

Module - 3

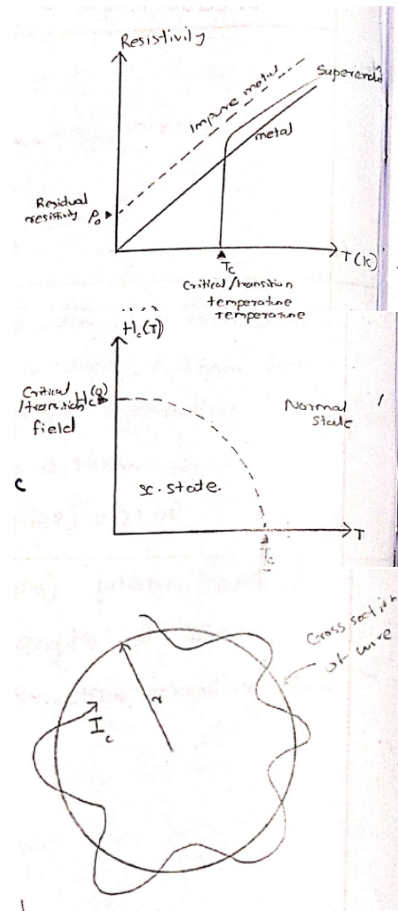
Superconductivity & Nanomaterials

Resistivity (ρ) & conductivity (σ)

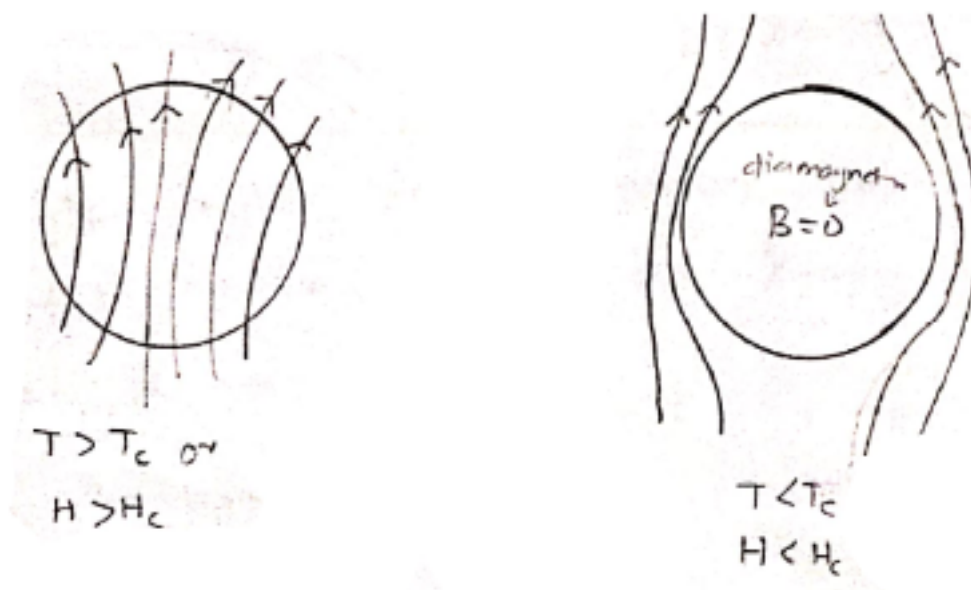
- For superconductor, $\rho \rightarrow 0, \sigma \rightarrow \infty$
- At a particular Temperature (T_C), superconductor has zero resistivity
- Impure metals always have minimums resistivity at 0K due to impurities
- If H & T are below the $H - T$ curve, material shows superconducting behaviour and above it, the material has usual properties.
- if current flowing through the superconductor is above I_c , material will lose its superconductivity.

$$H_c(T) = H_c(0) \left\{ 1 - \left(\frac{T}{T_c} \right)^2 \right\}$$

$$I_c = 2\pi r H_c$$



Meissner effect



Meissner effect is the expulsion of a magnetic field from a superconductor during its transition to the superconducting state when it is cooled below the critical temperature

Classification of superconductors

Type - I	Type -II
<p>Graph of magnetization $-M$ vs magnetic field H for Type I superconductor. The curve shows a linear increase in $-M$ with H up to H_c, then drops to zero. The region is labeled "normal".</p>	<p>Graph of magnetization $-M$ vs magnetic field H for Type II superconductor. The curve shows a linear increase in $-M$ with H up to H_{c1} (lower critical field), then a gradual increase in the "Vortex state mixed state" region, and finally drops to zero at H_{c2} (upper critical field). The region is labeled "normal state".</p>
Low transition temperature	High transition temperature
Low Critical magnetic field (< 1 T)	High Critical magnetic field (> 1 T)
Perfectly obey meissner effect	Partially meissner effect

