Superconductors for particle and radiation detectors

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with

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Pôle: Astroparticles, Astrophysics, Cosmology (A2C), Ingénierie

Outline

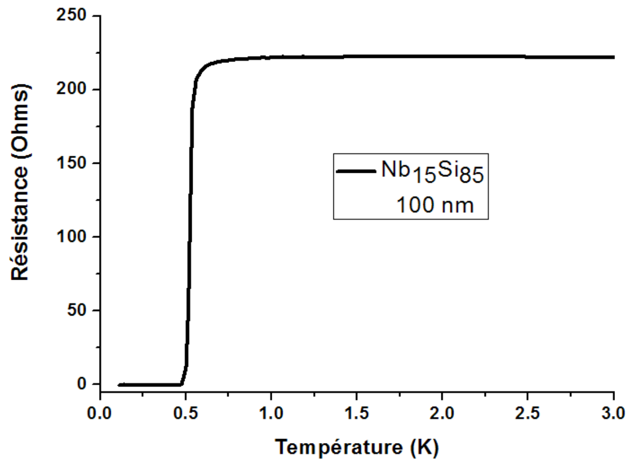
Physics of superconductors

Application to detectors

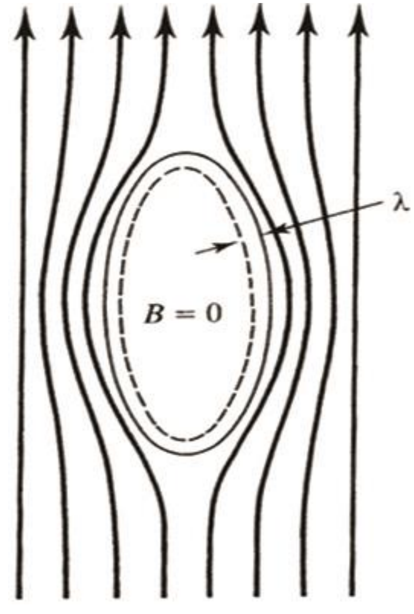
Future prospects

Superconductivity

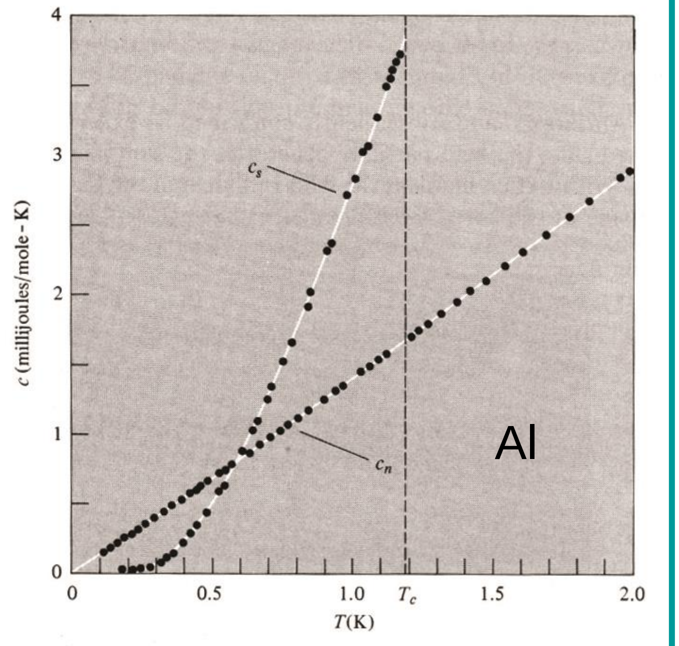
Quantum phenomenon + Collective phenomenon



