Vibration Control
Prof. Dr. S. P. Harsha
Department of Mechanical & Industrial Engineering
Indian Institute of Technology, Roorkee

Module - 7
Principles of Active Vibration Control
Lecture - 2
Piezoelectric Material – I

Hi, this is Dr. S. P. Harsha from Mechanical and Industrial Department, IIT Roorkee. In the course of Vibration Control, we are mainly discussing about the Principles of Active Vibration Control. So, in the last module, we discussed all conceptual feature, and even that what the design features are there, how we can exactly go for control of vibration using the passive vibration control. And we know that, there are certain limitations and there are certain good points in according to the system application, we can adopt to the passive vibration control.

But, now you see here, with the recent trend and when the sophisticated arrangements are there and according to the application and environment, we need to go with the active vibration control, which is the second mode of vibration control. So, in last lecture, we discussed about the basic features of the active vibration control, in which we know that, whatever the primary source, through which the excitation is occur, is occurring in the main system.

We can simply by putting the secondary source, a negative force can be generated and that can be counter balanced force is there. And in this particular mechanism, there are three main devices, which can straightway put to find out the desired properties. Like, first the sensor, when any force, voltage or anything is being or the stress, when it is being acted on the system. The sensor which can sense any dynamic parameter or anything you see, which is being happened to the system, simply sensing the part.

So, first part which is to be required is the sensor and then you see here, the other part is the actuation, just to actuate the system against the excitation force. So, actuator is now generating the force, which can balance whatever the vibration is being the vibrating features are there with the system, but this sensor and actuator is coupled with the control unit. So, this automatic control unit or we can say it is being basically featured with the analog or this digital control system, it has to balance, in which if amplifier is required or anything is required, it has to pass through.

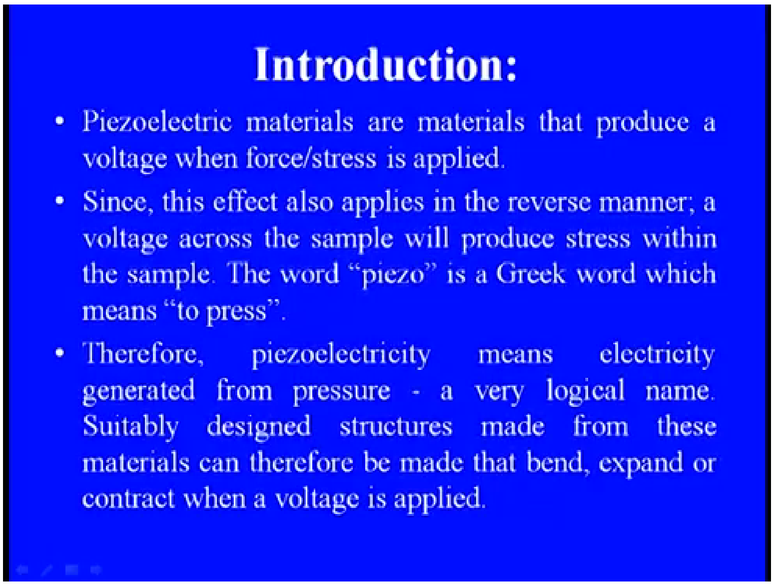
And we can say a magnified force can be generated through the exciter or we can say actuator. So, this is one way to control the vibration using this active vibration phenomena. But, sometimes you see here, even to put the micro sensors or even the sensors and actuator and then the entire control unit, is not the robustive sophisticated system. Then certain similar kind of application, if we can generate or if we can combine using the material known as the smart material then the purpose will be solved for a vibration separation using this active vibration.

So, we are saying that, when the intelligent or the smart materials, which can be framed in such a way that, we can get that various categories are there under that. Like the shape memory alloys and the shape memory functions in that, you see that how ingredients are there in the shape memory alloy material, in which such actions can be happen. Second, the rheological fluid, either based on the magneto rheological fluid or electro rheological fluids, even magneto restrictive fluids.

And the last, but not least, the vast category of the piezoelectric materials, right from a Madam Curie and Pierre Curie; they generate this somewhere in early 1990s or even the 18th century, 1880s that, some of the material can even generate the force when any mechanical part is being applied or due to the electrical voltage is changing or the force, when the force is being applied, there is a change in the electric voltage in across the material. So, all these materials, which can sense and automatically which can actuate as per the requirement are known as the smart materials. So, in today's lecture, we are going to discuss about one broader category of these smart materials is the piezoelectric materials in the conceptual features.

So, the piezoelectric materials are the materials that produce a voltage, when the force or the stress is being applied and the actuation is being happened due to that. And since this effect also applies in the reverse manner that means, when the voltage across the sample while change and when it is being applied, the stress within the sample can be produced or induced, because of the resistance. So, you see here in the vice versa concept, whatever the requirement is there, these materials can provide immediately the required actions.

(Refer Slide Time: 05:08)

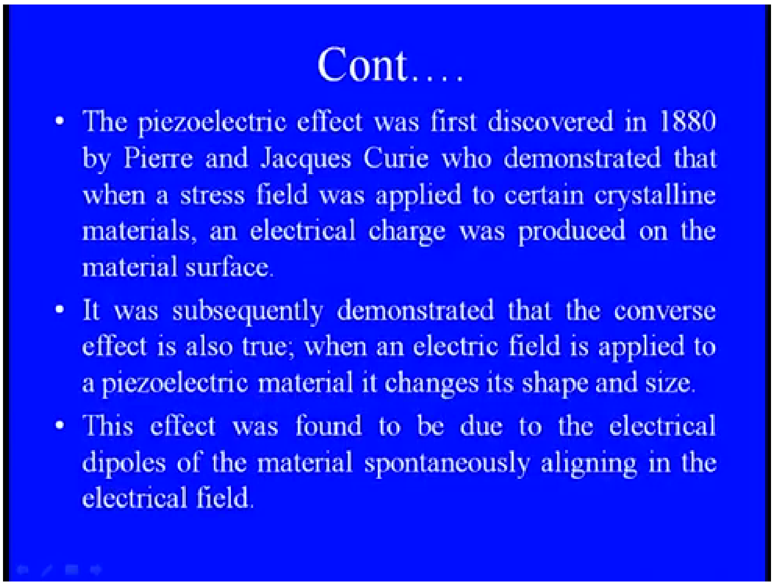


The word piezo is a Greek word that means, to press and whenever this pressing action is there, the required features are being coming out. Therefore, piezoelectricity means, the electricity generated from the pressure, the pressure variation or any kind of the intensity of these forces and that is you see, a very logical name is coming out from that, that piezoelectric materials.

And once a suitably designed structure, which is made from these materials can therefore be made, that the bend or expand or contract is any action is being happening, a voltage is being coming out from that. Or when the voltage is being applied then all these actions the bending, the expanding or the contraction, can be happened to the systems. So that means, whenever you see, the pressing actions are there, electricity is generating in that.

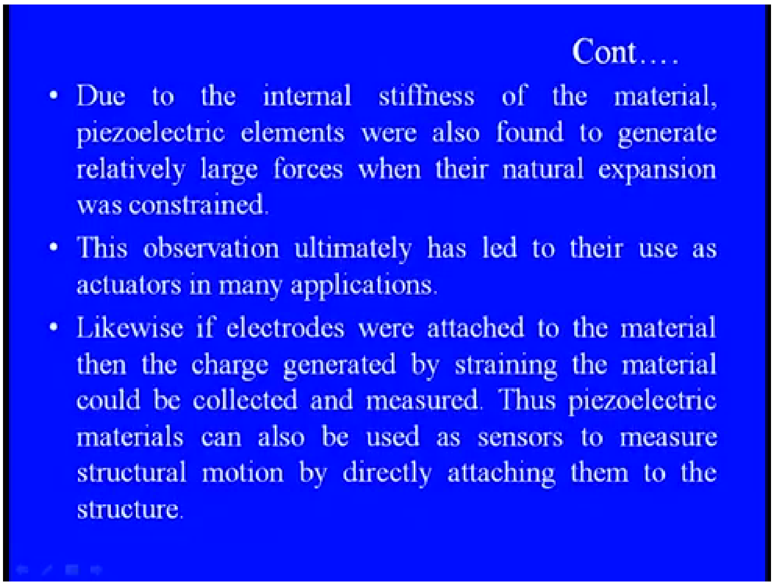
So, piezoelectric effect, if you are just going some back history, it was basically discovered by Pierre and the Jacques Curie, which they named by the Nobel prizes to both of them separately. And you see here, they simply demonstrate then when a stress field is being created or being the entire force field is being applied to a certain crystalline material, at that time it was a crystalline material, an electrical change was produced on the material surface.

(Refer Slide Time: 06:51)



So, that was the basic invention made by these Curies and it was subsequently demonstrated that, the converse effect is also true. When an electric field is applied to these materials, the crystalline materials then there is a change in it is shape or the size, which we are saying that the piezoelectric materials. So, this effect was found to be due to the electrical dipoles of the material in spontaneously align in the electric field. And because of this alignment, there is a clear change in the shape and size, according to the intensity of these field features of the dipole moment features.

(Refer Slide Time: 08:17)



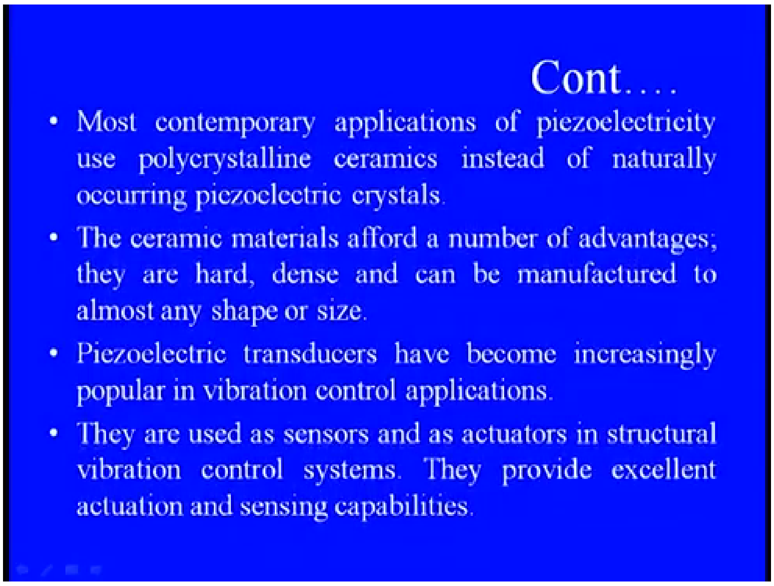
So, when we are just trying to look at the basic feature then you will find that, there are two main things, one due to internal stiffness of the material. The piezoelectric elements, they are also found to generate relatively large forces when the natural expansion was constraint. So that means, this observation ultimately lead their use as actuator, because we know that, whenever the internal stiffnesses are being just affected by these, we can say whatever the voltage changes are there, the large amount of the reactive forces are being coming out.

So that means, you can actuate the entire material by just changing their internal stiffnesses. So, you see, these piezoelectric materials can be acted as a actuator part and the same time, if the electrodes were attached to the material and whatever the charge generated by the straining, whatever the force which we are applying there or the pressure or the stress, by straining the material could be collected and then measured. So, we can say that, the piezoelectric material can also be used as the sensor to measure the structural motion by directly attaching them to the structure.

So, you can see that, because of the internal inherent property, the stiffness which is nothing but just measuring whatever the force per unit deformation. Because of this, whatever the variations are there in the stiffness, these materials are generating a large forces when their natural expansion, because of the stiffness variation is being constraint. And because of that constraint feature is there, the forces which are being coming out, the actuation feature is there from that. And the same time, whatever the molecular motions are there, they can sense, because of the change in there, whatever the electrode features and the strain features are being there associated with that. So, we can say that, the piezoelectric material can be acted as a sensor and can also be used as a actuator part.

