Chapter Two Superconductor

Some properties of superconductor (Meissner effect, Fundamentals Parameters of The Superconductivity, types of superconductor……… etc

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Meissner effect

When Superconductors, are cooled below the critical temperature, they expel magnetic field and do not allow the magnetic field to penetrate inside them. This phenomenon is called Meissner effect, was discovered by German physicists "Walther Meissner" and "Robert Ochsenfeld" in 1933 , as shown in figure(2-1)

They observed that when the sample got cooled below the transition (critical) temperature in the presence of an external magnetic field, the value of the magnetic field outside the sample increas

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

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

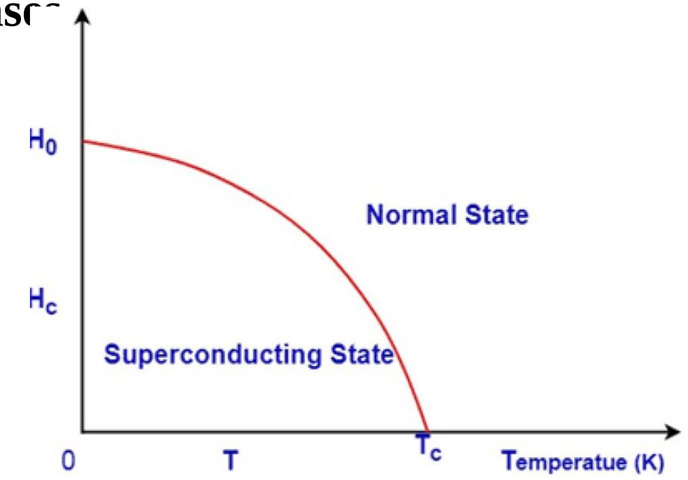


Figure (2-1)A : Variation in critical magnetic field with temperature

What is $\vec{B}$ inside SC?

For perfect conductor, $\sigma = \infty$.
Since $\vec{J} = \sigma\vec{E} < \infty$, $\vec{E} = 0$.
(Note: in electrostatics, $\vec{E} = 0$)

