RECENT DEVELOPMENTS AND FUTURE PROSPECTS OF CAPACITORS

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1. Introduction

The structure formed by placing a space/air or a dielectric material between the conductive plates is called a capacitor (Riaz & Kanwal, 2019). It is assumed that the capacitor will indeed be recharged by Q in a manner that corresponds to the voltage differential of V, if a voltage difference of V is supplied between both the planes (Zharin, 2010). The measure of how much a capacitor can be charged under the applied potential difference is called the capacitance of that capacitor (Pal et al., 2021).

The capacity of the space (air) capacitor is defined by the expression (Muñoz-Enano et al., 2021).

$$C_0 = \frac{Q}{\Delta V} \tag{1.1}$$

The unit of the capacitance (SI) is Farad (F), Q is the amount of charge stored in the capacitor and its unit is Coulomb, ΔV is the potential difference between the electrodes and its unit is Volt.

The capacitance value depends on the geometry of the capacitor and the characteristics of the region between the parallel plates (Ciftja, 2021).

If there is a gap between the capacitor plates, the capacitance of the capacitor is defined as

$$C_0 = \varepsilon_0 \frac{A}{d} \tag{1.2}$$

Here, A is the surface area of the electrodes, d is the distance between the electrodes, and ε_o is the permittivity of free space and its value is $8.85 \times 10^{-12} Fm^{-1}$.

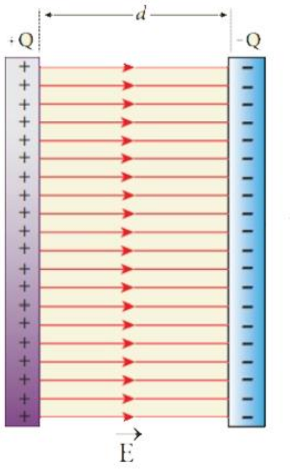

Figure. 1. Electric field lines between the parallel plates of a air capacitor (Rediansyah & Viridi, 2015).

When a potential difference is applied to the capacitor, the distance between the conductive plates must be very small in order from the surface area (d<<A) to create a uniform electric field between the conductive plates as in figure 1.

When a dielectric material is placed between the plates of the capacitor, the capacitance of the capacitor increases. C is the capacitance of the dielectric capacitor, ε is the permittivity of the dielectric material is expressed with,

$$C = \varepsilon \frac{A}{d} \quad (1.3)$$

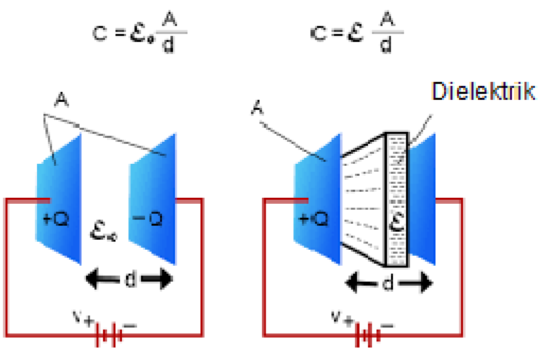

Figure 2. The capacitance of air and dielectric capacitor connected to the battery (Nishino, 1996).

The material placed between the plates of a capacitor with low electrical conductivity is called a dielectric (Matko & Milanovič, 2021). When a dielectric material is placed between the two plates of the capacitor, the capacitance of a capacitor increases. The dielectric material provides the following contributions to the capacitor:

A distinguishing characteristic of the piezoelectric medium that changes through one materials to the next and raises capacitance by a factor of is the dielectric constant (Burke, 2021). The mechanical support provided by the insulators allows the two panels to be placed closer to one another without actually touching.

A capacitor with a capacity of C_o is linked to a cell and recharged to a potential of V_o when there is a space among its layers.

The cell is unplugged when the capacitor has been fully charged. The charge Q_o is present on the plates, and the change in voltage between the two is calculated as V_o. It is seen that when a dielectric is placed between the plates, the potential difference drops to a smaller value such as V. It will be seen that the dielectric capacitor will be more charged than the gap capacitor as in Figure 2.

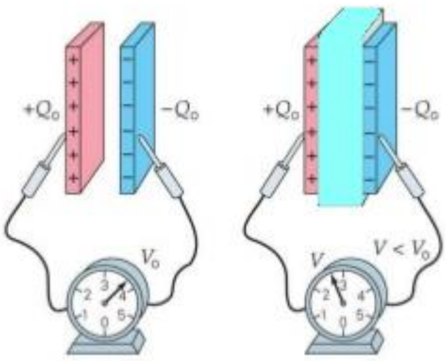

Figure 3. The charge amounts of the air and dielectric capacitor connected to the battery (Ippili et al., 2022).

When $\kappa > 1$, then $\Delta V < \Delta V_o$.

$$V = \frac{1}{\kappa} V_0 \qquad (1.4)$$

The constant κ in this equation is called the dielectric constant or relative permittivity of the material between the plates (Figure 3). The dielectric constant κ is just a number and it has no dimension.

