Insulation and Dielectric Materials
Learning outcome

At the end of this lecture you will be able to:

- Understand how dielectric materials react with an electric field
- List the typical failure modes of insulation materials
- List and explain the main polarization process of dielectric materials
- Analyze the requirements on the insulation materials in electrical machines

Electric fields and materials

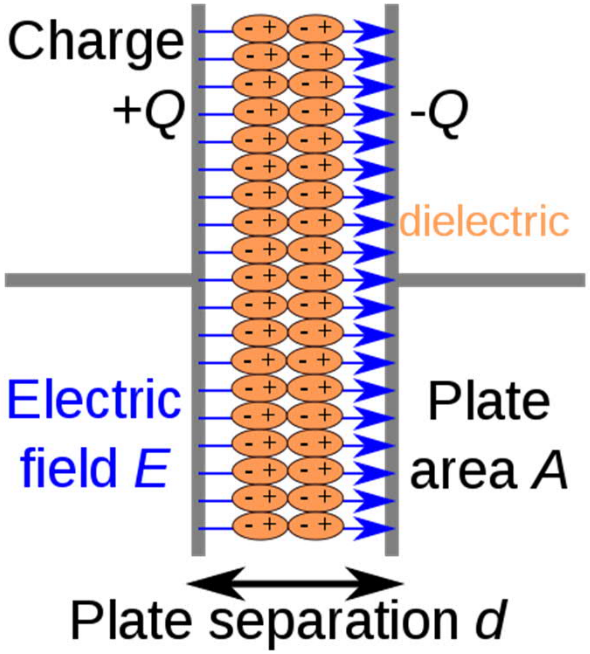
- Electric charges produce electric flux, or electric flux density ***D***; this reacts with the material to produce an electric field ***E***, which depends on how the material structure is able to polarize.

- An electrically charged particle in an electric field is subject to an electric force.

$$\mathrm{d}\boldsymbol{F} = \boldsymbol{E}\,\mathrm{d}\boldsymbol{Q}$$

- If the charge is free to move a current will follow.

- If the charge is not free, a polarization will take place
  - This ability to polarize is described by the permittivity



Electric field between two charged plates

- When the system is static, the electric field ***E*** produced by a charge is *curl-free* and the field can be expressed as the gradient of an electric potential *V*

$$\nabla \cdot \boldsymbol{D} = \rho;\ \boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times \boldsymbol{E} = 0$$

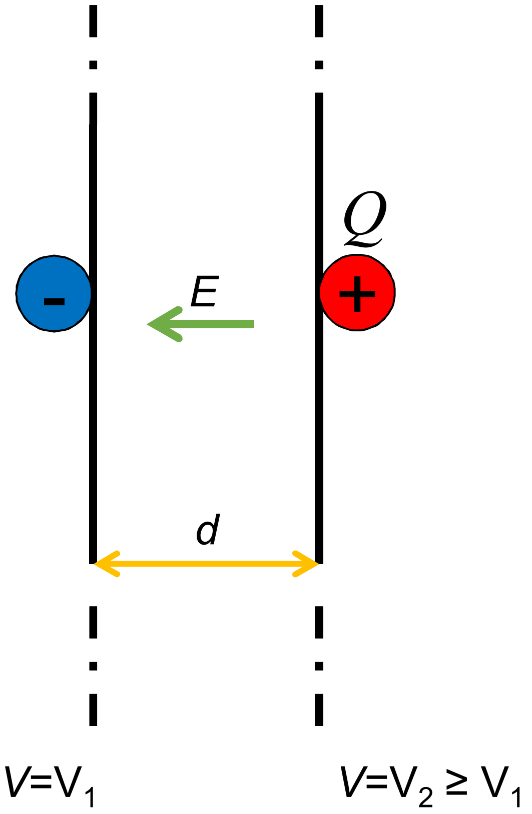
$$\boldsymbol{E} = -\nabla V$$

Poisson's equation

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

$$E = \frac{V_2 - V_1}{d} = \frac{U}{d}$$

$$U = V_2 - V_1$$



- *U* is the voltage or potential difference
- Capacitance is the ability to store electric energy

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

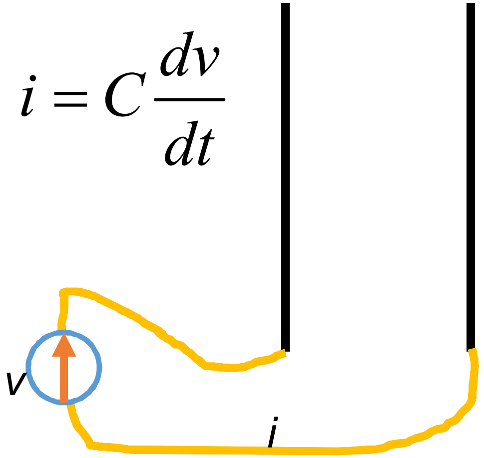
$$W_c = \frac{1}{2} C U^2$$

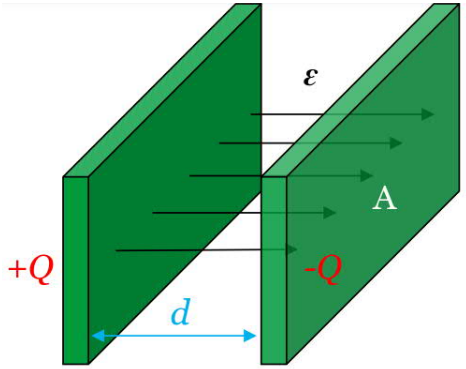
Capacitance

- Capacitance is an important parameter in electric circuits. It defines the relationship between current and voltage

- Although under DC voltage material is insulating, under alternating voltage the material becomes conducting due to charging and discharging, i.e., polarization.

$$i = C\frac{dv}{dt}$$

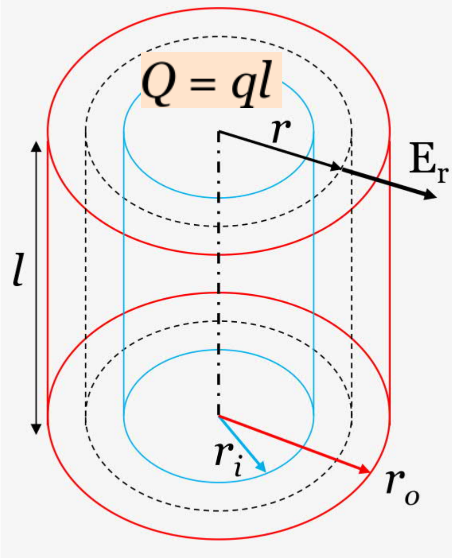




$$C = \frac{Q}{U} = \frac{A\varepsilon}{d}$$

$$C = \frac{A}{\sum_{i=1}^{n}\frac{d_i}{\varepsilon_i}}$$

$$E_i = \frac{U}{\varepsilon_i \sum_{j=1}^{n}\frac{d_j}{\varepsilon_j}}$$



$$E_r = \frac{q}{2\pi\varepsilon r} = \frac{Q}{2\pi\varepsilon l r}$$

$$E_r = \frac{U}{r\ln\left(r_o/r_i\right)}$$

$$C = \frac{2\pi\varepsilon l}{\ln\left(r_o/r_i\right)}$$

Electric fields and dielectric materials

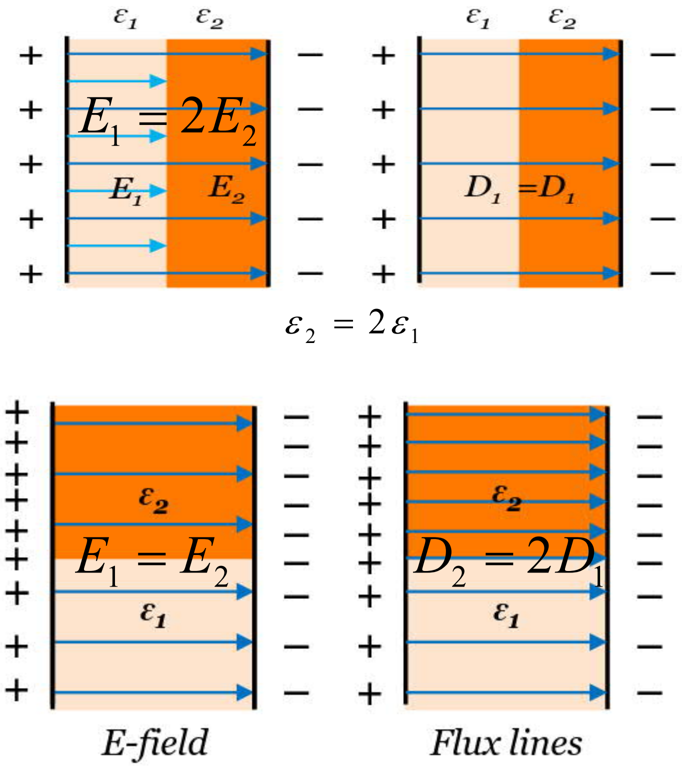
- The origin of an electric field is either a charge density or a time varying magnetic field
- Dielectric materials are insulators used in electrical devices
  - Their atoms have tightly bonded valence electrons (outermost electrons of an atom)
  - Their role is to prohibit the flow of charges, i.e., electric currents

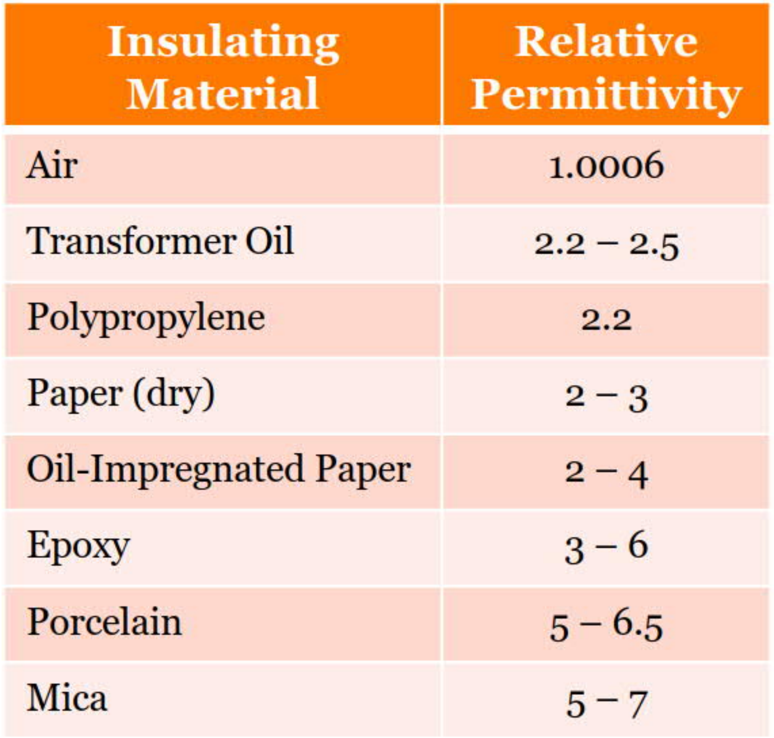
$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\varepsilon = \varepsilon_r \varepsilon_0$$





