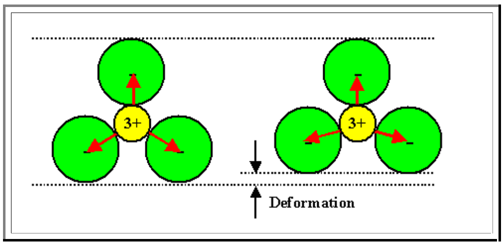
3.6 Special Dielectrics

3.6.1 Piezo Electricity and Related Effects

Piezo Electricity

- The polarization of a material must not necessarily be an effect of electrical fields only; it may come about by other means, too.
  - Most prominent is the *inducement of polarization by mechanical deformation*, which is called *piezo electricity*. The reverse mechanism, the inducement of mechanical deformation by polarization, also falls under this heading.
- The principle of piezo electricity is easy to understand:



  - Let'as consider a crystal with ionic components and some arrangement of ions as shown (in parts) in the picture above. In the undeformed symmetrical arrangement, we have three dipole moments (red arrows) that exactly cancel in vector addition.
  - If we induce some elastic deformation as shown, the **symmetry is broken** and the three dipole moments no longer cancel - we have induced polarization by mechanical deformation.
  - We also realize that symmetry is somehow important. If we were to deform the "crystal" in a direction perpendicular to the drawing plane, nothing with respect to polarization would happen. This tells us:
    - Piezo electricity can be pronounced in single crystals if they are deformed in the "right" direction, while it may be absent or weak in polycrystals with randomly oriented grains.
    - Piezo electricity must be described by a **tensor** of second rank. What this means is that we must consider the full tensor properties of the susceptibility χ or the dielectric constant ϵ_r when dealing with piezoelectricity proper.
  - If one looks more closely at this, it turns out that the crystal symmetry must meet certain conditions. Most important is that it must not have an **inversion center**.
- We won't look into the tensor properties of piezoelectricity but just note that for piezo electric materials we have a general relation between polarization ***P*** and deformation ***e*** of the form

$$P \;=\; \text{const.} \cdot e$$

  - With ***e*** **=** mechanical ***strain*** **=** $\Delta l / l$ = relative change of length. (Strain is usually written as ϵ; but here we use ***e*** to avoid confusion with the dielectric constant).
- In piezo electric materials, mechanical deformation produced polarization, i.e an electrical field inside the material. The reverse then must be true, too:
  - Piezo electrical materials exposed to an electrical field will experience a force and therfore undergo mechanical deformation, i.e. get somewhat shorter or longer.
- So piezo electricity is restricted to crystals with relatively low symmetry (there must be no center of symmetry; i.e. no inversion symmetry) in single crystalline form (or at least strongly textured poly crystals). While that appears to be a rather limiting conditions, piezo electricity nevertheless has major technical uses:
  - Most prominent, perhaps, are the **quartz oscillators**, where suitable (and small) pieces of single crystals of quartz are given a very precisely and purely mechanically defined resonance frequency (as in tuning forks). Crystalline quartz happens to be strongly piezo electric; if it is polarized by an electrical field of the right frequency, it will vibrate vigorously, otherwise it will not respond. This can be used to control frequencies at a very high level of precision. More about quartz oscillators (eventually) in the link
  - Probably just as prominent by now, although a rather recent big break-through, are **fuel injectors** for advanced ("common rail") Diesel engines. Makes for more fuel efficient and clean engines and is thus a good thing. More to that in this link.The materials of choice for this mass application is ***PZT***, Lead zirconate titanate. This link gives a short description.
  - While for fuel injectors relatively large mechanical displacements are needed, the piezoelectric effect can just as well be used for precisely controlled very small movements in the order of fractions of **nm** to **µm**, as it is, e.g., needed for the scanning tunnelling microscope.

- There are many more applications (consult the links from above), e.g. for
  - Microphones.
  - Ultrasound generators.
  - Surface acoustic wave filters (**SAW**).
  - Sensors (e.g. for pressure or length).

Electrostriction

- An effect that must be kept separate from the piezo electricity is **electrostriction**, where again mechanical deformation leads to polarization.
  - It is an effect observed in many material, but usually much weaker than the piezo electric effect. Much simplified, the effect results if dipoles induced by electronic polarization are not exactly in field direction (e.g. in covalent bonds) and then experience a mechanical force (leading to deformation) that tries to rotate them more into the field direction.
  - The deformation **e** in this case depends on the *square of the electrical field* because the field induces the dipoles *and* acts on them. We have

$$e = \frac{\Delta l}{l} = \text{const} \cdot E^2$$

  - Because of the quadratic dependence, the sign of the field does not matter (in contrast to piezo electricity).
  - There is *no* inverse effect - a deformation does not produce an electric field.
- Electrostriction can be used to produce extremely small deformations in a controlled way; but it is not really much used.

Pyro Electricity

- Polarization can also be induced by sudden changes in the temperature, this effect is called **pyro electricity**; it is most notably found in natural **tourmalin** crystals.
  - The effect comes about because pyro electrical crystals are naturally polarized on surfaces, but this polarization is compensated by mobile ions in a "dirt" skin, so that no net polarization is observed.
  - Changes in temperature change the natural polarization, but because the compensation process may take a rather long time, an outside polarization is observed for some time.

Electrets

- The word "electret" is a combination of *electr*icity and magn*et* - and that tells it all:
  - Electrets are the electrical analog of (permanent) magnets: Materials that have a permanent macroscopic polarization or a permanent charge. Ferroelectric materials (see next sub-chapter) might be considered to be a sub-species of electrets with a permanent polarization that is "felt" if the internal domains do not cancel each other.
  - Electrets that contain surplus charge that is not easily lost (like the charge on your hair after brushing it on dry days) are mostly polymers, like fluoropolymers or polyproylene.
- Electrets have been a kind of scientific curiosity since the early 18th century (when people did a lot of rubbing things to generate electricity), their name was coined in 1885 by Oliver **Heaviside**
  - Lately, however, they were put to work. Cheap electret microphones are now quite ubiquitous; electrostatic filters and copy machines might employ electrets, too.
  - It is a safe bet that some of the "exotic" materials mentioned in this sub-chapter 3.6 (and some materials not even mentioned or maybe not yet discovered) will be turned into products within *your* career as an engineer, dear student!