# Electroceramics

**Prof. Ashish Garg**
**Department of Materials Science and Engineering**
**Indian Institute of Technology, Kanpur**

## Lecture - 30

Again, we start a new lecture. We will just go through the last lecture and its contents and then we will start the new topic. Basically, this module is about the non-linear dielectrics. And, we started our discussion with the general discussion on dielectric materials, non-linear dielectric materials and how they can be distinguished on the basis of crystallography. We found out that, the classes that we are discussing relate to what is called as non-centrosymmetric materials. And, even among non-centrosymmetric materials, you can have variety of constraints.

Starting from that, we have started with ferroelectric materials. And, ferroelectric materials are actually most important of these, because they possess the properties, which are unique. And, other non-linear dielectrics basically are subsets are… Any ferroelectric becomes for instance, piezoelectric and pyroelectric. So, that is why, we started our discussion with ferroelectric. And, a characteristic of ferroelectric materials was that, they undergo a phase transition when cooled or heated. And, this phase transition is typically… When you cool it for instance from a high symmetry phase to a low symmetry phase; and, this is associated with occurrence of ferroelectricity in the low temperature phase. And, this you can see in terms of dielectric constant or susceptibility. And, depending upon how the polarization dielectric constant susceptibility changes, the phase transition can be of first order and second order.

And then, we stumbled across the ferroelectric hysteresis loop. And, in that, we found out how, what happens when we pole a ferroelectric; which means that, when you apply electric field to a ferroelectric material, what happens to its polarization. You come across a hysteresis loop. What is the reason for this hysteresis loop and two nonzero states at zero field? And, this was explained on the basis of domains now. Domain was basically defined as a region of uniform polarization. But, you cannot have a monodomain state, because that is energetically unfavorable state, because then the depolarizing field becomes extremely high. So, based on these constraints of depolarizing field and electrostatic energy, the monodomain state divides itself into multiple domain states. And, the type of domains that you will have is type of domain walls that you will have is determined by the crystallography. But, in general, you have variety of these domain walls, which gives rise to these domains.

Now, what happens at zero field essentially in a ferroelectric is that, you still have some domains oriented in the direction of applied field. And, one of the important things in ferroelectrics is that, when you switch the ferroelectric material or when you pole the ferroelectric material from highest electric field to lowest electric or vice versa – highest and lowest in terms of polarity; minus E to plus E for instance; then, since the domain have to switch back and forth from one orientation to another orientation in these materials, this happens by nucleation in growth. So, whenever you change the field polarity, it is always the new domains, which form by the process of nucleation; and then, they grow into the crystal at the expense of old domains.

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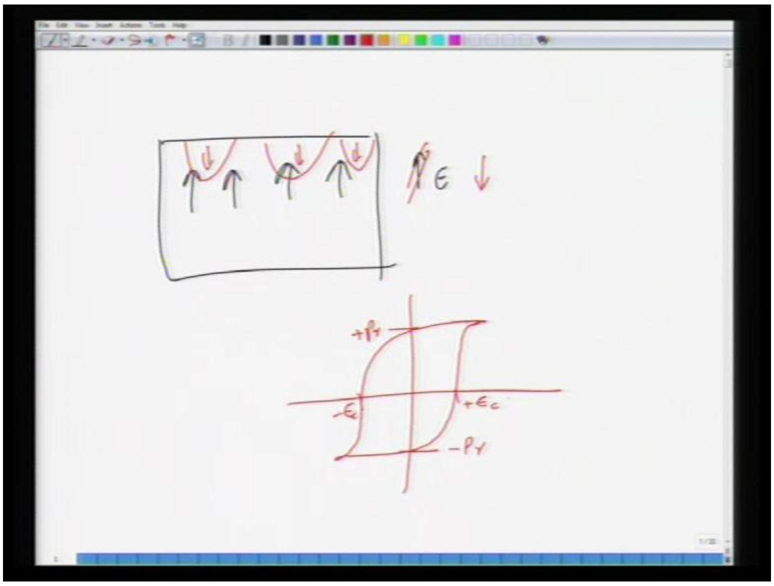

For instance, if you start from a domain state; let us say you start from a domain state like this; which means at this point, the electric field was also like this. When you now reverse the electric field, you go to this direction; then, you have these domains, which are nucleating; and, they are in the opposite direction. And, these domains grow as you reach the saturation field or field required for saturating all these domains. And, that is what results in this classic hysteresis loop. So, you have a hysteresis loop and these are the nonzero states – minus p r and plus p r; and, what you have is minus E c and plus E c. And then, we looked at some other… Then, we looked at an analytical treatment for domain wall width and we found out that this domain wall width is related to the polarization of the crystal as well as the surface energy of the domain wall itself. Naturally, larger the domain wall energy is, larger the domains will be, because you would then require to spend more energy in creating many more domains. As a result, the energy requirement forces the domains to achieve larger size. But, at the same time, if the polarization is larger, then again domain becomes smaller, because larger polarization means the larger depolarizing field and then more driving force towards forming domains. So, it is the competition between these two energies, which forces the domains to achieve a equilibrium configuration of a particular size.

And then, we looked at some other intricacies related to ferroelectric materials followed by the applications. Most touted application for ferroelectric material is the ferroelectric memory and due to inherent advantages as we discussed last time. But, it can also be used as a piezoelectric and pyroelectric. And, that is what they have been used for centuries.

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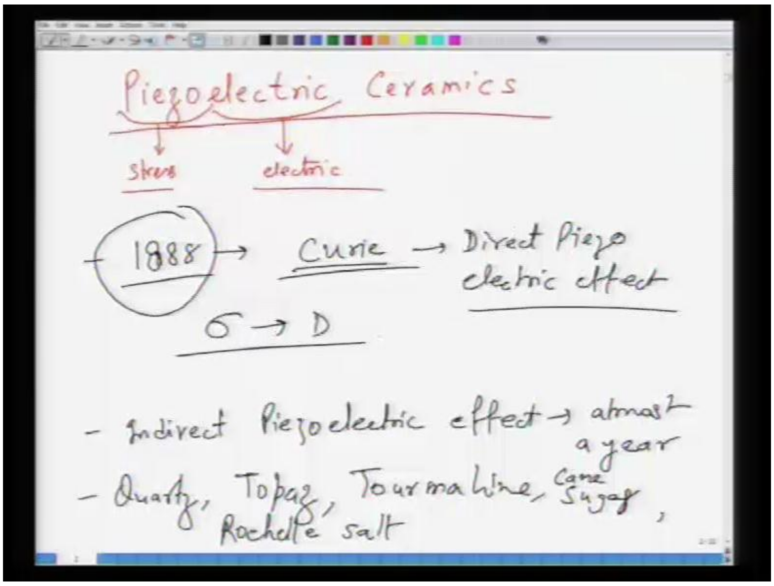


Now, the topic of this lecture is essentially piezoelectric ceramics. Now, piezoelectricity is basically an interesting effect, which is essentially, if you look at two terms: piezo and then electric; piezo relates to stress or force – piezo; and then, electric means you have electric. So, it is coupling of stress and electric field or coupling of mechanical parameters with respect to electrical parameters. And, this is what makes these materials extremely interesting, because when you apply stress to them, you have electrical response; or, vice versa when you apply electrical stimuli, you have a mechanical response. And, this makes them extremely useful for variety of applications as we will see later on.

