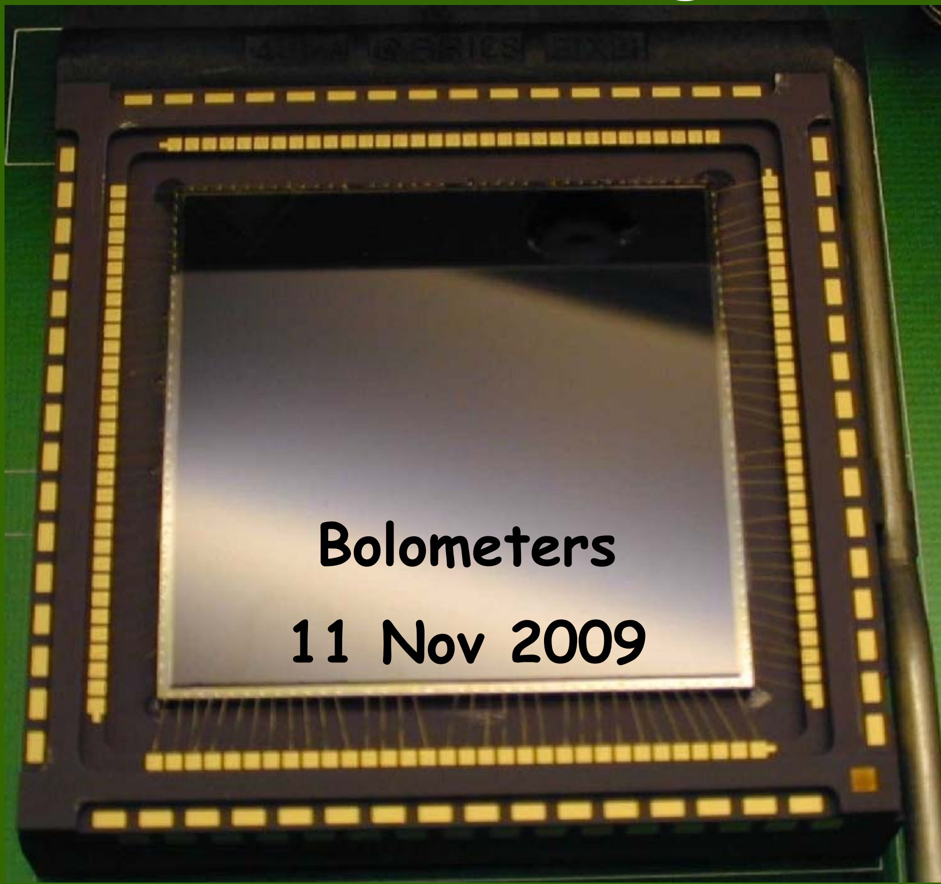
# Detection of Light




See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

## Remember: 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, photographic plates

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

# Bolometers: History

Not much happened in IR astronomy until the 1960ies.
Problem: the huge sky emission at 10μm required differential measurements
The success of *radio* astronomy demonstrated the scientific potential for astronomy in new spectral regions.

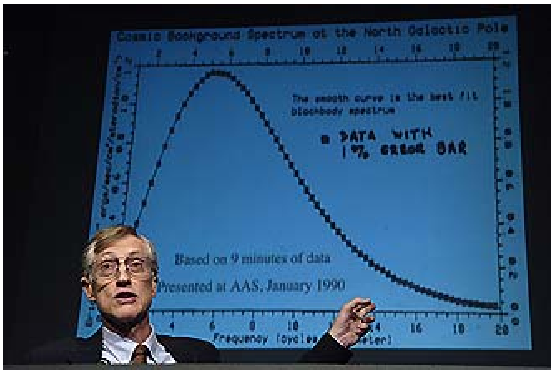
➔Frank Low, F. J.: Low-Temperature Germanium Bolometer. J. Opt. Soc. Am., 51, 1300 (1961)
(Operated initially at similar detection levels to the previously available mid-infrared photoconductors but improved quickly.)

Invention of the Ge:Ga bolometer in 1961 by Frank Low

Frank Low (with Steve Beckwith) receiving the Bruce medal of the AAS

# A Milestone in the History of Bolometers

Many references to John C. Mather (Appl.Opt. 21, 1125-29, 1982) in our text book!

