MEMS and Microsystems
Prof. SantiramKal
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Kharagpur
Lecture No. # 06
MEMS Material's Properties

Yesterday we have discussed on the MEMS materials.

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MEMS Materials' Properties

Santiram Kal
Department of Electronics & ECE
Indian Institute of Technology
Kharagpur – 721302
E Mail: srkal@iitkgp.ac.in

So different types of materials which are used for making micro sensors and micro systems, today we will discuss on the properties of the materials which are usedfor micro sensors MEMS and micro systems. Different kinds of properties of the materials are use for making sensors and actuators and those properties one by one,we will discuss in today's lecture. So now,first I start from the silicon. Because in the last class we have seen the different kinds of materials other than silicon also are used in MEMS;they may beceramics, they may be polymer, and they may be composite materials. But among the semi conductive materials, silicon is thechoicest material for MEMS because of various reasons and those reasons one by one will discuss now in today's lecture.

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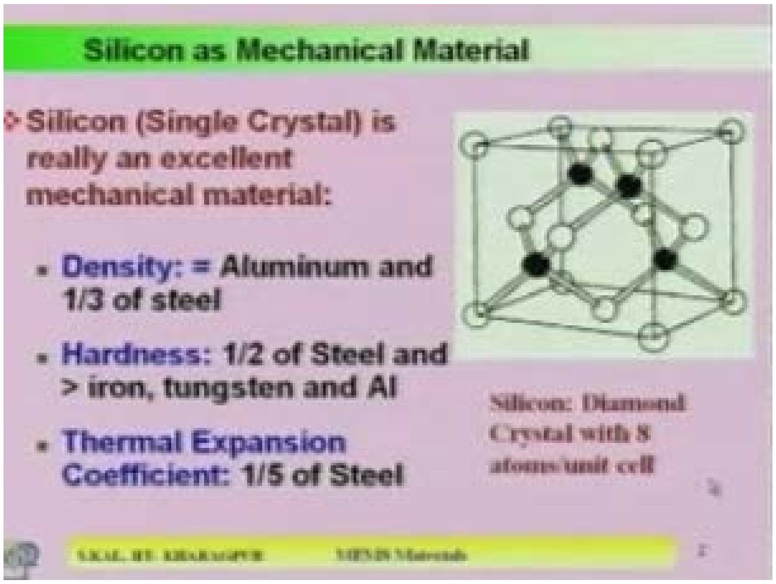

Silicon as Mechanical Material

- Silicon (Single Crystal) is really an excellent mechanical material:
  - **Density:** = Aluminum and 1/3 of steel
  - **Hardness:** 1/2 of Steel and > iron, tungsten and Al
  - **Thermal Expansion Coefficient:** 1/5 of Steel

Silicon: Diamond Crystal with 8 atoms/unit cell

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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 theirrespect the silicon is lighter than steel. In a second pointits hardness.Hardness is half of steel and greater than iron tungsten and aluminum. So called a hardness is concerned the silicon hardness is greater than the iron tungsten and aluminum. Thermal expansion coefficient is a half of steel.There is a good thing that in thermal expansion and coefficient is not very hard.

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Silicon as Mechanical Material

- **Yield Strength:** 2 times > Steel
- **Young's Modulus:** = Steel
- **Thermal Conductivity:** 1.5 of Steel
- **Deform elastically** (not plastically) and no mechanical hysteresis

- Silicon and its derivatives (SiO_2, Si_3N_4) are some of the best electrically characterized materials in the world.

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So now, other properties are yield strength. Yield strength is 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 has been discussed in last lecture. So the deform elasticity and it has no hysteresis. So silicon and its derivatives, particularly silicon dioxide and silicon nitride are some of the best electrically characterized materials in the world. So in different MEMS structure, we take help of these derivatives of silicon. That is silicon nitride and silicon dioxide and theirproperties and their characteristics are well known to us. That is one of the advantages in case of silicon.

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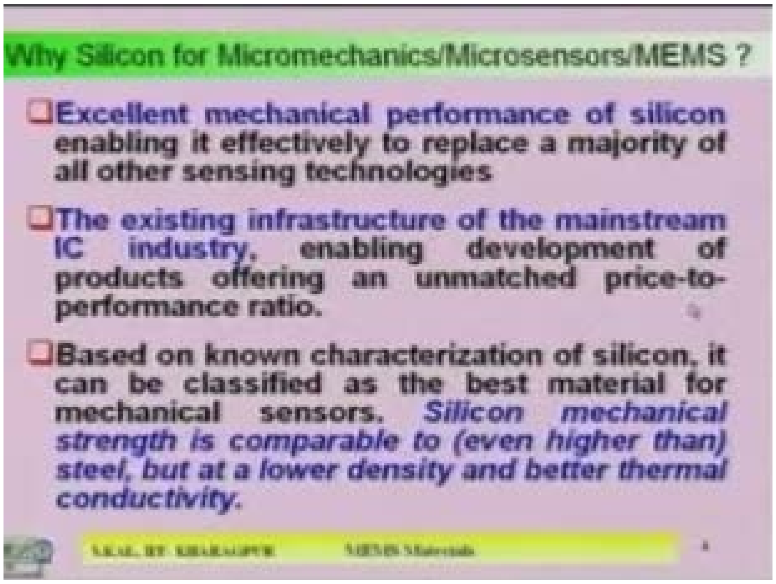

Why Silicon for Micromechanics/Microsensors/MEMS ?

- ❑ **Excellent mechanical performance of silicon enabling it effectively to replace a majority of all other sensing technologies**
- ❑ **The existing infrastructure of the mainstream IC industry, enabling development of products offering an unmatched price-to-performance ratio.**
- ❑ **Based on known characterization of silicon, it can be classified as the best material for mechanical sensors.** ***Silicon mechanical strength is comparable to (even higher than) steel, but at a lower density and better thermal conductivity.***

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 available. So that,we will use in case of MEMS fabricationor micro sensorsfabrication. So that is how it is very easy to develop products which offer and 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 available 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 that ratio will be extremely low.That is advantageous for commercial production.

So that is one advantage in case of silicon. The other one is a basedthis particular thing is based on known characterization of silicon.It can be classified as the best material for mechanical sensor. Silicon mechanical strength is comparable to even higher than steel but at a lower density and better thermal conductivity. In the last slide I showed you,its density its lower than iron and its thermal conductivity also veryhigh compared to1.5 times of that. So because of thatit cannot generate, lot of heatdistribution is more and that is advantageous compared to other materials, so that is desired thing. So these are the favorable points in case of silicon.

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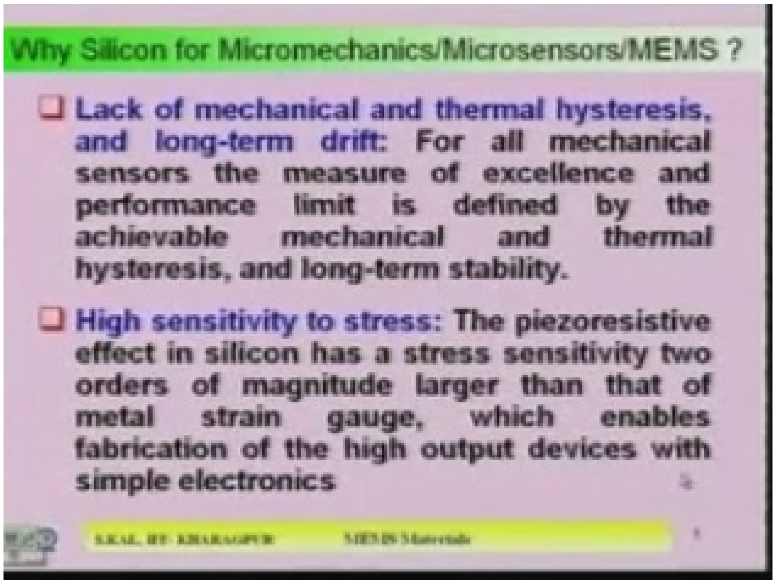

Why Silicon for Micromechanics/Microsensors/MEMS ?

- ❑ **Lack of mechanical and thermal hysteresis, and long-term drift:** For all mechanical sensors the measure of excellence and performance limit is defined by the achievable mechanical and thermal hysteresis, and long-term stability.
- ❑ **High sensitivity to stress:** The piezoresistive effect in silicon has a stress sensitivity two orders of magnitude larger than that of metal strain gauge, which enables fabrication of the high output devices with simple electronics

So other than those error other properties also lack ofmechanical or thermal hysteresis. What it hysteresis? I explained in the last lecture,so that hysteresis is not desirable property of any of the sensor material.Silicon, mechanical and thermal both hysteresis are extremely low. There is another hysteresis I mentioned here thermal hysteresis.Because change of property with thermal energy where thermal energy is withdrawn, so it will retains its original property. So that is the thermal hysteresis criteriaand mechanical also we have,you know it I explained.So if you apply some mechanical pressure or stress or strain, so then property will change if youreleasethe stress and strain it will get back its original property so that is known mechanical hysteresis. So those things are not desired things, if you choose the materials for making any case, any kind of sensor,so that is why silicon is one candidate, ofone strong candidate or making the micro sensorsbecause it does not have either mechanical hysteresis or it does not have any thermal hysteresis.

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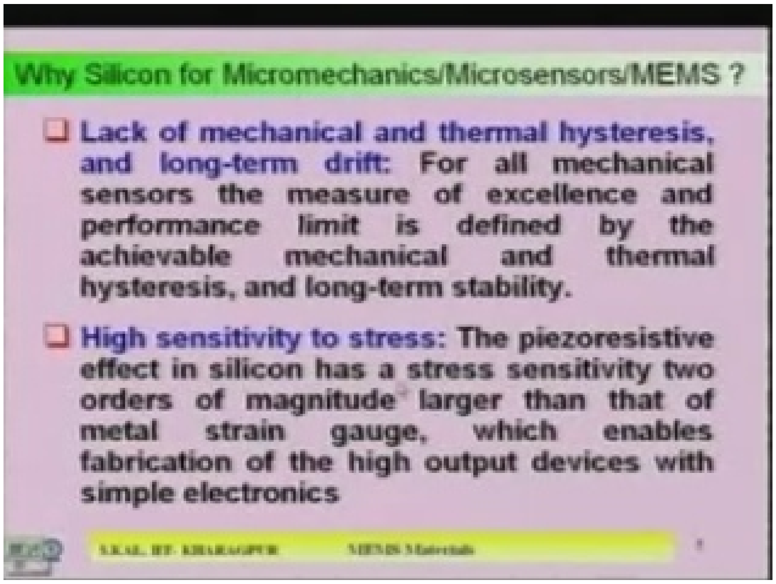

Why Silicon for Micromechanics/Microsensors/MEMS ?

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So other point is high sensitivity to stress and the piezoresistive effect in silicon has a stress sensitivity, two orders of magnitude, larger than that of the metal strain gauge which enables fabrication of high output devices with simple electronics. So that means it is highly sensitive to stress because it has got very good piezoresistive property. So thatmeans, its resistance will change in the application of pressure.How and what are the basic principle of changing the resistance if you apply pressure on silicon will be explain in next few slides

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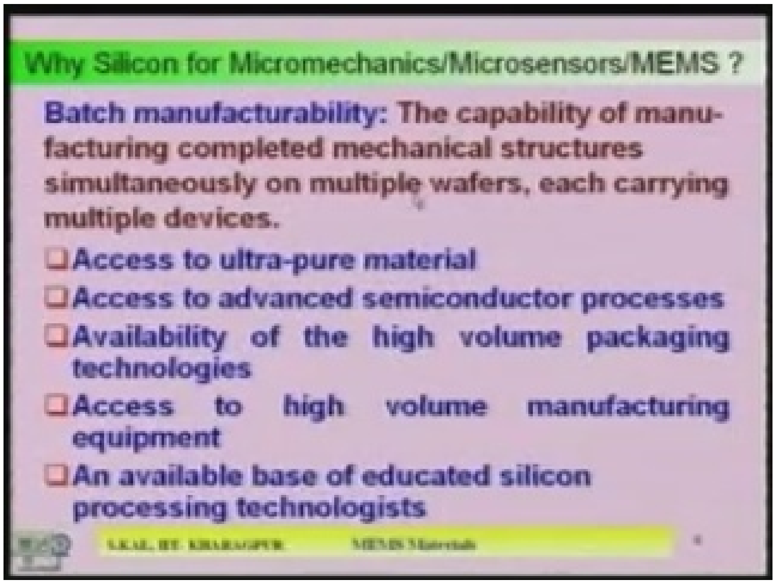

Why Silicon for Micromechanics/Microsensors/MEMS ?

