Superconductivity:

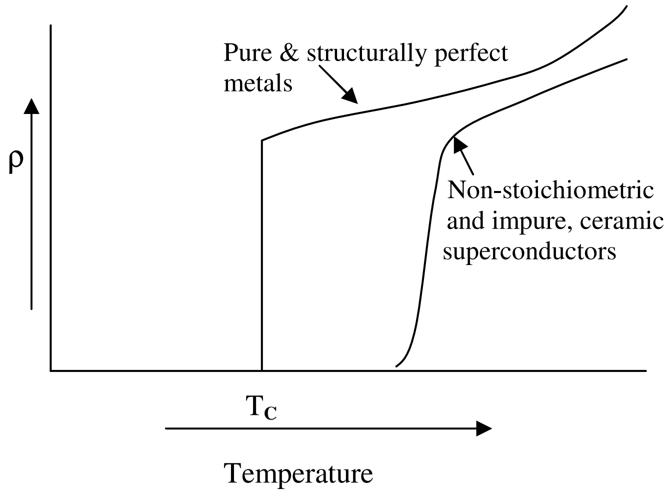
Superconductivity is defined as state of zero resistance. Superconductors are those materials, which possess zero resistance below certain temperature called critical or transition temperature (T_C). The most sensitive measurements show that resistance of these materials in the superconducting state is atleast 10^{16} times less than their room temperature values. Thus, the phenomenon of having zero resistance is called superconductivity.

Historical development of superconductors:

Materials	T_C (K)	Remark, (Discoverer, Year.) .
Tungsten (W)	0.01	………………..
Mercury (Hg)	4.15	Kamerlingh Onnes (in 1911) at Univ. of Leiden, (Holland), 3 years after he first liquified helium gas (He), given Noble prize for these discoveries in 1913.
Sulpher based compounds	8	S.S.P. Perkin et.al. (in 1983)
V_3Si	17.1	J.K.Hulm (in 1953)
Nb_3Sn	18.05	---
Nb_3Ge	23.2	1973
La-Ba-Cu-O	40	Bednorz & Muller (1986) at IBM lab in Zurich, Given Noble prize for his contribution to high T_C superconductivity in 1987
$YBa_2Cu_3O_7$	92	Wu Chu et.al (in 1987)
$RBa_2Cu_3O_{7-x}$	92	R = Gd, Dy, Ho, Er, Tm, Yb, Lu etc
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$	105	Maedna et. Al. (in 1988)
$Th_2CaBa_2Cu_2O_{10+x}$	125	Hermann et.al. (in 1988)
Hg-Ba-Ca-Cu-O	130	--------

About twenty seven of the chemical elements becomes superconductors at low temperatures. They are Ti, V, Zr, Nb, Mo, Tc, Ru, Rh, La, Hf, Ta, W, Re, Os, Ir, Al, Zn, Ga, Cd, In, Sn, Hg, Tl, Pb, and among lanthenides and actinides are Lu, Th, Pa, which become superconducting when subjected to high pressure. The critical temperatures is, however, very low for these elemental superconductors to become of imprtant use. In addition to these great many alloys & compounds both stoichiometric and non-stoichiometric are also superconductors.

Superconductors having a TC above 77K i.e., boiling point of nitrogen are of particular interest because they do not require liquid helium (BP, 4K) or liquid hydrogen (BP, 20K) for cooling, as liquefaction of He requires 25 times more energy than required for liquification of nitrogen. Super-conducting state is different state having higher degree of order – the entropy is zero. The super-conducting transition is reversible.



Transition temperature or critical temperature (T_C):

It is defined as the temperature below which a material/ substance exhibits zero resistance or behave as a superconductor. When temperature is lowered the transition from normal state to super-conducting state is generally quite sharp for pure and structurally perfect metals (over a temperature range of 10^{-4} K). In alloys the transition may be spread over a range of about 0.1 K. Ceramic superconductors generally display an even wider spread in transition temperature.

