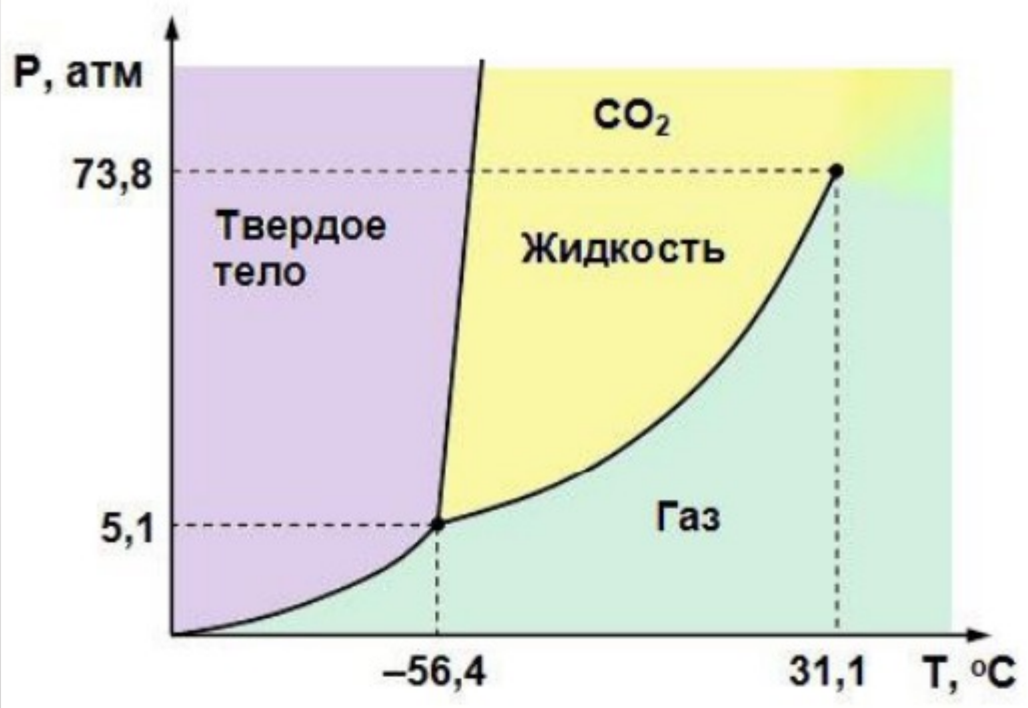
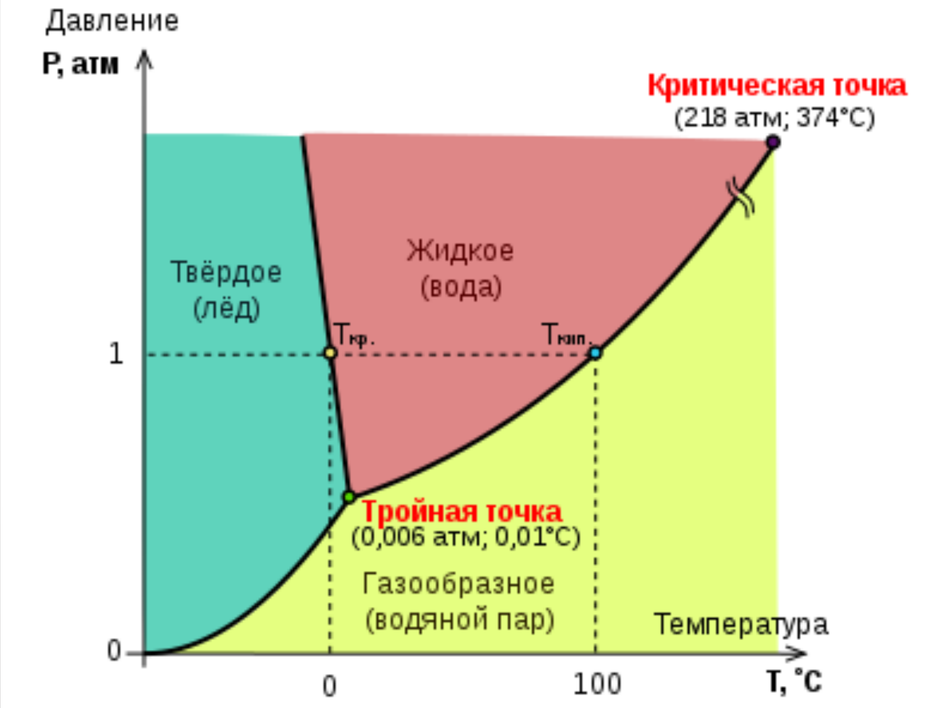
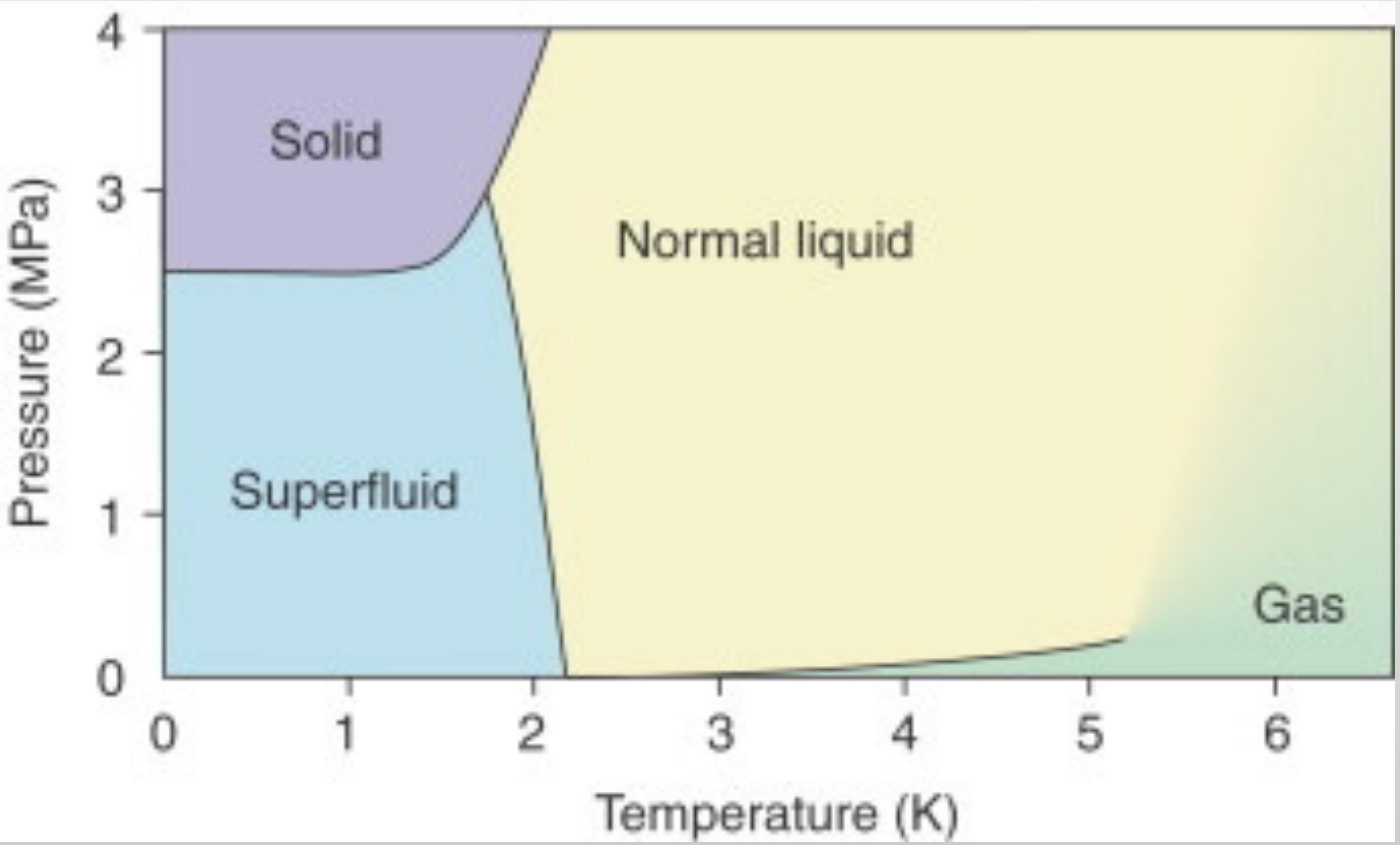
Superconductors and superfluid

Phase diagram

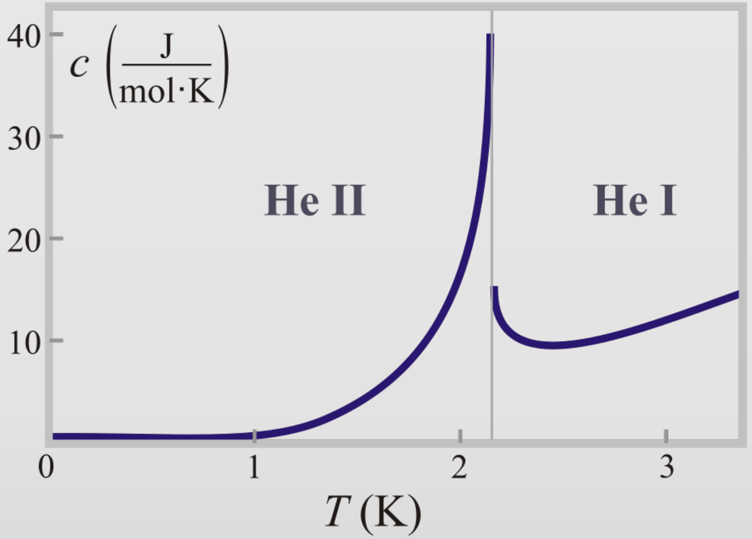




He -4



Why doesn't helium solidify?