1. Zero resistance for T<Tc



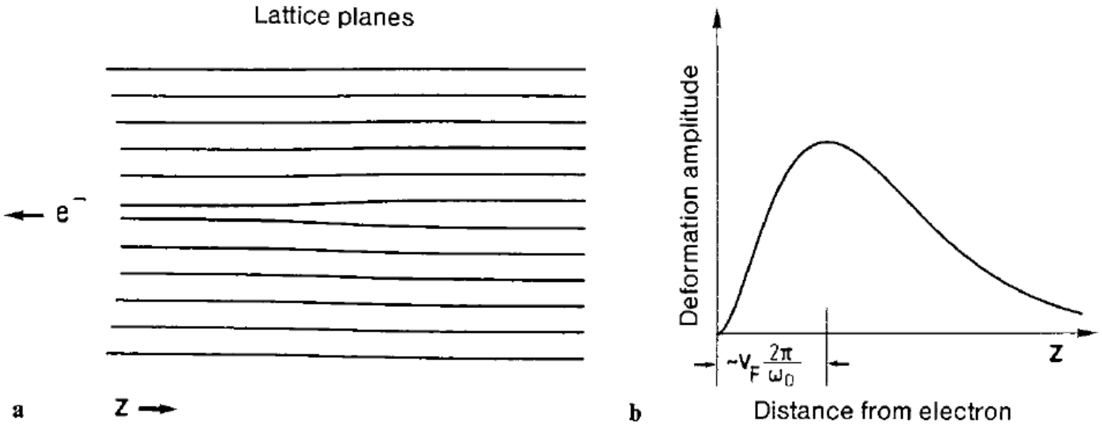
2. Exclusion of magnetic field



3. Strong decrease of specific heat

Superconductivity

Microscopic pairing mechanism: Cooper pairs



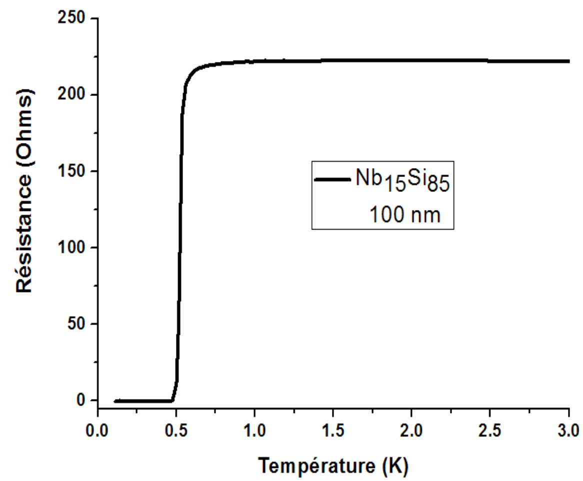
Δ = strength of the superconductivity

$$\Delta \propto k_B T_c$$

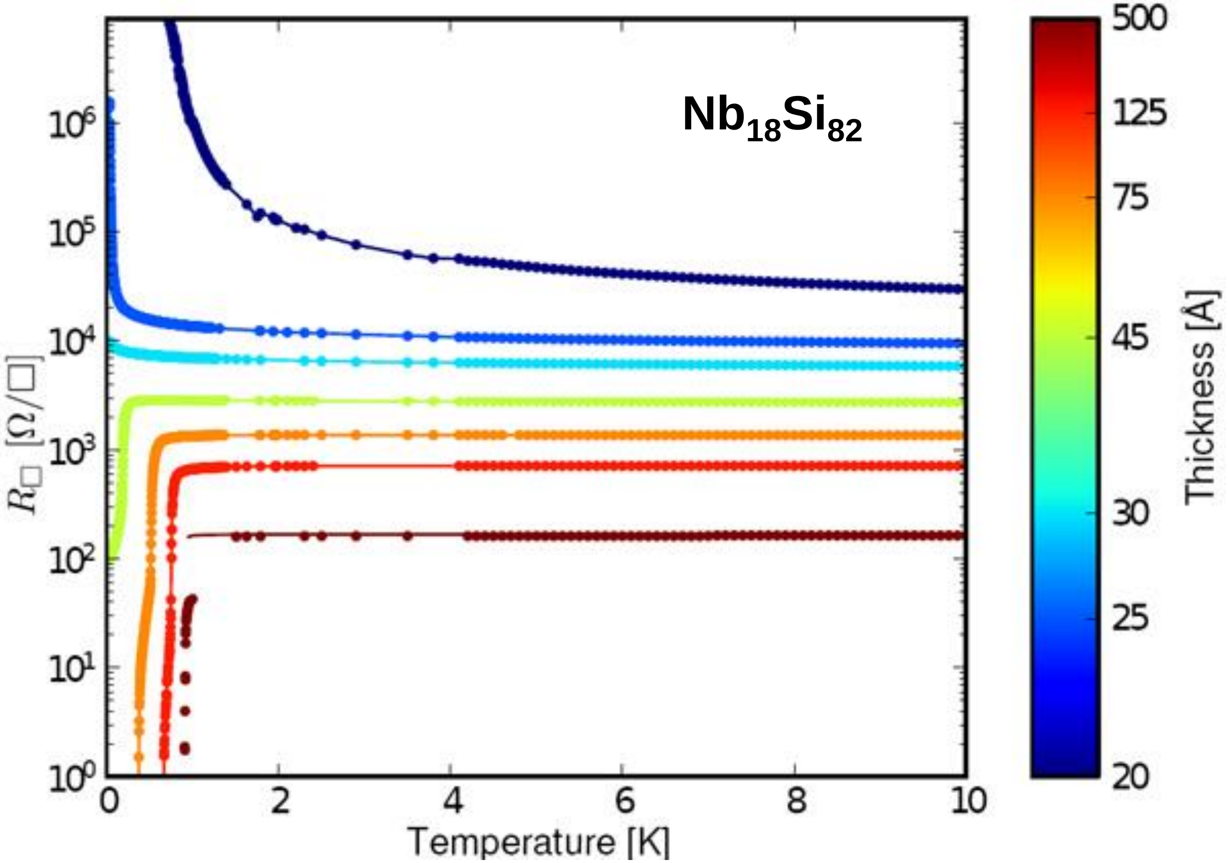
$$\xi = \frac{\hbar v_F}{k_B T_c}$$

Thin films of Nb_xSi_{1-x}

The films can be either superconducting or insulating depending upon different proportions of Nb and Si, as well as thickness and disorder