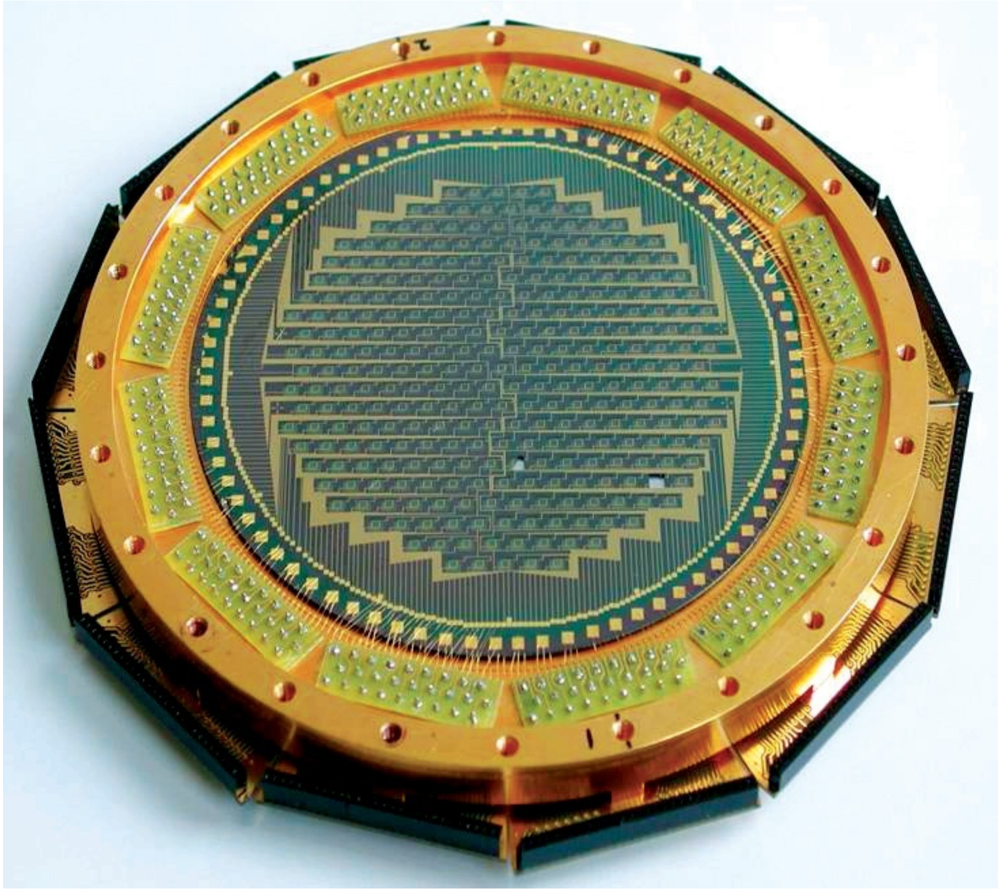



Nobel Prize in physics, 2006 (together with George Smoot)

- PI for the Far IR Absolute Spectrophotometer (FIRAS) on COBE
- Senior Project Scientist for the James Webb Space Telescope
- Advisor for the National Academy of Sciences, NASA, and the NSF
- Member of the Astrophysics Subcommittee etc.

From the Nobel Lecture, December 8, 2006: "*In developing concepts for the detectors, I pursued an idea I had from graduate school, to establish a convenient theory for the noise and ultimate sensitivity of bolometers. I worked on the manuscript while my future wife Jane was teaching ballet; I was driving her to work because we had broken her arm doing the samba. This work developed into a series of papers (e.g. Mather, 1984) which have ended up being my most cited publications*".