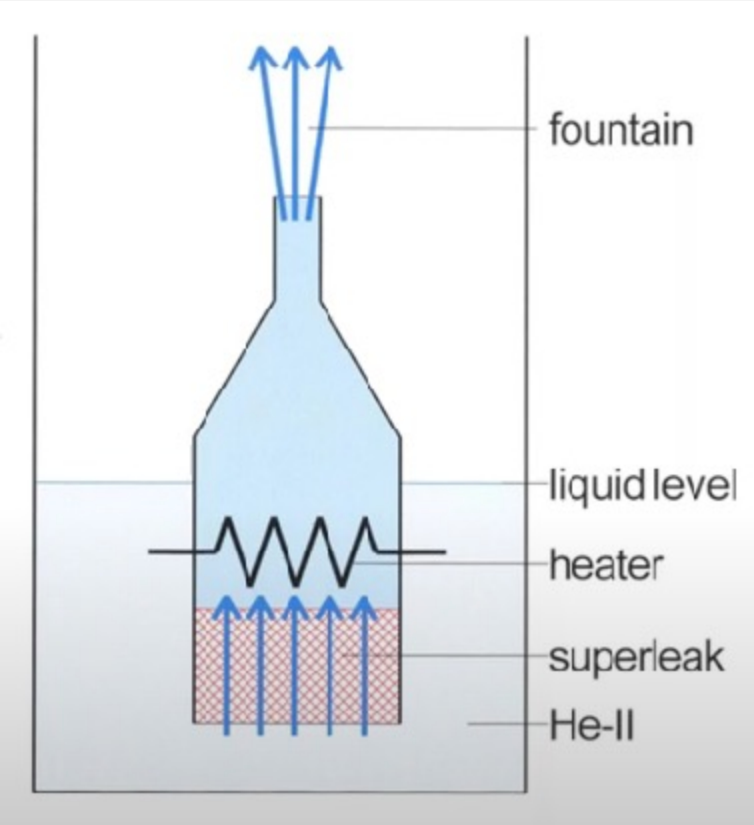


$$E_0 \simeq \frac{h^2}{8ma^2}$$

$$\lambda = \frac{E_0}{U}$$

3.05 He-3
2.64 He-4
1.73 H

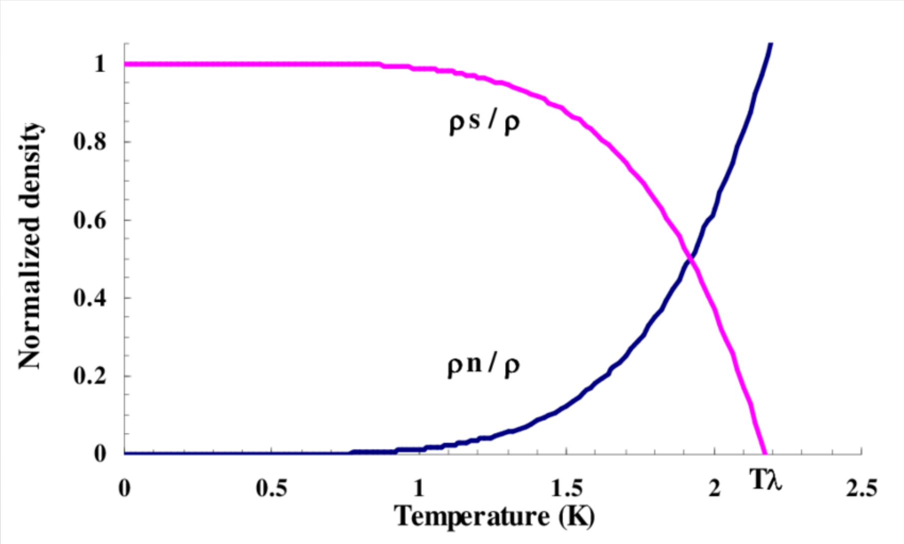
Theory of superfluid



Two components

Normal

Superfluid

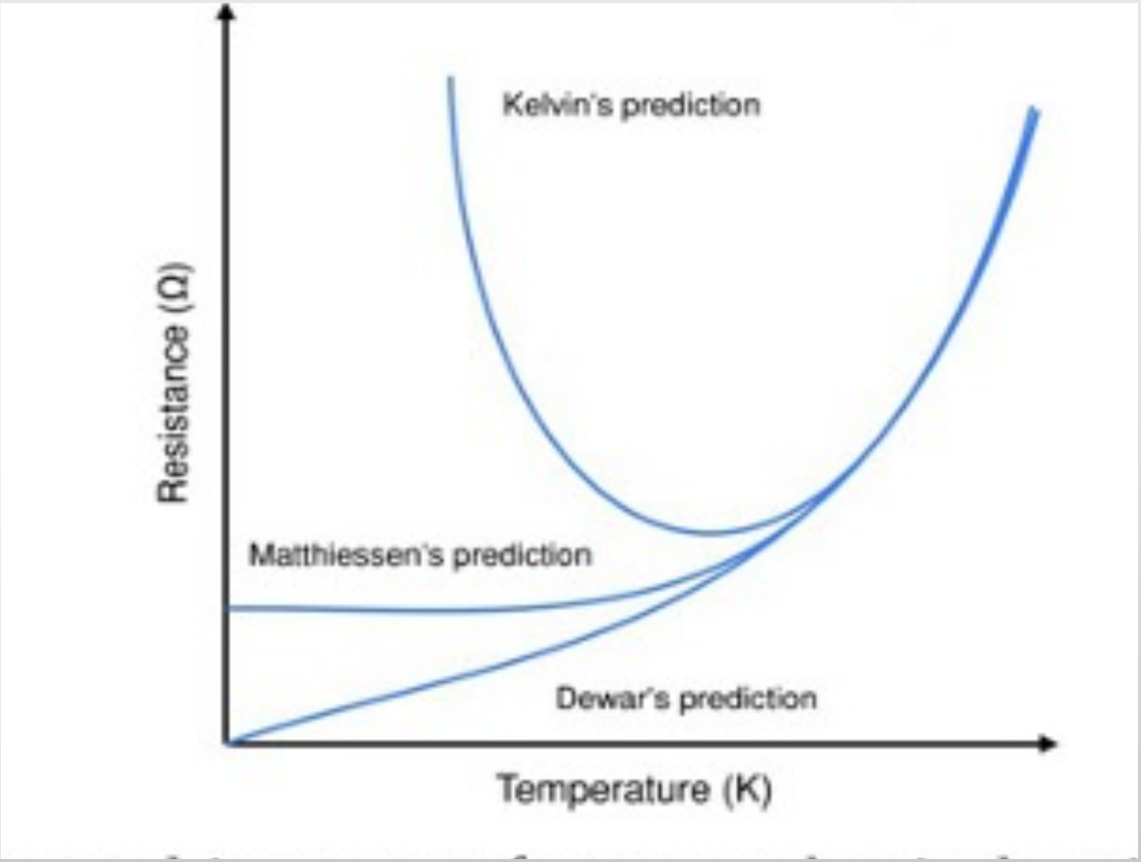


https://www.youtube.com/watch?v=2Z6UJbwxBZI&ab_channel=ryanhaart

OUTLINE SUPERFLUID

- Two components(n and s)
- Without viscosity
- Huge thermal conductivity
- Bose statistic

HISTORY REMARK



Dewar: all vibrations stop at zero Kelvin and thus electrons can move through the atomic lattice without resistance

Matthiessen: resistance is dominated by impurities and dislocations inside the atomic lattice and therefore resistance should be finite at low temperatures and towards zero Kelvin

Kelvin: all movement stops, also the electrons, therefore, no current can be present, which is represented as an infinitely large resistance

SUPERCONDUCTORS

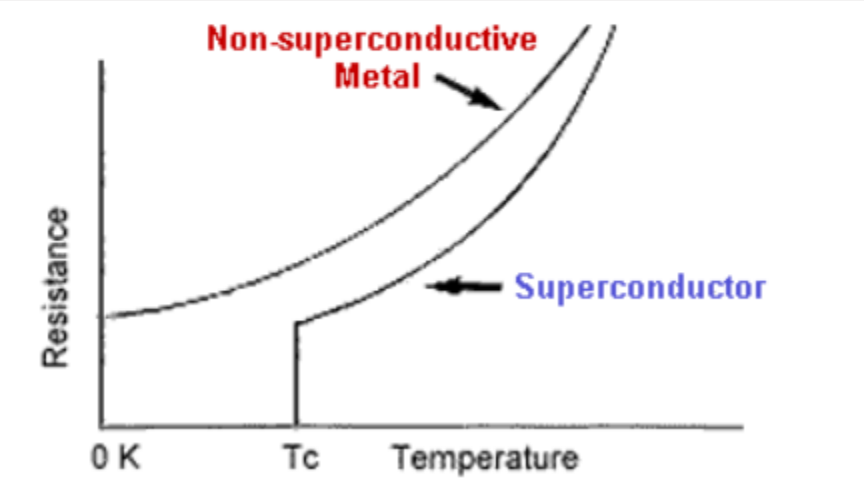
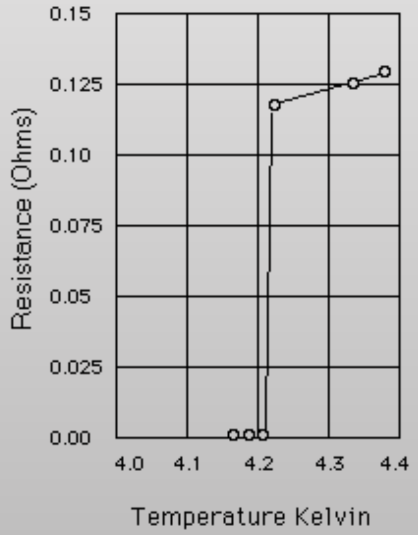
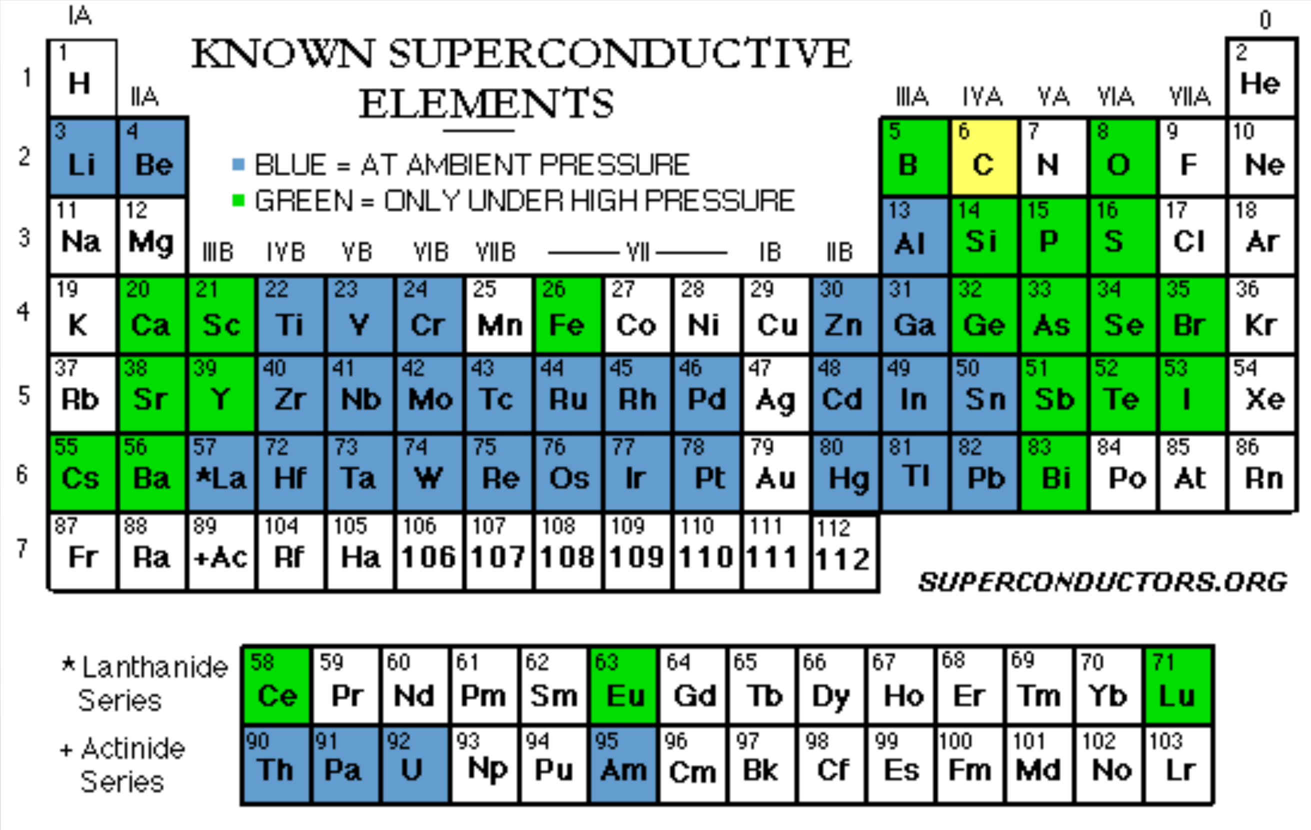


