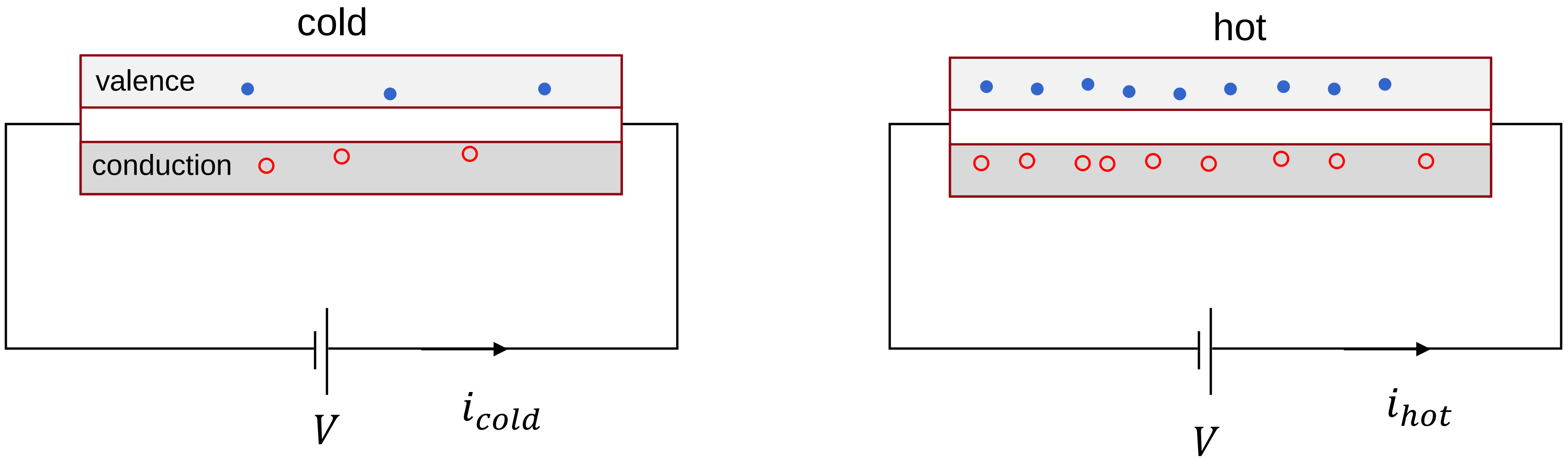
$i_{cold} > i_{hot}$

$\alpha \equiv \frac{1}{R}\frac{dR}{dT}$ (coefficient of resistivity)

$$\rho(T) = \rho(T_0)(1 + \alpha\Delta T)$$

for metals $\alpha > 0$

Bolometer: thermo-resistance in a semiconductor

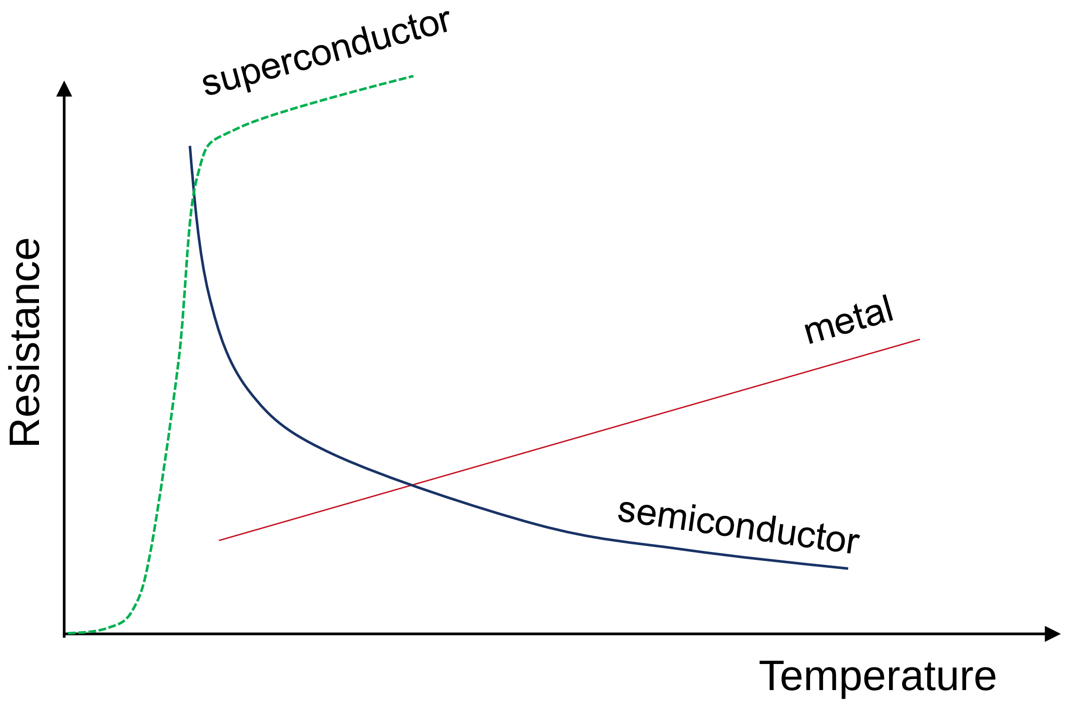


$$i_{cold} < i_{hot}$$

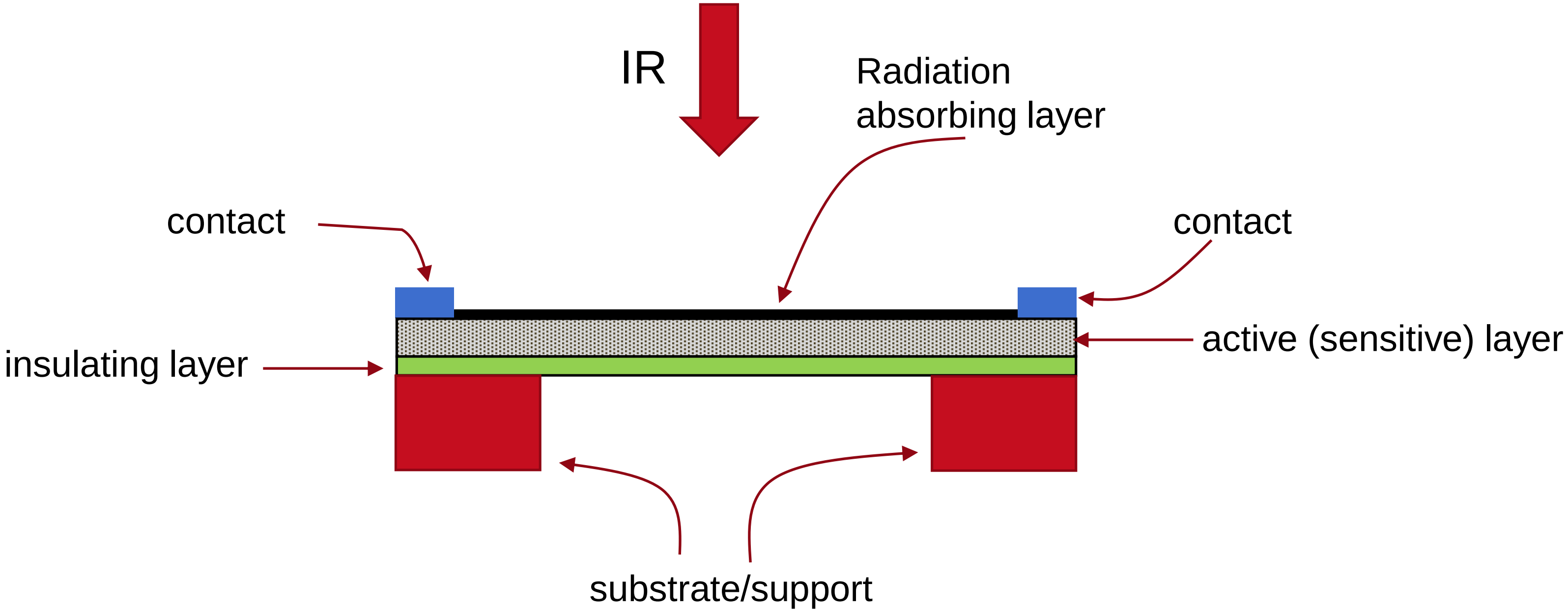
$$\rho \propto e^{\frac{2kT}{E_g}}$$

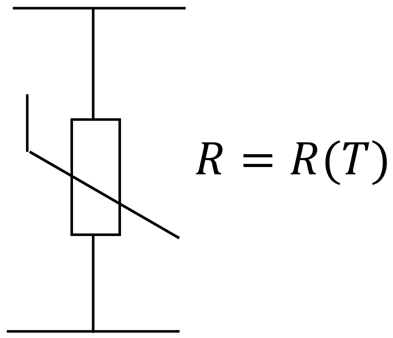
In a semiconductor, resistivity increases exponentially with temperature.

Resistance versus temperature for different materials



Bolometer

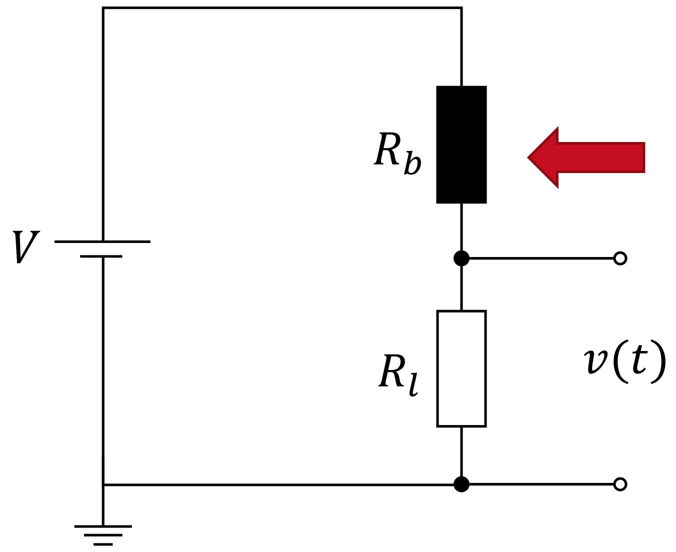




equivalent circuit

Cross-section of a bolometer (single cell)

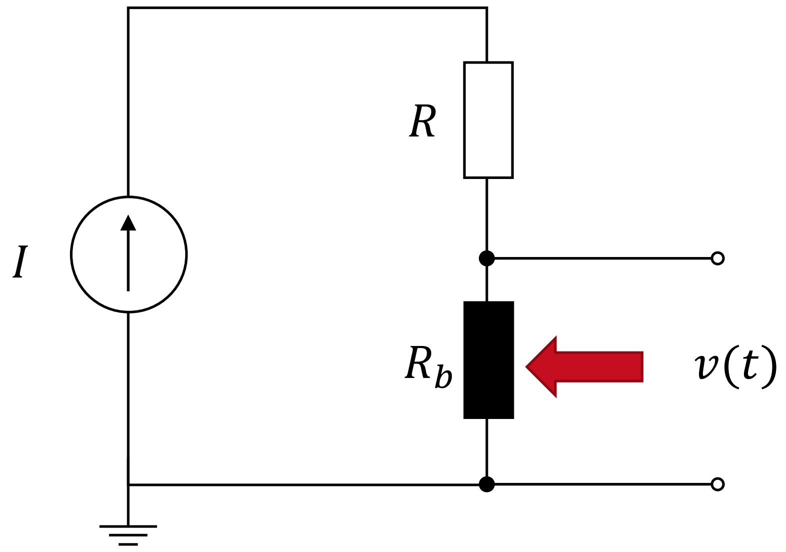
Bolometer: detection circuit



$$v(t) = V\frac{R_l}{R_l + R_b}$$

Concern: since the current is not constant, Joule heating in the bolometer is not constant either.

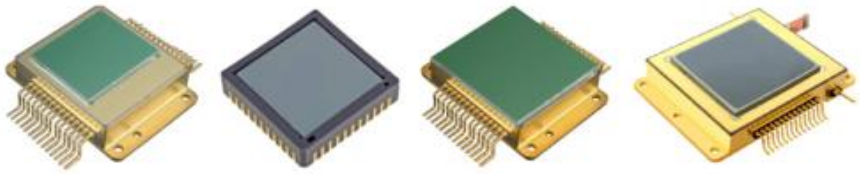
Bolometer: detection circuit



$$v(t) = IR_b$$

Concern: Joule's heating goes up as one increases I to boost the value of $v(t)$.