The capacitance of a dielectric capacitor,

$$C = \frac{Q_o}{V} = \frac{Q_o}{\frac{V_o}{\kappa}} = \kappa \frac{Q_o}{V_o} = \kappa C_0 \qquad (1.5)$$

Equation (1.5) states that by placing a dielectric material between the plates of capacitor, the capacitance can be increased by a factor κ. The electrical energy stored in a dielectric capacitor is also affected. The energy stored in air capacitor is U_o and the energy stored in a dielectric capacitor is U.

$$U = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}\frac{Q_o^2}{\kappa C_o} = \frac{1}{\kappa} U_o \qquad (1.6)$$

2. Dielectric in Microscopic Dimension

The electrical structure formed by the positive (+q) and negative (-q) charges with a distance d between them is called the electric dipole (Ambroziak & Ciężkowski, 2021). Electric dipoles are represented by dipole moments.

Electric dipole moment,

$$p = qd \qquad (2.1)$$

It is shown in Figure 4. Here d is the distance between the negative charge and the positive charge. The dipole moment vector is from negative charge to positive charge. The unit of dipole moment (SI) is coulomb-meter (Cm); however, the unit commonly used in atomic physics and chemistry is debye (D).

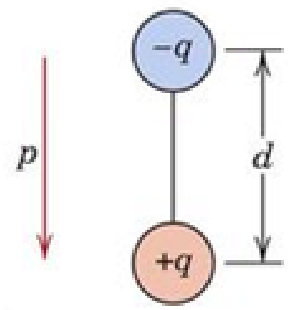

Figure 4. Electric dipole moment (Ambroziak & Ciężkowski, 2021).

When there is dielectric material between the capacitor plates, the total $\vec{E}$ electric field also decreases by the ratio of the decrease in the potential difference between the plates.

$$\vec{E} = \frac{\vec{E}_0}{\kappa} \qquad (2.2)$$

Let us explain the decrease in electric field by examining an ideal dielectric material.

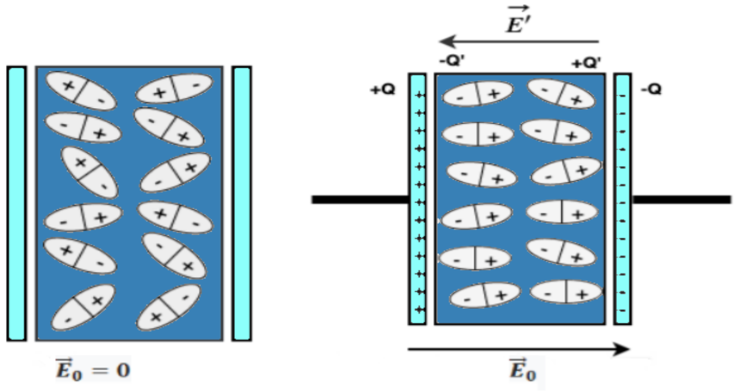

Figure 5. Distribution of dipoles under the absence and presence of external electric field (Du et al., 2022)

In in Figure 5, under the absence of electric field, dipoles are homogeneously distributed in the dielectric material. When a potential difference V_o is applied between the dielectric capacitor plates, a torque acts on the dipoles in the dielectric material between the plates. The dipoles are forced into a rotational motion in the electric field direction under the effect of torque, as shown in figure 5. The rotational motion of the dipoles depends on the frequency of the electric field and the temperature.

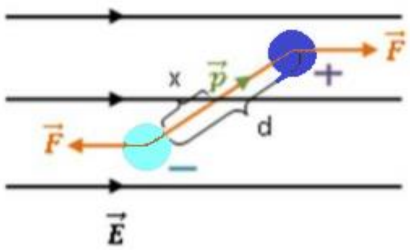

Figure 6. Torque acting on a positive and negative charge under a uniform electric field (Shoyama & Matsusaka, 2019).

Let's show this torque relationship mathematically; where $\vec{F}$ is the applied force

$$\vec{F} = q\,\vec{E} \tag{2.3}$$

Here E is the applied electric field and q is the distance between the charges. The expression $\vec{\tau}$ torque acting on the system,

$$\vec{\tau} = \vec{d} \times \vec{F} \tag{2.4}$$

The torque on the system can be calculated by using the above equation.

$$|\vec{\tau}| = \tau = |\vec{d}||\vec{F}|sin\theta \quad (2.5)$$

$$\tau = Fxsin\theta + F(d-x)sin\theta \quad (2.6)$$

$$\tau = Fd\ sin\theta \quad (2.7)$$

The applied force $\vec{F} = q\,\vec{E}$ and the distance between the charge centers d= p/q, the torque is written as

$$\tau = pEsin\theta \quad (2.8)$$

$$\vec{\tau} = \vec{p} \times \vec{E} \quad (2.9)$$

Torque is a vector quantity and its direction is inwards from the page plane as shown in figure 7.

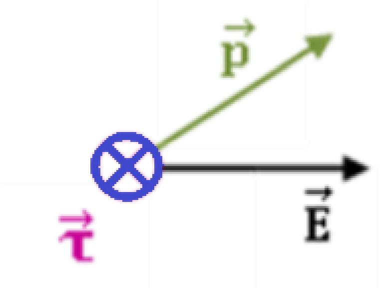

Figure 7. The torque that causes the rotational motion of the dipole (Melle et al., 2002).

By placing the dielectric material between the capacitor plates the decrease in the potential difference and the electric field $\vec{E}$ can be explained by using Gauss's Law.

