Advanced Ceramics for Strategic Applications
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Lecture - 21
Ferroelectric
Piezoelectric and Pyroelectric Ceramics
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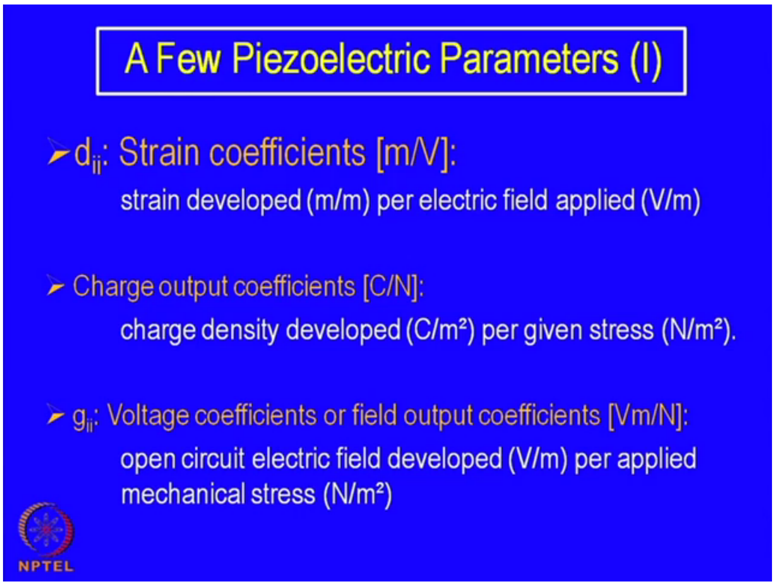

Let me try to continue my discussion in the area of Piezoelectric ceramics. We have been talking about the different coefficient used in Piezoelectric, Piezoelectric phenomena. This we have already discussed, the Strain coefficient as well as the Charge output coefficient and then the Voltage coefficients. We will define them corrects the stage how exactly it comes up.

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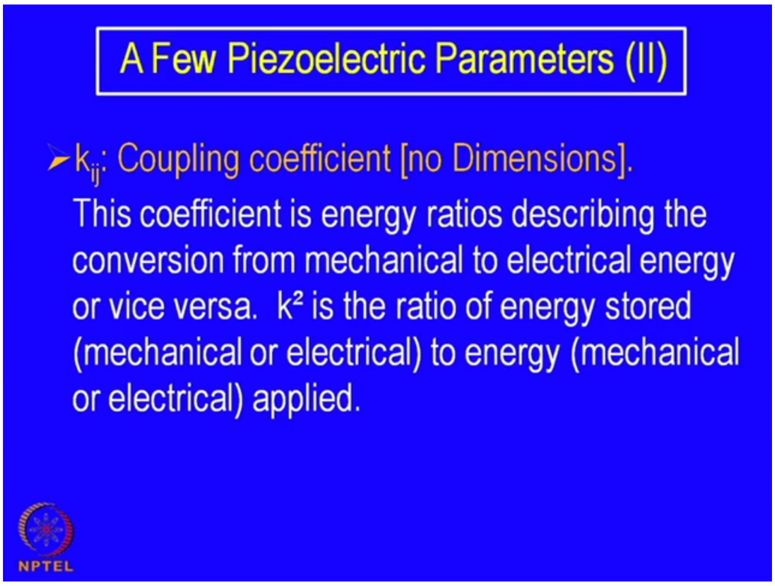

And, also another very important parameter is the Coupling coefficient, which is basically the energy efficiency of system of that particular material either from the electrical to material or mechanical to electrical.

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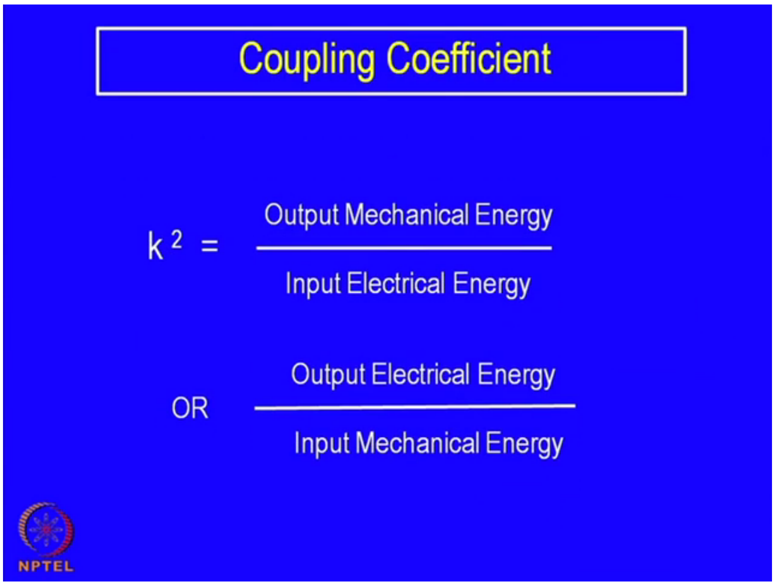

While keeping those things in mind; these we have already discussed the Coupling coefficient that is basically a ratio of the two energy terms.

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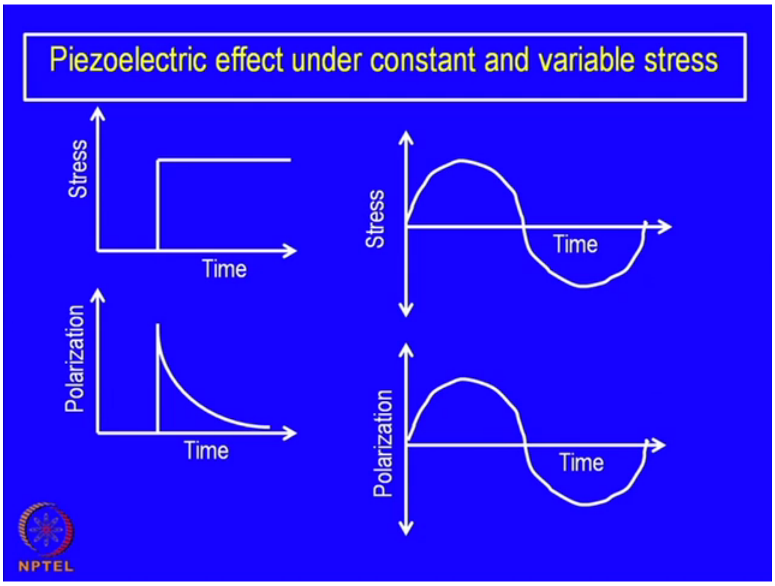

There is one more important aspect to be noted for piezoelectric effect. We have basically applying a stress and generating a Polarization or a voltage. Now, if you apply a instantaneous stress at certain time and then try to maintain that stress constant value; do not change the stress. Then, the polarization which is generated does not remain constant over a period of time. In fact it decades slowly; all the voltage drops down. So, it is basically a dynamic process under which you get this effect of Piezoelectricity. That is you have to continuously vary the stress; so that you get a continuous voltage. In fact most of the time what we do? We actually apply a sinusoidal stress; like in vibrations.

