Chapter 4 Electrical properties of liquid and solid dielectrics

Concepts of this chapter

- **Core concepts:** Electrical properties of dielectrics, the main parameters characterizing the electrical properties of dielectrics
  - ✓ Dielectrics, Polarization, Conductance, Dielectric power loss, Small bridge breakdown (Suspended solid particle mechanism), Electrical breakdown, thermal breakdown
  - ✓ Electrochemical breakdown, aging, cumulative effect, space charge
  - ✓ Oil-paper insulation, electric field in dielectrics
- **Other properties of dielectrics**
  - ✓ Thermal properties, heat resistance grade, cold resistance, mechanical properties
  - ✓ Moisture absorption, chemical properties, biological resistance

4.1.1 Basic knowledge of dielectric material structure

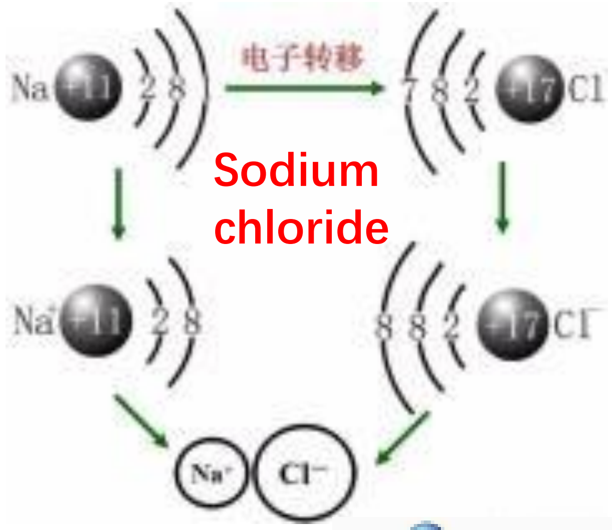
1. The basic concept of dielectrics

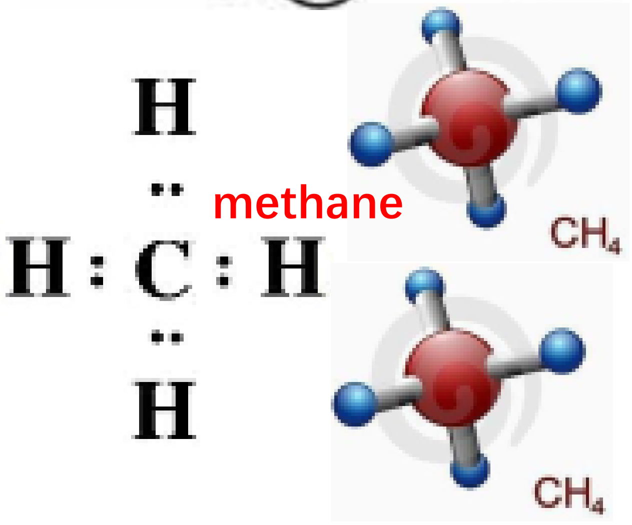
- **The basic concept of dielectrics**
  - ✓ Solids, liquids and gases that have no conductive electrons, and can be polarized in an electric field, are called dielectrics
- **The significance of dielectrics**
  - ✓ Similar to conductors, semiconductors and magnetic materials, dielectrics are an important part of electrical materials and an indispensable basis for electrical equipment
- **The function of dielectric**
  - ✓ **Functional materials:** insulation, energy storage, piezoelectric, pyroelectric, photoelectric, ferroelectric materials
  - ✓ **Insulating materials:** High insulation resistance for electrical insulation, high dielectric constant for energy storage

4.1.1 Basic knowledge of dielectric material structure

2. Various bonds that form molecular and condensed matter

- **Ionic bonds**
  - ✓ Positive and negative ions are combined into molecules by electrostatic coulomb forces, that is, ionic bonds formed between positive and negative ions (such as NaCl)
- **Covalent bonds**
  - ✓ A stable electron layer structure is achieved by combining two or more atoms with equal or little difference in electronegativity through shared electron pairs (such as tetrachloromethane CCl_4, methane CH_4)
- **Molecular bonds**
  - ✓ Molecules are bound together by mutual attraction (van der Waals forces) to form molecular bonds
- **Others?**

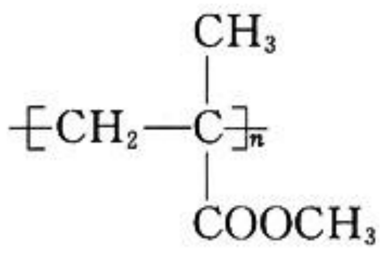




4.1.1 Basic knowledge of dielectric material structure

3. Classification of dielectrics (3 categories according to the chemical structure)

- **Non-polar and weakly polar dielectrics**
  - ✓ The dielectrics composed of non-polar molecules are called non-polar dielectrics, such as N_2 and PTFE (polytetrafluoroethylene)
  - ✓ Some non-polar dielectrics are of more or less polar due to the presence of molecular isomerism or branched chains, called weakly polar dielectrics, such as PS (polystyrene)
- **Polar dielectrics**
  - ✓ A dielectric composed of polar molecules, such as PVC (polyvinyl chloride, $-(CH_2-CHCl)_n-$), PMMA (polymethyl methacrylate/plexiglass) and etc.