Now, this effect – piezoelectricity was discovered in 1888; by Curie in 1988. And, this was essentially called as at that time… Or, this was later called on as direct piezoelectric effect. And basically, it was observed as some materials having capability to create an electrical potential in response to the application of mechanical stress. What was observed was that, a stress was applied; and, this gave rise to let us say a polarization or a field or whatever – some electrical response. So, this was observed by Curie in 1988. And, for variety of reasons, this application of a stress leads to the changes in the electrical parameters. So, one of the requirement for this was that material… And, another thing was the… Before we go into the requirements, another – the converse piezoelectric effect… And, soon after this discovery of piezoelectric effect in 1888 by Curie; then, you had this discovery of indirect piezoelectric effect. And, this was happened in almost a year later. So, roughly around 1880s, you had these studies by Curie, which led to direct piezoelectric effect followed by demonstration of indirect piezoelectric effect soon after. And, this was a later studied in a variety of materials. For instance, Quartz; Quartz was one of the early materials, which we have studied. And then, you had Topaz and Tourmaline sugar or rather cane sugar. And then, you had this Rochelle salt. All of these materials were studied in the beginning after the discovery of piezoelectric effect in 1880s by Curie and other scientists.

Now, this piezoelectricity – the moment people knew that, this is an effect, which couples the electrical and mechanical parameters; they soon started realizing variety of applications. And, from the application point of view, the major impetus to the piezoelectric devices came from world war – the requirement of devices in the world war. So, there was a major impetus given in world war 1. For a instance, the sonar devices, which were developed from piezoelectric effect, were first developed during first world war. And then, later on, lot of these applications came in second world war as well. New class of piezoelectric materials was made as a result of the requirement and ongoing research in development in this area. And, that is how piezoelectricity got lot of prominence during the world war. So, what we will do is that, we will first develop a general frame work for piezoelectric materials; what sort of… what is this effect; what sort of material show this effect; and then, later on, what are the types of different defects; and, look at the mathematical expressions on how to express this piezoelectric effect mathematically.

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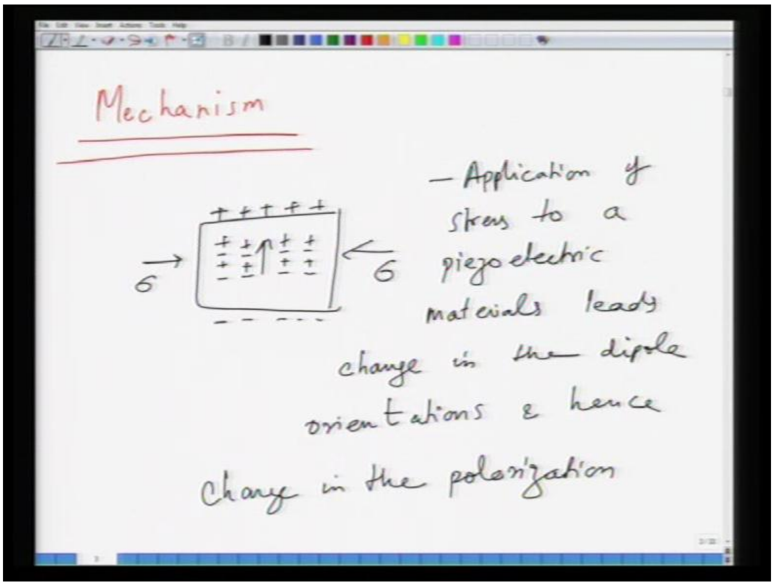


Essentially, if you look at the first topic, which is the mechanism – and, mechanism is essentially, when you apply stress; you take a material; and, when you apply stress to it, the stress essentially produces electric signal. And, this electric signal is in terms of some sort of charges on the surface of the (( )), so some sort of charges on the surface of the piezoelectric material. So, this is basically a polarization by (( )) only surface charge. Mind you, this is this is happening inside the piezoelectric. So, what you have inside the piezoelectric is the displacement of dipoles or the development of polar vectors of dipoles inside the piezoelectric. So, when you apply stress – application of a stress to a piezoelectric material leads to changes in the dipole orientations; and hence, changes in the polarization. So, you should not confuse piezoelectricity with only a surface effect; the effect of applied stress for instance, is felt inside the material. And, as a result of changes occurring inside the material in terms of dipolar arrangement, you have the surface charge, which is being developed. Normally, the field that you may require to apply to these materials can also be very small. It depends upon what is the coupling co-efficient of variety of materials. But for instance, if you apply…

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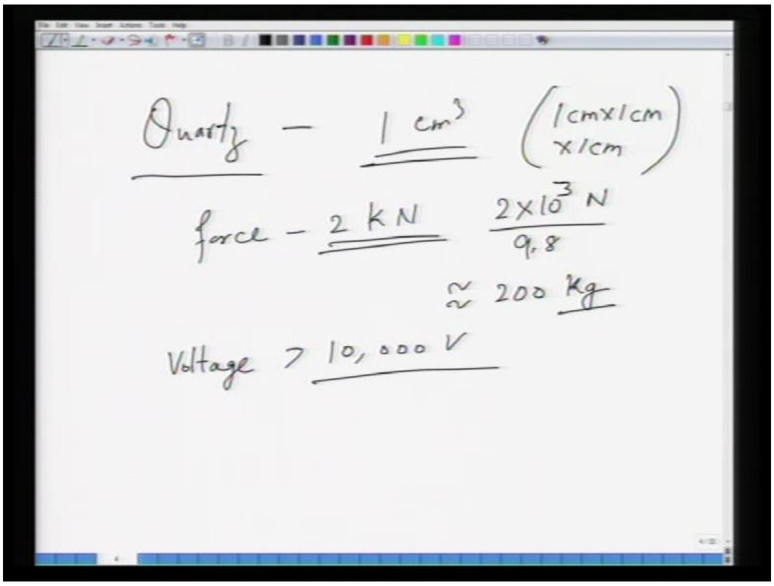


If you take Quartz, you do not require very large field. If you take a Quartz piece of 1 centimeter cube – 1 centimeter cube is essentially 1 centimeter by 1 centimeter by 1 centimeter; that is the simplest way to think of it; and then, when you apply a force for example, of 2 kilo newton. Now, this 2 kilo newton is very small force; I mean if you just divide it by 2 into 10 to power 3 Newton divided by 9.8, which is approximately 200 kg. So, if you apply it just this a smaller force – 200 k g equivalent of force, then what you get is a voltage – it can exceed 10,000 volt.

So, just by applying a force of 2 kilo newton, the voltages of the order of 10 kilo volt can be generated on a small crystal as small as 1 centimeter cube. So, this piezoelectric effect is extremely strong. So, it is not merely a surface effect, it is a bulk effect; it comes from the interaction; when you apply stress, it comes from the interaction of the dipoles with respect to each other and the tendency of them to align along a particular direction during the application of stress. And, the other effect, which is called as converse piezoelectric effect; where, you apply electric field. And, this causes the change in the mechanical dimensions or causes mechanical deformation in the crystal; which we will see in a while.

