B. Tech
Engg. Physics
ONE SHOT Revision
UNIT-5 : Superconductors
Notes + PYQs + DPP

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By Gulshan Sir

AKTU Syllabus

Unit-5: Superconductors and Nano-Materials

Superconductors: Temperature dependence of resistivity in superconducting materials, Meissner effect, Temperature dependence of critical field, Persistent current, Type I and Type II superconductors, High temperature superconductors, Properties and Applications of Super-conductors.

Nano-Materials: Introduction and properties of nano materials, Basics concept of Quantum Dots, Quantum wires and Quantum well, Fabrication of nano materials -Top- Down approach (CVD) and Bottom-Up approach (Sol Gel), Properties and Application of nano materials.

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Superconductivity

- The phenomenon of superconductivity was discovered by H. Kammerlingh onnes in 1911, when he was measuring the resistivity of mercury at low temperature.
- He observed that the electrical resistivity of pure mercury suddenly drops to zero at 4.2 K

Note : (i) Resistivity $(\rho) \propto \frac{1}{\text{Conductivity}\,(\sigma)}$

(ii) Resistance $(R) \propto$ Resistivity (ρ)

- The phenomenon of attaining zero resistivity or infinite conductivity by some materials at very low temperature is known as superconductivity.

Superconductors

- Superconductors are the materials having zero resistance or zero resistivity or infinite conductivity.
- The materials which show Superconductivity at very low temperature are called Superconductors.

Two main properties of superconductors are

(i) Zero resistance

(ii) Diamagnetic behavior

Liquid Helium $\approx -270\,°C \approx 0.15K$

Liquid Nitrogen $\approx -196\,°C \approx 78K$

Examples

Low-temperature superconductors (LTS)

(i) Mercury (Hg) = 4.15 K

(ii) Lead (Pb) = 7.19 K

(iii) Tin (Tn) = 3.72 K

(iv) Niobium (Nb) = 9.26 K

(v) Aluminum (Al) = 1.18 K

(vi) Tungsten (W) = 0.01 K etc.

High temperature superconductors (HTS)

(i) Yttrium Barium Copper Oxide (YBCO) = 92 K

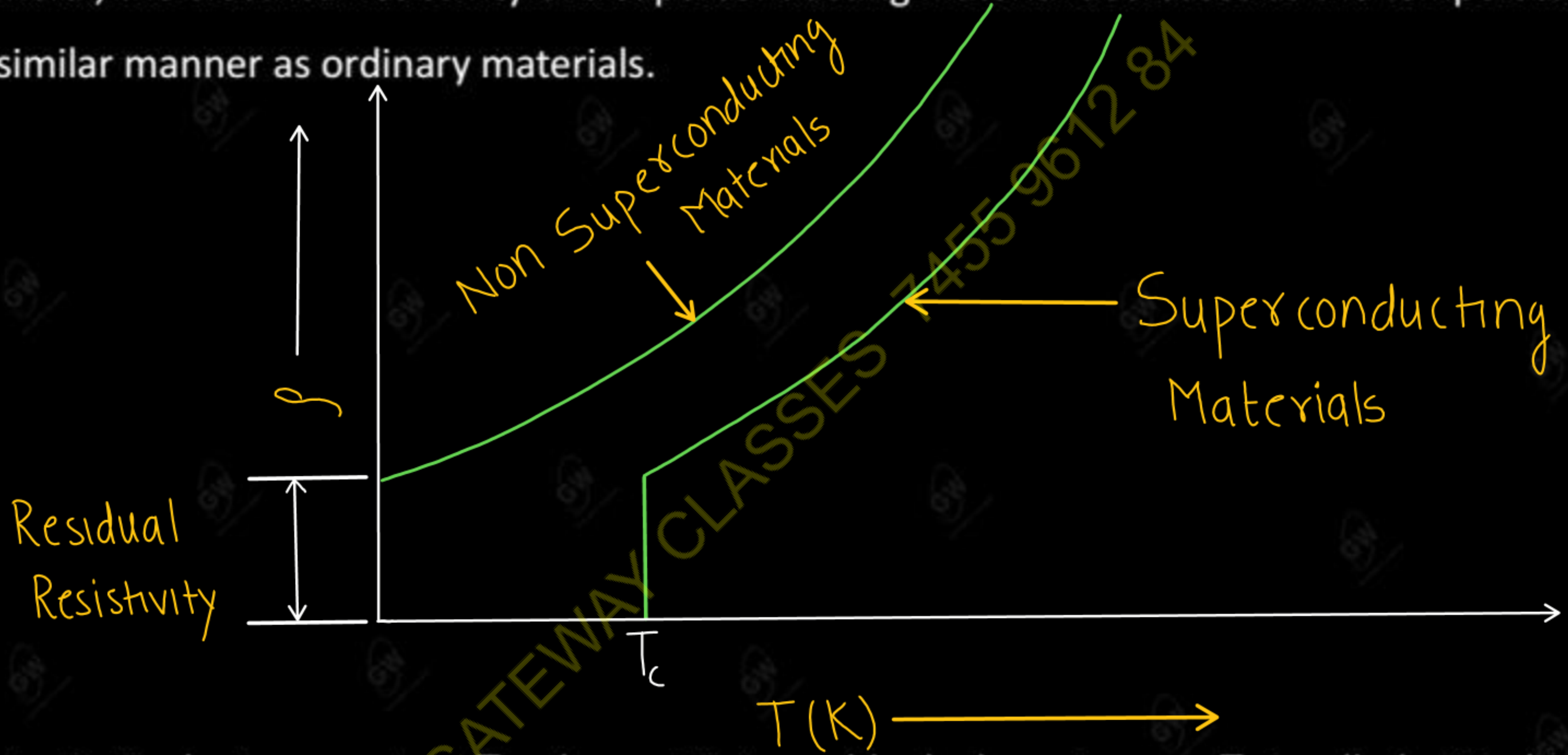
(ii) Bismuth Strontium Calcium Copper Oxide (BSCCO) = 110 K

