Advanced Ceramics for Strategic Applications
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Lecture - 22
Ferroelectric, Piezoelectric and Pyroelectric Ceramics (Contd.)

Today's discussion is also the continuation of our previous discussion that is on piezoelectric ceramics. We will also continue after this and complete on piezoelectric materials as well. Earlier we have introduced the concept of piezoelectricity, different coefficients and their directional properties as well as the tensor characteristics of the coefficients.

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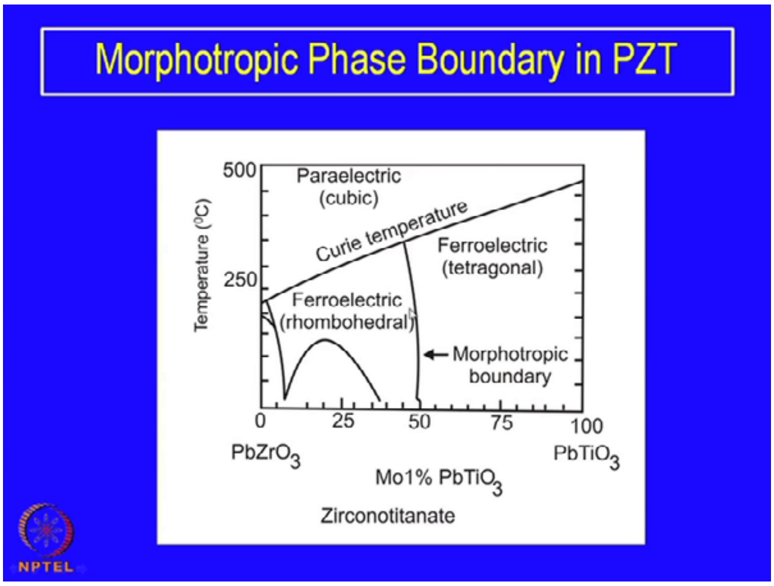

We started with the discussion of what we call the morphotropic phase boundary particularly for the most important ceramic materials that is known as PZT or lead zirconatotitanate. We are looking at the phase diagram of two components to peroxide compounds that is lead zirconate and lead titanate; both of them have the perovskite structure. So, they go into complete solid solubility, and we have the ferroelectric to non-ferroelectric phase boundary at around 50 mole percent; when you mix about 50-50 you have both ferroelectric phases, before that you have a rhombohedral phase and with the higher lead titanate content it goes to the tetragonal phase.

So, that is the morphotropic phase boundary which is around 50 mole percent, and the Curie temperature increases. It is lower from the lead zirconate, and it increases as we increase the percentage of lead titanate. Incidentally the Curie temperature of lead titanate is around very close to 500 degrees whereas that of lead zirconate is only around less than 25o degree centigrade. So, this is the variation of the Curie temperature, and this is the polymorphic phase transformation that is ferroelectric rhombohedral to ferroelectric tetragonal, and that is what is known as the designate as morphotropic phase boundary. Now this has a very significance so far as the particular property or the piezoelectric property of this composite at this solid solution is concerned, that is given in the next diagram

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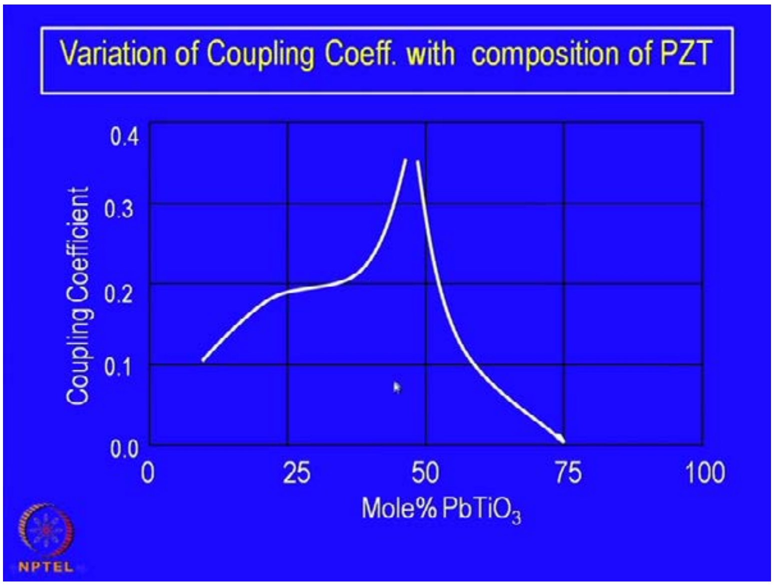

Once again it is plotted as a function of lead titanate percentage or mole percent lead titanate, and here what we plot is coupling coefficient. So, that is one of the very important properties of the piezoelectric materials. So, as we have discussed earlier it is the ratio of the energy conversion how much energy is given in or input energy to that of the or output energy to input energy, and one can see the coupling coefficient here is not only a function of the composition, but it goes to a maximum very close to the or exactly at the morphotropic phase boundary. So, that is the reason the composition of the morphotropic phase boundary at different temperatures are also important.

So, we get a peak of the coupling coefficient at the morphotropic phase boundary; that means when you are talking about PZT although it forms as complete solid solution between 0 percent to 100 percent composition either lead titanate or lead zirconate, but a useful more useful composition is in the round 48, 52 not exactly 50-50, but is allowed 48, 52. So, that is their importance because the coupling coefficient increases at the boundary composition not either rhombohedral or tetragonal phase. So, it is the boundary of that we get the maximum coupling coefficient.

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Piezoelectric Coefficients for a few selected Materials

Material	d_{33} (pC/N)	g_{33} (μV/N)
Quartz (SiO_2)	2.3	50
$BaTiO_3$	190	12
PZT	268-480	12-35
$PbNb_2O_6$	80	
$PbTiO_3$	47	
$LiNbO_3$	6	
$LiTaO_3$	5.7	

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With this background let us look at or comparison of the piezoelectric properties of certain important piezoelectric materials particularly ceramic materials here. Quartz although it does not have a perovskite structure, but quartz is a very good piezoelectric material, and its coefficient is about d 33 in this case; it is around 2.3 where as g 33 quartz coefficient is about 50. So, this is the coulomb per Newton and it is voltage per Newton. So, this is about 2.3 whereas that is 50. If you take barium titanate barium titanate is also a ferroelectric as well as piezoelectric material, and its piezoelectric coefficient d 33 is 190 whether where as the voltage coefficient is only 12. So, its impact less than the voltage coefficient are much less. It is about 12 compared to quartz whereas the strain coefficient and d 33 value is much more.