# State-of-the-Art Developments (1)



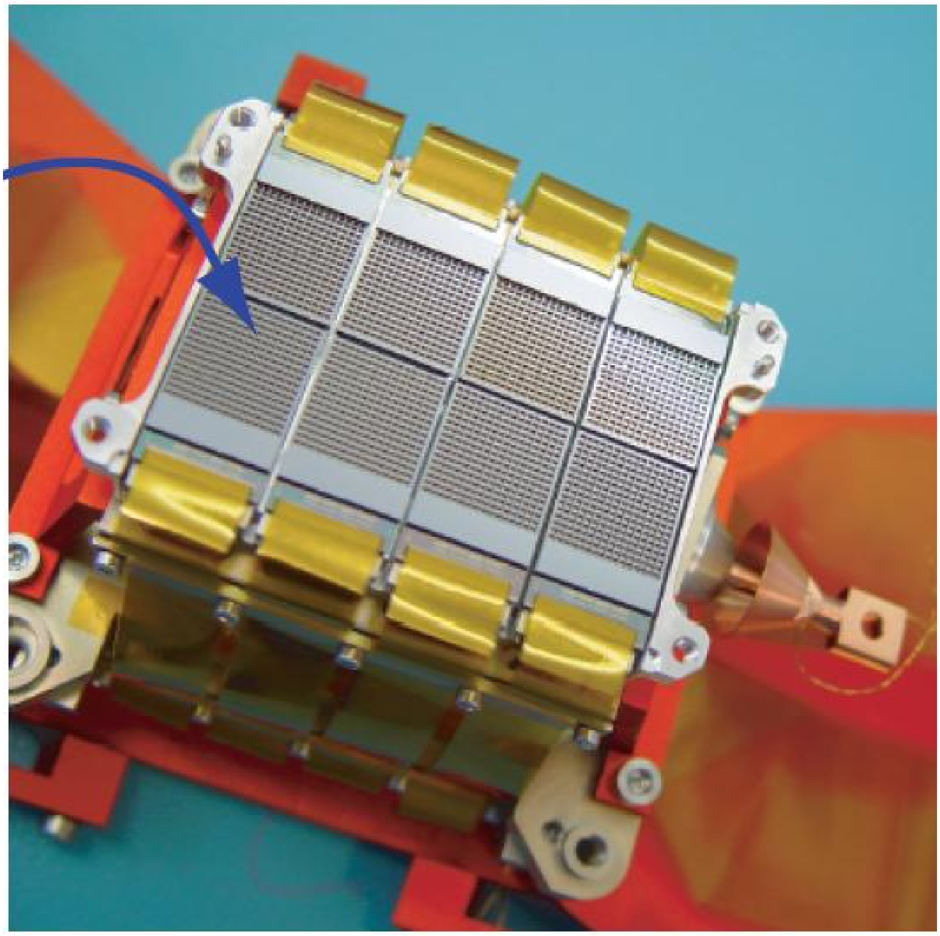
LABOCA – the multi-channel bolometer array for APEX operating in the 870 µm (345 GHz) atmospheric window.

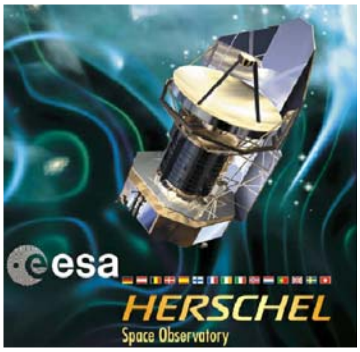
The signal photons are absorbed by a thin metal film cooled to about 280 mK.

The array consists of 295 channels in 9 concentric hexagons.
The array is under-sampled, thus special mapping techniques must be used.

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

# State-of-the-Art Developments (2)






Herschel/PACS bolometer: a cut-out of the 64x32 pixel bolometer array assembly.

4x2 monolithic matrices of 16x16 pixels are tiled together to form the short-wave focal plane array.

The 0.3 K multiplexers are bonded to the back of the sub-arrays. Ribbon cables lead to the 3K buffer electronics.

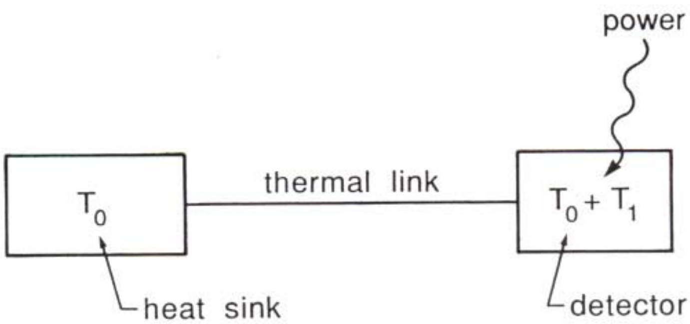
http://herschel.esac.esa.int/Docs/PACS/html/ch02s03.html

# Basic Principle

## Basic Operation

- Photon absorption and conversion into heat $h\nu \Rightarrow kT$
- Absorber is decoupled from the detection process
- Especially suited for low light levels
- Especially for the far-IR & sub-millimeter wavelength range

Detector absorbs the constant power $P_0$ and is connected via thermal link with thermal conductance $G$ to a heat sink of temperature $T_0$.




