

F. DIELECTRIC BEHAVIOR

Dielectric behavior occurs in all insulators - solids, liquids and gases, yet it is not yet fully understood, and certain generalizations apply, especially when considering aggregates, such as the polycrystalline ceramics.

DIELECTRIC POLARIZATION

Dielectric polarization arises due to the existence of atomic and molecular forces, and appears whenever charges in a material are somewhat displaced with respect to one another under the influence of an electric field.

In a capacitor, the negative charges within the dielectric are displaced toward the positive electrode, while the positive charges shift in the opposite direction. As charges are not free to move in an insulator, restoring forces are activated which either do work, or cause work to be done on the system, i.e. energy is transferred. On charging a capacitor, the polarization effect opposing the applied field draws charges onto the electrodes, storing energy. On discharge, this energy is released.

A result of the above interaction is that certain materials, which possess easily polarizable charges, will greatly influence the degree of charge which can be stored in a capacitor. The proportional increase in storage ability of a dielectric with respect to a vacuum is defined as the dielectric constant of the material.

The degree of polarization P is related to the dielectric constant K , and the electric field strength E as follows:

$$P = \epsilon_0 (K-1) E$$

where ϵ_0 is the permittivity of free space, (a constant).

The total polarization of a dielectric arises from four sources of charge displacement: (a) electronic displacement, (b) ionic displacement, (c) orientation of permanent dipoles and (d) space charge displacement. The total contribution of polarization to the dielectric constant is therefore a summation of the above:

$$P_t = P_e + P_i + P_d + P_s$$

Electronic Displacement: This effect is common to all materials, as it involves distortion of the center of charge symmetry of the basic atom. Under the influence of an applied field, the nucleus of an atom and the negative charge center of the electrons shift, creating a small dipole. This polarization effect is small, despite the vast number of atoms within the material, because the moment arm of the dipoles is very short, perhaps only a small fraction of an Angstrom ($1\text{\AA} = 10^{-10}$ meters).

Ionic Polarization: Ionic displacement is common in ceramic materials, which consist of crystal lattices occupied by cations and anions. Under the influence of an electric field, dipole moments are created by the shifting of these ions towards their respective (opposite) polarity of the field. The displacement, or moment arm of the dipoles can be relatively large in comparison to the electronic displacement, (although still much less than one Angstrom unit), and therefore can give rise to high dielectric constants in some ceramics.

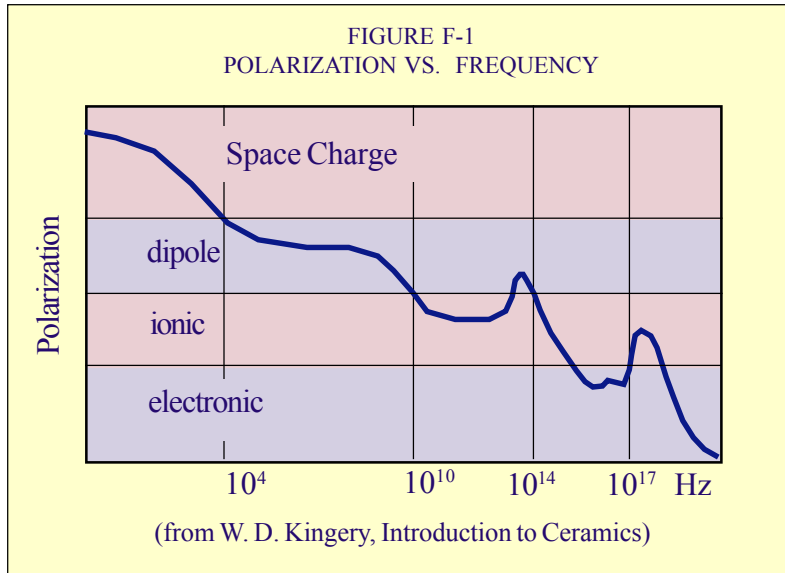
Dipole Orientation: This is a phenomenon involving rotation of permanent dipoles under an applied field. Although permanent dipoles exist in ceramic compounds, such as in SiO_2 , which has no center of symmetry for positive and negative charges, dipole orientation is not found to occur, as the dipole is restricted from shifting by the rigid crystal lattice; reorientation of the dipole is precluded as destruction of the lattice would ensue. Dipole orientation is more common in polymers which by virtue of their atomic structure permit reorientation. Note that this mechanism of permanent dipoles is not the same as that of induced dipoles of ionic polarization.

Space Charge Polarization: This mechanism is extrinsic to any crystal lattice. The phenomenon arises due to charges which exist due to contaminants or irregular geometry of the interfaces of polycrystalline ceramics, and is therefore an extraneous contribution. These charges are partly mobile and migrate under an applied field.

EFFECT OF FREQUENCY ON POLARIZATION

The mechanisms of polarization have varying time response capability to an applied field frequency, and the net contribution of polarization to the dielectric constant is therefore frequency dependent. Electronic displacement responds rapidly to the field reversals, and no lag of the polarization contribution occurs up to 10^{17} Hz. As is expected, ions, which are larger and must shift within the crystal structure, are less mobile, and have a less rapid response. The polarization effect of ionic displacement decreases at 10^{13} Hz. At this frequency, the ionic displacement begins to lag the field reversals, increasing the loss factor and contributing less to the dielectric constant. At higher frequency, the field reversals are such that the ions no longer “see” the field (the natural frequency of ions is less than the applied frequency), and no polarization (or loss factor) contribution is made by ionic displacement.