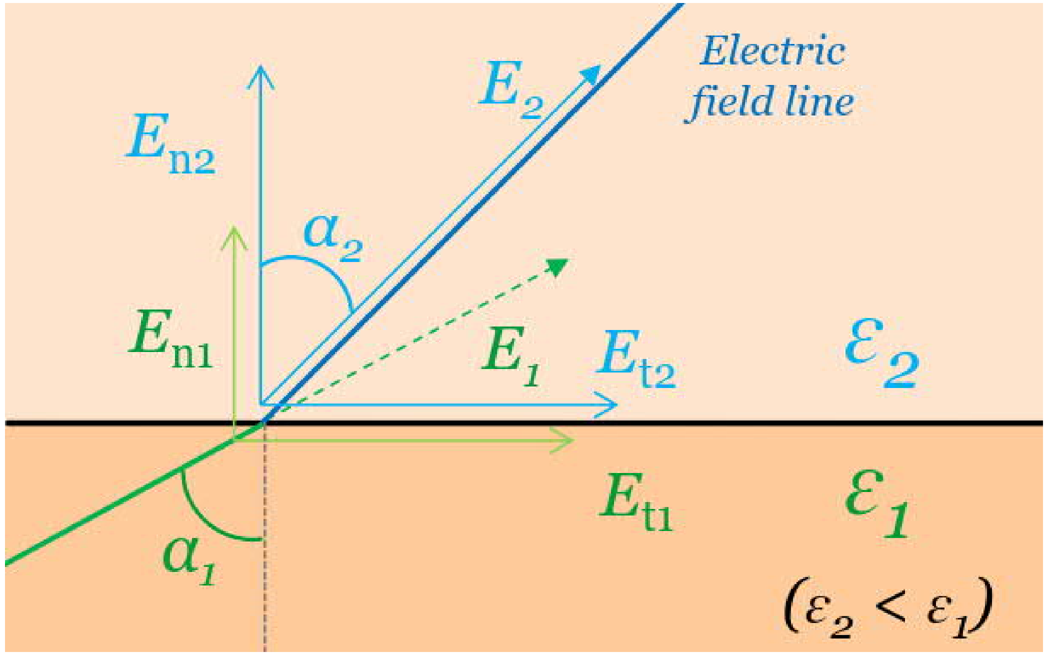
Insulating Material	Relative Permittivity
Air	1.0006
Transformer Oil	2.2 – 2.5
Polypropylene	2.2
Paper (dry)	2 – 3
Oil-Impregnated Paper	2 – 4
Epoxy	3 – 6
Porcelain	5 – 6.5
Mica	5 – 7

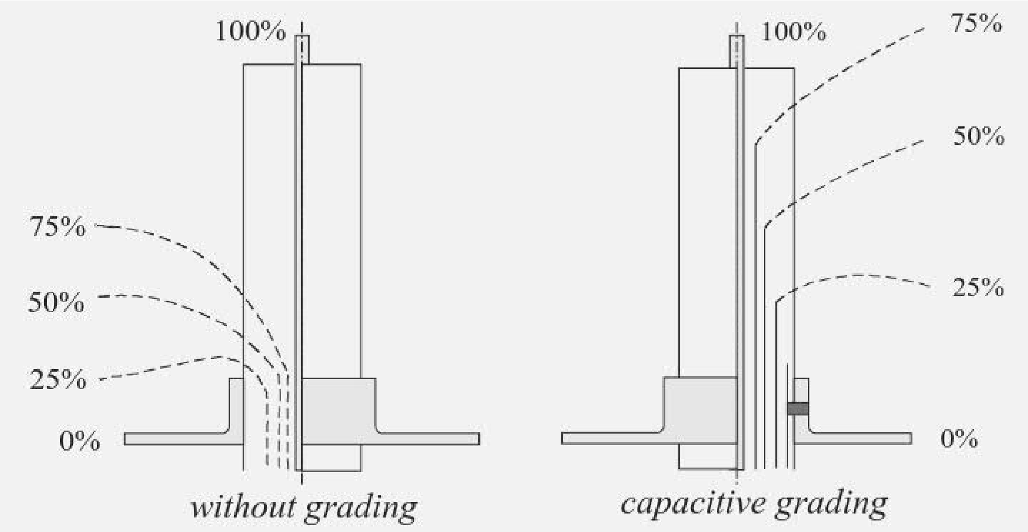
Electric fields and dielectric materials

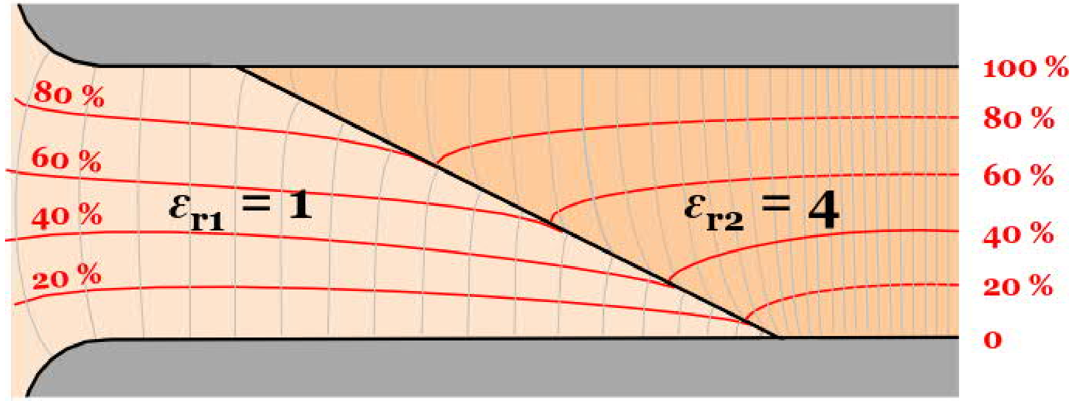
- Material boundraies are important and they define how the fields behave
  - The tangential component of the electric field is continous
  - The normal component of the elctric flux density is continous

$$E_{t1} = E_{t2}$$

$$D_{n1} = D_{n2}$$



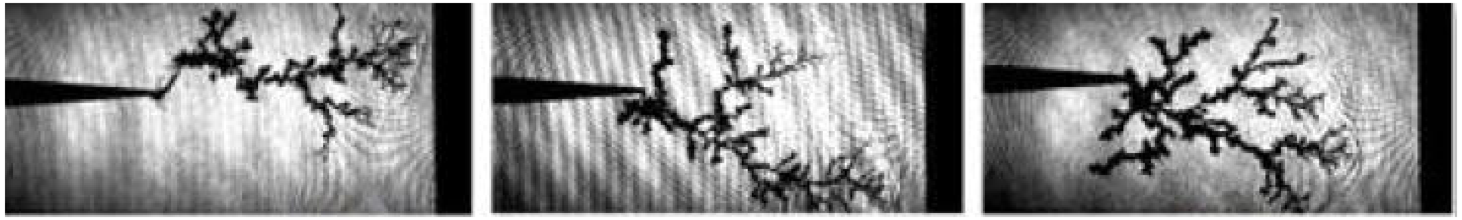




Electric fields and dielectric materials

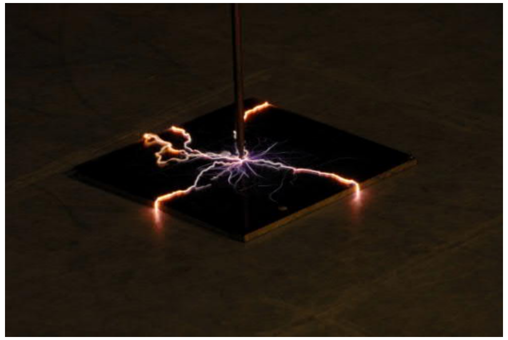
- Insulators might fail if the electric field is too high ($>E_b$).
- In air E_b= 3kV/mm
  - Field energy releases an electron from its orbit
  - Electric field accelerates the electron
  - More electrons are ejected due to collision
  - Flow of charged electrons = electric current

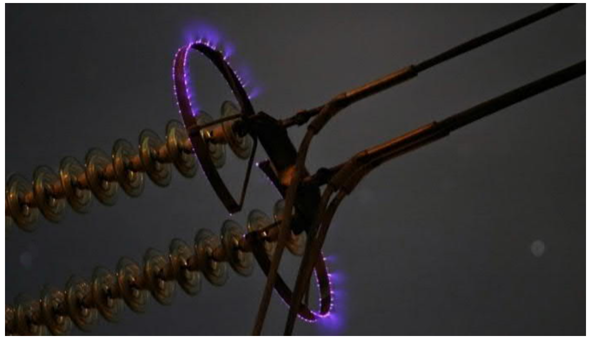
	**Insulation**	**Breakdown Field Strength [kV/mm]**
Organic	Paper (dry)	6
	Paper (oil impregnated)	40 – 75
	Rubber	20
	Wood (dry)	
	Wood (oil impregnated)	
	Press wood (dry)	6
Inorganic	Porcelain	30
	Glass	16
	Mica	80
Synthetic Polymer	Polythene	20
	Polystyrene	100
	Phenolic plastic (bakelite)	5 – 16
	Epoxy plastic	20 – 40
	Melamine	13 – 14



Some definitions and terminology

- Breakdown – insulation failure leading to the formation of a highly conducting channel bridging the electrodes (momentary event)
  - Typically refers to non-restoring insulation.
- Flashover – breakdown in gas or along solid insulation surface where the conducting channel "jumps" from one electrode to the other rather than traveling through the solid insulation.
  - Typically refers to self-restoring insulation.
- Partial Discharge – localized incomplete breakdown (conducting channel does not reach the opposite electrode)
- Corona – partial discharge in gas around the electrode surface.
- Arcing – long duration flashover (continuous discharge of current).
  - Typically used in connection to power systems.
- Discharge – any form of electrical breakdown (including partial discharge).