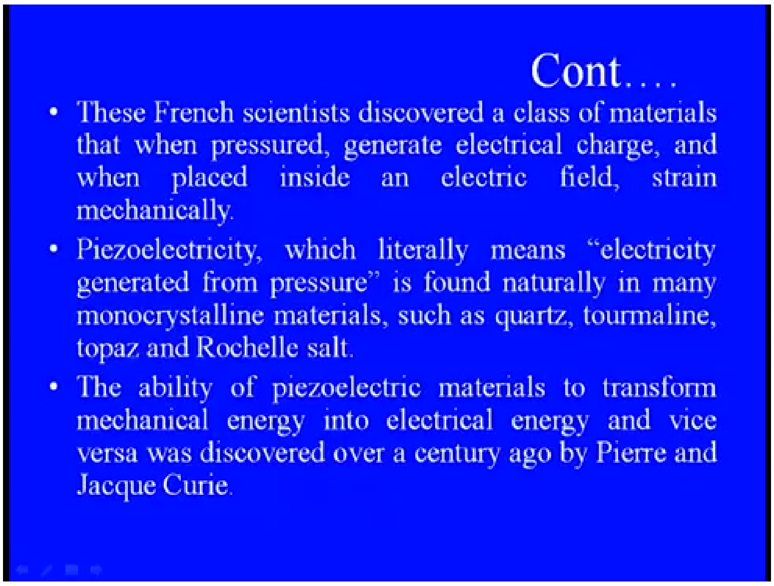
So, most contemporary application of the piezoelectric use is the polycrystalline ceramics, these materials have a lots of applications, instead of we can say the naturally occurred the piezoelectric crystals. So, the piezoelectric materials can be categorized into two main broad broader categories, which we are going to discuss; One the naturally occurred the piezoelectric feature or manmade piezoelectric materials.

(Refer Slide Time: 10:32)



So, the ceramic materials, which can afford the number of applications, they have lots of we can say advantages. Like they are hard, they are also dense and can be manufactured upto, we can say almost any size or the shape according to the applications. And they can provide a sufficient amount of the piezoelectric effect, because they have the polycrystalline ceramic material inside that. So, piezoelectric transducers have lots of applications, especially when we are using this piezoelectric material as the vibration controllers.

(Refer Slide Time: 12:10)

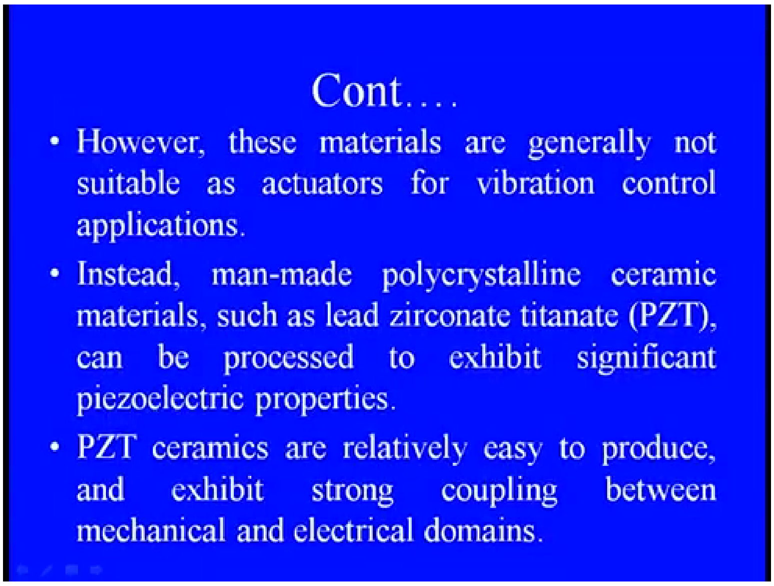


So, these transducers can be used as a sensor and the actuator in the structural vibration control system. And they can provide a sophisticated and you see that, the excellent applications towards the sensing and the actuating feature and their accuracy is also of a high level.

So, the Curie family whatever they discovered, the discover based on, they discovered simply a class of material that, when the pressurized generate electrical charge and when they placed inside the electrical field, a strain mechanically. So, this is the concise way of , we can represent the piezoelectric feature of the material. So, piezoelectricity when linearly, which we just want to define linearly that means, the electricity generate from the pressure and various materials like the monocrystalline materials as the quartz, the tourmaline, topaz and the Rochelle salts.

You see there are four, one is the quartz then we can say that, the tourmaline, the topaz and the Rochelle salt, they are the naturally occurred monocrystalline materials and they can generate the electricity just by applying the pressure or any kind of force application. So, these are the naturally occurred piezoelectric material, and the ability of these piezoelectric materials to transform mechanical energy into electric energy or vice versa was mainly discussed by these Curie family, the Pierre Curie and Jacques Curie.

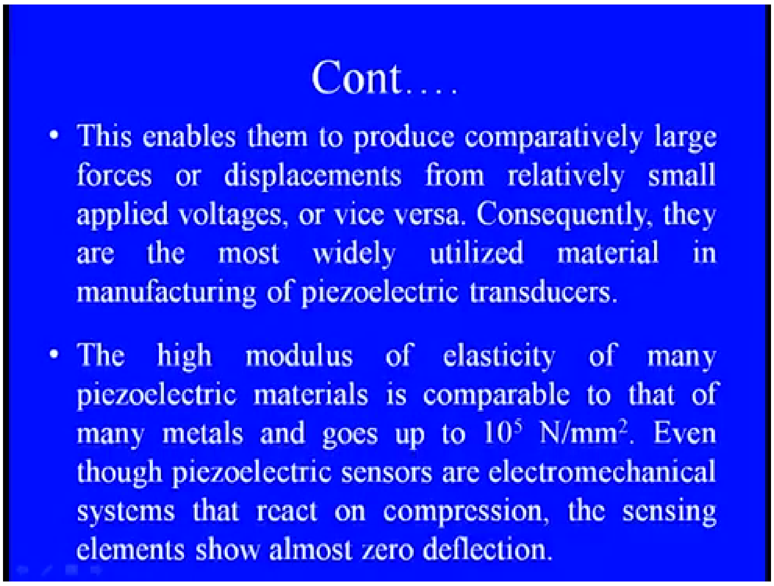
(Refer Slide Time: 13:37)



But, sometimes you see here, when we are applying these materials, they are not absolutely actuating in whatever the required force is, I am talking about the naturally occurred material. So, we need to go with the manmade piezoelectric material, which can be used as the sensor and actuator together like the polycrystalline ceramic material, as I told you. And one of the best feature in this is the lead zirconate titanium and this Lead means P, Zirconium Z and Titanium T.

So, PZT which is a very common in this piezoelectric material, the PZT can be processed to exhibit the significant piezoelectric properties in that. So, this is the manmade polycrystalline ceramic material, in which all three materials, the lead, the zirconate and the titanate, they are simply exhibiting a excellent features, which is being required to sense and the actuate, actuation feature in this material, so PZT ceramic, which we are saying that, it is the category of this polycrystalline ceramic material. So, PZT ceramics are relatively easy to produce, it is in manufacturing point of view and can also exhibit the strong coupling between the mechanical and electrical domains, when we are just trying to change mechanical energy to electrical energy or electrical voltage into the mechanical strain. So, that is why, you see the PZT patches are having excellent applications, wherever it is being required in that.

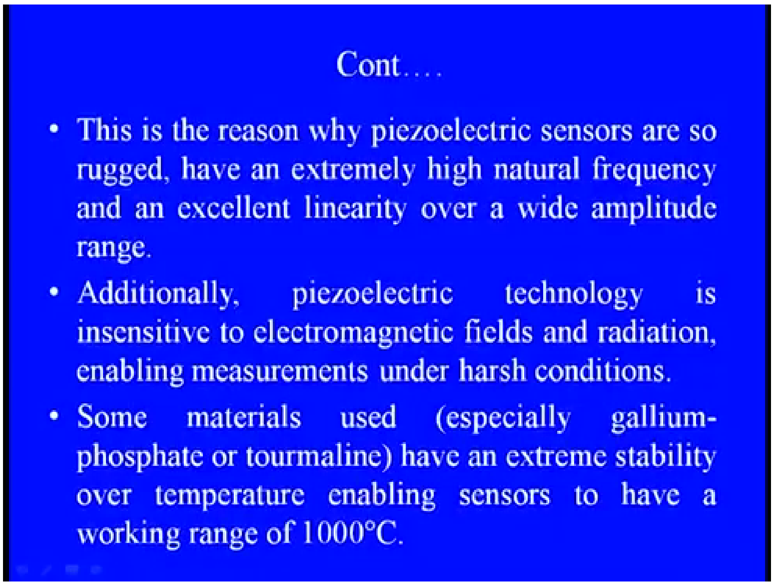
(Refer Slide Time: 15:23)



And this enables them to produce comparatively large forces or we can say the displacement especially, in terms of the actuation feature or in terms of the sensor feature, from relatively small applied voltage or even for relatively the small forces or the displacement, they can even produce the large voltage together. So, either of side you see here, this PZT patches can exhibit excellent features there. And they are the most widely utilized material in the manufacturing of the piezoelectric transducers for vibration control under the active vibration category.

So, the high modulus of elasticity, when we are just looking from the mechanical point of view under the elastic nature, they have excellent modulus of elasticity as compared to the material, even they can go beyond that limit. And even though piezoelectric sensors or electromechanical systems, which can react on compression, the sensing element is almost showing the zero deflection in it. So, there is an excellent feature you see here that, even since they are electromechanical systems, so their reaction against that, is really a stable part.

(Refer Slide Time: 16:43)



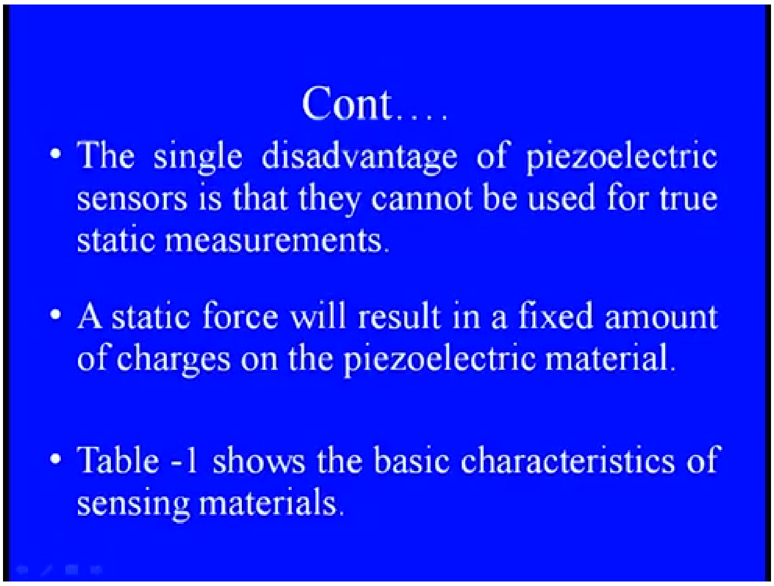
And this is the reason, why the piezoelectric sensors are so rugged and they have an extremely high natural frequency and they have an excellent linearity over a wide amplitude range of the excitations. So, when we are talking from the vibration point of view and we want to control the excitations and they have these piezoelectric materials or the sensors means, from sensor point of view, they have high natural frequency and the same time, they are showing their linear feature over the large amplitude parts.

So, the vibration in which you see, since the vibration is featured or by the exciting frequency and the amplitude, they are showing an excellent character from both the point of view. And along with that, the piezoelectric technology is insensitive to electromagnetic fields or the radiations. And that is why you see here, with these two features, since they are insensitive against these we can say that, the environmental features or whatever the outside part, it is enabling in the measurement or Hertz conditions for the application of these piezoelectric sensors.

So, that is one of the unique feature you see here that, they can be applied to any kind of conditions and they are insensitive to that outside conditions is, whether it is working in the electromagnetic field or whether it is the radiations are there all of side. Some of the material like we can say the gallium phosphate or the tourmaline, have an excellent stability, even over the temperature range of 1000 degree Celsius.

So, we can say that, with this piezo actuation and the sensing feature, even they can be applied to any severe conditions, outside condition and even the temperature ranges. These are the common advantages, which enable them to use in many of the applications against any kind of environmental features, irrespective of whatever the changes are there, the drastic changes are there, the cyclic changes are there in their environmental features.

(Refer Slide Time: 18:59)



But one of the disadvantage of this piezoelectric sensors is that, they cannot be used for true static measurement, because a static force will result in a fixed amount of charges on the piezoelectric material. So, that is one of the drawback that you see, whenever we are going for the static measurement, whatever the oscillations features are there with the charges, they are absolutely not showing the clear variation.

So, we cannot say that, what exactly changes, because the static means you see, even the force has a constant magnitude and whatever the constant features are there, that cannot be accurately featured out from these materials. But, whenever we are talking about the dynamic feature like in the vibration or any other, where the motions are being a clear part, this is one of the specific material, where we can straightaway apply and get the desired results.

