AML 883 Properties and selection of engineering materials

LECTURE 17. Electrical properties

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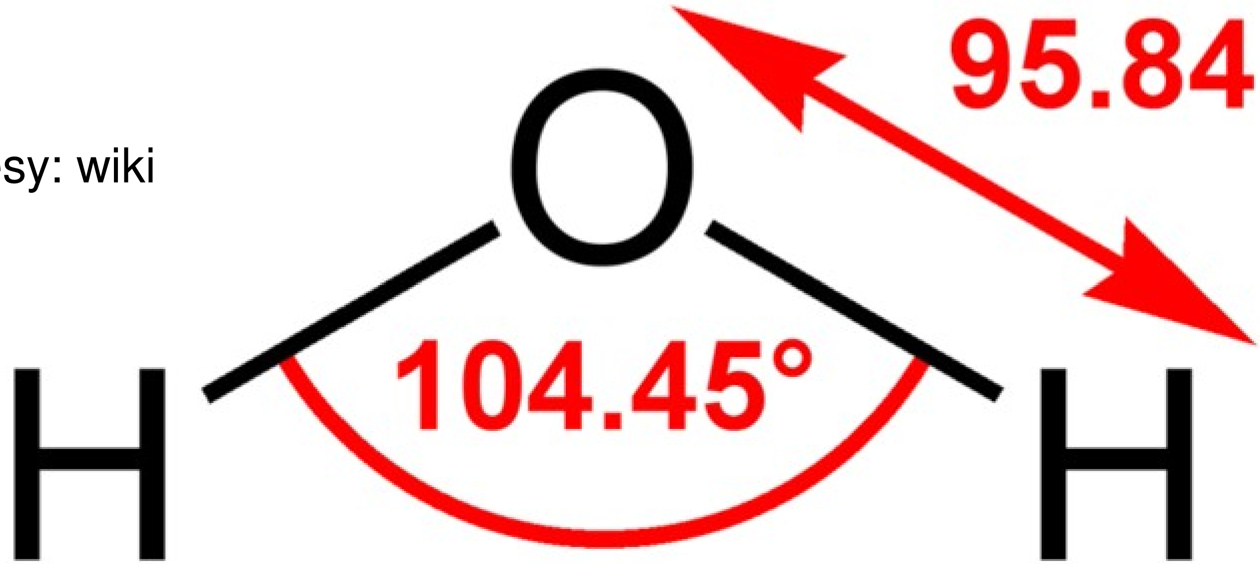
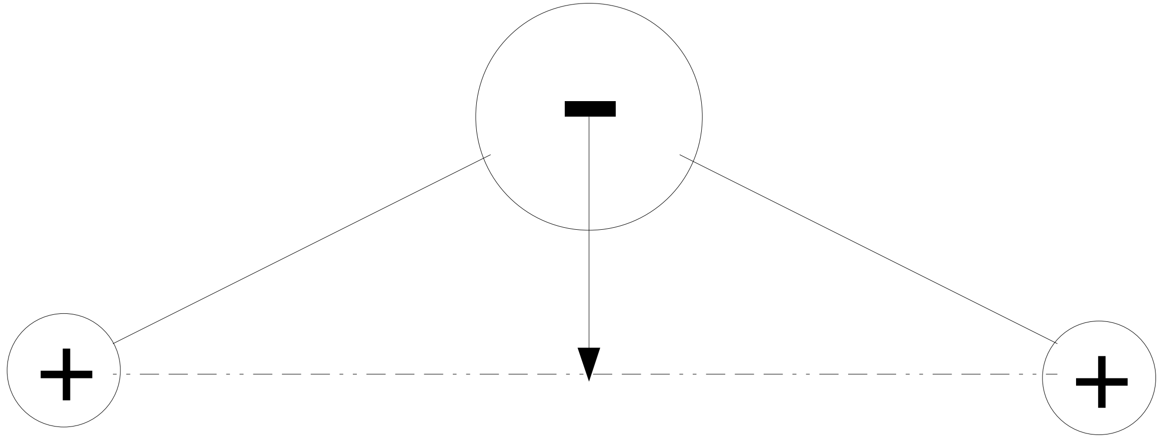
Types of electric behaviour