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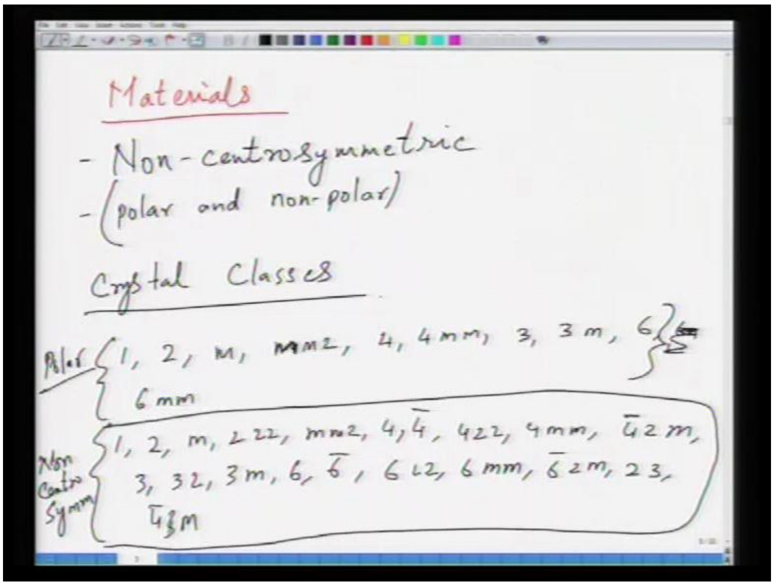


How do you express this effect? First of all, what sort of material do show this effect? Materials – firstly, the material needs to be non-centrosymmetric. And, this we have already discussed in the beginning of the module five. Non-centrosymmetric materials are the materials, which do not have a center of symmetry. So, any material which have a center of symmetry will not be piezoelectric. So, this is the most important requirement for a piezoelectric material. It has to be non-centrosymmetric. On top of that anything happens, that is further additional constraint; but, it has to be non-centrosymmetric in order to exhibit any kind of piezoelectric effect. And, what basically it means is that… And then, you can have polar and non-polar materials as well within this class. Now, whether it is polar or non-polar, will determine whether it is pyroelectric or ferroelectric. But, it does not concern with material being piezoelectric. As long as it is non-centrosymmetric, it is piezoelectric.

The crystal classes, which show this kind of effect are: you have 1, 2, m, mm 2, and then 4, 4 mm, and then 3, 3 m, 6, and then 6 mm. These are all polar groups – polar and non-centrosymmetric. And then, you have 1, 2, m, 2 2 2, mm 2, 4, 4 bar, 4 2 2, 4 mm, bar 4 2 m, and then 3, 3 2, 3 m, 6, 6 bar, 6 2 2, 6 mm, bar 6 2 m, 2 3, and then bar 4 3 m. So, you can count the polar groups, which are 1 2 3 4 5 6 7 8 9 10 – 10 are polar. All these 10 are included in these classes, which are written below. So, these are all non-centrosymmetric. So, these are all piezoelectric in nature. So, polar materials are the materials, which have a spontaneous polarization; which means they have a unique polar axis.

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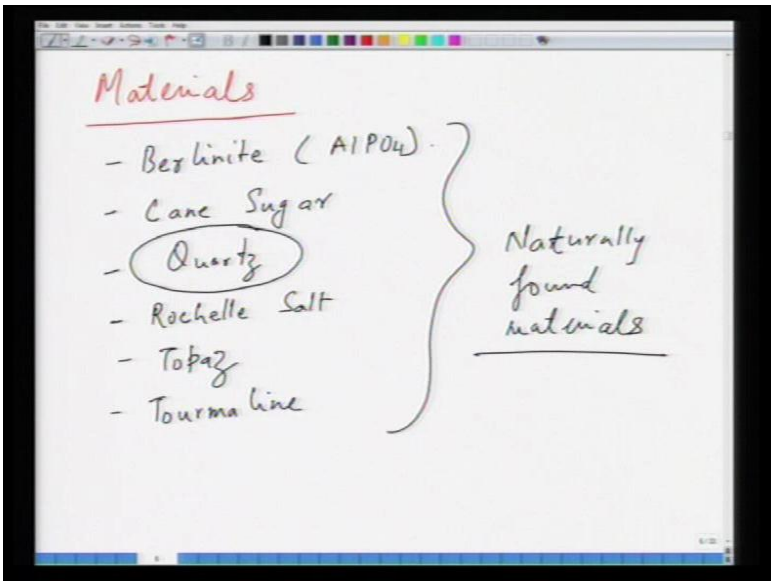


And, the materials, which show this effect, are both natural and artificially made. So, for instance, you have Berlinite. This Berlinite is basically aluminum phosphate. This is the very rarely found phosphate mineral, whose structure is pretty much similar to Quartz; and, this is again piezoelectric material. As I told earlier, cane sugar; and then, you have Quartz, and then you have Rochelle salt, and then you have Topaz, and then you have Tourmaline. All these are naturally found materials. So, nature provides us with materials, which are inherently piezoelectric in nature. And, the most important then being Quartz; Quartz has been used in variety of applications including the watches that we wear.

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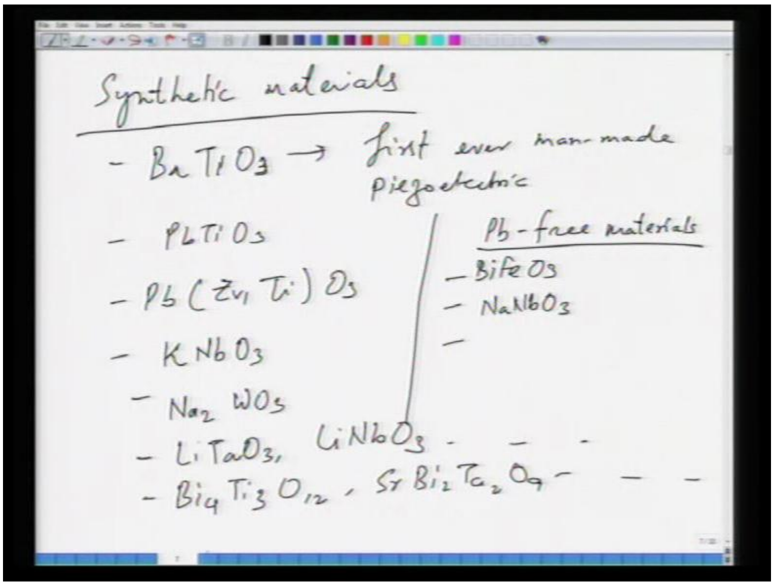


And then, the materials, which are synthetic materials; synthetic materials – you can have starting from barium titanate – a very famous… It is a ferroelectric actually; but, since ferroelectric material is by default piezoelectric, this has been used for piezoelectric. So, this was the first ever man-made piezoelectric, so barium titanate. Then, you have lead titanate; and then, you have lead zirconate titanate – solid solution of lead zirconate and lead titanate; and then, you have potassium niobate; and then, you have sodium tungstate – N a 2 W O 3; and then, you have lithium tantalite, lithium niobate and so on and so forth. This list is very long; you have complex oxides like B i 4, T i 3 O 12, S r B i 2 T a 2 O 9. So, all of these are man-made or synthetic piezoelectric material. You can have many other naturally occurring materials such as, bone is also a piezoelectric; it has some piezoelectric effect. And also, you can have wood, represents a piezoelectric material; you can have silk, which (( )) can have some piezoelectric (( )) But, majority of the piezoelectric materials that we discussed, which are naturally occurring are these. And, in the next slide, basically, these are the synthetic materials of piezoelectric type.