Dipole orientation and space charge polarization have slower frequency responses. The total net effect is illustrated in Figure F-1. The peaks which occur near the limiting frequency for ionic and electronic polarization are due to the resonance points, where the applied frequency equals the natural frequency of the material



The variation with frequency of the polarization mechanisms is reflected when measuring dielectric constant of a capacitor. As expected, capacitance value, i.e. dielectric constant, always decreases with increased frequency, for all ceramic materials, although with varying degrees, depending upon which type of polarization mechanism is dominant in any particular dielectric type.

DIELECTRIC LOSS

In an AC circuit, the voltage and current across an “ideal” capacitor are 90° out of phase. This is evident from the following relationships:

$$Q = CV$$

For an alternating applied field,

$$V = V_0 \sin \omega t$$

where V_0 is the amplitude of the sinusoidal signal, and ω is the frequency.

Therefore

$$Q = CV_0 \sin \omega t$$

The current

$$I = dQ/dt = d/dT CV_0 \sin \omega t$$

Therefore

$$I = CV_0 \omega \cos \omega t$$

Because

$$\cos \omega t = \sin (\omega t + 90^\circ)$$

the current flow is therefore 90° out of phase with the voltage. Real dielectrics, however, are not perfect devices, as the resistivity of the material is not infinite, and the lag or “relaxation time” of the polarization mechanisms with frequency generates losses.

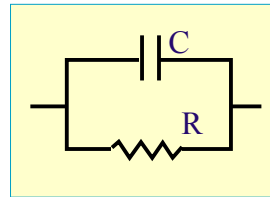
The above model for an “ideal” capacitor, in practical applications, must be modified; a practical model for a real capacitor can be considered to be an ideal capacitor in parallel with an ideal resistor.

Again, for the capacitor, the voltage

$$V = V_0 \sin \omega t$$

in an alternating field, and

$$I_c = CV_0 \omega \cos \omega t$$



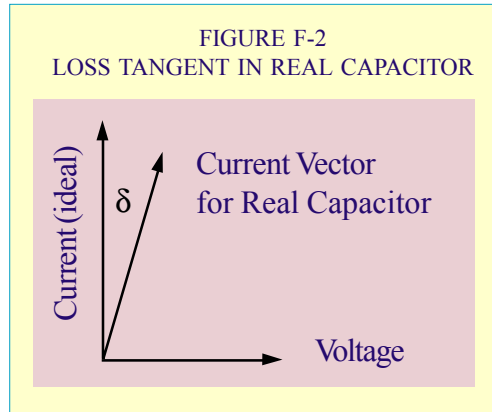
For the ideal resistor

$$I_r = V/R = V_0/R \sin \omega t$$

The net current flow is therefore

$$I_c + I_r = I_{net} = CV_0 \omega \cos \omega t + V_0/R \sin \omega t$$

The two portions of the current flow indicate that some current (that contributed by the resistive portion of the capacitor) will not be 90° out of phase with the voltage. The angle by which the current is out of phase from ideal can be determined, and the tangent of this angle is defined as the loss tangent or dissipation factor, as illustrated in Figure F-2:



The loss tangent, $\tan \delta$, is a material property, and is not dependent on geometry of a capacitor. The loss tangent greatly influences the usefulness of a dielectric in electronic applications. In practice it is found that lower dissipation factor is associated with materials of lower dielectric constant. Higher K materials, which develop this property by virtue of high polarization mechanisms, display higher dissipation factor.

EFFECT OF FREQUENCY ON DIELECTRIC LOSS

As was illustrated in paragraph F-2, the frequency at which a dielectric is used has an important effect on the polarization mechanisms, notably the “relaxation” process or time lag displayed by the material in following field reversals in an alternating circuit. Low relaxation time is associated with instantaneous polarization processes, large relaxation time with delayed polarization processes. Ceramic dielectrics consist of atoms and ions, the latter which contribute largely to the dielectric losses. The loss contribution is maximized at a frequency where the applied field has the same period of the relaxation process. To state the matter simply, losses are small when the relaxation time and period of the applied field differ greatly:

- a) relaxation time \gg field frequency, loss is small
- b) relaxation time \ll field frequency, loss is small
- c) relaxation time = field frequency, loss is maximized

Situation (a) generates little loss, as the polarization mechanism is much slower than the field reversals, and the ions cannot follow the field at all, hence creating no heat loss. The inverse occurs in situation (b), where the polarizing processes can easily follow the field frequency, with no lag. In case (c), however, ions can follow the field, but limited by their relaxation time, and thus generating the highest loss with frequency.

Ceramic dielectric formulations always show a range of relaxation times over the frequency spectrum, as these materials consist of polycrystalline matter. The variation of dielectric loss with frequency coincides with the change in dielectric constant, as the two are related to the polarizing mechanisms, as shown in Figure F-3. In high frequency applications, a figure of merit known as the “Q factor” is often used, which is the reciprocal of the loss tangent:

$$Q = 1 / \tan \delta$$