- Conduction
- Insulation
- Dielectrics – insulators; what we are talking about is the behaviour in an electric field

Dipole moment

Image courtesy: wiki



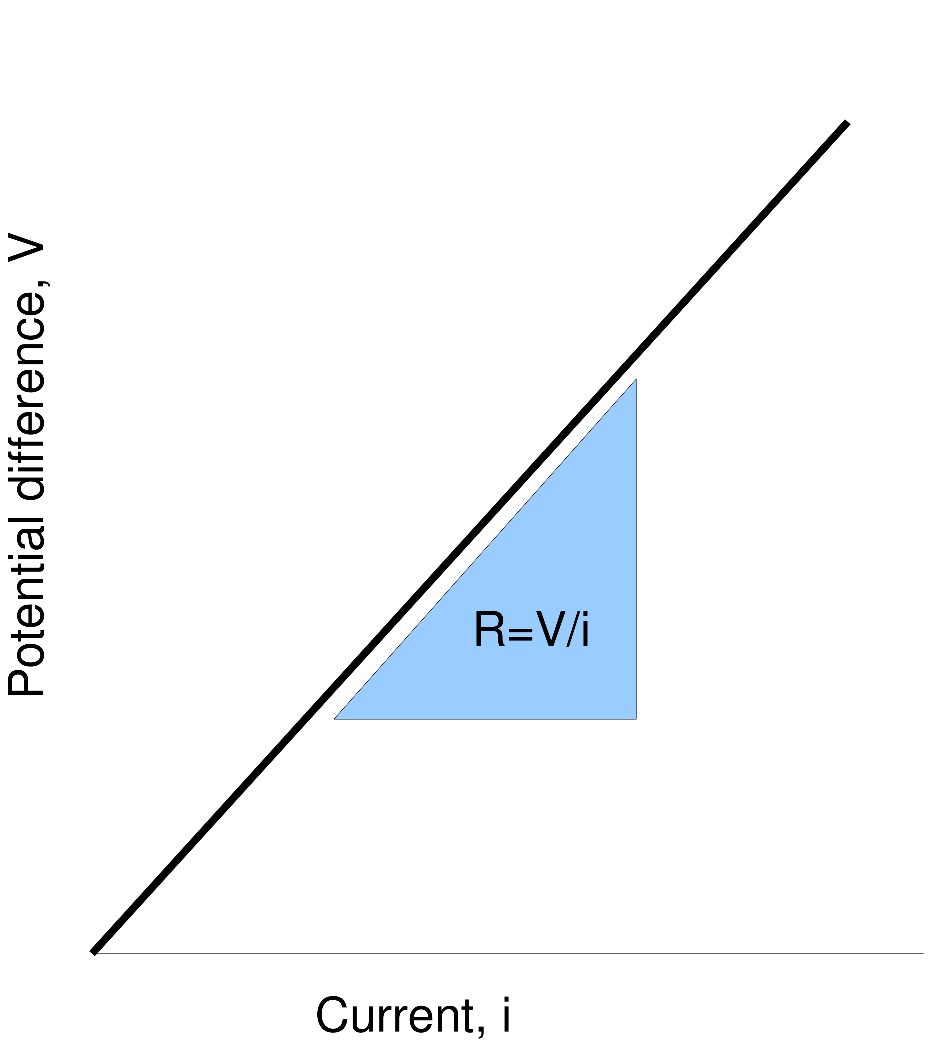


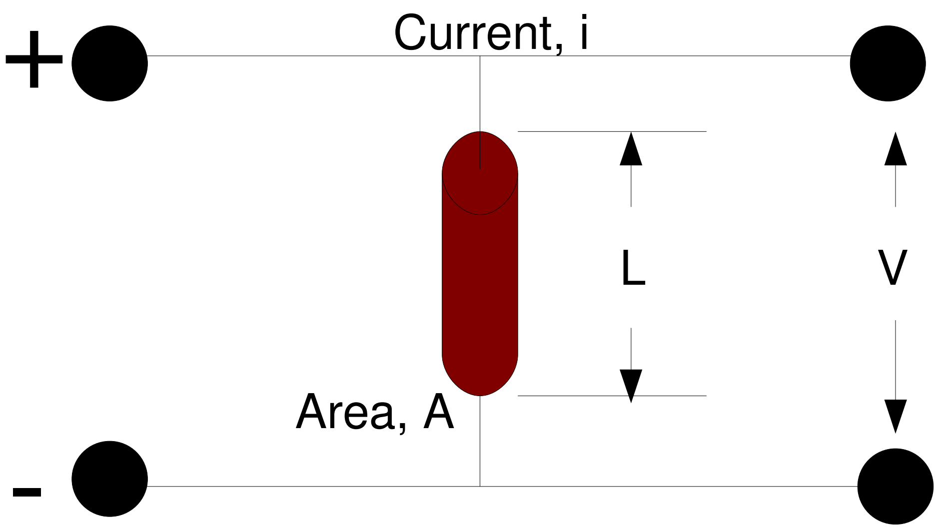
Permanent dipole moment of water molecule

Dielectrics

- Dielectric constant – relative permittivity: how much does a material polarize (acquires dipole moment)
- Dielectric loss factor: Energy dissipated when radio-frequency waves pass through the material (energy appears as heat, of course)
- Dielectric breakdown potential: damage due to dielectric losing its insulating properties

Resistivity and conductivity





Resistivity, $\rho = (A/L)\,R$

Resistivity

- Electrical resistance: ohms (Ω)
- Ohm's law: Electrical resistance in a material is the potential drop V across it, divided by the current i passing through it
- Potential drop: volts
- Current: amps
- Material property: electrical resistivity (get rid of the effects of geometry)

