Salahaddin University
Collage of Basic Education
Department of General Science
Fourth Stage
Second Course

Superconductor

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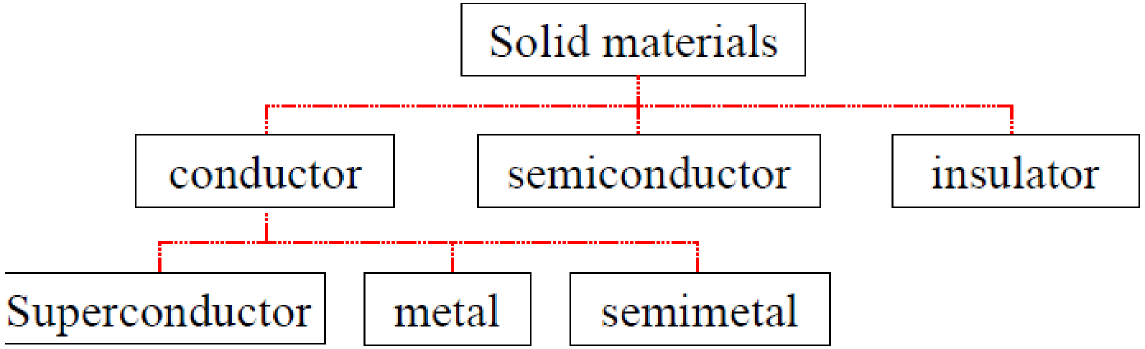
Chapter one Superconductor

Solids have different conductivity:



