Electrotechnical Materials

Chapter 4

Conductive and Superconducting Materials

I. INTRODUCTION

The mastery of materials science is inextricably linked to the control of electrical phenomena. Few material properties are as central to modern engineering and technology as the capacity to efficiently transport, or perfectly confine, electric charge. This chapter, Conductive and Superconducting Materials, serves as a detailed exploration of electrical transport, moving from the efficient electron flow in conventional metals to the zero-resistance quantum state of superconductors. The content is structured into two main parts, each detailing a unique regime of electrical behavior.

Conductive Materials establishes the foundational link between a material's atomic structure and its bulk electrical behavior. Our analysis begins with the principles of Energy Band Theory, introducing the concepts of the Valence Band, Conduction Band, and Forbidden Band (Energy Gap) to fundamentally differentiate metals, semiconductors, and insulators. Building upon this theoretical framework, we will define and quantify electrical conductivity (σ) and its inverse, resistivity (ρ), by examining the scattering mechanisms that impede electron motion. A critical focus will be placed on the practical consequences of current passage, particularly the resistive (Joule) effect, which leads to energy losses, and the Magnetic Effect (Skin Effect), a key factor in high-frequency alternating current applications. The final segment will present a practical Classification of Conductors based on their resistivity and specific technological function, covering materials used for power lines, electrical contacts, carbon electrodes, and specialized fuse elements.

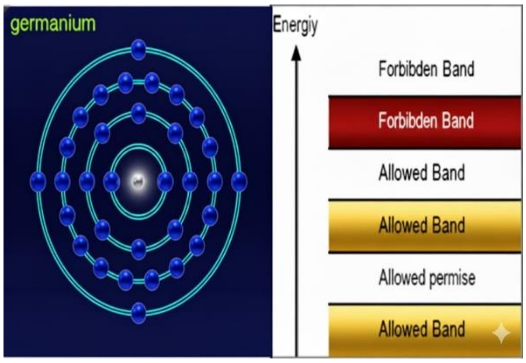
Superconducting Materials transitions to a realm of extraordinary physics where materials exhibit zero resistance below a characteristic critical temperature (T_c). We begin by reviewing the Experimental Evidence of this phenomenon and detailing the two defining features of the superconducting state: perfect conductivity and perfect diamagnetism (the Meissner Effect), which has direct consequences such as magnetic levitation. The core of the theory lies in the Bardeen-Cooper-Schrieffer (BCS) Theory, which explains the formation of Cooper pairs as the charge carriers. The chapter concludes by differentiating between Type I and Type II superconductors, reviewing the Key Dates in superconductivity research, and surveying the numerous, high-impact Applications that leverage zero resistance and powerful magnetic fields, including MRI systems, SQUID magnetometers, energy storage, and Maglev transport.

By integrating fundamental quantum mechanical principles with practical engineering and material selection, this chapter provides the foundational knowledge necessary to design, analyze, and optimize advanced electrical systems for future technological advancement.

A. Conductive Materials

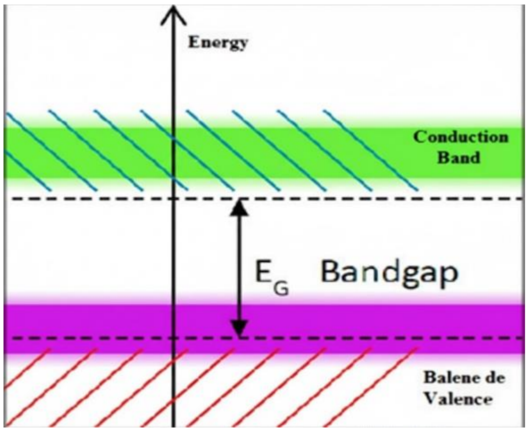
I.1. Energy levels and types of materials:

The Bohr model tells us that electrons from an isolated atom can only take on certain discrete well-defined energy values. In a crystal structure, the situation is intermediate: the energy of an electron can have any value within certain allowed intervals called energy bands which are separated by band gaps. The electrons of a crystal are distributed in the allowed energy levels.



At the fundamental state of matter, we find three:

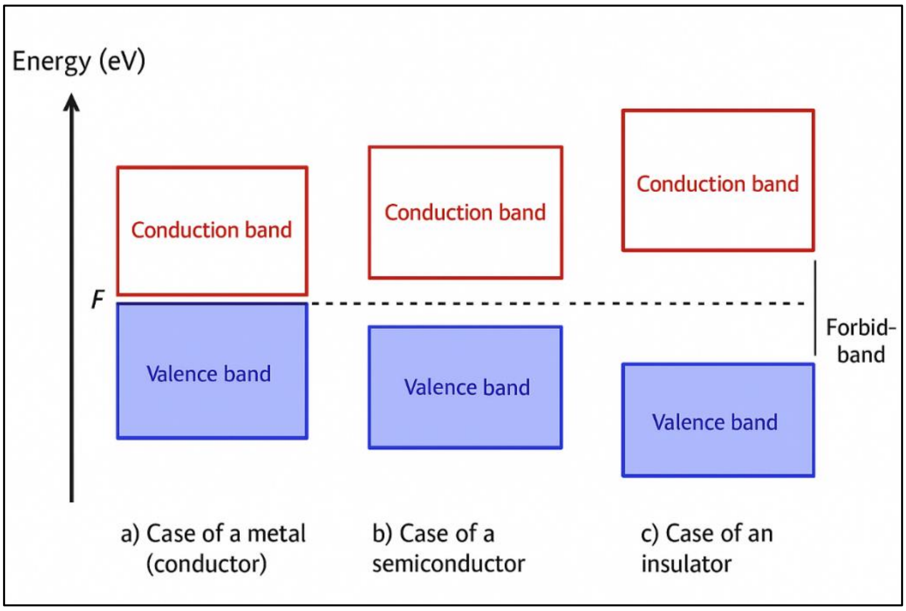
- The valence band is the last energy band completely filled
- with electrons;
- The conduction band is the energy band greater than or equal
- to that of the valence band, but which is not filled.
- The bandgap is the band that separates the valence and
- conduction bands. This band is called GAP band. It is
- characterized by a so-called gap energy.



The electrons belonging to the valence band allow the local cohesion of a solid or a material. They interact with neighboring atoms to make the structure stable. The electrons of the conduction band are said to be delocalized. They can move within the material, from atom to atom, to participate in electrical conduction.

To know if a material is insulating, conductive or semiconducting, it is necessary to observe the filling of the valence and conduction bands and at the size of the gap, in the ground state of the material.

* If the conduction band is partially filled, regardless of the gap size, electrons within of the material participate in electrical conduction: the material is Conductor
* If the conduction band is empty:
- If the band gap is sufficiently small (*1–3 eV*), the material is insulating at rest. However, the slightest thermal or electrical excitation allows some electrons in the valence band to cross the gap, and the material becomes conductive. The material is a semiconductor.
- If the band gap is large (around *5 eV*), no electron in the material can participate in conduction: the material is an insulator.



I.2. Definition of a Conductor

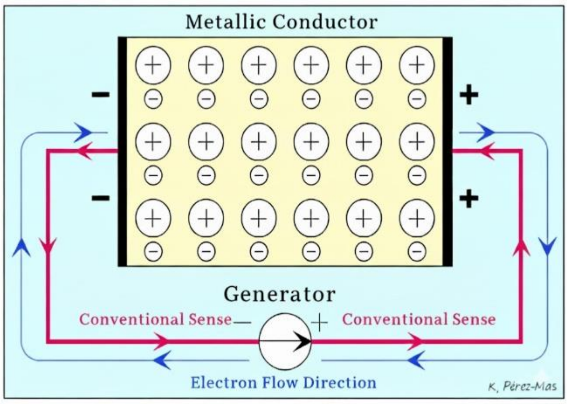
An electrical conductor is a material that readily allows the flow of an electric current when a voltage is applied across it, establishing an electric field *(E)*. This conductivity is due to the presence of a vast number of free electrons, typically exceeding 10^{22} per cubic centimeter. When the electric field is non-zero, each free electron (with charge $q = -1.602 \times 10^{-19}$ *C* experiences an electric force (*F*) described by the equation $\vec{F} = q\vec{E}$. This force causes the electrons to move directionally, or drift, creating the electric current. Conversely, when the electric field is absent ($E=0$), the conductor is in electrostatic equilibrium, meaning there is no net force on the interior charges and thus no net directional current flow

I.3. Effects related to the passage of current in conductor

The passage of electric current in a conductor mainly results in different physical effects, among which:

* Joule effect (heat)
* Magnetic effect (deflection of a powered needle)
* Chemical effect (electrolysis)

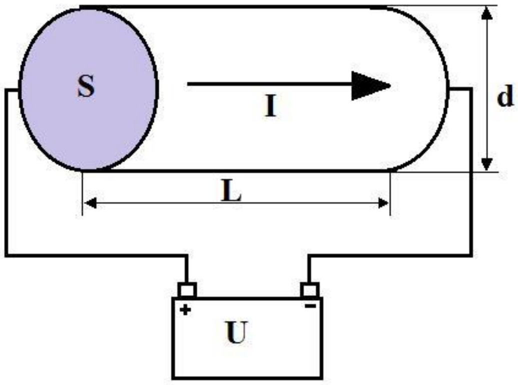
Most of these effects depend on how the voltage source is connected to the conductor's terminals. Indeed, electric current has a meaning, the conventional direction of the current is:



* From the point having the potential (stronger+) to the point having the lowest potential, outside of the voltage source (conventional direction of the current)
* From the point having the potential the (more +low) to the point having the strongest potential, inside of the voltage source (real physical sense of the current).

