Fundamentals of Semiconductor Devices
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Lecture - 06
Doping and intrinsic carrier concentration

So welcome back in the last class we have discussed about intrinsic semiconductor. What is an intrinsic semiconductor? It is a semiconductor that is pristine pure nothing has been added no impurities. It is an equilibrium if we talk about an equilibrium then an intrinsic semiconductor, the number of electrons and number of holes has to be exactly same.

Why? Because from conduction band if 10 electrons for example, from a valance band sorry; from a valance band if 10 electrons are excited to the conduction band then 10 holes are left behind or 10 vacancies are left behind. So, the number of electrons number of holes has to be exactly the same ok; that is what we were we needed the lecture last time.

Also told you that Fermi function is the probability of finding the electrons or holes and density of states tells you how many states are there for the electrons to occupy or for a holes to occupy. So, the product of the probability; times the density of states or then available states that product you have to integrate over entire energy landscape. That will give you the number of electrons or holes depending on you know Fermi function of electrons and holes that you are taking.

So, basically total number of electrons is always the product the integration of the product of probability times the energy states the density of states. So, that is what we had discussed last class; I told you that the final expression for electron or hole density depends on the product of something called effective density of states at conduction band or valence band times a Fermi Dirac integral. It look a mathematically little bit more fearful, but actually will simplify it down even further and will see that this is very simple actually ok.

So, this is connected very intimately with whether a semiconductor is intrinsic or not for example, ok. So, that is why introduced the concept of intrinsic semiconductor; all along we should not forget the basics that we are covering, the periodic potential in which the electrons or holes moves. The Fermi Dirac function, the EK diagram; the effective mass of electrons or holes they can be different right.

The curvature will give you the effective mass and E-K diagram essentially release energy to the momentum, these are the basics that we should never forget as we move forward ok. We shall always keep recapping them and that E-K diagram is in reciprocal order momentum space; whereas, the conduction band valence band that we draw Fermi level here it is a energy band in real space.

So, we talk about distance in x centimeter not momentum [FL]. So, now we will look into the whiteboard as to where we left last class and then from there we begin ok. So, you see here we had left in this page here.

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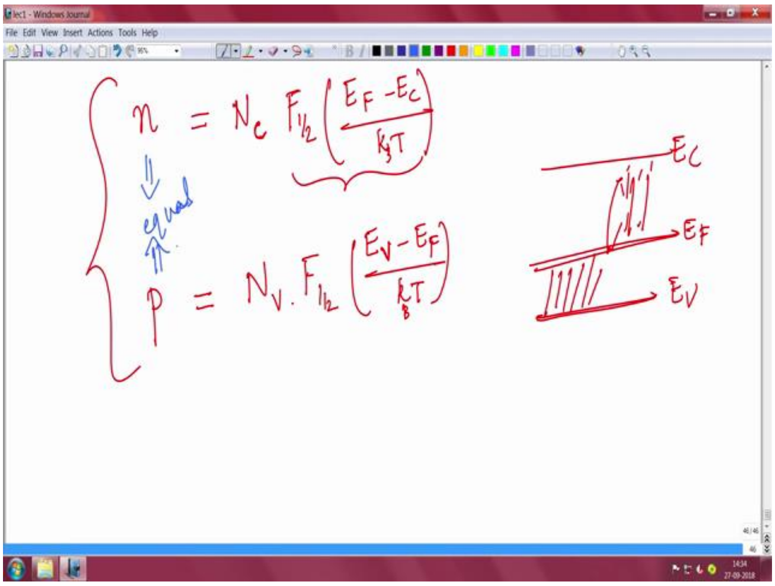

$$n = N_c F_{1/2}\underbrace{\left(\frac{E_F - E_c}{k_B T}\right)}$$

$$\Downarrow \text{ equal } \Uparrow$$

$$p = N_V . F_{1/2}\left(\frac{E_V - E_F}{k_B T}\right)$$

So, I told you intrinsic semiconductor is a semiconductor which does not have any impurity it is very pure and pristine. In that case the number of electrons and number of holes has to be exactly same and we call that n i or n i means intrinsic carrier concentration. Intrinsic carrier concentration means the number of electrons is also equal the number of holes and that is a fixed number; the unit is per centimeter cube, then per volume what is the number (Refer Time: 03:19) that what that is what it means. So, that is intrinsic carrier concentration.

Now, you recall the total number of electrons in a semiconductor will be given by

$$n = N_C F_{1/2}\left(\frac{E_F - E_C}{k_B T}\right)$$

Where Nc conduction band effective density of states which is per centimeter cube, E_F Fermi Dirac integral Fermi integral, E_C is the conduction band minimum, k_B is the Boltzmann constant and T is the temperature.

Of course, it looks little gigantic because this Fermi Dirac this Fermi integral is a little complicated function we do not want to come to that right now.

But holes will be given by

$$p = N_V F_{1/2}\left(\frac{E_V - E_F}{k_B T}\right)$$

Where N_V the valance band density of states which is per centimeter cube, E_F Fermi Dirac integral, E_V is the valence band maximum, k_B is the Boltzmann constant and T is the temperature.

