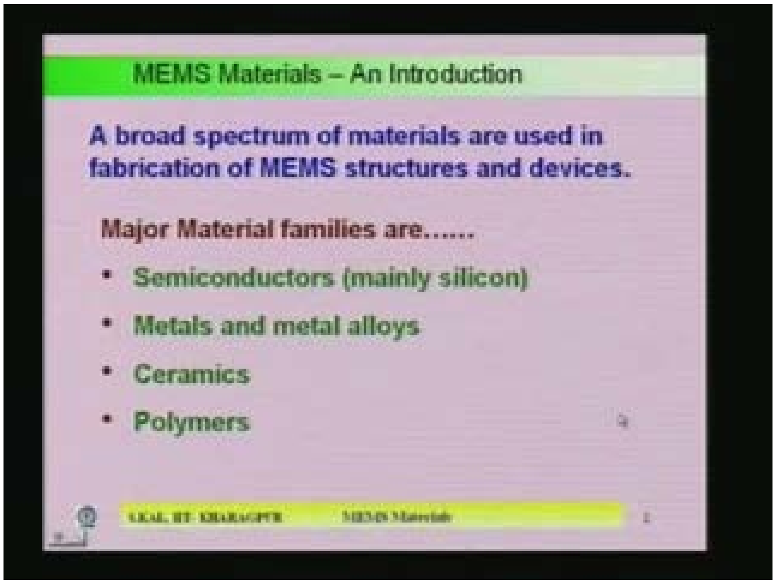
MEMS & Microsystems
Prof. Santiram Kal
Department of Electronic & Electrical Communication Engineering
Indian Institute of Technology, Kharagpur
Lecture No. #05
MEMS Materials

So today, we will discuss on materials which are used for MEMS and microsensor devices.

(Refer Slide Time: 01:02)

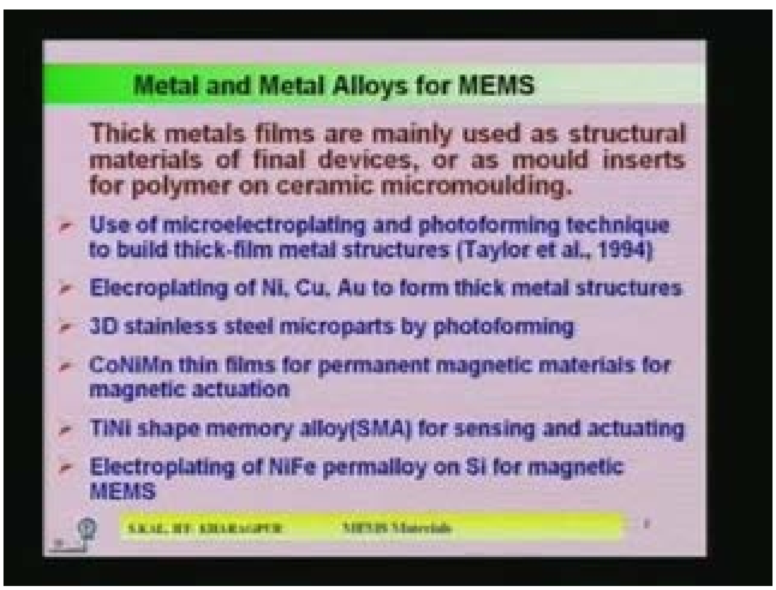
So you know, materials are the fundamental things or basic things based on which we develop various kinds of sensors, while exploiting the properties of materials and the materials are of different class and all those classes little bit I will discuss in today's lectures. So the materials which are used for MEMS are basically from different groups. Some group belong to the metals or metal alloys, some group of metals belongs to semiconductor.

(Refer Slide Time: 01:39)



Particularly silicon and metals and metal alloys other than those, sometimes we use some ceramic materials also and polymers materials. So these are the four classes of materials which are used for making various kinds of microsensors.

(Refer Slide Time: 02:04)



Now let us concentrate first on metal and metal alloys for MEMS. So we use thick metal films for those devices which are used for structural materials for final sensors and sometimes it is also used as a mould which has inserted into the polymer on ceramic micromoulding. What do you mean by micromoulding and what are the moulds? That I will discuss during the micromachining class. This is a technique by which you can make the mould or micromoulds that is in chapter micromachining. Now other than this micromoulding there are other techniques which are mainly microelectroplating or photoforming. These are used to build thick metal film structure for different components of the microsystems or MEMS devices. Electroplating is another technique which is used for making thick metal films. Thick means I want to say several microns may be 20 micron, 30 micron, 40 micron in that range.

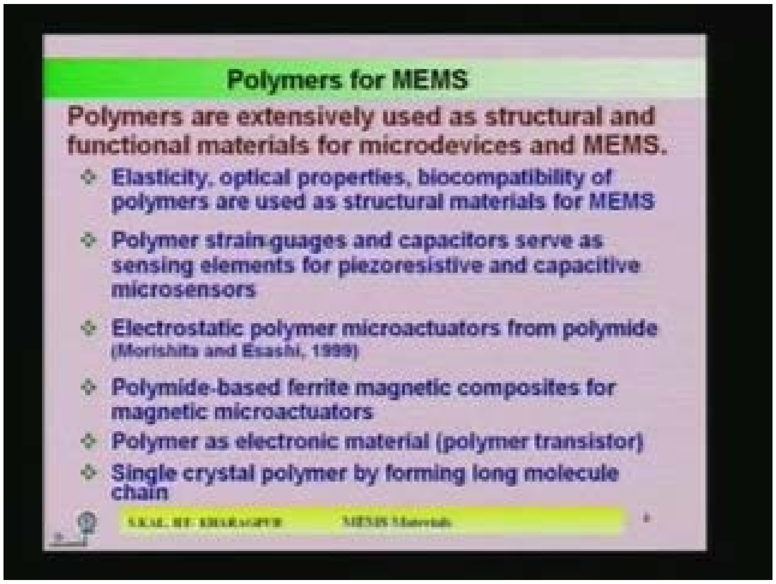
If you have to deposit the more than 10s microns then conventional the thin film evaporation technique or spattering technique cannot help. With that technique you can get films of the order of maximum 2 to 3 micron and if you want more than that, 10 micron, 15 microns, and 20 microns like that then you have to add of certain techniques those are mainly the CVD techniques and the electroplating technique. Electroplating technique is getting lot of importance now a day because this particular technique is a low temperature process where the chemical techniques are used and basically it is a electrolysis of some chemical solution and we have to have a cathode and an anode and you have to supply some current to that electrolytic cell, so that the chemical electrolyte will decompose and there are some part will be the metal and that metal will be deposited on cathode.

So that is the basic principle and with that principle we can have the metals of thicker film for example gold, nickel, copper, chromium those are deposited by electroplating techniques and various applications are their for the electroplating of gold, nickel and copper. Copper material particularly is used now a day in VLSI also for interconnects because of very low resistivity of the copper material. So conventional techniques which are used for VLSI metallization are mainly the thin film evaporation there are certain problems because of which copper cannot be evaporated in vacuum by resistive or electron beam evaporation is not possible. So electroplating is the only choice by which you can get the copper film on silicon or silicon dioxide which is used for interconnection VLSI.

But in case of MEMS the materials used in electroplating are mainly chromium and gold and chromium is used for addition of the gold film with the silicon or silicon dioxide substrate, is a buffer layer and basic material used for those purpose is gold. Now these are the techniques, another is a 3D stainless steel micro part by photoforming. So the stainless steel materials are also used for making 3D structure. So you have seen in my last lecture, lot of application where 3D micro parts are used in many actuators or many microsystems. So that which are made of steel, that cannot be evaporated, that cannot be electroplated, that is formed by photoforming is another technique. So that photoforming basic principles are how it is being made that I will discuss in separate lecture. The 3rd combination is metal alloys which are cobalt, nickel, manganese thin films, which are basically magnetic material.

This alloy cobalt, nickel, manganese is used for permanent magnetic materials for magnetic actuation. So sensors and actuators; some part are sensor and some parts are actuator and actuator principles are various kinds of principles are used for actuation. One such principle is magnetic actuation and for magnetic actuation you need magnetic material and those magnetic materials, one of the important material is copper, nickel, manganese alloy. So titanium and nickel are used for shape memory application. So this has tremendous application in MEMS and micros MEMS and actuators also and this is used sometimes for sensing and actuating also and in short it is know as SMA shape memory alloy. An electroplating of nickel and iron Permalloy on silicon for magnetic MEMS is also getting importance now a day. So these are the various kinds of metals and their alloys which are used for microsensors devices.