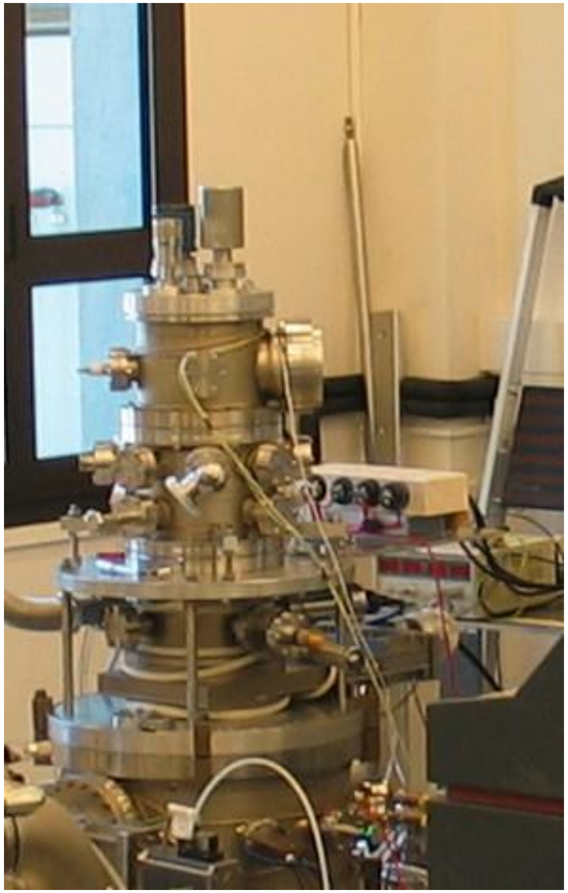
Superconductors and insulators

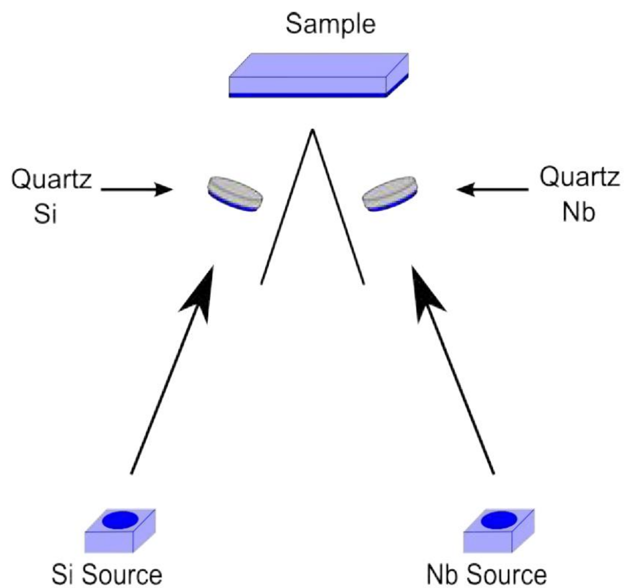


Phase transitions between different ground states

NbSi thin films

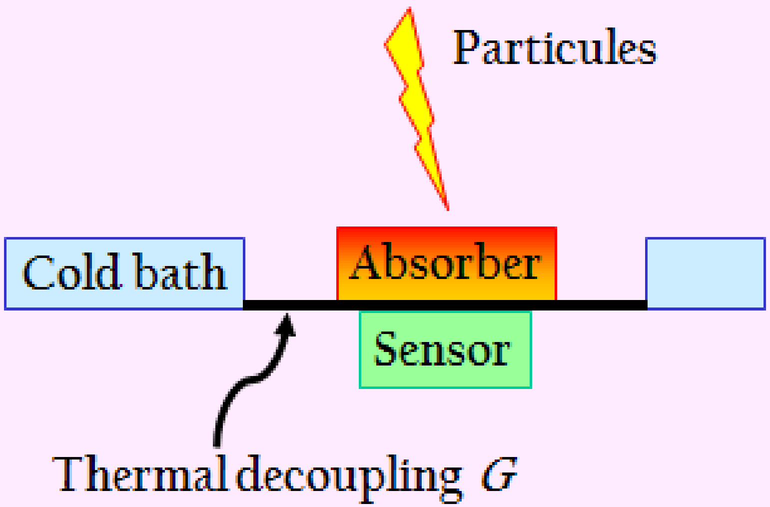
Synthesis

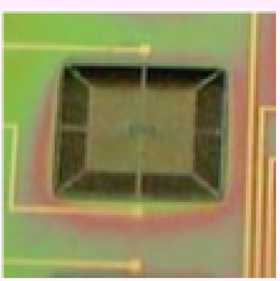




NbSi applied to detectors

Structure of current bolometers



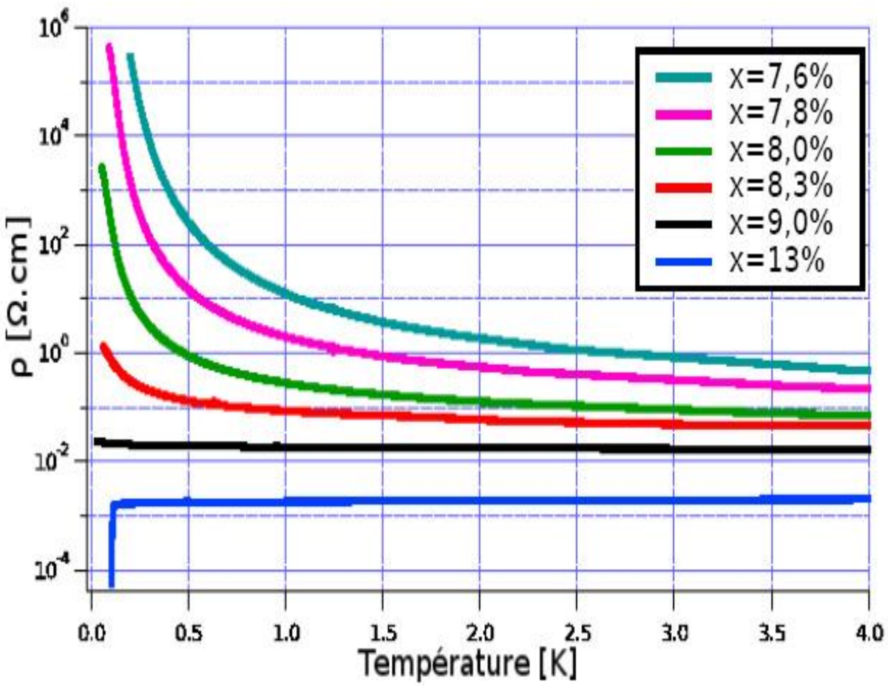


- Absorber (response time $\propto$ volume)
- Thermal sensor
- Thermal decoupling

Problems to solve

- Ultimate sensitivity limited by $NEP^2 = 4k_B T^2 G$
- G=10^{-11} W.K^{-1} for Planck experiment (dependent on the membrane
- All use phonons as vectors for energy transport

SIT in NbSi applied to detectors



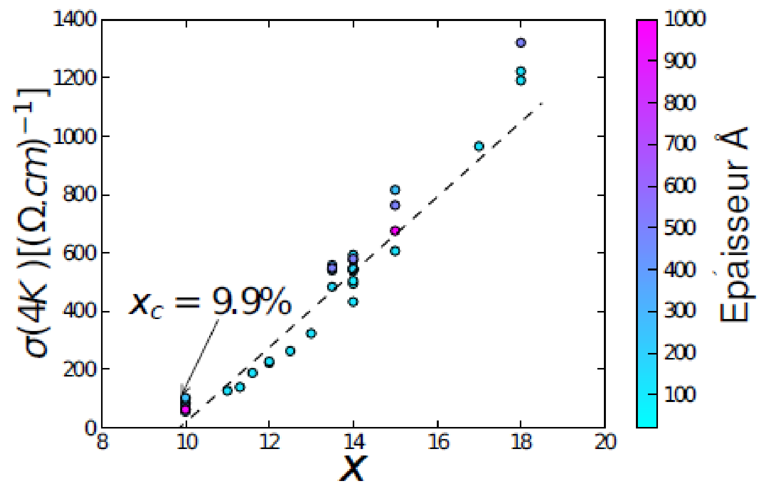


Fig.: Conductivité à 4 K fonction de la concentration x_{Nb}.