Then: $G = \frac{P_0}{T_1}$ [W/K]

Now we add a variable component $P_V(t)$ which represents the astronomical signal: $\eta P_V(t) = \frac{dQ}{dt} = C\frac{dT_1}{dt}$

where $\eta$ = quantum efficiency, Q = thermal energy, and $C = dQ/dT_1$ = the heat capacity [J/K].

# Basic Operation (2)

The total power absorbed by the detector is:

$$P_T(t) = P_0 + \eta P_V(t) = GT_1 + C\frac{dT_1}{dt}$$

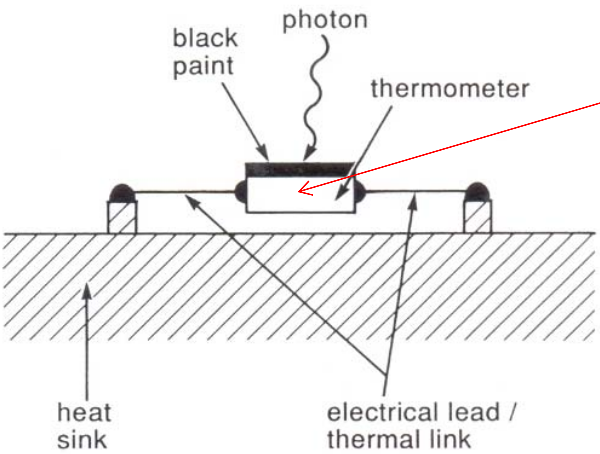
Turn on the signal at t = 0 such that $P_V = 0$ for t < 0, and $P_V = P_1$ for $t \geq 0$

$$T_1(t) = \frac{P_T}{G} - \frac{\eta P_V}{G} = \begin{cases} \frac{P_0}{G}, & t < 0 \\ \frac{P_0}{G} + \frac{\eta P_1}{G}\left(1 - e^{-t/(C/G)}\right), & t \geq 0 \end{cases}$$

The signal decays (cools) exponentially
→ the time constant $\tau$ of the detector is $\tau_T = C / G$.

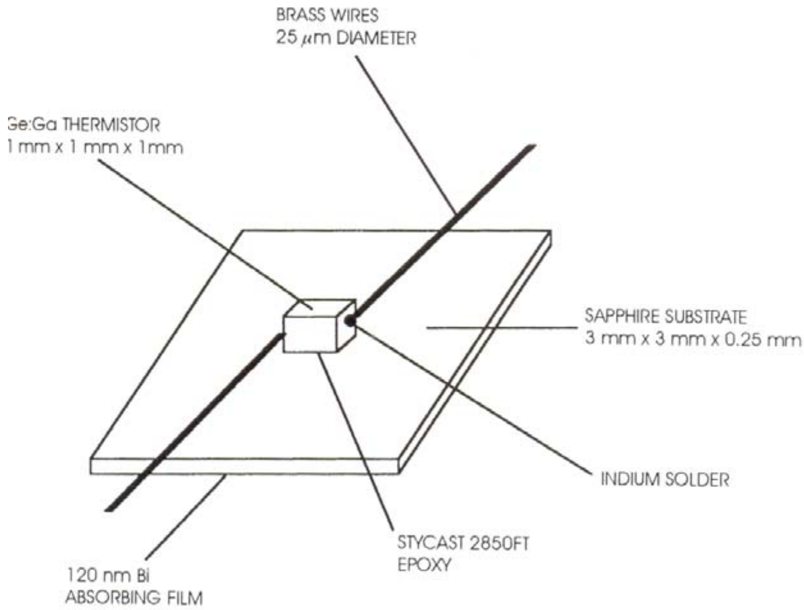
For $t \gg \tau_T$ the temperature $T_1 \sim (P_0 + \eta P_1)$ → measure $T_1$ → know $P_1$.

