Electroceramics
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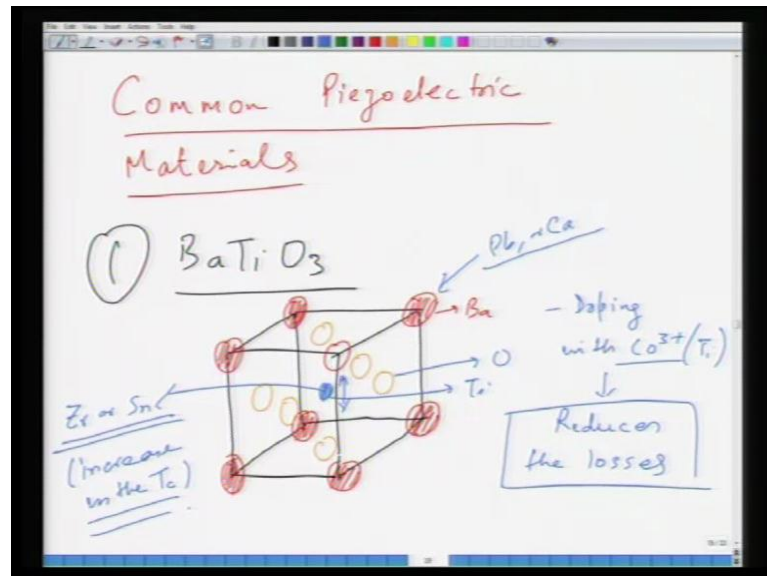
Lecture - 31

What we will first do is that, we will review the last lecture and then we will start the contents of this new lecture. In the last lecture, if you remember, we started our discussion on piezo electroceramics. Basically, piezoelectric effect can be divided into two effects: one is direct effect and second is indirect effect. And, direct effect is basically creation of polarization or change in polarization when you apply stress on the... And, this gives rise to change in the charged density on the phases of the piezoelectric material. And, the converse effect is essentially when you apply electric field, then you generate the strain in the piezoelectric or deformation in the phases of the piezoelectric. And, these two effects are very useful effect as we will see some of the applications.

And then, in order to make piezoelectric material useful, you need to pole it. And, poling essentially means is that, in the virgin state, piezoelectric does not have any remnant polarization; which means it is not very useful as a piezoelectric. It must have some remnant polarization to be used as piezoelectric. So, you pole it and then bring it back. When you pole it... Poling means application of electric field. So, when you apply electric field, the domains as you know from the ferroelectric discussion, domains start orienting themselves along the direction of an electric field; and then, you make the electric field back to 0; then, not all the domains change their orientation. As a result, the net polarization is not equal to 0. And then, when you apply stress, then you get polarization at the phases of piezoelectric. And, when you apply electric field, you get the deformation.

And there are variety of materials which show this effect. You have Quartz; you have Rochelle salt; you have barium titanate, lead titanate, lead zirconate titanate – variety of materials. And, the piezoelectric constant for these materials can be quite high. Some of these materials show piezoelectric constant as high as 200, 300 picometer per volt, which is a very large displacement from the device point of view. And then, finally, we looked at, just like you have to pole a piezoelectric material to use it, you can also depole it. And, depolarization of piezoelectric is essentially loss of polarization upon either thermal

cycling or electric cycling or stress cycling. So, we looked at all these three mechanisms in a cartoon and animation and then... So, you can go through them again.

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Now, what we will do in this lecture is we will look at some of the common piezoelectric materials. And, among this category, the first candidate, which is simple piezoelectric is barium titanate. And, this barium titanate – as you know already, it has a peroxide structure. So, you have this barium titanate unit cell; and, this material is ferroelectric below the Curie temperature; and, Curie temperature happens to be roughly 120 degree centigrade. And, this material is a very useful material; in the sense of uses, it is easy to make. And, the ionic positions if you remember; you have oxygen atoms sitting at the phases. And then, you have barium atom going on the corners of the unit cell. And then, you have a smaller titanium atom going at the centre of the unit cell. So, this is barium; this is titanium; and, this is oxygen.

And, this is a very useful material in a sense that, it has a simple crystal structure. It can also be doped by variety of elements like cobalt. So, doping with cobalt is cobalt 3 plus ions is very common. And, this leads to reduced losses in the material. So, cobalt reduces the losses. So, this is a useful property, which happens when you dope it. Now, doping – although it sounds very easy, one must take enough care during processing, so that you do not have reduction of cobalt 3 plus to cobalt 2 plus; which is also a possibility, because CoO is a stable state as well. And then, you can also replace. So, cobalt can

replace titanium. And then, you can also replace titanium atom by zirconium or tin. And, these lead to increase in the T c. So, it also tends to enhance the piezoelectric properties. And, you can also replace barium. Barium can be replaced by bigger ions such as lead or calcium. And, they happen to lower the T c of barium titanate especially from tetragonal to orthorhombic transition, which happens below 120 centigrade. So, basically, all these dopants can be used to control the piezoelectric property of the material. And, you know the polar vector of barium titanate is along 0 0 1 axis in the ferroelectric state; where, it has a tetragonal structure. So, I am not going to spend too much time on this structure, because we have already discussed this structure in the ferroelectric materials. But, just as a material of interest, I am going to tell you about this little bit.

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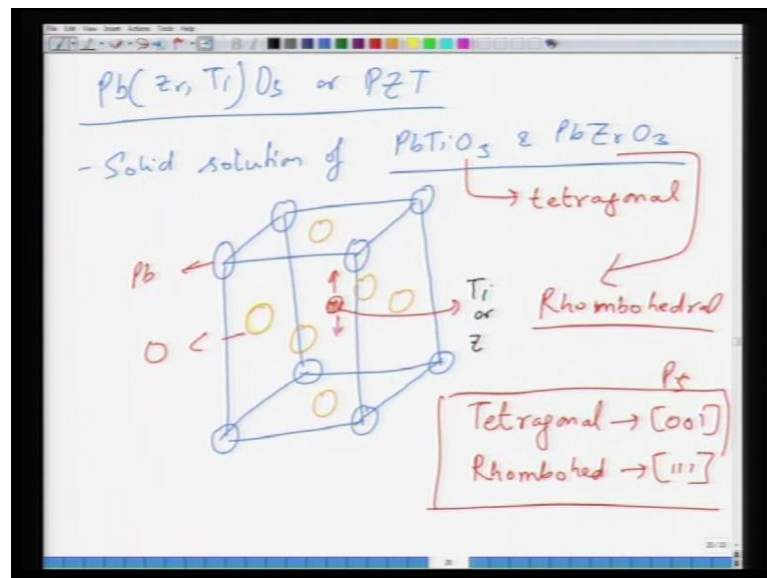
The next material of interest is which is actually more important than this material is lead zirconium titanium oxide or often called as PZT. And, this is a very important material. It is a solid solution of lead titanate and lead zirconate. So, basically, what it has is it has a peroxide structure of the type lead titanate, where the B-site is randomly occupied by either of titanium or zirconium ions. So, you have again the similar sort of structure. So, you have lead ions sitting here and oxygen ions go to the... Let me use a different colour. So, oxygen ions go to the phases – phase centres; the central atom is titanium. So, titanium is shifted towards this axis if the structure was tetragonal. And, if the structure was rhombohedral, then it would be shifted along 1 1 1. So, it has two structures essentially; the parent structure of lead titanate is tetragonal in the ferroelectric phase;

