Summary:

- On an atomic level, a unit cell will have a center of positive charge, and a center of negative charge. If these two are not co-located, the unit cell can be electrically defined as having a *dipole*. A dipole is described as two charges of equal magnitude and opposite charge being separated by a distance.
- As a dipole changes, its electric field also changes. All dipoles within such a solid will interact with each other. When a majority of dipoles within a solid are aligned with each other, the bulk material will exhibit charges developed on surfaces of the material resulting from the changing dipoles.
- If the dipoles are changed because the material is deformed (squeezed), it is said to be *piezoelectric*.
- If the dipoles are changed due to thermal expansion of the material (not under stress), it is said to be *pyroelectric*.
- All pyroelectric material is piezoelectric, but not all piezoelectric material is pyroelectric.
- Non-pyroelectric material that is piezoelectric relies on the property that in an unstressed condition, the centers of charge are indeed co-located. No dipole exists until the material is stressed (squeezed). With thermal expansion, the dimensions of the unit cell change proportionally with temperature, but since the centers of charge distance is zero, it remains zero at temperature and does not exhibit pyroelectric charge generation.
- Materials that are pyroelectric will have a dipole in an unstressed condition. They are said to have *spontaneous polarization*.
- Material that generates piezoelectric output from being stressed (squeezed) represents the phenomenon of the *primary piezoelectric effect*. If one surface develops some magnitude of positive charge, the opposite surface develops an equal magnitude of negative charge.
- Piezoelectric materials will have a characteristic charge coefficient based on the material and method of manufacture. For the primary piezoelectric effect, the coefficient units are *C/N*. That is, for every Newton of force the material will develop some amount of charge. For the secondary piezoelectric effect, the coefficient units are *m/V*. For every Volt applied, the material will deform a certain distance (meters).
- For any piezoelectric material, the charge coefficient value is the same. For example, if a material has a charge coefficient of 100pC/N, it will have a coefficient of 100pm/V. This is because the units are identical. This is easily derived from the equation of the force of a charge in an electric field. $F=qE$. This quickly breaks down to C/N=m/V.
- The most commonly used piezoelectric materials are in the form of *crystals*, *ceramics*, and *polymers*.
- Crystals can be found in nature, and also manufactured. For a crystal, each unit cell is an exact replica of those around it, and all the dipoles of the material are aligned. To create a piezoelectric element for a sensor, it is imperative to cut it relative to a precise orientation of the crystal matrix.

- Piezoelectric ceramics can be formed into a variety of specific shapes, fired and then polarized. The polarization operation gets the dipoles to align as best as practical. They will never be fully aligned as with a crystal structure. Appropriate ceramic piezoelectric materials can have their dipoles aligned and become polarized by an external electric. The polarization will be stable enough to serve as a reliable sensor, but it can also be erased when taken to a high temperature, notes as its *Curie temperature* above which, the ceramic no longer can possess piezoelectric properties. Below the Curie temperature, it can be re-polarized. Material having this property of being able to create and eliminate a dipole is said to be *ferroelectric*. This term is analogous to ferromagnetism where magnetic properties of some metals can be instilled and also removed.
- *Piezoelectric polymers* exist that are just what it says. It uses long polymer strands that can rotate in the presence of an electric field to polarize the material.

The Details:

This is either the properties of a piezoelectric crystal, or at the hand of a manufacturing company. Some material does not present a dipole until it is stressed. Others have them inherent to the material, and it is said they have *spontaneous polarization*

Common piezoelectric material can be in the form of a crystal, a manufactured ceramic, and polymers.

All materials deform with applied stress, and there's nothing magic about the dipole, it just goes along for the ride with the rest of the structure.

Apply a force to it (squeeze it), and the piezoelectric material generates an electrical signal. This is called the '*primary piezoelectric effect*'. An electric signal can be detected as electric charges develop on certain surfaces of the piezoelectric material. This signal can be used to determine the degree to which the piezoelectric element is being deformed. This action is the literal etymology of 'piezoelectric', where "piezo" is the Greek term for 'squeeze', and "electricity" is the common term for 'electricity'. When properly configured into a housing structure, this piezoelectric material forms the basis of effective accelerometers, pressure transducers and force transducers.

Apply voltage and it the piezoelectric material changes shape. This is called the 'secondary piezoelectric effect'. Apply a constant voltage, and the piezoelectric material stays deformed. This property is used to deform telescope mirrors and fine-tune its focus. Extremely small deformations can be precisely created and controlled. Apply a varying frequency signal will cause the material to vibrate, and if the oscillation has the proper frequency range it will produce sound, or ultra-sound waves.

