Properties of Materials (Nature and Properties of Materials: III)
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Lecture 40 - Extrinsic Semiconductors

So, welcome again to the new lecture of Properties of Materials. So, this is going to be the last lecture of this course in which we are going to mainly finish off the semiconductors with extrinsic semiconductors and then summarize the course. So, essentially, in the last lecture what we discussed was….

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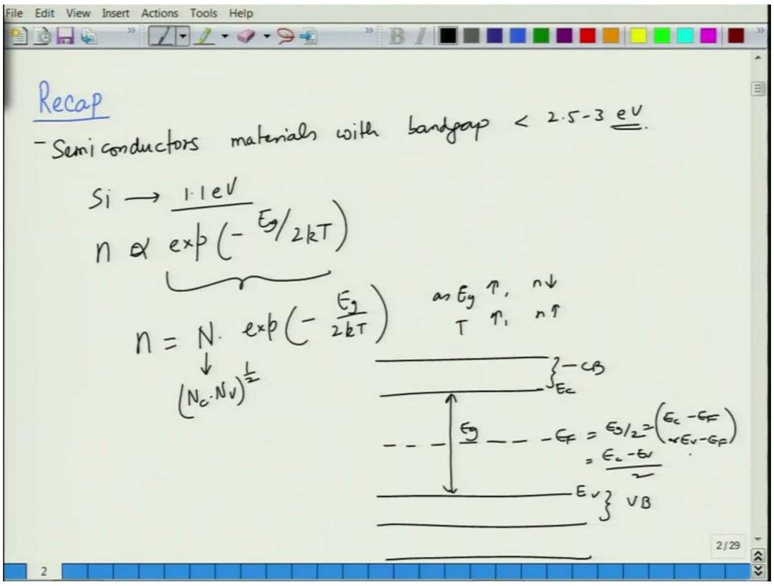

Recap

- Semiconductors materials with bandgap $< 2.5-3 \text{ eV}$.

$Si \rightarrow 1.1 eV$

$n \propto \underbrace{\exp\left(-E_g/2kT\right)}$

$n = N \cdot \exp\left(-\frac{E_g}{2kT}\right)$ as $E_g \uparrow$, $n \downarrow$; $T \uparrow$, $n \uparrow$

$N \downarrow (N_c \cdot N_v)^{\frac{1}{2}}$

$E_F = E_g/2 = \begin{pmatrix} E_c - E_F \\ \text{or } E_v - E_F \end{pmatrix} = \frac{E_c - E_v}{2}$

In the last lecture, we talked about semiconductors as materials with band gap smaller than let us say 2.5 to 3 eV. Silicon is the most common semiconductor. It has a band gap of 1.1 eV and the electron concentration in semiconductors is proportional to exponential minus E g by 2 k T.

Since the, as we solve the voltage required to move electron from conduction to, valence to conduction band is very large, thermal excitation is a very useful means to create some carrier density. And this is, so this n is equal to capital, small n which is nothing but N c into N v to the power half into exponential of minus E g by 2 k T. So, in this expression you can see as E g increases, n decreases and as T increases, n increases. So, this n is basically if you look at this picture, this is E c, this is E v, this is E g. So, this is conduction band and this is valence band.

So, E v is the conduction and valence band edge and E c is the conduction band edge and you can measure the energy either from the bottom or from the top, from the vacuum level depending up on how you may want to work. And the Fermi level for intrinsic semiconductor lies at E g by 2 value or you can say E c minus E F or E v minus E F. Or you can say E c minus E v divided by 2. That is also possible.