(Refer Slide Time: 20:01)

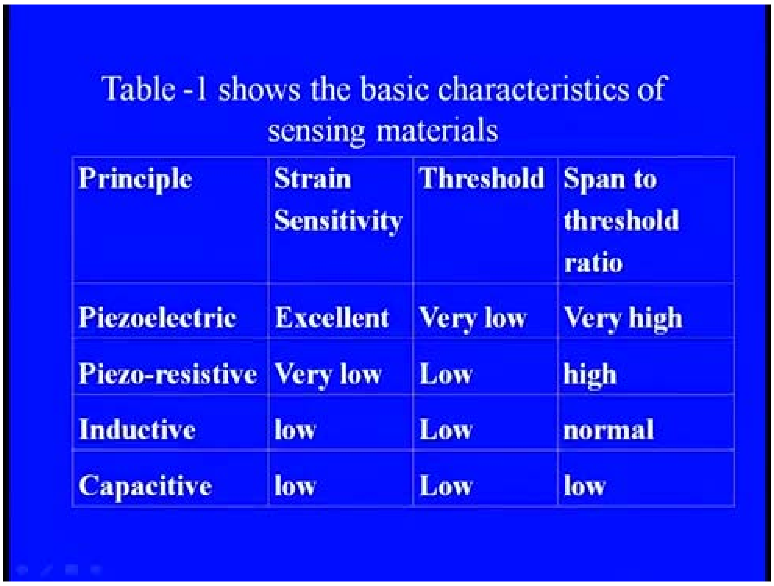


Table -1 shows the basic characteristics of sensing materials

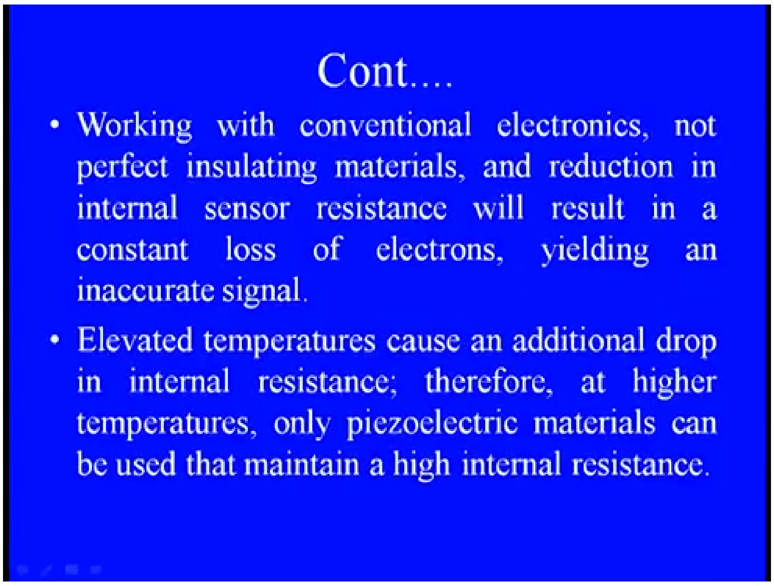
Principle	Strain Sensitivity	Threshold	Span to threshold ratio
Piezoelectric	Excellent	Very low	Very high
Piezo-resistive	Very low	Low	high
Inductive	low	Low	normal
Capacitive	low	Low	low

So, we can go with the basic characteristics of these sensing materials like you see here, we are categorizing say based on the four principles. First the piezoelectric, when we are using the piezoelectric material, their strain sensitivity as the voltage changes are there, corresponding is very excellent, the threshold value at that is very low and the span of this threshold ratio is very high, because of this piezoelectric action.

And if you are using the piezoresistive feature in these sensing material, their strain sensitivity is quite low, very, very low as compare to the other things. Even their threshold value is also low and this span to threshold ratio is really very high. And if we are going to other sensing material like inductive material we know that, the strain sensitivity is low, even the threshold value is also low and the span to threshold ratio is almost normal, they are almost insensitive to this part.

And capacitive based sensing material, they have also the strain sensitivity is very low, which is by that way, we cannot even make our sensors based on these features, their threshold values also low and the span to threshold ratio, the entire ratio part is also very low. So, if we compare these basic characteristics of these material then we will find that, as far as the vibration control is concerned, the piezoelectric materials are just showing an excellent properties, which is being required in the control feature from these material.

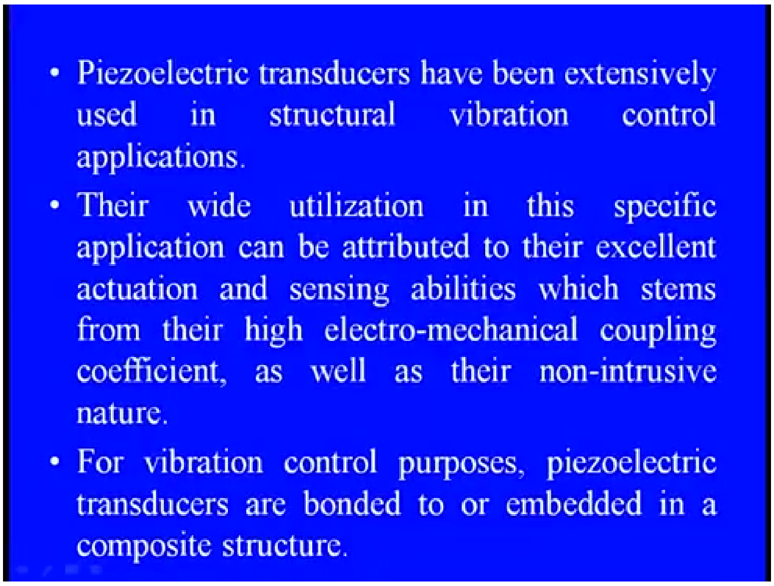
(Refer Slide Time: 21:50)



So, working with these conventional electronics we can say that, not the perfect insulating material or reduction in the internal sensor resistance will result in the constant loss of electrons and yielding an inaccurate signals. So, elevated temperature also, when the temperature raises there, causes an additional drop in internal resistances. And so a high temperature only piezoelectric material can be used to maintain the high level of internal resistances.

So, we know that, when we are just using of such kind of material, continuous loss of electrons are there. And then we can say that, the resistance which is been coming out, the internal resistance is very low from these things and then there is a clear inaccurate feature in the signals are there, which we can get. So, that is why you see here, the piezoelectric materials are one of the good materials, which can be used at these places, where the elevated temperature features are there. So, when we are talking about vibration control we know that, we can use this material as the transducers.

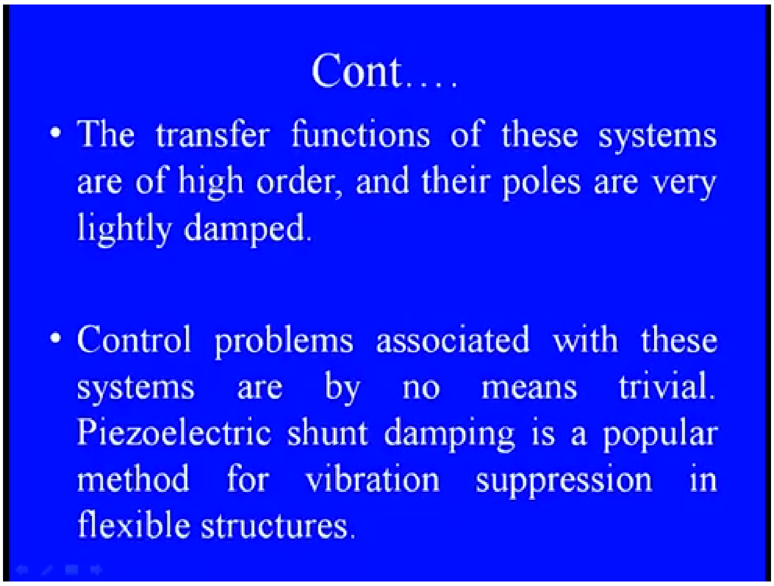
(Refer Slide Time: 23:01)



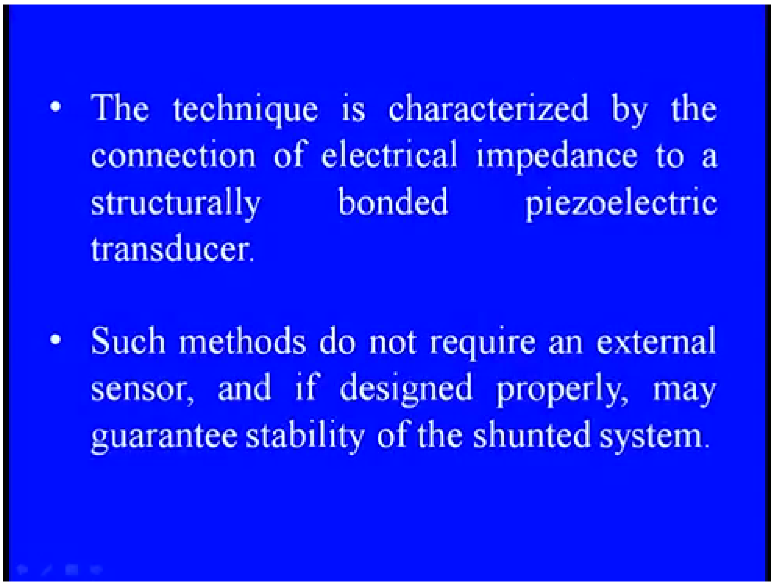
So, piezoelectric transducers have a wide utilization in their specific application and can be attributed to their excellent actuation and the sensing abilities, which stems from their high electromechanical coupling coefficient as well as the non intrusive nature. And because of these two feature, we can straightaway apply this piezoelectric transducers as the sensor and the actuators. And when we are thinking from that vibration control point of view, these transducers can be straightaway bounded or we can say, even they embedded in the composite structure. So that, whatever the feature is being required means, like the sensing or actuations, immediately it can be acted towards that.

And the transfer functions of these systems are of very high order and their poles are very lightly damped. So, the control problems associated with these systems are there by no means, trivial and one of the important thing is that, the piezoelectric shunt damping is very popular, as we have already discussed about the shunt damping. Because, you see whenever we just want to suppress the vibration for flexible structure, we need to go with shunt damping. And the piezoelectric based material, which provide the shunt damping is one of the popular part in suppression of vibration for a flexible structure.

(Refer Slide Time: 23:53)

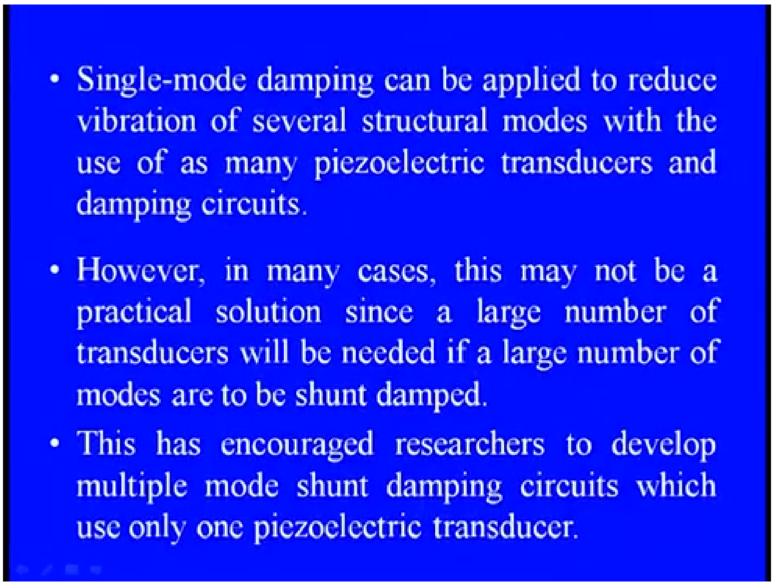


(Refer Slide Time: 24:36)



And in this technique you see here, we can simply characterized by the connection of this electrical impedance to structurally bonded piezoelectric transducers. So, we need to check it out the impedance feature in the mobility of these structure and such methods do not require an external sensor. If we design these things, they can certainly give a proper stability of the entire shunted system. So, that is the unique feature of these piezoelectric shunt damping, in which we can straightway get the stability and actuation and sensing feature from this piezoelectric part.