Both the primary and secondary effects of piezoelectric material are rooted in the same basic property, the fundamental unit cell develops an asymmetry of charge. This means that the center of all the positive charges and the center of all negative charges of this unit cell are separated by some distance. Examples are shown in following paragraphs. Technically, the condition where equal magnitude charges of opposite polarity are separated, a '*dipole*' is formed. Placing the material under stress can change the distance between the charges, forming a change to its electric field, an effect that can be straightforward to measure. Conversely, subjecting the material to an external electric field will cause the dipole distance to change, causing the piezoelectric material to deform. In a nutshell, that is what piezoelectric applications are all about. It is all about the dipole.

For the direct piezoelectric effect, the charge generated is directly proportional to the force applied, and the unit pertinent to this constant is pC/N. Based on the specific material properties (many different materials with many different properties). For example, assume a certain material has a charge coefficient of 100pC/N. For every Newton of force applied, the output charge will be 100pC.

For the indirect piezoelectric effect, the constant has units of meters/volt. Assume a material has a charge coefficient of 100pm/V. Then for every Volt applied, the displacement change will be 100picometers.

It is enlightening to realize that the coefficients are truly identical. It can be readily shown that a C/N is equivalent to a m/V. The material's coefficient applies to both the primary and secondary piezoelectric effect. The key to this is to realize that the force acting on a charge in an electric field has the equation

$F=qE$; or $F=q\ V/m$, which can be expressed as $q/F = V/m$, or $C/N = m/V$. Voilà.

When used to generate electricity, the charges generated are bound (confined) to the ceramic, and are not free to flow in a circuit (for the most part). If you want to have flowing electrons with mechanical stimulus, then a magnet moving in a coil is much, much better. Harvesting current from piezoelectric material is not very efficient, but it is definitely the study of significant research. Think of the piezoelectric material as being comprised of atomic-scale dipoles, with each dipole's change in electric field influencing its neighbors. It is an army of tiny dipole soldiers acting in lock-step.

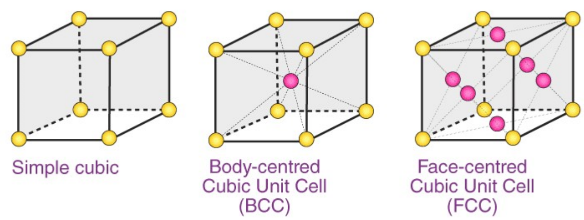
If one side of the piezoelectric material is generating an amount of positive charge, then the opposing side will develop the same amount of negative charge. Think of this like rubbing a rubber balloon on your hair and sticking it to a wall. It is the presence of charge on the surface of the rubber balloon that induces opposite (and attractive) charges on the wall which makes the balloon stick. Over time, those charges dissipate and the balloon falls from the wall. Piezoelectric sensors operate in similar fashion. The developed charges really don't go anywhere outside the piezoelectric element. They form throughout the bulk of the material when stressed and are detected on selected surface for measurement use, then eventually dissipate back into the piezoelectric material after the stress remains stable.

Think of a bucket of water gently sloshing back and forth. As the water level on one side of the bucket gets higher than the average water level, the level on the opposite side gets lower. Shortly after, the levels reverse. A gentle excitation force makes for relative low peak water levels, and with no excitation force the water level evens out and the water level on both sides of the bucket are the same. The bucket always contains the same amount of water, but the water just sloshes back and forth. This is similar to a piezoelectric element. With piezoelectric sensors, electronics can detect the amount of charge on specific surfaces, and make a useful electrical signal.

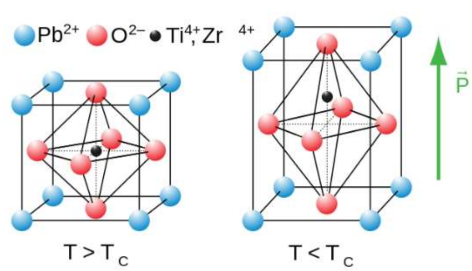
Conversely, apply an electric field across the piezoelectric and it will deform. In this secondary piezoelectric effect, the charges do not dissipate since they are provided and the material remains deformed proportional to the applied signal, whether varying or constant over time.

Now let's build a mental model of one type of a piezoelectric element, one step at a time.

Consider a cubic unit cell. Place ions (make the + charged) at the corners makes it a simple cubic unit cell. If we add ions (make them – charged) to the faces makes it a face-centered cubic unit cell. If we added an ion (+ charged) to the center, it becomes a body-centered cubic unit cell. But let's do all of them. Positive ions at the 8 corners, negative ions at the 6 faces, and one positive ion in the center.