- **Ionic dielectrics**
  - ✓ There are no individual molecules, only solid forms
  - ✓ Divided into crystal and amorphous two types, such as quartz, mica and ceramics

Generally, Inorganic compounds consist of ionic bonds, and organic compounds consist of molecule bonds. The molecules of organic compounds consist of covalent bonds.

4.1.2 Division of electrical properties of dielectrics

1. Electrical properties of dielectrics

- **Dielectric property**
  - ✓ The polarization and loss characteristics of the dielectrics
- **Electrical conduction property**
  - ✓ Such as carrier drift, electrical conduction under high field strength and etc.
- **Electrical breakdown property**
  - ✓ Including deterioration, breakdown and volt-second curve
- **Secondary effect**
  - ✓ Such as the effect of space charge, trap, local center of state, interface, chemical structure, morphology, impurity and environment

2. Parameters of electrical properties

- **Relative dielectric constant (ε_r)**
- **Resistivity/Conductivity**
- **Breakdown voltage/Electrical strength**
- **Loss angle tangent/Loss factor ($\tan\delta$)**

4.1.3 Electric parameters of common liquid and solid dielectrics

1. Classification of dielectrics by polarity

- Electric parameters are closely related to polarity of dielectrics
- According to the polarity, the electric parameters of common liquid and solid dielectrics are divided into non-polarity (or weakly polarity), polarity and strong polarity

2. Electric parameters test conditions

- Temperature, voltage waveform (AC/DC, impulse voltage, frequency), voltage amplitude, the thickness of dielectrics (distance between electrodes)
- For liquids, there are purity requirements (quality)

4.1.3 Electric parameters of common liquid and solid dielectrics

3. Electric parameters of common liquid dielectrics

Types	Liquid dielectrics	Relative dielectric constant	Resistivity / (Ω·cm)	Dielectric loss angle tangent	Breakdown Voltage / kV	Purity
Non-polarity and weak polarity	Transformer Oil	2.2	2×10^{12}	/	/	Unpurified (80℃)
		2.1	5×10^{14}	$<10^{-2}$	>40	Purified (80℃)
		2.1	2×10^{15}	$<10^{-2}$	>40	Twice Purified (80℃)
		2.1	$>10^{15}$	$<10^{-2}$	75	Highly Purified (80℃)
	Capacitor Oil	2.2	10^{15}	$<3\times10^{-3}$(100℃)	>60	
	Cable Oil	2.6	5×10^{15}	9.6×10^{-3}	>60	
	Silicone Oil	2. 53	$>5\times10^{15}$	$<10^{-2}$	65	
Polarity	Polychlorinated Biphenyl (PCB)	5.5	10^{13}	$<10^{-2}$	>50	Engineering Use (80℃)
	Castor Oil	4.5	10^{12}	$<10^{-2}$	>35	Engineering Use (20℃)
Strong polarity	Water	81	10^{7}	/	/	Highly Purified (20℃)
	Ethanol	25.7	10^{8}	/	/	Purified (20℃)

Note: Breakdown voltage is measured with a gap distance of 2.5 mm. Parameters not specified are measured at 20°C under power frequency voltage.

