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## ELECTROTECHNICAL MATERIALS SCIENCE

Study guide

5B071800 – “Power engineering” specialty

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## **ELECTROTECHNICAL MATERIALS SCIENCE**

Study guide

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## **Introduction**

Electrotechnical materials are characterized by specific properties with respect to the electromagnetic field and are applied in the technique in view of these properties. Based on their behavior in the electric field materials are divided into the following types: dielectrics or insulating materials; semiconductors; conductors.

Dielectrics are substances with high resistivity. They are used as insulating materials.

Diodes, transistors, thermistors, or other photoconductive semiconductor devices are made of semiconductor materials.

Conducting materials serve as conductors of electrical current. They have a low resistivity. They are used for the production of resistor heating elements, and others.

Magnetic materials have the ability to be magnetized, and some of them retain magnetization in case of absence of the magnetic field. They are used for making cores of inductors and transformers, magnetic systems, electric machines, storage devices, permanent magnets etc.

Theoretical foundation of electrotechnical materials is provided. Characteristics and properties of dielectrics, semiconductors and magnetic materials are described.

Study guide is recommended for bachelors of 'Power engineering' specialty.

## 1 Basic concepts of electricity

The electrons of different types of atoms have different degrees of freedom to move around. In some types of materials, such as metals, the outermost electrons in atoms are so loosely bound that they move chaotically in the space between the atoms of that material by nothing more than the influence of room-temperature heat energy. As these virtually unbound electrons are free to leave their respective atoms and float around in the space between adjacent atoms, they are often called free electrons.

In other types of materials such as glass the atoms' electrons have very little freedom to move around. While external forces such as physical ones as well as can force some of these electrons to leave their respective atoms and transfer to the atoms of another material, they do not move very easily between atoms within that material.

This relative mobility of electrons within a material is known as electric conductivity. Conductivity is determined by the types of atoms in a material (the number of protons in each atom's nucleus, determining its chemical identity) and how the atoms are linked together with one another. Materials with high electron mobility (many free electrons) are called conductors, while materials with low electron mobility (few or no free electrons) are called insulators.

Here are a few common examples of conductors and insulators:

1) Conductors are silver, copper, gold, aluminum, iron, steel, brass, bronze, mercury, graphite, dirty water, concrete.

2) Insulators are glass, rubber, oil, asphalt, fiberglass, porcelain, ceramic, quartz, (dry) cotton, (dry) paper, (dry) wood, plastic, air, diamond, pure water.

It should be understood that not all conductive materials have the same level of conductivity, and not all insulators are equally resistant to electron motion. Electrical conductivity is analogous to the transparency of certain materials to light: materials that "conduct" easily light are called "transparent," while those ones that don't are called "opaque." However, not all transparent materials are equally light conductive. Window glass is better than most plastics, and certainly better than "pure" fiberglass. So it is with electrical conductors, some being better than others.

For instance, silver is the best conductor in the "conductors" list, offering an easier passage for electrons than any other cited material. Dirty water and concrete are also listed as conductors, but these materials are much less conductive than any metal.

It should also be noted that some materials experience changes in their electrical properties under different conditions. Glass, for instance, is a very good insulator at room temperature, but it becomes a conductor when heated to a very high temperature. Gases such as air are normally insulating materials, also become conductive if heated to very high temperatures. Most metals become poorer conductors when heated, and better conductors when cooled. Many conductive materials become perfectly conductive (this is called superconductivity) at extremely low temperatures.

While the normal motion of "free" electrons in a conductor is random, with no particular direction or speed, electrons can be influenced to move in a coordinated

way through a conductive material. This uniform motion of electrons is what we call electricity, or electric current. To be more precise, it could be called dynamic electricity in contrast to static electricity, which is an unmoving accumulation of an electric charge. The motion of electrons through a conductor is often referred to as a “flow.”

As each electron moves uniformly along a conductor, it pushes on the one ahead of it, so that all the electrons move together as a group. Starting and stopping an electron flow along the conductive path is instantaneous from one end of a conductor to the other, even though the motion of each electron may be very slow.

If we want electrons to flow in a certain direction toward a certain place, we should provide the proper path for them to move. To facilitate this, wires are made of highly conductive metals such as copper or aluminum in a wide variety of sizes.

Electrons can flow only when they have the opportunity to move in the space between the atoms of a material. This means that there can be an electric current only where there exists a continuous path of conductive material providing a passage for electrons to travel along. Look at a diagram to illustrate how this works:

A thin, solid line (as shown below) is a conventional symbol for a continuous piece of wire. Since the wire is made of a conductive material, such as copper, its constituent atoms have many free electrons which can easily move along the wire. However, there will never be a continuous or uniform flow of electrons within this wire unless they have a place to come from and a place to go to. Add a hypothetical electron “Source” and “Destination” as shown in figure 1.



Figure 1.1 – The flow of electrons within a wire

Now, with the Electron Source pushing new electrons into the wire on the left-hand side, the electron flow can go along the wire (as indicated by the arrows pointing from left to right). However, the flow will be interrupted if the conductive path formed by the wire is broken (figure 2).

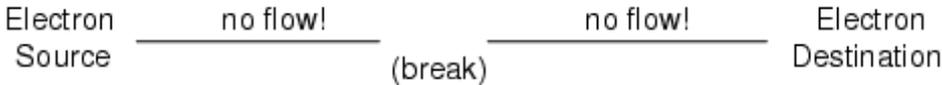


Figure 1.2 – The flow will be interrupted if the conductive path formed by the wire is broken

Since air is an insulating material, and an air gap separates two pieces of wire, the once-continuous path has now been broken, and electrons cannot flow from Source to Destination.

If we were to take another piece of wire leading to the Destination and simply make a physical contact with the wire leading to the Source, we would have a continuous path for electrons to flow. The two dots in the diagram (figure 3) indicate a physical (metal-to-metal) contact between the wire pieces:

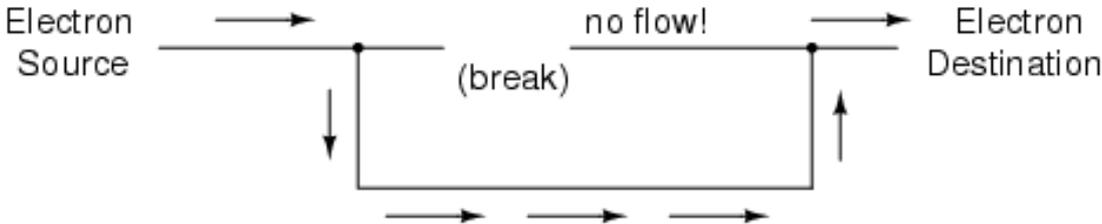


Figure 1.3 – Metal-to-metal contact between the two dots in the diagram

In conclusion:

- 1) In conductive materials, outer electrons in each atom can come easily or go away, and are called free electrons.
- 2) In insulating materials, outer electrons are not so free to move.
- 3) All metals are electrically conductive.
- 4) Dynamic electricity, or electric current, is an uniform motion of electrons through a conductor.
- 5) Static electricity is unmoving (if on an insulator), an accumulated charge formed by either an excess or deficiency of electrons in an object. It is typically formed by charge separation by contact and separation of dissimilar materials.

A continuous unlimited flow of electrons must go along a complete, unbroken path moving both towards and backwards.

## 2 Dielectrics

### 2.1 Macroscopic approach to dielectric materials

A dielectric is characterized by its dielectric constant  $\epsilon$ , which relates the electric flux density to the electric field by the relationship,

$$D = \epsilon \epsilon_0 \mathbf{E} \tag{2.1}$$

In the SI system  $\epsilon$  is the product of  $\epsilon_0$  (permittivity of free space) and  $\epsilon_r$  (relative dielectric constant).

The basic experimental evidence (as discovered by Faraday) comes from the condenser experiment in which the capacitance increases by a factor,  $\epsilon_r$ , when a dielectric is inserted between the condenser plates. It results in the appearance of

charges on the dielectric surface (figure 2.1) necessitating the arrival of fresh charges from the battery to keep the voltage constant.

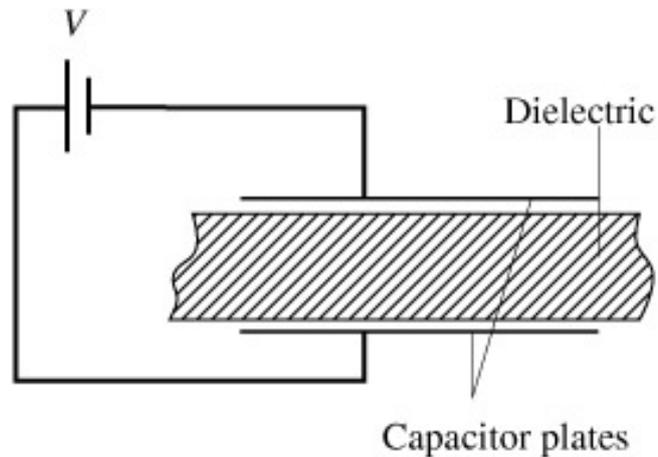


Figure 2.1 – Inserting a dielectric between the plates of a capacitor increases the surface charge

In vacuum the surface charge density on the condenser plates is

$$Q = \epsilon_0 \frac{V}{d}, \quad (2.2)$$

where  $d$  is the distance between the plates. Due to the dielectric the surface charge density increases to

$$Q' = \epsilon_0 \epsilon_r \frac{V}{d}. \quad (2.3)$$

The dielectric displacement,  $D$ , is equal to the surface charge on a metal plate. Denoting the increase in surface charge density by  $P$ , we define the “dielectric susceptibility” by

$$\chi = \epsilon_r - 1, \quad (2.4)$$

from eqns (2.2) and (2.3) we get the ratio

$$P = D - \epsilon_0 \epsilon \quad \text{and} \quad P = \epsilon_0 \chi \epsilon. \quad (2.5)$$

Microscopic approach.

The effect of atomic behaviour, how individual atoms react to an electric field will be considered. It has a positively charged nucleus surrounded by an electron cloud. In the absence of an electric field the statistical centres of positive and negative charges coincide. (This is actually true for a class of molecules as well.) When an electric field is applied, there is a shift in charge centres, particularly of electrons. If this separation is  $\delta$ , and the total charge is  $q$ , the molecule has an *induced dipole* moment,

$$\mu = q\delta. \quad (2.6)$$

Switch back to the macroscopic description and calculate the amount of charge appearing on the surface of the dielectric. If the centre of electron charge moves by an amount  $\delta$ , then the total volume occupied by these electrons is  $A\delta$ , where  $A$  is the area. Denoting the number of molecules per unit volume by  $N_m$  and taking into account of fact that each molecule has charge  $q$ , the total charge appearing in the volume  $A\delta$  is  $A\delta N_m q$ , or simply  $N_m q \delta$  per unit of the area – this is what we mean by surface charge density.

This polarized surface charge density (denoted previously by  $P$ , known also as induced polarization or simply polarization) is exactly equal to the amount of dipole moment per unit of volume, which from eqn (2.6) is also  $N_m q \delta$ , so the first relationship between the microscopic and macroscopic quantities is obtained

$$P = N_m \mu. \quad (2.7)$$

For low electric fields, we may assume that the dipole moment is proportional to the local electric field,  $\mathcal{E}'$ :

$$\mu = \alpha \mathcal{E}'. \quad (2.8)$$

$\alpha$  is a constant called the polarizability.

The presence of dipoles increases the local field (figure 2.2), which will thus always be larger than the applied electric field.

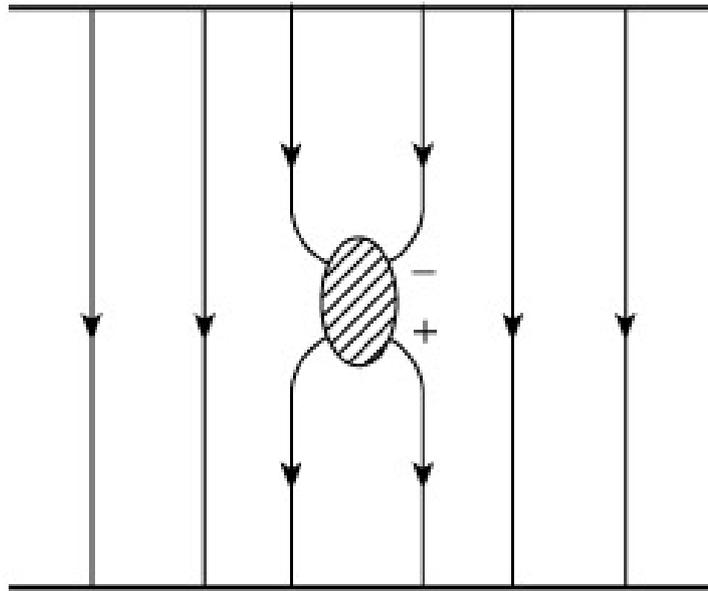


Figure 2.2 – The presence of an electric dipole increases the local electric field

## 2.2 Types of Polarization

*Electronic.* All materials consist of ions surrounded by electron clouds. As electrons are very light, they have a rapid response to field changes; they may even follow the field at optical frequencies.

*Molecular.* Bonds between atoms are stretched by applied electric fields when the lattice ions are charged. This is easily visualized with an alkali halide crystal (figure 2.3), where small deformations of the ionic bond will occur when a field is applied, increasing the dipole moment of the lattice.

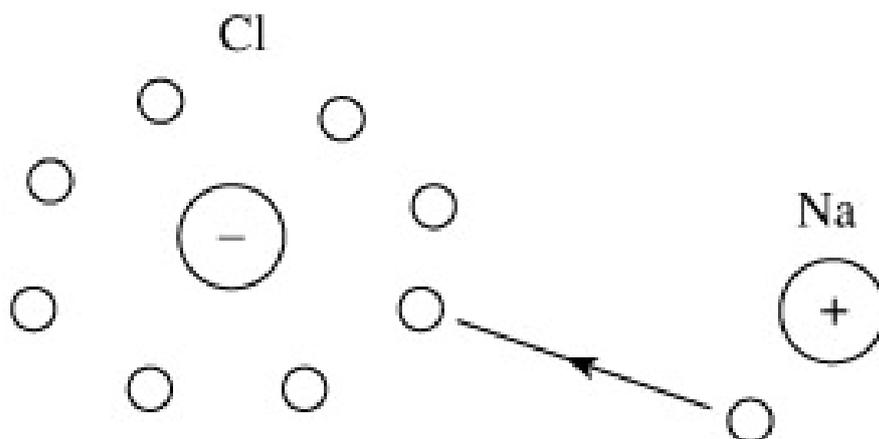


Figure 2.3 – The inter-atomic bond in NaCl is caused by Coulomb attraction

An external electric field will change the separation, thus changing a dipole moment.

*Orientational.* This occurs in liquids or gases when whole molecules, having a permanent or induced dipole moment, move into line with the applied field. Why do not the molecules in a weak static field eventually align just like a weather vane languidly follows the direction of a gentle breeze? If they did, that would be the lowest energy state for the system, but we know from Boltzmann statistics that in thermal equilibrium the number of molecules with energy  $E$  is proportional to  $\exp(-E/kT)$ ; so at any finite temperature other orientations will also be present.

Since the energy of a dipole in an electric field, is  $\mathcal{E}$  (figure 2.4)

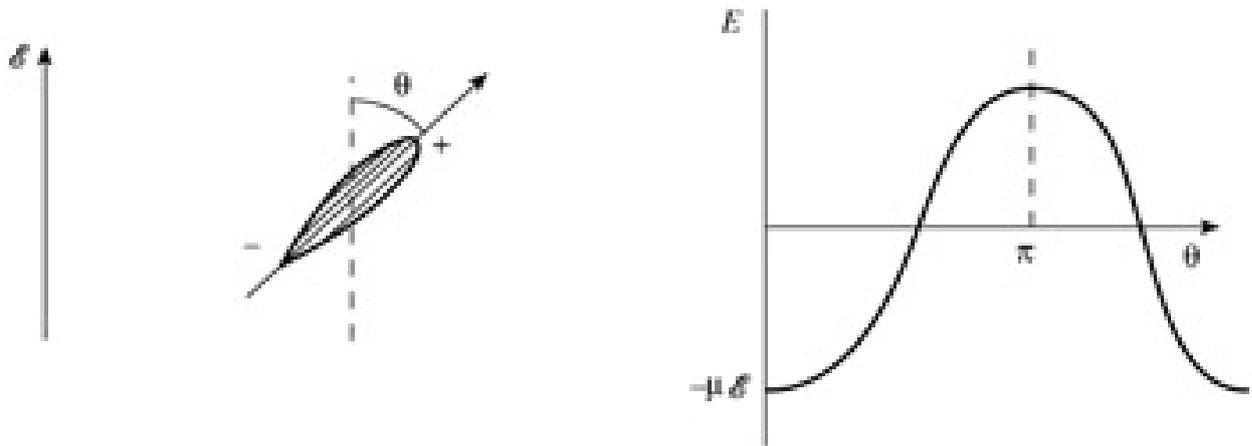


Figure 2.4 – Energy of a dipole in an electric field

$$E = -\mu\epsilon \cos\theta, \quad (2.9)$$

the number of dipoles in a solid angle,  $d\Omega$ , is

$$A \exp\left(\frac{\mu\epsilon \cos\theta}{kT}\right) 2\pi \sin\theta d\theta. \quad (2.10)$$

$A$  is a constant.

Hence, the average dipole moment is given as

$$\begin{aligned} \langle \mu \rangle &= \frac{\text{net moment of the assembly}}{\text{total number of dipoles}} \\ &= \frac{\int_0^\pi A \exp\left(\frac{\mu \mathcal{E} \cos \theta}{kT}\right) (\mu \cos \theta) 2\pi \sin \theta d\theta}{\int_0^\pi A \exp\left(\frac{\mu \mathcal{E} \cos \theta}{kT}\right) 2\pi \sin \theta d\theta}. \end{aligned} \quad (2.11)$$

Equation (2.11) turns out to be integrable, receiving

$$\frac{\langle \mu \rangle}{\mu} = L(a) = \coth a - \frac{1}{a}. \quad (2.12)$$

$a = (\mu \mathcal{E} / kT)$ , and  $L(a)$  is called the Langevin function.

If  $a$  is small, which is true under quite wide conditions, eqn (2.12) may be approximated by

$$\langle \mu \rangle = \frac{\mu^2 \mathcal{E}}{3kT}. \quad (2.13)$$

That is, the polarizability is inversely proportional to the absolute temperature.

### 2.3 The complex dielectric constant and the refractive index

In engineering practice the dielectric constant is often divided up into real and imaginary parts. This can be derived from Maxwell's equations by rewriting the current term in the following manner:

$$\begin{aligned} J - i\omega \epsilon \mathcal{E} &= \sigma \mathcal{E} - i\omega \epsilon \mathcal{E} \\ &= -i\omega \left( \epsilon + i \frac{\sigma}{\omega} \right) \mathcal{E}. \end{aligned} \quad (2.14)$$

The loss tangent is defined as  $\tan \delta = \epsilon'' / \epsilon'$ , where the term in the bracket is usually referred to as the complex dielectric constant.

The usual notation is

$$\epsilon = \epsilon' \epsilon_0 \quad \text{and} \quad \frac{\sigma}{\omega} = \epsilon'' \epsilon_0. \quad (2.15)$$

The refractive index is defined as the ratio of light speed in a vacuum to that in the material,

$$n = \frac{c}{v} = \sqrt{\epsilon_r \mu_r} = \sqrt{\epsilon'} \quad (2.16)$$

since  $\mu_r = 1$  for most materials that transmit light.

We talk of “dielectric constant” (or permittivity) for lower frequencies in the electromagnetic spectrum and refractive index for light. Equation (2.16) shows that they are the same thing as the measure of the polarizability of a material in an alternating electric field.

A recent and important application of dielectrics in optics has been that of multiply-reflecting thin films. Let us consider a layered structure represented in figure 2.5 with alternate layers of transparent material having refractive indices  $n_1$  and  $n_2$ , respectively. At each interface there will be some reflected and some transmitted light. The reflection coefficient according to electromagnetic theory, at an interface will be like (a) in figure 2.5.

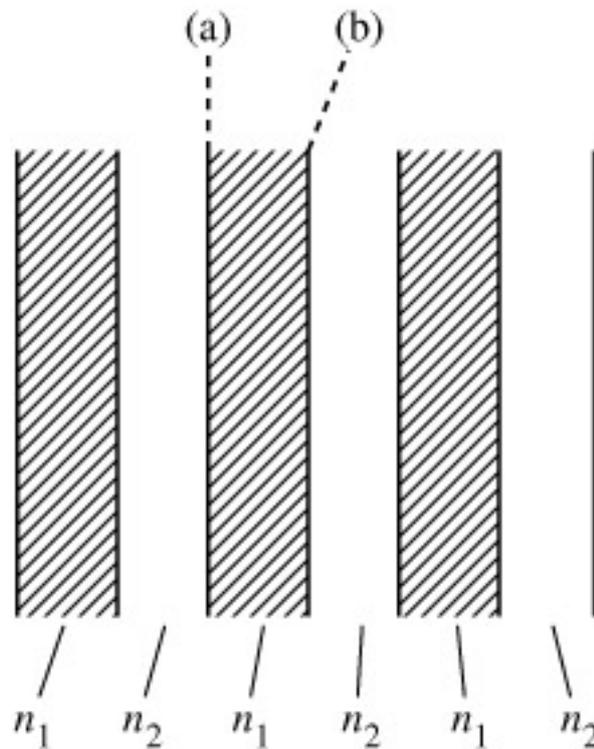


Figure 2.5 – Quarter wavelength layers used to make dielectric mirrors

$$r_a = \frac{n_2 - n_1}{n_2 + n_1} \quad (2.17)$$

By symmetry, the reflection coefficient at (b) will be the reverse of this one

$$r_b = \frac{n_1 - n_2}{n_1 + n_2} = -r_a. \quad (2.18)$$

Now let us suppose that all the layers are a quarter wavelength thick – their actual thickness will be  $n_1(\lambda/4)$  and  $n_2(\lambda/4)$ , respectively. Then the wave reflected back from (b) will be  $\pi$  radians out of phase with the wave reflected back from (a) because of its extra path length, and another  $\pi$  radians because of the phase difference in eqn (2.18). So, the two reflected waves  $2\pi$  radians are different; that is, they add up in phase.