Imaging with bolometer(s)



Microbolometer arrays

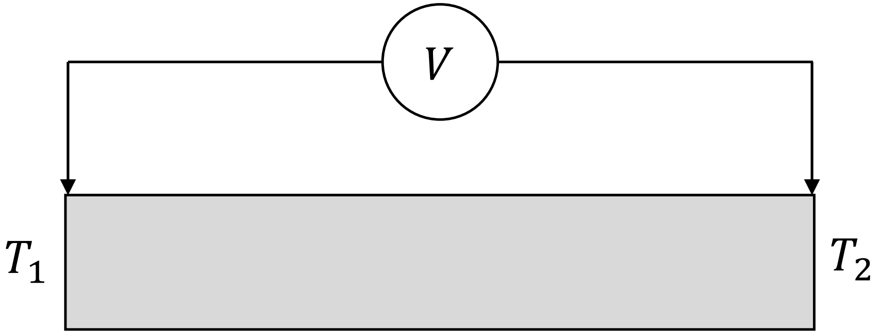
Source: “MEASUREMENT OF THERMAL BEHAVIOR OF DETECTOR ARRAY SURFACE WITH THE USE OF MICROSCOPIC THERMAL CAMERA”, Grzegorz Bieszczad, Mariusz Kastek, Metrol. Meas. Syst., Vol. XVIII (2011), No. 4, pp. 679-690

Benefits of a bolometer

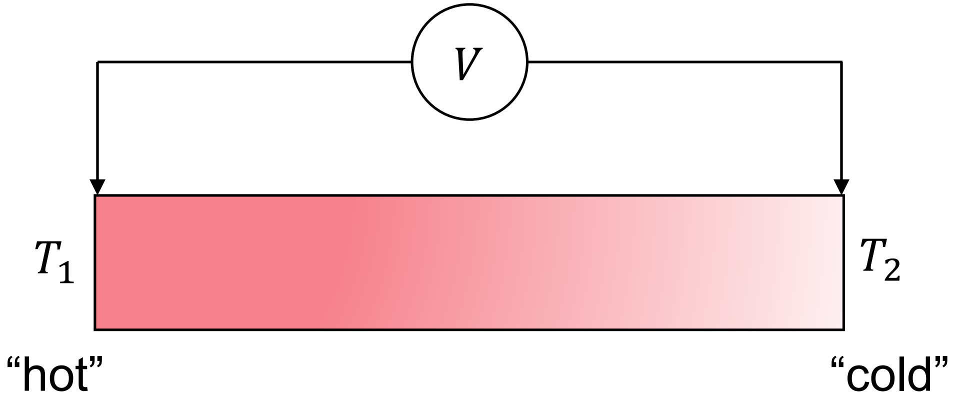
1. Operates at room temperature
2. Can detect both ionizing particles and light (all wavelengths)
3. Efficient in energy resolution and sensitivity, albeit slow

Thermal detectors: thermopiles

Seebeck effect

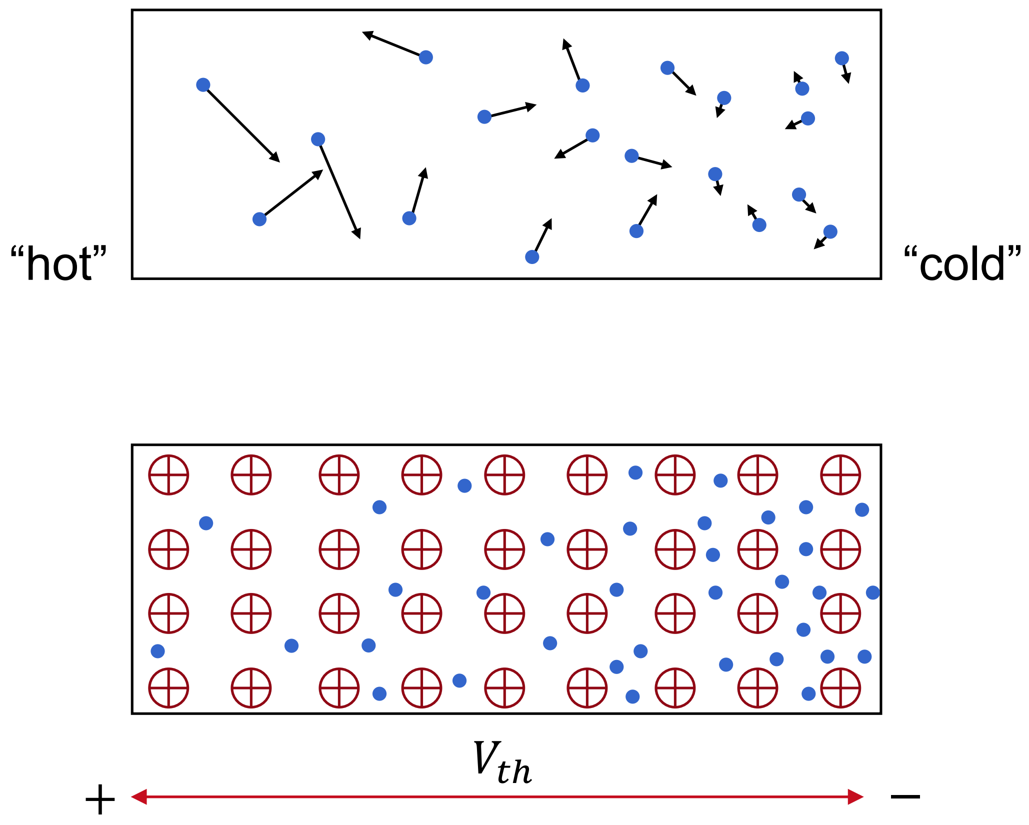


If $T_1 = T_2, V = 0$ Volts

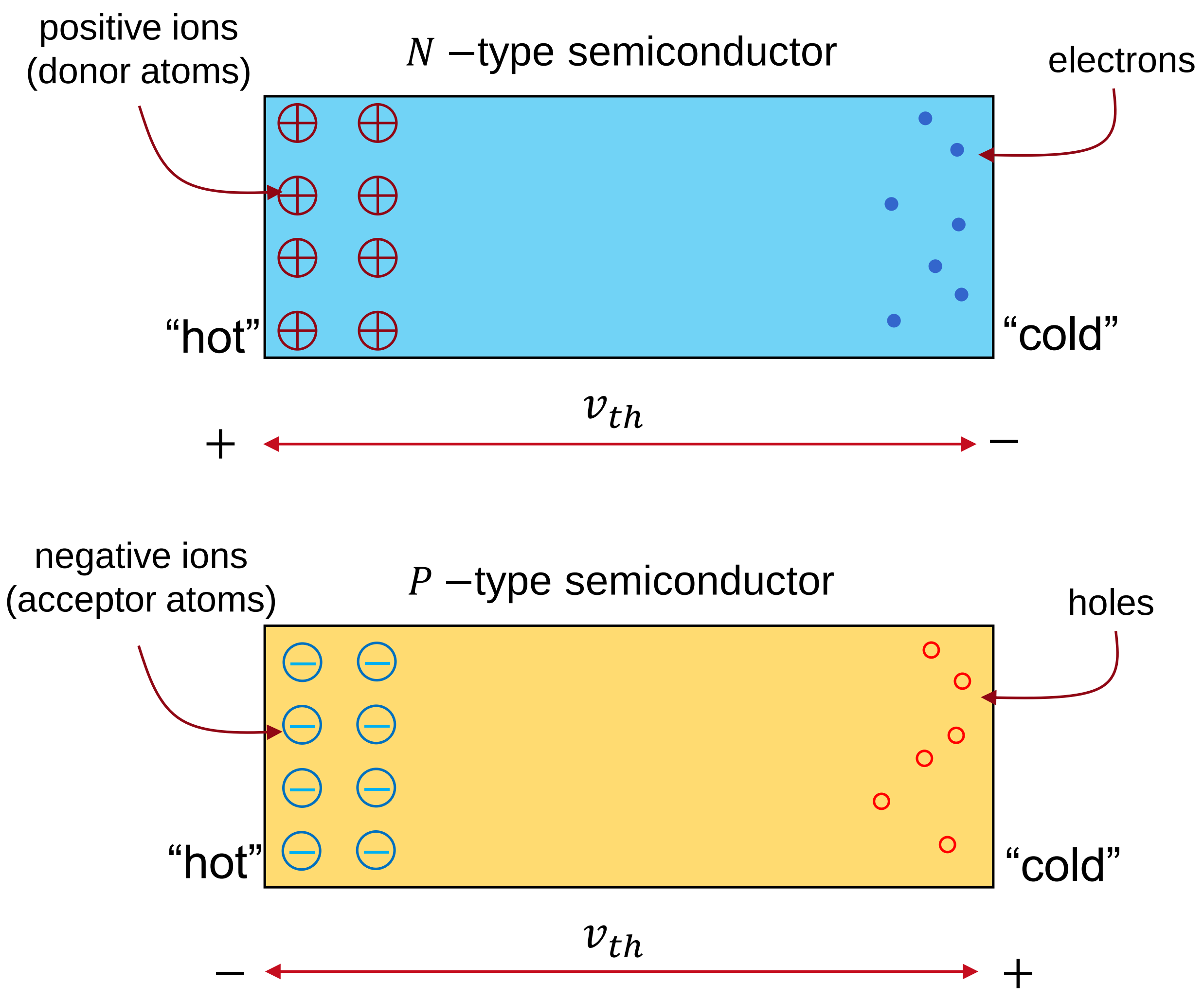


If $T_1 \neq T_2, V \neq 0$ Volts

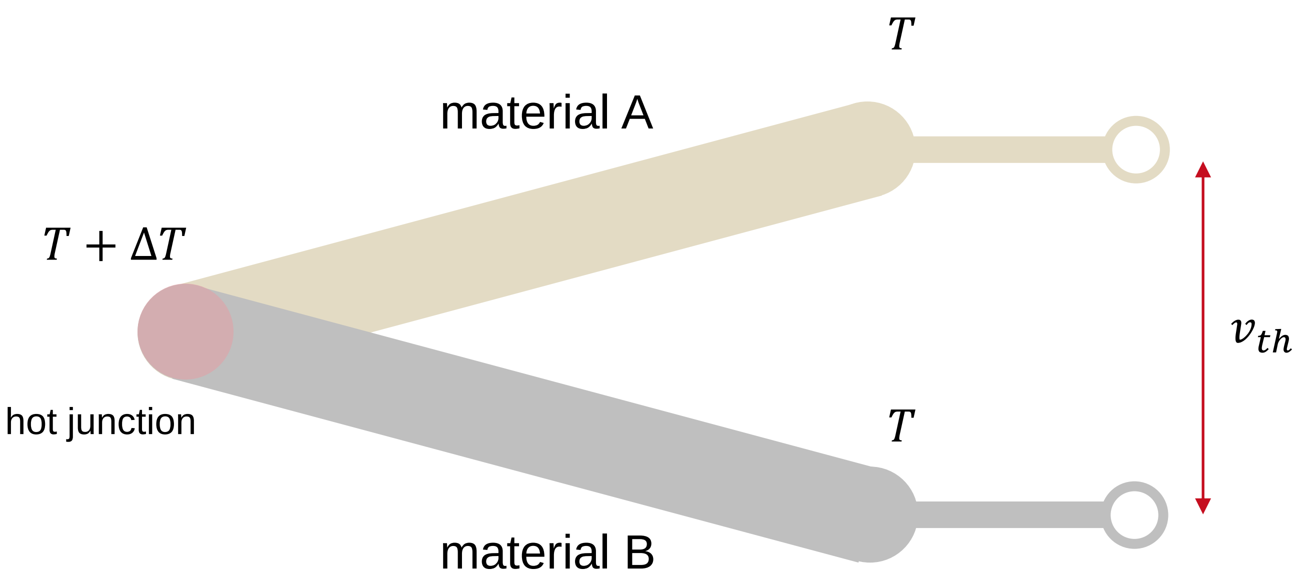
Understanding Seebeck effect (metal)