PZT is one of the most important and widely used piezoelectric material that is 268 it can vary; it can vary with composition with kind of impurities it contains, additional dopants you add. So, depending on that although we are just talking about PZT here, but actually it has many variations, and the composition may vary from different percentages of lead zirconate and lead titanate and also one can add different intentional impurities. So, it varies over a wide range about 268 to 480 which is much much larger which is much much larger than any of the other pyroelectric materials we consider here. In fact, these are the most important piezoelectric material and normally used in different devices.

So, far as the d 33 value is concerned is very very high. Its g 33 is also fairly large. Now in addition we have few other titanates or niabates; for example lead niabate d 33 is 80, lead titanate is another piezoelectric material, and it also has another important property we will consider that; it is also a pyroelectric material. It is about 47, lithium niabate is six, and lithium tantalate is still small. So, one has a very wide range of d 33 values piezoelectric coefficient and among them PZT is of course a much greater advantage compared to others.

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Selected Properties of PZT Ceramics

Property	PZT 5H (Soft)	PZT4 (Hard)
Permittivity (1kHZ)	3400	1300
Dielectric Loss (1kHz)	0.02	0,004
Curie Temperature (° C)	193	328
Piezoelectric Coeff. (10^{-12} m/V)		
d_{33}	593	289
d_{31}	-274	-123
d_{15}	741	496
Coupling Factor		
K_{33}	0.752	0.70
K_{31}	- 0.388	- 0.334
K_{15}	0.675	0.71

Now looking at PZT in particular it has different other properties an average property has been shown in the earlier table, but here we have presented detailed properties only of PZT. Incidentally PZT can be different industrial standards, industrial standards have been prepared for PZT material, and they have been designated by some numbers. For example, PZT 5H it is called soft PZT or soft piezoelectric material where as PZT 4 another industrial standard material, and it is called hard piezoelectric material. Well basically they differ in different compositions, there are different additions of impurities that maybe antimony, niobium oxide and so on are added and also one controls the microstructure.

So, by doing that just like soft ferrite and hard ferrite, hard ferrite means you have a large BH curve; similarly a soft ferrite has a very large area of the ferroelectric hysteresis curve whereas this has a smaller ferroelectric hysteresis curve. So, hard ferrite hard PZT means it is difficult to poll, polling needs higher voltage and however once you have polarized it, it is difficult to depolarize it whereas these needs relatively low voltage and also the Curie temperatures are different. So, Curie temperature for example, you can see here; this is much higher this is much much higher Curie temperature 323 whereas this is 193. So, compared to this one can enhance the Curie temperature to fairly large values.

So, there is one group of materials called soft piezoelectric materials soft PZT basically and this is hard PZT, and they have some kind of designations as well. Permittivity varies from 3400 to 1300. In this case it is about 3400, it is only 1300. Dielectric loss it is little higher whereas this is little lower. Curie temperature as mentioned this is 193 around 200 whereas it is 320 more than 320. Piezoelectric coefficients there are three different coefficients have been given here. One is d 33 it is 593, and this is for this group of compounds it is 289; this is minus 274 and 123. So, this group of material or this particular standard used for one certain application, and this has different applications.

So, 15, 741 and 496; coupling factor that is the energy conversion ratio is fairly high, we can say 0.75 75 percent and this is 70 percent. These are comparable. This is 38 and 33 whereas k 15 is about 67 and 70. So, these are more or less comparable, but the most important thing is their coupling coefficients are quite different and the Curie temperatures are quite different. So, in addition of course the permittivity that is the dielectric constant; dielectric constants are also quite different. So, you have two different standards industrial standards depending on their composition and depending on their micro structure. So, you have four different properties; you can vary the property to some extent.

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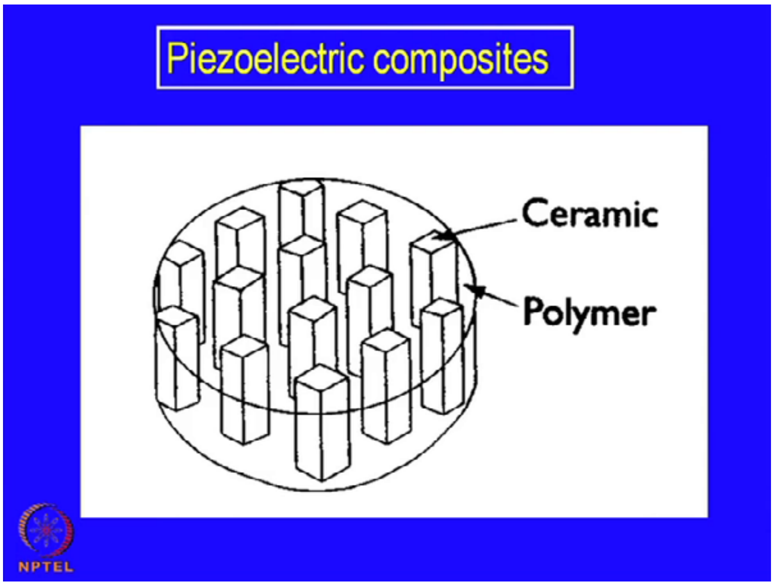

As you have seen PZT is one of the very important piezoelectric ceramics used in industry. We will see large number of applications in a few moments, but before that we like to introduce another group of compound another group of materials based on PZT or based on other piezoelectric material as well; that is called piezoelectric composites. Now they have a very useful application and useful properties. One has to consider here the ceramics is basically brittle material as we have discussed earlier as well, and in a piezoelectric effect we have both mechanical stress and electrical polarization. So, there is a correlation between that and each ceramics any ceramics which is used as a piezoelectric material has to be stressed mechanical stressed, but ceramics although have a high piezoelectric coefficient, but they have a very poor mechanical property particularly their elasticity is very low and sorry the their quite brittle materials.

So, you cannot stress; one cannot stress them to a large extent and therefore you have a limited application, the mechanical property because of the poor mechanical property, poor elasticity you do not get to utilize the real piezoelectric effect in whole range of stress. One way of avoiding it or improving the property is to make a composite with some polymer, and polymer may or may not have some piezoelectric property. Some of the polymers do to have some feeble piezoelectric property, but most of the polymer do not have the piezoelectric property, but it provides you the most important mechanical advantage. So, there is a important range of compounds or important range of materials or composites which have been prepared out of piezoelectric PZT and polymer.