A large number of these layers, often as many as 17, makes an excellent mirror. In fact, provided good dielectrics (ones with low losses), are used, an overall reflection coefficient of 99.5% is possible, whereas the best metallic mirror reflects about 97–98%. This great reduction in losses with dielectric mirrors has made their use with low-gain gas lasers almost universal.

The two reflections have a phase difference of  $\pi$  radians.

Another application of this principle occurs when the layer thickness is one half wavelength. Successive reflections are canceled then, and we have a reflectionless or 'bloomed' coating, much used for the lenses of microscopes and binoculars. A simpler form of 'blooming' uses only one intermediate layer on the glass surface (figure 2.6) chosen so that

$$n_1 = \sqrt{n_2}. \quad (2.19)$$

The layer of the material of refractive index  $n_1$  is this time one quarter wavelength, as it can be seen by applying eqn (2.17).

The complex dielectric constant used by electrical engineers is invariably in the form  $\epsilon = \epsilon_0(\epsilon' - j\epsilon'')$ . It is a different sign because the physicists' time variation,  $\exp(-i\omega t)$  was adopted.

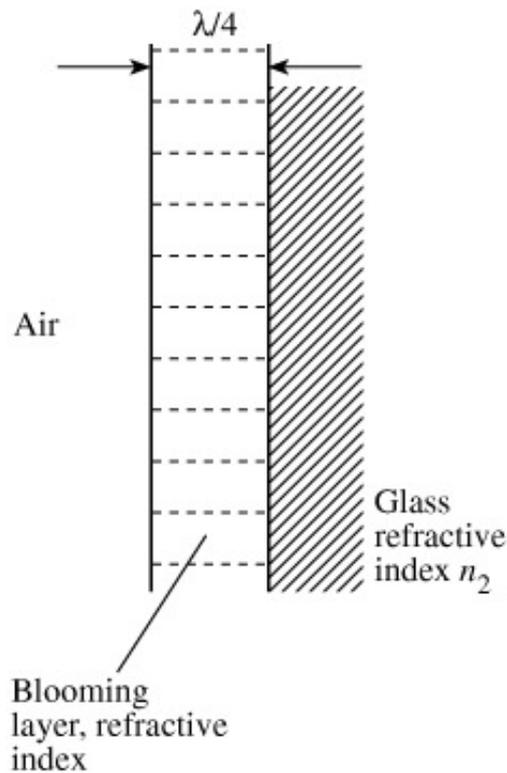


Figure 2.6 – Simple coating for a 'bloomed' lens

## 2.4 Frequency response

Most materials are polarizable in several different ways. As each type has a different frequency of response, the dielectric constant will vary with frequency in a complicated manner; for example at the highest frequencies (light waves) only the electronic polarization will 'keep up' with the applied field. Thus, we may measure the electronic contribution to the dielectric constant by measuring the refractive index at optical frequencies. An important dielectric – water – has a dielectric constant of about 80 at radio frequencies, but its refractive index is 1.3, not  $(80)^{1/2}$ . The electronic contribution is about 1.7, and the rest is probably due to the orientational polarizability of H<sub>2</sub>O molecule.

The general behaviour is shown in figure 2.7. At every frequency where  $\epsilon'$  varies rapidly, there tends to be a peak of the  $\epsilon''$  curve. In some cases this is analogous to the maximum losses that occur at resonance in a tuned circuit: the molecules have a natural resonant frequency because of their binding in the crystal, and they will transfer maximum energy of an electromagnetic wave at this frequency. Another case is the "viscous lag" occurring between the field and a polarized charge which is described by the Debye's equations, which we shall presently consider. A consequence of all this is that materials that transmit light often absorb strongly in the ultraviolet and infrared regions, for example, most forms of glass. Radio reception indoors is comparatively easy because (dry) bricks transmit wireless waves but absorb light.

The visible light region (about  $10^{14}$ – $10^{15}$  Hz) has, of course, been of greatest importance to the evolution of life on Earth.

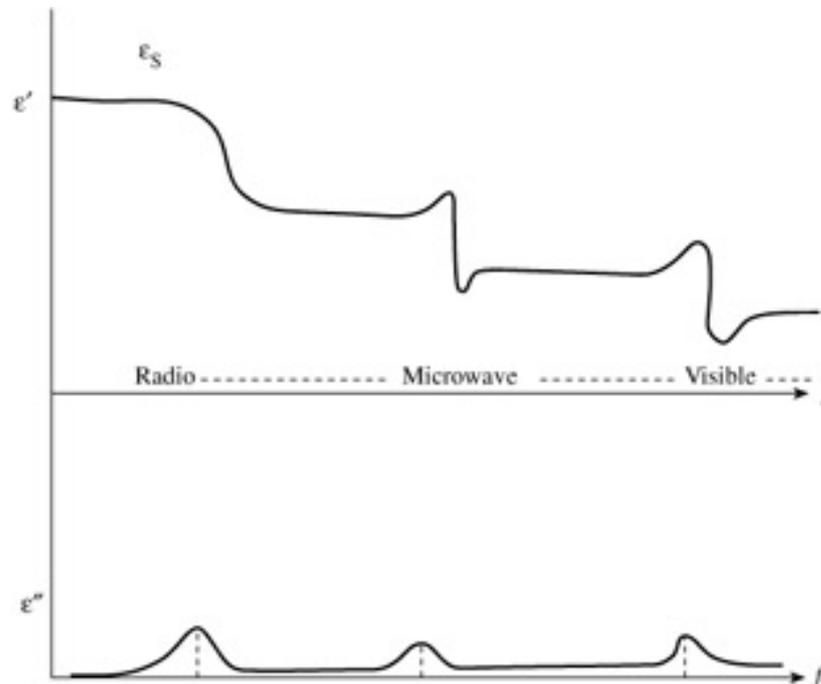


Figure 2.7 – Typical variation of  $\epsilon'$  and  $\epsilon''$  with frequency

## 2.5 Polar and non-polar materials

A non-polar material is one with no permanent dipoles. For example, Si, Ge, and C (diamond) are non-polar. The somewhat analogous III–V compounds, such as GaAs, InSb, and GaP, share their valency electrons, so that the ions forming the lattice tend to be positive (group V) or negative (group III).

Hence, the lattice is a mass of permanent dipoles, whose moment changes when a field is applied. As well as these ionic bonded materials, there are two other broad classes of polar materials. There are compounds, such as the hydrocarbons ( $C_6H_6$  and paraffins) that have permanent dipole arrangements but still have a net dipole moment of zero (one can see this very easily for the benzene ring). Then there are molecules such as water and many transformer oils that have permanent dipole moments, and the total dipole moment is determined by their orientational polarizability.

A characteristic of non-polar materials is that, as all the polarization is electronic, the refractive index at optical wavelengths is approximately equal to the square root of the relative dielectric constant at low frequencies.

Starting with our favourite (simplest) model of a solid, cubic lattice with a lattice spacing  $a$ . Let us suppose that the atoms are closely packed, each having a radius  $r$ , so that

$$a = 2r. \quad (2.20)$$

For an optical property we need to consider only electronic polarizability as ionic, and molecular responses are too slow.

Let us suppose that each atomic volume,  $(4/3)\pi r^3$  is uniformly occupied by total electronic charge,  $Ze$ .

When electric field,  $\mathcal{E}$ , is applied, the centre of charge of the electronic cloud shifts at distance  $r$  up to  $C^-$  from the nucleus at  $C$  (figure 2.8).

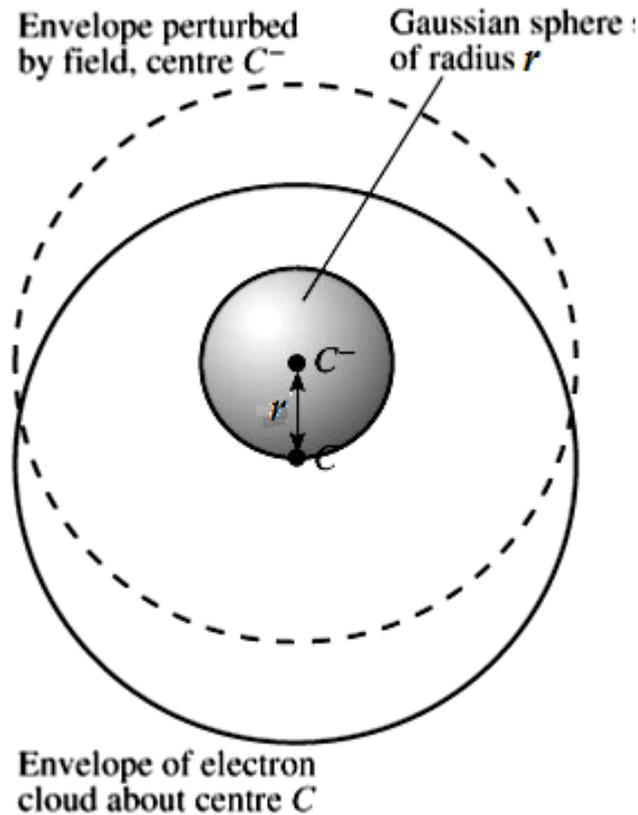


Figure 2.8 – Displacement of electron cloud about an atom centred on  $C$  by a distance  $r$ , by an applied electric field

To find the restoring force attracting the electrons back towards the nucleus, we can construct a Gaussian surface of radius  $d$  about  $C^-$ , so that  $C$  is just excluded. The negative charge inside the Gaussian sphere is equal to  $Ze(d/r)^3$  according to the uniform charge approximation.

So, attractive force,  $F$ , towards the nucleus is

$$F = \frac{(Ze)^2 d}{4\pi \epsilon_0 r^3}. \quad (2.21)$$

This must be balanced by the field force causing the charge displacement,

$$F = Ze\varepsilon. \quad (2.22)$$

So, by eqns (2.21) and (2.22)

$$Zed = 4\pi r^3 \epsilon_0 \varepsilon. \quad (2.23)$$

According to eqn (2.8) the polarizability is

$$\alpha = 4\pi r^3 \epsilon_0. \quad (2.24)$$

Now let us return to eqn (2.7),  $P = N_m \mu$ , to find the induced polarization.

The density of atoms per unit of volume is

$$N_m = \frac{1}{a^3} = \frac{1}{(2r)^3}. \quad (2.25)$$

The LHS is the quantity defined as the dipole moment,  $\mu$ , in eqn (2.6), leading to

$$P = \frac{1}{(2r)^3} 4\pi r^3 \epsilon_0 \varepsilon = \frac{\pi}{2} \epsilon_0 \varepsilon. \quad (2.26)$$

From eqns (2.4) and (2.5) it follows then that

$$\chi = \frac{P}{\epsilon_0 \varepsilon} = \frac{\pi}{2}, \quad (2.27)$$

whence

$$\epsilon_r = 1 + \chi \cong 2.57, \quad (2.28)$$

and

$$n = \sqrt{\epsilon_r} \cong 1.6. \quad (2.29)$$

This model is refined if to give a different fit by remarking that less close packing would give  $N_m < 1/(2r)^3$  and also take into account quantum orbits.

## 2.6 Dielectric breakdown

A well-designed insulator (in the laboratory) breaks down in service if the wind changes direction or if a fog descends. An oil-filled high-voltage condenser will have bad performance, irrespective of the oil used, if there is 0.01 % of water present. The presence of grease, dirt, and moisture is the dominant factor in most insulator design. The onset of dielectric breakdown is an important economic as well as technical limit in capacitor design. Generally, one wishes to make capacitors with a maximum amount of stored energy. Since the energy stored per unit of volume is  $\epsilon \mathcal{E}^2/2$ , the capacitor designers value high breakdown strength even more highly than high dielectric constant.

There are three main mechanisms that usually cause dielectric breakdown:

- (1) intrinsic;
- (2) thermal;
- (3) discharge breakdown.

In general, breakdown is manifested by a sudden increase in current when the voltage exceeds critical value  $U_b$  as shown in figure 2.9. Below  $U_b$  there is a small current due to the few free electrons that must be in the conduction band at finite temperature. When breakdown occurs it does so very quickly, typically within  $10^{-8}$  s in a solid.

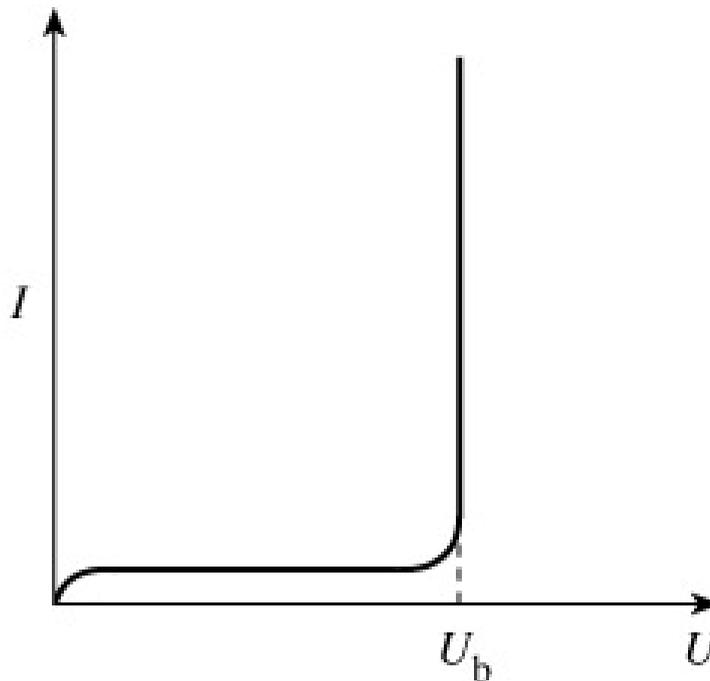


Figure 2.9 – Current voltage characteristics for an insulator. The current increases very rapidly at breakdown voltage,  $U_b$

## 2.7 Intrinsic Breakdown

When few present electrons are sufficiently accelerated (and lattice collisions are unable to absorb the energy) by the electric field, they can ionize lattice atoms. The minimum requirement for this is that they give to the bound (valence) electron enough energy to excite it across the energy gap of the material.

## 2.8 Thermal Breakdown

This occurs when operating or test conditions heat the lattice. For example, an a.c. test on a material in the region of its relaxation frequency, where  $\epsilon''$  is large would cause heating by the lossy dipole interaction rather than by accelerating free electrons.

The heated lattice ions could then be more easily ionized by free electrons, and hence the breakdown field could be less than the intrinsic breakdown field measured with d.c. voltages.

The typical polymer, polyethylene, has a breakdown field from 3 to  $5 \times 10^8$   $\text{V}\cdot\text{m}^{-1}$  for very low frequencies, but this falls to about  $5 \times 10^6$   $\text{V}\cdot\text{m}^{-1}$  around  $10^6$  Hz, where a molecular relaxation frequency occurs. Ceramics such as steatite and alumina exhibit similar effects.

If it were not for dielectric heating effects, breakdown fields would be lower at high frequencies simply because the free electrons have only half a period to be accelerated in one direction. A typical breakdown time is  $10^{-8}$  s; so at frequencies above  $10^8$  Hz breakdown would be somewhat inhibited.

But a fast electron striking an ion lattice still has a greater speed after collision than a slow one, and some of these fast electrons will be further accelerated by the field. Thus, quite spectacular breakdown may sometimes occur at microwave frequencies ( $10^{10}$  Hz) when high power densities are passed through ceramic windows of klystrons or magnetrons.

The work with high-power lasers has shown that dielectric breakdown still occurs at optical frequencies. In fact, the maximum power available from a solid-state laser is about  $10^{12}$  W from a series of cascaded neodymium glass amplifier lasers. The reason why further amplification is not possible is that the optical field strength disrupts the glass laser material.

## 2.9 Discharge Breakdown

In materials such as mica or porous ceramics, where there is occluded gas, the gas often ionizes before the solid breaks down. The gas ions can cause surface damage, which accelerates breakdown. This shows up as intermittent sparking and then breakdown in the test field is increased. Gases properties are shown in table 2.1.

Table 2.1 – Properties of gases

<i>Material</i>	<i>t/°C</i>	$10^4 (\epsilon_r - 1)$	<i>Material</i>	<i>t/°C</i>	$10^4 (\epsilon_r - 1)$
Air dry	20	5.36 <sub>1</sub>	Nitrous oxide	25	10.3
Nitrogen	20	5.47 <sub>4</sub>	Ethylene	25	13.2
Oxygen	20	4.94 <sub>3</sub>	Carbon disulphide	29	29.0
Argon	20	5.17 <sub>7</sub>	Benzene	100	32.7
Hydrogen	0	2.72	Methanol	100	57
Deuterium	0	2.69 <sub>6</sub>	Ethanol	100	78
Helium	0	0.7	Ammonia	1	71
Neon	0	1.3	Sulphur dioxide	22	82
Carbon dioxide	20	9.21 <sub>6</sub>	Water	100	60
Carbon monoxide	25	6.4	Water (10 mm Hg)	20	1.24 <sub>4</sub>

## 2.10 Dielectric properties of materials

The absolute complex permittivity of a material is represented by symbol  $\epsilon$ , where  $\epsilon = \epsilon' - j \epsilon''$ . This is related to the dimensionless relative complex permittivity  $\epsilon_r$ , where  $\epsilon_r = \epsilon'_r - j \epsilon''_r$ , by the expression  $\epsilon = \epsilon_0 \epsilon_r$ ,  $\epsilon_0$  being the permittivity of free space, a fixed constant given approximately by  $\epsilon_0 = 8.85 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$ . In general,  $\epsilon$  depends on temperature and, in less extent on pressure.

It also depends on frequency, although  $\epsilon'$  and  $\epsilon''$  cannot vary independently with frequency, since their frequent variations are connected through the Kramers–Krönig relationship: a drop in  $\epsilon'$  with increasing frequency is necessarily associated with a peak in  $\epsilon''$ . Except for exceedingly high applied fields,  $\epsilon$  is independent of the value of the applied electric field for all dielectric materials used in practice, excluding ferroelectrics.

A capacitor filled with a dielectric material has a real capacitance  $\epsilon'_r$  times greater than a capacitor with the same electrodes would have in vacuum. The dielectric-filled capacitor would also have dissipation power  $W$  per unit of volume at each point when, resulting from an applied voltage, a sinusoidal electric field of frequency  $f$  and root-mean-square value  $E$  exists at that point. This dissipation power is given by  $W = 2\pi f E^2 \epsilon''$ . Thus  $\epsilon''$  is a measure of the dissipation energy per period, and for this reason it is known as the loss-factor.

The complex permittivity  $\epsilon$  is often represented in the Argand plane with  $\epsilon'$  as abscissa and  $\epsilon''$  as ordinate, giving a curve with frequency as parameter. To join any point on this curve to the origin point one represents the complex conjugate  $\epsilon^*$  of the complex permittivity  $\epsilon$  where  $\epsilon^* = \epsilon' + j \epsilon''$ .

Unfortunately, the use of symbol  $\epsilon^*$  to represent the complex permittivity is widespread and has become established in the literature, and care is needed if confusion over signs is to be avoided. The join to the origin point makes an angle  $\delta$  with the abscissa, so that  $\tan \delta = \epsilon'' / \epsilon'$ . Thus  $W$  may be rewritten as  $W = 2\pi f E^2 \epsilon' \tan \delta$ . Hence  $\delta$  is known as the loss angle, and  $\tan \delta$  is known as the loss tangent.

The application of a sinusoidal voltage of root-mean-square value  $V$  in the dielectric-filled capacitor results in a current flow in the external circuit which leads the voltage by a phase angle or power-factor angle  $\phi$ , where  $\phi$  is the complement of  $\delta$ .

Thus, the dissipation power in the capacitor, given by  $IV \cos \phi$ , may also be expressed as  $IV \sin \delta$ . Since in most cases in engineering practice  $\delta$  is small,  $\sin \delta \simeq \tan \delta$  and the dissipation power is given to a good approximation by  $IV \tan \delta$ . It should be noted that no such approximation is involved in the expression for  $W$  in the previous paragraph.

When the wavelength of electromagnetic radiation is in the optical region, the speed  $v$  of propagation without a loss-free transmitting medium is refractive index  $n$  and is given by  $v = c/n$ , where  $c$  is the speed in free space. The speed is also given by  $v = c/(\mu_r \epsilon_r')^{1/2}$  where  $\mu_r$  is the relative permeability.

Thus, for loss-free non-magnetic materials  $\mu_r = 1$ ,  $\epsilon_r' = n^2$ . However, in general, losses do occur, and the material is characterized by a complex refractive index given by  $\hat{n} = n - jk$ , where  $k$  is the absorption coefficient. Then  $\epsilon_r = \hat{n}^2$ , or  $\epsilon_r' - j\epsilon_r'' = (n - jk)^2$ , from which it follows that  $\epsilon_r' = n^2 - k^2$  and  $\epsilon_r'' = 2nk$ . Nevertheless, when the loss is small, so that  $k \ll n$ , then  $\epsilon_r' \simeq n^2$ . The use of these relationships allows values of  $\epsilon_r$  at high frequencies to be derived from optical measurements. As the frequency is reduced, specially designed interferometers (infra-red), free radiation methods (sub-millimetric wavelengths), wave-guides, coaxial lines and resonant cavities (centimetric wavelengths), and  $Q$  meters and bridges (radio frequencies up to d.c.) have all been used. Time-domain spectroscopy, involving the analysis of medium response to a step-function field, capable in principle, and has had some success in practice, gives a rapid measurement of  $\epsilon$  over a very wide frequency spectrum.