(iii) Thallium Barium Calcium Copper Oxide (TBCCO) = 125 K

(iv) Mercury – Barium – calcium – copper – oxide (HBCCO) = 135K

Temperature Dependence of Resistivity in Super Conducting Materials

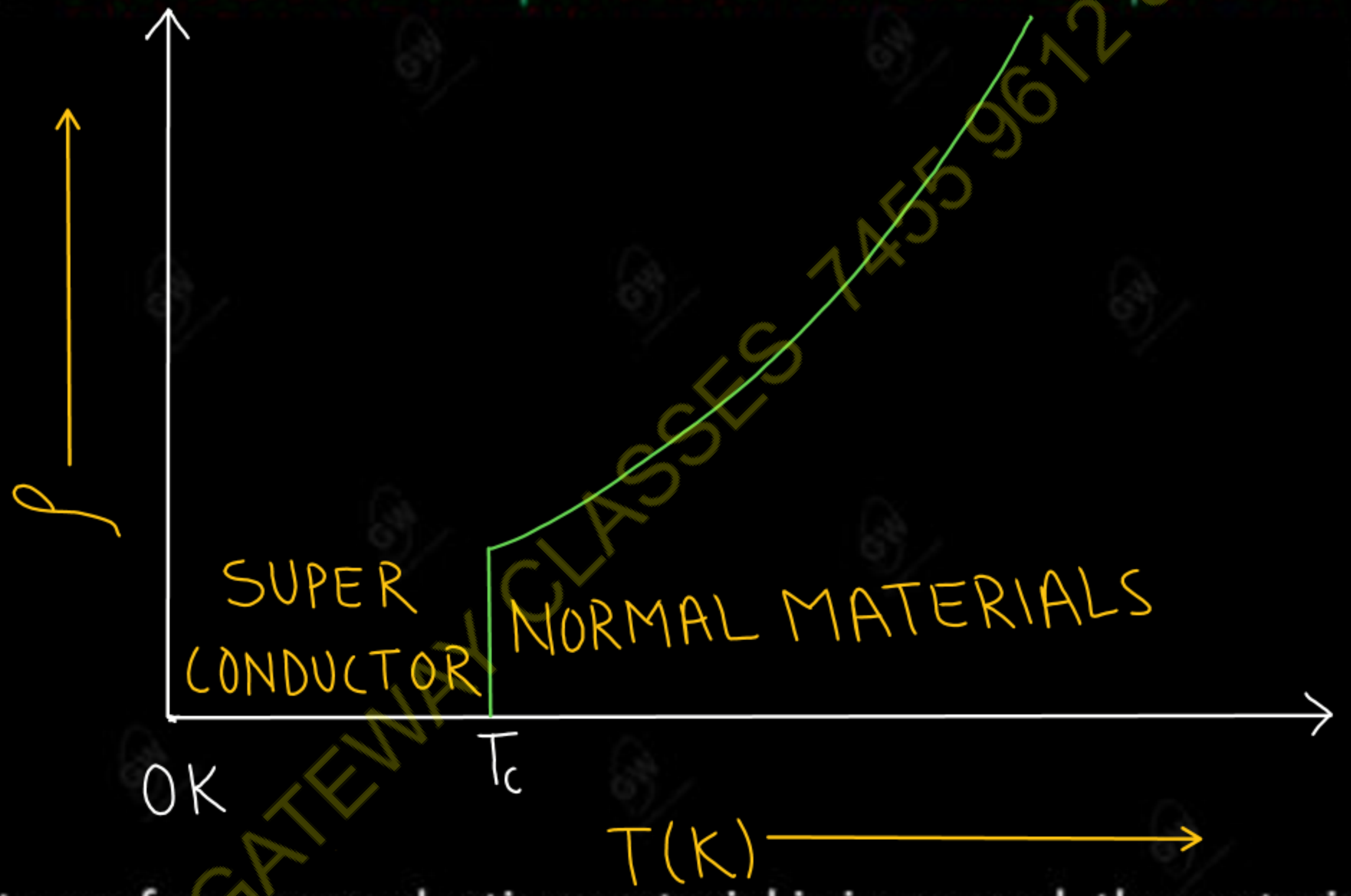
➢ In General, the electrical resistivity of a superconducting material decreases as the temperature is reduced, in a similar manner as ordinary materials.



➢ But at a Particular temperature T_c , the resistivity suddenly drops to zero. T_c is called critical temperature

Critical Temperature (T_c)

- The temperature at which the resistivity of a normal material drops to zero and normal material convert in to a super conductor is called critical temperature or transition temperature.



Note:- If the temperature of super conducting material is increased, the material transform in to a normal material above the critical temperature.

Critical temperature of some super conducting materials

Low – Temperature Super conductors (LTS)

(i) Mercury (Hg) = 4.15 K

(ii) Lead (Pb) = 7.19 K

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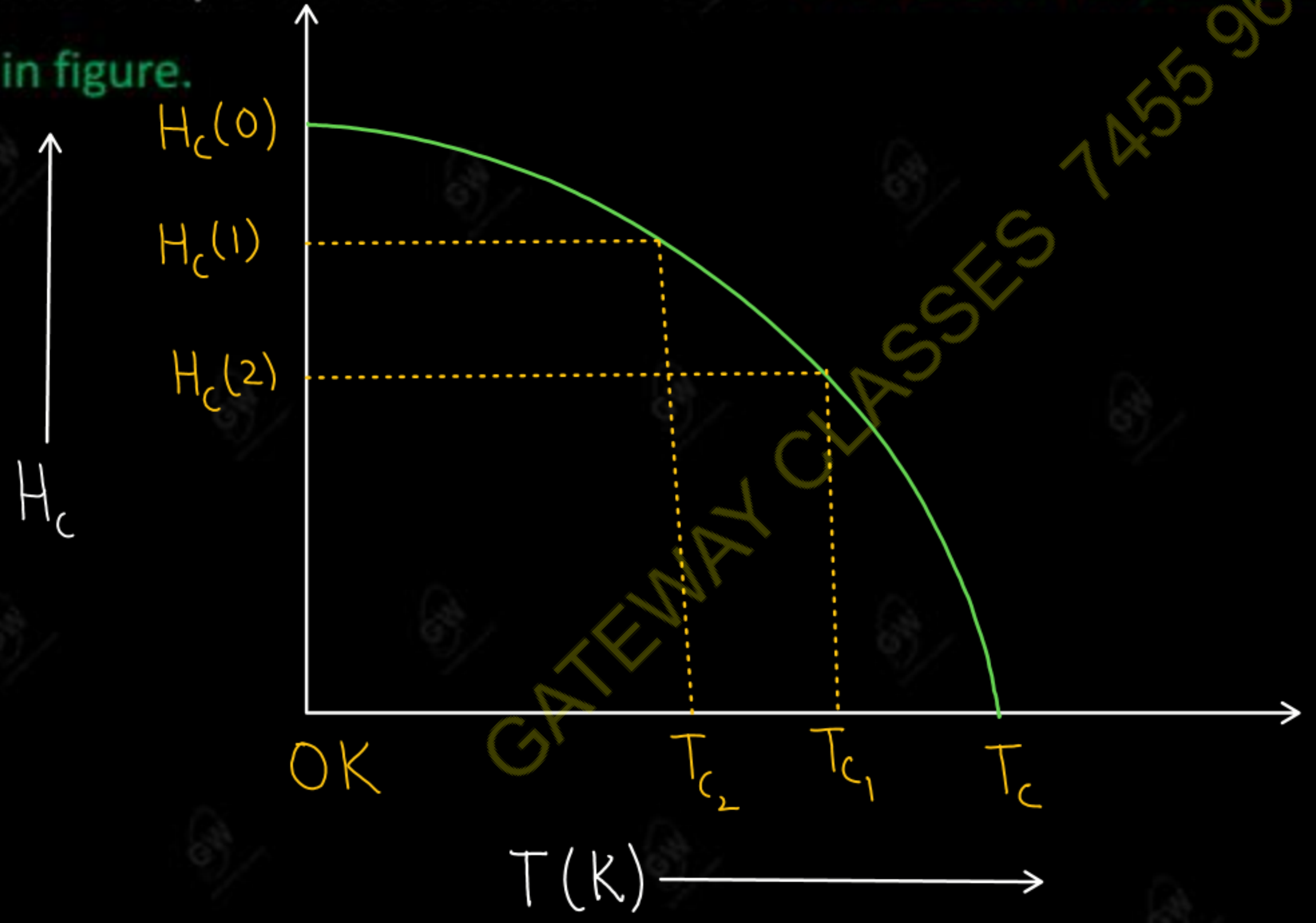
Effect of External Magnetic Field on Superconductor