(Refer Slide Time: 07:42)

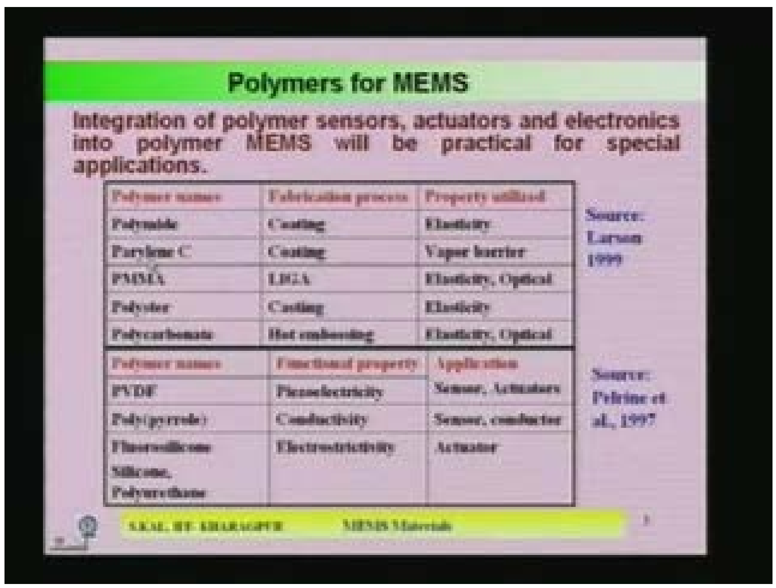


Now next I will discuss on polymer and polymers are extensively used now days as both structural and functional materials for microdevices and MEMS. Polymer can be used as a structural as well as it can be used as a functional material also. And I will show you some table which properties are used for making functional layer or functional device and which property of polymers are used for structural device, I will show you in the next slide. Now the main properties used for polymers are elasticity, optical properties of polymer, biocompatibility of the polymer. These are the main advantages of the polymer because of that it can be used as the structural materials for MEMS. Now polymer strain gauges and capacitors serve as a sensing element of piezoresistive and capacitive microsensors.

Piezoresistive and capacitive microsensors from the application I mentioned in last lecture, that is, in these piezosensor and there also you can use the polymer material and it can be used as a strain gauge. Electrostatic polymer microactuators can be formed from polymide. Polymide is a one class of polymer it has got electrostatic properties and it is used for making microactuators. Polymide based ferrite magnetic composites for magnetic microactuator is another application. Polymer as electronic material and that electronic material like, semiconductor silicon, germanium. Similarly polymer can be used as a electronic material because now a day polymer transistor has come up and has win successfully fabricated using polymer and people are thinking a polymer can be used for active device fabrication also.

So that both passive and active components and MEMS components can be integrated together. And as a whole, total will be known as polymer MEMS. So is I will take one separate lecture on polymer MEMS in future. Single crystal polymer is also possible. Earlier people could not think that single crystal is basically the properties of semiconductor materials and here you can have polymer has a single crystal. Because you can have certain chain and some series of chains, polymer chains are created and those chains are regularly repeated in a particular material. If you arrange those chains in a regular way then it will work as a as a crystal. So that is also, research is going on how to get good quality polymer crystal also.

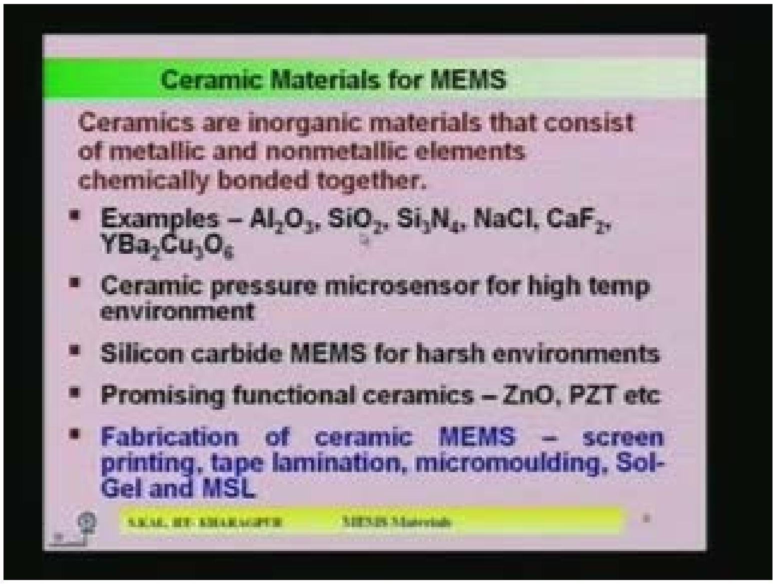
(Refer Slide Time: 10:35)



Now this table shows the properties of the polymers and its fabrication techniques and in which case it is used as a MEMS device. Now some of the polymer names I am showing here polymide, parylene C, PMMA. PMMA is basically used as a photoresist material also, polymethylmethacrylate, polyester, polycarbonate. And polymide its fabrication process is coating technique, parylene C is also coating technique, PMMA is used fabrication is LIGA technique, polyester is casting technique and polycarbonate hot embossing. So these are the fabrication process and polymide material when it is used, the elasticity property of polymide is used for those devices. Similarly in case of parylene C, wafer barrier property is utilized.

For PMMA elasticity and optical properties are utilized. In case of polyester, elasticity property is utilized and polycarbonate both elasticity and optical properties are utilized. So when you use polymer as functional material, then we use some functional property and those functional properties are piezoelectricity, conductivity and electrostrictivity. So these are the functional properties and its main applications are either sensor or actuators and the names of the polymers used for sensors and actuator are used as employing the functional properties are: PVDF, polypyrrole and fluorosilicone silicone and polyurethane. These are the polymer materials which are being used now a day in different kinds of microsensors.

(Refer Slide Time: 12:34)

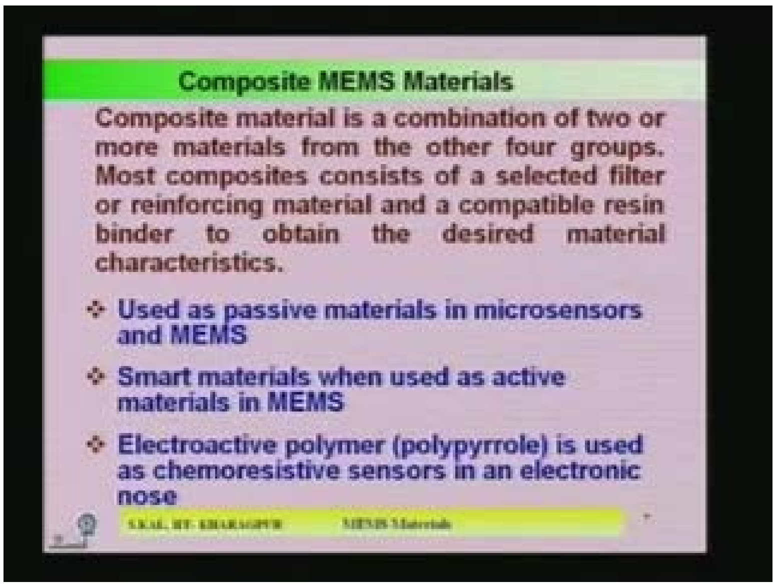


Now come to the ceramic materials for MEMS. So we discussed on metals, metal alloys, then we discussed on polymers. Now we will discuss on ceramic materials. So ceramics are inorganic materials that consist of metallic and nonmetallic elements chemically bonded together. That is the definition of ceramics and the materials used or ceramic materials used in MEMS are aluminium oxide, silicon dioxide, silicon nitrite, sodium chloride, calcium fluoride and YBa_2 Cu_3 O_6. So this is a new ceramic material we have started using in case of MEMS devices ceramic pressure microsensor for high temperature environment in which area ceramic materials are promising, particularly two areas; one is high temperature, another is harsh environment.

So in high temperature and harsh environment you cannot use the metallic MEMS because most of the metal at that high temperature will become soften and its property will be lost. Another thing is, semiconductor material if you use for high temperature, then problem is, semiconductor properties are highly dependent on the temperature. So there, if you use piezoelectrive property, then at high temperature, that property will change. So the change of piezoresistance due to the strain and as well as due to the temperature change will combine together and you cannot separate each other. So those are the problems at very high temperature. So there, the normal metal or polymide polymer or you can a semiconductors are not promising, there we have to go for certain ceramic material which can withstand very high temperature and other is in a harsh environment.

That is also another application of ceramics so silicon carbide a promising material for MEMS for harsh environment silicon carbide is a new is a very important material now a days used in case of the optical devices in VLSI also. Other promising functional ceramics are zinc oxide and PZT. Lead Zirconate and Titanate that is PZT and Zinc Oxide. These two materials are extensively used now a day as the functional material for MEMS. Fabrications of ceramic MEMS, techniques used are screen printing, tape lamination, micromoulding, Sol Gel and MSL. MSL stands for Microstereolithography, so microstereolithography technique is used to get 3D structure in polymer, in ceramics and in sometimes in case of the composing materials also. So that the MSL technique is a special technique which is not being used in VLSI, but is extensively used in MEMS and in detail I will discuss in microstereolithography technique in a separate lecture.