Fig. 1



The Kamerlingh Onnes resistance measurement of mercury. At 4.15K the resistance suddenly dropped to zero



KNOWN SUPERCONDUCTIVE ELEMENTS

🟦 BLUE = AT AMBIENT PRESSURE
🟩 GREEN = ONLY UNDER HIGH PRESSURE

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li 🟦	4 Be 🟦											5 B 🟩	6 C 🟨	7 N	8 O 🟩	9 F	10 Ne
3	11 Na	12 Mg											13 Al 🟦	14 Si 🟩	15 P 🟩	16 S 🟩	17 Cl	18 Ar
4	19 K	20 Ca 🟩	21 Sc 🟩	22 Ti 🟦	23 V 🟦	24 Cr 🟦	25 Mn	26 Fe 🟩	27 Co	28 Ni	29 Cu	30 Zn 🟦	31 Ga 🟦	32 Ge 🟩	33 As 🟩	34 Se 🟩	35 Br 🟩	36 Kr
5	37 Rb	38 Sr 🟩	39 Y 🟩	40 Zr 🟦	41 Nb 🟦	42 Mo 🟦	43 Tc 🟦	44 Ru 🟦	45 Rh 🟦	46 Pd 🟦	47 Ag	48 Cd 🟦	49 In 🟦	50 Sn 🟦	51 Sb 🟩	52 Te 🟩	53 I 🟩	54 Xe
6	55 Cs 🟩	56 Ba 🟩	57 *La 🟦	72 Hf 🟦	73 Ta 🟦	74 W 🟦	75 Re 🟦	76 Os 🟦	77 Ir 🟦	78 Pt 🟦	79 Au	80 Hg 🟦	81 Tl 🟦	82 Pb 🟦	83 Bi 🟩	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

SUPERCONDUCTORS.ORG

* Lanthanide Series	58 Ce 🟩	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu 🟩	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu 🟩
+ Actinide Series	90 Th 🟦	91 Pa 🟦	92 U 🟦	93 Np	94 Pu	95 Am 🟦	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

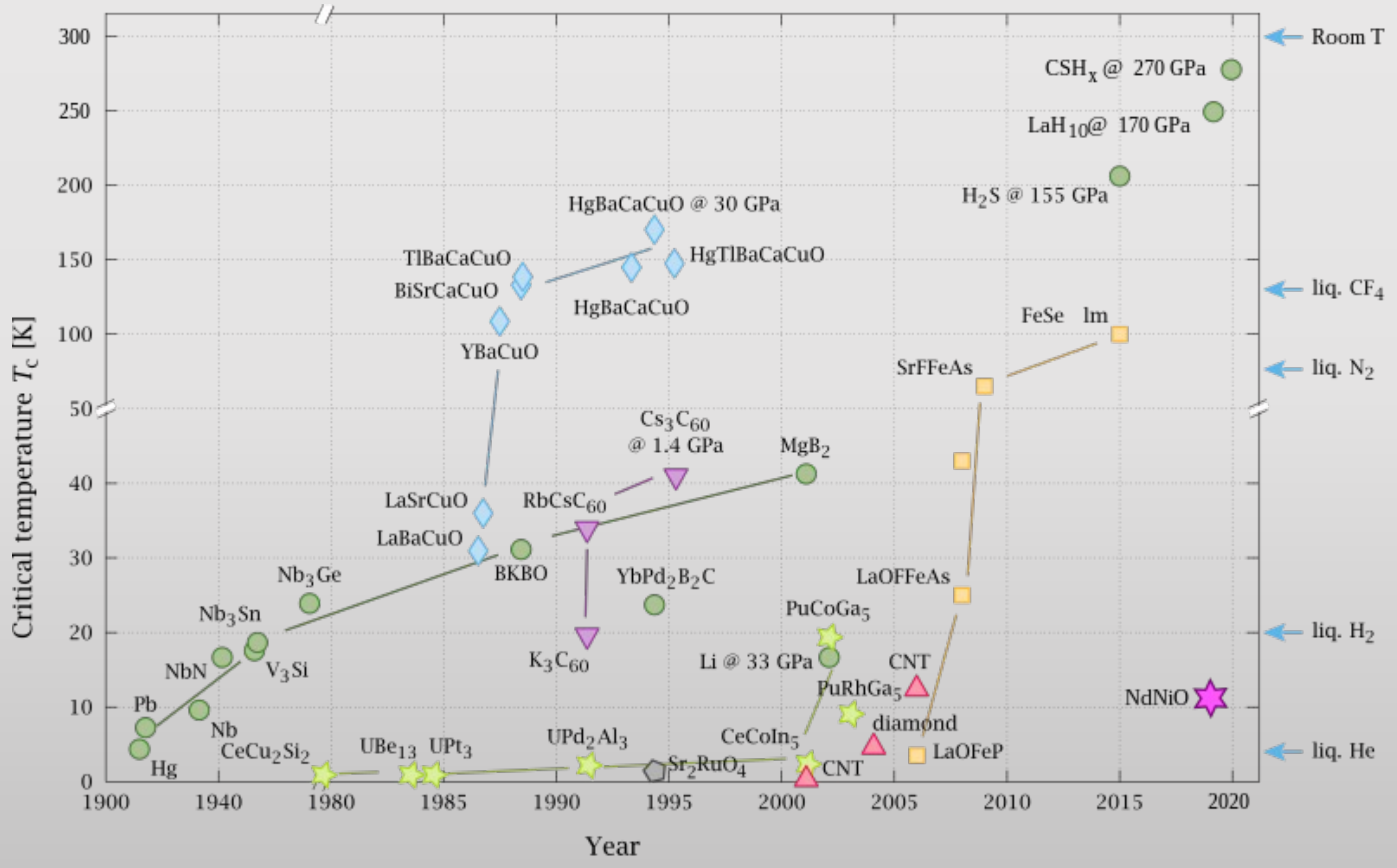
MOTIVATION

- Cheap electricity
- High magnetic field

What is needed for that?

- Room temperature
- High current

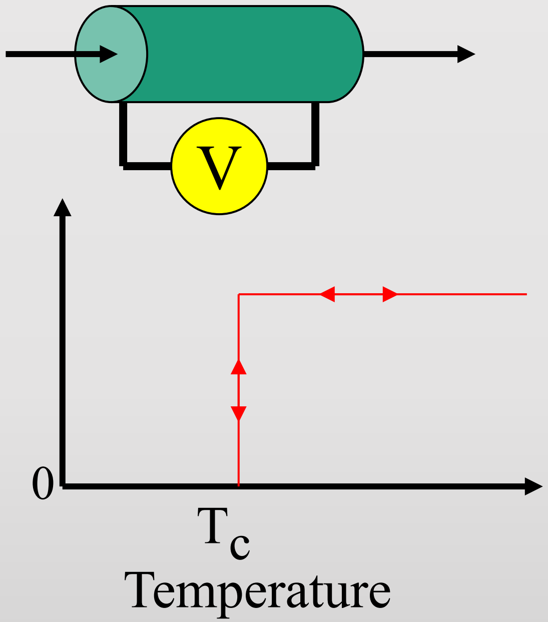
TIMELINE OF CRITICAL TEMPERATURE



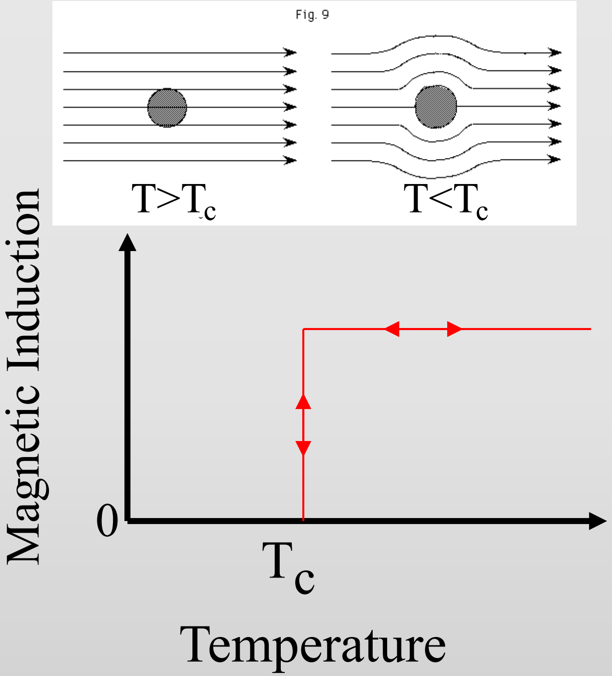
How to understand if it is a superconductor?