and, this is rhombohedral. So, depending upon the composition, depending upon the proportion of lead titanate and lead zirconate with respect to each other, the material is PZT either adopts a tetragonal structure or rhombohedral structure. Tetragonal structure has a polar vector along 0 0 1; and, rhombohedral structure has along 1 1 1. So, this is a difference, which occurs when you go from tetragonal to rhombohedral side. And, the phase diagram of this material is... Just before we go to phase diagram, let me complete this. So, you have here lead atom. Then, these are oxygen atoms. And, this atom is titanium or zirconium – Ti or Zr. So, this B-site is randomly occupied by either of titanium and zirconium ions.

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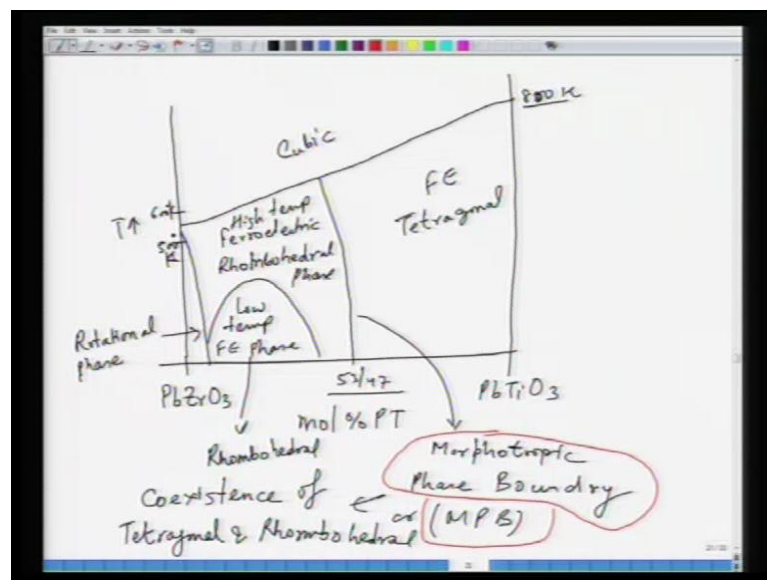
Let me show you the phase diagram of this material. You have... It makes a continuous solid solution. What you have is on one end, it is a pseudo binary diagram, phase diagram. So, you have Pb Zr O 3. And then, you have Pb Ti O 3. And, if you plot with respect to mole percent PT, which is lead titanate; you get something like... And then... This point corresponds to... What you have here is, you have a cubic phase here; and, this is temperature. And, this is somewhere between... So, this is about 500 degree centigrade and this is somewhere around 600 degree centigrade. And, here you have lead titanate, whose Tc is significant – kelvin, not centigrade. So, you have kelvin and this is approximately 850 kelvin or so; or, maybe 800 kelvin or so.

You have cubic at the top, which is above this phase boundary, which is on the top. And then, between these phase boundaries, you have here in this region, what you have is called as a rotational phase. In this phase boundary, you have ferroelectric rhombohedral phase. And, what you have here is... This is high temperature rhombohedral phase and then this is low temperature rhombohedral phase. Now, there is some demarcation, which has been shown by scientist between these two phases; details of which we are not going to go into; it is beyond the scope of this thing. But, what you have is some distinction between these two phases. So, low temperature ferroelectric phase here; and then, again, this is rhombohedral in nature.

And then, you have tetragonal phase here – ferroelectric tetragonal phase here. So, you can see that, across this boundary, which is this phase boundary; on one side on the lead titanate (( )) side, you have tetragonal ferroelectric phase; below the top phase boundary, below the transition, because this top phase boundary depicts a transition from ferroelectric to paraelectric phase; or cubic – this is paraelectric phase. And, on the left of this phase boundary – vertical phase boundary, you have a rhombohedral ferroelectric phase, which is again below the cubic region.

Now, this boundary, which separates these two regions, is called as a morphotropic phase boundary or it is called as MPB. So, this MPB is of immense importance, because what happens is that, across MPB, you have existence of either rhombohedral structure or tetragonal structure. But, the moment we come to MPB, whose composition happens to be around 53-47. So, 53... or roughly about 50-50 let us say. So, around this morphotropic phase boundary, what you have is coexistence of both these phases. So, at these MPB, you have coexistence of tetragonal and rhombohedral phases. So, if you take morphotropic phase boundary composition, you are likely to have both of these phases present if you have made the sample properly.

And, this morphotropic phase boundary as a result results in a large enhancement in the property. Why it happens is, because since you have both the phases present; you have tetragonal phase present; you have rhombohedral present; and, both of these phases have polar vector in different directions. As a result, when you use the material when you apply electric field or stress to it, you have many polar directions, which are available for piezoelectric activity. As a result, the poling of this material becomes very easy. So, this material near MPB composition, which is 50-50 composition has a very significant

importance for variety of applications simply because the properties are enhanced significantly near this composition. And, remember, this is called as a morphotropic phase boundary; let me just circle it for you; or, often called as MPB. And, this MPB composition in PZT is an extremely important composition from the technological point of view because of enhancement of properties.

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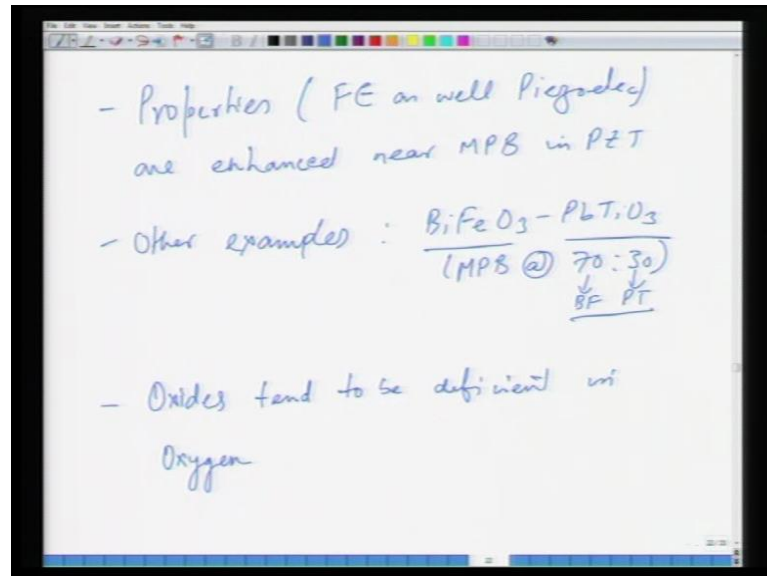
You can write here – properties which are ferroelectric as well as piezoelectric are enhanced near MPB in PZT. And, this is also true about other systems as well. Not only PZT; other examples are for instance, Bi Fe O 3, Pb Ti O 3. So, again, Bi Fe O 3 is also ferroelectric Pb Ti O 3 is also ferroelectric. And, both of these make a continuous solid solution. And again, they also exhibit an MPB at 70:30 composition – 70 percent bismuth ferrite and 30 percent lead titanate mole percent. And, at this composition, again in this system, one – the transition temperature is high, because lead titanate, bismuth ferrite transition temperature is much higher than lead titanate transition temperature. So, overall solid solution has reasonably high transition temperature to the piezoelectric coefficient as well as polarization attain a large enhancement near the MPB at least in the bulk form and thin film form. So, this is... So, PZT is a very important material from this point of view that, especially near the morphotropic phase boundary composition.

