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Handout of the course on materials electrotechnics intended for electromechanical degree students

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Chapter 01: Magnetic materials

1.10. Introduction

Just like electric current, we can only observe the effects of magnetism. We cannot see the lines of force that exist around a magnet. The magnetic properties of some materials are due to the rotation of electrons on themselves in the atom: This phenomenon is called SPIN.

1.11. Magnetic materials are classified into three categories

1.2.1. Ferromagnetic materials:They can be strongly magnetized. Their magnetization persists more or less when the magnetizing field is removed. Examples: Iron, Nickel, Steel, Cobalt.

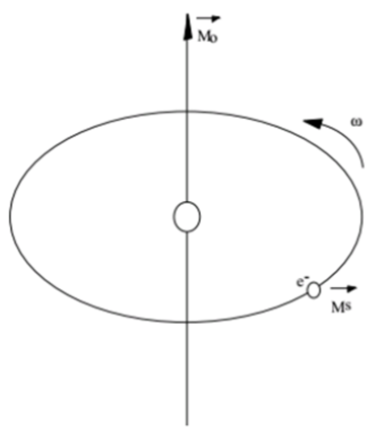
1.2.2. Paramagnetic materials: They are weakly magnetized in the direction of the magnetizing field. Their magnetization ceases as soon as the magnetizing field is removed. Examples: Aluminum, Platinum, Manganese.

1.2.3. Diamagnetic materials: They are weakly magnetized in the direction opposite to the magnetizing field. Their magnetization ceases as soon as the magnetizing field is removed. Examples: Copper, Zinc, Gold, Silver.

To explain these different types of magnetization, we must consider the magnetic moment of each atom and that of a particle of a body comprising a large number of atoms.

The atomic magnetic moment results from the movements of electrons that gravitate around the nucleus and at the same time rotate on themselves. The rotation of the electron on itself, Spin, causes a magnetic moment

The rotation of the electron on itself, Spin causes a magnetic moment $\overrightarrow{M_s}$



In an atom, these different magnetic moments combine to give the

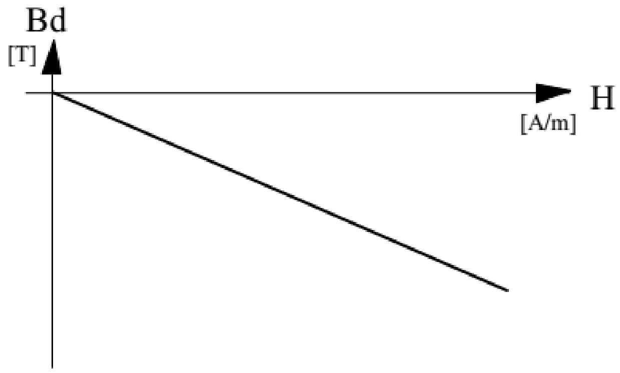
Atomic magnetic moment $\overrightarrow{M_a} = \sum \overrightarrow{M_o} + \overrightarrow{M_s}$

For diamagnetic materials this moment is zero. For paramagnetic materials it is not zero, but the moments of all the atoms are zero.$\overrightarrow{M}_a$

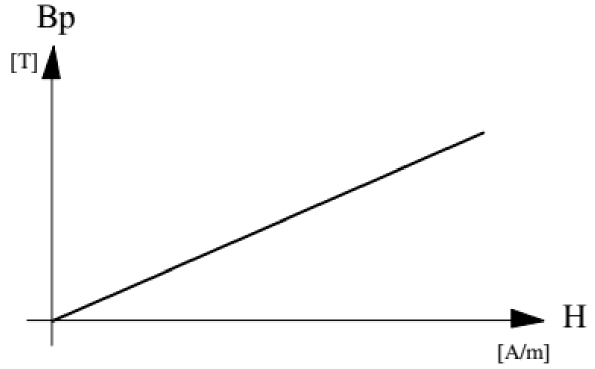
For ferromagnetic materials, patches of matter called Weiss domains have a non-zero magnetic moment. But in the absence of an external magnetic field, all the moments of these patches cancel each other out.$\overrightarrow{M}_a$

In the presence of an external magnetizing field, the body becomes magnetized and all the particles of this body have a magnetic moment. The magnetization thus obtained depends on the nature of the body.

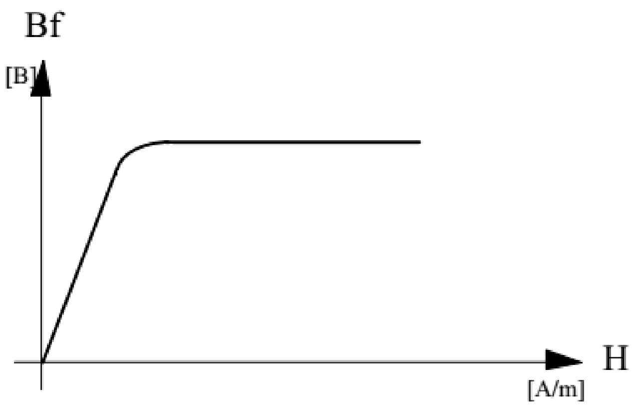
Diamagnetic materials become magnetized proportionally to the field in which they are placed, but in the opposite direction. The ratio between the value of the magnetization of the body and that of the field that produces it is small



Paramagnetic materials exhibit a magnetization proportional to the field in which they are placed, and in the same direction. The ratio between the value of the magnetization of the body and that of the field which produces it is small



Ferromagnetic materials are capable of magnetizing themselves much more strongly. Their magnetization is in the same direction as the inducing field, but it is not proportional. It increases with the inducing field and tends towards a limit



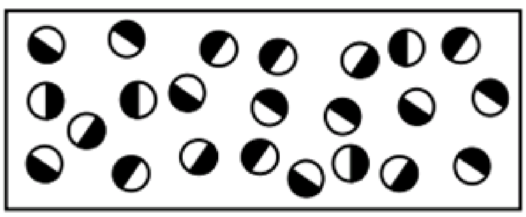
The materials we are going to study are part of the last category. They are the ones used for all magnetic applications in electrical engineering.

1.12. Permanent magnets

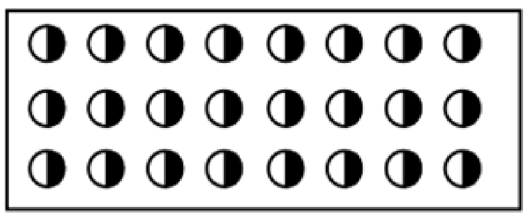
Permanent magnets were first developed from steel or cobalt-chromium. Around 1935, research began on alloys of iron-aluminum, nickel, cobalt, and copper. These fused or sintered alloys are known as ticonal or alnico. In 1951, barium and strontium ferrites were used. Today, ticonal and ferrite alloys are in common use and are the two most commonly used types of permanent magnet materials.

With modern materials, demagnetization due to aging or the action of a magnetic field (not too intense) can be considered negligible. This property also makes it possible to produce magnets with opposite poles very close to each other. These different properties have made it possible to abandon the classic forms of permanent magnets in horseshoe or long bar. It is now possible to produce magnets of various and very practical shapes.

In electrical measuring devices (galvanometers, ammeters and voltmeters), they have allowed in particular a great improvement in sensitivity and reliability. In some engines and generators (car alternators, dynamos, magnetos), they are used instead of electromagnets. They are also used in electronics for loudspeakers and microphones.

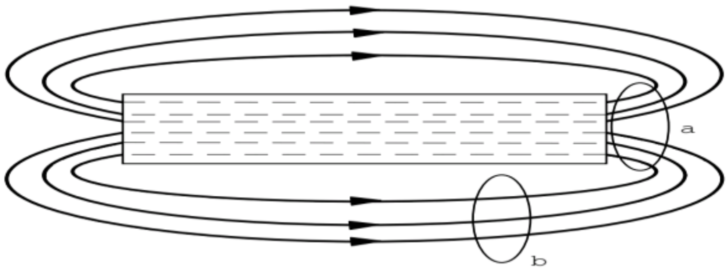


non-magnetic bar



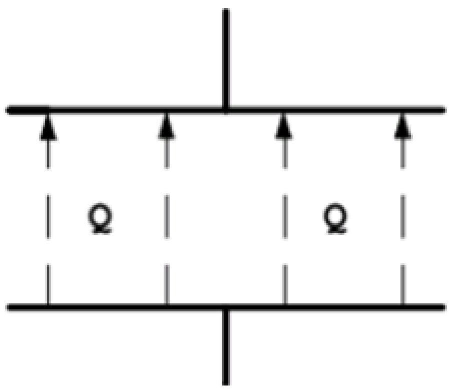
magnetic bar

In the region around a permanent magnet, there is a magnetic field that can be represented by means of magnetic lines of force similar to electric lines of force. Unlike electric lines of force, magnetic lines of force do not start from any point and do not end at any point; instead, they appear as loops



The lines of force run from the north pole to the south pole on the outside of the bar magnet, and from the south pole to the north pole on the inside. They are equally spaced and symmetrically distributed around the bar.
The lines of force occupy the smallest possible area and their interpolar length is minimal. The strength of the magnetic field of any region depends directly on the number of lines of force per unit area. In the figure above, the field strength is twice as great at point a as at point b, while the two areas are identical.

The intensity of the magnetic field $\vec{H}$ has the same characteristics as the electric field $\vec{E}$.
By analogy with the electric field $\vec{E}$, we see that when they move, the electrostatic charges $\vec{Q}$ cause an electromagnetic force $\vec{F}$ capable of attracting the needles of a compass.



1.13. Magnetic potential

In a vacuum or in air, the intensity of the magnetic field H is a source of current and can be defined by the notion of magnetic potential.

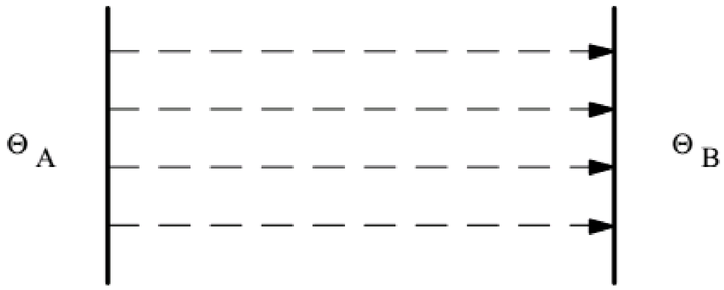
To imagine this notion of potential, let's compare it to the flow of cars on a three-lane highway.

Each track is a road traffic tube with a different number of cars on a well-defined length due to different speeds. We can therefore compare it to a certain potential for car passage.

1.14. Magnetic potential difference

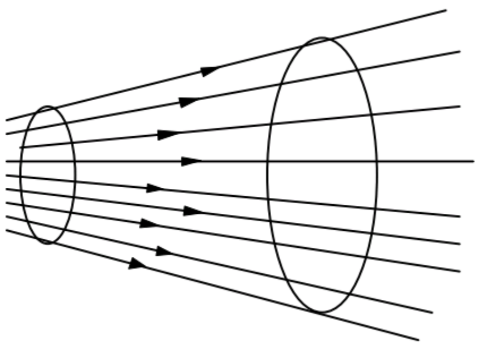
Magnetic potential difference is defined as the presence of a magnetic field intensity H between points A and B. Charges move in air with some ease.