Now this is one example what we have just shown this is one example of how these composites have been prepared or have been conceptualized. As we have discussed earlier that piezoelectric properties are directional properties. So, the alignment or the way the ceramics are aligned with respect to the matrix is quite important. Here one example has been given as if some of the rods square cross section rods have been embedded in a matrix of polymer. So, this is one example where all of them all the ceramic materials are aligned in a particular direction; they are not randomly placed. They are intentionally been placed in a particular direction. So, this particular compound or this particular composite, the kind of connectivity it has what they call the connectivity of these compounds or the composites this is one called the one three connectivity; that means the polymer is a continuous phase.

Polymer is a continuous phase and ceramics has connectivity only in one particular direction either z direction and one can say it is in the z direction. So, it is a one three connectivity. Polymer is connected in all the three different directions whereas they are isolated one can say rods or fibers whatever, you can call them depending on the dimensions; one can say it as rods or one can have these days with the advent or with the preparation of the nano fibers one can also have nano fibers of ceramics, but they are all aligned in a particular direction. Similarly you can have many different kind of composites once again with ceramic polymer composites. For example, one can have zero-three connectivity; zero-three connectivity means ceramics is actually in the form of particles or isolated grains, they are not even like rods or fibers.

So, rods and fibers are one dimensional whereas if you have isolated particles that will be zero dimension. So, from that concept it is actually a polymer be enforced with particulates PZT particulates or piezoelectric particulates can be called a zero-three connectivity. One can also have various other connectivity's like it can get be a three-three connectivity it is quite may difficult to make, but if you have a continuous porous structure of ceramic one can make a continuous porous structure of ceramics and that pores are filled up with polymer, that can be a three-three composite. One can have also a two-two composite; two-two in the sense polymer is continuous in the two dimension and the ceramics as well in the continuous in the two directions. So, basically that will be that will mean that we have a lamellar structure or an alternate layers, alternate layers of ceramics and polymers.

So, that can be, so polymer is continuous in the x y direction, ceramics is also continuous in the x y direction, but in the z direction none of them are continuous. So, one can have a lamellar structure or a layered structure of ceramic and polymer. So, there are many different ways; in this illustration we have just given only one that is one-three connectivity, but we can have many different connectives, and depending on that one can have different properties.

So, in which direction the stress is applied or will be applied in a particular device, and in which direction the voltage will be measured or reverse way which direction the voltage have to be applied and the stress is required. So, that way one can have different connectivity's and different composite materials. So, ceramic polymer composite in addition to pure ceramics is also a very important group of piezoelectric materials, and they have tremendous amount of industrial applications; we will try to discuss few of them in a few minutes. So, this is all about ceramic polymer composites.

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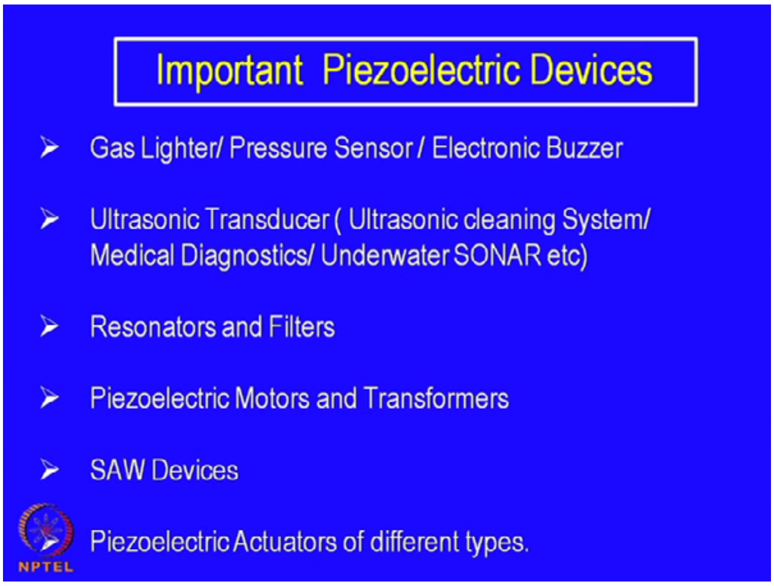

Well with this background we come to some of the important piezoelectric devices; that means the applications, application of the piezoelectric material. Well some of them we have encountered in our daily life; for example, a gas lighter, gas lightering in your kitchen one use as a gas lighter, and that is nothing but a piezoelectric or pyroelectric ceramics is suddenly a very high stress is generated which generates a very high voltage and then it is allowed to go to the ground. So, you have a spark. So, that is very simple but quite important application of piezoelectric material. Normally PZTs are used. Then you have electronic buzzers. Well if you want to make an electronic sound electronically by applying electric field you like to vibrate a particular by morph, and the frequencies can be varied by changing the dimension, changing the composition, changing the design of the vibrators.

So, one can really make different kind of frequencies generate different kind of speech for the same sound, and that is how most of the buzzers we use these days in different forms including the bell rings or the door bells or computers, alarm clocks, so many; so, many of them including your musical instruments all the musical instruments today you have the so called synthesizers, and the sound is actually made with the help of piezoelectric buzzers of different frequencies and different tones, different speech and so on. So, one can generate electronically different sounds. The loudspeakers today most of the loudspeakers even the even the mouthpieces are all made of a piezoelectric devices or pyroelectric; either it absorbs a sound wave and generates electricity electrical electronic signal which can be amplified or the reverse way one can give electronic signal and then generates sounds.

So, all this public address system most of them actually generate is based on piezoelectric buzzers or sensors. By the same principle one can use a huge variety a large variety of pressure sensors, load cells, load cells of different instruments and wherever we need to either measure the total load or the total or the particular pressure one can use this kind of a system. We are not going to the details of the designs and all these, but just using the basic principle of piezoelectric material or piezoelectric coefficient one can design different kind of load cells from few grams to several tons. So, there are of course complicated designs, but at the heart of these sensors there is always a small piezoelectric material of right property. So, gas lighters, pressure sensors and electronic buzzers are some very common examples or common uses of piezoelectric material.

In fact, one can say that among the electronic ceramics or electronic materials piezoelectric materials are most widely used, and the total number of devices one can make out of this is enormous various different types. Next we come to the ultrasonic transducers; once again this is another area where piezoelectric material has been extensively used for different applications. We all know about ultrasonic cleaners, ultrasonic baths or even for cleaning any particular system you generate expose it to ultrasonic waves and that actually losing the dots and so on.

