EXPERIMENT 3

Dielectric Constant of Different Materials

Purpose:

- To find the relationship between the applied voltage V_s across the plates of a parallel plate capacitor and the accumulated charge Q.
- To determine the permittivity of free space, ε_0.
- To show that capacitance is inversely proportional with the distance between the plates of the parallel plate capacitor.
- To examine how the plastic plate that is placed between the plates changes the capacitance of the parallel plate capacitor.

Experimental Instruments:

- High voltage supply unit
- Amplifier
- Parallel plate capacitor
- Plastic plate
- 10 MΩ resistor
- 218 nF capacitor
- Avometer
- Connection Cables

Theoretical Information:

Maxwell's equations represent the laws of electricity and magnetism. Electrostatic processes (electric charges at rest) in vacuum can be investigated by using the following integral form of Maxwell's equations:

$$\oint_S \vec{E}.d\vec{a} = \frac{Q}{\varepsilon_0} \tag{3.1}$$

$$\oint \vec{E}.d\vec{s} = 0 \tag{3.2}$$

According to Gauss's law as introduced in Eq. (3.1) the total electric flux through any closed surface equals the net charge *Q* inside that surface divided by the permittivity of free space, ε_0. Equation (3.2) states that the electromotor force, which is the line integral of electric field around any closed path (*s*), equals to zero for electrostatic processes.

If a voltage of V_s is applied between the plates of a parallel plate capacitor, electric field **E** which is described by Eq. (3.3) is generated:

$$\vec{E} = -\frac{dV_s}{d\vec{s}} \tag{3.3}$$

Figure 3.1 shows the electric field lines between the plates of a parallel plate capacitor. The two plates of parallel plate capacitor are of equal dimensions and they are connected to the power supply. The plate, connected to the positive terminal of the power supply, acquires positive charges. On the other hand, the plate, connected to the negative terminal of the power supply acquires negative charges. Electric field lines flow from positive to the negative terminal of the parallel plates and they are always perpendicular to the plates (except at edges), since the distance between the plates is very small in comparison with the size of the plates.

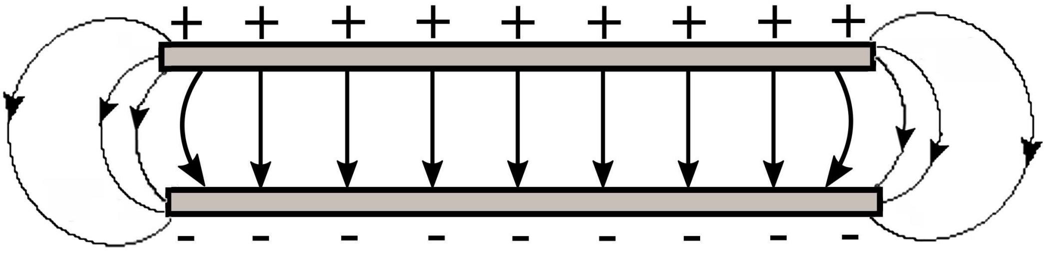

Figure 3.1 Electric field lines between the plates of a parallel plate capacitor.

The electric field outside the parallel plate capacitor is zero because the total charge that circumvents the parallel plate capacitor is zero. The charge on the parallel plate capacitor is linearly proportional with the applied voltage and the proportion constant is capacitance, C. Capacitance determines the amount of charge that a capacitor can store under a constant applied voltage. Using the Eq. (3.1) and Eq. (3.4), the permittivity of free space can be calculated (Eq. 3.8) by the information of the voltage V through the plates, induced charge Q on one plate and the area A of one plate.

