Nature and Properties of Materials
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Lecture 23
Smart Materials 1

Today I am going to talk about Smart materials. We have so far discussed about various types of materials where we have mainly focused on the mechanical properties of the materials. However, Smart material is one such group of materials where the mechanical property invariably gets coupled with other properties like electrical property, magnetic property, et cetera. And that actually generates a very beautiful from the engineering point of view and also from the science point of view, some very beautiful effects in this particular group of material, so let us look into that.

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So what we are 1st going to talk about is that what is a Smart material after all? Okay. And then we will talk about the applications of Smart materials, what motivates us to work on the smart materials. And not only the materials, you can actually develop Smart system using Smart materials, so we will talk a little bit about that, then the smart actuators and direct and reverse effects in such Smart materials. So let us unfold the story one by one.

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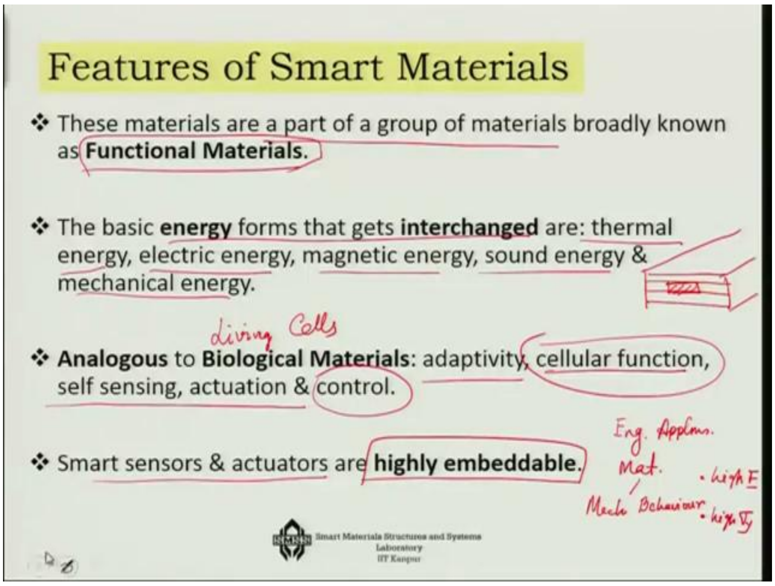

Now, the 1st important thing is that the smart materials are actually a part or a subgroup of a bigger group of materials which are broadly known as Functional material, so this we have to understand what does it mean? Does it mean that not every material is functional or there are materials which are non-functional, it is not like that? All materials have some or the other functions.

But when we say functional material what we mean here is that generally for engineering applications let us say generally from engineering applications point of view, from any material what we expect mostly is a mechanical behavior that means you have seen that from steel, from concrete from iron, from aluminium, we always look for things like high stiffness right, high modulus of elasticity or high yield different, these are the things that we generally look for.

But, can there be a material which can give me a high stiffness along with something more? Let us say something like a changeable stiffness that means variable stiffness with some signals be it electric, be it magnetic. And similarly, the strength of the system can be increased reinforced.

And similarly other behaviors like the dynamic properties or the deformation of the system that means you can generate both positive and negative deformations in a system with the help of a non-mechanical way of doing for example, with the help of electrical signals. So the materials which can respond to those types of other kind of behaviors also, these are the Functional material and Smart materials are subgroup of this kind of Functional material.

Now naturally this means that there is energy transformation that is taking place in Smart materials, so indeed the basic energy forms that get interchanged are generally thermal energy, electric energy, magnetic energy, sound energy and mechanical energy. Basically, it is transformation between mechanical energy and all this energy. One important thing of Smart materials is that they are very much analogous to biological materials or so called the living systems, right.

So they are many times actually the living cells, they are many times actually kind of an analogy people draw between them and the living systems. Why because they are adaptive, you can I told you just now that the stiffness you can change, so similarly you can change the shape, et cetera in some materials, so they are adaptive. They are cellular in function, what does it mean by cellularity in function?

It means that even if you break this kind of a Smart system into 2 parts, 3 parts okay, if you break a clock into 3 parts, the clock none of the parts would work. But if you take a Smart material and break it into say 3 parts, each part even though its performance will degrade a little bit, but each part will be fully working so that is the cellularity that is present in such materials. They are self sensing and actuation, so which means that you can actually generate forces from them, also you can use them as a sensor, so that is why they are self sensing and actuation. And not only that, you can actually control them, you can change these behaviors.

Finally, these sensors and actuators are highly embeddable okay. We have talked about composites, in that context this point is important because the composite is developed in a laminar manner, so there are several laminas suppose in a composite beam, suppose we are looking at a composite beam like this, you can very nicely embed one smart sensor inside, which will give us all the information related to the stress, related to the strain, temperature, cracks propagating and so on and so forth, so that is these are some of the advantages of the Smart materials.

