Physical properties and basic theory of dielectric

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Abstract. At the beginning of human understanding and application of electricity, dielectric materials have been in the world. At that time, however, the dielectric was used only as an insulating material to separate the current. Until the 1930s, the main object of research was insulating materials, mainly focusing on the dielectric constant, loss, conductance and breakdown of insulating materials. After the 1930s, with the emergence and development of new technology, dielectric has been far from being only used as insulation materials to the application, especially the appearance of polar dielectric and widely used, making people's understanding of dielectric and its category and the past is very different. The research capacity has gradually evolved from the four main parameters of insulators to the study of the internal polarization process. This article from the dielectric polarization, dielectric loss, dielectric conductance and breakdown, dielectric thermal side note relaxation theory and its application of four chapters of the system to learn related content. The properties of dielectric are analyzed from the microscopic point of view, and the related theoretical hypotheses are established to reveal the corresponding macroscopic phenomena. The polarization, loss, conductance and breakdown properties of dielectric are analyzed. The dielectric constant $\varepsilon$, loss Angle tangent $\tan\delta$, conductivity $\gamma$ and breakdown field intensity $E$ are used to describe the properties of dielectric quantitatively.

Keywords: Polarization, Loss, Conductance, The breakdown.

1. Introduction
A dielectric is defined by the International Electrotechnical Commission as a substance with a large band gap between the ground state and the first excited state, which is occupied by the ground state. The definition of the Soviet Academy of Sciences is: the object with the ability to polarize under the action of electric field, and can exist electric field for a long time as its main property.

In electrical engineering, the dielectric is used primarily as electrical insulation. Human beings have been studying the electrical properties of dielectric since the 19th century. In the beginning, natural materials were used as the dielectric for electrical equipment. With the development of theory, the dielectric of synthetic polymer materials appeared. Due to the development of electronic science and technology, higher requirements are put forward for dielectric materials, which include not only insulating dielectric, but also various electronic functional materials.
2. Polarization of the dielectric

The polarization process of dielectric is closely related to material structure. The central problem of dielectric research is electric polarization and relaxation, so it involves the distribution of bound charge in material structure, fluctuation and interaction between charged particles, as well as the movement and relaxation of these particles under the action of external electric field.

2.1. A major parameter describing the polarization behavior of a dielectric

The main parameters describing dielectric polarization behavior include relative dielectric constant $\varepsilon_r$, polarization intensity $P$, effective electric field $E_e$, polarizability $\alpha$, and polarization coefficient $\chi$, etc.

$$\varepsilon_r = \frac{c}{c_0}$$
$$p = N\mu$$
$$\alpha = \frac{\mu}{E_e}$$
$$\chi = \varepsilon_r - 1$$

Relative dielectric constant a physical parameter that characterizes the dielectric or polarization properties of a dielectric material. The value is equal to the ratio of the capacitance of a capacitor of the same size made of the predicted material as the medium and a vacuum as the medium. The polarization intensity represents the vector sum of the induced dipole moments per unit volume under the action of an external electric field. The effective electric field represents the local electric field acting on the polarized particle and is the electric field generated by all free charges and dipoles in space except for the self-planned particle at that point. The polarizability alpha represents the dipole moment generated per unit effective electric field. The polarization coefficient $\chi$ is similar to the relative permittivity.

2.2. The Crosius equation

2.2.1. The Crosius equation. The significance of Crosius equation is to quantitatively describe the relationship between macroscopic parameters $\varepsilon_r$ and microscopic parameters $N$, $\alpha$ and $E_e$ in the polarization process.

$$\varepsilon = \varepsilon_0 + N\alpha \frac{E_e}{E}$$

This formula needs to predict the relationship between the effective electric field and the macroscopic external electric field. For different kinds of dielectric, different calculation methods of the effective electric field are established.