Understanding Seebeck effect (semiconductor)

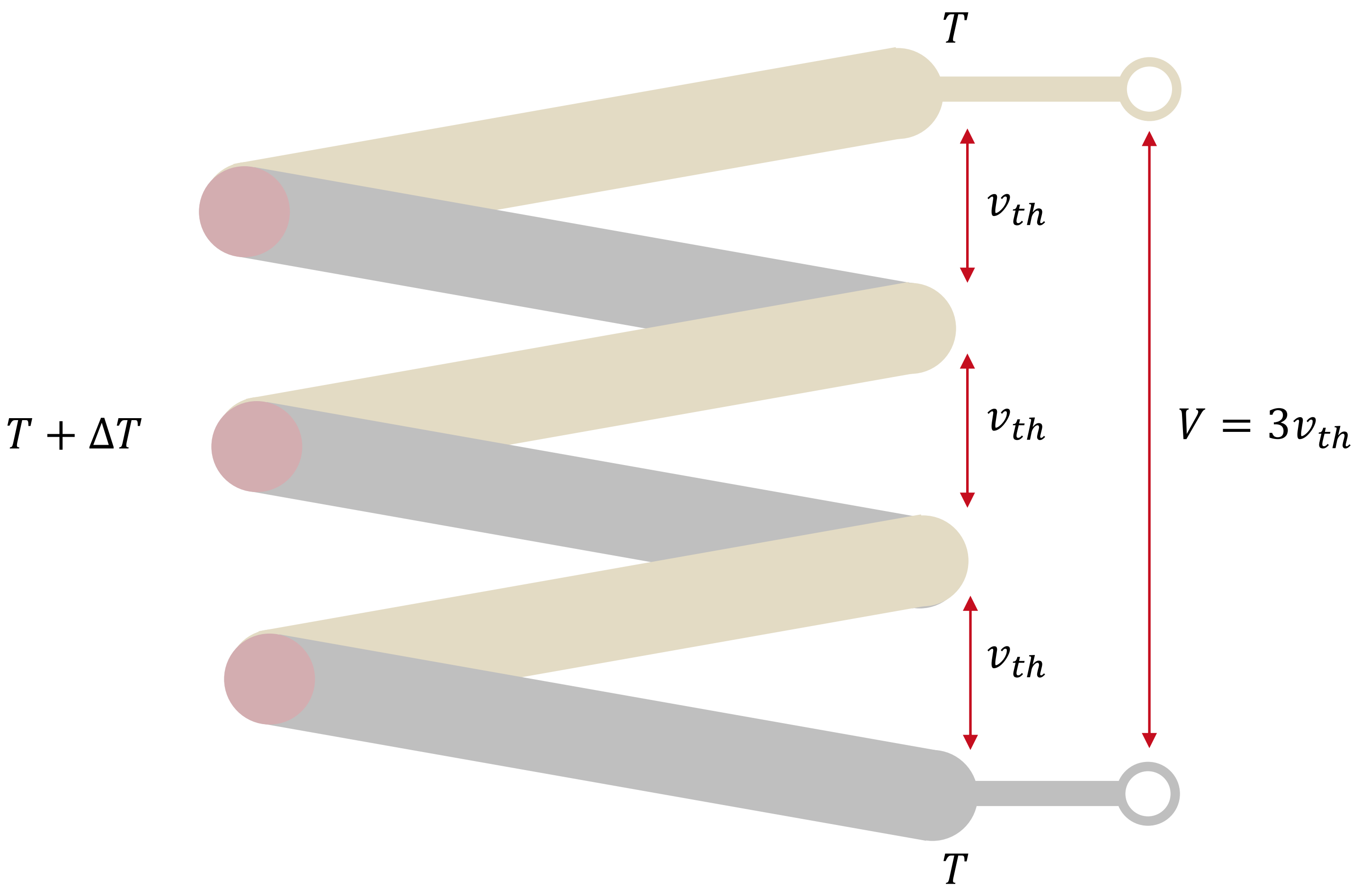


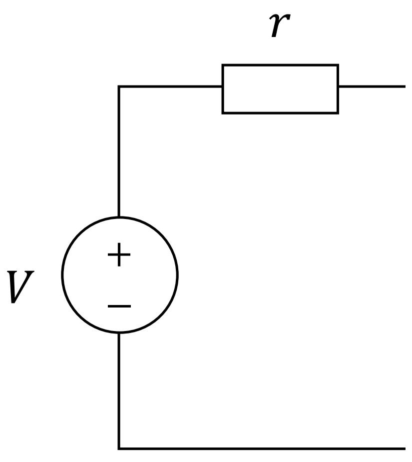
Thermocouple



$$V_{th} = \alpha_{S,AB} \Delta T$$

Thermopile

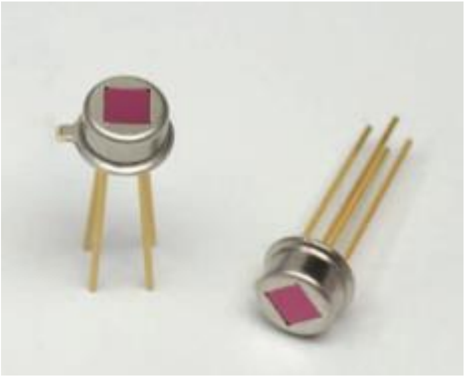


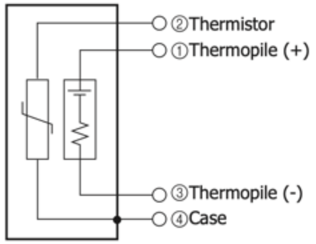


$$V = \gamma T$$

equivalent circuit

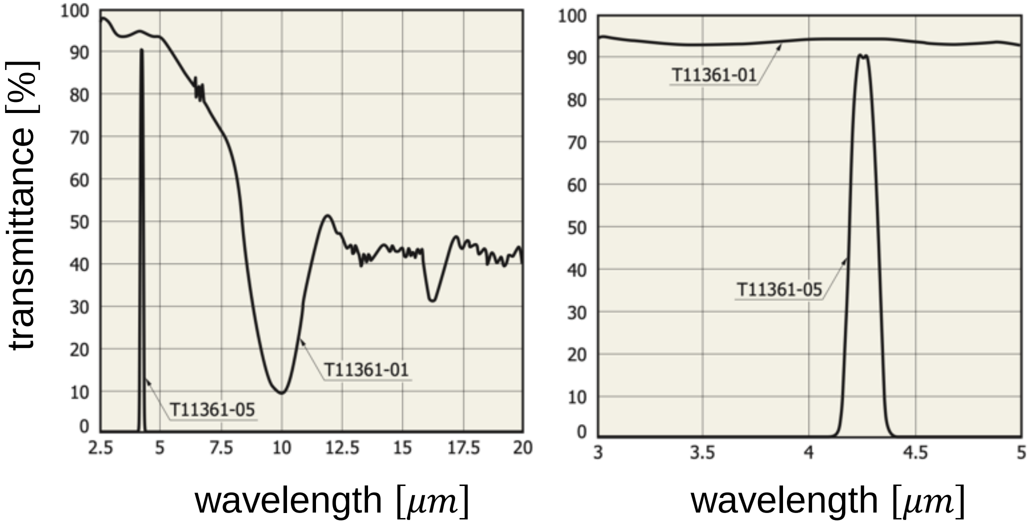
Thermopile





Example of Hamamatsu thermopile T11361 series

window materials



Electrical and optical characteristics (Ta=25 °C)

Parameter	Symbol	Condition	T11361-01			T11361-05			Unit
			Min.	Typ.	Max.	Min.	Typ.	Max.	
Spectral response	λ		-	3 to 5	-	-	4.3	-	µm
Photosensitivity	S	1 Hz, 500 K	40	50	60	40	50	60	V/W
Element resistance	Re		100	125	150	100	125	150	kΩ
Noise voltage	Vn	Johnson noise	-	45	50	-	45	50	nV/Hz$^{1/2}$
Noise equivalent power	NEP		-	0.9	1.3	-	0.9	1.3	nW/Hz$^{1/2}$
Detectivity	D*		0.9×10^8	1.3×10^8	-	0.9×10^8	1.3×10^8	-	cm·Hz$^{1/2}$/W
Rise time	tr	0 to 63%	-	20	30	-	20	30	ms
Temperature coefficient of element resistance	TCR		-	±0.1	-	-	±0.1	-	%/°C
Field of view	FOV	Photosensitivity 50%	-	90	-	-	90	-	degrees
Thermistor resistance	Rth		9	10	11	9	10	11	kΩ
Constant B	B	25/75 °C	3800	3900	4000	3800	3900	4000	K

Benefits of a thermopile

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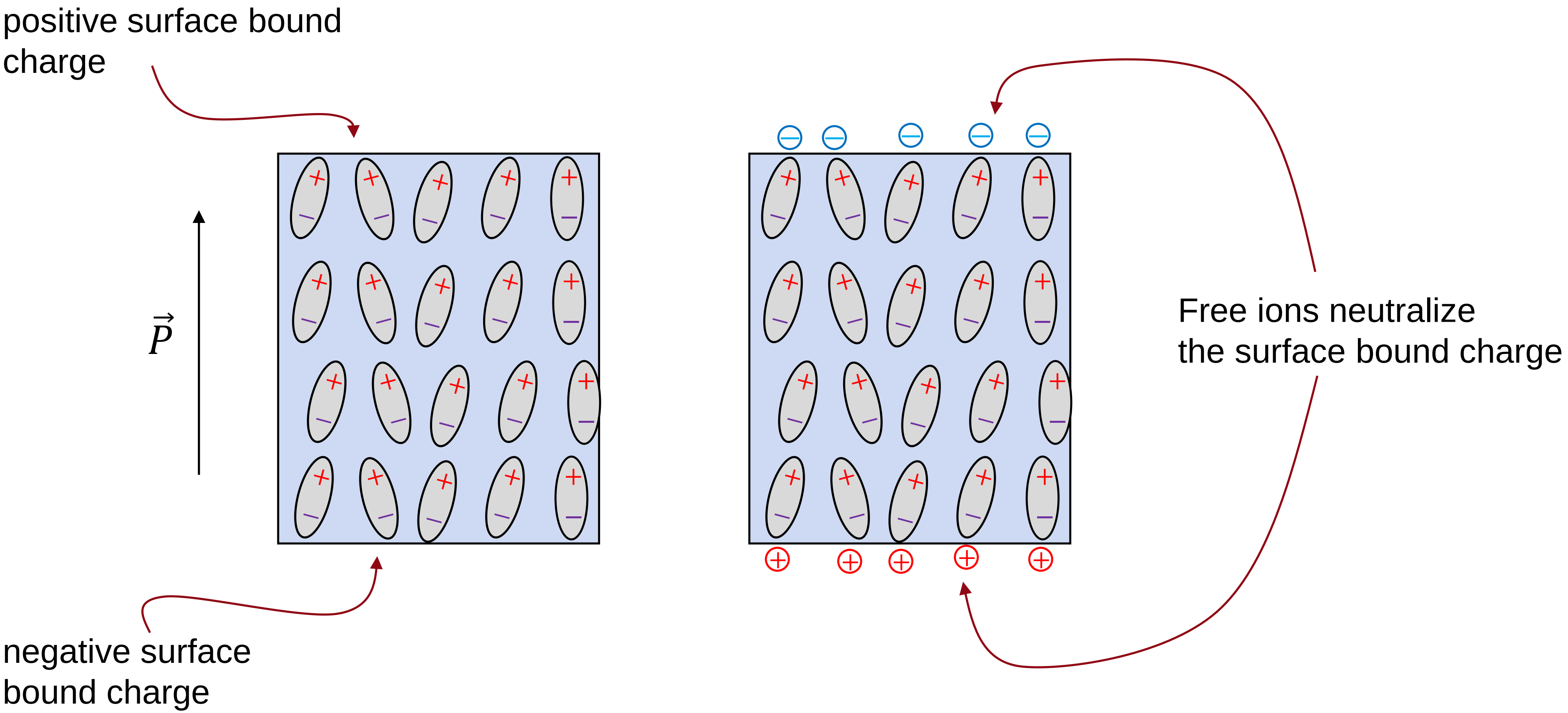
1. Inexpensive, simple in construction, and rugged. Often used as temperature sensors.
2. Can be made very small and inserted in difficult-to-access places.
3. Can be used to measure wide range of temperatures.