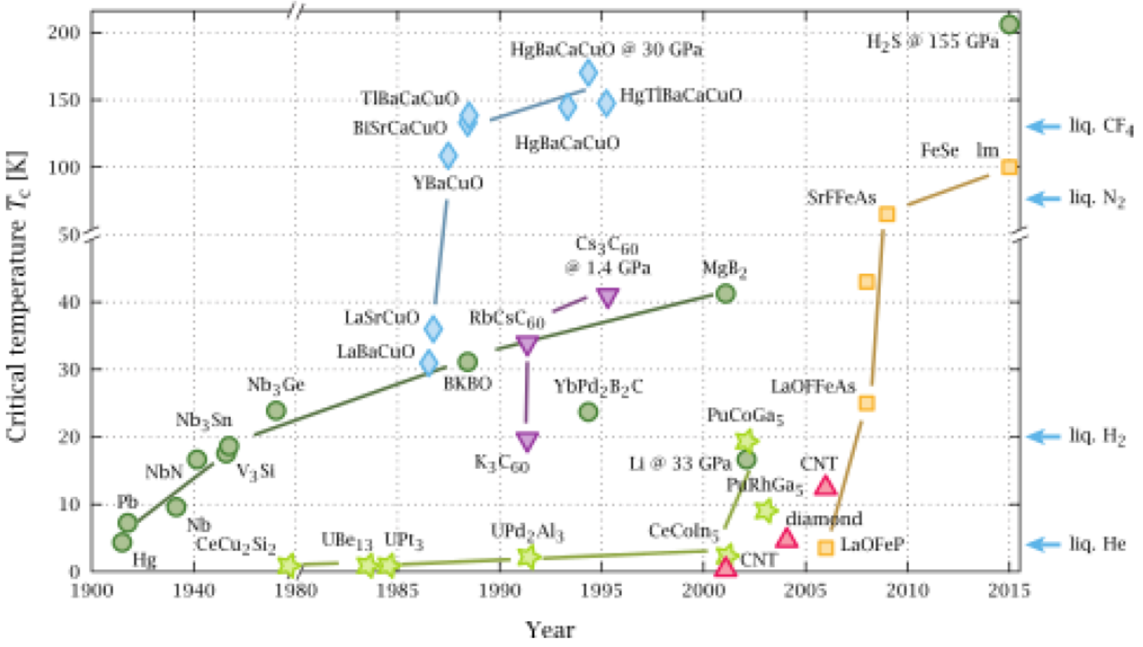
Superconductivity

A perfect superconductor is a material that exhibits two characteristic properties, namely zero electrical resistance and perfect diamagnetism, when it is cooled below a particular temperature Tc, called the critical temperature. At higher temperatures it is a normal metal, and ordinarily is not a very good conductor. For example, lead, tantalum, and tin become superconductors, while copper, silver, and gold, which are much better conductors, do not superconduct. In the normal state some super-conducting metals are weakly diamagnetic and some are paramagnetic. Below Tc they exhibit perfect electrical conductivity and also perfect or quite pronounced diamagnetism

A brief history of low temperature

- 1800 Charles and Gay-Lusac (from *P*-*T* relationship) proposed that the lowest temperature is -273 C (= 0 *K*)
- 1877 Cailletet and Pictet liquified Oxygen (-183 C or 90 *K*)
- soon after, Nitrogen (77 *K*) is liquified
- 1898 Dewar liquified Hydrogen (20 *K*)
- 1908 Onnes liquified Helium (4.2 *K*)

- 1911 Onnes measured the resistance of metal at such a low *T*. To remove residual resistance, he chose mercury. Near 4 *K*, the resistance drops to 0.



evolution of critical temperatures since the discovery of superconductivity

Timeline of superconducting materials

Brief history of the theories of superconductors

- 1935 London: superconductivity is a quantum phenomenon on a macroscopic scale. There is a "rigid" (due to the energy gap) superconducting wave function Ψ.
- 1950
  - Frohlich: electron-phonon interaction maybe crucial.
  - Reynolds et al, Maxwell: isotope effect
  - Ginzburg-Landau theory: ρ_S can be varied in space. Suggested the connection $\rho_S(\vec{r}) = |\psi(\vec{r})|^2$

    and wrote down the eq. for order parameter Ψ(r) (App. I)
- 1956 Cooper pair: attractive interaction between electrons (with the help of crystal vibrations) near the FS forms a bound state.
- 1957 Bardeen, Cooper, Schrieffer: BCS theory

Microscopic wave function for the condensation of Cooper pairs.

Ref: 1972 Nobel lectures by Bardeen, Cooper, and Schrieffer

BRIEF HISTORY

In 1908, H. Kamerlingh Onnes initiated the field of low-temperature by liquifying helium in his laboratory at the University of Leiden. Three years later (1911) Low temperature superconductivity was discovered by Kamerlingh Onnes below 4.15 K of the dc resistance of mercury dropped to zero. He was awarded in 1913 the Nobel Prize in Physics, partly for this discovery.

He was one of the famous scientists of the world. In 1933, Meissner and Ochsenfeld observed yet another interesting phenomenon called Meissner effect.

Two years later in 1935, the London brothers (London F., and London H. 1935) published a theory to explain the behavior of superconductors. The London theory was insufficient and could not explain all aspects of superconductivity..

The next theoretical advance came in 1950 with the theory of Ginzburg and Landau, which described superconductivty in terms of an order parameter and provided a derivation for the London equations. Both of these theories are macroscopic in character.

In the same year it was predicted theoretically by H. Fröhlich (1950) that the transition temperature would decrease as the average isotopic mass increased. This effect, called the isotope effect.

The isotope effect provided support for the electron–phonon interaction mechanism of superconductivity.

The London penetration depth λ and the London equation. In 1953, the London theory was extended by Pippard (Pippard, 1953). He introduced the concept of coherence length ξ, which is one of the fundamental parameters in the theory of superconductivity.

The Ginzburg–Landau (1950) and London (1950) results fit well into the BCS formalism. ***Much of the present theoretical debate centers around how well the BCS theory explains the properties of the new high- temperature superconductors*****.**

On April 17, 1986, a brief article, entitled "Possible High Tc Superconductivity in the Ba–La–Cu–O System," written by J. G. Bednorz and K. A. Müller initiating the high-temperature superconductivity. Sharp drops in resistance attributed to "high-Tc" superconductivity had appeared from time to time over the years, but when examined they had always failed to show the required diamagnetic response.