This type of structure is called a '*Perovskite*'. Perovskite was discovered in 1839 Russia and named after minerologist Lev Perovski. The discovered mineral was calcium titanate. Calcium titanate is a symmetric crystal structure, and does not exhibit piezoelectric properties. But there are other Perovskites that definitely do. One of the first examples studied was barium titanate, a piezoelectric material. For our example, place lead ions in the corner, oxygen ions at the faces, and a zircon ion in the center. Here is where it gets very interesting. Consider that up to a certain temperature, the space for the center zircon ion is a larger space than it needs, and it has room to move around. It is not pinned to the center, not just yet. Now consider that this positive ion in the center will be attracted to one of the six negative ions at the faces, and will migrate to one of those faces and remain stable (for the most part). In the graphic above, the right figure shows that the center ion has moved towards the upper oxygen ion. But it could have been happy in either of the other 5 locations.

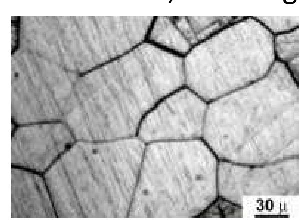


Once the center ion has found its home, realize that the center of negative charge is in the center of the unit cell, and the center of positive charge has shifted upwards from the center (as shown in the diagram above on the right side). We now have our dipole, and this cell now possesses piezoelectric properties. Not that when this dipole is in existence, the shape of the unit cell grows in the direction of the center ion displacement. This can be said that the shape changes from cubic to tetragonal… a box with a square base, and a height a little longer than a side of the cube base.

Think of a jack (a really, really tiny jack), and imagine that the center of the jack is located at the center of the unit cube, and that the zircon ion will be placed at one of the 6 ends of this jack. Each end of the jack will be pointing towards one of the oxygen ions in the face of our unit cube. This jack represents the space where the zircon ion is allowed to locate. As the material heats up, the atoms will 'jiggle' as they get more excited with increased temperature. This essentially reduces the dimensions of the jack, and further the limiting of the allowed location for the center ion. At a certain temperature, the 'wiggle room' for the center ion is reduced to zero, the dimensions of this jack are reduced to zero, and the zircon ion is locked into the center of the unit cell. This cell no longer possesses piezoelectric properties. The temperature at which this happens is referred to as the '*Curie temperature*'.

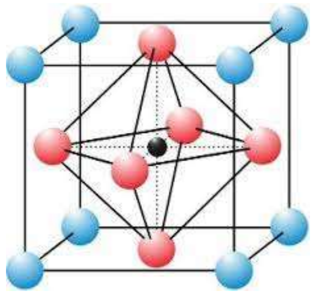
Let's recap some. Regarding Perovskite material, below the Curie temperature, the cell will sport a dipole and have piezoelectric properties. The direction of the dipole is considered random at this point.

It turns out that a blend of lead zirconate crystals and lead titanate crystals are quite powerful in the piezoelectric industry. This marriage happens by creating oxide powders of each, blending and sintering them together as a ceramic. The material is composed of small crystals, on the order of a few microns. Each of these grains have unit cells oriented in the same direction, but each grain generally has a random orientation compared to it's adjacent neighbors.



In order for the piezoelectric effect to arise, there needs to be a dipole. This will be the condition where a cell's center of positive charge is separated from its center of negative charge.

There are some materials that have a dipole moment in an unstressed condition. These are said to have '*spontaneous polarization*'. Other materials do not have spontaneous polarization, but do develop polarization when stressed (squeezed). Quartz is a naturally occurring example of a piezoelectric material with no spontaneous polarization, and tourmaline is a natural example of a piezoelectric material that does exhibit spontaneous polarization. The difference between these two becomes very interesting and important.



The piezoelectric effect arises by an asymmetry within the atomic structure, or unit cell. Imagine a unit cell in the shape of a cube with atoms of positive valence in the corners (8 corners). Then place atoms with negative valence into each of the six faces. This forms a body-centered-cubic (BCC) structure. In this configuration, the center of positive charge is at the exact center of the cube, as is the center of negative charge. This unit cell is very symmetric. Now consider inserting another atom with positive valence into the center of this BCC structure. In this model, there's plenty of space for this atom to fit, and actually has some 'wiggle room'. It is not stable in the exact center of this unit cell, and this structure will become more stable when this center atom shifts slightly towards one of the negative atoms of the 6 faces. This unit cell then has piezoelectric properties, with the center positive atom offset a little bit from the center. This configuration, shown in the adjacent image, is called a Perovskite structure. As an example, consider the blue atoms to be lead (positive valence), the red atoms to be oxygen (negative valence) and the black atom (positive valence) to be zircon, or titanium. Once the center atom shifts a bit, this unit cell changes its shape and becomes slightly longer in the direction of the shifted center atom. This unit cell with a shifted center atoms makes the center of positive charge offset from the center of negative charge. As this atomic sized cube is stretched or compressed, the distance of this offset changes. This is the basis of the piezoelectric effect. The existence of a separation distance between the center of positive charge and the center of negative charge is called a *dipole*.