Now, you can change the properties of PZT by doping again. Just like in case of barium titanate, if you dope it with other elements, the properties change. Now, typically, what

happens is that, most of these oxides tend to be... Oxides tend to be deficient in oxygen. And, from the defect chemistry, you know...

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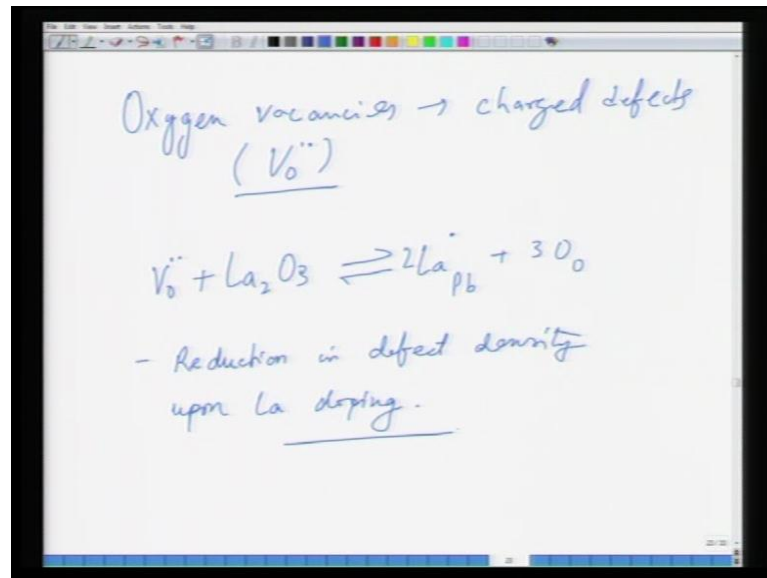
Now, oxygen vacancy is... Now, these are charged defects. The moment you have charged defects, you have problem with the conduction. As a result, the conductivity of sample is higher and the sample tends to be lossy and conducting. Now, how to get rid of this problem? If you have oxygen vacancies, which are noted by V o o dot dot; which means they contain two positive charges. If you dope the material by let us say element like lanthanum; if you dope the material like La 2 O 3; lanthanum goes to let us say on lead site or titanium site; it goes to lead site and P Z L T S. And then, what you have is basically, lanthanum carries one extra charge. As a result, it carries one positive charge. Now, two lanthanum will go to 2 lead sites; three oxygens will go to three oxygen sites. So, you need to create... So, what can happen is you need to create either... Now site balance is not maintained, because for each lead, you have one oxygen.

Now, here we are using three oxygens for two leads. So, site balance is not maintained. In order to do that, if you have an oxygen vacancy here, V o o; this V o o is compensated by this extra oxygen. So, not only... So, two oxygens go to the regular oxygen sites and another oxygen goes to the vacant oxygen site. Thereby, if you look at the charged balance, two positive on the oxygen vacancy; two positive on the two lanthanum sites; and, lanthanum occupying lead sites. And, this maintains the charge and site balance.

But, also, it reduces the reduction in the oxygen vacancy. And, this leads to improved properties of the material. So, basically, reduction in defect density upon lanthanum doping. And, these defects also have... Not only they increase the conductivity, but they also tend to impede the domain motion, because you know that, the domain in the ferroelectric materials – they nucleate and then they grow. So, this growth of these domains; or, when you switch the material, the switching of domains is impeded by these defects. These defects typically pin these boundaries. And, these boundaries are not able to move the way you would like them to move. As a result, the properties degrade. So, this particular aspect can be tackled by doping with appropriate elements, which lead to reduction in the defect density. And, this has also other advantages – it reduces the dielectric losses; it also improves the coupling coefficient; and, it also leads to reduction in the coercivity as a result of easy domain motion.

What we are going to now do is... We have discussed these two materials, which are important materials. There are variety of other materials as well, which are reported in the literature. If you go to the journals and some books, you can find discussion on other materials as well.

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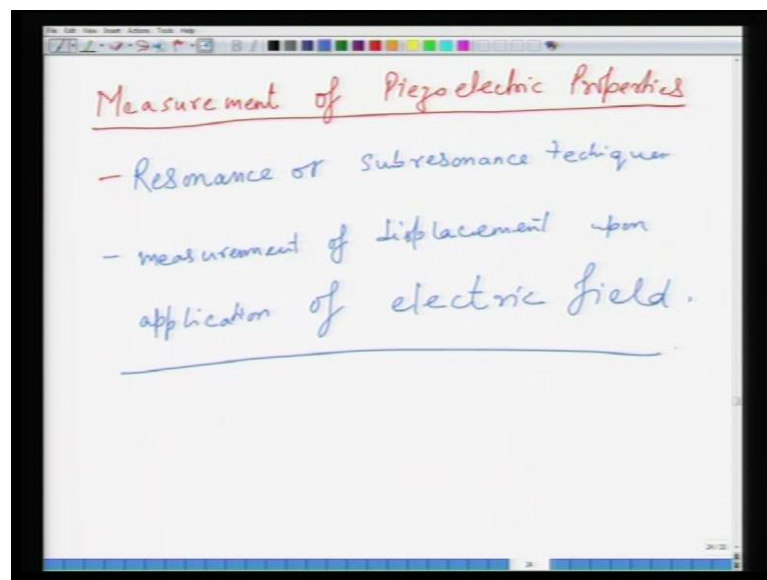
Now, what we will do is that, we will look at how these properties are measured. The measurement of piezoelectric property or piezoelectric material is important. And, these techniques are typically called as resonance. And basically, these measurements are used

to measure a displacement when you apply electric field. So, basically, they rely on measurement of displacement upon electric field.