Early in 1988, superconductivity reached 110 K with the discovery of BiSr- CaCuO, and then the 120–125 K range with TIBaCaCuO. More recently, Berkley et al. (1993) reported

Significant parameters of superconducting state

There are three significant critical parameters that keep up the superconducting state

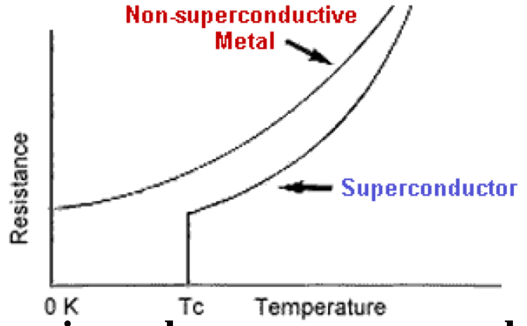
1- Critical temperature (T_C) 2- Critical magnetic field (H_C) 3- Critical current density (J_C)

1- Critical temperature (T_C)

Critical temperature is the temperature at which phase transition is observed from normal to superconducting state. The value of electrical resistivity also vanishes at this point.

The critical temperature is the temperature that marks the difference between superconducting and non-superconducting properties within a superconducting material. Above this temperature, the superconductor will behave normally. In the case of metals, the resistance will decrease with a drop in temperature, similar to non-superconducting metals. When the critical temperature is reached, the resistance suddenly drops to zero, and the material behaves as a superconductor. This temperature is not constant for all superconductors, but varies depending on the material, with some superconductors have a lower critical temperature than others.

Those with a critical temperature above 30K are called high temperature superconductors, such as Y- Ba-Cu-O with a critical temperature of 90 K. High temperature superconductors are especially useful due to it being easier to achieve superconductance in these materials because they do not need to be cooled to such low temperatures.



Comparisons between superconductor and non superconductor

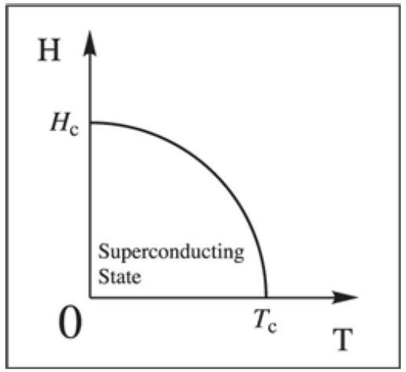
2- Critical magnetic field (H_C)

This field is basically responsible for the destruction in the superconducting properties of a superconductors. Consider a superconductor placed in magnetic field. The superconductivity is destroyed with the increase in in the magnetic field till the critical value of magnetic field is achieved. As the value of applied field exceeds the critical value, the material comes back to the normal superconducting state. Fig shows the critical magnetic field being a temperature dependent quantity.

Mathematically it is given as
$$H_C(T) = H_C(0)\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

Where $H_C(0)$ is the maximum value of applied field at T=0

$H_c(T_c) = 0$ (at $T = T_c$)



Critical magnetic field versus temperature

3- Critical current density (Jc)

In order to minimize the resistance and energy losses and maximize the amount of current, thin wires of superconductivity are used. Whenever a superconductor is placed in a colder place it carries large amount of currents i.e. critical current density is temperature subordinate

Magnetic Terminology

When a solid is placed in a magnetic field, it gets magnetized. The magnetic moment per unit volume developed inside a solid is called magnetization (M)

X is magnetic susceptibility which is a measure of the quality of the magnetic material and is defined as the magnetization produced per unit applied magnetic field

$$\chi = \frac{M}{H}$$

Where H is strength of the applied magnetic field , also referred to as the magnetic field intensity. M and H are measured inamperes per meter and χ **is a dimensionless quantity. The magnitude and sign of susceptibility vary with the type of magnetism.**