# Basic Operation (3)

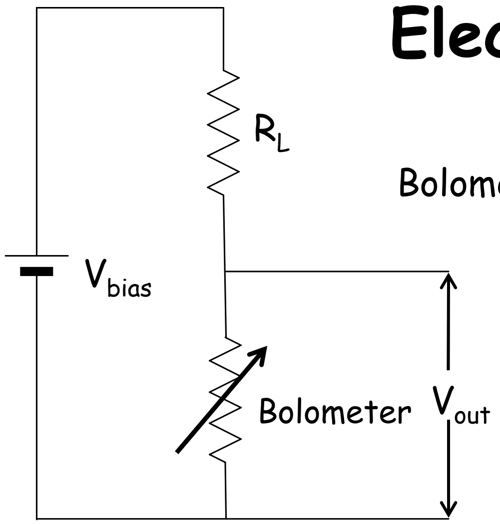



Chip of doped silicon or germanium

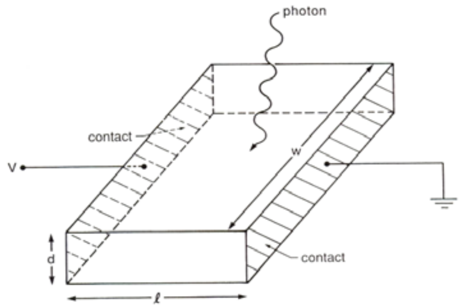
- High input impedance amplifier measures the voltage
- Voltage depends on resistance
- Resistance depends on temperature



# Electrical Properties




Bolometers measure the resistance R via $V_{out}$.




From the previous lecture we know: $R_d = \frac{1}{\sigma}\frac{l}{wd} = \frac{1}{qn_0\mu_n}\frac{l}{wd}$

and the number of charge carriers is: $n_0 = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \cdot e^{-(E_C - E_F)/kT}$

Hence, R depends on the temperature as $\boxed{R = R_0 T^{-3/2} e^{B/T}}$
where $R_0$ and $B$ are constants.

# Electrical Properties (2)

• Bolometers suffer from the same fundamental noise mechanisms as photoconductors *plus* the noise arising from thermal fluctuations
→ requires very low operating temperatures.

• To obtain good properties at T < 5K the semiconductor must be doped more heavily than assumed by $R = R_0 T^{-3/2} e^{B/T}$ to make hopping the dominant mode.

Hopping means that the wavefunctions ψ of the impurity atoms overlap →
Electrons don't have to enter the conduction band.

# Electrical Properties (3)

The resistance for hopping can be described by $R = R_0 e^{(\Delta/T)^{\xi}}$

where $\xi \approx \frac{1}{2}$, and $\Delta$ is a characteristic temperature ≈ 4 – 10 K.

[The temperature coefficient is the relative change of a physical property when the temperature is changed by 1 K]

→ The temperature coefficient of resistance is defined as: $\alpha(T) = \frac{1}{R}\frac{dR}{dT}$

With the above relation we get for **T « Δ** :

$$\alpha(T) = \frac{1}{R}\frac{dR}{dT} = \frac{1}{R_0 e^{(\Delta/T)^{1/2}}} \frac{d\left(R_0 e^{(\Delta/T)^{1/2}}\right)}{dT} \approx \boxed{-\frac{1}{2}\left(\frac{\Delta}{T^3}\right)^{1/2}}$$

For **T>Δ** one gets *empirically* that $R = R_0\left(\frac{T}{T_0}\right)^{-A}$ and thus: $\boxed{\alpha(T) \overset{A\approx 4}{\approx} -\frac{A}{T}}$

*However, in both cases α = f(T)*

# Time Response of a Bolometer

We know: electrical power $P_I = I^2 R(T)$, but T is changing

$GT_1 = P_0$ (see above) ➔ $GT_1 = P_I + (dP_I/dT)T_1$

The electrical time constant of a bolometer is:
(see Rieke book p. 243)

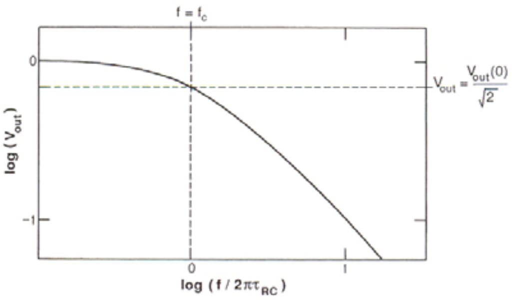
$$\boxed{\tau_E = \frac{C}{G - \alpha(T)P_I}}$$