- ρ: Ohm-m

Georg Simon Ohm

Image courtesy: wiki

Count Alessandro Antanio Anastasio Volta

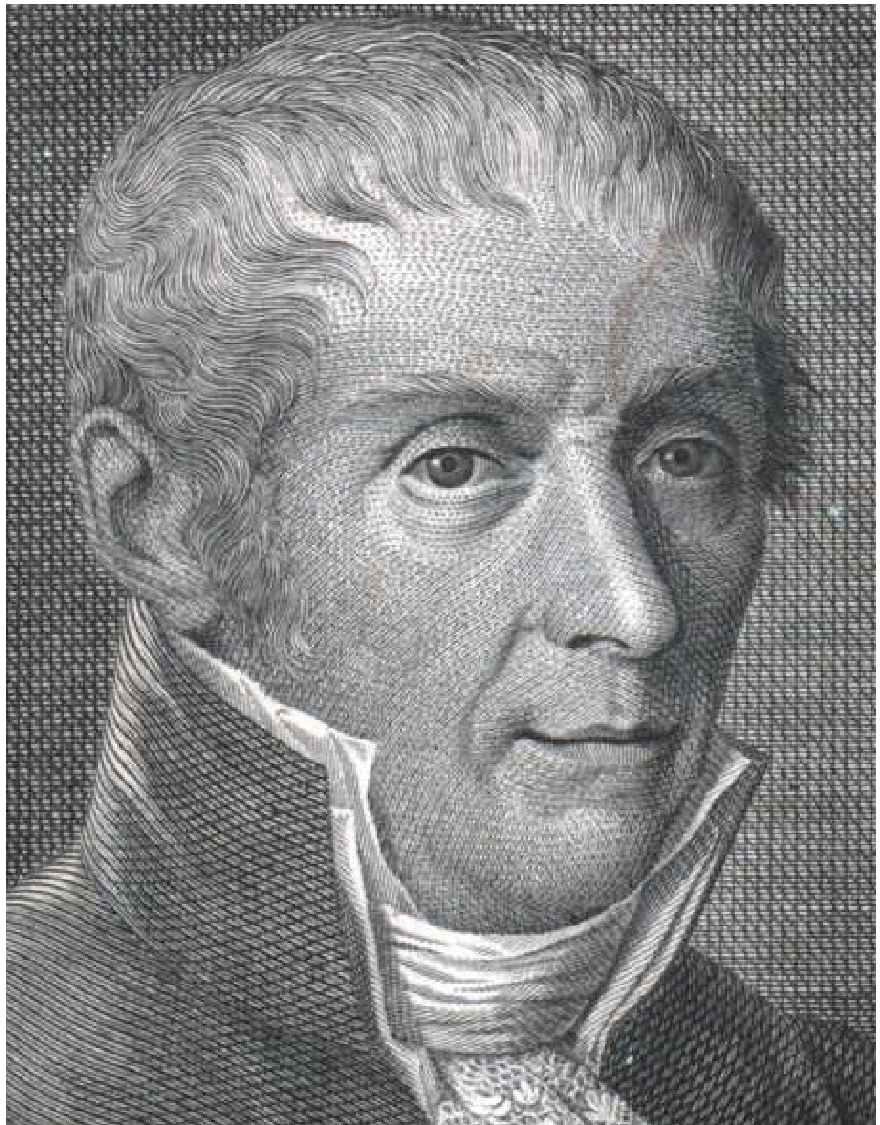


Image courtesy: wiki

Andre-Marie Ampere

Image courtesy: wiki

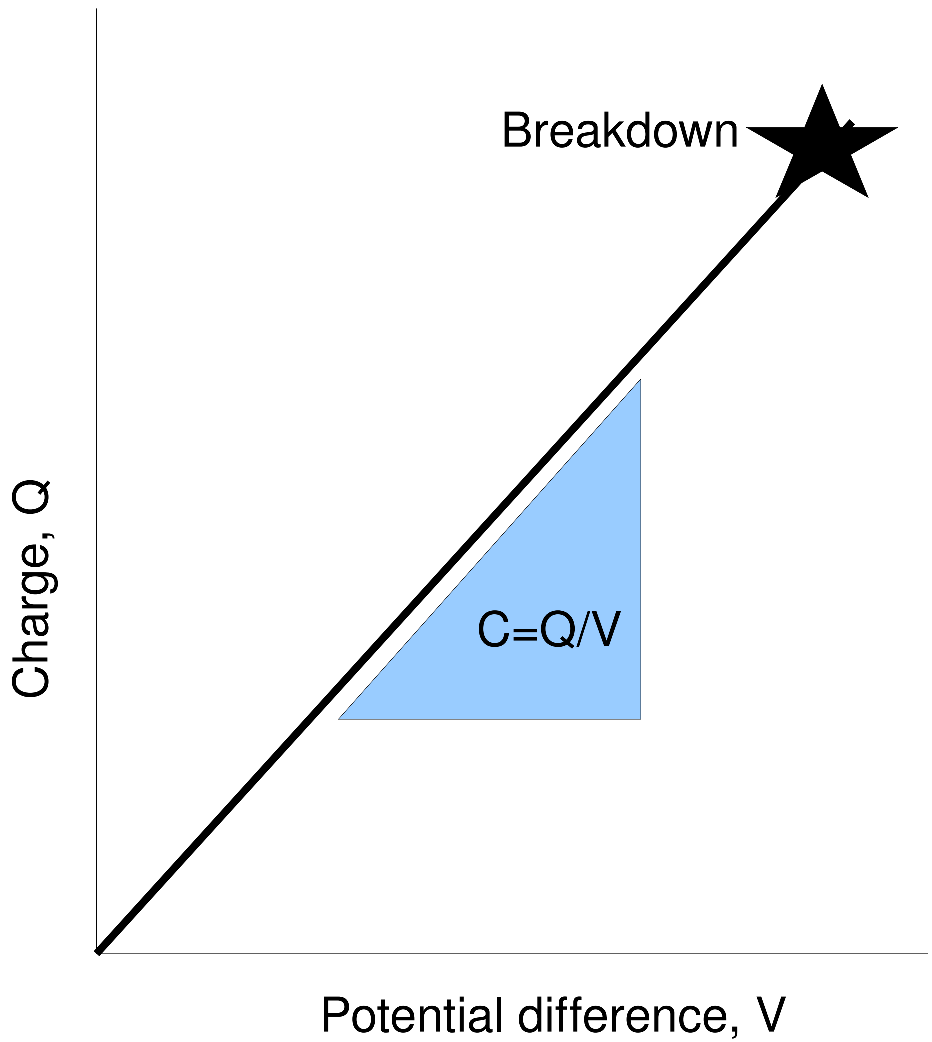
Electrical resistivity

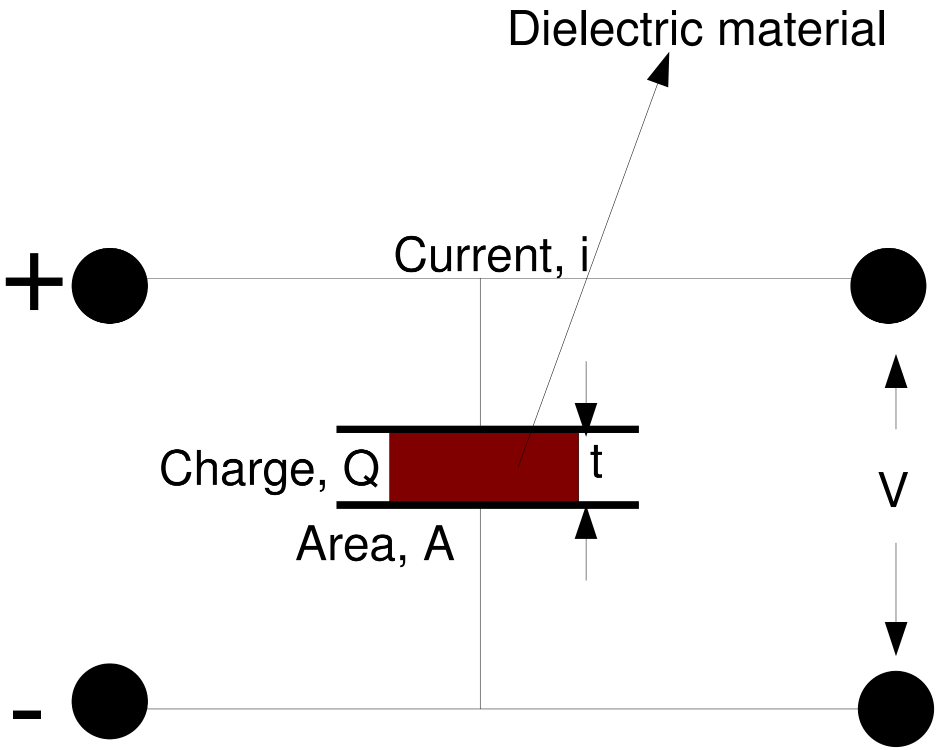
- A quantity of immense range
- Conductors: little more than $10^{-8}\,\Omega\, m$
- Best insulators: $10^{16}\,\Omega\, m$
- Electrical conductivity: reciprocal of electrical resistivity!
- Units of conductivity: siemens per m

Ernest Werner von Siemens

Image courtesy: wiki

Dielectric properties





$$\text{Dielectric constant, } \varepsilon = \frac{\text{C (with dielectric)}}{\text{C (without dielectric)}}$$

Field

- Region of space in which objects experience forces