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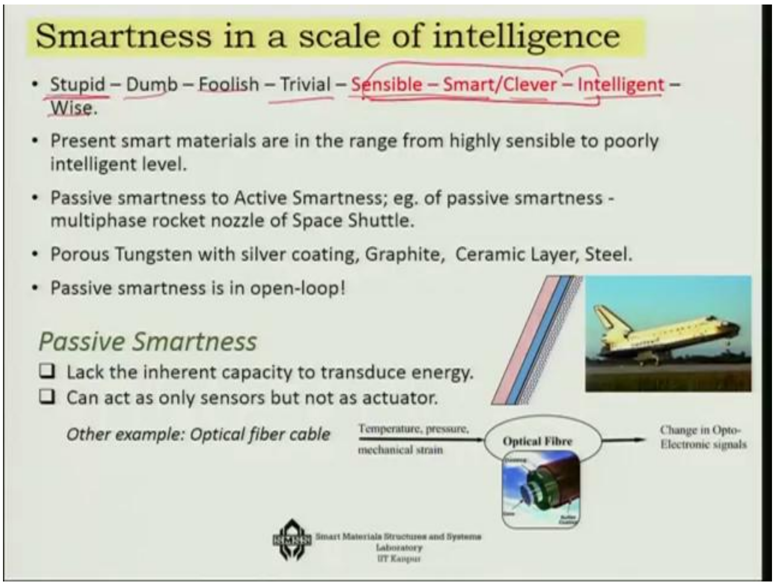

Now, smartness how do we define? If you look into a dictionary, then you would see that something which is not smart at all, the worst sense is something which is stupid, then may be dumb, foolish, trivial and then as the intelligence increases, you will start to get terms like sensible, smart, clever, intelligent, wise, etc, so where are we in the Smart material systems in terms of the intelligence?

Now currently we are somewhere in the domain of highly sensible, so here till smart, clever or maybe just reaching the poorly intelligent level that means till we are not able to replace a living system completely by an artificial system that is something is a something like a science fiction for us, but we can go very close to that with today's advanced material.

Now, there are actually 2 types of smartness, one is Passive smartness and another is Active smartness. Passive smartness I can give you one example, it is like the rocket of a space shuttle if you look at it. You would see that it consists of several layers for example, it has a layer of silver coating, then it has graphite, it has silver coating graphite, ceramic layer and steel.

Each layer is intelligently kept in order to do certain things for example, silver coating what does it do? It actually spreads the temperature over the graphite layer very uniformly and that actually kind of helps to avoiding thermal stress concentration. Then there is ceramic layer, similarly it also works in a slightly lesser temperature range and then there is steel. So as and below the steel you have basically the system itself inside okay.

So as you are going through the space or re-entering mostly into the earth, you are getting high-temperature due to the friction with the environment and that temperature should not affect the environment inside, every system should remain functional inside that is the kind of the driving force because of it we actually develop this kind of a multilayered system.

But one point, this system is in open loop, tomorrow because of some reason the temperature changes or some other factor comes into picture corrosiveness, let us say we are entering not earth, but some other planet, the system would not work. So that is the problem of passive smartness that is usually a one-time design. It lacks also the inherent capacity to transduce the energy.

And sometimes it can at best work as sensors, the passive systems, but not as actuators, so active systems on the other hand can actually change themselves.

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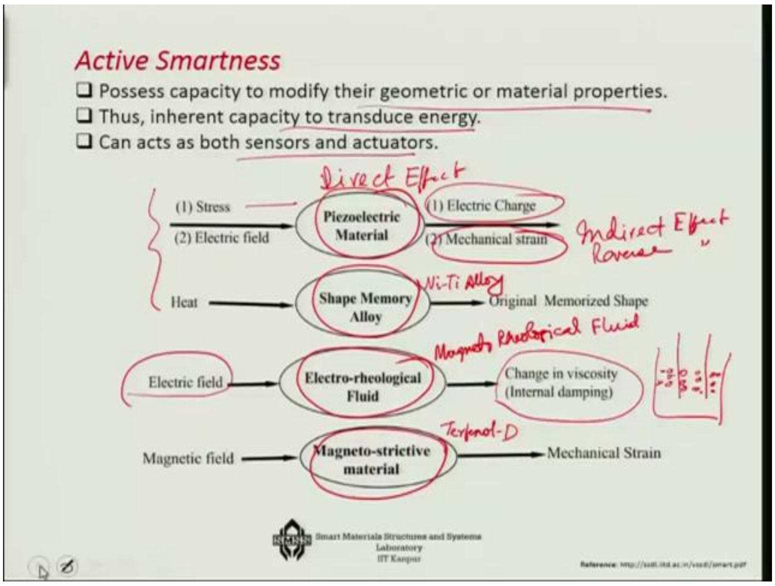

Now if you look at active smartness, then the feature that you will see is that they can modify their geometric or material properties, thus they have an inherent capacity to transduce the energy and they can act both as sensors and actuators. Of course there are some very specific materials which are like optical fibre which are generally not used as actuators, only as sensors.

Now the 4 very important materials which are used in the group of smart materials almost in regular basis are piezo electric material, shape memory alloy, electrorheological fluid and magnetostrictive material. For piezo electric material, if I apply stress I will see a change in terms of the electric field. It was like you can do a small test for example, you take a good size sugar crystal and in a completely dark room you hit it with a hammer, you are definitely going to see a streak of light coming out and that is actually electric discharge that is happening in system.