So, we talk about this minus this negative of this or you talk about negative of this because that is E V minus E F actually. So, these are the number of electrons and number of holes in general it is always; it this need not be intrinsic only this can be anything. Except that in intrinsic concentration this will be equal; this will be equal to this equal to P. But if it is not intrinsic; they will not be equal, but even then if it not intrinsic this will this will hold true this expressions are not only for intrinsic ok. What I am saying is in intrinsic they are equal, but in if it they not; if intrinsic these are equal, but if they are not intrinsic then these are not equal, but individually they whole true that is good.

Now, this is a little complicated expression for example, this and this can we make it simple? We should make them simple know. So, I told you; so, let us come to a new page for example, where is the cursor yeah it is here. So, I will come here.

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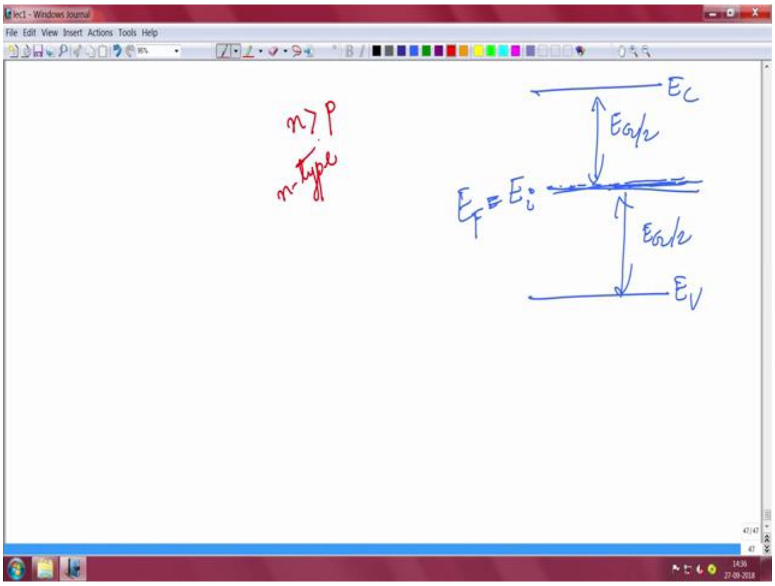

So, I told you that this is say conduction band this is say valence band. A very quick information that may not be very obvious in many textbooks; I told you this is the middle of the gap hm.

In an intrinsic semiconductor; in an intrinsic semiconductor the Fermi level lies exactly in the middle. Actually it is not exactly the middle, but I will come to that exception little later, but it is Fermi level will lie at the middle of the band gap its called E i; E i means the intrinsic energy level.

Intrinsic energy level always be here at the middle of the gap; this is half of the band gap Eg by 2 this is half of the band gap Eg by 2. Intrinsic energy level will always lie in a middle of the gap, but if it is a pure semiconductor; intrinsic semiconductor then the Fermi level also will lie exactly at the intrinsic level only which is the middle; it is at the middle.

If the number of electrons is more than the number of holes n greater than p; n is the number of electron p is the number of holes. So, if electrons are more than holes we call it n type semiconductor I told you in the last class. And in n type semiconductor and n type semiconductor what is the thing? In n type semiconductor the Fermi level will be in the upper half the Fermi level will be here.

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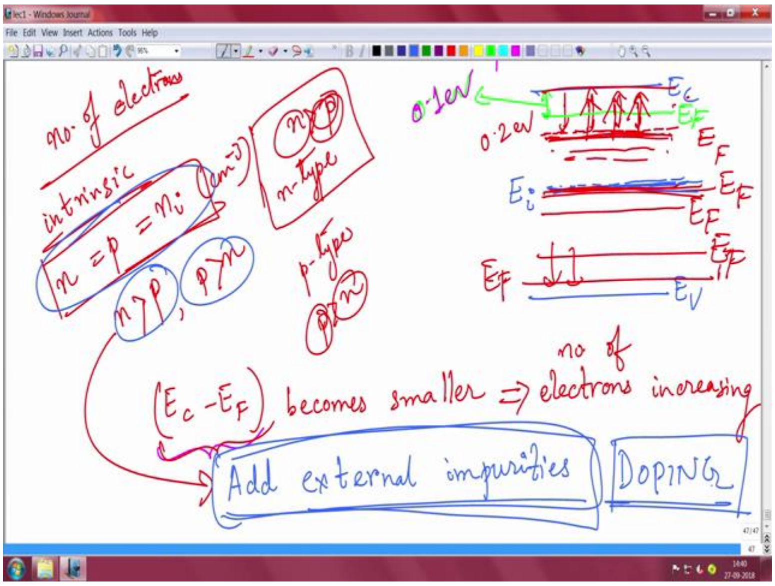

Intrinsic level will always be here, but the Fermi level will be here and if it is p type; which means holes is greater than electron in number then your Fermi level will be in the bottom half will be bottom half.

So, let us now talk about electron for example. So, if your semiconductor is n type which means there are more electrons than holes; then a Fermi level will lie in the upper half. Now here is the important point that many textbooks may not be telling you. The more the Fermi level comes closer and closer to conduction band it means the number of electron keeps increasing. Which means this gap you see this gap this gap energy gap of course, that gap is E C minus E F, correct.

That is E C; E C is bottom of the conduction band by the way E C minus E F; this gap becomes smaller; that means, the Fermi level is approaching the conduction band more and more. Suppose this gap in one case is 0.2 electron volt; in another case suppose I take the pink color here in; I will take I will take the green color here ok.

