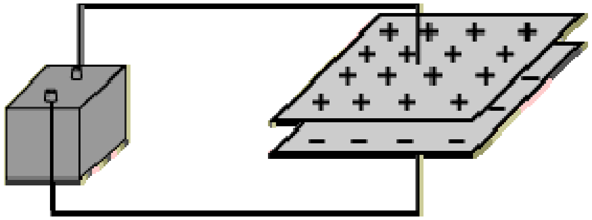
Today’s objectives-Dielectrics

- What happens to a material when an electric field is applied across it (ie. in a capacitor)
  - How does the electric field change, and how does the charge/area change?
- Equations for capacitance and polarization
- Why is a dielectric better if it is a polar crystal?
- What are the 4 primary contributions to the dielectric constant.
  - Be able to order the frequency at which they occur.
- Describe the 4 primary dielectric breakdown mechanisms.
- How can breakdown strength be improved?

Capacitance

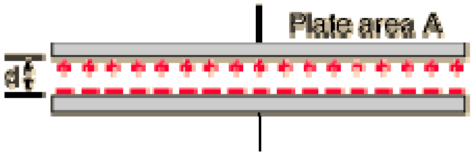
- Two electrodes separated by a gap define a capacitor.
- When a bias is applied across the capacitor plates, one charges positively, the other negatively.
- The measure for a capacitor's quality is called the 'capacitance' (C)
    - This is how much charge the device stores (Q) for a given voltage (V).
- The capacitance is related to the area of the plates (A), their separation (d), and the ***Dielectric Constant (εε$_o$)*** of the 'dielectric' material between the plates.
    - ➢ $\varepsilon_o = 8.85\times10^{-12}$ F/m
    - ➢ $\varepsilon_o = 55.2$ Me/(V*m)
    - ➢ But what about ε?
        - ➢ Related to charge building up ***within*** the capacitor



A battery will transport charge from one plate to the other until the voltage produced by the charge buildup is equal to the battery voltage.

$$C = \frac{Q}{V}$$

$$\text{Unit} = \frac{\text{coulomb}}{\text{volt}} = \text{Farad}$$



$$C = \frac{\varepsilon\varepsilon_o A}{d}$$

$$Q = \frac{\varepsilon\varepsilon_o A}{d} V = \frac{{}^{e^-}\!/_{V*m} * m^2}{m} * V = e^-$$

Why does charge built up?

- There is generally not a built-in electric field between the plates of an *unbiased* capacitor.
- When an electric field is applied, any charged carriers or species within the material will respond.
    - For a conductor or semiconductor, e^- will flow to the + plate, and possibly also holes will flow to the - plate. *Current is carried. NO charge buildup.*
    - For an insulator, there aren't a significant number of free carriers. There can be highly ionic species, but they aren't very mobile at low temperatures. *NO appreciable current is carried.*
    - Bound carriers won't conduct, but they will still shift in response to the electric field. *=more charge can buildup*. **="Polarization"**
        1. **True for e^- around an atom.**
        2. **True for cations and anions.**
        3. **True for polar molecules.**
        4. **True for charged interfaces.**

