Dielectrics in Capacitors

INTRODUCTION

When a dielectric material is placed in an electric field, each molecule is polarized creating a microscopic dipole. In the bulk of the dielectric material, these induced microscopic dipoles tend to cancel each other (why?) leaving a net charge on the surface. For small electric fields, the molecule's response is linear and the induced polarization can be represented by a single number, the dielectric constant κ. The microscopic physics describing the polarizability of materials is pretty complicated, but today we will learn a little about the macroscopic behavior of dielectrics.

PRE-LAB

The capacitance of a system is given by a proportionality relating charge to voltage: Q = CV, where Q is the charge on each conductor (opposite signs), V is the potential difference between the two conductors, and C is the capacitance. This is analogous to the resistance in Ohm's law which is just a proportionality relating voltage to the current: V = IR. **Question: If the distance between the plates of a parallel plate capacitor is δ, why does the expression for the capacitance of parallel plates vary like $1/\delta$?**

MEASURING CAPACITANCE

Use the Fluke capacitance meter or hand held meter to measure the capacitance of a parallel plate capacitor. Set the frequency of the device to ~1 kHz for now. The device puts the capacitor in an ac circuit and measures the complex impedance... don't worry about these details now. Use the 6 x 6 inch plates separated by four 1x 1 inch thin plastic spacers (be sure to measure the thickness in meters). Now do the measurement again with a full sheet of a dielectric material (same thickness as the spacers). Does the capacitance depend on the amount of dielectric between the plates?

In mks units, the capacitance of a parallel plate capacitor is

$$C = \frac{\kappa \varepsilon_0 A}{\delta},$$

where A is the area of one of the plates in m^2 (measure this), δ is the separation of the plates in m (measure this too), and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m. The mks unit of capacitance is a farad F. Is your measured capacitance consistent with this prediction? Because ε_0 is such a tiny number, one farad is a lot of capacitance... your homemade capacitors today will be in the range of several 10^{-12} F or picofarads (sometimes called "puff" for pF).

Verify the $1/\delta$ dependence of the parallel plate capacitance formula by measuring C with one, then two, then three, etc. thicknesses of the same kind of dielectric. Push down on the stack to make sure the separation is minimized. Plot C vs $1/\delta$ and fit the data to $C = const_1 + const_2(1/\delta)$. From the fit, calculate the dielectric constant κ of the dielectric.

Repeat the measurement of κ for at least 3 other materials. Make a table showing your measured dielectric constants κ for several (at least 4) of the materials. Check on the internet to see if you can verify any of the measured constants. Check also table 10.1 in Purcell for a few values. We'll make a table compiling measurements from the whole class.

If the capacitor is charged to 10 volts with one sheet of dielectric between the plates, about how much charge is on the surface of the dielectric (roughly)? Now, estimate how many dielectric molecules there are on the surface of your 6 x 6 inch sheet (molecules are typically separated by a few Å). Suppose there were one exposed electron associated with each molecule on the surface. How much charge would that be? Explain the discrepancy.

DESIGN A PLASTIC CAPACITOR

Suppose you want to design a capacitor to store energy. In mks units, the energy stored in a capacitor is

$$W = \frac{1}{2}CV^2.$$

If we want to store a lot of energy, we should operate at high voltage with a large capacitance. What factors increase C? Discuss how you would make a capacitor to store the maximum amount of energy. How much energy could your capacitor store (in joules)? How high a voltage do you think you could use with these homemade capacitors? You might want to track down numbers like the "dielectric strength" of materials and the breakdown strength of air (air will spontaneously arc between wires a mm apart with a potential difference of a few kV).

BUILD A WATER CAPACITOR

Use a glass tray and your 1 inch spacers to build a water capacitor. It is known that a water molecule H_2O is very polar and that pure water has a very high dielectric constant. Table 10.1 in your book says $\kappa_{water} = 80$! What happens? Does your water capacitor have 80 times the capacitance of the air capacitor?

LAB BOOK CHECKLIST

Plot of C vs $1/\delta$ with the fit, table showing your measured dielectric constants κ for several (at least 4) of the materials. Discuss how you would make a capacitor to store the maximum amount of energy. Check the internet to see if you can verify any of the measured constants. Discuss the difference between the amount of charge stored on your home-made capacitor and the estimate based on the (large) number of molecules on the surface. Discuss your results with the water capacitor.