I.3.1. Resistive effect and resistance of a conductor

Ohm's Law and Resistance



According to **Ohm's Law**, the **resistance** (R) of a conductor is defined as the ratio of the voltage (U) applied across its terminals to the current (I) flowing through it. Resistance is measured in **Ohms** (Ω).

$$R = \frac{U}{I}$$

The resistance (R) of a conductor depends on its physical dimensions (cross-sectional area and length) and its material nature (resistivity). The resistance of a uniform conductor is calculated using the following formula:

$$R = \rho \frac{L}{S}$$

Where:

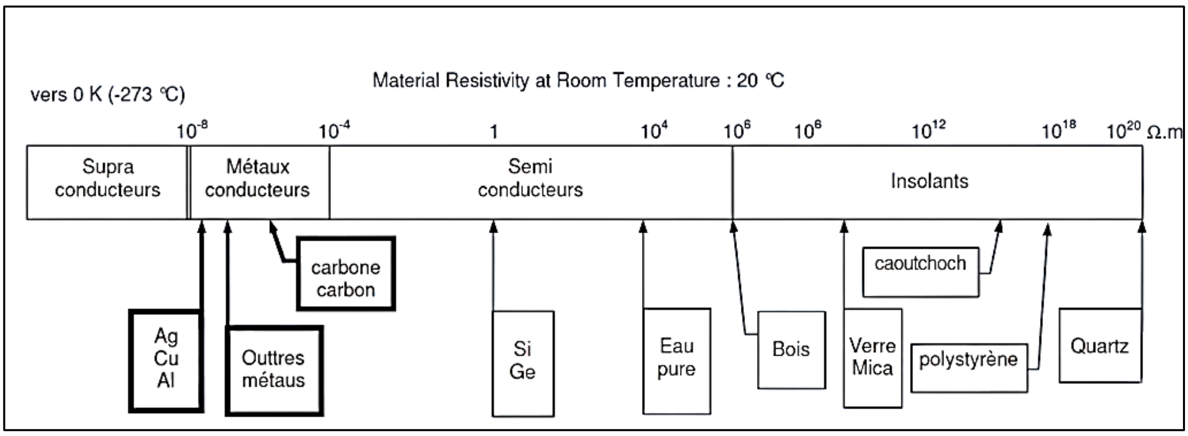
* R: Resistance of the conductor, measured in Ohms (Ω).
* L: Length of the conductor, measured in meters (m).
* S: Cross-sectional area of the conductor, measured in square meters (m^2). For a circular wire, $S = \frac{\pi d^2}{4}$, where d is the diameter.
* ρ: Resistivity of the conductor material, measured in Ohm-meters ($\Omega\cdot\text{m}$).

Conductivity

Conductors can also be characterized by their **conductivity** (σ), which is the inverse of resistivity:

$$\sigma = \frac{1}{\rho}$$

The unit of conductivity is the Siemens per meter ($S.m^{-1}$) or generally ($\Omega^{-1}.\ m^{-1}$). The quality of conduction of a material is measured by its resistivity (or conductivity). For good conductors, the value of resistivity is very low, typically ranging from 10^{-4} to 10^{-8} $\Omega.\ m$.



Resistivity for Different Types of Materials

Temperature Dependence of Resistivity

For conductors, resistivity is not constant; it depends significantly on the ambient temperature (θ). The resistivity (ρ) as a function of temperature variation is given by $\rho = \rho_0(1 + \alpha\theta)$

Where:

* ρ_0: The resistivity of the material at a reference temperature, usually 0^0 C.
* θ: The temperature in degrees Celsius ^{0} C.
* α: The temperature coefficient of resistivity, which is material-dependent. For pure metal conductors, a typical value is $\alpha \approx 4 \times 10^{-3}\ (^\circ\mathrm{C})^{-1}$

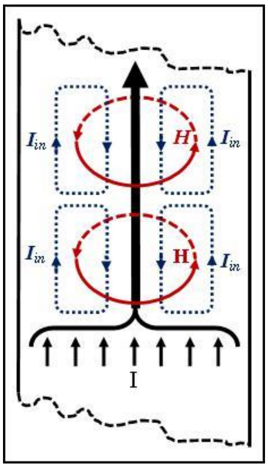
Joule Effect Losses

The presence of resistance in a conductor means that the circulation of current generates energy losses known as thermal losses or Joule effect losses. This is the power dissipated as heat and is calculated by:

$$P_{joule} = RI^2$$

Where P_{Joule} is the power loss measured in Watts (W).

I.3.2. Magnetic effect and Skin effect



As indicated in the previous chapters, the movement of an electric charge generates a circular magnetic field around it. Given that the current is only a set of charges, then it generates fields (magnetic) around the latter.