Suppose in another case the Fermi level is here and the gap between Fermi level and conduction band is suppose 0.1 E V ok; 0.1 E; then the second case is has more electrons. So, if E C minus E F this gap, E C minus E F becomes smaller; then it means number of electrons is increasing ok.

As the Fermi level; as the Fermi level approaches the conduction band more and more which means the gap between E C and E F is reducing; it means the electrons the number density of electron is also increasing. And the Fermi level if the if it comes below and below it means the number of electrons is decreasing decreasing. Eventually when the Fermi level comes here where exactly at the mid gap it means electrons have decreased so much that now electrons and holes are equal in number.

And as the Fermi level moves here it means the number of holes as increased compared to the number of electrons. So, it is now p type if the Fermi level comes here; it is more p type there are more holes if it comes here there even more holes. So, the more the Fermi level comes closer to valence band more holes are there or the p type conductivity of the holes number is increasing ok.

So, there is there right; so now why am I telling you this because I can help you simplify that because this very important I can help you simplify the Fermi integral actually. And when I say you are changing the Fermi level you know like this position; you are approaching the Fermi level conduction then how are you changing the Fermi level? You are changing the Fermi level by increasing the number of electrons; by increasing the number of electrons over number of holes.

Or if you are approaching here it means you are increasing the number of holes with respect to electrons. How do you do that? That you do by increasing whatever you are doing to actually increase the number of electrons. What I mean is that your number of electrons cannot arbitrarily be increased. I told you in an intrinsic semiconductor; in an intrinsic semiconductor number of electrons is equal to number of holes and that is equal to intrinsic area concentration some value is there.

This is exactly when the semiconductor fermi level is at the middle of the gap. Now to actually get more electrons than holes or to get more holes than electrons; you have to you have to add external impurities ok, you have to add external impurities. Only when you add external impurities you are going to get this conditions; if you do not add external impurities then you will have this condition, that is electrons and holes are equal in number that is equal to n i.

When you add external impurities this process is called doping ok. Everything is connected to everything actually that is why I am covering everything in parallel you see.

Adding the processor adding external impurities is called doping and by doping, you can actually either increase the number of electrons or increase the number of holes.

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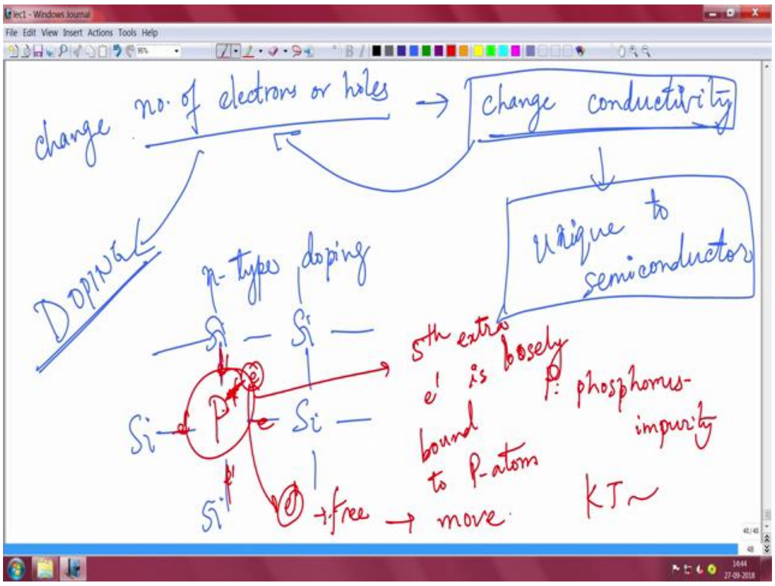

Ok and that increase in the number of electrons or holes sorry either increase in the number of electrons or holes electrons or holes. If you increase the number of electrons or holes by doing that if you change this number electrons or holes; what will happen?

You change the conductivity of the material, you change the conductivity of the material. And this changing of the conductivity of the material is unique to only semiconductor; that is the beauty of semiconductor as to why modern electronics revolution has built around semiconductor. All electronics everything that you see around today the laptops, cellphones, PDAs and all the things satellite, radar communication all the electronics depends on transistors integrated circuits ICs; you know these are possible only because of semiconductors.

And that semiconductor has this unique property that you can change the conductivity by changing the number of electrons and holes which can be done by doping. This is not possible in metal this is not possible in insulator like wood or a piece of glass or something ok; it is only possible in semiconductor.

So, when you do an n type doping; you can do n type doping it means you are increasing the number of electrons over holes. And if you do p type doping and increasing the holes with respect to electron actually physically how you do doping is that very simplistically if you take silicon this 4 bonds.

Now, if you take silicon just 4 bonds like this right that is all these kind of bonds here S i S i and so on. So, if you replace one silicon with suppose phosphorous atom. So, phosphorous is the impurity you are adding; (Refer Time: 13:22) P is phosphorous ok. And phosphorous is the impurity that you are adding it is a impurity right that you are adding it has 5 actually electrons.

So, 1 electron what with this 5 electrons you know; 1 electron will satisfy this bond, 1 electron will satisfy this bond, one will do this, one will this, 5th electron is free. So, that 5th electron is loosely bound that 5th extra electron is loosely bound by columbic forces it is loosely bound to phosphorous atom by columbic forces.