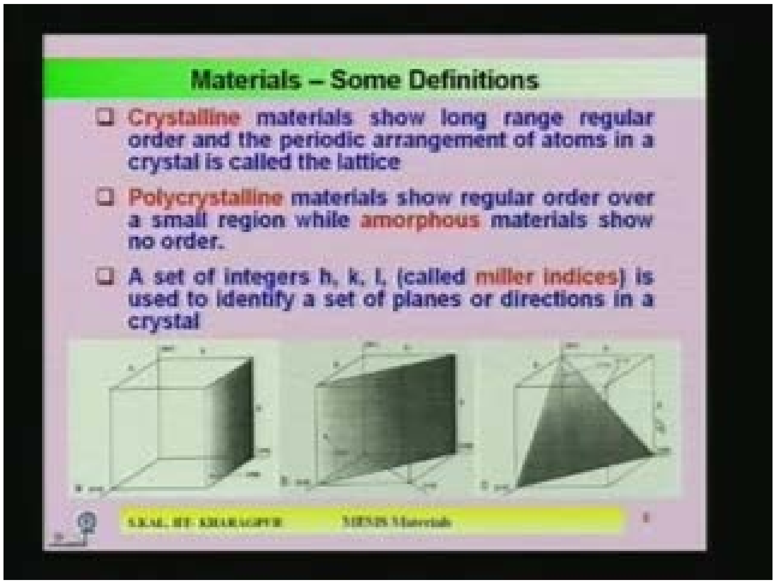
(Refer Slide Time: 16:01)



Now let us come onto composite MEMS material. Composite materials are basically combination of materials from different groups which I mentioned 4 groups are a metal, semiconductor, polymer and ceramic. Of these 4 groups, if you combine materials from different group to obtain the desired material characteristic, then it is known as a composite material and lot of research is going on composite material to achieve various specific properties. If you combine the metal with ceramic, you can combine polymer ceramic and metal. Sometimes, semiconductor materials are also used to have some composite thing which has got unique properties or unique application. So these materials are used as passive materials in microsensors and MEMS. Smart materials when used as an active material in MEMS.

Smart mean it will have certain unique properties we does not have in case of we does not have a metal semiconductor ceramic and polymer. So that is why it is known as smart. So it has specific property you can create by combining materials in different proportion. Electroactive polymers example is polypyrrole that is used as chemoresistive sensors in an electronic nose. So electronic nose on device, which can sense different

gasses, different sting, that is why known as an electronic nose and there, the polypyrrole material is one, is electroactive polymer. So that is used in those cases. So now these are the different classes of materials used in case of MEMS.
(Refer Slide Time: 17:58)



Now let us discuss little bit on the semiconductor. Semiconductor, mostly we use silicon. So there silicon is the single crystal silicon. So in that respect, now I will discuss sometime on the some material properties and some definitions. Already you know some definitions relating to the crystal, relating to the properties of silicon, relating to mechanical properties of the materials. Even then, I will just further spend sometimes on the basic definitions which are very much used when you are going for designing certain sensor. So crystal, there are 3 kinds of material crystalline, polycrystalline and amorphous. There is a difference between the crystal and polycrystal crystal and, amorphous material and amorphous and polycrystalline.

You should not confuse yourself between polycrystalline and amorphous. Crystalline is known because it will have long range regular order and a periodic arrangement of atoms in a crystal and that periodic arrangement of atom, these are known as the lattice and all the atoms in a crystal are located in the lattice points and the distance between the lattice points is known as the lattice constant. So this periodic nature in a long range will maintain. That is single crystal silicon. But if you look into the polycrystalline, then it is not long range, in a short range, locally the regularity is maintained, the structure is maintained, but over the long range it is not maintained.

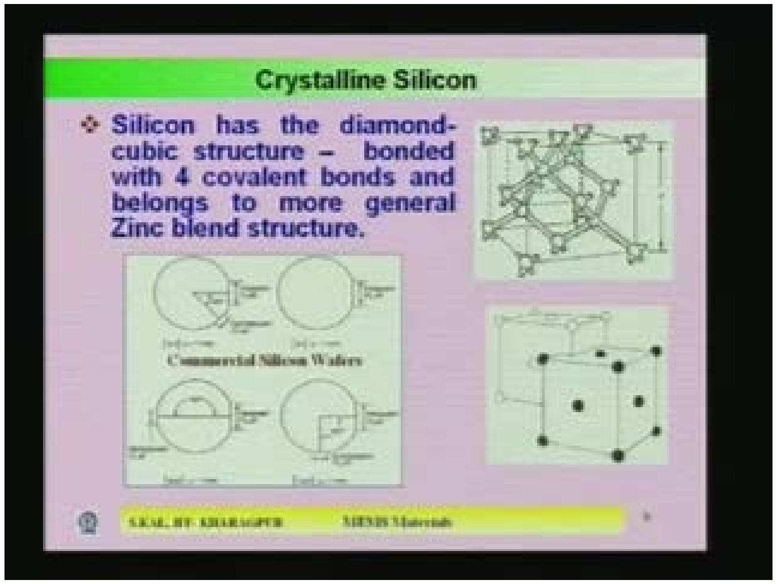
So, that is polycrystalline or the microcrystal you can say in a small region it is crystalline but throughout the whole bulk of the material, it is not crystalline, it is a polycrystalline. On the other hand, the amorphous, there is no regularity between the crystal lattice structures. It is a highly irregular and the crystal are or atoms inside the crystal are oriented or all placed in different direction. So in the half hazard direction, so it is known as amorphous material. One example is if you evaporate certain metal film on a single crystal silicon substrate, this film is amorphous film. For example, if you implant silicon by certain ion, in ion implanter, the region where the implanted spaces will locate, will sit, those regions initially, it will be highly amorphous.

Later on, we have to do the centering or annulling, so that again you will get back the regular silicon single crystal structure. So those are the amorphous examples. Polycrystalline is all also an important material which is used as sacrificial layer sometime, sometimes structural layer in case of a MEMS, so that is achieved by CVD technique or some times by ion beam deposition also you can get the polycrystalline material. Now in these crystals, a set of integer know as h k l, those are also called miller indices is used to indentify a set of planes or directions in a crystal. So when you are using that silicon, sometime you will see that is a 1 0 0 silicon, 1 1 1 silicon or 1 1 0 silicon. Different crystal planes are also sited along with the single crystal silicon and those planes, how to define those planes.

Those planes are defined with the help of the integers which are miller indices. For example silicon basic is the cubic crystal structure. You can see that the x y and z, these 3 axis and this is a cubic crystal structure. Now here this, if a plane which is perpendicular, say this is x, this is so y, this is z. So, a plane on the x axis here is parallel to the, say y and z plane. So this plane particularly is known as 1 0 0 plane. So in this direction, you have taken h, for example you have taken 1 and k l l, 0 1 0. Similarly this plane here, the top is known as 0 0 1 and on the other hand, this plane in this surface here is known as 0 1 0. So in this way, if you take a plane like that, that means, this is the origin, from here you have taken one, from here you are taken one, so and this is a parallel to this axis. Then this plane is known as 1 1 0 plane.

Similarly here, you can this diagram you can see, so this here is one, here is one and here is one. If you take a plane along this, so like this, so it is known as 1 1 1 plane. Now the crystal plane how we can define it so it is defined from the manufacture will crystal will make the slice certain direction. Accordingly the crystal, it is known as the crystal in which plane you are cutting and slicing the crystal that is either 111100 and 001 or 110 like that and different crystal plane will have different atomic densities. Because, the silicon atoms are placed in a certain manner inside the crystal. So if you cut the plane in different parallel to certain axis, so in that particular plane the number density of the silicon atom will not be the same in all the directions.

(Refer Slide Time: 24:19)



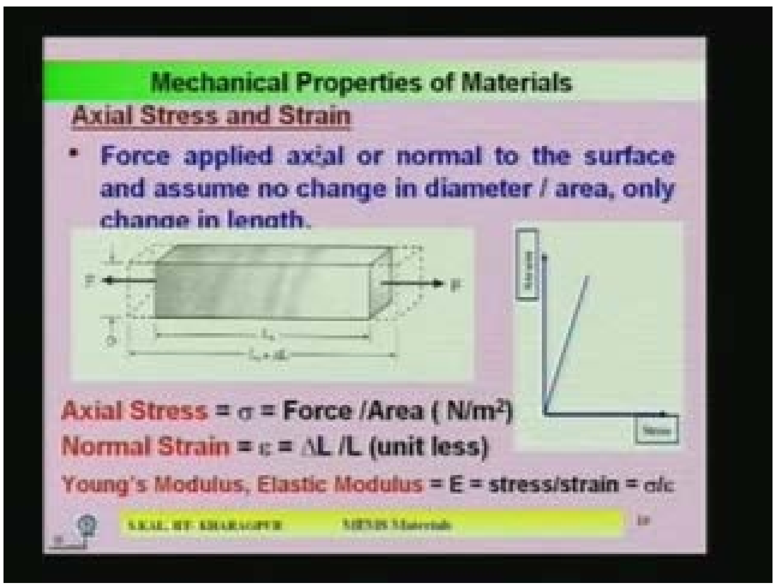
Now, one point is also important how do you identify a crystal is 111 or 100 or 001 or how do you identify? So one technique is by x-ray technique. But always in the laboratory you will not have the x-ray techniques. So there are certain nomenclature is followed everywhere by the manufacturer silicon wafers. So accordingly by seeing a silicon wafer we can identify whether the silicon crystal slice is 111 directions or 100 directions or 110 directions. So here are some figures you can see, so here you can see this is the cut here this is known as a primary flat. This is circular thing so here is a flat is known as primary flat and here is another flat which is known as secondary flat. Now this is a center of the slice. So from the center with a primary flat and a secondary flat the angle is 45 degree.