The relative permittivity is directly related to electronic, atomic and orientational polarization of the material. The first two ones of these are induced by the applied field, and are caused by displacement of the electrons within the atom, and atoms within the molecule, respectively. The third one exists only in polar materials, i.e. those with molecules having a permanent dipole moment. Electronic and atomic polarization are temperature independent, but orientational polarization, depending on the extent at which the applied field can order the permanent dipoles against disordering effect of the thermal energy of their medium, varies inversely to the absolute temperature. All of these polarization mechanisms can operate only up to a limited frequency, after that further frequency increase will result in their disappearance. Because of the spring-like nature of the forces involved, this is accompanied by an absorption of the resonance type for electronic and atomic polarization, as well as for orientational polarization of disappearance is accompanied by a broader peak in the loss factor and is more gradual, because the mechanism involved is of the relaxation type, and may include a broad distribution of relaxation time. Indeed, the decline in  $\epsilon'$  may be so gradual that  $\epsilon''$  may appear as almost constant, and be correspondingly small, over a wide frequency range. This applies particularly to some polymers commonly used in engineering practice, many of

which are polar. Those which are non-polar, usually with  $\epsilon_r' < 2.5$ , show nearly constant values of  $\epsilon'$  and  $\epsilon''$  over the entire electrical frequency spectrum.

The frequency at which these mechanisms drop out is related to the inertia of the moving entities involved. Typically, electronic polarization persists until a frequency of about  $10^{16}$  Hz, atomic polarization until about  $10^{13}$  Hz, while the dispersion for orientational polarization may lie anywhere within a wide frequency range, e.g.  $10^2$ – $10^{10}$  Hz, depending on the material and its temperature. In addition to these polarization mechanisms, the existence of interfacial effects such as macroscopic discontinuities in the material, or blocking at the electrodes, causes the trapping of charge carriers, and such phenomena, as the inclusion in the dielectric of impurities giving rise to conducting regions, result in their behaviour classified as Maxwell–Wagner’s effects. These give rise to an effective polarization and associated loss, the frequency behaviour of which is similar to that of orientational polarization, with a dispersion region which may lie in the region of 1 Hz or lower.

When orientational polarization is operative, it is usually the dominant polarization mechanism present. This mechanism is described in Debye’s classical theory. For a single relaxation time  $\tau$ , the variation of  $\epsilon_r$  with angular frequency  $\omega$  is given by the Debye equation,  $(\epsilon_r - \epsilon_\infty)/(\epsilon_s - \epsilon_\infty) = (1 - j\omega\tau)/(1 + \omega^2\tau^2)$ , where  $\epsilon_s$  and  $\epsilon_\infty$  are the relative permittivities at frequencies much lower and much higher (but not high enough to involve any reduction in atomic or electronic polarizations), respectively, than an anomalous dispersion region. Equating real and imaginary parts gives

$$(\epsilon_r' - \epsilon_\infty) / (\epsilon_s - \epsilon_\infty) = 1/(1 + \omega^2\tau^2) \quad \text{and} \quad \epsilon''/(\epsilon_s - \epsilon_\infty) = \omega\tau/(1 + \omega^2\tau^2).$$

$\epsilon''$  is plotted against  $\epsilon'$ , results in Cole–Cole plot. This is a semicircle if the Debye’s equation is obeyed. Frequently experimental results yield a circular arc, rather than a semicircle, with its centre below the abscissa. Such behaviour can be expressed as a suitable distribution of relaxation times, though no satisfactory physical reason for doing so has been established yet. There is a variety of other shapes obtained in practice, such as the skewed arc in which the high frequency end of the arc transforms into a straight line. Anything other than a perfect semi-circle is now taken as evidence of co-operative effects within the dielectric.

The permittivity of many substances changes not only with frequency and temperature, but also with specimen age and history. Two specimens of nominally the same material may have significantly different permittivities because of different manufacturing processes, different amounts of oxidation, and different inclusions, some of which might have been deliberately introduced, e.g. anti-oxidants. For such reasons, tables of values should be used as an indication of the values to be expected, and not as a source of precise data which can be repeated by accurate measurements on particular test specimens, except in cases in which the physical and chemical state of both the reference material and the test specimen are very closely specified. The properties of ferroelectric materials depend on so many factors that it is inappropriate to include them in tables of data. Generally, they have permittivities of the order of a

thousand, strongly dependent on applied voltage and temperature, and exhibit considerable power loss.

## 2.11 Relative permittivity and loss tangent

Temperature ( $t$ ) is measured in °C, and frequency ( $f$ ) in Hz. Temperature coefficient of  $\epsilon_r'$  is denoted by  $\alpha = 10^5 \frac{d\epsilon_r'}{\epsilon_r' dt}$  and density in  $\text{g}\cdot\text{cm}^{-3}$  by  $d$ . For non-cubic crystals, the symbols  $\perp$ ,  $\parallel$ , indicate measurements with field respectively perpendicular to and parallel to the  $c$ -axis. Ranges of quantities are indicated by the numerical limits of the range, separated by dashes. For commercial materials, the values should be regarded as examples only, since some vary greatly depending on composition and purity. This applies also to decrease the loss angle of some pure materials, which may depend on traces of impurity. The ranges of  $\epsilon_r'$  and  $\tan \delta$ , however, are intended to indicate not these variations, but only the variation within the stated ranges of temperature and/or frequency. However, because data relating to different temperatures and frequencies often have to be taken from more than one source, even for what is nominally the same material, it is commonly impossible to be certain of the cause of the variations.

## 2.12 Determination of dielectric permittivity and dielectric loss angle tangent of insulation materials

Determination of the main characteristics of insulation materials: a relative permittivity ( $\epsilon$ ) and a loss angle tangent ( $\text{tg } \delta$ ). Learn to measure electric circuit parameters, using device E7-22.

The laboratory installation and electric circuit diagram.

For the determination of the relative permittivity and the dielectric loss angle tangent of various insulation materials parameters of the sequential equivalent circuit of the capacitor (C and R) with a test material dielectric are measured. The electric circuit diagram to measure capacitor parameters is shown in Figure 2.10. The plate capacitor (block 2355), between the plates of which the test dielectric is placed, is connected to the tester E7-22 RLC (block 533). Power supply units 218 and 224.1 provide a source voltage of + 12V for E7-22:

A capacitance of the capacitor with the test dielectric is determined by formula:

$$C = \epsilon \epsilon_0 \frac{S}{d},$$

where  $\epsilon_0 \approx 8,854 \cdot 10^{-12} \frac{\text{F}}{\text{m}}$  - an electric constant (a permittivity of free space);

$\epsilon$  - the relative permittivity of the test dielectric;

$S$  - the area of the capacitor plates, [ $\text{m}^2$ ]. In the experiment the area of the upper plate of the capacitor is taken into account.

The influence of the edge effect is neglected:  $d$  – the distance between the capacitor plates in meters, which is equal to the thickness of the test dielectric.

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To calculate the relative permittivity of the test dielectric the measured capacitance  $C$ , is compared with the calculated capacitance of the condenser  $C_0$  with the same geometric dimensions, but without a dielectric (the medium between the plates - the vacuum with permittivity  $\epsilon_0$ ). The value of the calculated capacitance is:

$$C_0 = \epsilon_0 \frac{S}{d}.$$

The ratio of capacitances is:

$$\frac{C}{C_0} = \frac{\epsilon\epsilon_0 S/d}{\epsilon_0 S/d} = \epsilon,$$

i.e. it is equal to the relative dielectric permittivity of the test dielectric.

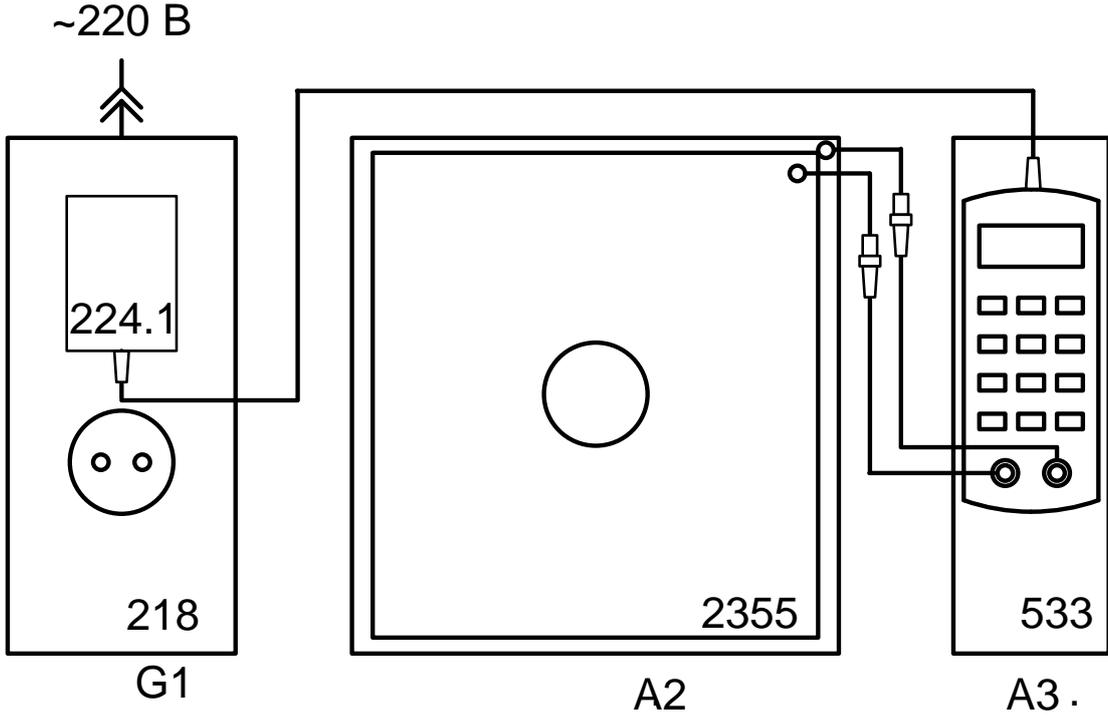


Figure 2.10 – The electric circuit diagram to measure parameters of the capacitor with a test dielectric

Dielectric loss angle tangent is determined for the capacitor sequential equivalent circuit consisting of an ideal capacitor with capacitance  $C$  and resistance  $R$  connected in series with it. When measured at frequency  $\omega$

$$\operatorname{tg} \delta = \frac{R}{1/\omega C},$$

i.e. dielectric loss tangent is equal to the ratio of active ( $R$ ) and capacitive resistances ( $1/\omega C$ ) of the circuit. Hence, it is possible to determine resistance  $R$  of the capacitor sequential equivalent circuit:

$$R = \frac{\operatorname{tg} \delta}{\omega C}.$$

Guidelines for doing an experiment.

1. Make sure that “Network” blocks switches used in the experiment are turned off.
2. Connect power supply unit 224.1 to “Meter R-L-C” (533) unit and to the outlet “220 V” of G1 single-phase power source (unit 218) in accordance with scheme 1.1.
3. Turn on the protection tripping device and the automatic circuit breaker in G1 single-phase power source.
4. Turn on the circuit breaker **ⓘ** of the «Meter R-L-C» (533).
5. Select:
  - a type of measured parameter – a capacitance  $C$  (button «L/C/R»);
  - an auxiliary measured parameter – delta  $D \tan$  (button «Q/D/R»);
  - an element equivalent circuit – series (button «PAR/SEQ», «SER» on the display);
  - a frequency of the measurement – 120 Hz (button «FREQ»).
6. Insert a test dielectric sample between the plates of the capacitor and connect a capacitor to the meter RLC. The upper plate of the capacitor unit 2355 must be installed approximately in the middle of the bottom plate with a uniform offset from the edges around the perimeter of the plate.
7. Unauthorized and conductive objects should not be at a distance of at least 10 ... 15 cm from the capacitor unit 2355. Voltage supply from external sources to the device input and the capacitor unit plates is inadmissible!
8. Calculate the capacitance  $C$  and  $\operatorname{tg} \delta$  ( $D$ ) of the capacitor 2355 with the dielectric.
9. Calculate the capacitance of the capacitor without dielectric  $C_0 = \epsilon_0 \frac{S}{d}$ . Area  $S$  is indicated on the upper plate of the capacitor 2355, and the distance between the plates  $d$  is equal to a dielectric thickness indicated in the test sample.
10. Calculate the relative dielectric permittivity of the test dielectric and the sequential equivalent circuit resistance

$$\varepsilon = \frac{\tilde{N}}{\tilde{N}_0}, R = \frac{tg\delta}{\omega C}.$$

11. Turn off the unit power supply G1 (218).

### 2.13 Liquids

Except when a frequency is stated the permittivities in table 2.2 are ‘static’ values, relating to frequencies high enough to exclude ionic conductivity, but below any region of dispersion. For non-polar liquids ( $\epsilon_r' \simeq 2$ ) the lower limit depends only upon ionic impurities, while the higher one is usually above 10 GHz. Within these limits, the permittivity is constant, and the loss is unlikely to exceed by several times  $10^{-4}$ . For polar liquids, denoted by ‘P’, the lower frequency limit depends both upon purity and the intrinsic dissociation of the liquid, while the upper limit varies sharply with temperature. The two limits may overlap, and the permittivity is then nowhere constant, and the loss tangent is small. For these reasons, frequency and loss tangent are given only for a few liquids of controlled purity which are used for electrical purposes.

Table 2.2 – Relative permittivity and loss tangent of materials

Material	$t/^\circ\text{C}$	$f$	$\epsilon_r'$	$10^4 \times \tan \delta$
Castor oil	20	1 kHz	4.5	
Chlordiphenyl (tri)	-10/100	50 Hz/20 kHz	7/5	2000/2
Chlordiphenyl (penta-)	0/100	50 Hz	5.2/4.3	700/3
Parafin oil	20	1 kHz	2.2	1
Silicone fluid (0.65 cS)	20	50 Hz/3 GHz	2.2	2/19
Silicone fluid (1000 cS)	20	50 Hz/3 GHz	2.78/2.74	1/100
Transformer oil (BS 138)	20	50 MHz/100 GHz	2.2	1/42
Transformer oil (BS 138)	20	100 MHz/10 GHz	2.2	42/8

Water is strongly polar, with a region of dispersion, at 20 °C, centred around 17 GHz. It is also intrinsically dissociated, so that even de-ionized water cannot be treated as a dielectric at frequencies much below 1 MHz. Before about 1953 measurements at high frequencies of the dispersion range contain, before about 1953, many errors shown by values of  $\epsilon'$  and  $\epsilon''$  mutually inconsistent with simple Debye's

equations. It is established that water obeys them with some accuracy, the value of the dispersion coefficient  $\alpha$  in the Cole–Cole equation doesn't exceed 0.05.

At frequencies higher than about 1 MHz (where the loss tangent passes through a minimum of about  $5 \times 10^{-3}$ ) values of  $\epsilon'$  and  $\epsilon''$  can be calculated from Debye's equations given in the introduction to this section, with accuracy better than one can obtain by interpolation in the table. The necessary values of  $\epsilon_s$ ,  $\epsilon_\infty$  and  $\tau$  are chosen to give the best fit with internally consistent data.

The static relative permittivity as a function of temperature, within the range 0–60°C, is given with an accuracy of  $\pm 0.1$  unit by

$$\epsilon_s = 88.15 - 41.4\theta + 13.1\theta^2 - 4.6\theta^3,$$

where  $\theta = \text{Celsius temperature}/100^\circ\text{C}$ .

The relaxation time as a function of temperature is as follows, with an accuracy of about  $\pm 2\%$  is shown in table 2.3.

Table 2.3 – The relaxation time and temperature

t/°C	0	10	20	30	40	50	60
$\tau/\text{ps}$	17.7	12.6	9.2	7.1	5.7	4.8	3.9

The 'infinite frequency' dielectric constant,  $\epsilon_\infty$ , occurs in the infra-red, and cannot be directly measured electrically. The value of 5.0 is appropriate for the use with the foregoing data.  $\epsilon_r$  decreases continuously from this value throughout the infra-red to the value of 1.8 in the optical region. Therefore Debye's equations become increasingly inaccurate for  $\omega\tau \gg 1$ .

## 2.14 Gases and vapours

Excepting the final entry the values relate to a pressure of one standard atmosphere, and are given for all frequencies below the start of the infra-red spectrum. Other values may be calculated over a limited range of temperature and pressure, for non-polar permanent gases, by assuming that  $(\epsilon_r - 1)$  is proportional to density. This does not hold for polar gases, but if the polarity is strong (e.g. water vapour) a close approximation is

$$(\epsilon_r - 1) \propto \text{°C pressure}/(\text{absolute temperature})^2,$$

provided that the vapour is not near its condensation point, under the conditions either of the data used, or of the desired result. This relation can safely be used, for example, to obtain values for damp air, the densities and pressures involved being then the partial values, and the contributions from the two components additive. The ratio should not be applied to mixtures of two polar vapours.

Values of relative permittivity may also be obtained from the data on refractive indices at radio frequencies by using the relation  $\mu_r \epsilon_r = n^2$  which is applied for non-absorbing gases shown in table 2.4.  $\mu_r = 1$  for all gases except O<sub>2</sub> where  $\mu_r = 1 + 1.9 \times 10^{-6}$ .

Table 2.4 – Relative permittivity of gases and vapours

<i>Material</i>	<i>t/°C</i>	$10^4 (\epsilon_r - 1)$	<i>Material</i>	<i>t/°C</i>	$10^4 (\epsilon_r - 1)$
Air dry	20	5.36 <sub>1</sub>	Nitrous oxide	25	10.3
Nitrogen	20	5.47 <sub>4</sub>	Ethylene	25	13.2
Oxygen	20	4.94 <sub>3</sub>	Carbon disulphide	29	29.0
Argon	20	5.17 <sub>7</sub>	Benzene	100	32.7
Hydrogen	0	2.72	Methanol	100	57
Deuterium	0	2.69 <sub>6</sub>	Ethanol	100	78
Helium	0	0.7	Ammonia	1	71
Neon	0	1.3	Sulphur dioxide	22	82
Carbon dioxide	20	9.21 <sub>6</sub>	Water	100	60
Carbon monoxide	25	6.4	Water (10 mmHg)	20	1.24

## 2.15 Optical Fibres

Dielectric properties are of great importance in optics as well as at more conventional electrical engineering frequencies. That there are no sacred boundaries in the electromagnetic spectrum is shown very clearly by a fairly recent development in communications engineering. This involves the transmission (guiding) of electromagnetic waves. The principle of operation is very simple. The optical power remains inside the fibre because the rays are reflected at the boundaries.

This could be done at any frequency, but dielectric waveguides have distinct advantages only in the region around  $\mu$  m wavelengths. The particular configuration used is a fibre of rather small diameter (e.g. 5–50  $\mu$  m) made of glass or silica. Whether this transmission line is practical or not will clearly depend on the attenuation. A formula for the propagation coefficient of a plane wave in a lossy medium, and that gives a sufficiently good approximation.

$$k = (\omega^2 \mu \epsilon + i\omega \mu \sigma)^{1/2},$$

and assuming this time that

$$\omega \epsilon \gg \sigma,$$

getting the attenuation coefficient

$$k_{AC} = \frac{1}{2} \frac{\omega \sqrt{\epsilon'} \sigma}{c \omega \epsilon} = \frac{1}{2} \frac{\omega \sqrt{\epsilon'}}{c} \tan \delta.$$

The usual measure is the attenuation in decibels for a length of one kilometre, which may be expressed as follows:

$$A = 20 \log_{10} \exp(1000 k_{AC}) = 8680 k_{AC} = 4340 \frac{\omega \sqrt{\epsilon'}}{c} \tan \delta \text{ db km}^{-1}.$$

For optical communication to become feasible,  $A$  should not exceed 20 db  $\text{km}^{-1}$ .

Taking an operational frequency of  $f = 3 \times 10^{14}$  Hz, a typical dielectric constant  $\epsilon' = 2.25$ , and the best material available at the time with  $\tan \delta \approx 10^{-7}$ , get

$$A \approx 4 \times 10^3 \text{ db km}^{-1},$$

far from 20. No doubt, materials can be improved, but an improvement in  $\tan \delta$  of more than two orders of magnitude looked at the time somewhat beyond the realm of practical possibilities.

The most usual material used for these successful fibres has been purified by silica ( $\text{SiO}_2$ ) with various dopants to produce the refractive index profile across the diameter to contain the light ray in a small tube along the axis, with total internal reflection from the lower refractive index cladding. To get very low attenuations, the wavelength of the light has to be carefully controlled. Even with highly purified silica, there are some hydroxyl (OH) impurity radicals, which are stimulated into vibrations and, hence, absorb bands of frequencies. There are 'windows' in this absorption spectrum, one of which between 1.5 and 1.7  $\mu\text{m}$  of wavelength was used to obtain 0.2 db  $\text{km}^{-1}$  result. A new impetus to the in any case fast-growing optical fibre communications has been given by the invention of a fibre amplifier, that makes repeaters superfluous.

### 3 Semiconductors

Semiconductors occupy an intermediate position between metals and insulators. Semiconductors resistivity at room temperature is  $10^{-6} - 10^{-9}$  Ohm·m. Resistivity of a semiconductor is heavily dependent on external factors, type and amount of impurities contained therein. Semiconductors have a positive temperature coefficient of conductivity (figure 3.1).

Semiconductors (technologically the newest class) have found their application only in the last century, and their more widespread application dates from the 1950s.

During this period the electronics industry has been (to use a hackneyed word justifiably) revolutionized, first by a transistor, then by microelectronic circuitry. By

making circuitry much cheaper and more compact each of these in succession has led to the wider use of electronic aids, such as computers, in a way that is revolutionary in the social sense too.