Isotopic effect:

The transition temperature T_C often varies with the atomic mass M_a according to the relation

$$M_a^{\alpha} T_C = \text{constant}$$

Where α is a material constant. As an example for mercury (Hg), T_C varies from 4.185 K to 4.146 K when M_a changes from 199.5 to 203.4 atomic unit.

The critical temperature of superconductor depends on mass of the atoms in the solid. This mass dependence can be confirmed by measuring T_C for superconductor composed of different isotopes of the same chemical element, which differs only in the masses of their atoms. The transition temperature found to be proportional to M_a^{α} , where α has a value of about 0.5, although it is slightly different for different superconductors. Historically, the isotopic effect pointed the way to a workable theory of superconductivity. The temperature dependence of T_C on the isotope mass indicate that lattice vibrations and hence electron-lattice interactions are deeply involved in superconductivity. There is no other reason for super-conducting transition temperature to depend on the number of neutrons in the nucleus.

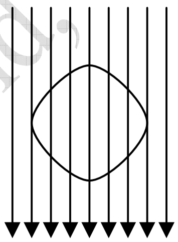
Flux exclusion and the Meissner's effect:

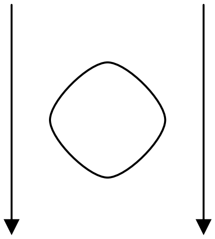
Magnetic flux is excluded from the interior of a superconductor in an applied magnetic field. Figure below shows induction field lines near normal and super-conducting sample in identical applied field. Field lines that penetrates the normal sample bend around the edges of super-conducting sample, making the induction field higher at points near the surface than at analogous points near the normal sample. This phenomenon of ejection of magnetic flux lines out of the superconductor is known as *Meissner's effect*. For this reason superconductors are often described as perfect diamagnet with magnetic succeptibility of –1. As,

$B = \mu_o(H+M) = \mu_o(H+ \chi H) = \mu_o(1+ \chi)M$

Since B=0 in the interior, it implies

$\mu_o(1+ \chi)=0 \Rightarrow \chi = -1$





Flux exclusion is not complete near the sample surface, rather the induction field decays into the sample exponentially with distance from the surface. The characteristic penetration depth is typically a few hundred angstroms. The external field, in fact does penetrates the sample from the surface into the bulk, but the magnitude of this penetrating field decreases exponentially from the surface. If the field at surface of superconductor is B_o then at a distance x from the surface, the field is given by an exponential decay

$$B(x) = B_o \exp(-x/\lambda)$$

where, λ is a characteristic length of penetration called penetration depth and depends on the temperature and T_C of the material. The penetration depth is a distance at which the penetrating magnetic field falls to 1/e times of its value at the surface. At T_C penetration depth λ is infinite and any magnetic field can penetrate the sample and destroy the super-conducting state. At absolute 0K the typical penetration depth are 10-100 nm.

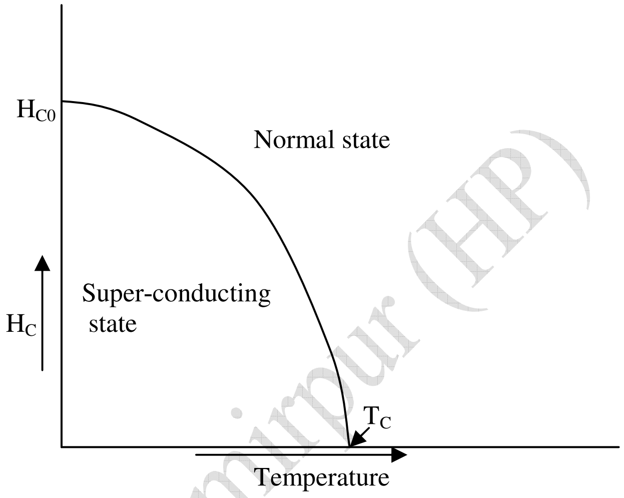
Effect of Magnetic field:

Destruction of super-conducting state does not only occur by raising the temperature, but also by subjecting the material to a magnetic field. The critical magnetic field strength H_C above which super-conductivity is destroyed, depends on the temperature to which it has been cooled. In general, lower is the sample temperature the higher the critical field H_C. One can write

$$H_C = H_{C0}\,(1 - T^2/T_C^2) \qquad \text{for } T < T_C$$

where, H_{C0} is critical magnetic field at 0 K. Ceramic superconductors usually have smaller H_C than metallic superconductors i.e. they are more vulnerable to lose super-conducting state by moderate magnetic filed.