If you are vibrating, there is positive stress they that is the compression and then tension or tension followed by compression. And so that, then that condition you get almost a polarization development of polarization or development of voltage in phase, in phase with the applied stress. So, if you really want to use one really wants to use the piezoelectric behavior piezoelectric behavior of any material and make a device out of it. It has to be designed in such a way that there is a variable stress and or in reverse sweep polarization also in change. Sorry, polarization also can be vary; so that these stress in generated in phase with the polarization or applied electric field.

So, that is that is one of the reason most of the piezoelectric devices are actually operating under the alternative field not under direct field. Direct field applies only on their certain applications. There are certain applications; whereas, direct will be applied or direct voltage is generated. But that is instantaneous; you cannot maintain that voltage were longtime.

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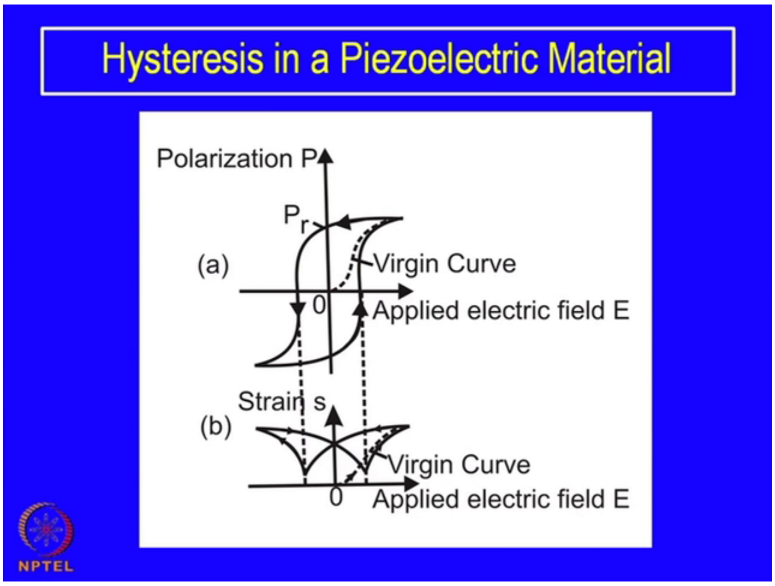

So, coming back to Hysteresis, because we have discussed these things in details why the hysteresis comes up, what is the basic addition of a hysteresis curve or polarization verses electric curve field. It is basically because of the domains structure. Since, us piezoelectric or suppose to be ferroelectric material as well; so, we have a domains structure here as well and you have hysteresis curve. So, this is hysteresis curve is also very typical characteristics of piezoelectric material; as in case of ferroelectric material. In fact they have the ferroelectricity in it.

So, you have a virgin curve; that means, it starts from the 0 field, initially. It follows this curve and then goes to the saturation point. Well, all the domains are align parallel to the electric field and then if the electric field is reversed; then it does not come back to the 0 polarization at 0 field, but there is a reverent polarization. And then you have a coercive field in the negative direction to utilize it and then it follows and goes through saturation and in the negative direction. So, that is the Hysteresis curve, we have with piezoelectric material as well as in case of Ferroelectric material.

However, we have a additional feature here; that is change of strain, change of strain as a function of the electric field. So, in the ferroelectricity, we did not have that effect; so, we did not have this kind of a curve. Here, since we are talking about a mechanical energy or mechanical stress generated as a not only polarization, but it is also generates mechanical strength. And one can find out what is the strain apply, one is strain generated a function of electric field.

So, it is obviously as initially that is again the virgin curve; that is from initial stage the polled material; of course, these are all poll materials. And also in a polling poll material if you apply electric field, the strain increases, polling this started curve. Then if the electric field gets reduced strain gets reduced comes back to comes to 0; once again following a kind of hysteresis pattern. You have herman stern here and then there is a cohesive fields to neutralize eminent stress strain. However, there is a something different happens here, when the electric field goes further in the negative direction. The strain actually increases, strain does not go below or it is there is no strain negative strain that way. So, the strain again increases and you can you can get a reverse direction also in the same manner and then it goes there.

So, it is a kind of butterfly curve. So, against a hysteresis curve in polarization versus electric field in the strain field on strain domain, you get slightly different kind behavior. Strain does not go negative; so, you have a basically a kind of butterfly curve which is generated; so all the time you have a positive strength. So, this is the difference you are in the additional feature, what we get in a piezoelectric material as a function of applied field.

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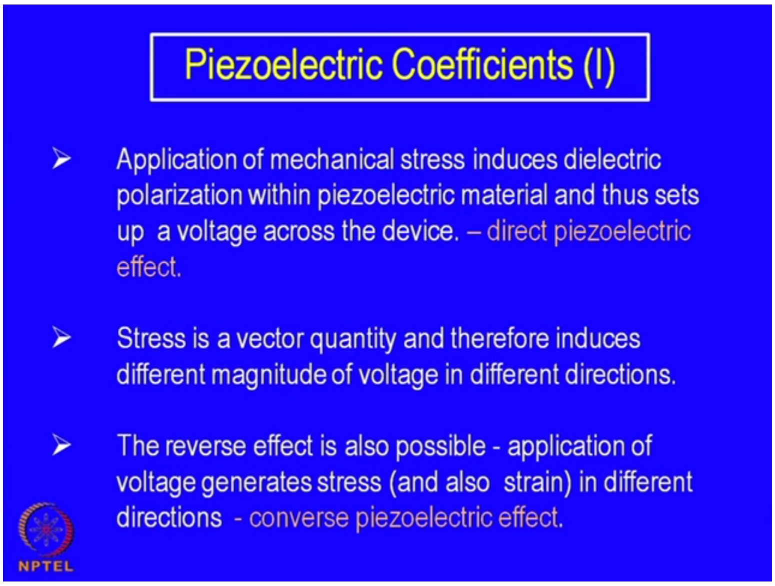

Well, with this descriptives whatever descriptions I have given qualitatively, let us try to understand what are the different kind of coefficients and what is their mathematical representation. Or mathematically, how one can relate to different compound different parameters. Applications of mechanical stress induces dielectric polarization within piezoelectric material piezoelectric material and thus sets up a voltage across the device. That we have already seen and we have discussed. So, that is called direct piezoelectric effect. Stress is a vector quantity and therefore, induces different magnitude of voltage in different directions. So, the stress is not a singular stress, it has a different components. Because we will see later on; if you apply a stress in one direction it has its effect on the other directions as well. As we have seen the very first picture there is a either a reduction in the diameter, when you applies tensile force or if you have compressive force the diameter get increased.