Now if a primary flat and secondary flat is made like this, then this silicon slice is 111 n-type. Similarly if only this primary flat is their then it is known as 111 p-types. So those flats are made from the manufacturer, so their company will make those flat. So accordingly, by seeing a silicon wafer you will identify this is p-type 111, this is n-type 111. So in the other hand if there is a flat here and in 180 degree there is a secondary flat, the distinction between primary at secondary is the primary flat you can see is longer than the secondary flat. Now here, if we 180 degree direction there are 2 flat then it is known 100 n-type silicon wafer. Similarly if there is a 90 degree orientation of the primary flat and the secondary flat then it is known as 100 p-type silicon wafers.

So in case of the MEMS device or even in VLSI devices, so normal wafers we use now a day is 100 silicon wafers mainly. There are certain advantages of that; main advantage is that the 100 silicon can be cut into small pieces regularly in regular way. Because whatever devices you made, either in a VLSI chip or MEMS at the end you have to separate the chip, you have to break the chip. So 100 wafers can be broken in a regular fashion and you can have the small pieces of dye, but in 111 you cannot break in regularly. You have to use some diamond saw and even then some of the pieces will break in different angles.

So some of the pieces you can lose in this way. So that is why 100 is a popular oriented crystal that is used, but for certain specific application in MEMS, we also use say 110 as well as 111 oriented silicon wafers. This is the crystal structure of the single crystal silicon. That is you can see is a bond. This is basically a diamond cubic structure and bonded with 4 covalent bonds and it belongs to more general zinc blend structure. So a face center cubic, so if this is a cube structure, each faces there is also single crystal silicon. This is silicon, silicon, silicon and silicon at the face also another is known as a face center cubic structure, is the basic structure of crystal in silicon.

(Refer Slide Time: 28:18)

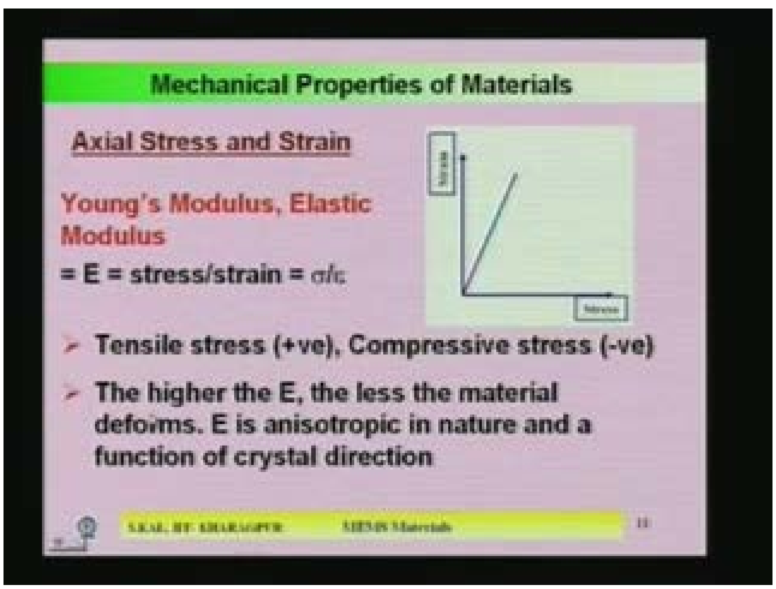


Now, will discuss something on mechanical properties on materials. Because MEMS is you know is a microelectro mechanical system. So mechanical properties and its definition you should know, so although some definitions are known to you again I will recapitulate those definition, I will remind those definitions because when you are going to design, is very important to know or to aware those definitions accurate. Now some is axial stress and strain and some are known as shear stress and strain. So what is the different between axial stress and strain and other is shear stress and strain. So in this slide axial stress and strain is described. For example this is a bar, rectangular bar. Now if you apply force axially or normal to the surface, because the force is applied normal to this surface and along the axis. Along the axis the force is applied.

So now if you apply the force in axial direction, so is length has been increased in this direction as well as in this direction. But we assume that diameter is not changed. In ideal condition let us assume the diameter is not changed, but length is only changed. Now this is known as the axial strain. If you apply stress only on perpendicular surface along the axis, then diameter is not changing but length is changing, then it is known as the applied axial stress and strain is axial. The axial stress is defined as the force per unit area that is Newton per meter square. The F is a Newton and per unit area is meter square and normal strain which is given by, you see epsilon is equal to delta L. What is delta L? The change in the length. This is the L0 and total change is a L0 plus delta L.

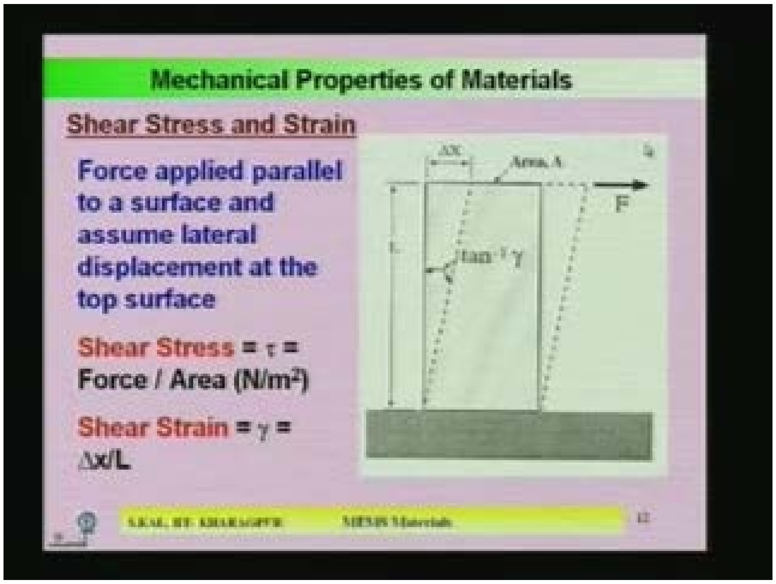
So how much increase in the length direction, that is a delta L divided by L is known as normal strain and Young's modulus or elastic modulus is defined by stress by strain which is sigma by epsilon that is the Young's modulus or elastic modulus is an important mechanical property which is will be used for designing any micromechanical structure using silicon and this is the curve stress versus strain. If you increase stress, it will just follow a straight line path and strain will means elongation will be their in certain particular direction. So this is a stress strain curve and so long it is linear, it is used and as it becomes nonlinearity, so then it some other deformation takes place basically. In this, so long it is linear if you reduce the state, stress, strain also will be reduced. So that is, you expect there should not be any hysteresis also. Stress strain curve, this linear region is used for making micro mechanical devices or sensors.

(Refer Slide Time: 31:52)



Now, the Young's modulus and elastic modulus is basically stress by strain. I have shown it sigma divided by epsilon and there are two kinds of stress. One is known as tensile stress which is positive in nature; other is a compressive stress which is negative in nature. Compressive stress we call it negative stress and tensile stress we call it as a positive stress and the higher the E, you will see Young's modulus or the elastic modulus, the less the material deforms. Because E value is more, the deformation will be less. E is anisotropic in nature is very important and a function of crystal direction. That E means Young's modulus or elastic modulus is anisotropic. That means in different crystal oriented direction, crystal plane value is different. It is not same and that property may be used to make certain sensors for certain applications. So other is a shear stress and shear strain.