So that is kind of tertiary sign of piezo electric material, so sugar crystals, rochelle salts these are some of the naturally available piezo electric material which will show this piezo electric effect. And this effect that the stress is producing an electric field discharge is also I will talk about it later on that it is also known as the Direct effect of piezo electric.

But there exists another effect which is known as Indirect effect that means instead of applying mechanical force and getting some change of electrical field, what if you apply electrical field to piezo electric material, you are going to see a change in the mechanical strain that means it is going to deform, it is going to change its shape and that is the indirect effect okay. So or sometime people also call it as reverse effect or the converse effect, they have very similar names of it, so that is about the piezo electric material.

Then you have materials like Shape memory alloy, which is basically one of the very popular material is Nickel titanium alloys and here if you apply temperature, you are going to see a huge change in terms of the deformation. Not only that, in many cases if you actually reduce the temperature, you are going to get back to the original memorized shape. So there are actually 2 types of this effect I will later on discuss, one is called Two way shape memory, another is called One way shape memory.

So in Two way, it actually memorizes both the high-temperature as well as the low-temperature shape, but in One way it memorizes only one that is the high-temperature, the shape the original she at high-temperature. Then this too of course respond to the electric field or the thermal field in terms of change in mechanical strength, but there are some materials like electrorheological fluid where if you apply the electric field, you will see there is a change in viscosity.

Once again in laboratory, you can try this kind of very simple test that you can take a colloidal suspension of starch or suppose something like this Maida kind of a thing okay so Wheat powder, so that you actually disperse it in a slightly acidic material and then you apply high-voltage, what you will see is that the colloidal solution will start to get, so if you apply high-voltage in two electron you will see that there is a bridging effect happening okay close to this.

So all the particles will start to flock around these and there is a bridging effect, so that means the viscosity is going to get change these electrodes. So this is electric field which is responsible for change in viscosity. There are many fantastic applications particularly not with electric field, but with magnetic field and we call such materials to be Magneto rheological material.

Very similar to this effect, but the source responsible is not electric field but magnetic field, so magnetorheological field. Now, the magnetic field can also be used to generate mechanical strain and that happens for a group of material like Terfenol-D, terbium, iron and amount of dysprosium can actually bring this change. So there are whole lot of smart materials which manifest this type of very interesting changes.

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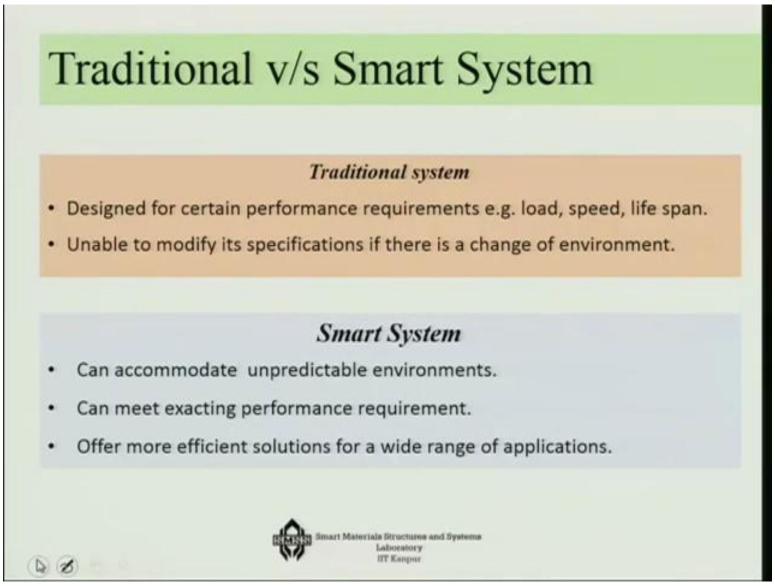

So is we compare between a traditional versus smart system, traditional systems are designed for certain performance requirements for example, for certain load, certain speed, certain lifespan, they are unable to modify its specifications if there is a change of environment. Whereas, for smart systems we have to re-emphasise that they can accommodate unpredictable environments, they can meet exacting performance requirements and they offer more efficient solutions for a wide range of applications.

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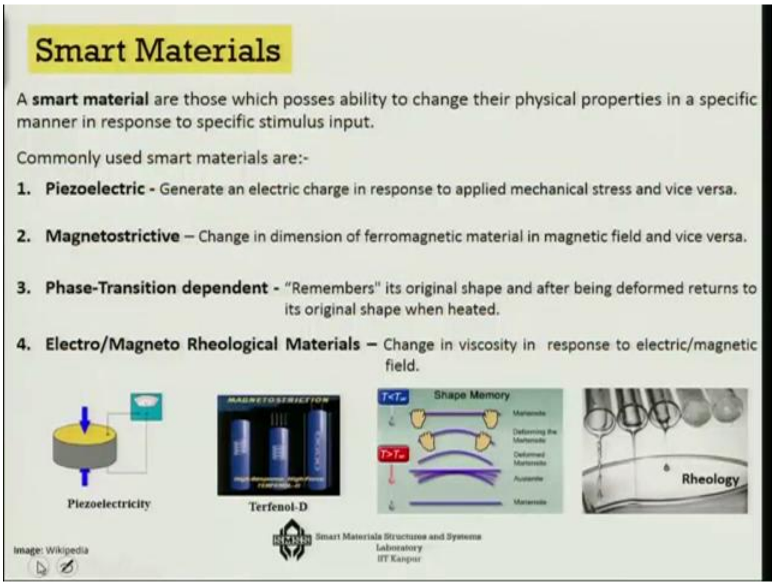