Faraday's law: $\nabla \times \vec{E} = -\frac{\partial B}{\partial t}$

$$\therefore \frac{\partial B}{\partial t} = 0.$$

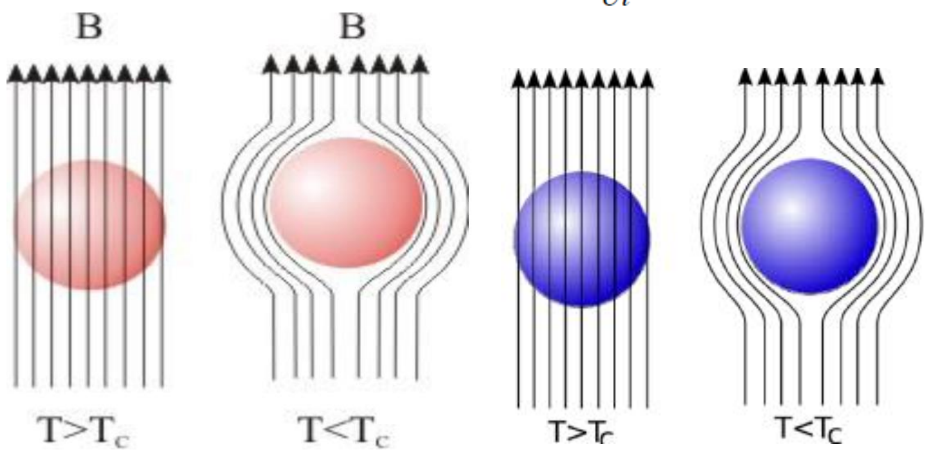


Figure : (2-1) B: Meissner effect

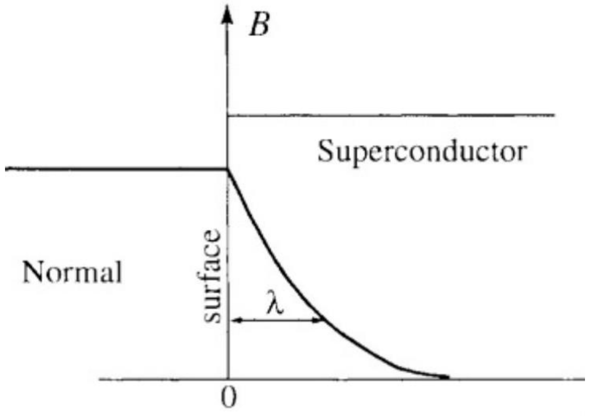
Fundamentals Parameters of The Superconductivity

(a) Penetration Depth (λ)

While studying Meissner effect, that the superconductor expels a (weak) magnetic field B from its interior, i.e. $\bar{B} = 0$. (the Meissner effect) is by establishing a persistent supercurrent on its surface which exactly cancels the applied field inside the superconductor. The finer experiments reveal that the applied external, magnetic field does not suddenly drop to zero, but actually penetrates into the superconductor within a very thin layer of the surface), the magnitude of the penetration depth depends on the material and temperature, and decreases exponentially towards the core of a superconductor, as shown in Figure (2-2). A

The magnetic field thus decays exponentially with distance into the superconductor with a characteristic length scale λ, known as the penetration depth, as shown in Fig (2-2) B, this penetrate decays exponentially according to the relation

$$H_{(X)} = H_{(0)} exp(-\frac{x}{\lambda})$$



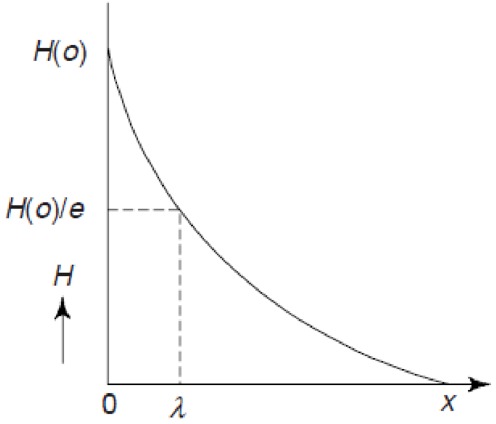


Figure (2-2) A: The penetration of the magnetic field into the superconducting

Figure (2-2) B : Decay of the magnetic field in the interior of a superconductor

(b) The Coherence Length (ξ)

The Coherence Length (ξ) It is a measure of the distance over which the gap parameter (Δ),

It was is also referred as the distance between two electrons of the cooper pair within the highly coherent superconducting state. Th coherence length ξ_0 is defined as :

$$\xi_0 = \frac{\hbar \upsilon_F}{\pi \Delta}$$

where v_F is the Fermi velocity (on the Fermi surface). and Δ is the energy gap. Using order of magnitude values for v_F and Δ.

In the framework of the BCS theory, the coherence length ξ and the energy gap relate to each other at $T = 0$

The quantity ξ_0 is the intrinsic coherence length which is temperature-independent. In the framework of the Ginzburg-Landau theory, the relation between the temperature dependent coherence length and the intrinsic coherence length is given by $\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{l}$ where l is the mean free path of an electron. Since at low temperature can l be centimeters long, then $\xi \approx \xi_0$ The coherence length is large in metal superconductors. In spite of the fact that two electrons in a Cooper pair are far apart from each other, the other Cooper pairs are only a few nanometers away . In most unconventional superconductors, the "size" of the Cooper pairs is very small.

(c) The Cooper Pairs

When A superconductor material is cooled below the critical temperature , transforms the free electron gas from the normal state to a quantum fluid of coherent electron pairs . These charge carriers are called the Cooper pairs

(d) Ginzburg-Landau Parameter (K

Is the ratio of two characteristic lengths, λ and ξ is called the Ginzburg-Landau ratio. The GL parameter defines The ratio of the characteristic lengths

$$\kappa(T) = \frac{\lambda(T)}{\xi(T)}.$$

Close to κ is independent of temperature and if allows one to distinguish between type 1 and type 11 superconductors.