NbSi : superconducting or insulating sensor

SIT in NbSi applied to detectors

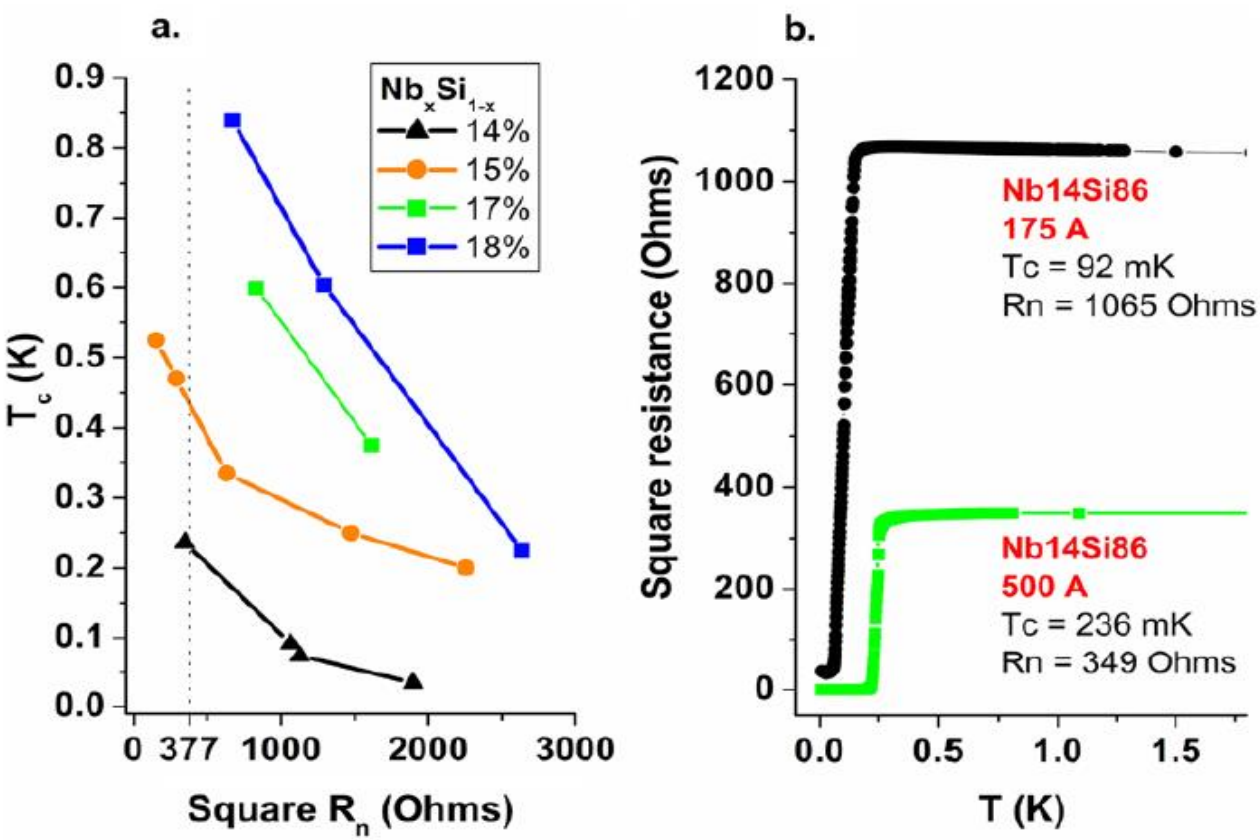
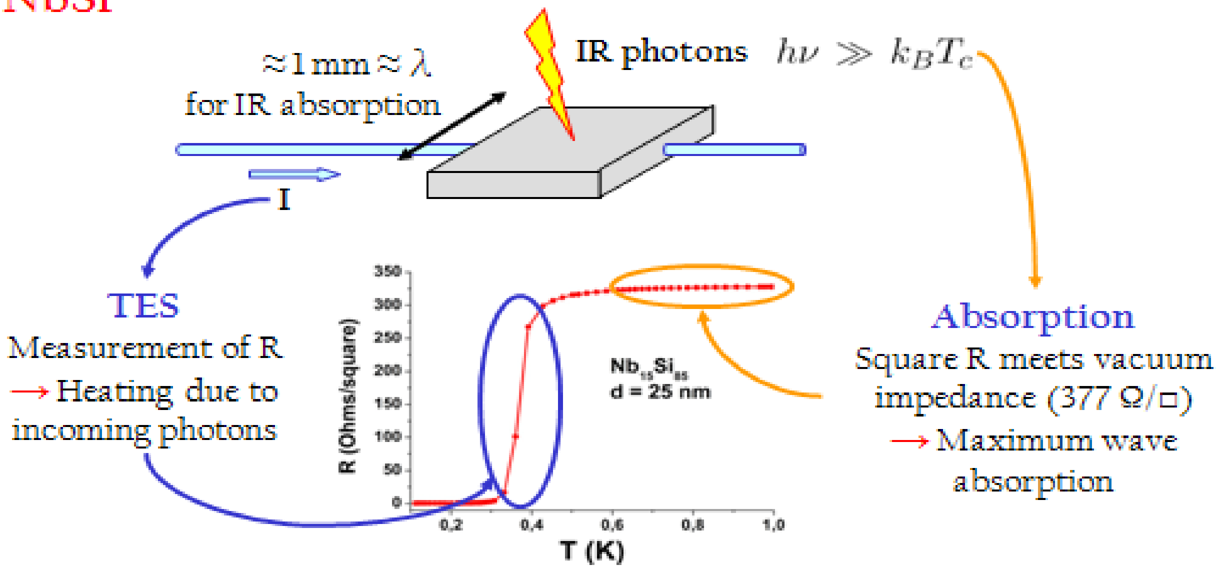