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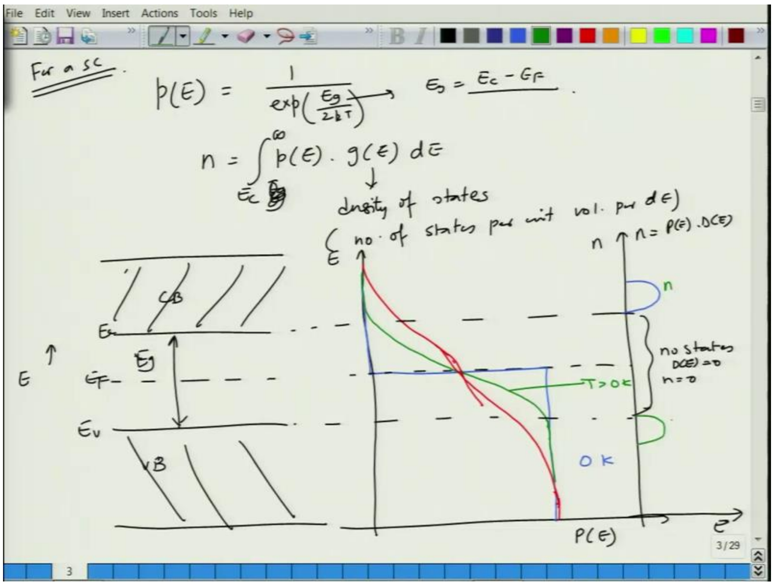

For a SC.

$$p(E) = \frac{1}{\exp\left(\frac{E_g}{2kT}\right)} \rightarrow E_g = \underline{E_c - E_F}.$$

$$n = \int_{E_c}^{\infty} p(E) \cdot g(E)\, dE$$

density of states

{ no. of states per unit vol. per dE)

$n = P(E) . D(E)$

no states

$D(E) = 0$

$n = 0$

And so basically, we saw that the probability of occupation is basically, we sort of reduced it to 1 over exponential of E g by 2 k T for a semiconductor considering E g was equal to E c minus E F. And number of electrons is basically determined as we can say P E probability of occupation into density of the states and you have to integrate it for all the energies from E g to infinity, sorry E c to infinity where g E is nothing but density of states. We have not talked about it but basically density of states means number of states per unit volume per d E, per small energy state d E.

So, basically if you plot this, so let us say this is a conduction band, this is a valence band. This is VB, this is CB. And this is what we have E g. This is we have E c, this is we E v and this is we have E F and this is the scale E.

So, now if I want to plot on the same plot let us say E versus P E or F e, I cannot remember what I wrote in the previous lecture. But so, we know that at 0 Kelvin P E goes like this, at 0 Kelvin. At some finite temperature it will now become so, around 0.5 it will sort of, so this will be the sort of relation at T greater than 0 K and as you increase the temperature this curve will, so as you keep moving the temperature if you plot now the electron concentration at the same column, so this is n and this is E and n is nothing but the product of let us say P E into density of states, the states available. We can see that in this region there are no states available.

So, no states available so, if D E is 0 in this region, then n is also going to be equal to 0. So, as a result what happens is that when you plot n in this semiconductor so, you will create most of the n is going to be around this. Correspondingly, you will have another region which is holes, this is n and it is equal number of holes.

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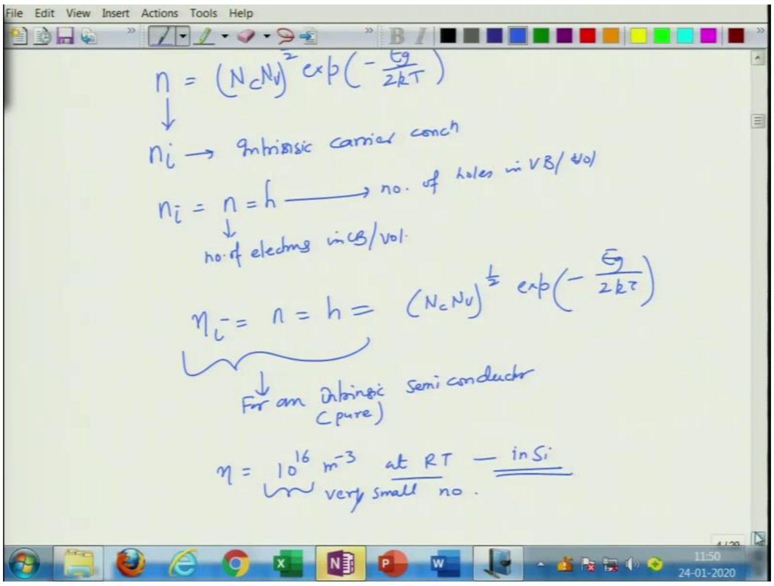

$n = (N_c N_v)^{\frac{1}{2}} \exp\left(-\frac{E_g}{2kT}\right)$

$\downarrow$

$n_i \rightarrow$ Intrinsic carrier concn

$n_i = n = h \longrightarrow$ no. of holes in VB/vol

$\downarrow$ no. of electrons in CB/vol.