They transition sharply and abruptly from a superconducting to a normal state under external magnetic fields.	Superconductivity gradually transition from a superconducting to normal state under external magnetic fields. At lower critical magnetic field (H_{C1}), it starts losing its superconductivity. At upper critical magnetic field (H_{C2}), it completely loses its superconductivity.
Doesn't show <i>flux pinning</i>	Doesn't show <i>flux pinning</i>
These are completely diamagnetic	These are not completely diamagnetic
Exhibits single critical magnetic field	Exhibits two critical magnetic field
Easily lose the superconducting state by low-intensity magnetic field.	Does not easily lose the superconducting state by external magnetic field.
Also known as soft superconductors	Also known as hard superconductors.
BCS theory can be used to explain the superconductivity of type-I	BCS theory cannot be used to explain the superconductivity of type-II
Examples: Al, Hg, Pb, Zn,...	Examples: Zr, Nb, V, NbTi, Nb ₃ Sn, etc.

1 Calculate critical current for a wire of lead Having a diameter 1 mm of at 4.2 K, T_c for lead is 7.18K, $H_c(0) = 6.5 \times 10^4$ A/m

Answer

$$\begin{aligned}
 H_c(4.2K) &= H_c(0) \left\{ 1 - \left(\frac{T}{T_c} \right)^2 \right\} \\
 &= 6.5 \times 10^4 \times \left(1 - \frac{4.2^2}{7.18^2} \right) \\
 &= 42758 \text{ T} \\
 \therefore I_c &= 2\pi r H_c = 2 \times 3.141 \times \frac{1 \times 10^{-3}}{2} \times 42758 \\
 &= 135 \text{ A}
 \end{aligned}$$

2 Calculate I_c that flows through a long thin superconducting wire of Aluminium of diameter 10^{-3} m, ($H_c(T)=7.9 \times 10^3$ T)

Answer

$$I_c = 2\pi r H_c(T) = 2 \times 3.141 \times \frac{10^{-3}}{2} \times 7.9 \times 10^3 = 24.8 \text{ A}$$

Isotope effect

$T_c \times M^\beta$ is constant. Where T_c = critical temperature, M = atomic mass and β = correction constant = $\frac{1}{2}$

$$T_c \propto M^{-\beta}$$

1 For Hg, $T_c=4.185$ K, and isotopic mass = 199.5. If the isotopic mass changes to 203.4, calculate its critical temperature.

Answer

$$T_c(Hg) \propto \frac{1}{\sqrt{M_{Hg}}}$$

$$T_c(Hg) = \lambda \frac{1}{\sqrt{M_{Hg}}}$$

$$\text{ie } 4.185 = \lambda \frac{1}{\sqrt{199.5}}$$

$$\lambda = 4.185\sqrt{199.5}$$

$$\begin{aligned}\therefore T_c \text{ of Hg with mass } 203.4 &= \lambda \frac{1}{\sqrt{203.4}} \\ &= 4.185 \times \sqrt{\frac{199.5}{203.4}} \\ &= 4.145K\end{aligned}$$

BCS Theory

Bardeen-Cooper-Schriffer theory (1957)

Cooper pair: When electrons enters a positive-lattice they get trapped in the lattice due to attractive and repulsive forces. And they may exchange energy in the form of phonons. and form cooper pair if they happened to have opposite spin numbers.

Super electrons: Pair of electrons that are bound to each other.

BCS Theory: This theory could explain many observed effects such as zero resistivity meissner effect, isotope effect, etc. It is based on advanced quantum theory. Consider an electron posing through a lattice of positive ions, the electron is attracted by neighbouring positive ions, form a positive ion core. This greatly reduces the effect charges of electron. Due to the attraction between electron and ion core, lattice gets deformed. If another electron passes by the side of the assembly of first electron and ion core, it gets attracted to wards the assembly. The second electron interacts with first electron through lattice deformations. This interaction is due to exchange of virtual phonons between two electrons. The momentum is transferred between

electrons. These two electrons together forms a cooper pair the electrons are known as **cooper electrons or super electrons**.