So, ultrasonic cleaners and ultrasonic baths are extensively used for cleaning purposes whether it is semiconductor industry or any chemical industry everywhere many even in laboratory conditions we use ultrasonic baths or sometimes even what we call the sonification; sonification these days is a very important processing chemical processing instrument or technique by which one can make different kind of products or different kind of even ceramic powders can be made by sonification. So, all those ultrasonic sources use piezoelectric system or piezoelectric materials. So, that is one another very important area of piezoelectric application.

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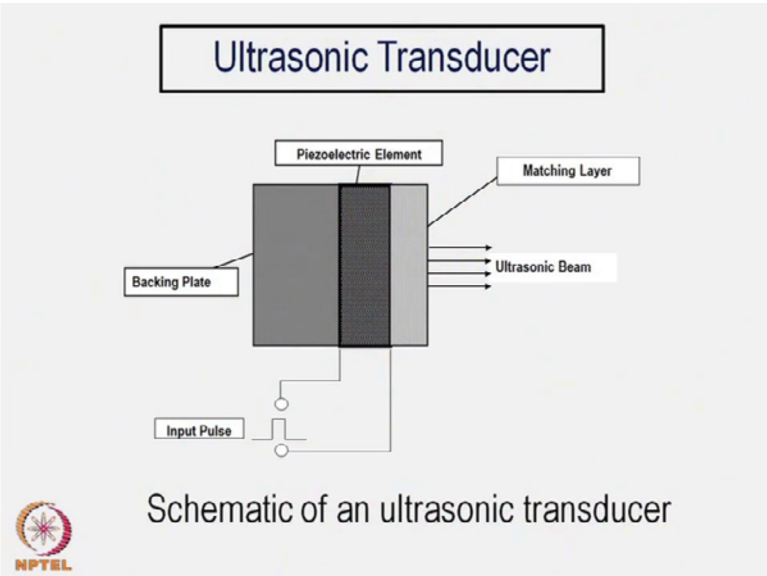

This is the basic structure of an ultrasonic transducer. Basically you have a piezoelectric material which is sandwiched between two layers; one is what we call the backing plate, other is called a matching layer. So, apply different pulses; it is of different frequencies and that responds this responds and generates ultrasonic waves or sound waves. So, it is mechanical, obviously, mechanical web. So, electrical signal is converted to a mechanical wave, and different frequencies can be made. It is not just by changing the pulse or pulse width or the frequency of the pulse, but by designing this particular structure one can change the frequency. It can be varied from kilo hertz to mega hertz and a it is a very very useful source for ultrasonic sounds or ultrasonic waves, and these are very thin of course; it is not very thin, both thick and thin depending on how much power you need.

So, if you need small power you can have a smaller device; if you need a very large power then one can think of even ring type PZT ceramics, very large size bulk PZT ceramics can also be used as transducers for different purposes. We will see some of the we will mention there is one application in submarines where they call it sonar's they can be several hundred kg's of PZT material can be used for that purposes. So, ultrasonic wave generators can be very thin very large sizes.

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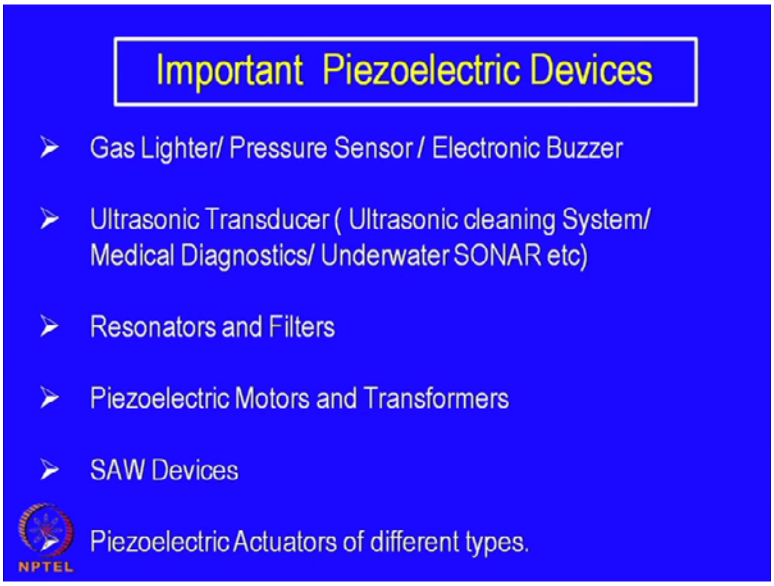
d 

Coming back now these ultrasonic transducers are extensively used for two very important applications, one is medical diagnostics. Medical diagnostics is an important area where we use ultrasonic transducers. Another area of course as I mentioned underwater sonar where one can detect any way sub marines; even sometimes one can detect the different kind of other species like fish and other things by ultrasonic sounds. So, the basic thing is you generate an ultrasonic the basic principle is for detection I would say; first of all you generate a ultrasonic wave, and that will allow it to reflect back. So, ultrasonic wave moves forward, reflects at a particular surface or an obstacle and then it comes back. So, it comes back. So, the same thing also acts as a source.

So, it is not only ultrasonic generator, but it also acts as ultrasonic source sensor. So, these source or the source and detectors becomes more or less becomes the same with some page lack. So, that is how because of the reverse property or the direct as well as converse property of the piezoelectric material the same material or the same system can be used either as a source to generate ultrasonic sound ultrasonic waves and also detect ultrasonic waves in the reverse manner. So, this is basically the technique by which a ultrasonic transducers is used of course, in cleaning systems you do not need feedback you do not need any kind of sensor it just generate the wave or it generate the ultrasonic beam.

But in medical diagnostics or underwater sonar we need both; you need a source and then the reflected beam or the reflected wave must be detected and it is characteristics both in intensity and the phase lack has to be measured. Now in medical diagnostics as you know we always use ultrasonic ultrasound techniques. So, all of them actually use basically a piezoelectric system. Now in these two systems we are actually trying to diagnose a fluid system, right, underwater it is the ultrasound is moving through a fluid medium and when it is moving to a fluid medium not to a solid medium.