Air between capacitor plates: Gauss's Law is used to find the electric field ($\vec{E_o}$) between the plates of a parallel plate capacitor when there is air between the plates. The net flux through the Gaussian Surface:

$$\phi_e = \oint \vec{E}.d\vec{A} = E_o A = \frac{Q}{\varepsilon_o} \quad (2.10)$$

$$E_o = \frac{Q}{\varepsilon_o A} \quad (2.11)$$

It is the expression of the electric field for air capacitor. Q/A is the charge per unit area, σ is the charge density. Electric field expression based on charge density

$$E = \frac{\sigma}{\varepsilon_o} \quad (2.12)$$

Dielectric material between the plates: If there is a dielectric material between the plates of the capacitor, a Gaussian surface can be chosen as in figure 8, and the electric field expression

$$\oint \vec{E}.d\vec{A} = EA = \frac{Q-Q'}{\varepsilon_o} \quad (2.13)$$

$$E = \frac{Q-Q'}{\varepsilon_o A} \quad (2.14)$$

$$E = \frac{Q}{\varepsilon_o A} - \frac{Q\prime}{\varepsilon_o A} \tag{2.15}$$

Q' is induced charge of dielectric capacitor. Q and Q´ charges are oppositely signed charges. Q – Q´ represents the charge on the specified Gaussian surface.

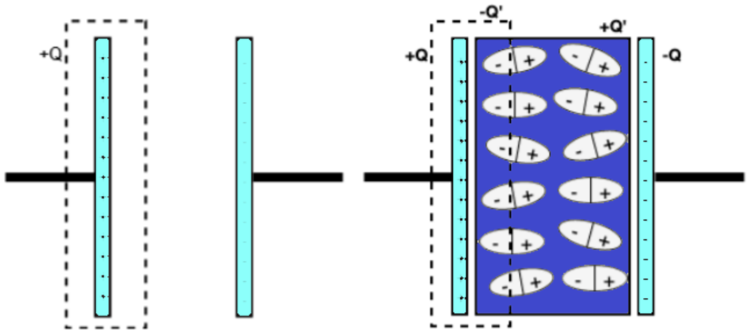

Figure 8. Selective Gaussian surface in air and dielectric capacitor (Li & Behdad, 2013).

Equation (2.15), If the magnitude of the electric field is written in terms of charge,

$$E = \frac{E_o}{\kappa} = \frac{Q}{\kappa \varepsilon_o A} = \frac{Q - Q\prime}{\varepsilon_o A} \tag{2.16}$$

$$\frac{Q}{\kappa \varepsilon_o A} = \frac{Q}{\varepsilon_o A} - \frac{Q'}{\varepsilon_o A} \tag{2.17}$$

$$Q' = Q\left(1 - \frac{1}{\kappa}\right) \tag{2.18}$$

The amount of charge induced on the surface of the dielectric is always less than the amount of charge on the plate surface ($Q' < Q$).

If written as charge density, it becomes

$$\sigma' = \sigma\left(1 - \frac{1}{\kappa}\right) \tag{2.19}$$

When the equation (2.17) is simplified it can be written as

$$\frac{Q}{A} = \varepsilon_o\left(\frac{Q}{\kappa \varepsilon_o A}\right) + \left(\frac{Q'}{A}\right) \tag{2.20}$$

Vector representation of equation (2.20)

$$\vec{D} = \varepsilon_o \vec{E} + \vec{P} \tag{2.21}$$

Here in equation (2.21), the first term corresponds to the displacement field, the second term corresponds to the applied field between the plates, and the last term corresponds to the field due to polarization.

3. Polarization Mechanisms

The dielectric material responds to the electric field by polarizing it. Polarization results from the response of dipoles to the electric field effect. The polarization vector is related to the neutralized charges on the surfaces of the capacitor plates (Chiu, 2014). Average dipole moment, can be written as

$$\vec{p} = \alpha \vec{E'} \tag{3.1}$$

Here α is the polarizability coefficient and E′ is defined as the local electric field. The polarization vector,

$$\vec{P} = (\kappa - 1)\varepsilon_o \vec{E} = N\alpha \vec{E} \tag{3.2}$$

This equation relates the dielectric constant κ, which is the microscopic parameter of the dielectric, to the molecular parameters N, α and E.

3.1. Electronic Polarization

Considering the structure of an atom, its nucleus consists of electrically neutrons and positively charged protons, and a cloud of randomly moving electrons. When the external electric field is applied, the nucleus of the atom and the negative electron cloud around it are separated from each other. This light charge separation makes one side of the atom slightly positive and the other slightly negative. The resulting polarization is called electronic polarization and is illustrated in figure 9. In dielectric materials, electronic polarization is observed. Electronic polarization takes place within a short time (Nunes & Vanderbilt, 1994). Electronic polarization is observed at high frequencies at approximately 10^{15}Hz. α_e represents the ability of the electron cloud to move the nucleus under the influence of the electric field, in other words it is the coefficient of electronic polarizability.

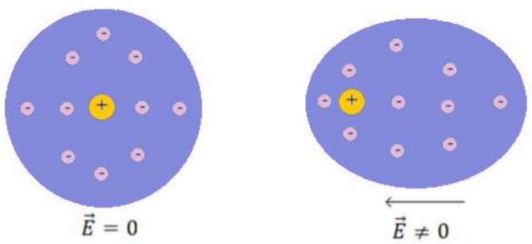

Figure 9. Electronic Polarization (Nunes & Vanderbilt, 1994).