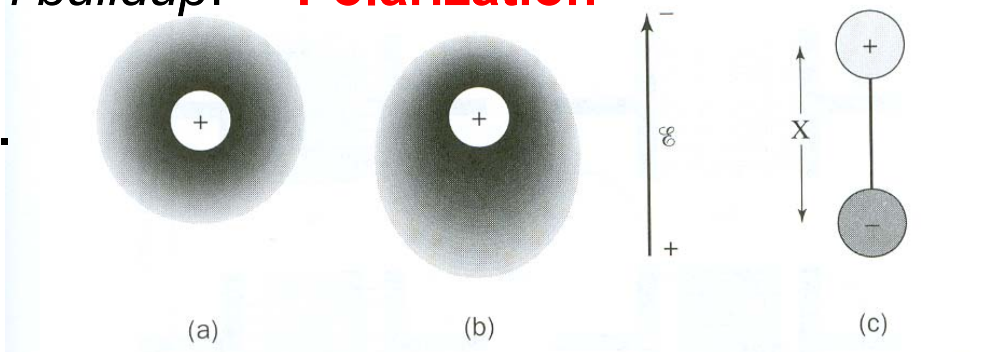
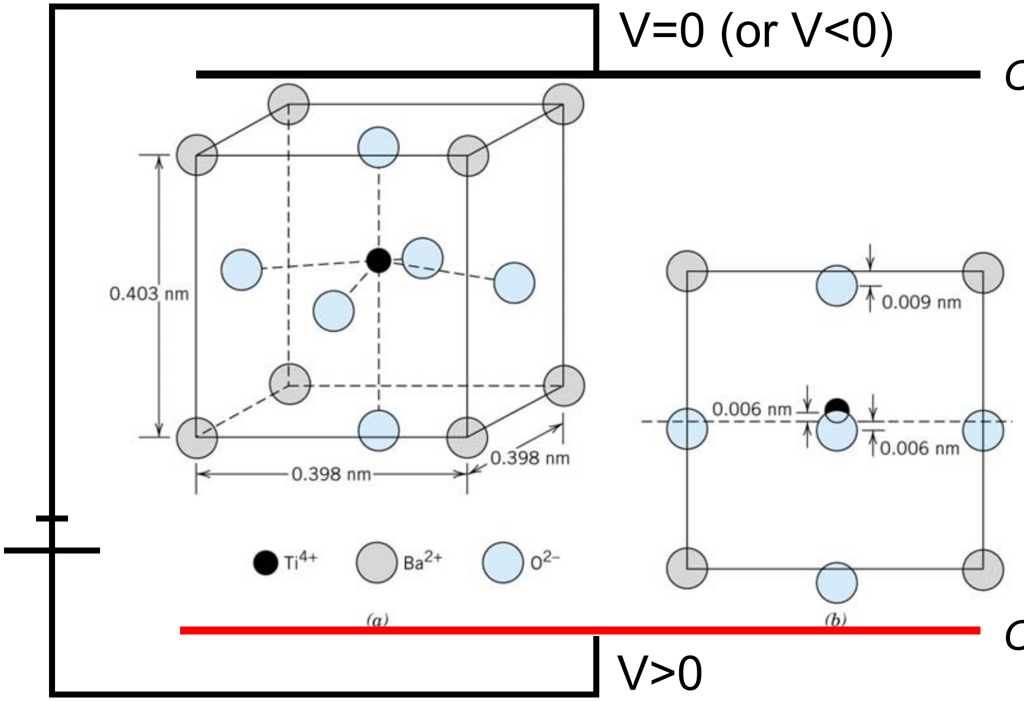


Figure 9.17. An atom is represented by a positively charged core and a surrounding, negatively charged, electron cloud (a) in equilibrium and (b) in an external electric field. (c) Schematic representation of an electric dipole as, for example, created by separation of the negative and positive charges by an electric field, as seen in (b).

Ionic contribution to ε:

- When the plates are biased, any ions within the dielectric can and will move ever so slightly (usually much less than their radius).
  - The positive ions shift toward the negative electrode (up) and the negative ions shift towards the positive electrode (down).



V=0 (or V<0)