- Provided of course they are of the right type
- Electric field: field created by charges
- Electric field strength between two oppositely charged plates separated by a distance t with potential difference V between them is

$$E = V/t$$

- E is independent of position (except near the edges of the plate)

Capacitor

- Two conducting plates separated by a dielectric
- Capacitors (or, condensers) store charge
- Charge Q (coulombs) is directly proportional to the potential difference between the plates V (volts): $Q = C V$
- C – capacitance (farads)

Charles-Augustin de Coulomb

Image courtesy: wiki

Michael Faraday

Image courtesy: wiki

Permittivity

- The capacitance of a parallel plate capacitor of area A, separated by empty space is
  $c = \varepsilon_0 A/t$
- ε_0 is the permittivity of free space (farad metre)
- Replace the empty space by a dielectric, capacitance increases. Why?

Permittivity

- Dielectric polarizes
- The field created by polarization opposes the field E
- So, the voltage difference needed to support the charge is reduced
- Thus, the capacity of the condenser is increased
- $C = \varepsilon A/t$
- ε is the permittivity of the dielectric

Dielectric constant

- Relative permittivity – dielectric cosntant:
- $\varepsilon_r = C(\text{with dielectric})/C(\text{without didlectric}) = \varepsilon/\varepsilon_0$
- $C = \varepsilon_r \varepsilon_0 A/t$
- Dielectric constant is dimensionless (ratio)
- Dielectric constant for air is unity (as well as gases, for all practical purposes); for most dielectrics it lies between 2 and 20; for ferroelectrics, it could be as high as 20,000

