Introduction to low temperature detectors

Manuel Gonzalez - DRTBT 2024
Aussois France

Outline

- Motivation
- History
- Low temperature detectors
    - Coherent
    - Incoherent
        - Quasi-equilibrium
        - Non-equilibrium
- Recent technologies

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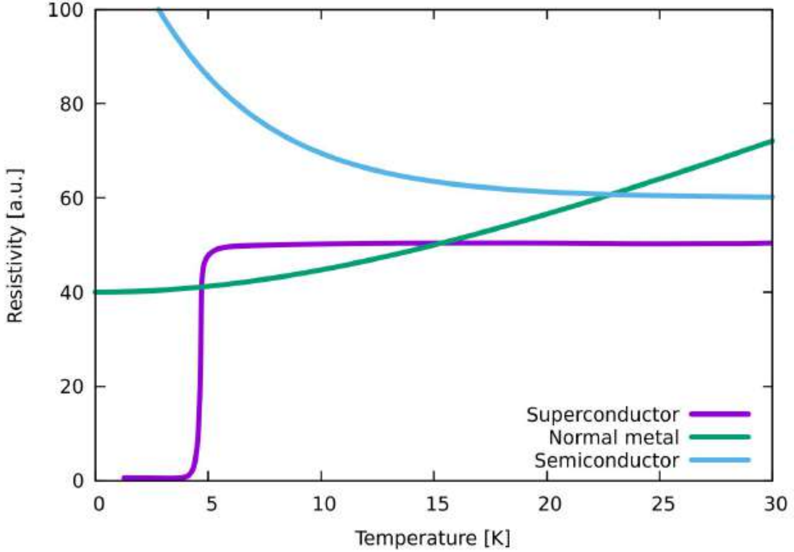
Motivation

Low temperature detectors (LTD) are a must in applications requiring the **lowest noise-equivalent-power** or **the highest energy resolution**.

Interesting physical properties of materials @ cryogenic temperatures:

- **Electric transport**
- Magnetic properties
- Heat capacity
- Superconductivity



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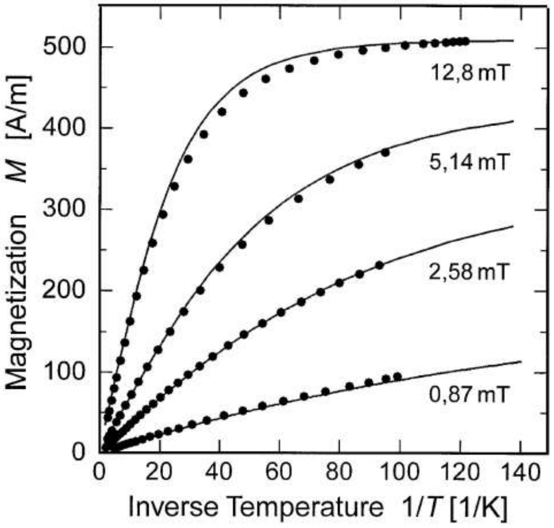
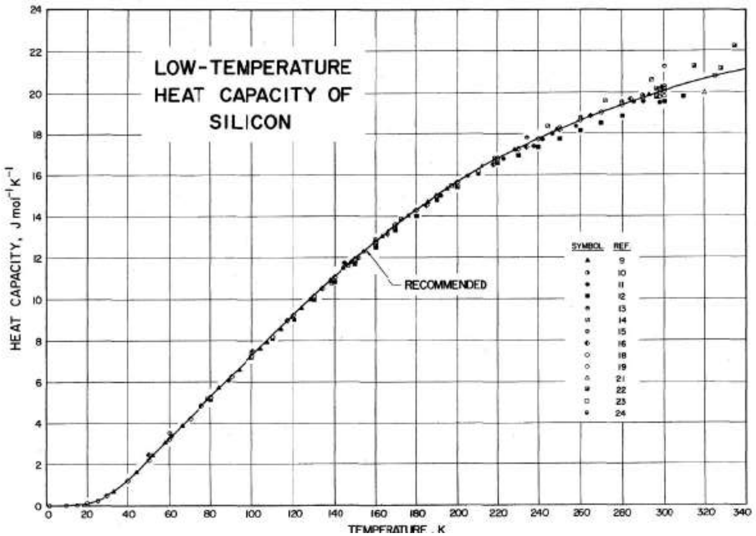


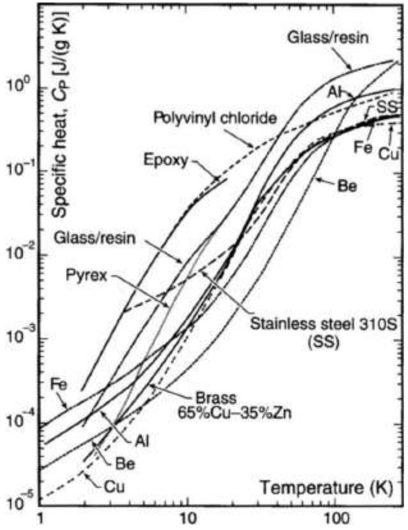
Motivation

Low temperature detectors (LTD) are a must in applications requiring the **lowest noise-equivalent-power** or **the highest energy resolution**.

Interesting physical properties of materials @ cryogenic temperatures:

- Electric transport
- Magnetic properties
- **Thermal properties**
- Superconductivity





P. D. Desai; Thermodynamic Properties of Iron and Silicon. J. Phys. Chem. Ref. Data 1 July 1986; 15 (3): 967–983

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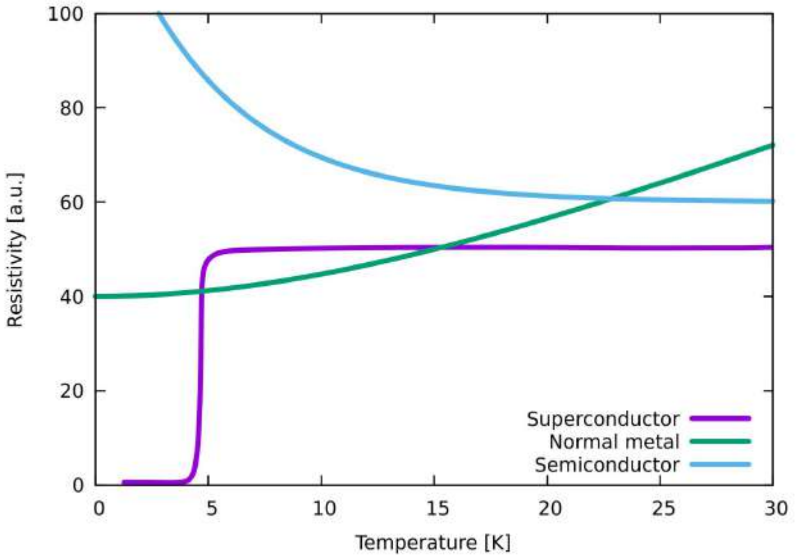
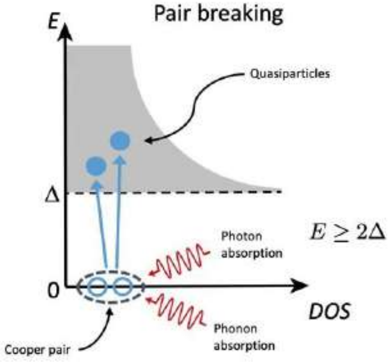
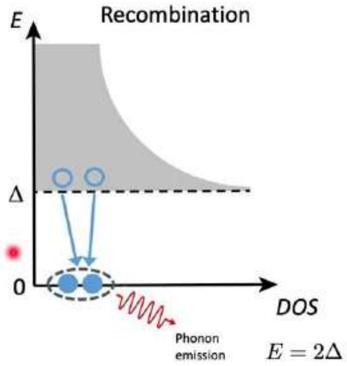
- Heat capacity
- **Superconductivity**



Superconductivity teaser

- Sharp transition at Tc
- Perfect conductor (DC, I<Ic)
- Energy gap of a few meV (depends on Tc)





Drude's model conductance:

$$\sigma = \frac{ne^2\tau}{m(1+\omega^2\tau^2)} - i\frac{ne^2\omega\tau^2}{m(1+\omega^2\tau^2)}$$

In a normal metal ($\tau \to 10^{-14}$s)

In SC electrons bound in Cooper pairs that don't interact with the lattice ($\tau \to \infty$)

This gives rise to the **kinetic inductance**.

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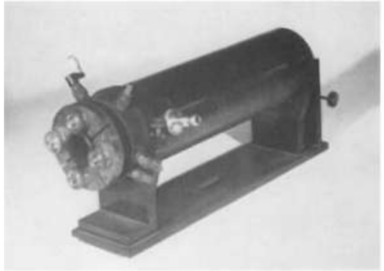
History



- ~1880 Langley First bolometer for IR

Langley’s bolometers were constructed by the instrument maker William Grunow.

Letter to Langley in 1893:

“I feel sorry to perceive my inability to follow up the making of bolometers, on account of the circumstances of my situation, the bad effect on my health (eyes and nerves) caused by the anxiety which the making of bolometers always creates on me, and [by the knowledge] that I should give up the making of them, rather than continue without being able to improve or perfect them…”*

- 1903 Curie/Laborte Calorimetic detection of radioactivity

- 1935 Simon Low temperature enhances performance

  “The sensitivity [] can be increased by many orders of magnitude by working at very low temperatures”

- ~1940 Andrews Superconducting transition detector

*Samuel Pierpont Langley and his Contributions to the Empirical Basis of Black-Body Radiation

History - Good ideas are usually old

JULY, 1942 R. S. I. VOLUME 13

Attenuated Superconductors

I. For Measuring Infra-Red Radiation

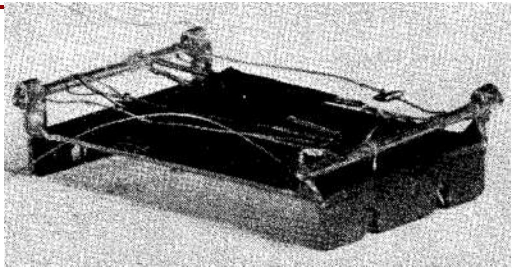
D. H. ANDREWS, W. F. BRUCKSCH, JR., W. T. ZIEGLER, AND E. R. BLANCHARD
Chemistry Department, The Johns Hopkins University, Baltimore, Maryland
(Received February 27, 1942)

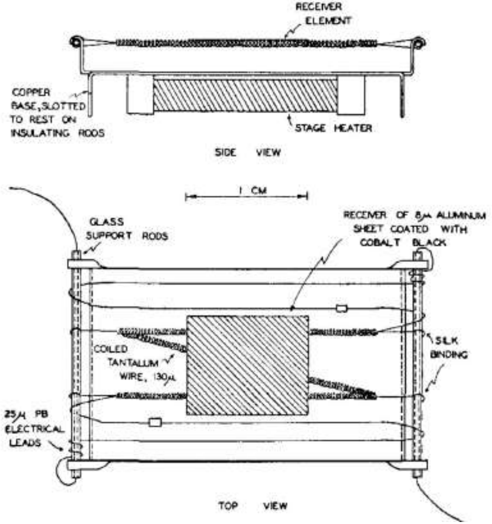
An apparatus for measuring infra-red radiation has been constructed of fine tantalum wire, operating at a temperature of 3.22–3.23°K in the transition zone between superconduction and normal conduction. The tantalum coil is mounted on a thermostated plate with temperature electrically controlled and operates in a special self-regulating shunt circuit by which its own temperature is automatically maintained constant. The ratio of developed electrical potential to radiation flux received is 150 μv (erg cm^{-2} sec.$^{-1}$)$^{-1}$. Minimum detectable flux is *ca.* 10^{-3} erg sec.$^{-1}$. Absolute measurements of intensity of radiation from sources at temperatures between 24° and 55° are consistent with the Stefan-Boltzmann law showing that instrument corrections for reflectivity, window-absorption, and changes with wave-length are very small.