Break down field comparison example

Courtesy of Joni Klüss

- Insulation = Air ($\varepsilon_r = 1$, $E_b = 3.0$ kV/mm)
- Distance between electrodes = 100 mm ($r_i = 50$ mm, $r_o = 150$ mm)
- Voltage = 100 kV

PLANE

$$E_{\max} = \frac{U}{d}$$

CYLINDER

$$E_{\max} = \frac{U}{r_i \ln\left(r_o / r_i\right)}$$

SPHERE

$$E_{\max} = \frac{r_o}{r_i\left(r_o - r_i\right)} U$$

1 kV/mm ➔ **1.8 kV/mm** ➔ **3 kV/mm**

Investigation work 20 min

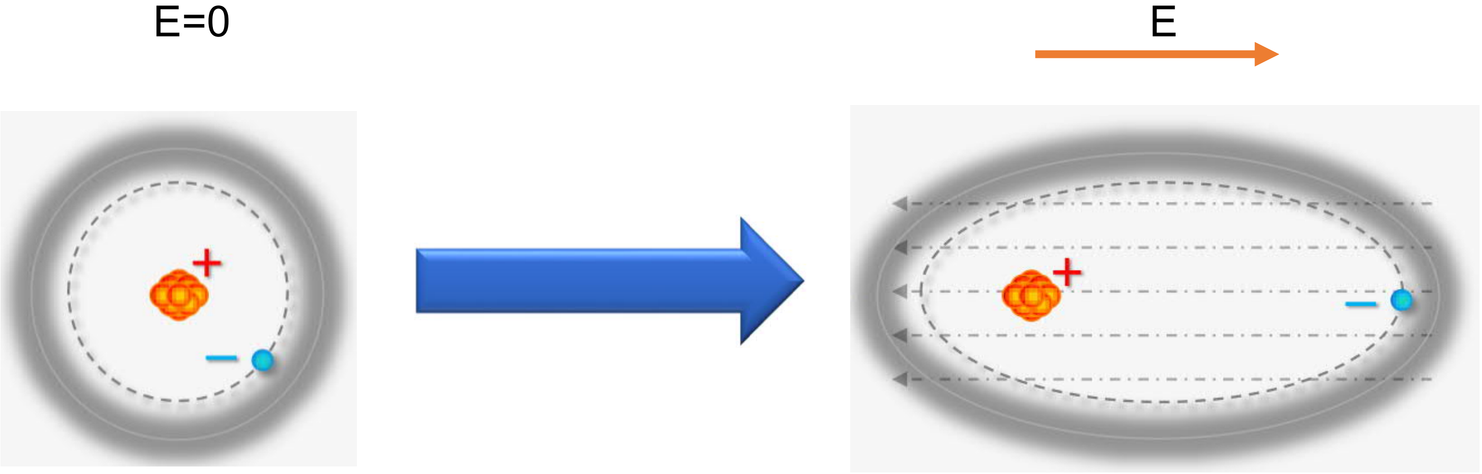
- Look in internet what are the different types of electric polarization of materials at atomic scale(10 min)

    - Try to explain these types

- List of polarization types:

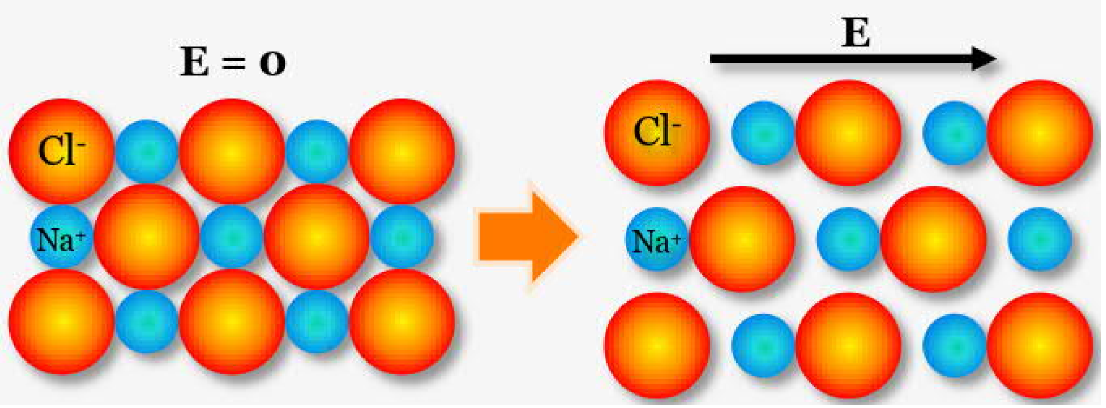
Polarization mechanisms at molecular scale

- Electron or atomic polarization
  - Happens in all atoms regardless of the material structure
  - The electric field produces small asymmetry in the electron clouds around the nucleus
  - 1 V/m electric field produce displacement of about 10 nm
  - Small contribution to atomic scale relative permittivity (1,8 .. 4)



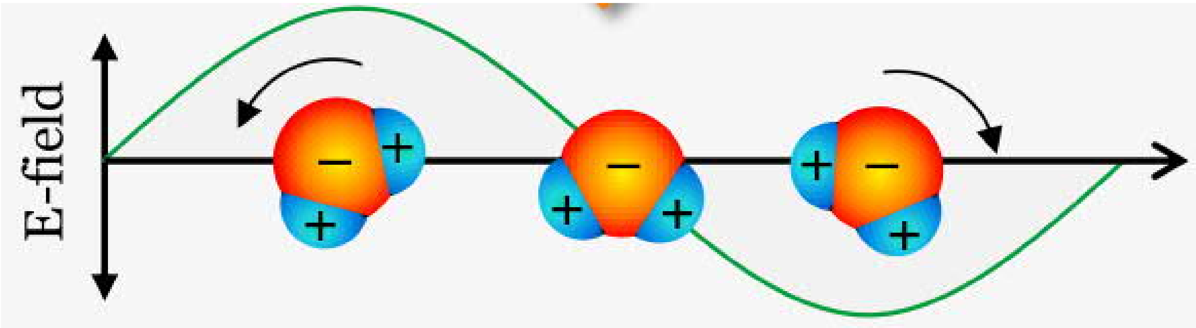
Polarization mechanisms

- Ionic/atomic polarization
  - Happens in crystals with ionic structure lattice, usually solid phase materials
  - The electric field produces disturbance of the equilibrium state of the lattice
  - Large effect in regular structures, atomic scale relative permittivity (10)
  - Effect can be quantified by measurements under different frequencies



Polarization mechanisms

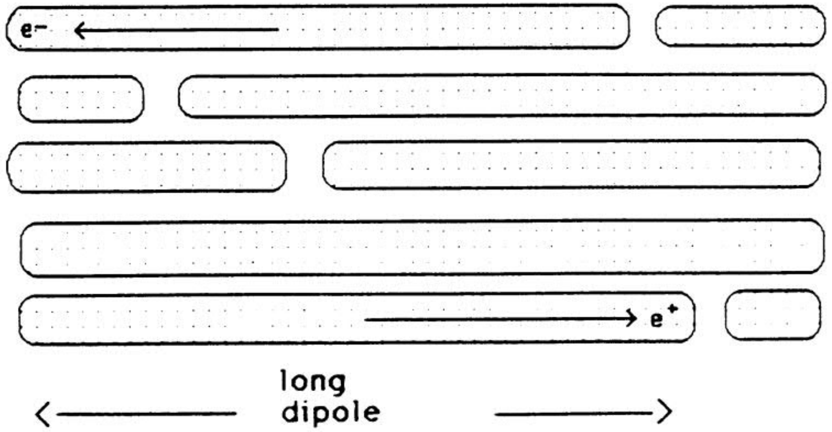
- Dipole polarization
  - Molecules with atoms having different affinity form electric dipoles, which tend to rotate and align with the external electric field
  - Typically in gases and liquids but also some solid; water (H2O), nitric oxide (NO), and polyvinyl chloride (PVC (C2H3Cl)n)
  - Medium effect on atomic scale relative permittivity (78 for H2O, e.g.)
  - Depends strongly on the frequency and is subject to saturation



Polarization mechanisms

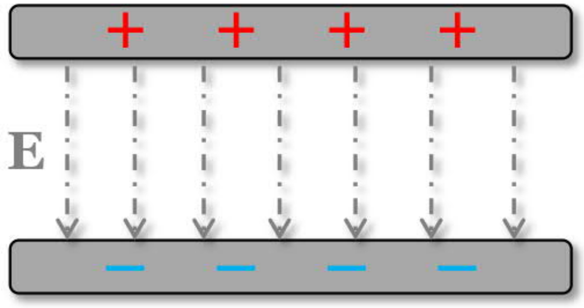
- Nomadic polarization

  - Discovered in 1970’s
  - Occurs at high longer scal than atomic or molecular scale (10^2 – 10^5 Å vs. 10^{-8} in atomic polarization)
  - Explained by the fact that the electrons are free to move at the molecular scale but not from one molecule to the other
  - The molecular scale is large and the resulting polarization too (realtive permittivity 10^5)

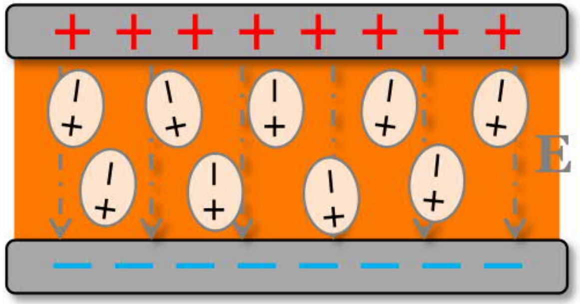


Advantages and disadvantages of Polarization

- Polarization increases the capacitance and thus the stored energy:
  - Charges are shifted with the electric field
  - To cancel this shift, the electrodes accumulate additional charges



Vacuum ($\varepsilon_r = 1$)



Dielectric ($\varepsilon_r > 1$)

  - Stored energy

$$W_c = \frac{1}{2} C U^2$$

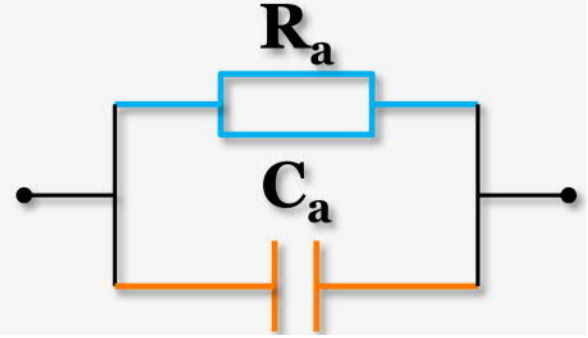
- Under Ac fields, the ”motion” of charges is accompanied with a net current
- The dielectric can be considered as a capacitor in parallel with a resistor
  - Dielectric losses

