Solid-state bolometric sensors

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dépasser les frontières

Astroparticles Solid-State Detectors (ASSD)

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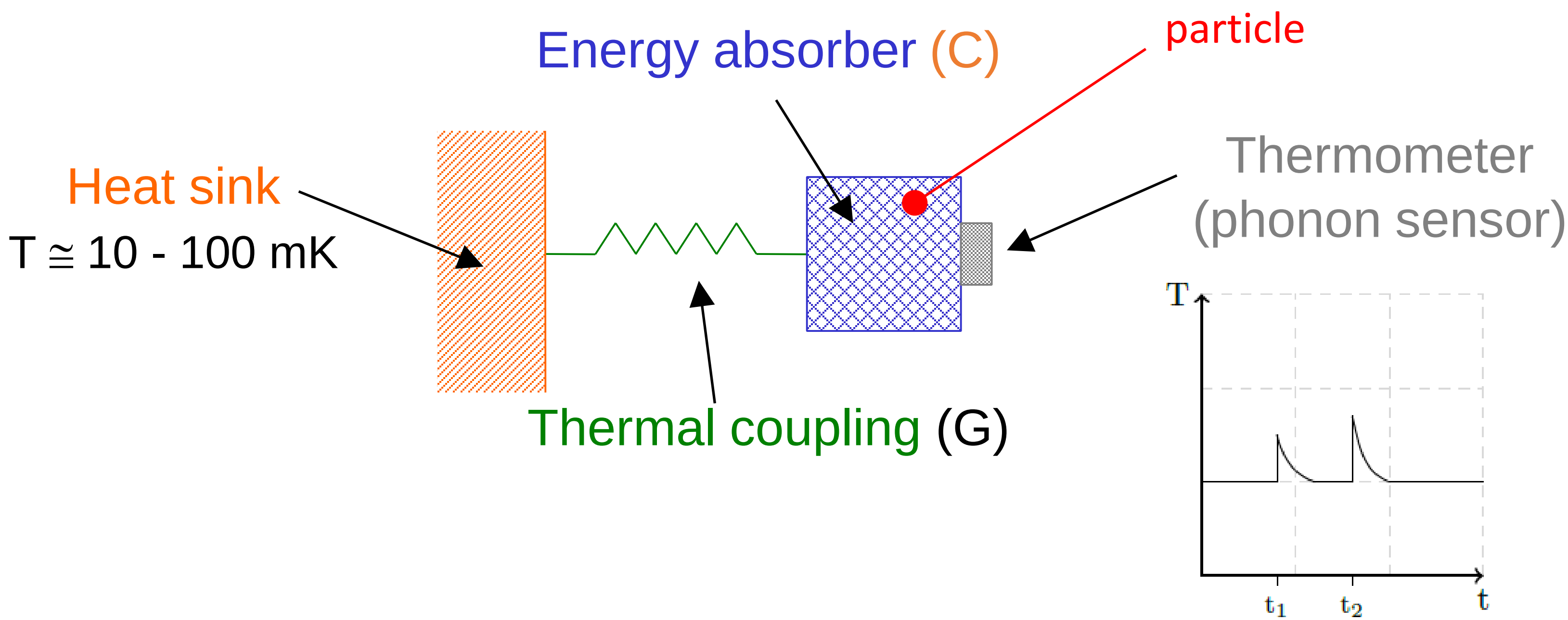
Basic principles of calorimeters



- The only relevant parameter for the energy absorber is the heat capacity C.
- The thermal conductance to the bath G enables the temperature recover.

signal → $\Delta T = E/C$

$\tau = C/G$ ← relaxation time

- Dielectric diamagnetic materials are preferred

→ $C \propto (T/\Theta_D)^3$ (Debye Law)

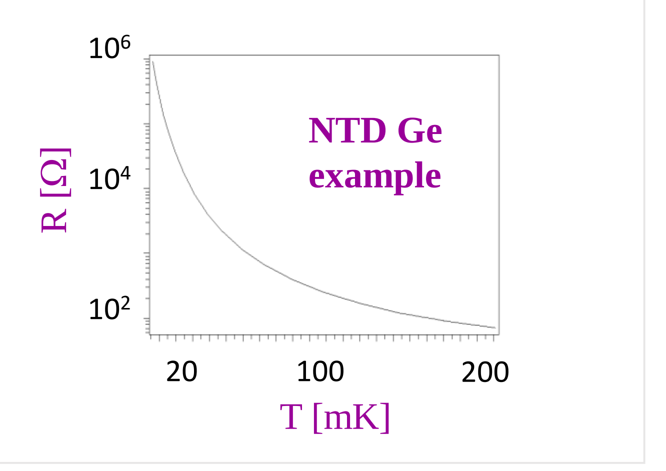
Semiconductor thermistors

Doped semiconductors close to the Metal to Insulator Transition (MIT)

At low temperatures (< ~10 K), the resistivity is given by:
(Variable Range Hopping with Coulomb gap conduction regime)

$$\rho(T) = \rho_0 \exp[(T_0/T)^{1/2}]$$

T_0 depends on the doping level → it fixes ρ_0 and the sensitivity



Two main types:

① **Neutron Transmutation Doped** (NTD) **Ge** thermistors

- Ge crystal exposed to neutron bombardment
- Neutron capture and subsequent β decay and electronic capture produce p and n doping
- Neutron dose fixes net doping
- MIT: 6 x 10^{16} cm $^{-3}$

② **Si-implanted** thermistors

- Standard microelectronic technology
- Implantation of P, As (n-doping), B (p-doping)
- MIT (Si:P): 3 x 10^{18} cm $^{-3}$