$$Q = CV \tag{3.4}$$

$$EA = \frac{Q}{\varepsilon_0} \tag{3.5}$$

$$\frac{V}{d} A = \frac{Q}{\varepsilon_0} \tag{3.6}$$

$$Q = \varepsilon_0 \frac{A}{d} V \tag{3.7}$$

$$\varepsilon_0 = \frac{d}{A}\frac{Q}{V} = \frac{d}{A} C \tag{3.8}$$

When a dielectric is placed between the plates of a parallel plate capacitor, since dielectrics do not have free charges, the atoms and molecules that constitute the dielectric polarize along the direction of the electric field and form bound charges. In this situation, the atoms and molecules behave like small dipoles. As it is seen in **Figure 3.2**, the positive charges align with the electric field and the negative charges align against it. The electric field of the bound charges becomes in opposite direction to the applied electric field. Therefore, total electric field (**E**$_{\text{net}}$) decreases.

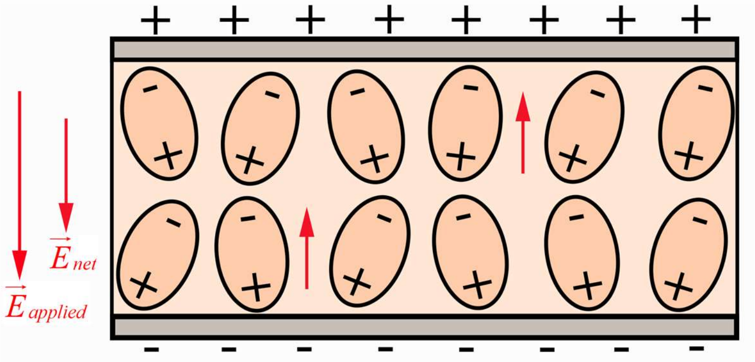

Figure 3.2 Polarization of bound charges inside the dielectric by an applied electric field.

The decrease in electric field is determined by the relative permittivity (also called dielectric constant) κ,

$$\vec{E} = \frac{\vec{E}_0}{\kappa} \tag{3.9}$$

which is defined by

$$\kappa = \frac{\varepsilon}{\varepsilon_0} \qquad (3.10)$$

In Equation (3.9), $\mathbf{E}_0$ is the electric field when the parallel plate capacitor is empty and $\mathbf{E}$ is the electric field when the parallel plate capacitor is filled with a dielectric. Relative permittivity is equal to 1 for free space and it is larger than 1 for other dielectric materials.

Similarly, total voltage decreases by κ when a dielectric is placed between the plates of a parallel plate capacitor:

$$V = \frac{V_0}{\kappa} \qquad (3.11)$$

The capacitance of the parallel plate capacitor *increases* by a factor of κ when the parallel plate is filled with a dielectric.

$$C = \kappa C_0 \qquad (3.12)$$

The general form of Eq. (3.7) thus is,

$$Q = \kappa \varepsilon_0 \frac{A}{d} V_0 \qquad (3.13)$$

Using Equation (3.7) and (3.13), relative permittivity can also be defined as,

$$\kappa = \frac{Q}{Q_0} \qquad (3.14)$$

Equation (3.14) shows that the amount of charge that a capacitor stores can be increased by placing a dielectric across the plates.

Experimental Procedure:

The experimental set-up is shown in **Figure 3.3**. The highly insulated capacitor plate is connected to the upper terminal of the high voltage power supply over a 10 MΩ protective resistor. The middle connector of the high voltage power supply is directly grounded. The opposite plate of the capacitor is grounded over 218 nF capacitor.