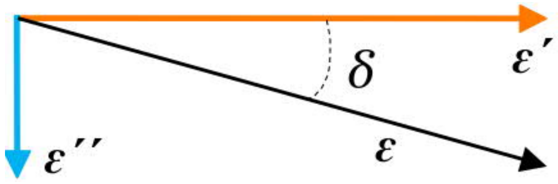
RC-representation of dielectric materials

- The material permittivity depends on the frequency
- In time harmonic analysis, the permittivity takes a complex form

$$\begin{aligned}\varepsilon &= \varepsilon' + j\varepsilon'' \\ &= \|\varepsilon\| \angle \delta\end{aligned}$$

- The loss angle δ defines how non ideal the insulator is
- It can be defined for materials as well as for insulation systems

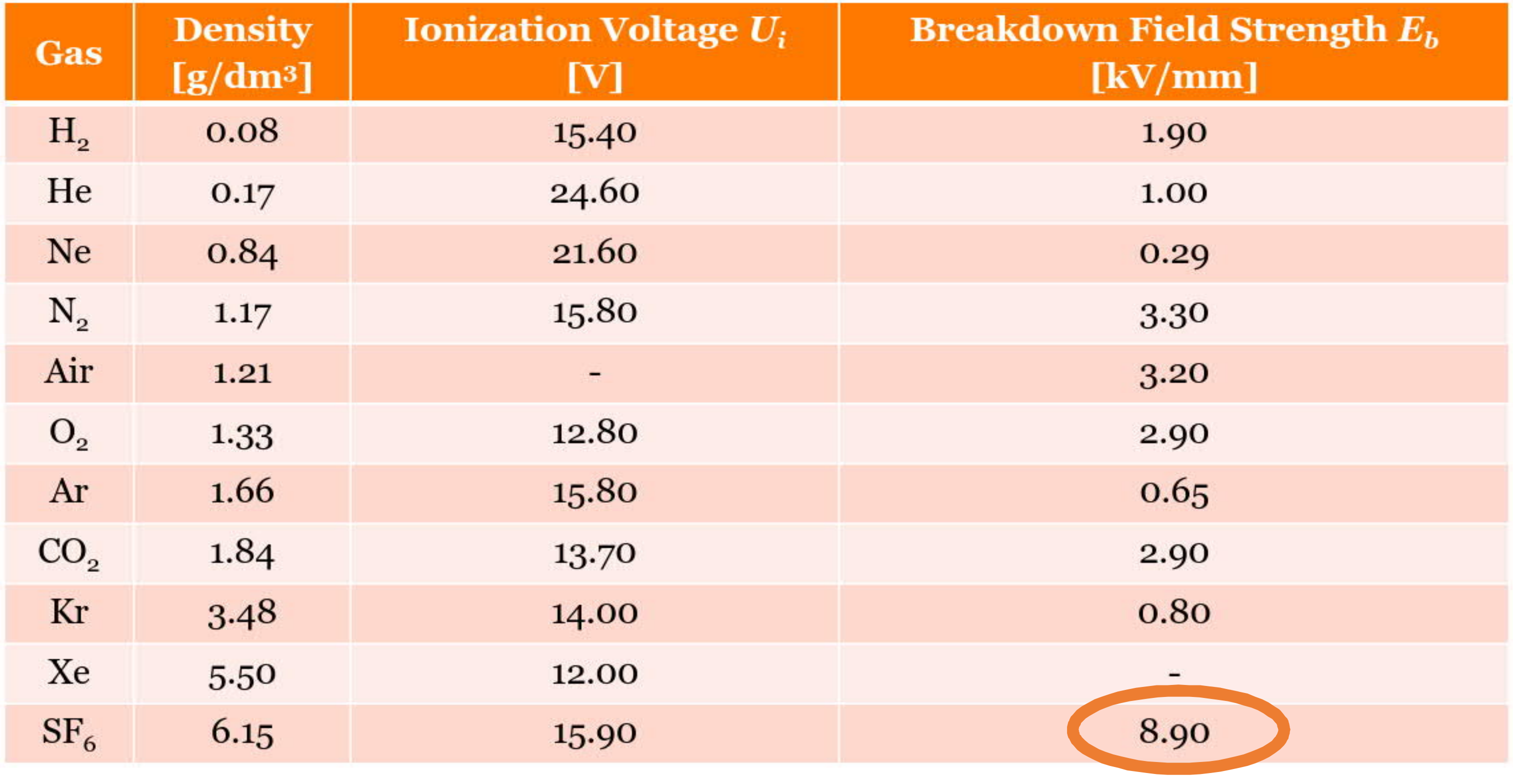




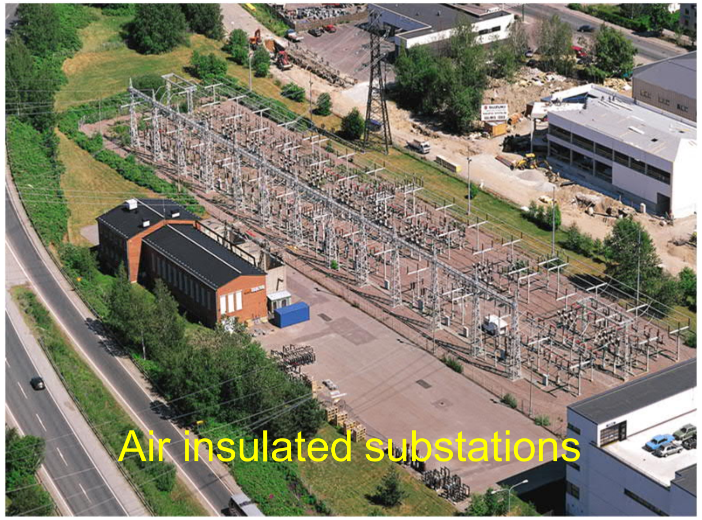
$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

Gas insulators

- Air and Nitrogen are the most used natural insulators
- Self-restoring – insulation properties restored after discharge is extinguished
- SF6 is the most used industrial insulator gas
  - Significantly reduces the size of electric components
  - Maximum pressure 20 Mpa



Gas	Density [g/dm³]	Ionization Voltage U_i [V]	Breakdown Field Strength E_b [kV/mm]
H_2	0.08	15.40	1.90
He	0.17	24.60	1.00
Ne	0.84	21.60	0.29
N_2	1.17	15.80	3.30
Air	1.21	-	3.20
O_2	1.33	12.80	2.90
Ar	1.66	15.80	0.65
CO_2	1.84	13.70	2.90
Kr	3.48	14.00	0.80
Xe	5.50	12.00	-
SF_6	6.15	15.90	8.90



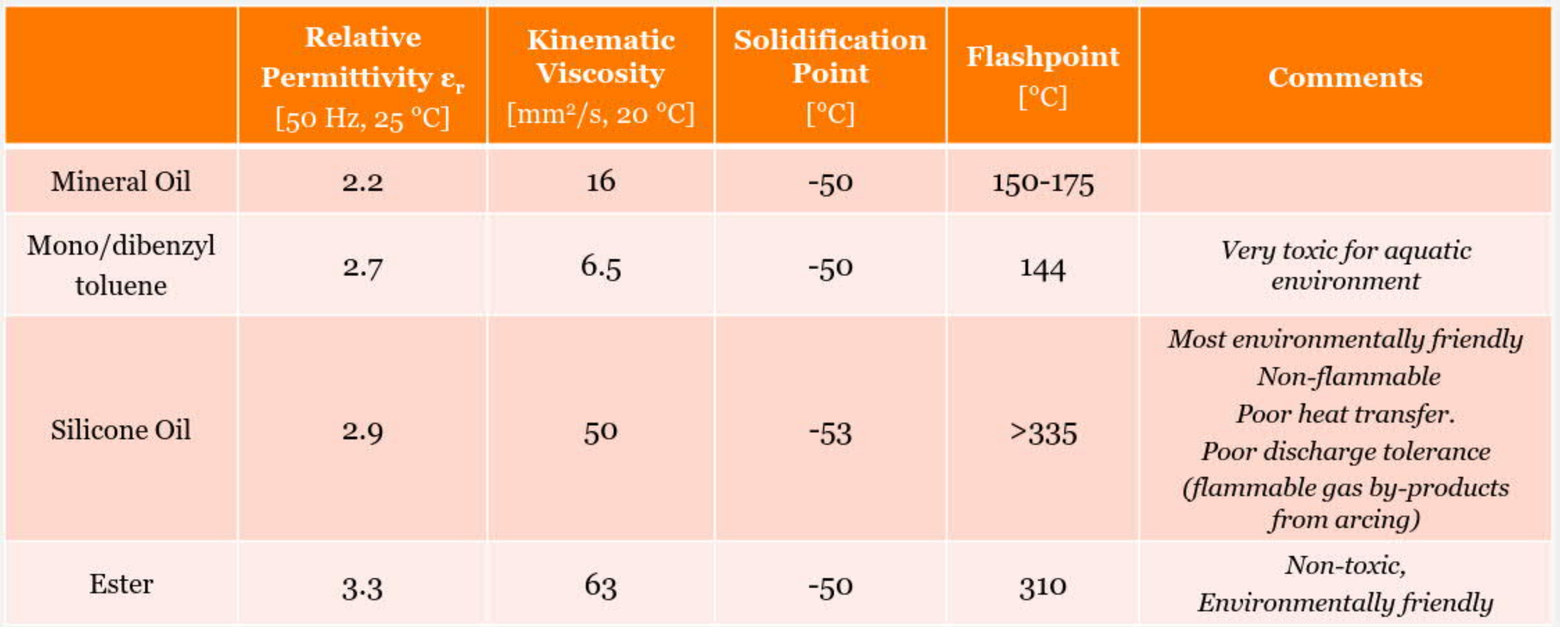
Air insulated substations

Courtesy of Pirjo Heine

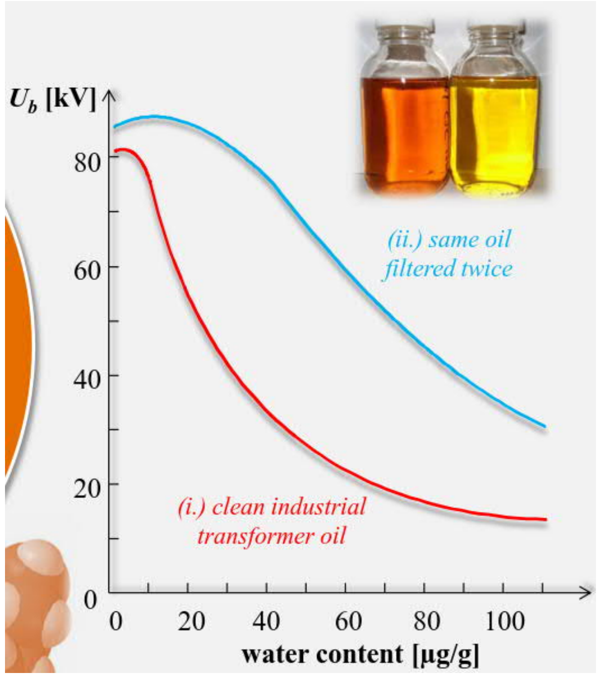
SF6 insulated substations

Liquid insulators

- Typical mineral oil is transformer oil
  - Easy availability and economical
  - Properties defined in IEC 60296
  - Good dielectric properties for insulation and low viscosity for cooling
  - Prone to oxidization and flammability (flash point over 130 °C)
  - Moisture and impurities affect insulating properties
  - Discharge leaves by-products, which deteriorates insulation properties