Fig. 1 (Color online) **a**. Superconducting critical temperature as a function of the normal sheet resistance for different compositions. The two parameters can thus be independently tuned. The lines are guides to the eye. **b**. Resistance characteristics of the 175 Å and 500 Å thick $Nb_{14}Si_{86}$ samples

SIT in NbSi applied to detectors

Case 1 : absorber = thermometer = superconducting NbSi

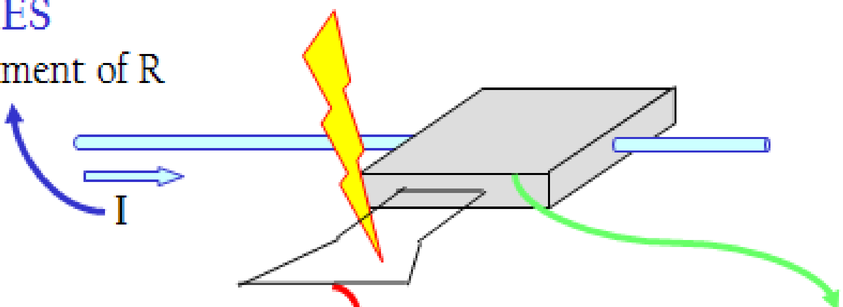


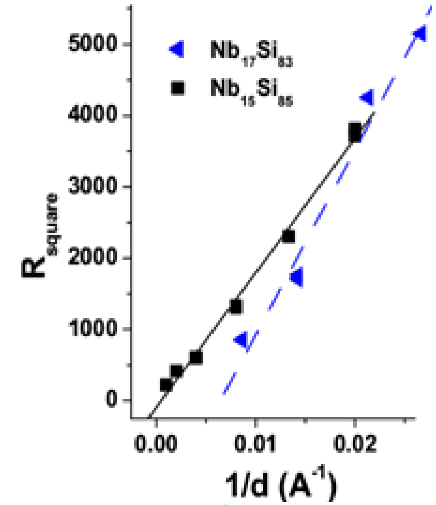
Advantages

- Composition and thickness adjustable for operating temperature of 50-100 mK
- Optimal thermal decoupling (10^{-11} $W.K^{-1}$ for a typical film of 100 µm x 100 µm x 100 nm @ 70 mK)
- Short response time (≈ 1 ms @ 70 mK)
- Read-out via interdigited electrodes → SQUID-based electronics
- Read-out via meander-shaped electrodes → transistor-based electronics

SIT in NbSi applied to detectors

Case 2 : absorption through antennas ; thermometer = superconducting NbSi (TES)





Antennas

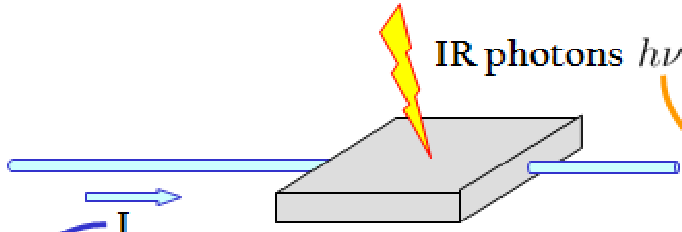
- High selectivity for the energy spectrum & polarization
- Good filling factor
- Smaller NbSi film → lower *G*

NbSi film

- Good matching impedance with antennas → transfer of the absorbed energy directly into TES' electrons via tunable normal R of the film