Neganov-Trofimov-Luke (NTL) effect

Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches

V. Novati [a], L. Bergé [a], L. Dumoulin [a], A. Giuliani [a,b], M. Mancuso [a], P. de Marcillac [a], S. Marnieros [a], E. Olivieri [a,*], D.V. Poda [a,d], M. Tenconi [a], A.S. Zolotarova [c]

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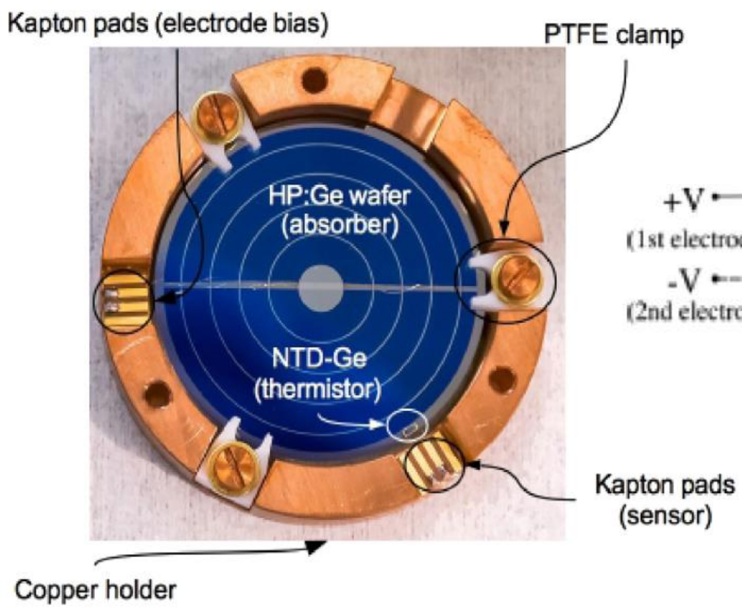
[d] Institute for Nuclear Research, 03028 Kyiv, Ukraine

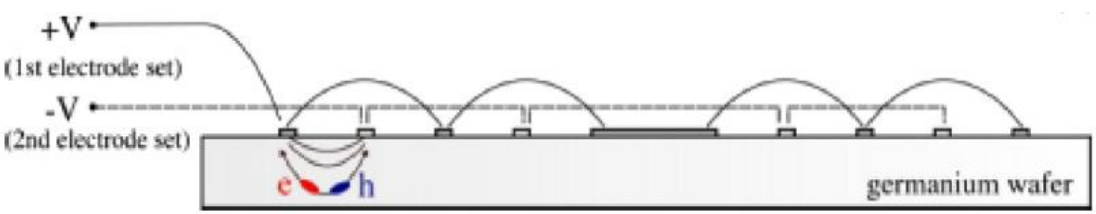
Nuclear Inst. and Methods in Physics Research, A 940, 320–327 (2019)

Large area Ge light detectors



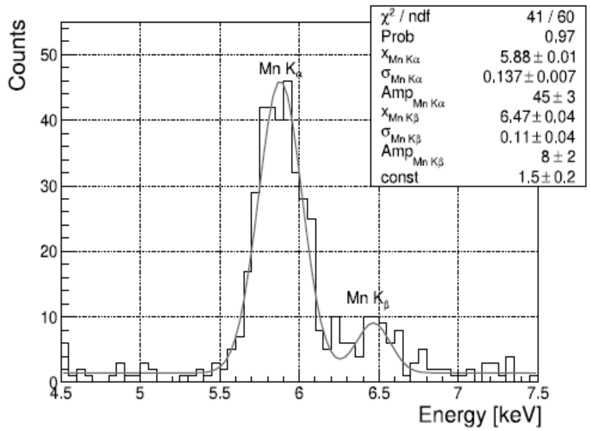
Electric voltage used to amplify charge signal

$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right) = E_0 \cdot G_{NTL}$$

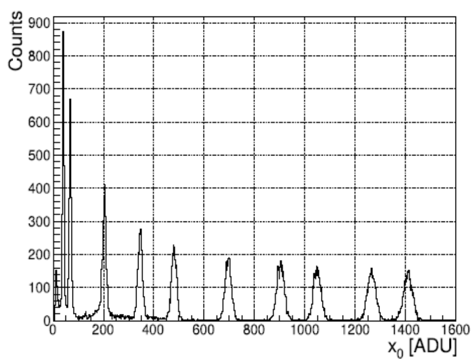


Neganov-Trofimov-Luke (NTL) effect

Calibration is done with X-rays, background cosmic rays etc.

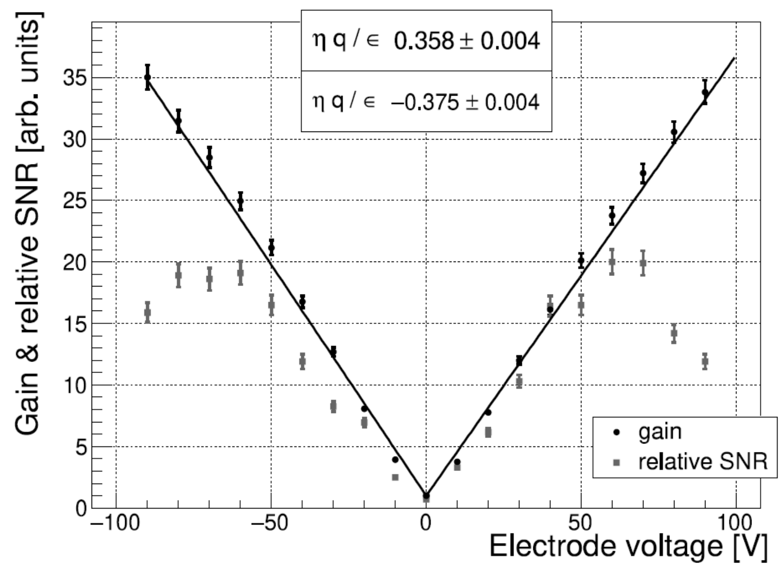


(a) Energy spectrum of an X-ray ^{55}Fe source, irradiating the NTLLD1 detector.