Relation : $H_{AB} = \frac{\Theta_A - \Theta_B}{d}$



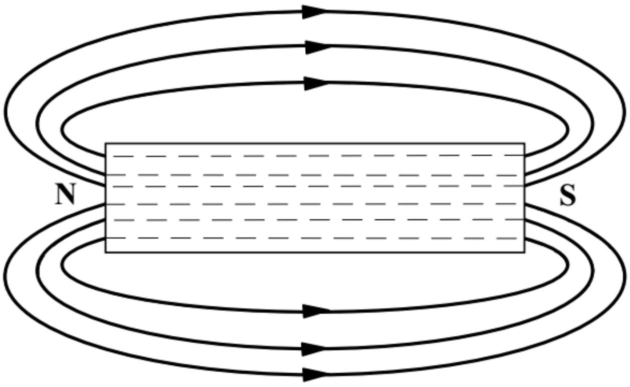
1.15. Lines of force or lines of induction

The induction lines or lines of force represent the vectors of the induction field influencing space.



1.16. Magnetic spectrum

The magnetic spectrum represents ALL the lines of force



These lines of force come from a pole admitted by convention, the North pole, perpendicular to area A, passing through a medium which could be space or something else, to close at another pole admitted by convention, the South pole.

Each line of force necessarily closes. As with the electric current I, it circulates in a closed circuit.

Which implies a line of force flowing from the South Pole to the North Pole inside the element constituting the induction field generator B. This generator can be a permanent magnet, an electromagnet or a current passing through a conductor.

1.17. Relationship between magnetic field strength, air permeability µ0 and relative permeability µr$\vec{H}$

Charges Q moving in a magnetic tube with a certain speed cause an electromagnetic force.$\vec{F}$. This force is related to the material of the magnetic tube and the intensity of the magnetic field.$\vec{H}$

$$\frac{F}{Q.v} = \mu_0.\mu_r\,.H$$

The quotient$\frac{F}{Q.v}$is called the magnetic induction field.$\vec{B}$

We therefore obtain the following relation, assuming the perpendicularity between the vectors:

$$B = \mu_0.\mu_r\,.H$$

1.18. Magnetic induction field B

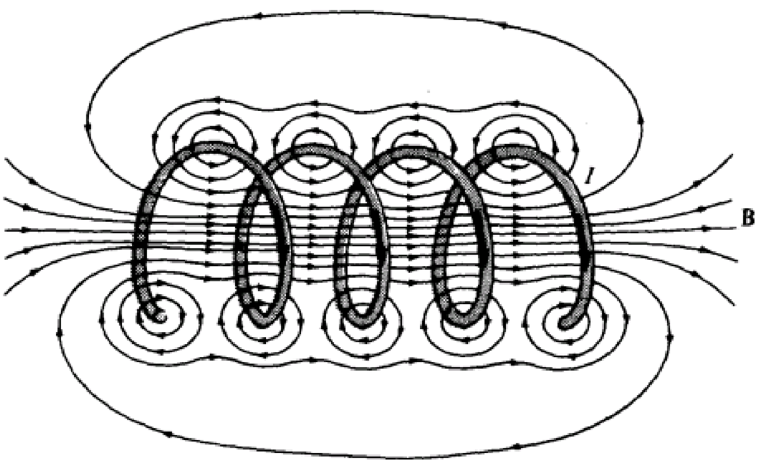
In the vicinity of permanent magnets and electric current conductors, that is to say near moving electric charges, space is modified by a magnetic induction field. Symbol of the quantity: B Symbol of the unit: T tesla

An induction of 1 tesla corresponds to a magnetic flux of weber for a surface of 1 [m^2] Once again, induction can only be demonstrated by its effects.

Average values of the magnetic induction field B			
Earth	$0.3\mu T$	electromagnet	0.1 to > $1T$
Sun	$5mT$	Magnet to Superconductor	➢ 10

To describe the properties of space, it is necessary to give a vector character to the quantity B. The electromagnetic force F exerted on electric charges can be characterized by a vector representing a set of elementary electromagnetic forces.

A coil of great length and having a large number of contiguous circular turns is called a solenoid. When an electric current passes through this coil, an induction B is produced. The magnetic field inside the solenoid is almost uniform, which is an advantage



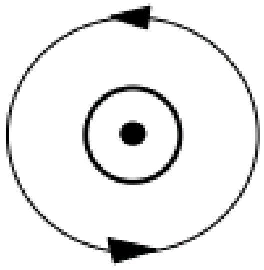
1.19. Properties of the induction field B

As soon as a current passes through a conductor, magnetic lines of force are established around it. The DIRECTION of the induction lines can be defined as circular relative to the conductor through which the current I flows. The DIRECTION of the lines of force is defined by several rules. That of the right hand, the corkscrew, or that of the screw.

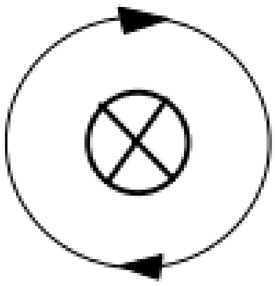
In the drawings we will always find the current in the conductors represented in the same way. It relates to the screw rule. When the current enters the conductor, we see the head of the screw, so we will draw a cross. When the current leaves the conductor, we will see the tip of the screw and we will draw a point.

The point indicatesthat the current flows out of the conductor.

The arrow gives the direction of the lines of force



The cross indicatesthat the current enters in the driver. The arrow gives the sense of lines of force



Chapter 02 : Ferromagnetic materials

2.1. Introduction

Ferromagnetic media are widely used in industry: electrical machines, transformers, but also in spin microelectronics (hard disks). Here we are considering the notion of magnetization of a magnetic medium, a new source of the magnetic field, which requires adding a term to the Maxwell-Ampère equation. We then define the magnetic excitation, directly linked to the free electric current, a quantity that can be controlled by the experimenter. Ferromagnets are non-linear media and the curve connecting the magnetic field to the magnetic excitation has a hysteresis cycle. For most of the applications that we will study, where we want to minimize the energy losses associated with the hysteresis phenomenon, we will prefer narrow-cycle, quasi-linear ferromagnets: soft ferromagnets.

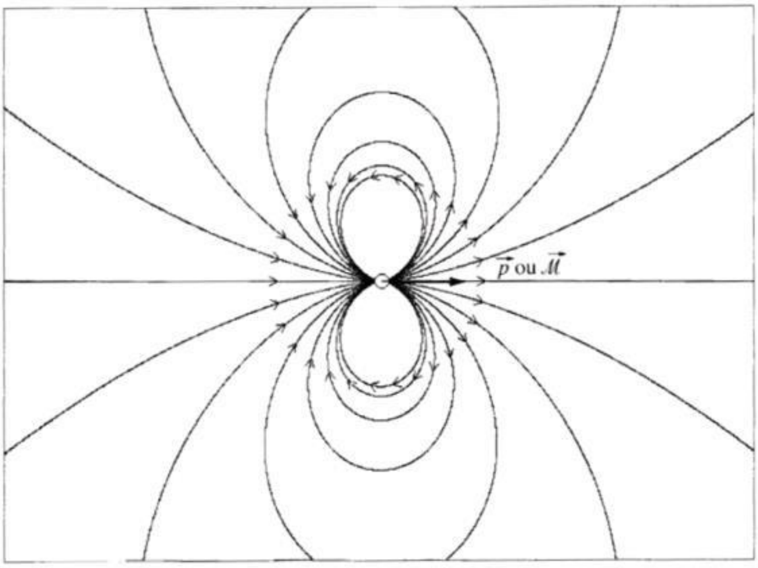
2.2. Description of the field created and the actions undergone by a magnet

2.2.1. Map of the magnetic field created by a magnet

A magnet is similar to a magnetic dipole, characterized by its magnetic moment . A magnetic moment creates a magnetic field, for which an approximate expression can be given at any point sufficiently far from the magnet. For a point identified by the spherical coordinates , the axis being chosen according to , the expression below is only valid for r 'large enough' (large compared to the size of the magnet for example):$\vec{M}(r,\theta,\varphi)\vec{u}_z\vec{M}$

$$\vec{B} = \frac{u_0}{4\pi r^3}\begin{bmatrix} 2M\cos\theta \\ M\sin\theta \\ 0 \end{bmatrix}$$

This expression is allowed and does not need to be memorized. The program states that one should be able to draw the field map from this formula, given the formula. Note that the field decreases rapidly with distance.



2.3. Actions undergone by a magnet in an external magnetic field

Here we consider a magnetic dipole (magnet for example) subjected to a magnetic field created by an unspecified external device. We will not confuse the external magnetic field with that created by the dipole, the latter not being involved here.$\vec{B}_{ext}$

In any external magnetostatic field:$\vec{B}_{ext}$

The torque exerted on the dipole tends to align the dipole in the same direction and sense as:$\vec{B}_{ext}$

$$\vec{T} = \vec{M}\Delta\vec{B}_{ext}$$

The potential energy of the dipole subjected to the external field is written:E_{pmag}

$$E_{pmag} = -\vec{M}.\vec{B}_{ext}$$

If is non-uniform, the dipole is also subject to a force:$\vec{B}_{ext}$

$\vec{F} = -\overrightarrow{grad}\left(E_{pmag}\right) = \overrightarrow{grad}(\vec{M}.\vec{B}_{ext})$

A magnet placed in a non-uniform field rotates to become colinear with the external field, then moves toward areas of strong field.$\vec{B}_{ext}$

2.4. Properties of ferromagnetic media

2.4.1. Magnetization of a magnetic medium

Under the effect of a magnetic field, certain bodies can acquire and maintain a significant magnetization, called induced; they remain sources of magnetic field even in the absence of electric current: they are called ferromagnetic. Examples: iron, Ni, Co and some of their oxides.

In 1821, Ampère suggested that the magnetic fields created by material media originated from small elementary current loops, on a microscopic scale, similar to magnetic dipoles. There are indeed at the atomic scale magnetic moments due on the one hand to the movement of electrons (orbital magnetic moments) and on the other hand to their spin (spin magnetic moments). It is mainly the latter which are at the origin of ferromagnetism. It should be noted that the existence of a permanent magnet cannot therefore be understood without quantum physics (the notion of spin is purely quantum).

2.4.2. Definition of magnetization

Let the magnetic moment of a small volume of matter be:$d\vec{M}\, d\tau$

$$d\vec{M} = \vec{M}\, d\tau$$

The power supply is therefore the volume density of magnetic moment.$\vec{M}$

2.4.3. MA equation in magnetic media

The modeling proposed by Ampère stipulates the existence of internal currents in matter, at the origin of microscopic magnetic moments, whose magnetization is the density at the mesoscopic scale. This is a natural idea within the framework of the planetary model of the atom, the electrons orbiting the nucleus appearing as currents linked to the atom. This term is chosen in opposition to free currents, created by the movement of free charge carriers.