The magnetic induction or magnetic flux density B produced inside the medium as a consequence of the applied magnetic field H is given by

$$B = \mu_0 (H + M)$$

Where μ_0 **is the permeability of the free space or vacuum and is equal to** $\left(\mu_0 = 4\pi \times 10^{-7} \frac{Henry}{meter}\right)$**. The quantity B is measured in Weber per square metre** $\left(\frac{Weber}{m^2}\right)$ **.or Tesla** (T)

$$B = \mu_0 (1 + \chi) H \qquad B = \mu H$$

Where μ ***is called the absolute permeabity of the medium .*** **For the isotopic medium ,it represents a scalar quantity having dimensionless same as that of** μ_o**. It is more convenient to introduce a dimensionless parameter** μ_r **which is called the relative permeability of the medium and is given by**

$$B = \mu_0 \mu_r H \qquad \mu_r = 1 + \chi \qquad \mu = \mu_0 \mu_r$$

For free space in the absence of any material medium $M = 0$**,** $\chi = 0$ $\mu = \mu_o$ **and** $\mu_1 = 0$ **, and from the above relation, we obtain** $B = \mu_0$ $B = H$ $B = \mu_0 H$

Superconductor

The superconductivity was first discovered by H. K. Onnes in 1911 when he used liquid helium to cool down a sample of mercury (Kamerlingh-Onnes, H. 1911). He observed a sudden drop in resistance to an immeasurably small value when the temperature of the sample reached a value below 4.2 K. Unfortunately, there was no plausible explanation for the event at the time of the experiment because the quantum theory of metals was not yet developed to its full potential

Superconductivity is a phenomenon in which the electromagnetic properties of certain materials change considerably when they are cooled down under a critical temperature that is characteristic of a material. The well-known properties include perfect conductivity and perfect diamagnetism figure (1-1) demonstrates the former. Thermodynamically the transition of a material into the superconducting state is a second-order phase transition, e.g. there is no change of the crystallographic structure of the material.

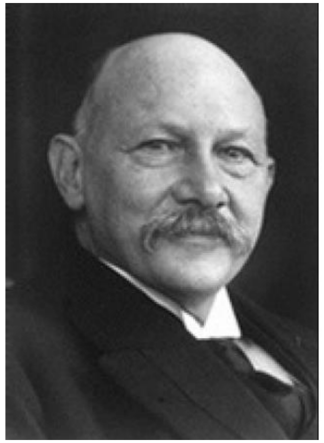
Superconductors have four important characteristics, namely, zero resistivity, Miessner effect, Josephson effect and quantization of magnetic field. Zero resistivity means, a material in its superconducting stage offers no resistance to the flow of direct electric current or in other words superconductor is a perfect electrical conductor. Meissner effect: a superconductor will expel magnetic flux from its interior by an internally induced magnetic field. Thus a superconductor in a weak magnetic field will act as a perfect diamagnetic. Josephson effect is the remarkable electrical property associated with the tunneling of superconducting electron pairs from a superconductor through a thin layer of an insulator in to another superconductor

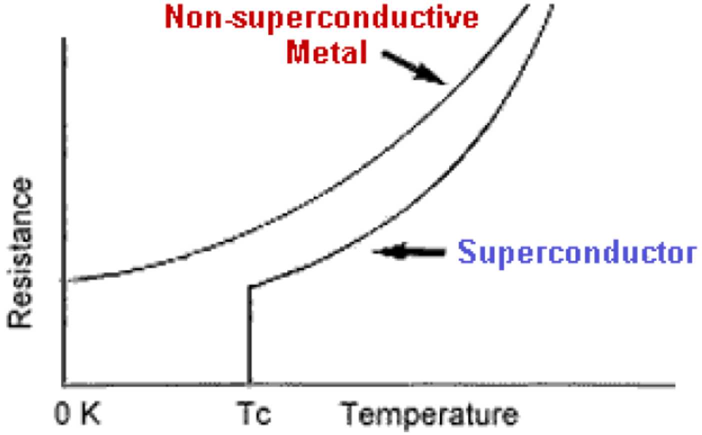
first two properties are related to electric power application and the last two properties are related to microelectronic applications

Onnes called it supra-conductivity and later ***superconductivity***.