ALTHOUGH superconductivity has been studied extensively for a number of years, no use has ever been made of the striking possibilities which it presents for the measurement of very small temperature changes and the detection of minute quantities of energy.[1,2] The advantages in using superconductivity for such purposes may best be seen by reviewing briefly the essential problems in the measurement of radiant energy.

Electrical detectors of radiant energy, such as bolometers and thermopiles, consist, functionally, of two elements: a solid body, called the receiver, which absorbs the radiation to be measured and is warmed thereby, and a sensitive thermometer which measures the temperature

[1] D. H. Andrews, *American Philosophical Society Year Book* (1938), p. 132.
[2] A. Goetz, Phys. Rev. **55**, 1270 (1939).





D. H. Andrews, W. F. Brucksch, W. T. Ziegler, E. R. Blanchard; Attenuated Superconductors I. For Measuring Infra-Red Radiation. Rev. Sci. Instrum. 1 July 1942; 13 (7): 281–292.

Present day

Big community of scientist

Pushing the limits of performances

Moving towards large arrays

Large variety of designs and techniques

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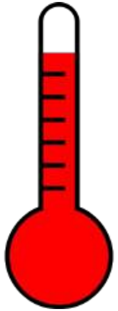
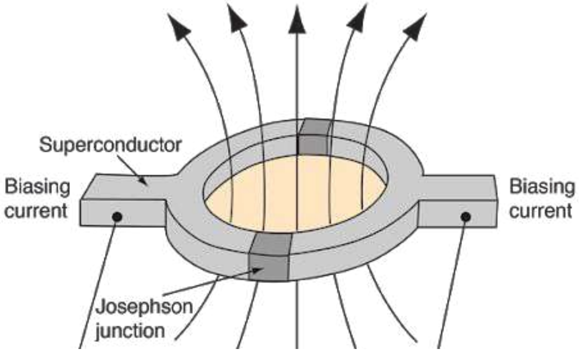
LTDs toy model

Radiation coupling element: antenna, absorber, massive crystal…

Sensor: thermometer (SC, semiconductor, paramagnetic, etc.), SC resonator, SIS junction

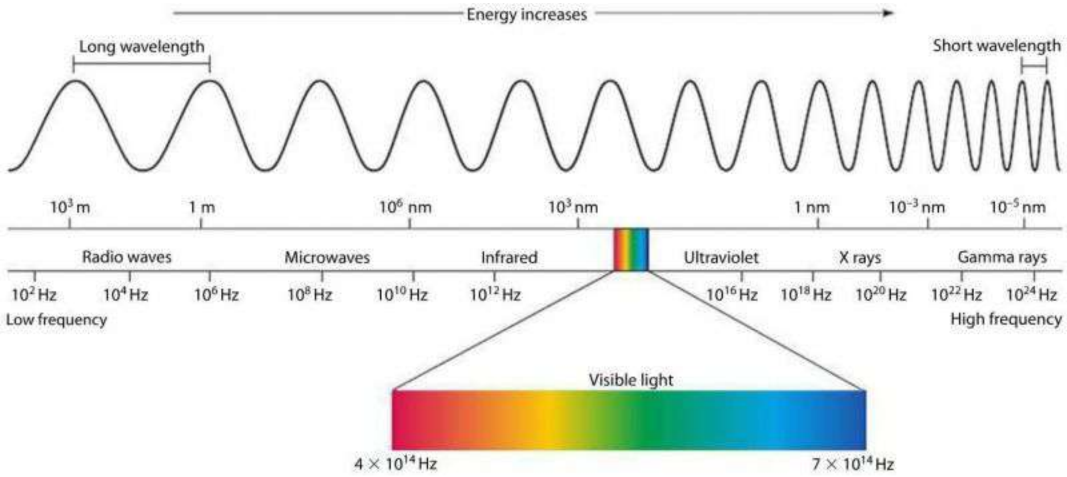
Electronics or mechanical elements necessary for operation and or **readout**: membranes, transmission line, detector geometry, SQUIDs, etc.





LTDs large domain of applications

Electromagnetic spectrum: from mm waves to gamma rays



Particle detection:

- Alpha
- Beta
- Heavy ions
- Dark matter search

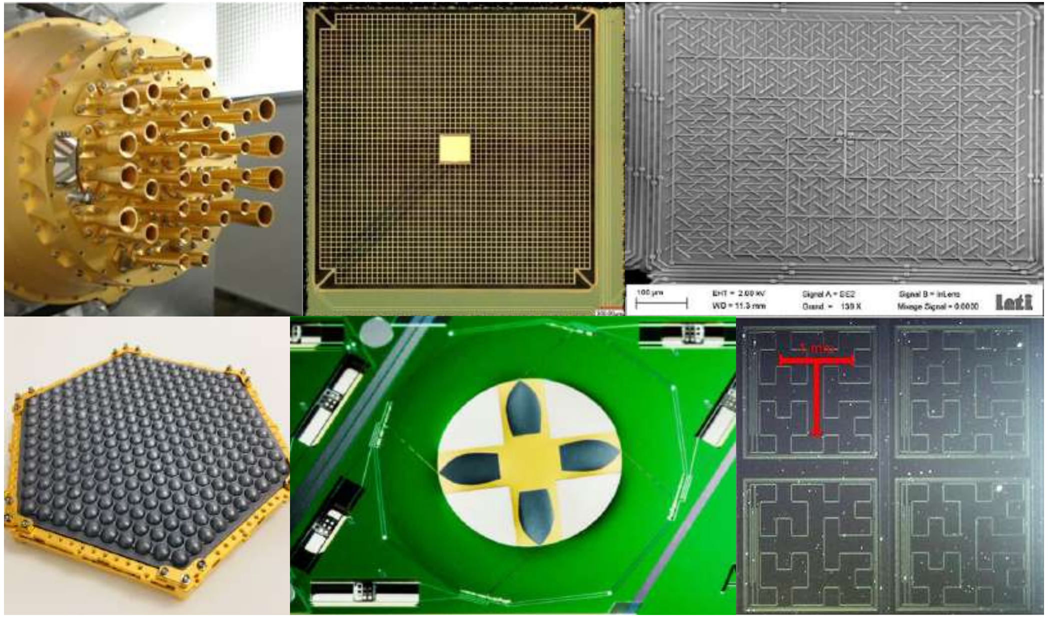
Broad range of applications

- Astro/Particle physics
- Condensed matter/Materials science
- Nuclear physics

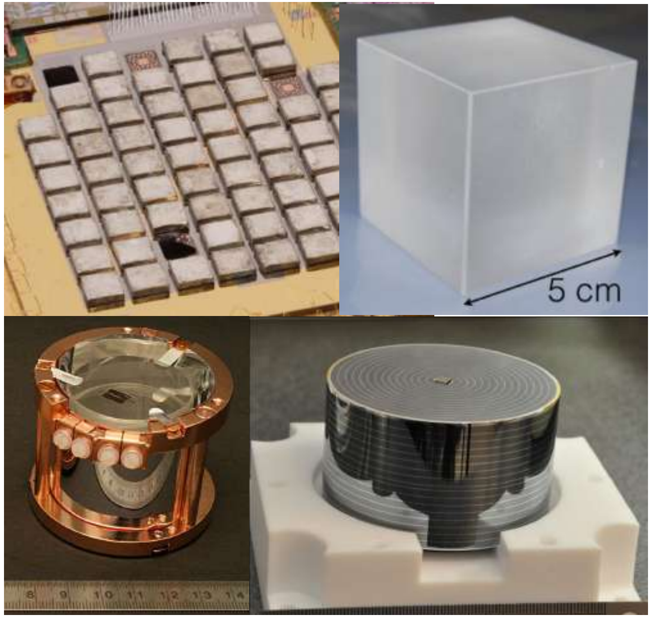
Radiation coupling element(s)

Coupling element is highly dependent on the type of radiation we want to detect!

“Wave-like” behavior



“Particle-like” behavior



Sensors

Coherent detectors

- **Simultaneous amplitude and phase**
- Active devices
- Quantum noise
- Signal can be correlated after detection

Examples:

- Hot electron bolometers
- SIS mixers

Incoherent or direct detectors

- **Quadratic (amplitude) detection**
- Active or passive devices
- Wave nature only for coupling

Examples:

- Bolometers
- Calorimeters
- KIDs
- SNSPDs
- …

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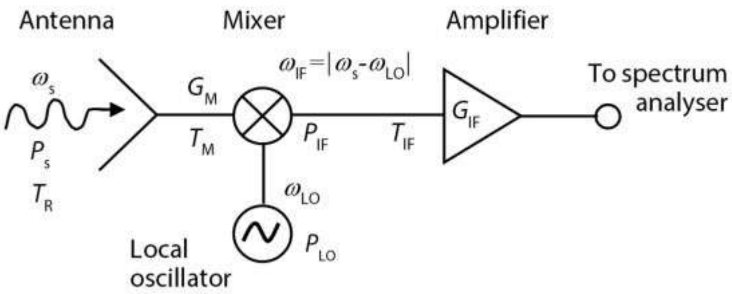
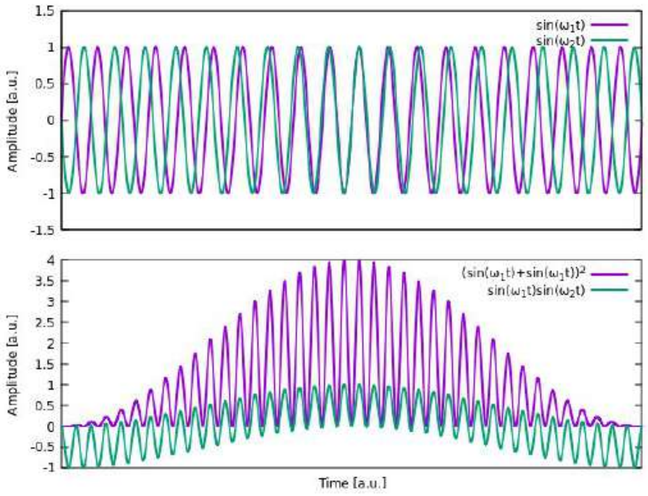
Coherent detectors

Superconducting devices allow for **heterodyne receivers** at higher frequency

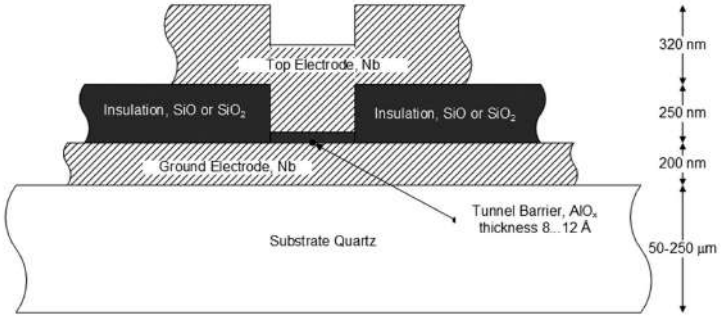
Typically used for **sub-mm and far-IR** astronomy (~100 GHz to 1 THz)