4.1.3 Electric parameters of common liquid and solid dielectrics

4. Electric parameters of common solid dielectrics

Types	Solid dielectrics	Relative dielectric constant	Resistivity / (Ω·cm)	Dielectric loss angle tangent	Breakdown Voltage / (kV·mm^{-1})
Non-polarity and weak polarity	Fluoropolymers	2	10^{16}	$<2\times10^{-4}$(1 MHz)	18
	Polyethylene	2.25~2. 35	10^{15}	3×10^{-4} (1 MHz)	18-24
	High-density Polyethylene (HDPE)	2.2~2.4	10^{15}	<0.05	26~28
	Cross-linked Polyethylene (XLPE)	2.3	10^{16}	5×10^{-4}	35
	Polypropylene	2.0~2.6	$>10^{16}$	$<2\times10^{-4}$	>200(dc),30(ac)
	Polystyrene	2.45-3.1	10^{15}	$<4\times10^{-4}$	>110(dc)
	Asphalt	2.5~3.0	10^{15}~10^{16}	10^{-2}~2×10^{-2}	100~300(dc)
Polarity	Chloroprene Rubber (Neoprene)	6	10^{9}	0.1(1 MHz)	10~20
	Butyl Rubber	2.5~3.5	10^{15}	3~8×10^{-3}(1 MHz)	16~25
	Ethylene Propylene Rubber (EPR)	3.0	10^{15}	3×10^{-3}	30~40
	Silicone Rubber	3.2	10^{13}	0.01(1 MHz)	15~20
	Polyester Film	3.2	10^{16}	3×10^{-3}	>160(dc)
	Epoxy Resin	3. 6	10^{16}	4×10^{-3}~5×10^{-2}	16~18
	Polycarbonate	3.0	10^{16}	0. 005	17~22
	Oil Impregnated Paper	3.3~4.4	10^{15}	10^{-3}	>40
	Cable Oil-paper	3.5	10^{14}	3×10^{-3}	30~40
	Capacitor Paper	2.5~3.4	10^{15}	2×10^{-3}	>30
	Polyvinyl chloride (PVC)	3.3~3.5	10^{14}	0.09~0.10(1 MHz)	12~16
	Nylon 6	4.1	10^{14}~10^{17}	0.08	22
	Nylon 66	4.0	10^{14}	0.01	15~19

4.1.3 Electric parameters of common liquid and solid dielectrics

4. Electric parameters of common solid dielectrics (continued)

Types	Solid dielectrics	Relative dielectric constant	Resistivity / (Ω·cm)	Dielectric loss angle tangent	Breakdown Voltage / ($kV \cdot mm^{-1}$)
Ionic Dielectric	Quartz glass	3.5~4.5	10^{19}	~3×10^{-4}(1~10 MHz)	25~40
	Borosilicate glass	4.5~5.0	$>10^{14}$	15~35$\times10^{-4}$ (1~10 MHz)	20~35
	Lead glass	7~10	$>10^{13}$	5~40$\times10^{-4}$ (1~10 MHz)	5~20
	Phlogopite	5.0~6.0	10^{13}~10^{15}	5~50$\times10^{-3}$ (0.1~1kHz)	80~100(dc,0.05~0.1 mm)
	Muscovite	6.0~8.0	10^{14}~10^{15}	1~50$\times10^{-4}$ (0.1~1kHz)	90~120(dc,0.05~0.1 mm)
	Electrical porcelain (Talc)	5.5~6.5	10^{14}	3~5$\times10^{-4}$ (1~10 MHz)	35~45
	Rutile	100	10^{10}~10^{11}	0.4	15~25
	Barium titanate	Thousands to tens of thousands	10^{11}	0.03	5~20