The Three Hallmarks of Superconductivity

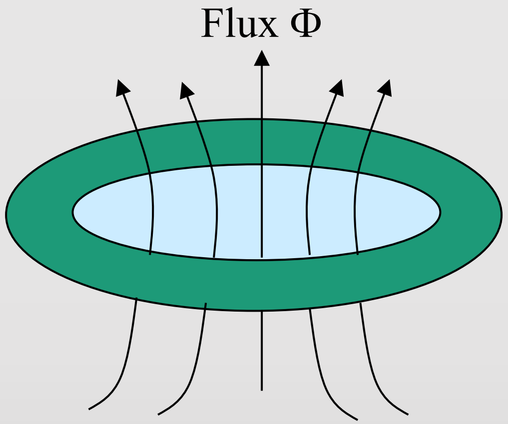
Zero Resistance



Complete Diamagnetism



Macroscopic Quantum Effects

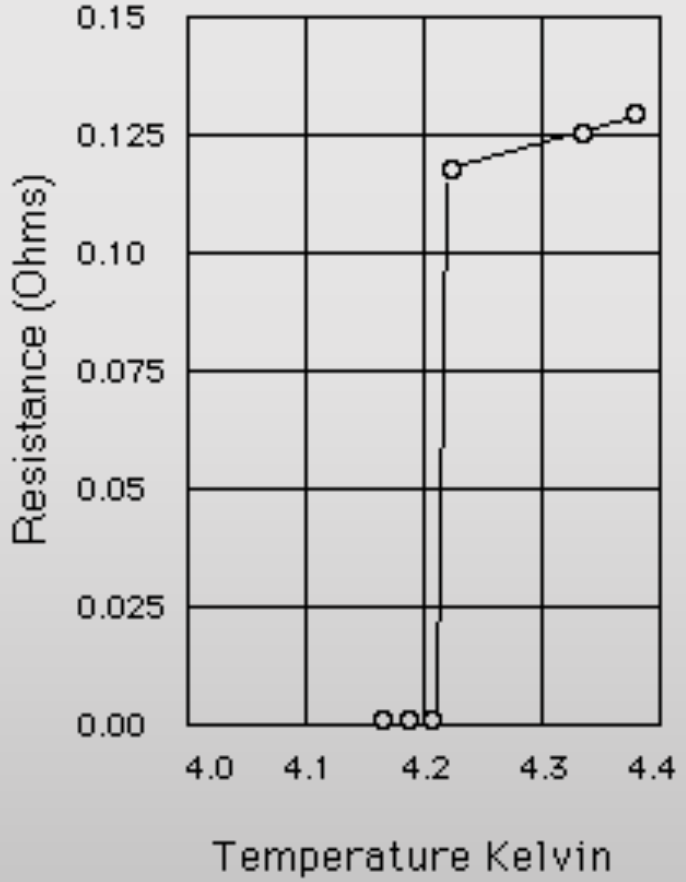


Flux quantization $\Phi = n\Phi_0$

Josephson Effects

Zero resistance

Fig. 1



Complete Diamagnetism

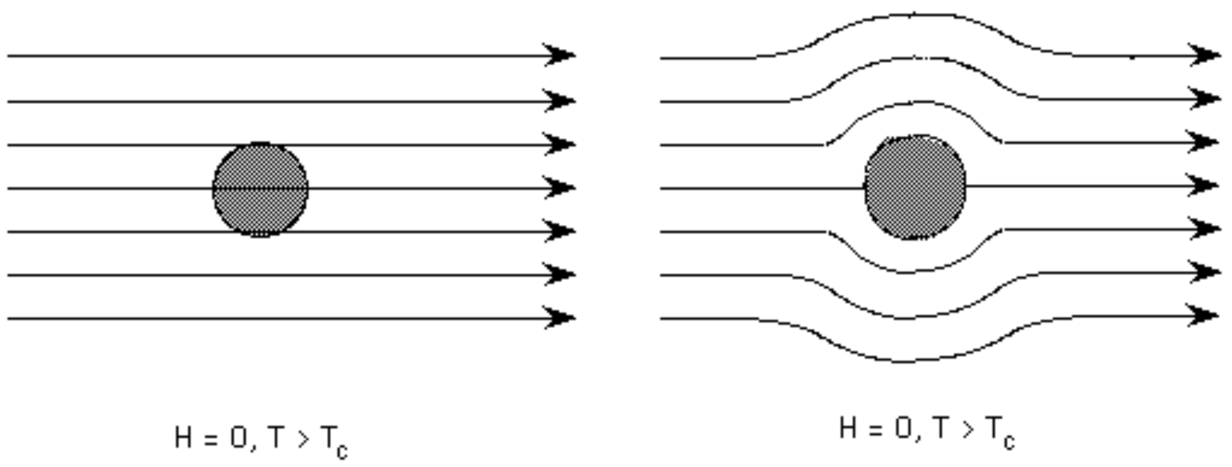


Fig. 9

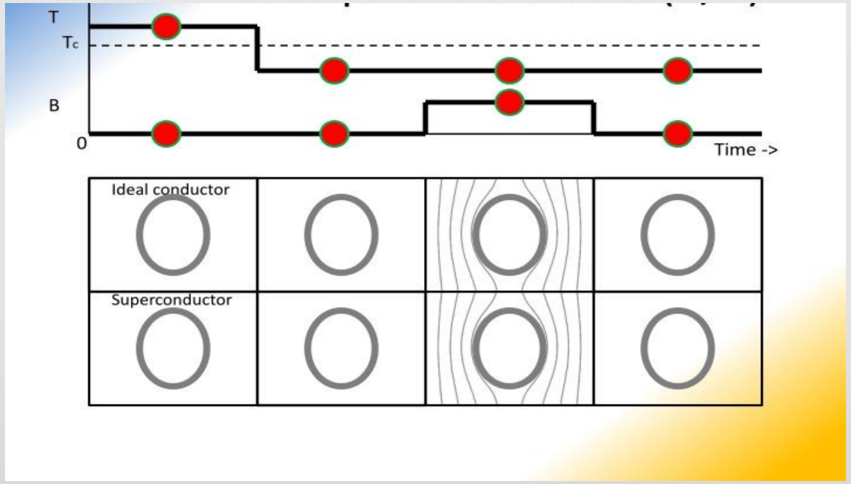
The Yamanashi MLX01 MagLev test vehicle achieved a speed of 343 mph (552 kph) on April 14, 1999

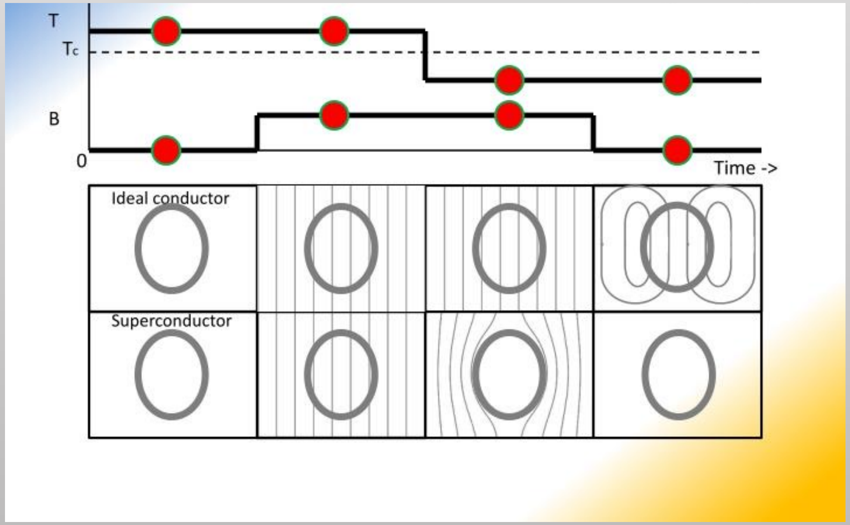
https://www.youtube.com/watch?v=4lE8QWtrEvQ&ab_channel=FalconFalzone

Complete Diamagnetism

Is an ideal conductor being a superconductor?