Very small energy even at room temperature the thermal energy k T; the thermal energy k T the thermal energy k T is sufficient to actually break this bond; this columbic interaction between the phosphorous and the free the 5th electron and make this electron free. And if this electron is free; that means, it can move now. So, it can take part in conduction ok; actually that is a very important thing.

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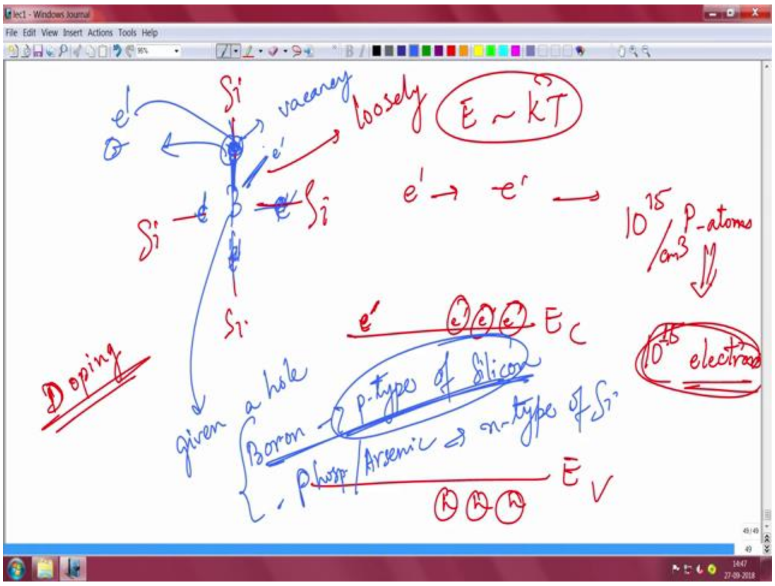

What it means is that; the phosphorous is satisfying all the silicon for this one extra electron; this is loosely bound by columbic forces. And that bounding energy that energy which it is bound is very small; it is in the order of room temperature energy only.

So, the room temperature thermal energy k T, the thermal vibration is sufficient to kick this electron out from this bonding of this loose bonding of phosphorous and electron becomes free to move. So, what happens is that if it is the conduction band; this is valance band if you add one phosphorous atom you are going to get one extra electron here.

Remember there is always some electrons here; there is always some holes here. In an intrinsic semiconductor ok; the moment you add one phosphorus atom you get one extra electron, but there is no extra hole ok. So, by doing this doping this is called the process of doping by processive of doping which means you are adding some impurity; you are able to increase the number of electrons.

So, if you add 10 to the power 15 phosphorous atoms per centimeter cube of course, everything is centimeter cube; it means you are going to get 10 to the power 15 extra electrons will come, but no holes will come which is very interesting; 10 to the power 15 extra electrons we will get.

You see the conductivity with this many electrons will increase know. So, that is the beauty by adding phosphorous atoms; you can increase the extra electrons and so, each phosphorous atom gives 1 electron and so many electron atoms will give you so many electrons; it is beautiful. Instead of phosphorous if you had added boron, then boron has only 3 electrons one here, one here, one here boron has only 3 electrons; one it could not satisfy. So, there is a broken here there is a vacancy here.

So, we can say that boron has given has given a hole, because it could not satisfy its bond; so this is a hole. And you can say this hole is also loosely bound to boron atom which means the hole can actually break free and participate. In other words electrons some somewhere can actually come and occupy this and there will be hole here. So, in other ways the hole has move there right.

So, boron can give holes it is a trivalent atom 3 bonds are there; 3 atoms are there phosphorous has pentavalent. So, 5; so you get n type. So, this will give you a p type doping. So, boron can be used to do p type doping of silicon; I am talking about silicon only silicon ok.

And phosphorous or even arsenic for example, can be used for doping n type doping where electrons will increase. And boron at if you add boron then actually increase the p type or hole increase the hole concentration and silicon; that is the thing ok. Of course, in compound semiconductor more semi you know more complicated semiconductors; this picture is not very in valid that you have 3 atoms and then one atom you know 3 electrons and 1 electron is dangling or extra electron is there is actually is more complicated than that, but as of now we this is sufficient to understand what it is going on ok.

So, this energy to which the hole is bound or in a phosphorous the energy it is the electron is bound that is the very small energy that is a very small energy and we call that ionization energy.

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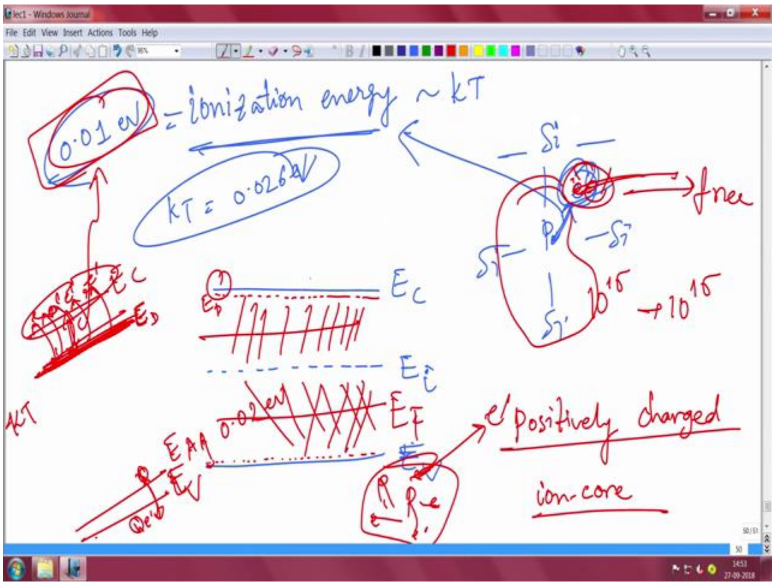