Batch manufacturability: The capability of manufacturing completed mechanical structures simultaneously on multiple wafers, each carrying multiple devices.

- ☐ Access to ultra-pure material
- ☐ Access to advanced semiconductor processes
- ☐ Availability of the high volume packaging technologies
- ☐ Access to high volume manufacturing equipment
- ☐ An available base of educated silicon processing technologists

So these are the points other than those, there are other points batch manufacturability,that is batch production, the capability of manufacturing, completed mechanical structures simultaneously on multiple wafers each carrying multiple devices.That is the basic principle of batch manufacturability.So that also reduces the price and other than those points few other advantageous points in case of silicon is access to ultra-pure material.That means you can get verygood quality, very pure silicon material,because it is used in various sides. Automatically that technology is established, you can get ultra-pure silicon materialaccess to advanced semiconductor process.No needs of discussion, availability of the high volume packaging technologies.Here some points I would like to mention.Although the packaging technologies are available for various sides,but in case of MEMS,the packaging will be little bit critical and those critical points how to circumferencethose point, how to recover from those problems, that still lot of research is going onand heresome custom package is required which needs someR and Dalso in case of MEMS and microsystem.

Access to high volume manufacturing equipmentand available base for educated silicon processing technologies. So that means the manpower is available. So man power is the one basic thing when you go for any technological development.Because you are going to use all the VLSIequipment,so trained man power for running those equipment forVLSI process are already available. Those man powers can be used for making MEMS and micro system. So that is why, since available man power is there,so there is no extra investment for train the man power. That is one advantage in case of silicon MEMS.So those points basicallyenable us to goahead with silicon MEMS to a great extent

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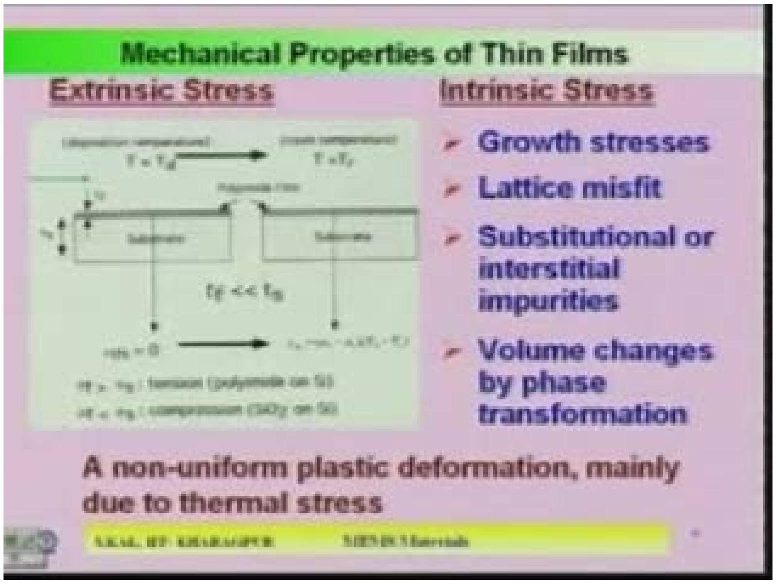

Mechanical Properties of Thin Films

Extrinsic Stress

Intrinsic Stress

- Growth stresses
- Lattice misfit
- Substitutional or interstitial impurities
- Volume changes by phase transformation

A non-uniform plastic deformation, mainly due to thermal stress

Now some mechanical properties of silicon already I discussed and here since we are going to use some thin films of semiconductor materials along with its derivative,means silicon dioxide or silicon nitrite. So some of the properties related to thin filmsare discussed here. There are two kinds of stress; one is extrinsic stress, other is intrinsic stress.So what do you mean by intrinsic stress? Intrinsic stress means the stress which has developedinside the single crystal silicon during the growth process. What are those? They may be due to the growth stresseswhen youare growing the crystal.So during that time lattice misfit,if there is a misfit between the crystal lattice points, a stressmay be developed. Substitutional or interstitial impurities,they will create some stress. Volume changes by phase transformation when you grow the crystal. Because of that reason also stress may be develop and those all belong to the intrinsic stress.

What are the extrinsic stress? When all silicon, this is a silicon substanceyou can see in the figureand this is the thin film. For example polyimide film you are you are depositing on single crystal substance. Now you see during deposition,in many cases the temperature may be increased. So it is may be greater than room temperature, Td is a deposition temperature and here the room temperature is say Tr. So now, when during the position in many cases,the strain or stress may be develop at the inter phase, because if you go for deposition more than room temperature then or even less than room temperature, very low temperature also, in both cases, because of the difference of the thermal expansion coefficient of the deposited film and basic substrate.

So there will be a miss match between the expansion coefficient and as a result of which a stress may be develop at the interphase. That is basically theextrinsic stress and normally the tf means the filmwe are going to deposit, its thickness is extremely low compact to ts. So because of that also sometimes the stress will be developedat interphase between the deposited film and silicon substrate. So now,if alpha is aexpansion coefficient of the film and alpha A's is the expansion and coefficient of thesubstrate. Now it has been observedso when alpha f means expansion coefficient of the film is greater than alpha A's expansion coefficient of the substrate,then the developed stress istensile stress.That example is polyimide onsilicon that is the example. Becausealpha A's in case of the polyimide the alpha A is greater compared to the alpha A's so their tensile stress will be developed.

On the other hand, if the film expansion, thermal expansion coefficient is less than the thermal expansioncoefficient of the substrate, example is silicon dioxide on silicon then the stress developedis a compressive stress. So this is the two reason when the tensile will be producedor when the compressive stress only produced,it depends on the thermal expansion coefficient of the deposited film and the substrate. So these are the extrinsic stress and intrinsic stress already I told you so those are sometimes responsible for some change of the properties of the device. Because if that are not matched, then what will happens, there is a deformation.Deformation of the structure, because of these theinherent developed stress which may be intrinsic or may be extrinsic.

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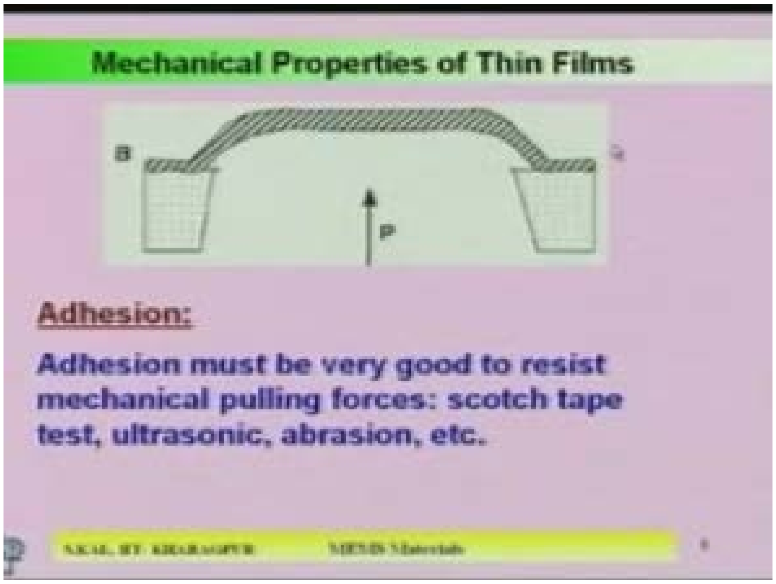

Mechanical Properties of Thin Films

Adhesion:

Adhesion must be very good to resist mechanical pulling forces: scotch tape test, ultrasonic, abrasion, etc.

Now here is another thing is mentioned which is also very important in case of the fabrication of thesensor which involves lot of deposition of the thin films. So adhesion that is another property which we must look into. Because when you depositing many kinds of filmson different kinds of substrate,so the adhesion between the film and the substrate will be very good.If it is not good,then in the subsequent process those films may peel off. So in order to avoid that, we have to study the adhesion property of the film with the substrate. Now this picture shows, you see because this is the film deposited on substrate and after that by micro machining you haveremoved the substrate from the bottom. So now,if we apply pressure, so then the pressure is applied on the film. That film may be silicon dioxide,silicon nitrate or may be mechanic film, may be polyimide film,whatever it is.

Then if we apply pressure on the film you see it isthe there is a chance of peeling off from the substrate. So these to prevent that you need the addition of the film and the substrateshould be extremely good.So in that case if you evenly apply pressurethen this portion and this portion the film will not come out. So that is required and in many cases during processing you can use the ultrasonic hesitation,sometime abrasion also used.So those are mechanical energy you are applying to the substrate during processing. So that means during the ultrasonic vibration, the film should not come out.That is another criteria. There are some cases of scotch tape test is being done to see how the adhesionis with the basic substrate.

So then addition is another important property which we have to look into beforefinalizing a process tape for making films on substrate, different kinds of film and different kinds of substrate. For example, the gold, if you want to deposit gold on silicon and silicon dioxide it has been observed the addition of the gold is not very good with silicon or siliconoxide. So then,sometime is may be required to put an interfacial layer which will help addition of that deposited filmwith a substrate. In gold we normally use chromium. Many of you know the chromium helps adhesion of the gold film with the silicon substrate. So that information is available any hand book of thin film from where you have to collect the information and accordingly you shouldgoahead with the process steps.

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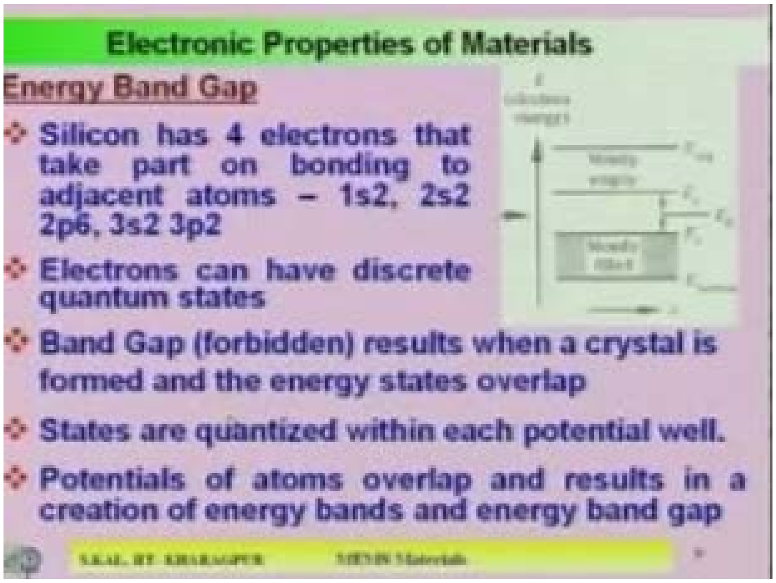

Electronic Properties of Materials

Energy Band Gap

- Silicon has 4 electrons that take part on bonding to adjacent atoms – 1s2, 2s2 2p6, 3s2 3p2
- Electrons can have discrete quantum states
- Band Gap (forbidden) results when a crystal is formed and the energy states overlap
- States are quantized within each potential well.
- Potentials of atoms overlap and results in a creation of energy bands and energy band gap

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Now will come to electronic properties of materials. So electronic properties, materials many of the properties you know already. So quickly I will just recapitulate those properties, so that you will refresh yourself,therelevant propertieswhich is necessary for making, or for modeling or forconsuming some of the newdevices MEMS devicesusing semiconductormaterial. One important property isenergy band gap and energy band gap is known to you know it I believe every body of you know.So there are 4 electrons that take part on bonding to adjacent atoms because 2, 3s2 and 3p2.So here, in p2 there should be 6 capability but 4 less that is why these are the 4valenceelectronwhich are taking part in current conduction mechanism. So those 4 electrons are can easily detachedfrom the silicon.

