Material Science
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Indian Institute of Technology Delhi
Lecture No 38
Semiconductors (Contd.)

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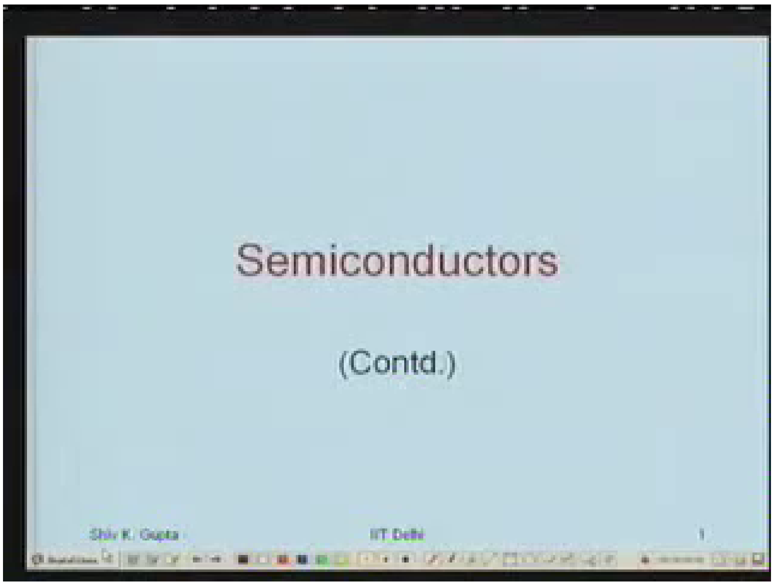
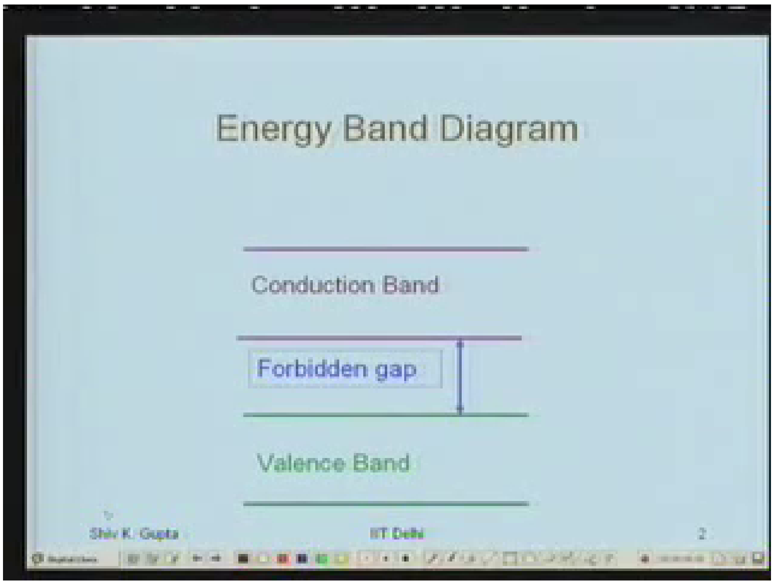

Semiconductors

(Contd.)


Energy Band Diagram

Conduction Band

Forbidden gap

Valence Band

In the last class we were talking about semiconductors and we saw in this by looking at the semiconductors that the free electrons or the outermost electrons in the solid are distributed over different energy and this can be divided in energy bands. Each band can accommodate twice the number of atoms in the solids if you consider per unit volume then it is twice the number of atoms per unit volume and remaining one have to go to another band and between the 2 band there is an energy gap, in some materials this gap is small, in some materials it is large and some materials it is not there as a result they happen to be bad conductors, semiconductors and good conductors that is what we were talking about, so this is the configuration we have the valence band where the electrons are there and then there is a band gap then there is a conduction band in which there are maybe no electrons to start with.

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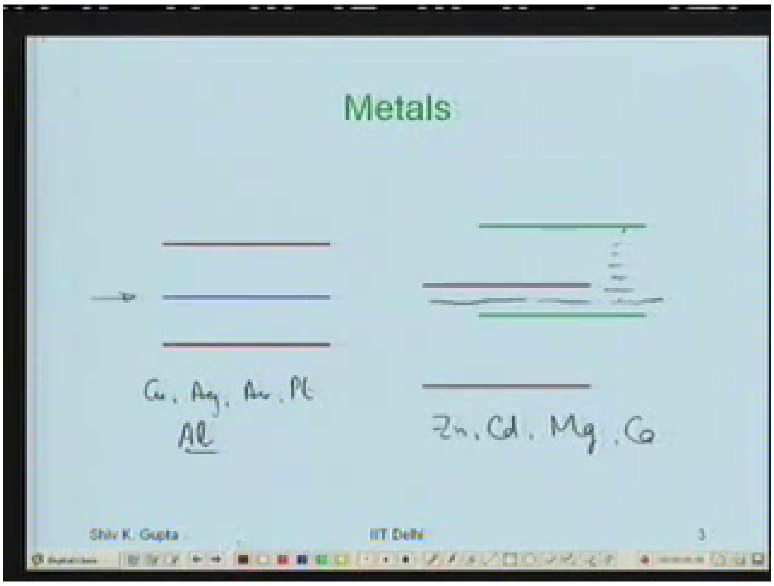

Metals

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In metals particularly those who are from group 1, group 3 like you have copper, silver, gold, platinum aluminium is from group 3, the valence band is half full that is up to this level is the Fermi level here and remaining energy levels in this band are empty and these can be occupied by these electrons which are nearly Fermi level once they get excited they can go to this and start conducting. While those from group 2 like zinc, cadmium, magnesium, calcium, et cetera the 2 bands overlap because of the different directions they do not give rise to any effective band gap. Valence band is full because it can accommodate twice the number of atoms and there are 2 electrons per atom, so therefore this is full but because of the overlap this portion is half filled here and half-filled there, so electrons are here available to go for conduction because energy levels are available in this band and these are these happen to be good conductors again but not as good as these ones because the electrons have to change the direction and going to the next band because of the different direction being there that is what we discussed in the last class.

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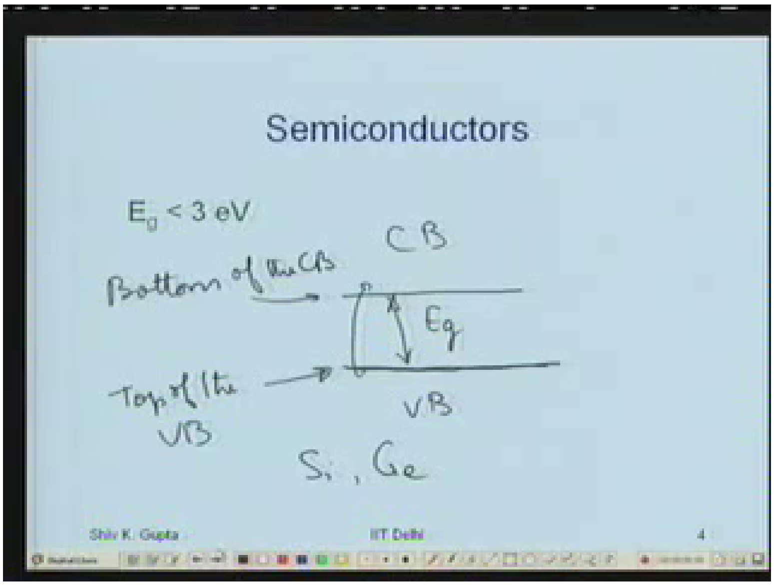

Semiconductors

$E_g < 3$ eV

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Now semiconductors this band gap is less than 3 electron volt this is the band gap here I have the conduction band here I have the valence band this is called the top of the valence band this is called the bottom of the conduction band this energy level I mean and this is the top of the valence band and this gap between them is less than 3 electron volt. These elements like silicon and germanium are from group 4 and they are the compounds 50-50 compounds which also have the similar kind of behaviour, the group 4 provides 4 electrons they go in 2 valence bands one I can call the lower valence band, the upper valence band that is completely full up to here. Now these conductions has to take place these electrons have to be excited to go there and only then they can start conducting otherwise they can be no conduction.