In the context of this model, it is therefore necessary to add a term to the Maxwell-Ampère equation. This is naturally the only Maxwell equation that needs to be modified. By referring to the definition of the magnetic moment of a current loop and thanks to Stokes' Theorem, it can be shown that these linked currents can be expressed as a function of the magnetization by the expression:$\vec{J}_{lie}$

$$\vec{J}_{lie} = \overrightarrow{rot}\,(\vec{M})$$

These bound currents are not controllable by the experimenter. The free currents are. Thus it is interesting to reformulate the MA equation by leaving as a source term on the right of the equality only the term of the free currents.

2.4.4. Definition of magnetic excitation$\vec{H}$

$$\vec{H} = \frac{\vec{B}}{u_0} - \vec{M}$$

2.4.5. Maxwell-Ampère in a magnetic medium

$$\overrightarrow{rot}\,(\overrightarrow{H}) = \vec{J}_{libre}$$

$$\oint \vec{H}\,.\,\overrightarrow{dl} = I_{libre\ enlacés}$$

Remarks :

- In this version of MA and Ampere's Theorem, the constant u0 does not appear
- Another vocabulary can be used in magnetic media and are then respectively called induction field and magnetic field…$\vec{B}\vec{H}$
- Free currents are the source of magnetic excitation$\vec{H}$
- Free currents and magnetization are the two sources of the magnetic field$\vec{B}$

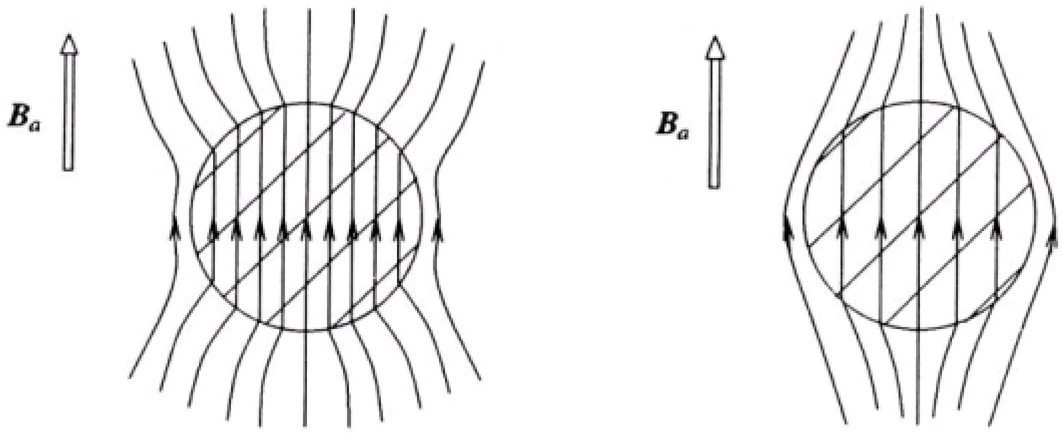
The experimenter generally controls the free currents, therefore the field. This is why this field is used to excite the magnetic material. It is this excitation which fixes the magnetization of the material, therefore the magnetic field inside the material.$\vec{H}$

2.5. Different types of magnetic media

For most crystalline substances, the magnetization is weak. We distinguish:

- paramagnetic bodies: and are of the same direction, so the response of the material adds to the excitation to give a magnetic field greater than that which would have been created by the free currents alone (Al, Ca, O2, etc.). In the left figure below, the magnetic field lines clearly show that the field is greater in the material than in the outside air.$\vec{M}$ $\vec{H}$

- diamagnetic bodies: and are in opposite directions, so the response of the material moderates the excitation to give a magnetic field lower than that which would have been created by free currents alone (Cu, Pb, Ag, water, etc.). In the figure on the right below, the magnetic field lines clearly show that the field is weaker in the material than in the outside air.$\vec{\mathrm{M}}$ $\vec{\mathrm{H}}$



On the contrary, a certain number of materials have a strong magnetization. Ferromagnetic materials are among them (Ex simple bodies: Fe, Ni, Co) (Ex composite bodies: CrO_2) (Ex alloys: AlNiCo, TiCoNAl). They have a behavior similar to paramagnetic materials: their induced magnetization tends to align in the same direction as the excitation to give a magnetic field greater than that which would be obtained in a vacuum. There are other types of magnetic media: antiferromagnetic, ferrimagnetic, etc. The French physicist Louis Néel was awarded the Nobel Prize in Physics for his studies in this field (1970).

Ferrimagnetism: for high frequency transformers, eddy current losses, proportional to the square of the frequency, are predominant: ferrites are then used because they are insulating.

Ferrites are compounds with the formula MO,Fe_2O_3, where M is a divalent metal (Mg, Fe, Co...). They are not ferromagnets but ferrimagnets: the macroscopic properties are similar; their hysteresis cycles are practically square, which is why they have long been used as bistables in computer memories.

2.6. Magnetization curve – Hysteresis cycle of a ferromagnet

Ferromagnetic media are nonlinear: there is no simple relationship between excitation and response. The behavior of a ferromagnet is described by its magnetization curve: or .$M = f(H)$ $B = f(H)$.

Subsequently, the scalar fields denoted M, H, B are the projections of the vector fields according to the direction of the excitation. The latter being fixed by the experimenter, its direction is generally known.$\vec{H}$

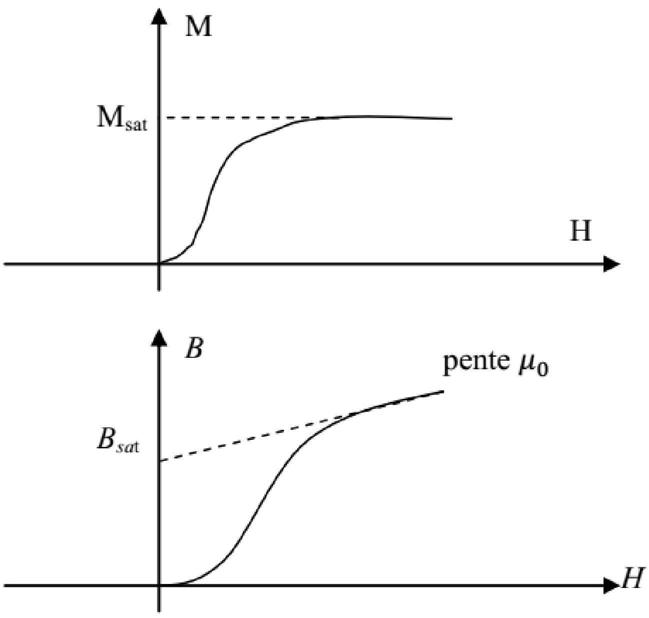
2.6.1. First magnetization curve

If a ferromagnetic material that has never been magnetized is excited, the resulting M(H) curve is called the first magnetization curve. As H increases, M tends toward a limit called saturation magnetization.M_{sat}

Likewise the first magnetization curve giving .$B(H) = u_0(H + M(H))$

At the following pace:

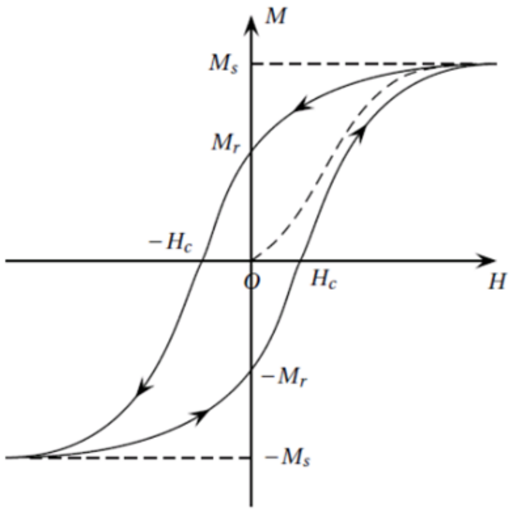
Order of magnitude, It depends on the material.$B_{sat} = u_0 M_{sat} = 1.5$ T



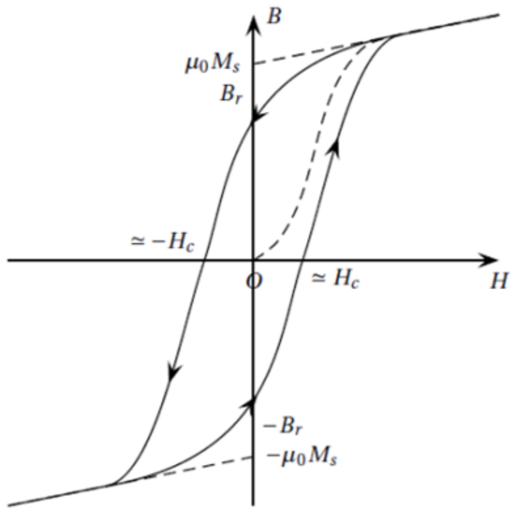
- ***Hysteresis cycle***

After having magnetized a magnetic material, we note that if H decreases, M does not return to the values obtained at the first magnetization: there is hysteresis.

By continuing the variations of H, we finally obtain a symmetrical cycle called the hysteresis cycle M(H). The curve B(H) also presents a hysteresis cycle which can of course be deduced from that of M(H).



cycle in magnetization M(H)



cycle in magnetic field B(H)

When H is zero, M keeps a non-zero value Mr: Mr is the remanent magnetization. This explains why a piece of iron subjected to magnetic excitation (free currents, or external magnet) remains magnetized after the excitation is removed. The corresponding field B is the remanent field. A permanent magnet has then been produced. $B_r = u_0 . M_r$

2.7. Applications

 soft ferro: power conversion (transformers, high inductance coil) because we will see that the hysteresis phenomenon is the cause of energy losses, all the lower as the cycle is narrow.

 hard ferro: permanent magnets because their high coercive excitation makes them insensitive to external magnetic disturbances which could demagnetize them.

2.7. Soft ferromagnets – Relative permeability

Ferromagnets used in industry generally have a cycle narrow enough to be assimilated to a straight line outside the saturation zone.

Linear approximation of soft ferromagnets

A proportionality relationship between and allows us to define the absolute permeability μ of the material:$\vec{B}$ $\vec{H}$$\vec{\boldsymbol{B}} = \boldsymbol{\mu}\vec{\boldsymbol{H}}$

To compare it to the permeability of a vacuum, we jointly define the relative permeability by:μ_r μ_r $\frac{\mu}{\mu_0}$

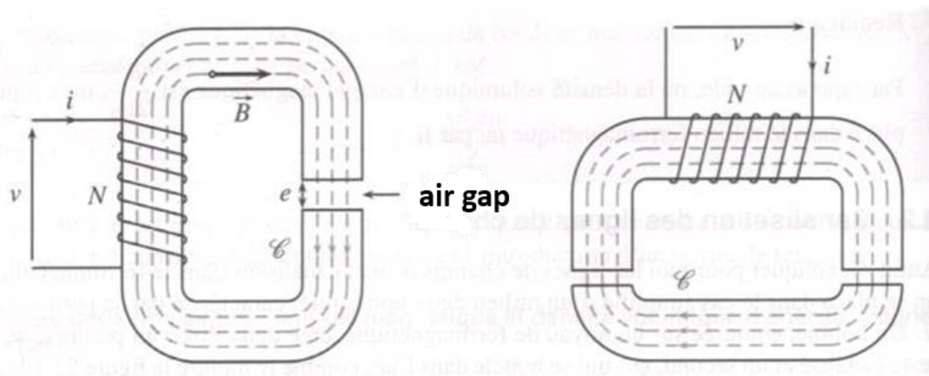
It can be interpreted as a factor of amplification of the field due to the presence of the ferromagnet.$\vec{B}$

Orders of magnitude: relative permeability varies from approximately 100 to 106.