2.2.2. Lorentz effective electric field calculation model. The model assumes that the studied molecule is located at the center of a sphere of radius, that the sphere is sufficiently large in microcosm, that the sphere is considered as a continuum, and that the role of the planned molecule can be treated by a macroscopic method. On a macroscopic scale, it is small enough that the electric field of the dielectric is not affected by empty spheres. Exospheric molecules have only long-range properties on the center and can be treated as continuum (electromagnetic force). The molecular interaction with the center in the sphere is short-range, and the specific structure (molecular chain) of the medium must be considered.

$$E_e = \frac{\varepsilon_r + 2}{3}\varepsilon_0$$
Figure 1. Lorentz effective electric field model

The K-M equation can be obtained by substituting the Lorentz effective electric field into the Crosius equation

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N\alpha}{3\varepsilon_0}$$

Lorentz effective electric field model is applicable to non-polar gas dielectric, low pressure polar gas and high symmetry cubic lattice atoms.

2.2.3. Onsag effective electric field calculation model. Onshaag assumed that a hollow sphere of radius A, with an electric dipole at its center, was surrounded by a uniformly polar liquid medium, and

$$\frac{4}{3} \pi a^3 N = 1$$

The effective electric field consists of an empty sphere electric field $G$ and a reaction electric field $R$.

$$E_r = G + R = \frac{3\varepsilon_r}{2\varepsilon + 1} E + \frac{\mu}{4\pi\varepsilon a^2} \frac{2(\varepsilon_r - 1)}{2\varepsilon_r + 1}$$

The above equation is applicable not only to polar liquid dielectric, but also to non-polar liquid dielectric, $\mu = 0$ is sufficient. The equation is reduced to the Lorentz effective electric field.

2.3. Polarization mechanism of dielectric

The polarization of dielectric is composed of electron displacement polarization, ion displacement polarization, dipole polarization (turning), space charge polarization (interlayer) and thermonic relaxation polarization, in which the electron and ion displacement polarization turn into lossless polarization, the direction polarization and interlayer polarization turn into lossy polarization.

2.3.1. Electron displacement polarization. Electronic displacement polarization can be divided into three models, namely spherical tube atomic model, circular orbit model, material ball model. According to the calculation results of the model, the greater the atomic volume, the greater the polarizability. Electronic displacement polarization has a short completion time, is basically independent of frequency, and occurs in almost all media.
2.3.2. Ion displacement polarization. Ionic displacement polarization is mainly the polarization phenomenon of ionic crystal (solid) under the action of electric field. The models mainly include harmonic oscillator model and interaction potential model. Polarization time is also short, the electric field frequency is lower than the infrared frequency can complete the polarization.

2.3.3. Dipole displacement polarization. Dipole reversal polarization only occurs in polar dielectric, and the polarization time is long, and there is energy loss.

2.3.4. Thermionic relaxation polarization. Relaxation polarization of thermionic particles is the polarization generated by the directional movement of charged particles with certain connections under the action of electric field. The change of the polarization lags behind the change of electric field direction, and the time is relatively long. It is also a kind of lossy polarization, but it is generally small.

2.3.5. Space charge polarization. The polarization of space charge, also known as sandwich polarization, occurs only in an inhomogeneous dielectric with the slowest rate of polarization, and there is often a cumulative charge at the interface. The positive and negative properties of the cumulative charge are determined by the following equation

$$\lambda_4 E_2 - \lambda_5 E_1$$

3. Loss of dielectric

3.1. The basic concept of dielectric loss
The physical process by which a portion of electrical energy is converted to heat. The loss is divided into conductance loss, relaxation polarization loss and resonance loss. Conductance loss occurs in both DC and AC, and is actually the current flowing through the resistor doing work. Relaxation polarization exists only for AC. Resonance loss is the loss caused when the dielectric resonates with the incident light.

Excessive loss of dielectric will cause attenuation of line signal and damage the normal work of components.