If it is solid medium that is not a big issue because the material or the sense the generator is also a kind of solid, right, and the interface, interface if it is a solid-solid interface the problem is less; if it is a solid-liquid interface then the transmission becomes difficult because at the interface you have what we called a big impedance acoustic impedance. Acoustic impedance gets generated when the sound wave or the ultrasonic wave is generated within a solid medium and then moving to a liquid medium. So, there the impedance matching is very very important.

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Typical Properties of Ultrasonic Transducer Materials

	PZT Ceramics	ZnO Film	PVDF	PZT-Polymer Composite
k (Coupling Coeff.	0.45-0.55	0.2-0.3	0.2-0.3	0.6-0.7
$\varepsilon_{33} / \varepsilon_o$	2000-5000	~10	~10	50 -2500
Tanδ (%)	<1	<1	<1	1.5-5.0
Q_m	10 -10000	~10	5-10	2-50
ρ(g/cm³)	5.5 -8.0	3.0-6.0	1.0-2.0	2.0-5.0
Z (Mrayls)	20-30	~35	1.5-4.0	50-2500

And some of the properties which are important, alright; some of the properties which are listed here you can see one of them is z. One of them is z is the acoustic impedance just like electrical impedance an equivalent of resistance. So, here also you have an acoustic impedance and that is very important; that is very important for proper transmission of the wave from the solid medium to the liquid medium, and you can see PZT ceramics this is about 20 to 30 that is the impedance whereas there is one variety of polymer which is PVDF polyvinylidene fluoride that is also a piezoelectric pyroelectric material of course, with a very low coupling coefficient relatively low coupling coefficient and the epsilon prime is also quite low. So, the dielectric constant here is quite low about 10 whereas the dielectric constant of ceramics is very very high and that makes that creates little bit of problem so far as the z value is concerned.

So, that z value I think there is little mistakes here. It should not be this value must be low, this value must be low I have to check; I have to check this value, I think it is not right, because the dielectric constant of PVDF is much smaller but for that matter for any polymer dielectric constant is relatively low whereas PZT being a ceramic material and the dielectric constant is much higher. So, one needs a lower dielectric constant material at the same time better coupling coefficient as well as the quality factor, the quality factor mechanical q comes from the high coefficient the piezoelectric coefficient. So, its piezoelectric coefficient is less, but it is density also low, and the dielectric constant is also low whereas these three values for the PZT ceramics or any ceramics for that matter is very high; density is high, the dielectric constant is very high and consequently we have a very high z value.

So, normally to reduce the z I will check and find out this is not the value. This is one we mix; we have talked about PZT polymer composite or ceramic polymer composite for the piezoelectric materials, and in such cases where you need low impedance and lower dielectric constant you mix up with PZT with polymer. So, you make a polymer ceramic composite, and those are very important; those are very important for the medical diagnostics as well as some of the sonar applications. So, this is a very important compound which is used for the transducer applications, compared to PVDF of PZT we get a much better properties here, and that is where polymer ceramic composite becomes quite handy so far as the transducer application is concerned.

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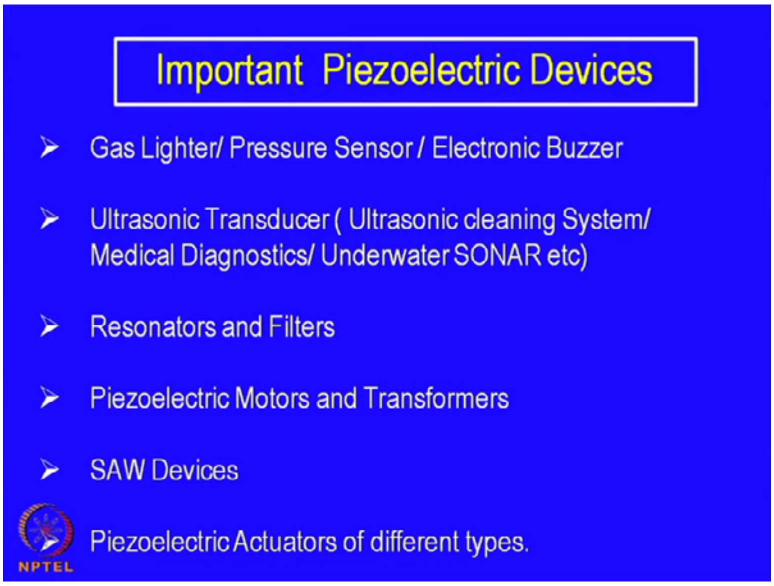

So, medical diagnostics we have discussed and then underwater sonar; underwater sonar of course, again one needs a good impedance matching with water and therefore, polymers ceramic composites are quite useful. The purpose of the sonar is basically general. It is use primarily in sonar in submarines or the navy ships where you want to detect under the water any enemy ship or enemy submarine and so on. So, you generated ultrasonic wave, get it reflected from the enemy ships and then you detect it. So, by that process one can find out the detection of the some obstacles in presence or in front of the navy ships or navy submarines.

Another very important area which has not been listed here, but once again ultrasonic transducers are very important for that; that is for flaw detection, flaw detection in metallic systems or even any other material systems. It is the ultrasonic flaw detection system, and there also you generate some flaw and then generate some ultrasonic wave ultrasonic signal, then let it transmit through the material and after it is getting reflected from a crack or a grain boundary and so on one can particularly if there is a pore or a flaw crack particularly. So, a crack gets deflected and you get the detection. So, that is a very important technique of ultrasonic flaw detection system. So, that is all so, far as ultrasonic transducers are concerned there may be many other applications, but these are more important applications.

Then the other category is resonators and filters once again a very important component of electronic systems; in many of the electronic systems one needs either resonators with some frequencies, and then also you need filters where one particular frequency has to be isolated from a band of frequencies and there also this piezoelectric detections piezoelectric filters are important and the construction of such filters is like this; no this we have discussed earlier.