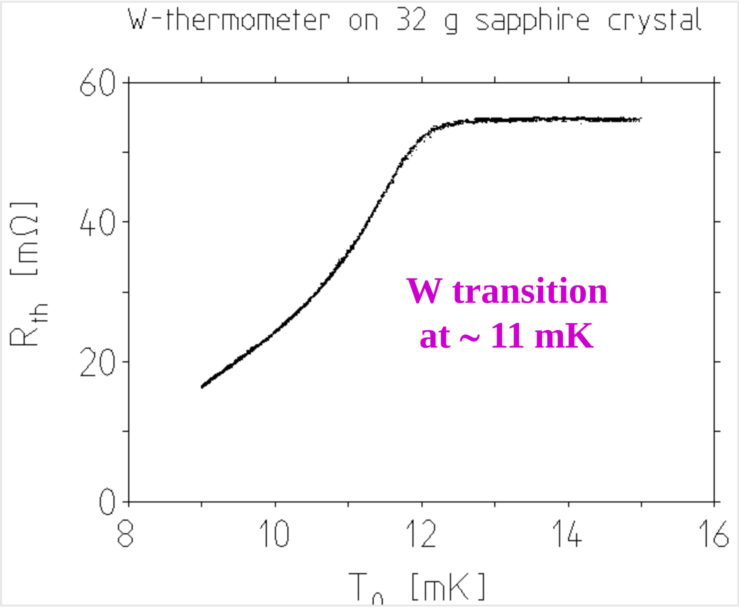
(c) LED pulses (bursts) of different intensities delivered to the detector (NTLLD2), which records signal of x_0 amplitude (uncalibrated). Each peak has $(x_0)_i$ mean and σ_i^2 width.

Most of the tests were done with photons from infrared LED setup



Transition edge sensors (TES)

- TES is a superconducting film kept around T_C
- It exploits the steep temperature dependence of the resistance in these conditions



if we define the sensitivity as

$$A \equiv \left| d\,\log R / d\,\log T \right|$$

A≅10 for ST

⇕

A≅1000 for TES

Low impedance thermistors

⇒ SQUID readout

→ Much higher S/N ratio with respect to ST

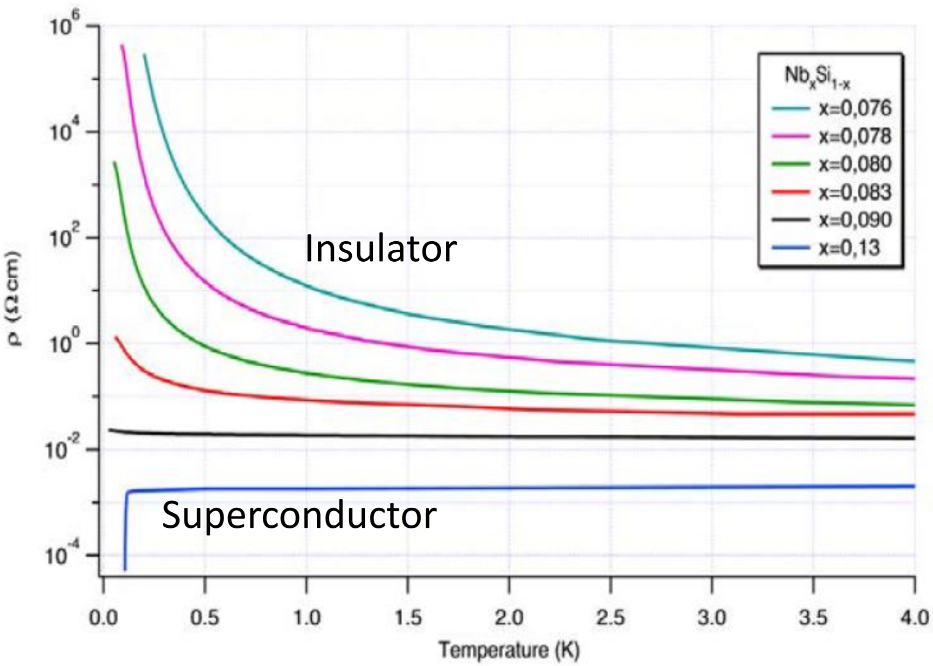
Superconductor-Insulator transition (SIT)

- It is important to have low T_C in order to operate detectors at low temperatures
- Only a few SCs have $T_C < 110$ mK
- Sometimes it is useful to tune T_C at a desired value

Percentage of Nb in the alloy of Nb and Si drastically changes the transport properties