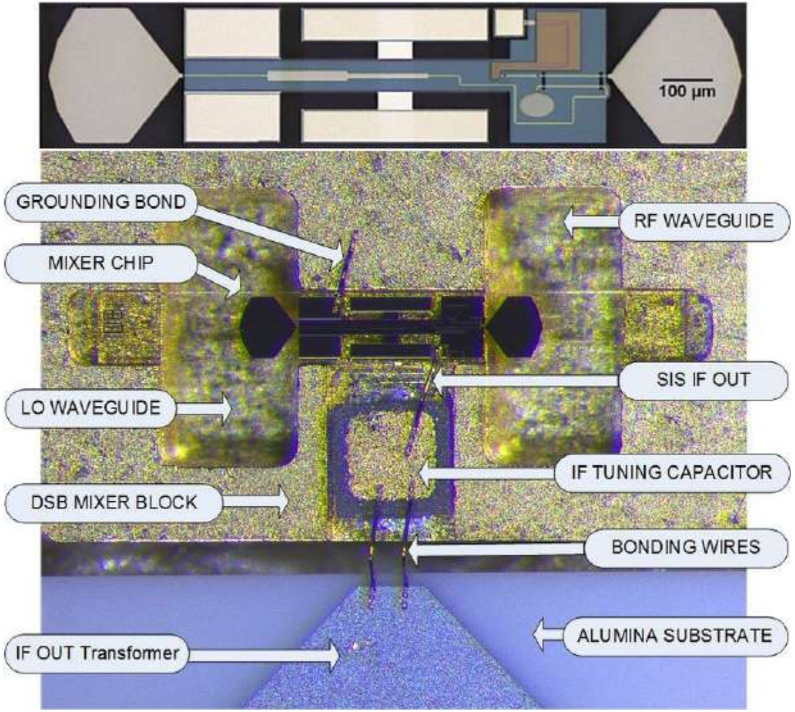


SIS junction mixers

Superconductor–insulator–superconductor tunnel junction (SIS)



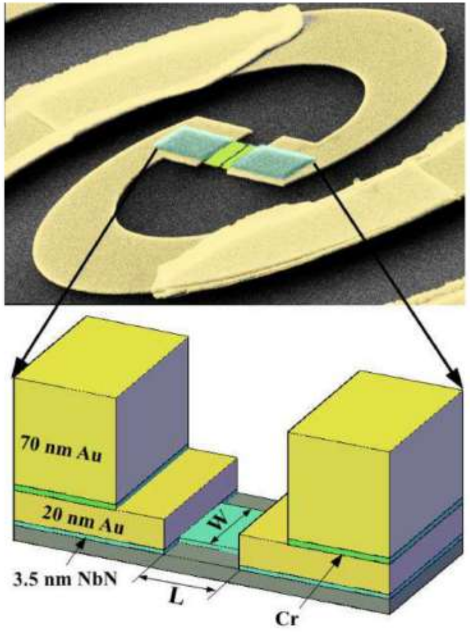
The junction is made of a trilayer sandwich of Nb-Al-Al_xO_y-Nb

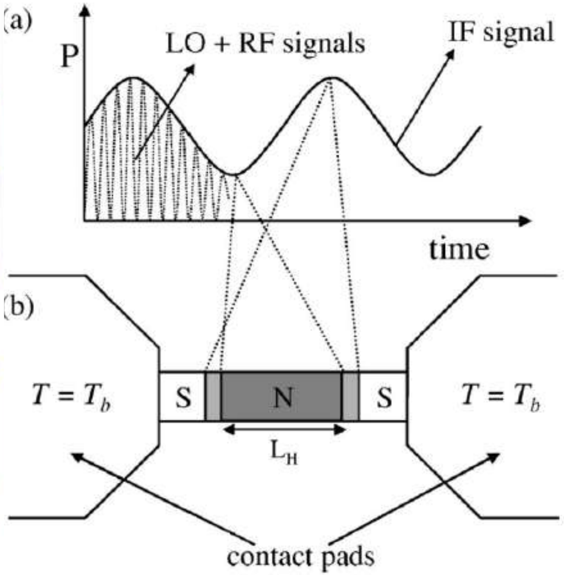


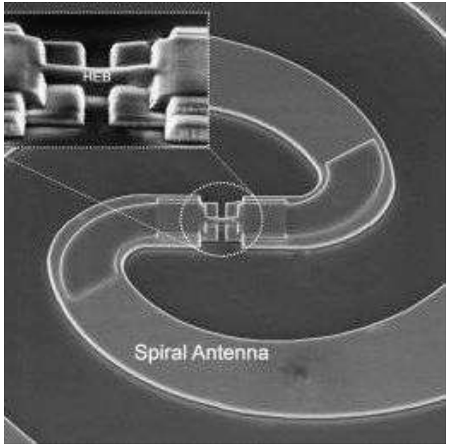
Hot electron bolometer

Decoupling of electron and lattice temperature - 2T model

Bandwidth at the IF determined by the electron phonon relaxation time







physics. In developing the understanding of the physics of hot-electron bolometers, the simplicity of the device has turned into a multi-headed snake, which could only be conquered by the Herculean task of the superconducting community (Fig. 1).

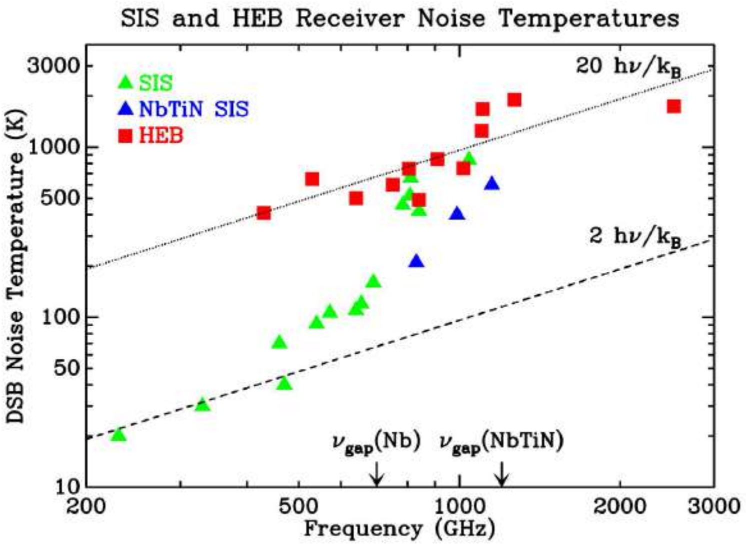
T. M. Klapwijk and A. V. Semenov, "Engineering Physics of Superconducting Hot-Electron Bolometer Mixers," T-TST, vol. 7, no. 6, pp. 627-648, Nov. 2017

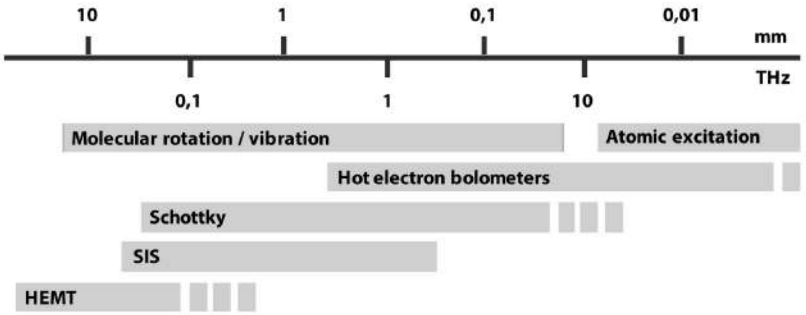
Coherent detectors

Excellent performance in radio astronomy

Limited by quantum noise. Mixer noise temperature: $T_M = hf/k_B \quad T_R = T_M + T_{IF}/G_M$

$$S/N = T_S/T_R\sqrt{\Delta t \Delta f}$$





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Incoherent detectors

Quasi-equilibrium

Mostly all the incoming energy is converted to heat and the dT is measured.

$$S(E) = dT(E) = \frac{E}{C}$$

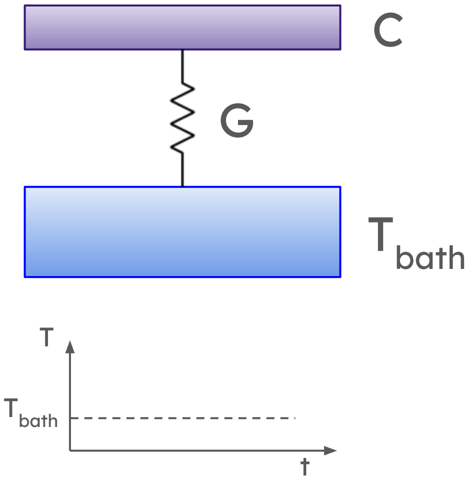
Non-equilibrium

- Fraction of the energy is lost to heat
- Fast
- Cut-off energy

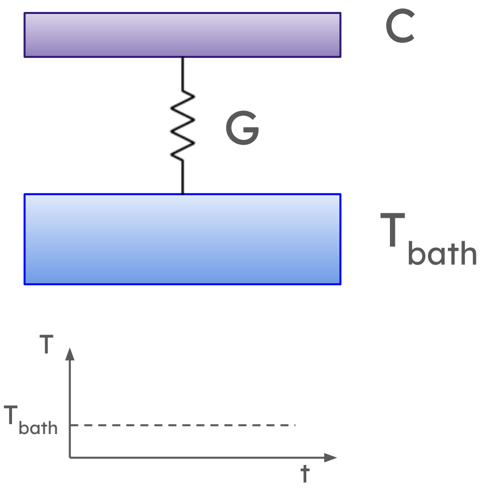
$$S(E) = N(E) \sim \frac{E}{E_{ex}}$$

Bolometer vs calorimeter

Bolometer



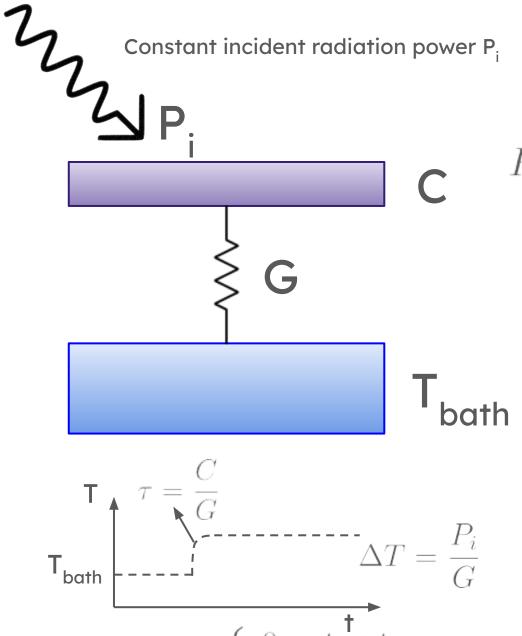
Calorimeter



Bolometer vs calorimeter

Bolometer

Constant incident radiation power P_i



$$P_i(t) = \begin{cases} 0 & t < t_0 \\ P_i & t > t_0 \end{cases}$$

$$P(t) = P_i(t) - G(T(t) - T_{bath})$$

$$C = \frac{\partial E}{\partial T}$$

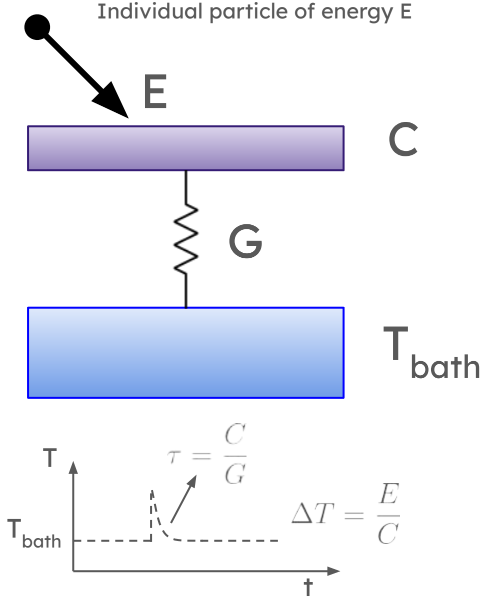
$$P(t) = \frac{\partial E}{\partial T}\frac{dT}{dt} = C\frac{dT}{dt}$$

$$P_i(t) = C\frac{dT(t)}{dt} + G(T(t) - T_{bath})$$

$$\Delta P_i(t) = C\frac{d\Delta T}{dt} + G\Delta T$$

Calorimeter

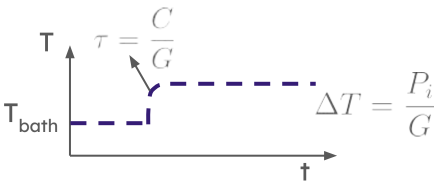
Individual particle of energy E



$$P_i(t) = E\delta(t - t_0)$$

Bolometer vs calorimeter

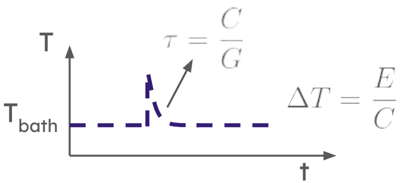
Bolometer



- Detection of a flux of radiation with incident power Pi
- $\Delta T = \frac{P_i}{G}$
- Figure of merit noise equivalent power:

$$NEP = \sqrt{4K_B T^2 G}\,[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