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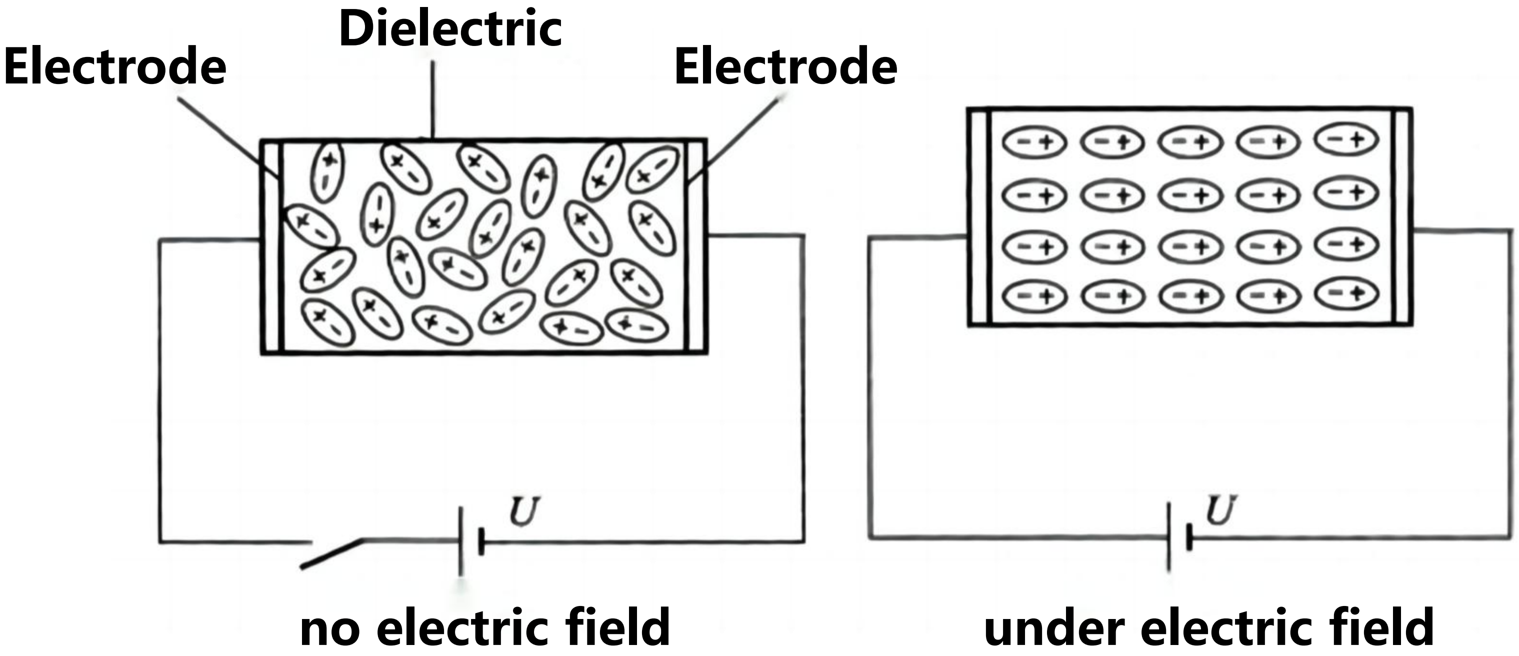
  - ✓ Thermal properties, heat resistance grade, cold resistance, mechanical properties
  - ✓ Moisture absorption, chemical properties, biological resistance

4.2.1 Polarization and relative permittivity of dielectrics

1. The basic concept of polarization

The dipole moment formed along the electric field due to the micro-displacement of positive and negative charges, or the phenomenon of induction bound charges on the surface of the dielectric is called dielectric polarization.



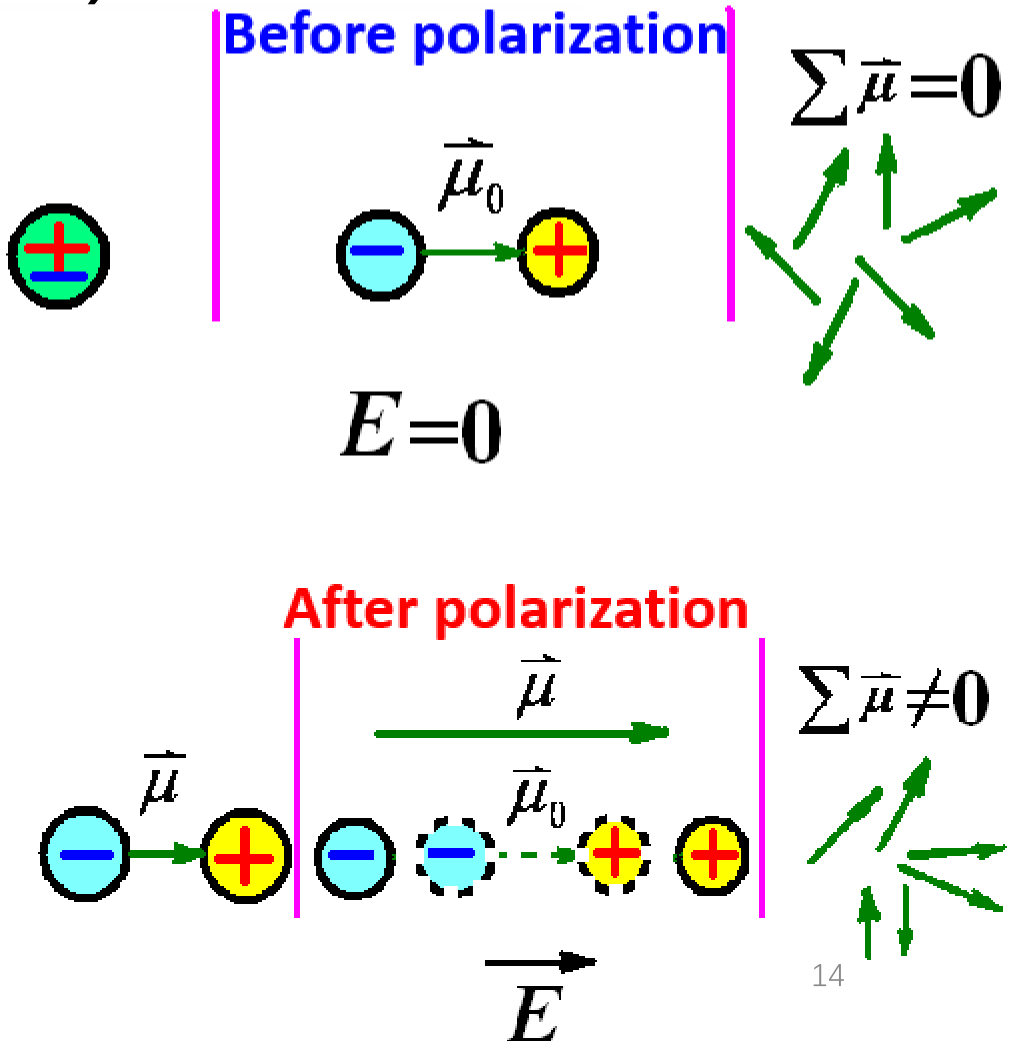
4.2.1 Polarization and relative permittivity of dielectrics