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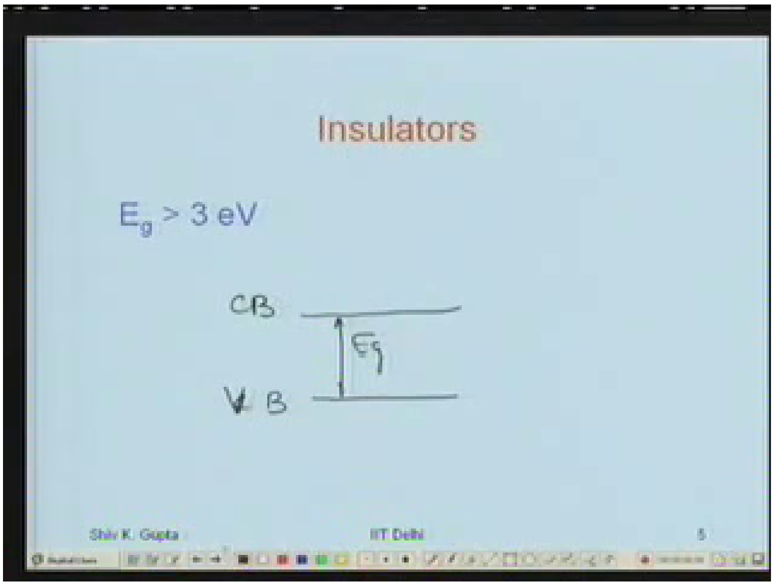

Insulators

$E_g > 3$ eV

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Well once the band gap is greater than 3 electron volts these are insulators by any mean it is not possible to excite these electrons once this is greater than 3 electrons volts this is again the top of the conduction band sorry valence band and this is bottom of the conduction band and the moment it is greater than 3 electron volts they will not be able to be…these electrons from here will not be excited to reach there and once they do not reach they do not conduct, there are no energy level available here for them to get excited to so that they can do the conduction. These are insulators like materials oxides diamond is one from group 4 itself and these materials do not conduct.

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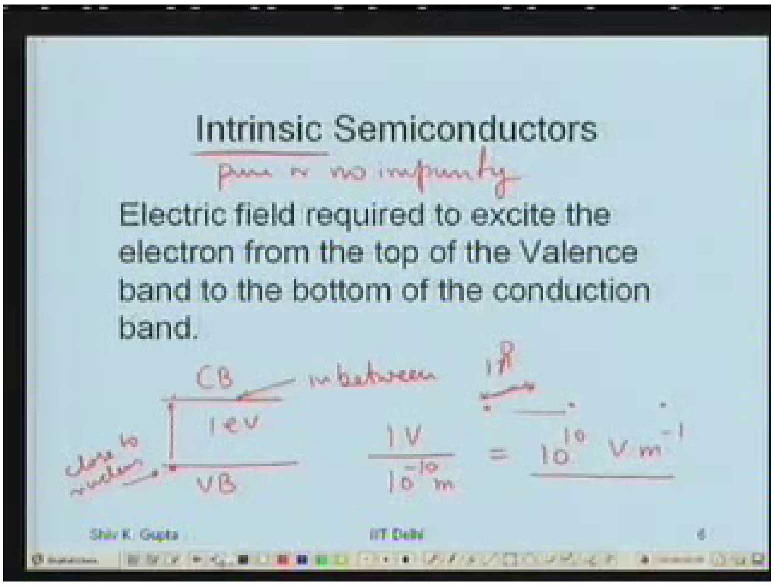

Intrinsic Semiconductors

pure ~ no impurity

Electric field required to excite the electron from the top of the Valence band to the bottom of the conduction band.

$\frac{1\,V}{10^{-10}\,m} = 10^{10}\ V\,m^{-1}$

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Now I shall talk about the intrinsic semiconductors, intrinsic semiconductors by the word I say intrinsic there is no impurities present pure substances with themselves, no impurities in the material that is the meaning of the word intrinsic. Now let us see we while discussing the diffraction of these electrons in the crystal said that 2 localised states are obtained one close to the nucleus other one away from the nucleus may be between the 2 nuclei. The one which is close on to the nucleus is got a low potential energy, the one which is in between as high potential energy knowing this fact we have looked at the band gap in other word if am talking about this as the valence band this as the conduction band, the electrons which are here they are the ones close to nucleus.

Student: Then how can see them?

Prof: This is the one which is in between, energy consideration better this is what is the energy of the electron in the free electron theory be considered total energy to be kinetic energy but now I have the potential energy when there is a diffraction taking place because the low potential energy this has a lower energy level and this will be higher potential energy this goes there kinetic energy for the same because the moment term is the same for the 2 and these are the 2 which are getting diffracted but this one with slight excitation can acquire a higher energy and will not be diffracted will start conducting.

In other words if the electrons from here can be taken to there, let us say in silicon this gap is 1.1 electron volt let us say this is 1 electron volt and in my solid electron which is close by here is to be taken to somewhere between the 2 nuclei this distance is of the order of 1 Angstrom, the radius of the atom and the energy is to be increased of this electron by 1 electron volt how much energy or electric field should I supply? 1 volt and over the distance it has to be applied is 1 Angstrom. How much is this field? By any structure imagination can you prepare this field? So my friend asked me yesterday in (())(9:57) by applying any kind of electric field I cannot excite this electron to go there, it is not possible, however what helps us in this excitation is the thermal energy. Thermal energy provides a random distribution of these energies during collision they are changing their energies and all that and that will take care of the thermal energy.

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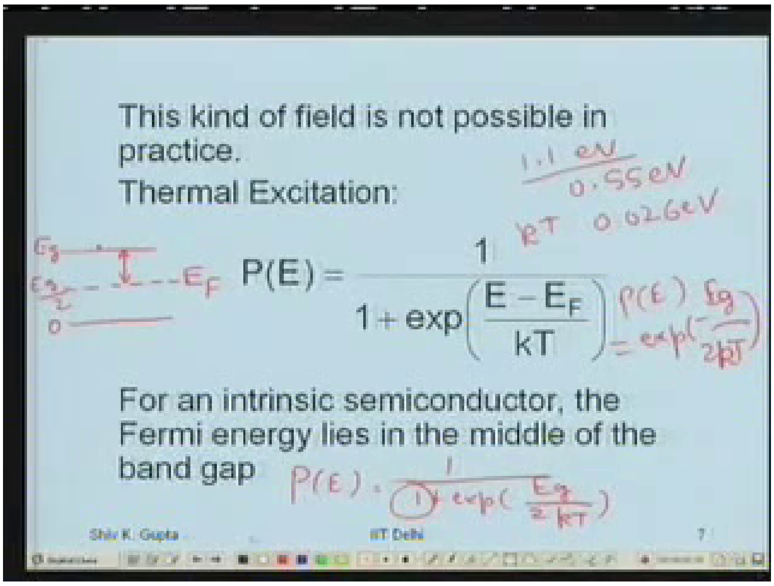

This kind of field is not possible in practice.

Thermal Excitation:

$$P(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

For an intrinsic semiconductor, the Fermi energy lies in the middle of the band gap

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So in practice once this electric field is not possible the thermal excitation is certainly possible the probability may be small and the probability as given by the Fermi Dirac statistics we discussed earlier one divided by one plus exponential of E minus E F by kT. Now in intrinsic semiconductors the form energy lives in the middle of the band gap, mobility of occupation is 50 percent but there is no energy state there allowed state is not there it is a forbidden gap there will be no electron there right so that is the situation Fermi energy is here if I want to know what is the probability of occupying this level of energy or to use this difference between E and E F.

If I consider this to be 0 level this will be Eg and the difference will be Eg minus E F and E F since it is in the middle it is Eg by 2, so E minus E F will be E g by 2 kT so… Alright this E g value if I consider the silicon which is E g is 1.1 electron volt, E g by 2 would be 0.55 electron volt and kT at room temperature if I consider as 0.026 electron volt right this is more than 20 exponential of more than 20 which will be much greater than 1 and I can neglect this one here and this can be written simply as exponential of minus E g upon 2 kT, is it clear? because this is brought in the numerator after it neglecting 1.