$\tau_E$ is shorter than the thermal time constant:
(derived above)

$$\tau_T = \frac{C}{G}$$

Exponential response → qualitatively:

$$S(f) = \frac{S(0)}{\left[1 + (2\pi f \tau_E)^2\right]^{1/2}}$$




where S(0) is the low frequency responsivity in units of [V/W]
[see Rieke book equation 1.38 for derivation]

# Responsivity (1)

Let *dR*, *dT*, and *dT* be the changes in resistance, temperature and voltage across the bolometer, caused by the absorbed power *dP*.

$$dV = IdR = I[\alpha(T)RdT] = \alpha(T)VdT = \frac{\alpha(T)VdP}{G-\alpha(T)P_I}$$

with (Rieke p. 244): $$dT = \frac{dP}{G-\alpha(T)P_I}$$

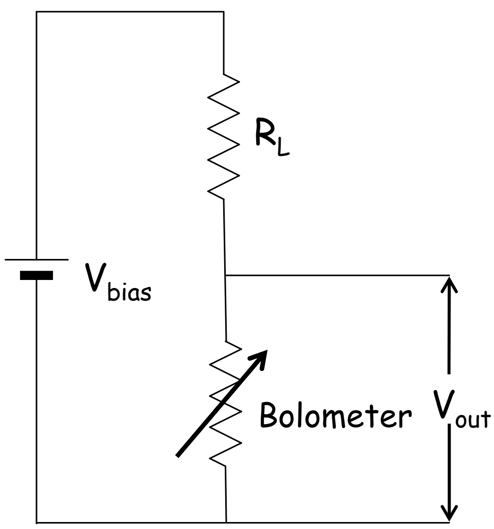
Hence we get: $$S_E \equiv \frac{dV}{dP} = \frac{\alpha(T)V}{G-\alpha(T)P_I}$$

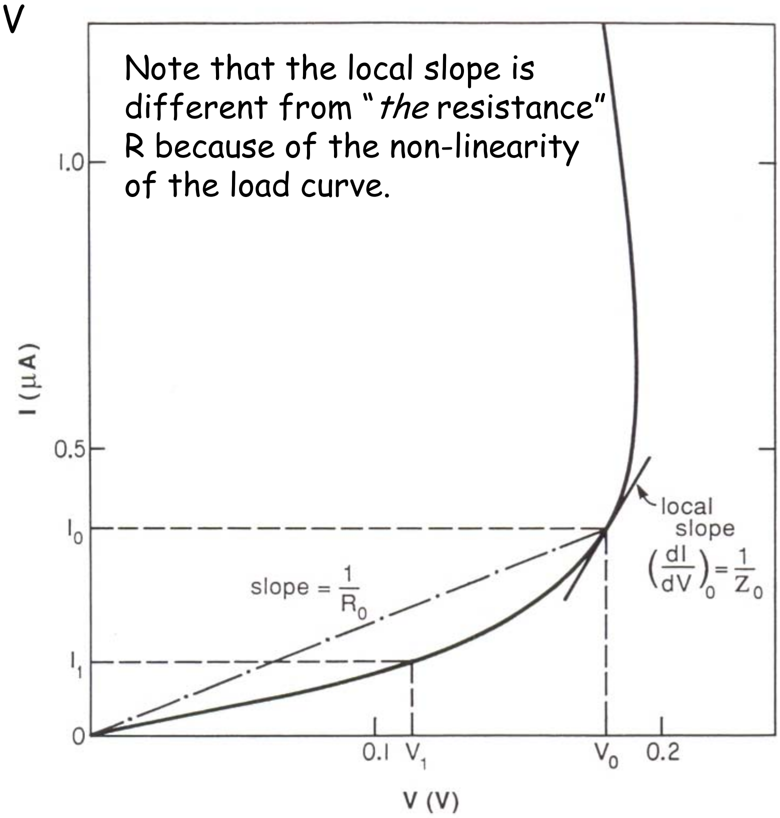
In other words, <u>the responsivity is entirely determined by the electrical properties of the detector</u> (hence, also called electrical responsivity).

# Responsivity (2)

Unfortunately, the detector properties *G* and *a(T)* are not always known and need to be determined by measurement.