2. Basic types of dielectric polarization

(Classified by particle type and motion characteristics)

- **Five types of dielectric polarization**
  - ✓ Electronic displacement polarization
  - ✓ Ionic displacement polarization
  - ✓ Orientation polarization
  - ✓ Space-charge polarization
  - ✓ Interfacial polarization of sandwich dielectric

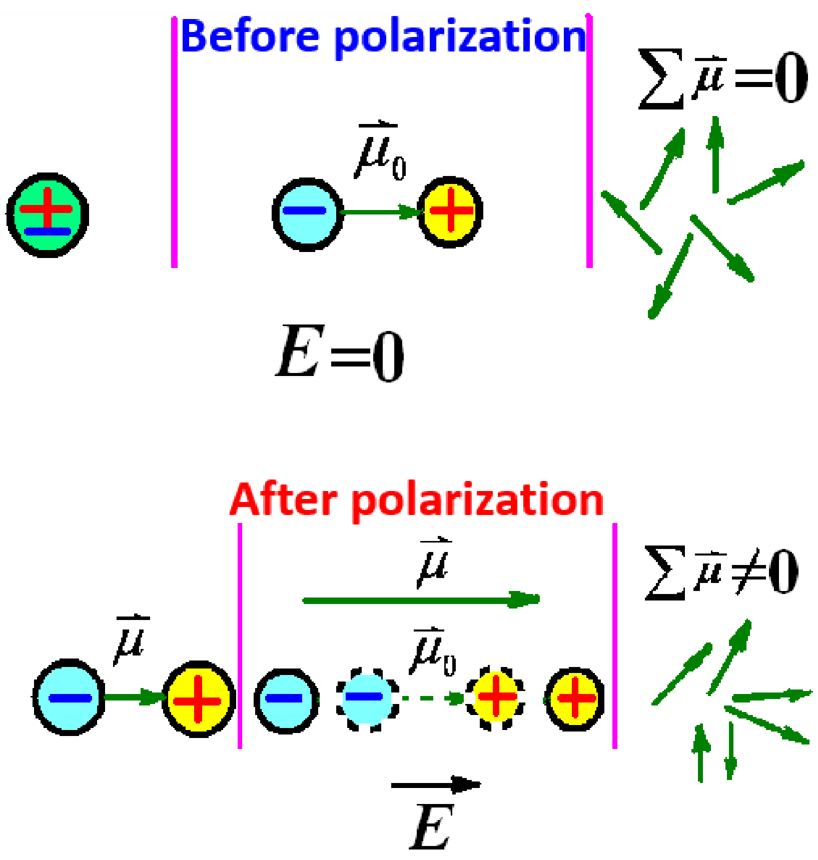
The former two both are referred to as displacement polarization. The latter two are referred to as mobile polarization



(1) Electron displacement polarization

Electrons in atoms, molecules, or ions of the dielectric are shifted relative to the nucleus by an external electric field, resulting in an induced electric moment:

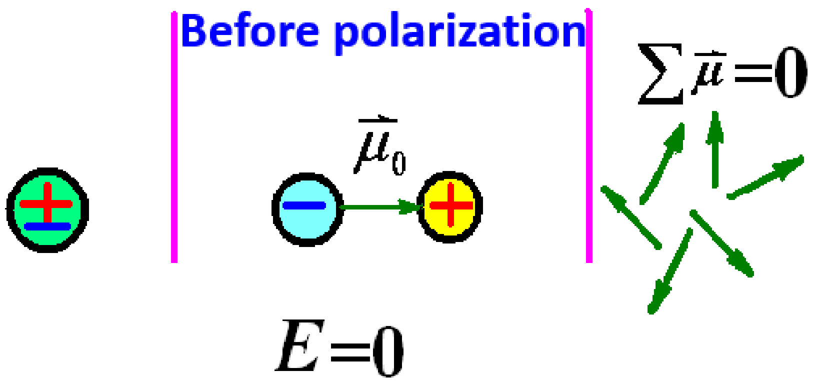
- ✓ Polarized microscopic particles: electrons
- ✓ Types of dielectrics: all dielectrics
- ✓ Polarization establishing time: 10^{-15}~10^{-14} s
- ✓ Polarization Elasticity: elasticity
- ✓ Energy consumption: no dielectric loss
- ✓ Factors affecting the degree of polarization:
  - Electric field: decisive effect
  - Supply frequency: Unrelated
  - Temperature: Unrelated
- ✓ Polarization recovered after the removal of the external electric field

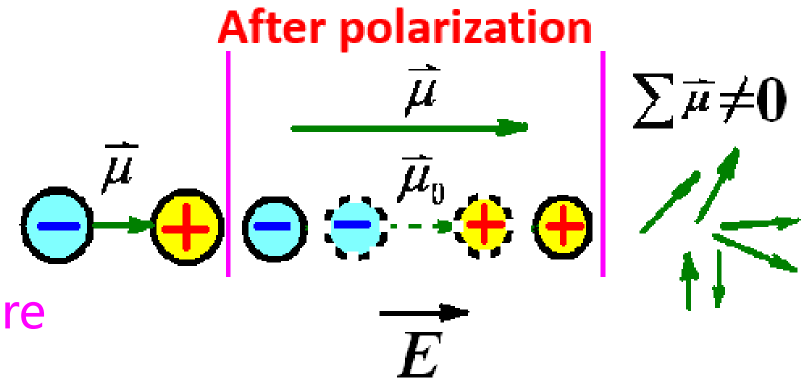


(2) Ionic displacement polarization

The positive and negative ions in the ionic dielectric have a small displacement under the external electric field, and have an average dipole moment in the direction of the external electric field:

- ✓ Polarized microscopic particles: ion
- ✓ Types of dielectrics: ionic structure dielectrics
- ✓ Polarization establishing time: 10^{-13}~10^{-12} s
- ✓ Polarization Elasticity: elasticity
- ✓ Energy consumption: no dielectric loss
- ✓ Influencing factors of polarization degree:
  - Electric field: decisive effect
  - Supply frequency: unrelated
  - Temperature: rise, ε_r generally has a positive temperature coefficient
- ✓ Polarization is recoverable after the removal of the external electric field