When the current (*I*)flowing in the conductor is continuous, the potential difference is uniform and the (charges) move in the conductor uniformly, which gives a constant magnetic field (*H*). In this case, there will be no induced currents in the conductor.

When the current flowing in the conductor is alternating, the charges oscillate and the resulting magnetic field is variable. In this case, the conductor sees the birth of loops of induced currents (I_{in})around the lines of this variable field. At the center of the conductor, the direction of induced currents opposes the direction of circulation of the main current, while at the periphery of the conductor, the directions of induced and main currents are the same. Thus, the sum of the main current with that of the loop is always lower at the center of the conductor whereas these two currents add up at the periphery.

Therefore, the current does not flow uniformly throughout the section of the conductor, the electrical charges (currents) have the tendency to migrate towards the conductor's peripheral. This phenomenon, which occurs when all the conductors are traversed by an alternating current, is called a skin effect, a film-like effect or sometimes, Kelvin effect.

The thickness δ of the skin (peripheral area where the electric current concentrates) depends on:

- frequency of the currents flowing in the conductor (f).
- The permeability of magnetic material (μ).
- The conductivity σ or the resistivity ρ of the material.

This thickness is given by:

$$\delta = \sqrt{\frac{\rho}{\mu\pi f}} = \frac{1}{\sqrt{\sigma\mu\pi f}}\ (m)$$

At 50 Hz, copper has a skin of 8.5 mm, aluminum 10.5 mm so the useful diameters of the bars of these materials are, respectively, 16 mm for copper and 20 mm for aluminum. Therefore, it will be a waste of material to use higher thicknesses.

With the skin effect, one can imagine that the useful surface of conduction is reduced which leads to an increase in conduction resistance (see the resistance formula). Therefore, the skin effect contributes to the increase in joule losses.

Under the skin effect, the effective resistance (in alternating current) of a cylindrical conductor becomes:

$$\begin{cases} R_{eff} = K x R_{dc} \\ K = \sqrt[6]{\left(\frac{3}{4}\right)^6 + \left(\frac{S}{P\delta}\right)^6} + 0.25 \end{cases} ,\quad K \geq 1$$

With:

- R_{eff}: It is the continuous resistance (fixed)
- R_{dc} : It's the resistance considering the skin effect
- S: This is the driver's section

$P = \pi.\ d$: This is the driver's perimeter

I.4. Classification of conductive materials and their applications

Conductive materials represent the basic elements in the field of electrical engineering, they are classified by:

- The resistivity or conductivity
- The fields of application.

I.4.1. Classification of conductive materials according to resistivity:

In this category, we find materials with low resistivity (high conductivity) and materials with high resistivity (low conductivity).

a. Materials used as conductors for electrical machine coils:

Materials with low resistivity such as copper, silver, and aluminum are used to manufacture electrical machine coils. However, regarding optimal conductivity, mechanical strength and cost, copper is well suited for this application.

b. Materials used for transmission lines:

The materials used for the manufacture of transmission lines must have the following properties:

- Low resistivity (high conductivity)
- High tensile strength
- Light weight
- High resistance to corrosion
- High thermal stability
- Low coefficient of thermal expansion
- At a low price

Among the materials used for transmission lines, find:

- Copper
- Aluminium
- Cadmium-copper alloys
- Phosphorous bronze
- Galvanized steel
- Copper steel core
- Aluminum steel core

c. Materials used for lamp filaments:

These are materials with high resistivity such as carbon, Tantalum, Tungsten, etc. which are used for the manufacture of filaments for incandescent lamps, indeed, they must possess the following properties:

High melting point

- Low vapour pressure
- Non-oxidation in a medium under inert gas (argon, nitrogen, etc.) at the operating temperature
- High resistivity
- Low coefficient of thermal expansion
- Low coefficient of resistance to temperature
- Possibility to be converted into filament shape
- Cost should be minimum

d. Materials used for heating elements:

These are materials with high resistivity such as Nichrome, Cupronickel, Platinum, which are used for the manufacture of heating elements. The materials used must have the following properties:

- High melting point
- Non-oxidation in the working atmosphere
- High tensile strength

e. Materials used for bimetallic membranes:

In this case, a combination of metals, with different coefficients of linear thermal expansion, is used to form the bimetal sheets. Among the combinations, commonly used to make bimetallic strips, are:

- The combination: Iron + Nickel + constantan (high coefficient of linear thermal expansion)
- The combination: Iron + Nickel (coefficient of linear thermal expansion) f.