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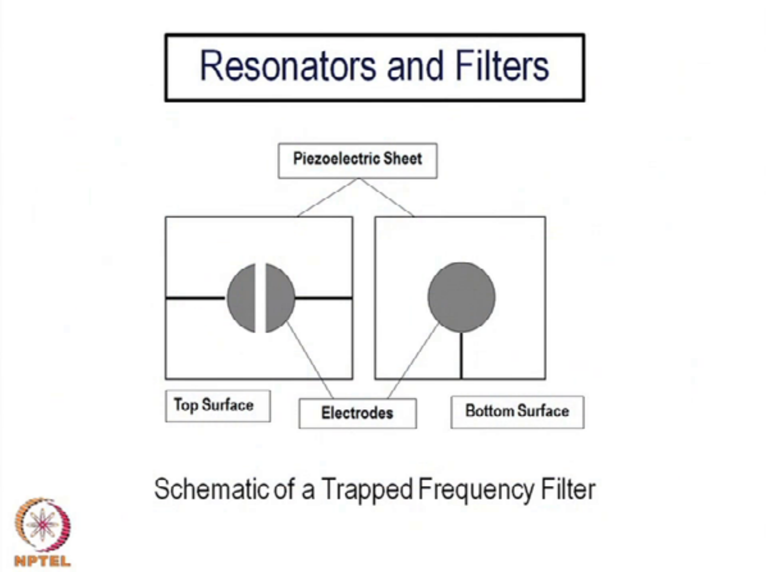

So, this is a resonators and filters. In fact, it is a thin wafer kind of piezoelectric system, and then you have two electrodes. One is the bottom electrode which is fully circle or circular electrode whereas the top electron one of the electrodes has been bifurcated into two pieces or isolated by an insulator. So, these are conducting layers where as one surface is full circle where as the other surface is actually a half circles and by that because of the electronic or piezoelectric coupling one gets a very bandwidth particular signal is allowed to pass through; the other particular other signals or other frequencies are not allowed pass through and therefore, you have what they call a trapped frequency filter. So, there are many different kind of filters, but these are piezoelectric filters is one also another application where you use this piezoelectric materials

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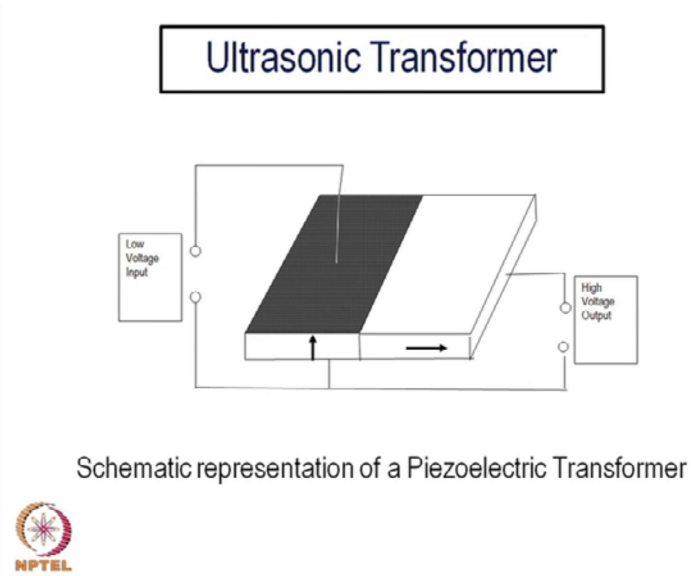

Piezoelectric materials are also can be used as what they call ultrasonic transformers. Here again you have two pieces of material impact as one knows that in a transformer actually you isolate two different electrical signals; they are not connected, but they are isolated, and one arm of the isolated has a one particular signal, another arm of the transformer another signal. Here also one has this kind of an isolation; one is isolation, the other is a of course the multiplication. The low voltage can be transformed converted into high voltage whereas of course one can see two different types of two pieces of piezoelectric material they are polarized in two different directions. One is along the z axis and another one is along the x or y axis.

So, by that process one also can get an ultrasonic transform, but the most another very important area of application of ultrasonic or piezoelectric material is ultra piezoelectric rotors or piezoelectric motors. So, it is not only transformer one can have a piezoelectric motor in which actually something can be allowed or made to move made to move or rotate. So, that is unfortunately I do not have the particular schematic picture of that, but one can make very very thin or very tiny tiny motors just like a rotor and stator in a electromagnetic system.

Here of course it is not an electromagnetic system; it is actually a piezoelectric system and piezoelectric system can be made and can be designed to make very tiny motors. These tiny motors are in fact one of the tiniest size possible; I understand it is about two to three millimeter in diameter and about a centimeter in length. So, as small as that motors can be manufactured and can be designed with the help of piezoelectric material then they are actually used in many of the electronic cameras particularly the autofocus cameras where the lens is allowed to move through the help of piezoelectric motors.

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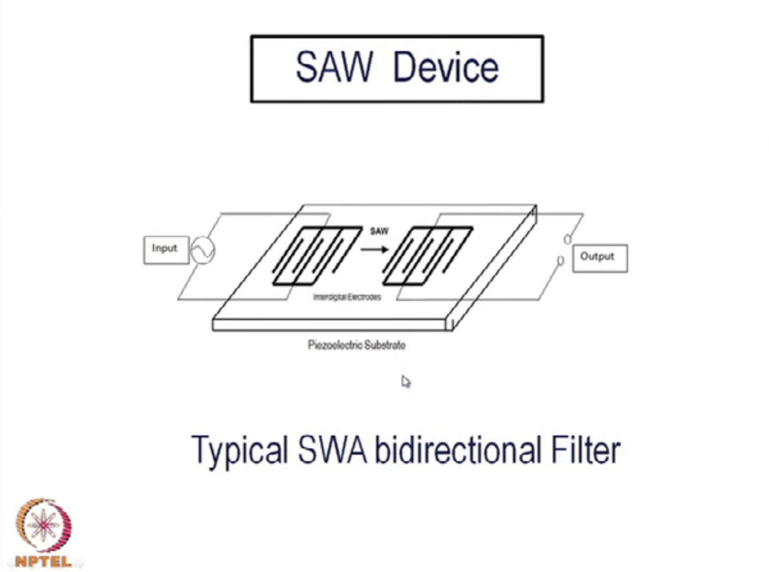

Other important device or one important use of piezoelectric system or piezoelectric material is what I call SAW devices. Its saw sensors sometime saw sensors are also used for many gas detection or moisture detection and so on, but in addition more importantly they are used in many different kinds of electronic systems. Saw device is basically a surface acoustic waves. So, by what I called inter digitized electrodes a finger kind of electrodes on the surface of a substrate the piezoelectric surfaces is this one; it can be used either PZT is not normally used, it is mostly zinc oxide or lithium tantanate, lithium niabates that kind of substrates are mostly used for making a saw device surface acoustic waves.