Because these are not closely bound to the nucleus.So electrons can have discrete quantum states. Because energy band is coming from the concept of discrete energy quantum states.Band gap which is also known as the forbidden gap is a result when a crystal is formed and the energy states overlap. Here is theconduction banding, is a valence banding,this is the vacuum level E top and is the E bottom is the bottom level and we know the below valency band the complete band is mostly filled,above conduction band the it is mostly empty. So the gap between the conduction and valency band is known as the band gap and it is define by Eg. So potentials of some atoms overlap and results in a creation of energy bands and energy band gap. That is known to you.

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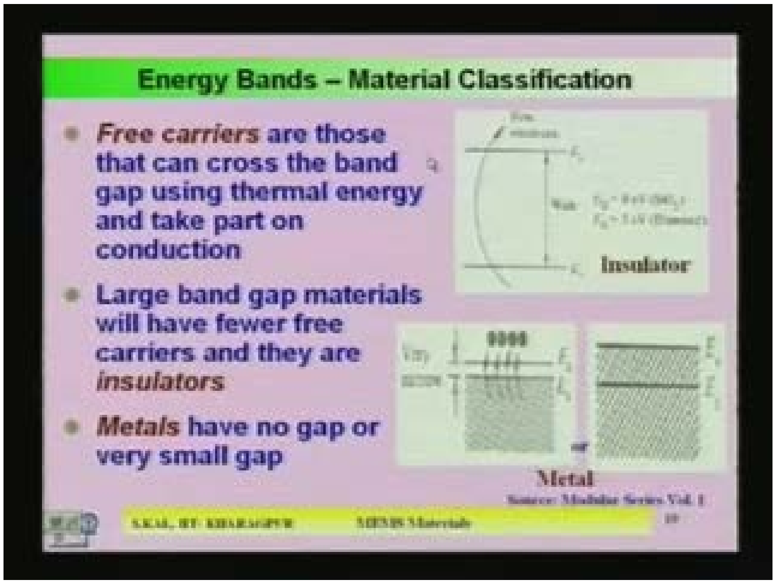

Energy Bands – Material Classification

- ***Free carriers*** **are those that can cross the band gap using thermal energy and take part on conduction**
- **Large band gap materials will have fewer free carriers and they are** ***insulators***
- ***Metals*** **have no gap or very small gap**

Source: Modular Series Vol. 1

Now free carriers are those that can cross the band gap using thermal energy and take part on conduction mechanism. So that means for conduction you need some electrons which are free and that is all the possible if you from valency band some electrons are transported into conduction band by applying energy. So there are 3 kinds of materials, we know is a insulator, metal and another a semiconductor.In case of insulator we know the band gap is extremely large and is for silicon dioxide is also insulator it is band gap, it has got the band gap of 8electron volt. On other hand diamond has 5 electron volt.So these are the band gap of insulator materials andit will be very difficult for transporting electrons form valency to conduction band in case of silicon dioxide and diamondbecause it needs enormous amount of energy,if you want to transfer electron from valencyto conduction band.On other hand, another extreme case is a metal and metals have no gaps or it may be having very small gap, because is a conduction band to valency band here you see it is overlapped and in this case is extremely narrow band gap in some of the materials is available. So there, even a small amount of energy enormous amount electrons will be transported or transformed from valency band to conduction band and as a result3 electrons density is extremely high and it will have very large conductivity.

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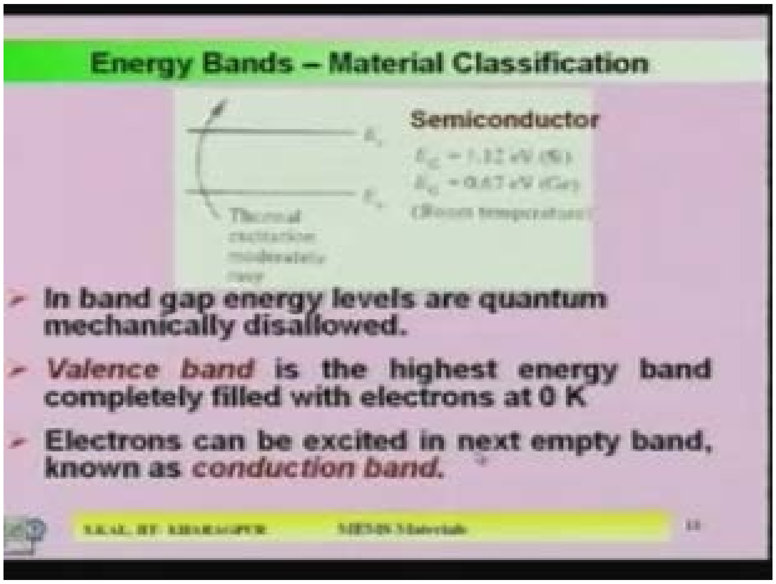

Energy Bands – Material Classification

Semiconductor

$E_G = 1.12$ eV (Si)
$E_G = 0.67$ eV (Ge)
(Room temperature)

- In band gap energy levels are quantum mechanically disallowed.
- *Valence band* is the highest energy band completely filled with electrons at 0 K
- Electrons can be excited in next empty band, known as *conduction band.*

So semiconductor is a 3rd class of materials.So here,3rd category of materials, here the band gap in case of silicon is 1.12in case ofthe germanium is a 0.67 electron voltat room temperature and on thermal energy, the electrons are excited fromvalency band to conduction band and those electronswill take part in current conduction mechanism. As a result of the transfer of electrons from valency to conduction band, some vacancies will be created which are known as holes, all of you know. So in semiconductor,in intrinsic semiconductor,both electrons and hole take part in current conduction mechanism and in band gap, energy levels are quantum mechanically disallowed. Valency band is the highest energy band completely filled with electrons at 0 Kelvin. On the other end, electrons can be excited in next empty band which is known as a conduction band.So these are definitions.

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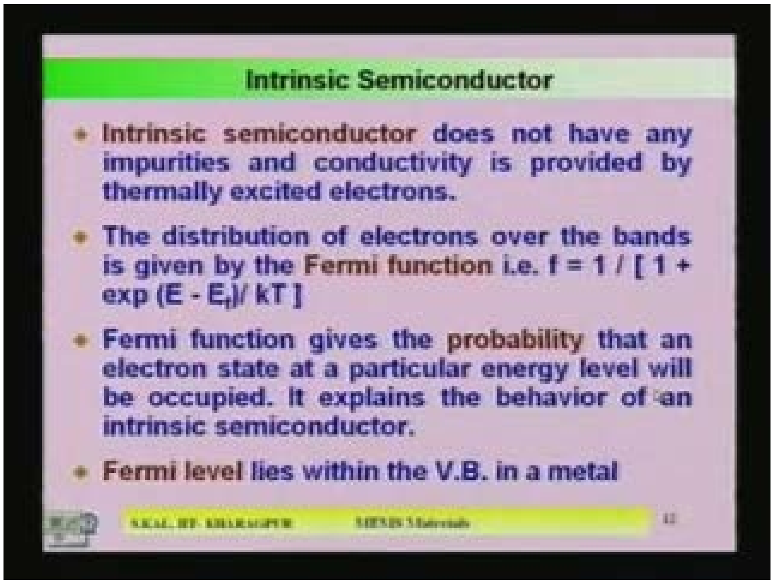

Intrinsic Semiconductor

- Intrinsic semiconductor does not have any impurities and conductivity is provided by thermally excited electrons.
- The distribution of electrons over the bands is given by the Fermi function i.e. $f = 1 / [1 + \exp (E - E_f)/ kT]$
- Fermi function gives the probability that an electron state at a particular energy level will be occupied. It explains the behavior of an intrinsic semiconductor.
- Fermi level lies within the V.B. in a metal

So now,intrinsic semiconductor does not have any impurity and conductivity is provided by thermal excited electrons.Because there is no impurities doped in intrinsic semiconductor, so impurity atoms will not,impurity electrons will not take part in a current conduction only intrinsic electrons and volts which are available they will take part in current conduction.So obviously its conductivity will not be very high. The distribution of electrons over the bands is given by the Fermi function which is basically equal to f equal to 1 by 1 plus E to the power of E minus Efby kT,whereEf is the Fermi level energy and k Boltzmann constant,T is the temperature in term of scale. All these things as already been thought in your semiconductor devices classes. So Fermi function gives you the probability that an electron state at a particular energy levelwill be occupied. It explains the behaviourof an intrinsic semiconductor. Fermi level lies within the valency band in a metal. In a metal Fermi level will be ina valency because valency level conduction may available in case of metal so obviously it will within the valency band.

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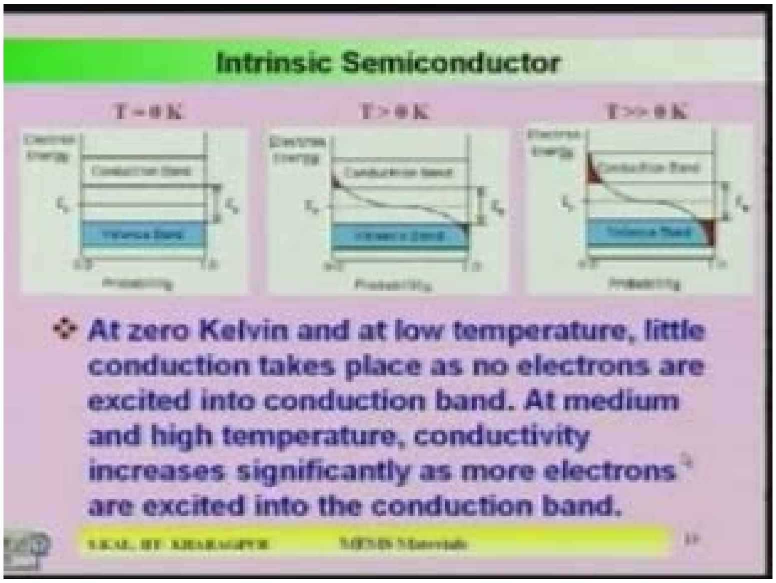

Intrinsic Semiconductor

- At zero Kelvin and at low temperature, little conduction takes place as no electrons are excited into conduction band. At medium and high temperature, conductivity increases significantly as more electrons are excited into the conduction band.

So now, these are the picture the probability of electron in the conduction band and the probability of jump inthe electrons from valency band is a conduction band shown in the 3 diagram.One is a 0Kelvin here is a temperature is little bit more than 0and here temperature is large compared to 0 Kelvin.So you see at 0 Kelvin in conduction when there is no electron but if you increase the temperature from 0 Kelvin to certain extent, so small amount of electrons will be jumping to the conduction band. So as a result ifthe probability with a Fermi function, because of the Fermi functions you will have the probability of very small probability of electron in the conduction band. But at the same time ifyou increase the temperaturemedium to high,so lot of electrons will jump and you have seen here the probability of occupying states in the conduction band will be larger as a result of which the conductivity also will be higher.