- When a superconductor is placed in an external magnetic field, its super conductivity decreases with increases in the intensity of external magnetic field (H).
- At a particular value of H, the super conductivity of the specimen vanishes. This particular value is known as critical field H_c

CRITICAL MAGNETIC FIELD (H_c)

- The minimum value of applied magnetic field at which the superconductor loses its super conductivity is called critical magnetic field.
- Temperature dependence of critical field or the variation of critical magnetic field with temperature is shown in figure.



- Normal conducting state of the material is restored if

  (i) Magnetic field is greater then the critical value

  (ii) The Temperature of the specimen is raised above critical temperature

- The curve between temperature and magnetic field is nearly parabolic and can be represented by following relation

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

Where

$H_c(T)$ = Maximum critical field at T K

$H_c(0)$ = Maximum critical field at O K

T_c = Critical Temperature

Note : The critical field which destroy superconductivity need not necessarily be an external field but it may also arise as result of an electric current flowing through the superconductor specimen itself

Q.1 Lead in the superconducting state has critical temperature 6.2 K at zero magnetic field and a critical field 0.064 MA/m at 0 K. Calculate the critical field at 4K.

Given

$T_c = 6.2\,K$

$H_c(0) = 0.064\ MA/m$

$T = 4K$

$H_c(T) = ?$

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

$$H_c(T) = 0.064\left[1 - \left(\frac{4}{6.2}\right)^2\right]$$

$$\boxed{H_c(T) = 0.037\ MA/m}$$

Q.2 The transition temperature for Pb is 7.2K, however, at 5K it loses the superconducting property subjected to a magnetic field of 3.3×10^4 A/m. Find the maximum value of H which allow the metal to retain its superconductivity at 0 K. **(AKTU-2022-23)**

Given

$T_c = 7.2\,K$

$T = 5\,K$

$H_c(T) = 3.3 \times 10^4\ A/m$

$H_c(0) = ?$

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

$$3.3 \times 10^4 = H_c(0)\left[1 - \left(\frac{5}{7.2}\right)^2\right]$$

$$3.3 \times 10^4 = H_c(0) \times 0.5177$$

$$\boxed{H_c(0) = 6.37 \times 10^4\ A/m}$$

Q.3 The transition temperature for lead is 7.26K. The maximum critical field for the material is 8×10^5 A/m. lead has to be used as a superconductor subjected to magnetic field of 4×10^4 A/m. What precaution will have to be taken?

Given

$T_c = 7.26\,K$

$H_c(0) = 8 \times 10^5\ A/m$

$H_c(T) = 4 \times 10^4\ A/m$

$T = ?$

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

$$4 \times 10^4 = 8 \times 10^5\left[1 - \left(\frac{T}{7.26}\right)^2\right]$$

$$1 - \left(\frac{T}{7.26}\right)^2 = \frac{\cancel{4} \times \cancel{10^4}}{\cancel{8}_{2} \times 10^{\cancel{5}}}$$

$$\left(\frac{T}{7.26}\right)^2 = 1 - \frac{1}{20}$$

$$\left(\frac{T}{7.26}\right)^2 = \frac{19}{20}$$

$$\frac{T}{7.26} = \sqrt{\frac{19}{20}}$$

$$\boxed{T = 7.08\,K}$$

Temperature of lead must be less than 7.08 K

Q.4 The critical values of magnetic field are 2×10^5 A/m and 10^5 A/m for niobium at 0K and 8K respectively. Determine its critical temperature.

Given

$H_c(0) = 2 \times 10^5$ A/m

$H_c(T) = 10^5$ A/m

$T = 8$ K

$T_c = ?$

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

$$\cancel{10^5} = 2 \times \cancel{10^5}\left[1 - \left(\frac{8}{T_c}\right)^2\right]$$