Now, if I actually look at these smart materials which possess this ability to change their physical properties in a specific manner in response to specific stimulus input, then commonly used materials are the Piezo electric material as you can see here in this little animation that you are changing the electric field, which is generating the charges and in response to that this whole thing realigns itself and as a result, you are getting a mechanical deformation in the system.

Similar thing you will notice in magnetostrictive material with the change of magnetic field. In fact, first it was noticed in the ferromagnetic material like iron okay, so Joule 1st noticed that the change in the shape of a magnet is happening with the change of the magnetic field and that is the magnetostrictive. For phase transition depended materials like shape memory alloy wares, what happens is that you use a temperature which is high enough, what will happen is it will go from Martin side to Austenite phase.

You can do all sorts of deformation okay, but so if it is one way for example, you can deform it in the Martin side phase itself and then if you increase the temperature, it will exactly go back to its original shape. And if it is Two way one, then this happens between both low and the high temperature, that is Two way shape memory effect. Electro/magneto rheological materials I already told you that the change in viscosity in response to electric or magnetic field.

For example, the magnetorheological material one of the best examples is Iron nano particles in solution like silicone oil, so silicone oil plus Iron nano particle suspension. And then you apply magnetic field, you will see a similar bridging effect and that completely dramatically changes the viscosity of solution. So why smart sensors and actuators are important today?

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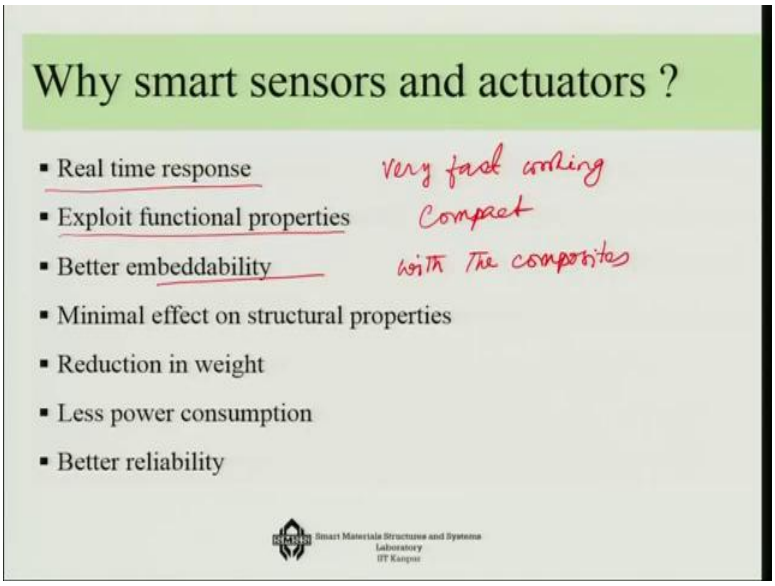

The first important thing is that the response real-time response, it is very fast, so it is very fast very fast working okay. In today's world for example, you think of your single lens reflectors, SLR camera, you want a quick change of focus and who does that, a Piezo electric crystal, so a really fast response you get. It exploits the functional properties that means a material both works as a mechanical load carrying system as well as it does functional work, so that means it makes the system very compact.

And it has better embeddedability with the composites I told you already that with the advent of composites, smart material applications increased like anything. It has minimum effects on structural properties; some of the smart materials are quite good in terms of their structural properties, reduction in weight of course, less power consumption and better reliability. So these are all the driving factors why smart materials are increasingly being used for developing sensors and actuators.

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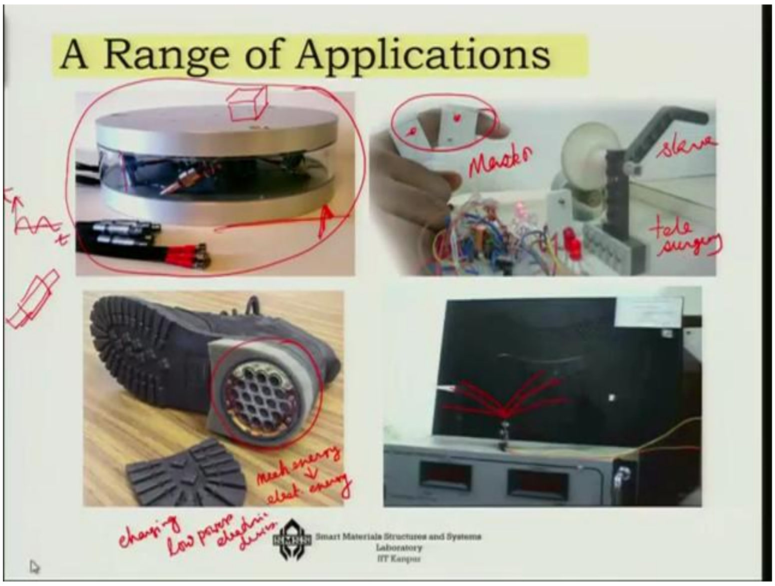