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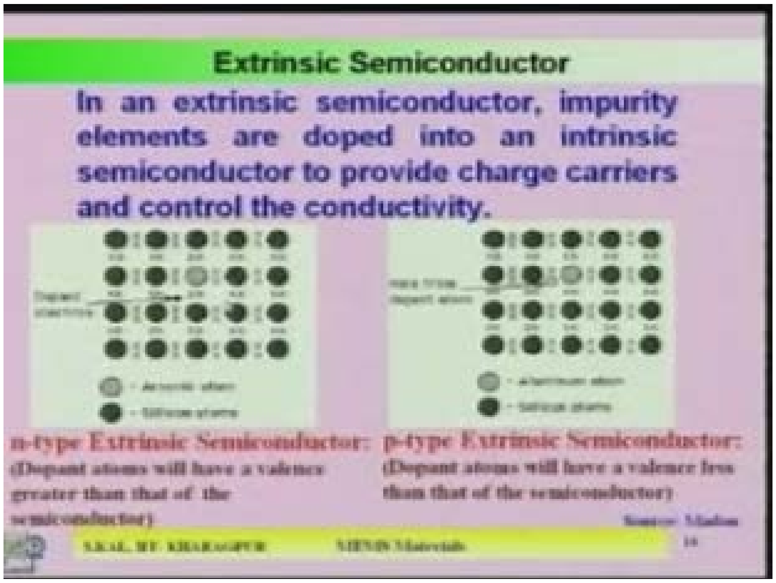

Extrinsic Semiconductor

In an extrinsic semiconductor, impurity elements are doped into an intrinsic semiconductor to provide charge carriers and control the conductivity.

n-type Extrinsic Semiconductor: (Dopant atoms will have a valence greater than that of the semiconductor)

p-type Extrinsic Semiconductor: (Dopant atoms will have a valence less than that of the semiconductor)

So now, I will discuss on the extrinsic semiconductor.Extrinsic semiconductor, here you have to dope some extrinsic impuritymaterialsand because of doping of thematerial, if youdopeimpurity atoms which have gota higher level of the silicon. That meansfor example,higher groupif you dope with a phosphorus atoms or arsenic atomswhich is having 5 which is having five electrons in the outermost orbit. So here, ifit replaces a silicon there so then 1 extra electron is available for conduction. Here you see in addition to the thermallygenerated electron you are having much more carrier. These are the free carriers from the impurity atoms. Now impurity atom, ifyou dope to a large extent, so there are 2 kinds of carrierswants are thermally generatedcarriers in addition to the extra carriers available from the impurity atoms. So both the carriers will take part in current conduction mechanism. So as a result to be conductivity will be higher in case of extensive semiconductor in time.

On the other hand if you look into the p type semiconductor,then the dopantatoms are obviouslythevalency electrons will be less than the silicon. Either group three elements will be doped there, boron or aluminumor indium may be doped there. So there are the valency electrons is all less. So obviously one vacancy is created if a silicon is replaced by an impurity atom. So now that vacancy will be filled by some extra electron which is available because of thermal generation. So as a consequent of that the electron which is coming from other place to fill the vacancy there,vacancy will be created. So as a result to be, there is a movement of the vacancy and you will have some current in the semiconductor material? So those are the basic mechanism of n type and p type semiconductorconductivity or current conduction mechanism in case of extensive semiconductor.

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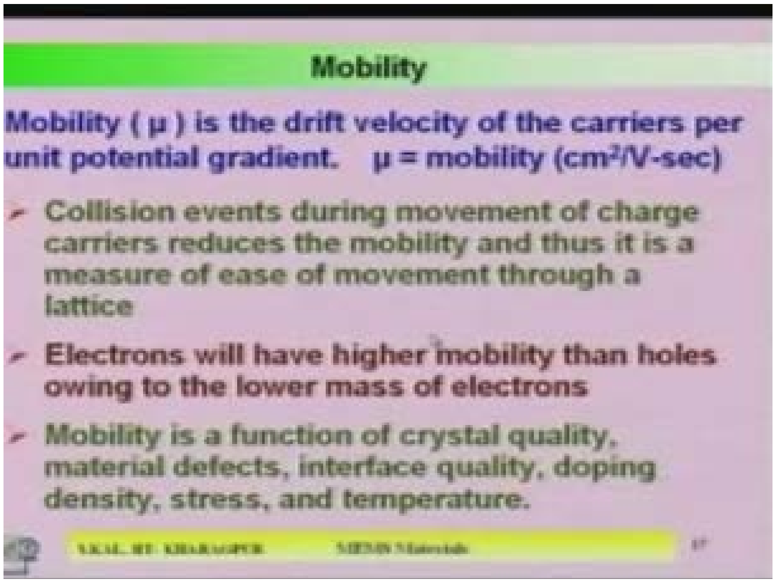

Mobility

Mobility (μ) is the drift velocity of the carriers per unit potential gradient. μ = mobility (cm^2/V-sec)

- Collision events during movement of charge carriers reduces the mobility and thus it is a measure of ease of movement through a lattice
- Electrons will have higher mobility than holes owing to the lower mass of electrons
- Mobility is a function of crystal quality, material defects, interface quality, doping density, stress, and temperature.

Now,another important property of the semiconductor is the mobility. So mobility is defined as the drift velocity of the carriers per unit potential gradient. So it is denoted by the term mu and its unit is centimeter square per volt second. So now, there is lot of phenomena which changes the mobility property. One is the doping concentration. If the doping concentrations are more in a crystal, so then the mobility may degrade. Because,if dopings are more, so lot of carriers will be there. There will be chances of high collisionsand because of the enhanced collision probability so mobility may reduce. So high concentration in an extrinsic semiconductor,in some cases mobility degradesand basically in that case, it is a measure of ease of movement through a lattice. If the collisions are less so mobility will be higher. Electrons will have a higher mobility than holes owing to the lower mass of electrons.That is why you know in case of n type semiconductor themobility is very high compared to the p type semiconductor. Electron mobility is higher than hole mobility we know it because electron will have lower mass. Mobility is a function of crystal quality,material defects, interface quantity,doping density, stress and temperature. These are various parameters which a changes the value of the mobility.

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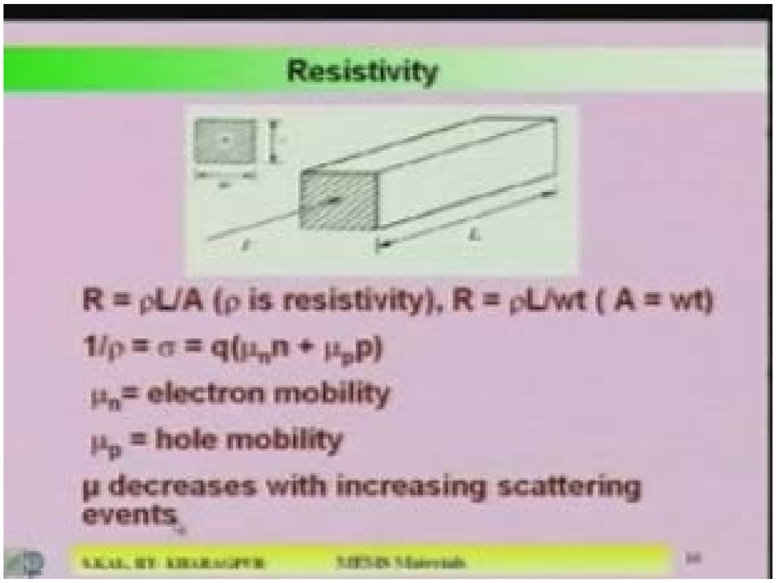

Resistivity

$R = \rho L/A$ (ρ is resistivity), $R = \rho L/wt$ ($A = wt$)

$1/\rho = \sigma = q(\mu_n n + \mu_p p)$

μ_n= electron mobility

μ_p = hole mobility

μ decreases with increasing scattering events

Now resistivitythat is another important property and that is also known to you. Resistivity in a semiconductor bar is a given by rho into L by A;where L is the length of the semiconductor material and A is the cross sectional area. So rho is the resistivity.On the other hand R is given by rho into L by A is given by w into t so rho L by wt and 1 by rho which is basically the conductivity is given by q into mu$_n$n plus mu$_p$ P, wheremu$_n$ and mu$_p$ are electron and hole mobility and n and p are electron and hole concentration, P is the electronic charge.mu decreases with increasing scattering events.If scatterings are more mu value itdecrease when the scatterings will be more. So if there impurity atoms are more, so where this scattering probabilitywill be more, in that case mu also decreases. These are known as impurity scattering. There another scattering which is known as a lattice scattering.Because of that also mobility can degrade. So now the mobility variation with the doping concentration is shown in this particular curve.

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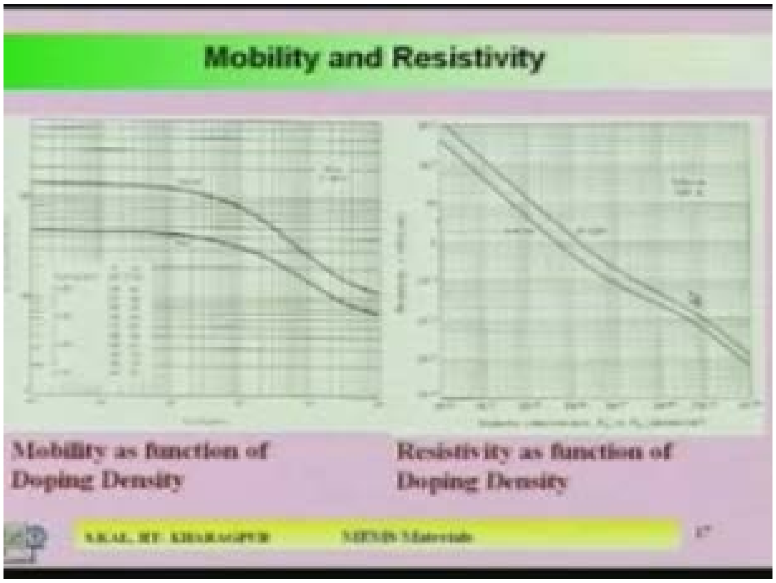

Mobility and Resistivity

Mobility as function of Doping Density

Resistivity as function of Doping Density

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So here, you see the increase of the doping is hereand this is the mobility,muin case of electron and hole mobility both are plotted here at 300 Kelvin room temperature. The curve shows that if you increase the doping concentration, the mobility reduces. Mobility reduces either hole or electron both are reducing.This particular curve shows the resistivity variation with impurity concentration. So if the impurity concentrations are large so resistivity reduces;conductivity increases. Because in a conductivity relation you know it is a n into mu$_n$ plus p into mu$_p$ this term isthere. If n increases there or p increases the doping density increases, obviouslythe conductivity increase as a result ofwhich resistivity will go down. This is the reasonof the of this kind of change of the resistivity and the mobility with doping concentration.

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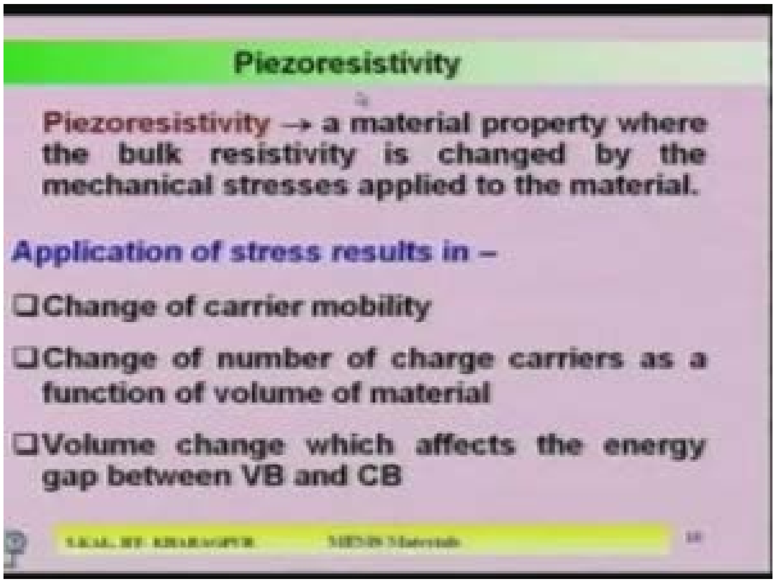

Piezoresistivity

Piezoresistivity → a material property where the bulk resistivity is changed by the mechanical stresses applied to the material.