That is ionization energy of the dopant. So, for example, I am adding phosphorous right I am adding; there is an extra electron what is the energy to which it is bound? That is called your ionization energy and it is on the range of k T only it has very close to k T. For example, k T is equal to I told you right 0.026. So, ionization energy might be smaller than that actually. So, the ionization energy might be equal to say 0.01 or 0.012 may be; this is smaller than k T for example.

So, then room temperature energy is sufficient to basically it will lose break the electron lose so that electrons can now take part in conduction ok. So, this ionization energy is typically very small. So, if this is your conduction band this is your valence band then a we model and their Fermi level the intrinsic level will always be mid gap here. If I am talking about n type impurity or n type doping with adding phosphorus, then that donor ionization energy level is very small know; it is around in the range of say 0.01; that will be very close here.

It is a straight line of course, it is a very small line here that is called donor ionization energy. And this you know it will be E C and it will be this is E D; everything else is much below here. This energy gap is called the donor ionization energy which is equal to this say 0.01; room temperature energy is more than this. So, room temperature can easily that this E D represents the ionization energy of the donor atoms.

So, it is very close here; so, 10 millielectron volt it means room temperature energy k T is sufficient to actually this has many electrons here to take put the electrons in the conduction band; this valence band is much here do not worry valence band is much much deeper. This donor ionization energy actually represents the phosphorous atoms, they will be able to donate the electrons which means the extra electron here will be easily free from the columbic interaction and can take part electrons.

The moment electrons goes away from the phosphorous atom and takes part in conduction it becomes free you know extra electrons have come here. So, I told you if 10 to the power 15 phosphorous atoms are added; then 10 to the power 15 electrons also will be obtained, thus extra electron. But when electron goes away what leaves behind here is a positively charged ion core; positively charged ion core.

Because phosphorous at 5 electrons right it had 5 electrons and that was neutral; 1 electron 4 have been satisfied one of them has broken flow and gone away. So, what has remained? There is one extra positive charge is there no because only 1 electron comes it will become neutral. So, it leaves behind a positively charged ion ion core.

So, this E D and electrons that donate to conduction band they will be positively charged ion has core. Similarly for p type doping boron for example, in introductory level very close to valance band here ok. So, if boron and this is called acceptance energy level and ionization energy level E A; so, also in range of k T. So, very close to k T for example, this gap might be you know the ionization energy of acceptor might be say 0.02 E V ok.

And the so it is almost smaller than k t. So, you know what will happen is the electrons can go and occupy this vacancies and so the holes it means like the holes is coming here. So, essentially boron is like giving holes to the valence band right. So, if I draw a new picture here for example, if I talk about p type doping this is E C.

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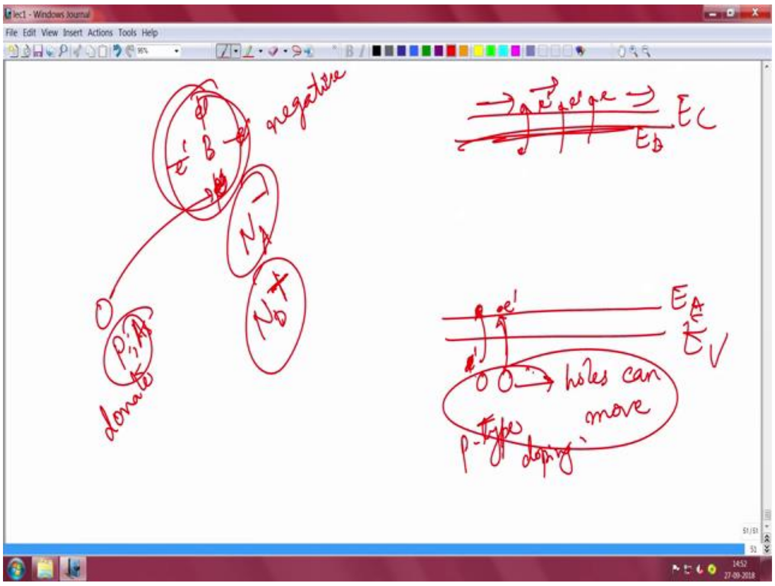

This is E V; I told you this is suppose; I am not drawing the Fermi level now this is acceptor energy level. It has it can give holes what it means is the electrons can go and occupy these vacancies here.

What means is that there is a vacancy that is left here now. So, again electron goes becomes will occupy here. So, vacancy is left behind; so, a boron atom I told you has 3 electrons to satisfy this one is this thing. So, electron can come and occupy this; so, there will be hole here.