3.2. Polarization establishment process under constant electric field
Under a constant electric field, any polarization of the medium can be established in time, and the dielectric constant of the medium is almost equal to the static dielectric constant.

$$\varepsilon_r \rightarrow \varepsilon_s$$

The polarization intensity of medium is composed of fast polarization intensity and relaxation polarization intensity. The polarization strength of the dielectric can be expressed by the following formula
Capacitance parameters can also be divided into steady state capacitance $C$, fast polarization capacitance $C_\infty$ and relaxation polarization capacitance $C_r$. The relationship between the three can be expressed in the following formula:

$$C = C_\infty + C_r$$

### 3.3. Loss of actual dielectric

In real dielectric, active current is composed of conductance current and relaxation active current, and reactive current is composed of pure capacitive current and relaxation reactive current.

Conductivity loss and relaxation polarization loss can be respectively expressed by the following equation:

$$W_k = \frac{V^2}{R}, \quad W_p = g \frac{A}{d} V^2, \quad g = \frac{\varepsilon_\infty (\varepsilon_0 - \varepsilon_\infty) \omega^2 \tau}{1 + \omega^2 \tau^2}$$

Unit volume loss:

$$p = W_k + W_p = (\gamma + g) E^2$$

Tangent of loss Angle:

$$\tan \delta = \frac{\tau + g}{\omega \varepsilon_0 \varepsilon_r}$$

When the time constant $\omega \tau \ll 1$ is, the dielectric is in the ultra-low frequency region, and the tangent of the loss Angle decreases with the increase of frequency. The imaginary part of the complex permittivity is close to zero and the real part is the static permittivity. When the time constant $\omega \tau \approx 1$, the dielectric is located in the anomalous dispersion region of the intermediate frequency region, the dielectric loss tangent has a maximum value, the imaginary part of the complex dielectric constant $\varepsilon^*$ reaches the peak value, and the imaginary part decreases rapidly. The dielectric is located in the high frequency region and the tangent of the loss Angle does not change much when $\omega \tau$ is separated by 1. The imaginary part of the complex permittivity is close to zero and the real part is the high frequency permittivity.

### 4. Conductivity and breakdown of dielectric

#### 4.1. Conductivity and breakdown of gaseous dielectric

### 4.1.1. The conductivity of a gaseous dielectric

Gas dielectric can be divided into three regions according to the different voltage, namely ohmic resistance region, saturation current region and current surge region.

When no electric field is applied, the ionization of carrier in gas dielectric is equal to recombination, and the carrier concentration can be expressed by the following equation:

$$N = \sqrt{\frac{n^*}{\beta}}$$

When the electric field is applied, the carrier generation rate is equal to the electrode neutralization rate plus the space recombination rate:

$$n' d = \beta N^2 d + \frac{J}{q}$$

When the gas dielectric is located in the saturated current region and the electric field is further increased, the spatial recombination can be ignored, the carrier generation rate is approximately equal to the neutralization rate of the electrode, and the current density approaches to a constant:

$$J = n'dq$$
When the gas dielectric is located in the current surge region, in the case of strong electric field, the molecular ionization energy of the gas dielectric will be greater than the collision ionization energy. At this time, the generation of charge carriers will increase, the current density and the electric field intensity will increase exponentially. When the electric field reaches a certain value, the dielectric will be broken down.

\[ J = J_0 e^{\alpha x} \]

4.1.2. Townsend discharge theory. Townsend discharge theory is a discharge model of uniform electric field. According to the model, there are three processes of carrier generation, namely \( \alpha \) process, \( \beta \) process and \( \gamma \) process.

The \( \alpha \) process is the number of free electrons produced when an electron collides with a gas particle every 1 cm from cathode to anode, which is also called collision ionization. If the external ionization factor is small, the current density is equal to zero, which belongs to the non-self-sustaining discharge. The ionization coefficient can be measured by the following equation

\[ \alpha = \frac{1}{d_2 - d_1} \ln \frac{I_2}{I_1}. \]

The \( \beta \) process is the number of free electrons produced when a positive ion collides with a gas particle every 1 cm from anode to cathode. Due to the large mass of positive ions, the acceleration speed in the electric field is small and the energy is small, so the process is considered to be small in the analysis.