3.2. Ionic Polarization

Ionic polarization (Kumar et al., 2020) takes place in ionic crystal elements. In the absence of an external electric field, the positive ions within the crystal cancel out the negative ions and the total charge becomes zero. When an external electric field is applied, the negative and positive charge ions are displaced, resulting in an induced polarization. Figure 9 illustrates the displacement of ions due to the electric field. The ionic polarization is represented by α_i. Since the ions that make up the crystal lattice are heavier in mass than the electrons, electronic polarization takes longer to occur. Ionic polarization generally occurs in ionic materials and is observed at low frequencies compared to electronic polarization. Ionic polarization is observed at approximately 10^{13}Hz.

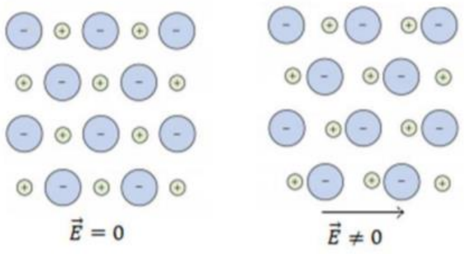

Figure 10. Ionic Polarization (Kumar et al., 2020).

3.3. Dipolar Polarization

Dipolar polarization (Shin et al., 2015) occurs in molecules that have dipoles when there is no electric field. When an external electric field is applied to these molecules, a torque acts on the dipole moments in the structure. As a result, the molecules tend to align as required by the applied electric field. When the electric field is removed, the dipoles return to their original position. This is called dipolar polarization and is represented by α_d. This polarization mechanism occurs in the range of 10^{-3}-10^{-9} seconds and is observed in the frequency range 1kHz-1MHz.

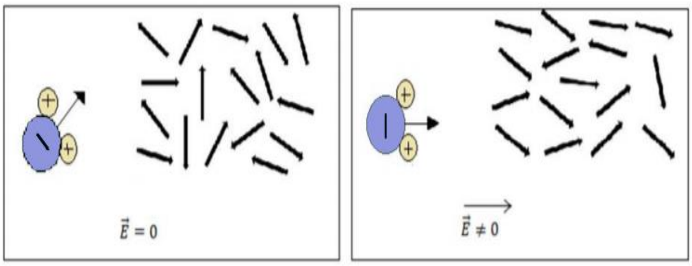

Figure 11. Dipolar Polarization (Shin et al., 2015).

3.4. Interface Polarization

When there is an accumulating of charge at an interface between two materials or between two areas inside a material as a result of an external electric field, this phenomenon is known as interfacial or space charge polarisation (Hermann & Schmidt, 2020). Interfacial polarisation is different from ionic polarisation in that it impacts free charges in addition to the bound positive and negative charges, i.e., ionic and covalently bonded structures. As a result, interfacial polarisation is typically seen in polycrystalline or amorphous substances. According to Figure 12. Due to the dielectric material's insulating qualities, the electric field will result in a charge imbalance and happen at a frequency of roughly 10-2 Hz, where α_s is the polarizability coefficient of the interfaces.

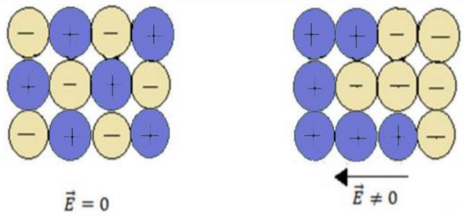

Figure 12. Interface Polarization (Hermann & Schmidt, 2020).

The polarization mechanisms of the frequency with respect to the dielectric constant and the dielectric loss are shown in Figure 13.

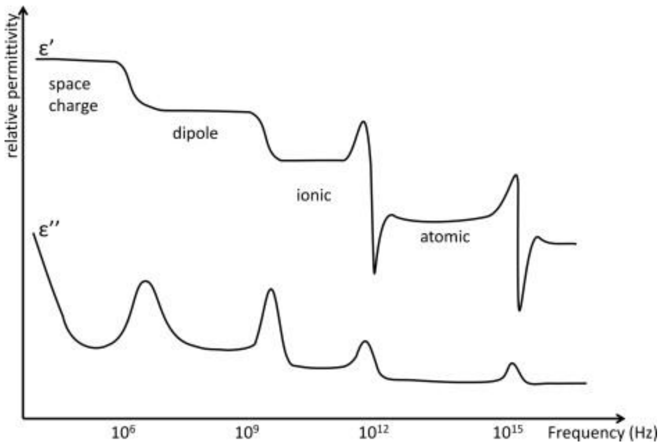

Figure 13. Polarization mechanisms according to frequency, dielectric constant and dielectric loss (Kim et al., 2021).