If $\kappa < 0.7$ ***material in type* 1 *superconductor and if*** $\kappa > 0$**, thematerial is type 11 superconductor. The exact critical value of K which separates type 1 from type 11 between is** $\frac{1}{\sqrt{2}}$ (~ 0.7) **case the magnetic flux does penetrate the sample in the form of the cylindrical of tubes called vortices**

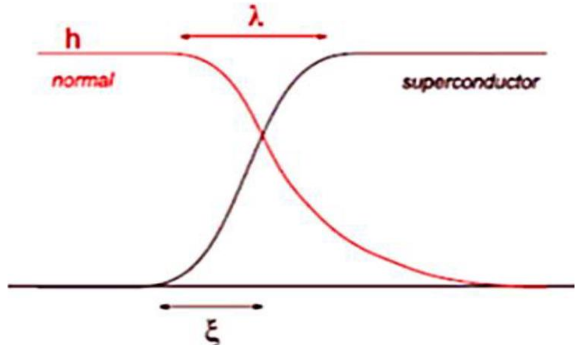


Figure (2-3) :The Coherence Length (ξ) and Penetration Depth (λ) at superconducting / normal surface boundary.

Coherence length and penetration depth

Two new characteristic lengths were predicted by Ginzburg-landau equations namely coherence length and penetration depth.

When an external force is applied on a superconducting material, it disturbs the number of superconducting electrons per unit volume.

This disturbance travels through the material for a certain distance. Coherence length is basically a characteristic scale over which variations in an order parameter ψ occurs. Coherence length or Ginzburg-Landau coherence is represented by ξ. Mathematically it is given by

$$\xi = \sqrt{\frac{\hbar^2}{2m|\alpha|}}$$

In the above equation α is a constant in GL equation for ψ. $\hbar$ is a reduced Planck's constant whereas m represents the mass of cooper pairs which is double the mass of a single electron.

In a material having both normal and the superconducting region, most of the properties of superconductors progressively disappear over a distance ξ. The change moves from superconducting to normal region. In case of high Tc superconductors ξ is of the order of 1 to 10 angstroms. If the value of ξ is small, it affects the electromagnetic and thermodynamic properties of a superconductor. Due to small value of coherence length,

$$\lambda = \left(\frac{m}{\mu_0 n_s e^2}\right)^{1/2}$$

type II superconductors having large value of upper critical field and small value of critical current. Penetration depth attributes to the exponential decay of magnetic field in the interior of the superconducting material. It depends upon the number density of the superconducting electrons in the material.

Above equation easily describes the physical meaning of penetration depth of a superconductor.

Isotope effect (1950)

In 1950 during experiment with different isotopes of mercury in order to understand the effect of the mass on superconductivity a very astonishing effect appears: different mass of the isotope have different T_C as in figure (2-4). This discovery gives the key to understand the basic mechanism for superconductivity (formation of Cooper pairs by electron -phonon- electron interaction).

Theory of superconductivity which is the BCS theory in 1957. T_C varied with the mass of the atom for different isotopes from figure (2-4) a relation can be found T_C and atomic mass as in the following figure.