When μr, it can be considered infinite in calculations. The ferromagnetic material is said to be perfect.

2.8. Examples of use of ferromagnets

2.8.1. Study of the electromagnet



Electromagnets: single on the left, lifting on the right

An electromagnet is a device consisting of a coil surrounding a quasi-closed "magnetic circuit" with one or more air gaps. The aim is to create a strong magnetic field at the air gap.

If part of the magnetic circuit is movable (on one side of the air gap) the electromagnet can then be used to generate a magnetic force.

2.8.2. Field lines in the presence of a ferromagnetic material

Magnetic field lines are channeled along magnetic materials. When a field line exits a ferromagnet into air, it exits orthogonally to the interface.

We admit these two properties:

The first statement can be made by analogy with electrokinetics: the current flows through the areas of the circuit with the greatest conductivity. Here the magnetic field lines flow through the areas of space with the greatest permeability.

The second statement can be demonstrated from the magnetic passage relations. They are obviously modified in the presence of a ferromagnet since these replace MA in the case of a surface current modeling, and MA is modified in the presence of a ferro. The new passage relations are to be written with H and without . In short, it can be demonstrated that the field lines undergo at the interface between two linear magnetic media a sort of "refraction" mathematically similar to Descartes' laws, by replacing the index by the relative permeability. Those of the ferros being very large compared to 1, we understand that the field lines exit orthogonally at the interface whatever their orientation in the ferro.$\mu 0$

2.8.3. Energy losses in a core coil

Energy losses that occur inside a ferromagnetic material are called "iron losses".

They appear when the medium is subjected to a time-dependent excitation.

There are two distinct phenomena that cause these losses:

- hysteresis losses: generated by the irreversible displacement of the Bloch walls
- eddy current losses: Joule losses associated with currents induced in the ferro.

Eddy current losses are proportional:

- Squared frequencyf^2
- Squared as the amplitude of the magnetic field.B^2

- Squared by the section of the conductor S4 (power 4 of the radius a4 if circular section) It has been shown that these losses can be minimized by laminating the material. Alloys can also be produced that reduce the conductivity while maintaining a high relative permeability.

2.9. Other applications

A computer hard drive consists of several aluminum or glass disks covered with a layer of ferromagnetic material on both sides. This ferromagnetic layer is protected by a thin layer of carbon.

Two reading heads are used to read the information recorded on both sides of each disk. These heads move at a distance of about 10 nm from the surface. Their position is controlled with a precision of the order of a few micrometers. A head makes about 50 round trips between the center and the periphery of the platter in one second.

The writing head consists of a coil that creates a magnetic field in the ferromagnetic layer of the disk. This field is greater than the coercive field of the material: it therefore allows the material to be permanently magnetized. Magnetization in one direction codes "0", magnetization in the other direction codes "1": this technique therefore allows any message to be recorded in binary.

The reading head is made of a material with a characteristic discovered in 1988 by Albert Fert (Nobel Prize in 2007): giant magnetoresistance. The resistance of these materials varies greatly when they are immersed in a magnetic field (the resistance is sensitive to the orientation of the electron spin). This effect makes it possible to read the direction of the magnetic field created by the disk. The shield makes it possible to attenuate, in the vicinity of the reading head, the magnetic field created by the area adjacent to the one being read.

Spintronics studies spin transport in circuits, just as electronics studies charge transport in circuits. Since the main manifestation of electron spin is the associated magnetic moment, it will come as no surprise that spintronics uses the properties of magnetic materials to interact with electrons via their spin.

Chapter 03: Dielectric materials

3.1. Introduction:

According to the energy band model, when the conduction and valence bands are separated by an energy greater than$5ev$ in the atoms of a material, it becomes a poor conductor of electricity, thus the material is dielectric or insulator.

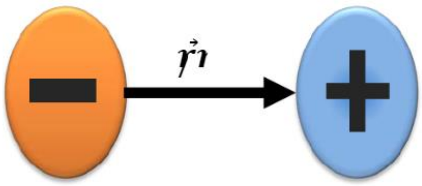
A medium is dielectric (a word composed of the prefix dia (through) and electric) if it does not contain any electrical charges capable of moving macroscopically. The medium cannot therefore conduct electric current, and by definition is an electrical insulator. Some examples of dielectric media: vacuum, glass, dry wood, many plastics, etc.

3.2. Physics and characteristics of dielectrics

Despite the impossibility of dielectric media to conduct current, they have many electrical characteristics. Indeed, and under the effect of an external electric field, a very small displacement of negative and positive charges occurs. The electrons present in a dielectric medium cannot, by definition, move over large distances. On the other hand, they can present movements of very small amplitude on a macroscopic scale which can attribute to the dielectric different characteristics such as: The phenomenon of polarization, Electrical susceptibility, Dielectric permittivity, Dielectric rigidity, etc.

2.2.1. Electrostatic dipole

An electrostatic dipole results from a distribution of distinct electric charges, such that the barycenter of the positive charges does not coincide with that of the negative charges. The simplest dipole consists of a pair of opposite charges +q and −q distant from$|\vec{r}|$



To quantify this phenomenon, a physical quantity called dipole moment is introduced. The dipole moment vector is given by:

$$\vec{M}_p = q.\vec{r}$$

The SI unit used is coulomb-meter (Cm). Sometimes, the debye (D) is used: 1D=3.336 10-30 Cm. In materials, we can distinguish three types of dipoles.

2.2.1.1. Permanent dipole

In chemistry, a permanent dipole results from an asymmetry in the distribution of electronic charges within a molecule. In the case of a linear molecule, the permanent dipole results from the difference in electronegativity between the atoms, which leads to the appearance of a negative pole on the most electronegative atom and a positive pole, equal in absolute value, on the least electronegative atom. Examples include: HCl, H2O, NH3, CO, etc.

2.2.1.2. Induced Dipole

This dipole results from the deformation of an electron cloud (originally neutral) of an atom under the action of an external electric field. Indeed, the positive charges will move in the direct direction of the field, while the negative charges will move in the opposite direction of the field.

2.2.1.3. Instantaneous dipole

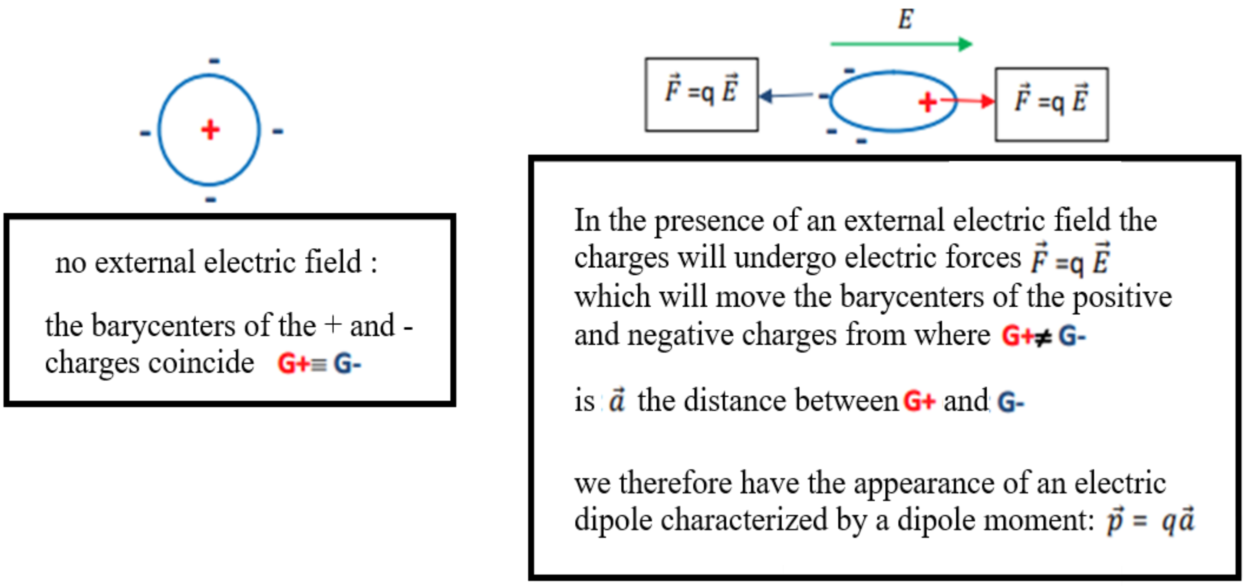
Resulting from an asymmetrical distribution of the valence electrons of an atom for a short instant.

2.2.1.4. Electric field of a dipole

In an electrostatic dipole, the field lines start from the positive charges and go either to a negative charge or to infinity. Near a point charge, the field lines are radial, almost identical to those of a single charge. An electrostatic field line is never closed on itself.

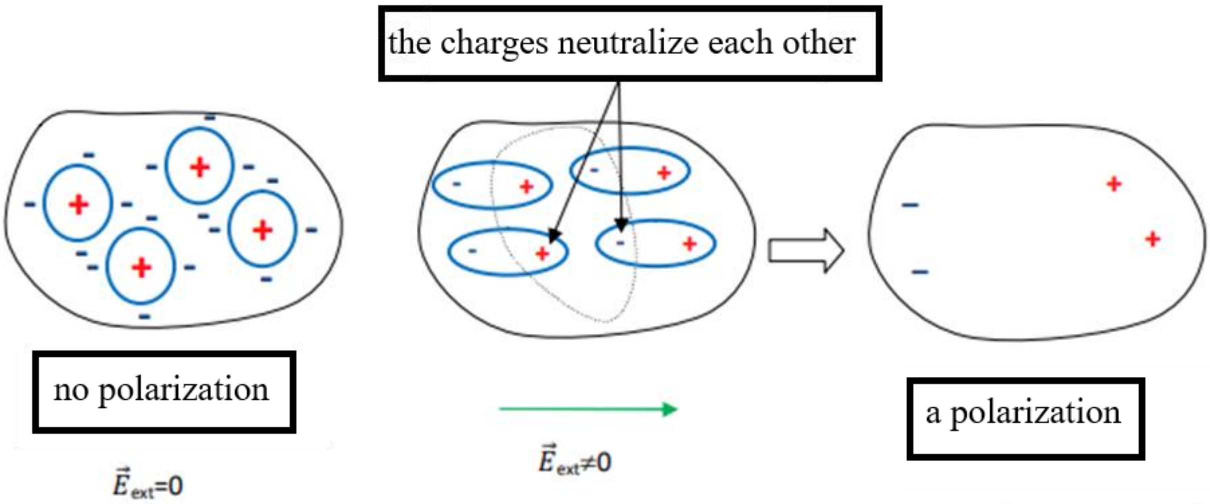
3.2.2. Polarization in dielectric media

3.2.2.1. Atomic polarization



3.2.2.2. Macroscopic polarization

Let us examine a set of atoms or molecules in a dielectric (electrically neutral) in the absence and then in the presence of an electric field. $\vec{E}$



Polarization is proportional to the field that created it. It is noted and is defined as being the dipole moment per unit volume: $\vec{P}$

$$\vec{\mathbf{P}} = \frac{\mathbf{d}\vec{\mathbf{p}}}{\mathbf{d\tau}}$$

3.2.3. Electrical susceptibility:

Electric susceptibility is a quantity characterizing the polarization created by an electric field. This phenomenon occurs only through a material medium (often a dielectric material). Electric susceptibility () is a dimensionless complex number. To calculate electric susceptibility, the types of polarization must be taken into account:γ

- Electronic polarization, always present, due to the displacement and deformation of the electronic cloud.
- Atomic or ionic polarization due to the movement of atoms or ions in the structure of the material.
- Macroscopic polarization due to charge displacements throughout the material.