Materials used for electrical contacts

The proper functioning of electrical contacts depends on various factors. When selecting a suitable material for electrical contact, it is necessary to take into account:

- Contact resistance
- Contact force
- Voltage and current

g. Electric carbon materials

Carbon is widely used in electrical engineering. Carbon electrical materials are made from graphite and other forms of carbon. Among the applications of this type of carbon, we find:

- Incandescent lamp filament
- For the electrical contacts
- To make the resistors
- For the manufacture of brushes (collectors) for direct current electrical machines, alternators, etc.
- To make battery cells
- Carbon electrodes for electric furnaces
- Welding electrodes

h. Materials used for fuse elements

The fuse element (wire) is the main component of a fuse unit. The fusible element must have the following properties

- Low resistance to prevent unwanted voltage drop across the fuse element, in order to effect normal circuit or device operation.
- Low melting point: the fuse element must have a low melting point, so that it easily deteriorates in case of excessive heating during overload or short circuit.

Different types of metals and alloys are used for fusible elements, such as:

- Aluminium
- Lead and tin
- Copper
- Silver.

B. *Superconducting Materials*

Electrons are responsible for the flow of electric current in conductive materials. As they move, electrons undergo numerous stresses (impacts) that slow them down. Electrical resistance is the property of a material to slow down the passage of electric current. This resistance causes the material to heat up due to the Joule effect. This effect causes significant losses in electrical systems and equipment. In an electrical network, Joule effect losses represent on average 10% of the power transported. Furthermore, the intensity of a magnetic field that can be created by ordinary conductors is very limited (around 2 Tesla maximum), resulting in a very small range of action. To overcome these constraints, researchers are constantly seeking to develop new materials with the potential to:

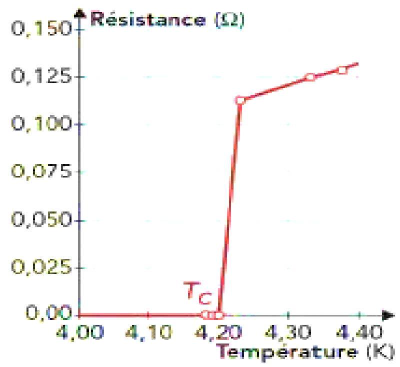
- Circulate very high (infinite) currents without damaging the conductors and with minimal or no loss
- Create very intense magnetic fields without the need for gigantic and cumbersome magnetic circuits.

The solution is to replace ordinary electrical conductors with conductors known as ***Superconductors***.

II.1. Physics and principle of superconductors

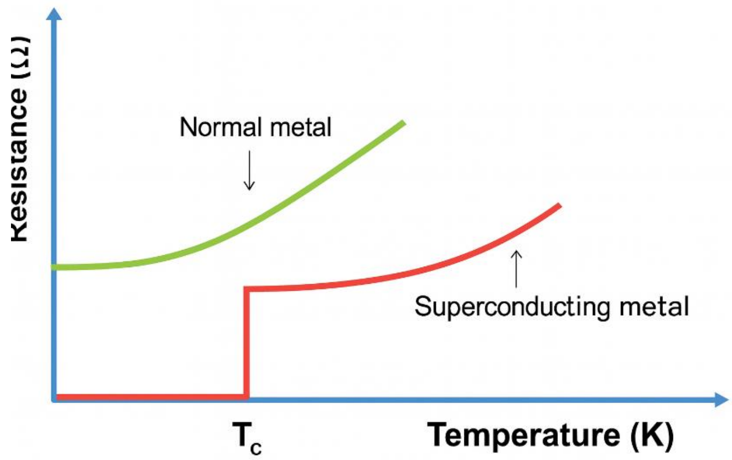
II.1.1. Experimental evidence of superconductivity

In 1911, ***H. Kamerlingh Onnes*** studied the electrical resistance of mercury at very low temperatures. He discovered that below a certain temperature, called the critical temperature, Tc, the resistance of mercury disappears. He named this phenomenon "***superconductivity***." Superconductivity was born and seemed to apply to many metals and alloys.



Résistance du mercure.

The phenomenon of superconductivity only occurs below a certain temperature called the critical temperature Tc, but there is also a limit to current intensity limit, called the critical current Ic . In practice, the resistivity of a superconductor is less than $\mathbf{10^{-25}}\ \boldsymbol{\Omega\ m}$ compared to that of copper, which is is of the order of $\mathbf{10^{-7}}\ \boldsymbol{\Omega \cdot m}$ at 300 K



Effect of Temperature on Electrical Resistance in Superconductors

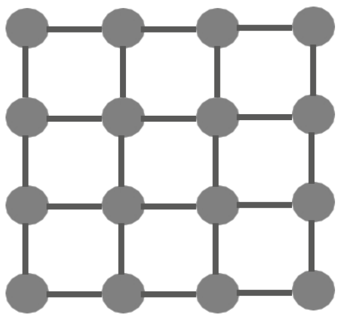
II.1.2. Concept of superconductivity – the BCS theory:

Our understanding of superconductivity took a step forward in 1957 with three American physicists, ***John Bardeen***, ***Leon Cooper***, and ***John Schrieffer***, and their theory on superconductivity, known as the ***BCS*** theory.