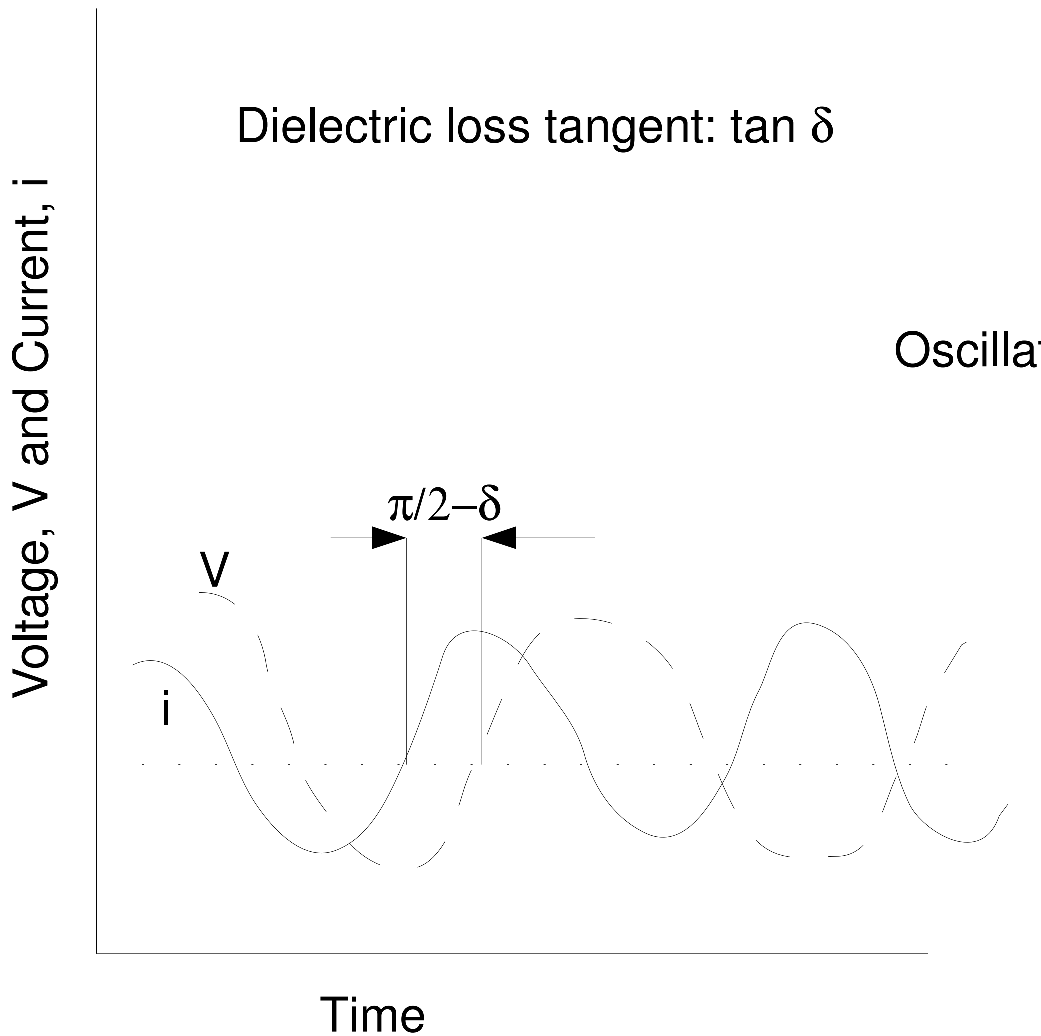
Capacitors

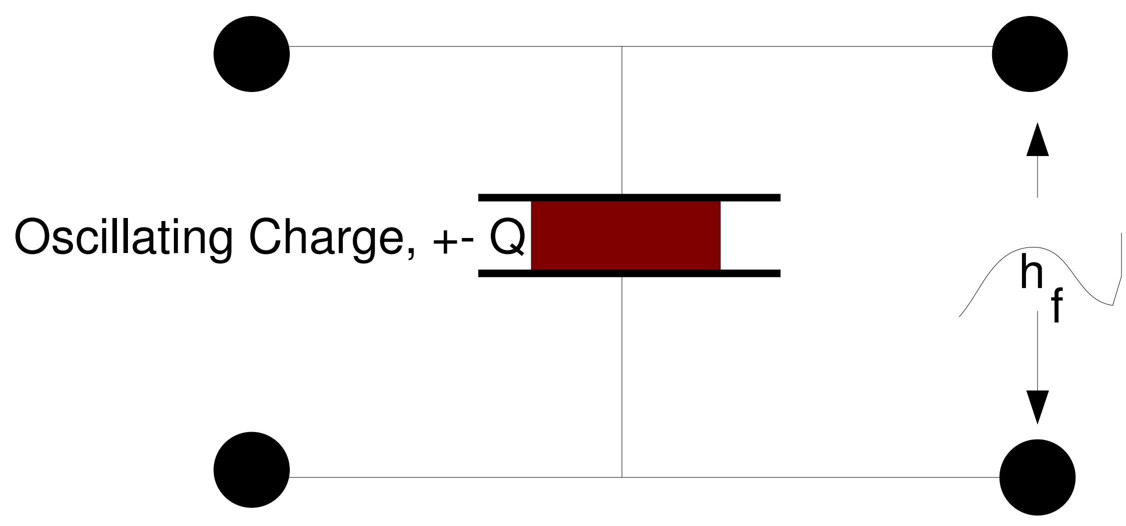
- Time constant for charging or discharging a capacitor in series with a resistor is $\tau = RC$; R is the resistance of the circuit
- When charged, the energy stored in a capacitor is $(\frac{1}{2})\, Q\, V = (\frac{1}{2})\, C\, V^2$
- The energy stored can be large; super-capactiors store enough energy to power a hybrid car
- Small capacitors are used in circuits to tune oscillations and give controlled time delays

Breakdown potential or dielectric strength

- Units V/m (Typically, MV/m)
- The electrical gradient at which an insulator breaks down and a damaging surge of current flows through it
- Measured by increasing, at a uniform rate, a 60 Hz alternating potential applied across the faces of a plate of the material until breakdown occurs

Dielectric properties





Loss tangent or loss factor

- Polarization involves the small displacement of charge (either of electrons or of ions) or molecules that carry a dipole moment when an electric field is applied to the material
- Alternating field – drives the charge between two alternating configurations
- Charge motion – like an electric current which is out of phase with the voltage – by 90 degrees if there were no losses

Loss tangent

- In real dielectric, current dissipates energy – giving it a small phase shift δ
- The loss tangent, tan δ (or the dissipation factor, D) is the tangent of the loss angle
- The power factor is the sine of the loss angle
- When the angle is small, all three, namely, dissipation factor, power factor, and loss angle are the same
- Loss factor – loss tangent times the dielectric constant

Loss factor