Calorimeter



- Detection of incoming particles with energy E
- $\Delta T = \frac{E}{C}$
- Figure of merit energy resolution:

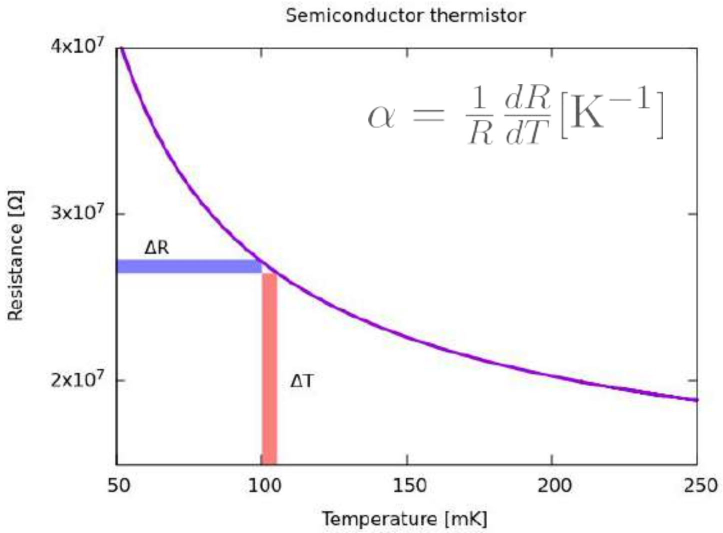
$$\Delta E = \sqrt{K_B T^2 C}\,[\mathrm{eV}]$$

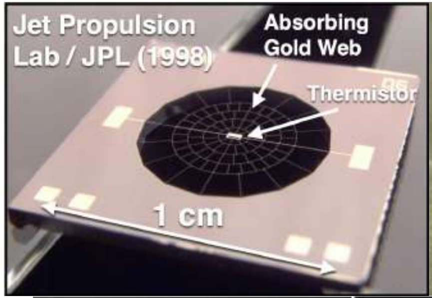
Interest to work at low temperature:

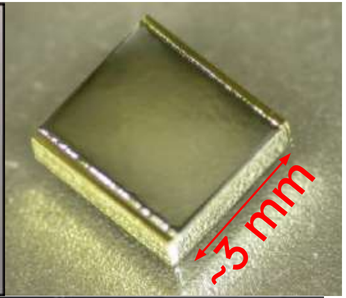
- Improved (fundamental) noise performances or energy resolution
- Faster detectors (lower thermal time constant, to be continued…)

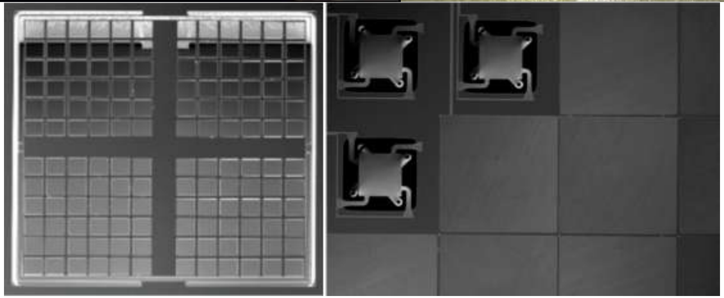
Doped semiconductor detectors

$$R = R_0 \exp \sqrt{T_0/T}$$



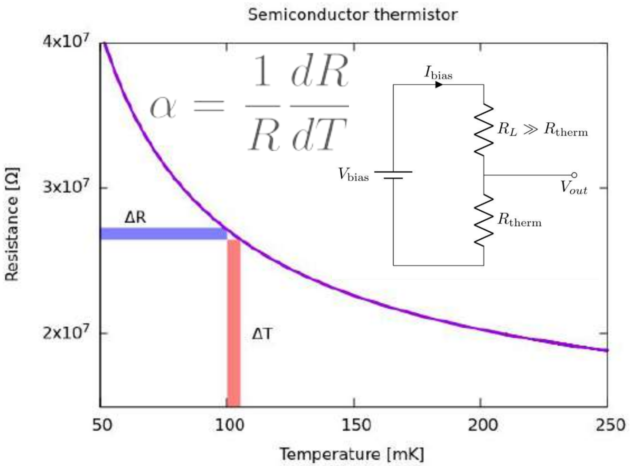


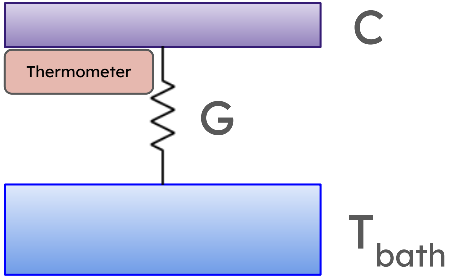




Heavily doped semiconductor (e.g. neutron transmutation doped NTD Ge, ion-implanted Si:P,B) to obtain conductive properties at very low temperatures. Impurities sufficiently close for hopping.

Doped semiconductor detectors - ETF





Electrothermal feedback

$$P_T = P_i - G(T - T_{bath}) + P_J \qquad P_J = IV$$

- if we bias in current $P_J = RI^2$ T↗,R↘,P_J↘,T↘

$$\Delta P_J = I^2 \frac{dR}{dT}\Delta T = \alpha P_J \Delta T$$

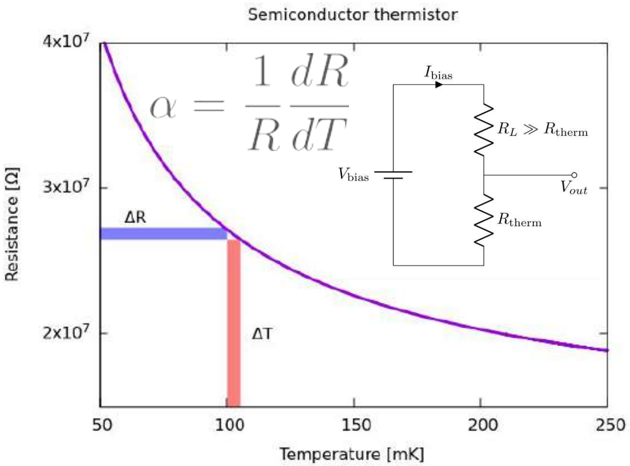
Putting everything together:

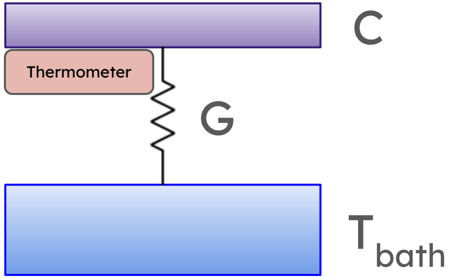
$$\Delta P_i(t) = C\frac{d\Delta T}{dt} + (G - \alpha P_J)\Delta T$$

The effective time constant becomes shorter:

$$\tau_e = \frac{C}{G - \alpha P_J} = \tau \frac{1}{1 - \frac{\alpha P_j}{G}} = \frac{\tau}{1 + \mathcal{L}}$$

Doped semiconductor detectors - Responsivity





We want to calculate the output response to a change in incident power:

$$S = \frac{dV}{dP_i} = \frac{dV}{dR}\frac{dR}{dT}\frac{dT}{dP_i} = I\alpha R\frac{dT}{dP_i} = \alpha V\frac{dT}{dP_i}$$

For a harmonic perturbation of frequency ω:

$$\Delta P_i(t) = \Delta P_i e^{i\omega t} \qquad \Delta P_i(t) = C\frac{d\Delta T}{dt} + (G - \alpha P_J)\Delta T$$

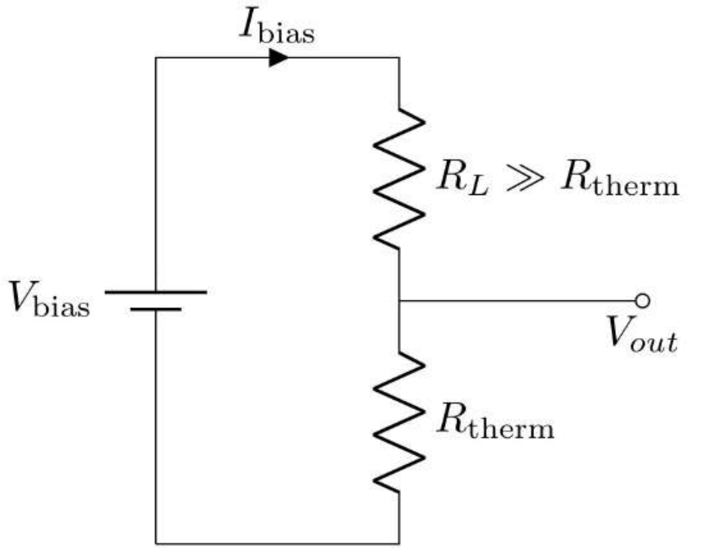
$$\Delta T(t) = \frac{1}{G - \alpha P_J}\frac{1}{1 + i\omega\tau_e}\Delta P_i(t)$$

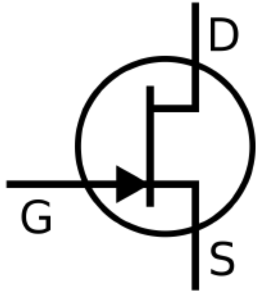
Combining these results:

$$S(\omega) = \frac{\alpha V}{G - \alpha P_J}\frac{1}{1 + i\omega\tau_e} = \frac{\alpha V}{G}\frac{1}{1 + \mathcal{L}}\frac{1}{1 + i\omega\tau_e}$$

Doped semiconductor detectors readout

- High impedance and low noise (tipically JFETs or HEMTs)
- Minimize parasitic capacitance (bandwidth)

