

When classifying solids on the basis of their band structure, we referred to the group of solids, called insulators, which have an energy gap of 3 eV or more, recall Sec. 15.1. The large magnitude of the energy gap in an ideal insulator precludes the possibility of electrons being excited from the valence band to the conduction band by thermal means, much less so by an externally applied electric field. Insulators are therefore very poor conductors of electricity, recall the resistivity range for insulators from Table 14.1. Insulators are known as dielectrics. Dielectric materials find extensive use in the electrical industry for insulation purposes and as capacitors.

In this chapter, polarization processes in dielectric materials and their temperature and frequency dependence are discussed. Besides, the causes of electric breakdown are described. In the end, the nature of ferroelectric crystals is considered briefly.

Units

Quantity	SI units	
	<i>Unit</i>	<i>Symbol</i>
Flux density D	coulomb per square metre	C m^{-2}
Electric field strength E	volt per metre	V m^{-1}
Dielectric strength	or	or
	newton per coulomb	N C^{-1}
Capacitance C	farad or coulomb per volt	F or C V^{-1}
Dielectric constant of free space ϵ_0	farad per metre	F m^{-1}
Relative dielectric constant ϵ_r	—	—
Dipole moment	coulomb metre	C m
Polarization P	coulomb per square metre	C m^{-2}
Saturation polarization P_s		
Electronic polarizability	farad metre squared	F m^2
Frequency ν	hertz (per second)	$\text{Hz (s}^{-1}\text{)}$

Constants

Dielectric constant of free space ϵ_0	$= 8.854 \times 10^{-12} \text{ F m}^{-1}$
Electronic charge e	$= 1.602 \times 10^{-19} \text{ C}$

17.1 Polarization

The relation between the electric flux density D (charge per unit area in units of C m^{-2}) at a point in a material and the electric field strength E (force per unit charge in units of N C^{-1} or V m^{-1}) at that point in space is given by

$$D = \epsilon_r \epsilon_0 E \quad (17.1)$$

where ϵ_0 is the dielectric constant or permittivity of free space (vacuum) and ϵ_r is the relative dielectric constant or relative permittivity of the material. ϵ_r is dimensionless and is a property of the material related to its atomic structure. Its value is 1 for free space and is greater than one for all materials. In SI units, $\epsilon_0 = 8.854 \times 10^{-12}$ farad per metre. ϵ_0 has this particular value as a result of conversion from cgs units to SI units.

$$\epsilon_0 = \frac{D}{\epsilon_r E} = \frac{\text{C m}^{-2}}{\text{V m}^{-1}} = \text{F m}^{-1}$$

When an electric field is applied to a solid containing positive and negative charges, the positive charges are displaced in the direction of the field towards the negative end, while the negative charges are displaced in the opposite direction. This displacement produces local dipoles throughout the solid. *The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the polarization P of the solid.* As the polarization measures the additional flux density arising from the presence of the material as compared to free space, it has the same units as D and is related to it as follows:

$$D = \epsilon_0 E + P \quad (17.2)$$

As may be seen by comparing Eq. (17.2) with Eq. (16.3), polarization P is the electrical analog of magnetization M . Combining Eqs. (17.1) and (17.2), we can write

$$P = \epsilon_0 (\epsilon_r - 1) E \quad (17.3)$$

Macroscopically, the polarization or the relative dielectric constant can be measured, using a parallel-plate capacitor. When a voltage V is applied to the capacitor, with the plates separated by vacuum, a charge develops on the plates. The capacitance C of the capacitor is a measure of this charge and is defined by

$$C = \frac{\epsilon_0 A}{d} \quad (17.4)$$

where A is the area of the parallel plates and d is the distance of separation between them. If a dielectric material is inserted between the plates, the charge on the plates increases due to polarization in the material. The capacitance is now given by

$$C = \epsilon_r \epsilon_0 \frac{A}{d} \quad (17.5)$$

ϵ_r and hence P can be determined by measuring the capacitance with and without the dielectric.

Example 17.1 Calculate the relative dielectric constant of a barium titanate crystal, which, when inserted in a parallel plate condenser of area $10 \text{ mm} \times 10 \text{ mm}$ and distance of separation of 2 mm , gives a capacitance of 10^{-9} F .