Nobel Prize (1913)

Heike Kamerlingh Onnes
(1853 - 1926)





Superconductors

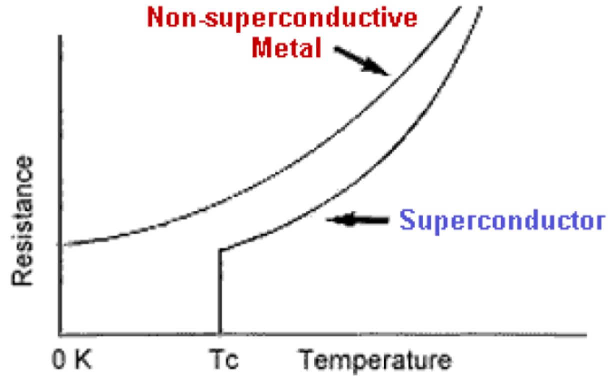
Fundamentally, superconductor is an element or a metallic alloy that possesses two distinguishing properties.

- **Zero dc-resistivity**
- **Perfect diamagnetism**

Zero dc resistivity

A superconductor, when cooled below a certain temperature, loses all its electrical resistance dramatically as shown in fig. 1.1. Eventually the metallic alloy allows all the current to flow through it without any effective electrical resistance. This current flowing through the metal is known as "Supercurrent"[

The certain temperature below which this transition of state occurs is designated as Tc,which stands for Critical Temperature. Superconductivity is a quantum phenomenon occurring at a macroscopic level[7]. All the elements that possess this property, have their own value of Critical Temperature. Fig 1.1 (a) shows the graph between resistance and temperature for a superconductor.



Perfect diamagnetism

Diamagnetism is the alignment of magnetic moments in such a way that they oppose the externally applied field". A perfect conductor is perfect diamagnetic in nature. In addition to zero dc resistivity, superconductors exhibit another property of perfect diamagnetism in which they cancel or oppose all the magnetic flux inside the material when placed in an externally applied magnetic field[8]. The magnetism exhibited by these materials is perfect diamagnetism. For example; copper, air, hydrogen, gold, nitrogen. Figure 1.2 shows the perfect diamagnetic behavior of a superconductor.

As magnetic field is applied, current is induced in atomic orbitals causing diamagnetism. This induced current produces magnetization within the diamagnetic material which opposes the applied field, so cancels out it. As the applied field is removed, magnetization also disappears.