4. Variable Electric Field and Dielectric Loss in the Capacitor

If a potential difference with angular frequency ω is applied between the plates of air capacitor, the potential difference can be written as

$$V = V_{\circ}e^{i\omega t} \quad (4.1)$$

The charge on the surface plates of the capacitor is,

$$Q = C_{\circ}V = C_{\circ}V_{\circ}e^{i\omega t} \quad (4.2)$$

The current caused by these charges is;

$$I_c = \frac{dQ}{dt} = \frac{d}{dt}(C_{\circ}V_{\circ}e^{i\omega t}) = i\omega C_{\circ}V_{\circ}e^{i\omega t} \quad (4.3)$$

rearrange this equation

$$cos\frac{\pi}{2} + isin\frac{\pi}{2} = i \quad (4.4)$$

By substituting $i = e^{i\frac{\pi}{2}}$ in the equation (4.1),

$$I_c = e^{i\frac{\pi}{2}}\omega C_{\circ}V_{\circ}e^{i\omega t} = \omega C_{\circ}V_{\circ}e^{i(\omega t+\frac{\pi}{2})} \quad (4.5)$$

By substituting $I_{\circ} = \omega C_{\circ} V_{\circ}$ in above equation, we get

$$I_c = I_{\circ} e^{i(\omega t + \frac{\pi}{2})} \tag{4.6}$$

As you can see, there is a 90° phase difference between the loading current and the applied potential. In other words, the current is 90˚ ahead of the applied voltage. This is explained with the phasor diagram in the figure. This is valid only for the capacitor with air between the plates. The capacitor belonging to such a structure is defined as the ideal capacitor.

If a potential difference is applied to the capacitor while there is a dielectric material between the capacitor plates, energy is lost when the dielectric structure becomes polarized. In this case, there will be a loss of current due to energy loss in the dielectric and it is indicated by I_R. In a dielectric capacitor, the phase difference between the charging current and the applied voltage will be different than 90°, that is, it will be 90-δ. This situation is represented by a phasor diagram.

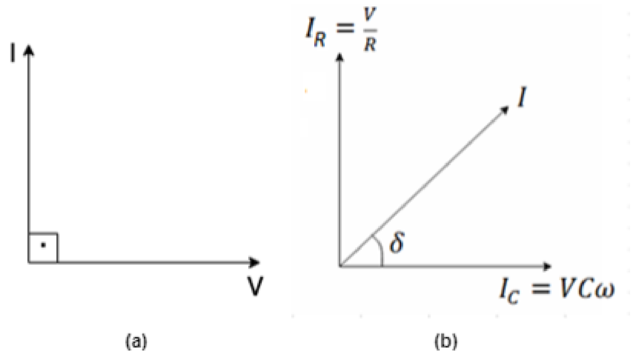

Figure 14. Phasor diagram representation of capacitor under variable electric field (AC), (a) For Air Capacitor (b) For Dielectric Capacitor (Wang et al., 2021).

Conductance is $G = 1/R$

$$I_R = GV \tag{4.7}$$

The total current of the capacitor is,

$$I = I_c + I_R = (i\omega C + G)V \tag{4.8}$$

Tangent of phase angle between charge current and total current is

$$tan\delta = \frac{I_R}{I_c} = \frac{1}{\omega RC} \tag{4.9}$$

known as the loss factor. Considering the phase difference between the charging current and the loss currents in the effect of the variable electric field, an expression that can be defined as the charging and loss components in the dielectric material can be used. For this purpose, here the dielectric complex permittivity is one of the distinguishing properties of the dielectric, and its expression is

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{4.10}$$

By using this expression, the total current is;

$$I = (i\omega\varepsilon' + \omega\varepsilon'')\frac{C_\circ}{\varepsilon_\circ}V \quad (4.11)$$

$$I = i\omega C_\circ \frac{\varepsilon' - i\varepsilon''}{\varepsilon_\circ}V \quad (4.12)$$

ε' the real component of the electric permittivity, and ε'' the imaginary component of the electric permittivity,

κ^*, complex dielectric constant is defined as

$$\kappa^* = \frac{\varepsilon^*}{\varepsilon_\circ} \quad (4.13)$$

and the expression

$$\kappa^* = \kappa' - i\kappa'' \quad (4.14)$$

κ' dielectric constant, κ'' is the dielectric energy loss.

Considering the phasor diagram for a dielectric capacitor, the total current expression is,

$$I' = \frac{dQ}{dt} = \frac{d}{dt}CV_\circ e^{i\omega t} = i\omega CV_\circ e^{i\omega t} \quad (4.15)$$

$$C = \kappa^* C_\circ \quad (4.16)$$

$$I' = i\omega(\kappa' - i\kappa'')C_\circ V_\circ e^{i\omega t} \quad (4.17)$$

$$I' = i\omega\kappa' C_\circ V_\circ e^{i\omega t} + \omega\kappa'' C_\circ V_\circ e^{i\omega t} \quad (4.18)$$

$$tan\delta = \frac{I_R}{I_C} = \frac{\omega\kappa'' C_\circ V_\circ e^{i\omega t}}{\omega\kappa' C_\circ V_\circ e^{i\omega t}} = \frac{\kappa''}{\kappa'} \quad (4.19)$$

Here it is seen from the expression of the loss factor that the dielectric constant is the ratio of the real and imaginary parts.

The currents observed in the dielectric are expressed in terms of the current density.

