Measuring the electric field strength inside a plate capacitor as a function of the dielectrics

Objects of the experiments

- To determine the electrical field strength E for various dielectrics at a constant voltage U
- To determine the electrical field strength E for various dielectrics at a constant charge Q

Principles

The simplest form of capacitor is the plate capacitor. If the distance between the plates is significantly less than the dimensions of the plates, the electric field strength between the plates E can be regarded as homogeneous. It is caused by the charges $+Q$ and $–Q$ which are created by connecting a voltage U to the plates (see fig. 1). The electric field strength is the higher the larger the surface charge density Q/A, i.e. the more charge that is present on the plates and the smaller the surface area A of the plates. It also depends on the dielectric constant ε_r of the material between the two plates.

$$E = \frac{Q}{\varepsilon_0 \cdot \varepsilon_r \cdot A} \qquad \text{(I)}$$

The dielectric constant ε_r describes the increase in capacitance by introducing the material $C = Q / U = \frac{\varepsilon_0 \varepsilon_r A}{d}$ of the plate capacitor compared to the vacuum value.

Alternatively the electric field strength E can be determined from the applied voltage U and the distance d between the plates:

$$E = \frac{U}{d} \qquad \text{(II)}$$

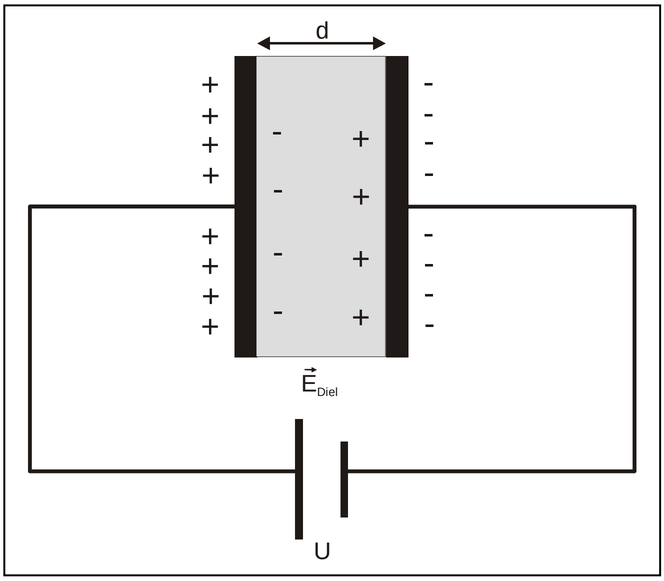

Fig. 1: Plate capacitor with dielectric

Fig. 2: Experimental setup

With a constant charge Q (capacitor plates separated from the voltage supply) the introduction of a dielectric with $\varepsilon_r > 1$ results in a reduction of the electric field E between the capacitor plates. The capacitor field causes a polarisation in the dielectric and therefore an opposing field which causes a resulting smaller field.

When the voltage U remains constant the electric field strength E does not change if a dielectric is introduced between the capacitor plates. The necessary additional charge for the increase of the capacitance is supplied by the voltage supply.

If the dielectric does not completely fill the space between the capacitor plates the electric field strengths differ in the regions with dielectric compared to those without dielectric (see fig. 3). The field strength E_0 in the regions without dielectric is given by the equation (I) with $\varepsilon_r = 1$, the field strength E_r in the regions with dielectric is given by the equation (I) with the dielectric constant ε_r of the dielectric used. The charge Q on the capacitor plates for a connected voltage U is given by: $Q = C_{gesamt} \cdot U$ with the capacitance C_{total} of the capacitor with the dielectric.