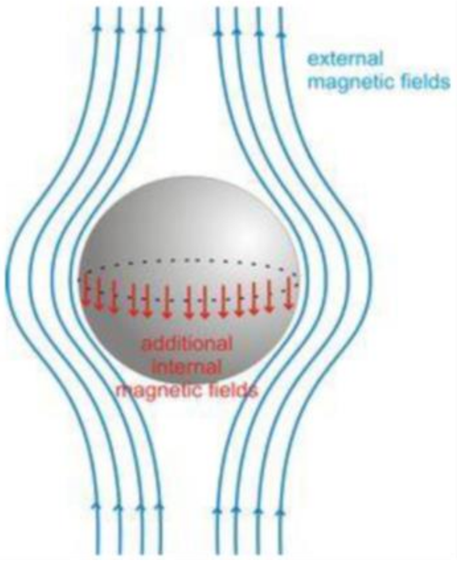


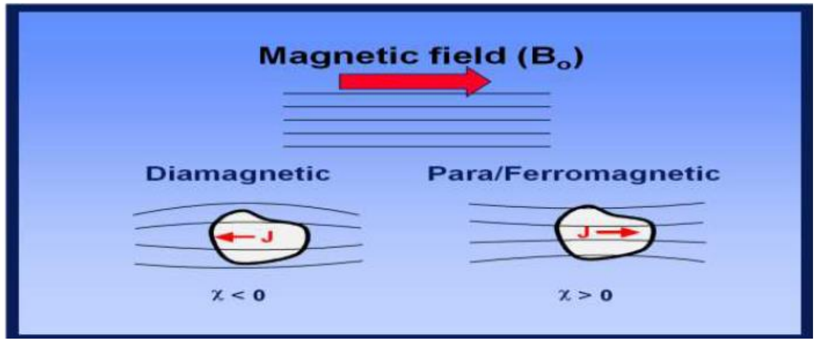
Figure : Perfect diamagnetic behavior of superconductor

In diamagnetic material $B = \mu_o (H + M)$

Since in superconductors B=0 (the field is completely screened out from the interior of the material), hence

$0 = \mu_o (H + M)$ $M = -H$ $\chi = \frac{M}{H} = -1$

Hence magnetic susceptibility of a superconductor can be given as

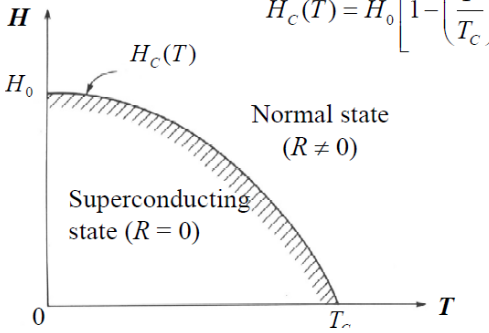


Susceptibility in the presence of magnetic field

Perfect diamagnetism is basically due to the result of a continuous current flowing in the opposite direction to that of the externally applied magnetic field i.e. Meissner effect. Fig 1.2 (c) shows the behaviour of susceptibility because of externally applied magnetic field. The value of susceptibility varies from some positive number to -1. χ =1 is the perfect value of diamagnetism

The superconducting state can be maintained only when $I < I_C$ and $H < H_C$.

H_c depends on temperature: $H_C(T) = H_0\left[1 - \left(\frac{T}{T_C}\right)^2\right]$



Current-carrying wire generates magnetic field:

The magnetic field on the wire surface is $B = \frac{\mu_0 I}{2\pi r}$.

Assume there is no external magnetic field ($H_a = 0$).
In order to maintain superconducting state, the current must not exceed a critical value I_C so that the generated field on wire surface $B \le \mu_0 H_C$.

Critical current: $\frac{\mu_0 I_C}{2\pi r} \approx \mu_0 H_C \Rightarrow I_C \approx 2\pi r H_C$

For applied magnetic field $H_a = 0$, $I_C \propto H_C$.

$$I_C = I_0\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

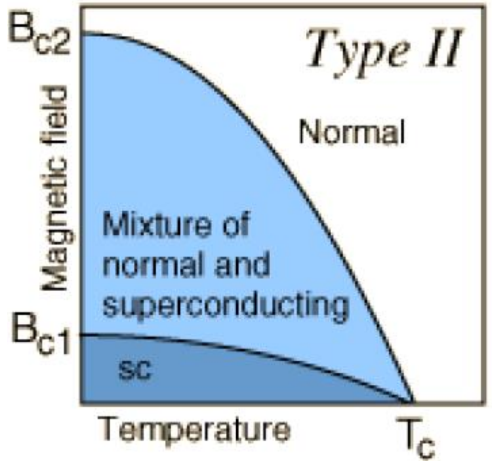
Definition of a Superconductor

A Type I superconductor exhibits two characteristic properties, namely zero dc electrical resistance and perfect diamagnetism, when it is cooled below its critical temperature T_c. Above T_c it is a normal metal, but ordinarily not a very good conductor. The second property of perfect diamagnetism, also called the Meissner effect, means that the magnetic susceptibility has the value $\chi = -1$ in mks or SI units, so a magnetic field (i.e., magnetic flux) cannot exist inside the material. There is a critical magnetic field B_c with the property that at the temperature 0 K applied fields $B_{app} \geq B_c$ drive the material normal. The temperature dependence of the critical field $B_c(T)$ can often be approximated by the expression, where we use the notation $B_c(0) = B_c$,