$$T_C = \frac{1}{\sqrt{M}}$$

$$\frac{T_c}{T'_c} = \frac{(M')^{1/2}}{(M)^{1/2}}$$

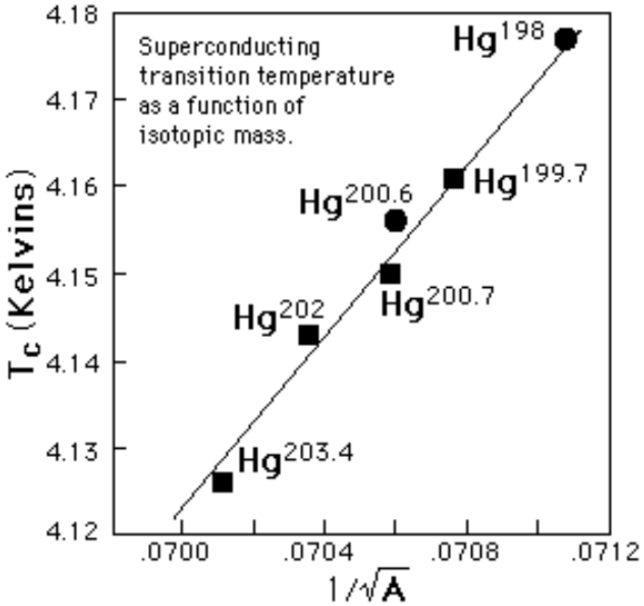


Figure (2-4) :Superconducting transition temperature as a function of isotopic mass.

Josephson effect

1- when two superconductors are joined by a thin insulating layer, it is easier for electron pairs to pass from one superconductor to another without resistance. This effect called the Josephson effect

This effect has applications for superfast electrical switches that can be used to make small , high speed computer.

Heat capacity jump at SC-Normal state transition

As we know, as increase of temperature, there would be a phase transition from superconductivity to normal state. Experimentally, at critical temperature, the heat capacity has a discontinuity as shown in Fig. (2-5)

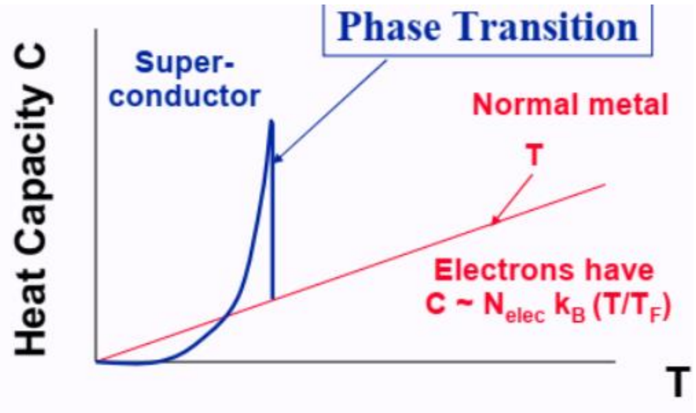


Figure (2-5): Heat capacity jump at critical temperature and exponential decay for *T* < *Tc*

When *T* < *Tc*, the gapped excitations exponentially suppressed heat capacity. The quasiparticle density is approximately the same

$$n \sim e^{-\Delta/T}$$

Where Δ is the gap above the ground state. Thus, heat capacity is

$$C_v^{T<T_c} \sim k_B e^{-2T_c/T}$$

Types of superconductors

Depending upon the response of superconductors in magnetic field, Nicholas Gerbis classified them into two main types.