Now, what we will do is that, we will look at now the mathematical expressions, which are used to express the piezoelectric behavior. Before we do that, just a small remark on the previous slide; if you look at here, most of the materials, which have piezoelectric effect tend to contain lead. And, this lead nowadays has been termed by variety of countries as a poisonous material. So, one needs to find alternative to the lead containing materials; which means we need to find lead-free materials. And, there are some lead-free materials. And, those are Pb-free materials; Pb-free materials can be Bi Fe O 3 although it has issues with respect to being used as a piezoelectric. Then, N a N b O 3 – sodium niobate and then sodium potassium niobate, etcetera. So, many of these materials, which do not contain lead are in contention nowadays simply because of the fact that lead is not a very healthy material, healthy element.

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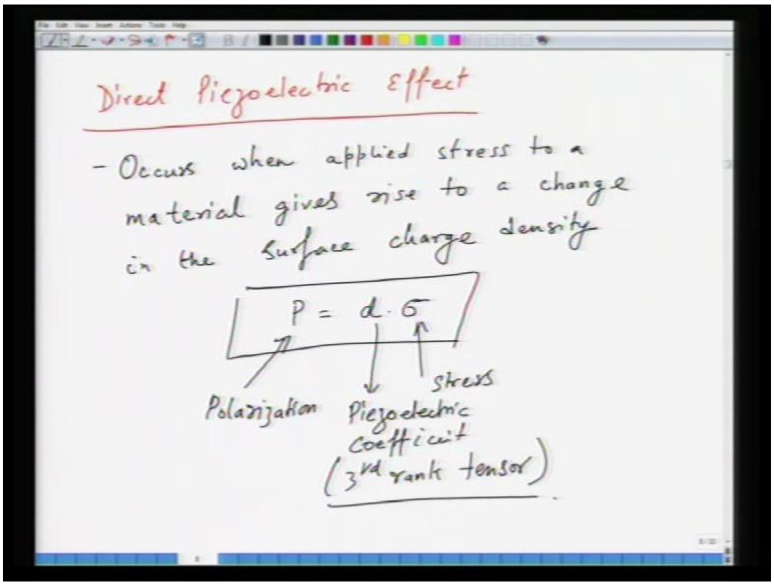


Now, what we will do is that, we will look at the… First, we will look at the direct piezoelectric effect; a little bit more quantitatively, so that we are able to understand it better. So, direct piezoelectric effect occurs when applied stress to a material gives rise to change in the surface charge density or change in the polarization; and, which can be detected as either electric field or potential across the sample. So, essentially, mathematically, what it means is that, P – the polarization is equal to d dot sigma. Now, these have to be explained more correctly in the vector notation; which I will show in a while. This direct effect in the most easiest form is expressed by this equation, P is equal to d dot delta; where, P is polarization; sigma is the stress; and, d naturally is called as the piezoelectric coefficient. And, this is actually a third rank tensor.

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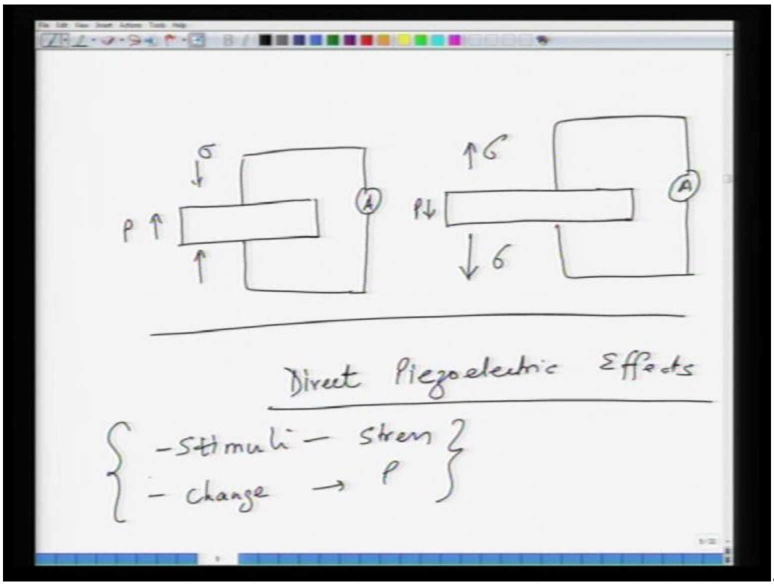


Now, what basically it means is that, pictorially, you have a material; and, when you apply a stress to this material – let us say like this – sigma; then, you have polarization appearing like this. And, when you reverse the magnitude of stress; if you make the stress like this; then, polarization also reverses its direction. So, this is what is direct piezoelectric effect. And essentially, here the stimuli… This is sigma. So, stimuli is stress and change is in polarization or direct recharge density, whatever you may want to call it. So, this is what is direct piezoelectric (( )) in the simplest form.

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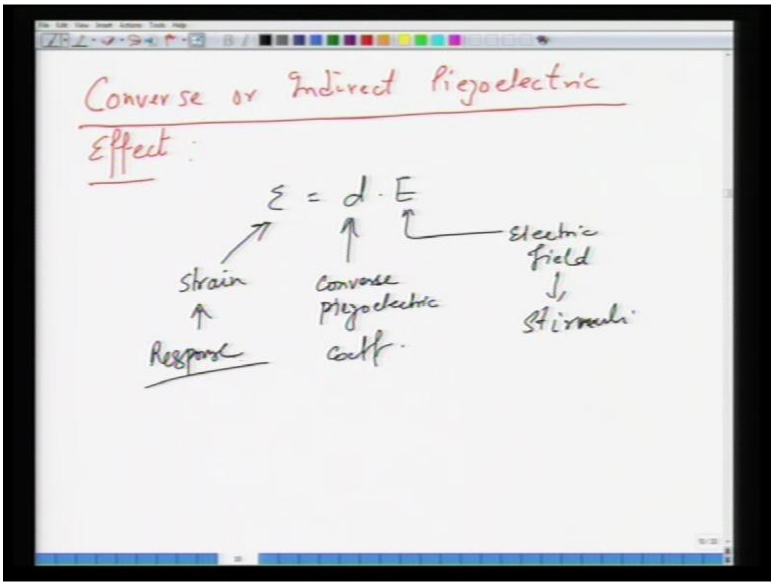

Now, the second effect is converse or indirect piezoelectric effect. Now, in the indirect piezoelectric effect, what happens is; when you apply electric field, you have deformation in the crystal. So, what basically it has is; it is represented by epsilon is equal to E multiplied by d. So, this epsilon is the strain; E is the electric field; and, d is the converse piezoelectric coefficient. Here this electric field acts as a stimuli; and, this strain is the response. So, you can understand the converseness with respect to the previous effect.