Both metallic and insulating states are possible

These films can be used both for low impedance and high impedance TESs

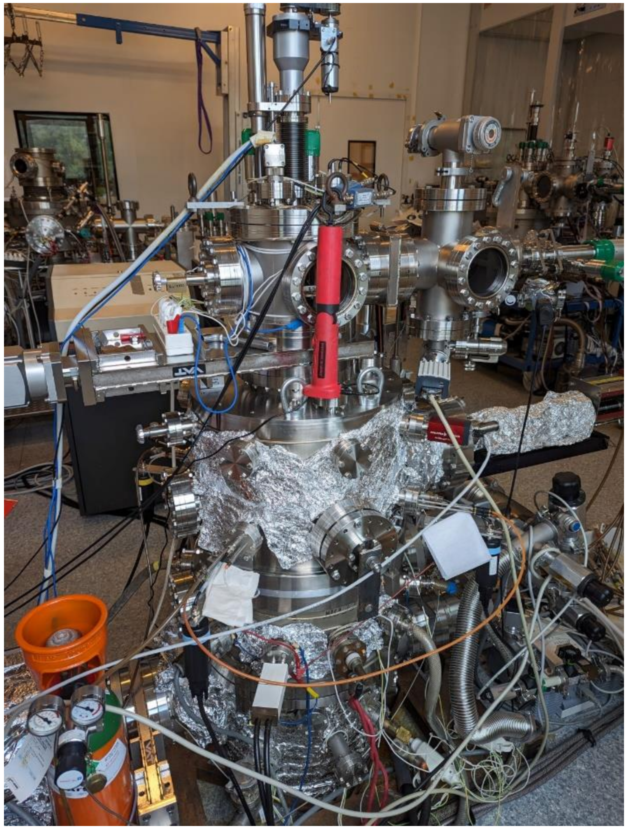


Stefanos Marnieros, PhD thesis, 1998

Different ways to tune T_c :
Film thickness, composition, annealing temperature

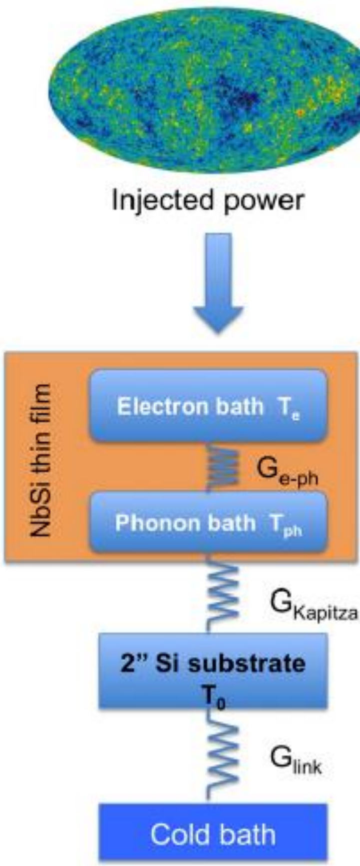
Lab facilities

Coevaporation system



Dilution fridge

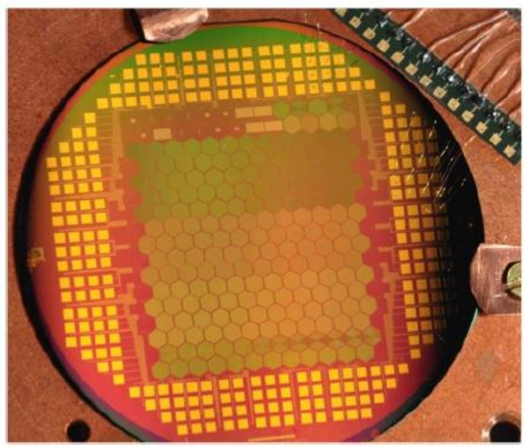
Arrays of TESs

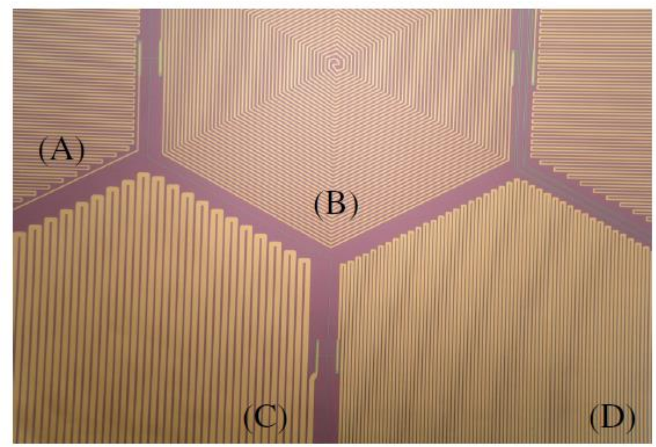


Components of a single pixel :

- Radiation absorber
- Thermometer
- Thermally isolated holder

204-pixel array of amorphous $Nb_{0.14}Si_{0.86}$ with a meander structure





High-impedance NbSi TES sensors for studying the cosmic microwave background radiation
C. Nones et al., Astronomy & Astrophysics 548, A17 (2012)