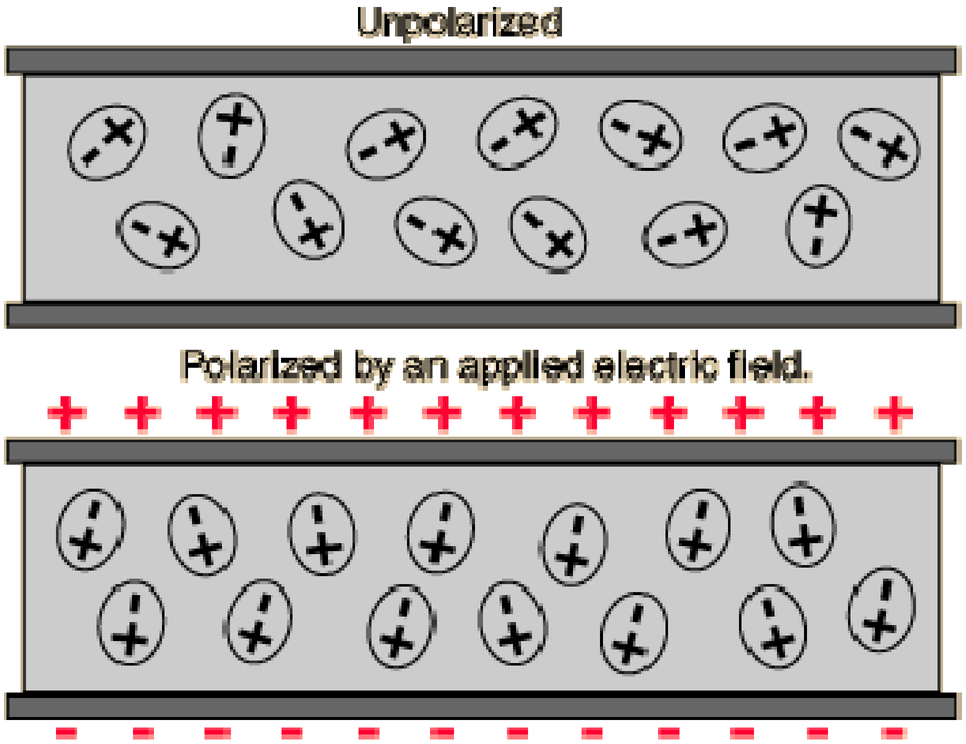
Capacitor electrode

Capacitor electrode

V>0

Shifting ions

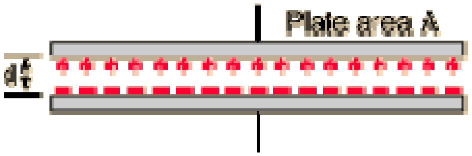
- This internal polarization, essentially between pairs of ions, creates an overall polarization across the whole crystal that is oriented opposite to the electric field.
- As a result, the internal $P_{crystal}$ diminishes $E_{overall}$



- The overall ('effective') electric field is easily described by taking the applied external field and then subtracting the corresponding internal dielectric polarization field

$$E_{effective} = E_{applied} - E_{dielectric\ \ polarization}$$

How is the dielectric described mathematically?



$$C = \frac{\varepsilon\varepsilon_o A}{d}$$

$$Q = CV = \frac{\varepsilon\varepsilon_o A}{d}V$$

- The capacitance is defined as a function of $\varepsilon\varepsilon_o$, which relates to the internal polarization (P).
- Solve for charge/area (Q/A, ='D' in book)
- Rewrite accounting for Polarization
- Solve for P
- Solve for ε alone

$$\frac{Q}{A} = \varepsilon\varepsilon_o \frac{V}{d}$$

$$D = \frac{Q}{A} = \varepsilon\varepsilon_o E$$

$$\frac{Q}{A} = \varepsilon_o E + P$$

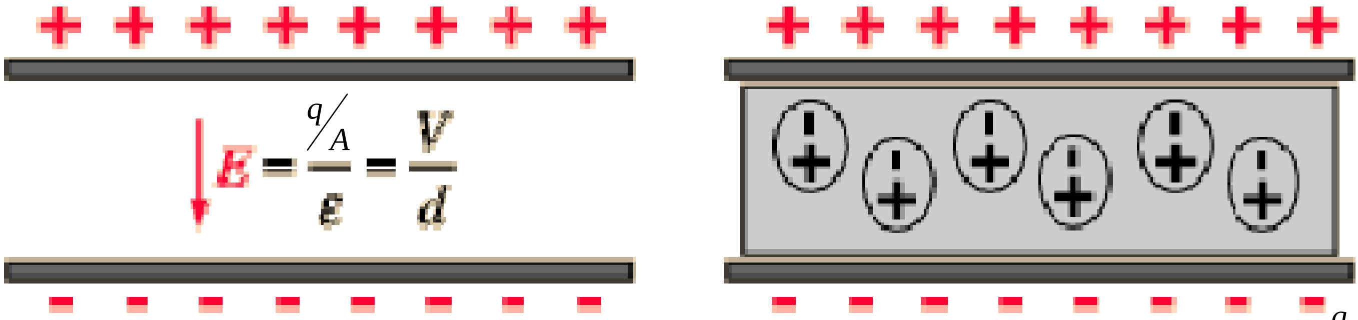
$$\frac{Q}{A} = \varepsilon\varepsilon_o E = \varepsilon_o E + P$$

$$P = \varepsilon_o E(\varepsilon - 1)$$

$$\varepsilon = 1 + \frac{P}{\varepsilon_o E}$$

Review of $\varepsilon\varepsilon_o$

- For materials with random initial polarization, the external field induces oriented dipole moments.
  - These set up oppositely oriented fields.
  - The greater the dipoles, the greater the charge which can be stored.
  - Thus, the better the dielectric.



$$E = \frac{q/A}{\varepsilon} = \frac{V}{d}$$

For air, $\varepsilon \approx \varepsilon_0$

$$E_{\text{effective}} = E - E_{\text{polarization}} = \frac{q/A}{\varepsilon\,\varepsilon_0}$$

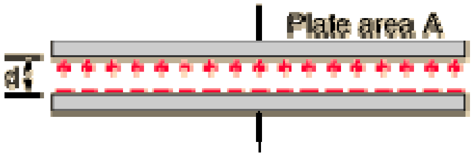
$$C = \frac{\varepsilon_0 A}{d}$$

The capacitance is increased by the factor ε (or k)