Consider the distribution of electron in metals (see fermi-dirac formula). At $T = 0K$ all the energy states below fermi level are completely filled and all the states above are completely empty. When two electrons are added to the metal at absolute zero, since all the quantum states with energies $E < E_{\text{fermi}}$ are filled, they're forced to occupy states having energies $E > E_{\text{fermi}}$. they forced to occupy states having energies $E > E_{\text{fermi}}$. Cooper showed that if there's an attraction between two electrons, they are able to form a bound state so that their total energy will be less than $2E_{\text{fermi}}$. These electrons are paired to form a single system. This system is called cooper pair and the electrons are called cooper electrons. Their motions are co-related. The binding is strongest when the electrons forming the pair have opposite momenta and opposite spins. So all the electron pairs lying in the neighbourhood of fermi surface form super electrons. These super electrons are responsible for superconductivity.

Fermi-dirac equation:

$$f(E) = \frac{1}{e^{(E-E_f)/(\sigma_E)} + 1}$$

Fermi surface: Surface in reciprocate space which separates occupied a unpaired electron

Nanomaterials

Classification

- Based on dimension:
 - ID-material or thin films (if any one of the dimension is $< 10^{-9}$ m)
 - 2D-material or thin wires (if any two of the dimension are $< 10^{-9}$ m)
 - 3D-material or quantum dots (if all dimensions are $< 10^{-9}$ m)
- Based on structure:
 - Fullerene
 - * Single walled carbon nanotubs
 - * Double walled carbon nanotubs
 - Nanomaterials (general terms for inorgoric structures)
 - * Nanoparticle
 - * Nanopowder
 - * Nanocrystal
 - * Nanoring
 - * Nanoshell

Why nanomaterial show excellent/different properties?

Answer

- **Surface area to volume ratio:** When this increases, more atoms will be in surface and becomes highly energetic and reactive due to unsatisfied bonds
- **Quantum confinement effect:** Since electrons are confined to small volume, density increases and becomes more reactive.

Fullerene

Fullerene are a class of allotropes of carbon which are graphene sheets rolled into tubes or hollow spheres. Spherical fullerene are also called buck balls and cylindrical one called carbon nanotube or buckytubes. Fullerenes are similar in structure to graphite, but they may contain pentagonal rings. First fullerene discovered was Buckminster fullerene. (C_{60}) in 1985.

Carbon nanotubes are allotropes of Carbon with a Cylindrical nano structure. These are categorized as single walled nanotubes (SW) and multi walled (MW) nanotubes. These cylindrical carbon molecules have noble properties. They are potentially useful in many applications in nanotechnology, electronics, optics and material Science. They exhibit extraordinary strength and unique electrical properties. They are efficient conductors of heat.

Nanoshell

A nanoshell is a type of spherical nano particle consisting of a dielectric core which is covered by a thin metallic shell, which is usually a gold. Gold shelled nano particles with silica core are used in cancer therapy and bio. imaging enhancement.

Nanorods

These are one morphology of nanoscale objects. Their dimensions range from 1-100 nm. Standard aspect ratio (length/width). are 3-5. They can be produced by direct chemical synthesis. Applications of nanorods include in display technology, micro-electro-mechanical systems, LED

Nanoring

These are small ring formed crystals these are made up of fine nano belts. These that are rolled up as coils layer by layer with as many as 100 loops. The first handling was made of ZnO with thickness 10-30nm. with diameter of 1.4 microns. These have applications in MEMS and nano-electro-mechanical systems (NEMS).

Smart materials

Liquid Crystal

Liquid crystals is a state of matter frow have properties bowen "crystal and "liquid. It is sometimes difficult to determine whether a material is in a crystal is in liquid/liquid crystalline state Substance that are not is ordered as a solid yet have some degree of alignment are properly called liquid crystals

LC materials generally have several common characteristics. Rod like molecular structure, rigidness along long axis, and strong dipoles. Distinguishing characteristics of liquid crystalline state is the tendency of its molecules to point along a common axis called 'director'. ie, liquid crystal is a substance that flows like a liquid but maintains Some of the ordered structural characteristics of crystals.

Under certain circumstances LC have liquid like behaviour and during others, they have opposite behaviors. Most LC compounds exhibit polymorphism, a condition where more than one phase is observed in LC state.

The following parameters describe LC structure:

- Positional order
 - Orientational order
 - Bond orientational order
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- **Positional Order** refers to extend to which an average molecule or group of molecules show translational symmetry as crystalline materials shows.
 - **Orientational Order** represents the tendency of the molecules to align along the director on a long range basis.
 - **Bond orientational Order** describes a line joining the centers of nearest neighbouring molecules without requiring a regular spacing along that line.