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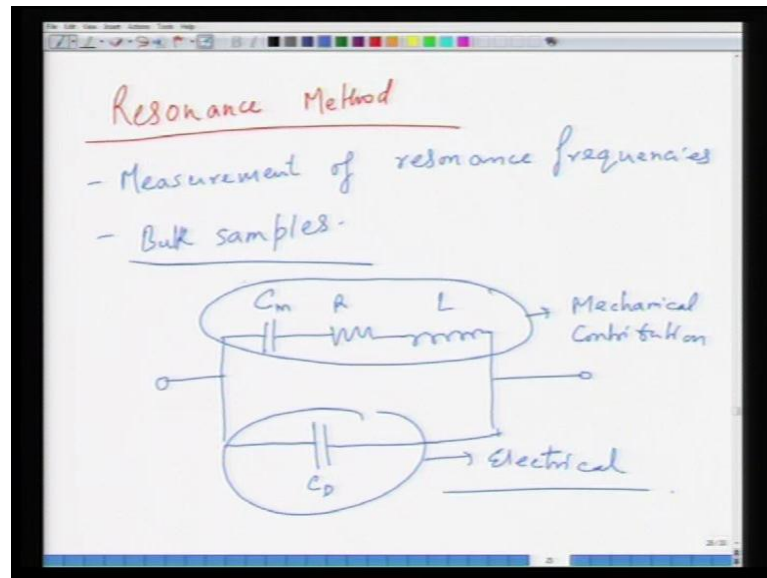
Now, what happens is in the resonance of... First, we will discuss the resonance technique. In the resonance technique, you measure the characteristic resonance frequency of the material, which depends upon the frequency application of the alternative field. And, this is ideally used for bulk samples. So, essentially, it is about measurement of resonance frequencies. And typically, it is used for bulk samples. And now, we can also model this response of the material by electrical circuit. So, basically, you have this electrical circuit. You have this capacitance; and, C is with the resistance; and then, you have an inductance, which is in parallel with the capacitance again. So, this part of the circuit... Basically, this is C m, R, L, and this is C D. So, the variety... And, this equivalent circuit gives you the sort of models and behaviour of the material well enough.

And, this part – top part of the circuit represents the mechanical contribution. And, this part represents the electrical contribution. And so, this... So, basically what the response of the material is electromechanical. As a result, you have coupling of electrical and mechanical parameters. As a result, you need to separate out the electrical part and the mechanical part. And, this is what the circuit does. It separates the electrical and

mechanical parts. And, this happens... And, this is applicable when the frequencies are close to a characteristic or resonance frequencies.

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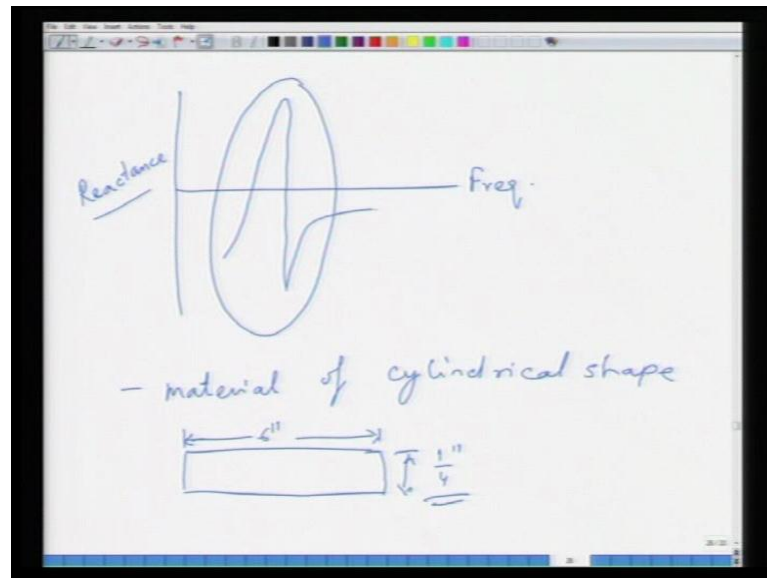
What you basically do is that, when you plot as a function of frequency, because you are applying AC field. AC field is frequency dependent. At some frequency, you are going to have resonance, which is going to occur. So, what you have if you measure the reactance; now, this reactance goes as... So, this is your resonance. And basically, you are interested in calculating the frequency around which this resonance occurs. And typically, for these measurements, you take a material of cylindrical shape – essentially a rod. And, this rod could be about 6 inch in length; and, diameter – it is about quarter inch. So, these kinds of samples are taken for these measurements. And, when you plot electrical reactance as a frequency, then you come across the characteristic frequency, which is basically the frequency that you want to measure. And, there are two frequencies here: one is the series frequency; second is the parallel frequency. And, you need to be able to... And, you can utilize these frequencies to determine what is called as a coupling coefficient.

This coupling coefficient, which is k 3 3 – this can be expressed in terms of series and parallel resonance frequencies. So, this k 3 3 can be... This k 3 3 is square basically, is equal to pi by 2 into f s by f p multiplied by tan of pi by 2 into f p minus f s divided by f p. This f s is series resonance frequency and f p is parallel resonance frequency.

And, if you use this relation along with the elastic compliance; elastic compliance as we know is denoted as s E 3 3 at constant field. And then, low frequency dielectric constant is epsilon 3 3 r. And then, piezoelectric coefficient is d 3 3. And, if you couple the k 3 3,

the coupling coefficient as we measured in the previous slide; as we wrote in the previous slide, if you couple with these two parameters, you can determine d 3 3. So, d 3 3 is equal to k 3 3 multiplied by s E 3 3 into epsilon 3 3 x to the power half. So, this is the expression for determination of d 3 3. So, just by applying electric field to a rod sample, you measure the reactance of this sample by modeling in terms of electrical circuit. Find out the series and parallel frequencies and then put these frequencies in the expression of k 3 3 to find out k 3 3. And, if you know the elastic compliance of the material and low frequency the electric constant, which can be found out from the dielectric measurement, you can determine what is the piezoelectric coupling coefficient.

Now, the limitation with this process is that, resonance frequencies of the sample are determined by the fundamental vibration modes. Now, this is a typically in case of piezoelectric samples. It happens in the gigahertz frequency range. And, these gigahertz frequencies are very high frequencies. Making measurements in these frequency ranges is not easy.