There are range of applications of them, I have only shown few of them here for example, this one in the left side as you can see that this is a platform, so this is also known as the Stewart platform, so it has actually various legs in it. The idea is that if there is an excitation force at the base of the system, there is an excitation force happening and you are not going to allow this excitation force to pass through this system and excite a little very highly precise machine that is sitting on top of it.

You want to stop that, how would you stop it? Well, one way to stop it is that suppose it is getting excited at a particular frequency level okay, so with respect to time suppose there is particular amplitude of this system. Now, you want to design these legs in such a manner that it is completely de-tuned from this frequency that means it is not going to resonate. If it does not resonate, then it is generally going to absorb this vibration within itself.

So how do I do it because this base excitation can keep on varying? One way to do it is you use piezo electric material, which can change its size okay. So you can increase or decrease the leg as and when required and through that you can stop the excitation to pass through. There is another very interesting application of smart materials that is in the shoes for example that if you keep such smart materials below the shoe, you can actually get energy transfer from mechanical to electrical energy here.

So as you are working, your mechanical energy is getting generated and you can transform it to electrical energy and you can store this electrical energy and as a result, you can use it for charging low-power charging low-power electronic devices, so that is something like this is coming up in a big way, low-power electronic devices. There are many other applications for example, this one is not very clear this is like a butterfly wing.

And this is a if you apply temperature, you are going to see that this thing is going to flak, so you can generate a kind of a insect flaking with the help of this kind of system. And here is another system where this is a master slave, so this is the master finger, the idea is that whatever the master finger is doing okay, the smart sensors here are actually mapping that and then this is the slave finger, so the slave finger is going to copy it.

So this you can use for in future for things like applications like tele-surgery okay, so master finger far away can do something and the slave finger can actually copy that movement. Now then if we actually summarize all the smart materials from the sensing and actuation point of view, we will get this beautiful matrix.

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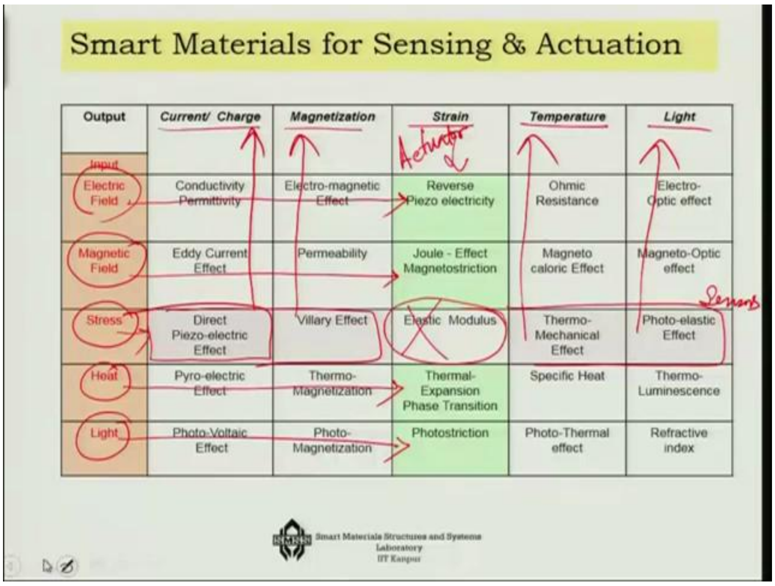

On this matrix, if you look at these columns as outputs, current charge, magnetization, strain, temperature and light. If you look at the input electric field, magnetic field, stress, heat and light. So, if I consider a diagonal element in this matrix that is stress versus strain, then what comes in the diagonal element is the elastic model. So that is not smartness because every material deforms under stress. Then what is smartness?

Smartness is if I can generate strain not with help of stress; let us say with the help of an electric field, so you come here and you are generating strain, that is what is known as Reverse piezo electricity that is smartness. Or with the help of magnetic field you want to generate, then it is Joule effect magneto-striction that is smartness. With heat, shape memory application that is smartness, with light photostriction that is smartness.