Application of stress results in –

- ❑ Change of carrier mobility
- ❑ Change of number of charge carriers as a function of volume of material
- ❑ Volume change which affects the energy gap between VB and CB

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Next property is the Piezoresistivity.That is anotherelectronic property of the semiconductor material which is very important and which is used for making micro sensors, either it is amany kinds of micro sensors, MEMS micro sensors like the pressure sensors,gyrosor accelerometer. These are basedonthe piezoresistive property of silicon materials. Now what is piezoresistivity? It is a property of a material where the bulk resistivity is changed by mechanical stresses applied to the material. If you apply mechanical stressor force on abulk material,then its property particularly resistivity will change. That is the piezoresistivity. Now why it is changing? It is because of different reasons. What are those reasons? There are three reasons. One reason is change of carrier. Mobility will take place if you apply pressure on a particular semiconductor body.

There is a possibility of change of carrier mobility. What is a second thing change of number of charge carriers as a function of volume of material? So if we apply stress on a body its volume may change and because of change of volume, the number of the charge carriers may change and because of that,also resistivity may change. Because resistivityis added to mobility,resistivity related to the charge carrier with doping concentration.Isn't it?So because of these two changes,the resistivity may change. What is the 3rd parameter?That is volume change which affect the energy gap between valency band and conduction band. That is another property, important electronic property, if you apply pressure or stress on a particular semiconductor material its band gap that means the energy gap between the conduction and valency band may change.

Because of the change of the band gap there is there is a change you will be there will be a change of the carrier density. Because if band gap reduces,so more and more the there is a possibility more and more electrons fromvalency band cross the band gap and it will reach the conduction band. So as a result of which resistivity will change.Isn't it?So those three things one is mobility change,another is number carrier number density change, then third is the band gap change. So because of these three changes,the resistivity will change,as a result of applied pressure or stress on semiconductor material.

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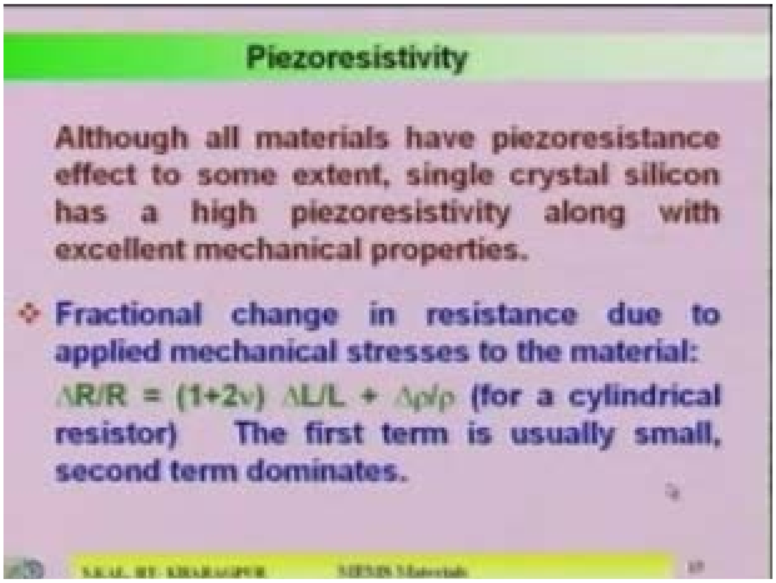

Piezoresistivity

Although all materials have piezoresistance effect to some extent, single crystal silicon has a high piezoresistivity along with excellent mechanical properties.

- Fractional change in resistance due to applied mechanical stresses to the material: $\Delta R/R = (1+2v)\ \Delta L/L + \Delta\rho/\rho$ (for a cylindrical resistor) The first term is usually small, second term dominates.

So now let us discuss little bit detail on the piezoresistivity effect. Although all materials have piezoresistance effect to some extent, single crystal silicon has a high piezoresistivity along with excellent mechanical property. Piezoresistance property is available in most of the materials. But in some cases it is very small in some cases is very large.Fortunately, silicon material will have very large piezoresistance effect and along with the good mechanical property. So it is a good conduct for micro sensors. So fractional change in resistance due to applied mechanical stresses to the material is given by the relation deltaR by R is a change of resistance is given by 1 plus twice nu delta Lby L plus delta rho by rho. So here, nu is the Poisson's ratio.

So this is coming from the mechanical propertiesand that is basically delta L by L that is deformation length changes of the a particular the semiconductor material with a cylindrical rectangular delta will change as a result of whichthere is a change in the in the Poisson's ratio valueand that is reflect in the first term. Second term delta rho by rho. Delta rho by rhomeans resistivity change and that is because of this mobility change,number density change and all these things. So there are two things are reflected in two terms for a cylindrical resistor. This expression is validthe first term is usually very small and the second term is the dominant term in case of piezoresistance propertyand the second term is basically coming for two reasons. One is the mobility change another is the band gap change.

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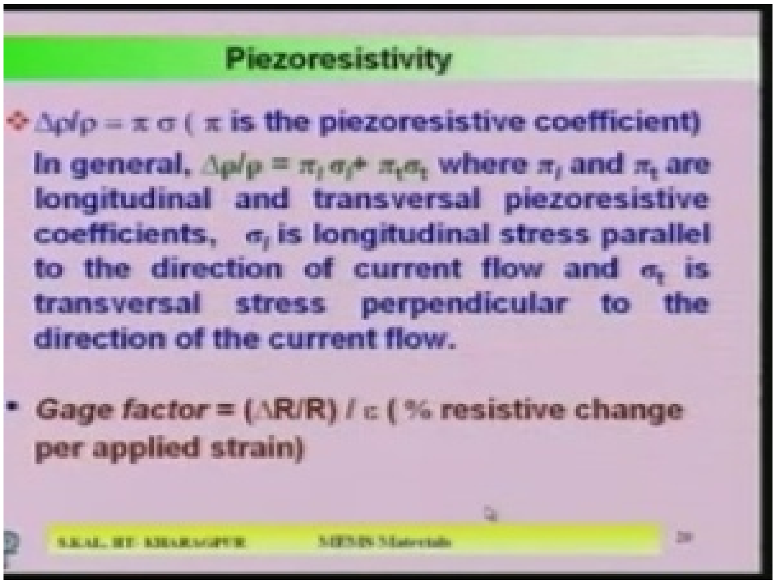

Piezoresistivity

- $\Delta\rho/\rho = \pi\sigma$ (π is the piezoresistive coefficient) In general, $\Delta\rho/\rho = \pi_l\sigma_l + \pi_t\sigma_t$ where π_l and π_t are longitudinal and transversal piezoresistive coefficients, σ_l is longitudinal stress parallel to the direction of current flow and σ_t is transversal stress perpendicular to the direction of the current flow.
- *Gage factor* = (ΔR/R) / ε (% resistive change per applied strain)

So that you will see how this effect is coming and what are the reasons? So delta rho by rho, the second term of that expression is given by pi into sigma. What is the pi? Pi is a piezoresistive coefficient. In general delta rho by rho is given bypi$_l$ sigma l plus pi$_t$into sigma t,wherepi$_l$ andpi$_t$are lateral and transverse piezoresistive coefficients.pi$_l$ is the lateral piezoresistivitycoefficient,pi$_t$ is a transversal piezoresistive coefficientand sigma$_t$ is a transversal stress perpendicular to the direction of the current flow and sigma$_l$ is the longitudinal stress parallel to the direction of current flow. So these are the general equation for change of the resistivity. There is another parameter which is known as the gage factor,which also defined in last lecture is deltaR by R divided by the epsilon and is expressed in percent resistive change per applied strain, that is the gage factor. Change of the strain by application of change application of strain, the change of resistanceis basically the gagefactor.

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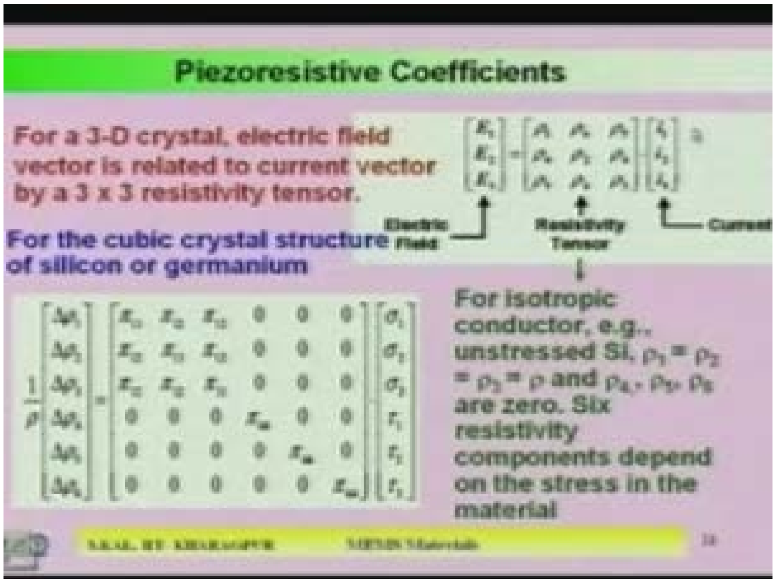

Piezoresistive Coefficients

For a 3-D crystal, electric field vector is related to current vector by a 3 x 3 resistivity tensor.

For the cubic crystal structure of silicon or germanium

For isotropic conductor, e.g., unstressed Si, $\rho_1 = \rho_2 = \rho_3 = \rho$ and ρ_4, ρ_5, ρ_6 are zero. Six resistivity components depend on the stress in the material

Now,this is the relation of electric field and current with the resistivity tensor. So for a 3D crystal, the electric field vector is related to the current vector by 3 by 3 resistivity tensor. So here is E_1, E_2, E_3electric field vectors; I_1, I_2, $I_3$is the current vectors is related by these resistivity tensorand if you see theseparticular,this rho$_{1,}$rho$_{2,}$rho$_5$basically, these are resistivity tensor and this resistivity tensor is given by this expression and that resistivity tensor is a delta rho$_{1,}$rho$_{2,}$ rho$_3$, rho$_4$, rho$_5$, rho$_6$is given by in terms of pi and sigma. So here for isotropic conductor, for example in case of unstressed silicon rho$_{1,}$rho$_2$and rho$_3$is equal to rho. So rho$_{1,}$ rho$_{2,}$ rho$_3$will be rhoand rho$_{4,}$ rho$_5$and rho$_6$these are 0. So automatically, the whole thing in case of isotropic conductor when there is no stress then complete the E is equal to sigma into I is a conventional relation but for nonisotropiccase means when we apply stress. So in that condition,E equal to rho into I is that simple relation will not hold because,in that case in differentcrystallographic direction the stress component will be different and in that case there are piezoresistivity coefficients will involveand those piezoresistivitycoefficient indifferent crystallographic direction are different.

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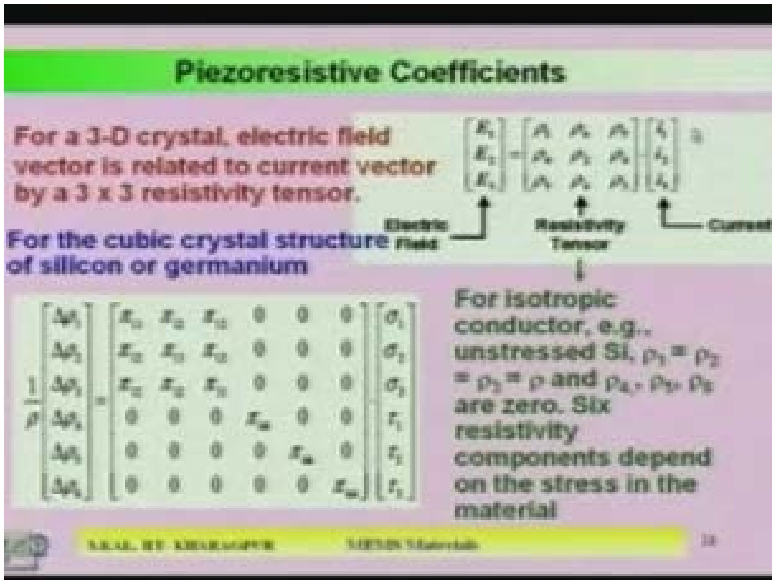

Piezoresistive Coefficients

For a 3-D crystal, electric field vector is related to current vector by a 3 x 3 resistivity tensor.