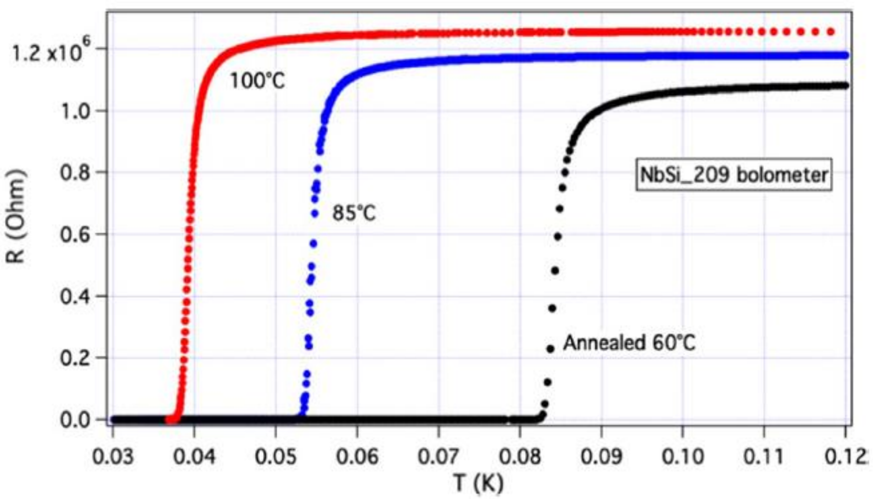
Geometry name	d [μm]	Gap [μm]	Surface [mm^2]
Thin horizontal (A)*	10	10	1.51
Thin circular (B)	10	10	1.55
Thick vertical (C)	30	10	2.25
Thin vertical (D)	10	10	1.54
Medium vertical	15	5	2.31

High impedance thermistors

High Impedance TES Bolometers for EDELWEISS

S. Marnieros[1] · E. Armengaud[2] · Q. Arnaud[3] · C. Augier[3] · A. Benoît[4] · L. Bergé[1] · J. Billard[3] · A. Broniatowski[1] · P. Camus[4] · A. Cazes[3] · M. Chapellier[1] · F. Charlieux[3] · M. De Jésus[3] · L. Dumoulin[1] · K. Eitel[5] · J.-B. Fillipini[3] · D. Filosofov[6] · J. Gascon[3] · A. Giuliani[1] · M. Gros[2] · Y. Jin[7] · A. Juillard[3] · M. Kleifges[8] · H. Lattaud[3] · D. Misiak[3] · X.-F. Navick[2] · C. Nones[2] · E. Olivieri[1] · C. Oriol[1] · P. Pari[9] · B. Paul[2] · D. Poda[1] · S. Rozov[6] · T. Salagnac[3] · V. Sanglard[3] · L. Vagneron[3] · E. Yakushev[6] · A. Zolotarova[1]

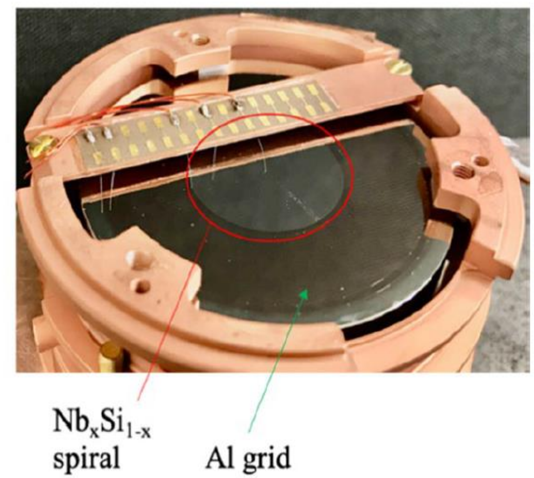
Journal of Low Temperature Physics (2023) 211:214–219



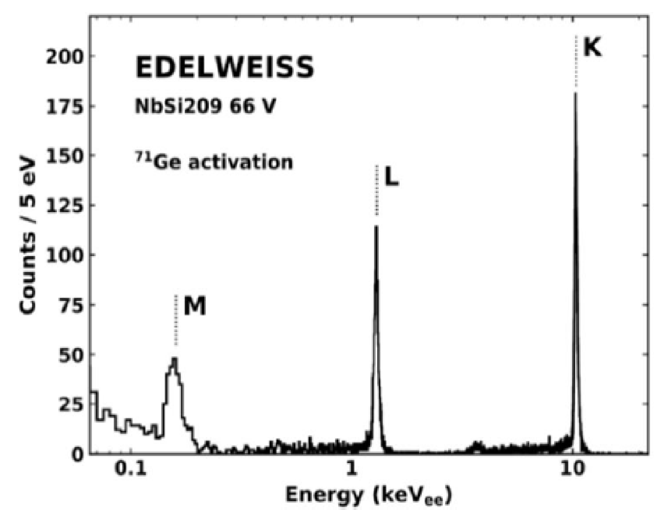
High impedance allows readout with JFET electronics