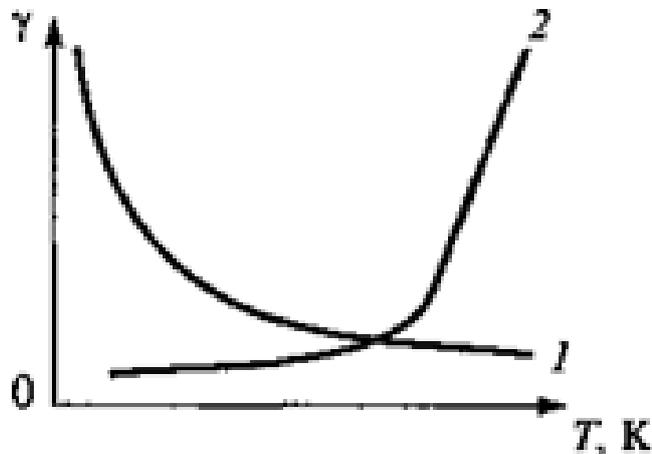


Figure 3.1 – Dependence of  $\gamma = f(T)$  for metals is 1 and semiconductor is 2

Perhaps the key reason for this sudden change has been the preparation of the extremely pure semiconductors, and hence the possibility of controlling impurity; this was a development of the 1940s and 1950s. By crystal pulling, zone-refining, and epitaxial methods it is possible to prepare silicon and germanium with an impurity of only 1 part in 10<sup>10</sup>. Compare this with long-established engineering materials, such as steel, brass, or copper where impurities of a few parts per million are still virtually unattainable (and for most purposes, it must be admitted, not required). Probably the only other material that has ever been prepared with purity comparable to that of silicon and germanium is uranium.

### 3.1 Fundamentals

Electron and hole charge:  $e = 1.6 \cdot 10^{-19} \text{ C}$

Effective mass:  $m^*$ , rest mass  $m_0$

$$F = -eE = m_0 \, dv/dt \quad \text{in vacuum,}$$

$$F = -eE = m^* \, dv/dt \quad \text{in solid,}$$

in Si,  $m_n^*/m_0 = 1.18$ ,  $m_h^*/m_0 = 0.81$  at 300 K.

Intrinsic properties.

In Si,  $n = p = 10^{10} \text{ cm}^{-3}$  at 300K  $N = 5 \cdot 10^{22} \text{ atoms} \cdot \text{cm}^{-3}$ .

Extrinsic properties.

Donors – group V

Acceptors – group III (are shown in table 3.1).

Table 3.1- Donors and acceptors

Acceptors	Donors
B	N
Al	P
Ga	As
In	Sb
Tl	Bi

Band diagrams:  $E_c$  = conduction band edge,  $E_v$  = valence band edge.

Band gaps: Si 1.12 eV;  
 diamond 5.4 eV;  
 silica 5 eV.

Energies of dopant levels, in meV, in silicon ( $kT = 26$  meV 300 K)

P	45	B	45
As	54	Al	67
		Ga	72

Carrier distributions (intrinsic).

$g(E) dE$  = density of electron states  $\text{cm}^{-3}$  in the interval  $(E, E+dE)$ , units  $\#/eV \cdot \text{cm}^{-3}$ ,

$$g_c(E) dE = m_n \sqrt{2m_n (\bar{E} - E_c)} / (\pi^2 h^3) dE,$$

$$g_v(E) dE = m_p \sqrt{2m_p (\bar{E}_v - E)} / (\pi^2 h^3) dE.$$

In these states, the electrons distribute according to Fermi function

$$f(E) = 1 / \{1 + \exp (E - E_f)/kT \}.$$

Number of electrons in the interval  $(E, E+dE)$  is therefore  $f(E)g(E)dE$ . In a doped semiconductor, the position of  $E_f$  with respect to the band gap determines whether there are more electrons or holes.

Total number of electrons: by integrating  $f(E)g(E)dE$

$$n = n_i \exp (E_f - E_i)/kT \quad p = n_i \exp (E_i - E_f)/kT,$$

where

$$n_i = N_c \exp (E_i - E_c)/kT.$$

$N_c = 2 \{2\pi m_n^* kT/h^2\}^{3/2}$  = 'effective density of conduction band states'.  
 $E_i$  is the position of the Fermi level in the intrinsic case.

Similarly for  $N_v$ .

Hence,

$$np = n_i^2 \text{ at equilibrium,}$$

$$n_i^2 = N_c N_v \exp (E_v - E_c)/kT = N_c N_v \exp (-E_g)/kT.$$

Intrinsic case:

$$E_i = (E_v + E_c)/2 + 3/4 kT \ln (m_p^*/ m_n^*).$$

In a doped material, where  $n \sim N_D$  or  $p \sim N_A$ ,

$$\begin{array}{ll} E_f - E_i = kT \ln (n/ n_i) & = - kT \ln (p/ n_i), \\ \sim kT \ln (N_D / n_i) & \text{or } - kT \ln (N_A / n_i), \\ \text{n-type} & \text{p-type.} \end{array}$$

### 3.2 Intrinsic semiconductors

The aim in semiconductor technology is to purify the material as much as possible and then to introduce impurities in a controlled manner. The pure semiconductor is called 'intrinsic' because its behaviour is determined by its intrinsic properties alone, and the semiconductor is called 'extrinsic' after external interference has changed its inherent properties.

Extrinsic semiconductors in devices are mostly used.

To be specific, about silicon, although most of remarks will be qualitatively true for germanium and other semiconductors. Silicon has the diamond crystalline structure; the four covalent bonds are symmetrically arranged. All the four valence electrons of each atom participate in the covalent bonds. All the electrons are in the

valence band at 0 K. There is an energy gap of 1.1 eV above this before the conduction band starts.

Thus, to get an electron in a state in which it can take up kinetic energy from an electric field and can contribute to an electric current, first one have to give it a package of at least 1.1 eV of energy. This can come from thermal excitation, or by photon excitation quite independently of temperature.

First of all only electrons and holes are near the bottom of the conduction band and the top of the valence band, respectively. Thus, one may assume that

$$k_x a, \quad k_y b, \quad k_z c \ll 1, \quad (3.1)$$

and to get the energy in the form,

$$E = E_1 - 2A_x \left(1 - \frac{1}{2} k_x^2 a^2\right) - 2A_y \left(1 - \frac{1}{2} k_y^2 b^2\right) - 2A_z \left(1 - \frac{1}{2} k_z^2 c^2\right). \quad (3.2)$$

Using definition of effective mass, it can easily show from the above equation that

$$m_x^* = \frac{\hbar^2}{2A_x a^2}; \quad m_y^* = \frac{\hbar^2}{2A_y b^2}; \quad m_z^* = \frac{\hbar^2}{2A_z c^2}. \quad (3.3)$$

Substituting the values of  $A_x a^2$ ,  $A_y b^2$ , and  $A_z c^2$  from eqn (3.3) back into eqn (3.2) and condensing the constant terms into a single symbol,  $E_0$ , it may now express the energy as

$$E = E_0 + \frac{\hbar^2}{2} \left( \frac{k_x^2}{m_x^*} + \frac{k_y^2}{m_y^*} + \frac{k_z^2}{m_z^*} \right). \quad (3.4)$$

Taking further  $E_0 = 0$ , and assuming that everything is symmetric, that is

$$m_x^* = m_y^* = m_z^* = m^*, \quad (3.5)$$

we get

$$E = \frac{\hbar^2}{2m^*} (k_x^2 + k_y^2 + k_z^2). \quad (3.6)$$

The mass in the denominator is not the real mass of an electron but the effective mass.

However that is the only difference between eqn (3.6) and the free electron model. The only difference is that the density of states must increase downwards for holes.

Choosing now the zero of energy at the top of the valence band, we may write the density of states in the following form

$$Z(E) = C_e (E - E_g)^{1/2}, \quad C_e = 4\pi(2m_e^*)^{3/2} / h^3 \quad (3.7)$$

for electrons, and

$$Z(E) = C_h (-E)^{1/2}, \quad C_h = 4\pi(2m_h^*)^{3/2} / h^3 \quad (3.8)$$

for holes, both of them per volume unit. This is shown in Figure 3.2, where  $E$  is plotted against  $Z(E)$ . Of course the density of states has the meaning only in the allowed energy band and must be identically equal to zero in the gap between the two bands.

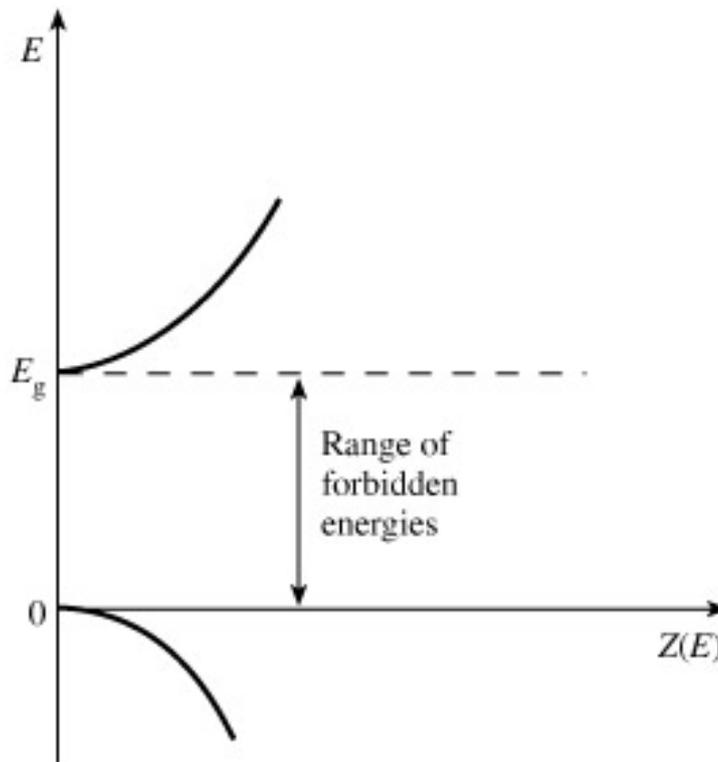


Figure 3.2 – Density of states plotted as a function of energy for the bottom of the conduction (electrons) and top of the valence (holes) bands

$$N_e = \int_{\text{bottom of conduction band}}^{\text{top of conduction band}} (\text{density of states})(\text{Fermi Function}) dE \quad (3.9)$$

### 3.3 Extrinsic semiconductors

Let's consider silicon as our specific example, but now with a controlled addition of impurity group V (this refers to column five in the periodic table of elements) as, for example, antimony (Sb), arsenic (As), or phosphorus (P). Each atom in group V will replace a silicon atom and use up to four of its valence electrons for covalent bonding (figure 3.3(a)). There will, however, be a spare electron. It will no longer be so tightly bound to its nucleus as in a free group V atom, since the outer shell is now occupied (we might look at it this way) by eight electrons, the number of electrons in an inert gas; so the dangling spare electron cannot be very tightly bound. However, the impurity nucleus still has a net positive charge to distinguish it from its neighbouring silicon atoms. Hence, one should suppose that the electron still has some affinity for its parent atom. In terms of band theory the energy gap represents the minimum energy required to ionize a silicon atom by taking one of its valence electrons. The electron belonging to the impurity atom clearly needs much less energy than this will become available for conduction. Its energy level is expected to be something like  $E_D$  in figure 3.3(b). (e.g.  $-E_D$ ) is typically of the order of  $10^{-2}$  eV (table 3.2). At absolute zero temperature an electron occupies this energy level, and it is not available for conduction. But at finite temperatures this electron needs no more than about  $10^{-2}$  eV of energy to be put into the conduction band. This phenomenon is usually referred to as an electron donated by the impurity atom. For this reason  $E_D$  is called the donor level. The energy difference between the donor levels and the bottom of the conduction band is shown in table 3.2 for several impurities.

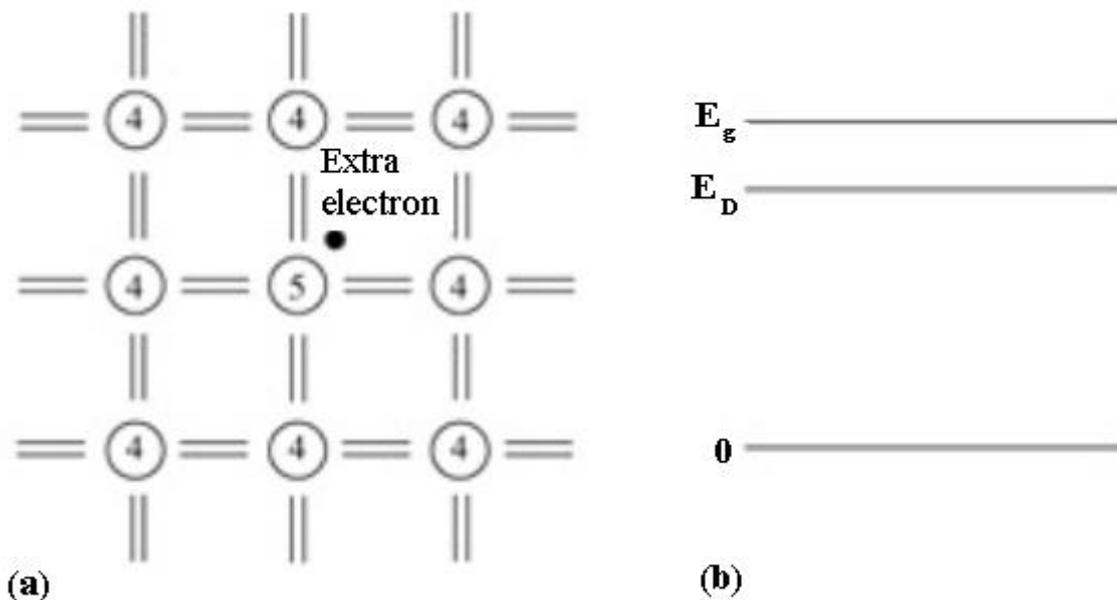


Figure 3.3 - (a) The extra electron 'belonging' to the group V impurity is much more weakly bound to its parent atom than the electrons taking part in the covalent

bond, (b) This is equivalent to a donor level close to the conduction band in the band representation

If the impurity is less than 1 in 10<sup>6</sup> silicon atoms, the lattice will be hardly different from that of a pure silicon crystal.

Table 3.2 – Energy levels of donor (group V) and acceptor (group III) impurities in Ge and Si. The given energies are the ionization energies, that is, the distance of the impurity level from the band edge is given in electron volts)

	Impurity	Ge	Si
Donors	Antimony (Sb)	0.0096	0.039
	Phosphorus (P)	0.0120	0.045
	Arsenic (As)	0.0127	0.049
Acceptors	Indium (In)	0.0112	0.049
	Gallium (Ga)	0.0108	0.065
	Boron (B)	0.0104	0.045
	Aluminium (Al)	0.0102	0.057

A very rough model serves to give a quantitative estimation of the donor levels. The energy of an electron in a hydrogen atom is

$$E = -me^4/8\epsilon_0^2 h^2. \quad (3.10)$$

Now one may state that the excess electron of the impurity atom is held by the excess charge of the impurity nucleus; that is, the situation is like that in the hydrogen atom, with two minor differences.

1. The dielectric constant of free space should be replaced by the dielectric constant of the material.

2. The free electron mass should be replaced by the effective mass of an electron at the bottom of the conduction band.

Thus, this model leads to the following estimation

$$E_g - E_D = m^* e^4 / 8\epsilon^2 h^2, \quad (3.11)$$

which for silicon, with a relative dielectric constant of 12 and an effective mass about half the free electron mass, gives a value of about 0.05 eV for  $(E_g - E_D)$ , which is not far from what is actually measured. However, it should be noted that the parameters in eqn (3.11) depend only on the properties of the host material, so this model cannot possibly indicate anything on how  $E_g - E_D$  varies with the type of dopant.

If instead of a group V impurity we had some group III atoms, as, for example, indium (In), aluminium (Al), or boron (B), there would be an electron missing from one of the covalent bonds (see figure 3.4). If one electron is missing, there must be a hole present.

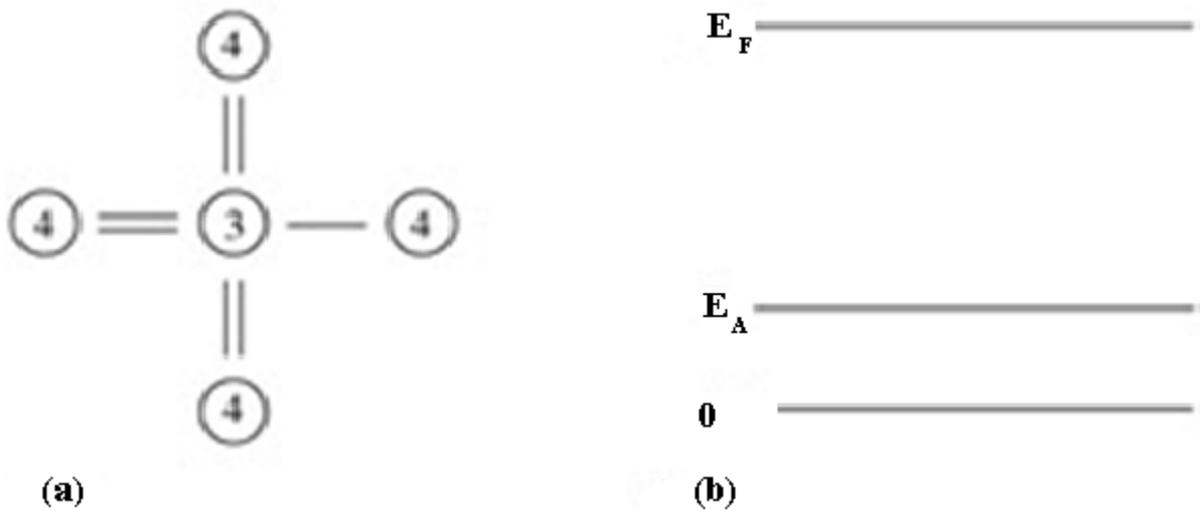


Figure 3.4 – (a) In the case of a group III impurity one bonding electron is missing – there is a 'hole' which any valence electron with a little surplus energy can fall into, (b) This shows in the band representation that an acceptor level is just above the valence band edge

A group III atom has three valence electrons. So when it replaces a silicon atom at a certain atomic site, it will try to contribute to bonding as much as it can. However, it possesses only three electrons for four bonds. Any electron wandering around would thus be welcomed to help out. More aggressive impurity nuclei might even consider stealing an electron from the next site.

The essential point is that a low energy state is available for electrons – not as low an energy as at the host atom but low enough to come into consideration when an electron has acquired some extra energy and feels an urge to jump somewhere. Therefore, the energy levels due to group III impurities must be just above the valence band. Since these atoms accept electrons so willingly, they are called acceptors and the corresponding energy levels are referred to acceptor levels.

A real material will usually have both electron donors and acceptors present (not necessarily group V and group III elements; these were chosen for simplicity of discussion and because they are most often used in practice).

However, usually one type of impurity exceeds the other, and we can talk of impurity semiconductors as n- (negative carrier) or p- (positive carrier) types according to whether the dominant charge carriers are electrons or holes. If there was some silicon with 1020 atoms per cubic metre of trivalent indium, it would be a p-type semiconductor. If somehow to add pentavalent phosphorus, the spare phosphorus electrons would not only get to the conduction band but would also populate the acceptor levels, thus obliterating the p characteristics of the silicon and turning it into n-type semiconductor.

### 3.4 Relationship between electron and hole densities

For a given semiconductor (i.e. for known values of  $m_c^*$ ,  $m_h^*$ , and  $E_g$  and temperature) we can define the product  $N_e N_h$  exactly, whatever the Fermi energy and hence whatever the impurity density. In particular, for an intrinsic material, where  $N_e = N_h = N_i$  we get

$$N_e N_h = N_i^2. \quad (3.12)$$

If the number of electrons increases, the number of holes must decrease.

Start with an intrinsic semiconductor having equal numbers of electrons and holes. Now add some donor atoms. The number of electrons must then increase, but according to eqn (3.11) the product must remain constant. At first this seems rather odd. By increasing the concentration of donors, the total number of electrons in the conduction band is increased, but the number of electrons excited across the gap is decreased (not only in their relative proportion but in their absolute number too). Why?

It means that electron-hole pairs are constantly created and annihilated and there is an equilibrium when the rate of creation equals the rate of annihilation (the latter event is more usually referred to as 'recombination').

Now it is not unreasonable to assume that electrons and holes can find each other more easily if there are most of them. For an intrinsic material one can write

$$r_{\text{intrinsic}} = aN_i^2, \quad g_{\text{intrinsic}} = aN_i^2, \quad (3.13)$$

The rate of recombination must be proportional to the densities of holes and electrons. Where  $a$  is a proportionality constant, and  $r$  and  $g$  are the rates of recombination and creation, respectively.

Now one may state that by adding a small amount of impurity, neither the rate of creation nor the proportionality constant should change. So, for an extrinsic semiconductor is still valid.

$$g_{\text{extrinsic}} = aN_i^2. \quad (3.14)$$

The rate of recombination should, however, depend on the actual densities of electrons and holes, that is

$$r_{\text{extrinsic}} = aN_e N_h. \quad (3.15)$$

From the equality of eqns (3.14) and (3.15) we get the required relationship

$$N_i^2 = N_e N_h. \quad (3.16)$$

As the density of electrons is increased above the intrinsic value, the density of holes must decrease below the intrinsic value in order that the rate of recombination of electron-hole pairs may remain at a constant value equal to the rate of thermal creation of pairs.

This can be illustrated by a chemical reaction between A and B, giving rise to a compound AB.



If to represent the molecular concentration of each component by writing its symbol in square brackets, the quantity is a constant at a given temperature.

$$[A][B][AB]^{-1} = \text{constant}. \quad (3.18)$$

Now the 'reaction' is



As the number of bound electrons is constant, this means that the number of holes will also be constant.

$$[\text{electron}][\text{hole}] = N_e N_h. \quad (3.20)$$

### 3.5 III–V and II–VI compounds

Germanium and silicon are typical semiconductors, their technology was the earliest mastered. They are both tetravalent, so they can be found in column IVB of the periodic table. There are, of course, many other semiconductors. Two other types which are compounds of elements from columns IIIB, VB, IIB, and VIB, respectively will be considered, respectively.