So, there is a poison effect and therefore, the strain has different contexts. It is not always in one particular direction with respect to the geometric of the specimen or geometric of the device. So, we have to consider different directional properties both for the applied voltage as well as the applied the resultant strength or vice versa. The reverse effect is also there, those these are mention earlier. The reverse effect is also possible applications of voltage generate stress and also strain. Stress and strain are actually related terms, by Hooke's law; we will discuss that in a few minutes. So, it generates in different directions and therefore, a converse piezoelectric effect also exists.

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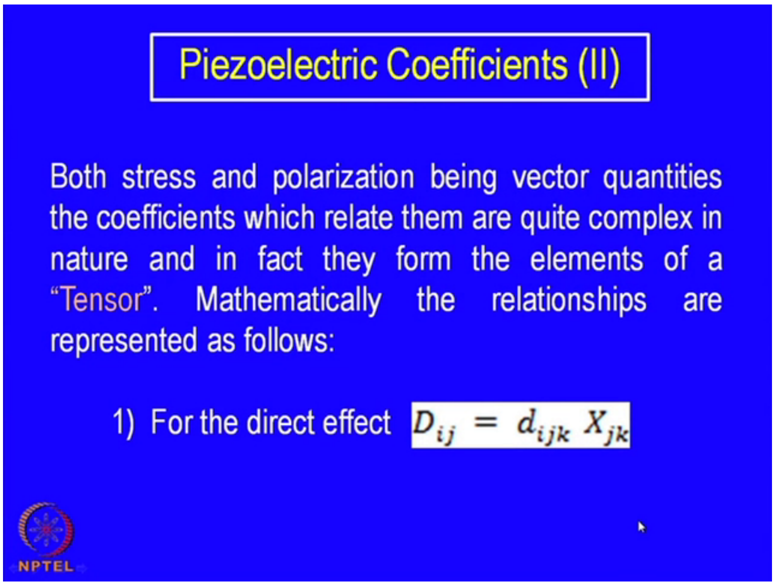

Both stress and polarization being vector quantities the coefficients which relate them are quite complex in nature and in fact they form the elements of a Tensor. So, the coefficient which correlates mathematically correlates the mechanical stress or strain to the dielectric polarization or the voltage. These coefficients are not singular numbers, they are a setup complex number, setup larger numbers. And depending on the different detections in which these stress is generated or the voltage is getting generated. So, the form actually a tensor and we will see how many of the elements are there in the tensor.

Mathematically, the relationships are represented as follows. There are different ways to correlate them. For the direct effect, we say D i j; D is the flux density and small d i j k. So, there are three orthogonal detections; so, these are i j k and that is the coefficient and the stress patterns. Stress is X j k; so, the X that these stress is generated or stress is applied in one particular direction and the flux density on voltage maybe appear on different directions. So, that is why we have subscripts i j or i j k and then j k will come up with little details of these things.

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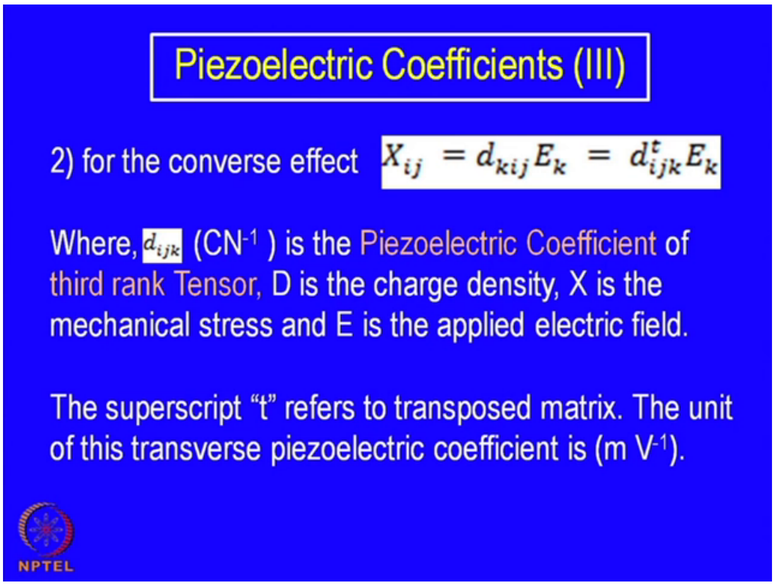

The converse effect is can also the related like that where is stress is the X i j is d k i j. So, it is actually the transposed matrix, d is actually matrix now and you will find Ek, E k is the field. So, these i j k, d k i j is actually the transpose matrix of d i j k. So, it can be written as k i j and Ek; of course, is the electric field; electric field vector in the k direction. So, you have E k direction and then we are measuring the stress and i and j other directions; then this particular type of coefficients will appear. Well, has been explained just now; where, d i j k it is unit is column per newton is the piezoelectric coefficient of the third rank tensor is called third rank tensor. We will see, what is the third rank tensor? d is the charged density or also flux density sometimes called and X is the mechanical stress and E is the applied electric field.

So, these are the parameters which has been used in the two equations just presented a subscript t, superscript t, which again has been explained just now, is the refers to the transpose matrix of d i j k. So, d i j k transpose becomes d k i j. The unit of this transverse piezoelectric coefficient is meter per volt meter per volt. So, it is basically how much is the extension a function of volt.

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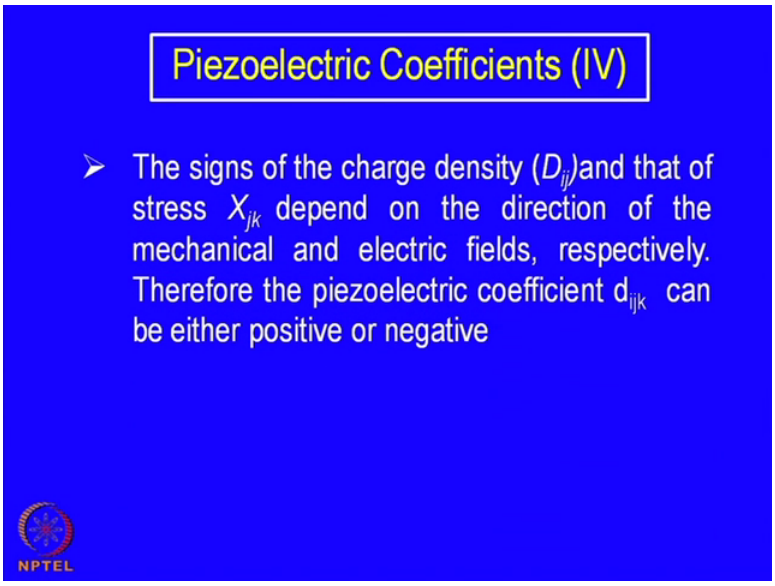

Now, the signs of the charged density thus d, d i j and that of X j k depend on the direction of the mechanical and the electric fields respectively. Therefore, the piezoelectric coefficient d i j k can be either positive or negative, because we have different possibilities of these stresses as well as the strain sorry the flux density.