→ measure the "load curve" of I—V by adjusting the load resistor $R_L$:

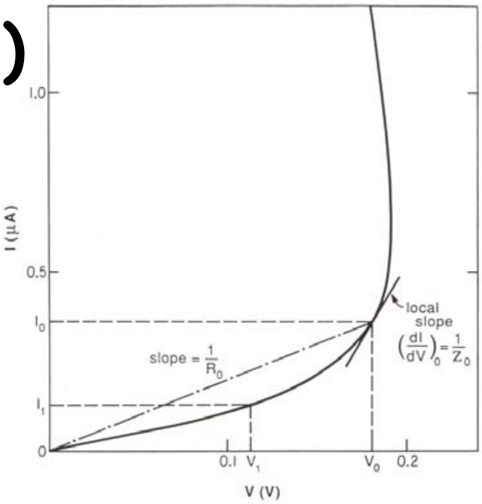


# Responsivity (3)

Goal: determine responsivity at point $V_0$.

- The resistance at that point is $R_0 = V_0 / I_0$
- The local slope is $(dI / dV)_0 = 1 / Z_0$




$$Z = \frac{dV}{dI} = R\frac{d(\log V)}{d(\log I)} = R\frac{\left[\frac{d(\log P)}{d(\log R)} + 1\right]}{\left[\frac{d(\log P)}{d(\log R)} - 1\right]}$$

*(see exercises for derivation)*

$$G \equiv \frac{P}{T} \qquad \alpha(T) = \frac{1}{R}\frac{dR}{dT} \qquad P = V \cdot I = I^2 R$$

$$\frac{d(\log P)}{d(\log R)} = \frac{1}{I^2}\frac{dP}{dR} = \frac{1}{I^2}\frac{dP}{dT}\frac{dT}{dR} = \frac{G}{a(T)I^2R} = \boxed{\frac{G}{a(T)P} \equiv H}$$

$$\Rightarrow Z = R\frac{[H+1]}{[H-1]} \Rightarrow H = \frac{Z+R}{Z-R}$$

*Z* and *R* can be measured → *H* → *G* and *a(T)*

# Responsivity (4)

...back to the electrical responsivity:

$$S_E = \frac{\alpha(T)V}{G - \alpha(T)P_I} = \frac{\alpha(T)V}{a(T)HP - \alpha(T)P} = \frac{V}{P(H-1)} = \frac{V}{P\left(\frac{Z+R}{Z-R} - 1\right)} =$$

$$G = a(T)HP$$

$$= \frac{V(Z-R)}{2RP} = \frac{V}{2P}\left(\frac{Z}{R} - 1\right) = \boxed{\frac{1}{2I}\left(\frac{Z}{R} - 1\right)}$$

On the other hand, if *a(T)* is known *G* = *a(T)HP* permits the determination of the thermal conductance *G* from the load curve.

...and the electrical time constant:

$$\tau_T = \frac{C}{G}$$

$$\tau_E = \frac{C}{G - \alpha(T)P} = \frac{C}{G - \frac{G}{H}} = \frac{\tau_T}{1 - \frac{1}{H}} = \frac{\tau_T}{1 - \frac{Z-R}{Z+R}} = \tau_T\frac{Z+R}{2R}$$

# Responsivity (5)

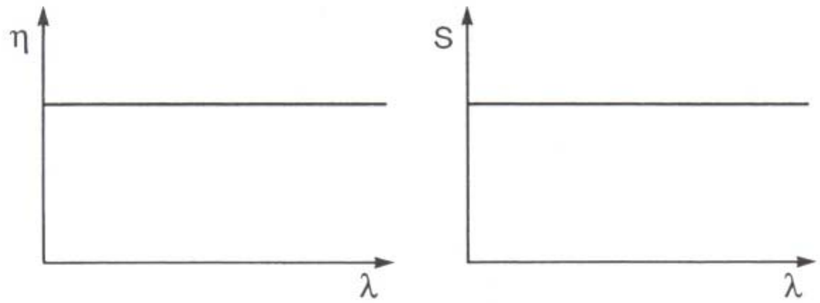
However, Mather's (1982) exact derivation includes a correction factor $(R_L+R)/(R_L+Z)$:

$$\tau_E = \tau_T \left(\frac{Z+R}{2R}\right)\left(\frac{R_L+R}{R_L+Z}\right)$$

This equation can be used to determine the heat capacity $C$ (= $\tau_T G$) of the bolometer in terms of $\tau_E$ [which can be measured from $S(f)$ ].