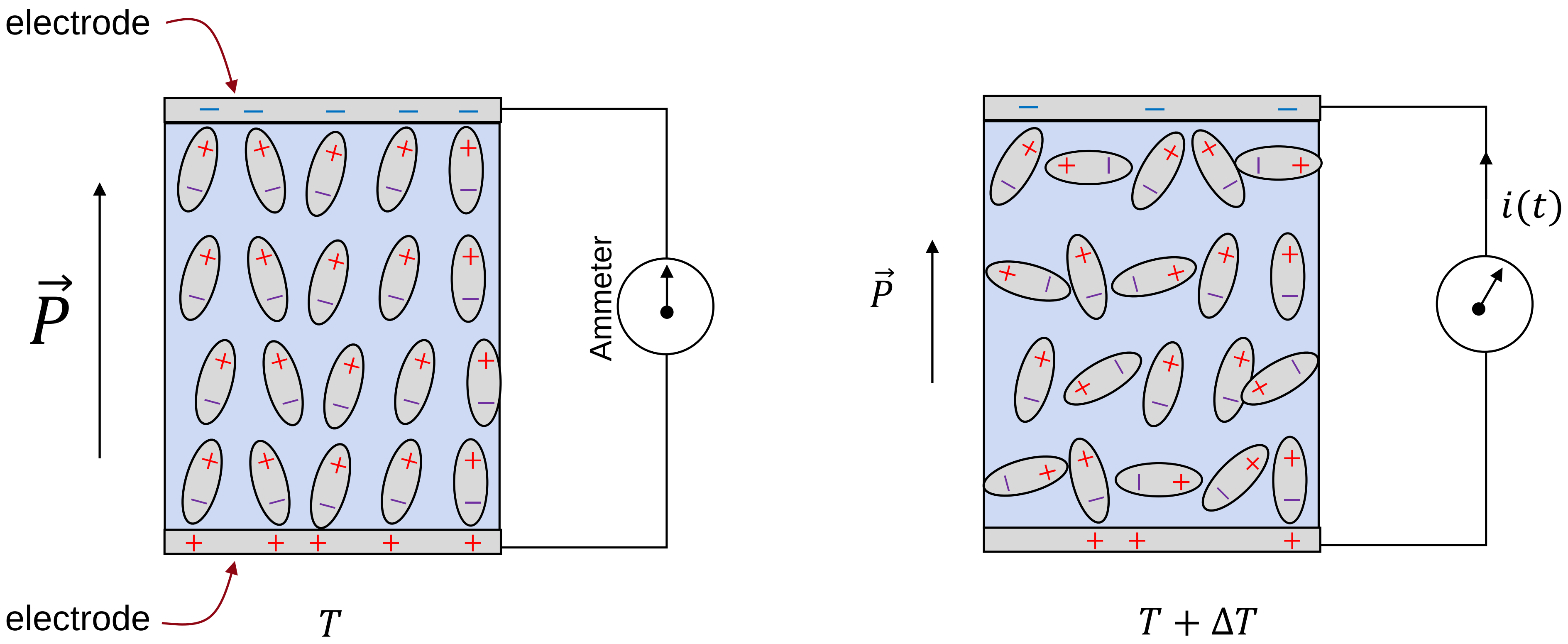
Thermal detectors: pyroelectric detectors

Pyroelectricity



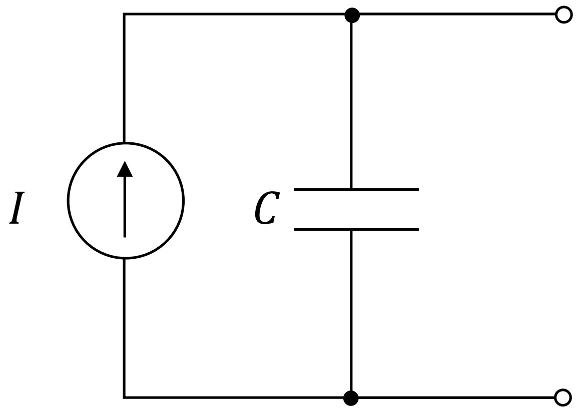
Pyroelectric crystal, such as Tourmaline, at temperature T and cut so that the intrinsic polarization $\vec{P}$ is in the vertical direction.

Pyroelectricity



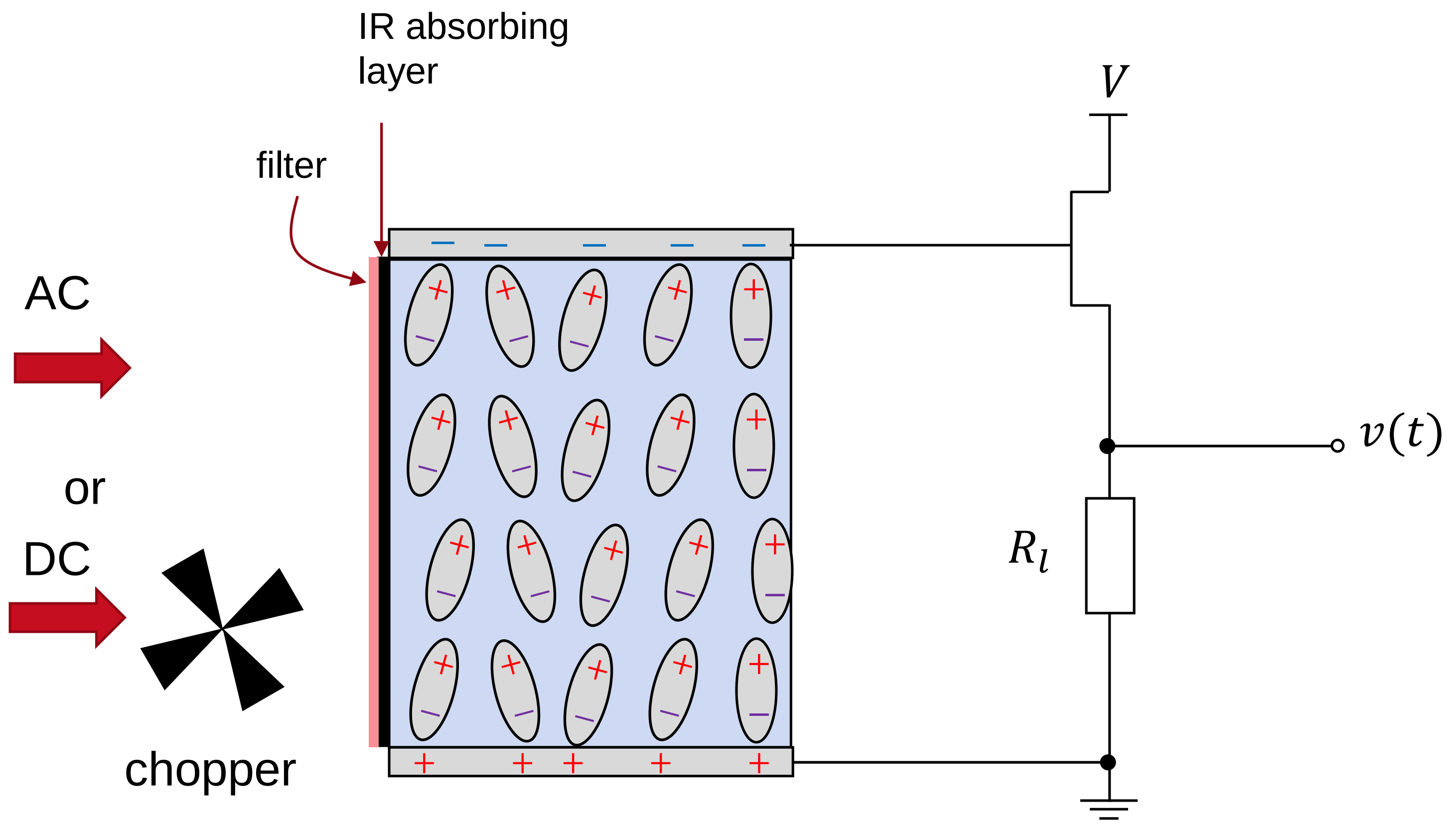
When temperature of the crystal changes (increases), the polarization decreases, and current flows though the ammeter until a new equilibrium is reached.

Equivalent circuit



$$I(t) = p\frac{dT}{dt}$$

Pyroelectric IR detector



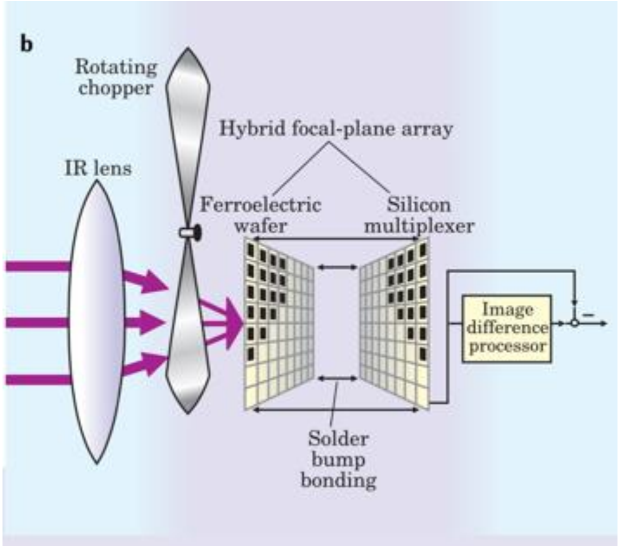
A pyroelectric sensor can detect temperature changes on the of μK.

Benefits of pyroelectric IR detector

1. Sensitivity over a very large spectral bandwidth
2. Sensitivity over a very wide temperature range – from a few degrees kelvin to hundreds, depending on pyroelectric material
3. Low power requirement
4. Fast response
5. Low-cost manufacture from inexpensive material

Source: “Pyroelectricity: From Ancient Curiosity to Modern Imaging Tool”, Sidney B. Lang, Physics Today **58**, 8, 31 (2005)

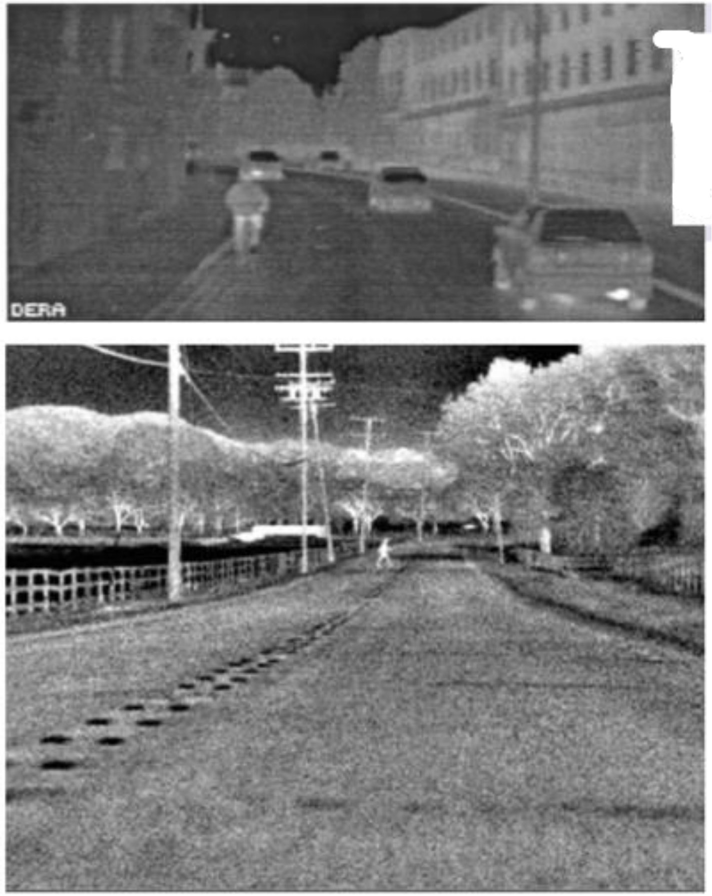
Imaging with pyroelectric sensors



A ferroelectric-hybrid focal-plane device comprises a lens, usually made of germanium to block visible light, and an array of individual ferroelectric elements that are each bonded by tiny balls of solder to elements from a silicon multiplexer. The incident IR radiation must be periodically blocked, here by a chopper, to ensure that a temperature variation is measured.