$$1 - \left(\frac{8}{T_c}\right)^2 = \frac{1}{2}$$

$$\left(\frac{8}{T_c}\right)^2 = 1 - \frac{1}{2}$$

$$= \frac{1}{2}$$

$$\frac{8}{T_c} = \frac{1}{\sqrt{2}}$$

$$T_c = 8\sqrt{2}$$

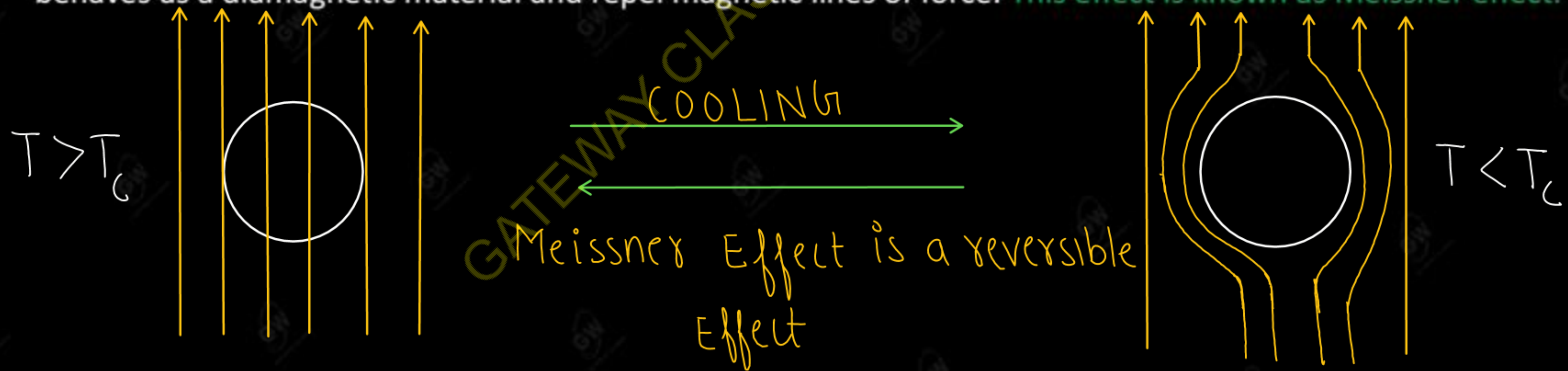
$$\boxed{T_c = 11.3137 \text{ K}}$$

Meissner Effect (1933)

- Two main properties of superconductors are

  (i) Zero resistance (ii) Diamagnetic behavior

- The diamagnetic materials repel the magnetic field lines
- The superconductors are perfectly diamagnetic materials
- So, Superconductors also repel the magnetic field lines
- Diamagnetic behavior of superconductors was discovered by Meissner
- When a superconducting material is placed in a magnetic field and cooled below the critical temperature, it behaves as a diamagnetic material and repel magnetic lines of force. This effect is known as Meissner effect.



Normal conducting State + Magnetic field Superconducting State + Magnetic field

In this case, super conducting material rejects all the magnetic lines of force and no magnetic lines of force are allowed to penetrate through it

Prove that the super conductors are perfect diamagnetic Materials

We know that the magnetic induction developed within the superconducting material is given by

$$\boxed{B = \mu_0(H+M)}$$

Where

B = Magnetic induction

μ_0 = Permeability of free space

H = Intensity of magnetic field

M = intensity of magnetisation

For Superconductors

$$B = 0$$

$$\mu_0(H+M) = 0$$

$$H+M = 0$$

$$H = -M \quad \text{——— (1)}$$

Magnetic Susceptibility is given by

$$\chi = \frac{M}{H} \quad \text{——— (2)}$$

Using (1) in (2)

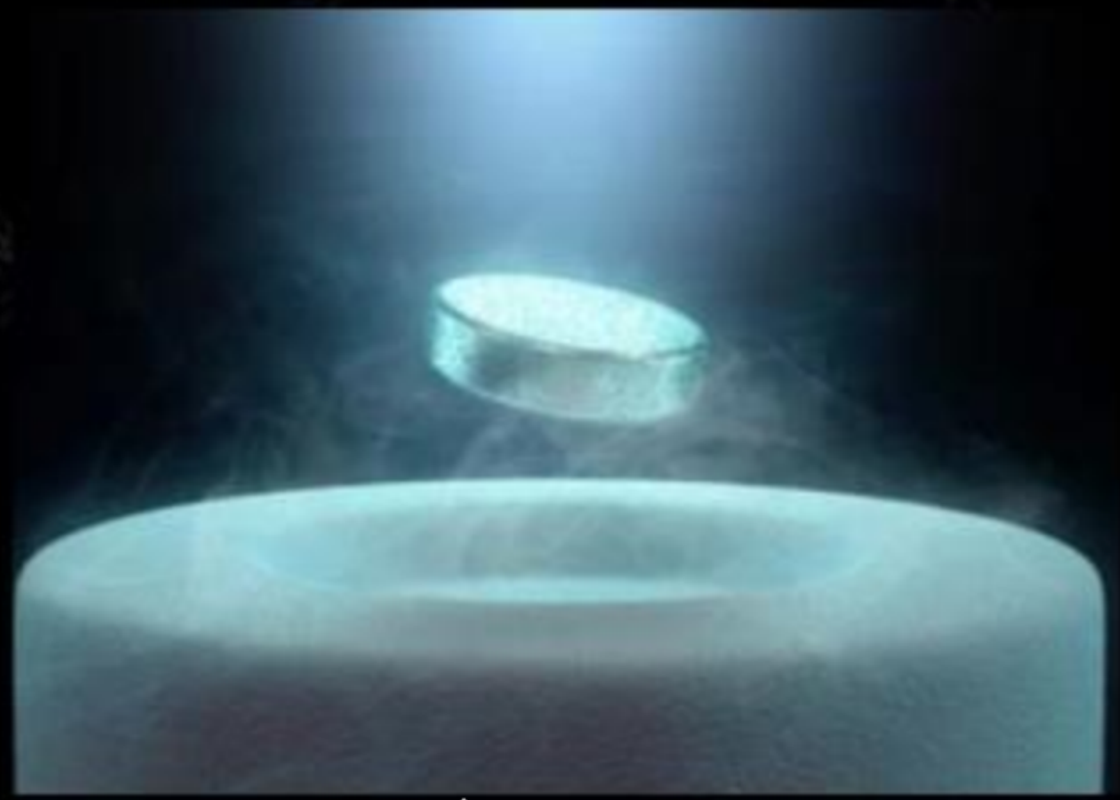
$$\chi = \frac{\cancel{M}}{-\cancel{M}} = -1 \quad \text{--- (3)}$$

Also relative Permeability is given as

$$\mu_r = 1 + \chi = 1 - 1$$

$$\mu_r = 0 \quad \text{--- (4)}$$

From (3) and (4) it is clear that Superconductors are perfect diamagnetic materials