Current density,

$$J = \frac{I_R}{A} = \frac{\omega\kappa'' C_\circ V_\circ e^{i\omega t}}{A} \quad (4.20)$$

Electric field can be expressed as;

$$|\vec{E}| = \frac{V}{d} \quad (4.21)$$

$$C_\circ = \frac{A}{d}\varepsilon_\circ \quad (4.22)$$

By adding equations 4.21 and 4.22, in the current density equation 4.20, we get

$$J = \frac{I_R}{A} = \frac{A}{d}\frac{\omega\varepsilon_\circ\kappa'' E_\circ d e^{i\omega t}}{A} \quad (4.23)$$

$$J = \omega\varepsilon'' E \quad (4.24)$$

$$\sigma_{AC} = \omega\varepsilon'' \quad (4.25)$$

Equation (4.25) is called variable field conductivity of dielectric medium.

5. The Clausius-Mossotti Equation

The polarization is dependent on the magnitude of the electric field acting on the dipoles (Duerinckx & Gloria, 2022). The value of polarization is,

$$\vec{P} = N\vec{\mu} \quad (5.1)$$

In Equation 1.56, N is the number of dipoles per unit volume, $\vec{\mu}$ is the mean dipole moment. α is Polarization coefficient, $\vec{E'}$ local electric field, Polarization can be written as

$$\vec{P} = N\alpha\vec{E}' \quad (5.2)$$

Let's examine the model of dipoles formed by non-polar molecules under the influence of an external electric field. The local field acting on a reference molecule is caused by the effect of the external electric field. It is explained by considering the model in Figure 15.

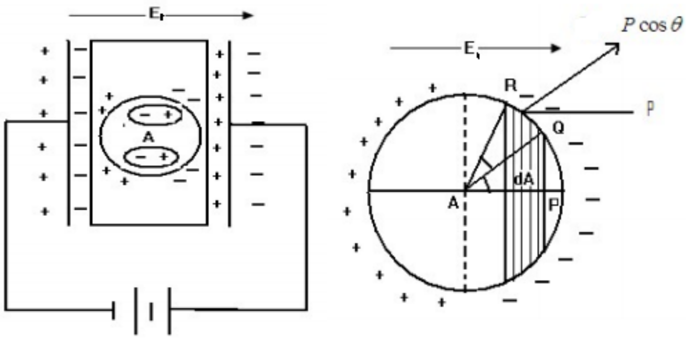

Figure 15. The local electric field that occurs in the dielectric material (Duerinckx & Gloria, 2022).

Let's suppose for the purposes of this model that a virtual sphere surrounds the reference molecule A in the physical world. $\vec{E_1}$ is the electric field between the plates, $\vec{E}_2$ is the electric field between the dipoles, and $\vec{E}_3$ is the electric field resulting from the surrounding dipoles. As a consequence, A is the electric field acting on the reference molecule.

$$\vec{E}' = \vec{E}_1 + \vec{E_2} + \vec{E_3} \quad (5.3)$$

Here $\vec{E}_1$ is taken as $\vec{E}$ since it is the external electric field and $\vec{E}_3$ electric field can be neglected since it is very small relative to $\vec{E}_1$ and $\vec{E}_2$. If we choose $\vec{dA}$ surface area within the sphere, there will be an electric field corresponding to each field. Electric fields in the horizontal direction neutralize each other. For the fairly small electric field $\vec{E}_2$,

$$d\vec{E}_2 = \frac{1}{4\pi\varepsilon_o}\frac{dq\cos\theta}{r^2} \quad (5.4)$$

$$dq = dA \times P_N \quad (5.5)$$

$$dq = dA \times P\cos\theta \quad (5.6)$$

$$dA = 2\pi r^2 \sin\theta d\theta \qquad (5.7)$$

$$dq = 2\pi r^2\, P \cos\theta\ \sin\theta d\theta \qquad (5.8)$$

$$dE_2 = \frac{1}{4\pi\varepsilon_o} \frac{2\pi r^2\, P \cos^2\theta \sin\theta d\theta}{r^2} \qquad (5.9)$$

$$dE_2 = \frac{1}{4\pi\varepsilon_o} 2\pi\, P \cos^2\theta \sin\theta d\theta \qquad (5.10)$$

Equation (5.10) is obtained. By integral the solution $\int dE_2 = E_2$

$$E_2 = \frac{2\pi P}{4\pi\varepsilon_o} \int_0^{\pi} \cos^2\theta \sin\theta d\theta \qquad (5.11)$$

$$\vec{E}_2 = \frac{\vec{P}}{3\varepsilon_0} \qquad (5.12)$$

$$\vec{P} = \varepsilon_0 (\kappa^{'} - 1)\vec{E} \qquad (5.13)$$

$$\vec{E}_2 = \frac{\vec{E}}{3}(\kappa^{'} - 1) \qquad (5.14)$$

Get this result.

Substituting this result

$$\vec{E}' = \vec{E}^1 + \overrightarrow{E^2} = \vec{E} + \frac{\vec{E}}{3}(\kappa^{'} - 1) = \frac{\vec{E}}{3}(\kappa^{'} + 2) \qquad (5.15)$$

By equating equation 3.2 with equation 5.15 we get,

$$\vec{P} = (\kappa^{'} - 1)\varepsilon_0 \vec{E} = N\alpha\vec{E}' = \frac{\vec{E}}{3}(\kappa^{'} + 2) \qquad (5.16)$$

By rearranging the equation, we get

$$\frac{\kappa^{'} - 1}{\kappa^{'} + 2} = \frac{N\alpha}{3\varepsilon_0} \qquad (5.17)$$

and this equality is called Clausius-Mossotti equation. The Clausius-Mossotti equation establishes a relationship between the dielectric constant $\kappa^{'}$ (macroscopic magnitude) and the polarization constant α (microscopic magnitude).