High aspect ratio meander:
Line length to line width : $10^3 – 10^4$

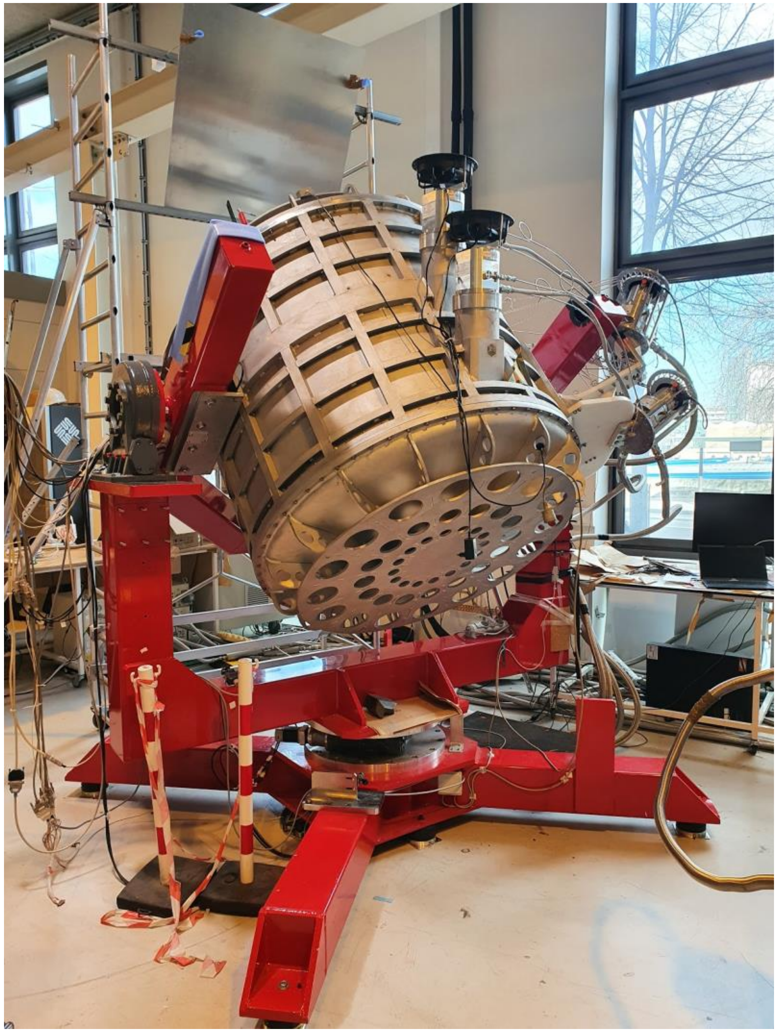
Composition :
$Nb_{0.132}Si_{0.868}$



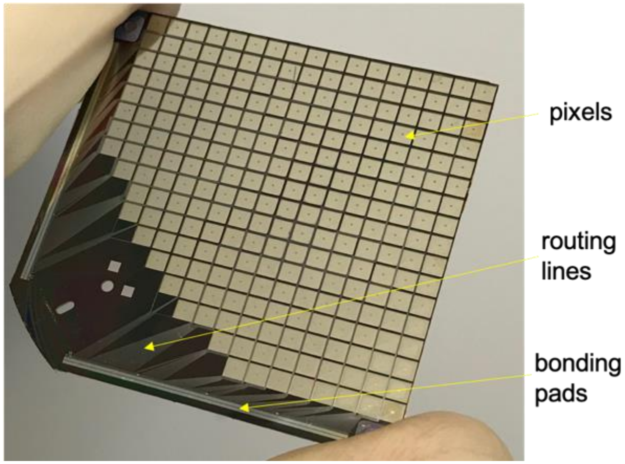
Calibration of a 200 g NbSi - Ge bolometer using ^{71}Ge activation by neutrons. The Ge crystal was biased at 66 V for NTL amplification.