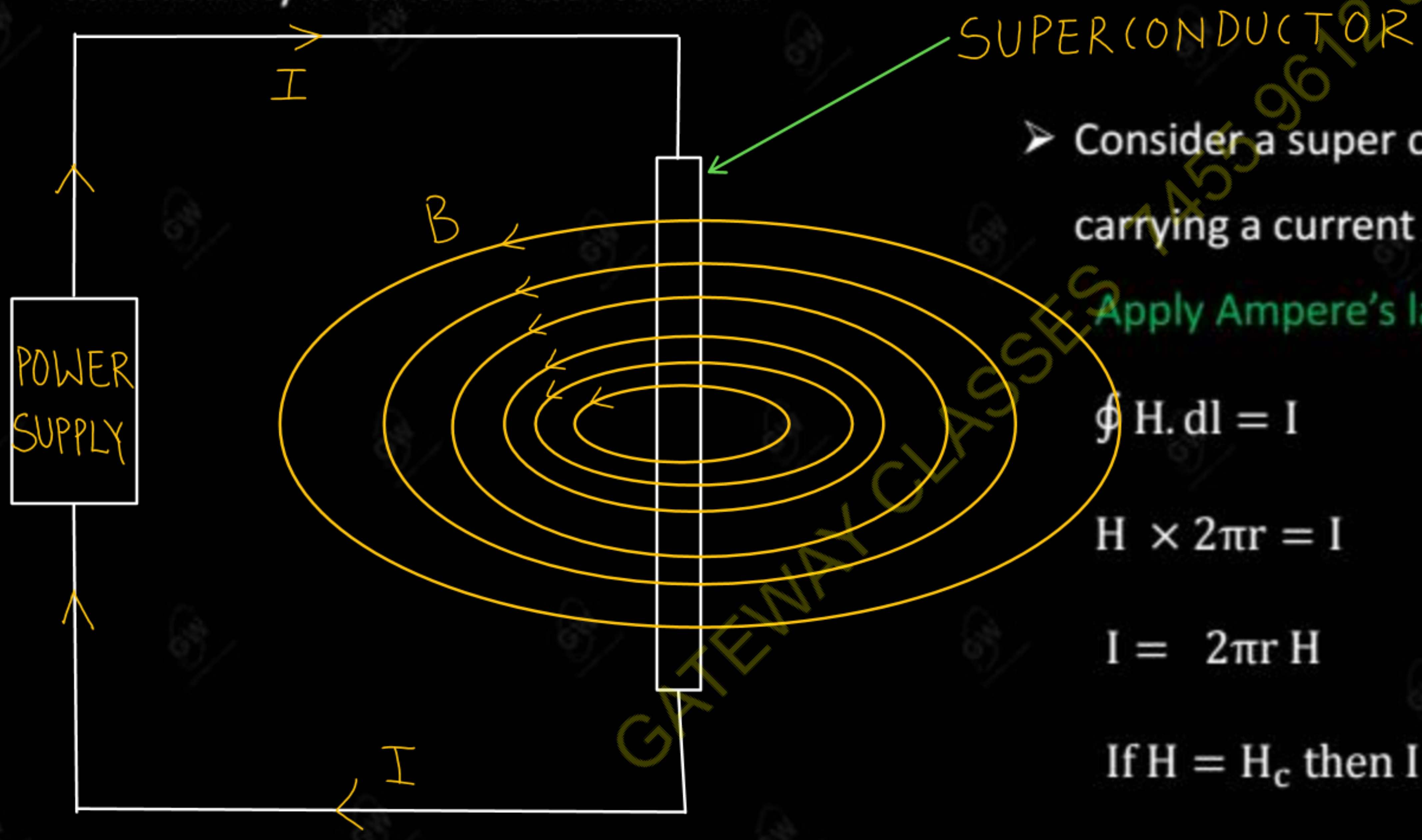


Magnetic Levitation

- When a small magnet is placed on a super conductor and liquid nitrogen is poured around it, the magnet rises and float in the air. This experimental observation is known as magnetic levitation. This effect is observed in super conductors due to their diamagnetic nature.

Critical Current (I_c)

➤ The maximum current that can be passed in a super conductor without destroying its super conductivity is called critical current.



➤ Consider a super conducting wire of radius (r) and carrying a current I

Apply Ampere's law

$$\oint H.dl = I$$

$$H \times 2\pi r = I$$

$$I = 2\pi r H$$

$$\text{If } H = H_c \text{ then } I = I_c$$

Critical current

$$I_c = 2\pi r H_c$$

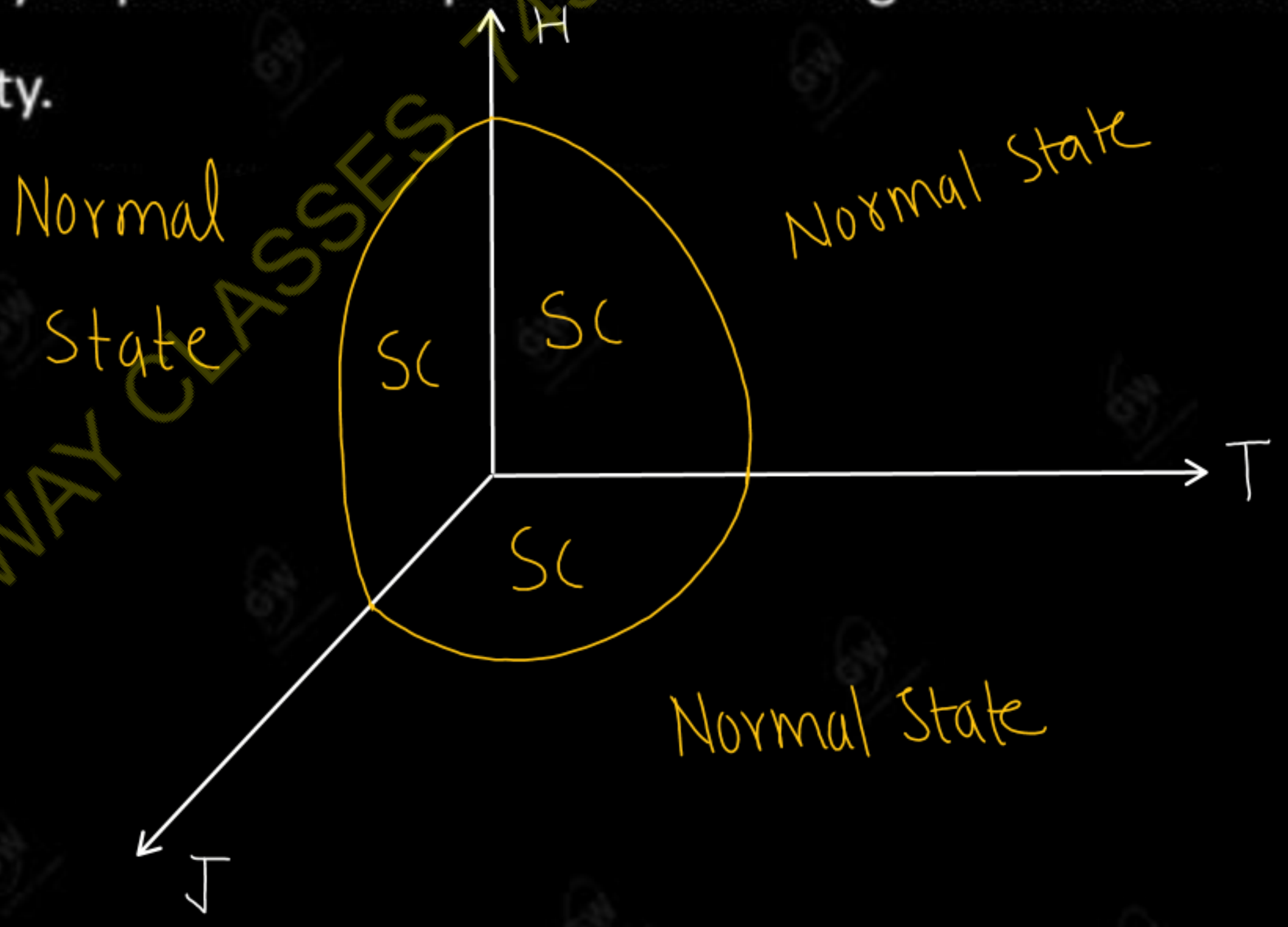
Critical current density (J_c)