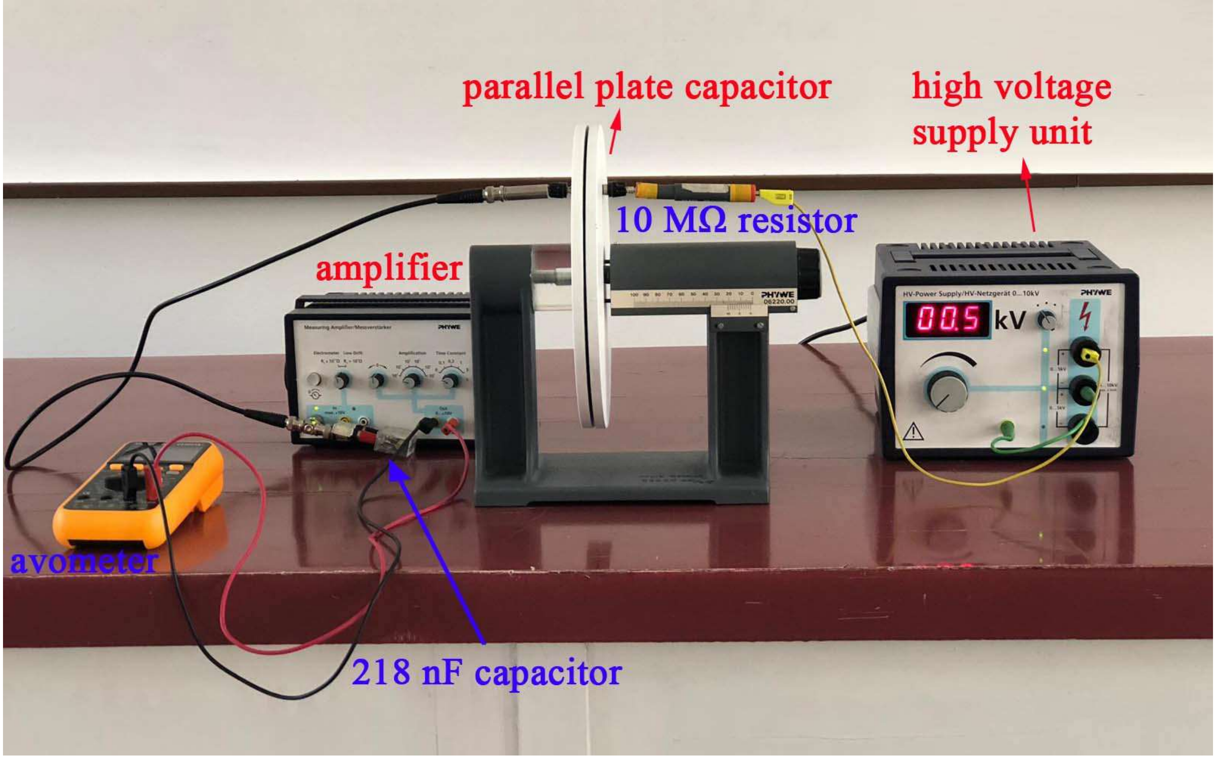

Figure 3.3 Experimental set-up.

Warning: The devices used in this experiment work with high voltage. Therefore, do not touch the capacitor and cables.

EXPERIMENT 3

Dielectric Constant of Different Materials

DATE :

GROUP ID :

Student ID	**Name Surname**	**Signature**

Experiment Expectation	

CALCULATIONS AND RESULTS:

Set the amplifier to high input resistance (10^{13} Ω), the amplification factor to 1 (10^0) and time constant to 0. As first step, the parallel plate capacitor is charged with high voltage power supply. As second step, disconnect the high voltage power supply. Measure the voltage over the 218 nF capacitor using an avometer. Use Eq. (3.4) and write down the charge of the parallel plate capacitor.

Q = ……………… nC

The magnitude of the charge is equal on mutual plates of the parallel plate capacitor.

Section 1: Determination of permittivity of free space

1. Adjust the distance between the plates to 0.2 cm by using the caliper of the parallel plate capacitor.
2. Open the high voltage supply unit. Apply voltages in 0.5 kV steps and record what you read from the voltmeter to Table 3.1. Make sure that you reset the voltage of the high voltage supply unit to zero (wait for the voltage indication of the high power supply unit to fall to zero) every time you record to Table 3.1. In addition, make sure that you press the button at the left of the amplifier every time you record to Table 3.1 in order to ground the charge of the capacitor.

   Record the *first* value seen on the voltmeter to Table 3.1 because the electric discharges between the plates with time. The voltage of the parallel plate capacitor decreases, whereas the voltage of the 218 nF capacitor increases over time.