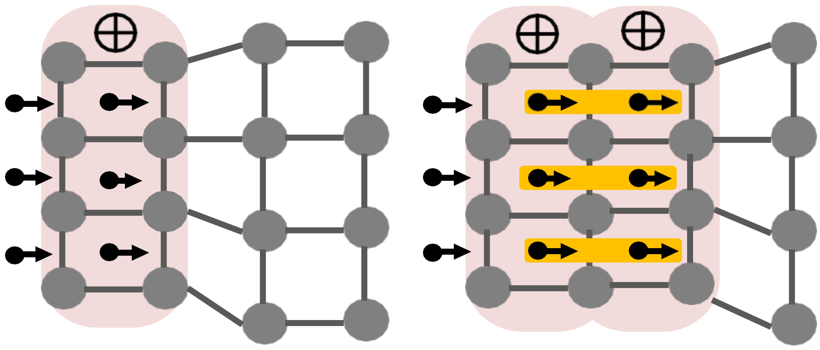
According to the BCS theory, electrons could group together in pairs at very low temperatures. This seems impossible at first glance, since electrons are negatively charged particles and should normally repel each other. In fact, in a conductive material, atoms shed one of their electrons, which is used to conduct current, and become positive ions. At room temperature, the atoms vibrate significantly due to the influence of other atoms, the influence of electrons, and the thermal effect. These vibrations can affect the movement of certain electrons, which lose energy and slow down: this is the resistive effect in ordinary electrical conductors.

However, for certain materials and at very low temperatures, atoms vibrate very little (very low thermal agitation), and when an electron passes close to them, they are all attracted because they are positive. Except that these ions are heavier than electrons and take longer to return to their initial position. A positive zone therefore appears, and a second electron begins to follow the first: ***the Cooper pair*** is formed thanks to the vibrations of the ion lattice, called phonons. Three stages have been identified in the formation of Cooper pairs in superconductors:

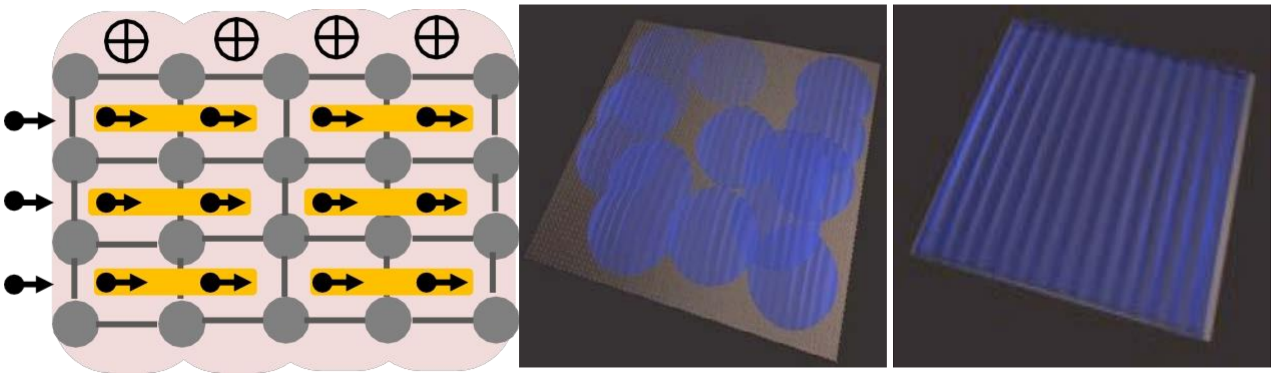
* **Stage 1**: The positively charged ions in the superconductor are all far apart from each other. No electrons have passed through yet.
* **Stage 2**: A first negatively charged electron passes between the positively charged ions, and the electron then attracts the positively charged ions thanks to its negative charge. However, the ions are slower to move than the electron because of their greater mass: it has already left before the ions have had time to touch it. The area where this first electron passed is a positively charged deformation zone that attracts a second electron to form a Cooper pair. In order to achieve this coupling, the first electron emits a phonon and the second absorbs it, creating an attraction that overcomes the natural repulsion between electrons of the same charge.
* **Step 3**: As the electrons advance, the behavior of the previous step is repeated along the material. Thus, a set of Cooper pair chains is formed. In quantum physics, these Cooper chains are called waves. The waves formed all have the same phase (the waves therefore have the same shift relative to a given point). The waves add together to form a single quantum wave, since each wave has the same characteristics. As a result, the electron pairs all propagate as a single wave called "***the condensate***." The electrons are therefore no longer slowed down by the atoms that make up the material, since Cooper pairs are not sensitive to atomic defects in the material due to the much larger size of the collective wave, given that at least $\mathbf{10^{21}}$ electrons are grouped together. The resistance that was due to collisions between free electrons and atoms constituting the material can therefore no longer exert itself here, hence the appearance of superconductivity.