So, when electron comes through boron atom it becomes negatively charged right. So, basically acceptor ions becomes negatively charged when they are ionized; when they have given the holes. And the things like phosphorous to arsenic when they basically donate the electron that is why they are called donor; they donate the electron they give you the electron then they become positively charged because they have given the extra electron and that is why become positively charged.

Now, the electron when the electron is there extra electron was there; then they were neutral when the extra hole was here then there was neutral, the hole has been given; so, it becomes negatively charged. And the phosphorous or arsenic which have been donating electrons becomes positively charged. And this elect this holes for example, have come here this holes can now move.

So, this is how you do p type doping; you have no holes then electrons ok. And if you add an ionization energy level here phosphorous very close example; then electrons will come here and electrons can move. So, that is n type conductivity this is p type conductivity. So, both electrons and holes number can be individually tuned or tailored by either p type doping or n type doping; making it you know pentavalent or trivalent impurities that can be added to the crystal for example, and making it for example, here right.

So, that is how you and whether or not your semiconductor is p type or n type that will actually decide whether your Fermi level is in the top half or in the bottom half. If you have more n type doping then you will have more you know n type like semiconductor; so, the Fermi level will be somewhere here. If it is more p type where you have more holes than the electrons then the Fermi level will come in the bottom half of the band gap right that is how we basically differentiate [FL].

So, now, for example I told you that if I do not do any doping if there is no doping; it is an intrinsic semiconductor.

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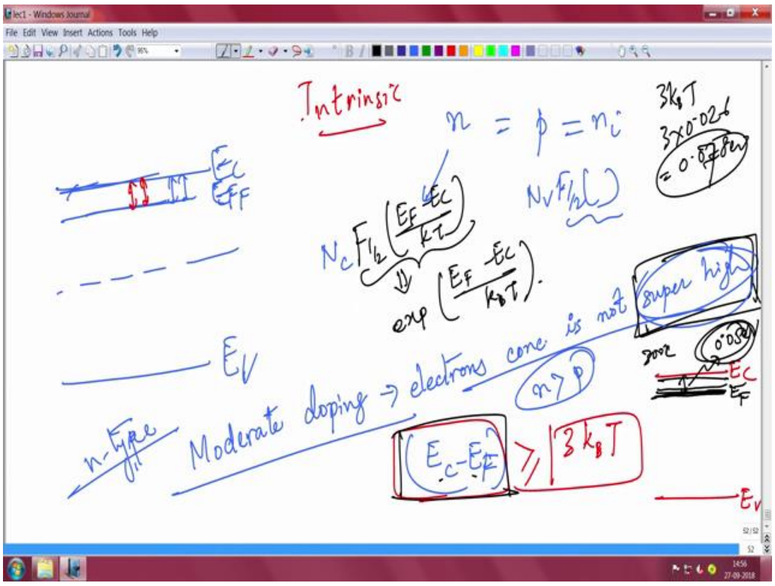

It is an intrinsic semiconductor; I told you that number of electrons is equal to number of holes, no doping, no extra electron holes no ionization nothing is equal to n i. Now this I told you is N C Fermi integral some x that x is this thing and this is also N V into integral x.

Now, I want to simplify this. So, for example, I told you if you remember this is mid gap ok. The more the Fermi level approaches the conduction the more the n type doping it is or more electrons are there. So, if the Fermi level is very close to conduction band; it means the doping is very high n type doping is very high there are many electrons there. So, if I consider a moderate doping; which means the number of electrons or holes. I will talk about n type conductivity; so I will talk about only electron.

Same thing can be done for holes not an issue same thing can be done for holes absolutely not an issue. So, if I talk about moderate doping which means the Fermi level is not very close to conduction band ok. If the Fermi level is not very close to conduction if the Fermi level is very close to conduction band; it means the doping is very high. It means your electron concentration is also very high; we are not we are not talking about the situation; we are talking about moderate doping when the electron concentration is not so high.

Electrons are more than holes of course, electrons are more than hole, but electron concentration is not super high. But it is of course, n type doping electron is always more than holes not an issue, but electron concentration is not super high. Now how do you quantify super high? It means your E C minus E F; if you recall here in this diagram.

You see you have E C and then you have E F right; you have E C and then you have E F. I keep telling that as E F approaches conduction when E C closer and closer electron concentration grows higher and higher. So, there has to a minimum distance within which the conduction band and Fermi level should not come; otherwise it will become super high.

That is if E F minus E C this quantity this gap should be at least should be at least 3 times room temperature energy k B T; excuse me. In that we can say that the doping is not super high; we can say that electron concentration is not super high. If your conduction band and Fermi level come within 3 k T ok; if you have conduction band is here, valance band is here and your Fermi level comes very close.

Suppose the Fermi level here is 0.05 electron volt at room temperature 300 Kelvin; 0.05 electron volt is less than 3 k T no; 3 k T will be how much? 3 into 0.026 room temperature; 0.078 E V; 7 8. If it is 0.05; that means, it is less than 0.08 know then you know that Fermi level is way to close to conduction band the doping is super high electron concentration is super high.

We are not talking of situation like that; when the doping is moderately low it is that conduction band and Fermi level are separated by at least 3 k T, then this Fermi Dirac integral can be simplified. This Fermi Dirac integral of E F minus E C by k T; this quantity can be approximated as exponential of E F minus E C by k T that is beautiful.