(i) Type-I superconductors

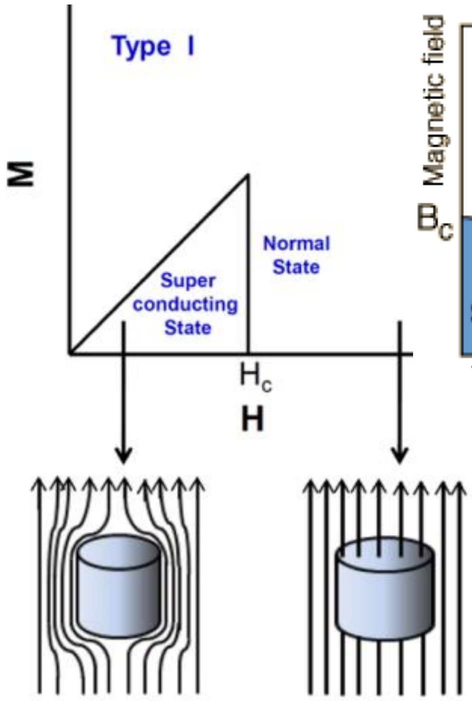
(ii) Type-II superconductors

Type-I superconductors

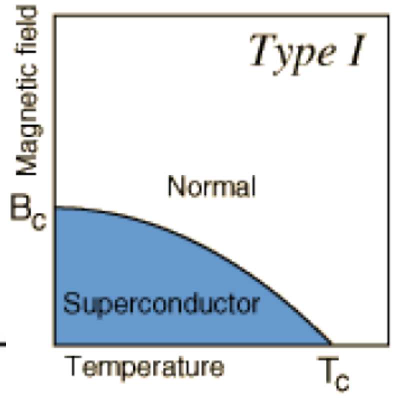
These superconductors exhibit the property of zero electrical resistivity below critical temperature Tc. They also possess the property of expulsion of magnetic field from the interior of the superconductor (Meissner Effect).

Moreover, there is a critical magnetic field in the case of Type I superconductors above which superconductivity ceases. At this value of critical applied field, they undergo sudden transition from diamagnetic to paramagnetic state. Figure: (2-8) a shows the magnetization versus externally applied magnetic field and the H-T phase diagram for Type-I superconductors figure (2-9) (b) .

The phenomenon of superconductivity in Type-I superconductors is well explained by BCS theory which depends upon electron pairs coupled by lattice vibration interactions.



(a)



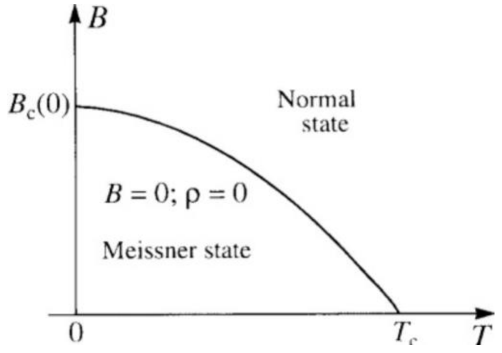
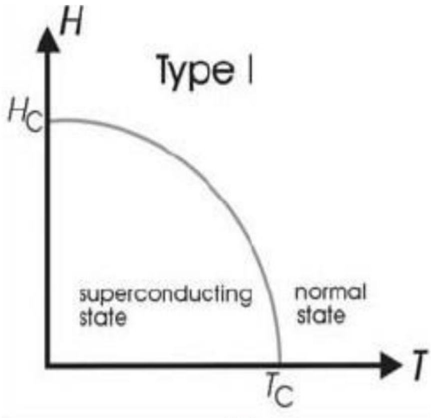


Fig.: (2-9) (a) Magnetization vs External Magnetic Field for type-I superconductors

(b) H-T phase diagram of type-I superconductors



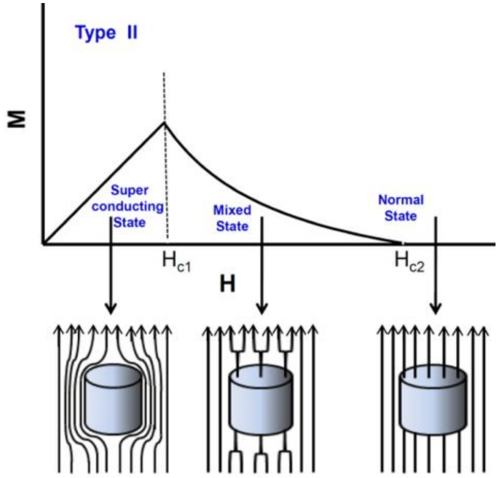
(b)