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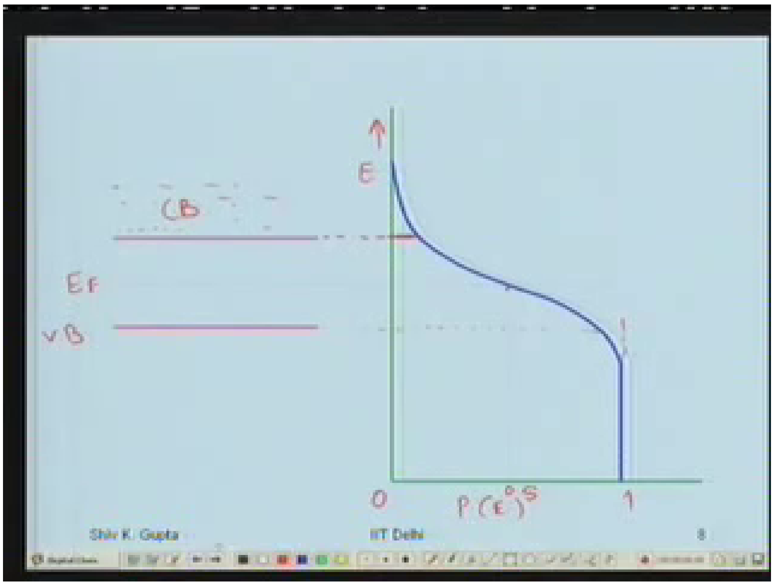

Right here is my top of the valence band this is my bottom of the conduction band this is my firmly level and here is this energy axis and this is the probability given by Fermi Dirac statistics 0 here one here 0.5 here, so it is 0.5 but there is no energy level here which can be occupied by an electron but you see at a given temperature it is not 0 here while similarly it is not one here it is less than 1, so these electrons from here are in a position to get excited to reach there at a given temperature probability is very small though there will be some that is why we are able to measure some conductivity of silicon and germanium at room temperature and these are the electrons here because of this probability and they are the ones which can be excited to go to higher energy levels and start conducting the number is small, so conductivity is small it is worse than the conductors we looked at the conductivity in the range of or the resistivity in the range of 10 minus 9 ohm metre, 10 minus 3 ohm meter these are the one which are between the range of 10 minus 3 to 10 to power 3 ohm meter alright, so that is about the thermal excitation and distribution of Fermi energy in these free electron gas.

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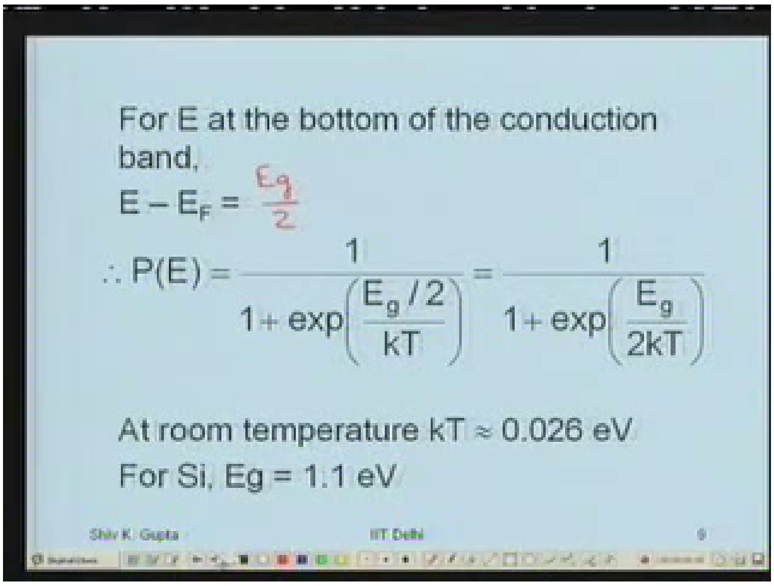

For E at the bottom of the conduction band,

$E - E_F = \frac{E_g}{2}$

$$\therefore P(E) = \frac{1}{1 + \exp\left(\frac{E_g/2}{kT}\right)} = \frac{1}{1 + \exp\left(\frac{E_g}{2kT}\right)}$$

At room temperature $kT \approx 0.026$ eV

For Si, $E_g = 1.1$ eV

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Well I think this Slide is here already for E at the bottom of the conduction band E minus E F going to be E g by 2 and when I substitute this here that is what it is coming out and I said this is the calculation which again I making and that is going to say that it is going to be exponential of minus E g upon 2 kT that is what it is.

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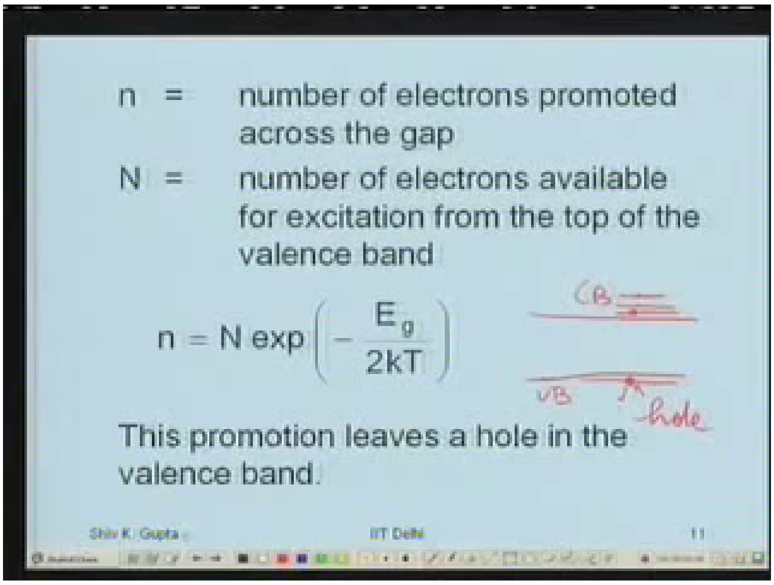

n = number of electrons promoted across the gap

N = number of electrons available for excitation from the top of the valence band

$$n = N \exp\left(-\frac{E_g}{2kT}\right)$$

This promotion leaves a hole in the valence band.

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Probability of occupational energy level is also equal to the fraction of electrons being there and that fraction of electrons that energy E is this probability and call this small n by capital N, small n is the number of electrons which are just at the bottom of the conduction band and capital N is number of electrons which could have been excited to reach there. There are number of models available in physics they have great details the work out this n, I being an engineer will not go into those theories those models which are approximations I shall try to work it out experimentally what is this number, let us try to do that.

So I define this small n as the number of electrons promoted across the gap, capital N as the number of electrons available for excitation from the top of the valence band right though I know in the valence band if it is full I have twice the number of atoms per unit volume as the total number of electrons but I have to want to find out what is this n actually and this promotion in turn leaves and energy level if some electrons from the top of the valence band has gone to the bottom of the conduction band that they are the energy level becomes empty right. If…this is my valence band this is my conduction band let us say this is the energy level here from where one electron has got excited and gone to this energy level here.

So this energy level has become empty and this energy level which has become empty in the valence band we call it hole like the call it vacancy in case of vacant sites in the lattice, this one we call hole and this hole can be occupied by some other electron which is lying below, it can come and occupy this in turn the hole would go down in the energy level. While getting excited electrons in the conduction band travel and go to the higher energy levels when get excited the holes starts travelling downwards go to lower and lower energy levels it is as if electron is negatively charged particles we know that so hole is a positively charged particle and moving in the direction opposite to the electrons and that is how we treat it, okay.

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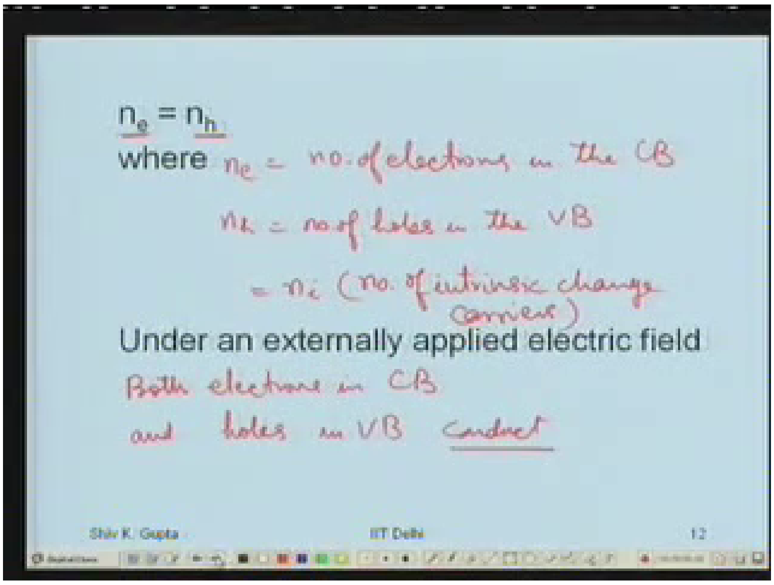

$\underline{n_e} = \underline{n_h}$

where n_e = no. of electrons in the CB

n_h = no of holes in the VB

= n_i (no. of intrinsic charge carriers)

Under an externally applied electric field

Both electrons in CB

and holes in VB <u>conduct</u>

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Therefore in an intrinsic semiconductors number of electrons in the conduction band equal to number of holes in the valence band right, so is equal to number of electrons in the conduction band of holes in the valence band and we also put this these are equal we put this equal to and I number of intrinsic charge carriers. Now under an externally applied electric field these electrons can get excited to go to higher energy level you see the energy difference between the 2 levels that we worked out earlier is above the order 10 to minus 34 joules so very small energy and the electric field can provide that much excitation and they can go to higher energy state and therefore start conducting.