Meissner – Ochsenfeld effect





For notes

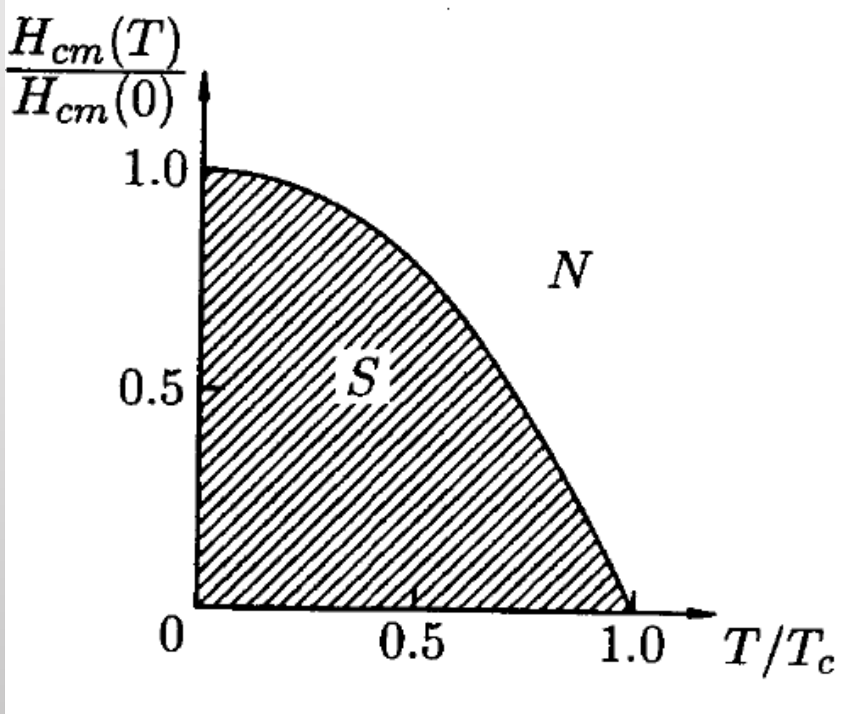
Superconductors type

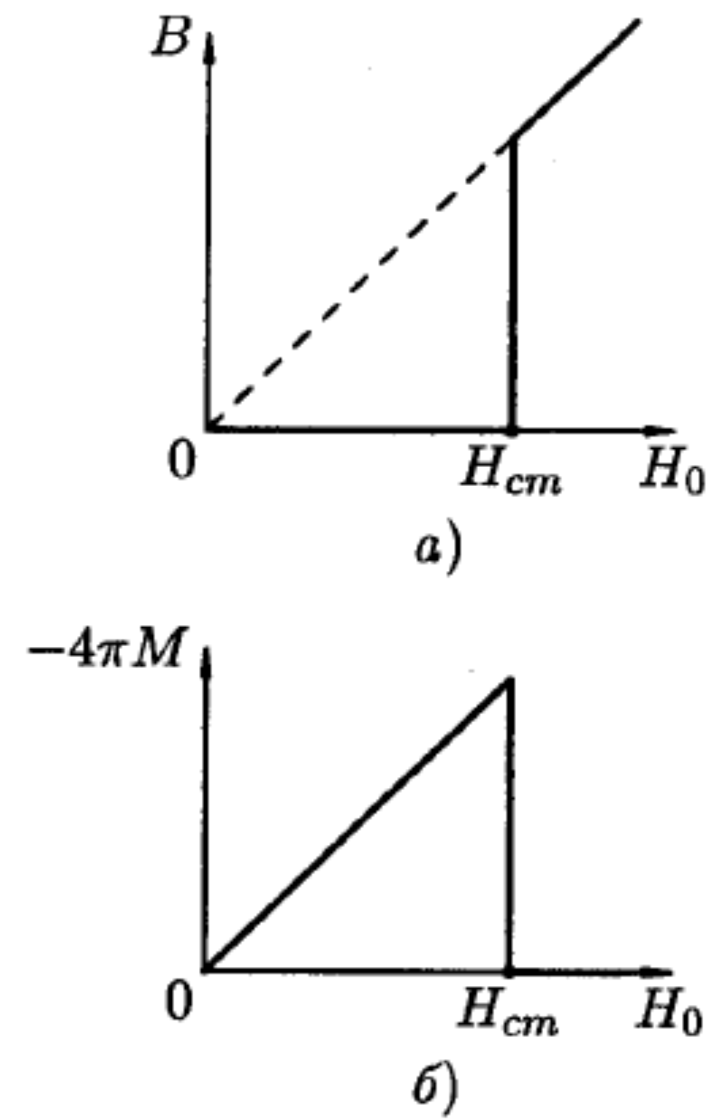
I type
All pure metal without Nb

II type
All other

Magnetic properties of a superconductor(I type)

$$\mathbf{B} = \mathbf{H}_0 + 4\pi \mathbf{M},$$

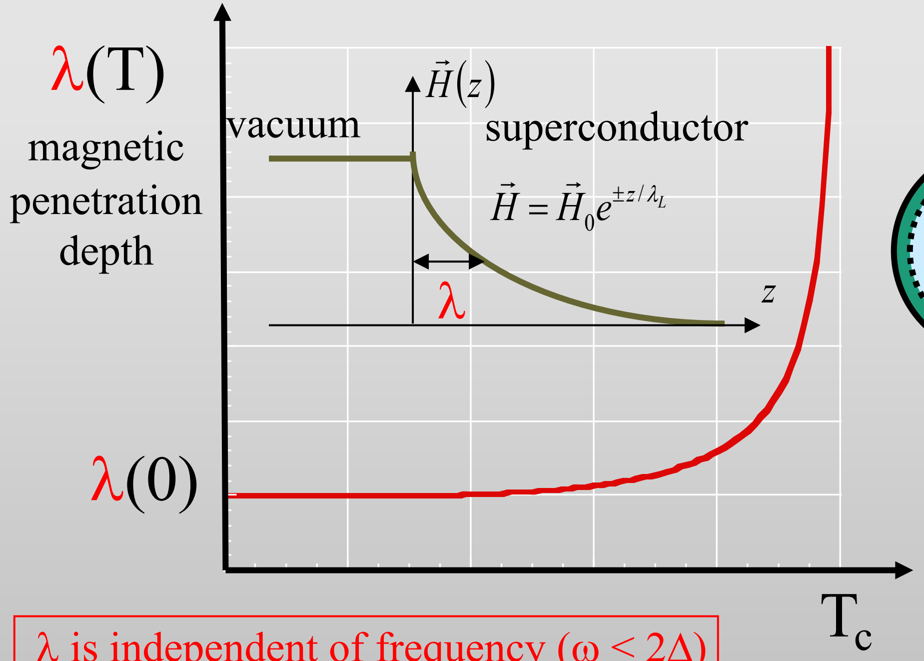




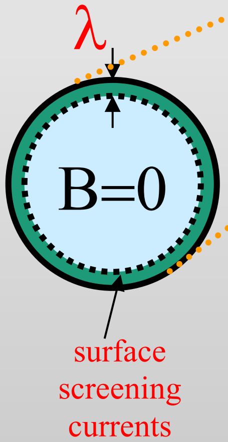
$$H_{cm}(T) = H_{cm}(0)\left[1 - (T/T_c)^2\right].$$

B - magnetic induction
H - magnetic field strength
M – magnetization

Magnetic penetration depth (type I superconductors)



λ is independent of frequency (ω < 2Δ)



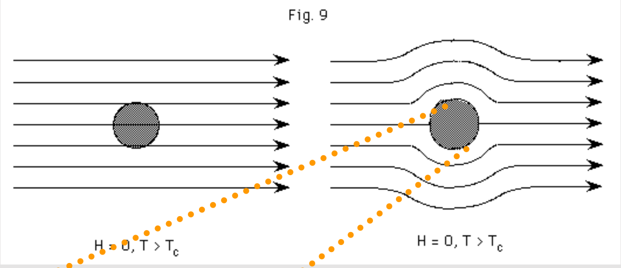
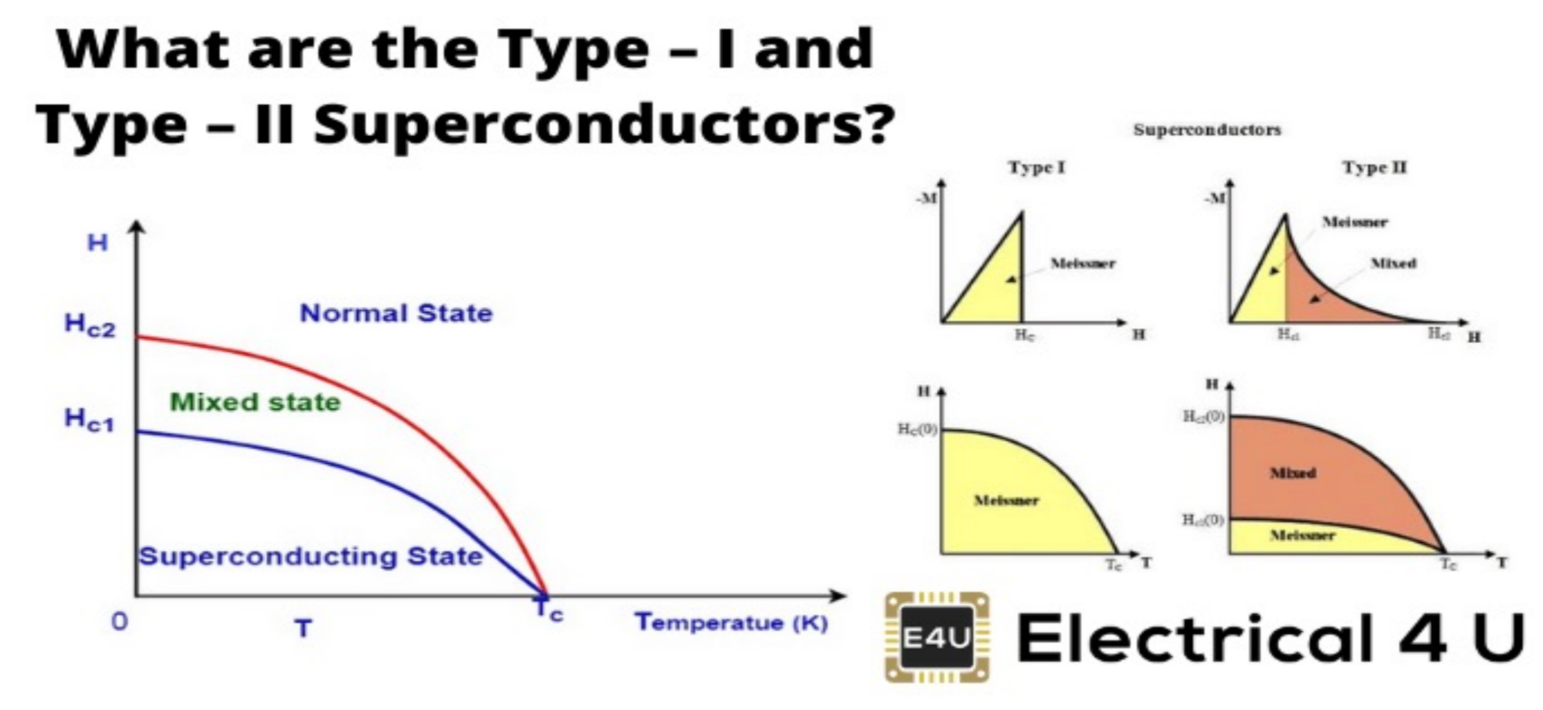
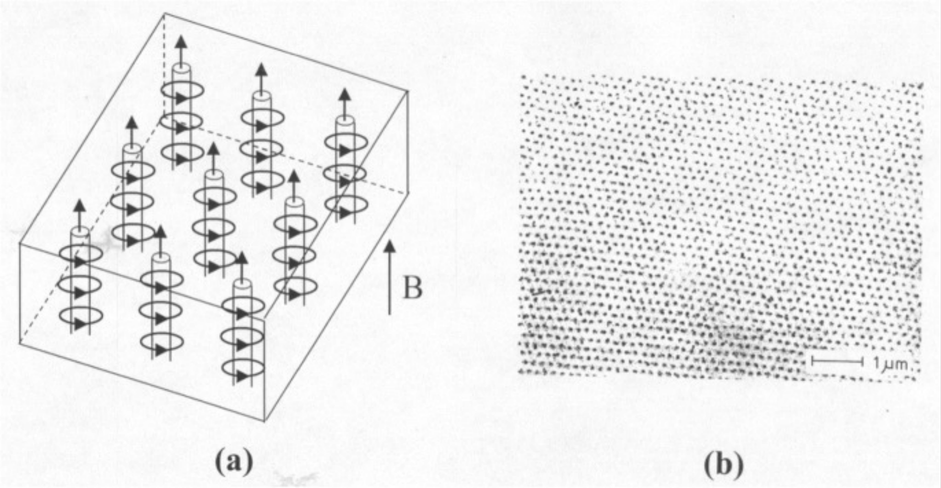