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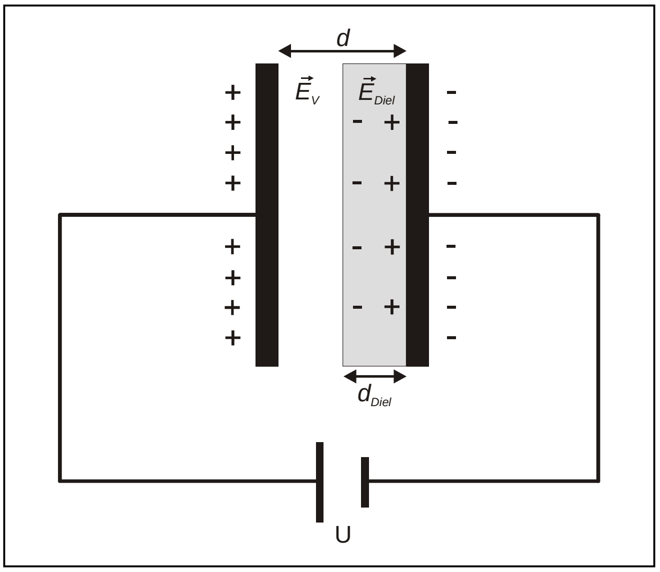

Fig. 3: Electric field in the plate capacitor with dielectric of the thickness $d_{diel} < d$

For calculation of the capacitance of the capacitor with the dielectric all regions must be viewed separately. Here the dielectric has the same surface area A as the plate capacitor, the thickness d_{diel} of the dielectric is however less than the distance d between the plates (see fig. 3) and this allows us to think of the areas with and without dielectric as a series connection of two capacitors with the plate distances d_{diel} and $d - d_{diel}$. The capacitance of the capacitor with the dielectric can be calculated from the formula below:

$$\frac{1}{C_{gesamt}} = \frac{1}{C_{Diel}} + \frac{1}{C_{Luft}} = \frac{d_{Diel}}{\varepsilon_0 \varepsilon_r A} + \frac{d - d_{Diel}}{\varepsilon_0 A} \qquad \text{(IV)}$$

When measuring with the electric field meter S, because of the measuring principle it is the field strength in air that is determined; the space between the plates can never be entirely filled with the dielectric.

If the voltage U remains constant, the electric field strength E does not change if a dielectric is introduced between the capacitor plates. The charge necessary for this is supplied by the voltage supply. In the area filled with air, however, the additional charge will result in a higher field strength, which is measured with the electric field meter. The increase in the measured field strength is therefore a direct measure of the increase in charge on the capacitor plates.

With a constant charge Q (capacitor plates separated from the voltage supply) the introduction in a dielectric with $\varepsilon_r > 1$ results in a reduction of the electric field E in the region with the dielectric and therefore also of the average field strength between the capacitor plates. The electric field strength in the areas with air (e.g. also at the location of the electric field meter) will however remain unchanged.

In the experiment, the influence of the dielectric constant ε_r on the field strength is determined. For this purpose, initially at a constant voltage U, a dielectric (glass, plastic) is inserted between the plates and the electric field strength is determined. Then the charged plate capacitor is first separated from the voltage supply and the dielectric is introduced and the electric field strength is measured. From the change in the field strength on introducing the dielectric, the capacitance of the capacitor with the dielectric and the dielectric constant ε_r of the introduced material is determined.

Apparatus

1 electric field meter S	524 080
1 set of accessories for the electric field meter S	540 540
1 universal measuring instrument P	531 835
1 cut-off switch	504 451
1 power supply 450 V	522 27
1 multimeter LDanalog 20	531 120
2 clamp riders with clamp 45/35	460 312
1 optical bench, S1 profile, 50 cm	460 317
3 safety connection leads, 50 cm, red	500 421
1 safety connection lead, 50 cm, blue	500 422
1 safety connection lead, 100 cm, blue	500 442

Note:

For carrying out this experiment, as an alternative to the universal measuring instrument P the following can be used:

1 mobile CASSY (524 009)

or

1 Sensor-CASSY (524 010USB) + CASSY Lab (524 200)) / CASSY-Display (524 020)

or

1 Pocket CASSY (524 009) + CASSY Lab (524 200)

Alternatively, instead of the power supply 450 V (522 27) and the multimeter LDanalog 20 (531 1200), the 10 kV high power supply (521 70) can be used. When carrying out the experiment with the 10 kV high voltage power supply, the maximum voltage of 300 V must **not** be exceeded because the cut-off switch cannot be loaded any higher!