So whenever I apply an external field the electrons in a conductor band go to the higher energy states and just start conducting similarly the holes start going to the lower energy levels because they get occupied by an electron which is lying somewhere down and they start moving down otherwise they also start conducting, so both holes and electrons are conducting they are carrying the negative charge with them and these are carrying the positive charge with them okay, so both the electrons and holes conduct electrons in conduction band and holes in valence band conduct and they are conducting electricity that is what we are looking for.

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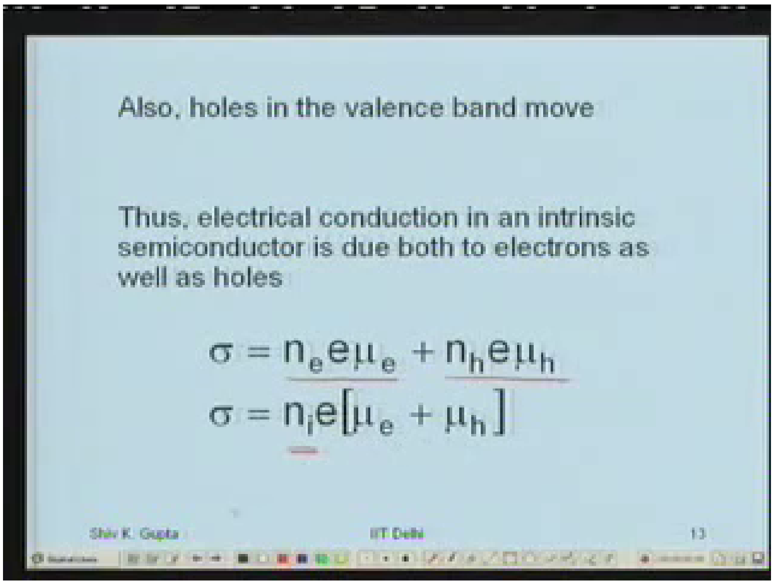

Also, holes in the valence band move

Thus, electrical conduction in an intrinsic semiconductor is due both to electrons as well as holes

$$\sigma = \underline{n_e e \mu_e} + \underline{n_h e \mu_h}$$

$$\sigma = \underline{n_i} e[\mu_e + \mu_h]$$

Therefore the electrical conduction in an intrinsic semiconductor is due both to electrons as well as holes and their component of conductivity due to electrons in the conduction band is this, this is the number of electrons per unit volume this is the charge on the electron and this is the mobility of the electrons in the conduction band, this is what is happening in the valence band, number of holes in the valence band per unit volume charge is the same as in charge of the electron because what is happening is the electrons are getting outgoing coming and occupying the holes essentially they are the conductors and holes, this is the mobility of holes, this mobility of holes is different from the mobility of electrons.

It is rather less mobile as far as holes are concerned because the hole has to be occupied by an electron from a lower level by excitation it can also be occupied by the electrons from a high-level by lowering its energy because of thermal extradition can always do that therefore the net moment is really decreasing and is not is not really as much at in the conduction band the higher energy levels are all empty any electron can get excited and go to higher and higher energy level we start conducting right, so that mobility is more, so number of electrons in the conduction band and number of holes in the valence band are equal which are called intrinsic charge carriers times the charge of these electrons and the mobility of the electrons plus the mobility of the hole.

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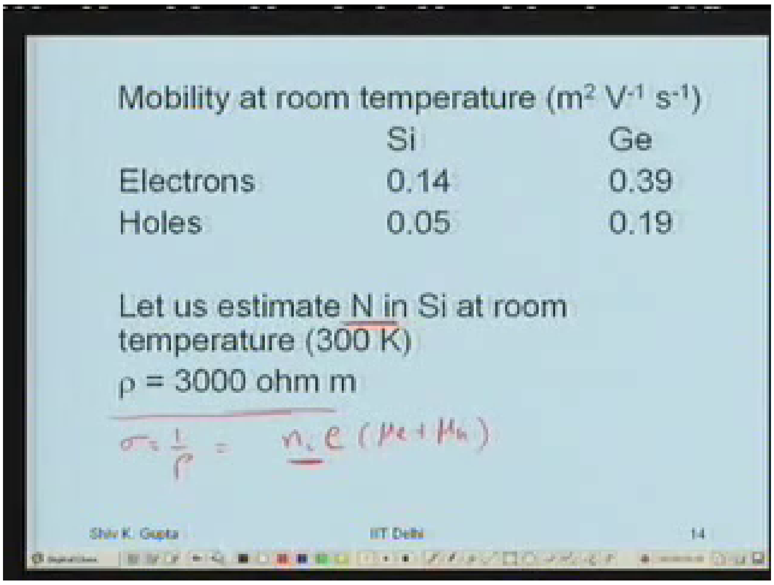

Mobility at room temperature (m^2 V^{-1} s^{-1})

	Si	Ge
Electrons	0.14	0.39
Holes	0.05	0.19

Let us estimate N in Si at room temperature (300 K)

ρ = 3000 ohm m

$$\sigma = \frac{1}{\rho} = n_i e (\mu_e + \mu_h)$$

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I will show you these mobility of the electron and holes are somewhat given here you can see that electron in silicon have a 0.14 metres square per mole per second while holes in silicon have 0.05 is about one 3rd and germanium 0.394 electrons in the conduction band holes in the valence band is 0.19 it is almost half, so that is the mobility of these electrons and holes at room temperature and the temperature dependent near about room temperature is very marginal and we do not consider it, we consider it to be constant. Now that is the question which I said I would like to estimate this N number of electrons available near the top of the valence band which can be excited to reach the bottom of the conduction band, to do that do the experiment at room temperature, measure its resistivity which turns out to be 3000 ohm meter and conductivity which is Sigma is one upon row and there is n i times e times meu e plus meu h.

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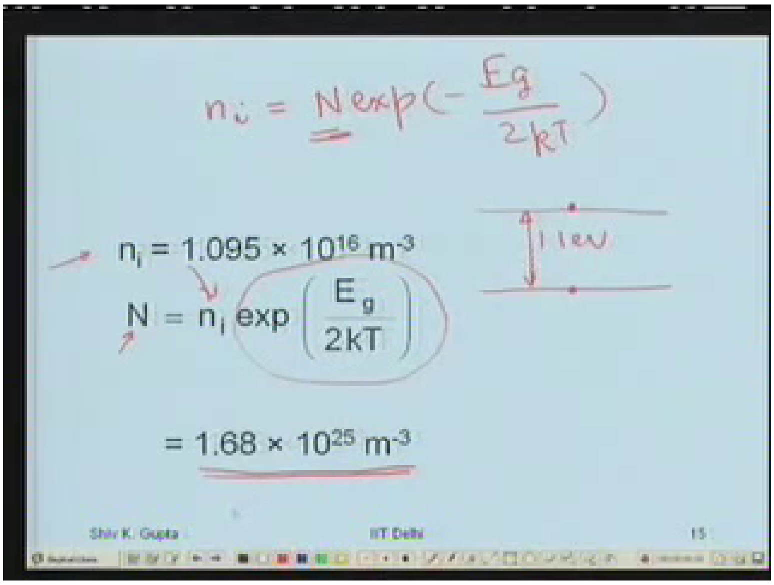

$$n_i = \underline{N}\exp\left(-\frac{E_g}{2kT}\right)$$

$$n_i = 1.095 \times 10^{16}\ m^{-3}$$

$$N = n_i \exp\left(\frac{E_g}{2kT}\right)$$

$$= \underline{1.68 \times 10^{25}\ m^{-3}}$$

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Substituting this it is possible for us to find out the intrinsic charge carriers and that is what you walk out turns out to be 1.095 10 to the power 16 per cubic meter. This is the band gap and the electron to be excited from here to reach there let us say these numbers which are available here is n, the probability it can reach there is exponential of minus E g upon 2 kT.