6. Debye Model

When an electric field is applied to a dielectric, the dipoles oscillate and rub against each other (Zhou et al., 2021). The polarization that occurs as a result of the movement of the dipoles under the influence of the electric field shows changes as a function of time. In accordance with this definition, polarization at t=0 can be written as

$$P_\infty = P_E + P_A \qquad (6.1)$$

Here P_∞ is instantaneous polarization with electric field effect, and P_E is the sum of electronic polarization and P_A is the atomic polarization. As time progresses, the dipoles will rotate due to the changing direction of the applied variable electric field, and the resulting polarization will change as a function of time. At any time t, a time dependent polarization is obtained, as in the equation of total polarization.

$$P(t) = P_\infty + P_{(dipol)} \tag{6.2}$$

Here,

$$P_{(dipol)} = (\varepsilon - \varepsilon_\infty)E(t) \tag{6.3}$$

Considering that the change in dipolar polarization can be proportional to the difference of the dipoles from the equilibrium position, it is assumed that the dipolar polarization will change with time. This situation is given by the equation,

$$\frac{dP_{(dipol)}}{dt} = \frac{1}{\tau}\left(P_{s(dipol)} - P_{(dipol)}\right) \tag{6.4}$$

Here, τ is the time between two equilibrium states of the dipoles after the electric field is applied, and is called the relaxation time. $P_{s(dipol)}$, is the polarization under constant electric field effect, and it can be written as,

$$P_{s(dipol)} = (\varepsilon_S - \varepsilon_\infty)E \tag{6.5}$$

The time-variance equation of polarization is written as,

$$\frac{dP_{(dipol)}}{dt} = \frac{1}{\tau}\left[(\varepsilon_S - \varepsilon_\infty)E - P_{(dipol)}\right] \tag{6.6}$$

If an alternating electric field is applied $\left(E = E_0 e^{i\omega t}\right)$,

$$\frac{dP_{(dipol)}}{dt} + \frac{1}{\tau}P_{(dipol)} = \frac{1}{\tau}(\varepsilon_S - \varepsilon_\infty)E_0 e^{i\omega t} \tag{6.7}$$

Above is obtained. By integrating the equation,

$$P_{(dipol)} = ce^{-\frac{t}{\tau}} + \frac{(\varepsilon_S - \varepsilon_\infty)E_0}{1+i\omega t}e^{i\omega t} \tag{6.8}$$

The first term of the equation explains the variable behavior, going to zero when t →∞. The second term explains its permanent state.

$$P_{(dipol)} = \frac{(\varepsilon_S - \varepsilon_\infty)E_0}{1+i\omega t}e^{i\omega t} \tag{6.9}$$

In the case of a variable electric field, the phase difference between the applied field and the polarization vector is

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{6.10}$$

The complex dielectric constant is shown in the figure. The complex dielectric constant is written in terms of relaxation time.

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+i\omega t} = \varepsilon_\infty + \frac{(\varepsilon_S - \varepsilon_\infty)(1-i\omega t)}{1+\omega^2 t^2} \tag{6.11}$$

If the above equation is divided into real and imaginary parts, the following equations are obtained.

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+\omega^2 t^2} \tag{6.12}$$

$$\varepsilon'' = \frac{(\varepsilon_S - \varepsilon_\infty)\omega t}{1+\omega^2 t^2} \tag{6.13}$$

These equations are called Debye's equations. Debye Equations reveal the effect of relaxation time on the polarization that occurs under a variable electric field in the dielectric, as shown in Figure 16.

The ratio of the real and imaginary parts gives the energy loss as a result of friction during the rotation of the dipoles.

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{(\varepsilon_S-\varepsilon_\infty)\omega t}{\varepsilon_S+\varepsilon_\infty\omega^2 t^2} \qquad (6.14)$$

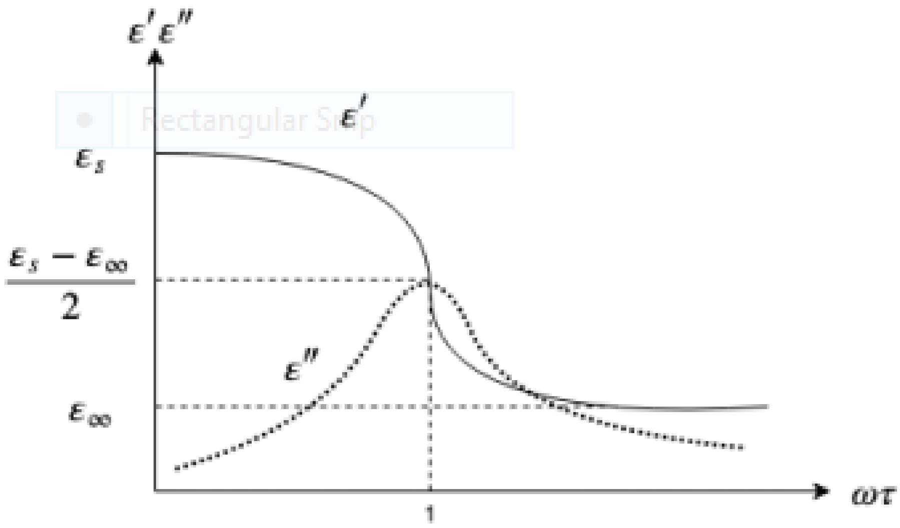

Figure 16. Debye Relaxation Graph (Gedeon, 2021).