Fig. 9

$$\lambda = \left(\frac{mc^2}{4\pi n_s e^2} \right)^{1/2} .$$

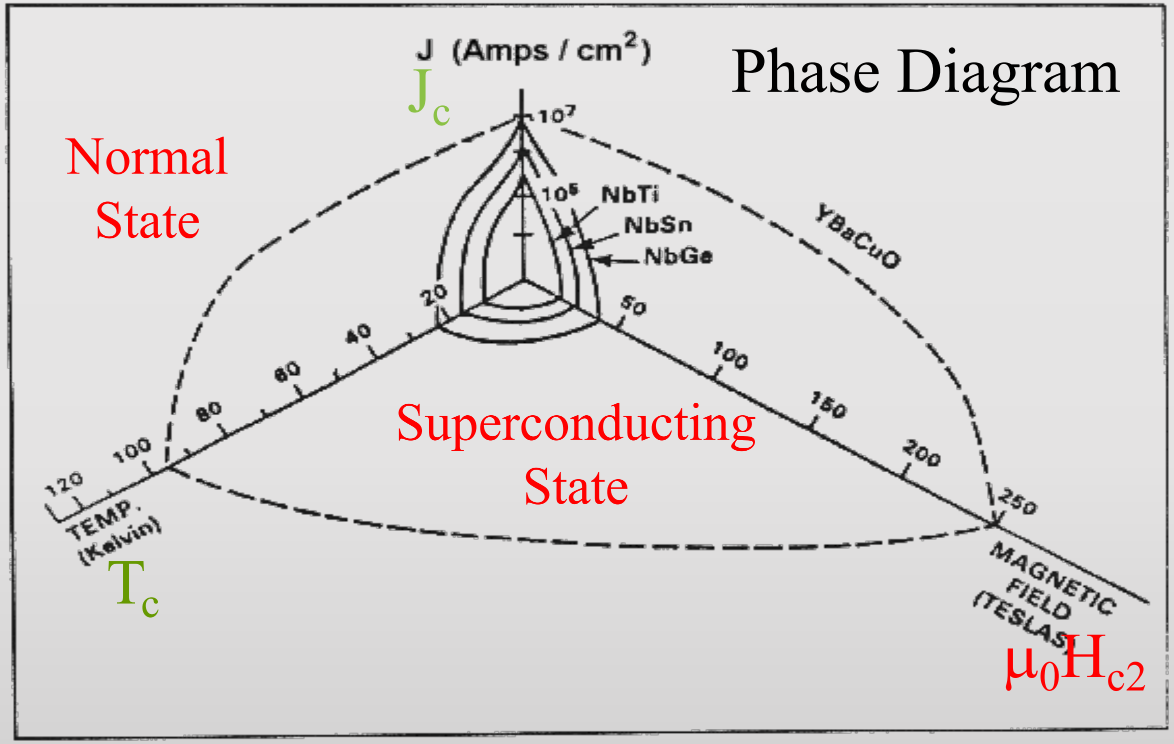
Magnetic penetration depth (type II superconductors)





Theory of superconductivity

What are the Limits of Superconductivity?



Phase Diagram

$$f_{\text{super}} = f_{\text{normal}} + \alpha(T)|\psi|^2 + \frac{\beta(T)}{2}|\psi|^4 + \frac{1}{2m^*}\left|\left(\frac{\hbar}{i}\vec{\nabla} - e^*\vec{A}\right)\psi\right|^2 + \frac{\mu_0 h^2}{2}$$

Ginzburg-Landau
free energy density

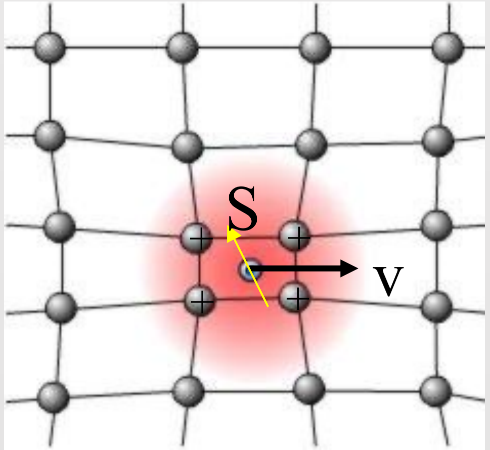
Temperature dependence

Currents

Applied magnetic field

BCS Theory of Superconductivity

Bardeen-Cooper-Schrieffer (BCS)

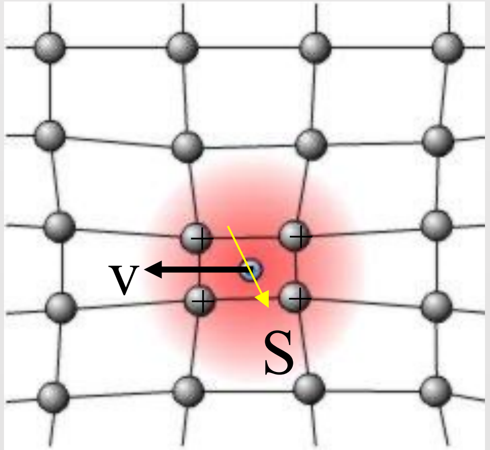


First electron polarizes the lattice

Cooper Pair

s-wave ($\ell = 0$) pairing

Spin singlet pair



Second electron is attracted to the concentration of positive charges left behind by the first electron

$$T_c \cong \Omega_{Debye}\, e^{-1/NV}$$

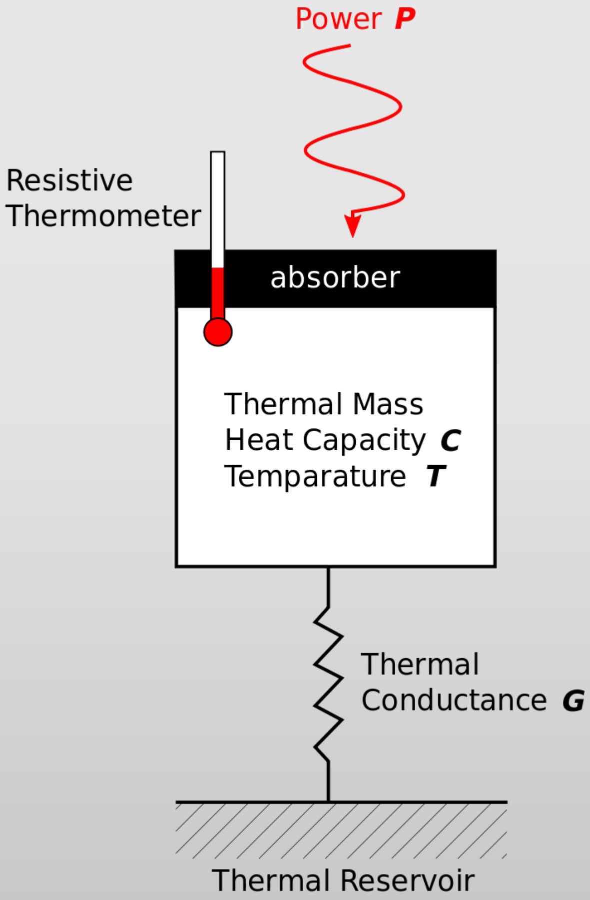
Ω_{Debye} is the characteristic phonon (lattice vibration) frequency
N is the electronic density of states at the Fermi Energy
V is the attractive electron-electron interaction

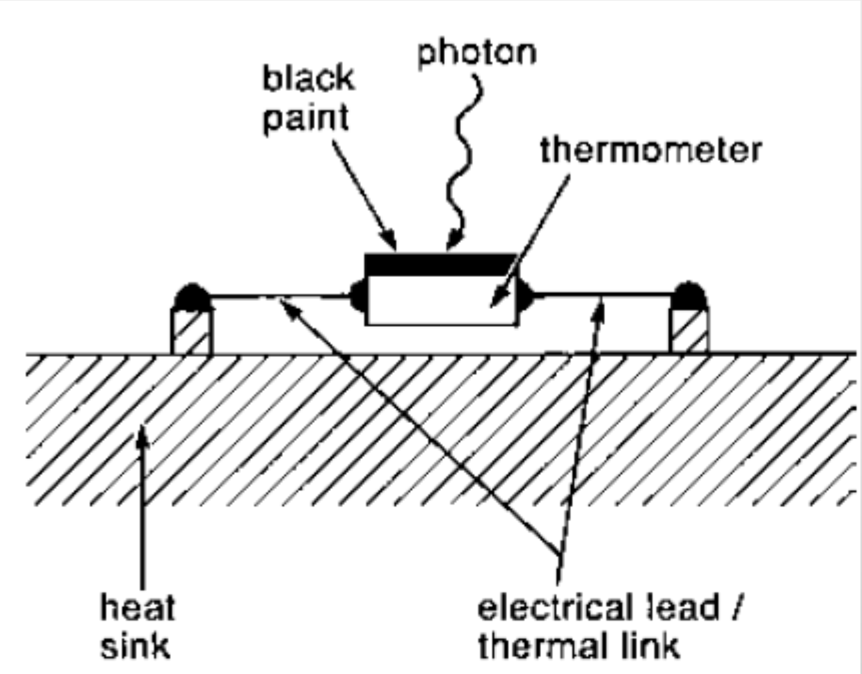
A many-electron quantum wavefunction Ψ made up of Cooper pairs is constructed with these properties:
An energy $2\Delta(T)$ is required to break a Cooper pair into two quasiparticles (roughly speaking)
Cooper pair size: $\xi = v_F \cdot \frac{\hbar}{\Delta}$

OUTLINE OF SUPERCONDUCTIVITY

- The Three Hallmarks of Superconductivity(Zero resistance, diamagnetic, flux quantization)
- Two types of superconductors
- Many applications