Source: "Pyroelectricity: From Ancient Curiosity to Modern Imaging Tool", Sidney B. Lang, Physics Today **58**, 8, 31 (2005)

Imaging with pyroelectric sensors



Pyroelectric imaging. These images were taken using a ferroelectric-hybrid focal-plane array (top) having 256 × 128 pixels (courtesy of DERA Malvern, Crown © 1989 and 1998) and a micromachined thin-film array (bottom) with 320 × 240 pixels (courtesy of Raytheon Commercial Electronics). Lighter colors correspond to warmer temperatures.

Source: “Pyroelectricity: From Ancient Curiosity to Modern Imaging Tool”, Sidney B. Lang, Physics Today **58**, 8, 31 (2005)

Frequency response of thermal detectors

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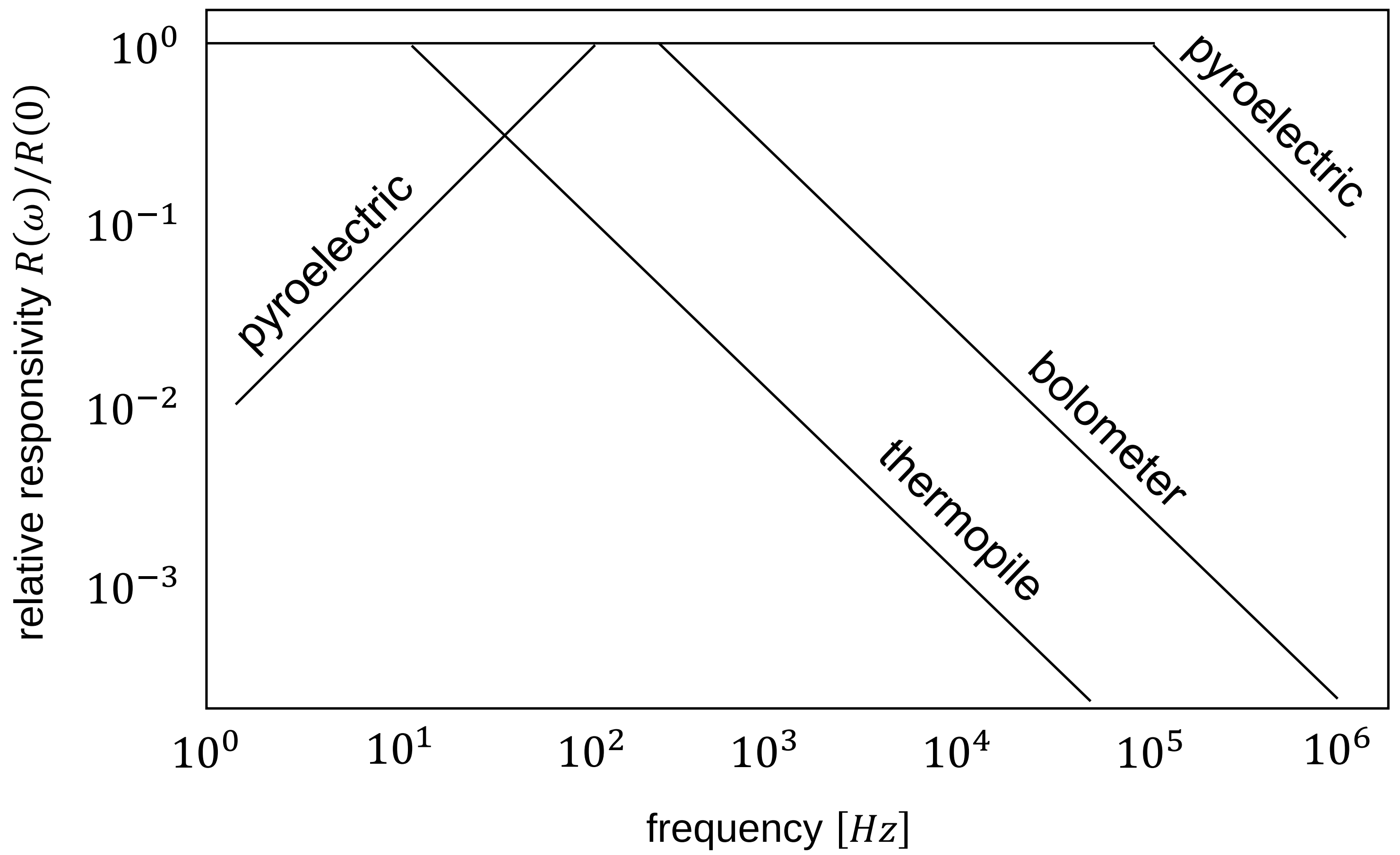

Adapted from “Photodetectors: Devices, Circuits, and Applications” by Silvano Donati (Fig. 6-4)

Takeaways

1. Thermal IR detectors operate at room (or ambient) temperature.
2. They have a very broad spectral response.
3. They are inexpensive and simple to use.
4. They can be used in imaging.
5. They are generally slower and have lower D^* compared to photonic devices.

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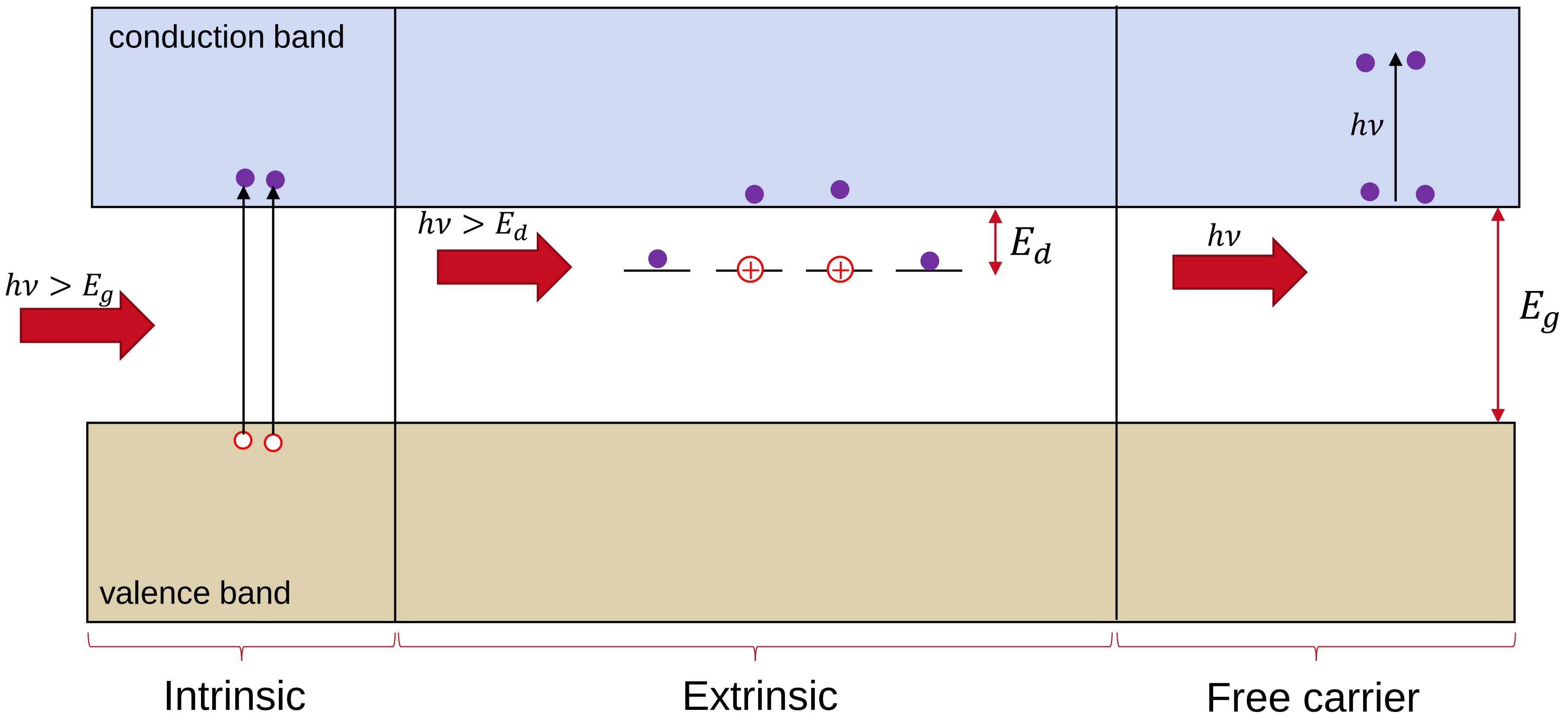
Photon detectors (brief overview)

Types of excitation in a semiconductor



Types of IR photodetectors

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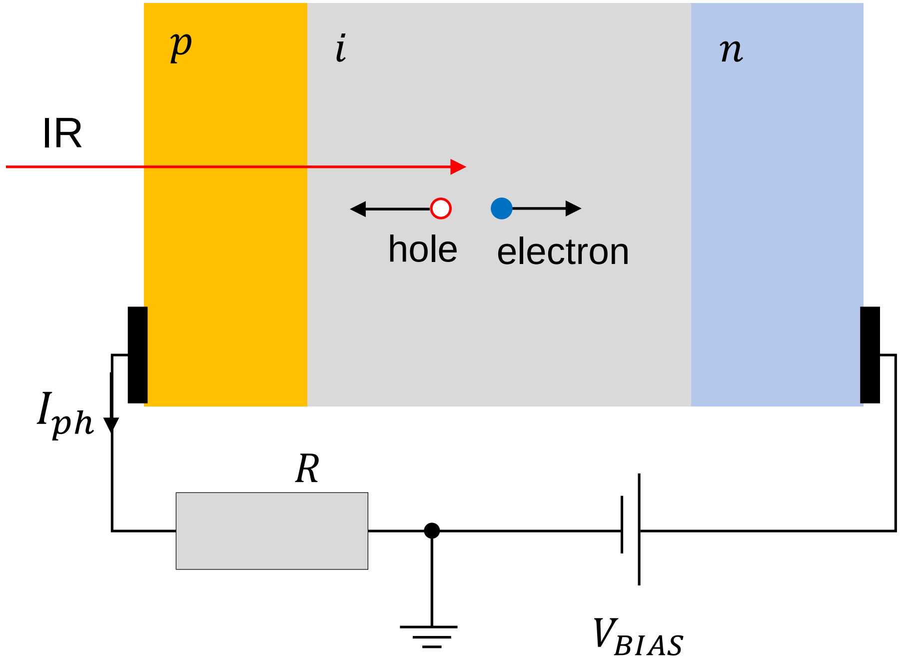
Type			Detector	Spectral response (μm)	Operating temperature (K)	D^* (cm · Hz$^{1/2}$ / W)
Thermal type	Thermocouple · Thermopile			Depends on window material	300	D^* (λ,10,1) = 6×10^8
	Bolometer				300	D^* (λ,10,1) = 1×10^8
	Pneumatic cell		Golay cell, condenser-microphone		300	D^* (λ,10,1) = 1×10^9
	Pyroelectric detector		PZT, TGS, $LiTaO_3$		300	D^* (λ,10,1) = 2×10^8
Quantum type	Intrinsic type	Photoconductive type	PbS	1 to 3.6	300	D^* (500,600,1) = 1×10^9
			PbSe	1.5 to 5.8	300	D^* (500,600,1) = 1×10^8
			InSb	2 to 6	213	D^* (500,1200,1) = 2×10^9
			HgCdTe	2 to 16	77	D^* (500,1000,1) = 2×10^{10}
		Photovoltaic type	Ge	0.8 to 1.8	300	D^* (λp) = 1×10^{11}
			InGaAs	0.7 to 1.7	300	D^* (λp) = 5×10^{12}
			Ex. InGaAs	1.2 to 2.55	253	D^* (λp) = 2×10^{11}
			InAs	1 to 3.1	77	D^* (500,1200,1) = 1×10^{10}
			InSb	1 to 5.5	77	D^* (500,1200,1) = 2×10^{10}
			HgCdTe	2 to 16	77	D^* (500,1000,1) = 1×10^{10}
	Extrinsic type		Ge : Au	1 to 10	77	D^* (500,900,1) = 1×10^{11}
			Ge : Hg	2 to 14	4.2	D^* (500,900,1) = 8×10^9
			Ge : Cu	2 to 30	4.2	D^* (500,900,1) = 5×10^9
			Ge : Zn	2 to 40	4.2	D^* (500,900,1) = 5×10^9
			Si : Ga	1 to 17	4.2	D^* (500,900,1) = 5×10^9
			Si : As	1 to 23	4.2	D^* (500,900,1) = 5×10^9