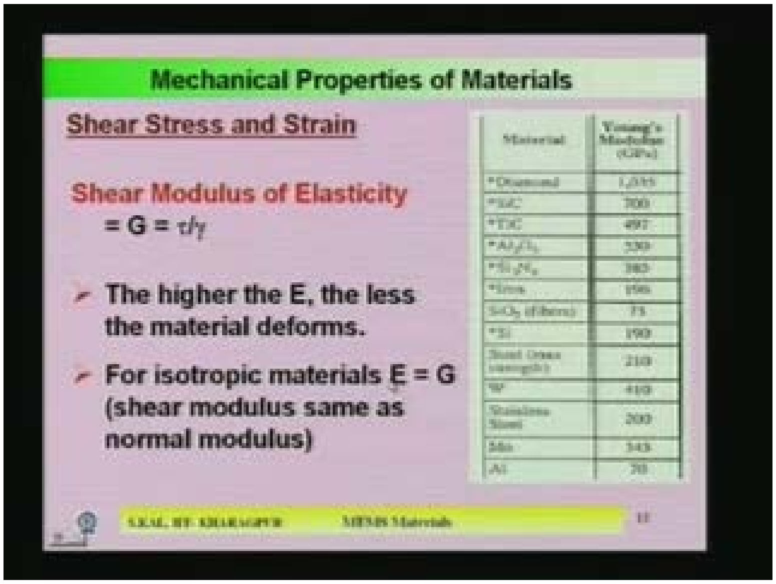
(Refer Slide Time: 33:05)



So let us see in this picture how you can define shear stress. For example this is a block and in that block, force is applied parallel to a surface. In other case we have shown axial force is applied perpendicular to a surface. Now this is a body, now this lower part of the body is fixed, so upper part of this body we have applied force in this direction parallel to this surface we are applying. So there, what happens, the top plane is deformed and bottom is fixed. Initially it was in this shape, so later on if you apply force at the top of the surface, so it bends in this direction, dotted line is a is a new position. So what is the change delta X? Delta X is change in this direction in which we have applied the force.

Now here the this displacement delta X divided by L, the one side of this particular object the delta X is a displacement by applying force F at the surface, divided by L is known as a shear strain. That is by gamma and shear stress is again force per unit area Newton per meter square. There is a tau, so shear stress is tau Newton per meter square force per unit area and shear strain gamma is delta X by L so displacement is delta X on this surface. Now the modulus of shear, modulus of elasticity, other you have seen Young's modulus in case of axial stress and strain.

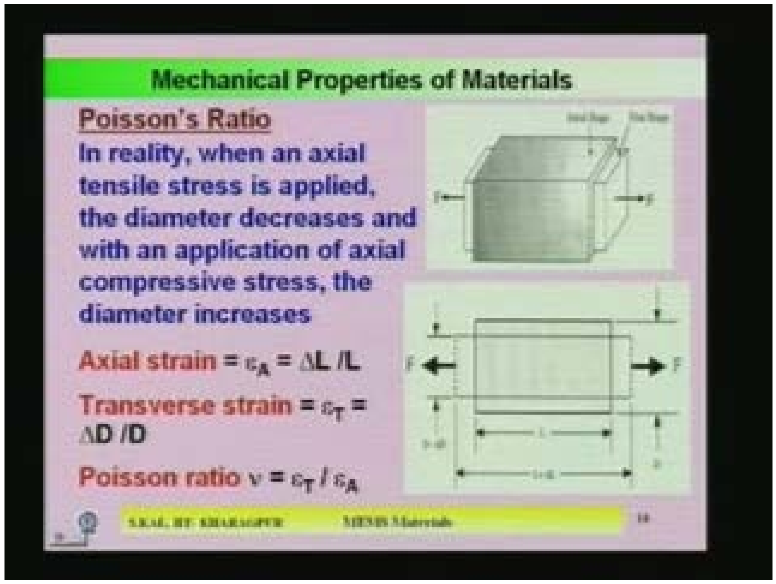
(Refer Slide Time: 34:50)



So here you will have shear stress and strain, shear modulus or shear modulus of elasticity. So that is known as G. G is again stress by strain which is tau divided by gamma in case of shear. So the higher the E the less the material deform like the axial strain. Another important point for isotropic material E equal to G. what is E? E is elastic stress and G is shear strain. Elastic modulus or the shear modulus. So elastic modulus and shear modulus will be equal for isotropic material and some of the materials are sited here, which are used in case of the microsensors.

Here you can see the ceramic is there, some cases of some metals are also there and for example aluminum, molybdenum, stainless steel, tungsten steel. These are belonged to the metal metallic group and Young's modulus is a Giga Pascal. That is 210, 410, 200, 343 something like that. Silicon is 190 and ceramic materials are also there. Aluminum oxide, silicon nitrates, silicon dioxide these and dynode is maximum Young's modulus 1035. So these are the values of the Young's modulus for certain material.

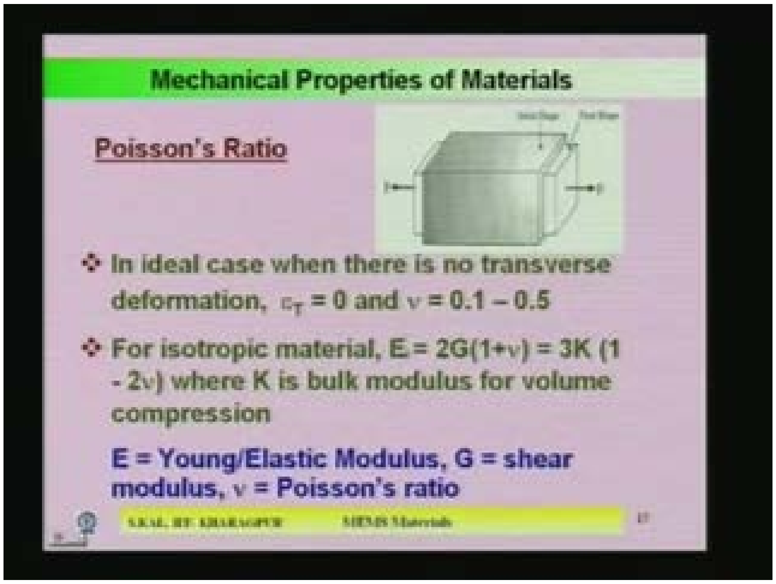
(Refer Slide Time: 36:29)



Now the Poisson's ratio is another important parameter which is required for the analysis of the mechanical or the stress strain analysis of silicon for mechanical microsensors is required. So this Poisson's ratio, when an axial tensile stress is applied, the diameter decreases. With an application of the axial compressive stress the diameter increases. So when I define the axial then I told you the diameter is not changed, only I on the length changed. But in real it is not the fact. So if you elongate a body, diameter will be same. Isn't? That is actual reality, so there; the diameter decreases if you apply a tensile strain for on another hand if you apply compressive stress the diameter increases. So the axial strain is EA delta L by L we defined earlier. There is a transverse strain that is epsilon T which is a delta D by D.

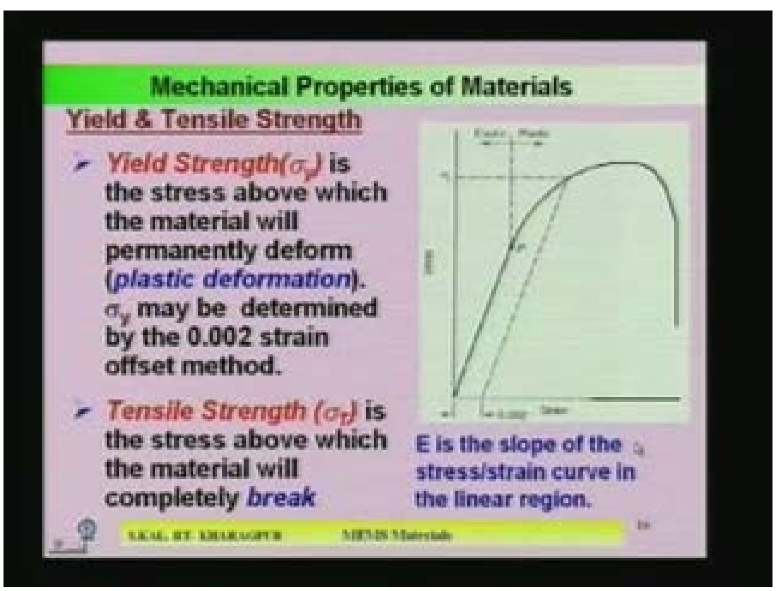
So delta D by D was not there when I defined the axial. We assume that time that the diameter no change. But if it also changes it shown in this diagram, you see the length changes in this direction and diameter from here also it is reducing. So you see this is D minus delta D and total say diameter is a D in this length. So D to D minus delta D, so change is the delta D. So if you take delta D divided by D. So that is known as a transverse strain or it is known as epsilon T. An earlier the axial strain is the epsilon A which is the elastic Young's modulus or elastic modulus I defined earlier. So now the ratio of epsilon T by epsilon A is Poisson's ratio. Poisson's ratio is the epsilon T divided by epsilon A. That mean transverse strain divided by axial strain is the Poisson's ratio now.