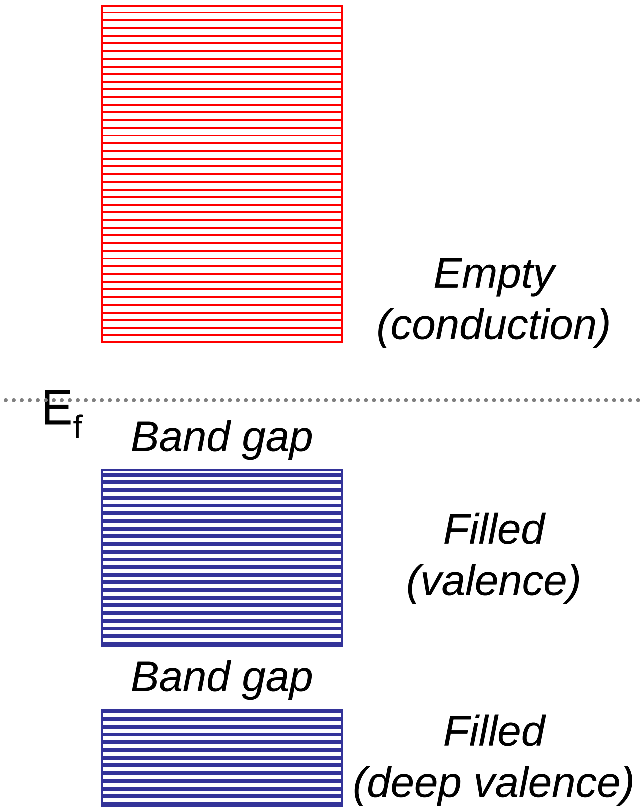
$$C = \frac{\varepsilon\,\varepsilon_0 A}{d}$$

Dielectric Constants (ratio * e/(Volt*m))

- Generally, the less conducting and more polar a material is, the greater will be its dielectric constant.



$$C = \frac{\varepsilon A}{d} = \frac{k\varepsilon_0 A}{d}$$



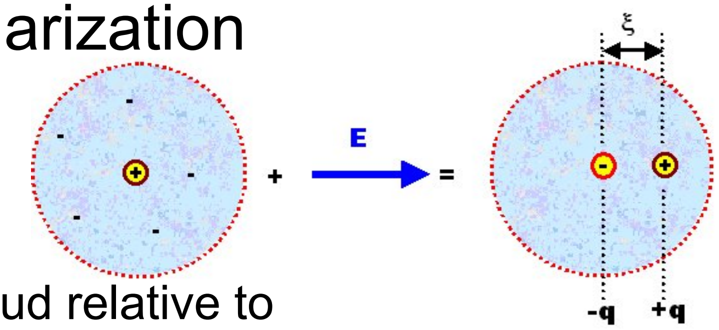
Insulator

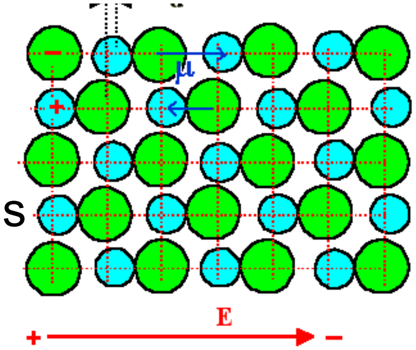
Material	**Dielectric Constant (ε)**
Vacuum	1
Air(1 atm)	1.00059
Teflon	2.1
Polyvinyl chloride	3.18
Glass	5-10
Germanium	16
Glycerin	42.5
Water	80.4
Titanium dioxide (rutile)	173 perp 86 para
Strontium titanate	310

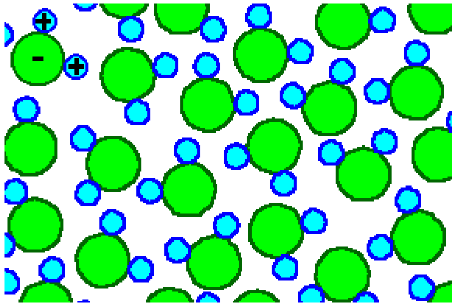
Dipole Mechanisms

$$P = P_{electronic} + P_{ionic} + P_{orientation} + P_{interfacial} = \left(\in \in_o - \in_o\right)E$$

- There are several possible polarization mechanisms:
  - Electronic
    - Possible for any/all atoms
    - Redistribution of the electron cloud relative to nucleus
  - Ionic
    - Only for ionic materials
    - Cations and anions displace in opposite directions
  - Orientation
    - Only for substances with permanent diploes
    - Rotation of the permanent dipole from the initial orientation to the applied field direction
    - Thermal vibration counteracts this, so increasing Temp decreases this contribution
  - Interfacial
    - Grain boundaries
    - Pore surfaces