$$B_c(T) = B_c[1 - (T/T_c)^2].$$

The Type I superconductors are elements, whereas alloys and compounds are Type II.

A Type 11 Superconductor isalso a perfect conductor of electricity, with zero dc resistance , but its magnetic properties are more complex. It totally excludes magnetic fluxin the meissner state when the applied magnetic field is below the lower critical field B_{C1} , as in figure below. Flux is only partially excluded when the applied field is in the range from B_{C1} to B_{C2}, and the material becomes normal for applied fields above the upper critical field B_{C2}.



Conduction Electron Transport

The number density n (electrons/ cm^3) of conduction electrons in a metallic element such as copper or aluminum of density Pm (g/ cm^3) , atomic mass number A (g/mole), and valence Z is given by

$$n = N_A Z \rho_m / A,$$

where N_A is Avogadro's number. A potential difference applied along a conducting wire produces an electric field E and hence the force $F = -eE = m\left(\frac{dv}{dt}\right)$, which accelerates the electrons. They undergo successive periods of acceleration interrupted by collisions, and during the average time r between collisions they attain a component of velocity along the field direction

$$v_{av} = -(eE/m)\tau,$$

which is called the drift velocity, The negative sign means that the electrons move in a direction opposite to that of the electric field. The current density J,

$$J = nev_{av},$$

can be written, wit current density in the form of

$$J = (ne^2\tau/m)E = \sigma_o E,$$

and we have for the dc electrical conductivity $\sigma_o$and its reciprocal the resistivity ρ

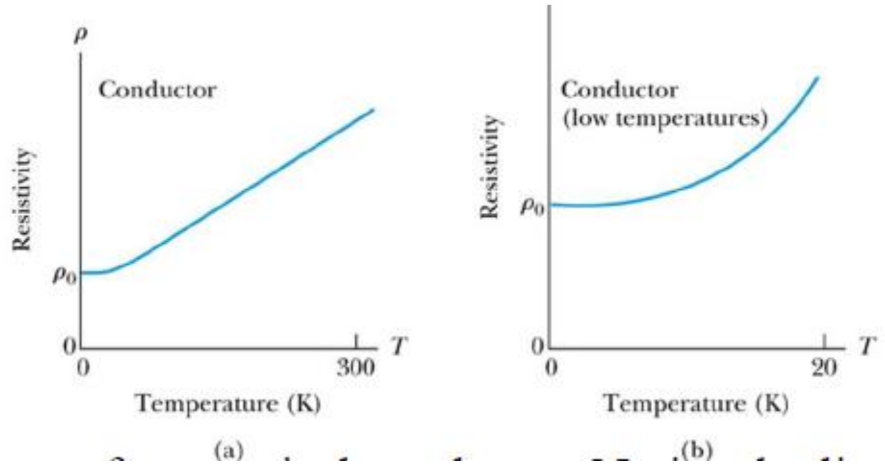
$$\sigma_o = ne^2\tau/m = 1/\rho.$$

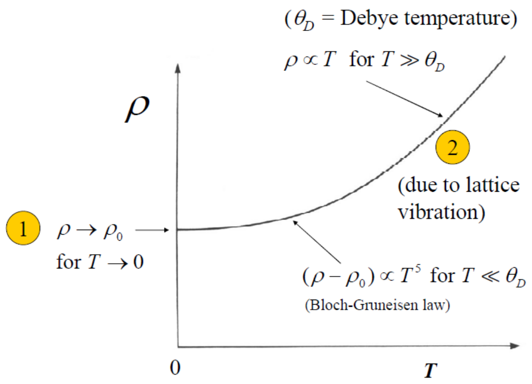
The drift velocity v_{av} Vav is much less than the Fermi velocity v_F at which the conduction electrons actually move on the Fermi surface. The mean free path *I*, or average distance traveled between collisions, is given by