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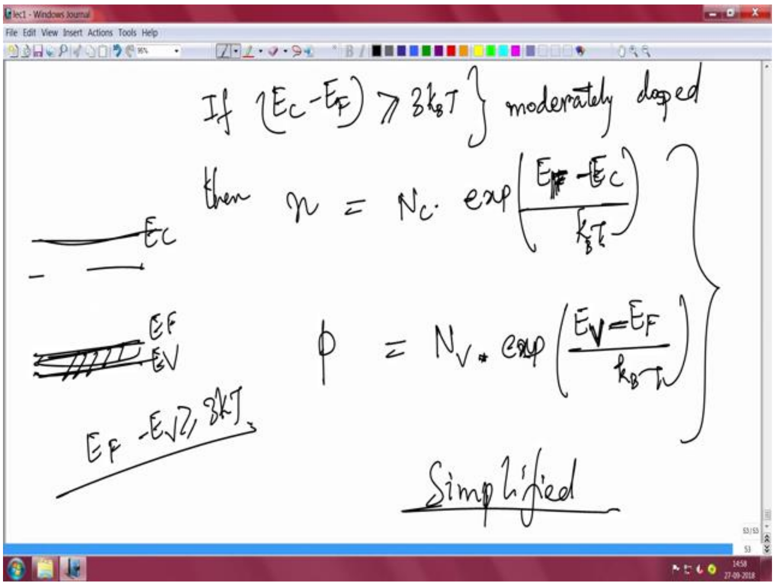

If $(E_C - E_F) \geqslant 3k_BT$ } moderately doped

then $n = N_C \cdot \exp\left(\frac{E_F - E_C}{k_BT}\right)$

E_C

E_F

E_V

$p = N_V \cdot \exp\left(\frac{E_V - E_F}{k_BT}\right)$

$E_F - E_V \geqslant 3kT$

Simplified

So, what it means is; if conduction band and Fermi level are at least 3 k T which means it is moderately doped or not super highly doped. Moderately doped which means that there are moderate number of electrons not super high number of electrons; then electron concentration n is given

$$n = N_C exp\left(\frac{E_F - E_C}{k_B T}\right)$$

Where Nc conduction band effective density of states which is per centimeter cube, E_F Fermi Dirac integral Fermi integral, E_C is the conduction band minimum, k_B is the Boltzmann constant and T is the temperature.

Similarly, for holes; this is E C, this is E V you know the Fermi level will be here. The gap between Fermi level E F and E V must be greater than equal to 3 k T. If that is the case then hole concentration can be written as

$$p = N_V exp\left(\frac{E_V - E_F}{k_B T}\right)$$

Where N_V the valance band density of states which is per centimeter cube, E_F Fermi Dirac integral, E_V is the valence band maximum, k_B is the Boltzmann constant and T is the temperature.

So, E V is lower minus E F which is higher; here E F which is lower in n type minus E C which is higher. So, it is always lower minus higher ok.

So, this 2 numbers are very simplified expressions now; this 2 numbers are very simplified expressions. And this 2 simplified expressions are possible because we assuming moderate doping ok; then what will happen? Just the last thing will cover here.

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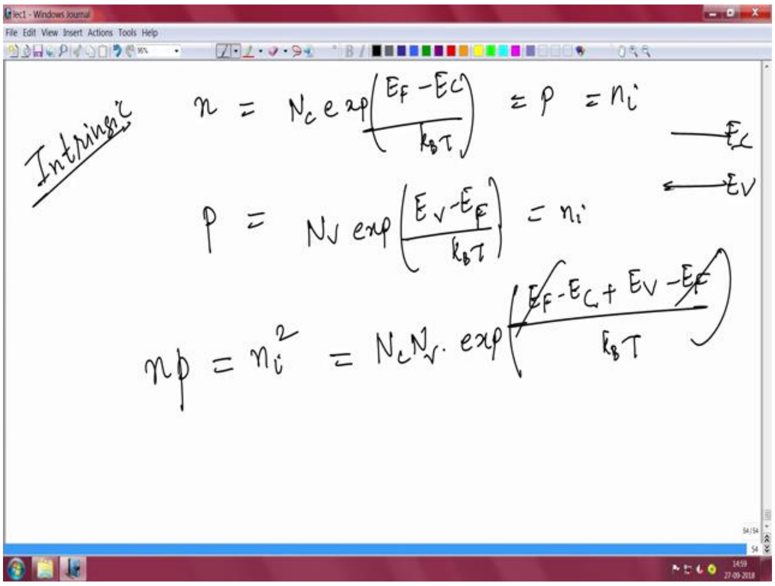

Intrinsic

$$n = N_c \exp\left(\frac{E_F - E_C}{k_B T}\right) = p = n_i$$

$$p = N_V \exp\left(\frac{E_V - E_F}{k_B T}\right) = n_i$$

$$np = n_i^2 = N_c N_V \cdot \exp\left(\frac{\cancel{E_F} - E_C + E_V - \cancel{E_F}}{k_B T}\right)$$

If n is equal to N C E to the power E F minus E C by k B T. For intrinsic semiconductor by the way for intrinsic semiconductor; this will be equal to p, this will be equal to n i and p is equal to N V exponential E V minus E F by k T which is equal to also n i.