For the cubic crystal structure of silicon or germanium

$$\frac{1}{\rho}\begin{bmatrix}\Delta\rho_1\\ \Delta\rho_2\\ \Delta\rho_3\\ \Delta\rho_4\\ \Delta\rho_5\\ \Delta\rho_6\end{bmatrix}=\begin{bmatrix}\pi_{11}&\pi_{12}&\pi_{12}&0&0&0\\ \pi_{12}&\pi_{11}&\pi_{12}&0&0&0\\ \pi_{12}&\pi_{12}&\pi_{11}&0&0&0\\ 0&0&0&\pi_{44}&0&0\\ 0&0&0&0&\pi_{44}&0\\ 0&0&0&0&0&\pi_{44}\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_1\\ \tau_2\\ \tau_3\end{bmatrix}$$

For isotropic conductor, e.g., unstressed Si, $\rho_1 = \rho_2 = \rho_3 = \rho$ and ρ_4, ρ_5, ρ_6 are zero. Six resistivity components depend on the stress in the material

Now let usdefine the piezoresistivity coefficient pi$_{11}$, pi$_{12}$andpi$_{44}$. These are the 3 pi$_{11}$, pi$_{12}$and pi$_{44}$. The 3 piezoresistivitycoefficient how they define.

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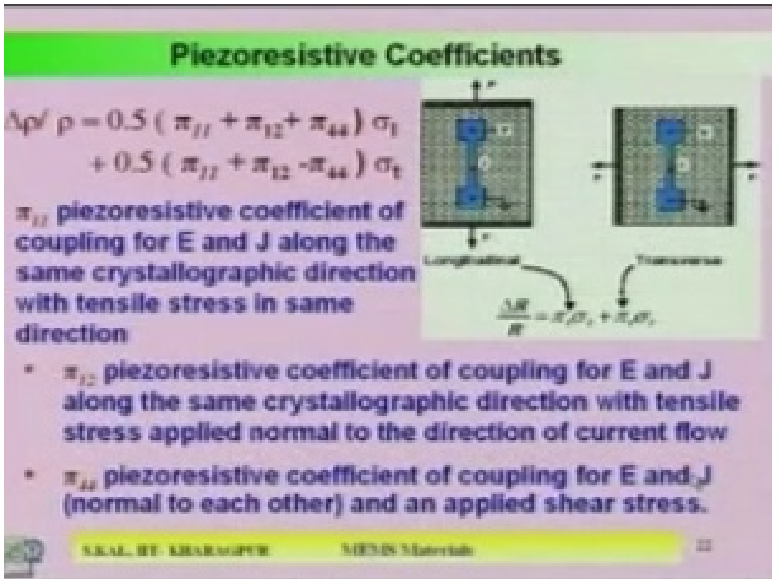

Piezoresistive Coefficients

$$\Delta\rho/\rho = 0.5\,(\pi_{11} + \pi_{12} + \pi_{44})\,\sigma_l + 0.5\,(\pi_{11} + \pi_{12} - \pi_{44})\,\sigma_t$$

$$\frac{\Delta R}{R} = \pi_l\sigma_l + \pi_t\sigma_t$$

π_{11} piezoresistive coefficient of coupling for E and J along the same crystallographic direction with tensile stress in same direction

- π_{12} piezoresistive coefficient of coupling for E and J along the same crystallographic direction with tensile stress applied normal to the direction of current flow
- π_{44} piezoresistive coefficient of coupling for E and J (normal to each other) and an applied shear stress.

They are defined in this way, you shown in this picture you see;this is a resistance for example. In this resistance if you apply force along the length of the resistance,then current will flow in the same length. Along across the length you are applying the force, current is flowing the same direction. That is a longitudinalstress you have applied. On the other hand in the second picture,the force you are applying current is flowing perpendicular tothe direction you are applying force in this direction. So current in the same, along the length of the resistance,so this is knownas the transverse effect. Total deltaR by R is given bypi$_{l}$, sigma$_{l}$, pi$_{t}$, sigma$_{t}$, pi$_{l}$ means longitudinal effect,pi$_{t}$ is the transverse effect. So now we apply a stress on a bulk semiconductor. So there is a component longitudinal component and transverse component may be separate so longitudinal component into sigma l plus transverse component into sigma 2 their sum will y the delta R by R.

Now definition is giving here delta rho by rho is given by 0.5 pi$_{11}$ plus pi$_{12}$ plus pi$_{44}$ into sigma l plus pi$_{15}$ intopi$_{11}$pluspi$_{12}$ minuspi$_{44}$into sigma t. Now thepi$_{11}$is a piezoresistive coefficient of coupling for E and J along the same crystallographic direction E and J. J is the current,,Eis the field. Field means you are applying voltage and current is also the same direction E and J along the same crystallographic direction with tensile stress in same directionpi$_{11}$is due to tensile stress. In the same directionnow pi$_{12}$its definition is piezoresistive coefficient of coupling for E and J along the same crystallographic direction with tensile stress applied normal to the direction of current flow.Here in this case pi$_{11}$in this caseand pi$_{12}$ in this case this is normal to the direction of the current flow we apply stresshere in the direction of the current flow we apply stress sopi$_{11}$ related to herepi$_{12}$related to this is case.

Now what ispi$_{44}$? pi$_{44}$is the piezoresistive coefficient of coupling for E and J. J is the current density in the field for E and J normal to each other and in applied shear stress.So this is related to shear stress not the tensile stress. So if you apply shear stress in that casethe pi$_{44}$ E will come into the picture here thepi$_{11,}$pi$_{12,}$pi$_{44}$ definition is given and there is a little bitdifferentiateamong these valuesofpi$_{12}$ and 14 in some casespi$_{11}$ and 12 is predominant in some casespi$_{44}$ is predominant and that is also dependent on the type of the crystal if that crystal is p type silicon or n type silicon depending on that the values will change in some cases. We will findthat pi$_{11}$ andpi$_{12}$ are dominate and in some type of crystal will find thepi$_{44}$ is dominate. So that is shown in the next view graph.

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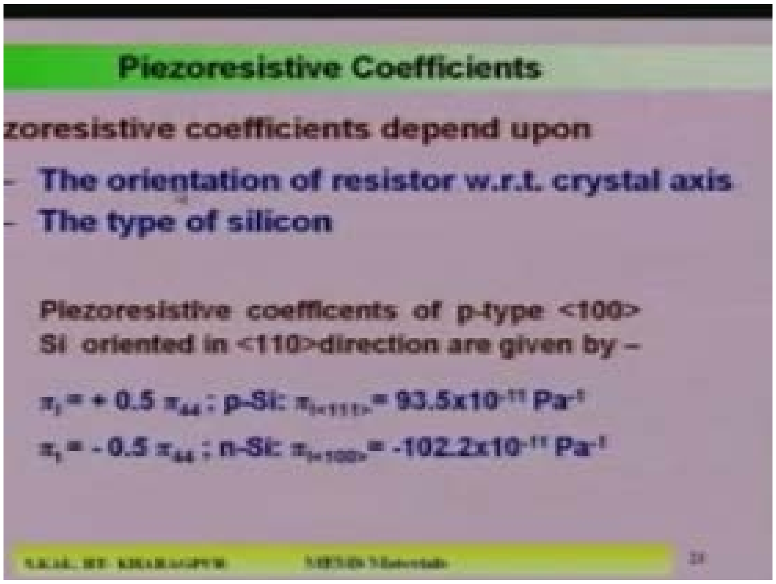

Piezoresistive Coefficients

zoresistive coefficients depend upon

- The orientation of resistor w.r.t. crystal axis
- The type of silicon

Piezoresistive coefficents of p-type <100> Si oriented in <110>direction are given by –

$\pi_l = + 0.5\ \pi_{44}$: p-Si: $\pi_{l<111>} = 93.5 \times 10^{-11}\ Pa^{-1}$

$\pi_t = - 0.5\ \pi_{44}$; n-Si: $\pi_{l<100>} = -102.2 \times 10^{-11}\ Pa^{-1}$

You will see piezoresistive coefficient depending on 2 things. The orientation of resistor with respect to crystal axis which I showed youthe type of silicon. One is the orientation that means weather the orientation of the resistance is along the crystallographic axis or perpendicular to the crystallographic. Crystallographic axis depends on thatand the second is type of silicon. Which type of silicon you are using p type or and type and for piezoresistive coefficient of p type 100 silicon oriented in 110 direction are given by this,pi l is a plus 0.05 pi$_{44}$ pit's minus 0.5pi$_{44}$ this is for p type silicon this is for n type silicon in other direction in 111 and100 aregiven by this values.

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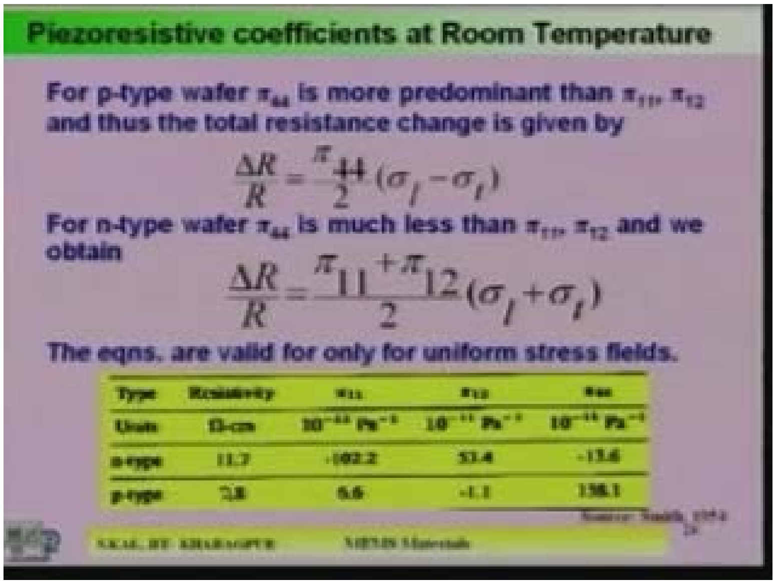

Piezoresistive coefficients at Room Temperature

For p-type wafer π_{44} is more predominant than π_{11}, π_{12} and thus the total resistance change is given by

$$\frac{\Delta R}{R} = \frac{\pi_{44}}{2}(\sigma_l - \sigma_t)$$

For n-type wafer π_{44} is much less than π_{11}, π_{12} and we obtain

$$\frac{\Delta R}{R} = \frac{\pi_{11} + \pi_{12}}{2}(\sigma_l + \sigma_t)$$

The eqns. are valid for only for uniform stress fields.

Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ω-cm	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1

So in the next slide these values are basically tabulated for compressor. You can see here that n type and p type,resistivity for n type is 11.51 centimeter, p type 7.8,so pi$_{11}$,pi$_{12}$,pi$_{44}$values are given. So units are here, these multiplied by 10 to the power minus11 Pascal inverse,multiplied by 10 to the power minus 11 Pascal inverse,multiply by 10 to the minus 11 Pascalinverse in case of pi$_{11}$, $_{12}$and $_{14}$. Now n type if you compare this value, you see for n type silicon pi$_{11}$ and pi$_{12}$ is a large compared to pi$_{44}$. That means these2 parametersare dominant. In case of p type will found that pi$_{44}$is dominant,138.1 into 10 to the power minus 11Pascal inverse, but pi$_{11}$ and pi$_{12}$are small in the range of 126 into 10 to the power minus 11 Pascal inverse. So if you write the sectional change of resistance, in case of p type, where the pi$_{44}$is more dominant thenrelation looks like this.Delta R by R is equal to pi$_{44}$by 2,sigma$_l$ minus sigma$_t$. For n type pi$_{44}$is much less than pi$_{11}$, the table shows and the fractional change of resistance is given by the relation pi$_{11}$plus pi$_{12}$divided by 2 into sigma$_l$plus sigma$_t$. These are the fractional change of resistance due to the piezoresistance effect in case of p type and n type silicon. These relations are very much useful when you do the model analysis of any sensor which utilizes the piezoresistive effect of the silicon material.