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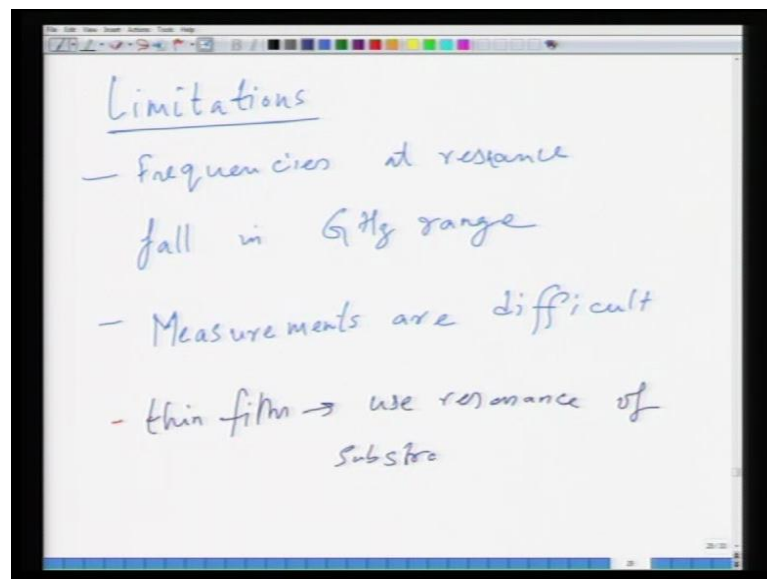
What you have limitations are frequencies at resonance fall in gigahertz range; measurements are difficult, because you need to adopt variety of precautions to make the measurements at gigahertz frequencies.
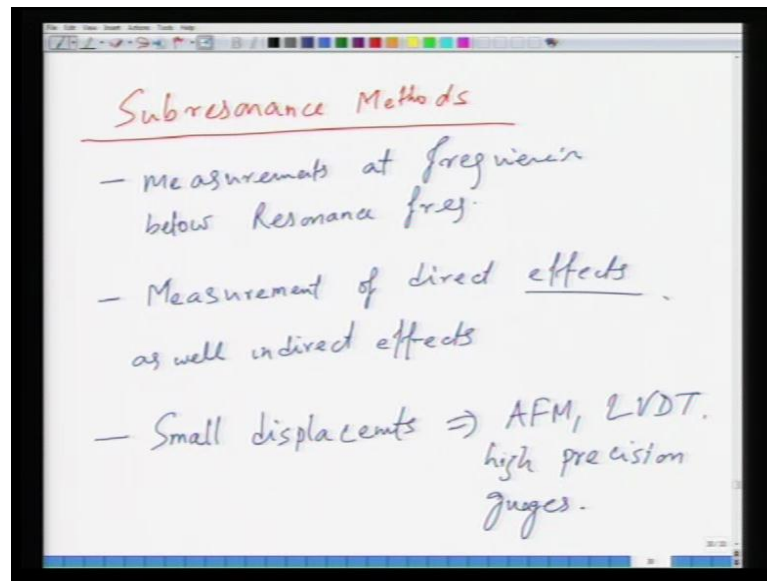
In such cases, what you do is that, basically, you do the measurement in the subresonance frequency. Subresonance methods – basically, in the subresonance method, what happens is that... Typically, for thin films, this is important. When you have thin films, thin films are always deposited on a substrate. So, the substrate can be used as a peak of... So, you can determine the... You can use the substrate as a means to determine the piezoelectric coupling of the film. So, again, the problem here is characteristic frequencies are also determined by electromechanical response of the material. And, if the electromechanical frequencies are not characteristic frequencies are smaller in number, then the measurement becomes difficult. Subresonance... In case of thin film... We can just review the previous slide. In case of let us say thin films, use resonance of substrates.

In the case of subresonance basically, measurements at frequencies below resonance frequencies; Basically, these frequencies are at much lower frequencies, which is attainable and without any difficulty and... So, at resonance frequency, which are nothing but characteristic (( )) fundamental vibration modes. And, this basically is nothing but measurement of direct effect. And, you know what direct effect is. Basically, you measure the charge, which is developed on the phases of piezoelectric under the application of stress; and, direct effect as well as indirect effect, which is the measurement of displacement or strain as a result of applied electric field. Although here the displacements can be very small, but nowadays, we have techniques, which can

measure these displacements such as AFM, etcetera. So, AFM – you can have strain gauges, high quality strain gauges, LVDT's, which is linear variable differential transformers. So, all these... So, basically, technological advances have enabled us to measure these small displacements. So, small displacements... But, they can be measured by techniques like AFM, LVDT, high precision gauges, etcetera.

Basically, in summary, there are two techniques: one is the resonance technique; second is subresonance technique. Resonance technique essentially relies upon the measurement of the characteristic frequencies of vibration. But, the problem here is that, these frequencies can be quite high; which means in the gigahertz or higher range. And, these frequencies make the life of a characterization person difficult. As a result, these are not often successful. What you have is subresonance method, where you measure either the polarization or the displacement. The trouble with these methods is that, the amount of charge, which is developed or amount of strain, which is developed, can be very small. But, nowadays, we have techniques, which can measure all these small changes. As a result, subresonance methods have become much more common.

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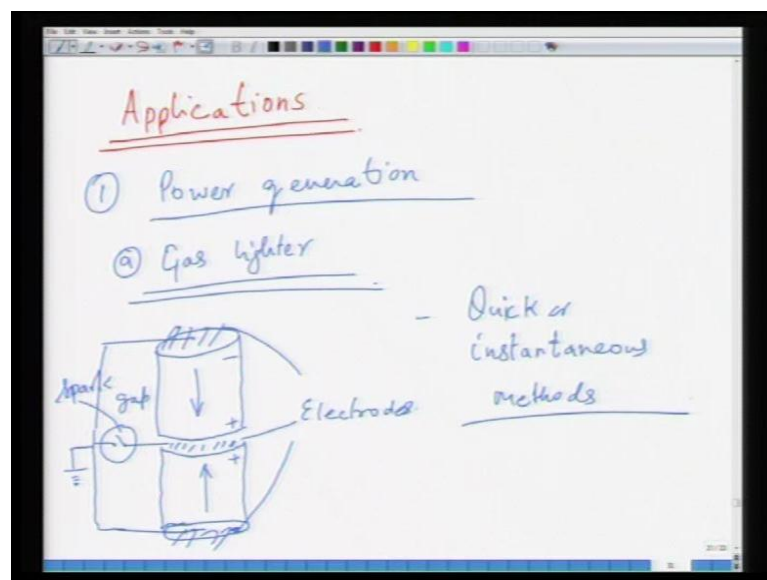
What we will do now is we will just have a look at some of the applications of piezoelectric materials before we move on to the next system. Now, as you know, piezoelectric materials, since they have direct effect in converse effect; which means they either give rise to changes in the polarization or changes in the dimension of the

sample or strain. You can use them in variety of applications. For instance, some of the early applications or some of the very trivial applications in the beginning; for instance, you must have seen a gas lighter. Now, gas lighter – when you press the button; it gives rise to a spark and through which you light the gas. And, this can be used... This is this is called as a power generation method. So, basically, in case of power generation, for instance, as a gas lighter, you can use a piezoelectric material. And, what basically you do is that, in this case, you require two piezoelectric pieces with different opposite polarization states.

What you have here is you have a piezoelectric material like this; and then, another piezoelectric material close to it. And, these two phases have similar charges. So, you have positive-positively oriented phases here. So, these positive... So, you have two phases, which are of same polarity next to each other. You need to put a (( )) You need to put electrodes on the phases. And essentially, you connect these together. And, this is basically the spark gap, because when you bring these together, then since they are of similar charges, there is this sparking. And, that sparking gives rise to this spark, which is used to light the flammable substances. So, application of basically stress; or, stress will induce a change in the polarization. So, when you apply stress... When you press the button, basically you are applying the stress. So, when you press the stress, this induces a change in the polarization of the phases. And, this gives rise to creation of charges; and, this creation of charges leads to creation of spark. And then, you have charge flow through the electrical circuit giving rise to light.