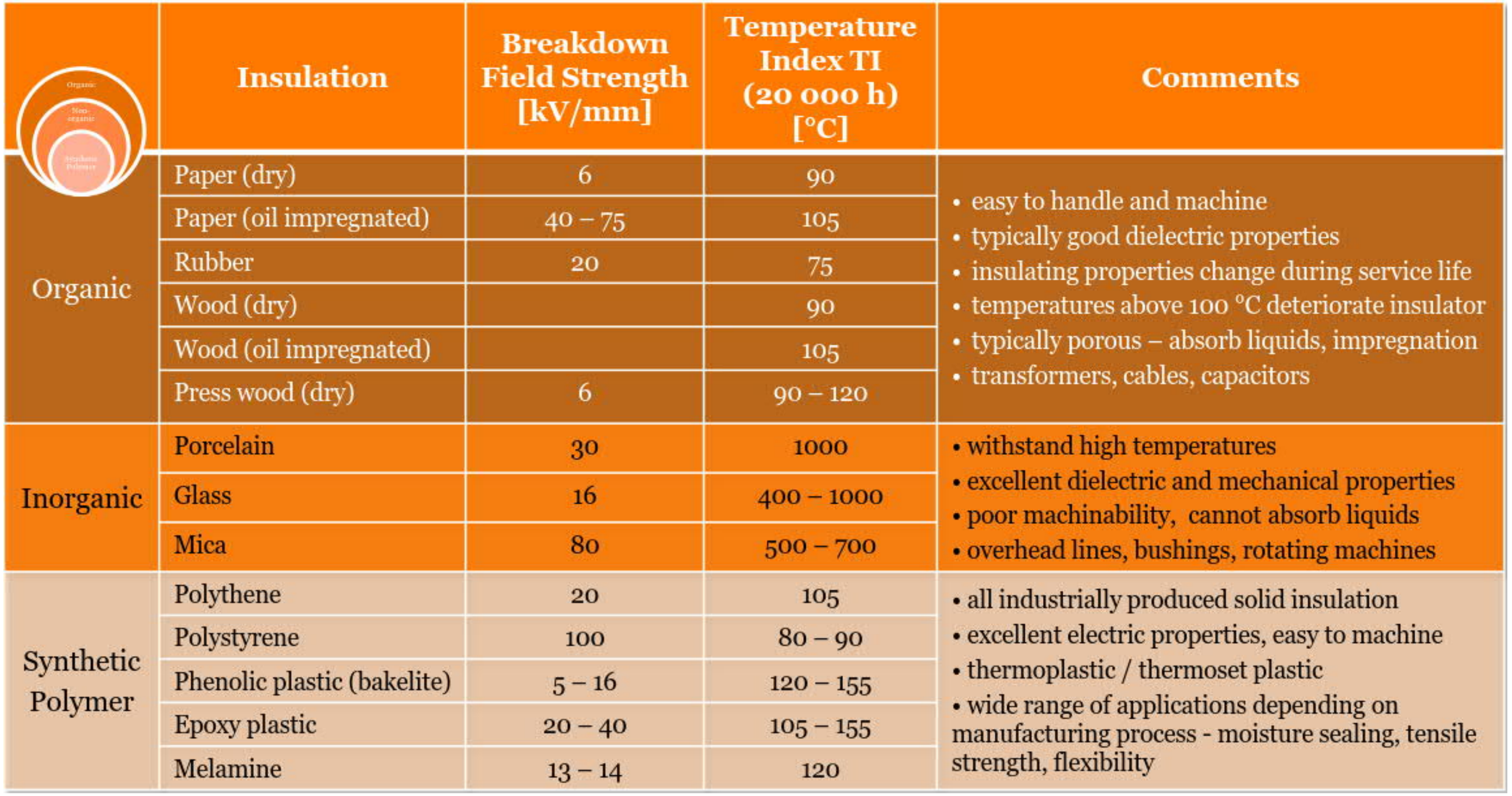


	Relative Permittivity ε_r [50 Hz, 25 °C]	**Kinematic Viscosity** [mm²/s, 20 °C]	**Solidification Point** [°C]	**Flashpoint** [°C]	**Comments**
Mineral Oil	2.2	16	-50	150-175	
Mono/dibenzyl toluene	2.7	6.5	-50	144	*Very toxic for aquatic environment*
Silicone Oil	2.9	50	-53	>335	*Most environmentally friendly* *Non-flammable* *Poor heat transfer.* *Poor discharge tolerance (flammable gas by-products from arcing)*
Ester	3.3	63	-50	310	*Non-toxic,* *Environmentally friendly*



Solid insulators

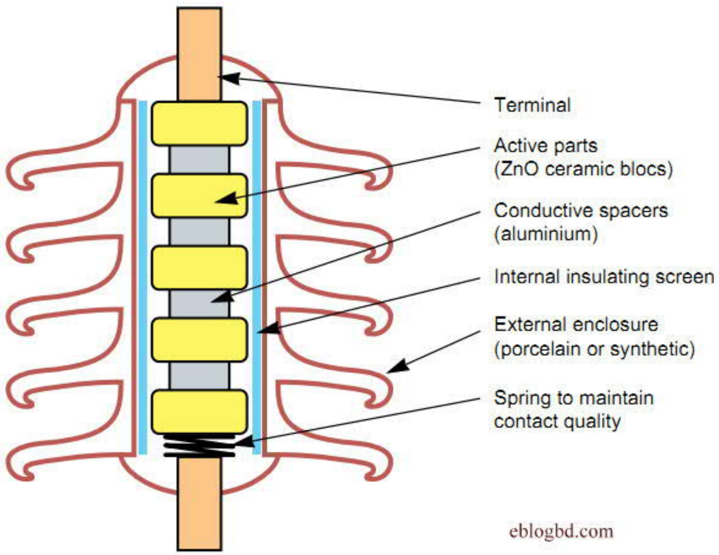
- Provide mechanical support for conducting elements
- Act as heat conductor to help cooling
- Provide insulation properties (dielectric)
  - Non-self-restoring – discharge leaves permanent channel, insulation properties seriously deteriorated



	Insulation	Breakdown Field Strength [kV/mm]	Temperature Index TI (20 000 h) [°C]	Comments
Organic	Paper (dry)	6	90	• easy to handle and machine • typically good dielectric properties • insulating properties change during service life • temperatures above 100 °C deteriorate insulator • typically porous – absorb liquids, impregnation • transformers, cables, capacitors
	Paper (oil impregnated)	40 – 75	105	
	Rubber	20	75	
	Wood (dry)		90	
	Wood (oil impregnated)		105	
	Press wood (dry)	6	90 – 120	
Inorganic	Porcelain	30	1000	• withstand high temperatures • excellent dielectric and mechanical properties • poor machinability, cannot absorb liquids • overhead lines, bushings, rotating machines
	Glass	16	400 – 1000	
	Mica	80	500 – 700	
Synthetic Polymer	Polythene	20	105	• all industrially produced solid insulation • excellent electric properties, easy to machine • thermoplastic / thermoset plastic • wide range of applications depending on manufacturing process - moisture sealing, tensile strength, flexibility
	Polystyrene	100	80 – 90	
	Phenolic plastic (bakelite)	5 – 16	120 – 155	
	Epoxy plastic	20 – 40	105 – 155	
	Melamine	13 – 14	120	