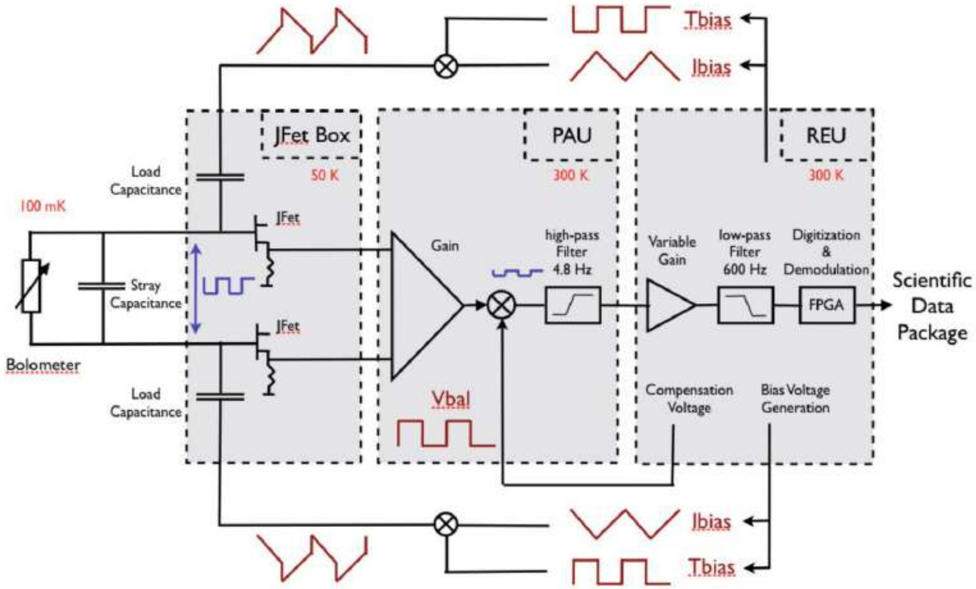




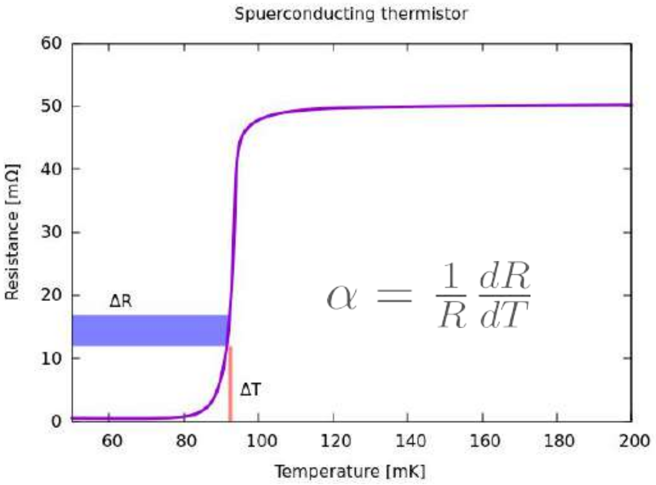
JFET transistor (best noise but ~100 K)
HEMT
CMOS (lower T but 1/f noise)

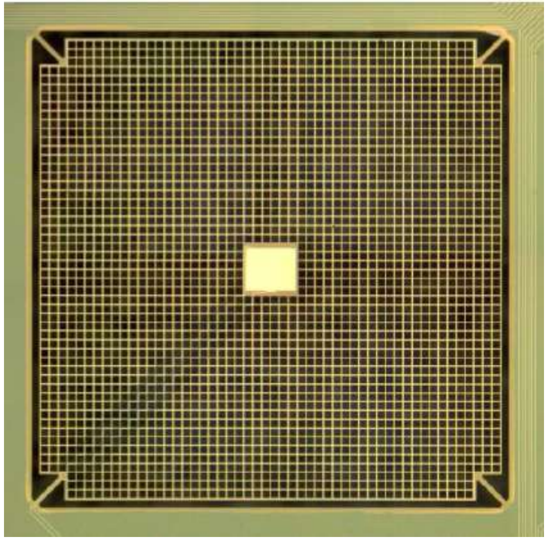
Doped semiconductor detectors readout II

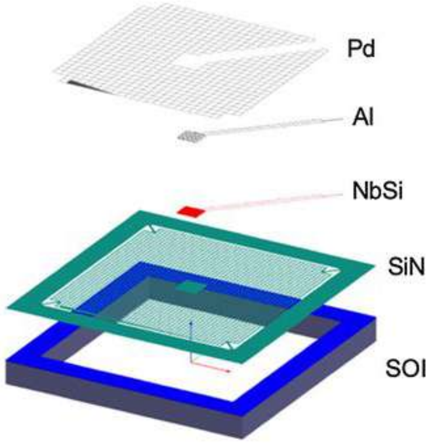
More complex readout example, Planck HFI:



Transition edge sensors (TES)

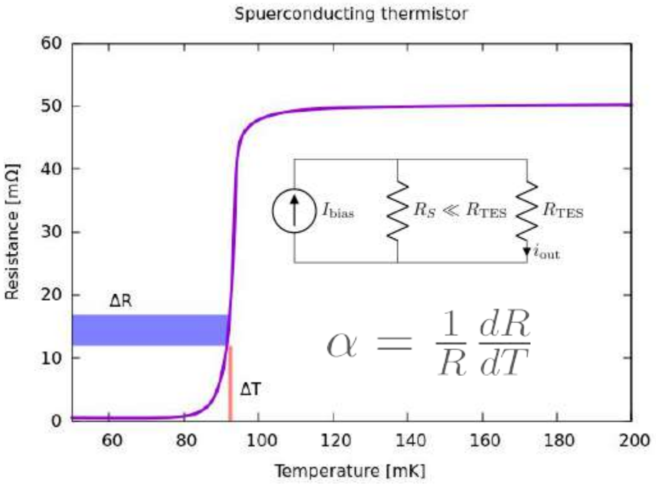


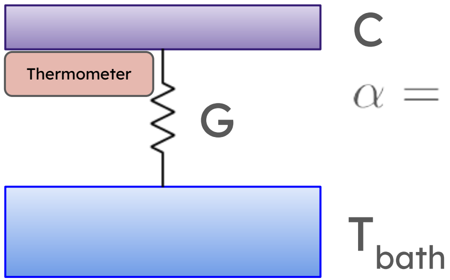




The Tc of the superconducting material determines the operation temperature

TES - strong ETF, time constant





$$\alpha = \frac{1}{R}\frac{dR}{dT}$$

Electrothermal feedback

$$P_T = P_i - G(T - T_{bath}) + P_J \qquad P_J = IV$$

if we bias in voltage $P_J = \frac{V^2}{R}$ (T↗,R↗,P_J↘,T↘):

$$\Delta P_J = -\frac{V^2}{R^2}\frac{dR}{dT}\Delta T = -\alpha P_J \Delta T$$

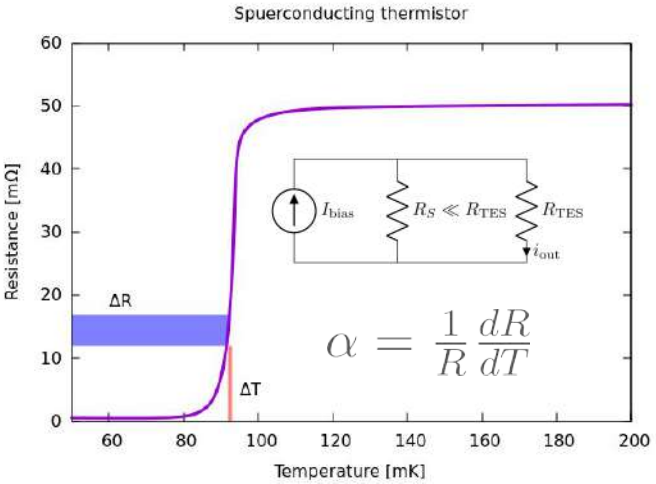
Putting everything together:

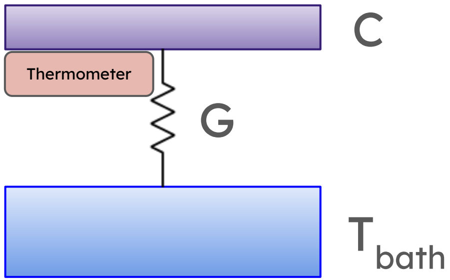
$$\Delta P_i(t) = C\frac{d\Delta T}{dt} + (G + \alpha P_J)\Delta T$$

The effective time constant becomes shorter:

$$\tau_e = \frac{C}{G+\alpha P_J} = \tau\frac{1}{1+\frac{\alpha P_j}{G}} = \frac{\tau}{1+\mathcal{L}}$$

TES - Responsivity





We want to calculate the output response to a change in incident power:

$$S = \frac{dI}{dP_i} = \frac{dI}{dR}\frac{dR}{dT}\frac{dT}{dP_i} = -\frac{V}{R^2}\alpha R\frac{dT}{dP_i} = -\alpha I\frac{dT}{dP_i}$$

For a harmonic perturbation of frequency **ω**:

$$\Delta P_i(t) = \Delta P_i e^{i\omega t} \quad \Delta P_i(t) = C\frac{d\Delta T}{dt} + (G + \alpha P_J)\Delta T$$

$$\Delta T(t) = \frac{1}{G + \alpha P_J}\frac{1}{1 + i\omega\tau_e}\Delta P_i(t)$$

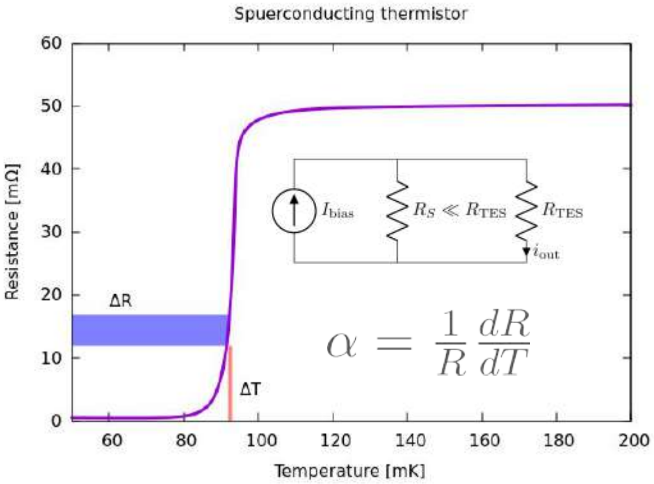
Combining these results:

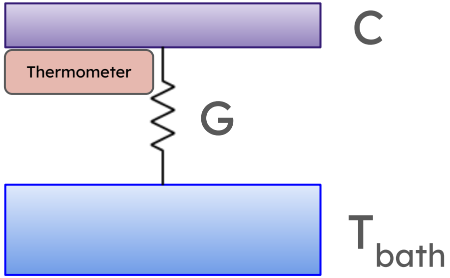
$$S(\omega) = -\frac{\alpha I}{G + \alpha P_J}\frac{1}{1 + i\omega\tau_e} = -\frac{\alpha I}{G}\frac{1}{1 + \mathcal{L}}\frac{1}{1 + i\omega\tau_e}$$

Because **α** is large:

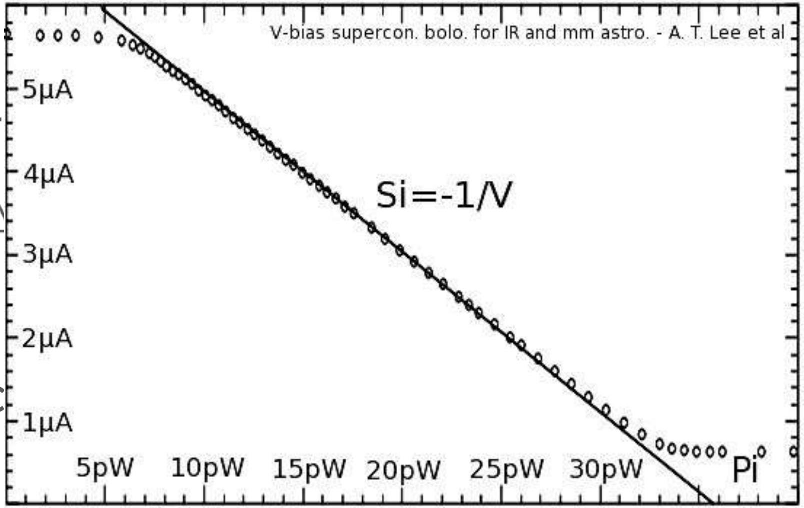
$$\alpha P_J \gg G \Rightarrow S(\omega) = -\frac{1}{V}\frac{1}{1 + i\omega\tau_e}$$

TES - Responsivity





We want to calculate the output response to a change in incident power:



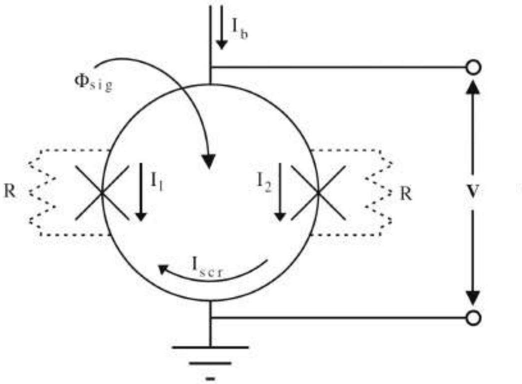
Because α is large:

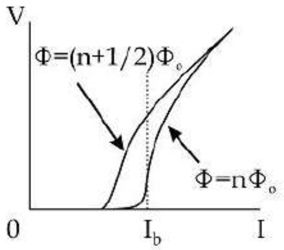
$$\alpha P_J \gg G \Rightarrow S(\omega) = -\frac{1}{V}\frac{1}{1+i\omega\tau_e}$$

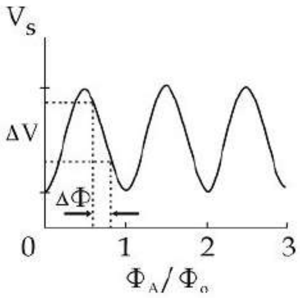
TES readout, SQUID

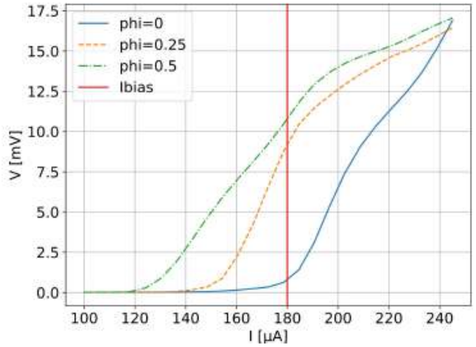
Superconductive Quantum Interference Device (SQUID)

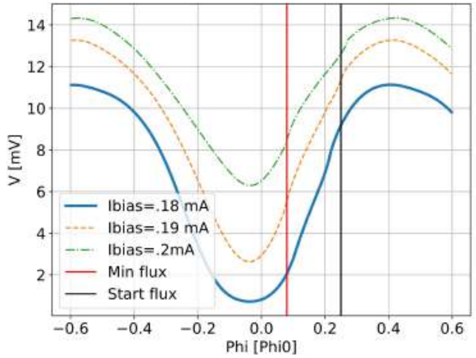
DC SQUID response







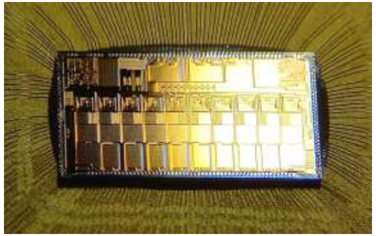


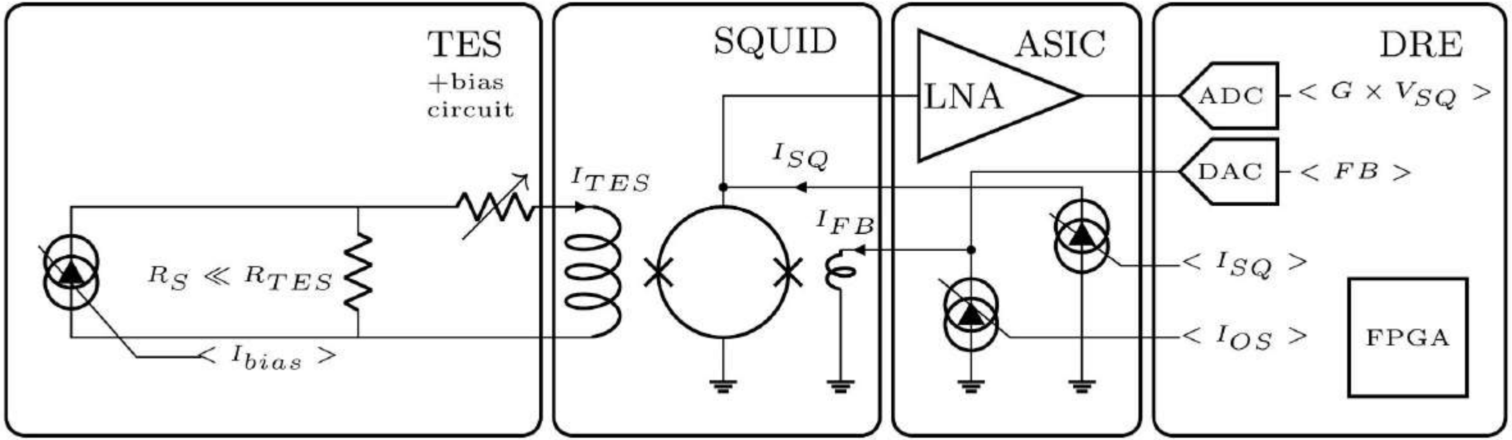


Superconducting magnetic flux quantum: $\Phi_0 = \frac{h}{2e}$

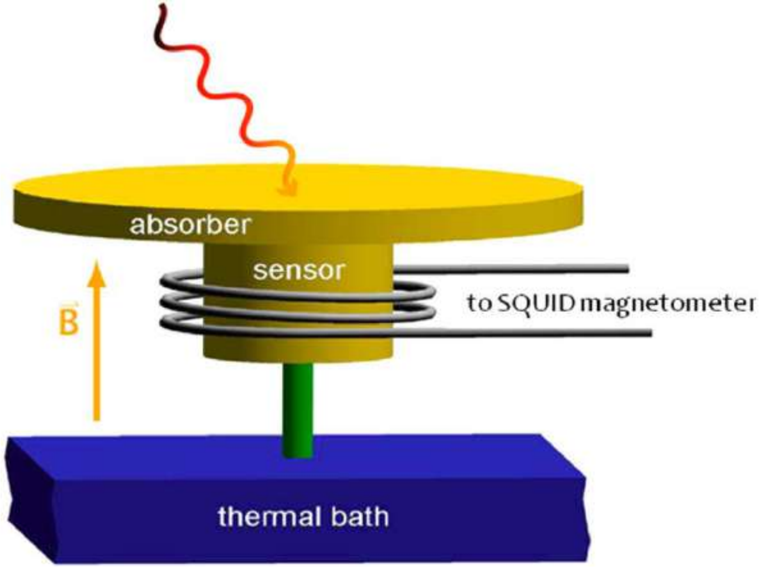
TES Readout

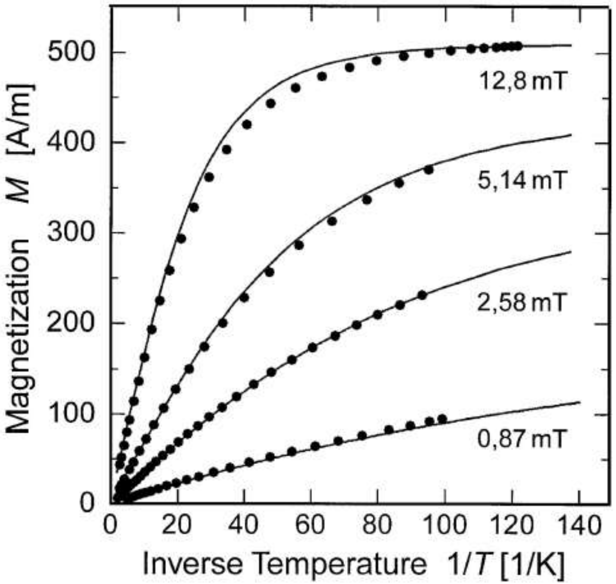
- Measure the TES current with an extremely low impedance SQUID!
- Power dissipation in the shunt
- FLL to linearize the SQUID





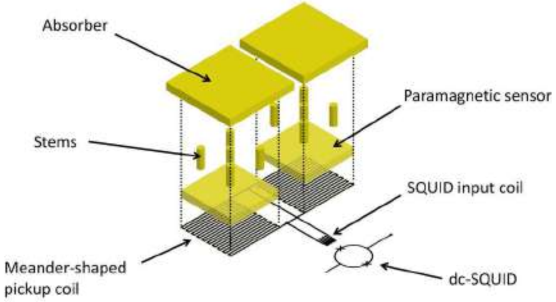
Metallic magnetic calorimeters (MMC)

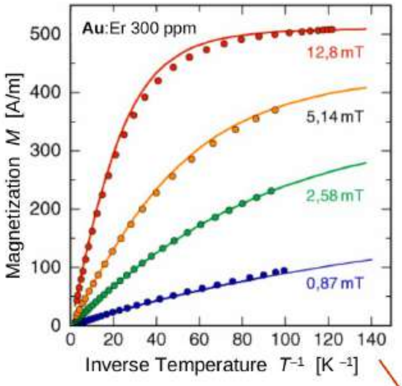


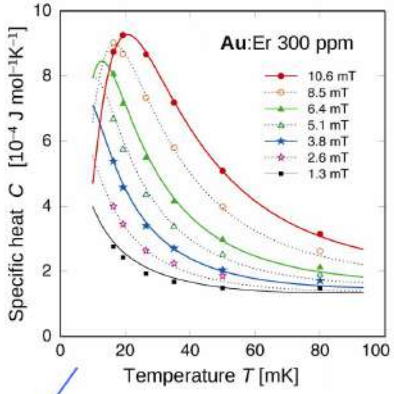


- Paramagnetic sensor typically dilute alloy of Er in Au (few ppms) or in Ag
- Applied field few mT
- Mostly used as calorimeters
- Operates at very low T to get the best response (< 30 mK)

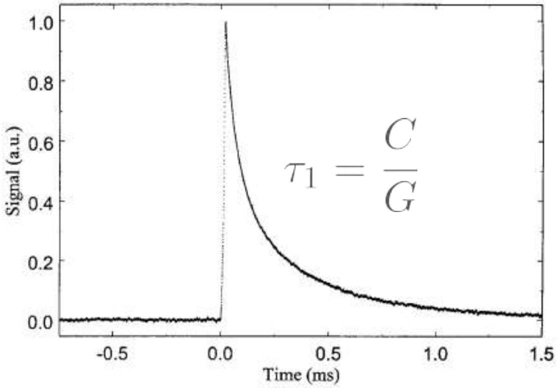
Metallic magnetic calorimeters



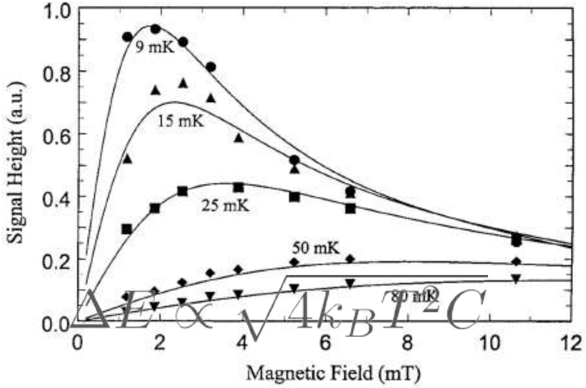




$$\delta \Phi_S \propto \frac{\partial M}{\partial T} \frac{1}{C_{tot}} \delta E$$



$$\tau_1 = \frac{C}{G}$$



$$\Delta E \propto \sqrt{4 k_B T^2 C}$$

Outline

- Motivation
- History and introduction
- Classification of LTDs
- LTD examples:
  - Coherent
  - Quasi-equilibrium
  - Non-equilibrium
- Recent technologies

Kinetic inductance detectors (KID)