Student: Minus?

Prof: Yes written other way round, so n i the one which have gone there is capital N times exponential of minus…I am interested in finding out this, how many are these? So that is why I have redone it with the plus sign there and I work out this number turns out to be after substituting this n i E g is known, k is known, T is room temperature it is 1.68 10 to the power 25 per cubic meter. What fraction is this of the total number of electrons available in the valence band? Okay, let us look at that.

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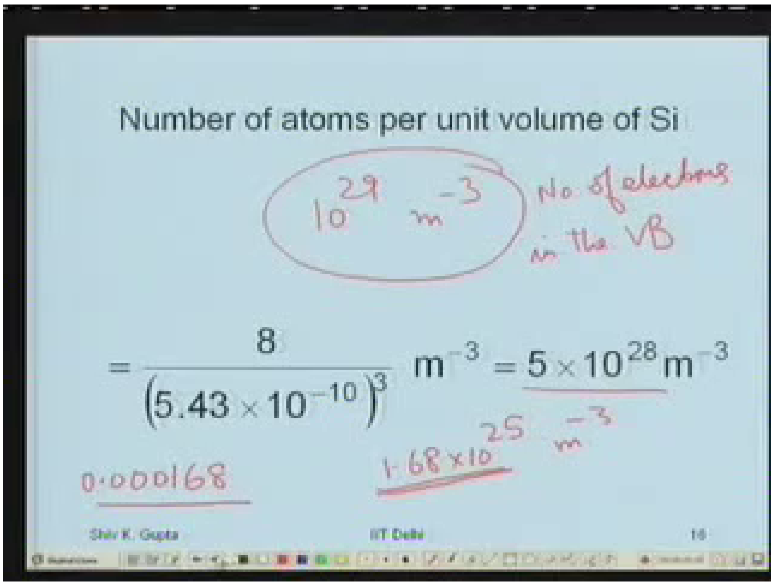

Number of atoms per unit volume of Si

$10^{29}\ m^{-3}$

No. of electrons in the VB

$$= \frac{8}{(5.43\times10^{-10})^3}\ m^{-3} = \underline{5\times10^{28}\ m^{-3}}$$

$\underline{0.000168}$

$\underline{1.68\times10^{25}}\ m^{-3}$

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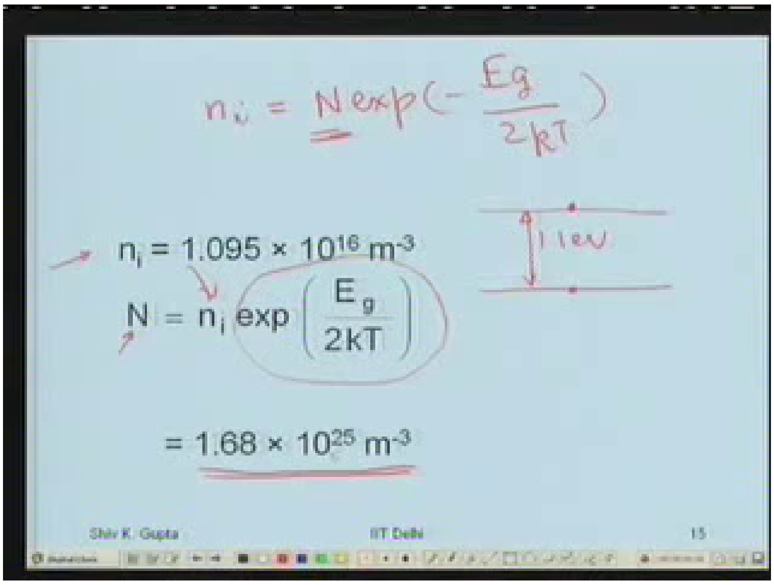

$$n_i = \underline{N}\exp\left(-\frac{E_g}{2kT}\right)$$

$n_i = 1.095\times10^{16}\ m^{-3}$

$N = n_i \exp\left(\frac{E_g}{2kT}\right)$

$= \underline{1.68\times10^{25}\ m^{-3}}$

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Number of atoms per unit volume of silicon is easy to find out in a unit cell they are 8 effective number is 8 I do not have to work it out now and the lattice parameter of the diameter cubic silicon is 5.43 Angstrom is the volume is 5.43 10 to minus 10 cube meter or meter cube, so per cubic meter I have so many silicon atoms 5 10 to power 28, so the valence band how many electrons do I have?

Student: There is a 29 band volume.

Prof: Double of this other are there in the lower valence band okay it is not 4 times it is only 2 times, so it is 10 to the power 29 per cubic meter is the number of electrons in the valence band. Out of these what can be excited is 1.68 10 to the power 25 at room temperature. What fraction is this? 1.68 10 to the power minus 4, it is a very small fraction okay. 0.00016 or

0168 you can call it 0 to if you want which means about 0.02 percent, it is a very small fraction of electrons available in the valence band it can be excited to go to the conduction (())(28:02) and well the numbers which have been the models which have been worked out also give probably a similar result. Next which I want to look at this since there is a thermal excitation which is taking the electrons from the top of the valence band to the conduction band, its conductivity would be affected by the temperature and (())(28:34) while discussing the materials I said these are the materials where conductivity increases with increase in temperature while in case of metals the conductors have decreases with increase in temperature alright.

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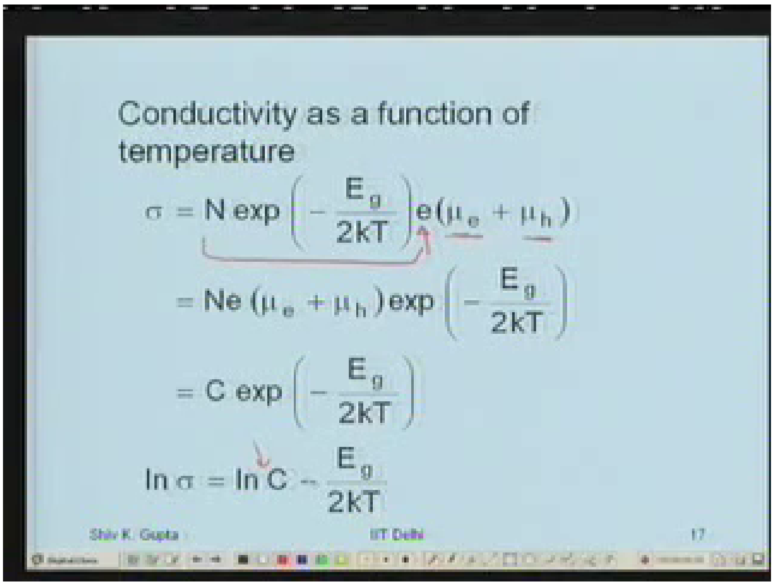

Conductivity as a function of temperature

$$\sigma = N\exp\left(-\frac{E_g}{2kT}\right)e(\underline{\mu_e} + \underline{\mu_h})$$

$$= Ne(\mu_e + \mu_h)\exp\left(-\frac{E_g}{2kT}\right)$$

$$= C\exp\left(-\frac{E_g}{2kT}\right)$$

$$\ln\sigma = \ln C - \frac{E_g}{2kT}$$

That is what we are going to look at, now conductivity as a function of temperature it can be written as this number of charge carriers N times exponential of minus E g upon 2 kT, this is a charge and the mobility of the electrons in the connection band mobility of holes in the valence band. There is small n i has been written like this capital N exponential of minus E g upon 2 kT when I take the constant term on one side and temperature term on the other so capital N is a constant E charge is a constant meu e plus meu h again I take the temperature dependence to be very marginal and therefore not considering temperature dependent like in constant. This is put as a constant and becomes exponential of minus E g upon 2 kT and when I take the logarithm of this I take logarithm of Sigma is equal to logarithm of a constant minus E g upon 2 kT right, so if I plot the logarithm Sigma versus one upon T I get a straight line with a slope minus E g upon 2 k that is the meaning of this equation and if you work it out experimentally also you get this.