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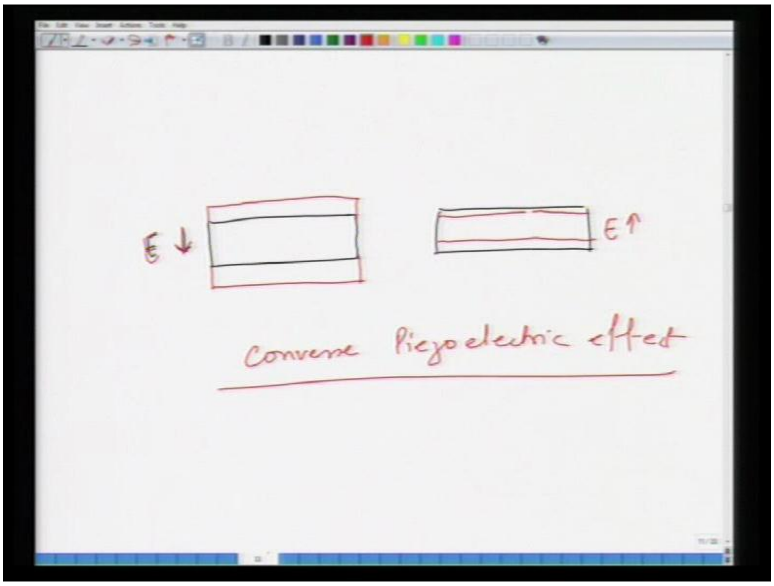


What it basically means is that, you take this crystal; when you apply electric field for instance in this direction; then, it sort of expands. So, this is the new direction. The electric field was in this direction. And, if you change the electric field to other direction; if you reverse the direction of electric field; if I make now electric field in this direction, this will contract. So, this is what is the converse piezoelectric effect. These are the two effects, which are of importance to from the point of view of fundamental understanding. And, what now we will do is that, we will have a look at… Now, these are all… If you look at here in the equations here the stress is a tensor; as a result, d is a tensor, which is the piezoelectric coefficient. Again, here electric field is a vector; strain is a vector. As a result, this is also a vector. So, it can also be expressed in the form of vectorial notation.

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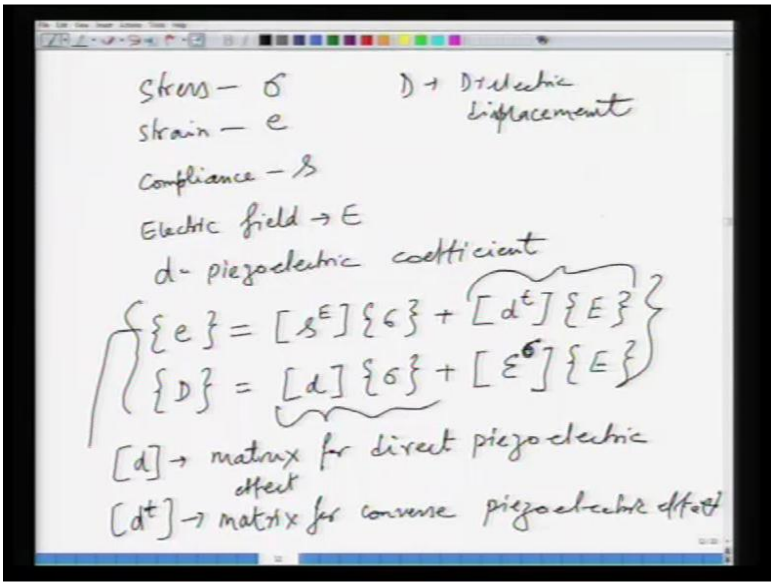


For instance, strain – let us say, epsilon; or, let us say… Here we define first the terms. So, if I say stress is sigma, strain is… Just not to confuse your dielectric constant; let us say strain is e; and, compliance is small s; electric field is E; and, what else? And then, we have d as a piezoelectric coefficient. So, we can write in the form of coupled equations. So, we can write this as… So, strain can be related to small s E into sigma plus d epsilon into E. And then, you can relate D – I forgot to mention D here – D is the dielectric displacement; and, this you remember from module four. So, D can be related as d into sigma plus epsilon sigma into E. So, here the first one is the, d is the matrix. So, this d basically is the matrix for… So, these are called as coupled equations, because they couple the electric and electric field and stress effects. So, d here makes a matrix for direct piezoelectric effect, which is this; and, d t makes the matrix for basically converse piezoelectric or piezoelectric effect. And, this small t term is basically the transposition of matrix. So, if d was a direct matrix for direct piezoelectric effect, the transpose of it would be the converse piezoelectric effect. So, you can basically express the piezoelectric effect.

Since the terms related here are vectors or tensors; as a result, you can express them in the form of a matrix. And basically, the subscript here… So, you have these subscripts here – a capital E sigma; and, these subscripts essentially mean a constant or a zero field. And similarly, zero electric field. And, subscript of sigma will mean constant or zero stress field. So, basically, this would be the converse piezoelectric effect and this is the direct piezoelectric effect. Now, you can do… Based on this, you have a variety of piezoelectric coefficients as well. And, in total, there are four piezoelectric coefficients because of this vector notation.

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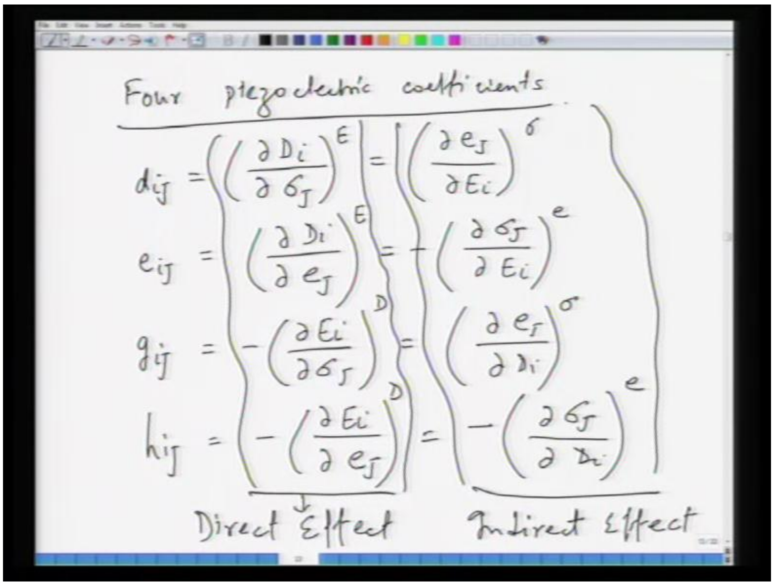


You have four piezoelectric coefficients. And, these coefficients are: first one is d i j; and, this d i j is del of d i to del of sigma j at constant field. And, this is also equal to del of e j to del of E i at constant stress. Similarly, you can also have another one as e i j. This could be del of D i to del of epsilon j or epsilon… Instead of epsilon, I should write e j at constant field to… And, this is also equal to del of sigma j to del of E i at constant strain, which is e. And then, you have g i j, which is minus of del E i to del of sigma j at constant D. And, this is equal to del of e j to del of D i at constant stress. And then, last one – h i j is equal to minus of del E i to del e j at constant D. And, this is equal to minus of del sigma j to del D i at constant strain. So, the first set of four terms, which is here – these are the direct coefficients related to direct effect; and, these ones – as you can see here, are related to indirect or converse effect. And, you can see details of these mathematics of piezoelectric materials, piezoelectric terminology in variety of books.