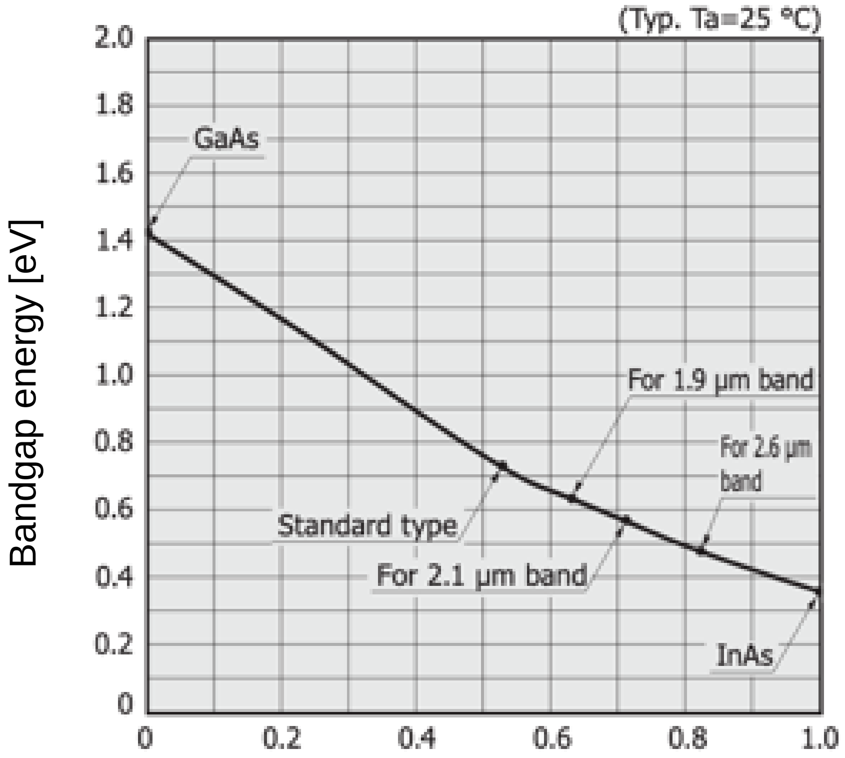
Photovoltaic: PIN photodiode (e.g., InGaAs)

structure of a PIN photodiode (not to scale)



Spectral response of InGaAs photodiodes ranges from $0.5 - 2.6\ \mu$m

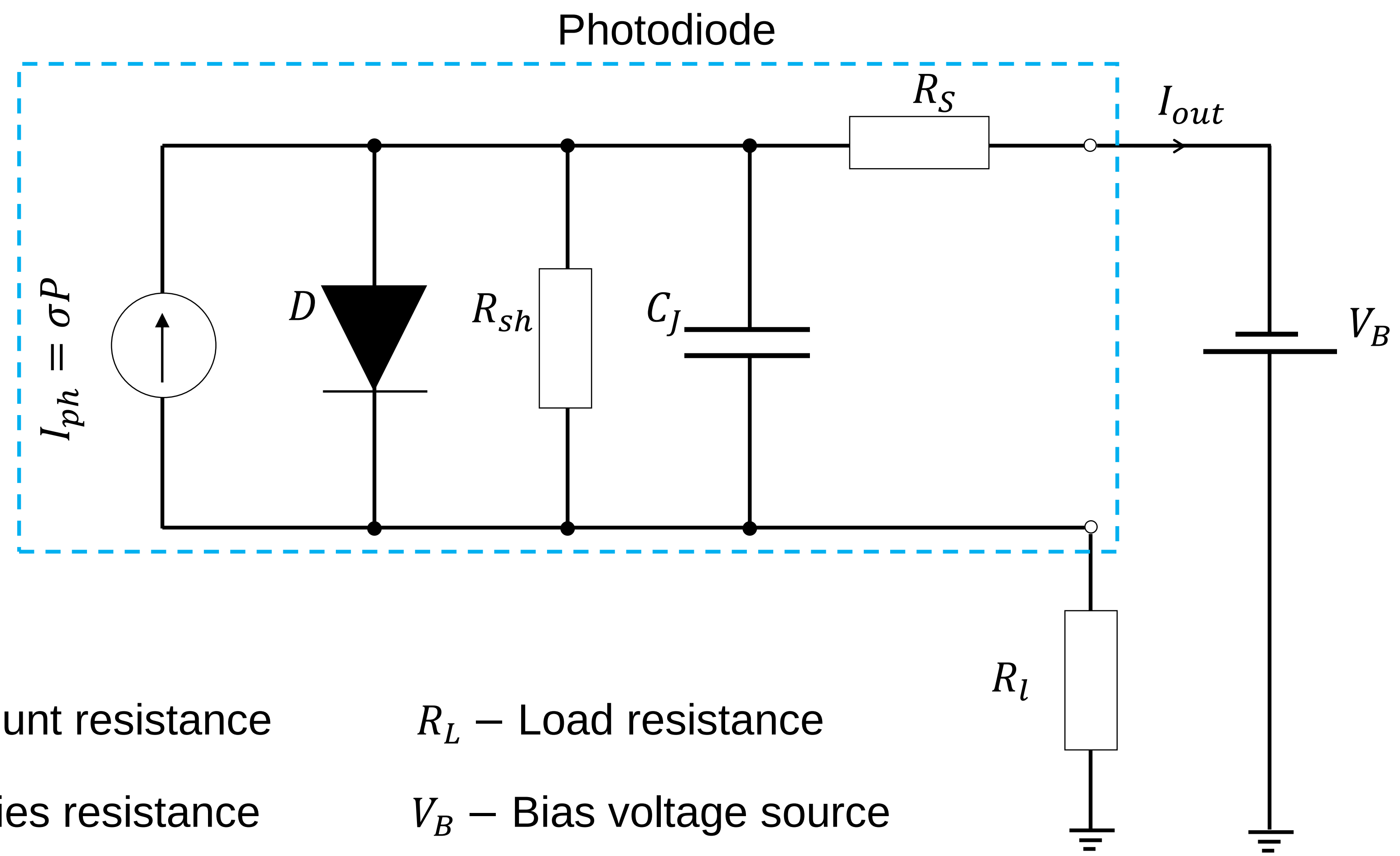
Bandgap energy of InGaAs



Composition ratio x of $InGa_{1-x}As$

Relative concentrations of In, Ga, and As determine the bandgap energy and, thus, spectral response.

Equivalent circuit



R_{sh} – Shunt resistance

R_S – Series resistance

C_J – Junction capacitance

R_L – Load resistance

V_B – Bias voltage source

I_{ph} – Photocurrent

Detectivity

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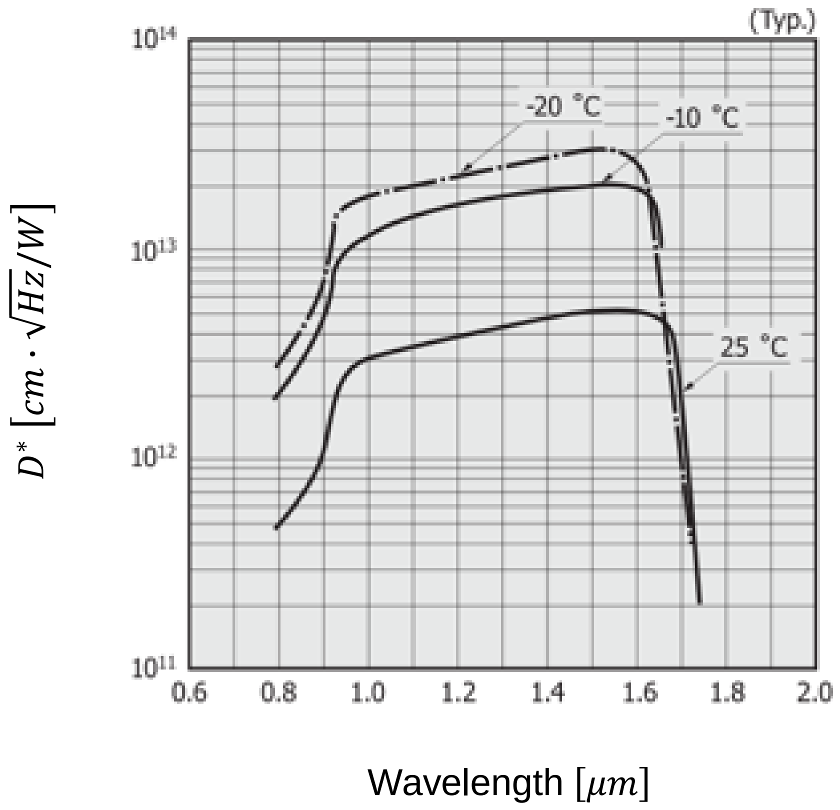
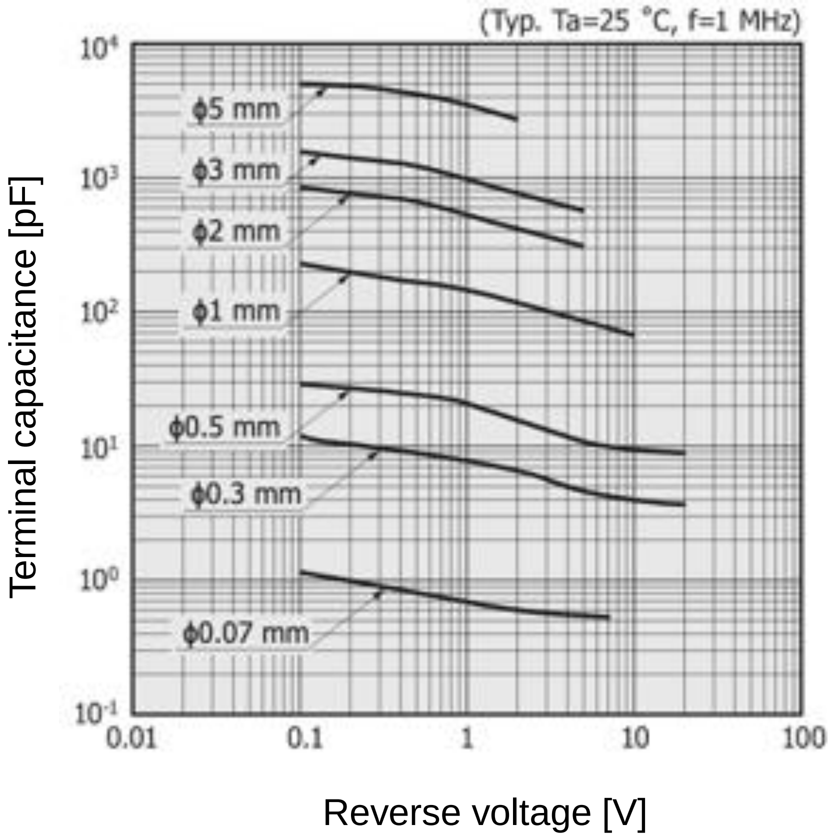