So, the acoustic waves are generated not through the bulk of the material, but it is on the surface, and that there are normally a pair of such things such interdigitized electrodes the surface waves comes there generates there and then gets detected here. So, one can generate the surface acoustic waves on this and then detect it here, and in presence of different environment as I just mentioned if there is a moisture or some gas this acoustic waves gets changed, all their characteristics as well as the velocity as well as the phase difference gets changed and therefore, one can detect the presence of such species, the environmental species like that. So, it needs a piezoelectric coupling to generate this kind of surface acoustic waves.

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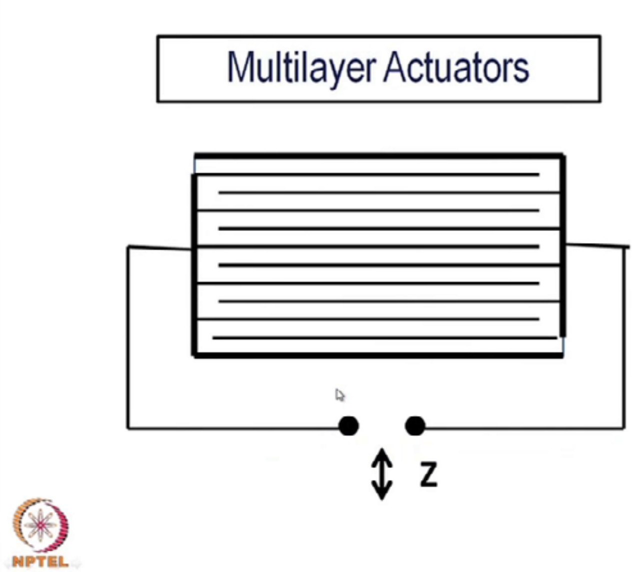

This we have mentioned earlier also that actuators impact piezoelectric materials are used both as sensors and actuators, because it has direct effect as well as converse effect. So, for pressure sensors we have that is basically a sensor whereas an actuator also makes a movement mechanical movement by application of an electric field. So, one can use a single layer actuator just like a singular layer capacitor or a disc capacitor, here also one can use a disc actuator a single layer actuator or a multilayer actuator, and the basic principle is very similar to the multilayer capacitor.

So, there are very thin layers of piezoelectric material and then we have metal electrodes in the form of thin films basically thick films, right. So, depending on the number of the layers the actual actuating of the load bearing capacity, load bearing capacity of this will be very very high or can be increased or decreased. So, this is another area where piezoelectric materials are extensively used actually multilayer actuators.

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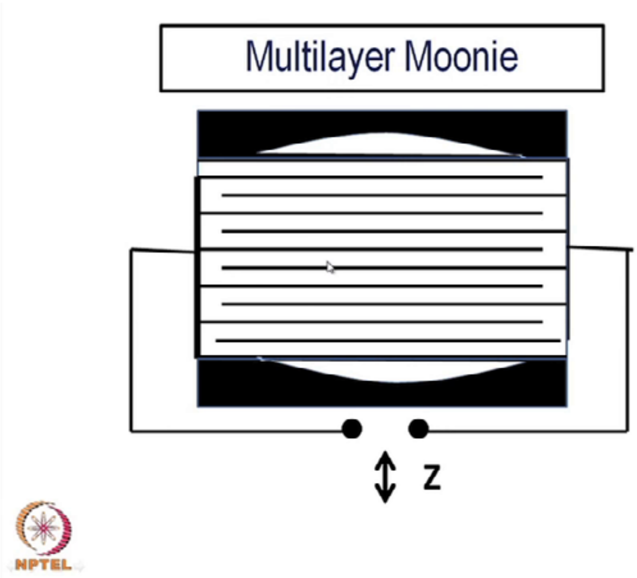

We have seen earlier the single layer Moonie, and this is also multilayer Moonie. So, just by we have a metal plate here, and that is to enhance the actuating property of the multilayer actuators.

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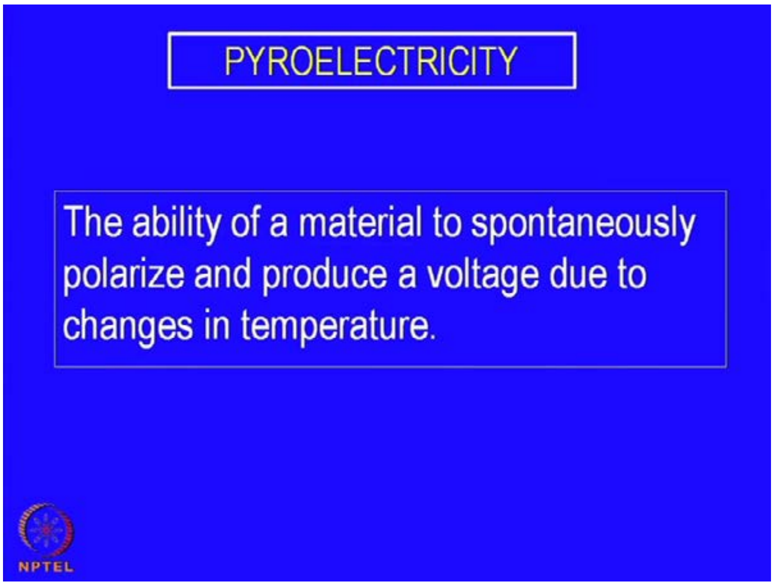

Well that was more or less one thing I forgot to mention. So, far as the ceramic or the piezoelectric motors are concerned, not only their miniature, miniature as in size, but their torque is very high compared to the electromagnetic motors the torque is very high at a much lower voltage, and it does not of course make any sound as it is very tiny, and there is no electromagnetic effect. It is only very tiny voltage is required to move and therefore, one can have almost noiseless movement, and the torque overall torque compared to a size much larger. Anyway that was more or less a discussion on piezoelectric material.

The last topic in this series is pyroelectricity; the ability of a material to spontaneously polarize and produce a voltage due to changes in temperature. We have seen earlier as you apply a electric field the material gets polarized in a dielectric material in a piezoelectric material as you apply a mechanical stress the material gets electrically polarized. Here is another phenomena where you change the temperature not electric field not the mechanical stress, but just change the temperature, and that will spontaneously polarize the electrically polarized material, and that kind of material is pyroelectric.

They are basically insulating material or dielectric material, and there is a relationship between ferroelectricity, piezoelectricity and pyroelectricity. So, all piezoelectric and ferroelectric material is actually pyroelectric, but their pyroelectric coefficients may not be very large. In principle they have a pyroelectric property, but there the coefficients may not be very large and therefore, all the materials are not used as a pyroelectric material.