Table 3.1 Voltage values of the parallel plate capacitor when d = 0.2 cm.

$A = 0.0531\ \text{m}^2$, $d = 0.2$ cm, $C = 218$ nF								
V_s(kV)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
V (V)								
Q (nC)								

3. Plot the Q–V_s graph on a millimeter graph paper. Show that charge Q is linearly proportional with the voltage of the capacitor.

   Write down the slope of the graph which equals to the capacitance of the parallel plate capacitor.

   C = ……………… nF

   By using Equation (3.8), find the experimental value of the permittivity of free space, ε_0, and write down below. Compare it with the actual value of the permittivity of free space.

   ε_0 (experimental) = ……………… A.s/V.m.

4. Fix the voltage of the high voltage supply unit to V_s = 1.5 kV. Increase the distance between the plates of the parallel plate capacitor by 0.5 cm steps. Record the measured voltage in Table 3.2.

Table 3.2 Voltage values of the parallel plate capacitor when V_s =1.5 kV.

$A = 0.0531\ \mathrm{m}^2$, V_s =1.5 kV, C = 218 nF					
d (cm)	0.1	0.2	0.3	0.4	0.5
1/d (cm^{-1})					
V (V)					
Q (nC)					

5. Plot Q – 1/d graph on a millimeter graph paper. Show that charge Q is inversely proportional to the distance between the plates of the parallel plate capacitor.

   By using Eq. (3.8), find the experimental value of the permittivity of free space, ε_0, and write down below. Compare it with the actual value.

   ε_0 (experimental) = ……………… A.s./V.m.

Section 2: Determination of relative permittivity of a dielectric material

6. Fix the distance between the plates d to 0.98 cm. Open the high voltage supply unit. Apply voltages in 0.5 kV steps. For the two cases in which the parallel plate capacitor is empty and is filled with a plastic plate, record the measured voltage values to Table 3.3. Note that V_{empty} in Table 3.3 is named for the first case and V is named for the second case when there is plastic plate between the plates of the parallel plate capacitor. Calculate Q by using Eq. (4).

Table 3.3 Voltage values of the parallel plate capacitor when d = 0.98 cm, the parallel plate capacitor is empty for the first case and filled with a plastic plate for the second case.

V_s (kV)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
V_{empty} (V)								
Q_{empty} (nC)								
$\kappa=Q_{empty}d/(\varepsilon_0 A V_s)$								
V (V)								
Q (nC)								
$\kappa=Q/Q_{empty}$								

Compare the relative permittivity values κ in Table 3.3 when the space between the plates of the parallel plate capacitor is empty and filled with plastic plate.

7. Fix the distance between the plates of the parallel plate capacitor to 0.17 cm, voltage of the high voltage power supply unit to 0.5 kV. For the two cases in which the parallel plate capacitor is empty and is filled with a glass plate, record the measured voltage values to Table 3.3. Note that V_{empty} in Table 3.3 is named for the first case and V is named for the second case when there is glass plate between the plates of the parallel plate capacitor. Calculate Q by using Eq. (3.4).

Table 3.4 Voltage values of the parallel plate capacitor when d = 0.17 cm, the parallel plate capacitor is empty for the first case and filled with a glass plate for the second case.

V_s (kV)	0.5
V_{empty} (V)	
Q_{empty} (nC)	
$\kappa = Q_{empty} d/(\varepsilon_0 A V_s)$	
V (V)	
Q (nC)	
$\kappa = Q/Q_{empty}$	

Compare the relative permittivity values κ in Table 3.4 when the space between the plates of the parallel plate capacitor is empty and filled with glass plate.

DISCUSSION AND COMMENTS:

1) Why does the electric field weaken within dielectric?

2) Explain how the dielectric constant relates to the electronic polarizability of a material.

3) Compare dielectrics and metals in terms of their response to an applied electric field.