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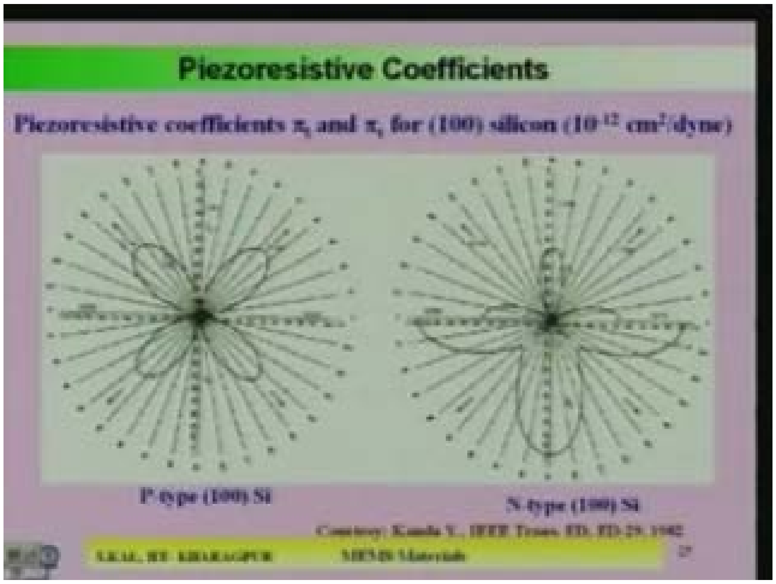

Piezoresistive Coefficients

Piezoresistive coefficients π_l and π_t for (100) silicon (10^{-12} cm^2/dyne)

Courtesy: Kanda Y., IEEE Trans. ED, ED-29, 1982

Now these are the charts pi$_l$ and pi$_t$in case of 100 silicon and in different orientationshow the values are changingin case of p type and n type silicon is shown in these view graph. Those graphs are taken from the IEEE transnactionof ED in 1982 from the paper of Y Kanda. So, different directions are shown for example is 110,100 and is a 010 and how the values will change in case of n type, the dominant parameter, so that is shown in thisview graph.

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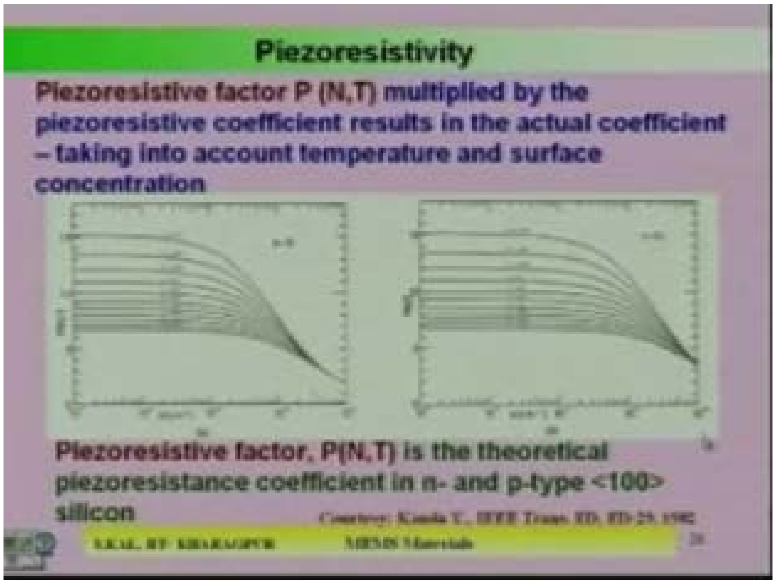

Piezoresistivity

Piezoresistive factor P (N,T) multiplied by the piezoresistive coefficient results in the actual coefficient – taking into account temperature and surface concentration

Piezoresistive factor, P(N,T) is the theoretical piezoresistance coefficient in n- and p-type <100> silicon

Courtesy: Kanda Y., IEEE Trans. ED, ED-29, 1982

Now the piezoresistivity which is usedin many cases is also another term defined which is known as P N into T. So P is function of N T that is know some time known as theoretical piezoresistance coefficient in n and p typeand that is basically thepiezoresistic factor multiplied by the piezoresistive coefficient, it results in actual coefficient which takes care of both temperature and surface concentrationand this P N T is nothing but the pi values and which includes the effect of temperature as well as surface concentration. So that P N T is plottedwith different concentrationof the doping concentration of the material and for p silicon and n silicon with doping concentration how the PN T is changing so that plot shows those valuesand that is sometimes from thiscurve we have to find out the values for ourthe model analysis of the mechanical microsensors.

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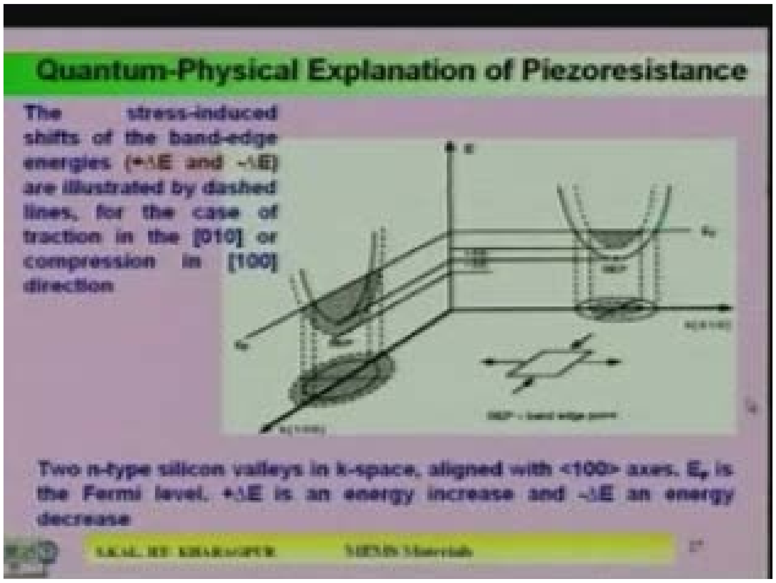

Quantum-Physical Explanation of Piezoresistance

The stress-induced shifts of the band-edge energies (+ΔE and -ΔE) are illustrated by dashed lines, for the case of traction in the [010] or compression in [100] direction

Two n-type silicon valleys in k-space, aligned with <100> axes. E_F is the Fermi level. +ΔE is an energy increase and -ΔE an energy decrease

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Now I will discuss little bit on the quantum physical explanation of piezoresistance effect. Quantum physical explanation means here, basically from the band theory. So from the band theory discretization of the bands, discretization of energy levelswhich gives me the bands. So from that angle how the piezoresistance effect is explained that I will discuss little bit with the help of this diagram. So this is the E-K diagram and if you apply stress,then band edges are shifted so for example in the E-K diagram this is 010and this is 100 K direction,the crystal axis direction and here the dash curve is basically the curve, if you apply stress then the band edges and band lineswill be shifted like that. Here in the E-K diagram, in the K space you see there one is known as traction.

Traction is in this axis means which is elongationis the traction axis is 010 and compression axis is 100, 100 is a 010. Now here you see if you apply stress,so in that case in the traction axis,this is original carbon and it is a dash curve is after application of the traction. So then it has class delta is shifted upward. So class delta if we shifting upwards.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 increase so what will happen? So less number of carrierswill have the probability to jump into that into that level conduction band. Because delta E energy band gap has increased,so probability of jumping that higher gap will less.

But onthe other hand if you apply the compression axis which is 100,so they are you see thisthe band edge of the conducts as the Fermilevel of the band edge reduces by minus delta E. So that means here, there is a probability of the carriers, so will be moved here. So that means if you apply the traction axisthat we elongate there, there is a probability of movement of the carrier from this axis to this axis. Because here usually they can jump,but here no,hereincrease. So the mobility of carrier may increase because there is a tendency of the movement of the carrier along this compression axis. So as a result of which here mobility will increase. Mobility increase means piezoresistance will decrease;conductivitywill increase. But here the opposite. So these are the explanation of the quantum physical explanation of piezoresistance effect.

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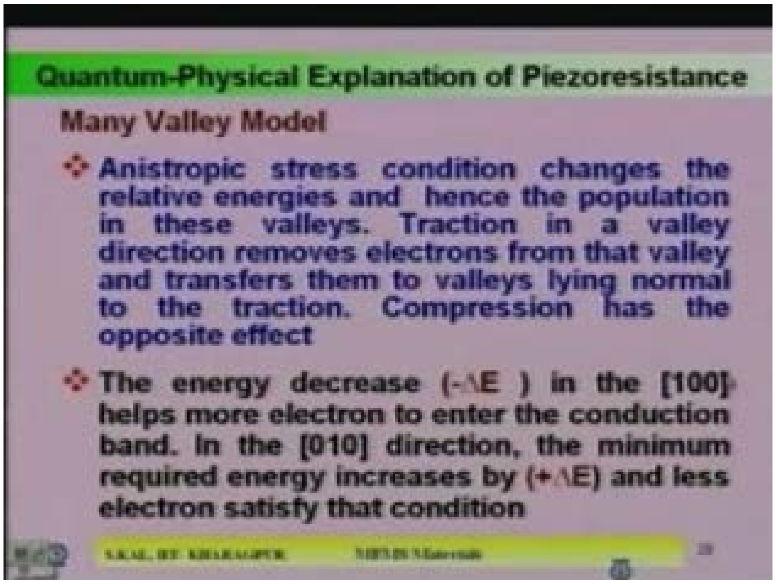

Quantum-Physical Explanation of Piezoresistance

Many Valley Model

- Anistropic stress condition changes the relative energies and hence the population in these valleys. Traction in a valley direction removes electrons from that valley and transfers them to valleys lying normal to the traction. Compression has the opposite effect
- The energy decrease $(-\Delta E)$ in the [100] helps more electron to enter the conduction band. In the [010] direction, the minimum required energy increases by $(+\Delta E)$ and less electron satisfy that condition

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

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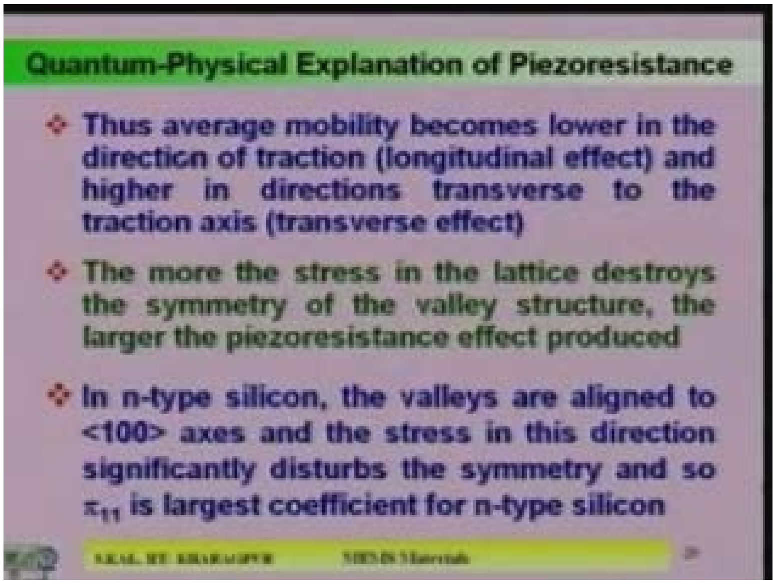

Quantum-Physical Explanation of Piezoresistance

- Thus average mobility becomes lower in the direction of traction (longitudinal effect) and higher in directions transverse to the traction axis (transverse effect)
- The more the stress in the lattice destroys the symmetry of the valley structure, the larger the piezoresistance effect produced
- In n-type silicon, the valleys are aligned to <100> axes and the stress in this direction significantly disturbs the symmetry and so π_{11} is largest coefficient for n-type silicon