(Refer Slide Time: 25:18)

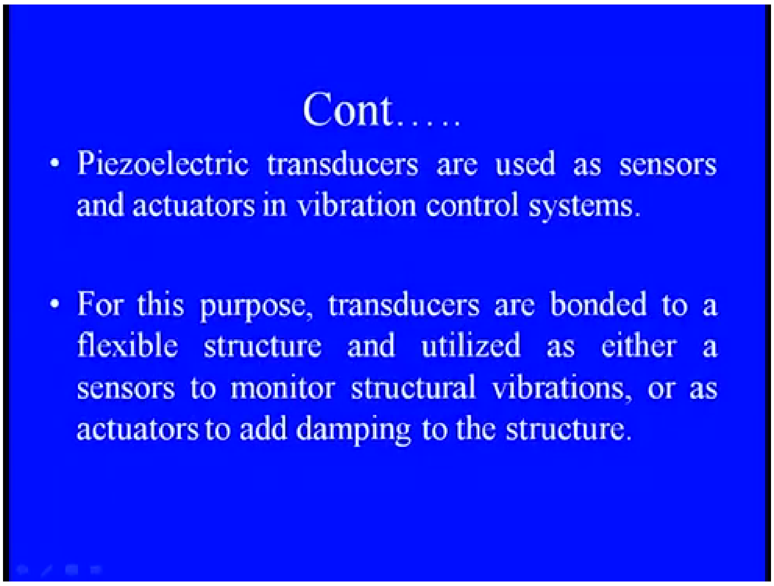


So, single mode damping can also be applied to reduce the vibration of several structural modes within the use of many piezoelectric transducers and the damping circuits. But, in many cases you see here, this is not the practical solution, sometimes because you see, whatever the modes are coming on the entire feature of the large system, we need to just check it out that, what are the variations are there. So, far as the practical solutions are concerned, when the large number of transducers will be requiring for the larger number of modes then certainly it is not a feasible solution.

And that is why you see here, when we are keeping various piezoelectric transducers and the damping circuits, they may not give the accurate result as well in the single mode damping. So, we can simply go just to develop a multiple mode shunt damping circuits, which can be used just one piezoelectric transducer and can be just gauze the entire modes and suppress the vibrations.

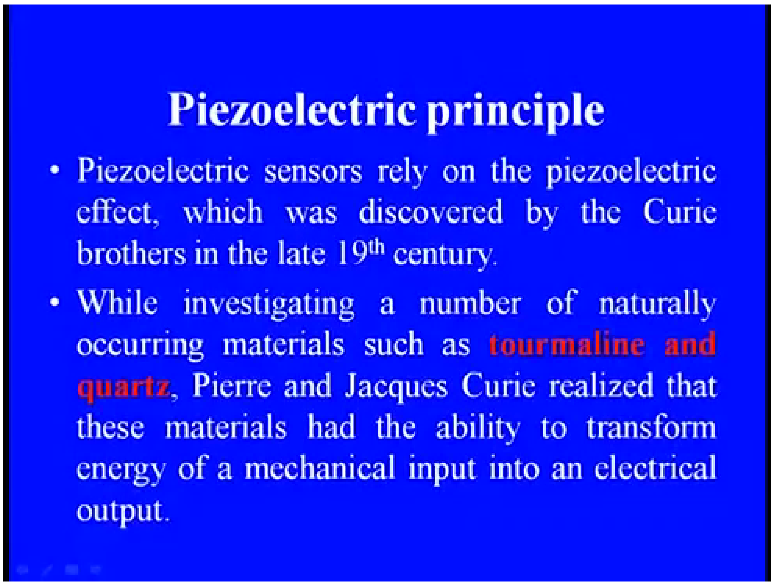
So, instead of going with the single mode damping with lots of the transducers and the damping circuit, we can straightaway use and many of the researchers, they have suggested the various things that, we can use the multiple mode shunt damping with piezoelectric transducers. And through that you see here, we can effectively control the vibration in entire mode shapes.

(Refer Slide Time: 26:58)



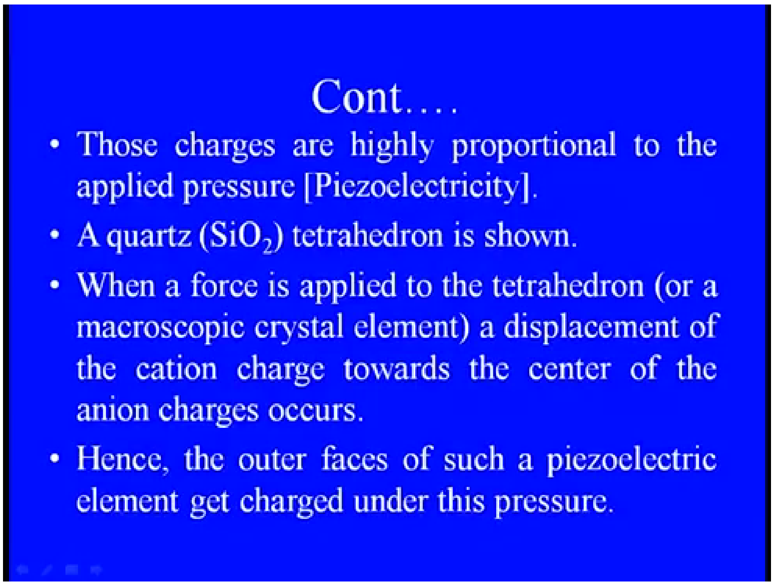
So, these transducers which are being acted as a sensor or we can say actuator, just we need to see what kind of applications are there. Because you see here, these transducers are simply bonded to the flexible structure and can be utilized, either as the sensor or actuate or sensor to monitor, the structural vibration or actuator to add the damping to the structure. So, this is the beauty of this piezoelectric device that, if we want the sensing feature just to monitor the movement, whatever the structural movement are there, they can provide the significant information. And if we want them to act as a structure, as a actuator to the structure, they can certainly provide through their reactive forces, this is a kind of damping is to be provided to the system.

(Refer Slide Time: 27:52)



Now, if we are going to the basic principle of piezoelectric part then we know that, the piezoelectric sensor rely on the piezoelectric effect, which was discovered by the Curie brothers in the 19th century. So, you see here, when we are just investing a number of naturally occurred material as we discussed, the quartz part or we can say the tourmaline, they have these materials have the ability to transform the energy even from mechanical input to electrical output or electrical input to mechanical output. So, this is what the principle, which was discovered by the Curies.

(Refer Slide Time: 28:31)



And those charges, which are highly proportional to the applied pressure, the piezoelectricity has a linear propagation towards that. The quartz which we are talking about the naturally shown, in that there are two main element, the silicon oxide and we can say, it is a tetrahedron feature is there in that. So, when the forces applied to the tetrahedron or we can say somewhat more macroscopic crystal element, which we are going to show, a displacement of the cation charge towards the centre of the anion charges are being occurred. And because of these, the transformation, the strain is being occurred in this and because of that you see, the voltage changes are there. So, the outer face of such piezoelectric element get charged under this pressure and we can simply measure the voltage difference in that.

(Refer Slide Time: 29:27)

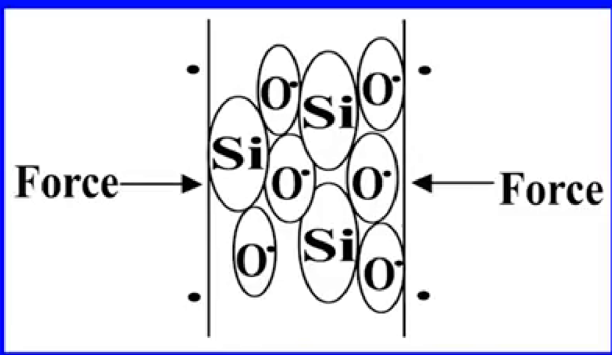
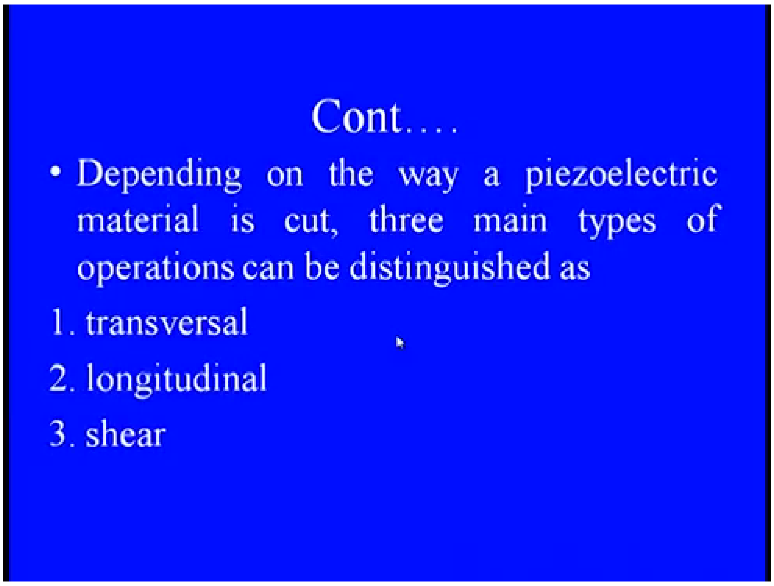


Fig. 1 Piezoelectricity of quartz

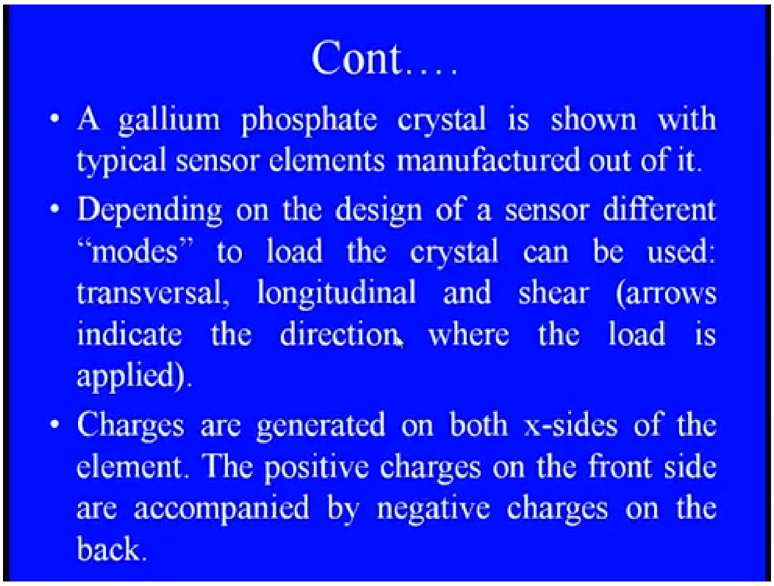
So, you can see on your screen that, whenever the force, either the compression, either we can say tension or the bending, whatever the force is being applied there, the reactive features. Because, the strain features are there, this is the mechanical force, mechanical input is there, the reactive features are being just changed according to the voltage drop at the outside. So, this is you see the arrangement of the silicon and oxide features are there, SiO 2. And according you see here, the proper actions from the mechanical input to electrical output or from electrical input to mechanical output can be occurred simultaneously.

(Refer Slide Time: 30:00)



So, depending on the way of piezoelectric material is cut, the three types of operation can be formed. One, the transversal means, what exactly the action is there of the force, the longitudinal and the shearing part.

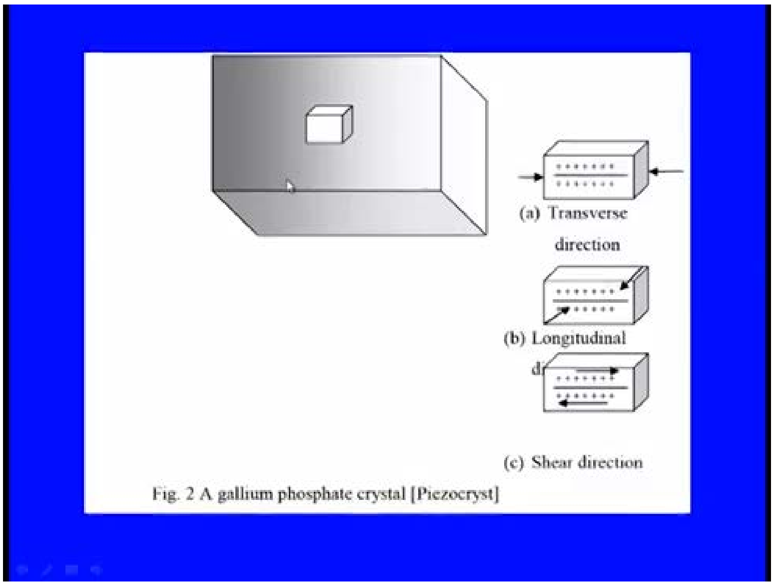
(Refer Slide Time: 30:23)



So, when we are saying that, we have a naturally or the manmade occur of this piezoelectric part., a gallium phosphate crystal which we are going to show with the typical sensor element, can be manufactured with these cuts. And depending on the design of the sensor with the different modes, which I discussed previously to load the crystal, can be used as the transversal, longitudinal or shear, according to the direction of the forces applied.

And the charges are straightaway generating on both side of x axis element and the positive charge on the front sides are accompanied by the negative charges on the backside. So, there is a clear voltage changes are there when these mechanical inputs are being provided in any of the direction transverse, longitudinal or the shear part.