$$l = v_F \tau.$$

Typically, v_F 106 m/s for good conductors (i.e., 1/300 the speed Of llight) and it is perhaps one-tenth of this value for A-15 compounds and high-temperature superconductors in their normal states.

Resistivity of a metal as a function of temperature:





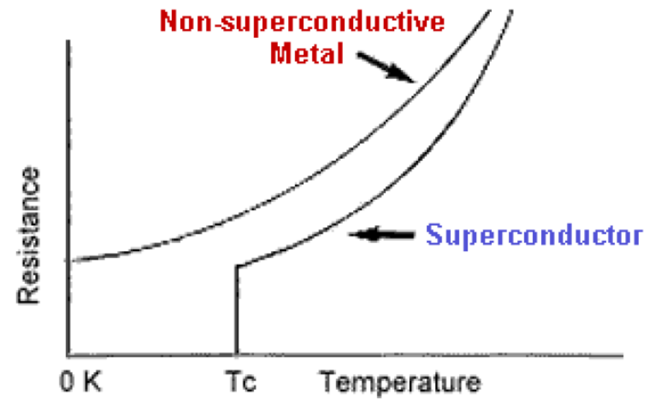


Figure : (a) Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as T → 0.

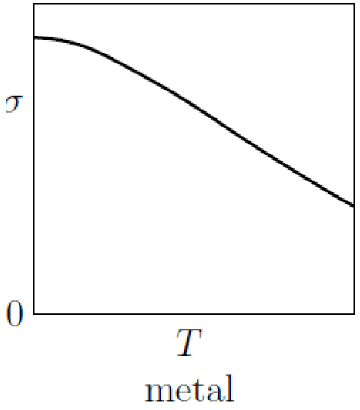
Origin of resistance:

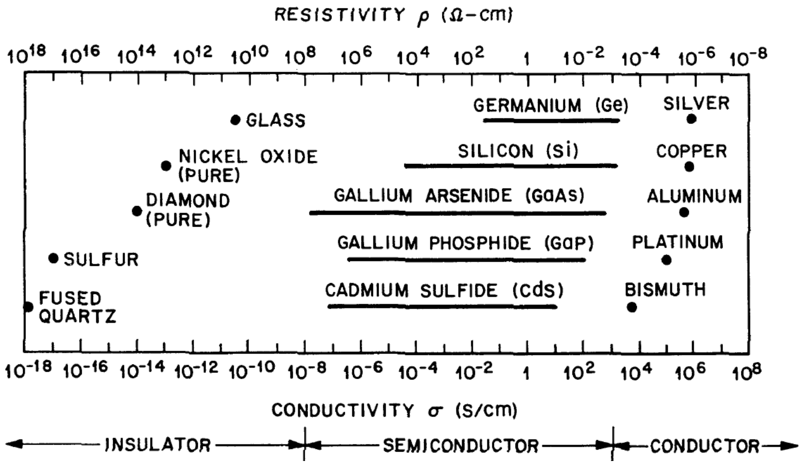
1. ρ_0 (residual resistivity) due to defects, impurities, etc.
2. temperature dependence of ρ depends on electron-ion scattering & lattice vibrations.

$$\rho \propto T \quad \text{for } T \gg \theta_D$$

$$(\rho - \rho_0) \propto T^5 \quad \text{for } T \ll \theta_D$$

If there are no defects and impurities then $\rho = \rho_0 = 0$ at $T = 0$.





Typical range of conductivities for insulators, semiconductors, and conductors