(Refer Slide Time: 38:36)



Now here, in ideal case, when there is no transverse deformation, obviously epsilon T equal to 0, then we will have only epsilon A and then epsilon A in that case we can call it is a new and it varies from 0.1 to 0.5 for isotropic material where E is equal to G and that is an ideal condition. But normally we have seen that E and G follows certain relation and that is E equal to twice G into 1 plus nu or 3 K into1 minus twice nu where K is the bulk modulus for volume compression. K is the bulk modulus for volume compression. E is here the Young's or elastic modulus. G is shear modulus and nu is the Poisson's ratio. So these are the different parameter which you should know before designing certain mechanical structure or mechanical microsensor.

(Refer Slide Time: 39:44)



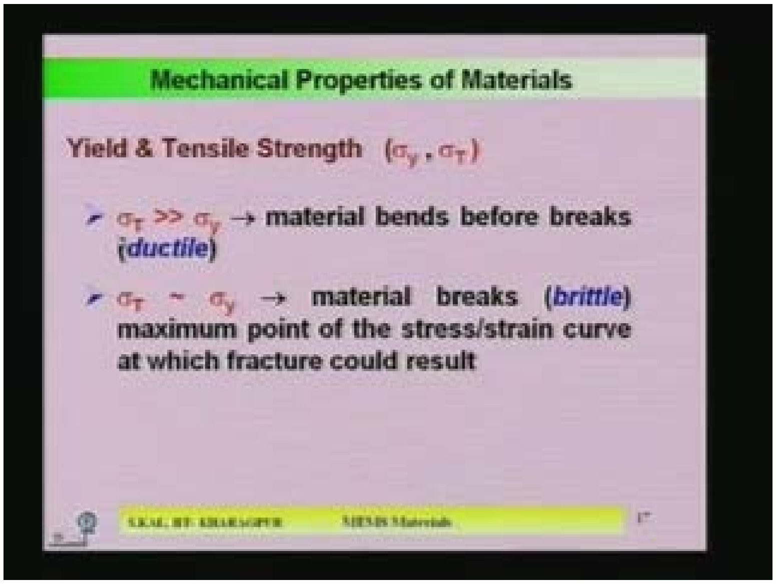
Now, another 2 parameter you should know, that is yield and tensile strength. Yield and tensile strength so stress and curve is shown here. You see stress versus strain, so initially it is a parallel sorry initially it is straight line in nature. So up to this P point it is a straight line in nature. So that we here I can say the strain and stress are proportional is exactly linear. Now after a certain point you see the curve is not linear, it is becoming nonlinear. So now after if you go on increasing this strain, then we find it reaches a maximum point of stress here, then again it falls, the curve goes down. That means the left of side of this point P where the linear nature of this stress strain relation is valid; this region is known as the elastic region. There, material is elastic behavior, is maintained.

But as soon as we exceed the point P, the behavior is a plastic behavior. So there is a difference between elastic and plastic. So elastic means stress strain relations are linear. Plastic means stress relation is nonlinear. So there, deformation takes place and these deformation leads to the permanent deformation. In this part up to point P, so if you release the stress, so it can go back to its original position that is the elastic property. So if you release the stress, it will go back to its original shape that is elastic property. But after that, after certain value of the stress, so it cannot go back to its original shape, so that is the permanent deformation. So this permanent deformation will go on up to certain point. So after that, the material, the stress, if it reaches a certain point, then the material will break. So that is why you are getting the curve just is goes down.

So that mean with this respect there are 2 other definitions; one is known as yield strength and other is known as tensile strength. What are those definitions? You can see here, the sigma y which is yield strength is a stress above which the material will permanently deform, which is known as plastic deformation. So that is this point, you see this from here to here is a plastic deformation and that is known as permanently deform. Sigma y may be determined by the 0.002 strain offset method. That is a 0.002 strain offset certain technique is there, by which you can you can determine the value of sigma y. On the other hand the tensile strength sigma t is a stress above which the material will completely break, that is a tensile strength. So that mean yield strength basically material deforms and that deformation is a permanent deformation. But in tensile strength means their material breaks. These are the difference between yield strength and tensile strength.

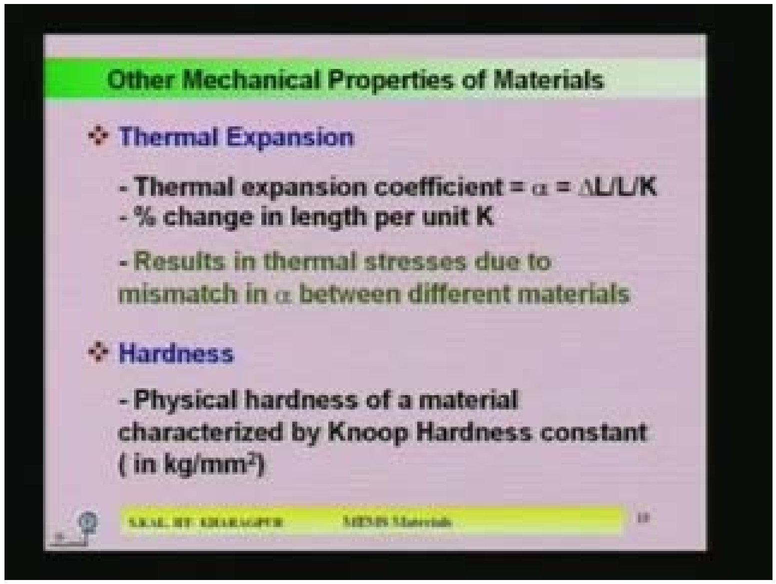
Basically strength means we are applying stress. So when you are working for certain sensor, you have to be cautious. So you should not apply stress so that the yield strength or tensile strength it reaches. So yield strength is higher is preferred knowledge. Isn’t it? So that you can use maximum amount of stress so we look for a material whose yield strength is higher. So I will, at the end to this lecture I will show you certain table which gives the yield strength value and tensile strength value of different metals and semiconductors and other ceramic materials also.

(Refer Slide Time: 43:55)



Now, the yield and tensile strength sigma Y and sigma T, when the sigma T is greater than sigma Y, the material bends before breaks is known as a ductile. So ductile or brittle, these two words are also used; one is ductile and another is brittle. What do you mean by ductile? Ductile is sigma T is greater large compared to the sigma Y then material bends before break. This property is known as ductile property. On the other hand when sigma T and sigma Y are comparable, then material breaks and is a brittle material, we call it maximum point of the shear, stress, strain, curve at which fracture could result. So I have shown you last diagram the maximum value after that the material brittle. So these are the mechanical properties which you should know before going for the design of any micromechanical structures.

(Refer Slide Time: 45:03)

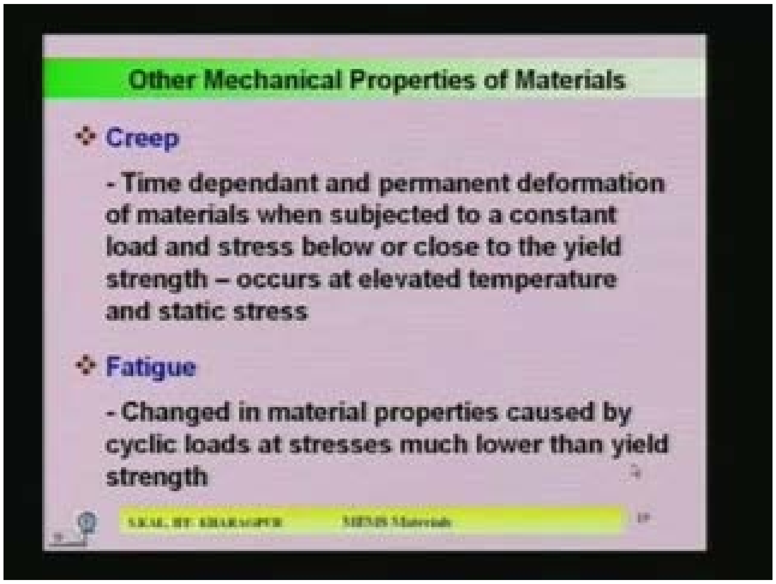


+

So now the other mechanical properties are also important when you go for designing any MEMS devices. These are thermal expansion hardness. What do you mean by the thermal expansion is known to you? Thermal expansion coefficient is known as alpha and it is basically delta L by L by K. K is in a basically the temperature in absolute scale. So it is defined percent change in length per unit K. So that is thermal expansion coefficient you should know it. It results in thermal stresses due to mismatch in alpha between different materials. So you see thermal stress, earlier stresses we discussed there is a mechanical stress. That we are applying certain mechanical force and as a result of that force means that stress, strain will be developed inside the material. So another stress is also there, that is a thermal stress. That means in a sensor you are not going make a sensor using only single material and you are using different kinds of materials, semiconductor, ceramic, metal and so on.