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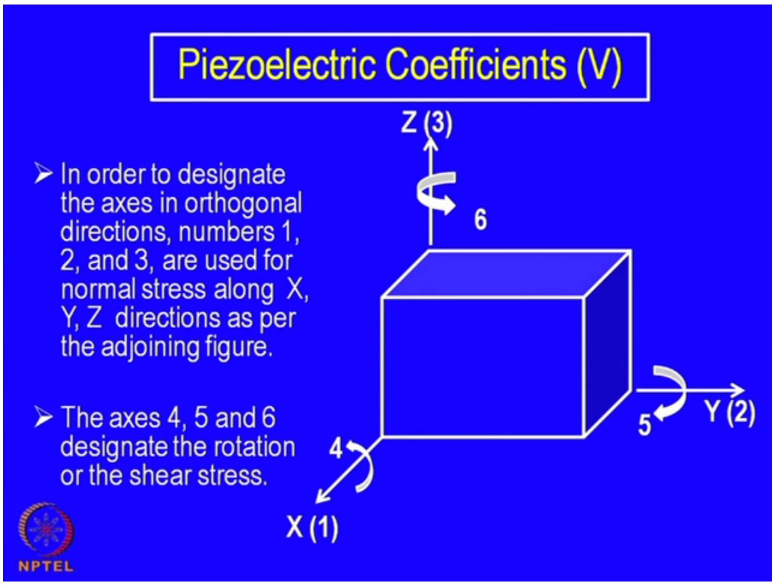

Now, how these different subscripts come? Subscript come from this kind of a concentration in order to designate in axes in orthogonal directions impact. One can have a orthogonal system of representation in the solid geometric like situation where X, Y, Z or X, Y, Z are the axes, orthogonal axes and they can be also represented as 1, 2, 3 in another form of rotation.

Now, when we apply an electric mechanical stress on this cube; for example, a general different kind of consequences any the stress can be normal to any of the axes either Z axes, X-axes or y-axes. So, this can be called as normal stress. However, if there is a incline stress at an angle. that will have different kind of components in different directions. Sometimes, a stress can also be not may not be a normal stress, but it can be uses a shear stress. So, one considers the shear module and normal stress. One considers the young modules to correlate stress and strain. Whereas, when there is a shear stress, the coefficient is different and one is to take into account the shear modules of the material.

So, there are these kind of rotational stress surrounding this particular axes. That means, these on the surface of this not perpendicular to the surface, any of the surfaces. So, these shear stress acts on the surface and they can be represented by a circular array like this. And there will be 4 shear stress 4, 5 and 6; so, this is how all the stress system extension can be represented. So, there are 6 elements of the stress 1, 2, 3, 4, 5, 6; 3 of them are normal stress and 3 of them an another three are actually shear stress. So, this is how actually we will represent and we will find out the equations as well as the coefficients a series of coefficient in different directions.

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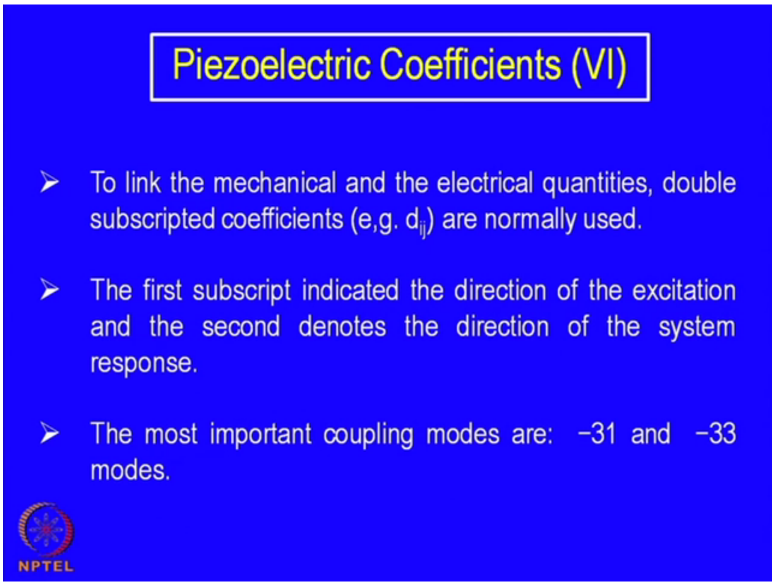

To link the mechanical and electrical quantities, double subscripted coefficients as for example, d i j are normally used. The first subscript indicates, indicated in the direction indicates it will be indicates indicates the direction of the excitation. And, the second subscript is actually second subscript denotes the direction of the system response. Just correct that the first subscript then indicates the direction of the excitation that is it may be applied voltage or applied stress and the second denotes the direction of the system response how it responds.

The d i j; it i is the direction; if it is 1, 2 for example; then one represents the direction of the applied stress and we are measuring the response the electrical field generated in the second direction, two directions. So, this is how actually notations have been used. The most important coupling modes are 3, 1 minus 3, 1 minus 3, 3; that is i equal to 3 and j equal to 1 and or i equal to 3; j also equal to 3. So, 3 3 is actually is the normal mode whereas, 31 becomes a shear mode. So, these are basically the how we denote the coefficients a piezoelectric coefficients.

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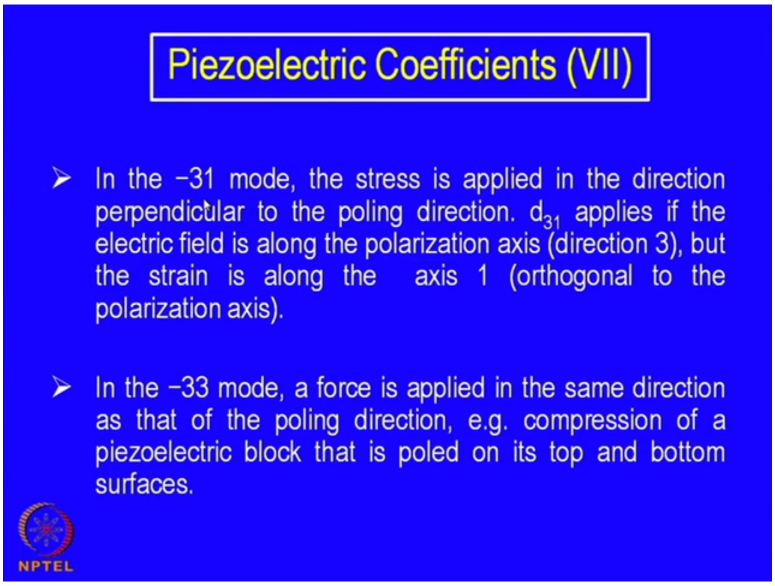

Well, there are few more things to discuss that is in the minus 31 mode; the stress is applied in a direction perpendicular to the poling direction. Here, poling direction is a reference and so 3 directions as if it is in the z direction. So, assuming that the poling direction is in the z direction. So, you are applying a stress in the perpendicular to the polling direction. And 31 implies if the electric field is along the polarization axes direction 3 again, but the strain along axes 1 orthogonal to the polarization axes. So, 3 basically depends or refers to the axes parallel to the polarization axes; the way the material has been polled. If it is a cylinder now normally it was a cylindrical specimen then it is a c-axes which is the poll normally poling axes. And, that is also here will be refer to as the number 3 axes.