$\underbrace{n_i = n = h}_{}$ $= (N_c N_v)^{\frac{1}{2}} \exp\left(-\frac{E_g}{2kT}\right)$

$\downarrow$ For an intrinsic (pure) semiconductor

$\underbrace{n = 10^{16}}_{}$ m^{-3} $\underline{\text{at RT}}$ — $\underline{\underline{\text{in Si}}}$

very small no.

So, for intrinsic semiconductor we write, n is equal to N c into exponential minus E g by 2 k T. N c N v to the power half to E g by 2 k T and this n is called as n i. So, this is intrinsic carrier concentration and this means, n i is equal to n which is equal to h.

So, this is number of electrons in conduction band and this will be number of holes in (conduct) valence band per unit volume, so, this is also per unit volume. So, n i is equal to n is equal to h is equal to N c N v to the power half exponential of minus E g by 2 k T for intrinsic semiconductor, semi, intrinsic means pure semiconductor which does not have a lot of impurities in it and we will see you can find out easily that the electron concentration basically is not very large, electron concentration happens to be n happens to be essentially nearly around 10 to the power 16 per meter cube at room temperature in these materials in silicon let us say, in silicon.

This is a very small number, so, this is a very small number. Because if you calculate now the conductivity of silicon with this…..

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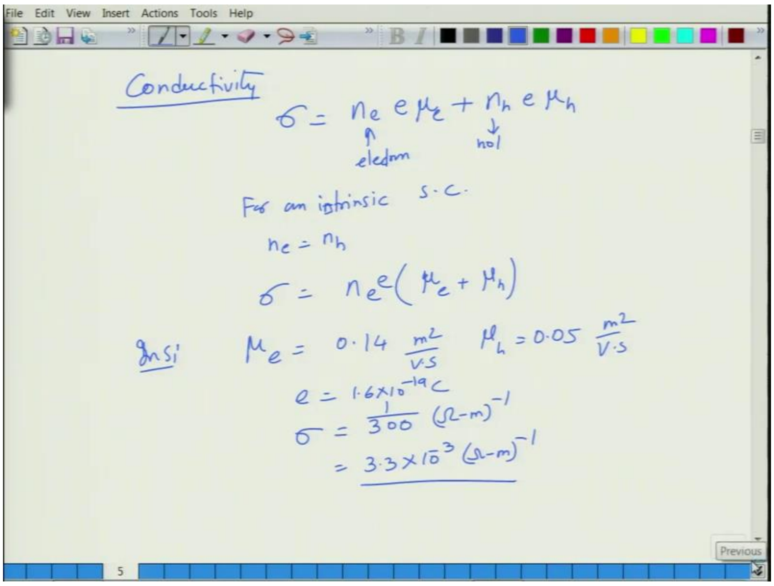

Conductivity

$$\sigma = \underset{\text{electron}}{\underset{\uparrow}{n_e}}\, e\mu_e + \underset{\text{hol}}{\underset{\downarrow}{n_h}}\, e\mu_h$$

For an intrinsic s.c.

$$n_e = n_h$$

$$\sigma = n_e e(\mu_e + \mu_h)$$

In Si $\mu_e = 0.14\ \frac{m^2}{V.S}$ $\mu_h = 0.05\ \frac{m^2}{V.S}$

$$e = 1.6 \times 10^{-19} C$$

$$\sigma = \frac{1}{300}\ (\Omega\text{-}m)^{-1}$$

$$= \underline{3.3 \times 10^{-3}\ (\Omega\text{-}m)^{-1}}$$

So, now conductivity if you want to calculate, conductivity. Conductivity sigma now will be equal to, for a metal it was n e e mu. For a semiconductor, it is now you have two carriers, n e e mu plus n p or n h e mu. So, this is electron concentration and this is hole concentration. So, they have similar charge so, for intrinsic semiconductor n e is equal to n h so, sigma can be equal to n e into e is also common this is mu e mu h.