Bolometers





$$\boldsymbol{G} = \frac{P_0}{T_1}$$

$$P_{\text{inc}} = G(T - T_b) + C\frac{\mathrm{d}T}{\mathrm{d}t}$$

$$T_1(t) = \left[\begin{array}{ll} \dfrac{P_0}{\boldsymbol{G}}, & t < 0 \\ \dfrac{P_0}{\boldsymbol{G}} + \dfrac{\eta P_1}{\boldsymbol{G}}\left(1 - e^{-t/(C/G)}\right), & t \geq 0. \end{array}\right.$$

$$\tau_{\mathrm{T}} = \frac{\boldsymbol{C}}{\boldsymbol{G}}.$$

Thermal property

$$P_{\mathrm{inc}}(t) = P_0 + \Delta P(\omega t)$$

$$\begin{tikzcd}
 & \dfrac{\Delta T}{\Delta P} = \dfrac{1}{C\omega} \arrow[dr, dash] & \\
\dfrac{\Delta T}{\Delta P} = \dfrac{1}{G\sqrt{1+\omega^2\tau^2}} \arrow[ur, "(\omega\tau >> 1)"] \arrow[dr, "(\omega\tau << 1)"'] & & S_{\mathrm{th}}\tau^{-1} = const. \propto C \\
 & \dfrac{\Delta T}{\Delta P} = \dfrac{1}{G} \arrow[ur, dash] &
\end{tikzcd}$$

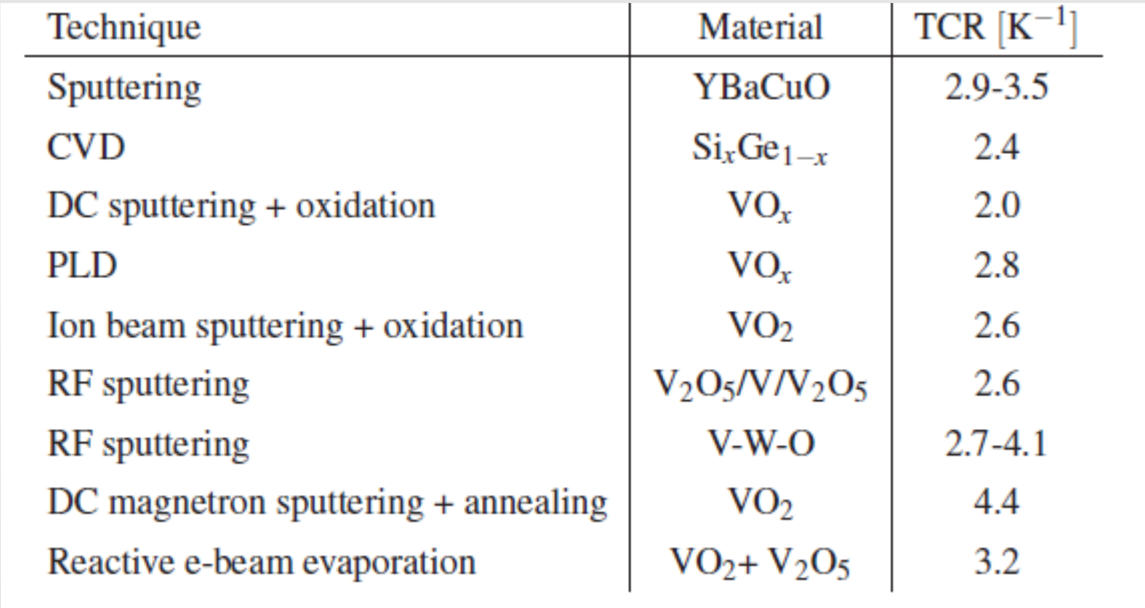
The electrical sensitivity

$$\Delta V = I_{\text{bias}} \Delta R \quad .$$

$$S = \frac{\Delta V}{\Delta P} = I_{\text{bias}} \frac{\Delta R}{\Delta T} \frac{1}{G} \frac{1}{\sqrt{1+\omega^2\tau^2}}$$

Room temperature bolometers

$$(TCR = \frac{1}{R}\frac{\Delta R}{\Delta T})$$

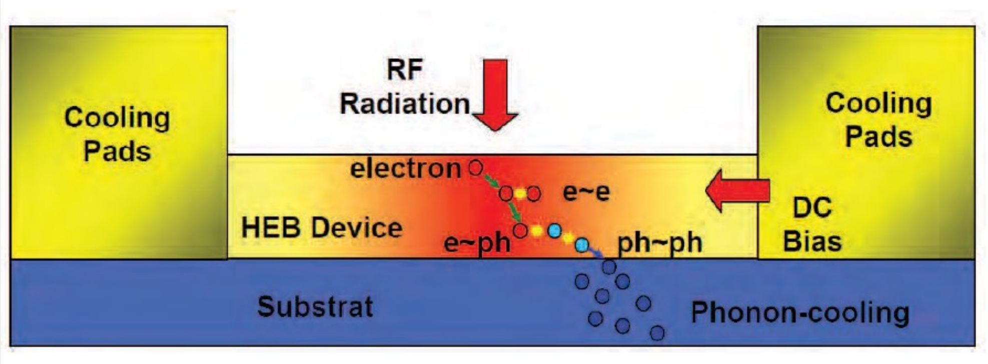


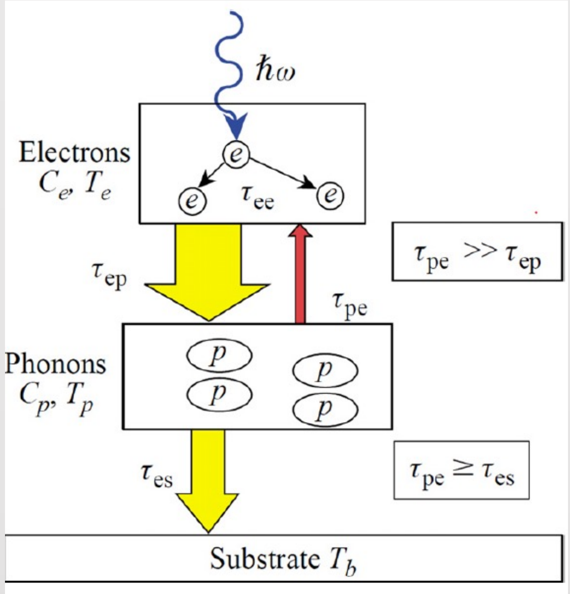
Technique	Material	TCR [K^{-1}]
Sputtering	YBaCuO	2.9-3.5
CVD	Si_xGe_{1-x}	2.4
DC sputtering + oxidation	VO_x	2.0
PLD	VO_x	2.8
Ion beam sputtering + oxidation	VO_2	2.6
RF sputtering	$V_2O_5/V/V_2O_5$	2.6
RF sputtering	V-W-O	2.7-4.1
DC magnetron sputtering + annealing	VO_2	4.4
Reactive e-beam evaporation	$VO_2+ V_2O_5$	3.2

OUTLINE BOLOMETERS

- Bolometers are radiation detectors with operation speed and sensitivity
- Dependence of C and G
- The product of the sensitivity and the speed of the bolometer is constant
- Strong dependence of temperature coefficient of the resistance

HOT ELECTRON BOLOMETERS





$$\tau_{e-e} = \frac{\hbar}{kT}\frac{2\pi\hbar}{e^2R_{Sq}}\ln^{-1}\frac{\pi\hbar}{e^2R_{Sq}}$$

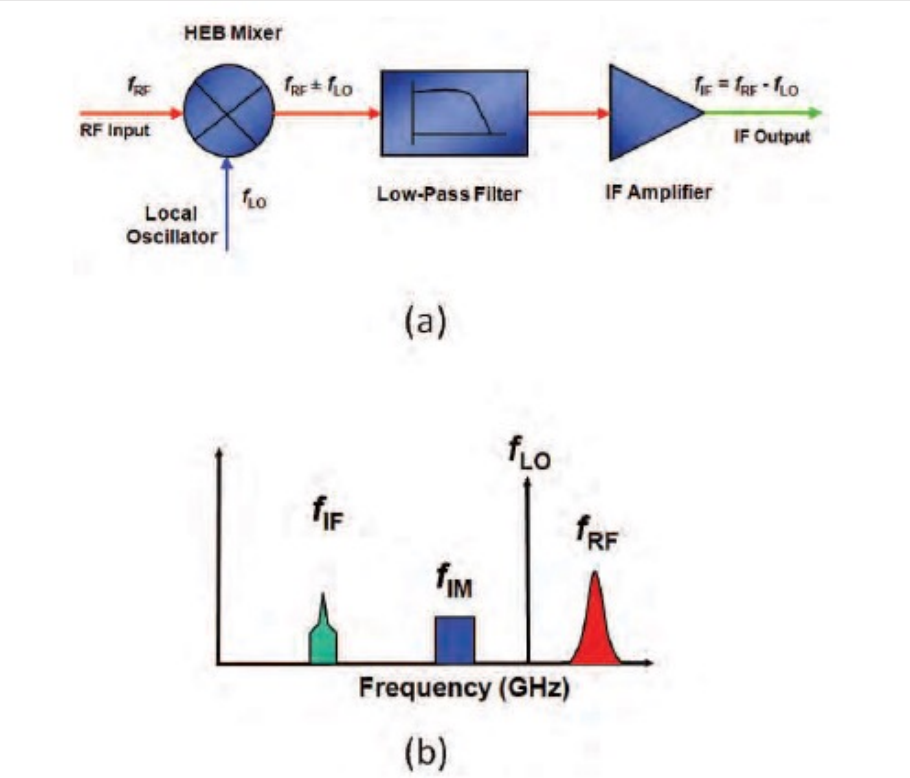
$$\lambda_{\text{th}} = \sqrt{\frac{K\tau_{e-ph}}{c_e}} = \sqrt{D\tau_{e-ph}},$$