Type-II superconductors

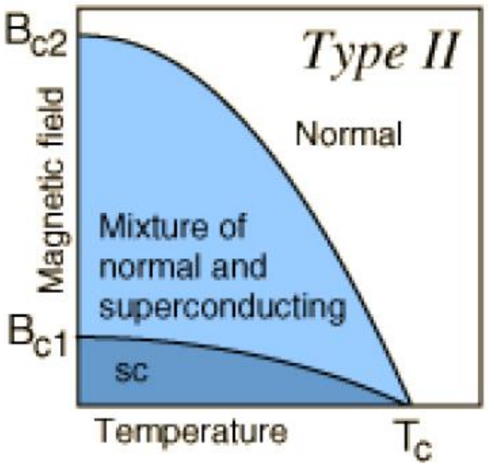
In the starting of 1930, many alloys exhibiting superconducting properties were found. They were classified as type-II superconductors. It was observed that these superconductors have higher values of critical fields and resistivity which allows them to withstand higher current densities. High field superconducting magnets are constructed using type-II superconductors for example niobium-titanium (NbTi).

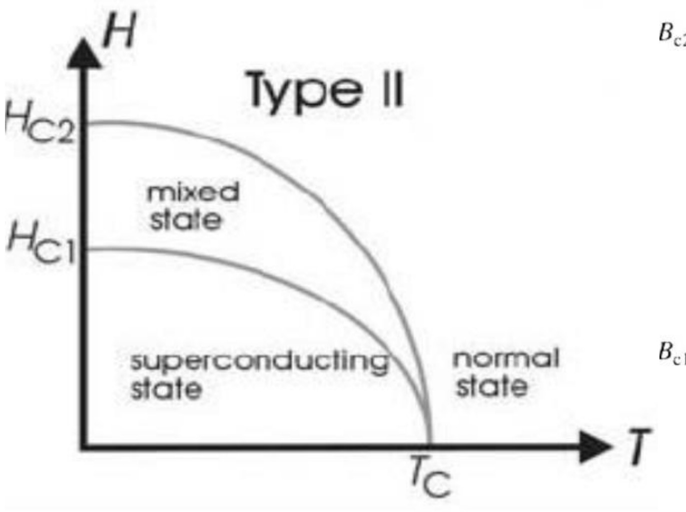
Type-II superconductors are those superconductors that mostly endure in mixed state i.e. normal and superconducting state. This mixed state is called "vortex state" because in this state vortices of superconducting currents surround cores or filaments of normal material hard superconductors". In the region $H_{C1} < H < H_{C2}$ superconductivity is partially destroyed. In this region the superconductor is in a mixed state. Whereas, in the region $H < H_{C1}$ superconductor completely obeys the Meissner effect i.e. material is perfect diamagnetic and does not allows the magnetic flux to penetrate.

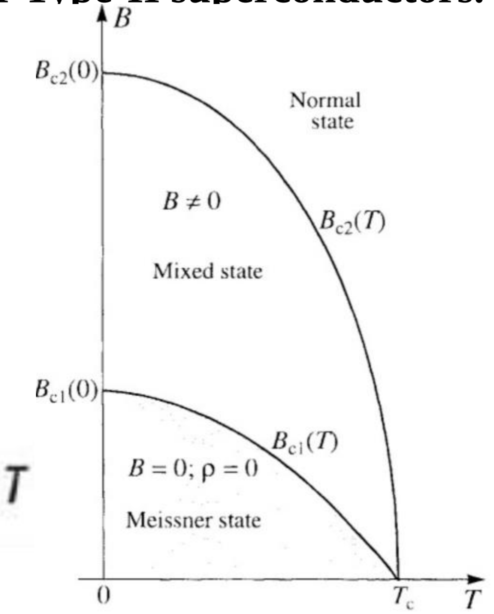
Figure 1.5(b) shows magnetization versus externally applied magnetic field and the H-T phase diagram for Type-II superconductors.