Different high voltage applications of insulation

Lightning arrester technology



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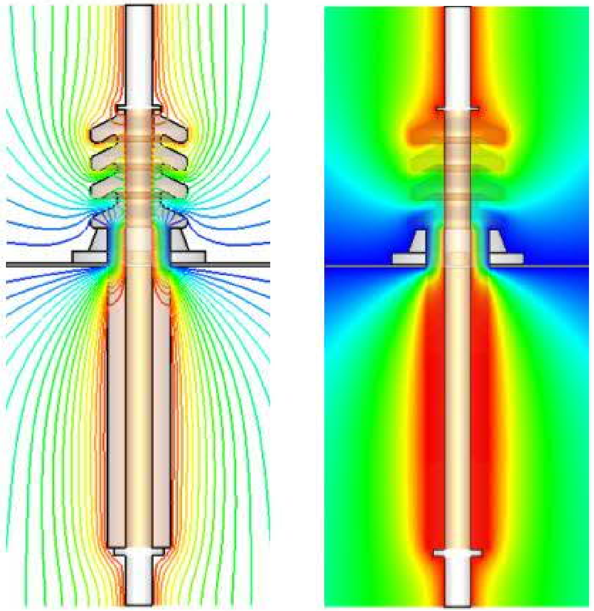
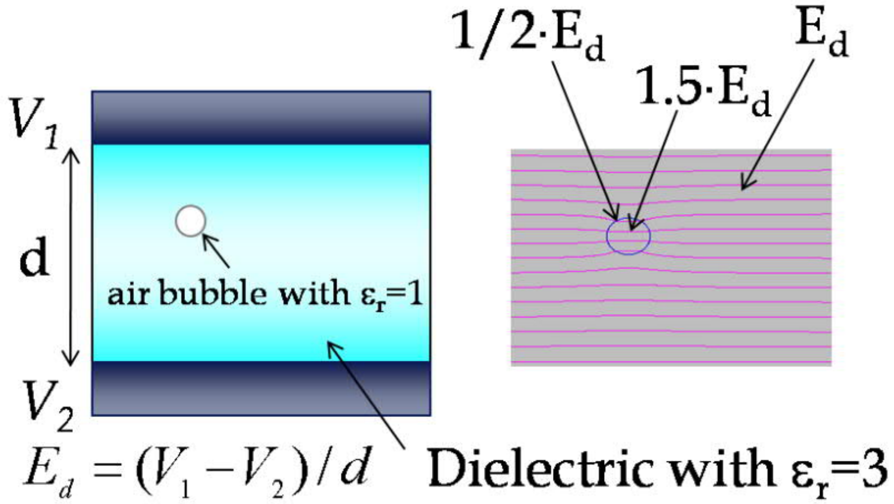
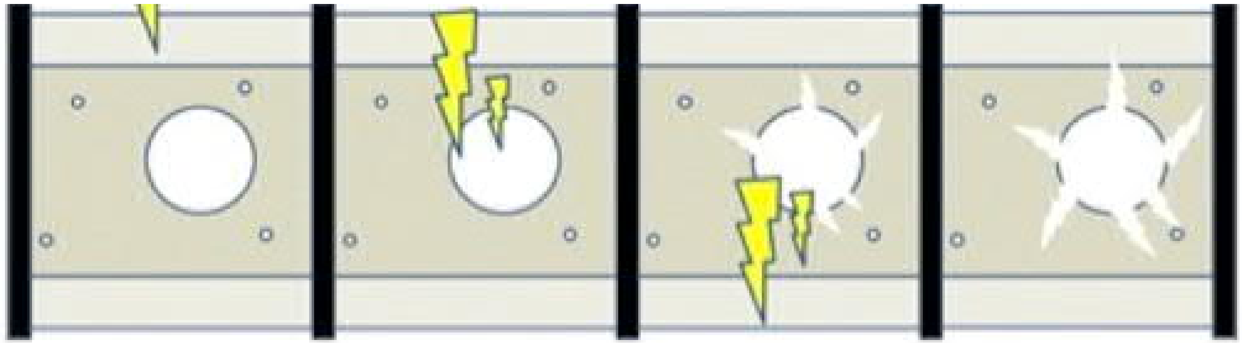


Partial discharge

- Solid insolators usually have void, liquid or gas bubbles inside them
- Their permittivity is lower than in the solid permittivity
  - Voltage stress is higher inside the bubble
  - Partial discharge occur in bubble at high field but not in solide
  - Bubble wall subjected to corrosion due to ion and electron release
  - Irregular wall favorise high field



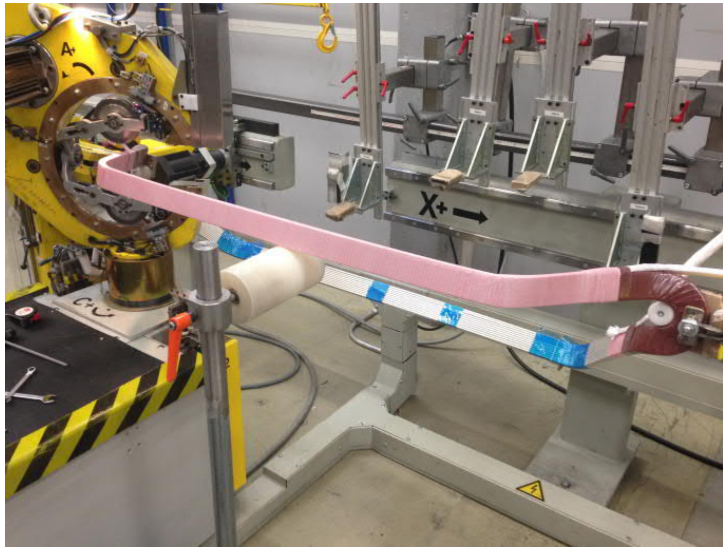


Investigation work 20 min

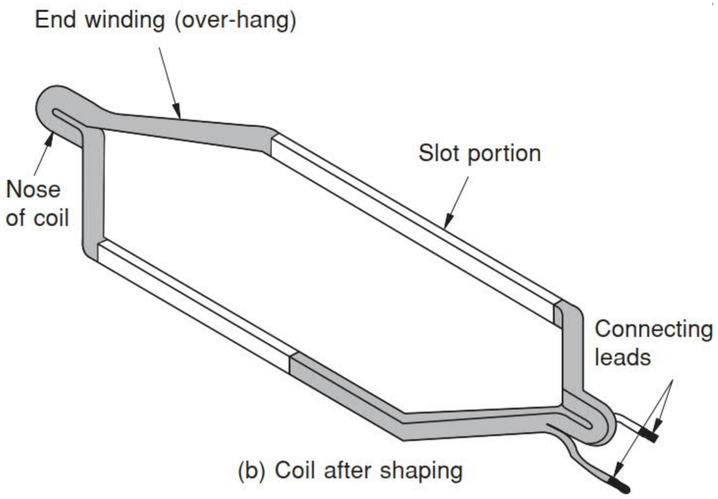
- Look in internet and find out what are the insulations/insulation systems used in and electrical machine (10 min)

- List of insulations and insulation systems:

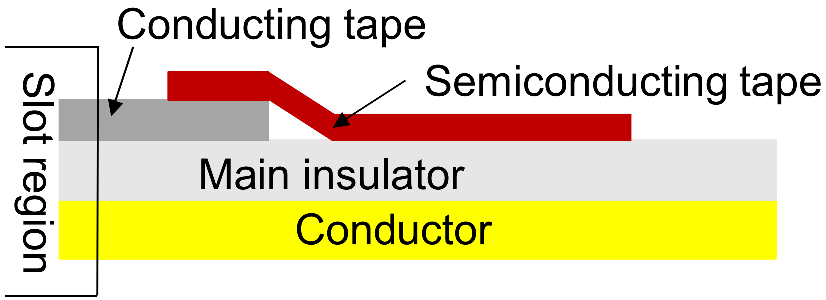
Insulation system of electrical machines



- Insulation is needed at different locations:
  - between conductor /coils and earth (phase-to-earth)
  - between conductor /coils of different phases (phase-to-phase)
  - between turns in a coil (inter-turn)
  - between the coils of the same phase (inter-coil)



(b) Coil after shaping



Conducting tape

Semiconducting tape

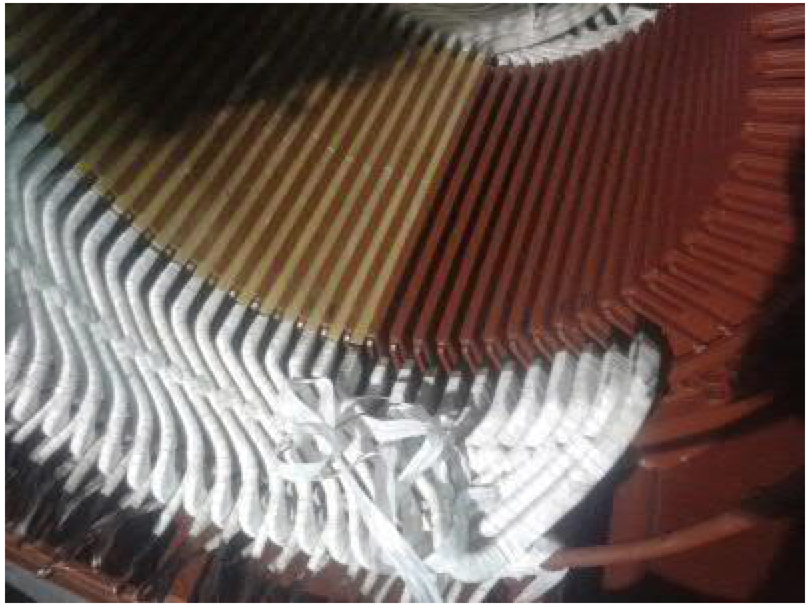
Slot region

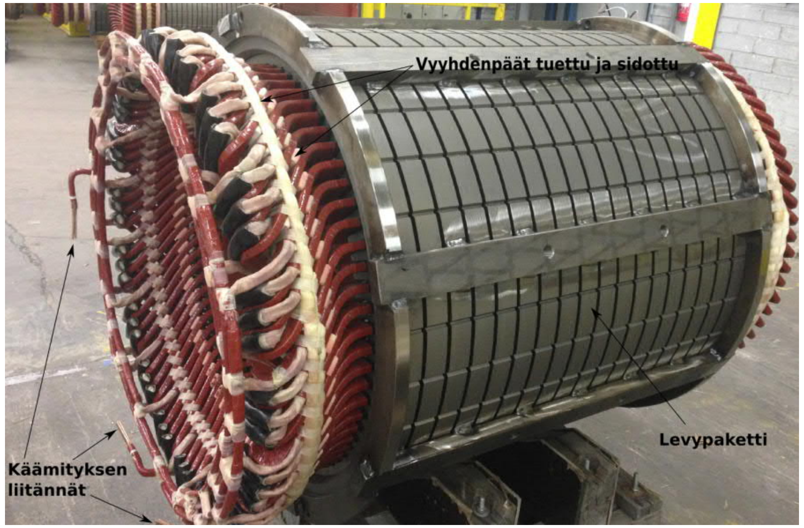
Main insulator

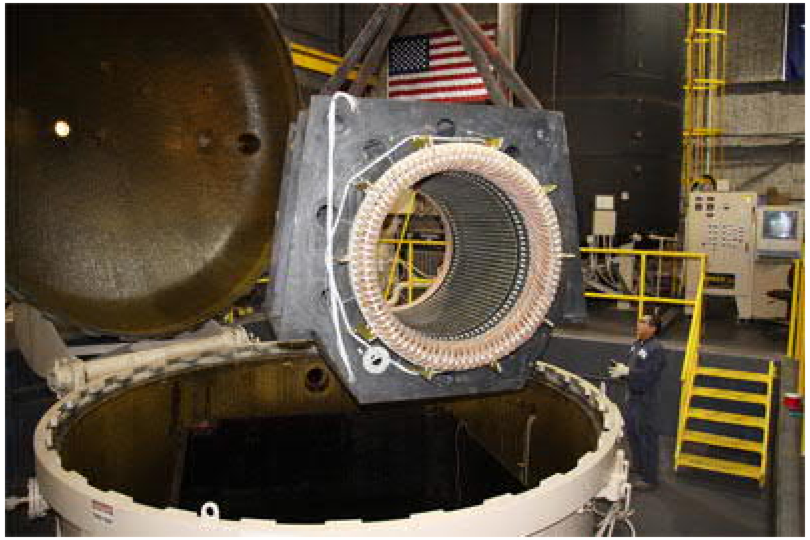
Conductor

Insulation system of electrical machines

- Insulation is needed at different locations:
  - between conductor /coils and earth (phase-to-earth)
  - between conductor /coils of different phases (phase-to-phase)
  - between turns in a coil (inter-turn)
  - between the coils of the same phase (inter-coil)