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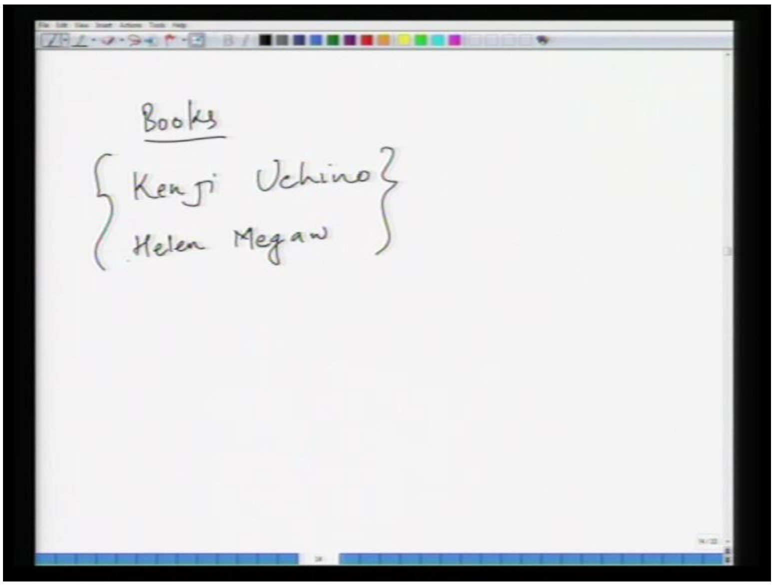


For example, there are books by Kenji Uchino; another book by Helen Megaw. These are the two authors, who have written very nice books on piezoelectricity. So, if you want to go into details of this, you can go to these books and refer for better understanding. What now we will do is that, we will now look at some of the aspects related to piezoelectric materials. Now, piezoelectric materials likewise ferroelectric materials – they also have domains. And these domains… Domain is a region of uniform polarization. What happens in a piezoelectric material is, you need to pole a piezoelectric material in order to get anything out of it. So, what happens is that, in the beginning of poling, before you pole it, all the domains are randomly distributed. So, what happens is that, if you draw a picture of… If I draw a schematic diagram of such an effect…

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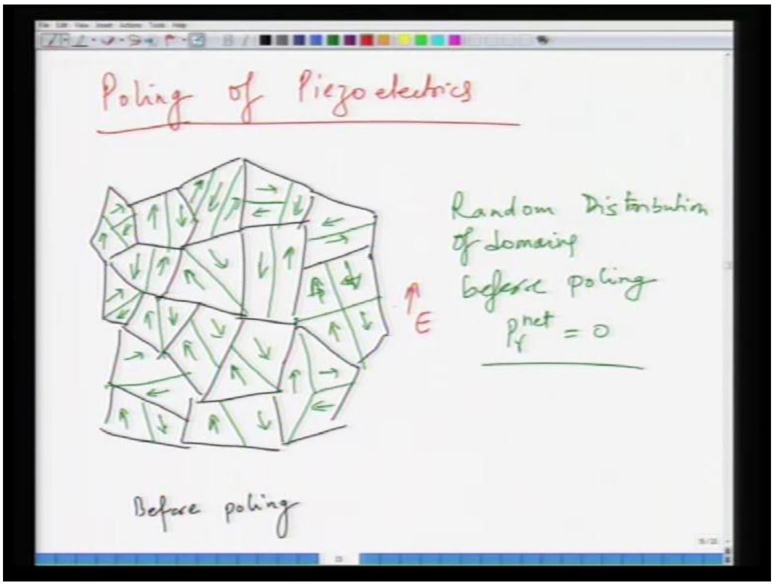


The topic is basically poling of piezoelectrics. If we take typically… This is let us say the grain size. This is the typical polycrystalline material or ceramic. So, this is polycrystalline ceramic. Now, before you have poled for a piezoelectric material; before poling; before poling what happens is that, in this material, let us say I divide this in variety of domains. So, these are of grains. And within these grains, you have domains. Let us say our domains are like this. Now, let us say we have a random distribution of… Before poling, what happens is that, we have a random distribution. So, this is the picture, which emerges just before the poling. And basically, what it means is that, you have a random distribution of domains before poling. If you have random distribution of domains; even though material is polar, it has individual domain having finite polarization. The net polarization – P r net is equal to 0. So, what you need to do that, in order to use this as a useful ferroelectric material, what you need to do is that, you need to apply electric field to this material. So, when you apply electric field to this material, let us say in this direction; then, what happens is that, this material changes its domain structure. As a result, what you have is, essentially, you have a change in the dipole alignment.

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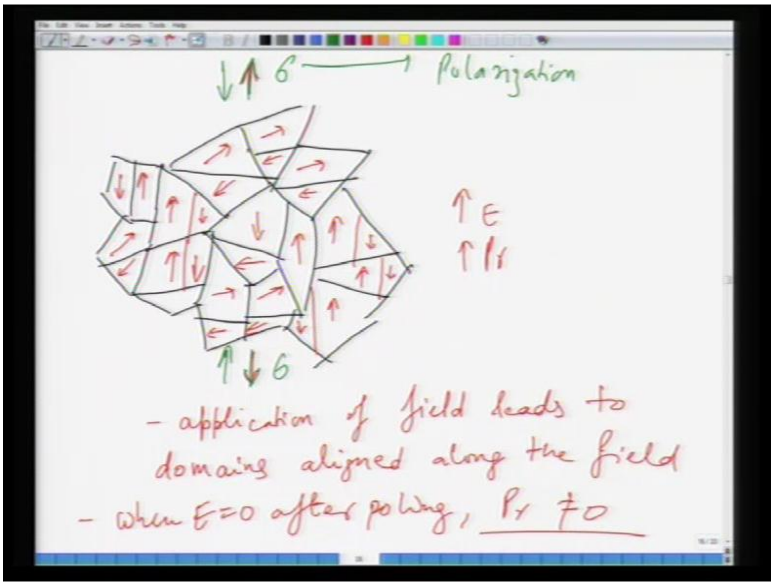


Now, the picture can be slightly different. If I draw now the electric field to this material; now, they are not going to look exactly the similar, because these are all handmade drawings. So, these are grains. Within these, you have grain boundaries. Essentially, if the electric field was like this, you have more domains in the direction of applied field. So, essentially, you have bigger domains, which are oriented in the direction of applied field. So, essentially, you have here… So, essentially, you have a larger. So, application of field leads to domains aligned along the field. As a result, what happens is that, when you remove the field; this E – as the E increases, the P r also increases; but when you remove the field, this… All these domains do not come back to their original situation.

As a result, what you have is, when E is equal to 0 after poling, P r is not equal to 0. This is what you want. You want some polarization to be present inside the material. So, you need to… So, the important requirement for a ferroelectric material is that, you need to… For a piezoelectric material is that, you need to pole it before you use it as a piezoelectric material.

Now, when you use this material; when apply stress – let me just use different color; when you apply stress, this gives rise to polarization. And, when you apply opposite stress, it reverses the direction of polarization. So, this is what you require to do with the ferroelectric material, a piezoelectric material; that you need to pole it before you use it as a piezoelectric. And, this poling process is nothing but application of electric field to a version material and then bringing it back to 0 to create a domain structure, which gives rise to a nonzero polarization.