Introductory remark

The glass plates and plastic plates used as the dielectric can easily be charged electrostatically. For this reason the plates should be discharged before the experiment, e.g. by rinsing the surfaces with running water (and, if applicable, washing up liquid) and dried in air. The surfaces must not be rubbed to dry them because that would again lead to electrostatic charging!

For the distance between the capacitor plate and the electric field meter S, which is decisive for the size for the electric field, 1 mm must be added. The measuring electrodes in the electric field meter are located 1 mm behind the capacitor plate which is used in the electric field meter. This is due to the construction of the meter.

Setup

The experimental setup is shown in fig. 2. For the setup the following steps are required:

- Fix one of the capacitor plates with a stand base onto the stand rod made from plastic and attach it using an optical rider with clamp onto the optical bench profile S1.
- Push the drilled capacitor plate onto the electric field meter S. Attach it also onto the optical bench profile S1 by means of an optics rider with clamp.
- Connect the electric field meter to the universal measuring instrument P.
- Connect the negative pole of the 450 V to the earthing socket on the back of the electric field meter.
- Connect the positive pole of the 450 V power supply to the cut-off switch.

- Connect the second output of the cut-off switch to the free capacitor plate. The connection cable should be suspended freely so that no surfaces (e.g. table top) are touched.
- Connect the multimeter LDanalog 20 for measuring the voltage to the output of the 450 V power supply.
- Set the distance between the plates to d = 9 mm. Ensure that the plates are aligned as parallel as possible.

Warning

It is absolutely necessary to provide correct earthing of the electric field meter S. Because typically the measurement is made using a high voltage, the electric field meter S must never be operated without the 4 mm socket on the back being connected to ground.

Carrying out the experiment

a) Measuring with constant voltage

- Increase the voltage on the capacitor plates step by step to 300 V and read the value of the electric field strength E. Then reduce the voltage to zero.
- Carefully insert the glass plate fully between the capacitor plates without changing the distance between the capacitor plates. Make sure the capacitor plates do not make contact with the glass plate because that might lead to the charging up of the glass plate, which would falsify the measuring result.
- Read the value of the electric field E for the voltage U = 0 V. If the value of the electric field is not equal to zero the plate is charged electrostatically and must be discharged (see introductory note).
- Increase the voltage on the capacitor plates step by step to 300 V and read the value of the electric field strength E. Then reduce the voltage to zero.
- Repeat the experiment using the plastic plate.

b) Measuring with constant charge

- Increase the distance between the capacitor plates to 19 mm.
- Increase the voltage on the capacitor without the dielectric to 200 V and read the value of the electric field strength E.
- Using the cut-off switch, separate the capacitor from the voltage source and read the value of the electric field strength E. If the field strength continuously falls, the charge leaks away from the capacitor plate. In this case it must be checked if the cable between the switch and the capacitor plate has contact with any other surface (e.g. the table top). If this is not the case, the stand rod used for attaching the plate must be cleaned (finally rinse with distilled water) because a conducting coating has formed on the surface.
- Reduce the voltage to zero and carefully insert the glass plate between the capacitor plates. The value of the electric field should be equal to zero (see above)
- Increase the voltage to 200 V and read the value for the electric field strength E_{glass}'.
- Separate the capacitor from the voltage supply by means of the cut-off switch. Check the value of the electric field strength.
- Carefully remove the glass plate from the capacitor without changing the distance between the capacitor plates or making contact with the capacitor plates.
- Read the value of the electric field strength E_Q.
- Using the cut-off switch reconnect the capacitor to the voltage source and read the electric field strength E_U.
- Repeat the experiment using the plastic plate.

Measuring example and evaluation

a) Measuring with constant voltage

In table 1 the measuring results for an example of a measurement of the electric field strength E_{air} without the dielectric is shown, E_{glass} with the glass plate and $E_{plastic}$ as a function of the voltage U and they are plotted in fig. 4.

The linear dependency of the field strength E on the applied voltage U can be clearly observed, with the electric field strength rising most rapidly for glass.