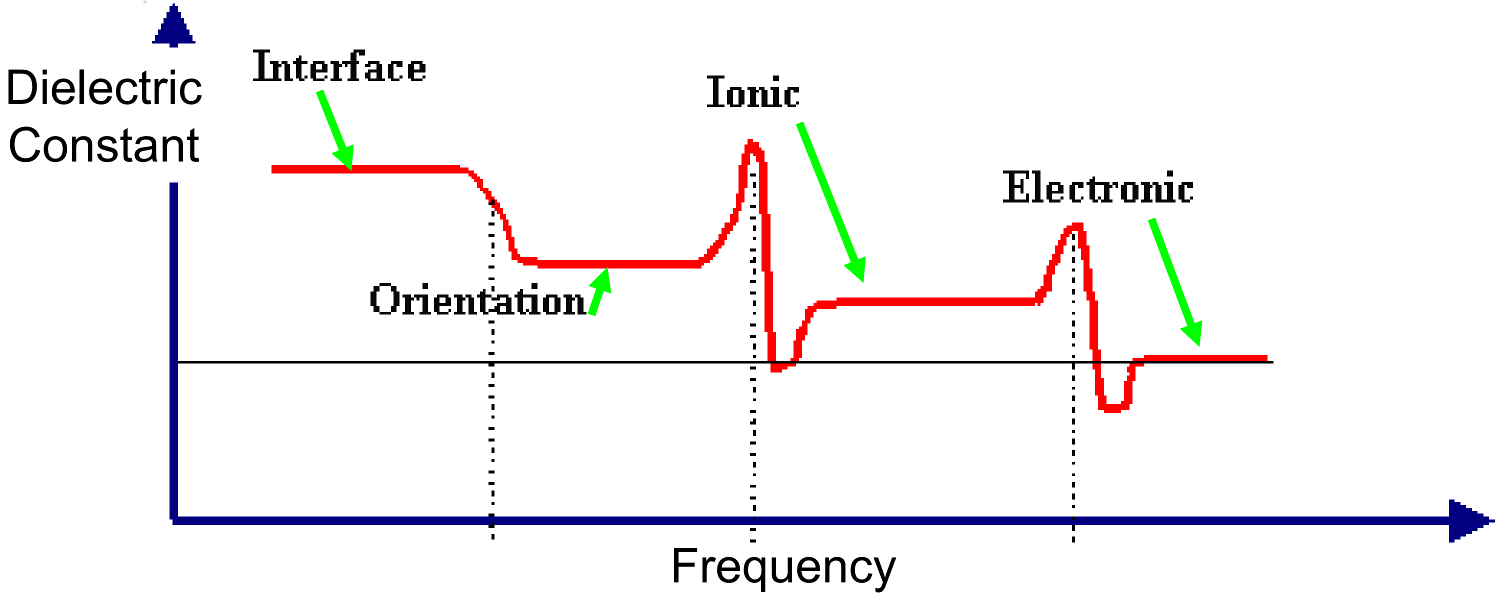




http://www.tf.uni-kiel.de/matwis/amat/elmat_en/index.html

Frequency dependence of Dielectricity

- The various polarization mechanisms respond at different rates.
  - Interfacial polarization is slower than orientation based polarization which is slower than Ionic which is slower than Electronic.

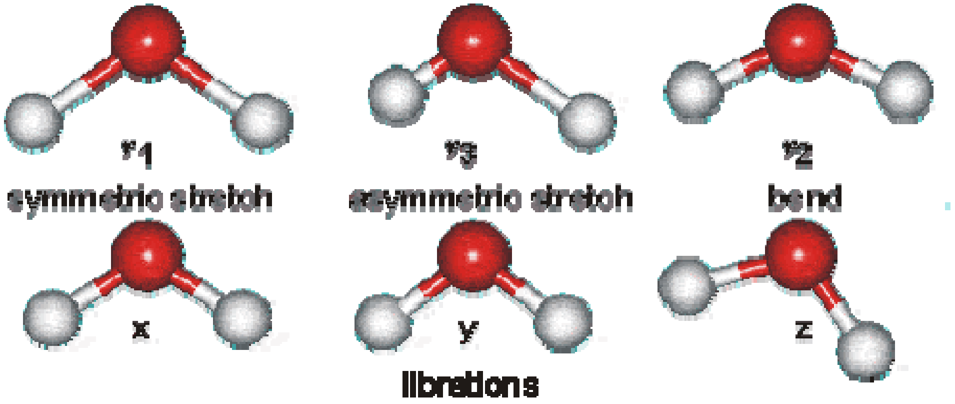


• Any of these mechanisms may be negligible depending on the material system (but the electronic component will *always* be present).