Figure shows dependence of critical strength H_C at which super-conductivity is destroyed in relation to temperature T for a typical superconductor

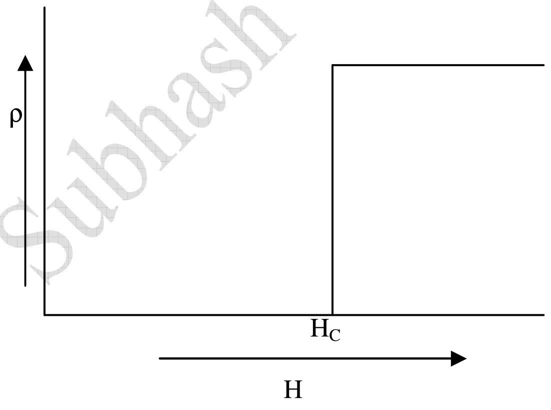


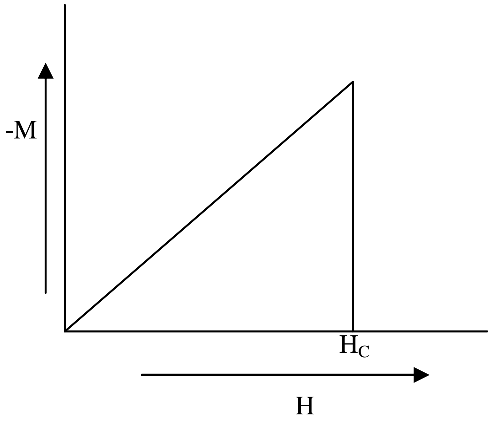
Type –I (or Soft Superconductors):

In these superconductors the destruction of the super-conducting state by a magnetic field i.e., transition between super-conducting to normal state occurs sharply (abruptly). Figure shows how resistivity below T_C varies as a function of applied magnetic field for such superconductors. The ideal superconductor, when placed in the magnetic field, repels the magnetic lines totally out, till the magnetic field attains the critical value H_C. The magnetization M induced in these superconductors is equal to –H up to H_C where it abruptly drops to zero as shown in figure below.

The H_C value is low for these superconductors to have any useful technical application in coils for super-conducting magnets. Typical values for some of them is as listed below.

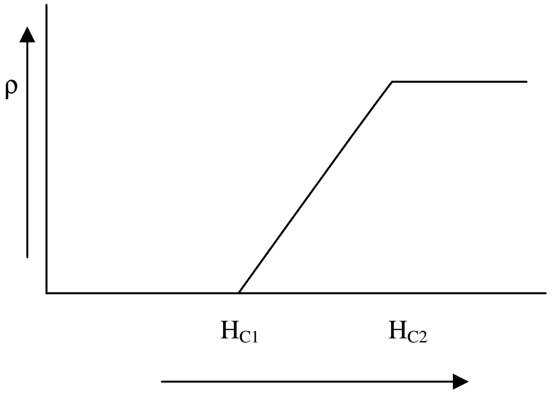
Materials:	Sn	Hg	V	$Cr_{0.1}Ti_{0.3}V_{0.6}$	Pb	Nb
T_C (K) :	3.72	4.15	5.3	5.6	7.19	8.46
B_C (T) :	0.03	0.041	0.1	0.136	0.08	0.199