And, the problem is the whole phenomenon happens very quickly. In order to use this as a method of power generation let us say; here very small power is generated. In order to use this device as a gas lighter, it has to happen extremely quickly, because the voltage, which would be generated between the phases, will quickly disappear. So, one needs to use this as very quick or sort of instantaneous method, because you must have seen that, the moment you press the lighter, the spark comes instantaneously; but, it does not stay for long. So, one must use this immediately.

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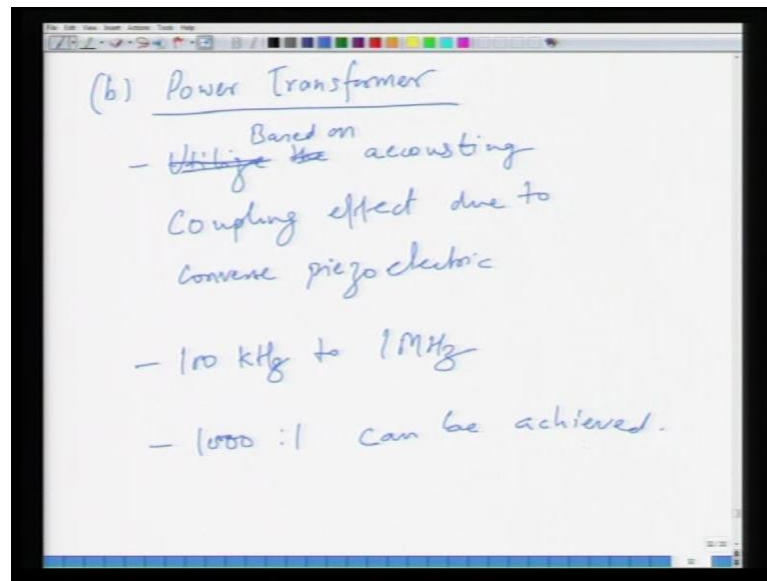
The second application, which is of importance using piezoelectric material in power generation, is power transformers. Now, in contrast to regular transformers, which basically use the electromagnetic coupling between the input and the output, here what you have is utilize... Here what you have piezoelectric materials, which utilize the acoustic coupling; rather which are based on acoustic coupling effect due to converse piezoelectric effect. And, what it means is that, when you apply electric field, the piezoelectric generates strength. And, these strengths can be large enough to give rise to the acoustic waves. And then, you can couple these waves in order to create high voltages. And, these can be used as compact devices. They do not necessarily need to be of large size. And essentially, this alternating stress, which is created by alternating field, can be quite large in nature. And essentially, in the frequency ranges that we are interested here is vibration frequencies of the order of 100 kilohertz to 1 megahertz. And, the step-up ratios of typically 1000 is to 1 can be achieved. A simple diagram for this is shown in the next slide. I will show you in the next slide.

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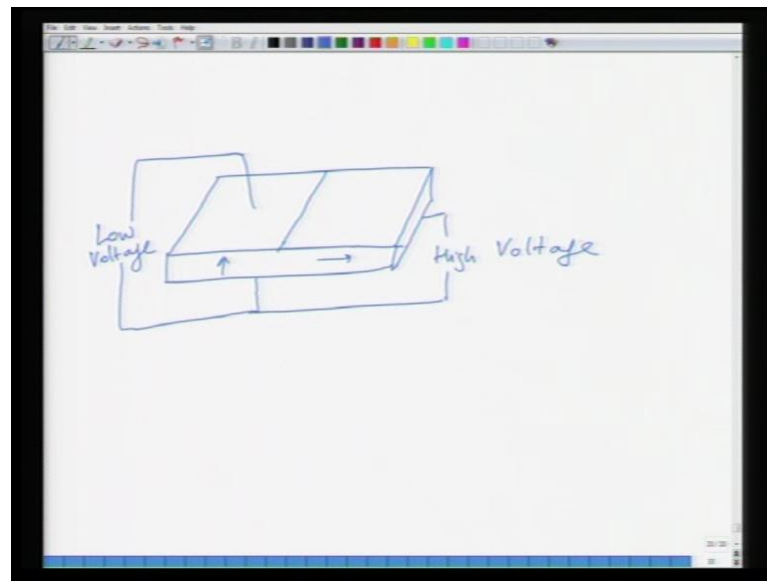
What you have here is essentially a piezoelectric material. So, the way the circuit is drawn here is you apply low voltage here. This is the low voltage side. And, coupling between the piezoelectrics give rise to high voltage on this side. Essentially, it is about applying electric field, alternating electric field, which gives rise to larger stresses, because of... in converse effect. And, this gives rise to acoustic waves. And, these acoustic waves couple with each other in order to give rise high voltages in the transformer made of piezoelectric material. So, in comparison to normal devices, this can be very small in size.