The gamma process is the number of free electrons released from the cathode by the impact of positive ions on the cathode. The current density can be obtained by analysis

\[ J(d) = J_0 e^{\alpha d} \left( \frac{1}{1 - \gamma(e^{\alpha d} - 1)} \right) \]

When \( 1 - \gamma(e^{\alpha d} - 1) > 0 \), remove the external factors, the discharge stops. When \( 1 - \gamma(e^{\alpha d} - 1) = 0 \), cancel the ionization factor, can still maintain large current. When \( 1 - \gamma(e^{\alpha d} - 1) < 0 \), can be self-sustaining discharge.

According to this condition, Baschen's law can be derived, and the maximum field strength that the gas dielectric can bear can be calculated to calculate the striking voltage. Under a uniform electric field, the breakdown voltage is only related to the pressure \( p \) distance \( d \).

4.1.3. Stream discharge theory. The flow theory takes into account the effect of space charge on the original electric field and photoionization. That is, the light generated by the compound ionizes the surrounding molecules generated by the secondary collapse, the formation of the plasma channel. The model is applicable to uneven electric field as well as uniform electric field.

And uneven electric field may produce corona discharge phenomenon, when the voltage is increased, there is a possibility of breakdown phenomenon. The corona starting voltage of positive bar and negative plate is greater than that of positive bar and negative plate, but the breakdown voltage of positive bar and negative plate is less than that of positive bar and negative plate.

4.2. Conductivity and breakdown of solid dielectric

4.2.1. Ionic conductance of solid dielectric. The main sources of ions in solid dielectric are intrinsic (intrinsic) ions and weakly linked ions.

The intrinsic conductance is significant at high temperature. The thermal defect theory has the Frankel defect and the Schottky defect. The former is suitable for dielectric with small conductive ions, which move between atoms. The latter applies to dielectric with large conductive ions, ions enter the surface of the crystal, and the holes inside the crystal conduct electricity.

Weakly linked ionic conductance is obvious at low temperature and is mainly composed of impurity ionic conductance and weakly bound intrinsic ions.
4.2.2. The electronic conductance of a solid dielectric. The dielectric can be regarded as a semiconductor with a wide band gap of more than 3–5eV. For such high bandgap widths, the intrinsic carriers have little effect on electronic conductance. The electronic conductance of dielectric is mainly caused by the ionization of the impurity itself and the level of the impurity formed by the impurity under the action of electric field.

4.3. Breakdown of solid dielectric

4.3.1. Thermal breakdown of solid dielectric. The thermal breakdown of solid dielectric is modeled by the Wagg thermal breakdown model, which assumes that there is a channel in the dielectric with much greater conductance than elsewhere. Current flows through the channel to generate heat, when the heat generated is less than the heat dissipation of the dielectric stable, when the heat is greater than the heat dissipation, dielectric instability, breakdown. But the model experiment did not confirm that.

4.3.2. Electrical breakdown of solid dielectric. The theoretical basis of electric breakdown is the theory of collision ionization. The collision of solid dielectric refers to the lattice collision, which obtains energy in the form of lattice wave. Breakdown occurs when the energy gained by the lattice from the electrons is greater than the energy gained by the lattice from the electrons. The judgment conditions of intrinsic electric breakdown and avalanche breakdown are different.

For electric breakdown theory there are the single atom approximation and the aggregate electron approximation. The two approximate methods are sufficient and necessary conditions for breakdown, which correspond to low energy breakdown and high energy breakdown respectively. The experimental breakdown voltage is between the two. The single electron approximation theory is applicable at low temperatures and the aggregate electron approximation theory is applicable at high temperatures.

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