So, if you are multiplying n and p this will be like n i into n i. So, this is n i square equal to I multiply this and this you know N C into N V exponential of you see E F minus E C plus E V minus E F by k B T. E F E F gone what is this is minus E C plus E; remember? This is conduction band E C this is valence band E V. So, this is E V minus E C is minus of band gap. So, I can write this as minus of band gap by k B T.

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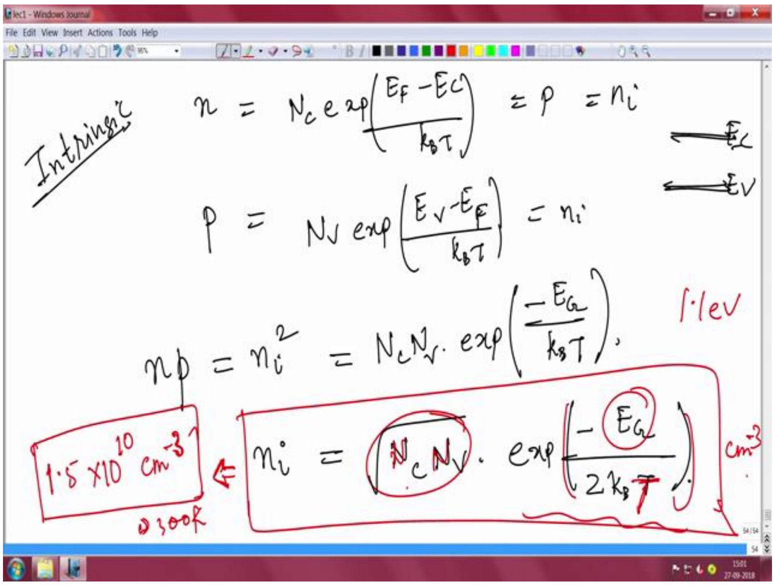

Intrinsic

$n = N_c \exp\left(\frac{E_F - E_C}{k_B T}\right) = p = n_i$

E_C

E_V

$p = N_V \exp\left(\frac{E_V - E_F}{k_B T}\right) = n_i$

$np = n_i^2 = N_c N_v \cdot \exp\left(\frac{-E_G}{k_B T}\right).$

1.1eV

$n_i = \sqrt{N_c N_V} \cdot \exp\left(\frac{-E_G}{2 k_B T}\right)$ cm^{-3}

1.5×10^{10} cm^{-3} @ 300K

So,

$$n_i = \sqrt{N_C N_V} \exp(\frac{-E_G}{k_B T})$$

Where ni is the intrinsic carrier concentration, N C is the conduction band effective density of states, N V is the valence band effective density of states, E G is the band gap, k B is the Boltzmann constant, T is the temperature.

This is your; this is your expression for intrinsic carrier concentration you need this per centimeter cube. It depends on the product of density of states of conduction band valence band density of states has square root.

Each of this is per centimeter cube, per centimeter cube square will be per centimeter cube this has no unit of course; exponential of minus band gap by 2 k B T. So, it goes as temperature also it also depends on band gap exponentially; this dependencies only like a linear you know, but square root this is exponential.

So, it depends much more strongly on band gap [FL]. I will come to that implications of band gap and intrinsic carrier concentration in next class, but if you look here carefully; if you know the band gap say silicon you know 1.1 E V; this N C and N V you can find out. Because you remember the expression for N C and N V actually is this is expression for N C.

So, you know everything here if you know the effective mass of electron, temperature you know; then you can find out N C and you can find out N V. If you do that and if you put the and gap of silicon then you find that n i intrinsic carrier concentration at room temperature is 1.5 into 10 to the power 10 per centimeter cube of both electrons and holes. They are equal number of electrons and equal number of holes.

So, 1.1; 1.5 into sorry 10 to the power 10 this value will come here; this value will come at room temperature ok. So, will end the class here now ok; so we end the class here and we have basically concluded with the expression for intrinsic carrier concentration as a function of N C N V and as a function of temperature and band gap. It critically depends on band gap as you can see, E to the power minus band gap.

So, if the band gap becomes large then your intrinsic carrier concentration becomes small that has a huge impact on devices. See intrinsic carrier concentration physically means that is the number of electrons or holes that will be always there in the semiconductor at that particular temperature. For example, at room temperature for silicon it is 1.5 into 10 to the power 10 and that number can be exactly derived from this expression.

It means at room temperature if you do not do anything to silicon no impurities, no doping then 10 to the power 10; 1.5 into 10 to the power 10 electrons and 1.5 into 10 to the power holes will always be there. You cannot do anything about it; it is the thermal, its intrinsic carrier concentration that will always be there and you know to increase that you can add external impurities, but you cannot decrease below that.

So, that is the limit of the minimum electron or hole concentration that will always be there in silicon ok. So, different materials depending on their band gap and depending on their N C and N V values will have different intrinsic carrier concentration ok. So, we will wrap up the class here and in the next class we shall start some more equations on understanding electron hole concentration.

And concepts like intrinsic energy level is not exactly the mid gap that I will also tell you in next class, the principle of mass action law. You know the relation between n and p so that we can understand doping. And we will solve some numerical problems so that our concepts become very clear and that will give us an idea of what we are talking about in terms of all this equations here [FL].

Thank you for your time and we will meet in the next class again.