7. Drude Model

The Drude model is also called the free electron model (Basu & Dhasmana, 2022). This model provides information about the heat capacity, magnetic permeability, thermal conductivity and electrodynamics of metals. In this model, electron-electron and electron-ion interactions are not taken into consideration and the force acting in the electric field is written as

$$\vec{F} = m\vec{a} = q\vec{E} \qquad (7.1)$$

$$\vec{a} = \frac{q\vec{E}}{m} \qquad (7.2)$$

Here q is the electron charge, m is the electron mass and $\vec{E}$ is the electric field and the velocity of these electrons can be written as

$$\vec{V}_S = \vec{V}_I + \vec{a}t \qquad (7.3)$$

Here $\vec{V}_S$is the drift velocity and $\vec{V}_I$ is the initial velocity. If $\vec{V}_I = 0$, by rearranging the equation,

$$\vec{V}_S = \frac{q\vec{E}}{m}\tau \qquad (7.4)$$

The current density is written as,

$$J = \frac{I}{A} = nqV_S \qquad (7.5)$$

Here, n is the number of charge carriers per unit volume. Substituting the expression V_S in the equation,

$$J = \frac{nq^2E}{m}\tau \tag{7.6}$$

$$J = \sigma.E \tag{7.7}$$

$$\sigma.E = \frac{nq^2E}{m}\tau \tag{7.8}$$

$$\sigma_0 = \frac{nq^2}{m}\tau \tag{7.9}$$

get conductivity equation. This expression is called DC conductivity and does not depend on the electric field.

8. Alternative Conductivity

When observing the motions of bound charges under an electric field, frictional forces should also be considered (Tan et al., 2022). The force acting on electron is

$$\vec{F} = m\vec{a} = q\vec{E} + \vec{F}_d \tag{8.1}$$

$\vec{F}_d$ is the friction force between charges, given by $\vec{F}_d = -\frac{m\vec{V}}{\tau}$. If we rearrange the equation, we get

$$m\vec{a} = q\vec{E} + \left(-\frac{m\vec{V}}{\tau}\right) \tag{8.2}$$

$$m\frac{d\vec{V}}{dt} = q\vec{E} - \frac{m\vec{V}}{\tau} \tag{8.3}$$

$$m\frac{d\vec{V}}{dt} + \frac{m\vec{V}}{\tau} = q\vec{E} \tag{8.4}$$

Under the alternating field area, electric field and velocity will depend on time, it is given by

$$E(t) = E_0 e^{i\omega t} \tag{8.5}$$

$$V(t) = V_0 e^{i\omega t} \Rightarrow \frac{d\vec{V}(t)}{dt} = i\omega V_0 e^{i\omega t} \tag{8.6}$$

As a result,

$$mi\omega V_0 e^{i\omega t} + \frac{m}{\tau}e^{i\omega t} = qE_0 e^{i\omega t} \tag{8.7}$$

$$V_0 m\left(i\omega + \frac{1}{\tau}\right) = qE_0 \tag{8.8}$$

$$V_0 = \left(\frac{q\tau}{m}\right)\frac{1}{1+i\omega t}E_0 \tag{8.9}$$

equation (8.9) will equal the drift velocity,

$$V_0 = V_S \tag{8.10}$$

By writing the current density,

$$J = nqV_S = \frac{nq^2\tau}{m}\frac{1}{1+i\omega\tau} \qquad (8.11)$$

and

$$J(\omega) = \sigma(\omega)E(\omega) \qquad (8.12)$$

By substituting conductivity in this expression;

$$\sigma(\omega) = \frac{\sigma_0}{1+i\omega\tau} \qquad (8.13)$$

By making the denominator of $\sigma(\omega)$ real, and then write it in imaginary and real part,

$$\sigma(\omega) = \frac{\sigma_0}{1+\omega^2\tau^2} - \frac{i\omega\tau\sigma_0}{1+\omega^2\tau^2} \qquad (8.14)$$

The first term in equation 8.14 is the real and the second term is imaginary. And the real term is called AC conductivity.

$$\sigma(\omega) = \frac{\sigma_0}{1+\omega^2\tau^2} \qquad (8.15)$$

As atotal DC and AC can be written as,

$$\sigma_{top}(\omega) = \sigma_0 + \sigma(\omega) \qquad (8.16)$$

9. Conclusion

Depending on the individual technology, modern capacitor technologies typically have the possibility to provide power and energy concentrations that are quite higher than expected. Cost considerations in the consumer, commercial, and industrial sectors will play a major role in the implementation of these possibly ever-more compact designs. The development of modest, crafts-level production capabilities would enable the demonstration of cost cutting execution and technologies expansion validated over a wide range of innovative packaging applications.

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