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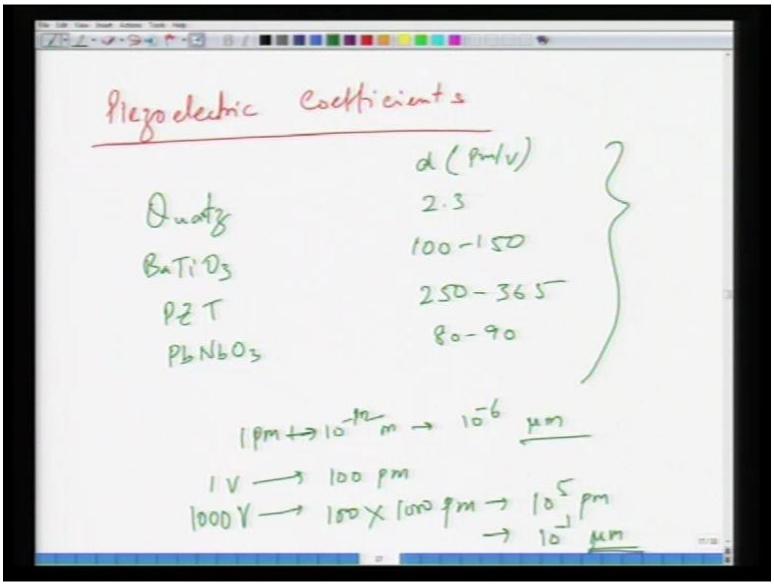


And now, I will give you some values of piezoelectric coefficients for variety of materials, because the magnitude of piezoelectric coefficient represents the extent of the effect. For example, for Quartz, you can have piezoelectric (( )) d – basically, picometer per volt and this is 2.3. If we look at the previous slides; here basically, I am looking at an indirect effect, so picometer per volt. Essentially, if you have this converse piezoelectric coefficient; which is nothing but strain divided by the field; and, this becomes centimeter per volt or… So, 2.3 picometer per volt; barium titanate has a value of 100 to 150 – reasonably, large displacement. P z T, which is lead zirconium titanium oxide – this has 250 to 365 of the compositions, which are close to morphotropic phase boundary. And then, lead niobate – this has about 80 to 90. So, these are the effective…

You can see that, when you apply a volt, you essentially get a displacement of the order of hundreds of picometers. Now, what this means is 1 picometer is essentially 10 to the power minus 12 meter. And, this is essentially 10 over minus 6 microns. So, when you apply just 1 volt, you have a displacement of the order of let us say 100 picometer. So, 1 volt gives you 100 picometer. So, when you apply 1000 volt, which is 1 kilo volt; you get 100 multiplied by 1000 picometer. And, this is of the order of 10 to the power of 5 picometer, which is 10 to the power of minus 1 micron. And, this is 0.1 micron. 0.1

micron is not a small displacement. It is a very large displacement, because when we talk about the material, the unit cells parameters are of the order of angstrom. So, if you look at the total displacement that the material has caused in terms of its dimension, it is very large. And, given that, if you talk of… now, this may not be appreciable for a very big material. But, when you talk about thick and thin film, this 0.1 micron is a very large displacement. And, this is what makes them very useful in the form of actuators, transducers, etcetera; where, this displacement is massive.

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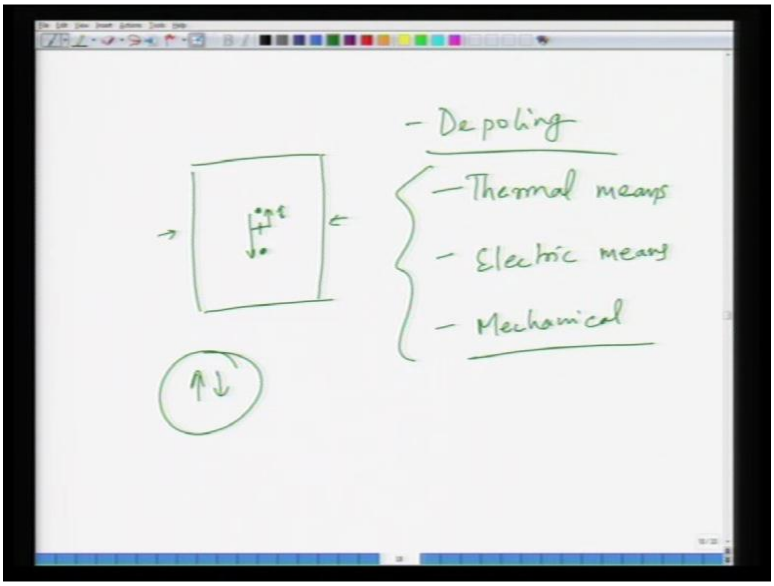


Now, just like you have a ferroelectric material, which can be poled; if you oppositely cycle a piezoelectric material or apply very high temperature; then, application of this high temperature and large mechanical stress can also lead to disappearance of polarization. For instance, for a ferroelectric material, you know that, as you increase the temperature, the polarization drops to 0. Just like in ferroelectric material, in piezoelectric material, when you apply large temperatures or when you apply large stresses, they can result in the depolarization.

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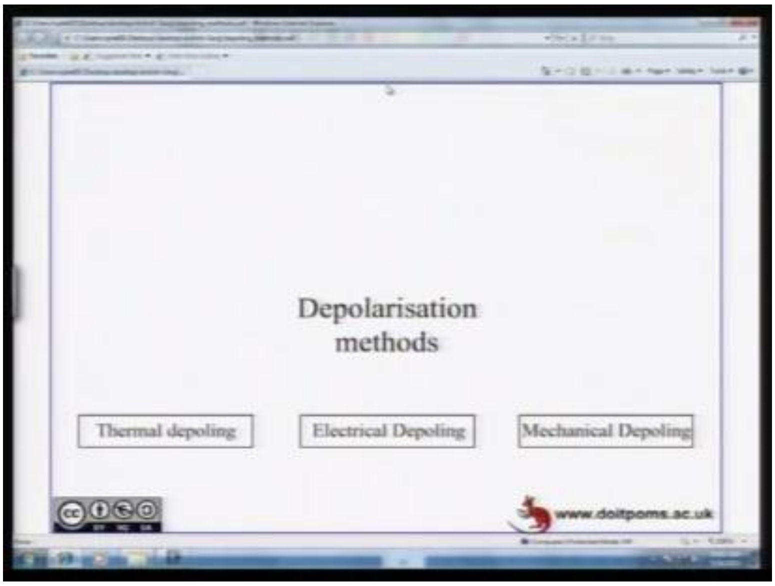


For this, I will show you a video. And, this video is taken from the doitpoms website. This is taken from this reference, which is doitpoms dot ac dot uk. So, you can go to this website. We acknowledge their support in putting up this on website.

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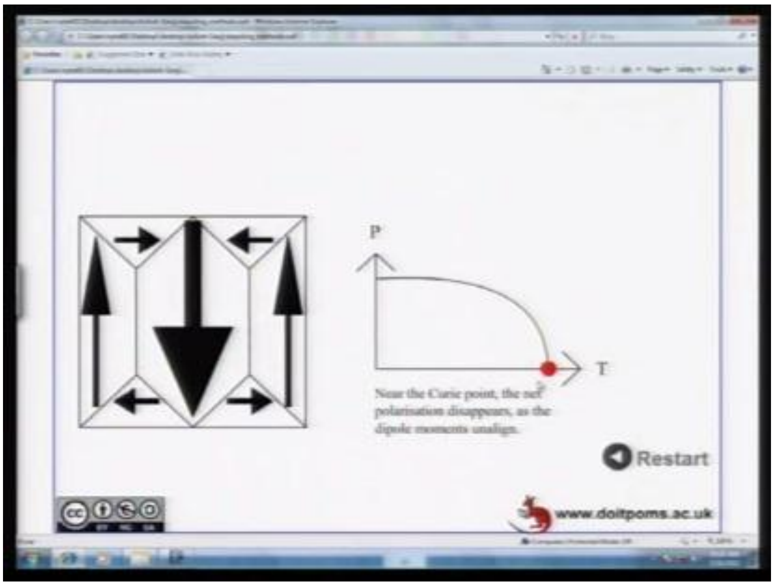


This thermal depoling for instance; you know the polarization; as it comes back to the Curie temperature, the polarization completely disappears; which means the dipole moments underline. If I restart this thermal poling as the temperature is increasing; now, you see how the polarizations moved; they were earlier in the reverse direction; and, they have now moved into the direction, so that net polarization of the material becomes equal to 0. This is what is called as thermal depoling. So, it is opposite to poling. Poling is done to create a polarization. Depoling is essentially a process, which leads to disappearance of polarization.