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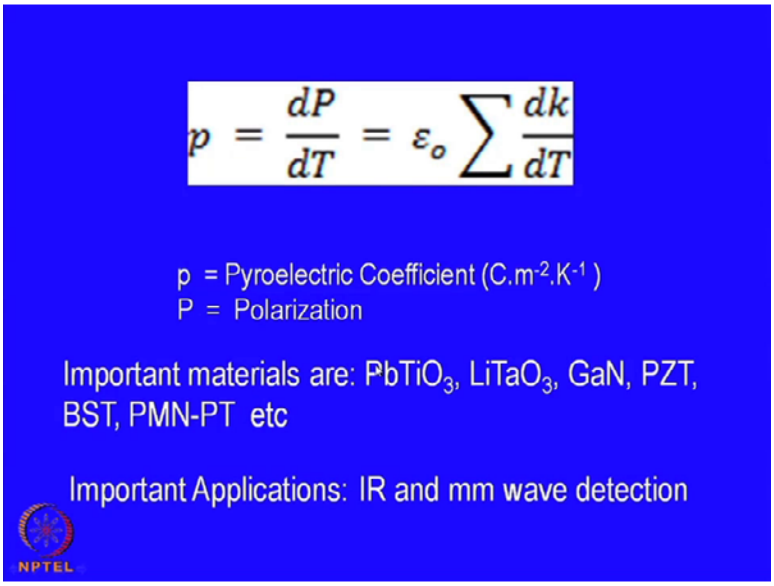

This is the pyroelectric relationship, the pyroelectric coefficient p equal to d p d T; P is the polarization electric polarization as a function of temperature, and that is the summation of different terms that is the permittivity of the free space. The important materials we will not be going to the details of this, just to summarize this effect important materials are lead titanate is one of them, lithium tantalate, gallium nitride, PZT also has some pyroelectric property although may not be used to that extent. BST is basically a barium strontium titanate and PMN-PT, PMN-PT we have discuss in terms of the ferroelectricity, and this is lead magnesium niabate and a solid solution of lead magnesium niabate with lead titanate; that also has a good pyroelectric property.

Important applications are primarily because it is the temperature effect. So, one can detect the infrared. If there is an infrared radiation one can certainly detect because it will generate some voltage, it generates some voltage and that can be processed; infrared cameras one can really design infrared cameras based on pyroelectric materials or pyroelectric sensors. So, that is a very very important area; it is in fact a strategy area. Infrared detection is one of the very important strategic techniques or used in strategic areas for detection of different items or different even different systems and millimeter wave of course is of same area. So, IR and then still further high up is the millimeter wave. So, pyroelectric materials have been used. There are many other sensor of course to detect IR, but pyroelectric material is one of the techniques by which one can measure IR interact.

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Pyroelectric Coefficients for a few selected Materials

Material	Coefficient (10^{-6} C/ m^2 K)
$BaTiO_3$	20
PZT	380
$PbTiO_3$	170
PVDF	27
Cement Paste	0.002
BST	
PMN-PT	

Different materials like this there are this is the coefficient pyroelectric coefficient of different materials, barium titanate you can see 3 z PZT is quite high, lead titanate is also fairly high, PVDF one of the pyroelectric polymers has also some pyroelectric effect, even cement paste have certain amount of pyroelectric coefficient. So, there are many BST and PMN-PT also have some pyroelectric importance from the point of view of pyroelectric property; unfortunately this coefficients are not with me at this point of time, but the materials are important.

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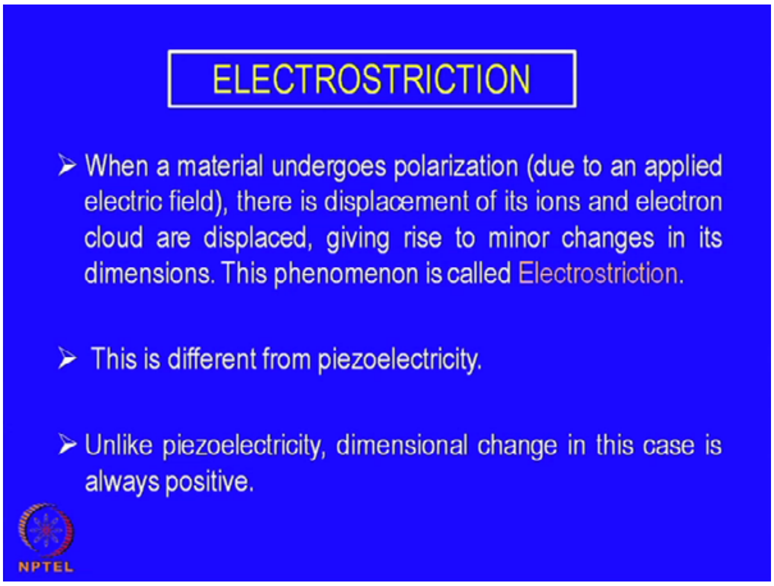

Finally the last slide in this I think is the electrostriction; maybe you were aware of the so called magnetostriction. Whenever there is a magnetic field there is volume change or dimensional change on the material, and similarly there is a effect called electrostrictive or electrostriction effect where a material undergoes polarization due to an applied electric field, there is a displacement of its ions and electron clouds are displaced giving rise to minor changes in its dimension. So, there is a lattice change and therefore, any polarization ultimately leads to a dimensional change, this phenomenon is called electrostriction. And this electrostrictive property or the electrostrictive property is quiet predominant in the relaxer ferroelectrics like lead magnesium niabate kind of materials.

And in fact, although it is little different from piezoelectricity, but this property can be also made use of in some cases. So, this is different from piezoelectricity, but it is also not a reversible process whenever there is a polarization there will be a dimensional change in the positive sense not normally a in the negative sense. So, electrostrictive is another area. In fact, the humming noise you get from the transformers is primarily for the magnetostrictive property. So, because of the magnetization you get a dimensional change, here because of the polarization electric polarization you also get a dimensional change and that is what we know about electrostrictive property. That completes more or less our discussion on the dielectric property that the insulators, we have a earlier discussed ferroelectricity, piezoelectricity as well as pyroelectricity, and their characteristics, their properties, as well as some of the important applications in brief. Of course I did not have much time to go into the details of the piezoelectric devices and the design, and the kind of basic working principal of them. But I have just given you some idea about how these piezoelectric materials can be used for different purposes.

Thank you so much for your attention.