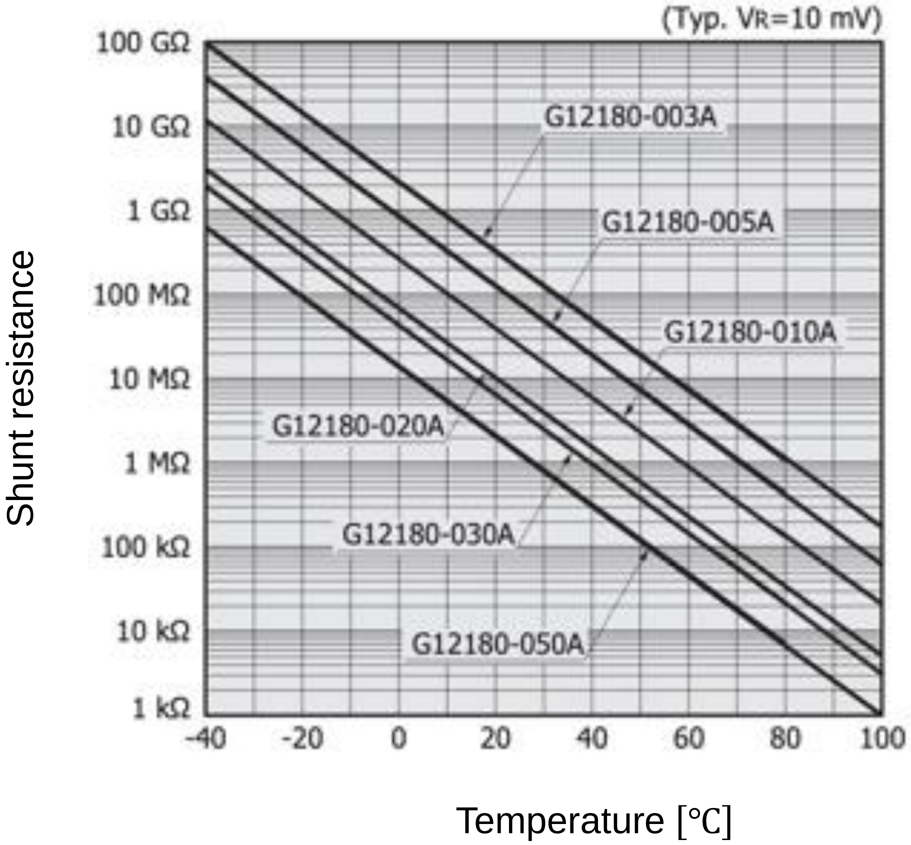
Example of InGaAs photodiode specific detectivity as a function of wavelength. Note how the detectivity improves as temperature decreases.

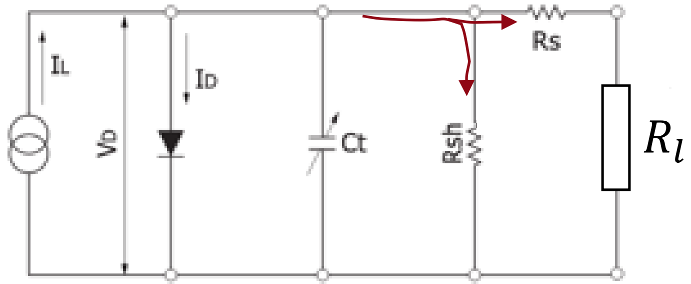
Frequency response



Terminal capacitance and detection electronics determine the frequency response. Note how terminal capacitance increases with active area.

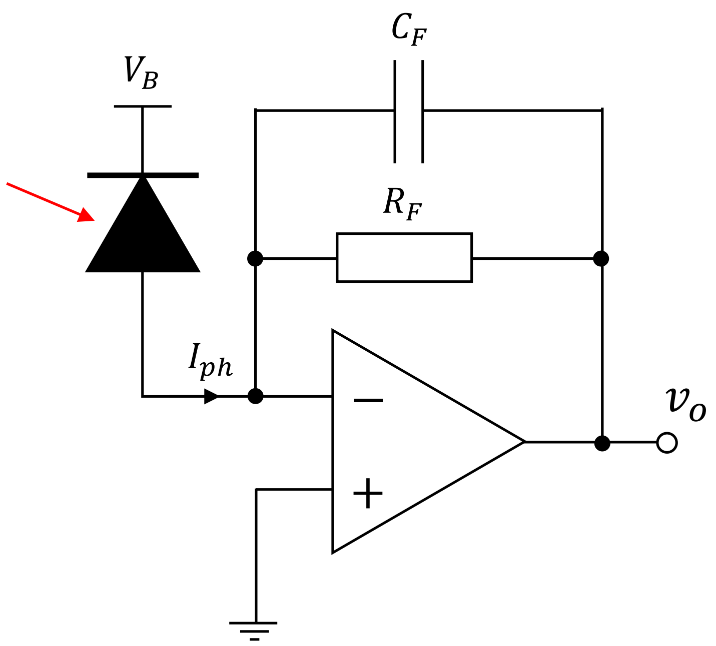
Shunt resistance versus temperature





Shunt resistance decreases with increasing temperature.

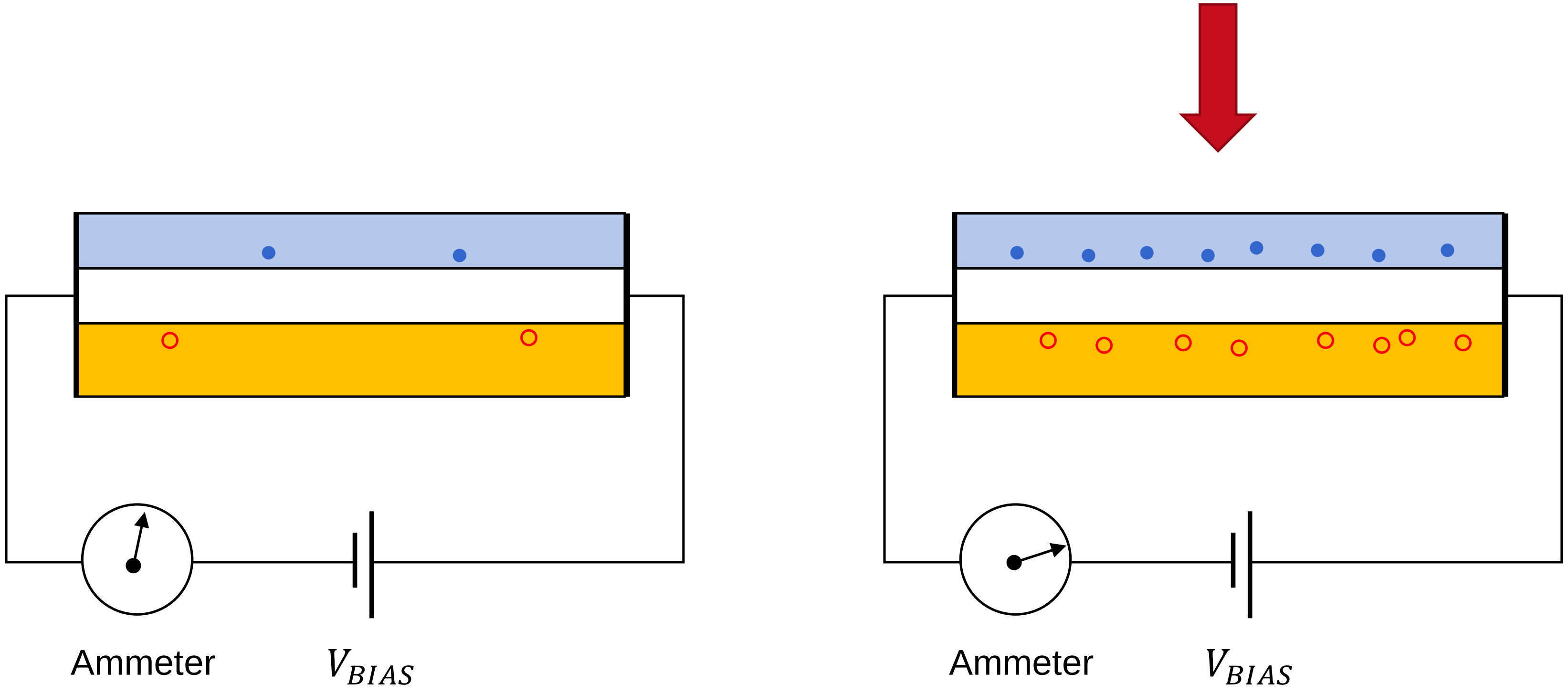
Detection circuit



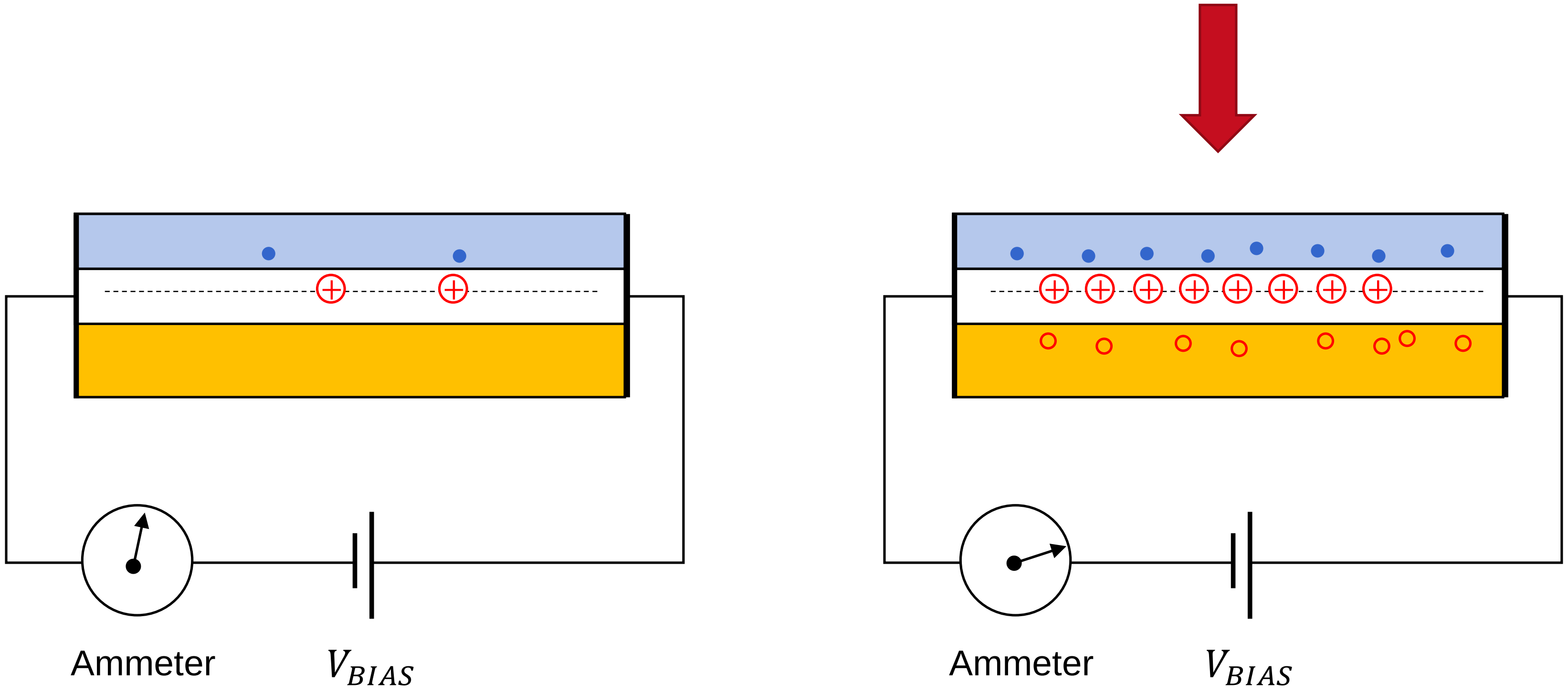
1. Bandwidth increases with V_B
2. Linear response but dynamic range limited by amplifier saturation
3. Dark current
4. At high-frequency operation, the TIA may exhibit gain peaking and instabilities.

This is one of the most popular configurations.