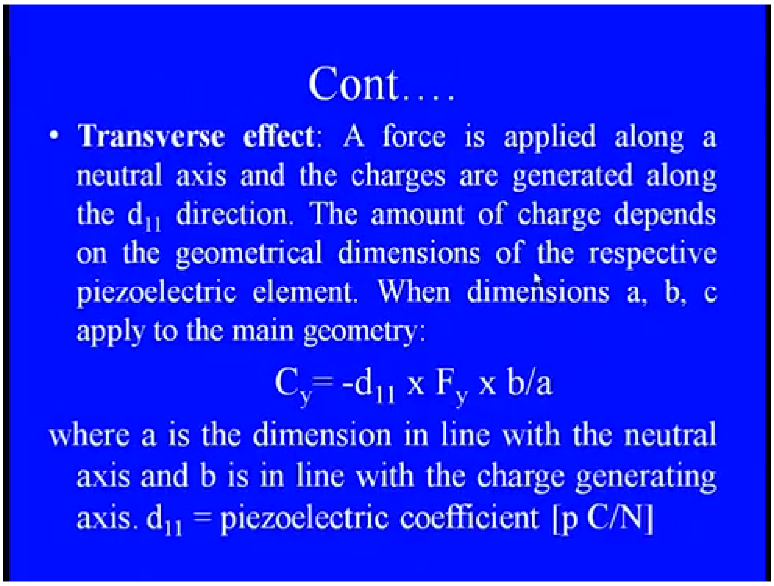
(Refer Slide Time: 31:10)



So, you can see that, we have this the gallium phosphate crystal, which is we are saying that, the piezo crystal part. In this you see here, when the traverse directions forces are there along the axis, the transverse part, the one axial part, so we know that, this the positive charge, which is being followed by the negative charges are being generated in that. Even if we have the longitudinal feature like you see, this is what the longitudinal part when the forces are being just there along these longitudinal directions then also you see the charges are being generated.

And when the shearing action is there along the plain parallel you see, not along one axis, but along the plain then also you see here, the chargers are being generated and we can get the voltage change at the outside surface. So, what exactly the mechanism is working when such kind of forces are being applied to the system.

(Refer Slide Time: 32:09)

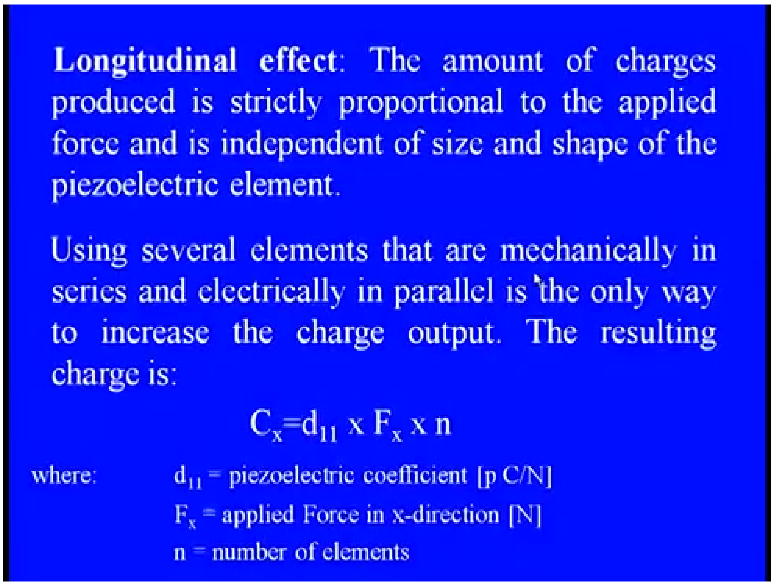


The first is the transverse force with the transverse effect, so the force when they are being applied along the neutral axis, the entire neutral axis you see here, the charges are generated along that particular direction, which we are saying that d 1 1, where the applied force and the generation means, the entire plain where these forces are being naturally occurred is in the same direction. And the amount of charge is absolutely depending on the geometrical dimension of the piezoelectric element.

So, if we are saying that, these dimensions are say a, b, whatever we can say that, the total geometry on that you see, which is being whatever the amount of charges are being generated. So, charge C y in the y direction when the forces are being applied in the x direction is nothing but equals to minus d 1 1 that is nothing but d 1 1 is my the piezoelectric coefficient is uniform in 1 1 direction. So, minus d 1 1 into F y, F y is the force, which is being there in the y direction into b by a, where a is the dimension in line with the neutral axis and b is just the dimension in the line with the charge generating.

So, here we can say that, when you have both the things together means, when the neutral axis and the charge generation, when both are just lying in the one plain, we can say that, the piezoelectric coefficients are just d 1 1, where we can say it is nothing but the pico C by N, because it is just along one neutral axis.

(Refer Slide Time: 34:00)

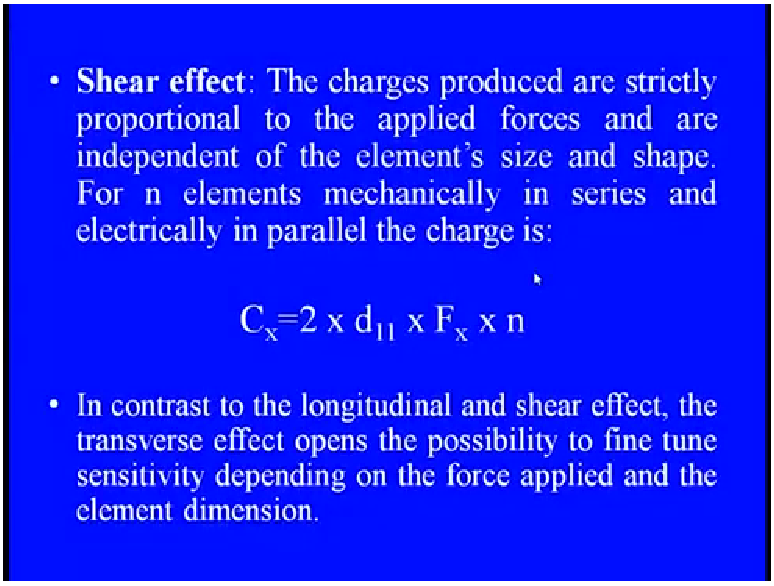


And if we are not going with this and if we are going with the longitudinal effect then the amount of charges produced the C x we can say now, is strictly proportional to the applied force, which is absolutely independent of the size and shape of the piezoelectric element. Because, now they are absolutely going along this direction and my neutral axis is this and we know that, when we are just trying to focus on the neutral axis, the layers of the entire fibers are well settled.

So, certainly whatever the piezoelectric coefficients and these neutral axis line, and the charges line, is to be considered separately, and since now it is absolutely independent in the longitudinal effect, these whatever the charges are being generated from the size and shape of piezoelectric element. So, we can simply go with that what how many number of elements are there, in which we can applied these forces and we can generate this electricity.

So, using several elements that are mechanically in series and electrically in parallel, because the charge generations are just perpendicular to that part, is the only way to increase the charge output when the longitudinal effect is being used. So, the resulting charge, say C x is nothing but equals to d 1 1, that is the piezoelectric coefficient into whatever the force, which is being applied in the x direction, because the charges in the x direction C x and into the n that is, number of elements. So, this is what you see, the amount of charges being produced when the force is being applied in the longitudinal direction is d 1 1 F x into n.

(Refer Slide Time: 35:41)

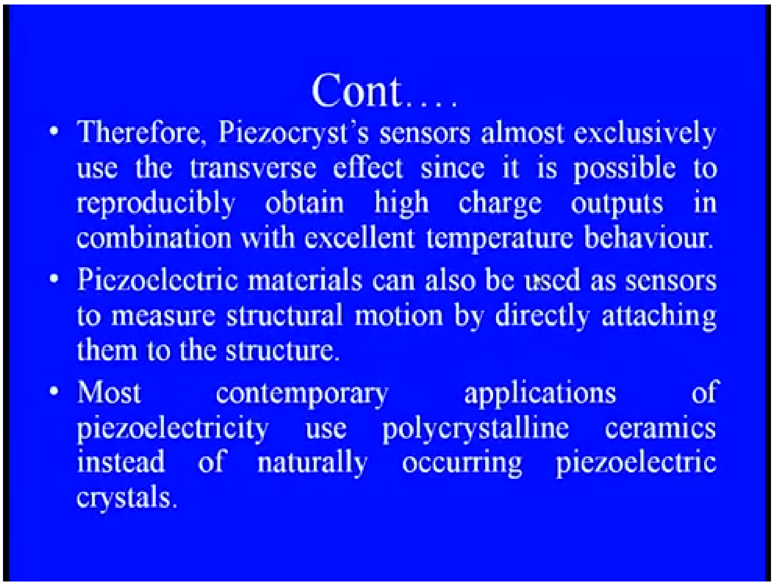


And if we are going to the shear effect, in this also the charges produced are straightaway proportional to the applied force, because now this is the shearing action is being there across the fibers and are independent of the elements size and the shape, just like the longitudinal part. And here also, the numbers of elements are supposed to be there in the series and it is supposed to be there parallel in the electrical part with the charges. So, the amount of charges produced is nothing but equals to 2 times of d 1 1 F x into n.

So, in contrast to the longitudinal and the shear effect, the transverse effect opens the possibility to fine tune sensitivity depending on the force applied and the element dimension. Because, this is a well structured pattern there along the neutral axis and then you see if we are really putting the electric charges then we need to take the shape and size of that.

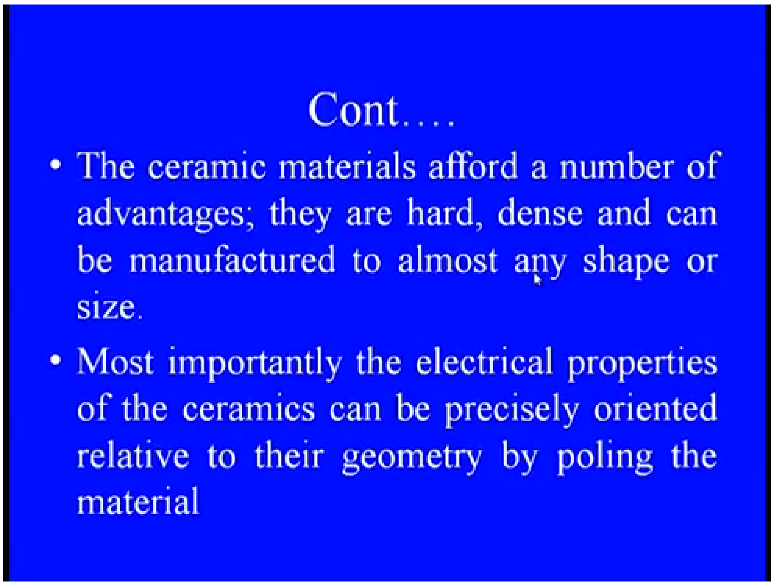
But, in other two, longitudinal and shear effect we know that, a kind of the effect on these element are just independent of the size or it only requiring that, how many number of elements are being arranged in the series mechanically or parallel to electrically, for featured out the amount of charge is being produced.

(Refer Slide Time: 36:56)



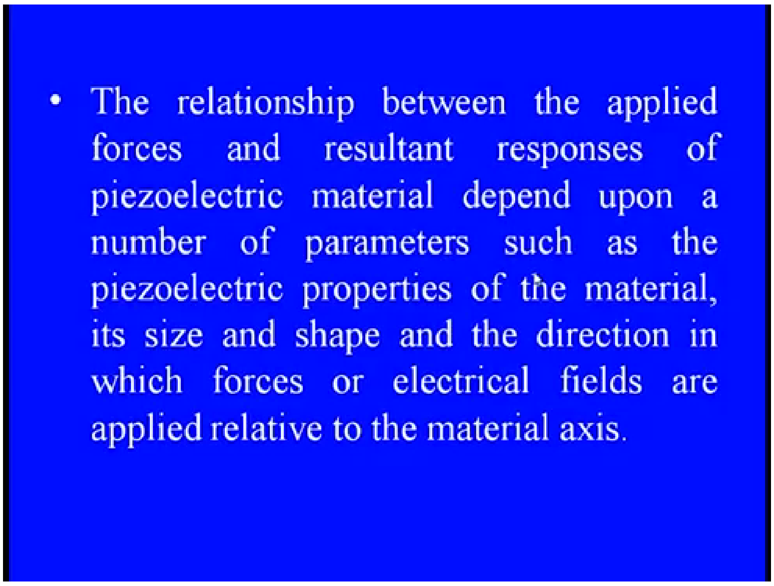
Therefore, you see we can say the piezoelectric sensor almost exclusively used the transverse effect. Please remember, when we are just going for sensing application from the piezoelectric part then we need to use the transverse effect, since it is possible to reproduce and obtain high charge output in combination with excellent temperature behavior. And the piezoelectric material can also be used as sensor to measure the structural motion by directly attaching them to the structure.