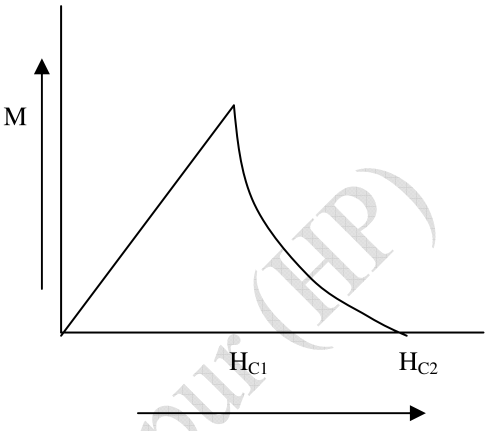




Type –II (or Hard Superconductors):

In type-II Superconductors the destruction of the super-conducting state by magnetic field is not sharp but is gradual taking place over a finite value. The Super-conducting state is extended from H_{C1} to a field H_{C2} which is about 100 times higher than H_{C1}. It implies that there is strong resistance against magnetically induced destruction of the super-conducting state. Fig below shows the variation of resistivity and magnetization with field for such superconductors.





These are generally called hard Superconductors where ideal behavior is seen up to a lower critical field H_{c1} beyond which magnetization gradually changes and attains zero at upper critical field H_{C2}. Type-II superconductors are used preferably for making super-conducting solenoids, where magnetic fields of several hundred KG are produced with these materials. Meissner's effect is incomplete in the region between H_{C1} and H_{C2}; the region is known as vortex region. The normal behavior of superconductor is observed beyond $H_{C2.}$ The magnetic flux lines gradually penetrate the solid as the field is increased beyond H_{C1} and penetration is complete only at H_{C2}. The interval between H_{C1} and H_{C2} represents as state in which super-conducting and normal conducting areas are mixed in the material. Specifically, one observes small circular regions, called vortices, which are in normal state. These vortices are surrounded by large super-conducting regions.

Examples:	Nb_3Sn	Nb_3Ge	$Ba_{2-x}Br_xCuO_4$	$YBa_2Cu_3O_7$	$Bi_2Sr_2Ca_2Cu_3O_{10}$	HgBaCaCuO
T_C (K)	18.05	23.2	30-35	93-95	110	130-135
B_C (T)	24.5	38	~150	~300		
J_C (A/cm^2)	10^7			10^4-10^7		

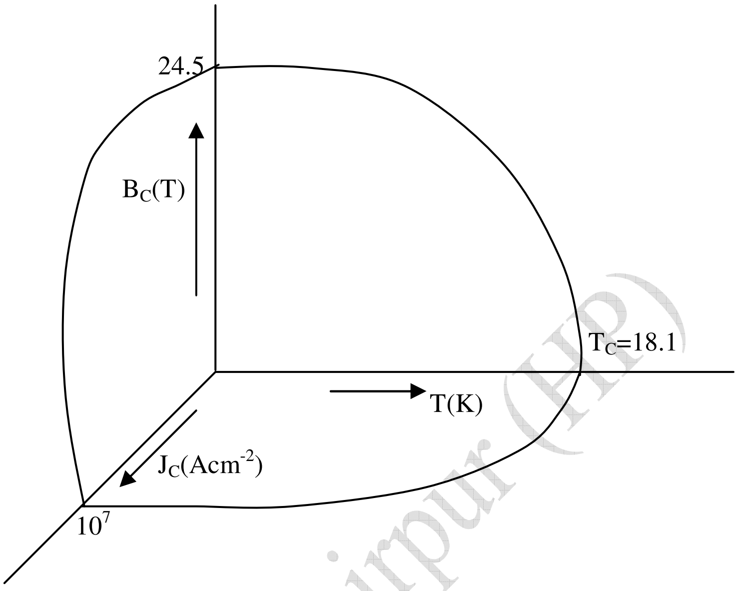
Here in this table B_C and J_C are values at 0K.

Critical current density:

Another characteristic feature of the super-conducting state is that when the current density through the sample exceeds a critical value J_C, it is found that superconductivity disappears. It is because current through superconductor will itself generate a magnetic field and sufficiently high current densities the magnetic field at the surface of the sample will exceed the critical field and extinguish superconductivity. This direct relation between B_C and J_C is only true for type-I superconductors, whereas in type-II superconductors J_C depends in a completed way on the interaction between the current and the flux vortices. New high T_C superconductors have exceedingly high critical fields, as apparent from the table above that do not seem to necessarily translate to high critical current densities. The critical current density in Type-II superconductors depends not only on the temperature and the applied magnetic field but also on the preparation and hence the microstructure (i.e., polycrystallinity) of the superconductor material.