- Loss factor – loss tangent times the dielectric constant
- Measure of energy dissipated in a dielectric when in an oscillating field
- Selection of materials that extremise dielectric loss – $L = \varepsilon_r \tan \delta$ is the measure

Power dissipation

- Place a dielectric in a cycle of electric field of amplitude E and frequency f
- A power P is dissipated and the field is correspondingly attenuated
- Power dissipated per unit volume (P) is f $E^2 \varepsilon_0 L$
- This power appears as heat and is generated uniformly throughout the material
- Higher the frequency or field strength, higher the heating
- Radio-frequency welding of polymers

Electrostriction and piezo-electricity

- All dielectrics change shape in an electric field; consequence of the small shift in charge that allows them to polarize
- Electro-striction – one sided relationship between electric field and deformation
- Piezo-electric materials – two-sided: electric field causes deformation and deformation induces charge differences between its surfaces, thus creating a field
- Piezo-electric – a true, linear effect

Pyro-electric materials

- Contain molecules with permanent dipole moments that, in a single crystal, are aligned, giving the crystal permanent polarization
- With temperature, polarization changes – creating surface charges, or, if surfaces are connected, a pyor-electric current
- Principle of intruder detection systems and of thermal imaging

Ferro-electric materials

- Materials with natural dipole moment
- Dipole moment align – like magnetic moments in a magnet
- Direction of polarisation can be changed with the application of electric fields
- This change leads to a change of shape!