First about the III–V compounds. Why are they semiconductors? The same thing about them is as about germanium and silicon. They are insulators at low temperatures because all the electrons participate in the bonding process: none of them is available for conduction. At higher temperatures, however, the electronic bond can be broken by thermal excitations, that is electrons can be excited into the conduction band.

The only difference relative to Ge and Si is that III–V compounds have an ionic contribution to the bonding. The ionic bond of NaCl formed because the one outer electron of sodium can join the seven outer electrons of chlorine to make up a

completed ring. So it is easy to see that, with Ga having three outer electrons and As having five outer electrons, they will also strike up a companionship in order to complete the ring.

Note, however, that a III–V ionic bond is weaker than a I–VII ionic bond.

Which are the most important III–V materials? The oldest one, and technologically the best developed technologically, is GaAs.

Measured curves of electron and hole mobilities against impurity concentration are shown in Figure 3.5.

What about the energy gap of GaAs? It is, 1.40 eV, much higher than that of Ge, the element between them in the periodic table. The energy gap is higher, which means that it is more difficult to break a bond in GaAs than in Ge.

There is something definite about the energy gaps of some other compounds relative to that of GaAs. If the element in the periodic table above As is combined with Ga, we obtain GaP with an energy gap of 2.25 eV. If the other element in the compound Sb, which is below As in the periodic table is chosen for, then GaSb with an energy gap of 0.7 eV is obtained. The same is if to combine various elements from column III with As. The energy gap of AlAs is 2.1 eV, whereas the energy gap declines to 0.35 eV for InAs.  $\mu$

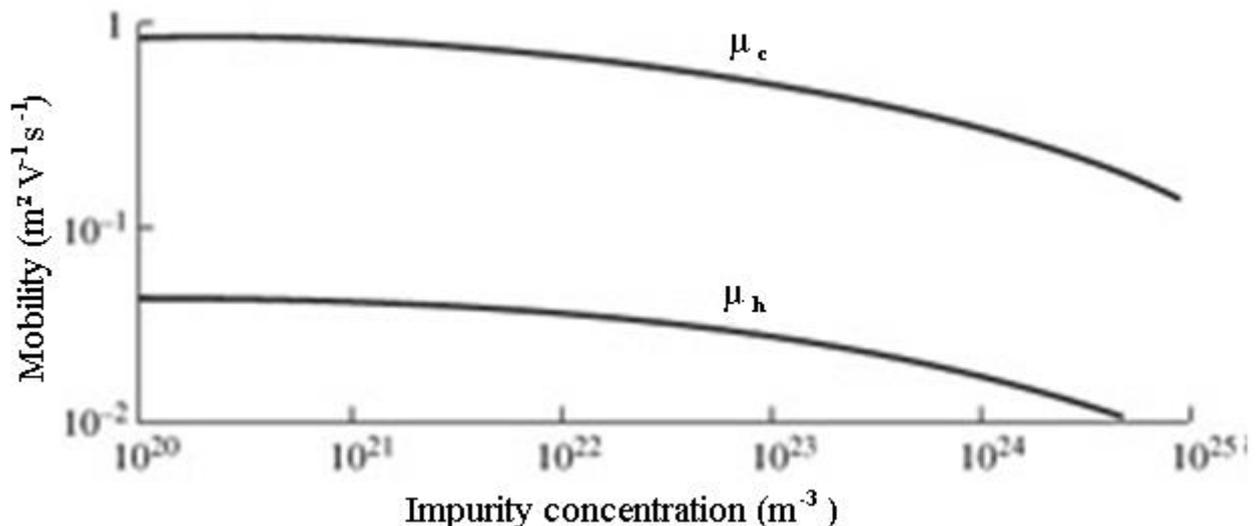


Figure 3.5 – Electron and hole mobilities in GaAs as a function of impurity concentration

The general rule is the lower elements go in the periodic table is the smaller gap.

How can one make a III–V material? Is GaAs n-type or p-type? If there is an excess of Ga it will be p-type, if there is an excess of As it will be n-type. Or one can

try as a dopant a column IV material, for example, silicon. It acts as a donor if it replaces a Ga atom, and as an acceptor if it replaces an As atom.

### 3.6 Non-equilibrium processes

A few cases where the equilibrium is disturbed are following.

The simplest way of disturbing the equilibrium is to make electromagnetic waves (in practice these are mostly in the visible range) illuminate upon the semiconductor. As a result a photoemission may occur, as in metals, but more interesting, the number of carriers available for conduction may significantly increase. This case is called a photoconductivity.

The three possible processes of producing carriers for conduction are shown in figure 3.6; (i) is creating an electron-hole pair, that is exciting an electron from the valence band into the conduction band; (ii) is exciting an electron from an impurity level into the conduction band; (iii) is exciting an electron from the top of the valence band into an impurity level, and thus leaving a hole behind.

Extra carriers are available for conduction as long as the semiconductor is illuminated.

What happens when the light is switched off? The number of carriers must fall gradually to the equilibrium value. The time in which the extra density is reduced by a factor  $e$  is called the lifetime of the carrier and is generally denoted by  $\tau$  (and is thus quite often confused with the collision time). It is an important parameter in the design of many semiconductor devices.

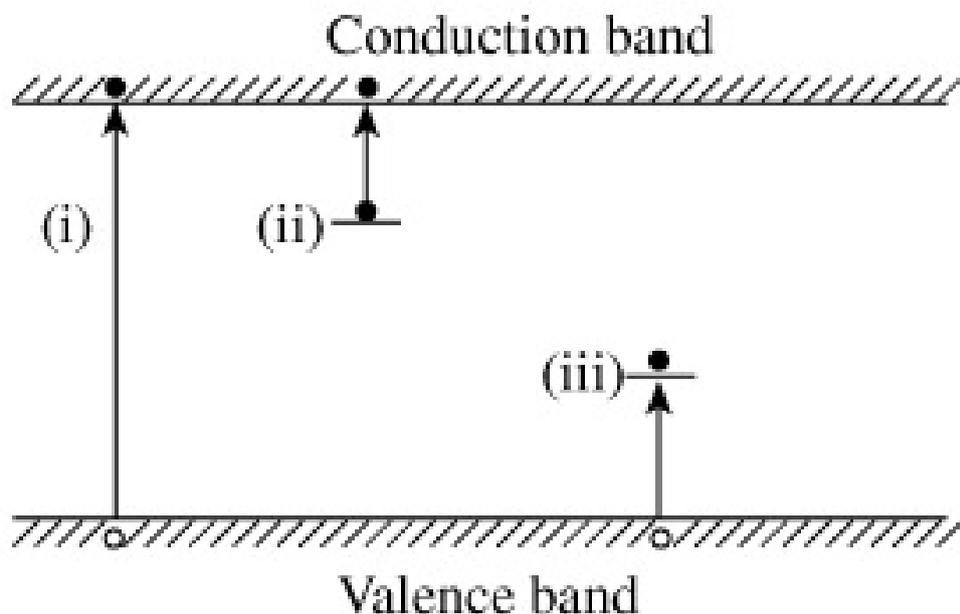


Figure 3.6 – Three models of obtaining free carriers by illumination – (i) band-to-band transitions yielding an electron-hole pair, (ii) ionization of donor atoms, (iii) ionization of acceptor atoms

### 3.7 Real semiconductors

All relationships have been based on some idealized model. Perhaps the greatest distortion of reality is that all semiconductors are crystallized in a simple cubical structure. They do not. The most commonly used semiconductors, silicon and germanium, are crystallized in the diamond structure, and this makes a significant difference.

Plotting the  $E$  vs  $k_x$  curve (figure 3.7) for the conduction band of silicon, it does not close resemblance to our simple curve, which had its minimum at  $k_x = 0$ . Even worse, the  $E(k_y)$  curve would be very different from the one plotted. The surfaces of constant energy in  $k$ -space are not spheres.

$$E = E_0 - 2A_x \cos k_x a.$$

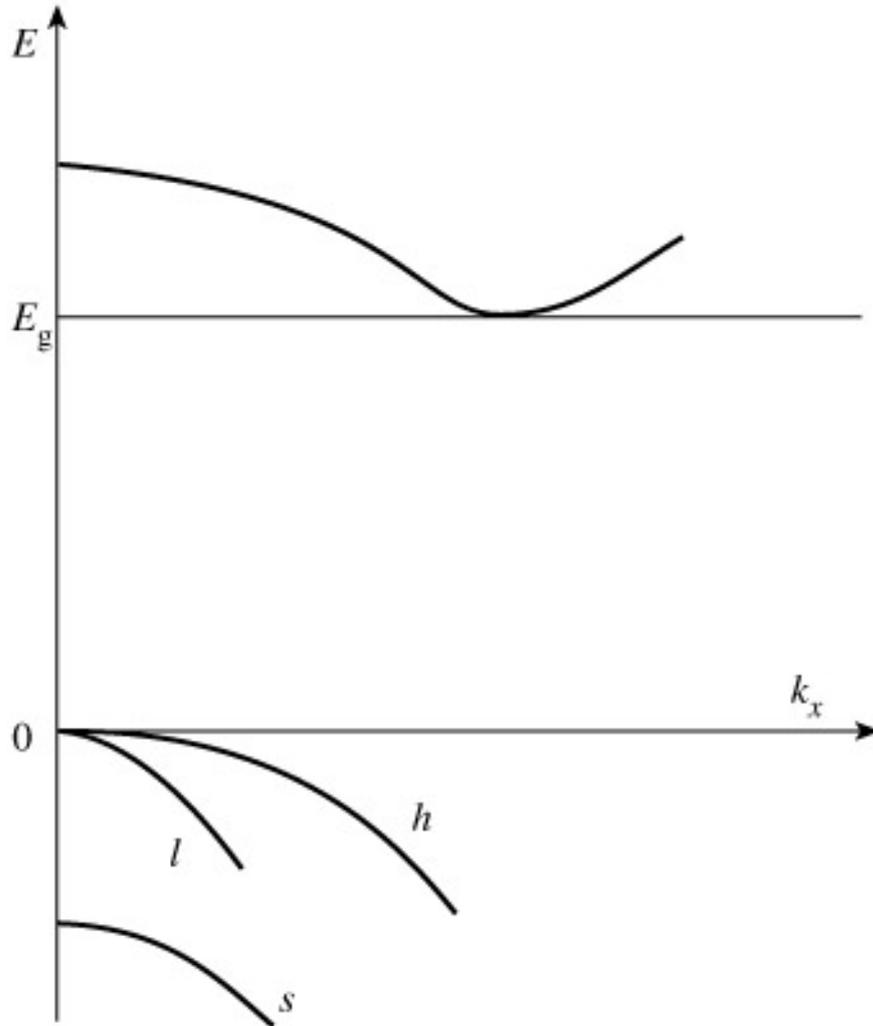


Figure 3.7 –  $E - k$  curve for silicon in a particular direction

Note that the minimum of the conduction band is not at  $k = 0$  and there are three different types of holes. The situation is similar in germanium, which is also an indirect-gap (minimum of conduction band not opposite to maximum of valence band) semiconductor.

The situation is not much better in the valence band, where the constant energy surfaces are nearly spheres but there are three different types of present holes. This is shown in figure 3.7, where the letters  $h$ ,  $l$ , and  $s$  stand for heavy, light, and split-off bands, respectively.

There are three different types of holes in the valence band of silicon but for device operation only the average effective mass and some sort of average collision time are needed.

Another important deviation from the idealized band structure occurs in a number of III–V compounds, where a subsidiary valley appears in the conduction band (is shown for GaAs in figure 3.8).

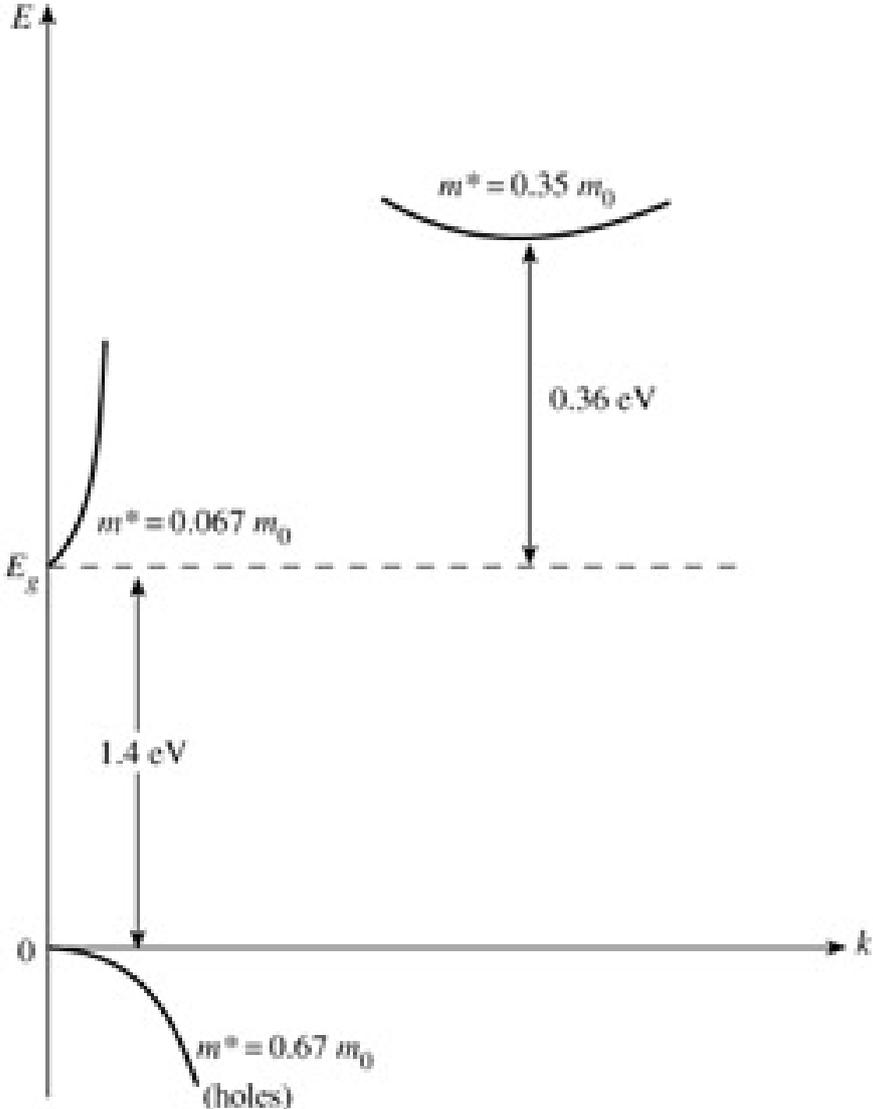


Figure 3.8 – Energy band diagram for gallium arsenide showing subsidiary

valley in conduction band

For most purposes (making a gallium arsenide transistor, for example) the existence of this additional valley can be ignored but it acquires special significance at high electric fields. It constitutes the basis for the operation of a new type of device. For the description and design of the large majority of semiconductor devices this model is quite adequate.

This is not true for graphite, for example, which has very different conductivities in different directions, but single crystal graphite is not widely used in semiconductor devices.

Fob/crystalline graphite has been used ever since the birth of the electrical and electronics industries (for brushes and microphones) but the operational principles of these devices are simple.

### **3.8 Amorphous semiconductors**

Very pure and regular crystal forms of Ge, Si, and other semiconductors have used simple models based on this symmetry to derive basic properties like energy gap and conductivity. What will happen if the material is not a single crystal let us suppose that one semiconductor evaporates a film of Si on to a suitable substrate? The film consists of randomly oriented clusters of crystallites (small crystals). The structure within the crystallites leads to an energy gap. Another effect of small crystallites is that the covalent bonds break off where the orientation changes, so that there are 'dangling bonds', where unpaired electrons can act as traps for both itinerant electrons and holes. Mobility is greatly reduced; and also doping is much less effective, as the carriers from the dopant are trapped. This effect ties the Fermi level near the middle of an energy gap, as it is both in intrinsic materials and insulators.

If an amorphous layer is formed in discharged gas containing hydrogen, the 'dangling bond' is dramatically reduced. The H atoms neutralize unpaired electrons, and the atomic nucleus has a minimal effect on lattice behaviour. In these circumstances amorphous Si can be doped into both p- and n-type.

The reason of the use of amorphous semiconductors is simply economical. The amorphous variety is used in large areas, such as in solar cells or in xerographic applications.

## **4 Magnetic Materials**

The lodestone was one of the earliest known applications of science in industry – the compass for shipping; and ferromagnetism is of even greater importance for industrial society today.

### **4.1 Types of magnetic materials**

The term “magnet” is typically reserved for objects that produce their own persistent magnetic field even in the absence of an applied magnetic field. Only certain classes of materials can do this. Most materials produce a magnetic field in response to an applied magnetic field – a phenomenon known as magnetism. There are several types of magnetism, and all materials have at least one of them.

The overall magnetic behavior of a material can vary widely, depending on the structure of the material, particularly on its electron configuration. Several forms of magnetic behavior have been observed in different materials, including:

1) Ferromagnetic and ferrimagnetic materials are attracted to a magnet strongly enough, so that the attraction can be felt. These materials are the only ones, that can retain magnetization and become magnets; a common example is a traditional refrigerator magnet.

2) Ferrimagnetic materials, which include ferrites and the oldest magnetic materials, magnetite and lodestone, are similar to but weaker than ferromagnetics. The difference between ferro- and ferrimagnetic materials is related to their microscopic structure. Ferromagnets have spontaneous magnetization, large permeability which depends on the history of the sample, and nonlinear, hysteretic behavior.

3) Paramagnetic substances, such as platinum, aluminum, and oxygen, are weakly attracted to either pole of a magnet. This attraction is hundreds of thousands of times weaker than that of ferromagnetic materials, so that it can only be detected by using sensitive instruments or using extremely strong magnets. Magnetic ferrofluids, although they are made of tiny ferromagnetic particles suspended in liquid, are sometimes considered paramagnetic ones since they cannot be magnetized. Paramagnet: atoms have a net moment but the spin directions are randomly arranged. An applied field can give weak alignment, hence a small susceptibility that varies with  $1/T$  ( $\mu_r > 1$ ).

Diamagnetic means are repelled by both poles. Compared to paramagnetic and ferromagnetic substances, diamagnetic substances, such as carbon, copper, water, and plastic, are repelled even more weakly by a magnet. The permeability of diamagnetic materials is less than that of vacuum.

All substances not possessing one of the other types of magnetism are diamagnetic; this includes most substances. Although the force of a diamagnetic object from an ordinary magnet is too weak to be felt, one can use extremely strong superconducting magnets. Superconductors repel magnetic fields from their interior and are strongly diamagnetic. Diamagnet: an atom has no net magnetic moment, but a field induces a small moment opposite to the field. Susceptibility is negative ( $\mu_r < 1$ ).

There are other various types of magnetism, such as spin glass, superparamagnetism, superdiamagnetism, and metamagnetism.

## **4.2 Magnetic properties of materials**

The properties of magnetic materials may vary considerably from specimen to specimen due to chemical composition and state of heat treatment.

Many magnetic properties of materials are expressed in terms:

- $B$  = magnetic flux density
- $B_r$  = remanence
- $H$  = magnetic field strength
- $H_{cB}$  = induction coercive force, coercivity
- $H_{cJ}$  = magnetization coercive force, coercivity
- $J$  = magnetic polarization
- $J_s = (B - \mu_0 H)_s$  = saturation polarization
- $Q_h$  = hysteresis loss per volume unit per cycle
- $\mu_r$  = relative magnetic permeability
- $\mu_i$  = initial relative magnetic permeability

The SI units of  $H$  and  $B$  are ampere per metre ( $A \cdot m^{-1}$ ) and tesla (T), respectively.

The presence of a magnetic material will enhance the magnetic flux density. Thus the ratio

$$B = \mu_0 H, \quad (4.1)$$

valid in vacuum, is modified to

$$B = \mu_0 (H + M), \quad (4.2)$$

where  $M$  is the magnetic dipole moment per volume unit, or shortly, magnetization in a magnetic material.

The magnetization is related to the magnetic field by the ratio

$$M = \chi_m H, \quad (4.3)$$

where  $\chi_m$  is the magnetic susceptibility.  
Substituting eqn (4.3) into eqn (4.2) we get

$$B = \mu_0 (1 + \chi_m) H = \mu_0 \mu_r H, \quad (4.4)$$

where  $\mu_r$  is called the relative permeability.

The relation between the quantities expressed in SI units is:

$$B = \mu_0 H + J,$$

in which  $\mu_0$  is  $4\pi \times 10^{-7} \text{ H m}^{-1}$ , the magnetic constant (permeability of free space). The absolute permeability,  $\mu = B/H$  and the volume susceptibility  $\kappa = J/\mu_0 H$ , are thus related by the equation:

$$\mu = \mu_0(1 + \kappa).$$

Mass susceptibility  $\chi$  is equal to  $\kappa/\rho$ , where  $\rho$  is the density.

Relative permeability  $\mu_r = \mu/\mu_0$  is the permeability of the material relative to a vacuum.

In ferromagnetic materials where  $H$  is increased steadily from zero, the permeability changes and is at first relatively small, its value being defined as the initial permeability, then reaches a maximum value, and finally decreases towards  $\mu_0$  as the polarization tends towards a limiting value ( $B - \mu_0 H$ ). The flux density remaining when  $H$  is reduced to zero is the remanent flux density and the negative  $H$  needed to reduce  $B$  to zero is the coercive force. The remanent flux density and coercive force for a cycle which proceeds to saturation are called the remanence,  $B_r$ , and the coercivity,  $H_{cB}$ . In an open magnetic circuit the variation of  $J$  with  $H$  is usually measured and the coercivity is then denoted by  $H_{cJ}$ .