Insulation classes according to IEC

- Class A 105 ^{o}C:
  - Impregnated paper, cotton, silk, natural rubber, polyvinyl chloride, plus nylon.
- Class B 130 ^{o}C:
  - Mica, fiberglass (alkali free alumino borosilicate), bituminized asbestos, Bakelite, polyester enamel.
- Class F 155 ^{o}C:
  - As class B but with alkyd and epoxy based resins, polyurethane.
- Class H 180 ^{o}C:
  - As class B with silicone resin binder, silicone rubber, aromatic polyamide (nomex paper and fiber), polyamide film (enamel, varnish and film) and estermide enamel.
- Insulation available in different forms too:
  - Tapes, rolls, sleeves, paper, cloth, and different kinds of varnishes

Electric requirements on insulation

- Insulation should withstand electrical stress
  - high breakdown voltage
  - long time performance
  - low partial discharges (minimum voids)
  - very small leakage currents (both inside and on the surface)

$$L = C\left(E - E_0\right)^{-m}$$

- Electric stress might be the result of overvoltage due to
  - On-off switching of voltage sources
  - Lightening
  - Voltage pulses, e.g., due to PWM frequency converter
- Most of insulation systems are designed for nominal voltage, but they survive short time overvoltage

Insulation design for high voltage electrical machines

$$U_{pick} = 4U_n + 5\,\mathrm{kV}$$

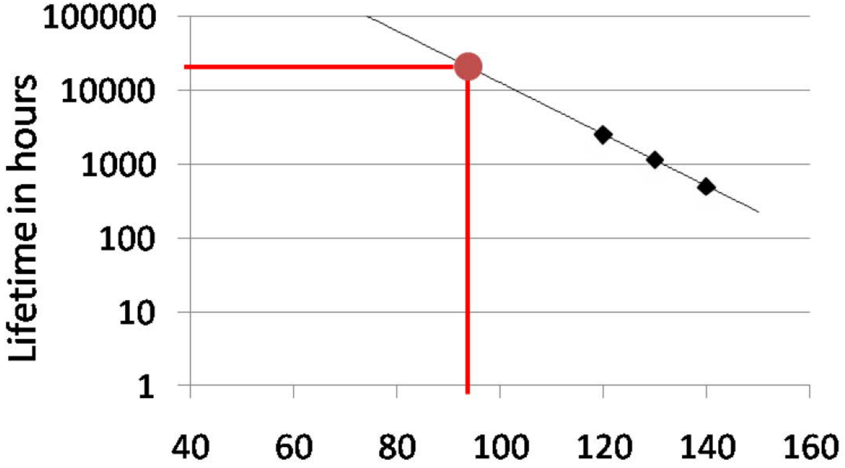
Nominal voltage (rms)	Overvoltage pick value	Waveform
6 kV	29 kV	1.2/50 μs
10 kV	45 kV	1.2/50 μs

(front time/ decay time to half value)

Thermal requirements on insulation

- Insulation systems should withstand different kind of thermal stresses
  - long time performance
    - 20 000 hours tests or equivalent
    - aging of insulations and degradation of material
    - thermal index for a single material and thermal class for insulation system

$$L = Ce^{\frac{B}{T}}$$



  - Short term temperature rise
    - few hours withstand
    - risk of melting
    - Risk of formation of gas and bubbles
    - Strong shrink or contraction results into cracks and large deformations
    - Carbonization or inflammation, risk of fire
  - Freezing
    - Material became brittle

Mechanical requirements on insulation

- Insulation systems should withstand mechanical stresses
  - High mechanical strength to sustain forces
    - Mechanical forces and handling
    - Magnetic forces on conductors
    - Vibrations

$$N = C\left(\sigma - \sigma_0\right)^{-m}$$

  - Low reduction of mechanical strength with operating temperature
  - High flexibility to accommodate deformation of conducting parts

  - Continuous heating and cooling results in condensation of water
  - Hygroscopic materials absorb water and become vulnerable to leakage currents
    - Can be avoided by using plastic and resin-based insulation materials
    - In some cases, heating systems are built inside the machine to keep it warm when not operated

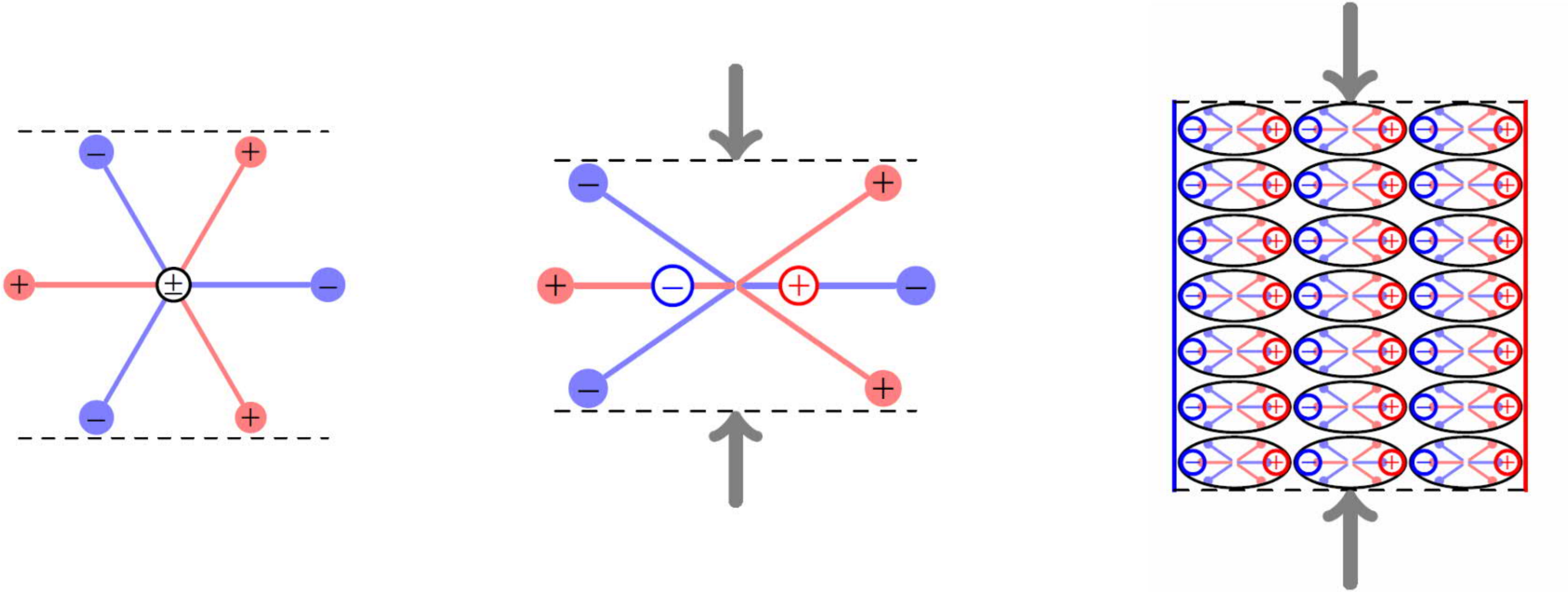
Investigation work 20 min

- Look in internet and find out what does piezoelectricity means and what kind of piezoelectric materials exists (10 min)

- List of piezoelectric materials:

Piezoelectricity

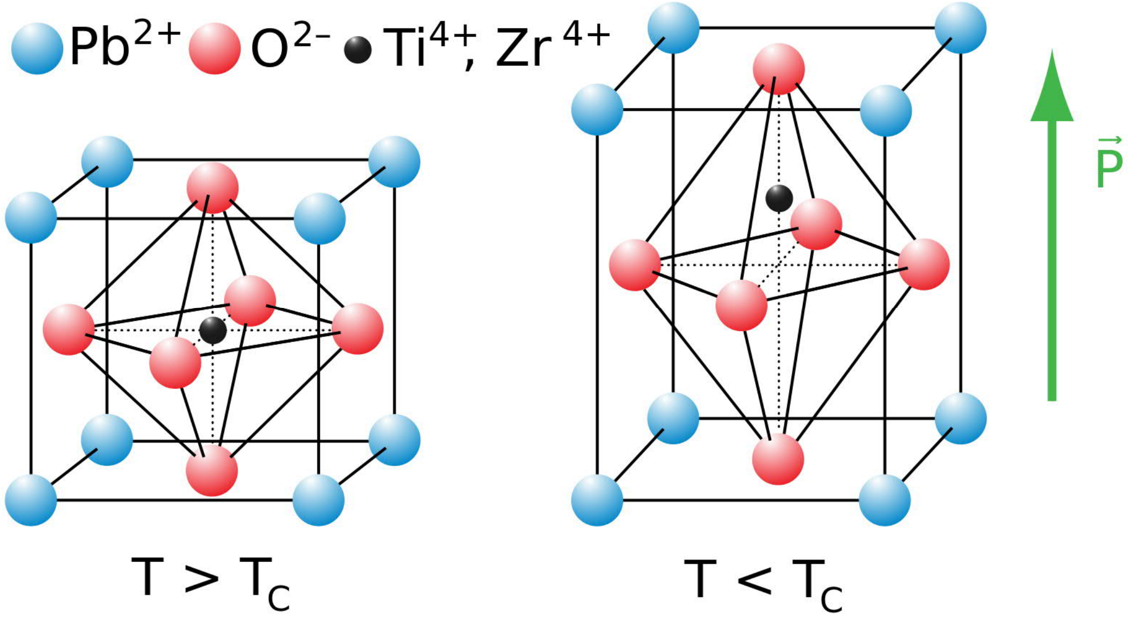
- Piezoelectricity is the ability of some materials to generate electric charges in response to a mechanical stress
    - Electromechanical reversible effect
- Direct effect: charge generation due to mechanical stress
- Inverse effect: deformation under external electric field



Piezoelectricity

- Natural piezoelectric materials
  - Crystals without symmetry center, 20 groups
  - Insulating materials
  - Ferroelectric and materials with permanent dipoles
  - Quarz, Topaz, Cane sugar