QUBIC installation at Argentina

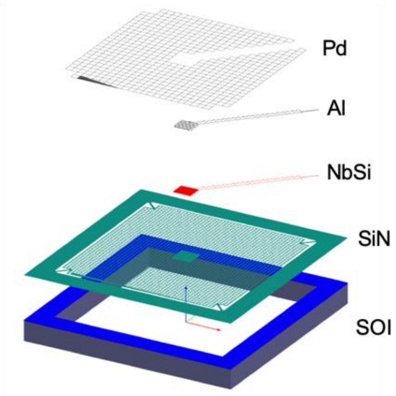


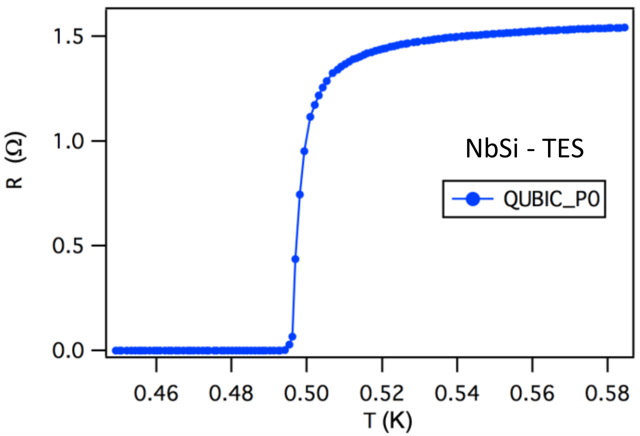
TES pixel array



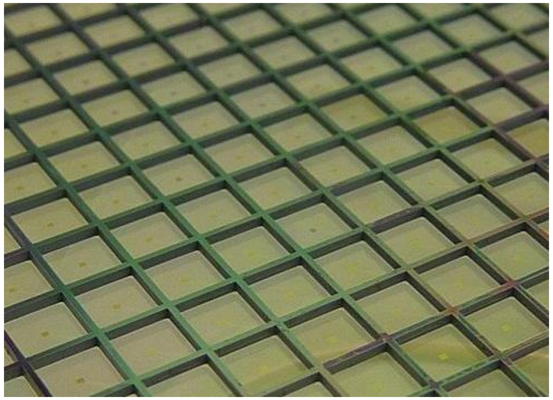
250 pixel array for QUBIC

Pixel architecture

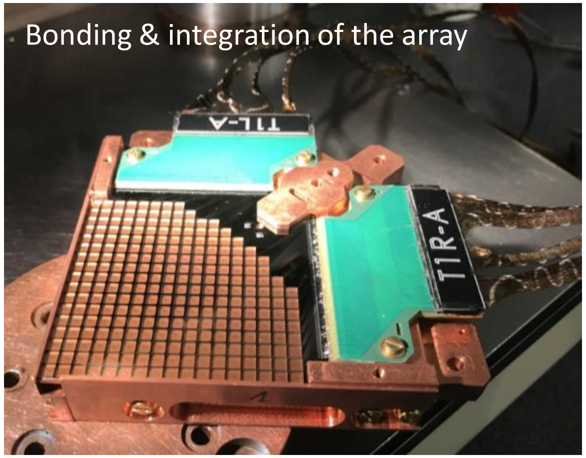




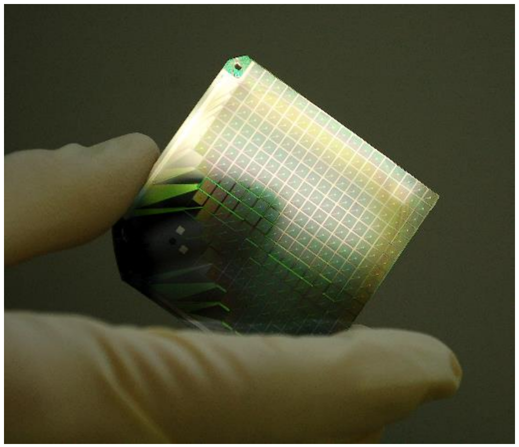
High sensitivity TES with adjustable T_C

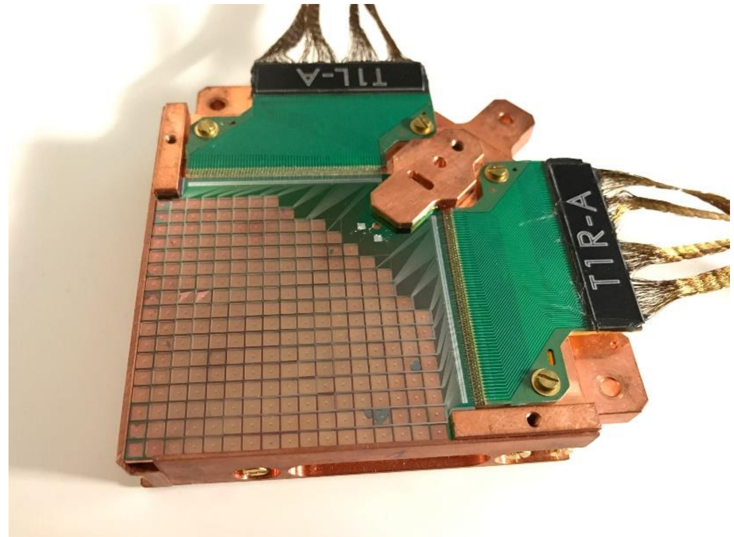


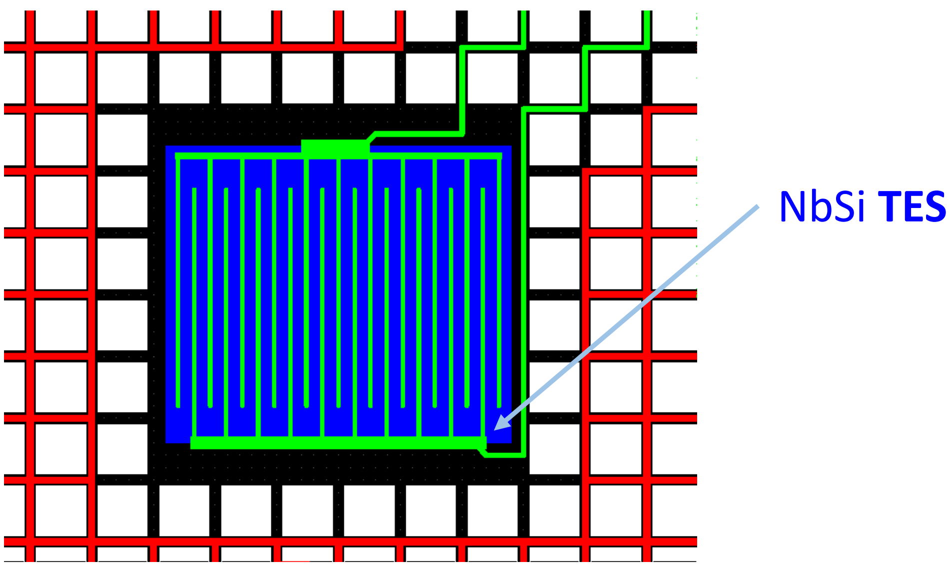
Deep silicon etching to realise the suspended membranes.
High thermal decoupling to optimise signal/noise