(Refer Slide Time: 37:48)



So, most contemporary application of the piezoelectricity used here is the piezocrystalline ceramics. That is what we discussed about the PZT part, in which we have all three part together the lead, the zirconium and the titanium feature is there, which can be excellently used there. So, ceramic materials can afford various advantage, which we discussed and even they can provide whatever the electric properties, which are being required.

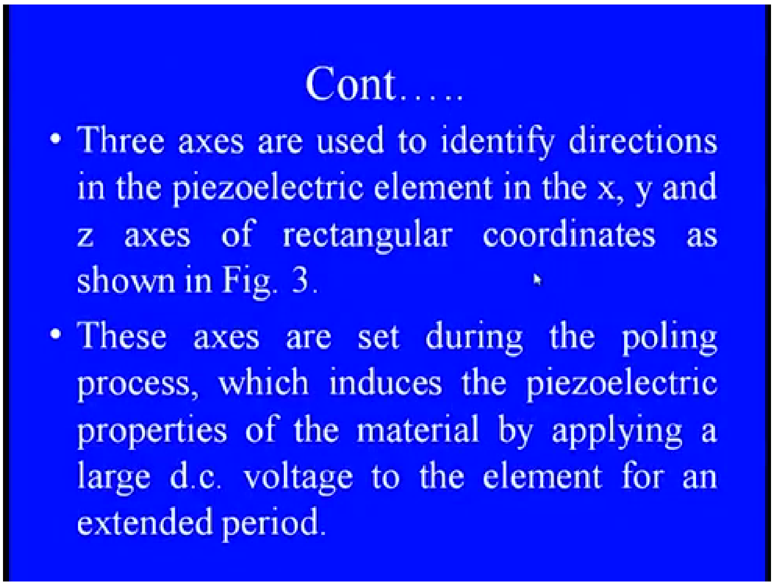
(Refer Slide Time: 37:58)



And the relationship between the applied force and resultant response can also be immediately get with the using of the appropriate property of piezoelectric material, it is size and shape and the direction of the forces, which is being applied or we can say the direction, where the electric fields are being generated with the relative to the material axis.

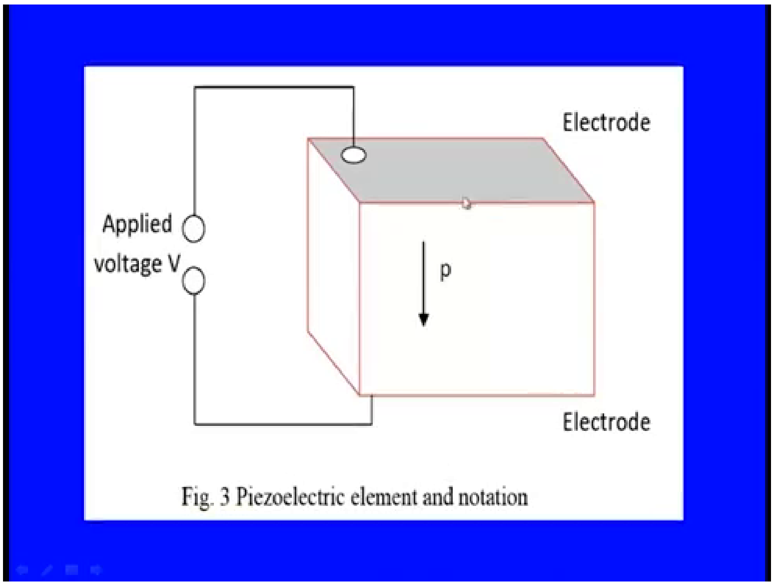
So, this is one of the beauty part here that, when you just want to apply the relations or we just want to apply these things in the real application, we can immediately go that, what exactly the requirement is and how we can generate the amount of charge or we can say, sense the forces when the voltage drops are there.

(Refer Slide Time: 38:41)



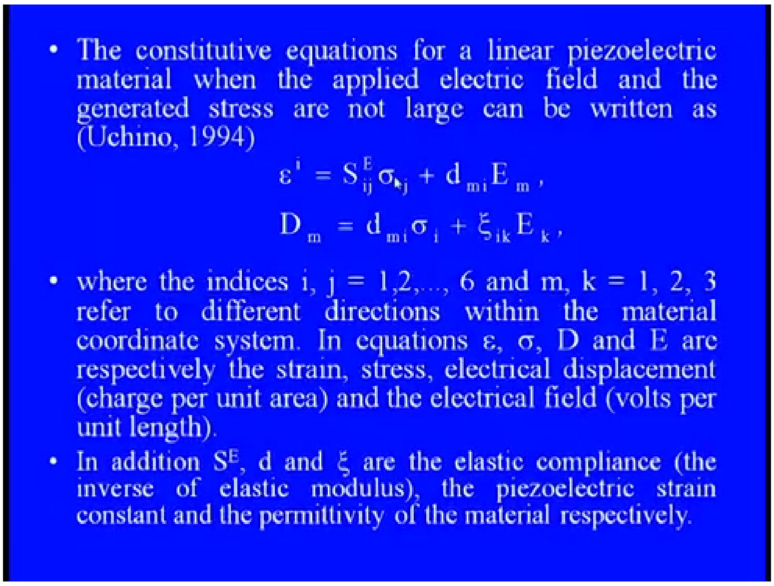
So, three axes can be used to identify the directions of the piezoelectric element and correspondingly you see here, we can use the rectangular coordinate or any kind of x y z coordinate systems are there. And these axes can be set during the poling process, which induce the piezoelectric properties of the material by applying the large dc voltage to the element upto certain period.

(Refer Slide Time: 39:07)



You can see that, you see this is what all three axes part is being there, the pressure is can be applied there on the particular electrode. And when we are simply applying the voltage drop or we just want to measure the voltage drop corresponding to the pressure, these things are being actuated and corresponding voltage drop can be measured. Because, whatever the changes are there within the element, when you see this piezoelectric featured are being there, the entire positive and negative charges are being separate out and they can simply generate the voltage all across the material.

(Refer Slide Time: 39:41)



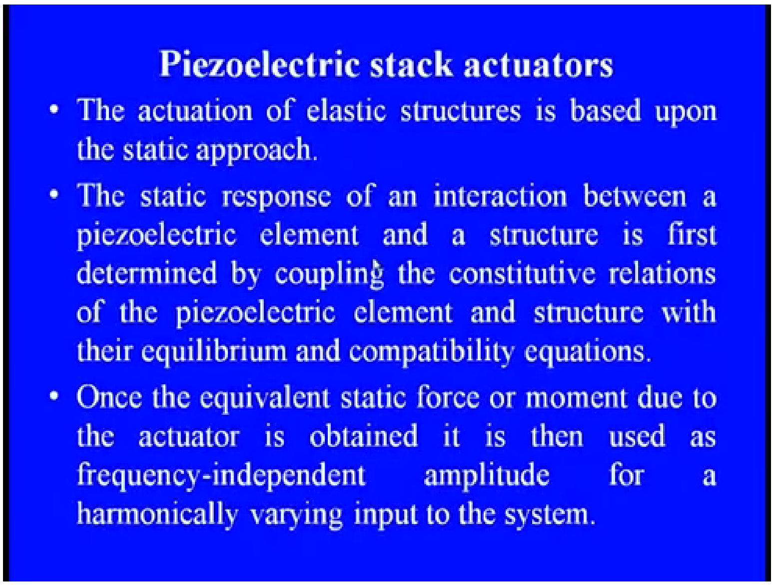
And the constitutive equations for the linear piezoelectric material when a simple uniform electric field is being applied and whatever the stresses are generated, which are almost being a elastic feature means, not very large stress generation is there, we can straightaway apply these voltage field and we can get the strain. As the strain j is nothing but equals to S i j E into sigma j plus d m i into E m, where the epsilon is nothing but equals to the strain, which is being there in the entire this piezoelectric material, S E is nothing but the elastic compliance.

Elastic compliance is nothing but it is just the inverse of the elastic modulus, so it is a elastic property as you can see, it is S to the power E. It is just the elastic property which just shows the variation in the two main indices i comma j as per the direction of material coordinate under the elastic deformation, which shows the linearity in the stress strain featured into sigma j. Sigma j is nothing but the stresses which is being there in the entire material plus d m, d m is nothing but the piezoelectric strain constant.

That, there is the constant according to the property into E m, E m as you know that, is nothing but the electric field which is being applied and this is volt per unit length. So, this is you see, we can say the strain can be obtained with the using of these elastic property and the strain part and the applied voltages. And second you see here, the d m, is nothing but equals to the electrical displacement, in which we can say that, that is nothing but the charge per unit area.

So, electrical displacement, so this is one part previously, which we show the strain that is, the mechanically part can be compared or can be obtained using the stress and the electric field. Now, we have the electrical displacement, which is nothing but equals to d m into sigma i and we know that, the d is nothing but the piezoelectric strain constant into sigma i is the stress in the i th direction plus epsilon i k and epsilon i k is nothing but equals to we have what exactly the permittivity of the material.

(Refer Slide Time: 42:57)



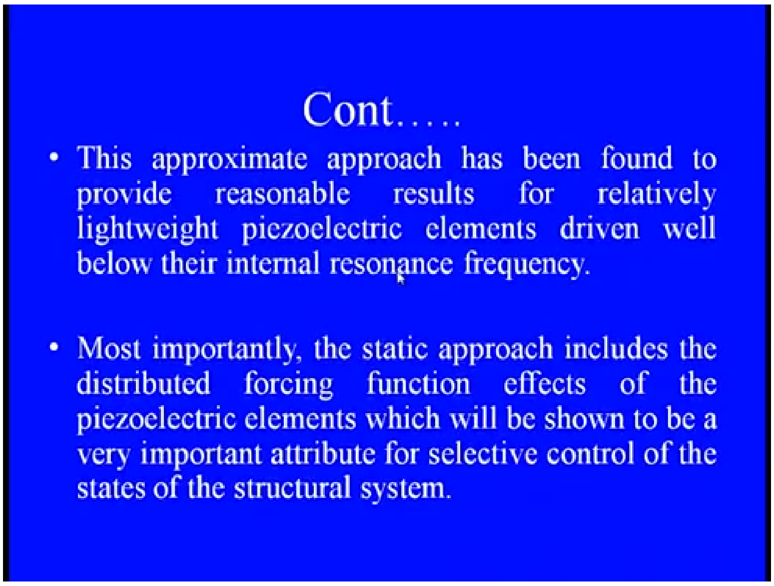
The permittivity is nothing but the material property which just shows that, how the material is going to react against the forces into E k and E k is nothing but as we discussed that, it is the electric field, which is being applied to the system. So, we can get either the strain or you see here, this d m that is nothing but when we are getting these electrical displacement of the charges, we can immediately get these two or we can simply relate when the small stresses or the strain are being generated with the electric field. So, this is one equation, these two equations which are clearly showing the relations between the electric field stress and strain along with the material properties.

So, when we are just using these piezoelectric features in the sensor and actuators then we need to see that, what the actuation feature is there in the elastic structure. Because, we know that, when we are applying to the static or any dynamic approach based then we need to see that, how these are being placed, how these actions are being taken within that. So, if you are talking about the static response then it is nothing but the interaction between the piezoelectric element and the structure, which first to be determined.

And then it is to be coupled with the constitute relations of the piezoelectric element and the structure with their equilibrium and the compatibility equation. Because, it cannot be abruptly applied there, wherever you see actuations are there or the sensing features are there and we can get the accuracy of the result now. We need to check it out the two things, one is the equilibrium part, the stable feature in that and second, the compatibility part.

And based on these things, we can simply frame the equations, either in the mechanical strain or the electrical displacement of that part. And once the equivalence of this static force or moment due to actuator is obtained then we can use the frequency independent amplitude for harmonically varying input of the system. So, this is one of we can say that, piezoelectric stack actuator can be used like that.