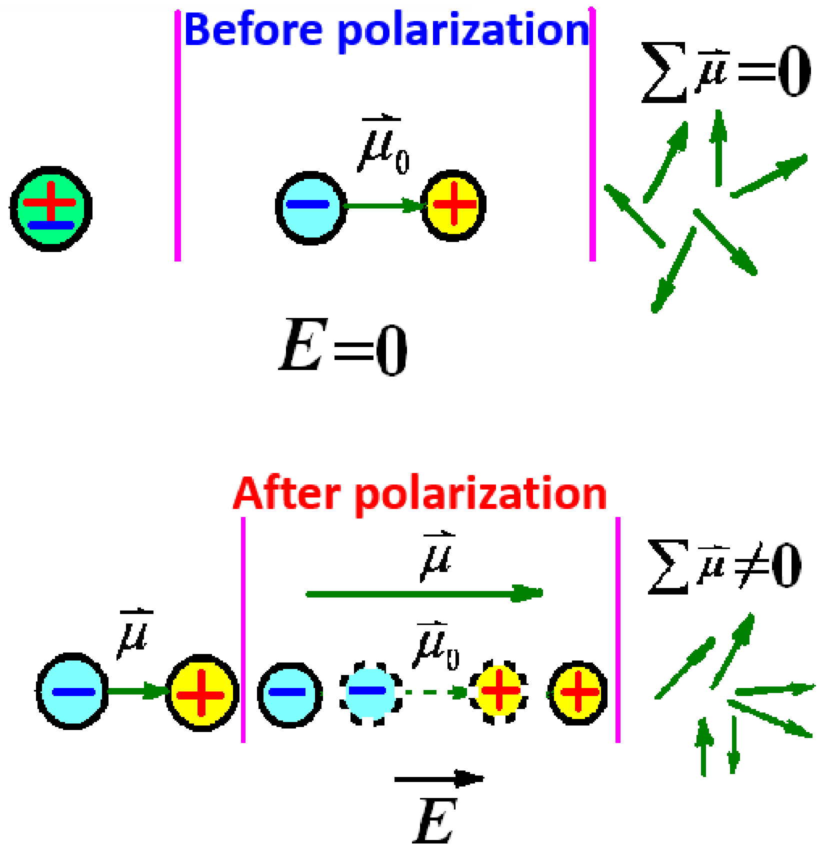


4.2.1 Polarization and relative permittivity of dielectrics

2. Basic types of dielectric polarization

(3) Orientation polarization

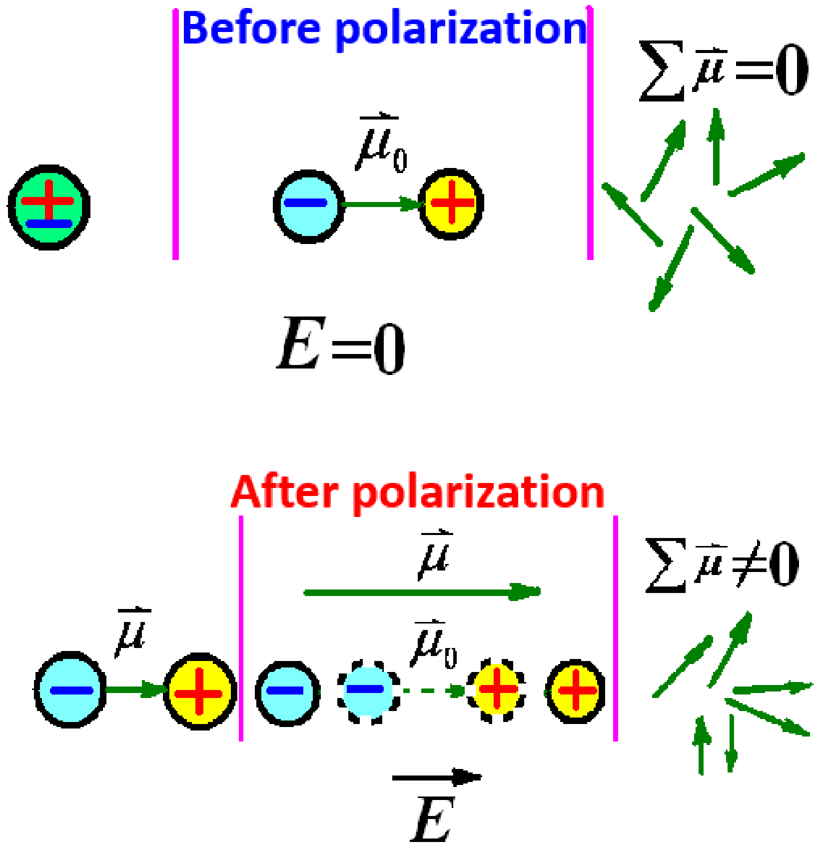
- Also known as dipole relaxation polarization or orientation polarization.
- In the polar dielectric, the positive and negative charge centers in the molecule do not coincide, and in terms of a single molecule, it has a dipole moment, called a dipolar molecule.
- In the absence of external electric field, the dipolar molecule is in thermal motion and has no dipole moment.
- The orientation probability of the dipolar molecule in the electric field direction increases, resulting in a macro-dipole moment in the electric field direction.



4.2.1 Polarization and relative permittivity of dielectrics

2. Basic types of dielectric polarization

(3) Orientation polarization



- ✓ Polarized microscopic particles: dipole, ion
- ✓ Types of dielectrics: dipolar dielectrics and ionic dielectrics with poorly structures
- ✓ Polarization establishing time: 10^{-6}~10^{-2} s
- ✓ Polarization elasticity: non-elasticity
- ✓ Energy consumption: yes
- ✓ Influencing factors of polarization degree:
  - Electric field: decisive effect
  - Supply frequency: related
  - Temperature: related, the polarization increases first and then decreases as T↑
- ✓ Polarization remained after the removal of the external electric field