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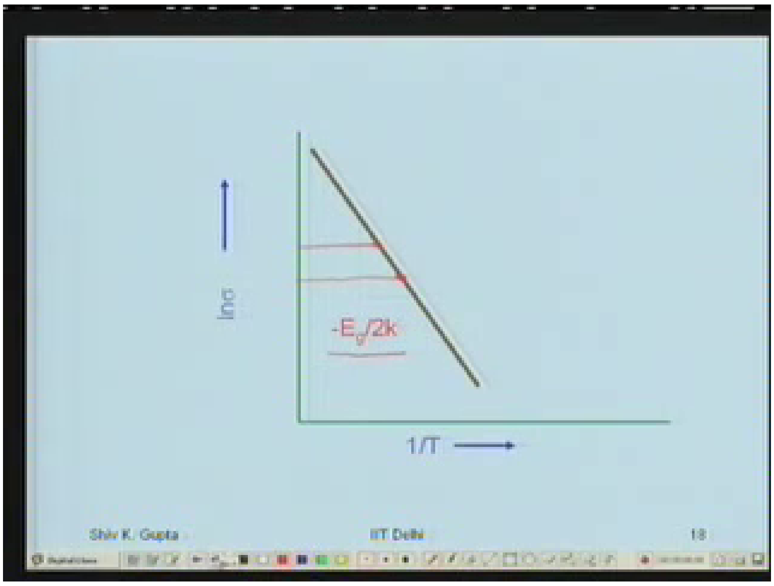

Logarithm of Sigma on the y-axis reciprocal the temperature of the x-axis you get this straight line and slope is minus E g upon 2 k is a straight line and this information is what you can exploit if you want to use a semiconductor as a thermometer to measure the temperature you have to work out conductivity at one temperature will get it another temperature like this and which can be calibrated to temperature because this is their reciprocal of the temperature one directly in terms of temperature you can do that, so that is how you can exploit these and can use this as some of the thermometers are made of semiconducting materials.

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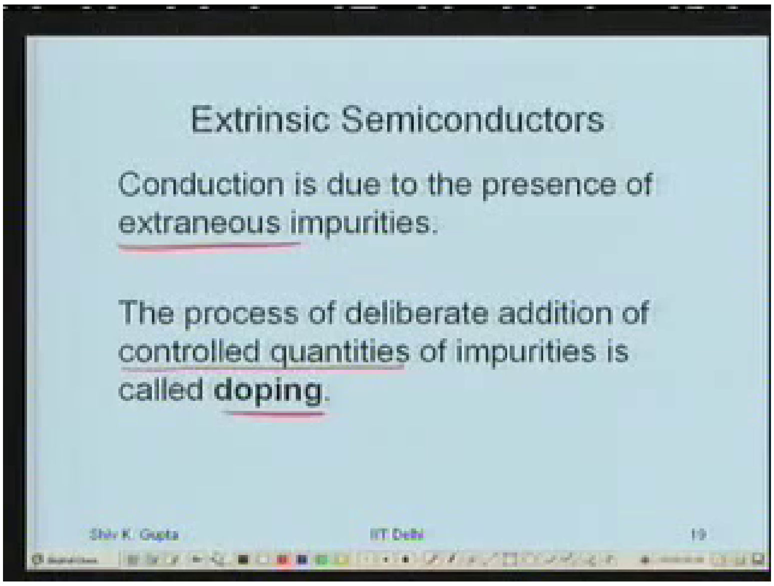

Extrinsic Semiconductors

Conduction is due to the presence of extraneous impurities.

The process of deliberate addition of controlled quantities of impurities is called **doping**.

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Now we shall talk about the semiconductors which are extrinsic in nature means some external impurities has been added to these and these impurities are the ones which are influencing the conductivity. While talking about conductors I did tell you that when the impurities are added the resistivity increases and these impurities, substitution impurities or the interstitial impurities are very bad in doing the job that is…

Student: Metals.

Prof: Yes metals I am talking about metals and conductors. Here you will find another way round when we add impurities they increase the conductivity okay. In extrinsic we call it extrinsic because if the conductivity or conduction is due to the presence of the extraneous impurities. These extraneous impurities we add knowingly to a very pure substance intentionally and that addition in the control quantity is called doping and all the processes of diffusion we talked of are the one which are exploited material is first deposited on the surface than it is dry wind side the material by heating or you can put semiconductor in a gaseous atmosphere through which you can allow the impurities to go in and you do this for a certain length of time at a given temperature to get a certain concentration of the impurities at a particular position in the solid okay that processes called doping.

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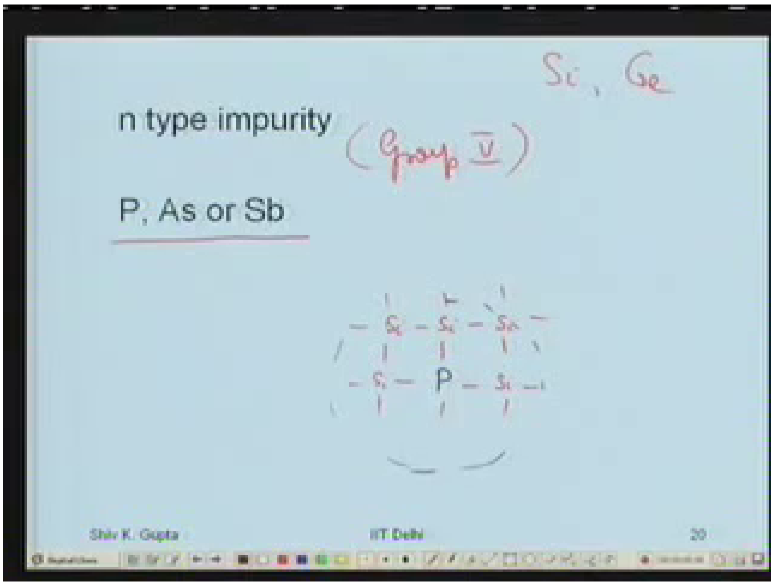

Si, Ge

n type impurity (Group V)

P, As or Sb

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Impurities which we add generally elemental semiconductors as I said silicon and germanium and more commonly what we use is silicon elemental semiconductors. Germanium really we started with in 1948 the semiconductors we started working with and slowly we found that (())(33:45) germanium is not so easy it is rather a difficult process because germanium oxide which we oxide is normally the one which we use for insulating the 2 components of the chip and it is soluble in water while silicon oxide which is from SIO 2 is not soluble in water it is a good insulator it can be used for isolating 2 components on the chip and therefore we found that the silicon is bad materials (())(34:18) use silicon.

Anyway elemental semiconductors we have are silicon and germanium, to make them extrinsic we add impurities and generally either from the left of this group 4 or from the right of the group 4, when I take from the right of the group 4 there is a group 5 impurities like phosphorus, arsenic or antimony these are added right, say for example I am showing them at 90 degrees we know you know that they are not at 90 degrees the bonds are at sorry SP 3 bonds where is my eraser so on and so forth there are 4 bonds to every silicon and silicon is bonded like that, so let us say I had phosphorus in one place it also forms for bonds SP 3 bonds but being from group 5 it is the 5 electrons in the outermost orbit, so this positive ion of phosphorus takes part in bonding and the 5th electron orbits around this…phosphorus. What is the size of that orbit is what I will just make a very crude estimate of that.

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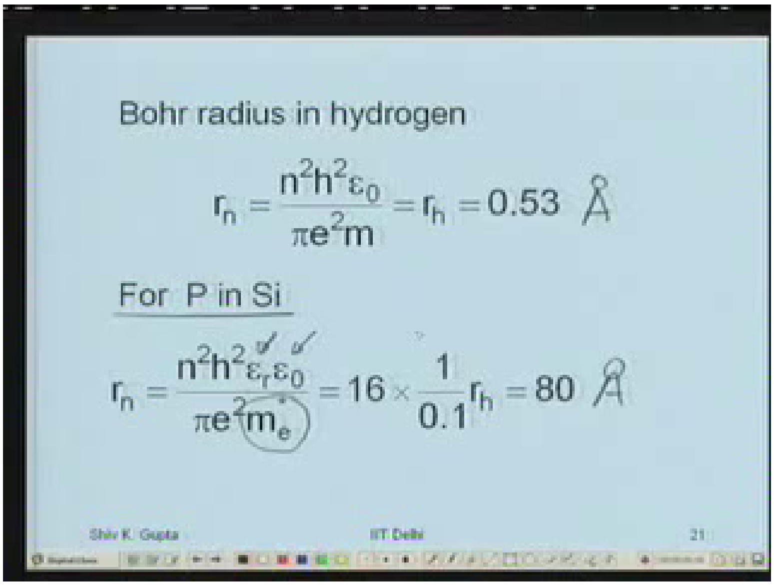

Bohr radius in hydrogen

$$r_n = \frac{n^2h^2\varepsilon_0}{\pi e^2 m} = r_h = 0.53\ \text{Å}$$

For P in Si

$$r_n = \frac{n^2h^2\overset{\checkmark}{\varepsilon_r}\overset{\checkmark}{\varepsilon_0}}{\pi e^2 \boxed{m_e}} = 16 \times \frac{1}{0.1} r_h = 80\ \text{Å}$$

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You have done this in school the bohr radius in hydrogen therefore I am not doing that. Electron orbiting around the proton which is the hydrogen nucleus as a radius and which is worked out using n as a quantum number 1, h square the is the Planck's constant, epsilon zero is the dielectric constant of the free space, pi is a constant is the charge m is the mass of the electron and that gives me the hydrogen or the radius of the orbit in hydrogen for the one electron is 0.53 Angstrom.