(b)







(b)

(a) Magnetization vs External Field of Type-II superconductor

(b) H-T phase diagram of Type-II superconductor

Type-I Superconductors	Type-II Superconductors
➢ Critical field is represented by "H_c"	➢ Critical field is represented by "H_{c1}, H_{c2}, H_{c3}"
➢ Low values of critical field.	➢ High values of critical field.
➢ Current flows through the surface only.	➢ Current flows through the whole material.
➢ Coherence length >> Penetration depth. ($\xi >> \lambda_L$)	➢ Coherence length <<< Penetration depth ($\xi << \lambda_L$)

Comparison table of Type-I and Type-II superconductors

Type-I: Meissner state B = H + M = 0 for H < H_c; normal state at H > H_c

Type-II: Meissner state B = H + M = 0 for H < H_{c1}; partial flux penetration f

H_{c1} < H < H_{c2}; normal state for H > H_{c2}

Type I and Type II superconductors

Superconductors are classified as type I (soft) and type II (hard) superconductors according to their magnetization behavior. Type I superconductors were discovered first and mainly observed in pure metallic elements. On the other hand, compounds and alloys are in general type II superconductors.

Type I superconductors shows a complete Meissner effect up to certain critical field, H_C, at which complete penetration occurs as the superconductor becomes normal. Unlike Type I superconductors, type II superconductors are characterized by two critical fields, the lower critical field, H_{C1}, and the upper critical field H_{C2}. Up to H_{C1} type II superconductors display perfect diamagnetism like the type I superconductors, then magnetic field starts penetrating the material partially.

. For fields H≥H_{C2} complete penetration takes place and the superconducting state disappears. Figure (2.3) shows the behavior of type I and type II superconductors. For type II superconductors, H_{C1} is known as the thermodynamic critical field, related to the stabilization of free energy of superconductor as:

Type I Superconductors

- These are pure and soft metals like lead and indium.
- The critical field of these conductors are low
- Hence these materials are not suitable for high field applications.
- They are called soft superconductors (or ideal)
- They have low melting point .
- These materials obeys silsbee's rule
- These materials shows meissner effect .the transition from normal to superconducting state is sharp.
- They have low value of H_c and T_c .

Type II Superconductors

- These are alloy and hard metals like lead and indium.
- The critical field of these conductors are high
- Hence these materials are suitable for high field applications.
- They are called hard superconductors
- They have high melting point .
- These materials breaks silsbee's rule
- These materials shows incomplete meissner effect , has broad transition region.
- They have high value of H_c and T_c .

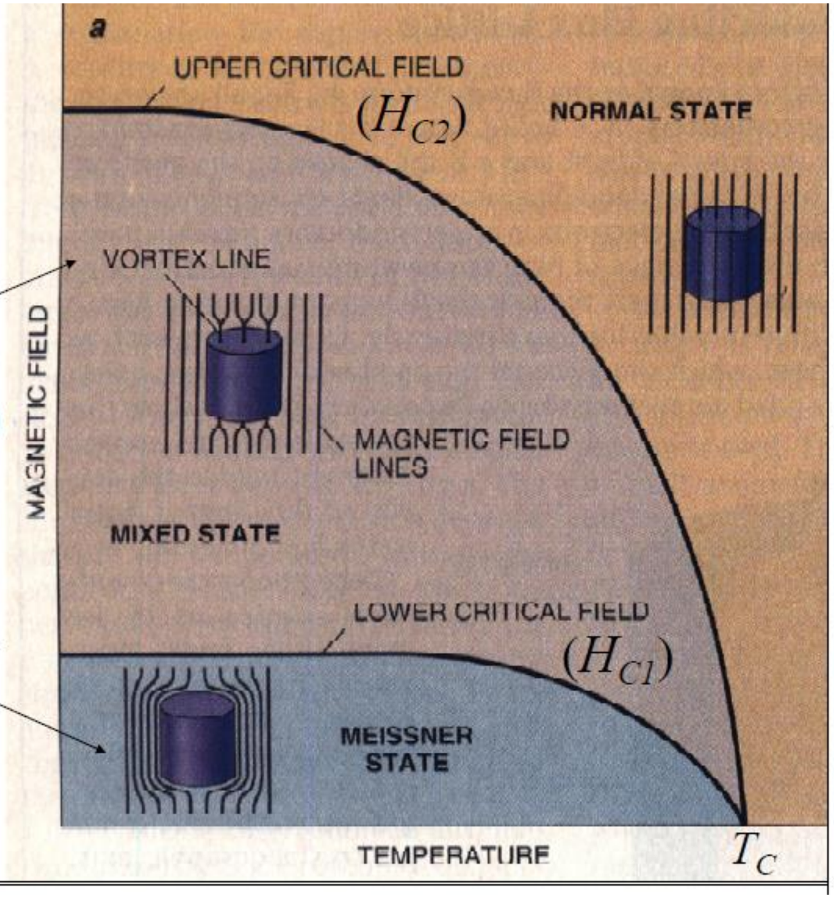
For Type II superconductor, there are two critical fields: $H_{C1}(T)$ & $H_{C2}(T)$