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

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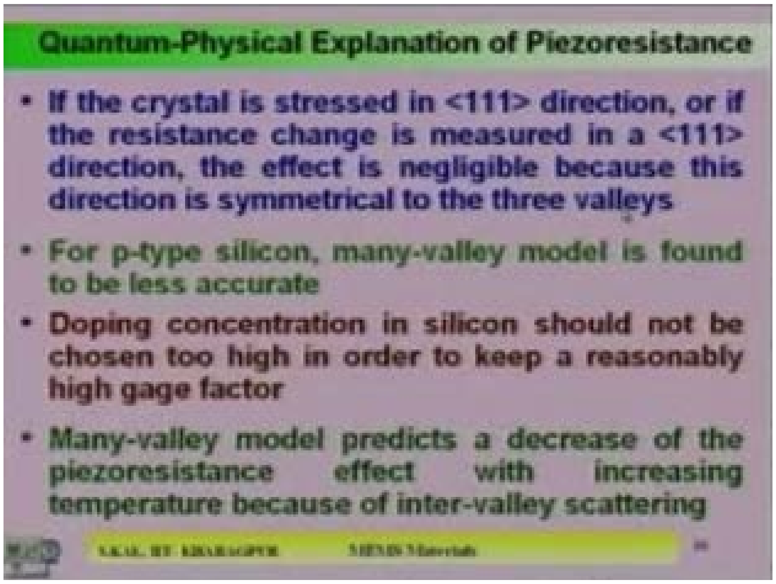

Quantum-Physical Explanation of Piezoresistance

- If the crystal is stressed in <111> direction, or if the resistance change is measured in a <111> direction, the effect is negligible because this direction is symmetrical to the three valleys
- For p-type silicon, many-valley model is found to be less accurate
- Doping concentration in silicon should not be chosen too high in order to keep a reasonably high gage factor
- Many-valley model predicts a decrease of the piezoresistance effect with increasing temperature because of inter-valley scattering

So that is because of this reason. 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 decrease of the piezoresistance effect with increasing temperaturebecause of inter-valleys scattering. So with temperature there is an inter-valley scattering,so because of the scattering increases it predicts decrease of the piezoresistance effect. So these are the few points some quantum physical explanation. So I stop today. Next class I will continue with the properties of the MEMS material which are mainly I will discuss the piezoelectric effect and a piezothermal effect. So all those effects will be discussed in the next class. Thank you very much.

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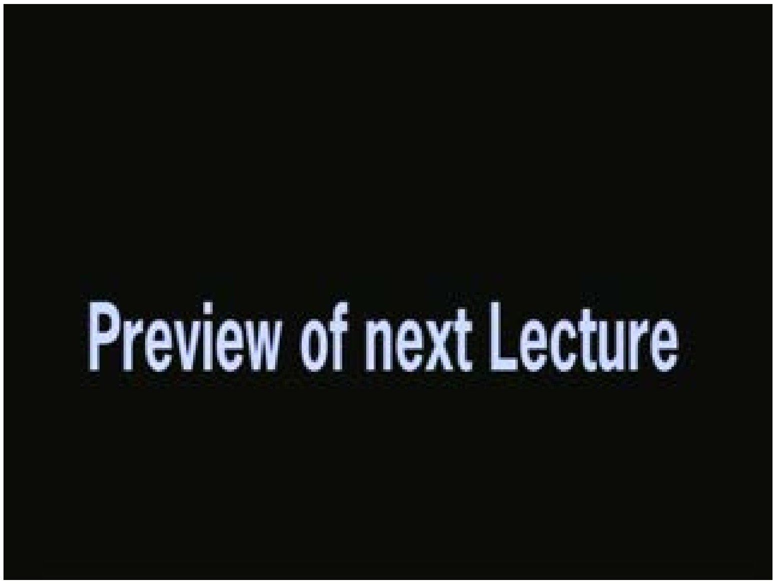

Preview of next Lecture

Preview of Next Lecture

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Lecture # 07

MEMS Materials Properties (Contd.) &
Microelectronic Technology for MEMS - I

MEMS Materials Properties (Contd.) & Microelectronic Technology for MEMS-I

In my last lecture, I was discussing on the MEMS materials properties. That was not completed. So today, for some time I will discuss about the same topic that is MEMS materials properties.

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MEMS Materials' Properties - Continued
Santiram Kal
Department of Electronics & ECE
Indian Institute of Technology
Kharagpur – 721302
E Mail: srkal@iitkgp.ac.in

MEMS Materials' Properties – Continued

After that, I will switch over on to different subject. That is microelectronics technology which is used for MEMS. So let us now continue the last lecture which is MEMS materials' properties.

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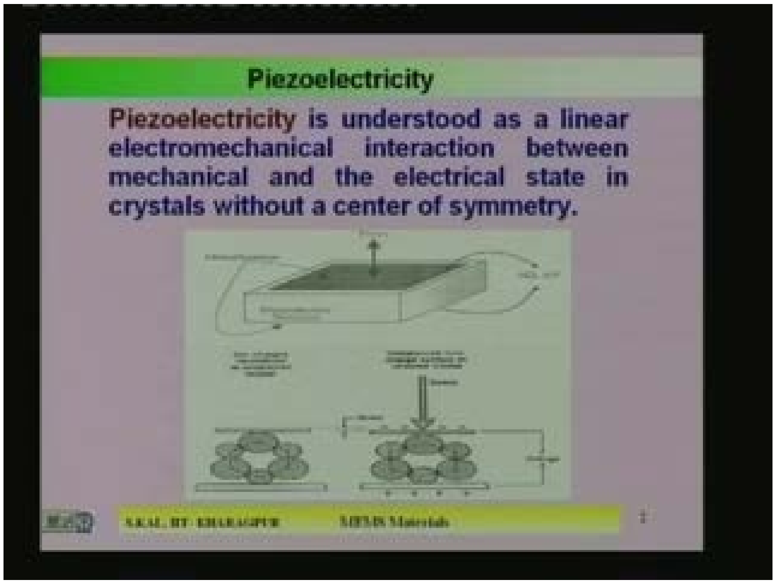

Piezoelectricity

Piezoelectricity is understood as a linear electromechanical interaction between mechanical and the electrical state in crystals without a center of symmetry.

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So, today I will discuss on different properties which I discussed in the last class. Those are the piezoelectric property of the materials. Sopiezoelectricity is understood as a linear electro mechanical interaction between mechanical and electrical state in crystal without the center of symmetry. Those crystal which does not have the center symmetry will show the piezoelectric property. So basically, in this figure you can say the piezoelectric material is here and if we apply the force in the surface of these two surface of the particular material, then you will find that at the surface of the material some charge will be accumulated and that phenomenon is known as piezoelectric phenomenon. That means if we apply force or pressure, the charge will be accumulated at the surface and there is a different, here if you see at the bottom, if you apply stress, that means as a result ofstress, a strain will be developed inside the material and as a result of which realignment of the ions will be there and at the surface will get positive and negative charges.

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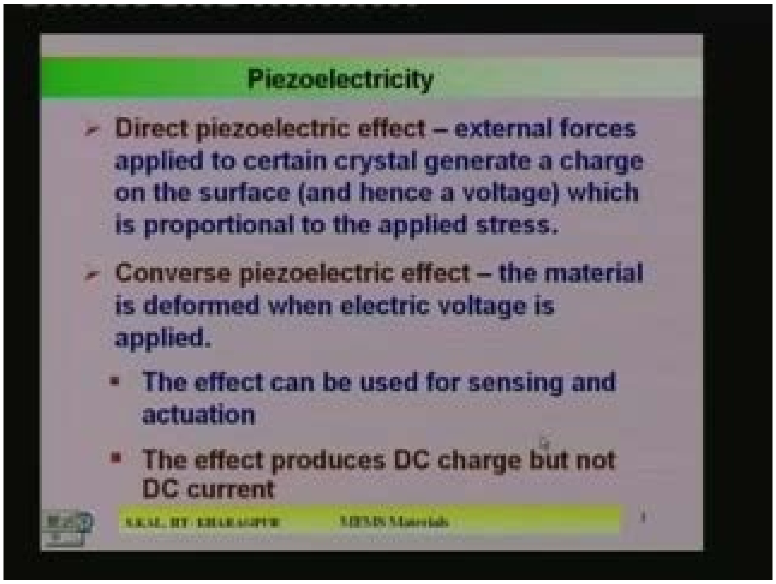

Piezoelectricity

- Direct piezoelectric effect – external forces applied to certain crystal generate a charge on the surface (and hence a voltage) which is proportional to the applied stress.
- Converse piezoelectric effect – the material is deformed when electric voltage is applied.
  - The effect can be used for sensing and actuation
  - The effect produces DC charge but not DC current

So this phenomenon is very useful in case of microsensors and microactuators. There are two types of piezoelectric effect. One is known as directpiezoelectric effect and another is known as converse piezoelectric effect. The direct piezoelectric effect is used for microsensors and the converse piezoelectric effect is used for actuators, microactuators. So direct piezoelectric effect basically, if we apply certain external force or pressure on the surface of the crystal, so some charge will accumulate at the surface. As a result you will get some voltage if you connect the two surface with a wire, you will get some voltage. So that means, the electro mechanical if you apply the mechanical pressure you are getting some electric field, that can be used as a micro sensor. On the other hand if you apply certain electric field at the surface of the crystal, then inside the crystal, there is a moment or strain will be developed. That means mechanical energy or mechanical force will generate. So that property will be used for designing the micro actuator.

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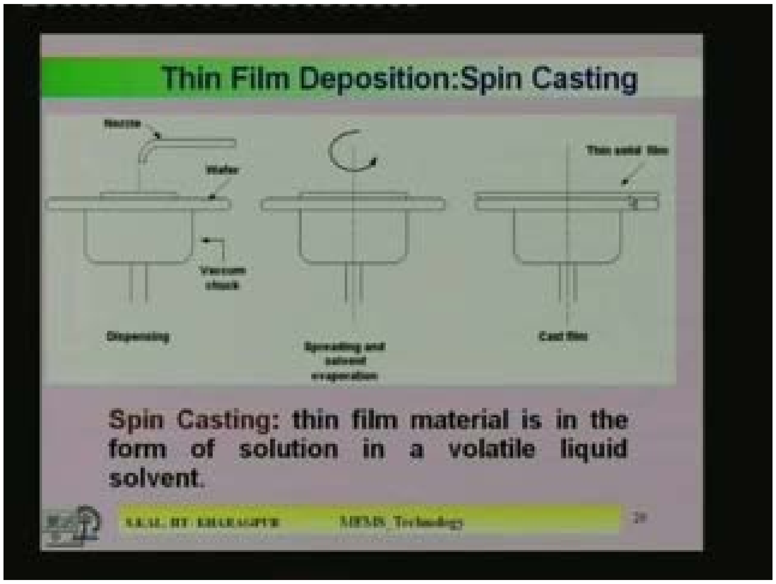

Thin Film Deposition:Spin Casting

Spin Casting: thin film material is in the form of solution in a volatile liquid solvent.

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Casted film on the, is some sort of spinner arrangement which is used for photoresist coating, similar kind of thing is used here. So here, one thing is the material mass in liquid form. Otherwise you cannot spread the entire slice.

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Thin Film Deposition: Spin Casting

Spin – Cast – Films : -

- intrinsically have a high – stress state
- less dense
- more susceptible to chemical attack

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So now, this particular thing has certain problem and this type of film have a high stress value.
It will have less dense and more susceptible to chemical attack. Why? The reason is that when you are spreading the film over the chuck, by rotating chuck you are putting the liquid and then at the same time evaporation takes place. During the evaporation, of the solvents, so it leaves some pores. Because of those pores, the film will not be highly dense. At the same time when

you subsequently use those films, so through that pores some other gases may enter and that is why it results into chemical attack. Because of its less dense. So that is why this particular technique is that much populartechnique alone is used in some typical cases and here is the actual system, the spin casting system is shown in the diagram. Now this one technique and other technique is the evaporation technique, that technique I will discuss in the next lecture. Thank You.