Solution Substituting the given values in Eq. (17.5), we obtain

$$\begin{aligned} \epsilon_r &= \frac{10^{-9} \times 2 \times 10^{-3}}{8.854 \times 10^{-12} \times 10^2 \times 10^{-6}} \\ &= 2259 \end{aligned}$$

Polarization occurs due to several atomic mechanisms. *Electronic polarization* (Fig. 17.1a) is the result of the displacement of the positively charged nucleus and the (negative) electrons of an atom in opposite directions on application of an electric field. On applying a field, the electron cloud around the nucleus readily shifts towards the positive end of the field. Such a shift results in a *dipole moment* within the atom, as a certain distance now separates the nucleus and the centre of the electron cloud. The extent of this shift is proportional to the field strength. As the dipole moment is defined as the product of the charge and the shift distance, it is also proportional to the field strength. The constant of proportionality is called the *electronic polarizability* α_e of the atom. For the inert gases, this polarizability increases with increasing volume of the atom, as illustrated in Table 17.1. Electronic polarizability is independent of temperature. Monoatomic gases exhibit only this kind of polarization.

TABLE 17.1
Electronic Polarizability α_e of Inert Gases

Inert gas	He	Ne	Ar	Kr	Xe
$\alpha_e, 10^{-40} \text{ F m}^2$	0.18	0.35	1.43	2.18	3.54

During chemical bonding, the atoms may acquire an excess negative or positive charge and form an ionic bond. When an electric field is applied to an ionic solid, cations and anions get displaced in opposite directions, see

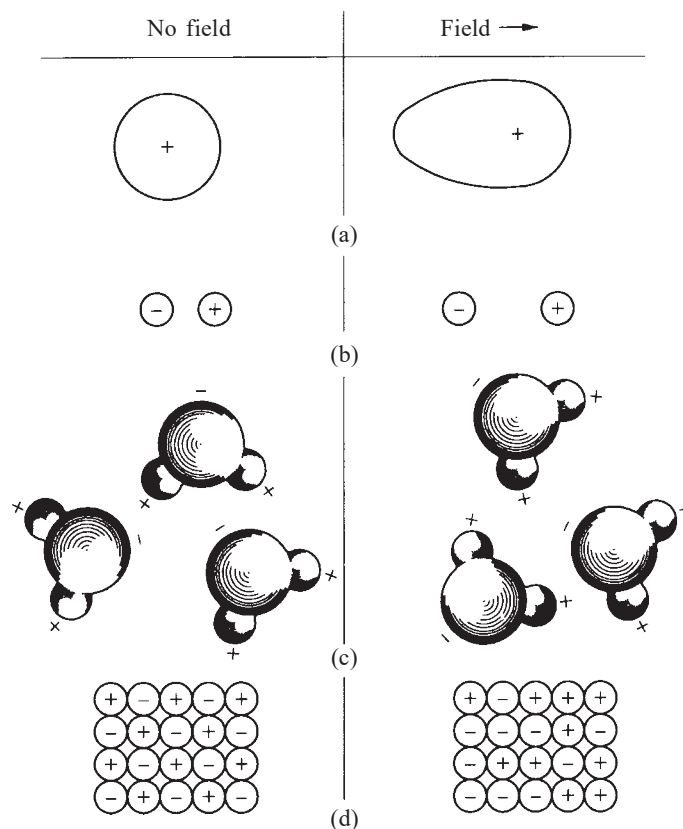


Fig. 17.1 Various polarization processes: (a) electronic polarization, (b) ionic polarization, (c) orientation polarization, and (d) space charge polarization.

Fig. 17.1b. The *ionic polarizability* is due to this shift of the ions relative to other oppositely-charged neighbours. It should be distinguished from electronic polarization, where the electron cloud of an atom shifts with reference to its own nucleus. Ionic polarization is also independent of temperature.

In methane molecule (CH_4), the centre of the negative and the positive charges coincide, so that there is no permanent dipole moment. On the other hand, in CH_3Cl , the positive and the negative charges do not coincide. The electronegativity of chlorine being more than that of hydrogen (recall Table 4.4), the chlorine atom pulls the bonding electrons to itself more strongly than hydrogen. So, this molecule carries a dipole moment even *in the absence of an electric field*. When an electric field is applied on such molecules, they tend to align themselves in the applied field, see Fig. 17.1c. (Recall that atoms with permanent magnetic moments tend to align themselves with the applied magnetic field giving rise to paramagnetism.) The polarization due to this alignment is called *orientation polarization* and is dependent on temperature. With increasing temperature, the thermal energy tends to randomize the alignment.