In some piezoelectric material, this dipole does not exist until the material is stressed. In the box model above, this would happen when the center (negatively charged) atom is located at the center of the cube, as is the center of positive charge (the average location of the atoms in the corners of the cube). There is no separation between the two centers of charge. They are co-located. There is no dipole. Now imagine that when this cube is stressed, the center negative atom moves closer to one of the 6 surfaces of the cube, away from the center. This mental model we have just created is that of a piezoelectric unit cell. The more force applied, the further the negative atom strays from the center. When the stress is removed, it returns to the center of the unit cell.

A naturally occurring example of this type is quartz. In an unstressed condition, there is no dipole, the centers of positive and negative charges are co-located in the unit cell. In other materials the displacement is present even in an unstressed condition. A naturally occurring example of this type is tourmaline. This is a very important difference. Consider the proportions of these two materials under the condition of changing temperature. Consider that for uniform heating, generally all dimensions of the cell generally change proportionally. The dimensions of the unit cell will increase with increasing temperature. And the dipole moment also changes with temperature. If the initial dipole moment is zero (quartz), then it remains zero at other temperatures as well. For tourmaline, the charge separation will increase with increasing temperature. An increase in the dipole moment caused by temperature change will have the same result as an increase in the dipole moment caused by physical stress. The electrical output effects will be indistinguishable. This type of material is called 'pyroelectric'. It generates charge output when subjected to temperature changes. All pyroelectric materials are piezoelectric, but not all piezoelectric materials are pyroelectric. For most piezoelectric sensor applications (accelerometers, pressure transducers, force transducers), the pyroelectric effect is most annoying and undesired.

Realize that naturally occurring piezoelectric materials generally have somewhat low (but often useful) reaction coefficients when 'squeezed'. During World War II, there were intense and desperate programs to enhance technology to shorten the war. In England, the piezoelectric effect was a technology being rapidly explored and understood. It quickly led to the development of sonar. This effort also led to the development of man-made materials with significantly enhanced properties. Most of these are ceramic based. A very common type is a mixture of lead zirconate material and lead titanate. When processed in the right proportions, the final piezoelectric product has several advantageous properties and as such is very common in commercial use. This material has a few different names (for the same thing) and can be noted as lead zirconate – lead titanate, lead zirconate-titanate, or simply PZT. Sensor manufacturing companies will likely have their own 'brand' and proprietary recipe. There are many other man-made piezoelectric materials that are useful for specific designs, such as for high temperature applications. PZT is an example of an almost cubic structure, with positively charged lead atoms at the corners. Once the ceramic is fired, the lead is bound into the molecular structure, and not free to roam around into our fingertips and lungs. The center atom is negatively charged and is either titanium or zircon. It will find a home very slightly offset from the center, in the direction of one of the faces of the unit cell… so there are 6 possible spots for it to go. As the ceramic is heated, the atoms jiggle with more energy. At a certain temperature, the available 'slop' for the center atom to go closes up. At and above this temperature, the negative atom is pinned into the geometric center, and piezoelectricity is no longer an option. This temperature is called the *Curie Temperature*. Operating a ceramic based piezoelectric sensor anywhere near the Curie Temperature will degrade or possibly eliminate the piezoelectric effect.

Piezoelectric ceramics have a major advantage in that they can be pressed and fired to almost any shape desired. They could be made into coffee mugs if desired. Very expensive coffee mugs. Considering PZT as an example, a basic shape is formed (maybe a disk, a tube or a plate) but after shaping and firing, the material has no piezoelectric properties. It is necessary to place this element into an electric field in order to induce the separation of charges to all be oriented in a desired direction (polarization). In reality, they don't all align, but enough of them do to make the element useful. Normally, a very high electric field is applied across electrodes placed on specific surfaces of the ceramic element. This usually happens in a high dielectric oil at a high temperature to prevent sparking. The oil serves to keep the electric field from sparking, and the elevated temperature makes it easier to polarize the ceramic. After completion of that process, the material exhibits piezoelectric properties. These piezoelectric properties tend to degrade over time and should stabilize at a certain polarization level.

There are naturally occurring piezoelectric crystals. Examples are quartz, tourmaline

Take a cell structure of a crystal which exhibits dipole properties… and there you have a piezoelectric element. That is exactly what a piezoelectric is. There are some crystals which form in nature having piezoelectric properties. Quartz, tourmaline, cane sugar, topaz, bone and Rochelle salt are examples. Rochelle salt was used to observe and quantify the piezoelectric effect in its early phase. Tourmaline and quartz are commonly used in today's applications.

** work in progress… much more to come**

We plan to add more content, and create graphics to add to the text content.

Thanks for your patience!