SIT in NbSi applied to detectors

Case 3 : absorber = thermometer = Anderson insulating NbSi



Absorption

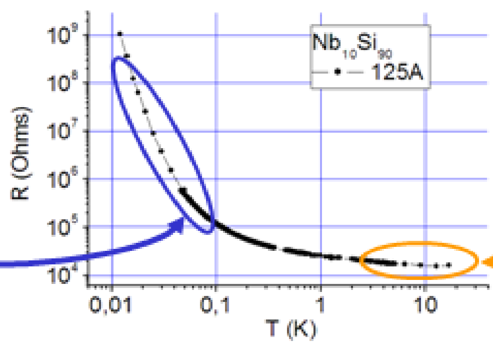
Temperature

- DC measurement of R

→ Heating due to incoming photons

- Suitable for JFET read-out

→ Square R may meet vacuum impedance (377 Ω/□) → Maximum wave absorption



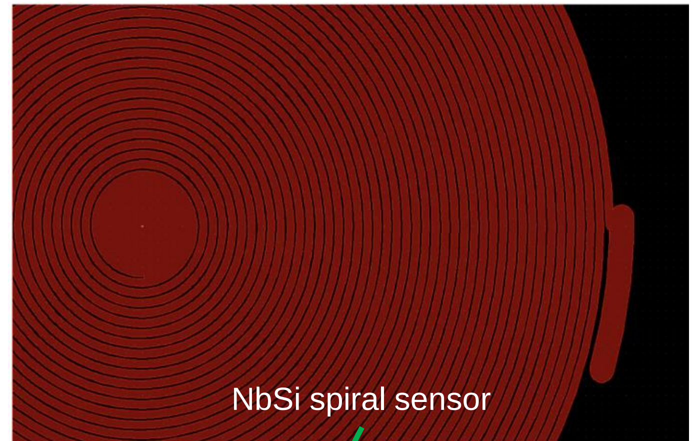
SIT in NbSi applied to detectors

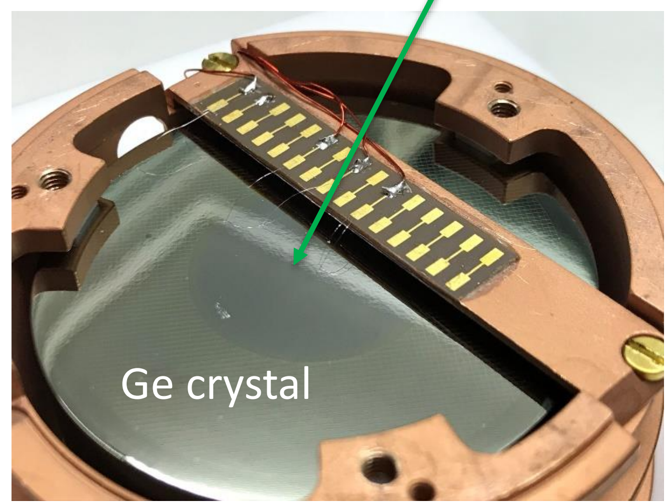
Massive bolometers

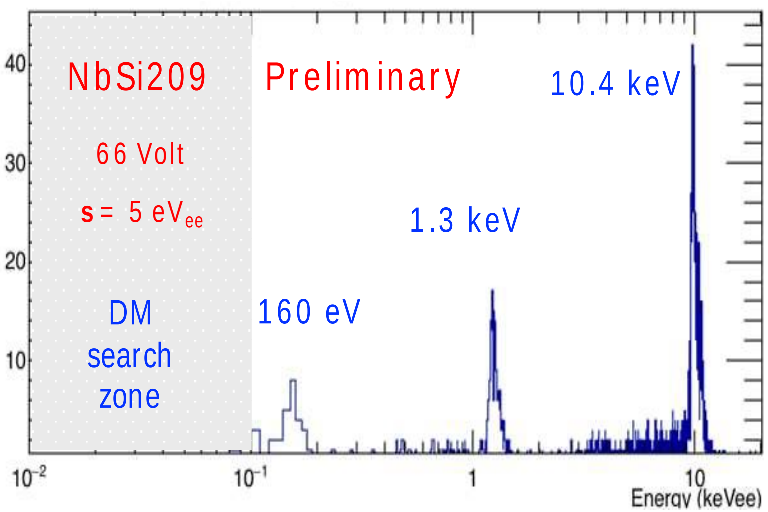
NbSi TES layers evaporated on massive crystals.

In the frame of the EDELWEISS project for dark matter research, 200 g Ge crystals combined to spiral-shaped TES were developed.

5 eV baseline resolution has been be demonstrated using “Neganov-Luke” amplification.

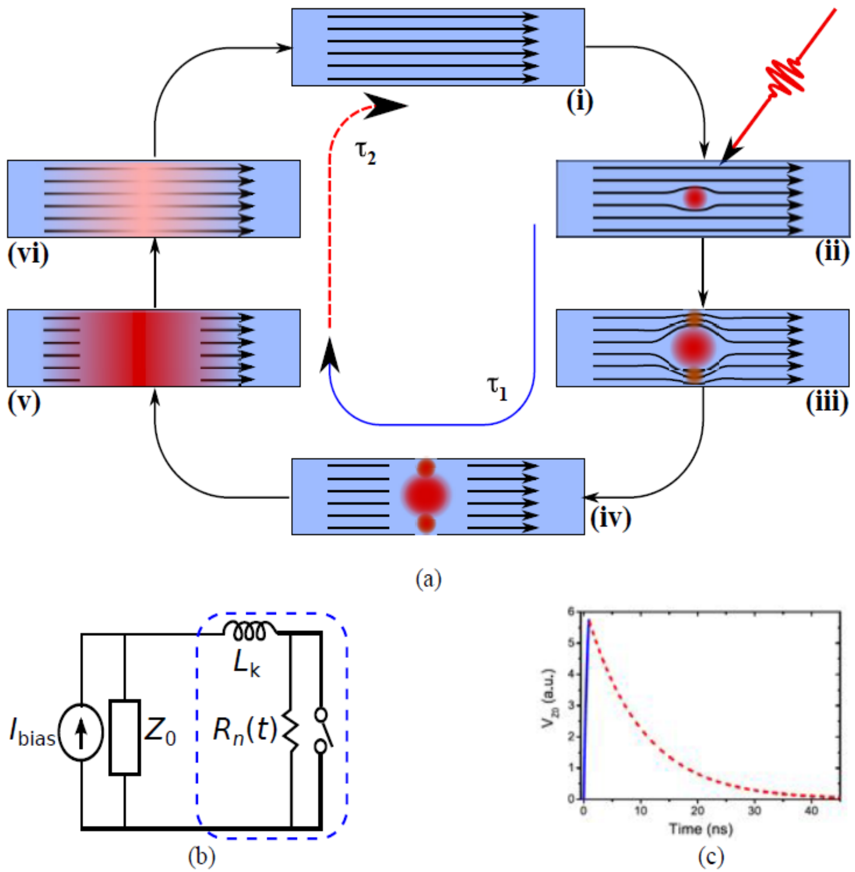




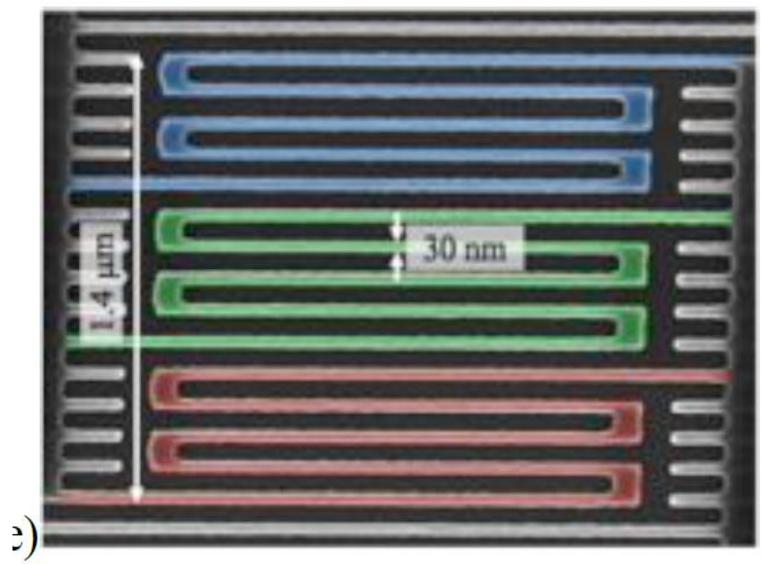


Superconducting nanowires

Superconducting nanowire single photon detector (SNSPD)