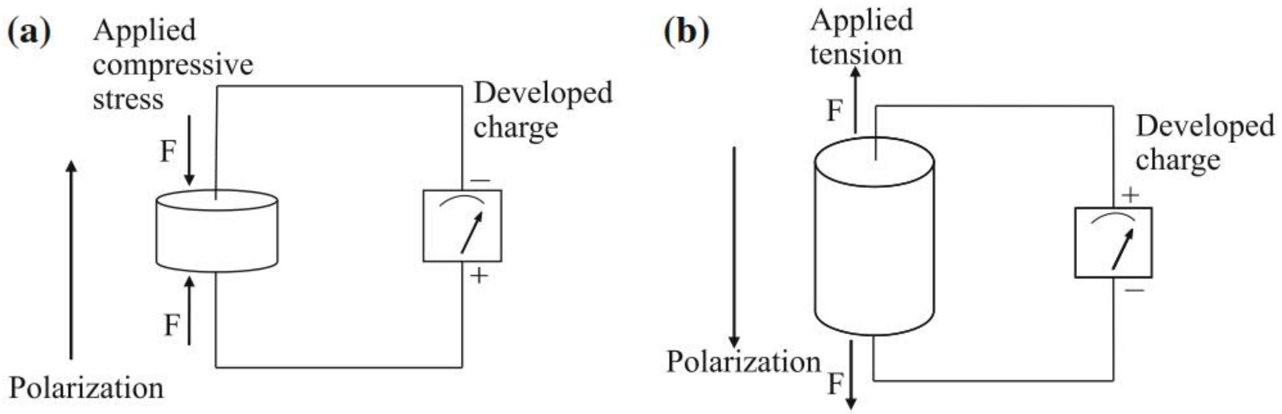
- Artificial piezoelectric materials
  - Several crystals
  - Gallium orthophosphate (GaPO4)
  - Langasite (La3Ga5SiO14)
  - Several ceramics
  - Barium titanate(BaTiO3)
  - Lead zirconate titanate (Pb[ZrxTi1−x]O3 0<x<1); PZT is most used today
  - Lithium niobate (LiNbO3)

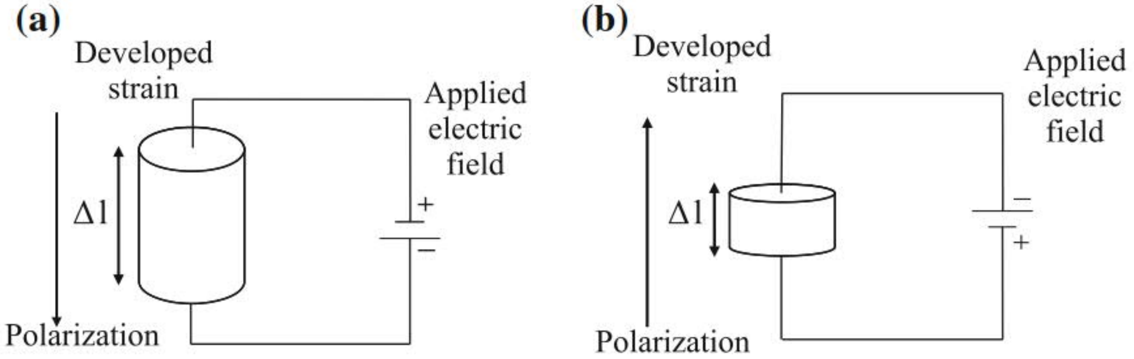


https://upload.wikimedia.org/wikipedia/commons/thumb/9/9a/Perovskite.svg/1615px-Perovskite.svg.png

Illustration of piezoelectric behavior

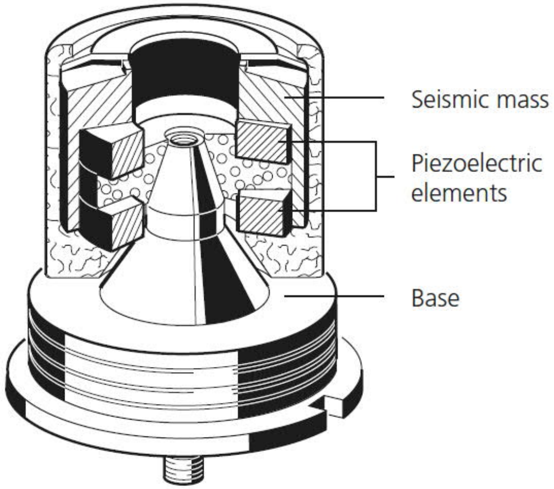
- The sign of stress and charges are respected
- The charges are measured as voltages (integrated charges)

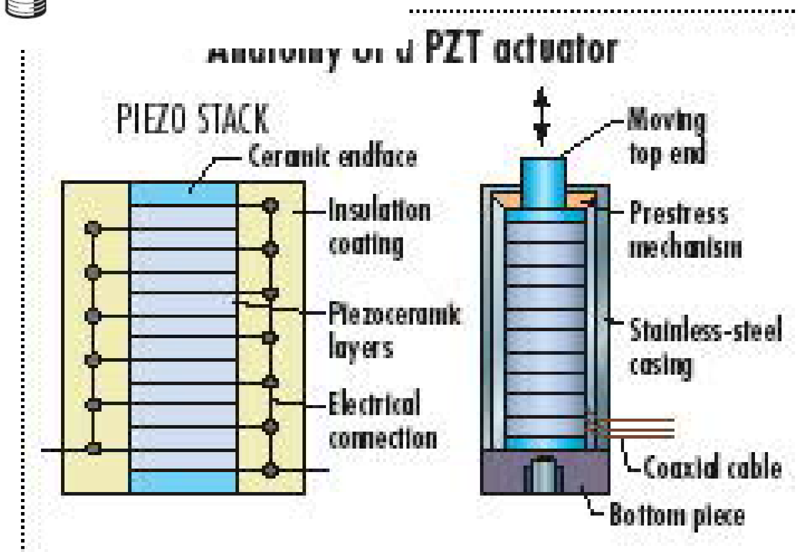




Applications of piezoelectric materials

- Sensor
  - Microphones, Pick-ups
  - Pressure sensor
  - Force sensor
  - Strain gauge
- Actuators
  - Loudspeaker
  - Piezoelectric motors
  - Nano positioning in AFM*, STM*
  - Acousto-optic modulators
  - Valves
- High voltage and power source
  - Lighters ignition
  - Energy harvesting





http://images.machinedesign.com/images/archive/anatomyjpg_00000035120.jpg

*STM: scanning tunneling microscope
*AFM: atomic force microscope

Short theory

- Piezoelectricity is a combination of elastic and electric behavior
- Hooks low of elasticity:

$$S = sT \qquad S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad s = \left[s_{\alpha\beta\lambda\chi} \right] \alpha, \beta, \lambda, \chi = 1..3$$

- Material electric behavior

$$D = \varepsilon E \qquad E = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad \varepsilon = \left[\varepsilon_{ij} \right] i, j = 1..3$$

- Piezoelectric behavior

$$S = s^{\mathrm{elas}} T + d^t E$$

$$D = \varepsilon E + dT$$

T **has the same structure as** ***S***
D **the same structure as** ***E***

- Piezoelectric coefficients:

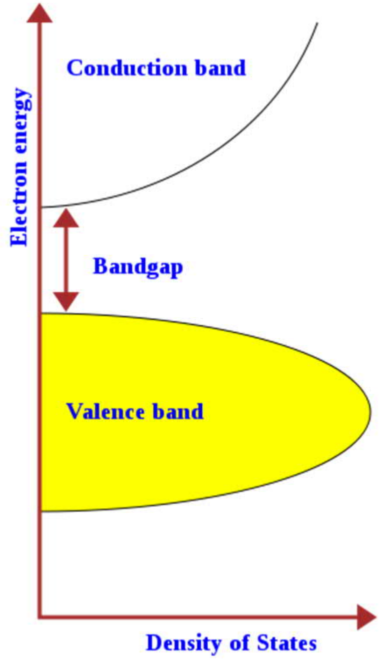
$$d_{ijk} = \frac{\partial S_{ij}}{\partial E_k}$$

$$d_{33} = 250..280 \, [\mathrm{pm/V}]$$

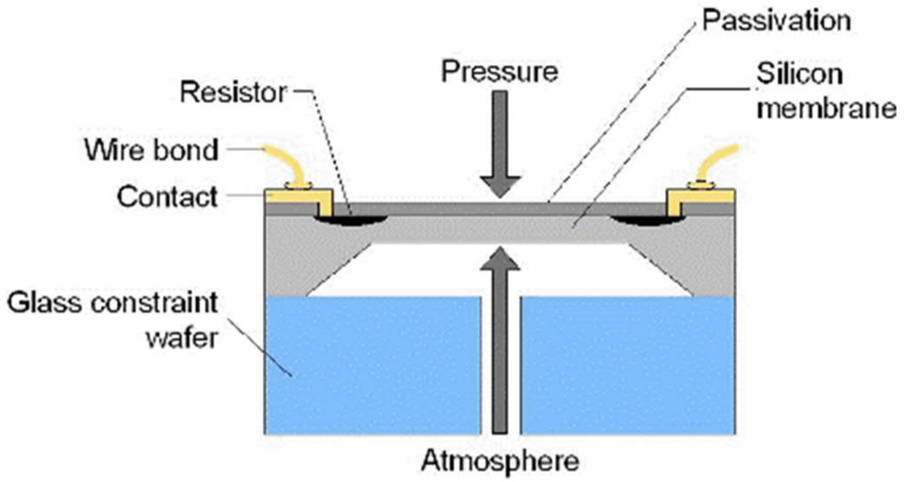
$$\mathrm{d}_{31} = 120..150 \, [\mathrm{pm/V}]$$

Piezoresistive effect

- Change in resistivity due to applied mechanical stress.
- Differs from Piezoelectric effect
  - It changes only resistivity and does not create an electric potential.
- Mainly seen in semiconductors
  - Germanium
  - Single crystal, polycrystalline, and amorphous silicon
  - silicon carbide



- Mechanism
  - Change in inter-atomic spacing affects bandgaps
  - Bandgaps might be shifted
- Usage
  - Strain gauge
  - accelerometers



Electrostriction

- Happens in almost all dielectric materials

- Very strong in some engineering materials
  - lead magnesium niobate (PMN)
  - lead magnesium niobate-lead titanate (PMN-PT)
  - lead lanthanum zirconate titanate (PLZT)
  - Up 0.1% at electric field of 2 MV/m

- Quadratic at low fields and linear at high fields