U / V	E_{air} / kV/m	E_{glass} / kV/m	$E_{plastic}$ / kV/m
0	0	0	0
100	9.9	20.0	12.7
200	19.7	41.0	25.7
300	29.5	61.0	38.0

Tab. 1: Measuring results for constant voltage U

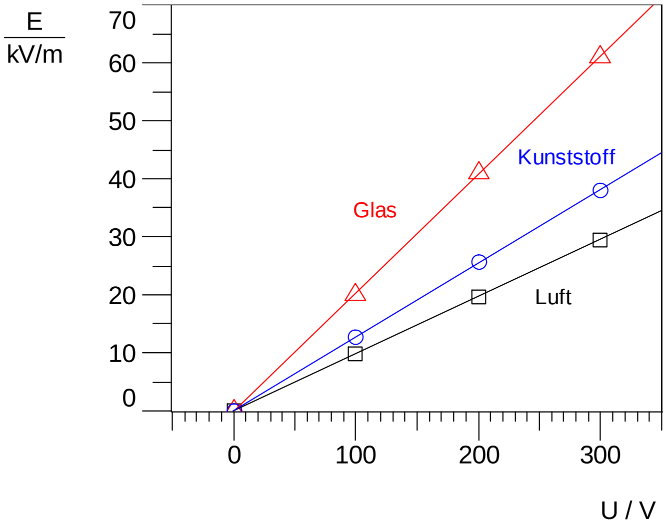

Fig. 4: The electric field strength E in a capacitor as a function of the applied voltage U without and with dielectric (glass, plastic)

As described in the introduction, the increase in the electric field strength on introducing the dielectric into the capacitor exactly mirrors the increase in the charge Q on the capacitor plates. It can be calculated using the formula $Q = \varepsilon_0 \cdot A \cdot E$ (see equation (I)). The values for Q obtained by inserting the measured values from table 1 for U = 300 V are listed in table 2. Using the equation $C_{total} = Q/U$ one obtains the total capacitance of the capacitor with the dielectric (table 2).

By solving the equation (IV) and inserting the values from table 2 one obtains the dielectric constant ε_r for the materials used:

$$\varepsilon_r = \frac{C_g \cdot d_{Diel}}{\varepsilon_0 A - C_g (d - d_{Diel})}$$

For the thickness of the dielectric, for air the plate distance d = 10 mm was used (see introductory note). The thickness of the glass plate was d_{glass} = 6 mm and the thickness of the plastic plate $d_{plastic}$ = 4 mm.

The value for the dielectric constant ε_r for air, plastic and glass correspond well to the literature value for air of ε_r = 1.0, for glass ε_r = 6 – 8 and polystyrene, the plastic used, ε_r = 2.5 .

Material	E_{air} / kV/m	Q / nC	C_{total} / pF	ε_r
Air	29.5	20.5	68.3	0.98
Plastic	38.0	26.4	87.9	2.1
Glass	61.0	42.3	141	6.5

Tab. 2: Results for the charge Q, the total capacitance C_{total} and the dielectric constant ε_r for various dielectrics

b) Measuring with constant charge

In the example measurement, the capacitor was charged without the dielectric to 200 V and then separated from the voltage supply. Over several minutes no reduction in the voltage was observed.

Then measurements were carried out for the glass plate and the plastic plate with the constant charge. The measured values are listed in table 3. The field strengths E' were measured with the dielectric, the field strengths E_Q after removing the dielectric while the voltage supply was still not connected and the field strengths E_U after the voltage supply had been reconnected.

The field strengths E' are different for plastic and glass on account of their dielectric constants, which had been investigated in more detail in section a. On account of the larger distance between the plates, the measured values are smaller than in section a.

Because the field strengths in the experimental setup used are always measured in air, whether or not a dielectric is also used, the measured values do not differ when the charge on the plate remains constant. The small change for plastic indicates that the plastic plate was slightly charged which falsified the measured result.

If the capacitor is then connected to the voltage supply, the charge flows off the capacitor plates and the measured field is smaller. The values are independent of the material located in the capacitor at the start because the electric field strength depends only on the applied voltage and the distance between the plates.

Material	E' / kV/m	E_Q / kV/m	E_U / kV/m
Plastic	9.3	10	8.7
Glass	12	12	8.8

Tab. 3: Measured values with constant charge

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