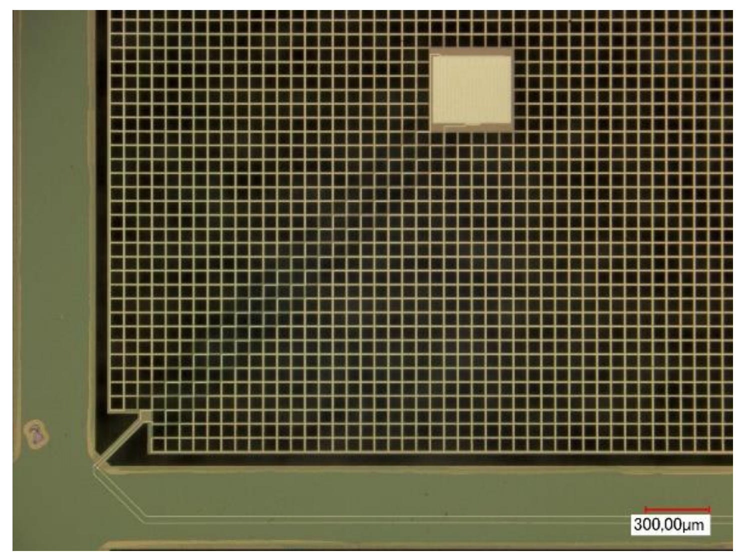


TES pixel array









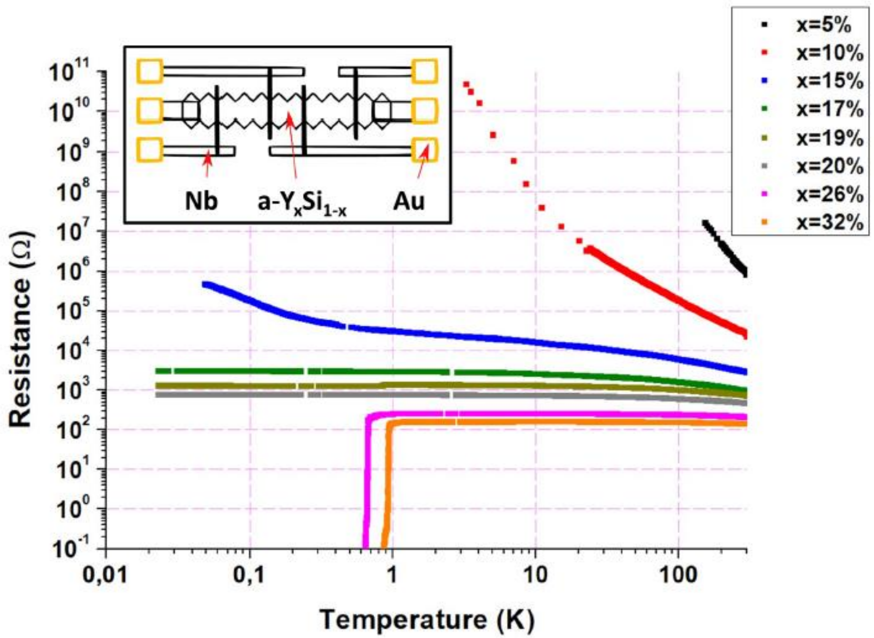
Phase diagram of Y_xSi_{1-x}

Composition-dependence of transport properties in YSi thermometric films

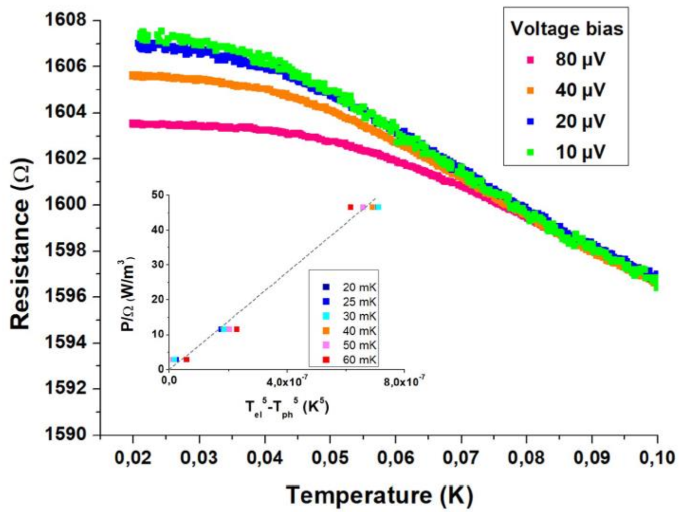
L. H. H. To · S. Sengupta · F. Pallier · L. Bergé · L. Dumoulin · S. Marnieros · C. Marrache-Kikuchi.

Journal of Low Temperature Physics, 209, 1104–1110 (2022)

Superconductor-Insulator transition with varying composition

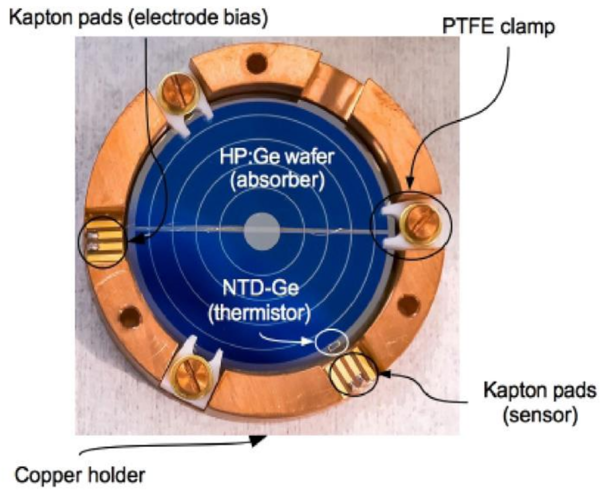


Resistance characteristics of insulating a-$Y_{20}Si_{80}$ film (thickness : 30 nm)

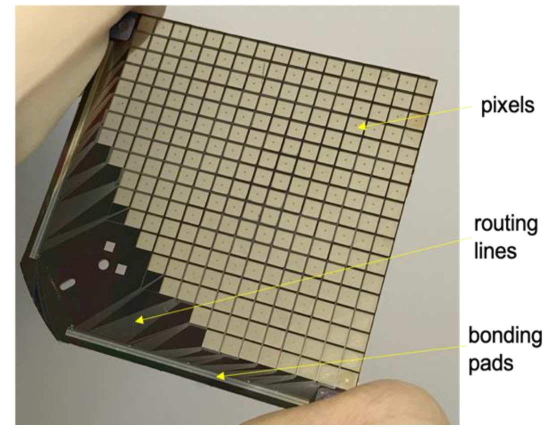


Highlights

Semiconductor thermistors and detectors



Transition edge sensors with superconductors



Study of new materials