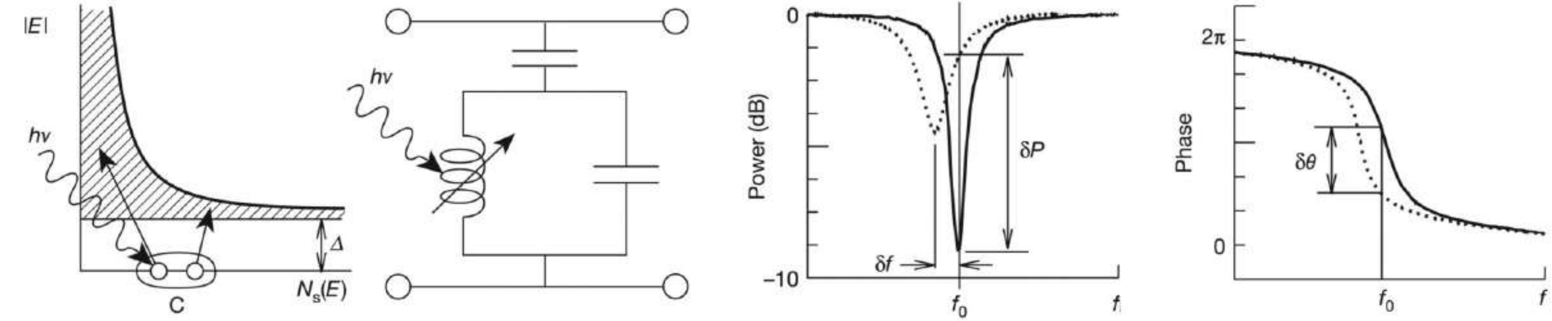
KIDs are based on the complex conductance of SC (Mattis-Bardeen)

For frequencies below the gap: $\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$

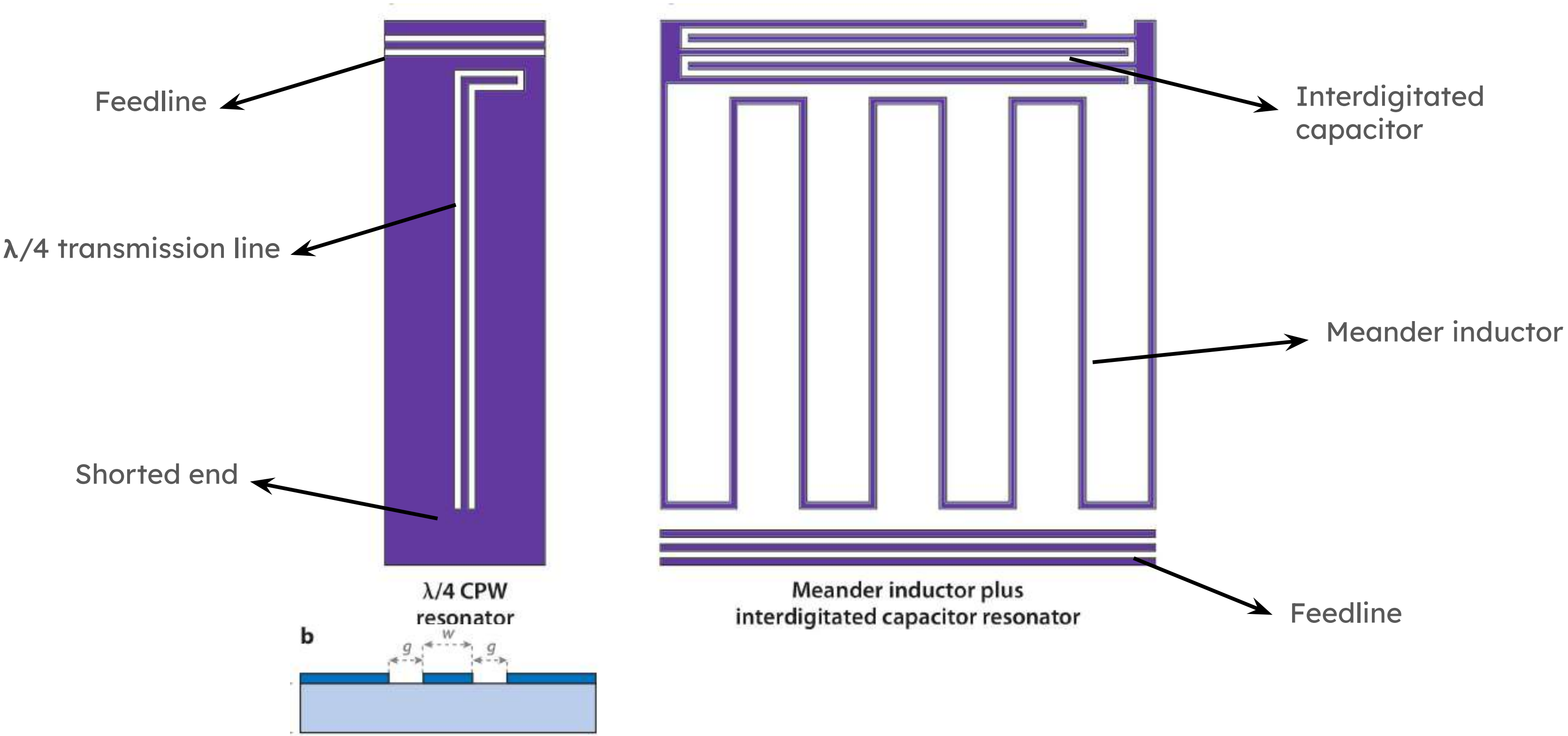
$$n_{qp}(T) \propto e^{-\frac{\Delta(0)}{k_B T}}$$

KIDs are operated at temperatures well below Tc (T < Tc/8): $\begin{cases} \sigma_1 \propto n_{qp} \\ \delta\sigma_2 = \sigma_2(\omega, T) - \sigma_2(\omega, 0) \propto n_{qp} \end{cases}$

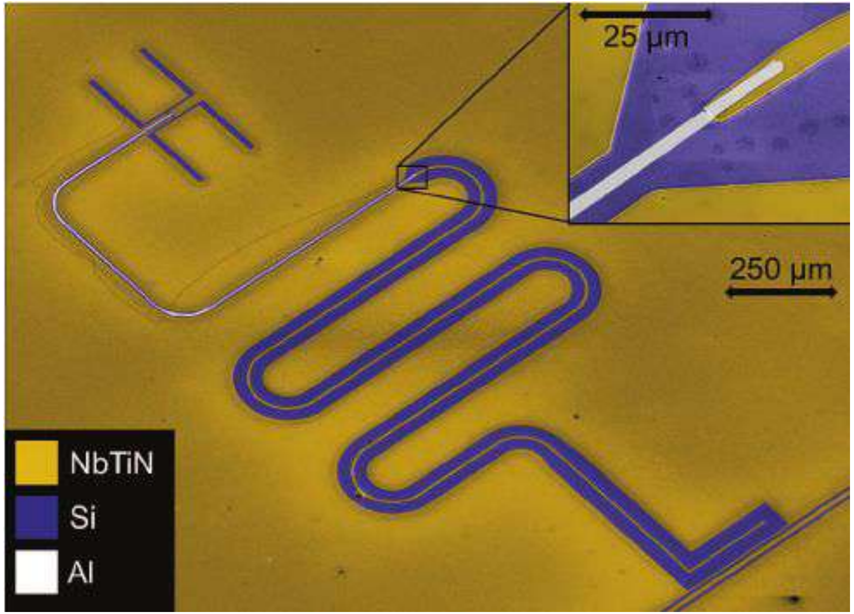
Both the resistive and inductive components of the SC conductivity grow with the quasiparticles density that can be increased by increasing the temperature or by absorbing photons.



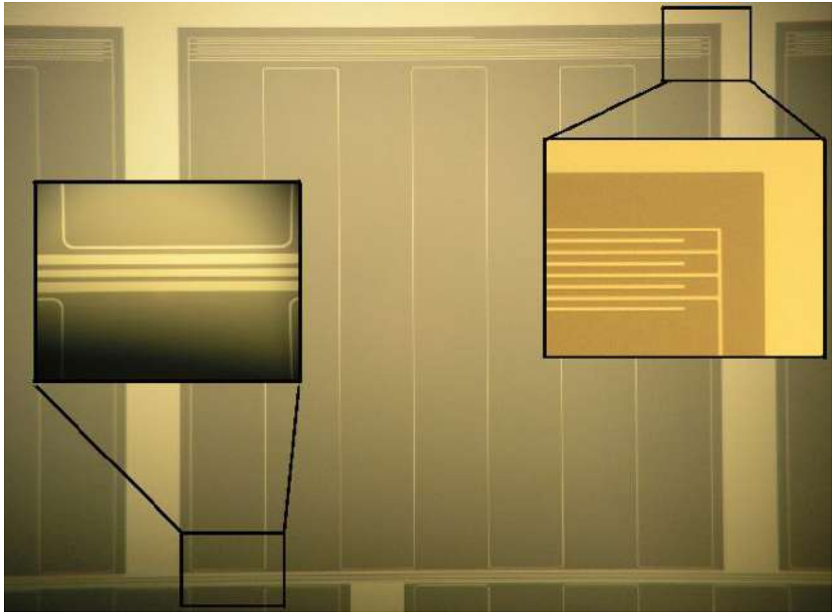
KIDs - Resonator: Distributed vs Lumped element



KIDs - Resonator: Distributed vs Lumped element



Credit: SRON



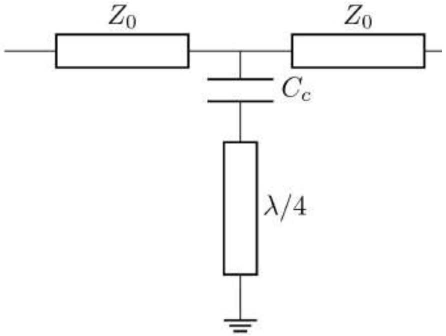
Credit: Institut Neel

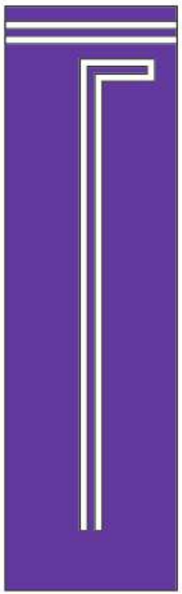
Several materials are commonly used in KIDs.

Relatively high Tc materials, like Nb or NbTiN, can be used in ground planes and antennas

Low-Tc materials are used for the sensor element or the whole structure, Al, TiN, Ti/TiN

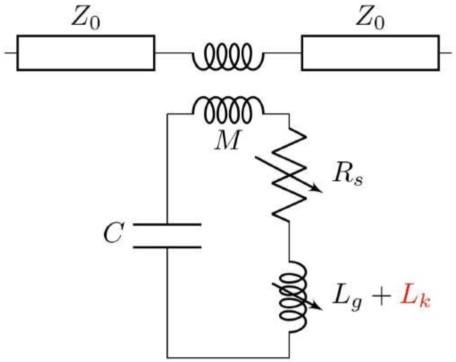
KIDs - Resonator: Distributed vs Lumped element





λ/4 CPW resonator

Meander inductor plus interdigitated capacitor resonator



Lumped element resonator model

Resonance frequency

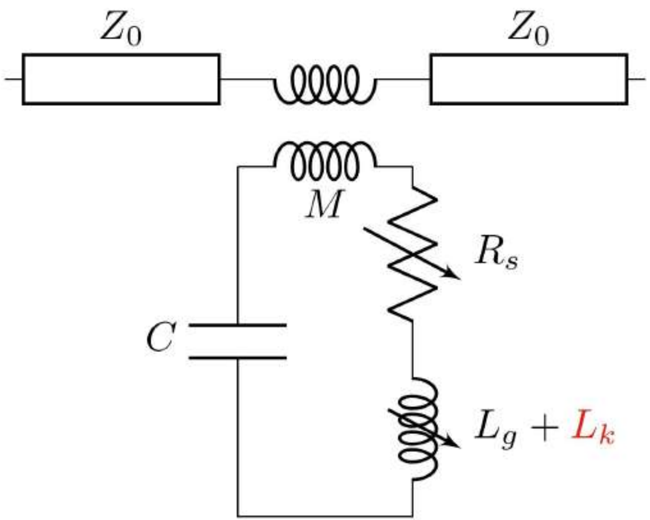
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