In most cases, several of these phenomena are present and cumulative. The main difficulty in the calculation lies in the fact that the macroscopic electric field in which the material is immersed is often different from the local electric field which actually acts on the microscopic constituents and therefore creates the polarization.

3.2.4. The dielectric constant

The dielectric constant or electric constant, also called vacuum permittivity or vacuum dielectric permittivity, is a physical constant. It is denoted by:$\varepsilon_0 \varepsilon_0 = \frac{1}{\mu_{0.}C^2}$

With :

$\mu_{0.}$: the magnetic constant.

C: the speed of light in a vacuum.

In the SI unit system, the dielectric constant has a well-defined value which is:$\varepsilon_0 = 8.854187817\,.\,10^{12}\ Fm^{-1}$

The dielectric constant is defined as the ratio between the permittivity of the material considered and that of vacuum. The dielectric constant describes the response of a given medium to an electric field. The dielectric constant (ε) can be seen as the intrinsic permittivity of vacuum. For a given material of permittivity ($\varepsilon 0$), it is possible to define the relative permittivity (ε_r), normalized with respect to that of vacuum. This value has no unit and is always greater than 1.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

3.2.5. Dielectric Strength

The dielectric strength of an insulating medium represents the maximum value of the electric field that the medium can withstand before the triggering of an electric arc (therefore a short circuit). We also use the expression disruptive field. The maximum value of the electric voltage applied to the terminals is called the breakdown voltage of the capacitor. If the electric field exceeds the dielectric strength of the material, we speak of breakdown, and the material can see its physical properties modified, sometimes reversibly, and sometimes irreversibly. In the case of a gaseous insulator, the dielectric strength depends on the pressure of the gas. The rigidity of a material is evaluated inMV/m

Material	dielectric strength (MV/m)
Air	3
Quartz	8
Strontium titanate	8
Neoprene	12
Nylon	14
Pyrex	14
Silicon buile	15

Chapter 04: Conductor and superconductor materials

Part 1: Conductor materials

4.1.1. Introduction

An electrical conductor is a medium in which electrical charges are free to move. These charges are electrons or ions. Metals, electrolytes, and plasmas (ionized gases) are conductive media.

4.1.2. Conductor in a static electric field

Let us place a piece of metal in a static electric field. Inside the metal, the conduction electrons, which are free to move throughout the volume, are subjected to a force that sets them in motion. The electrons are stopped when they reach the walls of the metal and accumulate there. Their accumulation creates an electric field that adds to the external field. After this transient phase, a state of equilibrium is reached.

At equilibrium, the electrons inside the conductor are immobile. This means that the electric field to which they are subjected is zero. The electric field is zero inside a conducting medium at equilibrium. We immediately deduce from Gauss's theorem that the total charge density is zero: the volumetric charge density is zero inside a conducting medium. In a metal for example, the negative charge density due to the electrons therefore exactly compensates for the positive charge density due to the nuclei.

Since the electric field outside the conductor is not zero, there is a discontinuity in the electric field at the surface of the conductor. Some of the charges have accumulated on the surface. The field created by this surface charge density inside the conductor exactly compensates for the external electric field.

When the external electric field is changed, the charges move so that the electric field remains zero inside. If the change is slow, the electric currents are surface currents.

4.1.3. Conductors in a changing electric field

When the electric field changes, the equilibrium cannot be instantaneous because the electric charges must start moving. Two phenomena then intervene: the inertia of the charges causes a delay in the response, the collisions of the carriers cause dissipation. Before studying real conductors, we will consider a model situation where these two phenomena are absent.

In this idealized situation, we will consider that there is no dissipation and that the response is instantaneous. We will then speak of a perfect conductor or an ideal conductor.

4.1.4. From the perfect driver to real drivers

The perfect conductor is an idealization of real conductors. The study of real conductors will make it possible to determine the parameter domains in which they can be considered ideal. Superconducting media where dissipation is perfectly zero are also a very good example of what an ideal conductor can be (it should be noted, however, that only dissipation is absent from these media: the electrons retain their inertia).

4.1.4. 1. The perfect driver

A perfect conductor behaves in dynamic mode in the same way as a conductor in static mode. For a perfect conductor, the internal electric field is zero:$\vec{E}_{int}$ $\vec{E}_{int}\,(\vec{r},t) = 0$

We deduce from the Maxwell-Gauss equation that the volume charge density is zero:

$$\rho_{int}\,(\vec{r},t) = \varepsilon_0\, div\, \vec{E}_{int} = 0$$

Therefore, only the surface charge density can be different from zero. The Maxwell-Faraday equation allows us to conclude that inside a perfect conductor the magnetic field cannot depend on time:

$$\frac{\partial \vec{B}}{\partial t} = -\overrightarrow{rot}\,\vec{E} = 0$$

In a perfect conductor the magnetic field is necessarily static. Note that in superconductors, the magnetic field is zero (Meissner effect: when a conductor passes from the normal state to the superconducting state, the magnetic field lines are expelled so that the magnetic field becomes zero inside the superconductor).

We then deduce from the Maxwell-Ampère equation that electric currents are necessarily stationary, that is to say independent of time:

$$\vec{J} = \frac{1}{u_0}\,\overrightarrow{rot}\vec{B} \;-\; \varepsilon_0\,\frac{\partial\vec{E}}{\partial t} = \frac{1}{u_0}\,\overrightarrow{rot}\vec{B}$$

The only currents that can depend on time are surface currents.

4.1.4. 2. Reflection on a perfect conductor

What happens when an electromagnetic wave hits a perfect conductor? This wave sets the charges on the surface of the conductor in motion. Inside the conductor, the electric field and the magnetic field remain zero. The electromagnetic field emitted by the charges moving on the surface of the conductor exactly compensates for the incident field inside the conductor: the surface emits a wave of the same amplitude as the incident field and in phase opposition. If the surface is a plane, we deduce by symmetry that the field emitted by these charges moving towards the outside of the conductor is the symmetrical of the field it emits towards the inside. We find what we expect from a mirror, with the additional fact that the reflected field undergoes a phase shift of π relative to the incident field.

4.1.5. Real Driver Models

The study of media is not a "principles" theory like electromagnetism in a vacuum. For electromagnetism in a vacuum, it is sufficient to take as postulates the four Maxwell equations, the expression of the Lorentz force and the fundamental relation of dynamics. Everything else is constructed from these equations and deduced by logical reasoning.

For media, we do not have a system of equations that could be considered as postulates. The most precise theories available are extremely complex and use quantum theory. Our goal here is rather to study large classes of generic behavior, particularly in limiting cases. For this, materials will be described on the one hand at the macroscopic level by “equations of state” (also called constitutive relations), i.e. coefficients such as electrical conductivity, permittivity, etc. We also have microscopic models that we call phenomenological because certain aspects are not deduced from first principles but added “by hand” so that the behavior obtained mimics as closely as possible the behavior observed in real materials. In addition to their predictive aspect, these models have the great interest of feeding physical intuition. However, we must remain vigilant and not necessarily take them literally. It should also be noted that while some of the justifications sometimes given for these models seem simplistic, there are very often very profound reasons for their effectiveness.

4.1.5.1. The damped electron

In the proposed model, electrons are considered to be responsible for the conduction of the medium. A free electron of mass me and electric charge q= -e obeys the following evolution equation:$m_e \frac{d\vec{v}}{dt} = \vec{F}_L - T_{\vec{v}}$

The first term, is the Lorentz force:$\vec{F}_L$

$$\vec{F}_L = q(\vec{E} + \vec{v} * \vec{B})$$

In the following, when the electric field and the magnetic field both come from the same electromagnetic wave, we will generally neglect the term due to the magnetic field, which is lower than that of the electric field by a factor , which is very small as long as the speeds are not relativistic. Be careful, when we are in the presence of an electromagnetic wave and a static magnetic field, only the magnetic field coming from the wave can be neglected, because it alone is proportional to the electric field. The static field can lead to a force comparable to that of the electric field of the wave even if the speeds are not relativistic. $\frac{v}{c}$

The second term is a viscous friction force added for phenomenological reasons. It accounts for the dissipative mechanisms present in the medium.$T_{\vec{v}}$

The friction coefficient cannot generally be calculated from first principles (Maxwell's equations, quantum mechanics, etc.); its value is generally obtained by relating it to the macroscopic parameters of the medium. In a plasma, friction is due to collisions of electrons with ions and with molecules that have remained neutral. In a metal, it is the interaction between electrons and mechanical vibrations of the crystal lattice.

In a static electric field the equation of evolution of the electron has the solution:$\vec{E}_0$

$$\vec{v}\,(t) = \vec{v}_0\, e^{t/\tau} + \left(1 - e^{t/\tau}\right)\frac{q}{T}\vec{E}_0$$

Where is the velocity of the electron at the initial time t =0. The characteristic damping time is $\tau.\vec{v}_0$

$$\tau = \frac{m_e}{T}$$

the initial speed is damped while the speed of the electron tends towards a limiting speed: $\vec{v}_L$

$$\vec{v}_L = \frac{q}{T}\vec{E}_0$$

4.1.5.2. Electrical conductivity

When the volume electron density is Ne, the steady-state current density is: $\vec{J}$

$$\vec{J} = q\, N_e\, \vec{v}_L = \frac{N_e\, e^2}{T}\vec{E}_0$$

This current density is proportional to the electric field: we thus find an ohmic behavior:

$$\vec{J} = \sigma_0 \vec{E}_0$$

corresponding to a conductivity: $\sigma_0 \sigma_0 = \frac{N_e\, e^2}{T}$

For a given medium, we can therefore reexpress the phenomenological friction coefficient Γ using fundamental constants or measured macroscopic quantities:

$$T = \frac{N_e\, e^2}{\sigma_0}$$

We also deduce the characteristic amortization time:

$$\tau^{-1} = \frac{N_e e^2}{\sigma_0 m_e}$$

If the electric field is no longer static but depends on time, as long as the characteristic time of evolution of the electric field is large compared to this damping time, the electrons are permanently at their limiting speed and the conductor is ohmic.