In the 33 mode a force is applied in the same direction as that of the poling direction. As for example, competition of a piezoelectric block that is poled on its top and the bottom surface. Once again the same thing and you are measuring the voltage generated also in the 3 directions same direction. Here, 31 for example, it is we are measuring the voltage in the orthogonal direction a perpendicular direction to the top and bottom surface. So, this is how the whole thing is designated.

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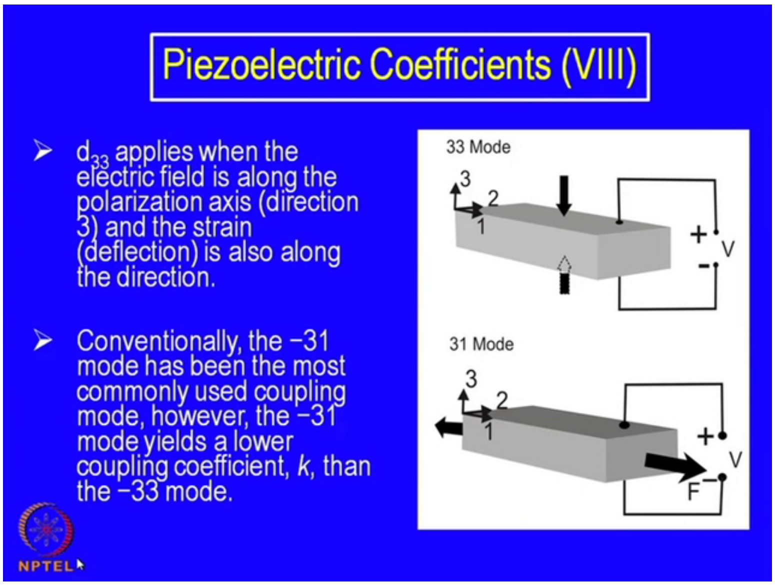

This is the example what exactly means by these are the modes which are normally used in any devices; and they are actually more important modes. Here, to exemplify the situation little clear in a clear term what we have taken is a strip, this is not a cylinder, but a strip a rectangular strip of a piezoelectric material. And, the directions are like this this is 2 direction, this is 1 direction and the vertical direction is 33 direction are the z axes, x axes and y axes you can say.

Now, this is what we called 33 modes. Where we applying the stress along the 3 direction the z direction; we are applying the stress along the z direction is a compressive stress. And, then we are measuring the voltage also along the same direction between the 2 bottom and the top surfaces. So, the axes actually parallel. So, the direction of the application of the stress and the measurement of the voltage is same. It may be reverse is also; that means to apply a voltage in this direction and try to measure. What is the deflection or the change in change of dimension along the same axes, then these becomes 33 mode.

Whereas, the same strip if it is stress differently. It may we are still measuring or voltage between the top and the bottom surfaces. Whereas, applying the stress in a orthogonal direction; we are now trying to pull along its length. And, then also you generate some voltage here, because this also as a component because of the persons or relationship. So, if you apply a stress on these actually there will be compressive stress between the top and the bottom surface. So, just like this here. So, this are there are some kind of a similarity either you apply a compressive stress along between the along the top and the bottom surface or apply a tensile stress along this. So, that will also result in a compressive stress between the 2 surfaces here; 2 parallel surfaces top and bottom.

So, this becomes your 31 mode. We are applying voltage one can say this is 31 or 13 depending on which kind of parameter or which kind of voltage; whether we are measuring the voltage by applying mechanical stress or the reverse of it. So, if we are 3 mode is this one which means 3 is first one. So, we are applying the voltage here and measuring the stress measuring the stress measuring the stress. If it is 13 if this is become 13 then is reverse. We are measuring we are applying the voltage sorry we are applying the stress along with the 1 direction and measuring the voltage in the 3 direction. So, one can have 13 also, there are many possibilities, there are many different combination are possible. Accordingly, you have different kind of are different coefficients with different subscripts.

So, conventionally minus 31 mode has been the most commonly used coupling modes. However, minus 31 mode yields a lower coupling coefficient k, than the 33 mode. So, 33 mode and 31 mode has been described here, but if given an option 31, 33 mode is much better because the 31 mode yields a lower coupling coefficient. So, the energy conversion is little low in case of 31 modes compared to 33 mode, because both of them are parallel to each other. So, this is a kind of interpretation physical interpretation of these modes on these subscripts.

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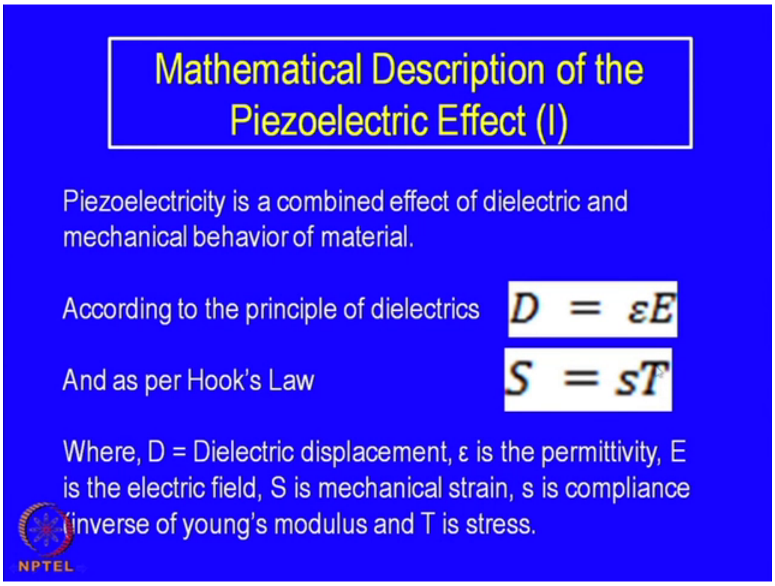

We have little complex description of the same thing which we have discussed just now. For that we consider in a slightly different way the Piezoelectricity is a combined effect of dielectric and mechanical behavior; that we have been mentioning for a long. According to the principle of dielectrics one can write this equation. This that is we have seen in case of a normal dielectrics this is D the flux density is equal to epsilon the permittivity; and the electric field. So, the flux density arises because of the application of the electric field and the coefficient is proportionality constant is actually the epsilon or the permittivity of the material or the dielectric constant.