The fourth type of polarization is called the *space charge polarization* and occurs due to the accumulation of charges at the electrodes or at the interfaces in a multiphase material, see Fig. 17.1d. The ions diffuse over appreciable distances in response to the applied field, giving rise to a redistribution of charges in the dielectric medium.

The *total polarization* of a material is the sum of the contributions from the various sources described above:

$$P_{\text{total}} = P_e + P_i + P_o + P_s \quad (17.6)$$

where the subscripts on the right refer to the four types: electronic, ionic, orientation and space-charge polarization.

17.2 Temperature and Frequency Effects

On application of an electric field, a polarization process occurs as a function of time. The polarization $P(t)$ as a function of time t is given by

$$P(t) = P \left[1 - \exp \left(- \frac{t}{t_r} \right) \right] \quad (17.7)$$

where P is the maximum polarization attained on prolonged application of a static field and t_r is the relaxation time for the particular polarization process. Recall Eq. (10.15), where the relaxation arising from anelastic processes was discussed. The relaxation time t_r is a measure of the time scale of a polarization process. It is the time taken for a polarization process to reach 0.63 of the maximum value.

The relaxation times vary widely for different polarization processes. Electronic polarization is *extremely rapid* and is essentially complete at the instant the voltage is applied. Even when the frequency of the applied voltage is very high in the optical range ($\sim 10^{15}$ Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is slower than electronic polarization, as the displacement involved here is that of the much heavier ion, as compared to the electron cloud in the above case. The frequency with which ions can be displaced over a small fraction of the interatomic distance will be of the same order as the lattice vibration frequency ($\sim 10^{13}$ Hz). If an electric field of frequency in the optical range ($\sim 10^{15}$ Hz) is now applied, the ions do not respond at all, as the time required by an ion for one vibration is 100 times larger than the period of the applied voltage. So, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 10^{13} Hz, the ions have enough time to

respond during each cycle. This is illustrated in Fig. 17.2, where the polarization consists of only the electronic part at optical frequencies and increases to include the ionic part, as the frequency is reduced to 10^{13} Hz in the infrared range.

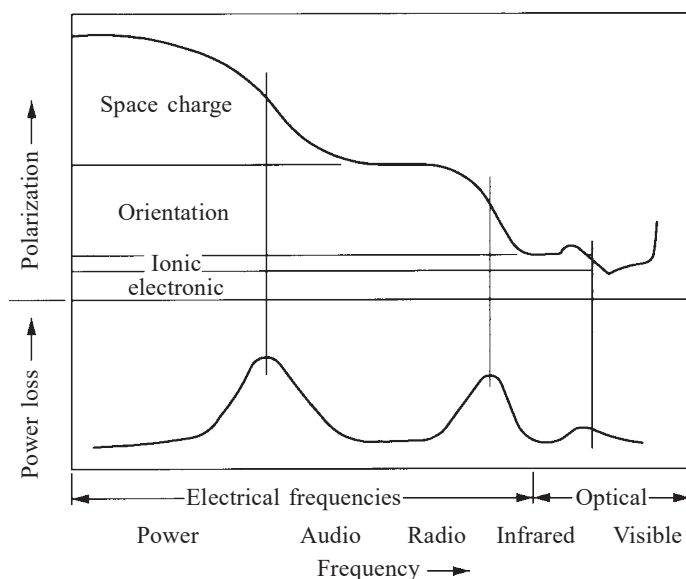


Fig. 17.2 Frequency dependence of polarization processes and peak power losses corresponding to each process.

Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in liquid propyl alcohol is about 10^{-10} s and in solid ice, it is 3×10^{-6} s. It is evidently easier for the polar molecules to reorient themselves in a liquid as compared to a solid. Orientation polarization occurs, when the frequency of the applied voltage is in the audio range, Fig. 17.2.

Space charge polarization is the *slowest process*, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to the frequency of successful jumps of ions under the influence of the applied field, a typical value being 10^2 Hz. Correspondingly, space charge polarization occurs at machine frequencies (50–60 Hz).

Referring to Fig. 17.2, all the four types of polarization are present at machine frequencies. As the frequency is increased, space charge, orientation and ionic polarization become inoperative in that order. When several polarization processes occur in a material, it follows that the dielectric constant will decrease with increasing frequency of the applied voltage. The dielectric constants of some typical dielectric materials are listed in Table 17.2 at frequencies of 60 Hz and 10^6 Hz.