http://www.tf.uni-kiel.de/matwis/amat/elmat_en/index.html

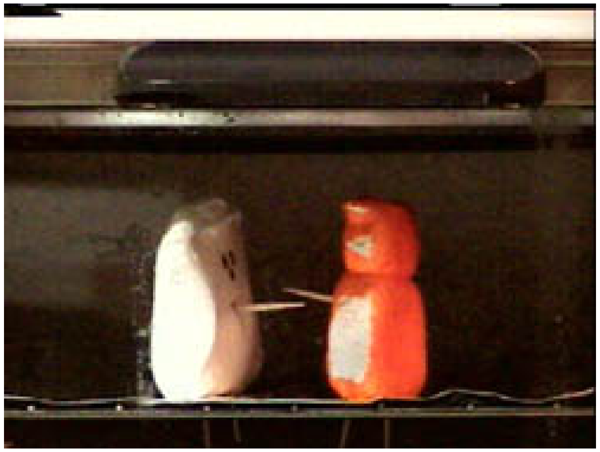
Microwave Ovens

- A microwave oven generates electromagnetic radiation at about 2.5 GHz. This energy is pretty good at causing H_2O molecules to oscillate their orientation (orientational dielectric constant changes greatly).
- Ice has a low dielectric constant, so not much energy is absorbed by it. Once there is a bit of melted ice, though, then you are really cooking.

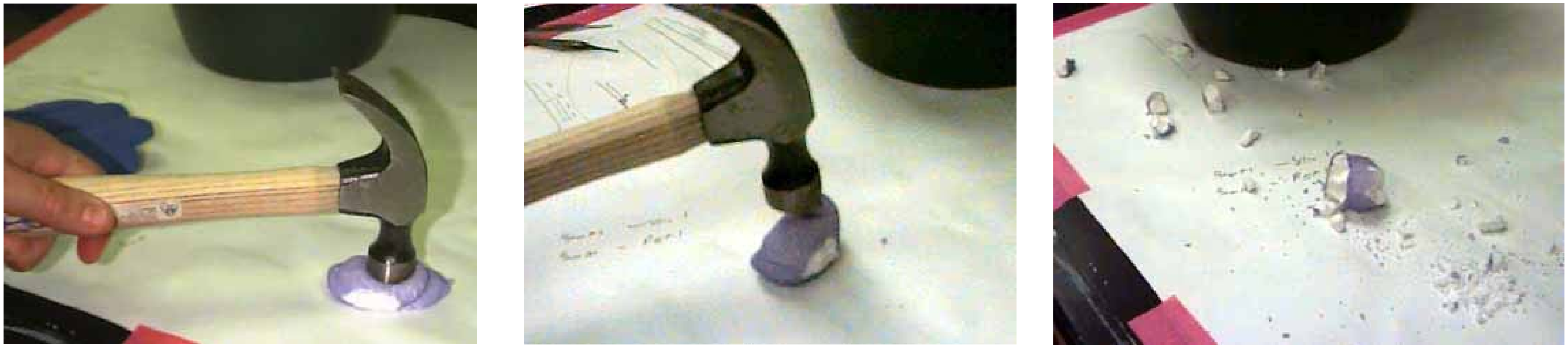


http://home.howstuffworks.com/framed.htm?parent=micriwave.htm&url=http://www.amasci.com/weird/microexp.html

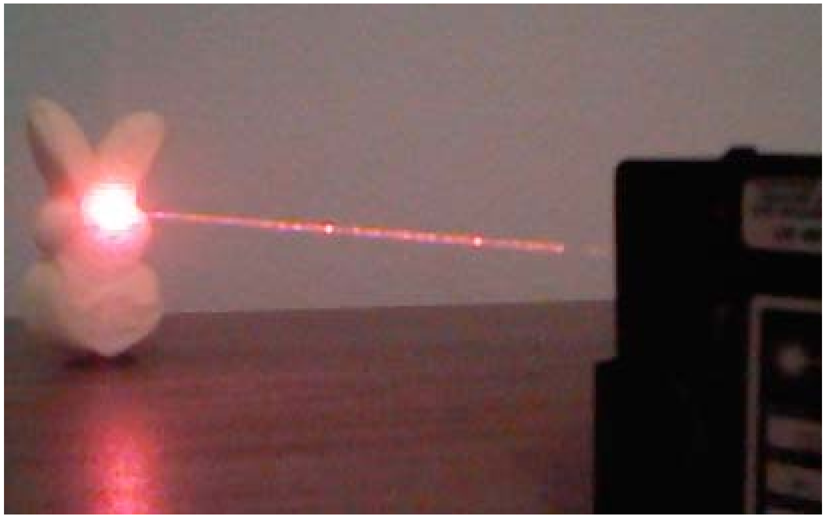
Microwaves and Peeps



- Marshmallow peep jousting
- Normal v. Frozen peeps (liquid nitrogen)