$$J_c = \frac{I_c}{A}$$

Thus, super conducting state not only depend on temperature and magnetic field but also depend on current or current density.

For Superconducting State

$$\boxed{\begin{array}{c} T < T_c \\ I < I_c \\ H < H_c \end{array}}$$



Q.5 Determine the critical current that can flow through a long thin superconducting wire of aluminium of diameter 10^{-3} m. The critical magnetic field for aluminium is 7.9×10^{3} A/m.

Given

$d = 10^{-3}$ m

$H_c = 7.9 \times 10^{3}$ A/m

We know that

$$I_c = 2\pi r H_c$$

$$= \cancel{2}\pi \times \frac{\cancel{10^{-3}}}{\cancel{2}} \times 7.9 \times \cancel{10^{3}}$$

$$\boxed{I_c = 24.81\ A}$$

Q.6 Determine the critical current density for a superconducting wire of lead having diameter 1 mm at 4.2 K. The critical temperature of lead is 7.18 K and the critical magnetic field at 0 K is 6.5×10^4 A/m.

Given

$d = 1\,mm = 10^{-3}\,m$

$T = 4.2\,K$

$T_c = 7.18\,K$

$H_c(0) = 6.5 \times 10^4\,A/m$

$J_c = ?$

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

$$H_c(T) = 6.5 \times 10^4\left[1 - \left(\frac{4.2}{7.18}\right)^2\right]$$

$$\boxed{H_c(T) = 4.276 \times 10^4\,A/m}$$

$$I_c = 2\pi r H_c$$

$$= \cancel{2}\pi \times \frac{10^{-3}}{\cancel{2}} \times 4.276 \times 10^4$$

$$\boxed{I_c = 134.3\,A}$$

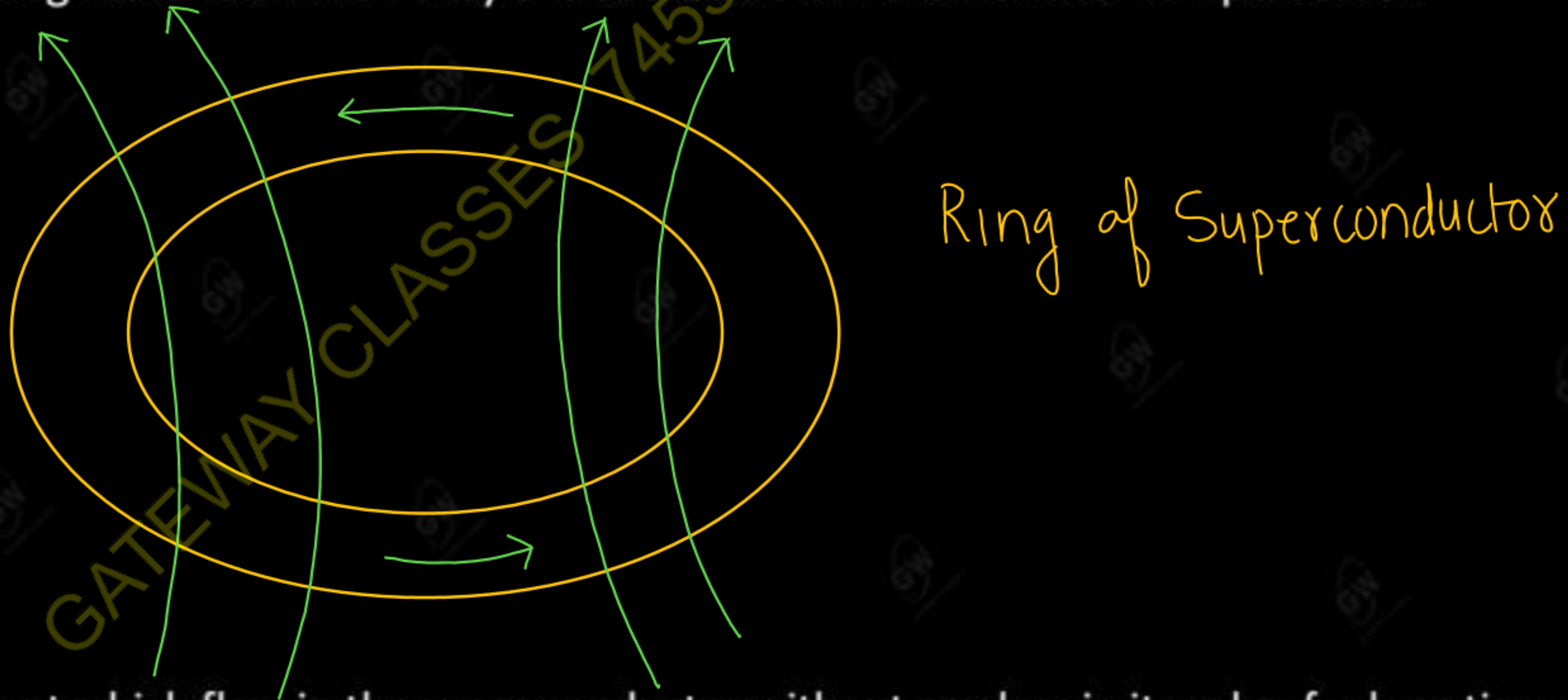
$$J_c = \frac{I_c}{A} = \frac{I_c}{\pi r^2}$$

$$J_c = \frac{134.3}{\pi \times \frac{10^{-3}}{2} \times \frac{10^{-3}}{2}}$$

$$\boxed{J_c = 1.71 \times 10^8\,A/m^2}$$

Persistent Current

- Steady flow of current in a ring of superconductors without any applied voltage or external source is called persistent current.
- This phenomenon is a key characteristic of superconductors and arises due to the absence of electrical resistance in super conducting materials when they are cooled below their critical temperature.