But electron and holes have different mobilities because they have different effective masses. So, if you take the values of mobility, the value of mobility for electron so, in silicon mu e is equal to 0.14 meter square per volt second. And mu h is equal to 0.39 sorry, 0.05 meter square per volt second. And if you plug in the values and if you take e as 1.6 into 10 minus 19 coulomb, you will get sigma value of 300, sorry 1 over 300 Ohm meter inverse.

So, essentially, you are saying it is basically nearly 3, 3.3 into 10 to the power minus 3 Ohm meter inverse. This is very low conductivity as compared to metals and this is not good enough to make silicon very useful. As a result, what you do is that so, this is about pure silicon.

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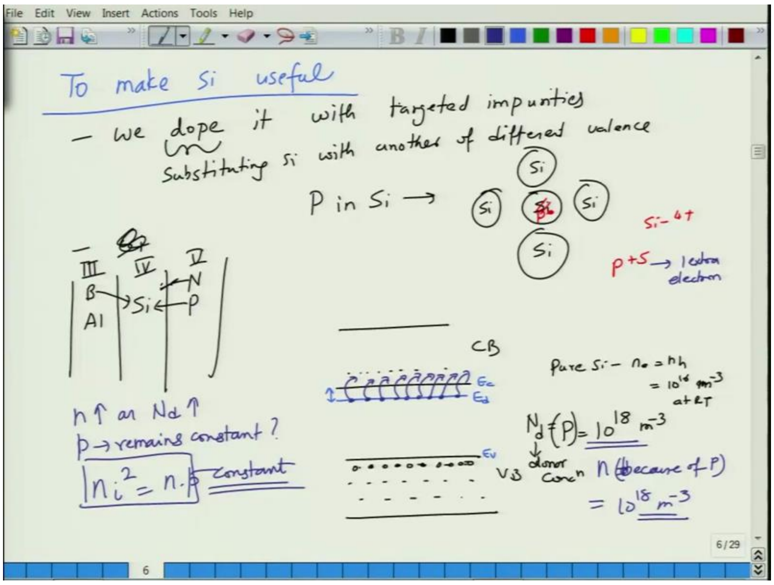

To make Si useful

- we dope it with targeted impurities
substituting Si with another of different valence

P in Si →

So, to make silicon useful or to make any semiconductor useful, we doped it with intentional or targeted impurities. So doping means basically substituting silicon with another atom of different valence. So, silicon if you look at the group 3, 4, 5. So, this is group 3, this is group 4, this is group 5. So, if I look at the periodic table in group 3 I have, in group 4, I have silicon. Okay. Let us say, let us take silicon here. Group 3 has boron, aluminium let us say and go down. And group 5 has top of the one's we have nitrogen and phosphorous.

It turns out so if you now replace, if you put some of the nitrogen or phosphorus or silicon, typically phosphorus and in this case boron. So, if you put phosphorus in silicon, then let us say this is the configuration we have. So, this is silicon, this is pure silicon. Let us say silicon is surrounded by four neighbours, this is pure silicon. Now let us say, if I replace one of this silicon with phosphorus. Now, this is not silicon this becomes phosphorus. A phosphorus has an extra electron because phosphorus is plus 5 and silicon is 4 plus. So, as a result what happens is that in the energy gap, so, this is valence band, this is conduction band.

You had some electrons here, some electrons here because of thermal excitation and you have some holes here correspondingly. This is for pure silicon. So, for pure silicon n e was equal to n h, which will be about 10 to the power 16 per meter cube at room temperature. When you put in phosphorus atoms in there. Let us say I put in phosphorus atoms of the order of 10 to the power 18 per meter cube. So let us say phosphorus is a, we call it as a donor atom so, let us say N d is donor concentration. This happens to be phosphorus.