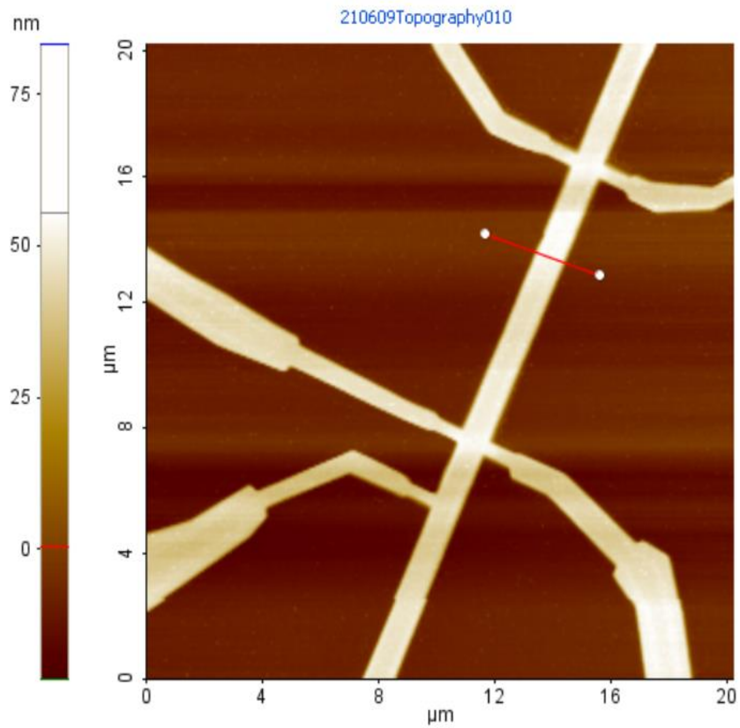


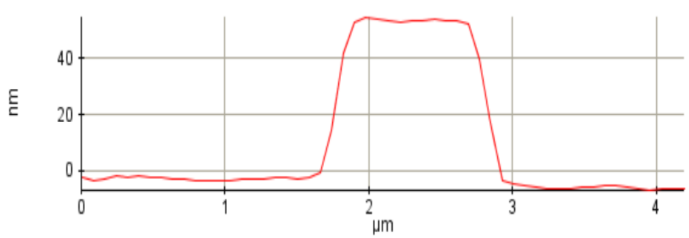
Natarajan et al., Supercond.Sci.Technol. 25 (2012)

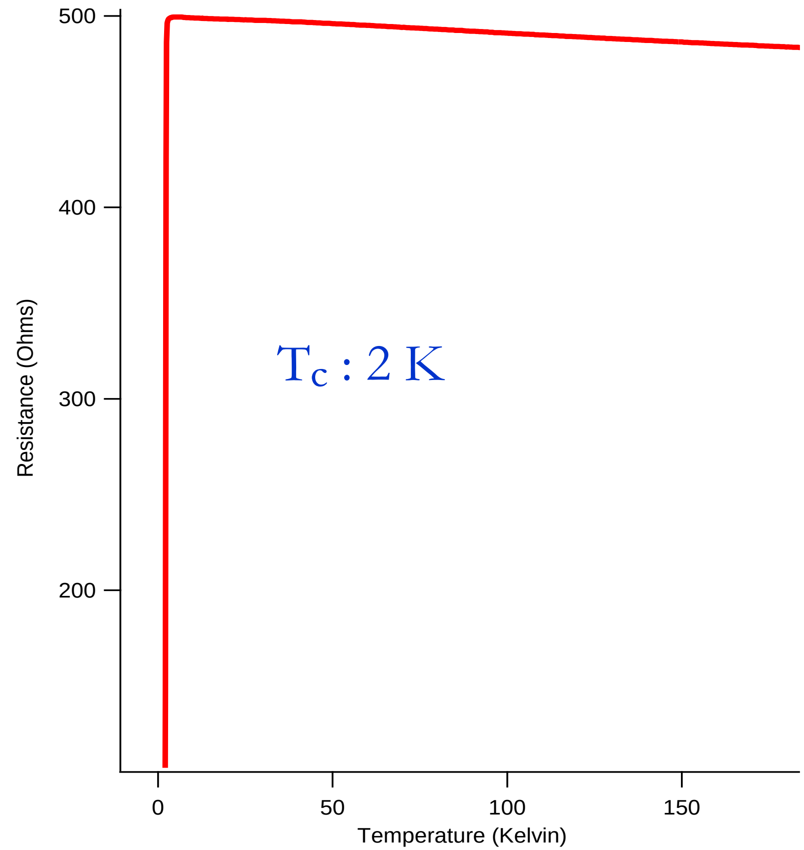


Marsili et al., Nano Lett. 11 (2011)