So, higher is the dielectric constant flux density will be high for the same applied field. And, since we are talking about the mechanical system as well because 2 things are different; they are to some extent compatible, but they have their own identity. So, not only dielectric behavior has to be represented, but also mechanical behavior you have to understand. And, we know Hook's law where stress and strain is related by young's modulus. So, basically the proportionality constant has been is the young's modulus, but this Hooks law has been here it has been written slightly inverse manner. That means, this is the stress is proportional to this is strain this S is capitals; s is strain; and T is the stress. So, young's modulus is actually stress by strain; strain by stress, whereas, here this proportionality constant small s is known as the compliance.

So, it is inverse of young’s modulus it is the inverse s is the compliance which is the inverse of young’s modulus. So, at all the terms has been explained here D equal to the dielectric displacement; epsilon is the permittivity; capital E is the dielectric field; capital S is the mechanical strain; this is mechanical strain. And, s is the compliance is the inverse of young’s modulus; and inverse of young’s modulus and T capital T is the stress mechanical stress. So, all these parameters are involved when a piezoelectric system is functioning. All these parameters are actually involved and some of the and some of them couple together and that is what makes our life little complex.

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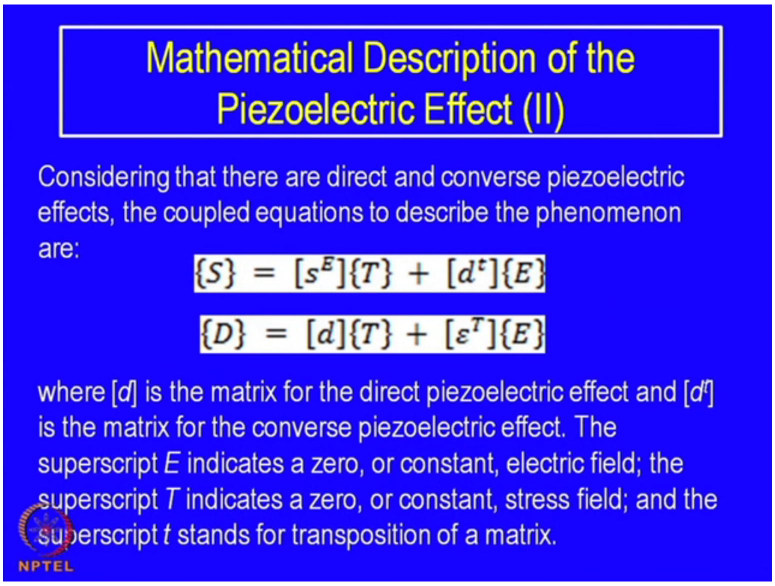

So, one can write in the form of a tension notation, considering that the direct and their converse piezoelectric effects at the coupled equations to describe the phenomenon. This phenomena is described by what we call a coupled equation because in the same system in this material we have 2 different effects of 2 different parameters. One is the stress T and another is the electric field. So, both these things are operating on the same system. So, you have this one what is the strain if you want to find out what will be the strain. That means, the formation of the material; it arises both because of the application stress here and also application of the electric field.

So, both these things are simultaneously operating. So, that a strain is generated in a particular direction. So, this is the kind of a coupled equation for expressing the stress a strain tensor a strain tensor. So, this is a strain and then if you talk about the electrical effect; then you have dielectric flux density D also generated from stress and it is also a effect of electric field. So, in both the cases whether this is stress and electric field; both is generating a stress in mechanical strain. And, also both of them can generate a dielectric displacement or the flux density.

So, that is why they are called coupled equation and these are the 2 effects. One is the direct piezoelectric effect, other is the converse piezoelectric effect; where D is this one, D is the coefficient proportional some kind of proportionality constant is the matrix actually. These becomes the third bracket or the square bracket actually represents the matrix and the second bracket here represents a tensor quantity.

So, the direct piezoelectric effect d T is the transpose matrix for the converse piezoelectric effect. The superscript E is here, E indicates either 0 or a constant electric field. That mean, stress strain of the electric field which is actually a coefficient. And, then we have the superscript T also there is a superscript T here the with the epsilon, epsilon superscript T that indicates a 0 or a constant stress field. And, the superscript T stands for transposition of the matrix which has been already mentioned. So, these are the basic equation which describes the overall phenomena of piezoelectricity. One is the direct piezoelectric effect, another is converse piezoelectric effect. Lower one the converse piezoelectric effect and upper one is the direct piezoelectric effect.

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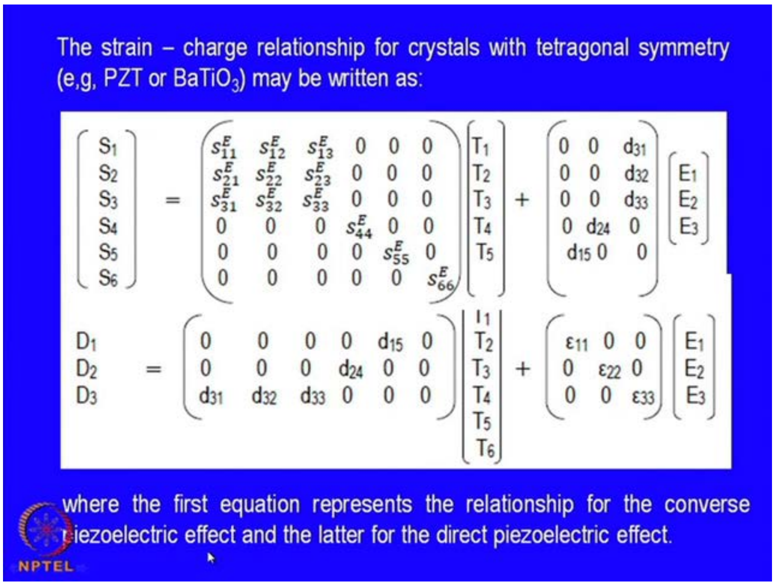

Now, this can be expanded this can be expanded to large extend. And, there are many symmetry elements or because of the symmetry or the geometry many of the coefficients are actually 0; but there are some real values here or finite values in this these are one kind of one setup coefficient, and these are another kind of coefficients. So, in fact there are 3 different coefficients, one is s coefficients are the strain coefficient, this is the piezoelectric coefficient d and this is the dielectric coefficient epsilon.

So, that also has different directional properties. So, here you have we have seen earlier this is the strain, strain can have 6 different axes, along 6 different axes; these 1, 2, 3 are the normal strain and 4, 5, 6 are the shear strain. So, these are 6 elements are here, and then stress sorry there is a missing link here it should be T6, these are T6, this is 0, 0, 0. These are I think I made a mistake I corrected somewhere it is not being. So, this is also T1, T2, T3, T4, T5, T6.