Step 1: Initial form of the atomic Structure



Step 2: Electron transition and formation of Cooper pairs



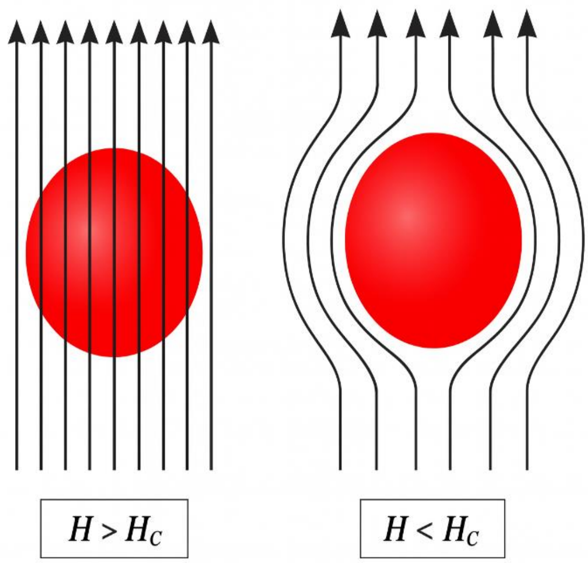
Step 3: Formation of Cooper pair waves

II.1.3. Meissner effect and levitation

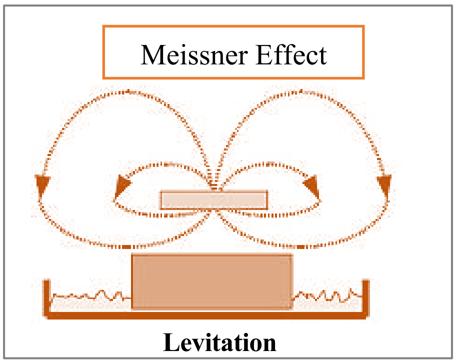
When a massive superconductor is placed in a weak magnetic field $\vec{H}$, it will act as a perfect diamagnetic material, with magnetic induction

$\vec{B}$ is zero in the superconductor. This is the Meissner effect. To explain this phenomenon, it should be remembered that

when a conductor is subjected to a magnetic field, current loops appear. In a superconductor, currents called shielding currents circulate around its surface, creating their own magnetic field, which is opposite to the external fields. Due to the absence of electrical resistance, these currents circulate freely without requiring energy. The fields created therefore exactly compensate for the fields present in the superconductor. The superconducting material behaves like a perfect diamagnetic material.

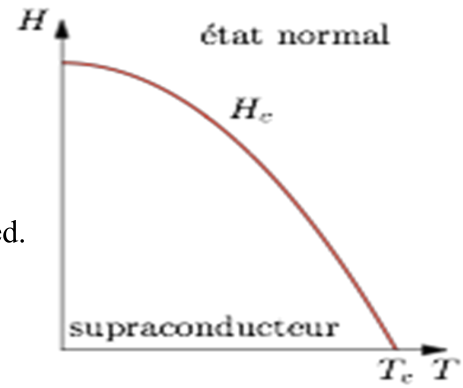


With the Meissner effect, a superconducting material can also exert a force on nearby magnetic materials. The superconductor can therefore levitate magnetic materials and leave them suspended in the air.



It should be noted that if the external magnetic field is strong enough, superconductivity can be destroyed. The threshold, or critical value, of the magnetic field that destroys superconductivity is noted as H_c , which depends on temperature.

II.1.4. Classification of superconductors

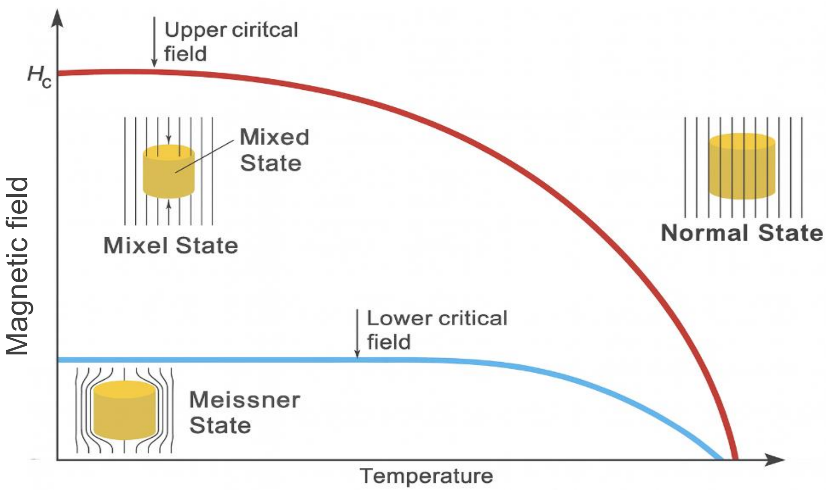


There are two types of superconductors: ***Type I and Type II***

* **Type I** superconductors are superconductors with a single critical field level, H_c , above which superconductivity is destroyed. For this type, the value of H_{c1} is too low for them to be used in Construction of coils for superconducting magnets.