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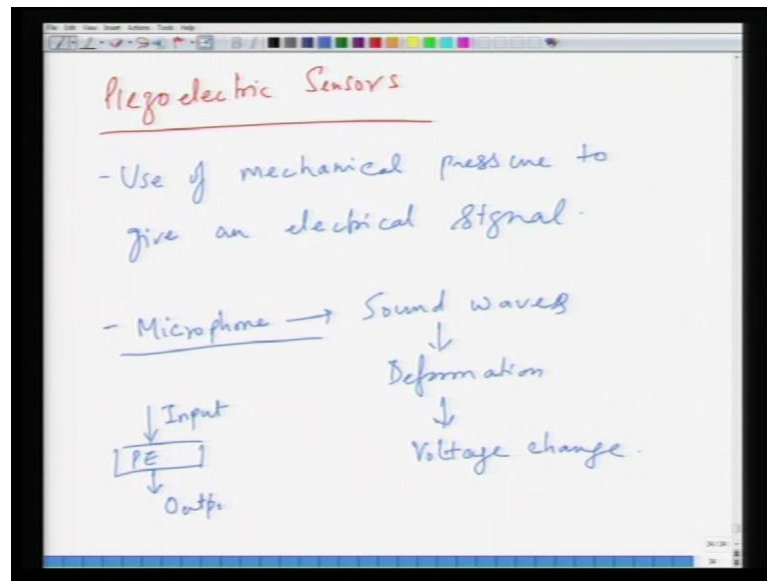
And, the next application that one could think is piezoelectric sensor. In these, typically, you use mechanical force or pressure – use of mechanical pressure to given electrical signal. Basically, for instance, this is used in microphone. In case of microphone, the sound waves can deform the piezoelectric element and this gives rise to a changing voltage. So, essentially, sound waves give rise to deformation and this gives rise to voltage change. And, this is a principle, which is also used for instance in variety of guitars and other microphones. So, this is one application, where you sense the input to give an output. Typically, it is based on use of mechanical pressure, which is the input to give an electrical output from a piezoelectric material. So, this is what it is. So, essentially, you have a piezoelectric material; you give an input; and, this input is typically mechanical; and, what you get in output.
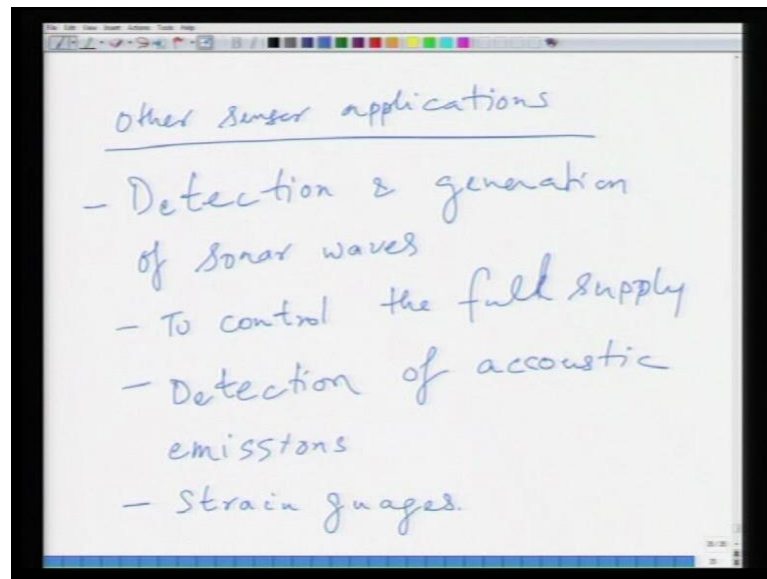
Other sensor applications are... For instance, you can have detection and generation of sonar waves. This is something which was used in world war as well. And, you can also determine, for instance, the precise movement of... you can use piezoelectric to control the fuel supply in an automotive engine. It can also be used for detection of acoustic emissions. And, it can also be used as strain gauge. In most of these applications, the input remains as mechanical signal and output as electrical signal.
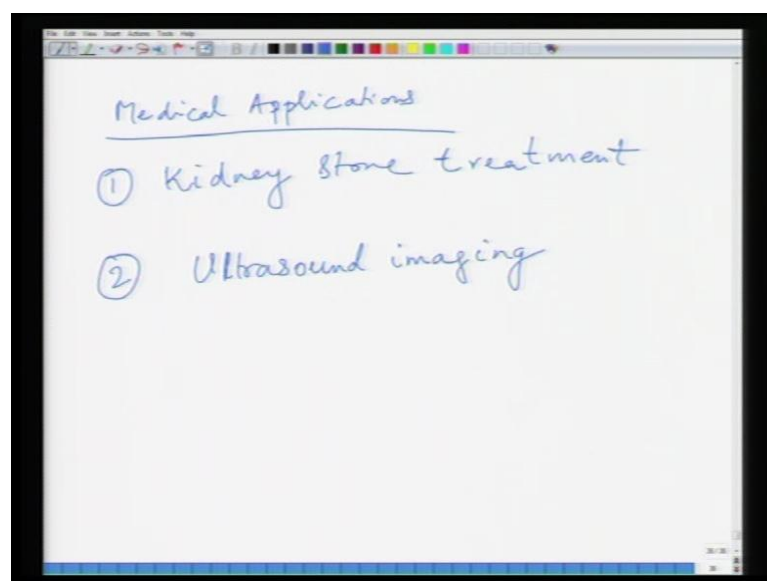
You can have many other applications. You can have medical applications. In case of medical applications, first, could be kidney stone treatment. Essentially, what happens is that, when you apply a high frequency field to the sample; and, this gives rise to change in the shape of the material; this gives rise to basically emission of waves, whose frequency in the ultrasound range. These are called the ultrasound waves. And, these ultrasound waves are then passed through the body; they hit the kidney stone and shatter it and then which can pass through the urine. I will show you the animation of this. And, the second could be ultrasound imaging. And, this is typically used in the case of pregnant women to determine the sex of the child before the birth in the foetus. So, I will show you the animation of this as well.

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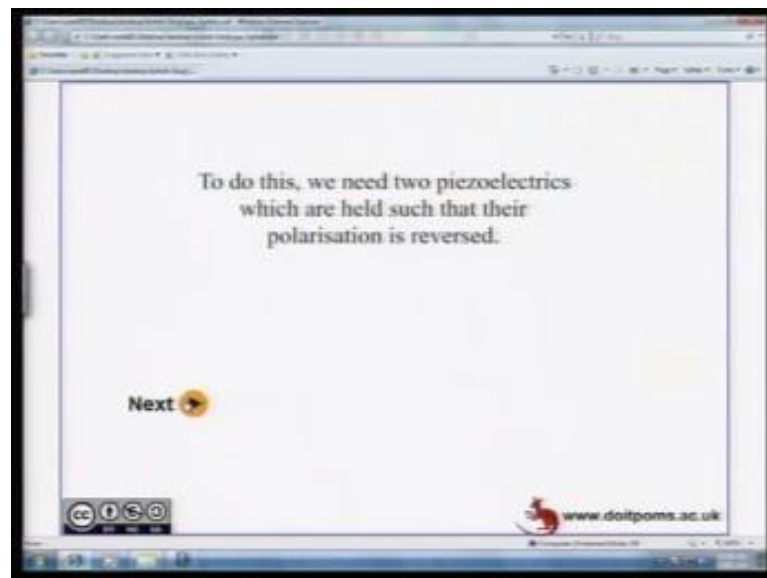
We will just go to the animation. This is the gas lighter. Just go back. If you remember, first application that we talked was the gas lighter. So, piezoelectric can be used to generate a spark, which ignites gases by generating a current. And again, just to acknowledge, this was taken from doitpoms dot ac dot uk. Basically, for this, we take two piezoelectric materials in such a manner so that their polarization is reversed. You have these two materials. And, the polarization of these two materials is in the opposite direction. And, when you apply the stress; the polarization changes as a result of application of stress; which means the increase in the polarization here. So, you bring the phases with the similar charges together in order to create a spark. These are the two similar phases. And then, they are connected to a circuit. And, when you bring them

together, they generate a charge when you apply stress. And, this charge travels through the circuit giving rise to a spark in the gap. And, this leads to creation of a flame. So, this is something, which has to happen very quickly as I said before.

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And, the other application was based on... Let me just find out. The first one... As I said, piezoelectrics are found applications in medical area. Again, this animation is taken from doitpoms dot ac dot uk. We acknowledge their help with this. The first one is non-invasive treatment, which is the kidney treatment. Basically, when you apply a field of high frequency to a piezoelectric, you have a result in change in the shape. And, that gives rise to creation of ultrasound waves. So, this is how you are doing; you are applying stress to the... You are changing the... You are applying a field of changing frequency. As a result, the material is compressive or expanding. And, this compression-expansion of materials alternating, gives rise to ultrasound waves. And, these ultrasound waves – when they are pointed towards a kidney stone for instance in a body, they can basically break it. And, this is a very good technique for breaking of kidney stones. And, this can pass through the body fluids later on when it becomes a smaller size.