So essentially this whole column here except this diagonal term, they are actually actuators okay, so where these of diagonal properties are the materials are used for building of the actuators. On the other hand, if I look at these properties when the strain is generating current or charge or it is generating change in magnetization, change in temperature or change in light then these regions are actually used as sensors. For the horizontal block is for smart sensing and the vertical block except the diagonal is for smart actuation

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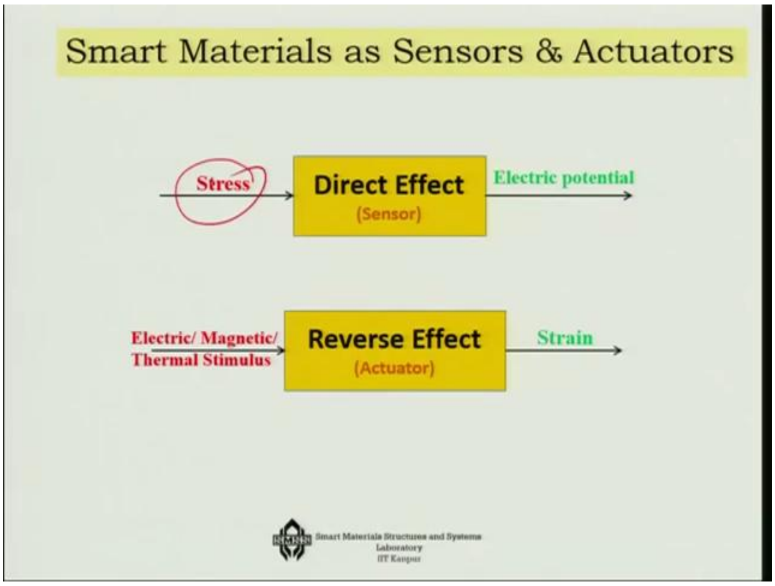

So, there are 2 types of this smart sensing and actuation. One is what, you are applying stress that is the mechanical load and you are getting a change in electric potential okay or magnetic potential or so on and so forth, and then this is called Direct effect. Now there is no reason for it, but this was one of the 1st things that were actually observed that by theorists that once you take a small crystal, you apply a stress you are going to get charges developed, that is a direct effect.

If you apply an electric field in fact, that was initially a theoretical proposition by Lippmann and then later on it was verified by people that if you apply the electric field, you are going to get strain generated in the sample and that is known as the reverse effect, so naturally the direct effective generally used as sensor and the reverse effect is generally used as actuators. So this is the 2 very important effects you have to keep in your mind as far as the smart materials for sensing and actuation comes into picture.

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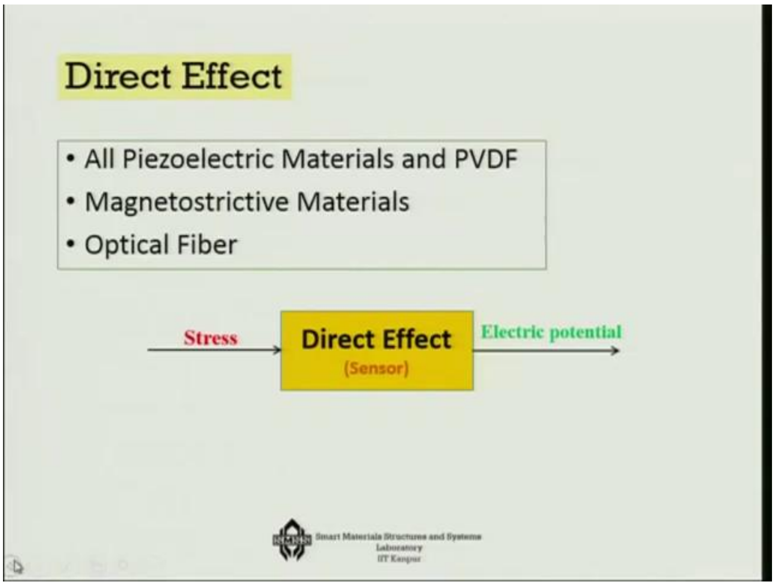

We are talking about the direct effect and this direct effect is available in piezoelectric materials and also the direct effect is available in material, which is a polymer and this polymer is actually known as PVDF Polyvinylidene fluoride. Now it is also available in magnetostrictive materials and in optical fibres. Remember that the direct effect means you are applying stress and you are finding a change in electric potential or in magnetization.

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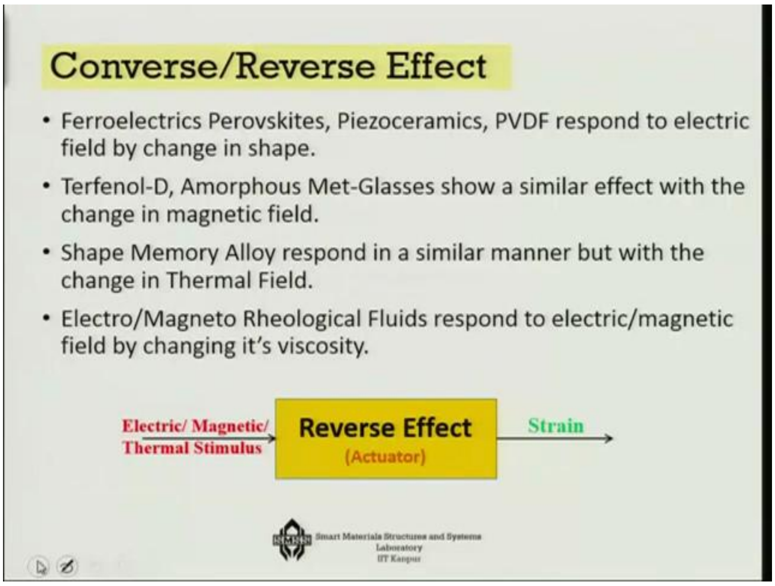

Now, converse effect on the other hand are found in ferroelectrics, Perovskites, Piezo-ceramics, PVDF, they all respond to electric filed by a change in shape. Similarly, Terfenol-D, Amorphous met-glasses they show similar effect to the change in magnetic field and shape memory alloy respond in similar manner, but with the change in thermal field.