Part 2: Superconductor

4.2.1. Introduction

The Thalys network is about to invade the whole of Europe. It allows you to reach any destination at the dizzying speed of 300 km/h. Did you say dizzying? ... For years, on the other side of the planet, the Japanese have been experimenting with a new railway technology, allowing them to reach speeds of over 600 km/h! These speeds are achieved thanks to the absence of contact between the train and the rails; the train literally flies above the track. The principle behind this technology and many others is called: SUPERCONDUCTIVITY

4.2.2. Electricity: a river of electrons

The universe and its structure are governed by four forces: gravitation, electrostatic forces, and weak and strong interactions. These four forces all arose from a single force some time after the birth of the universe. Electrostatic forces, responsible for the structure of the objects around us, and in particular for the very cohesion of the human body, are at the origin of electricity. Transposed to our daily experience, electricity is an energy vector, that is to say, it carries the energy produced in power plants to the various users.

Electricity, or more precisely electric current, is characterized by two quantities. On the one hand, voltage, which measures the potential difference, represents the electrical imbalance between two points. On the other hand, amperage, which measures the current intensity, refers to the electrical flow induced by the voltage.

4.2.2.1. Resistance: obstacle to electrons

What links voltage (V) and amperage (I) is none other than resistance (R). This link is given by the relation: .$R = \frac{V}{I}$

Resistance indicates how difficult it will be for current to flow through an electrical wire, and more generally through any conductive material. The higher the resistance, the less current there is. Conversely, the lower the resistance, the easier it will flow, and therefore the more current there is.

How does a material prevent current from flowing? Simply by placing many nuclei in the path of the electrons, which then have difficulty moving because they bump into the nuclei. For this reason, it turns out that all materials are at least somewhat resistant (there are always nuclei in the way).

What happens when current passes through a high-resistance material? The electrons have a hard time moving. They keep bumping into the nuclei.

Each of these shocks heats the nucleus and the electron; combined, these shocks cause the material to heat up to more than a thousand degrees. This heat production is in fact energy lost by the electrons.

Ultimately, a toaster or a light bulb is just that: passing current through highly resistant wires. As a result, the wires heat up so much that they start to glow, and the toast is toasted or the room is lit.

When a material is heated, its resistance increases. Conversely, when a material is cooled, its resistance decreases. Why? As we have seen, resistance occurs when nuclei are placed in the path of electrons. On our scale, called the macroscopic scale, what we feel as high temperature (heat) is evidence, on the microscopic scale, of the quantity of movement of atoms, of their vibration.

At high temperatures, the nuclei move strongly relative to each other. This general agitation makes the passage of electrons even more difficult. Conversely, at low temperatures, the nuclei vibrate much less, they are calmer. Electrons carrying electric current therefore have less difficulty passing through the nuclei. In the extreme, if the nuclei are immobile (at a temperature called absolute zero), the resistance is very low (note that it is not zero) and is only linked to the very presence of the nuclei, not to their agitation.

4.2.3. The phenomenon of superconductivity throughout the 20th century

Since electricity has no – or no longer has – any secrets for you, let's get to the heart of the matter. The first episode of this scientific adventure took place in 1911…

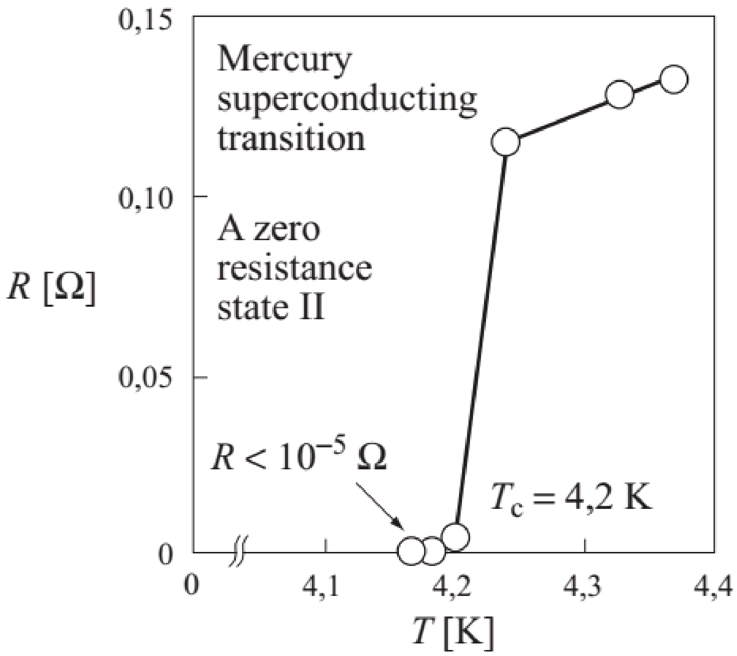
4.2.3.1. A little leap into the past

Theory has always been ahead of practice. Even today, many theories cannot be verified experimentally due to the lack of adequate techniques. Thus, at the beginning of the century, the hypothesis that resistance varies with the temperature of the material was present in the minds of researchers. But how can this phenomenon be verified for very low temperatures when the cooling processes were not efficient?

Before 1900, the lowest temperatures ever reached were still too high to answer this question. It was then that a sophisticated technique was developed that allowed helium to be liquefied. With liquid helium, it was now possible to bring any material to a temperature of –269 °C, very close to absolute zero! Liquid helium would be able to provide an answer to questions about changes in resistance at very low temperatures.

4.2.3.2. The discovery of superconductivity

Very quickly, physicists were experimenting with various materials cooled with liquid helium. In 1911, a Dutch researcher, Heike Kamerlingh Onnes, measured the resistance of mercury at increasingly lower temperatures. He observed that as the temperature dropped, the resistance declined. Up until then, everything was going according to plan. Suddenly, at a certain temperature called the critical temperature, the resistance abruptly dropped to zero, the material no longer offering any resistance to the passage of electric current.



4.1: Historical figure highlighting superconductivity

This unexpected phenomenon was named superconductivity. It indicates that below a critical temperature, electrons move without collisions with nuclei, and therefore without loss of energy.

Very quickly, the same phenomenon was observed for other materials. For each of these, the researchers found a specific critical temperature. Unfortunately, the first materials tested had very low critical temperatures, which made applications difficult to design for several decades. Superconductivity was gradually forgotten by the general public.

In 1987, a discovery made by a team of researchers revived the scientific community's interest in the phenomenon: a superconducting material at -183°C. This temperature can be reached using liquid nitrogen, ten times cheaper and much easier to use than liquid helium. This discovery shook up the scientific and industrial world, which believed that superconductivity was doomed to remain an obscure laboratory subject. It was talked about as a revolution of the same magnitude as that caused by the invention of the transistor. Just a few years later, the critical temperature record was set at -140 degrees. This temperature remains unbeaten to this day.

Today, the search for the highest critical temperature has given way to understanding the phenomenon and the synthesis of new types of superconductors. Progress is being made in a slower and more directed manner. Because while critical temperatures are now easy to reach, superconducting materials are among the most complex materials ever made.

4.2.4. The Bardeen–Cooper Schrieffer theory (BCS)

In the 1950s, three scientists, Bardeen, Cooper and Schrieffer, proposed an explanatory model of superconductivity to which they would give their names. The superconducting materials discovered after the work of the three scientists seemed to be outside the scope of their theory, but it continued to serve as the basis for the explanation of the superconductivity of these new complex materials.

To understand this theory, you just need to remember the two components of an atom, both actors of the electric current: the nuclei and the electrons. The first, the nuclei, are heavy and not very mobile; they are positively charged. We can imagine them as being fixed on a sort of infinite monkey cage, called a network; at each crossing, a nucleus vibrates around its equilibrium position, according to the temperature. The second, the electrons, are much smaller and much more mobile; they are negatively charged. We can imagine them as tiny little balls (1000 times smaller than the nuclei) which move between the nuclei.

When no current passes through the material in question, the electrons move little. There is no overall movement. When current passes, the electrons all start moving in the same direction. There is concerted movement. These electrons, by moving, cause an incalculable number of collisions with the nuclei. This implies a significant loss of energy in the form of heating. However, as we have seen, if the critical temperature of the material is reached, this loss of energy suddenly becomes zero. Why?

Let's imagine a superconducting material subjected to an electric current. Let's carefully observe a given electron. The electron, like all its companions, flies through the meshes of the network. As a reminder, the electron is negatively charged and the network is positively charged; but opposite charges attract each other!

The reasoning is as follows. Our electron passes between four nuclei; these are attracted by the negative charge of the electron. Due to this attraction, the network undergoes a local contraction. This contraction causes the appearance of a local excess of positive charge. This excess creates a small positive zone which attracts another electron. This one joins the first electron and now forms a Cooper pair with it. The first leads the way and the second only has to follow, and so on.

The result is no longer an anarchic flow of electrons advancing blindly, but an ordered current of electrons that literally slip through the meshes of the net, without ever bumping into the nuclei. No shocks, therefore no loss of energy, or even no resistance.

Why does the phenomenon only occur at a very low critical temperature? For electrons to be able to slide between the meshes of the network, the nuclei must still be relatively stable. It is clear that the critical temperature is a threshold: as soon as the nuclei have reached a certain degree of stability, the electrons suddenly switch from a chaotic movement to a perfectly ordered and concerted movement.

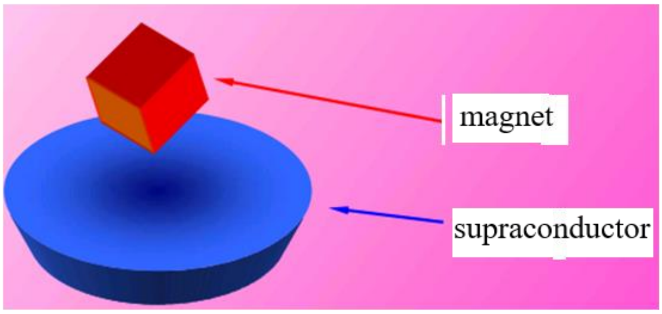
4.2.5. The experience of levitation or a challenge to gravity

The levitation experiment always amuses those who attend it and is also relatively simple to perform… It is undoubtedly thanks to this experiment that superconductivity has enjoyed a certain success with the general public. Indeed, it allows one to visualize at the macroscopic level one of the effects of superconductivity. Let's see that…

Let's take a material that is superconducting (i.e. it will be so below its critical temperature) at room temperature.

Next, let's bring this material below its critical temperature (Tc). It is now superconducting; that is to say, its resistance is annihilated, or the current can pass without hindrance.

Let's bring a small magnet above the superconductor. The magnet begins to levitate, that is, to float a few millimeters above the superconductor.