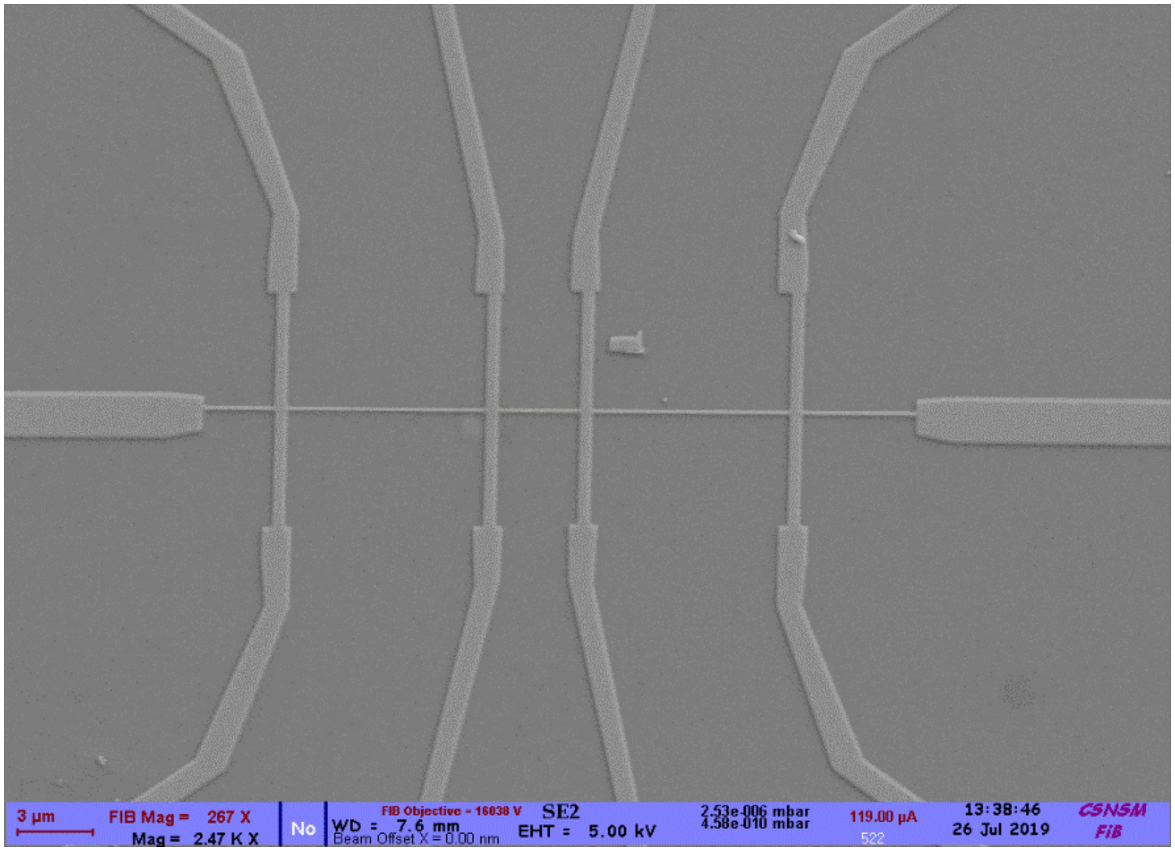
Superconducting nanowires







Superconducting nanowires



Nanowire with a 200 nm wide channel

Recent proposals

PHYSICAL REVIEW LETTERS **123,** 151802 (2019)

Detecting Sub-GeV Dark Matter with Superconducting Nanowires

Yonit Hochberg,[1,*] Ilya Charaev,[2,†] Sae-Woo Nam,[3,‡] Varun Verma,[3,§] Marco Colangelo,[2,∥] and Karl K. Berggren[2,¶]
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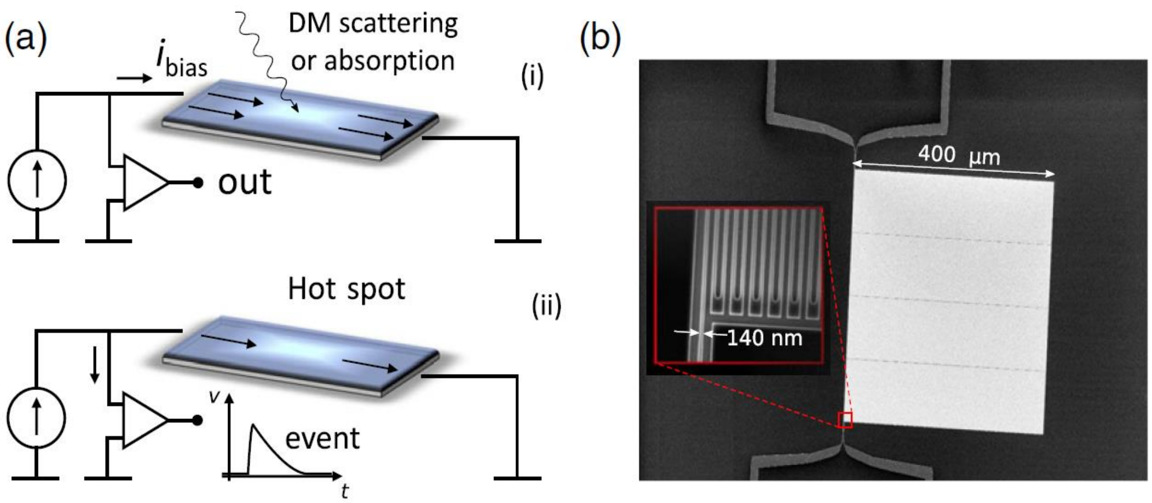

WSi superconductor nanowire

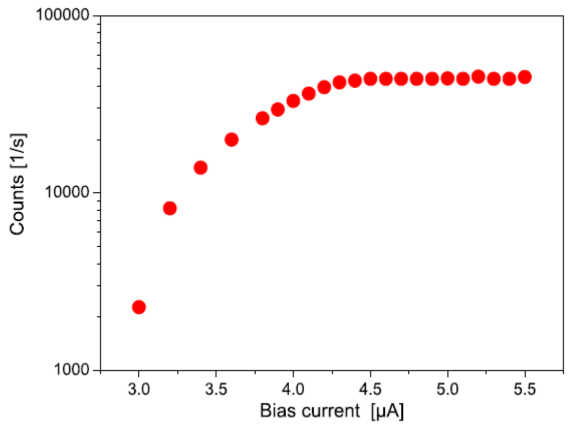

FIG. 2. The photon counts as a function of the absolute bias current, exhibited by the prototype WSi device tested in a fiber-coupled package at 300 mK.

1550 nm wavelength, ~0.8 eV

Summary

Several types of applications of superconductors can be developed for detecting radiation and particles.

Superconducting nanowires have emerged as candidates in the search for low mass dark matter.