When a ferromagnetic material is taken through a cycle of magnetization there is a loss of energy as heat due to the combined effects of hysteresis, induced eddy currents and domain wall motion. The hysteresis loss per unit volume,  $Q_h = \oint H dB$ , to vary as  $B_{\text{max}}^{1.6}$  over a limited range of peak flux density of up to about 1 T for high saturation materials, and 0.5 T for low saturation materials. The total power losses that will be dissipated in laminar material when an alternating flux is developed in it has a direct bearing on the efficiency that can be realized in equipment such as transformers and electric motors and should therefore be known accurately.

Many magnetic properties of ferromagnetic materials depend greatly on previous history, state of strain, temperature, size, perfection and orientation of crystals, and the effect of small traces of impurity may be enormous.

When heated, ferromagnetic materials become paramagnetic at a temperature known as the (ferromagnetic) Curie point.

Ferrimagnetic materials (ferrites) have all characteristics of ferromagnetic materials. However, due to their high resistivity, soft (low coercivity) ferrites are widely used in high frequency applications, in this case the following parameters are also interesting:

(a) Power loss density – this is another name for specific total power loss, but for ferrite materials the loss is usually expressed per unit volume.

(b) Loss factor – the performance of ferrites at low field strengths is often indicated by the expression  $\tan \delta$  where  $\delta$  is the loss angle, i.e. the phase angle between  $B$  and  $H$ . If information regarding power losses is usually given in the form of loss factors normalized to unit permeability,  $\mu$ , since this facilitates the calculation of loss coefficients of gapped ferrite cores. Hence the loss factor is:

$$\frac{\tan \delta}{\mu} = \frac{\tan \delta_h}{\mu} + \frac{\tan \delta_e}{\mu} + \frac{\tan \delta_r}{\mu},$$

where  $\tan \delta_h$ ,  $\tan \delta_e$  and  $\tan \delta_r$  are the loss angles for the hysteresis, eddy current and residual losses, respectively, all of which are present to a greater or less extent and combine to give the total loss,  $\tan \delta$ .

(c) IEC hysteresis coefficient  $\eta_B$  – in considering recommendations for standard forms of loss expression, the International Electrotechnical Commission agreed the following relationship for the hysteresis coefficient,  $\eta_B$ ,

$$\eta_B = \frac{\tan \delta_h}{\mu B_{max}}.$$

(d) Temperature factor is the permeability of a magnetic material may change for a variety of reasons, the most obvious being the change of temperature. Over a limited temperature range the relationship between the reversible change in magnetic permeability,  $\Delta\mu$ , and the corresponding change in temperature,  $\Delta\theta$ , is given by the temperature coefficient,  $TC$ :

$$TC = \frac{\Delta\mu}{\mu\Delta\theta}.$$

As with the loss factor, it is usual to normalize the values to unit permeability which gives the loss factor:

$$\text{Loss factors} = \frac{\Delta\mu}{\mu^2\Delta\theta}.$$

(e) Disaccommodation factor is the permeability of a magnetic material can also change with time after magnetization. This phenomenon is often called disaccommodation. If permeabilities  $\mu_1$  and  $\mu_2$  correspond to time  $t_1$  and  $t_2$  the disaccommodation is given by:

$$\frac{\mu_1 - \mu_2}{\mu_1} \times 100\%.$$

As with the loss and temperature factors, the disaccommodation factor is normalized to a permeability unit and is given by:

$$\text{disaccommodation factor} = \frac{\mu_1 - \mu_2}{\mu_1} \times 100\%.$$

Apart from changes in their magnetic permeability, some materials have other responses to changes in magnetic field strength. All conducting materials exhibit the Hall effect, of which there are two forms. In the transverse Hall effect a voltage is developed in a direction at right angles to a current passing through the material when

a magnetic field is applied in a mutually perpendicular direction. The ratio between the current flowing through the material  $I_x$ , output voltage,  $V_y$ , the thickness of the material,  $t_z$ , and the applied magnetic field strength,  $H_z$ , are given by:

$$V_y = (K_H I_x \mu_0 H_z) / t_z,$$

where  $K_H$  is the transverse Hall coefficient of the material. It has been found that some semiconducting materials have sufficiently high Hall coefficients to produce convenient, small size and low cost magnetic sensors. Indium arsenide having a Hall coefficient of 0.75 Vm/TA is a widely used material.

The same conditions that produce the transverse Hall effect also give rise to a voltage in the direction of the current and this is sometimes called the longitudinal Hall effect but more usually magnetoresistance. Until recently only small changes in resistance have been observed (up to 2% for the widely used  $\text{Ni}_{80}\text{Fe}_{20}$  material at room temperature) but the so-called giant magnetoresistance (GMR) has been observed in multilayers of Fe/Cr (50% change in resistance) and Co/Cu (120% change in resistance). However, strong magnetic field strengths ( $\approx 800$  kA/m) and the temperature of 4.2 K are required to observe GMR in a multilayer. In all cases the magnetoresistance of a material is a complex function of the applied magnetic field strength, temperature, material type and thickness.

### 4.3 Hysteresis curve

Freshly smelted iron does not act as a magnet. How is this possible? If, below the Curie temperature, all the magnetic moments line up spontaneously, how can the outcome be a material exhibiting no external magnetic field? Weiss postulated the existence of a domain structure. The magnetic moments do line up within a domain, but the magnetizations of the various domains are randomly oriented relative to each other, leading to zero net magnetism.

The magnetization curve of a typical ferromagnetic material exhibits hysteresis, as shown in figure 4.1. Starting with a completely demagnetized material, we move up the curve along 2, 3, 4, 5 as the magnetic field is increased. Reducing then the magnetic field, we get back to point 6, which is identical with point 4, but further decrease takes place along a different curve. At 7 there is no applied magnetic field, but  $B$  is finite. Its value,  $B = B_r$ , is the so called remanent flux density. Reducing further, the magnetic field  $B$  takes the values along 8, 9, 10. Returning from 10, we find that 11 is identical with 9 and then proceed further along 12 and 13 to reach finally 4.

The loop 4, 7, 8, 9, 12, 13, 4 is referred to as the hysteresis loop. It clearly indicates that the magnetization of iron is an irreversible phenomenon.

The value of  $H$  at 13 is called the coercivity, denoted by  $H_c$ . It represents the magnetic field needed for the flux density to vanish.

The paths 4, 5 and 9, 10 suggest that rotation from easy into difficult directions is reversible, thus the causes of irreversibility should be sought in domain movement.

Because of the presence of all sorts of defects in a real material, the domain walls move in little jerks, causing the magnetization to increase in a discontinuous manner (region 2, 3 magnified in figure 4.1). The walls get stuck once in a while and then suddenly surge forward, setting up in the process some eddy currents and sound waves, which consume energy. If energy is consumed, the process cannot be reversible, and that is the reason for the existence of the hysteresis loop.

If the material exhibits a large anisotropy and stresses are present as well, then there will be local easy directions resisting the movement of domain walls everywhere. The stresses may be caused by the usual defects in crystals and particularly by impurities. In addition, a cluster of non-magnetic impurity atoms might be surrounded by domains (figure 4.2). This is a stable configuration which cannot be easily changed.

How can we classify magnetic materials? There is a simple division into soft and hard magnetic materials. Why soft and hard? Well, the hard materials are those which are hard to magnetize and demagnetize. So materials which are easy to magnetize and demagnetize should be called *easy* materials. In fact, they are called soft materials. They are only very tenuously related to mechanical properties, which may also be hard and soft.

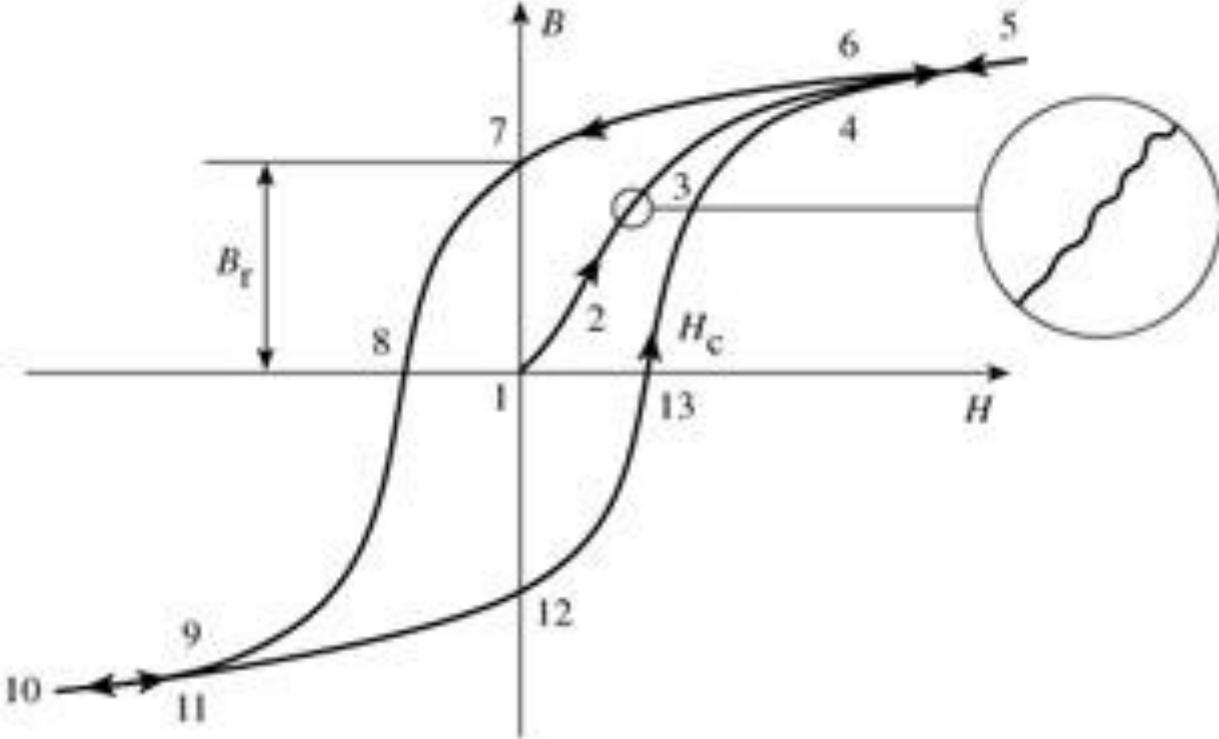


Figure 4.1 – The magnetization curve of a typical ferromagnetic material

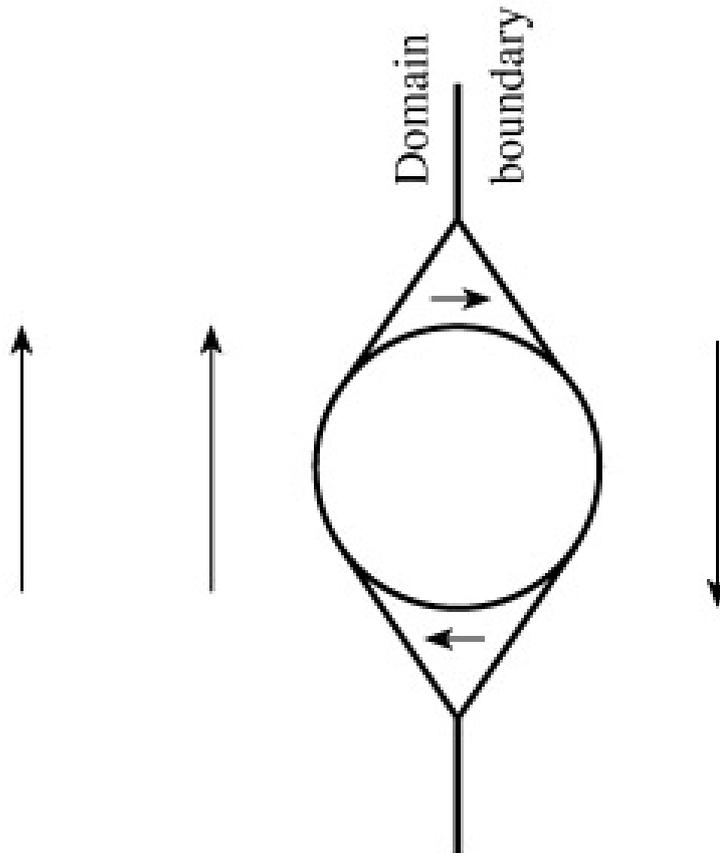


Figure 4.2 – Non-magnetic impurity surrounded by a domain

#### 4.4 Soft magnetic materials

Main role of soft magnetic materials is to enhance the magnetic effect produced by a current carrying coil. So, obviously, they should have large saturation magnetization and large permeability.

If the material is subjected to alternating voltages, then an important consideration is to reduce losses caused by the induced eddy currents, which can be done by increasing resistivity.

What else is needed in order to reduce losses? A narrow hysteresis loop is needed as shown below.

The energy dissipated in a coil for a period  $T$  may be expressed with the aid of the current and voltage as

$$E_d = \int_0^T V(t)i(t) dt. \quad (4.5)$$

Now, using Faraday's law (that the voltage is proportional to the derivative of the flux density) and Ampère's law (that the magnetic field is proportional to current) eqn (4.5) may be rewritten as

$$E_d = C \int H dB, \quad (4.6)$$

where  $C$  is a constant. Thus, clearly, the energy loss per cycle is proportional to the area of the hysteresis loop.

The most important parameter determining the desirable properties of soft magnetic materials is the frequency at which they are used. For d.c. applications the best material is the one with the largest saturation magnetization. As the frequency increases, it is still important to have large saturation magnetization, but low coercitivity is also a requirement.

At high frequencies, considering that eddy current losses are proportional to the square of the frequency, the most important property is high resistivity.

In practical terms this is probably the most important materials science problem that we have touched upon. Something like many millions of megawatts of electricity is being generated around the world, all by generators with hysteresis losses of order 0.5–1.0%. Then a large fraction of this electricity goes into motors and transformers with more iron losses. Anisotropy, magnetostriction, and local stresses are bad.

Iron containing silicon is used in most electrical machines. An alloy with about 2% silicon, a pinch of sulfur, and critical cold rolling and annealing processes are used for much rotating machinery. Silicon increases the resistivity, which is a good thing because it reduces eddy-current losses. Iron with a higher silicon content is even better and can be used in transformer laminations, but it is mechanically brittle and therefore no good for rotating machinery. Where small quantities of a very low-loss material are required and expense is not important, as for radio-frequency transformers, Permalloy (78.5% Ni, 21.5% Fe) is often used.

A further improvement is achieved in the material called 'Supermalloy' which contains a little molybdenum and manganese as well. It is very easily magnetizable in small fields (figure 4.3 (a)) and has no magnetostriction.

If anisotropy is bad, and anisotropy is due to crystal structure, it is necessary to get rid of the crystal structure. Obviously we need an amorphous material. How can an amorphous material be produced? By cooling the melt rapidly, so that the liquid state disorder is frozen in. The key word is 'rapidly'. In fact, the whole process is called Rapid Solidification Technology, abbreviated as RST.

The cooling should proceed at a speed of about a million degrees per second, so the technological problems have not been trivial. In the first successful commercial solution a stream of molten metal is squirted on a cooled rotating drum, followed usually by a stress relief anneal at about 300°C. The resulting magnetic material has the form of long thin ribbons typically about 50  $\mu\text{m}$  thick and a few millimetres wide.

New production methods, for example, the planar flow casting method, in which a stable rectangular melt 'puddle' feeds the material into the drum, have led to further improvements. It is now possible to obtain a uniform ribbon with a thickness of 20–30  $\mu\text{m}$  and up to 20 cm wide.

The main advantage of amorphous materials is that they can be produced easily and relatively cheaply, with magnetic properties nearly as good as those of commercial alloys, which require careful melting and elaborate sequences of rolling and annealing.

The presently available amorphous materials have not quite reached the quality of supermalloy, but they are quite close. The cobalt-based commercially available 2714 A material has a saturation magnetization of 0.5 T with a maximum permeability of a million. Another one, known as 2605S-3 A made of iron and chromium has a saturation magnetization of 1.4 T and a maximum permeability over a quarter of a million.

The latest line of soft magnetic materials is the nanocrystalline alloys with grain sizes of the order of 10 nm. They have been around for about 10 years. Typical representatives are Fe-B-Si-Cu-Nb alloys, which may reach relative permeabilities over 100000. The excellent soft magnetic properties may be explained by the reduction in effective crystal anisotropy expected when grain sizes are reduced below the bulk-domain wall thickness.

The situation is somewhat different in power applications, such as transformers. The traditional materials are cheaper, but amorphous materials may still represent the best choice on account of lower losses; their higher cost may be offset in the long term by lower power consumption.

At higher frequencies high resistivities are required for which a family of ferrites with chemical formula  $MO \cdot Fe_2O_3$  (where M is a metal, typically Ni, Al, Zn, or Mg) is used. If the metal M is iron, the material is iron ferrite,  $Fe_3O_4$ , the earliest-known magnetic material.

Ferrites are usually manufactured in four stages:

- 1) In the first stage the material is produced in the form of a powder with the required chemical composition.
- 2) In the second stage the powder is compressed.
- 3) In the third stage is sintering to bind the particles together.
- 4) The fourth stage is machining (grinding, since the material is brittle) to bring the material to its final shape.

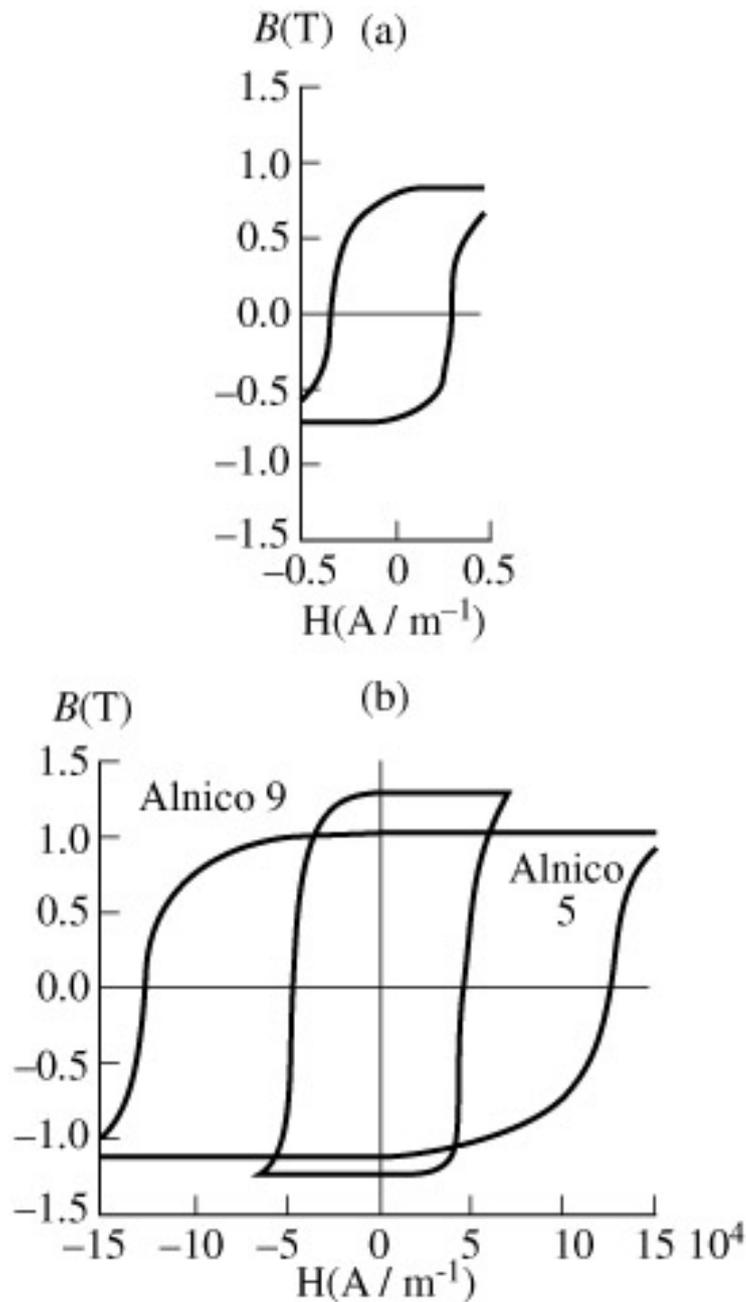


Figure 4.3 – Hysteresis loops of (a) Supermalloy and (b) Alnico 5 and 9.  
 Note the factor 105 between the horizontal scales of (a) and (b)

#### 4.5 Hard magnetic materials

What kind of materials is good for permanent magnets? If large flux density is produced, we need a large value of  $B_r$ . What else? A large  $H_c$ . Why? The high value of  $B_r$  needs to be protected. If for some reason is not at the  $H = 0$  point,  $B - H$  curve should be as wide as possible.

In a ring magnet (figure 4.4 (a))  $B = B_r = \text{constant}$  everywhere in the material to a very good approximation.

Such a permanent magnet may be made by cutting a narrow gap in the ring, as shown in Figure 4.4 (b). What will the values of  $B$  and  $H$  be in the gap? The flux

density in the gap will be the same as in the magnetic material. Will the flux density be the same in the presence of the gap as in its absence? Without the gap,  $B = B_r$  (figure 4.5). If the value of flux density is denoted by  $B = B_{r1}$  in the presence of the gap, the magnetic field in the gap will be  $H_g = B_{r1}/\mu_0$ .