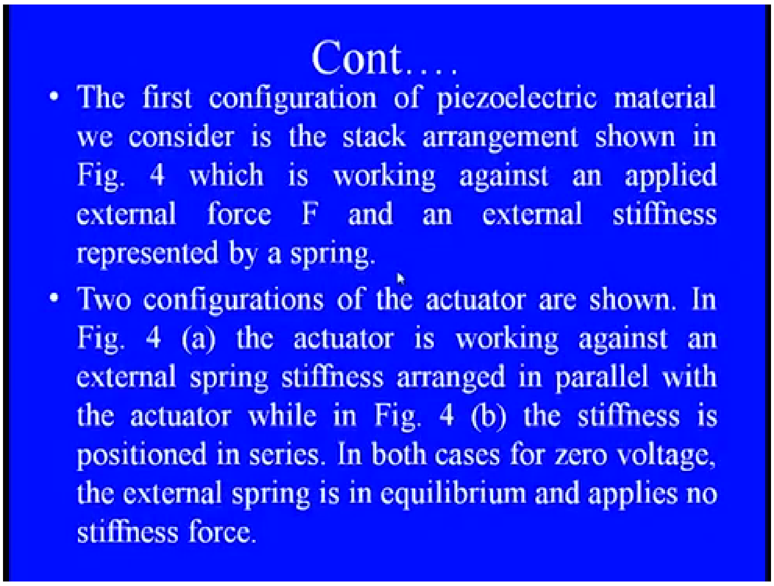
(Refer Slide Time: 44:16)



And this appropriate approach can be found in the reasonable good results, if we are just using a relatively lightweight piezoelectric elements, in which the internal resonance frequency should be very high as compared to whatever the exciting frequencies are. And most importantly, the static approach includes the disturbance forcing function, which is directly effecting the piezoelectric element and that can be shown laterally very important at this attribute for selectively control states for the structural system.

So, this is one of the important feature in this that, we need to check it out that, what exactly the internal resonance frequencies are. And then whatever the piezoelectric elements, which are being used to disturb the forcing functions, have to be selectively control all these state of these structurally excited systems. So, now we are using one more stack arrangement, in which the external force F is to be applied and we can say that, some external stiffness is to be represented by adding the spring there.

(Refer Slide Time: 45:30)



So, two configurations are just I am going to show in the next slide, in which the actuator is working against an external spring stiffness, which is arranged in parallel with the actuator. And second, the stiffness is position in the series and in both the cases, for zero voltage and external spring is in equilibrium and applied no stiffness force there itself.

(Refer Slide Time: 45:56)

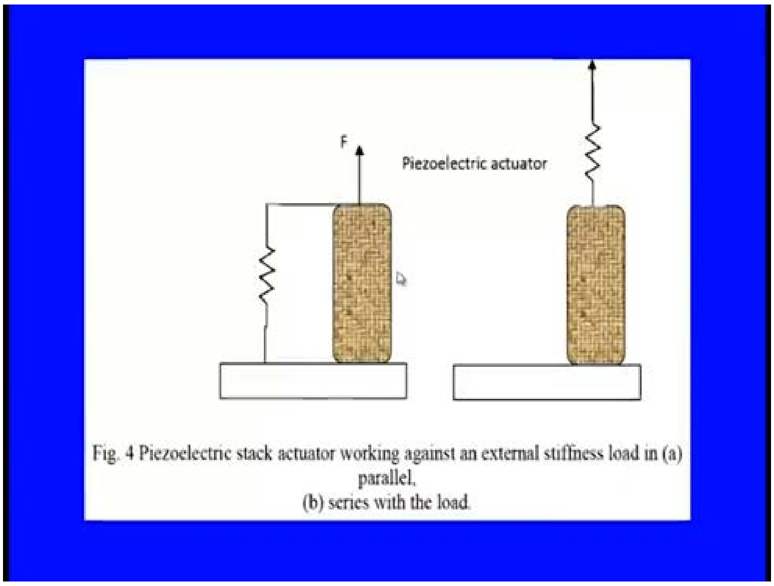


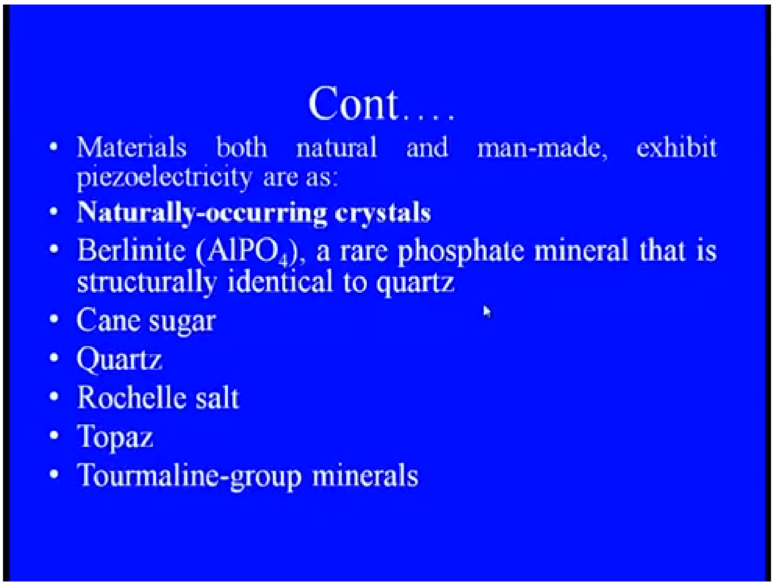
Fig. 4 Piezoelectric stack actuator working against an external stiffness load in (a) parallel, (b) series with the load.

So, this is what it is, the first part in which the piezoelectric stack actuator is working against the external stiffness, which is used as a parallel. So, you see here, this is what you see the forces are being there and parallely when we are applying the external stiffness part even with this actuating force, they are simply against the whatever the restoring forces are being coming out from this. And then they can make the balance of the entire feature, which is there on the below side.

And even you see here, this piezoelectric straight actuator can work against whatever the external stiffnesses are being there in the series formation and they can bring the entire the structure to the zero amplitude by applying the force against this part. So, these are the piezoelectric actuators, which I am just showing by the brown part and they are working against the spring force, which is being there, the external spring we can say.

And they can brought the entire system into the zero amplitude by applying their forces in these proper direction, which is showing on the diagram. So, as we discussed about the piezoelectric sensing and actuating applications we know that, there are two broader categories of this, according to their material properties.

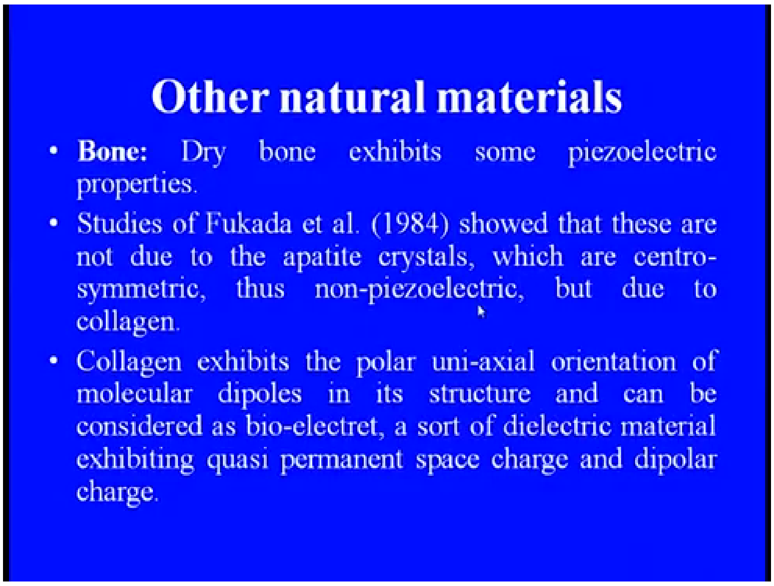
(Refer Slide Time: 47:13)



We can categorized in two broader category, the natural and manmade piezoelectric materials. If we are talking about first the natural, because they are very less and in comparison to this and they have lots of limitations together. So, naturally occurring crystals are first the berlinite, so berlinite which is nothing but AlPO 4 is a rare phosphate mineral and that can be even put category in terms of, because it has a similar character of the quartz.

So, we can say it is a naturally occurred this part, even the cane sugar, the quartz, the Rochelle salt, the topaz or even we can say that, the tourmaline group minerals. They are all coming under the naturally occurred crystal, which are showing the piezoelectric featured in that.

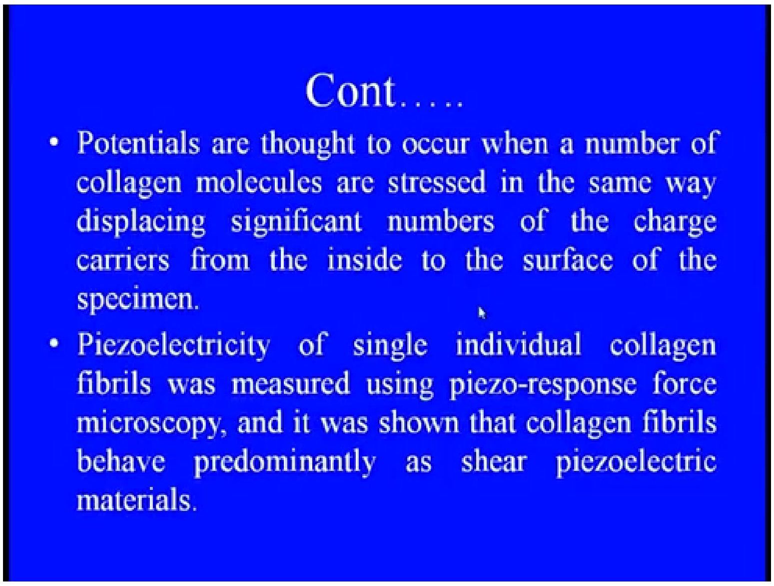
(Refer Slide Time: 48:05)



Even we can go with the other natural materials like the bone, the dry bone can exhibit sometime a similar kind of effect like the piezoelectric properties. And the Fukada et al in somewhere 1984, they shows during their studies that, these are not due to the apatite crystals in that, which are the Centro symmetric, but they have non piezoelectric. But, due to whatever the collagen and collagen is simply exhibiting the polar uniaxial orientation of the molecular, which dipoles in it is structure.

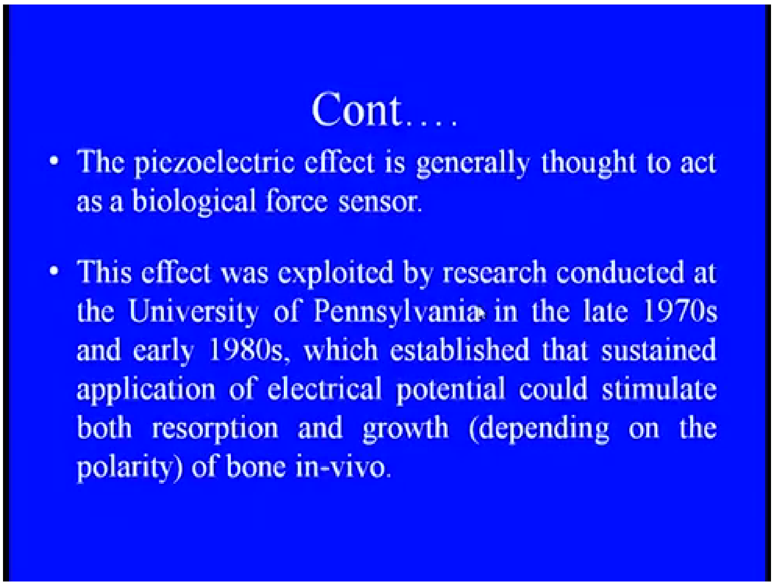
And can be considered as the bioelectric, which is a sort of dielectric material and they can exhibit a quasi permanent space charges and dipole charges. So, it is somewhat you see here, some inherent properties are there of the collagen and these collagen is absolutely forming these uniaxial or intuition part. And in this orientation what are the molecules are there, they can sometimes show a kind of the space charges or the dipole charges towards their formations.

(Refer Slide Time: 49:19)



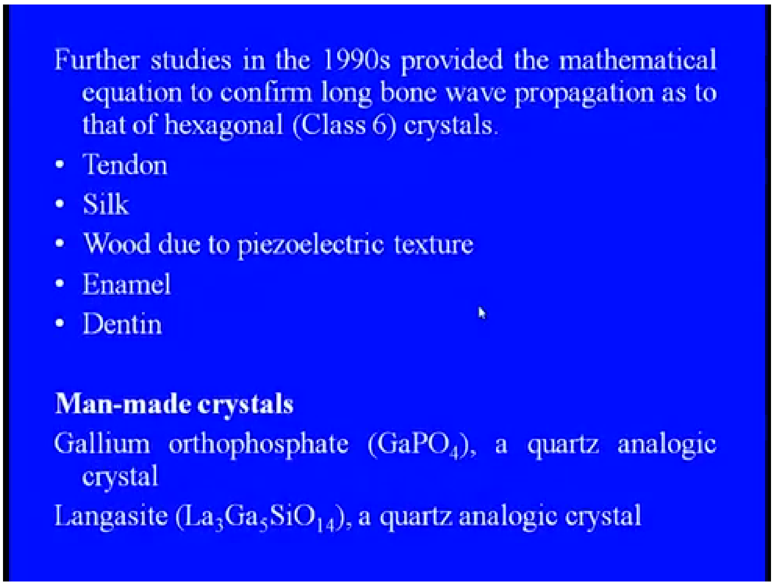
So, potentials are, though you see to occur when the number of collagen molecules are stressed in the same way like displacing significant number of charges, which carries from inside to the surface of the specimen. And piezoelectricity of single individual collagen fibrils was measured using the piezo responsive force microscopy and that can be shown that, the collagen fibrils behave predominantly as the shear piezoelectric materials. So, this is something you see, which has a clear exhibition of the piezoelectric feature when the force is being applied and the electrical outputs are there according to their action.