- Peeps and lasers



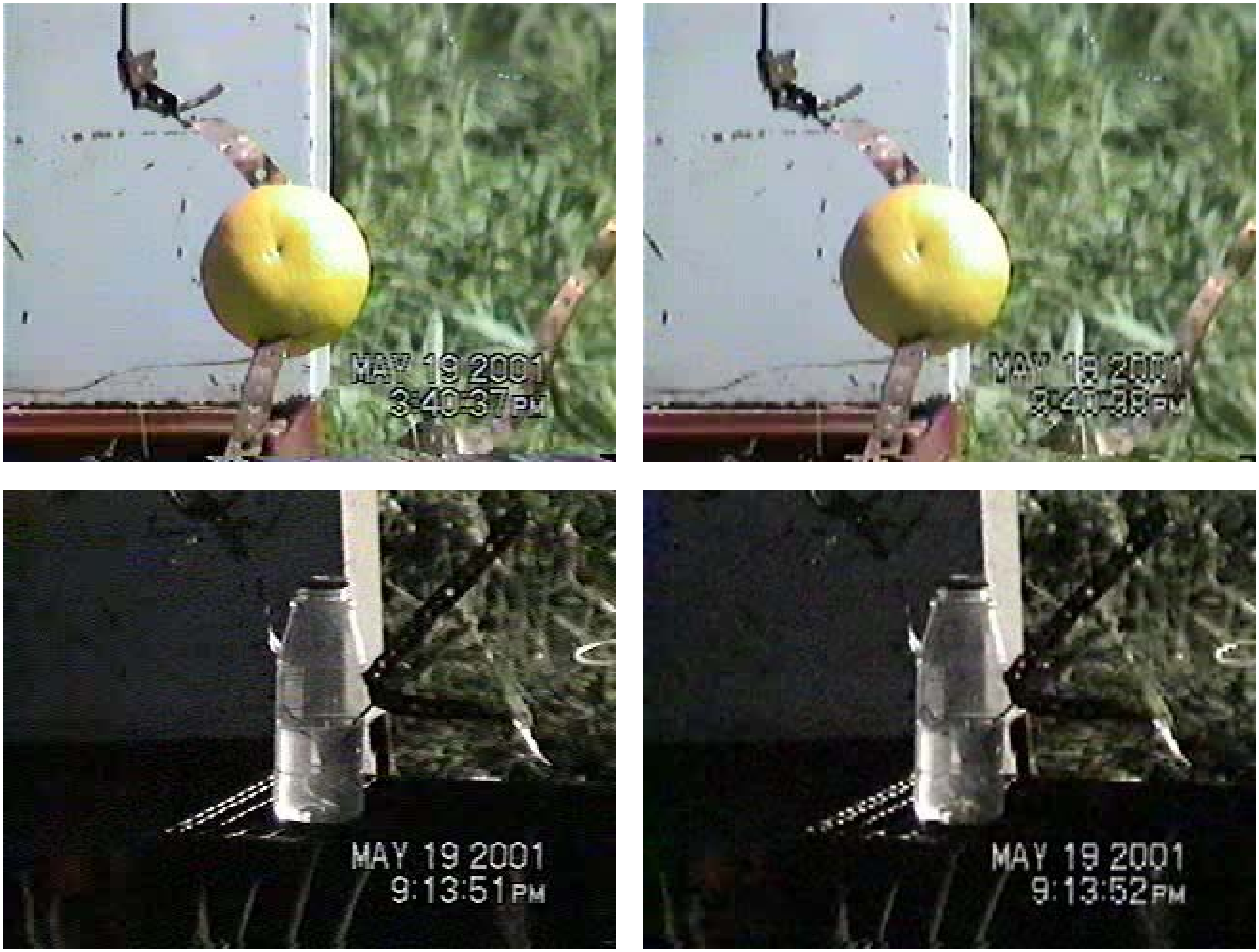
http://www.hanttula.com/exhibits/bunnies/
http://www.youtube.com/watch?v=I18FIrE5xfk&feature=related

Why do we need a large ε?