How does this experiment help us understand superconductivity? Let's start with the situation where the material is at room temperature; it is therefore still only a classical conductor. The magnet, by definition, continuously emits a magnetic field. As it approaches the material, its magnetic field generates a weak electric current within it, in accordance with Lenz's theorem. This electric current is not induced by the magnetic field as such but by the movement of this field. In other words, as soon as the magnet stops, the induced current disappears. Indeed, this current is of much too low intensity to be able to counter the resistance of the material.

Now let's bring the material below its critical temperature (Tc) so that it becomes superconducting. When the magnet stops, it no longer induces current in the material; however, the flow of electrons (or current) induced during the movement of the magnet continues to flow in it since the resistance is reduced to zero.

So far, these phenomena do not yet explain why the magnet levitates. There is only one element missing.

We have seen that a moving magnetic field induces an electric current. The reverse is also true. Indeed, an electric current also induces a magnetic field (you only have to hold a compass close to an electric wire to see this). Therefore, the current induced in the superconductor in turn induces a magnetic field. This is oriented upwards, therefore against the magnet. The opposition of the two magnetic fields (that of the superconductor and that of the magnet) will cause the magnet to levitate.

4.2.6. Superconductivity at the service of man

The applications of superconductivity are increasingly numerous. Medicine has already found several applications for this property. Particle accelerators and energy accumulators in the form of magnetic fields use superconductivity. The future potential of this phenomenon is infinite. Let us think, for example, of computing. The creation of microprocessors whose components would be built from superconducting material would increase the power of computers tenfold. Indeed, without resistance, there is no heating, and without heating, miniaturization – increasingly problematic – could resume with renewed vigor.

Let us recall the trains on magnetic cushions, prototypes of which are already running. The principle is simple: replace the wheels with magnets, and the rails with superconductors. No contact between the train and the rails, therefore no friction. This is why speeds of around 600 km/h can be reached.

Finally, let's not forget the primary advantage of the superconductor: the transport of electricity without energy loss. Today, despite the use of high voltage (100,000 volts) in high-voltage lines, several tens of percent of the energy transported is lost. This loss could be eliminated entirely with superconducting cables. The low critical temperature still remains the major obstacle to the realization of these projects. The day when a material that is superconducting at room temperature is discovered, the technology will undoubtedly experience a new golden age.

4.2.7. Other Important Applications of Superconductor

In Medicine

In the field of medical diagnostics, nuclear magnetic resonance imaging (MRI) consists of using the small magnets that the nuclei of atoms in the human body have to visualize what surrounds them (the brain, muscles, etc.). To do this, these magnets must first be aligned using a magnetic field in which the patient is placed. The larger the field, the better the image.

To produce intense fields, a strong electric current must be passed through a coil of several thousand turns of wire. If metal wires, such as copper, are used, they will heat up so much that they will eventually melt. This is why in all nuclear magnetic resonance imaging (MRI) devices, the coils are made of superconducting wire immersed in a very cold liquid such as helium.

Superconducting coils

Superconducting coils can produce magnetic fields of several teslas (1 tesla is about 10,000 times the Earth's field). They are obtained by using windings of several thousand turns of superconducting wire immersed in liquid helium, often based on alloys of niobium and titanium (NbTi) or niobium and tin (Nb_3Sn). These coils are often called "superconducting magnets" by abuse of language. These high magnetic fields are used for Nuclear Magnetic Resonance in chemistry and physics, in physics laboratories to study the effect of fields on solids and thus explore the magnetic properties of materials.

Electronics and telecommunications

Despite the disadvantage of the necessary low temperatures, the exceptional properties of superconductors make it possible to design high-performance and original electronic circuits. Electronics based on superconducting materials has therefore been developed, using conventional superconductors or superconductors with high critical temperatures. These systems are now reliable, and have left the laboratory setting for use by industrialists. Thus, the most efficient filters available for cell phone relay antennas use superconductors.

Other electronic systems protect circuits from overvoltages, or build ultra-sensitive magnetic field measuring devices. Other developments in superconducting electronics are currently being prepared in laboratories, and may lead to the next technological revolutions. For example, the Josephson junction may replace the silicon-based transistor in our current circuits, allowing computers to reach rates of 100 GHz?

Superconductivity could even be used to build a quantum computer, enabling massively parallel computing, but which currently only exists on paper. Superconducting electronics is therefore a reality today, even if its use remains limited by the temperatures required for its proper functioning.

Transport and storage of electrical energy

However, current electrical cables can only carry limited currents, otherwise they will heat up too much and melt. A network of superconducting cables would solve this problem because 10,000 times more electric current can flow through them: smaller cables for more current. Such a network is not yet cost-effective because the cables must be cooled to become superconductors. However, prototypes of superconducting cuprate cables cooled with liquid nitrogen are beginning to appear, over short distances.

Superconductors are also used as current limiters in power plants, a kind of super-fuse. Finally, superconductors are used for electrical energy storage solutions in devices called SMES. An electric current is stored in a superconducting coil that is closed on itself.

The current remains trapped in the coil indefinitely because there is absolutely no loss of energy, and this current can be recovered at will and above all in a very short time, unlike usual batteries.

Magnetic confinement

Fusion is the energy source of the Sun and other stars. A star begins to shine when the matter in its core reaches, under the effect of gravitational forces, sufficient densities and temperatures to trigger thermonuclear reactions that release energy. The tendency of the plasma to disperse, and therefore to cool, is counterbalanced by the gravitational force. On Earth, gravitational confinement is impossible.

Two ways are being studied to reproduce these reactions. Bring a small volume of matter to very high pressure and high temperature for an extremely short time. This is called inertial confinement. In this way, we seek to obtain the greatest possible number of fusion reactions before the plasma disperses.

Trap and maintain a plasma at very high temperature. This plasma is confined in an immaterial toroidal box created by magnetic fields; this is called magnetic confinement.

In order for the fuel, in the plasma state, to be able to produce sufficient thermonuclear reactions, it must be kept in a limited volume and kept away from any material wall in order to maintain its high temperature: this is confinement.

In a free-flowing plasma, the trajectory of the particles is random and the particles will escape. Since the plasma is formed of charged particles, intense magnetic fields can interact with them. If this same plasma is bathed in a rectilinear magnetic field, the particles wrap around the field lines and can no longer reach the side walls. In order to avoid losses at the ends, the magnetic box is closed by creating a torus. The magnetic field thus created by a series of superconducting magnets surrounding the plasma is called the toroidal magnetic field. The magnets generating this field are toroidal magnets.

Chapter 05: Semiconductor

5.1. Definition:

Semiconductoris therefore a crystalline body whose electrical conductivity properties are intermediate between those of metals and those of insulators. The semiconductor will be an insulating material at 0K but which can lead to temperatures close to room temperature.

5.2. BAND STRUCTURE

A semiconductor is a crystalline solid whose electrical conduction properties are determined by two particular energy bands: on the one hand, the valence band, which corresponds to the electrons involved in covalent bonds; on the other hand, the conduction band, comprising the electrons in an excited state, which can move in the crystal. These two bands are separated by a gap, a forbidden band that the electrons can only cross thanks to an external excitation (for example, the absorption of a photon). The forbidden band corresponds to an energy barrier, the order of magnitude of which is the electron Volt.

5.2.1 GAP:

The gap is by definition the width of the forbidden band, that is to say the difference in energy between the absolute minimum of the conduction band and the absolute maximum of the valence band.

5.2.2 The Fermi level EF:

This is the particular level called the Fermi level. EF corresponds to the average statistical level occupied at thermodynamic equilibrium by all the carriers. It is located approximately in the middle of the forbidden band of the material$E_F = \frac{E_C + E_V}{2}$

6. INTRINSIC SEMICONDUCTOR:

Pure semiconductor, without impurities (undoped). Charge carriers are obtained exclusively following the transitions of electrons from the valence band (BV) to the conduction band (BC) (fig. 1a) thanks to the thermal agitation energy. Each electron that makes a transition from BV to BC leaves a vacant (unoccupied) level in BV. To this vacant level we attribute a fictitious particle of positive charge q0, called a hole. Therefore the electrons of BC and the holes of BV are the charge carriers in an intrinsic semiconductor.

7. EXTRINSIC SEMICONDUCTOR:

It is obtained by doping, that is to say the addition of a very small number of doping atoms in an intrinsic semiconductor.

8. DOPING:

Doping involves introducing impurities into a material (e.g. silicon). The impurities introduced into silicon are of two types:

8.1. Pentavalent n-type extrinsic semiconductor:

Doping atoms have a number of valence electrons greater than the base (> 4 for Si and Ge which have 4 valence electrons). Phosphorus P, arsenic As or antimony Sb atoms, having five valence electrons, are commonly used as dopants in N-type semiconductors. These atoms are called donors because they provide electrons to the conduction band. These electrons represent the majority charge carriers.

The binding energy of the 5th electron is given by the following relation: $E_{lD}=E_C-E_D$

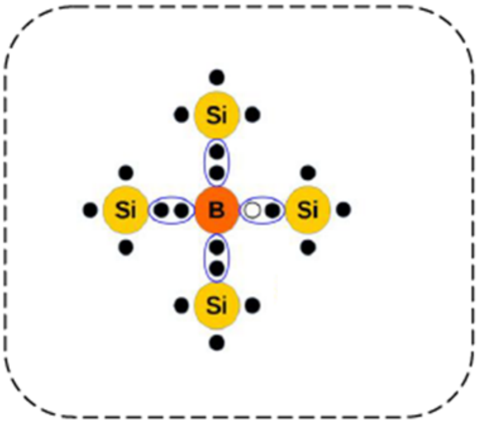
E_D:is the energy of the impurity donor level.

8.2. Extrinsic p-type semiconductor -trivalent-:

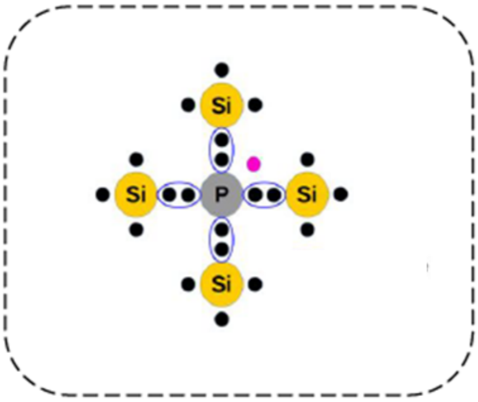
Doping atoms have a lower number of valence electrons than the base (< 4 for Si and Ge). Boron B, aluminum Al, indium In or gallium Ga atoms, having three valence electrons, are commonly used as dopants in P-type semiconductors. These doping atoms are called acceptors here, because they accept electrons from the valence band, creating vacant levels (holes) in the latter. Holes represent the majority charge carriers.

The hole binding energy is given by the following relation:$E_{lA}=E_A-E_V$

E_A:is the energy of the impurity acceptor level.



Semiconductor P-type



Semiconductor N-type

8.3 Position of the Fermi level in a semiconductor material

- The intrinsic Fermi level (corresponding to the intrinsic material), is located approximately in the middle of the material's band gap, theoretically in the middle at T = 0K.

- The Fermi level therefore gradually shifts from the middle of the band gap towards the conduction band when the n-type doping increases as shown in figure.