(Refer Slide Time: 50:00)



So, this piezoelectric effect can be generally thought to be act as a biological force sensor and this is effect was exploited by the research conducted in the UPENN. And they simply establish the sustained application of the electric potential, which could be stimulate both the resorption and the growth means, which is depending on the polarity of the bone in vivo robots. So, this is something, which has a clear application and people are using.

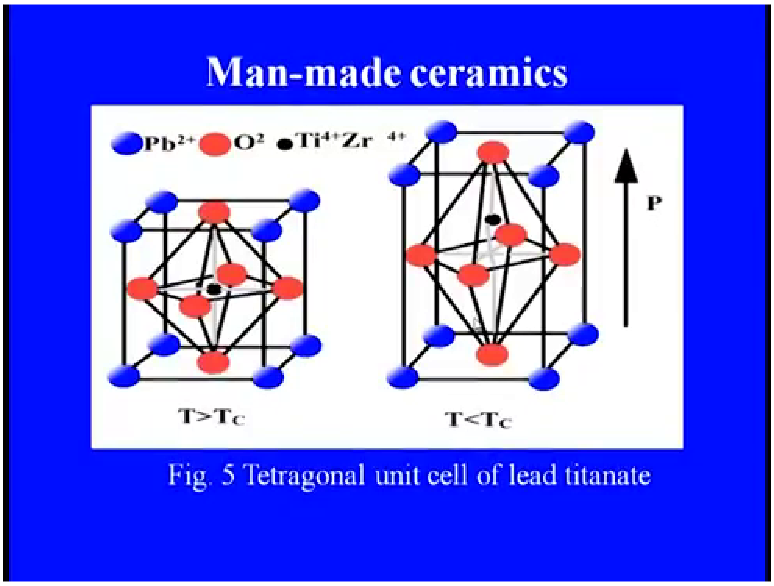
(Refer Slide Time: 50:34)



Further even, some of the mathematical equations can be brought out when the long bone wave propagations are there in their hexagonal crystals like the six crystals, like we can say tendon, silk, wood due to piezoelectric textures, enamel or we can say dentin, these are all one of few of the parts there itself. And when we are going towards the manmade crystals, the second category, in which we can say that, the gallium orthophosphate means, you see the GaPO 4 is one of the best quartz anagogic crystals.

So, you see here, they have the same feature as the natural quartz have and the gallium orthophosphate, it is just continuing these kind of all the piezoelectric featured, which can be act as a straight sensing part and the actuation features. Even langasite, which is nothing but having the La 3 Ga 5 SiO 14 means, it is especially we can say a quartz analogic crystal having all these arrangement and they are simply exhibiting the same properties together.

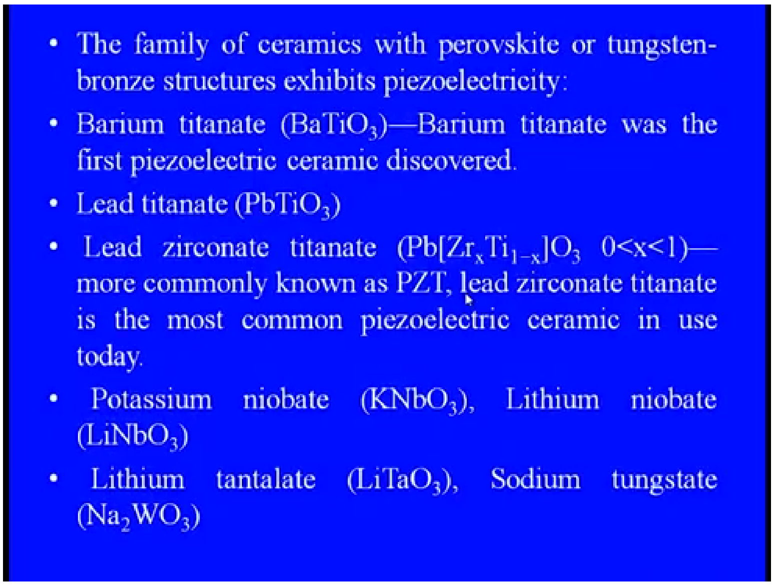
(Refer Slide Time: 51:48)



So, when we are talking about these two piezoelectric ceramics you can see that, we have the tetragonal unit cell, which has the lead titanium. So, when we are saying that, the titanium is just occurring with the critical part then we can say this blue part, which is showing the lead, the red part is showing the oxide part and you see in between, the centered part, which you are simply showing the black is nothing but the titanium and zirconium.

And when you see any force is being applied, you can see that, there is a clear stressed features are there, when this temperature is just beyond the critical temperature of that. When it is low then it is in these things and when it is being stressed out, because of that. So, this tetragonal unit cell is clearly showing that, what the interaction is there in between the lead, which is nothing but the blue and you see here, the oxide features along with we have the titanium, so lead titanium part.

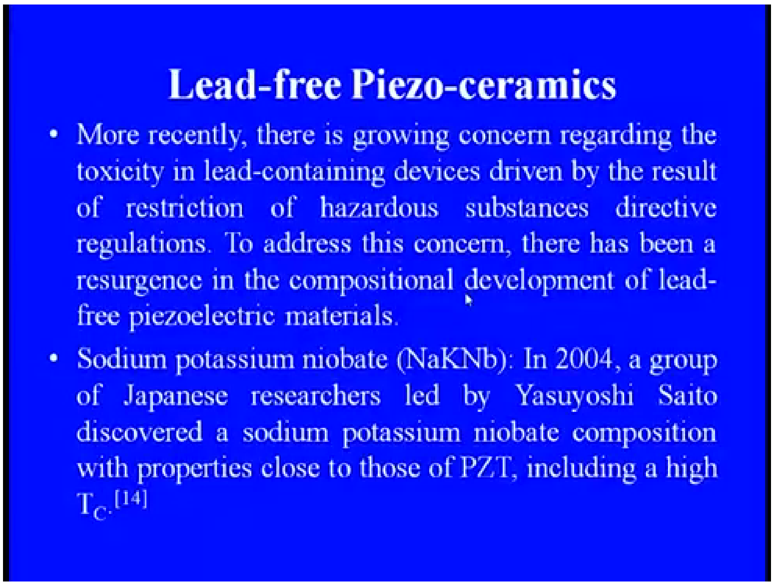
(Refer Slide Time: 52:49)



So, the family of ceramics with this perovskite or the tungsten bronze structure can also be exhibit the piezoelectricity. So, either we are just talking about the barium titanate, which is also one of the basic piezoelectric ceramic part or even when we are talking about the lead, this lead titanium which was previously, which I shown there. Lead zirconate titanium, which is one of the basic PZT part and has excellent features and that is why you see, commercially we are using these things.

Or even we can say, the potassium niobate, this KNbO 3, in which the lithium niobate is there, can be straightaway used either the potassium niobate, lithium niobate, the sodium tungsten, all these are clearly showing the piezoelectric features. But, main problem is coming in these that, there is a clear effect of the lead is.

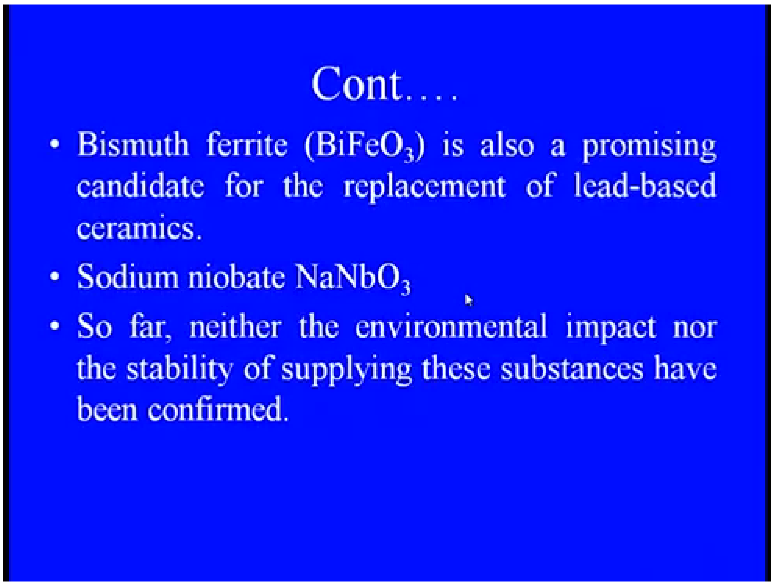
(Refer Slide Time: 53:42)



And this lead is always creating some problem as you see here, it is more concerned with the toxicity feature. And then you see here, there is a clear, because of this, it is a clear restriction of the hazardous substance, because of the directive regulations. So, to address this, there is lot of research being happened to make these material in the composition of lead free piezoelectric part.

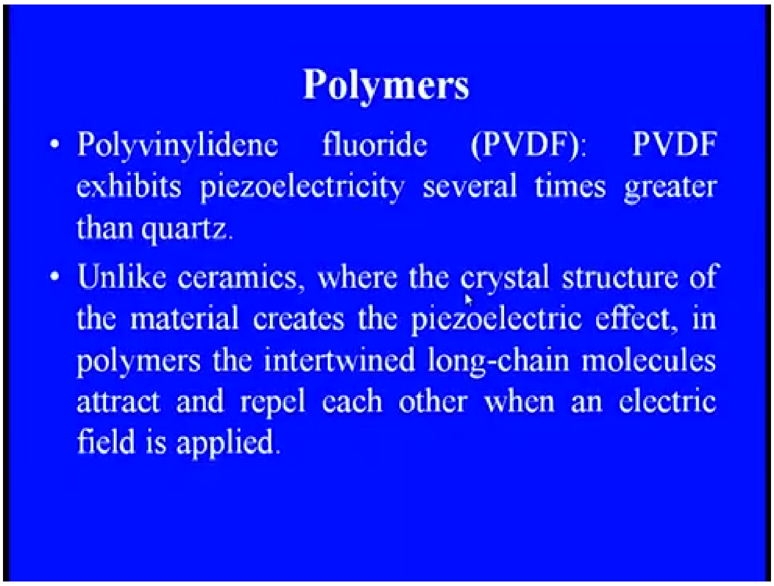
And in recent time you see here, somewhere in 2004, the Japanese researcher led by Yasuyoshi Saito is simply discovered one of the sodium based part. The sodium potassium niobate means, it incorporate both the features of the sodium and potassium and they simply made based on the niobate Nb part. And it is showing the same character as the PZT part is, with even the high critical temperatures.

(Refer Slide Time: 54:42)



Or else, even we can use the bismuth ferrite that is, you see what the bismuth part is there with the ferrite material, they can also show a clear lead based ceramic, is a replacement of that. Even the sodium niobate can also be a replacement of the lead based ceramics. But, still you see here, lots of things have to be confirmed, whether you see they have a environmental impact or not. So, still the research is going on, but this is there.

(Refer Slide Time: 55:10)



Lastly, if you are talking about the polymers, so till that you see, we discussed about the ceramics, the polymer based you see here, these piezoelectric part is polyvinylidene fluoride means, PVDF is a perfect material, which can exhibit the piezoelectric formation of crystals. And they have a lots of piezoelectricity featured, even almost several times greater than the quartz.

And unlike ceramics, where the crystal structure of material creates the piezoelectric effect under the action of anything, these polymers have the intertwined long chain molecules, which can attract and repel each other whenever the electric field is being applied and they can show the mechanical strain along with that. So, this is one of the unique feature, even whenever we are using ceramics or polymers, they can exhibit the piezoelectric feature in that. So, in the next lecture now, we are going to discuss about the active vibration control category, the piezoelectric materials, what exactly the applications are there, where we can apply these things, what exactly the different kind of the application features are there in these piezoelectric materials.

Thank you.