mixed state

$(H_{C1} < H < H_{C2})$ is neither fully superconducting nor fully normal.

Meissner state

$(0 < H < H_{C1})$ complete Meissner state



Two dominant scattering mechanism

1. **Phonon or lattice scattering**

2. **Ionized scattering**

1. Lattice scattering or phonon scattering

At temperature, T > 0 K, atoms randomly vibrate. This thermal vibrations cause a disruption of the periodic potential function. This resulting in an interaction between carrier and the vibrating lattice atoms.

Mobility due to lattice scattering, μ_L

$$\mu_L \propto T^{-3/2}$$

As temperature decreases, the probability of a scattering event decreases. Thus, mobility increases

Temperature ↓, Scattering Probability ↓, Mobility ↑,diffusion current density ↑
Temperature ↑, Scattering Probability ↑, Mobility ↓, diffusion current density ↓

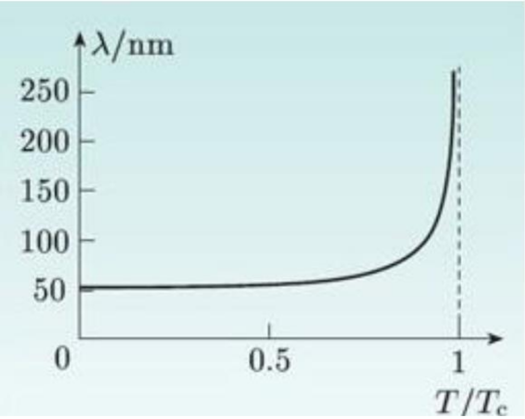


Figure : The penetration depth λ as a function of temperature for tin

$$\lambda = \frac{\lambda_0}{\sqrt{1-\left(\frac{T}{T_C}\right)^4}}$$

2. Ionized scattering

Coulomb interaction between carriers and ionized impurities produces scattering or collusion. This alter the velocity characteristics of the carriers.

Mobility due to ionized ion scattering, μ_I

$$\mu_I \propto \frac{T^{3/2}}{N_I}$$

← Total ionized impurity concentration

- If temperature increases, the random thermal velocity of a carrier increases, reducing the time the carrier spends in the vicinity of the ionized impurity center. This causes the scattering effect decreases and mobility increases.

Temperature ↑, Thermal velocity↑, Time around ionized impurity↓, scattering effect decreases **↓, Mobility ↑, diffusion current density ↑**

- If the number of ionized impurity centers increases, then the probability of a carrier encountering an ionized impurity centers increases, thus reducing mobility

Ionized Impurity ↑, Scattering Probability ↑, Mobility ↓, diffusion current density ↓

Normally, more than one source of scattering is present, for example both impurities and lattice phonons. It is normally a very good approximation to combine their influences using "Matthiessen's Rule" (developed from work by Augustus Matthiessen in 1864):

The net mobility is given by

$$\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

Due to phonon scattering (μ_L)

Due to ionized ion scattering (μ_I)

$$\frac{1}{\mu_{Total}} = \frac{1}{\mu_{Lattice}} + \frac{1}{\mu_{ion}}$$

Due to phonon scattering

Due to ionized ion scattering