- In the case of a p-type doped semiconductor, the Fermi level will be found closer to the top of the valence band, the more doped the material is.

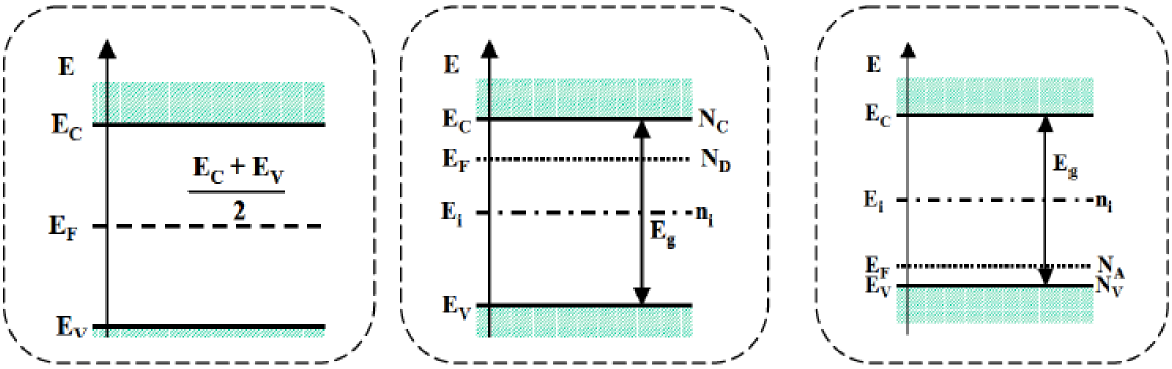


Figure: Position of the Fermi level and corresponding value of the dopant concentration in a semiconductor, at room temperature

8.4 Neutrality equation

Consider a semiconductor containing a donor density ND and an acceptor density NA, then:

N_D^+: is the number of ionized donors

N_A^-: is the numberof acceptorsionized

The total charge of the material is zero (principle of conservation of charges).

$$n + N_A^- = p + N_D^+$$

n and p are the electron and hole densities, respectively. At room temperature, the thermal energy kBT is of the same order of magnitude as the binding energies of the donor electron and the acceptor holes. This means that all donors and acceptors are ionized.

The previous neutrality equation is therefore written as: $? + ?_A = p + N_D$

NHASand NDare the densities of acceptors and donors.

8.4.1 n-type semiconductors:

In an n-type semiconductor, the donor density (ND) is greater than the acceptor density (NA). According to the neutrality equation, the electron density (n) is greater than the hole density (p).

$$N_D > N_A \text{ and } n > p$$

The electrons in this case are called the majority carriers and the holes are minority carriers.

$n + NA = p + N_D$

With: $n.p = n_i^2$

$N_D - N_A n = n^2 - pn$

From where: $n2 - N_D - N_A n - n_i 2 = 0$ The solutions to this equation are:

$n = N_D - N_A + (N_D - N_A {}^2 + 4 n_i 2) p = - N_D - N_A - (N_D - N_A 2 + 4 n_i 2)$

The absolute value gives the hole density.

In practice N_D, N_A and (N_D-N_A) are very high densities, they are higher than ni.

8.4.2 p-type semiconductors:

In this type of semiconductor the acceptor density (N_A) is higher than the donor density (ND). In this case, the majority carriers are holes. The carrier densities are:$N_A > N_D$ And $p > n$

$p \approx N_A - N_D$ and $n \approx n_i 2 (N_A - N_D)$

9. TRANSPORT PHENOMENA IN SEMICONDUCTORS

9.1 Mobility – Conductivity

Generally speaking, when an electric field is applied, there is a tendency to move the charge carriers, electrons and holes. In reality, the physical mechanism of driving by an electric field occurs on carriers that move randomly, in all directions of space, in the material, due to thermal agitation (at normal operating temperatures) and that perform a mean free path without shock.

The electron current density is expressed most simply by:$j\ n = -q\ n < v\ n >$
j_n: Current density generally expressed in Amperes per cm2,
n: Concentration of electrons,
$v\ n$: average speed of electrons, $< v\ n > = -\mu n E$
μn: Electron mobility (cm2/Vs)
So,$jn = -q\ n - \mu n E\ \ jn = qn\mu nE$The expression for the hole current density is then as follows, remembering that the holes move in the same direction as the electric field:$jp = qp\mu pE$

These two current densities are actually drift currents in the electric field. In some works, these current densities are called conduction current. We will see in this chapter that other phenomena allow conduction.
It may be noted that we find Ohm's law,$j = \varsigma . E$for each of the two types of carrier. σ is the conductivity.
We can therefore define a conductivity for electrons (ςn), and a conductivity for holes, (ςp) as follows:$\varsigma n = qn\mu n$And$\varsigma p = qp\mu p\ \ j\ Tot = j\ n + j\ p = qn\mu n + qp\mu p\ E = \varsigma . E$
Since ($\rho = 1\varsigma$), the resistivity of the material is expressed by:$\rho = 1qn\mu n + qp\mu p$

10. HETEROSTRUCTURES

10.1 The PN junction

The PN junction is a basic structure in electronic components. Since the components are made of differently doped semiconductors, PN or NP junctions are present at the interfaces. It is therefore essential to understand the physical phenomena that occur there. The PN junction is also a component in itself. The function of this component is to allow current to flow in one direction only.

10.2 Homojunction and energy band diagram alignment

It results from the juxtaposition in the same semiconductor material of two zones: one of type P and the other of type N. The energy band diagrams of the P–N junction were well understood through work by Shockley and others during the early days
of solid state electronics. The P–N junction can be represented by a conduction band bottom and a valence band top as shown in Figure 1. The Fermi level is close to the threshold of the conduction band and the valence band in the N-doped and P-doped region respectively.

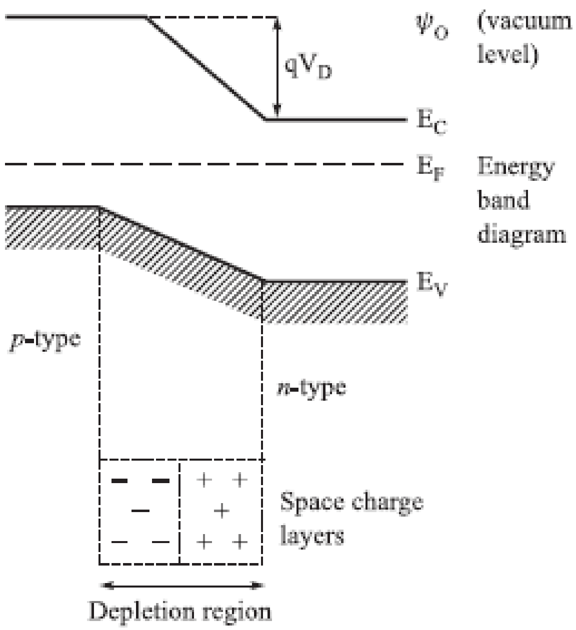


Figure 1:*Energy diagram of a homojunction.*
VD: the height of the barrier. EC: the bottom of the conduction band. EV: the top of the valence band. Ef: Fermi level

10.3 Heterojunction and energy band diagram alignment

It is due to the interface between two different semiconductor materials and is more complicated analogue of the P–N junction between two differently doped regions in the same material (homojunction). Heterojunctions result from the growth of one semiconductor on another. To construct an energy band diagram of a heterojunction, it must be taken into consideration that the band gap changes from one material ($Eg1$) to another material ($Eg2$). Thus, the discontinuities (Offset) $\Delta EV\ \ et\Delta EC$come from the heterojunction and their magnitudes must be found for each particular combination of materials, see Fig.2.

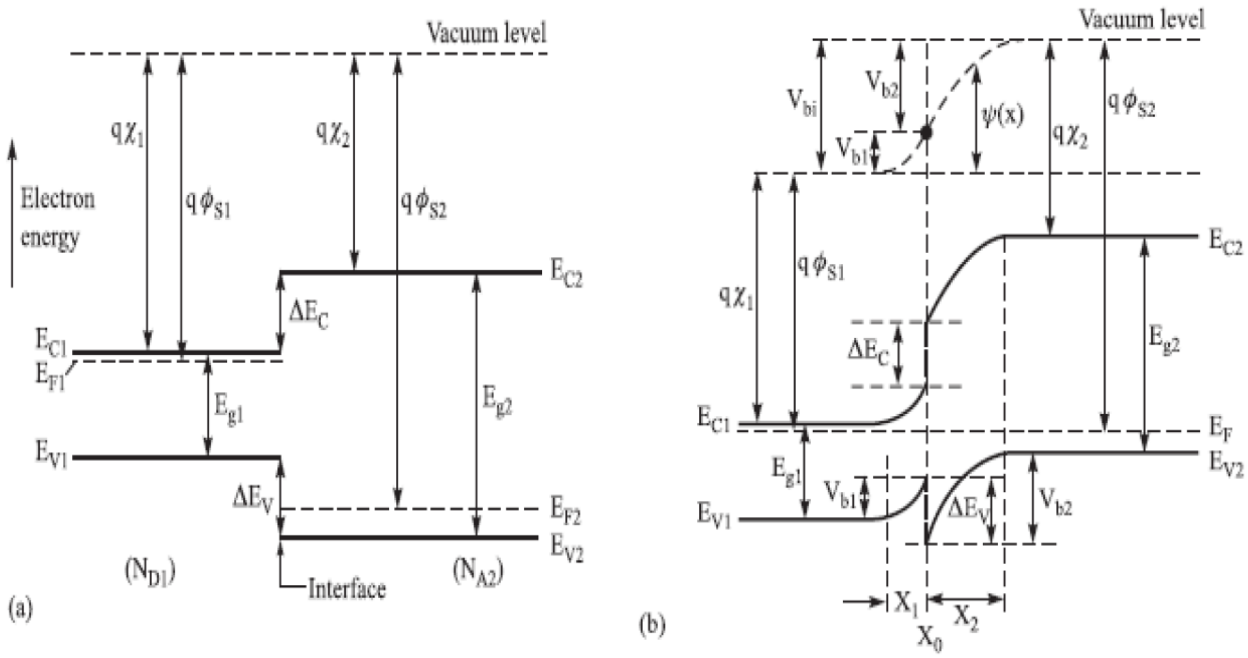


***Figure 2**: a- Band diagrams of semiconductors S1 and S2 before contact, S1 is an S/C with gap Eg1 and donor type so its Fermi level Ef1 is close to Ec1 while S2 is an S/C with gap Eg2 and acceptor type so its level Ef2 is close to Ev2, b- band diagrams of semiconductors S1 and S2 after contact.*

11. POWER SEMICONDUCTORS

Three types of power semiconductors are used:

- uncontrolled semiconductors:
  - →**Power diodes**;
- Controlled semiconductors without blocking command:
  - →**Thyristors**;
  - →**Triacs**;
- controlled semiconductors with blocking control:
  - →**Power bipolar transistors**;
  - →**Power MOSFET transistors**;
  - →**GTO (Gate Turn Off) thyristors**;
  - →**IGBT (Insulated Gate Bipolar Transistor)**.

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