- Persistent current is the current which flow in the super conductor without any loss in its value for long time.

Isotope Effect

- This effect was discovered by Maxwell and Reynold in 1950-51
- It has been observed that critical temperature (T_c) of Super conductors varies with the isotopic mass (m) according to the following relation

$$T_C = \frac{1}{m^{\propto}}$$

When $\propto$ = isotope coefficient

$\propto$ for H_g = 0.5

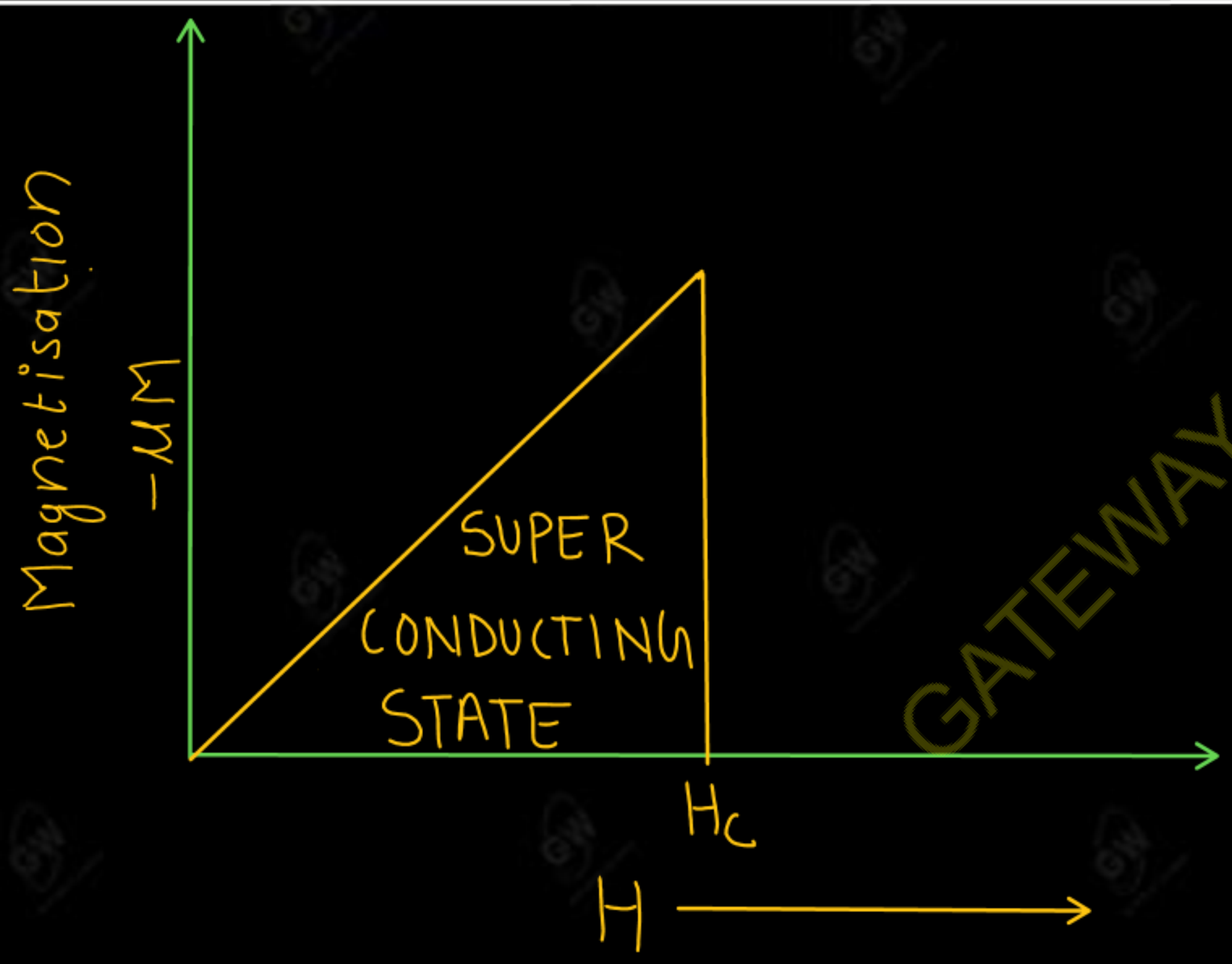
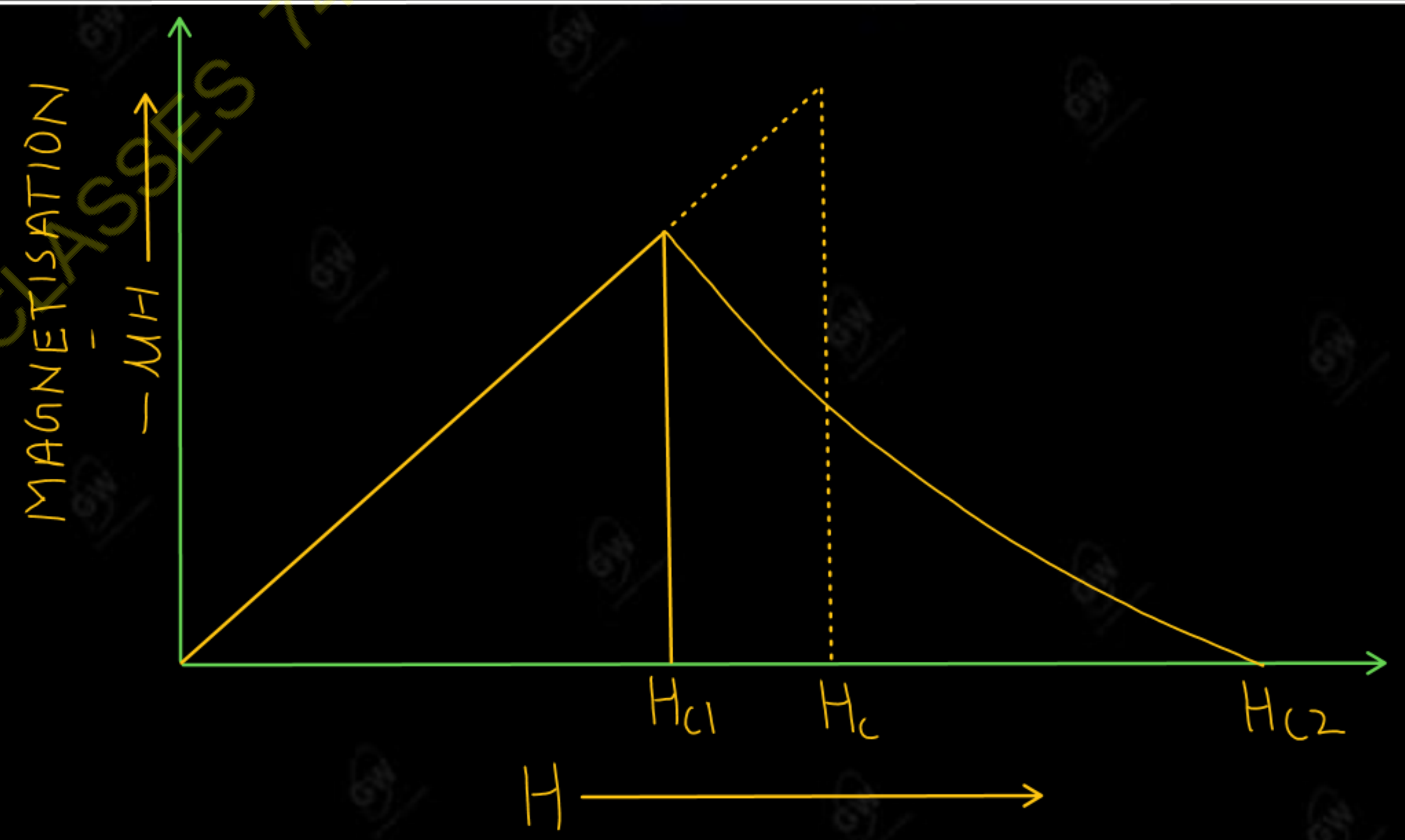
$$T_C = \frac{1}{\sqrt{m}}$$