**So far**: $S_E$ = electrical responsivity; **now**: derive the responsivity to incoming radiation → only a fraction $\eta$ of the incoming energy is absorbed ("QE"):

$$S_R = \eta S_E = \frac{\eta}{2I}\left(\frac{Z}{R}-1\right)$$



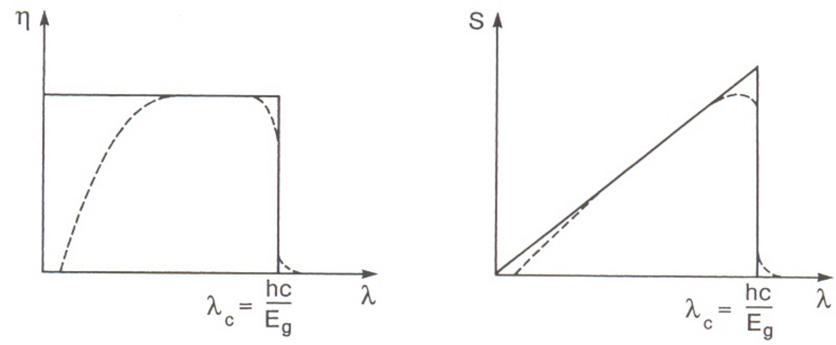

# Responsivity (6) – Comparison

Photoconductor

$$S_{Ph-cond} = \frac{\eta\lambda qG}{hc}$$

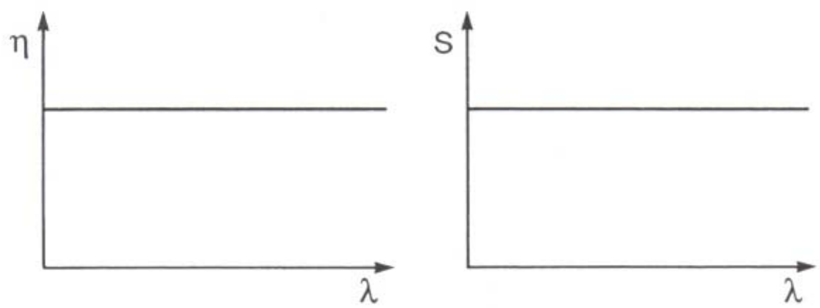
Photodiode:

$$S_{Ph-diod} = \frac{\eta\lambda q}{hc}$$




Bolometer:

$$S_{Bolo} = \frac{\eta}{2I}\left(\frac{Z}{R}-1\right)$$




Note: The bolometer responsivity is independent of the wavelength of operation (as long as the QE η is independent of λ)

# Noise and NEP

• As always, there is Johnson noise, characterized by the noise voltage $V_J$.

• case 1: If $V_J$ is added to the bias voltage → dissipated P increases → R decreases (because α(T)<0) → change in V across the detector decreases.

• case 2: If $V_J$ opposes the bias voltage → dissipated P decreases → R increases → net voltage change decreases.

• In both cases, the detector response opposes the ohmic voltage change resulting from Johnson noise (negative "electrothermal feedback").

→ noise should be less than predicted by $\langle I_J^2 \rangle = \frac{4kT\Delta f}{R}$

In fact ... (Rieke book p. 247f)

# Noise and NEP (2)

1. Johnson noise $NEP_J \approx \begin{cases} GT^2 & \text{for } \alpha(T) \approx T^{-3/2} \\ GT^{3/2} & \quad\;\; \alpha(T) \approx T^{-1} \end{cases}$ ← note the strong temperature dependence

due to fluctuations in the thermal motions of charge carriers (random currents due to Brownian motion).

2. Thermal noise $NEP_T = \frac{\left(4kT^2G\right)^{1/2}}{\eta}$

due to fluctuations of entropy across the thermal link that connects the detector and the heat sink.

3. Photon noise $NEP_{ph} = \frac{hc}{\lambda}\left(\frac{2\varphi}{\eta}\right)^{1/2}$

due to fluctuations in the photon flux (Bolometers are not subject to G-R noise!).

The total NEP is: $NEP = \left(NEP_J^2 + NEP_T^2 + NEP_{ph}^2 + \ldots\right)^{1/2}$