Now when I convert this for phosphorus in silicon well the (())(37:26) I can just consider like the proton of hydrogen then the electron, 5th electron which is this is the quantum number will be one for that Planck's constant square instead of now the dielectric constant of the free space I use the dielectric constant of silicon. This is the relative permittivity and this is the dielectric constant of the free space, so the product will become the dielectric constant of silicon.

That is the constant pi again e square and this is the effective mass for this electron I am not considering the mass of the electron, I will tell you why I am not considering this, it is close to that position where it gets diffracted and all those electrons which are close thereby have to use effective mass. Alright so here the other terms are there except these 2 terms and this mass, so mass divided by this is this 0.1 effective mass divided by the and this directive relative permittivity is 16 and therefore rest of it is 0.53 becomes about 80 Angstrom. 80 Angstrom is the radius of the orbit for this 5th electron around the phosphorus from the phosphorus atom to electron how many silicon might be there in between? Divided by diameter of the silicon and how much will be the diameter of the silicon? Any estimate, guess?

Student: 10.

Prof: Take 2.5 Angstrom safely it will be around that right, so if I take 2.5 Angstrom how many would be there? More than 30, more than 30 means very far separated from the phosphorus already and it is orbiting around. In other words what I am trying to say is to take it away from this orbit in other words away from the phosphorus I need to put a very small effort. I need to put a very small effort to take it away from this phosphorus or make it free from the phosphorus. (())(40:09) it can travel in the solid silicon anywhere like a free electron and that small excitation which is required is what I will show you here.

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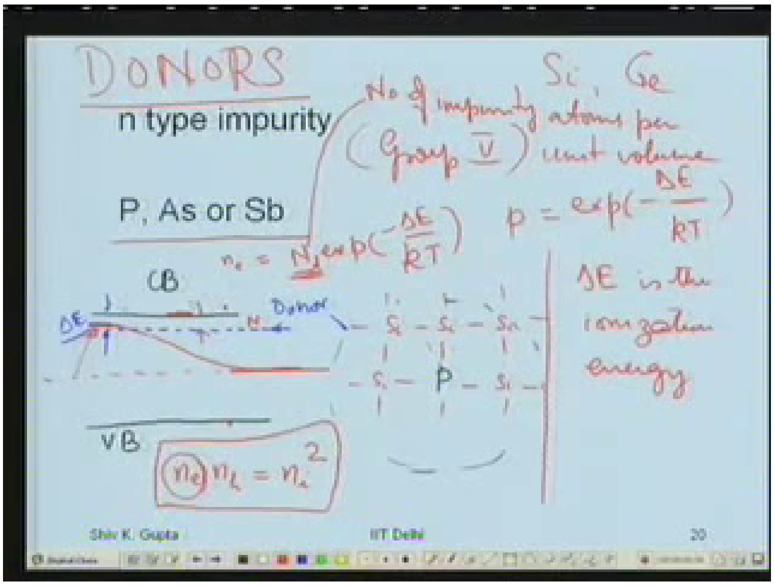

DONORS

n type impurity (Group V)

P, As or Sb

Si, Ge

No of impurity atoms per unit volume

$n_e = N_d \exp(-\frac{\Delta E}{RT})$ $p = \exp(-\frac{\Delta E}{RT})$

ΔE is the ionization energy

$n_e n_h = n_i^2$

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This is the valence band of the silicon this is the conduction band, this is the energy level at which this electrodes at the moment from the donor, phosphorus is called the donor because it has donated this electron to silicon, now this energy difference between the bottom of the conduction band and this energy of the impurity, energy level of the electrons of the impurity is very small is called the ionization energy of phosphorus in silica. If I provide this small delta e this phosphorus would have been ionized that means it will be remain like silicon bonded there and this electron is free to move around that means it has reached the conduction band it can conduct that is why the conductivity goes up. It has not affected the number of holes in the valence band at all, it has only provided me electrons in the conduction band really speaking right that is what has happened okay.

Student: This energy level shown in blue color this is or that…

Prof: Energy of this electron which is provided by the phosphorus the 5th electron of the phosphorus.

Student: Where does the Fermi level lie now?

Prof: Yes, I will come to that at 0 Kelvin Fermi level is close by to this energy level of the… Alright will put that in different color here and as the temperature rises this goes down and come to the middle of the band gap by the time it reaches high temperatures. So it is the function of the temperature this Fermi level, Fermi level at 0 Kelvin is close by this and then it goes on decreasing goes to the middle. What has happened at that temperature you have reached I will show you that, now the temperature is enough for the electrons from here to get excited in large number to reach there and this number becomes very small as compared to the ones which are coming from there.

So it becomes an intrinsic conductor impurities have really no role to play after that, impurities are playing role at low temperatures only okay alright, so that is very high temperature this number will be so high that it will be overtaking these electrons which are formed can be excited from here now 2nd thing so far for walking out the probability of occupying the energy levels at the bottom of the conduction band I use the Fermi Dirac statistics but for the excitation of these electrons of the impurities go from here to there it is a very small energy level we use the Maxwell Boltzmann statistics and the probability here would be exponential of minus delta E by kT, delta E is the ionisation energy. Right and now the electrons get excited from here, go there start conducting and the number of impurities which you have provided here that you know probability you know you can find out n this is less by delta E.

So more some of the electrons will be able to come here right there will be some holes produced and those electrons can also get excited in time due course of time. In other words there will be some holes in the valence band too but law mass action providers us the number of electrons in the conduction band times the number of holes in the valence band equal to the square of intrinsic charge carriers at that temperature whatever is the number. So this is further result which I have just taken from this law mass action and using it, it is possible for us to work it out it is not impossible for us to work out, what is getting excited to reach there and what is getting excited to reach there? Find out those 2 numbers, find the product, find this to be n i square alright this is the electron provided by the impurities to the conduction band, why I call them donors?

Student: So why cannot we use group 6 elements?

Prof: Pardon.

Student: Why can we use group 6 elements?

Prof: Why cannot I use group 6 elements? I can but they will be providing 2 electrons not one right then you have to take care of that, it is possible it should not be impossible to do that but normally we are using group 5 only one electron you can take care of this your models can work well because there will be 2 I do not know I have not come across the models for those 2 and we will have to work out, possible to work out you can use that okay.

Student: What is the capital N in this exponential…

Prof: This one?

Student: Yes.

Prof: This I am talking about the impurities, so this is number of impurities atoms per unit volume or if you want to call it donor and sub D so you will not confuse with the other capital N which I talked about the thermal excitation.

Student: If it had been an intrinsic conductor then n equals nh equals n i.

Prof: Yes.

Student: Here we have ne is also increasing nh is also increased.

Prof: No, nh is not increased.

Student: But sir have an extra level created at the donor level so there will be more holes that are produced.

Prof: You see it is like this, this number is so high which is provided by the donor what is coming from here is not possible because that would be able to go first here and then get excited there, so the holes which are produced is not equal to this there much smaller.

Student: They will be smaller but they will be larger than that in the case of intrinsic because now from valence band (())(48:06) can go to both conduction band as well as the extra level.

Prof: I agree with you but what we have to do is we have to find out how many can be excited from here to there and whatever you have getting excited from here to there, find the product it will turn out to be this where there is no effect… see in this case of impurity problem is there Fermi level is here and in the case of intrinsic the Fermi level is here that is making the difference. Once I have the impurities I have 2 have my Fermi level there and if I use that as a Fermi level then excitation of the from here to there also I use the Maxwell Boltzmann statistics from here to there also use Maxwell Boltzmann statistics but once my the Fermi level is here in the intrinsic carrier I am using the Fermi Dirac statistics to take it from here to there that is what the model is seems to be working with the experimental results you now.