So all the materials will not have the same thermal expansion coefficient. So, if the temperature changes, the operation temper because you are using sensor not in a fix temperature, at different temperature range you are using the sensor. So that the temperature range, the thermal expansion coefficient is not same and as a result of which there will be a stress and that stress is known as thermal stress. And because of that stress some of the sensor behavior or sensor output may also change. So that also you have to keep in mind. So other than the mechanical stress another stress is also involved which is known as a thermal stress. Hardness is another mechanical property. Physical hardness of a material characterized by Knoop hardness constant and it is in kg per millimeter square. Knoop is basically is a name of a scientist. He investigated that particular property of that material, that is why it is characterized by Knoop hardness and it is defined by kg per millimeter square, its unit.

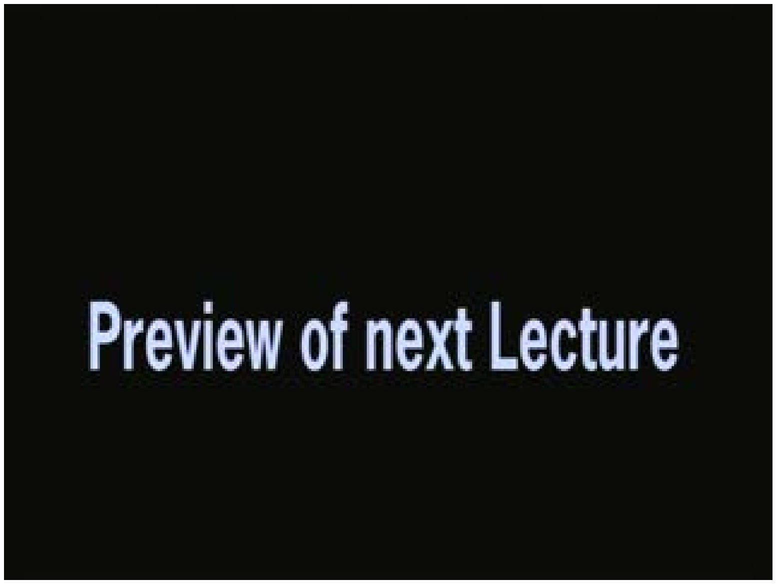
(Refer Slide Time: 47:12)



Now, others are creep and fatigue. These are all mechanical properties. What is a creep? Creep is basically time dependent and permanent deformation of materials when subjected to a constant load and stress below or close to the yield strength. It occurs at elevated temperature and static stress. If temperature is elevated and a static stress is applied, then this is known as the creep and other property is known as a fatigue. What is a fatigue? Changed in material properties caused by cyclic loads at stresses much lower than yield strength. That means you are applying stress lower than the yield strength, but if you are applying cyclic stress, that means once you are applying stress and then release it, again you are applying stress then release it, again you are applying stress then release it. In a cyclic way, if you apply stress and then release, then the material property, that particular mechanical property of the material will little bit change and that is known as a fatigue.

As if the material reached its fatigue condition, it may not follow the linear stress strain relation, so that is fatigue. So these are various kinds of the mechanical properties, the axial stress, shear stress, the yield strength, brittle, ductile, creep, fatigue, these are the various kinds of mechanical properties once you take care of when you are going for design of any microstructure using silicon or any other single crystal or even using the metal or metal alloys. So let me stop here today. So next class I will discuss on the different properties of the materials which are used for making microsensors and MEMS devices. Thank you very much.

(Refer Slide Time: 49:22)

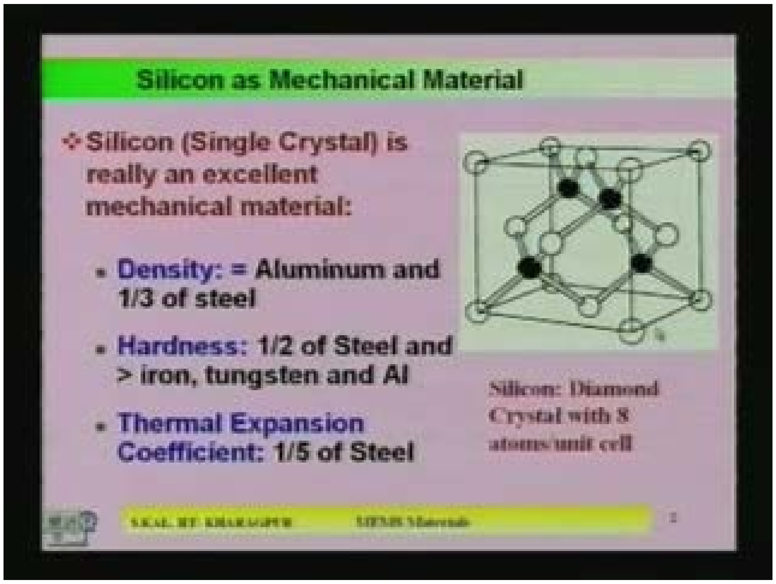


Preview of next Lecture

MEMS Materials' Properties

Yesterday we have discussed on the MEMS materials. So different types of materials which are used for making microsensors and microsystems today we will discuss on the properties of the materials which are used for microsensors MEMS and microsystems. Different kinds of properties of the materials are used for making sensors and actuators and those properties one by one, we will discuss in today's lecture. So now, first I will start from the silicon. Because in the last class we have seen that different kinds of materials other than silicon also are used in MEMS, they may be ceramics, they may be polymer, they may be composite materials. But among the semiconductor materials silicon is the choicest material for MEMS because of various reasons and those reasons one by one, we will discuss now in today's lecture.

(Refer Slide Time: 50:53)

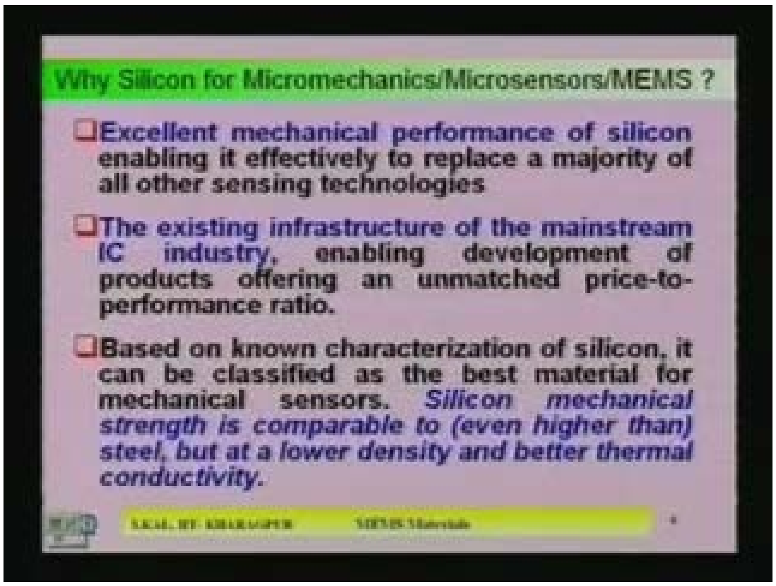


So silicon is a mechanical material and which is having single crystal and it has got diamond crystal structure. Its density we have seen is equal to aluminum, nearly equal to aluminum but one third of the steel. So in that respect the silicon is lighter than the steel. In a second point is the hardness, half of steel and greater than iron tungsten and aluminum. So far as hardness is constant concern the silicon hardness is greater than the iron tungsten and aluminum. Thermal expansion coefficient is a half of steel that is a good thing that a thermal expansion coefficient is not very high.

(Refer Slide Time: 51:43)

So now, other properties are yield strength. Yield strength 2 times greater than steel. Young's modulus is almost equal to steel, thermal conductivity that is 1.5 times of steel deform elasticity and remember not plasticity. Difference between elasticity and plasticity I have been discussed in last lecture. So the deform elasticity and it has no hysteresis. So silicon and its derivatives particularly silicon dioxide and silicon nitrite are some of the best electrically characterized materials in the world. So in different MEMS structure, we take help of these derivatives of silicon. T0hat is silicon nitrate and silicon dioxide and their properties and their characteristics are well known to us, that is one of the advantages in case of silicon.