Type – I and Type – II Superconductors

Depending upon the behavior of super conductor in the external magnetic field, they have been classified into two categories.

(i) Type – I Super conductors or Soft Superconductors

(ii) Type – II Super conductors or Hard Superconductors

Type – I Super conductors	Type – II Superconductors
	

Type – I Super conductors	Type – II Superconductors
(1) Above critical field H_c the Super conductor become normal conductor	(1) Between H_{C1} and H_{C2} the superconductor exist in mixed state called vortex state and above H_{C2} it comes in normal conductor
(2) No mixed state exists	(2) Mixed state exists
(3) They suddenly loose super conductivity	(3) They gradually loose superconductivity
(4) These superconductors shows perfect Meissner effect	(4) These superconductors do not shows perfect Meissner effect
(5) They are perfect diamagnetic material	(5) They are not perfect diamagnetic material
(6) There is only one critical magnetic field (H_C) for these super conductor	(6) There two critical magnetic field H_{C1} and H_{C2} for these super conductor
(7) The critical magnetic filed value is very low	(7) The critical magnetic filed value is very high

Type – I Super conductors	Type – II Superconductors
(8) These super conductors have limited technical applications	(8) These super conductors have wider technical applications
(9) These superconductors are known as soft superconductors	(9) These superconductors are known as hard superconductors
(10) Example - Al, Pb, Zn, Ga etc.	(10) Example (i) Yttrium Barium Copper Oxide (YBCO) (ii) Bismuth Strontium Calcium Copper Oxide (BSCCO) (iii) Thallium Barium Calcium Copper Oxide (TBCCO) (iv) Mercury Barium calcium copper oxide (HBCCO)

High temperature Super conductors (HTS)

- The substances which show superconductivity at relativity high temperature are known as high temperature Super conductors
- The high temperature superconductors are also called as high critical temperature material
- The high temperature superconductor with critical temperature more than 77 K are more useful and less costly compared to the low temperature superconductors.
- The substances which show superconductivity at very low temperature are known as low temperature superconductors (LTS)
- To maintain low temperature, low temperature superconductors are placed in liquid helium which is very costly
- Due to this new type of superconductors are discovered which are known as HTS
- High temperature Super conductors show superconductivity at relatively high temperature.
- To maintain relatively high temperature, HTS are placed in liquid nitrogen which is cheaper in cost

- Basically, HTS are salts of rare earth elements, which are mostly copper oxide containing elements.

Example

(i) Yttrium Barium Copper Oxide (YBCO) = 92 K

(ii) Bismuth Strontium Calcium Copper Oxide (BSCCO) = 110 K

(iii) Thallium Barium Calcium Copper Oxide (TBCCO) = 125 K

(iv) Mercury – Barium – calcium – copper – oxide (HBCCO) – 135K

Properties

- HTS have highly anisotropic structure
- HTS are brittle substances
- They can carry large amount of current
- They are type – II or hard super conductors
- High critical temperature
- High critical magnetic field

Properties of Superconductors

(1) Zero resistance or Zero resistivity or infinite conductivity

(2) Superconductors are perfectly diamagnetic materials

(3) Superconducting state is reversible

(4) It is a low temperature phenomenon

(5) Critical temperature is different for different substances.

(6) No loss in energy conduction due to extremely less resistance

(7) When some amount of impurities are added to a super conducting materials, the value of its critical temperature decreases.

(8) Magnetic field does not penetrate into the superconductor (Meissner effect)

(9) Superconductivity occur in those materials which have high normal resistivity.

(10) The entropy of a super conductor decreases rapidly on cooling below transition temperature.

(11) Generally, superconducting elements lie in the inner column of periodic table.

(12) The metal which are good conductors (Ag, Au and cu at room temperature) do not show superconductivity.

Applications of Super conductors

Due to unique properties of super conductors, they find application in several fields .

(i) Super conducting wires and cables are used in transmission of electric power

(ii) Used for making super conducting magnet

(iii) Used for making super conducting transformer and Generator

(iv) Used in Magnetic Resonance imaging (MRI) Machine

(vi) Used in making super conducting filters

(vii) Cryotrons (as a switch) in computers

(viii) SQUIDS (Super conducting quantum interface devices)

(ix) For progress of computer technology.

(x) Advanced spectroscopy and microscopy techniques.

Engineering Physics (By Gulshan Sir)

DPP-1

UNIT : Superconductors

Q.1 What is the difference between Type 1 and Type 2 superconductors? Why type-2 superconductors are more important than type 1 superconductor?

Q.2 Explain the Meissner effect and persistent current in superconductivity.

Q.3 What do you mean by super conductivity? Discuss high temperature superconductors and some potential applications.

Q.4 Discuss the effect of external magnetic field on superconductors. The transition temperature for Pb is 7.2K, however, at 5K it loses the superconducting property subjected to a magnetic field of 3.3×10^4 A/m. Find the maximum value of H which allow the metal to retain its superconductivity at 0 K.

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