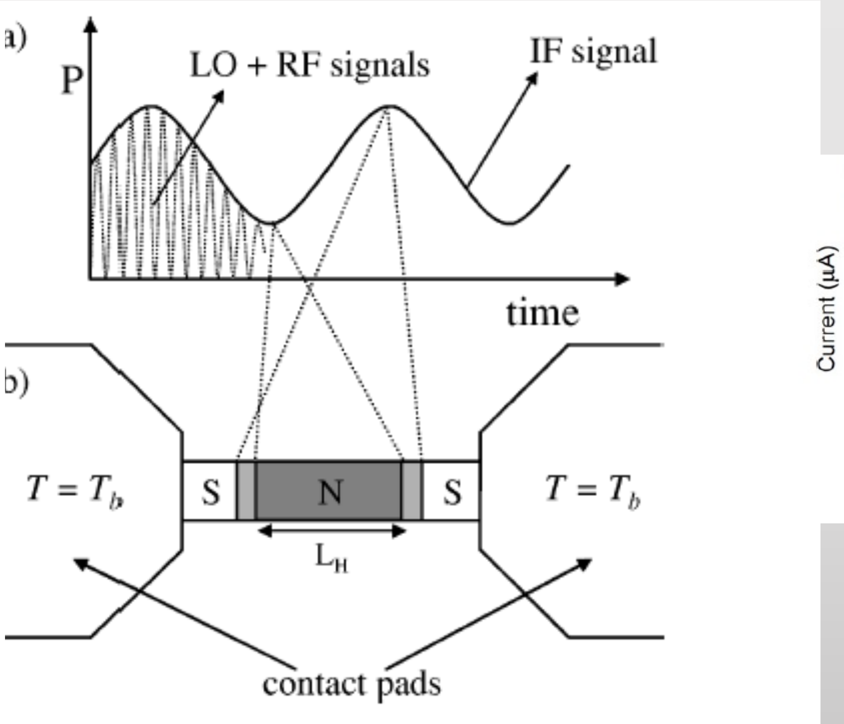
$L_b > \lambda_{th}$
phonon-cooled HEB

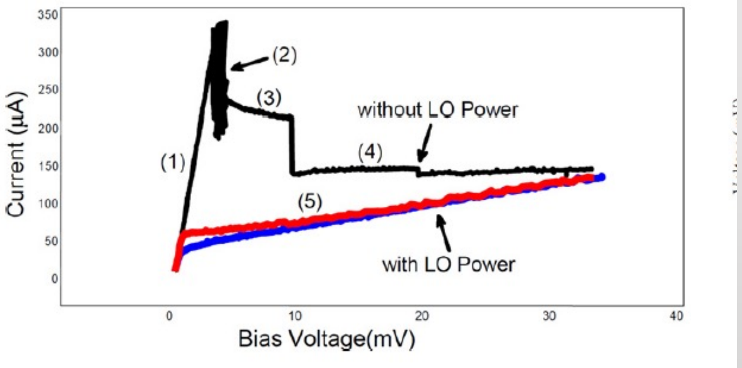
$L_b < \lambda_{th}$
Diffusion cooled HEB

Heterodyne scheme

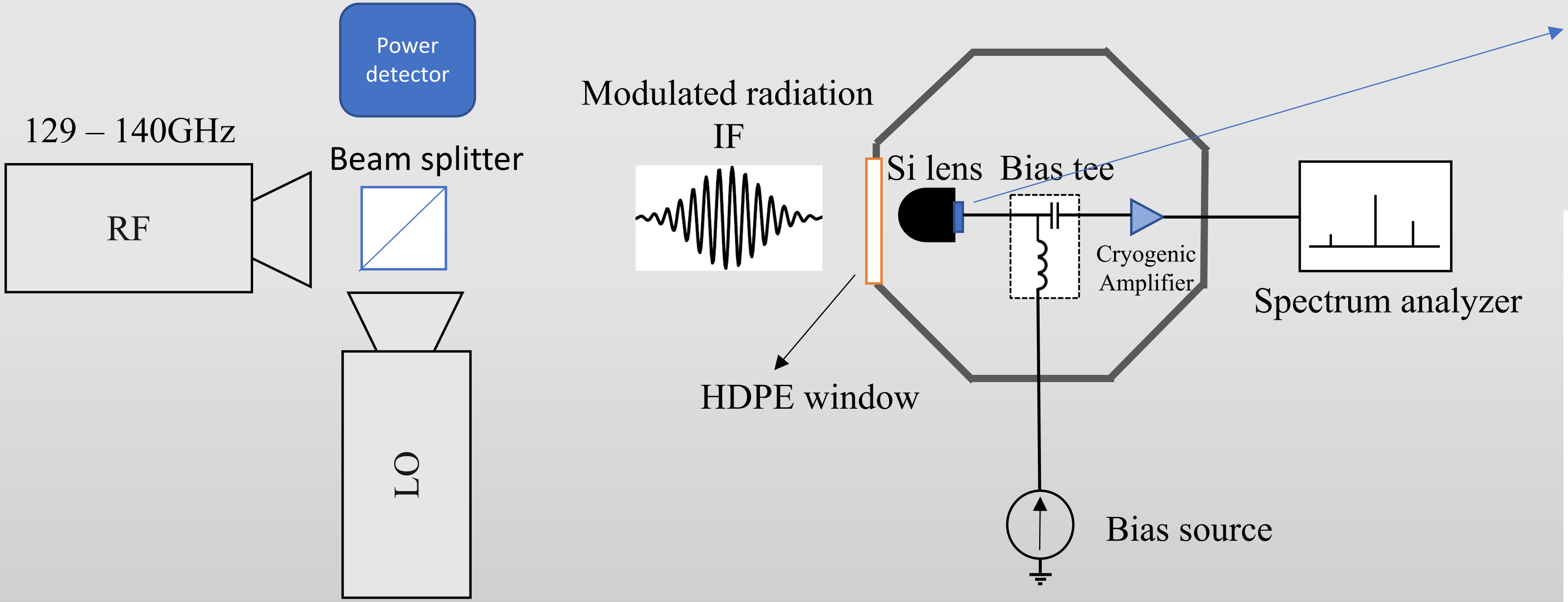
$$I = AV^2$$







Heterodyne scheme



129 – 140GHz

RF

Power detector

Beam splitter

LO

Modulated radiation IF

HDPE window

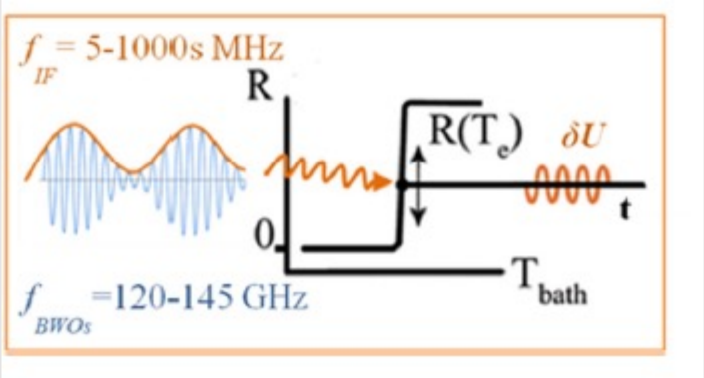
Si lens

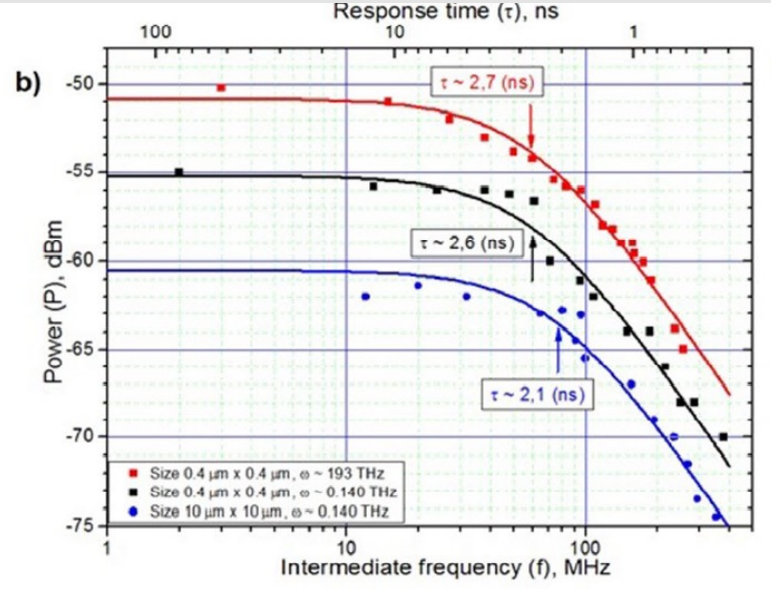
Bias tee

Cryogenic Amplifier

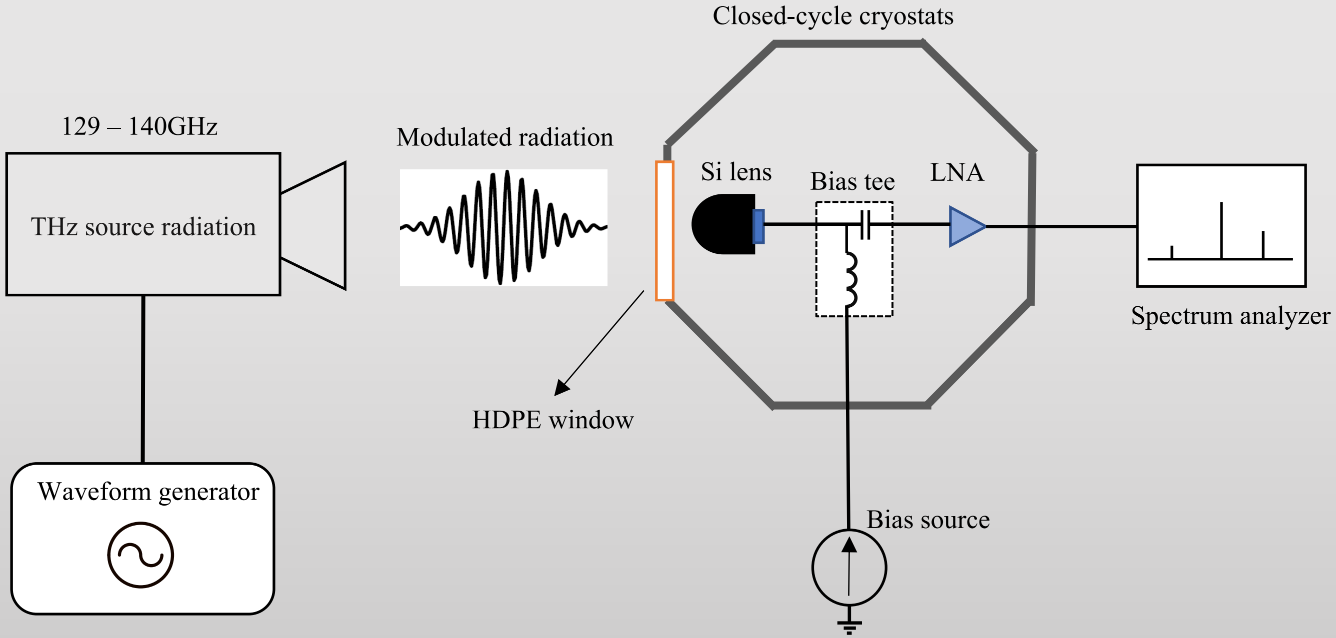
Spectrum analyzer

Bias source





Direct detection



Основные характеристики

NEP

Sensitivity