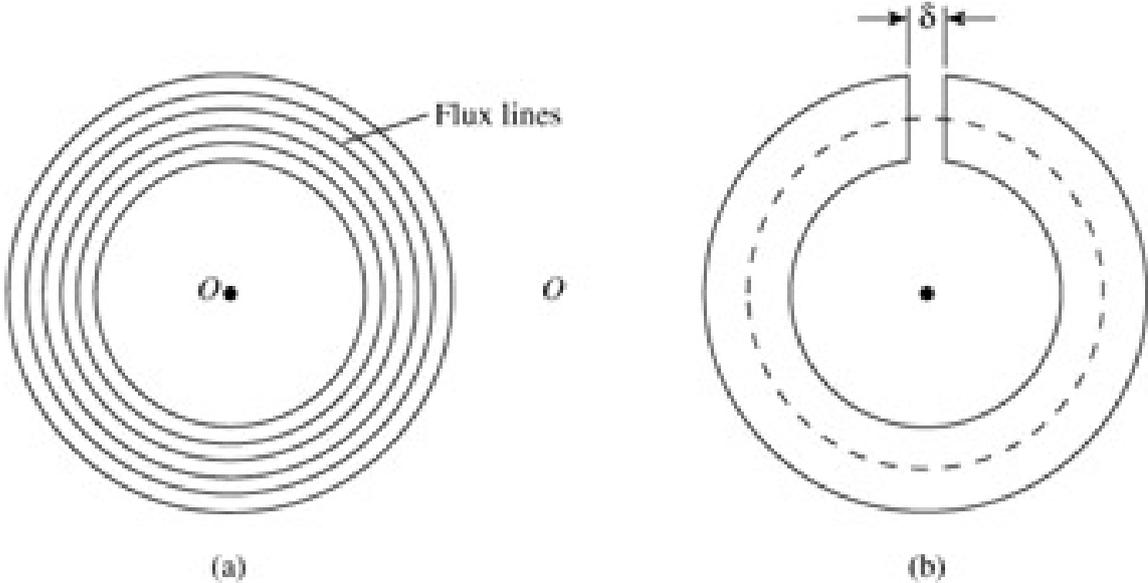
Ampère's law, which states that the line integral of the magnetic field in absence of current must be equal to  $\mathbf{0}$  for a closed path, it follows that

$$H_g \delta + H_m l = 0, \tag{4.7}$$

where  $H_m$  is the magnetic field in the material, and  $\delta$  and  $l$  are the lengths of the paths in the gap and in the material, respectively.

From the above equations we get

$$B_{r1} = -\frac{\mu_0 l}{\delta} H_m. \tag{4.8}$$



(a) Magnetic field lines inside a permanent magnet;  
 (b) The same magnet with a narrow gap.

Figure 4.4

The relationship between  $B_{r1}$  and  $H_m$  is given also by the hysteresis curve. Hence, the value of  $B_{r1}$  may be obtained by intersecting the hysteresis curve by the straight line of eqn (4.8) as shown in figure 4.5. The foregoing construction depends on the particular geometry of the permanent magnet, but similar 'demagnetization' will occur for other geometries as well. Hence, one may conclude in general that in order to have a large, useful flux density,  $B - H$  curve must be wide. One may therefore adopt, as a factor of quality, the product  $B_r H_c$  or, as it is more common, the product  $(BH)_{\max}$  in the second quadrant.

How can a large value of  $H_c$  be achieved? All the things which caused the quality of soft materials to deteriorate are good for permanent magnets. In particular, a domain gets stuck on an impurity, that is bad for a soft magnetic material but good for the hard variety. An obvious way to include impurities is to add some carbon. High-carbon steels were indeed the permanent magnet materials in the nineteenth century until they were displaced by tungsten steels at the end of the 20<sup>th</sup> century.

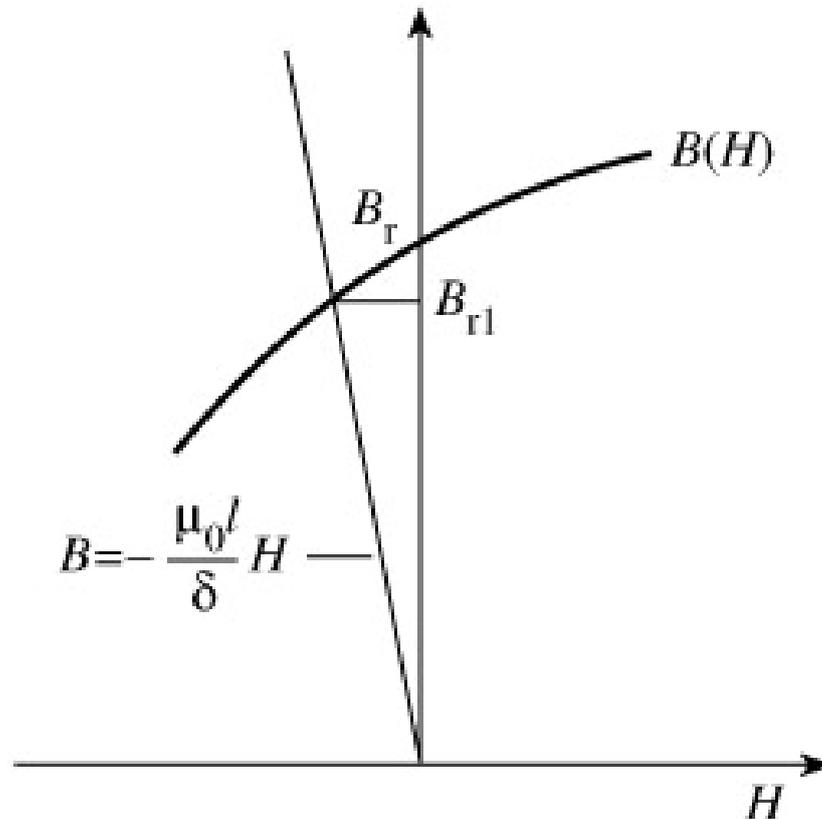


Figure 4.5 – Construction for finding  $B_{r1}$

The simplest permanent magnet would be a single crystal of a material that has a large anisotropy and has only one axis of easy magnetization. The anisotropy may be characterized by an effective field  $H_a$ , which attempts to keep the magnetization along the axis. If a single crystal material is magnetized along this axis, and a magnetic field is applied in the opposite direction, nothing should happen in principle until field  $H_a$  is reached, and then, suddenly, the magnetization of the whole crystal should reverse. Going one step further in this direction, one could state that any collection of anisotropic particles that are too small to contain a domain wall (having a diameter of the order of 20 nm) will have a large coercivity.

In particular, the so-called Elongated Single Domain (ESD) magnets owe their existence to the above concept. It is also likely that elongated particles play a significant role in the properties of the Alnico series of alloys, which contain aluminium, nickel, and cobalt besides iron. They first appeared in the early 1930 s but they have been steadily improving ever since.

A major early advance was the discovery that cooling in a magnetic field produced anisotropic magnets with improved properties in the field-annealed direction.

The hysteresis curves of their best-known representatives (Alnico 5 and 9) are shown in figure 4.3 (b).

Ferrites are also used for hard magnetic materials in the form  $MO \cdot (Fe_2O_3)_6$  (M= Ba, Sr, or Pb). They were introduced in the 1950 s. They have been steadily growing in tonnage ever since, overtaking the Alnico alloys in the late 1960 s and rising in the late 1980 s to 97.4% of world production. Their high coercivity derives from the high anisotropy of the hexagonal phase of the materials.

They have many advantages:

- they are cheap;
- easily manufactured;
- chemically stable;
- have low densities.

Disadvantages are:

- they have the relatively low remanence;
- declining performance for even moderate rises in temperature.

In fact, rare-earth elements are not particularly rare, but they occur in mixtures with each other which cannot easily be separated owing to their similar chemical properties. However, once the problem of separation was satisfactorily solved (early 1970s) these magnets could be produced at an economic price. Their first champion was the samarium-cobalt alloy  $SmCo_5$ , produced by powdering and sintering.

Experiments involving boron led to new (occasionally serendipitous) discoveries, culminating in the development of the  $Nd_2Fe_{14}B$ , which became known as 'neo' magnets, referring their neodymium content. They hold the current record of  $(BH)_{max} = 400 \text{ kJ} \cdot \text{m}^{-3}$ .

The commercially available value is about  $300 \text{ kJ} \cdot \text{m}^{-3}$ , as may be seen in table 4.1. They have, though, the major disadvantage of a fairly low Curie temperature. Note that these new materials have radically different looking hysteresis curves as shown in Figure 4.6 for the second quadrant only.

Table 4.1 – Hard magnetic materials

Material	$H_c$ ( $\text{Am}^{-1}$ )	$B_r$ (T)	$(BH)_{max}$ $\text{Jm}^{-3}$
Carbon steel 0.9%C, 1% Mn	$4.0 \times 10^3$	0.9	$8 \times 10^2$
Alnico 5 8% Al, 24% Co, 3% Cu, 14% Ni	$4.6 \times 10^4$	1.25	$2 \times 10^4$
'Ferroxdur' $(BaO)(Fe_2O_3)_6$	$1.6 \times 10^5$	0.35	$1.2 \times 10^4$
ESD Fe-Co	$8.2 \times 10^4$	0.9	$4 \times 10^4$
Alnico 9	$1.3 \times 10^5$	1.05	$10^5$
$SmCo_5$	$7 \times 10^5$	0.8	$2 \times 10^5$
$Nd_2Fe_{14}B$	$8.8 \times 10^5$	1.2	$3 \times 10^5$

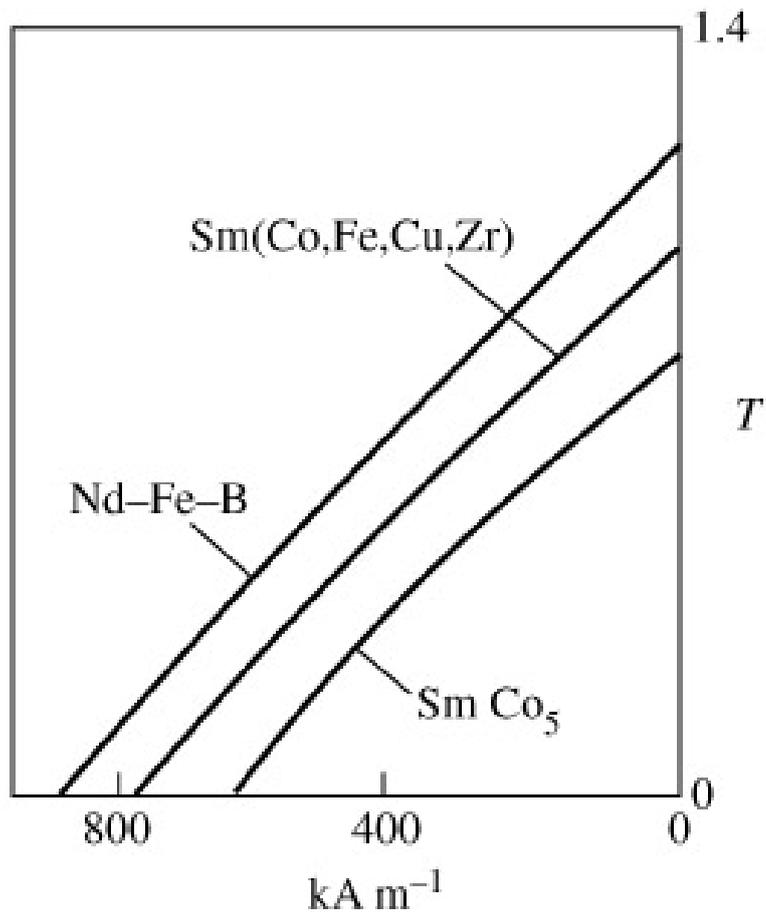


Figure 4.6 – Hysteresis curves of some rare-earth magnets in the second quadrant

#### 4.6 Ferroelectrics

There is one more class of dielectrics, which, as well as being piezoelectric, have permanent dipole moments and a polarization that is not necessarily zero when there is no electric field. In fact, they get their name by analogy with ferromagnetics, which have a  $B$ - $H$  loop, hysteresis, and remanent magnetism.

Ferroelectrics have a  $P$ - $E$  loop, hysteresis, and remanent polarized charge as shown in figure 4.7. They are very interesting scientifically but so far have not found much application. The high relative dielectric constants of the titanates ( $\text{BaTiO}_3$  is one of them; it is the example usually given of a ferroelectric material) are used in capacitor-making, where the essential ferroelectric effects of voltage and temperature changes of capacity are usually an embarrassment. At one time it seemed as if the voltage change of dielectric constant would find application in voltage-tunable capacitors, but varactor diodes won the race. Another potential application (as an externally tunable phase-shifter) has not materialized either because of the high hysteresis losses at high frequencies.

Both these situations could be changed by improved materials.

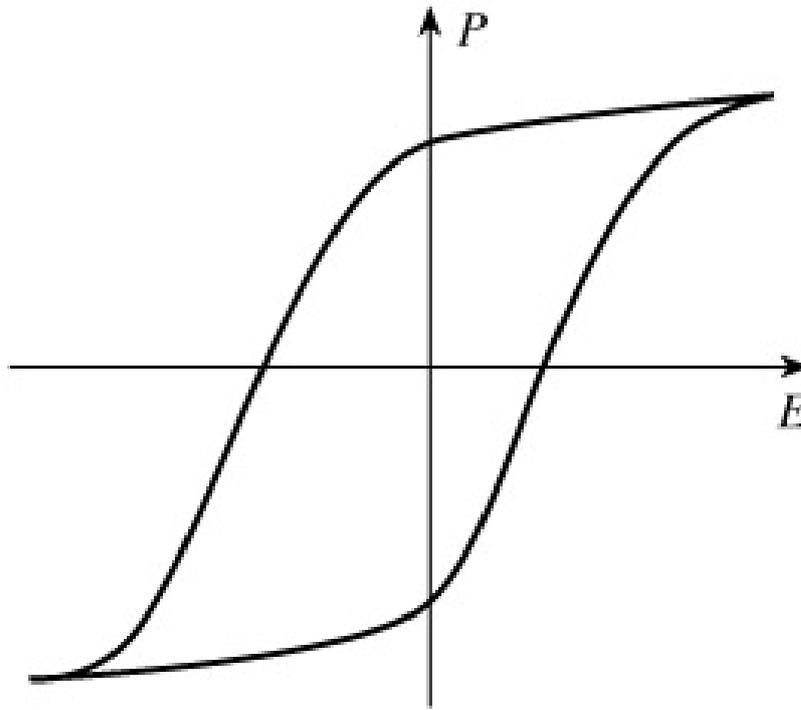


Figure 4.7 – Ferroelectric hysteresis loop

#### 4.7 Paramagnetism

When we apply a magnetic field, all the atoms will have some magnetic moments in the direction of the magnetic field. The relative number of atoms, possessing the same angular momentum, is determined again by Boltzmann statistics. The possible magnetic moments are

$$M_J g \mu_{mB}, \text{ where } M_J = J, J - 1, \dots, -J + 1, -J.$$

Hence, their energies are

$$E_{mag} = -M_J g \mu_{mB} \mu_0 H. \quad (4.9)$$

The average magnetic moment is shown in figure 4.9, where it is compared with the experimental results of Henry on potassium chromium alum. The vertical scale is in Bohr magnetons per ion. Note that experimental results for paramagnetic properties are often given for ions embedded in some salt. The reason is that in these compounds the ions responsible for magnetism ( $\text{Cr}^{3+}$  in the case of potassium chromium alum) are sufficiently far from each other for their interaction to be disregarded.

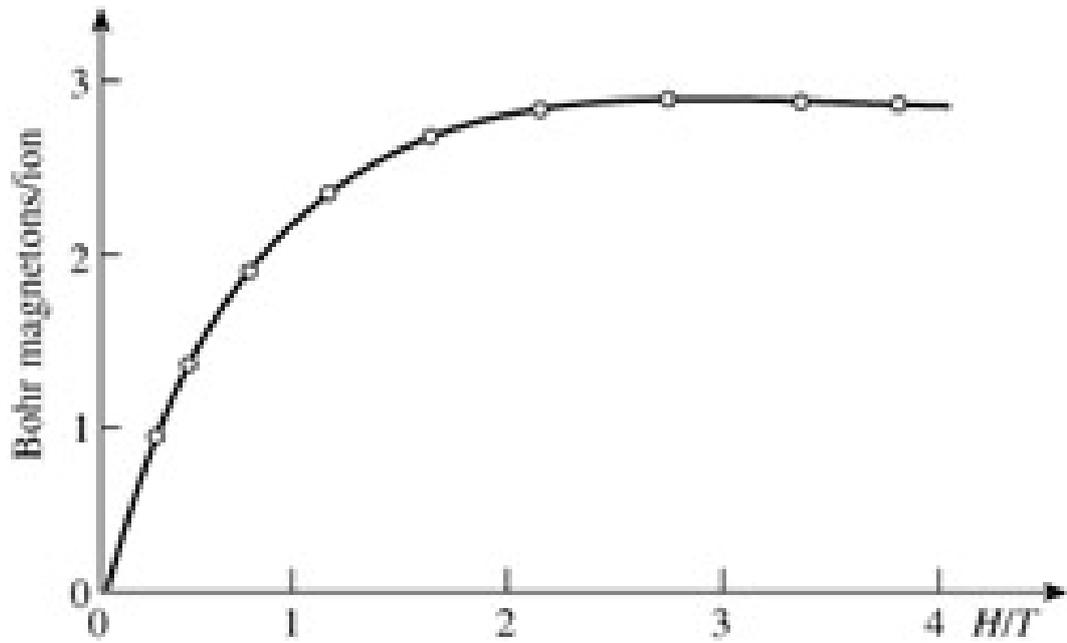


Figure 4.8 - The magnetic moment as a function of  $H/T$  for potassium chromium alum (after Henry)

$$\sum_{-J}^J M_J = 0. \quad (4.10)$$

The summation in eqn (4.10) is one of the simpler ones to perform, which gives finally

$$\langle \mu_m \rangle = g^2 \mu_{\text{mB}}^2 J(J+1) \mu_0 H / 3kT. \quad (4.11)$$

Now one may express the above equation in terms of the *total* angular momentum

$$\Pi = \hbar \{J(J+1)\}^{1/2}, \quad (4.12)$$

and total magnetic momentum

$$\mu_m = ge \Pi / 2m, \quad (4.13)$$

to get

$$\langle \mu_m \rangle = \mu_m^2 \mu_0 H / 3kT, \quad (4.14)$$

in agreement with the classical result.

## 4.8 Anisotropy and domains

Magnetic energy consists of the following terms:

- *exchange energy* (minimise by having all spins parallel);
- *magnetostatic energy* (minimise by having domains pointing in different directions so there is no external field);
- *Zeeman energy* (potential energy due to an external magnetic field,  $E = M \cdot H$ );
- *magnetocrystalline energy* (lower if the magnetization is pointing in certain crystallographic directions, eg the c- axis in Co).

Domain structures are formed to minimise energy. Domains are typically microns or larger; domain wall widths ~ 100 nm.

*Magnetocrystalline anisotropy* represents the energy needed to ‘pull’ the magnetization away from the preferred (easy) axis.

e.g. Co  $K_u = 4.1 \cdot 10^5 \text{ J/m}^3$  uniaxial, [0001] is easy,

Fe  $K_1 = 4.8 \cdot 10^4 \text{ J/m}^3$  cubic, <100> is easy,

Ni  $K_1 = -4.5 \cdot 10^3 \text{ J/m}^3$  cubic, <111> is easy.

Uniaxial: energy  $E = K_u \sin^2 \phi$ ,  $\phi$  = angle between M and easy axis.

Cubic:  $E = K_1 (\cos^2 \phi_1 \cos^2 \phi_2 + \cos^2 \phi_2 \cos^2 \phi_3 + \cos^2 \phi_3 \cos^2 \phi_1) + \text{higher order terms}$   
 $\phi_i$  = angle between M and the i axis.

Domain wall width is determined by a balance between exchange (favors wide walls) and magnetocrystalline anisotropy (favors narrow walls) ( $a$  = lattice parameter)

$$\text{wall width } d = \pi \sqrt{A/2Ka},$$

$$\text{wall energy } E_w = \pi \sqrt{2AK/a}.$$

For small enough particles it is not worth establishing a wall because the savings in magnetostatic energy are less than the wall energy. These are ‘single domain’ particles. Very small particles are thermally unstable because the net magnetic energy

$$K_{\text{tot}} V < 25 \text{ kT (here } V \text{ is the volume of the particle).}$$

*Magnetostatic energy (self-energy or demagnetizing energy).*

The energy in the field surrounding the magnetized object depends on the way the object is magnetized. For instance, a long thin object has less magnetostatic energy if it is magnetized along its length, compared to across its length. This can be expressed in the same way as a uniaxial anisotropy: if the long axis is z and the short axis is x, then

$$E = K_{\text{shape}} \sin^2 \phi,$$

$\varphi$  = angle between M and z axis,

where  $K_{\text{shape}} = 0.5(N_x - N_z)M_s$ .

The  $N_s$  are called demagnetizing factors and depend on the shape of the object. For instance, for an infinite cylinder with length in the z direction,  $N_z = 0$  and  $N_x = N_y = 0.5$ .

The field inside the object along the i axis due to its own magnetization is

$$H_d = -N_i M_s \quad M_s = \text{saturation magnetization.}$$

#### **4.9 Determination of the temperature coefficient of resistance for conductive materials**

While carrying out the experiment we determine temperature coefficients of:

- 1) The semi-conductive resistor with a positive temperature coefficient. Resistors KT110, KTY81 or the same are used. Marking: “600.13-1; MF”.
- 2) The metallic film of resistors MF, C2-33H or similar. Marking is: “600.19-1; MF”.
- 3) The carbon film of resistors CF, C2-14 or similar. Marking is: “600.19-2; C”.
- 4) The semi-conductive resistor with a negative temperature coefficient. Resistors B57861S, B57891M or similar are used. Mark is: “600.19-3; NTC”.
- 5) The copper wire (a copper resistance temperature detector C014-50M.B3.20/0.2. The nominal resistance at 0 ° C is 50 ohms) Marking is: “600.19-4; Cu”.
- 6) Straight voltage p-n transition of the silicon diode at direct current. Diodes KD522, 1N4148 or similar are used. Marking is: “600.19-5; diode Si”.

The laboratory installation and electric circuit diagram.

In performing the work an electric heater (394.2) is used. The heater with the temperature regulator is embedded in a block. The test sample is inserted into the hole on the front of the heater, and its output resistance or voltage is measured using a multi-meter.

Electric heating unit.

Electric heating unit is used to determine the temperature coefficient of the resistance of different materials. The unit allows you to set and automatically maintain the temperature of the heater. A low-power source + 5V is installed in the unit, which is used as an additional power supply source in some experiments.