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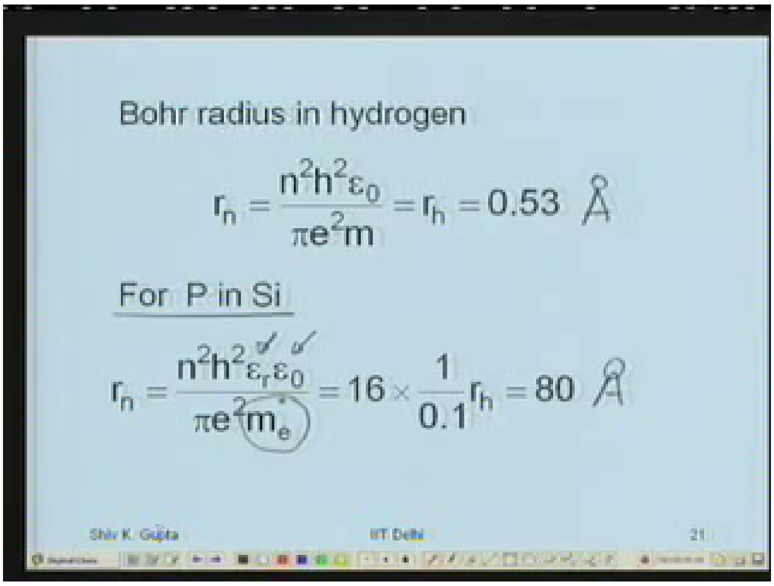

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Alright so that is what we were talking about the size or the orbit around the phosphorus nucleus is very large and the small energy is required to excite this electron to go away from the phosphorus and become almost a free electron in the silicon.

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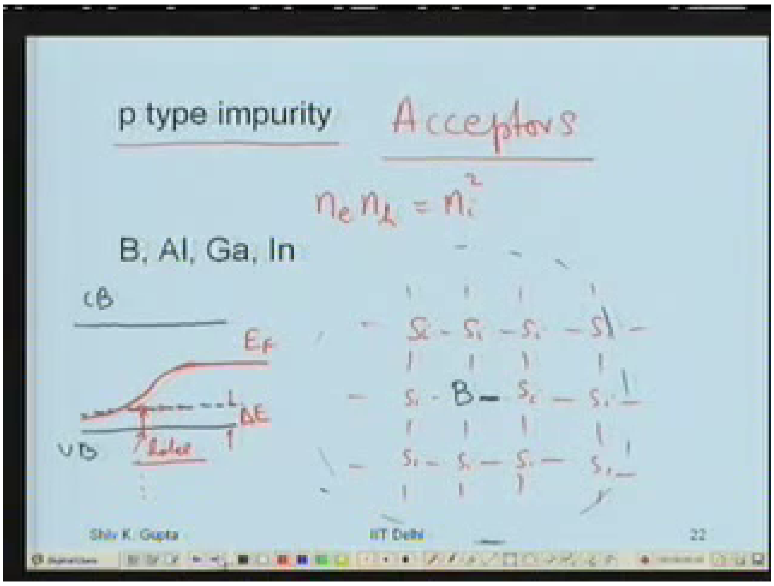

p type impurity Acceptors

$n_e n_h = n_i^2$

B, Al, Ga, In

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Then if you take elements from group 3 these are called p type impurities because the charge carriers here are the positive charge carriers not the electrons but the holes and this p type impurities are also called the acceptors because the except electrons right again let us look at these… Alright now let us put this this one as let us say boron. It has only 3 electrons but it has to take part in the SP 3 bonding, so one bond has only one electron shelling is not complete for this electrons can come from the neighbourhood and from how far this electron can come here that can be worked out in the same manner as it worked out for the phosphorus.

What is the distance of the orbit from the nucleus? Say way you can work out how far it can come with a distance of about 80 Angstrom from that far this electron can be provided to form the bond here and wherever it is coming from it is leaving there a lone pair and the bond okay and that is where the electron from the neighbourhood can always come. Now the situation is slightly different, here I have my conduction band bottom, this is the top of the valence band, the energy level here now for this is somewhere here and once again the Fermi level at low temperature is here and keep on increasing too high temperature it will go in the middle of the band gap because the Fermi level as a function of temperature.

So now these impurity levels which are present here are accepting electron from the valence band, this energy is very small again. Boron is getting accepting the electrons and thereby gaining ionised phosphorus had given all the electrons and got ionised this is except the electron getting ionised and this ionisation energy is again small, very small value and therefore you can find out how many electrons from here can come there almost all the impurities can be ionised depending upon what the temperature is even if as I said 99.8 percent or 9 percent is ionised I consider it to be almost 100 percent alright that is possible now it shall leave here holes and what is going to conduct other holes addition electrons have not reach there once again we have number of electrons in the conduction band and the number of holes in the valence band equal to m i square that remains the same and similarly the behaviour like the phosphorus.

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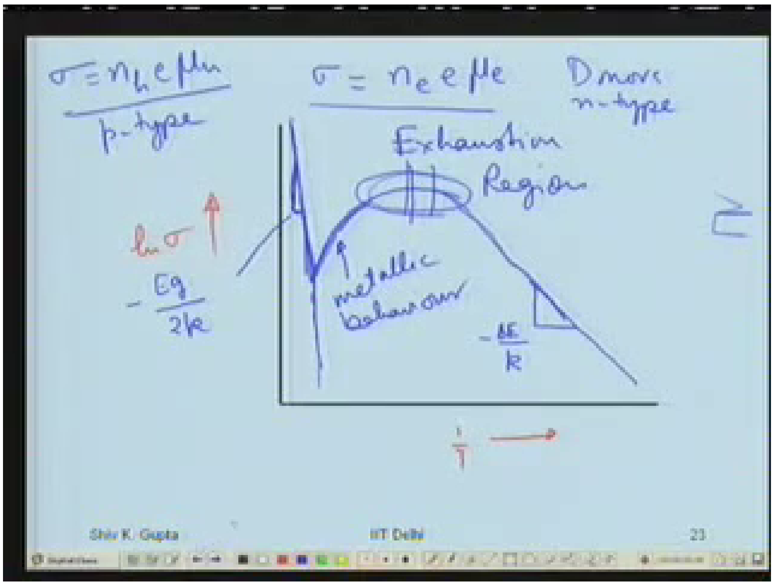

The conductivity as a function of temperature now if I look at this is reciprocal of the temperature, in this impure materials are doped materials rather they are n type or the p type in general the temperature ranges for the different stages could be different but this is the by and large the dependence alright. Alright you see that as the 1 upon T increases the temperature is decreasing becoming smaller and smaller at Infinity it will be 0 Kelvin. This is the extrinsic semiconductor the slope provides me s minus delta E by k, delta E is the (()) (55:29) energy k the Boltzmann constant right, so basically they are in the what should I say Sigma for n type it should be number of electrons in the conduction band e times meu e 2^nd^ term would be negligible similarly this is for the donors or n type and for the p type the same thing would be…

Then as the temperature rises you reach a stage where all the impurities which are present have been ionised they are no more impurities to be ionised and whatever conductivity you have reached will not change with increase in temperature that is called the exhaustion region I have exhausted all impurities. Now I have if it is n type I have all electrons in the conduction band and they start behaving like free electrons in the conductor and the conductivity decreases with increasing temperature it is a metallic behaviour.

Then you reach a temperature which is very high for the electrons from the valence band to get excited to reach the conduction band and it becomes an intrinsic charge carrier or intrinsic semiconductor the slope being here minus E g by 2k is very high slope is a very high slope here, so impurities have no effect really when the temperature becomes so high Fermi level has or the come in the middle and when that happens then there is no effect of the impurities present right. This is how the conductivity changes with n type and the p type and the function of temperature.

If you want the material to be used with which provides almost same conductivity over the period of time, the ambience temperature might be changing it is the exhaustion region which you should exploit. Resistivity would remain same, conductivity would remain same within certain temperature range and you can exploit that temperature range for this material to be used. If you want to use it as a thermometer this is the right region to be used it as a thermometer because sensitivity is high, the slope is high the sensitivity would be more right well that is about the applications we shall see in the next class.