So, when I put phosphorus in it what phosphorus does is, phosphorus creates energy level close to conduction band edge. This E c, this is E v and this is the donor level and the distance between the energy difference between donor level and the conduction band edge is such that phosphorus is able to, so phosphorus will have these extra electrons. All of these extra electrons then move to the conduction band of silicon. So, for every phosphorus atom you have one extra electron. So, if you are putting 10 to the power 18 phosphorus atoms now, then 10 to the power 18 atoms will basically contribute 1 electron each, as a result your n because of, so number of electrons contributed because of phosphorus will be equal to 10 to the power 18 per meter cube.

This number is at least two orders of magnitude higher. This number is two orders of magnitude higher. And if you put one order of magnitude higher for phosphorus atoms, then again this will be, this will increase further. So, basically, by putting phosphorus in silicon you have introduced electron density to higher level. But what it means is that your n increases as N d increases but does it means P remains constant?

So, which means your n has increased but P is similar to this, that does not happen. Because of law of mass conservation n i square which is equal to n p, this is always constant. Whether it is for extrinsic semiconductor or for intrinsic semiconductor.

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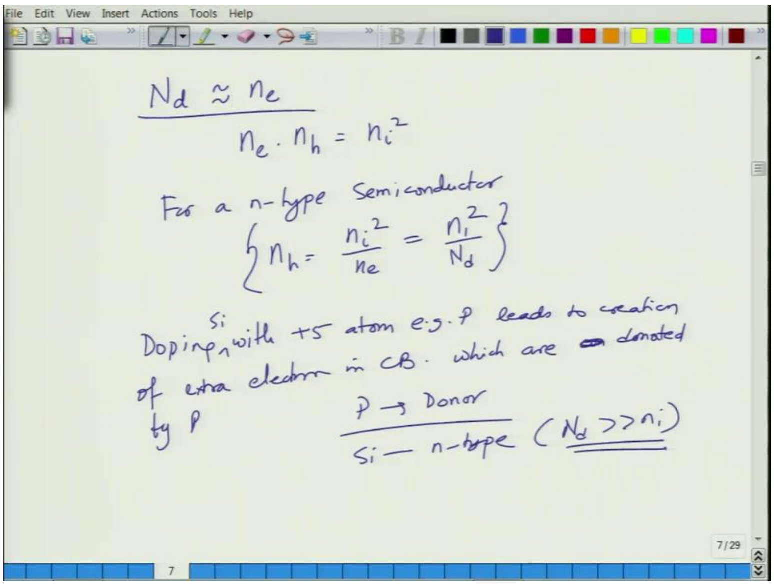


$$\underline{N_d \approx n_e}$$

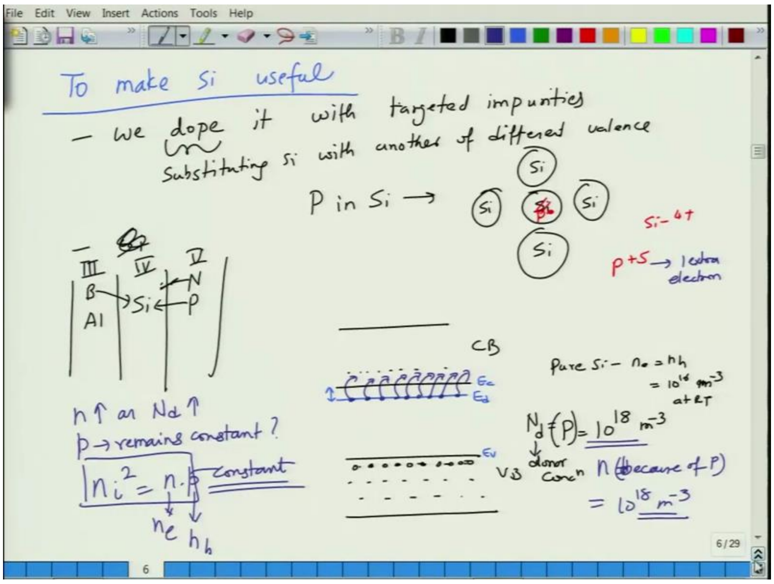
$$n_e \cdot n_h = n_i^2$$

For a n-type Semiconductor

$$\left\{ n_h = \frac{n_i^2}{n_e} = \frac{n_i^2}{N_d} \right\}$$

Doping Si with +5 atom e.g. P leads to creation of extra electron in CB. which are donated by P