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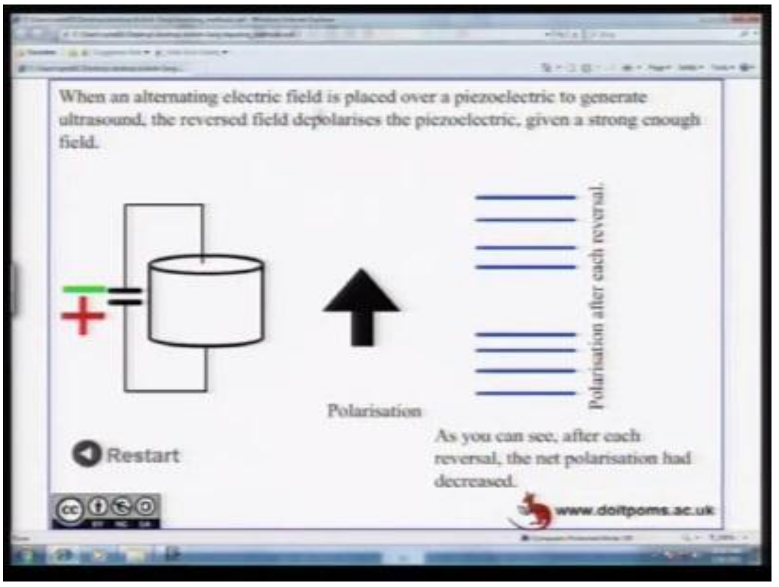


Now, not only effect of applied field leads to depoling, but also, effect of large electric field also leads to depoling. When you apply alternative electric field to a piezoelectric material and it generates a ultra sound, because it undergoes deformation. As a result, it creates ultra sound waves. Now, the reverse – when you apply the reverse field, it depolarizes the piezoelectric. And, this gives a strong enough field. So, if you restart this exercise; you look at it here; and, you look on the right side. So, the net polarization of the material has… So, this is, as you change the polarity; look at the polarity; positive to negative; positive to negative. As you do this kind of depoling, you have net decrease in the polarization of the material simply because the reverse field, which is created – that tends to depolarize the dielectric. This is because of converse piezoelectric effect. So, when you have direct piezoelectric effect, you create, you apply stress. And, this stress gives rise to polarization or electric field. But, whatever is created as a result of application; that also leads to converse piezoelectric effect. So, both of these tend to fight with each other resulting in the decrease in the polarization.

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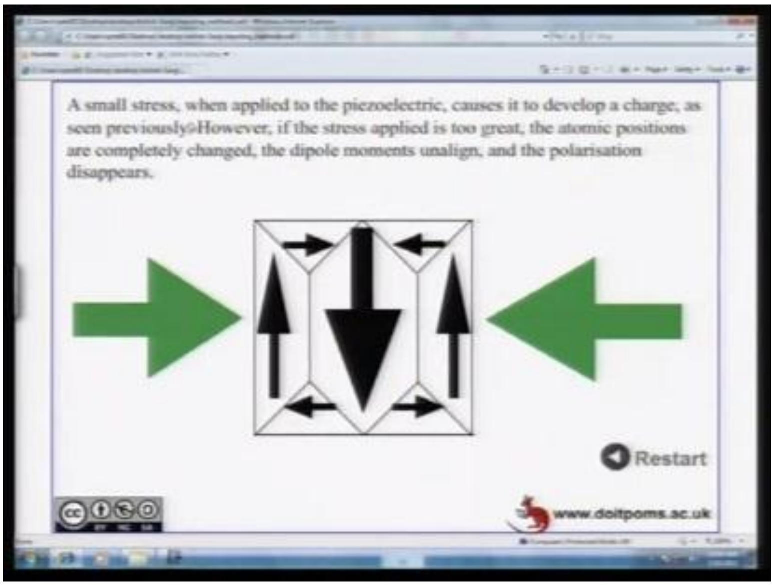


And finally, you can also do mechanical depoling. This mechanical depoling is essentially… Basically when you apply a small stress to a piezoelectric material, this leads to the development of a charge as you already know from the direct piezoelectric effect, but the stress if the… Normally, we are talking about the stress levels, which are small. But when the stress levels become very high, these atomic positions can completely change. So, they do not remain those positions at all. As a result, the dipole moment completely unaligned and hence the polarization disappears. So, if you restart it again; just watch this here. When the stress magnitude has become very high; then, the dipole moments do not remain as if they were doing in the case of small stresses.

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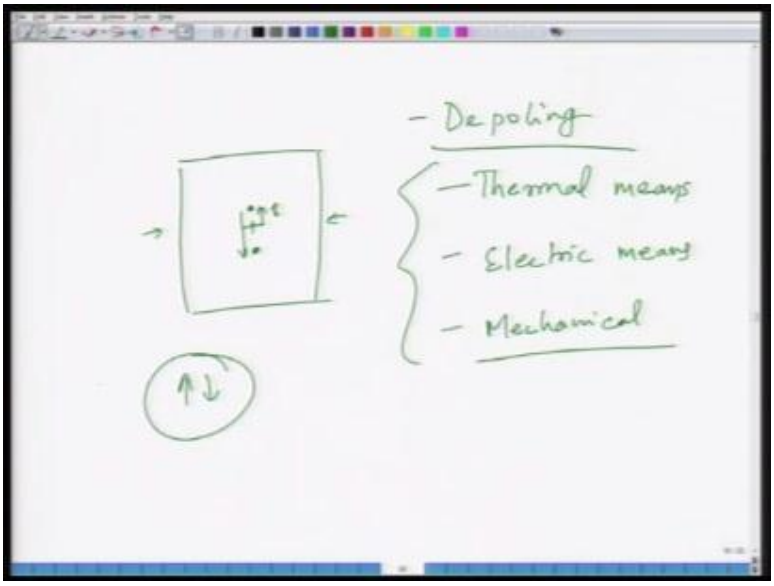


Essentially, what you have is… Let us say you have… This is the displacement from the central position of the central atom. When you apply a small stress, this keeps flipping back. But, when you apply a very large stress in the opposite direction, this completely comes back here. As a result, it flips over. So, the net polarization decreases. So, this is what was demonstrated in the previous animation. If you just look at it again; when the stress is small, it just flips up and down below the equilibrium position. However, when the stress becomes large, then the atoms completely flip over from the previous position to a new position. As a result, unalignment occurs.

Basically, what you have is depoling or disappearance of polarization by thermal means, by electric means and by mechanical means. And basically, the effect of all these three is to create conditions, which lead to either conditions, so that you have complete reversal of polarization in some region of crystal, so that you have zero polarization or you have flipping of atom from its position to another position; which leads to again flipping of polarization in some regions of the crystal giving zero polarization or thermal means such that it just loses its polarization completely due to phase transition. So, what you have here is depolarization of material.

In the next class, what we will talk about is, what are the kind of common piezoelectric materials; and, how do we make piezoelectric measurements; and then, what are the most common piezoelectric applications. So, we will stop here today. And, these topics we will take up in the next class.