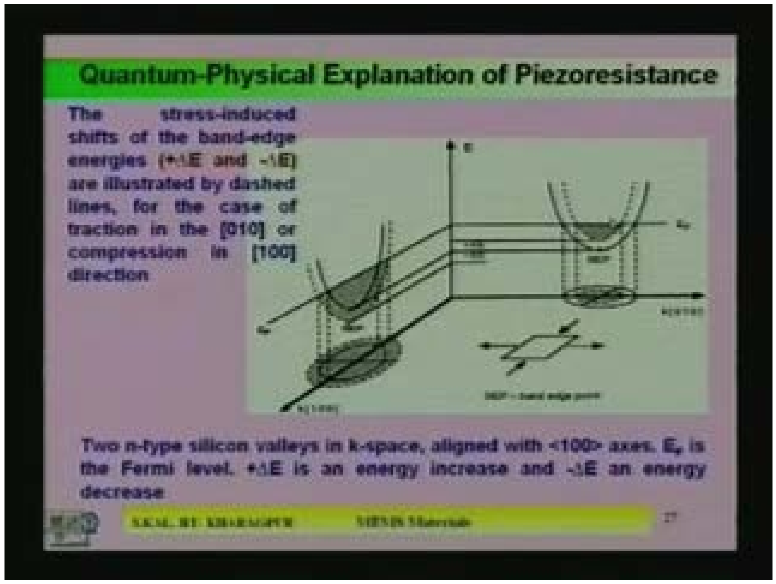
(Refer Slide Time: 52:48)



So other things are mentioned here in favor of silicon that is it has got excellent mechanical performance and it enables effectively to replace a majority of all other sensing technologies. The existing infrastructure of the mainstream IC industry is allowed so that will use in case of MEMS fabrication or microsensor fabrication. So that is why it is very easy to develop products which offer an unmatched price-to-performance ratio. Performance will be very good and price will be low. So the ratio of price-to-performance is extremely low in case of silicon because of the availability of the infrastructure which is very important. If you have to create new infrastructure, then obviously the price-to-performance ratio will be higher and higher.

So since it is available, so the ratio will be extremely low that is advantageous for commercial production so that is one advantage in case of silicon. The other one is best, this particular things is based on known characterization of silicon. It can be classified as the best material for mechanical sensors. Silicon mechanical strain is comparable to even higher than the steel but at a lower density at better thermal conductivity. In the last slide I show you its density lower than iron and its carbon conductivity also very high compared to 1.5 times of that. So because of that it cannot generate lot of heat. Dissipation is more and that is the advantageous compared to other traction.

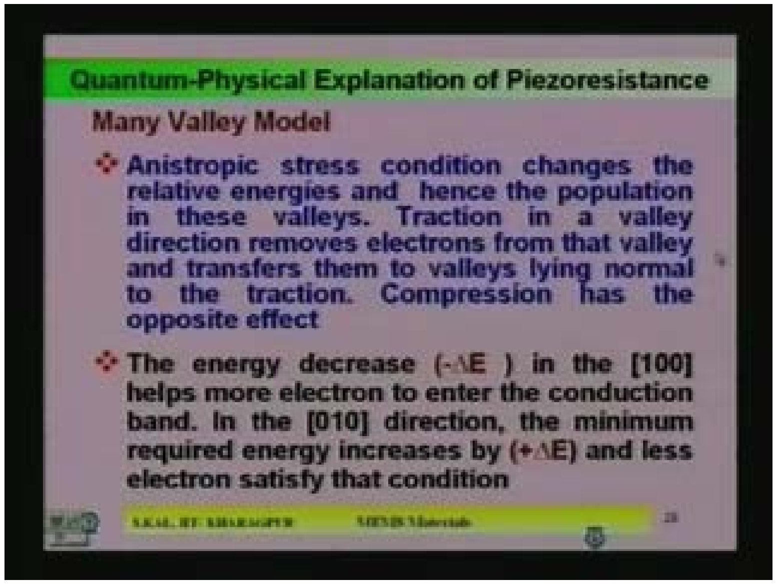
(Refer Slide Time: 54:37)



So then it has plus delta is shifted upward, so plus delta is shifting upward then what will happen so in the traction axis so the gap energy the delta is shift upward so the band gap increases. So because of the band gap increased, so what will happen? So less number of carriers will have the probability to jump into that level conduction band. Because delta E energy band gap has increased. So probability of jumping that higher gap will less. But on the other hand if you apply a compression axis which is 100, there you see this, the band edge of the conduct, the fermi level the band edge reduced by minus delta E. So that means here there is a probability of the carriers will be moved here.

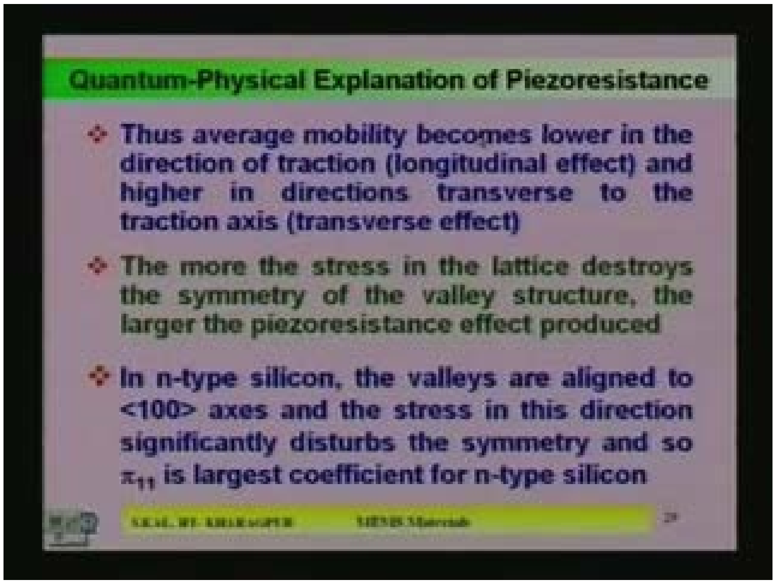
So that means if you apply the traction axis elongated there, there is probability of movement of the carrier from this axis to this axis, because here easily they can jump, but here no. Here increase, so the mobility of the carrier may increase because there is tendency of movement of the carrier along this compression axis. So as a result of which here mobility will increase. Mobility increase means piezoresistance will decrease, conductivity will increase, but here the opposite. So these are the explanation of the quantum physical explanation of the piezoresistance effect.

(Refer Slide Time: 56:15)



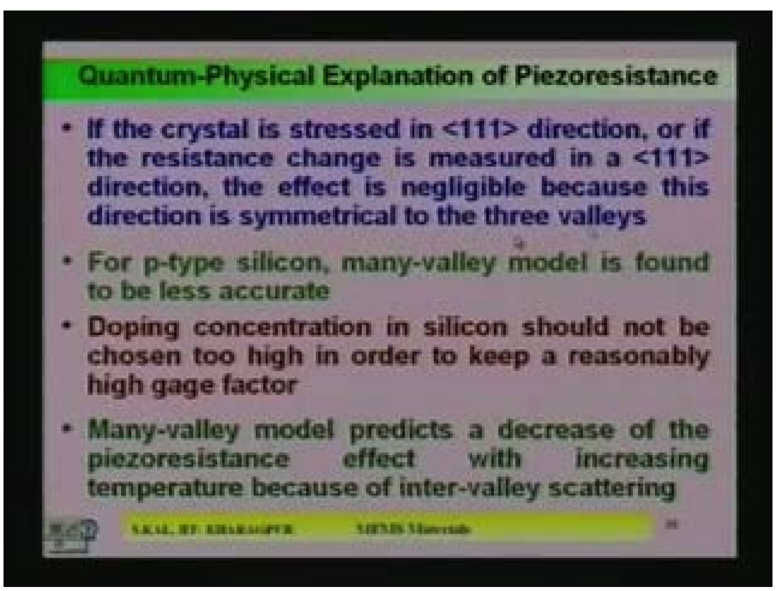
Now there are certain points this model is known as many-valley model. What I explain is narrated in this few points which you may go through. So anisotropic stress condition changes the relative energies and hence the populations in these valleys are high. I just explain why the population will increase traction in a valley direction removes electros from the valley and transfer them to valleys lying normal to the traction. Normal to the traction is a compressive this 100 that I explained. Compression has the opposite effect. The energy decreased minus delta E in 100 helps more electrons to enter in the conduction band, minus delta E helps more electrons in the conduction band. In 010 direction, the minimum required energy increases by delta E. That is shown in the last video graph and less electron satisfies this condition.

(Refer Slide Time: 57:17)



Other points are thus average mobility becomes lower in the direction of traction, which is longitudinal effect and higher in the direction of the transverse to the traction axis which is known as the transverse effect. The more the stress in the lattice destroys the symmetry of the valley structure, the larger the piezoresistance effect produced is another observation. Third observation is in n-type silicon the valleys are aligned to 100 axes and the stress in this direction significantly disturbs the symmetry and so phi 11 is a largest coefficient for n-type silicon. As a reason why for n-type silicon, phi 11 is a largest. Other hand for p-type silicon phi 12 and phi 11 will be higher than that phi 44, so that is because of this reason.

(Refer Slide Time: 58:08)



For p-type silicon, many-valley model is found to be less accurate. Doping concentration in n silicon should not be chosen too high in order to keep a reasonably high gage factor. Other comment, many-valley model predicts a decrease of the piezoresistance effect with increasing temperature because of inter-valley scattering. So which temperature there is an inter-valley scattering, so because of the scattering increases it produces decrease of the piezoresistance effects? So these are the few points on quantum physical explanation. So I will stop today, next class I will continue with the properties of the MEMS materials which are: mainly I will discuss the piezoelectric effect and the thermal effect. So all those effects will be discussed in the next class. Thank you very much.