So, these are along the 6 direction and the electric field is only along 3 different directions. The applied electric field is in 3 different directions we are not applying electronic field along any surface. So, electric field is applied along the orthogonal directions only. So, these are the total 1 is the direct and there is the converse effect. Now, all of them all the coefficients are really not effective. Some of them as you can see in all these matrixes some of them effective or some of them are not. And, that oppose it is particular symmetry element present the strain charge relationship for crystals with tetragonal symmetry. When the tetragonal symmetry these happens. If the structure is different or the geometry different then oppose others will be operative this may not be operative.

So, it all depends on the in an ideal case all these 6 into 6 36 and here 6 into 3 18 there are 9 here 3 into 3, and there are again 6 into 3 18. All of them will be have a finite value, but most of the cases because of the particular symmetry, cylindrical symmetry, or tetragonal symmetry; we have mention what we have mentioned here because of that some of them do not operate do not appear actually. So, we have seen here we are earlier discussing about 31 modes; these are d 31 mode and this is your 33 mode. So, displacement as a function of applied field as well as stress. The first equation represents the relationship for the converse piezoelectric effect; and the later sorry I mention differently this is the direct and this is the converse here has been reversed.

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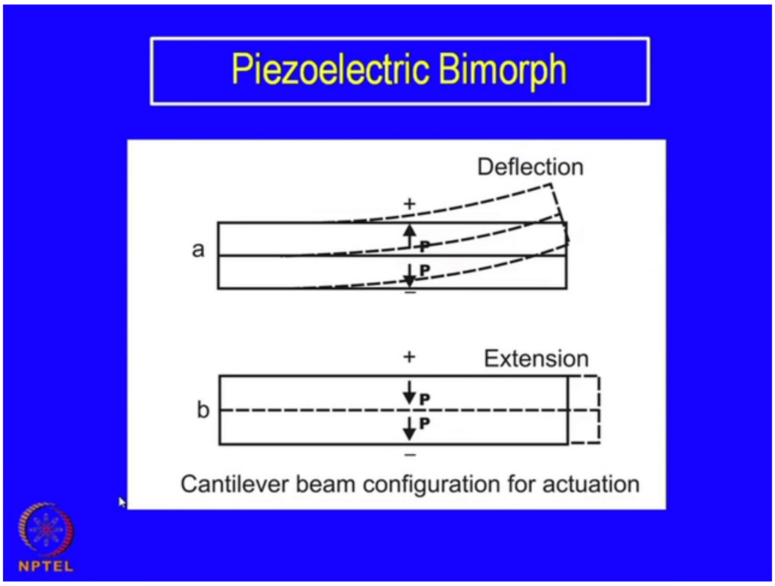

Well, with this little background; let us go what are the things we can design with with a piezoelectric or pyroelectric material; this is what we called piezoelectric Bimorph. Ok. It is actually a thin strip thin strip in fact it is not a monomorph it is called bimorph because there are 2 strips, 2 strips put together. One is the top one, another is the bottom one, lower there are 2 separate strips. And, they have been put together the difference between them oppose the dimensions are same. It is a rectangular strip very thin rectangular strip with the small thickness may be with a millimeter or show; and the major difference here you can see they may have 2 poling direction.

Both of them have they have been polled so they will have a poling direction. And, the result and polarize direction here this one for the bottom one it is pointing downwards and the top one and also is pointing downwards. So, when we are putting them together is actually we are putting them with the, with the use of a glue. Some attaching sometimes a metal can also be used in between, but when we are putting them together in such a way that in both the things, both the strips the polarization axes is same they are pointing downwards. And, we apply a voltage across this is a positive voltage and then the negative voltage of this side. If the polarization axes like this these strip will expand in this manner, will extend its length will increase in this manner uniformly because of this particular characteristics of relationships.

So, this is positive and this is negative. And, they it will expand in this direction. Whereas, in the top case you can see here this polarization direction are different. So, it has been the have been put in such a way that have been; while they have been group in together they have been put in such a way that the polarization axes at different. One pointing downwards another pointing upwards. In such a situation one will try to explain other will try to contract.

So, this lower one is trying to extend in this particular case. So, here one also both of them are trying to expand in along the length. Here, the lower one is trying to extend or expand whereas, the top one is trying to contract. As a result what will happen? It will bend, the whole strip will bend. So, just by designing the configuration the way you configure the materials one can have 2 different effects and both of them have their implications. For example, by this process you apply a very high- frequency it will basically try to vibrate. Once you to the positive, positive field here negative field on the other side and next moment if you change it will bend in the opposite direction.

So, as a result if you have a applied voltage high frequency applied voltage whole thing will be vibrating. And, it can generate noise or a particular frequency may not noise a sound wave audible; depending on the frequency audible sign come in a ultrasound ultrasonic sound can also be generated. So, this is a very useful design for utilizing the piezoelectric effect of the material. Here, of course this also have this own utility it is expanding expanding or contracting if you reverse the applied fault the applied field. It will try to contract.

So, there is a instead a vibration you are getting linear movement, a linear movement expansion or contraction. And, that can also be utilized very precisely and these movements are very small sometimes few microns or tense of microns. So, if you need that kind of translation so a actuators kinds of actuations one can make this kind of a system or a device; where piezoelectric actuators can be designed for many different purposes for small length of movements.

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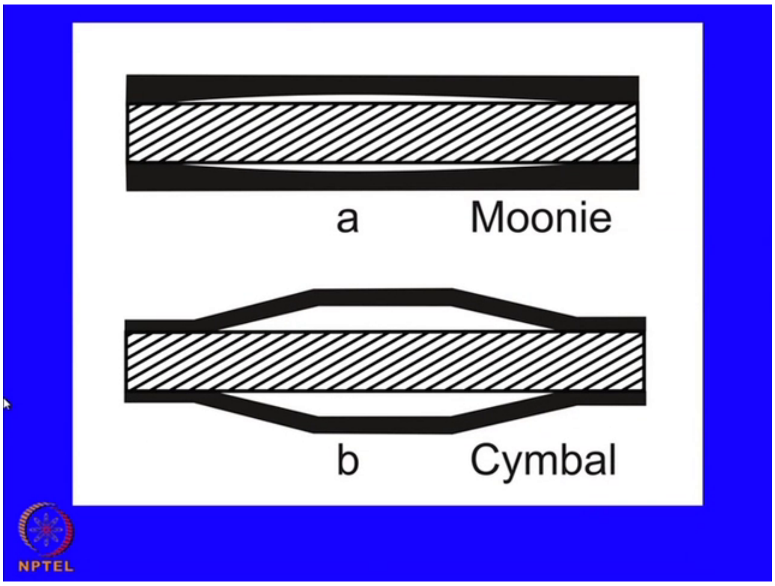

Well, this is another kind of design. These another kind of design where the piezoelectric ceramic have been sandwiched which have been sandwiched; which between two metal plates very thin layer of metal plates however, there is a gap in between. So, this is also this is basically to enhance the vibration enhance the vibration or increase the intensity of the. It is a kind of amplification one can generate by applying this metal plates. Of course, metal plates also have another very important usefulness because you know this is expanding or contracting and vibrating depending on what kind of electric field one applies. And, therefore, there is a lot of mechanical stress gets generated in this thin strips of ceramics.