Photoconductive (intrinsic)

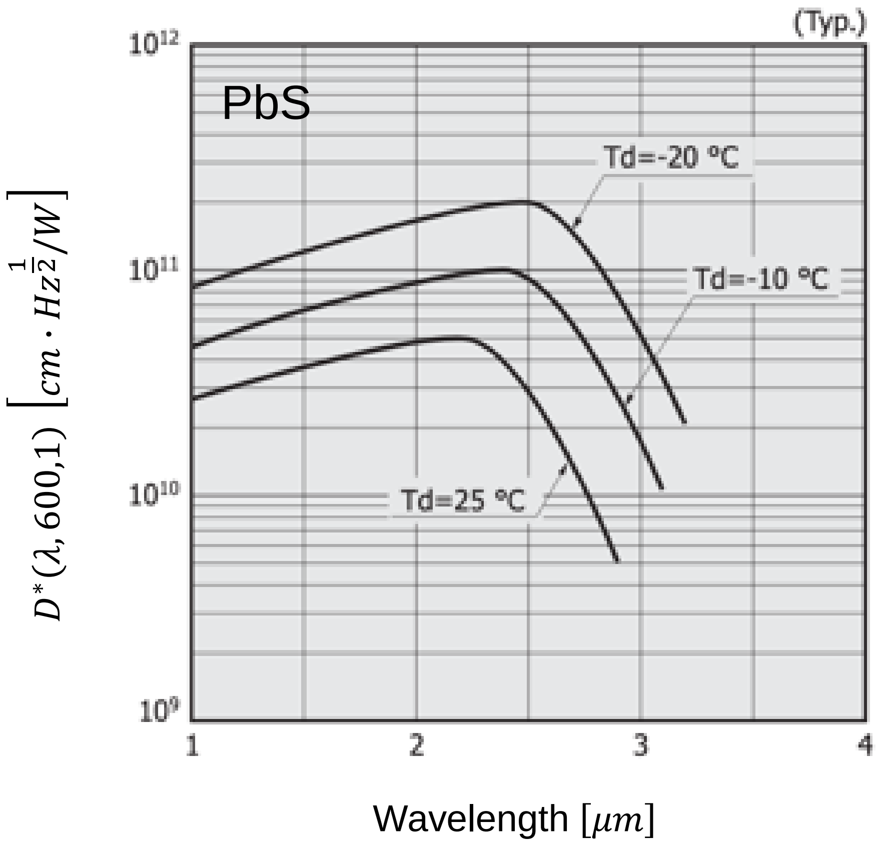


Photoconductive (extrinsic)



These detectors are operated at low temperatures.

Specific detectivity



Note how D^* increases with decreasing temperature and how the peak wavelength increases.

Frequency response

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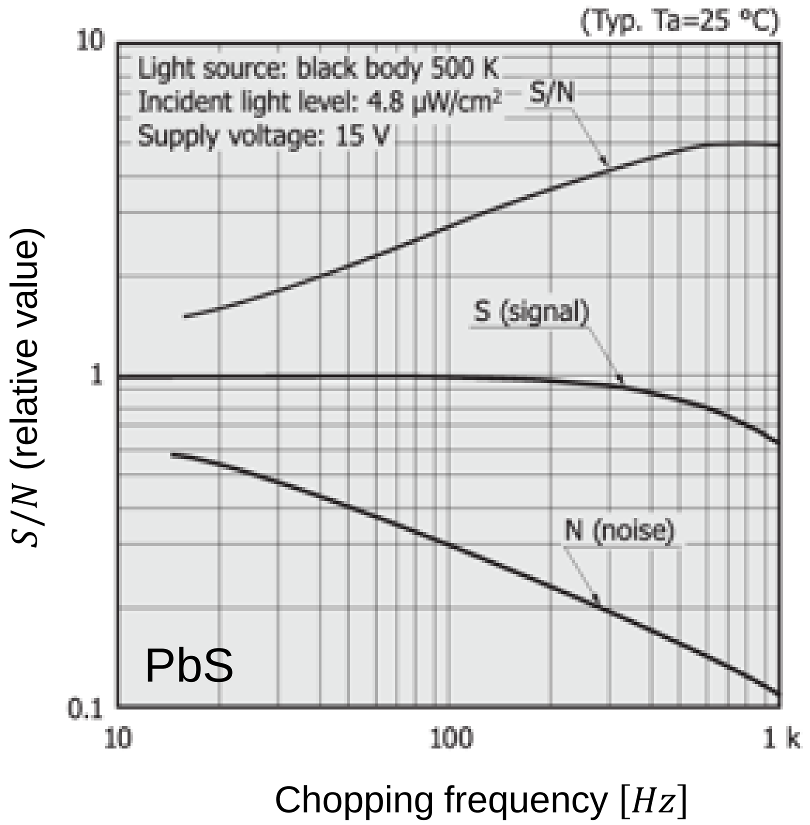
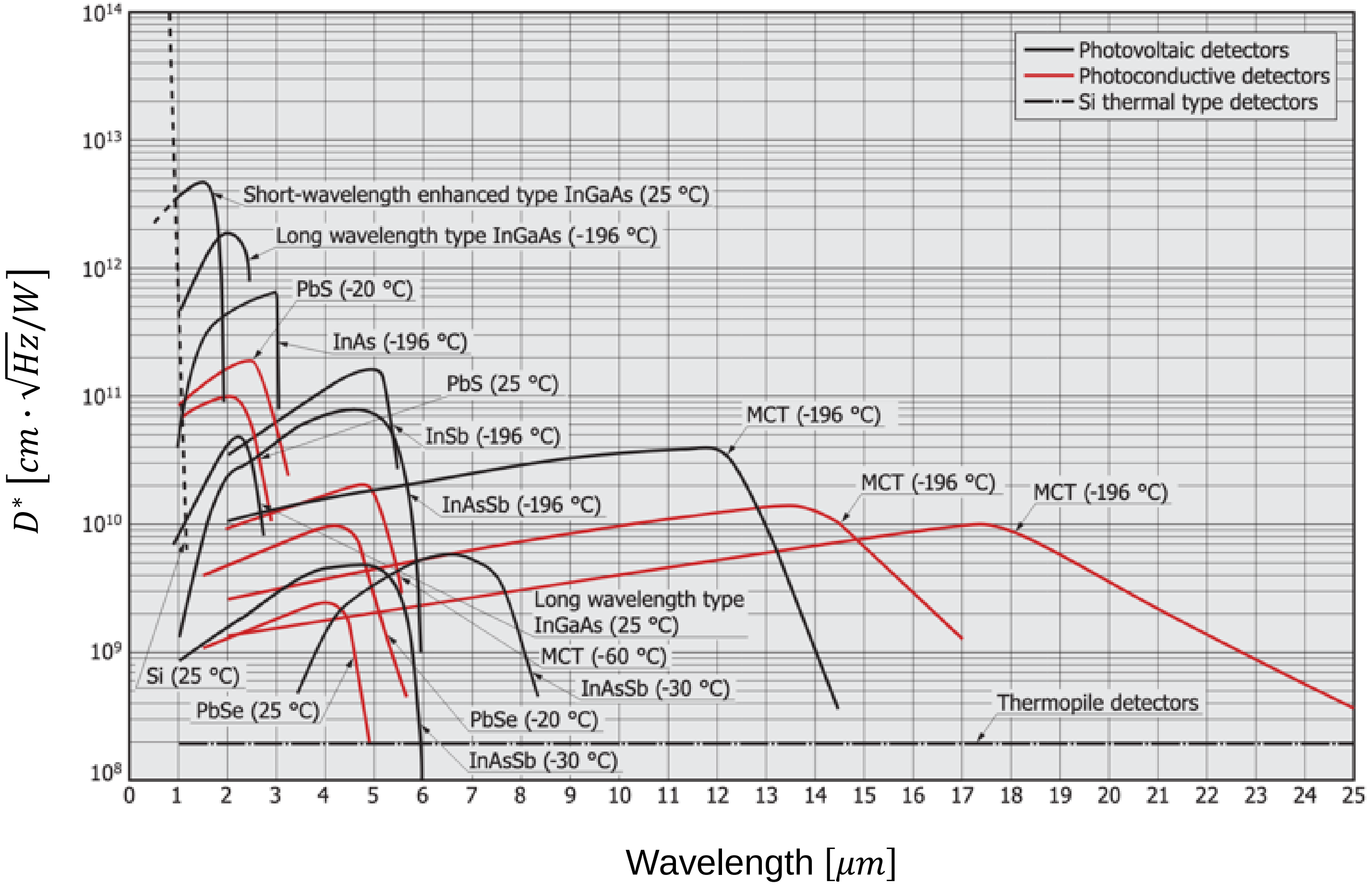


Both R and D^* are function of modulation frequency. As the plot shows, chopping the incident DC radiation improves ${}^{S}/_{N}$.

Detectivities of photonic IR detectors



Photon drag IR detectors

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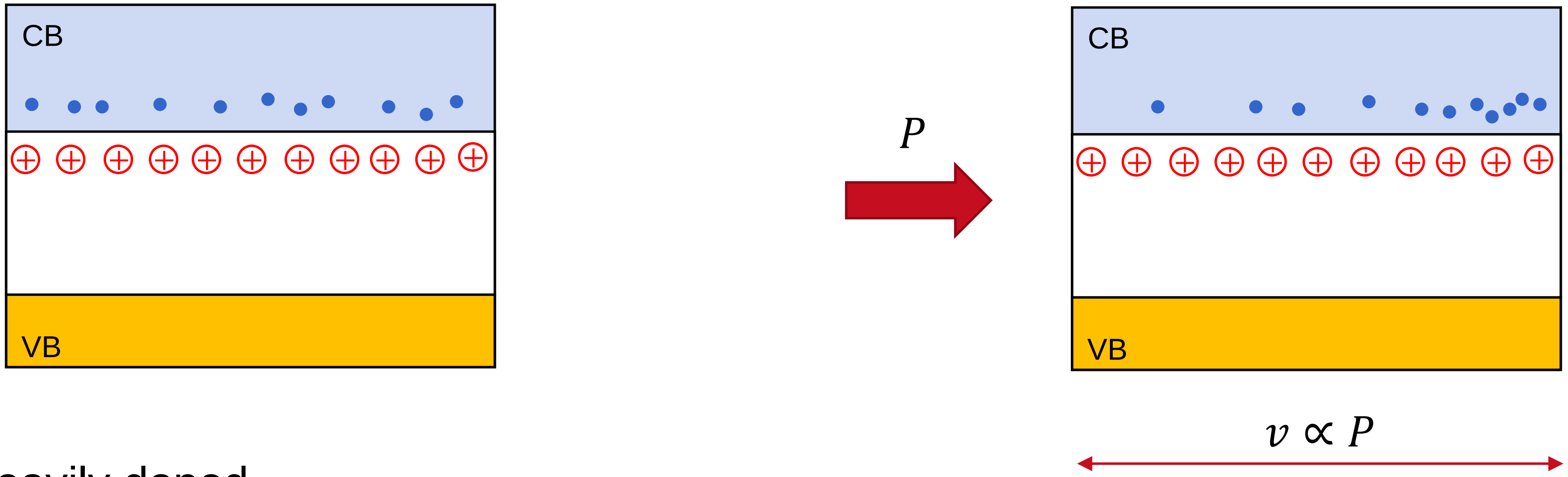

heavily doped
semiconductor (n or p type)

Photon drag detector by Hamamatsu

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Active material: germanium

Electrical and optical characteristics (Ta=25 °C)

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Photosensitivity	S	λ=10.6 μm	-	1.2	-	mV/kW
Rise time	tr	10 to 90%	-	-	1	ns
Noise equivalent power	NEP	λ=10.6 μm	-	4×10^{-3}	-	$W/Hz^{1/2}$
Output impedance	-		-	50	-	Ω

Used for CO_2 laser detection

Takeaways

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1. Photonic IR detectors offer larger D^* compared to thermal IR detectors.
2. Photovoltaic detectors tend to have the largest values of D^* but also the narrowest spectral response.
3. Photonic detectors need to be cooled, in some cases to a temperature as low as about $4\ K$.
4. Photonic IR detectors can be used in image arrays.

What IR detector should I use in my application?

The selection process is based on the following considerations:

1. Wavelength: longer the wavelength, fewer the choices.
2. Incident power: affects needed D^*. Typically, larger D^* implies a higher cost.
3. Characteristics of the incident IR radiation: collimated, diffuse, DC, pulse, modulated
4. Does my application allow cooling?
5. Cost

The selection process can vary from trivially simple to quite complex involving tradeoffs.
Contact HAMAMATSU for assistance and guidance.

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Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
1 Weeks Break				
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
1 Weeks Break				
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
1 Weeks Break				
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

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Thank you

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Thank you for listening

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