* **Type-II s**uperconductors are materials characterized by two critical magnetic field thresholds: a lower critical field Hc_1 and an upper critical field Hc_2 . These superconductors, generally metallic alloys, maintain their superconducting properties up to the upper critical field Hc_2. When the applied magnetic field is below the lower critical field Hc_1 , the Type-II superconductor behaves similarly to a Type-I superconductor, exhibiting a complete Meissner effect.

However, when the magnetic field lies between Hc_1 and Hc_2, the magnetic flux inside the material becomes non-zero, and the Meissner effect is incomplete. In this intermediate region, magnetic flux penetrates the superconductor in the form of quantized flux lines, and the material enters what is known as the **vortex state**.



Magnetic Field–Temperature Phase Diagram of a Type-II Superconductor

II.1.5. Key dates in superconductivity

- 1911: Heike Kammerlingh-Onnes discovers that certain metals cooled to very low temperatures conduct electricity perfectly, without resistance: the concept of superconductivity is born.
- 1933: Walter Meissner and Robert Ochsenfeld discover that superconductors have the property of expelling the surrounding magnetic field. This property has been called the "Meissner effect."
- 1957: John Bardeen, Leon N. Cooper, and John R. Schrieffer develop the BCS theory, which explains superconductivity in metals and alloys.
- 1957: Alexei A. Abrikosov hypothesizes the existence of magnetic vortices in certain superconductors.
- 1962: Brian David Josephson predicted the Josephson effect: when two superconducting materials are close to each other, without actually touching, the passage of electron pairs from one to the other via tunneling leads to the establishment of an electric current.
- 1986: Johannes Georg Bednorz and Karl Alexander Müller discover new "high critical temperature" (high Tc) superconductors, cuprates.
- 2008: An international team of researchers discovers a new family of high critical temperature superconducting materials, pnictides (iron-based).

II.2. Superconducting materials used

After the discovery of mercury superconductivity in 1911 by Onnes, all elements in the periodic table were tested. Most transition metals can become superconductors, although the best conductors at room temperature, namely copper, gold, and silver, do not exhibit superconducting properties, while insulating elements can become superconductors. The following table gives some examples of superconducting materials with their critical temperatures and critical fields.

<u>Superconducting Materials and Their Properties:</u>

Conventional Superconductors

Material	*Tc (K)*	*Bc (T)*
Al	*1*	*0.01*
Pb	*7.2*	*0.08*
Nb–Ti	*9*	*14*
Nb	*9.2*	*0.2*
$PbMo_6S_8$	*15*	*60*
Nb_3Ge	*23*	*38*

High-Temperature Superconductors

Material	*Tc (K)*	*Bc (T)*
$La_{2-x}Sr_xCuO_4$	*38*	*40*
MgB_2	*39*	*>50*
La(Fe,F)As	*55*	*–*
$YBa_2Cu_3O_{6.9}$	*92*	*>100*
$Bi_2Ca_2Sr_2Cu_3O_{10}$	*110*	*>120*
$Tl_2Ca_2Ba_2Cu_3O_{10}$	*125*	*>130*

II.3. Applications of superconductors

- Magnetic resonance imaging (MRI): The device's powerful magnetic field (4 T) is produced by a superconducting coil. An ordinary magnet would be too large and
- generate too much heat
- SQUID (Superconducting Quantum Interference Device) imaging: This can be used for magnetoencephalography (MEG), a medical technique that measures the magnetic field magnetic emitted by the brain. The activity of the brain is easily detected by electroencephalography (EEG).
- Particle accelerators: an instrument that uses electric or magnetic fields to accelerate electrically charged particles to high speeds.
- For levitation and transport: Maglev superconducting trains (the fastest in the world)
- In electricity
  - Creation of high magnetic fields
  - Manufacture of electrical cables
  - Use in energy storage,
  - Production of current limiters
  - Creation of more compact motors.
  - For detection and measurement in the field of magnetism: SQUID-based magnetometers can be used to detect and measure very weak magnetic fields.
  - Electromagnetic bomb: to create a microwave pulse powerful enough to disable the enemy's electronic equipment or the guidance systems of their missiles.

III. Conclusion

Conductive and superconducting materials represent two distinct electrical behaviors. Conductors allow electron flow with energy losses, governed by resistivity, heating effects, and the skin effect, making them essential for cables, contacts, and electronic components. Superconductors, however, exhibit zero resistance and perfect diamagnetism below their critical temperature, enabling lossless current and strong magnetic fields through the Meissner effect and Cooper pair formation. These unique properties support advanced technologies such as MRI machines, particle accelerators, SQUID sensors, and magnetic levitation. Together, they highlight how material properties shape modern electrical engineering.