Electro/magneto rheological fluids, they respond to electric/magnetic field by changing its viscosity.

So this is a whole group of materials which response to electric, magnetic or thermal stimulus and there is either a change in strain or a change in viscosity and that is what is our converse of the reverse effect which is used to build the actuators.

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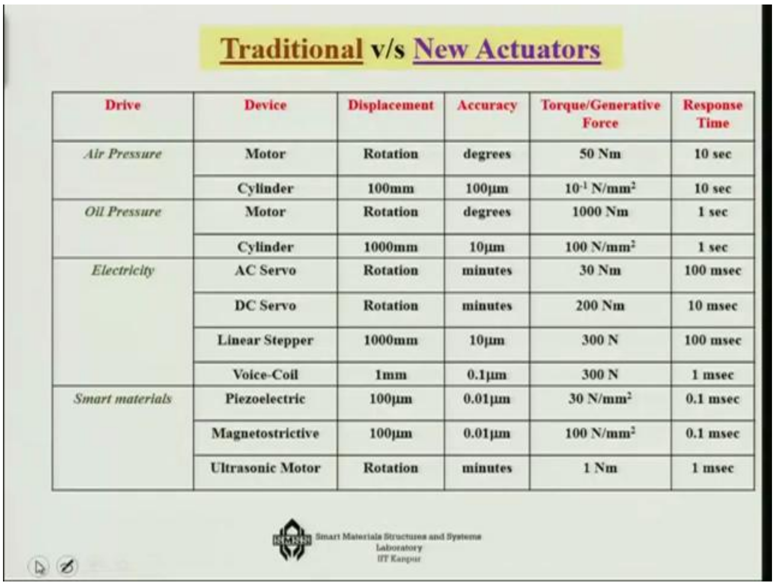
Traditional v/s New Actuators

Drive	Device	Displacement	Accuracy	Torque/Generative Force	Response Time
Air Pressure	Motor	Rotation	degrees	50 Nm	10 sec
	Cylinder	100mm	100μm	10^{-1} N/mm^2	10 sec
Oil Pressure	Motor	Rotation	degrees	1000 Nm	1 sec
	Cylinder	1000mm	10μm	100 N/mm^2	1 sec
Electricity	AC Servo	Rotation	minutes	30 Nm	100 msec
	DC Servo	Rotation	minutes	200 Nm	10 msec
	Linear Stepper	1000mm	10μm	300 N	100 msec
	Voice-Coil	1mm	0.1μm	300 N	1 msec
Smart materials	Piezoelectric	100μm	0.01μm	30 N/mm^2	0.1 msec
	Magnetostrictive	100μm	0.01μm	100 N/mm^2	0.1 msec
	Ultrasonic Motor	Rotation	minutes	1 Nm	1 msec

Now if I compare these additional verses near actuators that is the smart materials like Piezo electric, magnetostrictive or ultrasonic motors, you would see first thing interesting is that their displacements are quite small, but their accuracy is very high. And also their response time is very low that is why I told you that they are very fast in comparison to all the traditional materials they are actually much better off, so you can do a real-time control of a system using this material.

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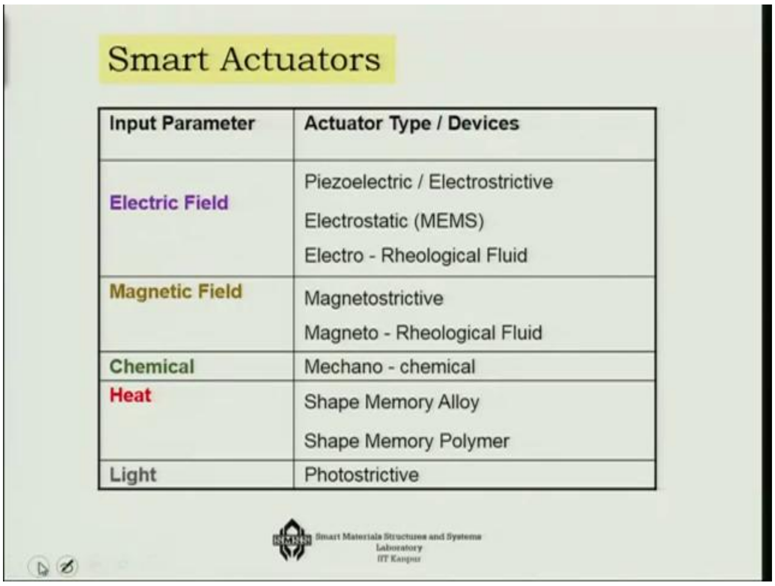

Input Parameter	Actuator Type / Devices
Electric Field	Piezoelectric / Electrostrictive Electrostatic (MEMS) Electro - Rheological Fluid
Magnetic Field	Magnetostrictive Magneto - Rheological Fluid
Chemical	Mechano - chemical
Heat	Shape Memory Alloy Shape Memory Polymer
Light	Photostrictive

Now, in the smart actuators there are whole lot of actuators like electric field those which exploits, there is piezo electric and electrostrictive actuators, then you have electrostatic actuator which are MEMS space and you have electrorheological fluids. In the magnetic field category you have magnetostrictive actuators and magneto rheological fluids. In the chemical, there are some coming up mechano chemicals you call them.