And, ceramics as is well known it is a basically of beetle material and it has its own problems of crack propagation and so on. So, when you are dealing with ceramics and also think the mechanically stress you have to be a little careful. So, that it does not break it does not crack because it cracks almost instantaneously that the character of beetle material. So, it is also acting as a kind of force meant metal can which stand much higher stress and it is plastic material it is not a beetle material. So, metal it is kind of a the enforcement for the ceramics, but at the same time also acts as an amplifier. So, if you one to generate a vibration or generate the sound. Just in case of a loudspeaker that kind of situations this kind of metal acts as a amplification, provides a amplification factor.

So, there are 2 different designs and with 2 different names have given. Only thing the ceramics is same, but the metal conservation is slightly different. Now, here we have shown only 1 layer of ceramics piezoelectric material, but one can also have a multilayer piezoelectric material. You know will come to that later on what are the main applications of the piezoelectric materials; one of course, is a sensor the together is actuators these are mostly different sensor and actuators and the amplification or the sensing, capability or the actual activation can be increase by many fold by multilayer.

Earlier, we have seen multilayer capacitor the effectiveness of the capacitance or the overall value of the capacitance; will be announced by multi layering with the sandwich structure between you have electrode metal electrodes. Here, also very similar amplification can be done. You can use very thin layers, thin layer of piezoelectric material and then screen printed metal film. So, multilayer structures are also used quite extensively for enhancing the actuation property, particularly the load-bearing property.

The load-bearing property because when you are trying to actuate actuating this sense we are trying to physically move something physically changed announce, physically change the position. So, you have to more different kinds of loads; you need different kind of mechanical stress. So that mechanical stress gets enhanced one in this vibrational enhancement that means amplitude of vibration.

So, that is one kind of enhancement or amplification. The other thing the amplification total load behind the capacity. That means, how much load it can move; physically moves from one position to other. So, that can be enhanced by multilayer. So, although the property. The property of the material remains same, but chance just by designing a different configuration one can enhance the property collage extent. So, these are some of the waves one can use piezoelectric materials.

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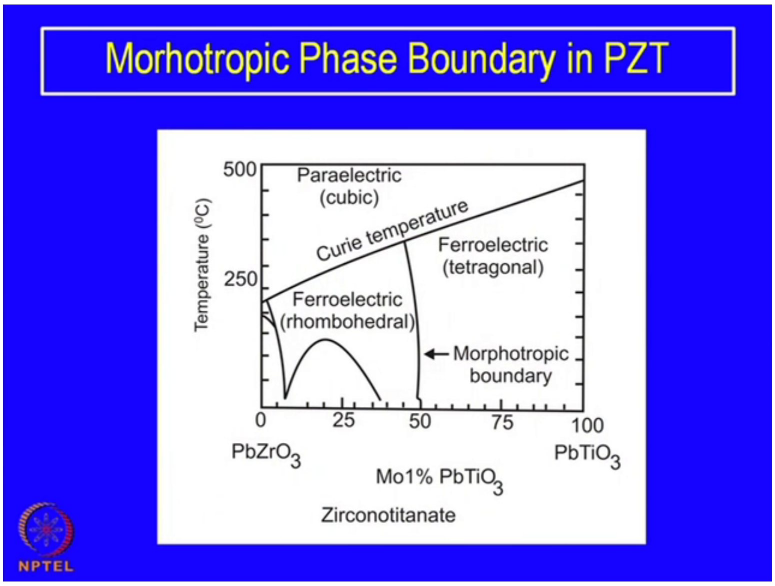

Well, coming back to the material property once again. We have not discussed too much about the materials so far, the generally we have discussed properties. And, how one can design what is the relationship between the poling direction and then how to, how a bimorph can be bend or increases dimensional and so on. The material is concerned, the best material. The most important materials available to us are once again a perovskite compound. Earlier, we have seen barium titanate as one of the very useful ferroelectric material, ferroelectric ceramics. Here, is another perovskite material in fact, a compound or a solid solution, solid solution of 2 perovskite.

One is lead zirconate another is lead titanate, both of them have perovskite structure. So, there is complete solid solubility so you can in fact, have lead zirconate is one side and lead titanate on another side, this is phased diagram in fact. So, it is basically phase diagram this is lead zirconate, 100 percent lead zirconate, and is 100 percent lead titanate. So, you have complete solid solubility.

You can fix the composition at any point on these axes, whether it is 25 percent, 50 percent, 70 percent and so on. Now, this is basically a phase diagram. And, it represents various different polymorphic forms of this compound, of this particular solid solutions. If you take pure lead zirconate you have this is the ferroelectric phase it is stable or a composition range. You can add about 50 percent of around about 50 more percent of lead titanate, you have a rhombohedral ferroelectric phase. So, the ferroelectricity as you remember is this is very intimately connected to the crystal structure.

So, this rhombohedral structure is actually ferroelectric phase. And, if you increase the temperature this is the temperature axes so if you increase the temperature beyond this line beyond this line then the ferroelectric get lost. So, you have a curie temperature which locals are like this. At 0 percent lead titanate that means 100 percent lead zirconate the curie temperature is around little less than 250 is, around 240 to 245 degrees.

Whereas, if you add lead titanate to add lead titanate continuously. You can see the curie temperature increases and it goes up to almost very close to 500 degree, 500 degree centigrade. So, the curie temperature changes, curie temperature change by adding more and more lead titanate to lead zirconate. However, throughout this range theer is a ferroelectric phase, there is a this also ferroelectric phase here. And, there is a curie temperature. Now, this region is a cubic phase. So, this is the cubic phase is symmetric phase it cannot have ferroelectricity or piezo electricity. So, it is actually cubic phase and paraelectric phase.

So, it is a simple dielectric or linear dielectrics. Whereas below this curie temperature it is both ferroelectric and also piezoelectric. Now, there is another point to be noted here. This particular boundary there is if a change here as a function of composition this is rhombohedral phase and this is tetragonal phase. Both of them are ferroelectric phase no doubt, but the structures are different. This is a rhombohedral phase this part is rhombohedral phase and this part is tetragonal phase this is what we called the boundary between rhombohedral.

The rhombohedral phase is changing to tetragonal phase. And, this particular boundary is called morhotropic boundary. And, that has a very important connotation on the property of the ferroelectric or the sorry the piezoelectric material particularly the lead zirconate and lead titanate solid solution of lead zirconate or led titanate which is in sort called PZT. So, it is a PZT or sometimes called PZET this is a very very important piezoelectric material. And, it will be extensively used in industries or many many different devices. We will discuss little bit of that in the next class so for the time being.

Good bye and thank you.