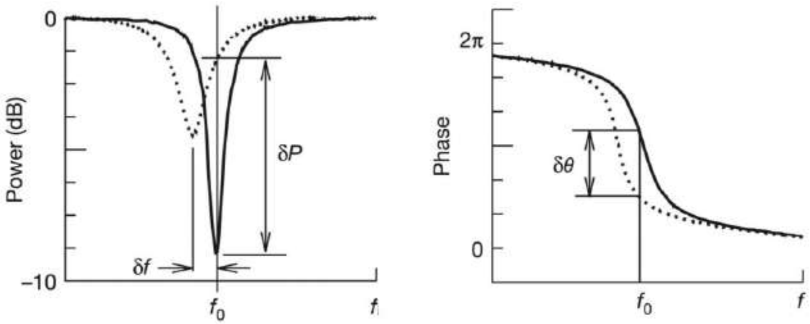
Quality factor:

$$Q = \frac{L}{R}\omega_0$$

When radiation is absorbed:

n_{qp}↗,R↗,L↗,Q↘,ω_0↘

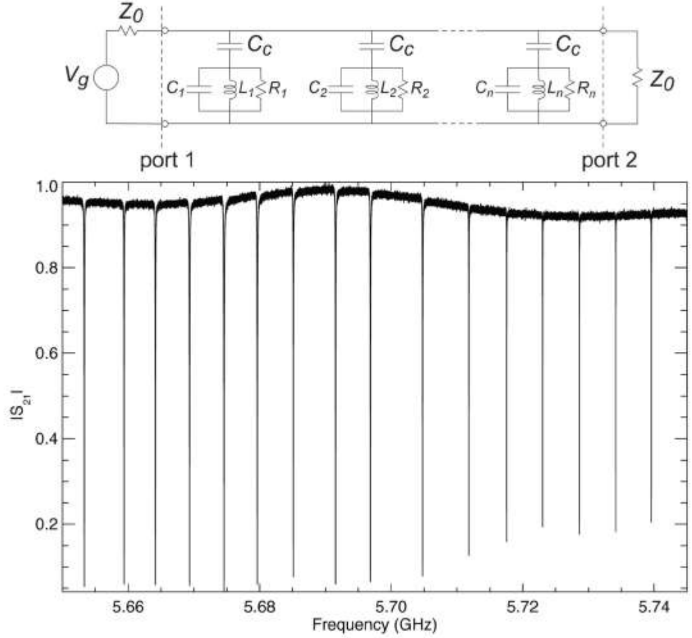




KIDs Multiplexing

One of their main advantages is their natural frequency multiplexing

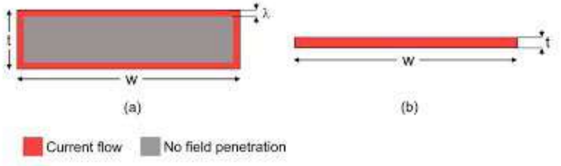
High Q (10 k to 100 k) □ high multiplexing factors (~1000) in single transmission line single amp



KIDs response

Performance and response depends on multiple parameters (material and geometry dependent):

- The kinetic inductance ratio $\alpha = \frac{L_k}{L_{tot}}$ $L_{tot} = L_k + L_M$
- Device volume
- Film thickness (London penetration depth)
- Quasiparticles lifetime (μs to ms)
- …



The minimum detectable frequency is: $\nu_{min} = \frac{2\Delta}{h}$

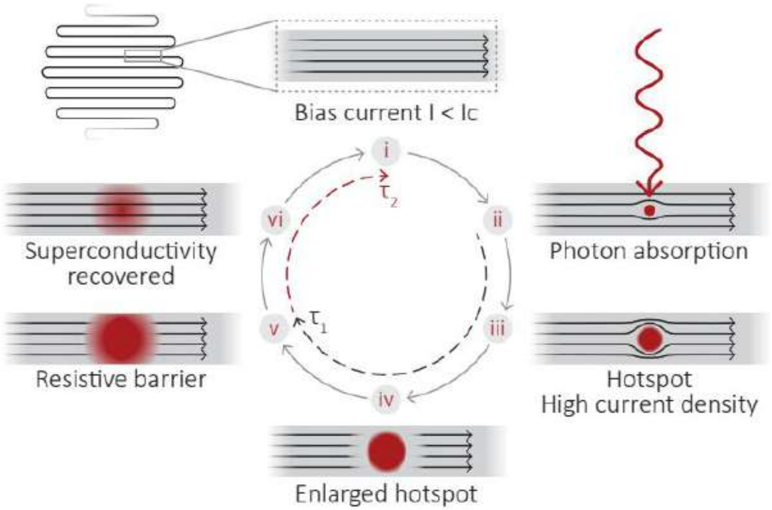
Fundamental noise: Cooper pairs generation-recombination statistics

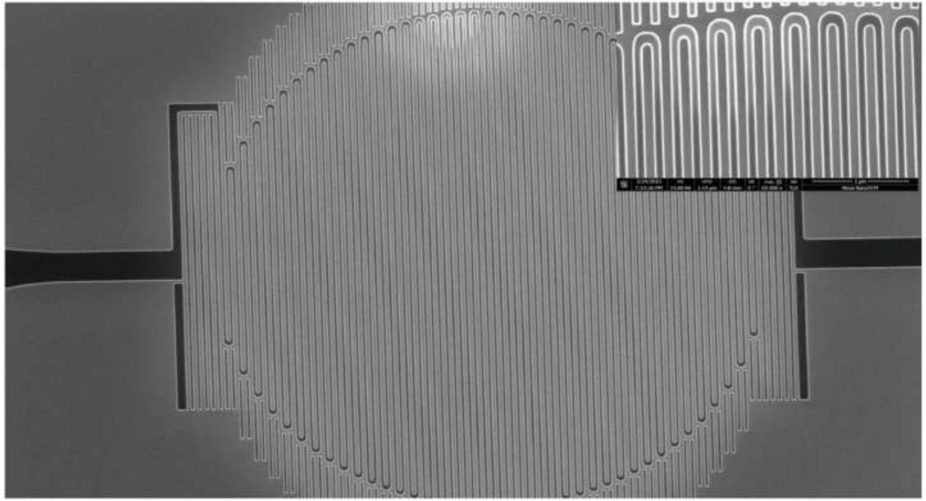
Excess noise: two level systems in SC-dielectric interfaces

SNSPD

~~Superconducting nanowire single photon detector~~ Superconducting strip detector

International Standard IEC 61788-22-1–Superconductivity–Part 22-1: We note the abbreviation SNSPD is often spelled out in literature as a “superconducting nanowire single-photon detector.” The latter is incorrect from the physics point of view, since in all cases presented so far in literature, the active element is a nanostrip that can be regarded a 2-D superconductor, but never a nanowire (1-D element).

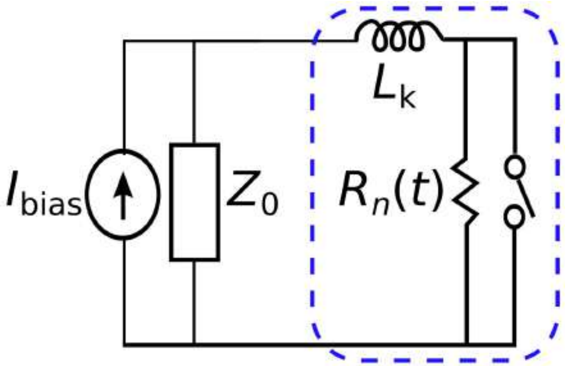


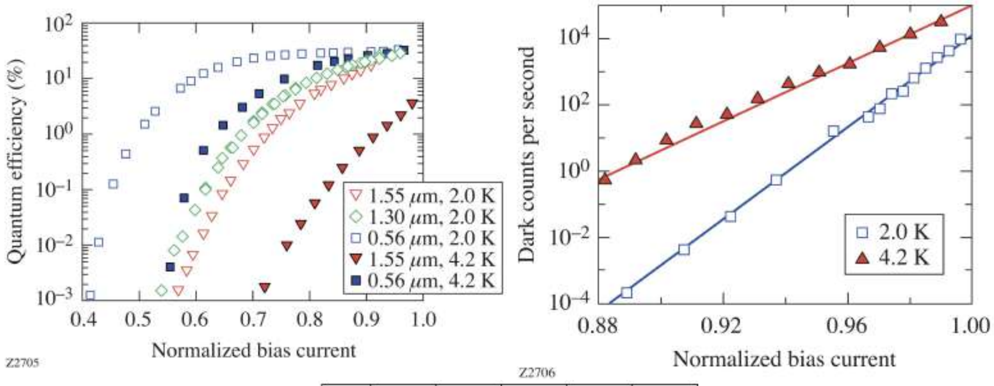


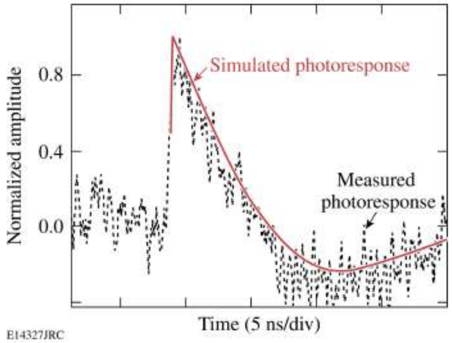
Photon counting on quantum communication and computing in optical and near-IR range

SNSPD response

Operates at T<<Tc



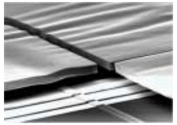




Photon detection:
Switch opens ⇒ voltage across Z_0
Pulse duration 10s of ns

A. Korneev *et al*., "Quantum efficiency and noise equivalent power of nanostructured, NbN, single-photon detectors in the wavelength range from visible to infrared," in *IEEE Transactions on Applied Superconductivity*, vol. 15, no. 2, pp. 571-574, June 2005
Appl. Phys. Lett. 88, 261113 (2006)

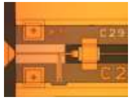
Low temperature detectors



MMC
Equilibrium
Quadratic
Magnetic

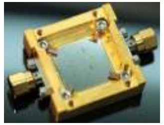
Semi bolometer
Equilibrium
Quadratic
High Z

HEB
Equilibrium
Coherent



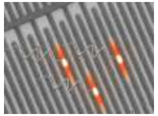
SIS mixer
Non-equil
Coherent

TES
Equilibrium
Quadratic
Low Z

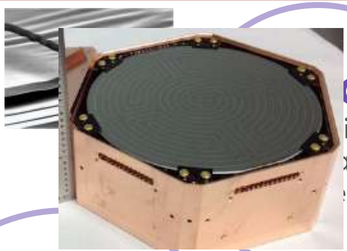


MKIDs
Non-equi
Quadratic
Microwave
MUX

SNSPD
Non-equil
Latching
Photon
counting



Low temperature detectors



C
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Athermal TES
Phonon sensor
Membrane

Semi bolom
Equili
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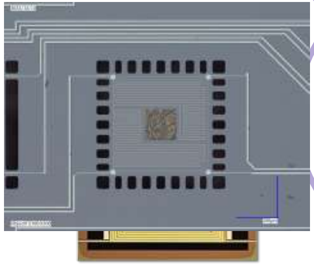
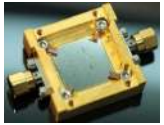
Hi Res TES
Superconducting
High impedance

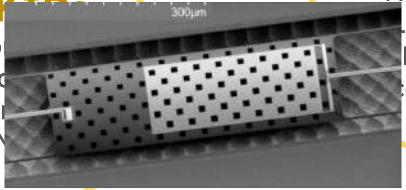


TES
Equilibrium
Quadratic
Low Z

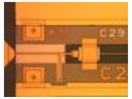
Thermal KIDs
Quasi-equilibri
um
Membrane



KID
No
Qu
Mic
N



AND many more
STJ, MPT, NIS,
nano bolo, etc.



SIS mixer
Non-equil
Coherent

SNSPD
Non-equil
Latching
Photon
counting