And in the heat, there are shape memory alloy and shape memory polymers. And in the light there is this photostrictive material, so there is a whole group of smart actuators that are available today. Just for comparison, properties of a few smart materials.

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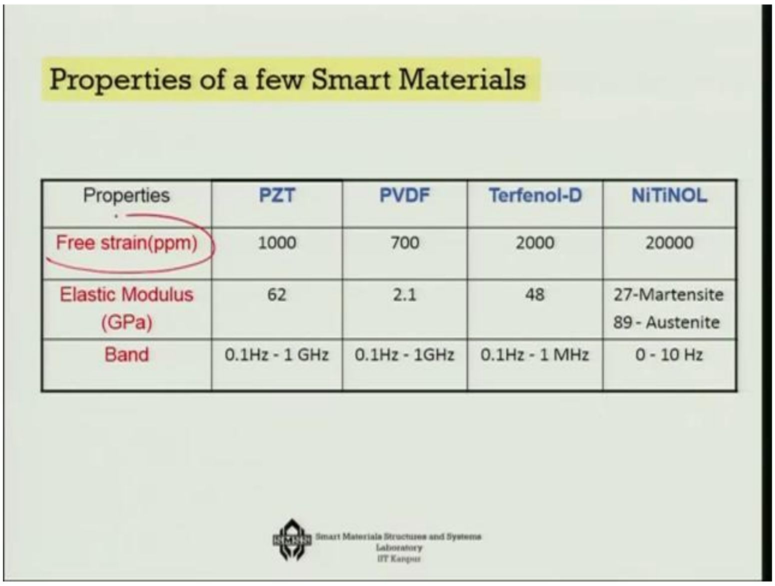

Properties	PZT	PVDF	Terfenol-D	NiTiNOL
Free strain(ppm)	1000	700	2000	20000
Elastic Modulus (GPa)	62	2.1	48	27-Martensite 89 - Austenite
Band	0.1Hz - 1 GHz	0.1Hz - 1GHz	0.1Hz - 1 MHz	0 - 10 Hz

One important property is the Free strain that means how much of deformation happens if it is not loaded. Piezo electric material you get something like 1000 parts per million and which can go as high as 20,000 for shape memory alloys like NITINOL. Elastic modulus on the other hand is about 62 gigapascal for the piezo electric material and for the shape memory material it varies between 27 to 89. PVDF is the lowest one, it is very soft, Terfenol-D somewhere in the middle.

Band is another interesting thing that means how fast the material can react, piezo electric, 0.1 hertz to 1 gigahertz, same for PVDF, little less for Terfenol-D, which means they are all very fast, but this 20000 one, they are not that fast, they are very slow that is the only one material smart material whose response time is quite slow, but the actuation strength is very high.

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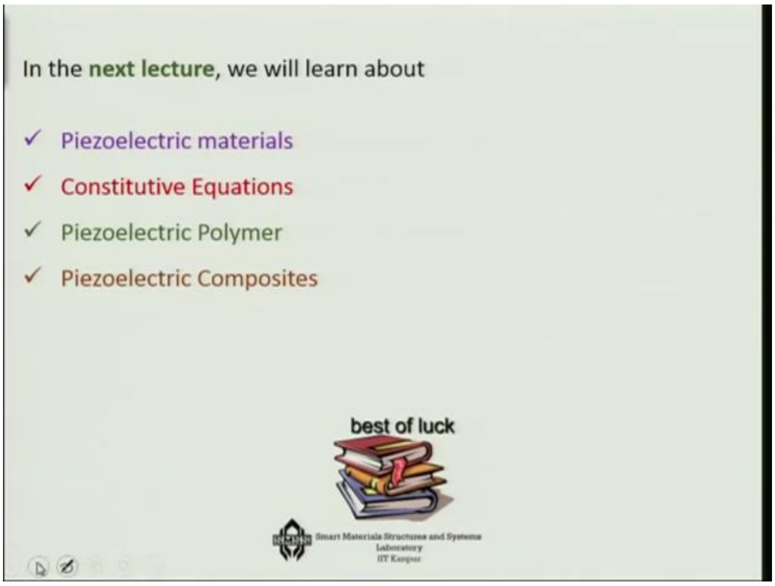

So this is where we will end and in the next lecture we will talk about this material Piezo electric material, their constitutive equations, polymers and composites in much more details, thank you.