To the left of the indicators 3 and 4 (figure 4.9), on the front panel of the temperature regulator, 4 light-emitting diodes (LEDs) are installed:

- a) K1 – turned on at heating;

- b) K2 – not used;
- c) AL – an indicator of limit values exceedance (not used);
- d) RS – an indicator of the automatic regulation mode. It should be turned on during the unit normal operation in the automatic regulation mode. At shutdown of the automatic regulation (see below) the device works only as an indicator of the heater temperature.

Temperature setting of the electric heater:

1) Press one of the control buttons 5 or 6 of the temperature regulator 2 (figure 4.9). The indicator of the given value of the heater temperature starts to flash on and off (SV, the green indicator 4).

2) For changing the given value of the temperature press repeatedly buttons 5 (decrease) or 6 (increase of temperature). Holding the button for some time turn on the mode of the value automatic accelerated change. The indicator continues to flash on and off in the process of temperature setting.

3) After setting of the required temperature value it is necessary to press once the button 7 (figure 4.9). The indicator 4 flashing stops. The temperature is set.

During the experiment performing it is recommended to begin from lower temperature values (higher than the room temperature for  $5...10^0$ ) and gradually to increase its value to  $100^0\text{C}$ , because cooling of the electric heater is much slower than heating.

Switching on (shutdown) of the automatic regulation mode.

At turning on the power supply of the electric heater the automatic regulation mode is switched off. During the experiment it is advisable to set the initial temperature value and after that to switch on the automatic regulation mode.

Switching the automatic regulation mode:

1) Press once the button 7 (figure 4.9) of the temperature regulator. On the indicator 3 (red, PV) the inscription “r-S” is displayed. On the indicator 4 (green, SV) the current condition of the regulator “StoP” (STOP) or “rUn” (Work) is displayed.

2) For changing the regulator condition press any of buttons 5 or 6 – the indicator 4 starts to flash. Repeated pressing the button 5 or 6 will switch the mode («StoP»↔«rUn»).

3) Pressing the button 7 fixes the chosen value (the indicator 4 is not flashing). A repeated pressing the button 7 returns the temperature regulator to the initial condition – the current and the given temperature values are displayed on the indicator. The Led RS signals about the regulator condition: switched on – the mode “rUn” (Work), switched off – “StoP” (STOP).

Operational modes of the temperature meter-regulator TP441 and the order of its program are described in details in literature: “The temperature meter-regulators TP440 и TP441 Operation Manual”. TALC.405111.040 PE. During the experiment any changes of parameters of the temperature regulator except from above mentioned are not allowed.

The electric circuit diagram.

The electric circuit diagram at determining the temperature coefficients of the resistance is shown in figure 4.10.

All samples are connected to sockets «VΩ» and «COM» of the multi-meter MY60T (block 1416) and one of the limits of measurement of the resistance, corresponding to the resistance of the sample, is set. At connecting the silicon diode (a sample 600.19-5, the diode Si) it is necessary to follow the polarity: an anode (the red wire) is connected to the socket “VΩ”, and a cathode (the black or blue wire) is connected to the socket “COM”. For determining the forward voltage on the diode in millivolts the limit of measurement «» is used. In this case the constant direct current in the range of 1...1.5 mA flows through the diode. The accurate current value can be measured by the additional multi-meter, connected in series with the test diode.

A single-phase power supply source G1 is designed for the safe supply of the electric heating unit 394.2.

#### Experiment Guidelines:

- 1) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.
- 2) Connect the units according to the electric circuit diagram shown in figure 4.10.
- 3) Select the temperature values at which you want to measure the resistance of samples. Due to the response time of the heater it is advisable to choose a maximum of 5 ... 7 points in the temperature range up to 100 ° C. The initial value is the room temperature.
- 4) Turn on the protection tripping device and the automatic circuit breaker in the single-phase power supply source G1.
- 5) Turn on the circuit breaker "NETWORK" of the electric heater unit (394.2).
- 6) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.
- 7) Connect the units according to the electric circuit diagram shown in Figure 4.10.
- 8) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.
- 9) Connect the units according to the electric circuit diagram shown in Figure 4.10.
- 10) Select the temperature values at which you want to measure the resistance of samples. Due to the inertia of the heater it is advisable to choose a maximum of 5 ... 7 points in the temperature range up to 100 ° C. The initial value is the room temperature.

11) Turn on the protection tripping device and the automatic circuit breaker in the single-phase power supply source G1.

12) Turn on the circuit breaker "NETWORK" of the electric heater unit (394.2).

13) When power supply is turned on, the automatic mode of the electric heater temperature regulator is turned off. Set the desired temperature (see "The electric heater unit"). Turn on the automatic mode of the temperature regulator. The heater warming up starts (LEDs of indicators K1 and RS are switched on).

14) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.

15) Connect the units according to the electric circuit diagram shown in figure 4.10.

16) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.

17) Connect the units according to the electric circuit diagram shown in Figure 4.10.

18) Select the temperature values at which you want to measure the resistance of samples. Due to the inertia of the heater it is advisable to choose a maximum of 5 ... 7 points in the temperature range up to 100 ° C. The initial value is the room temperature.

19) Turn on the protection tripping device and the automatic circuit breaker in the single-phase power supply source G1.

20) Turn on the circuit breaker "NETWORK" of the electric heater unit (394.2).

21) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.

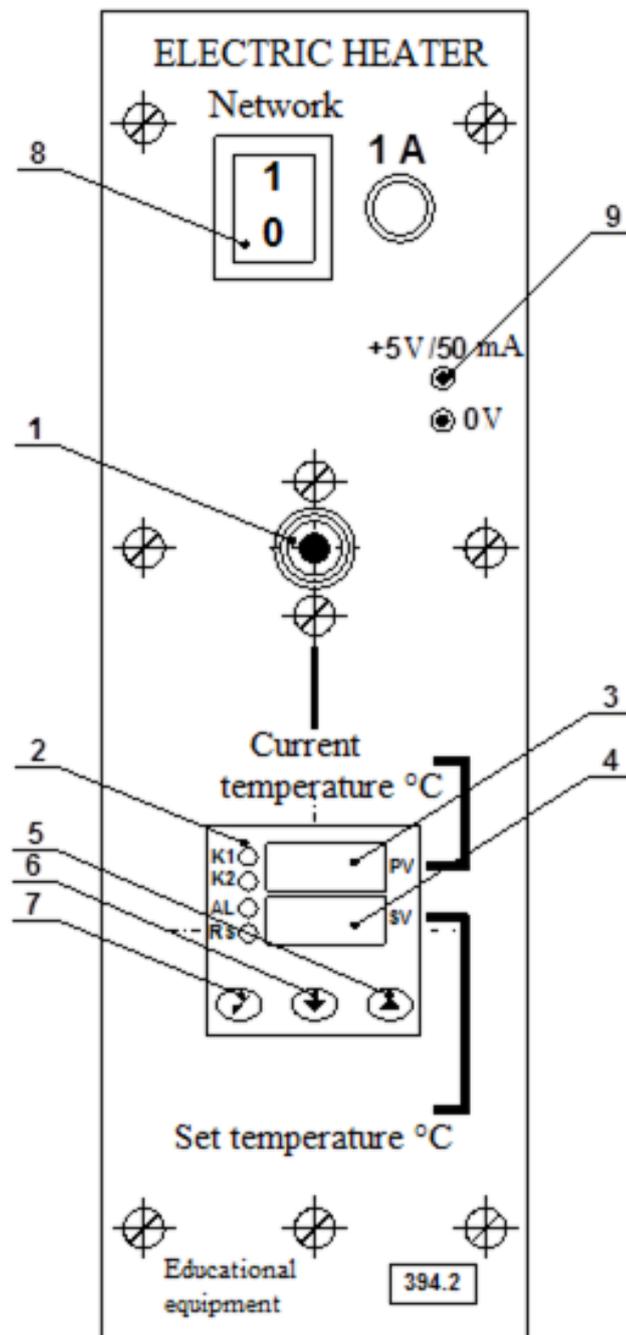
22) Connect the units according to the electric circuit diagram shown in figure 4.10.

23) Select the temperature values at which you want to measure the resistance of samples. Due to the inertia of the heater it is advisable to choose a maximum of 5 ... 7 points in the temperature range up to 100 ° C. The initial value is the room temperature.

24) Turn on the protection tripping device and the automatic circuit breaker in the single-phase power supply source G1.

25) Turn on the circuit breaker "NETWORK" of the electric heater unit (394.2).

26) When power supply is turned on, the automatic mode of the electric heater temperature regulator is turned off. Set the desired temperature (see "The electric heater unit"). Turn on the automatic mode of the temperature regulator. The heater warming up starts (LEDs of indicators K1 and RS are switched on).



1 – a hole of the electric heater; 2 – a temperature regulator; 3 – an indicator of the current value of the heater temperature (PV); 4 – an indicator of the given value of the heater temperature (SV); 5, 6, 7 – temperature control buttons; 8 – a power switch; 9 – power supply sockets of + 5V.

Figure 4.9 – The front panel of the electric heater (394.2)

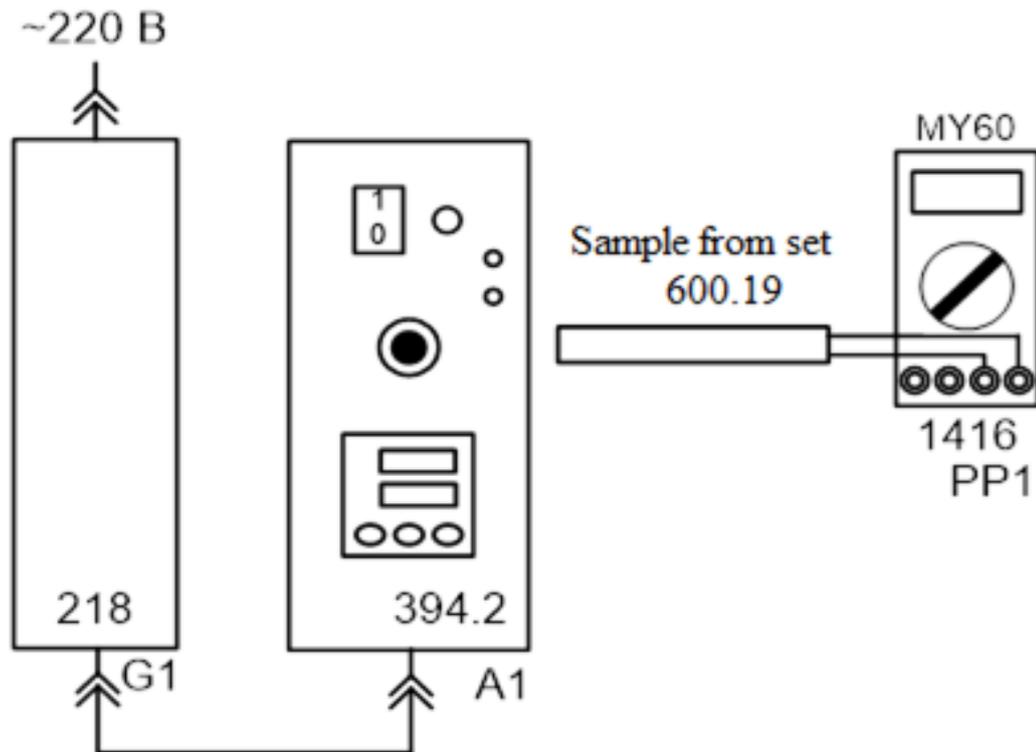


Figure 4.10 – The scheme for the determination of resistance temperature coefficients

27) Check the power supply circuit of the electric heater units (394.2) and the power source G1 (218). Make sure that the circuit breakers "NETWORK" of these units are disconnected.

28) Connect the units according to the electric circuit diagram shown in figure 4.10.

29) Select the temperature values at which you want to measure the resistance of samples. Due to the inertia of the heater it is advisable to choose a maximum of 5 ... 7 points in the temperature range up to 100 ° C. The initial value is the room temperature.

30) Turn on the protection tripping device and the automatic circuit breaker in the single-phase power supply source G1.

31) Turn on the circuit breaker "NETWORK" of the electric heater unit (394.2).

32) When power supply is turned on, the automatic mode of the electric heater temperature regulator is turned off. Set the desired temperature (see "The electric heater unit"). Turn on the automatic mode of the temperature regulator. The heater warming up starts (LEDs of indicators K1 and RS are switched on).

33) Measure the resistance of samples at the room temperature. To exclude the warming of samples of the hands you need to take the housing near the terminals.

34) After stabilizing the temperature of the heater near the set point, insert alternately each of the samples in to the heater hole until it stops. Wait 2...3 minutes to stabilize the temperature and measure the resistance of the sample.

35) Set the next temperature value, wait for its stabilization and re-measure the resistance of samples. At sample's high temperature be careful: do not touch the working part of the sample extracted from the heater.

36) Based on measurements, construct the dependency graph of the sample resistance (or the voltage for the diode) of the temperature.

37) Upon measurement completion, turn off the power for all units.

38) While completing, collect samples, having a linear relationship between the resistance and the temperature, and calculate their temperature coefficient of the resistance

$$\alpha = \frac{R(t_2) - R(t_1)}{R(t_1) \cdot t_2 - R(t_2) \cdot t_1},$$

where  $R(t_2)$ ,  $R(t_1)$  - the resistance of the sample, respectively, at a temperature  $t_2$  and  $t_1$ ;

$\alpha$  [ $\text{deg}^{-1}$ ] - a temperature coefficient of the sample resistance.

The resistance of the sample at an arbitrary temperature  $t$  is calculated by the formula

$$R(t) = R(t_1) \cdot \frac{1 + \alpha \cdot t}{1 + \alpha \cdot t_1}.$$

*Note.*

At determining the resistance of only one sample the order of experiment execution can be changed.

1. Assemble the circuit.
2. Place the test sample in the hole of the heater.
3. Set the temperature to 100 ° C and turn on the automatic mode of the temperature regulator («rUn», the mode "WORK", the indicator RS is turned on). Wait for the set temperature and turn off the automatic mode of the regulator («StoP», the mode "STOP", the indicator RS is turned off).

4. As the temperature of the heater decreases, measure the resistance of the sample (or the voltage for the diode) at several temperature values in the range of 100 ... 30 ° C. The approximate time of sensor cooling is 15 ... 30 minutes.

5. Process received experiment results in accordance with the above recommendations.

The Multi-meter.

The multi-meter is designed to measure voltages, currents, resistances, temperatures, and also to check diodes and transistors. Its general form is shown in Figure 4.11. The detailed technical information about the multi-meter and operating rules are provided in the operating instructions of the manufacturer. Here we present only the basic information.

To turn on the multi-meter, press the button «ON / OFF», located to the left under the indicator.

On the top of the multi-meter the reading device, there is a digital data display, is located. The mechanical switch of work modes and limits of measurement of devices are located below. The sockets for the conductor connection are located under the switch:

1) The socket "COM" is a common device connection socket in any measurements. When measuring DC voltage or current the socket corresponds to the "-" (minus) of the device. When measuring the resistance a "-" (minus) from an internal power source is fed to the socket «COM». The polarity of internal sources should be considered, for example, when checking diodes.

2) The socket «VΩ» is used to connect the device when the second conductor at the limits of measurement of voltage and resistance. When measuring DC voltage and current the socket corresponds to the "+" (plus) of the device. When measuring the resistance this socket is the "+" socket of the internal source.

3) The socket "A" of the multi-meter MY 60 is designed for connecting the current measuring circuit at all current measurement limits, except 10 A. The socket corresponds to the "+" (plus) of the device.

4) The socket "10 A" is designed for connecting the current measuring circuit at the limit of 10 A. The socket corresponds to the "+" (plus) of the device.

When measuring DC voltage, device readings are positive if the voltage is directed from socket «V» (i.e. "+") to socket "COM" (i.e. "-"). Similarly, the current is positive if it flows through the device in the direction away from the socket "+" (i.e. «mA», «A" or "10A") to the socket "-" ("COM").

A pair of sockets TEMP is designed to connect the thermocouple, which is included in the package of the device or a special cable, and to connect these jacks or sockets with a thermocouple mounted inside the mini-block (about the mini-blocks see below).

The sequence of operation with a multi-meter:

1) Initially, the device is disconnected from the measured circuit.

2) Set the kind of the measured value and the desired measurement range by the switch. If the value of the measured voltage or current is not known in advance, you must set the most appropriate measurement limit value, which excludes the breakdown of the device when power is fed to the test circuit. Energizing the inputs of multi-meters is possible only if their switches are set to the position of voltage or current measurement.

3) Connect the device to the de-energized test circuit. Turn on the power sources of the multi-meter and the test circuit and do measurements.

4) The transition to the lower measuring limit of the measured value is allowed: a range-control switch is set to the next with the original position.

When switching the limit, even briefly it is unacceptable, to set the switch to the position corresponding to the other measured values.

5) To switch the device to another part of the test circuit, you must turn off the power supply of the circuit, change the connection of a multi-meter, set a limit of measurement, and re-energize the test circuit.

6) When measuring the parameters of electric circuit elements, diodes, resistors, capacitors, it is unacceptable to energize the device input from external sources (it is not allowed to measure the parameters of the elements in the circuit under the voltage). Before measuring capacitance, capacitor must be discharged by shorting its terminals.

To ensure a reliable long-term operation of the multi-meter you should keep the following guidelines:

1) When the order of the measured value is unknown, set the measurement limits switch on the highest value.

2) When switching the limit, even briefly it is unacceptable, to set the switch to the position corresponding to the other measured values.

3) Before you turn the switch to change the type of work (not to change the measuring range!), disconnect the test leads from the circuit under test.

4) Do not measure the resistance in the circuit the voltage is applied to.

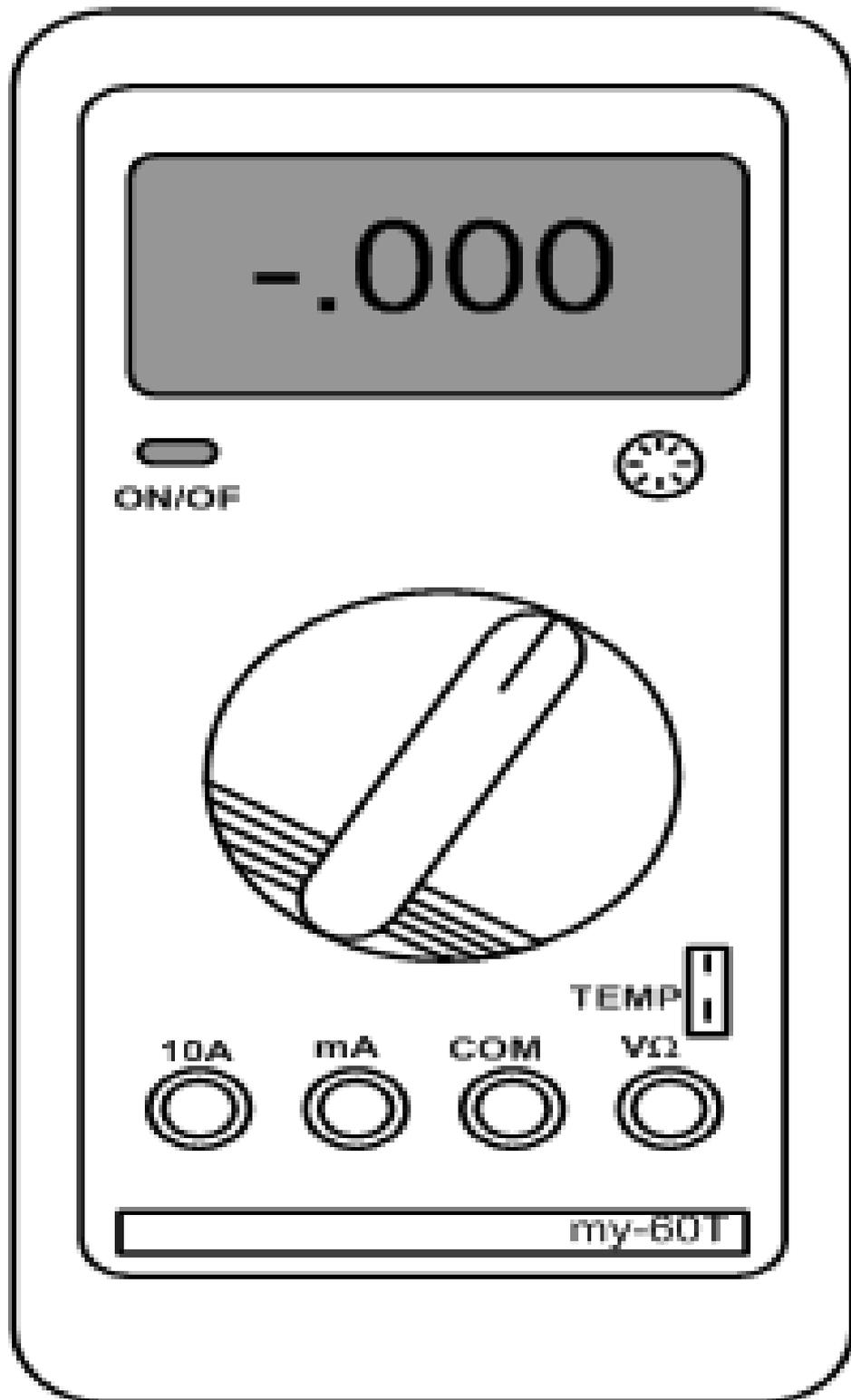


Figure 4.11 – General view of the multi-meter

## **Conclusion**

Theoretical foundation of electrotechnical materials (basic concepts of electricity; macroscopic approach to dielectric materials, polarization, breakdown; fundamentals of intrinsic and extrinsic semiconductors; domains and the hysteresis curves, ferroelectrics, paramagnetism) is provided in the study guide. Characteristics and properties of dielectrics, semiconductors and magnetic materials are described. The usage of electrotechnical materials is given.

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