- A large polarization (high dielectric constant) is important because as ε increases the amount of charge that can be stored by the capacitor increases:
  - The charge will last longer.
  - The signal is easier to detect.
  - Larger swings in voltage can be filtered (protecting downstream circuits).
  - Large charges can be very useful (and discharged *very* rapidly).

The power of capacitors

- Discharging a capacitor roughly the size of a coke can, weighing about 4 pounds, provides lots of energy.
  - – 8500 Joules in these examples



slow motion

http://www.thaltech.com/~laser/video/cap/videos.html

- Driving a railgun
  - Naval implementation by 2020
  - http://www.youtube.com/watch?v=4OqlTXwLG40
  - http://www.onr.navy.mil/emrg/electromagnetic-railgun.asp

Breakdown Strength

- You cannot charge a capacitor infinitely. Eventually, the capacitor will fail, usually catastrophically.
- The so-called breakdown strength of a dielectric is the electric field greater than which the material breaks down.
- The breakdown strength is separate from the dielectric properties of the material.
  - Improve by better manufacturing: **High purity, low defect densities, and low temperature are important.**

Material	**Critical Field Strength** (kV/cm)
Air	30
Oil	200
Glass, ceramics	200...400
Mica	200...700
Oiled paper	1800
Polymers	50...900
SiO_2 in **ICs**	> 10 000
Thin films in ICs	> 1 000 000

April 3, 2006: **CL&P Will Remove Pole-Top Devices** (23,800 over the next 3 years)

Dominant Dielectric Breakdown Mechanisms

- Thermal (heat=defects=ionic conduction=more heat=…)
- Avalanche (accelerated electrons free more electrons that accelerate and free more electrons…)
- Discharge (fields grow enough to arc across pores, leading to erosion, leading to more arcing, …)
- Electrolytic (conduction paths created over time due to ionic and/or environmental conduction)

Improving breakdown strength

- Thermal: heat=bad, so keep temperature low
- Avalanche: high electric fields=bad, so keep fields low.
  - For equivalent capacitance, thus use materials with high dielectric constants
- Discharge: arcing across pores=bad, so keep porosity to a minimum.
- Electrolytic: ionic conduction over time creating channels=bad, so limit temperature and ionic species mobility

New MSE course designed for you

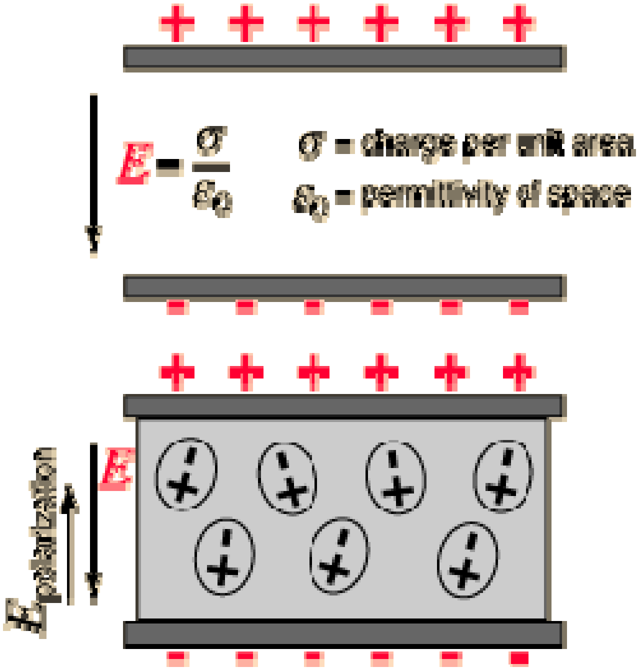
Experiments for Materials Outreach: MSE 4095, section 2

Organizer: Bryan Huey
Instructors: most MSE faculty

- Optional, 1 unit, pass/fail course
- Appropriate for students at all levels.
- The class, with many hands-on activities, will introduce basic materials concepts through hands-on demonstrations, providing:
    - a) insight into real materials applications;
    - b) background useful in MS&E courses;
    - c) the training necessary to assist in many outreach activities provided by MS&E students and faculty throughout the year;
    - d) a chance to **play** with and improve upon the demos.

- The course is applicable for elective credits, fulfilling a graduation requirement if coupled with 2 other units (e.g. labwork in various faculty research labs).

- *NOTE: The course will meet weekly from 1-2pm on Mondays.*



SUMMARY

- What happens to a material when an electric field is applied across it (ie. in a capacitor)?
  - How does the electric field change, and how does the charge/area change?
- Equations for capacitance and polarization
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Next up: magnetic properties
including levitating frogs