The critical current density is important in engineering because it limits the total current that can be passed through a superconductor wire or device. The limits of superconductivity are therefore defined by the critical temperature T_C critical magnetic field B_C (or B_{C2}) and critical current density J_C. These constitute a surface in three dimensions which separates the super-conducting state from the normal state. Any operating point (T_1 B_1 J_1) inside this surface is in the super-conducting state. The 123 cuperate superconductors when discovered had low J_C but over last decade advanced level of fabrication have increased J_C value to higher level to have number of technical application of these materials.

The critical surface for Nb_3Sn alloy which is superconductor below 18.1K.

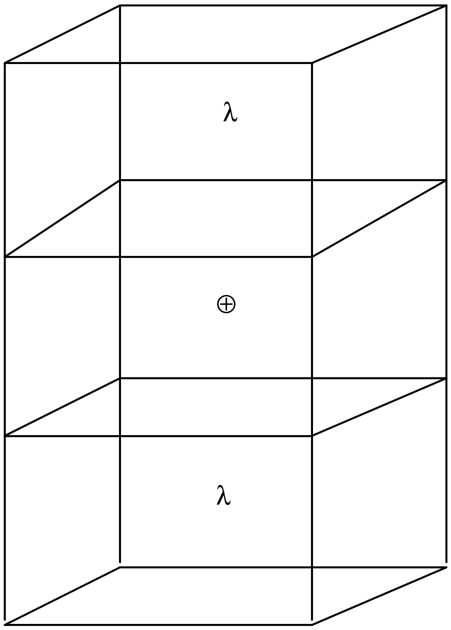


Effect of frequency:

The superconductor offers zero resistance to electric field having frequency up to 10^7 c/s. For higher frequencies the resistance of the superconductor increases with frequency.

Synthesis of 123-superconductors: These are ceramic compound superconductors, containing mixture of copper oxide, alkaline (Ca, Ba, Sr) oxide and rare earth oxides, such that proportion of rare earth metal is 1, alkaline metal is 2 and that of copper is 3. Their transition temperatures are above 77K the boiling point of liquid nitrogen. They are having perovskite type structure with unit cell of the following type.

Y_2O_3+$BaCO_3$+CuO
↓ 900-1100 °C
$BaCO_3$ = BaO +CO_2
↓ Anneal at ≈ 800 °C in O_2 atmosphere
$Y_1 Ba_2 Cu_3 O_{7\pm\delta}$



In unit cell as shown in figure the no of
⊕ : Y = 1
λ : Ba = 2
× : Cu = 8*(1/8)+8*(1/4) = 3
O : Oxygen = 12*(1/4)+8*(1/2) = 7
: Vacant oxygen sites

Technological applications of superconductors:

Superconducting coils can be used for producing very strong magnetic fields which otherwise can not be obtained from electromagnet as due to finite resistivity , at high currents appreciable i^2r heating takes place. Such high fields are useful in micro hydrodynamic (MHD) power generators.

As there is no I^2R loss in superconductors, loss less power transmission through superconducting cables will be possible from place to place. They can also be used to perform logic and storage functions in computers.

A Josephson junction consisting of a thin insulating layer between two superconductors have unique current-voltage characteristics suitable for memory elements in supercomputers with fast switching times.

As, according to Meissner effect a superconducting material experience repulsive force from a permanent magnet, this magnetic levitation phenomenon is suppose to make revolution in transportation, if superconductors operating at ambient temperatures are discovered. The idea is to make a superconducting railway track for train having magnetic wheels. The repulsive force between the superconducting rail and magnetic wheel make frictionless movement leading to easily driven, fast moving trains. Small laboratory models are already tested where toy trains accelerated once seen to move freely for long times.