Other technique is used in the imaging. And, here basically, it is based on... Again, you generate the ultrasound waves by application of electric field. And, these ultrasound waves in this case – they can reflect from the tissue boundaries. And, these reflected waves can be observed to produce the image of the internal body, for instance, a foetus.

And, basically, again as I said that, these ultrasound waves are produced by applying field of high frequency or reversing the electric field over it. So, the principle is same. These waves – they pass through the body until they hit a boundary and some of them will reflect. So, essentially, this is the body. And, the waves have travelled in this direction and some of them have reflected back. And, they again are collected through the same piezoelectric. And, when these waves will hit a piezoelectric, they will again create change in the polarization or give rise to charge. And, this can be used to monitor the magnitude of... This charge can be used to monitor the image. So, ultrasound waves cause the reverse effect, the converse effect by altering the shape of the piezoelectric. This causes a charge to be produced on the ends of the piezoelectric, which can be detected. And, as a result you get a... And, this is interpreted by the computer giving rise to a image. So, this is what I wanted to show you; basically, these slides – just to show you the applications.

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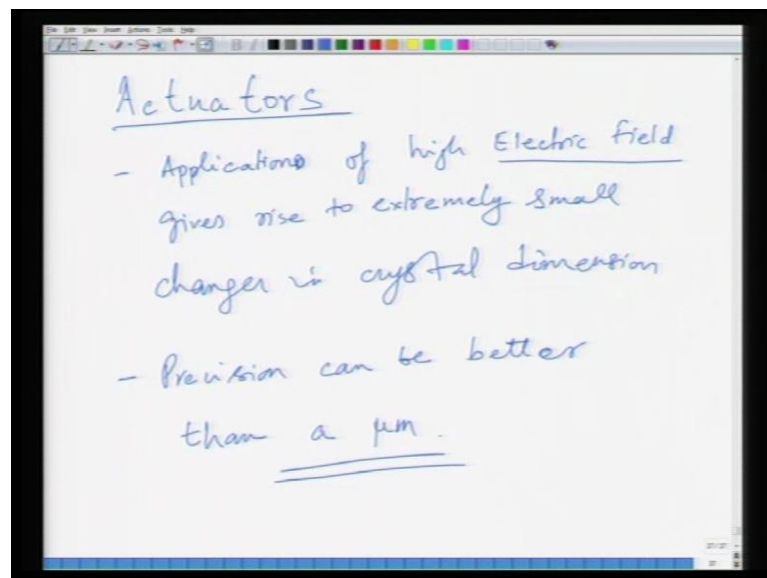
And, these are also used in some applications like actuators. Nowadays, the engineering or technological advances are very happened at a very precise scale. Earlier, the precision could be of millimetre level. But, now, the precisions have gone into the range of micron and submicron range. As a result, to achieve this technological perfection, the devices need translation, which is as precise. Basically, the linear motion or the rotational motion have to be of very high precision. So, in this case, piezoelectrics can be used quite well, because piezoelectrics as you know, when you apply electric field, they

have a displacement, which is of the order of microns or even submicrons or picometers to microns. And, this helps us in controlling the translation or rotation in a device to very high accuracy.

Essentially, here application of high electric field; and, this high electric field without... Now, you have to use it without the oscillations. This high electric field gives rise to extremely small changes in the crystal dimension. So, you have to use a material, whose piezoelectric constant is likewise appropriate. And, the precision here can be better than a micron. So, that tells you the level of accuracy that we are achieving here. That is why these piezoelectrics can be used as a very useful precised actuators, motors, etcetera. You can use voltages of the order of 150-200 volt. These can be used, for instance, in the material in the thin film form, which can give you displacements of the order of microns as you said.

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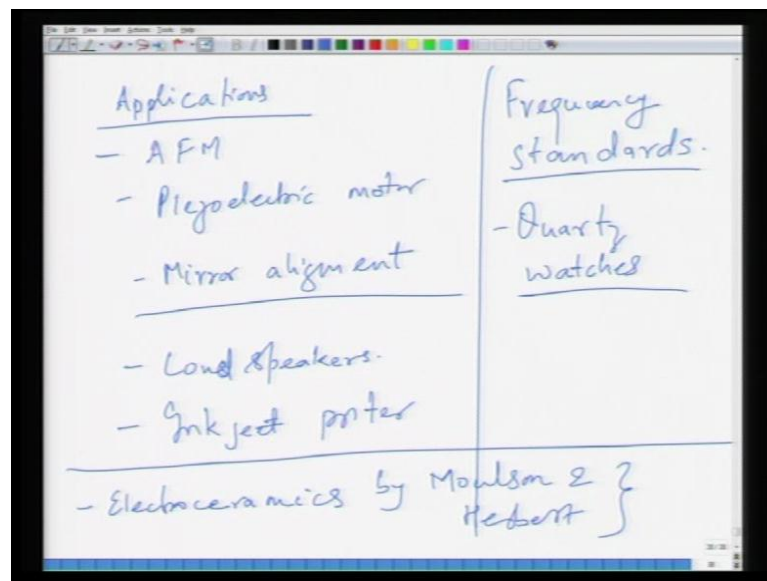
Again, let me just give you some of the applications of sensing these actuator applications. Actuator applications can be used, for instance, in AFM. In AFM – atomic force microscope, you move the tip of the sample by taking the tip up and down. And, this movement has to be very precise. And, this precise movement is achieved by the use of a piezoelectric material. You can have piezoelectric motors. And, these motors – basically, you have up and down movement through rotation. And, this happens extremely precisely since... And, this you can control by changing the electric field that

you apply. We can do mirror alignment especially in the laser area, where the laser mirror alignment has to be very precise. Loud speakers; and, ink jet printer – another very important use of piezoelectric material. Here by changing the electric field, you can control the precision of piezoelectric diaphragm to regulate the supply of ink on the paper. And, of course the fuel injectors in the engines, etcetera. All of these are very important applications.

And finally, last application that I am going to talk about is frequency standard. Frequency standards – basically, piezoelectric materials can be used as a standard of frequency. And, this is what happens in Quartz watches. The watches that we wear – they contain piezoelectric and they use... Basically you have a Quartz tuning fork, which uses a combination of direct and converse effect and to give you a regulated pulses, electrical pulses, which are used to correctly mark the time. And, they have... Since these materials have fundamental frequency of vibration at very specific frequencies, they can be used to stabilize the frequency.

When you apply a periodic voltage; then, you can stabilize the frequency of vibration. And, these frequencies are very precise frequencies. So, you can use this frequency as a standard. And, this is also used... Same principle is also used in radio transmitters as well as receivers; whose details I am not going into. But if you want to go into details of applications of piezoelectrics, I would suggest that, you go through the books on Electroceramics by Moulson and Herbert. These titles are also provided in the bibliography of the course as a separate link. So, you can go through them.

We will finish the lecture today here; which is essentially end of piezoelectric materials. In the next lecture, we will take up the case of pyroelectric materials; and then, we will finish the discussion on non-linear dielectrics.

Thank you.