4.2.1 Polarization and relative permittivity of dielectrics

2. Basic types of dielectric polarization

(3) Orientation polarization

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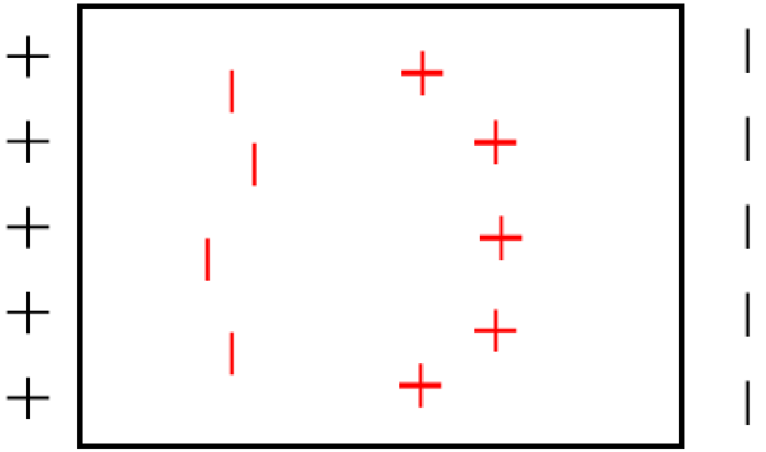
https://www.pnas.org/doi/10.1073/pnas.1818350116

(4) Space-charge polarization

The electrons and positive and negative ions in the dielectric move under the action of the electric field, changing the distribution condition, and forming the spatial charge between the electrodes

- ✓ Polarized microscopic particles: complex
- ✓ Types of dielectrics: engineering dielectrics
- ✓ Polarization establishing time: very long
- ✓ Polarization elasticity: non-elasticity
- ✓ Energy consumption: dielectric loss happened
- ✓ Influencing factors of polarization degree:
  - Electric field: decisive effect
  - Supply frequency: related, effective at low frequency
  - Temperature: related
- ✓ Polarization remained after the removal of the external electric field



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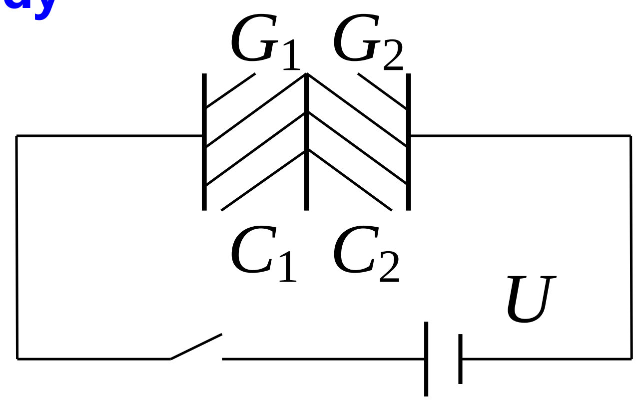
(5) Interfacial polarization of sandwich dielectric

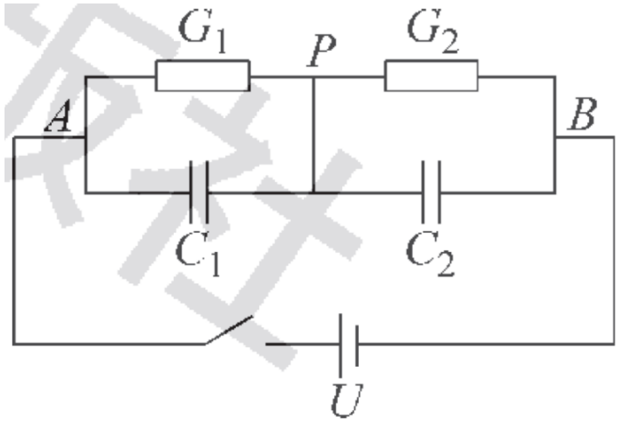
- **The voltage ratio of the two dielectric layers at the closing moment is determined by the capacitance while at the steady state is determined by the conductance**



transient, t = 0 $$\frac{U_1}{U_2}=\frac{C_2}{C_1}$$

steady, t = ∞ $$\frac{U_1}{U_2}=\frac{G_2}{G_1}$$

If $$\boxed{\frac{C_2}{C_1}=\frac{G_2}{G_1}}$$



Double-layer Dielectric Polarization Model

The surface charge of the double-layer dielectric is not redistributed. However, in fact, it is difficult to meet the above conditions, the charge must be redistributed, so that the charge will accumulate at the interface of the two layers of dielectric, this form of polarization is called interfacial polarization of the sandwich dielectric

4.2.1 Polarization and relative permittivity of dielectrics

2. Basic types of dielectric polarization

(5) Interfacial polarization of sandwich dielectric

- ✓ Polarized microscopic particles: complex
- ✓ Types of dielectrics: non-uniform sandwich dielectrics
- ✓ Polarization establishing time: very long
- ✓ Polarization elasticity: non-elasticity
- ✓ Energy consumption: dielectric loss happened
- ✓ Factors affecting the degree of polarization:
  - Electric field: decisive effect
  - Supply frequency: related, effective at low frequency
  - Temperature: related
- ✓ Polarization remained after the removal of the external electric field