$$\frac{P \rightarrow \text{Donor}}{Si \text{ — n-type } (\underline{\underline{N_d >> n_i}})}$$



To make Si useful

- we dope it with targeted impurities

substituting Si with another of different valence

P in Si →

Si – 4+

P +5 → 1 extra electron

Pure Si – $n_e = n_h = 10^{16}\ m^{-3}$ at RT

n ↑ as N_d ↑

p → remains constant ?

$$\boxed{n_i^2 = n \cdot p} \text{ constant}$$

n_e n_h

N_d (P) $= 10^{18}\ m^{-3}$

donor conc^n

n (because of P) $= 10^{18}\ m^{-3}$

So, as a result when you have put N d and let us say this N d is equal to n e. Then we are saying that n e into n h is equal to n i square or n h can be so, you can write this P as n h and this n as n e. Okay. So, for a n-type semiconductor which is doped by let say phosphorus, n h is equal to n i square divided by n e and n e is equal to N d so, it becomes n i square divided by N d. This is for a n-type semiconductor.

So, basically, you have doping with plus 5 atom, doping silicon with plus 5 atom so, example phosphorus leads to creation of extra electrons in CB, which are basically you can say the donated by phosphorus. So, phosphorus is a donor and as a result, silicon becomes n-type. Especially, one N d if far more than n i.

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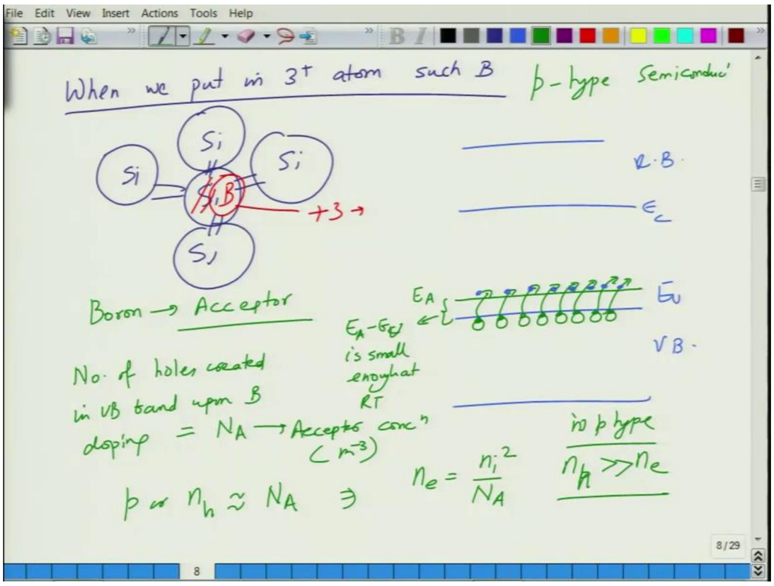

When we put in 3+ atom such B   p-type Semiconduc'

Boron → Acceptor

$E_A - E_V$ is small enough at RT

No. of holes created in VB band upon B doping $= N_A \rightarrow$ Acceptor conc^n (m^{-3})

p or $n_h \approx N_A \ni$ $n_e = \frac{n_i^2}{N_A}$

in p type

$n_h \gg n_e$

Similarly, when you put 3 plus atoms, so, now what happens is that when we put 3 plus atoms such as boron, so now consider a situation like this, you have silicon. These are all covalent bonds, now you replace this silicon with boron. So, boron has, boron is plus 3 so, there is basically one electron less so, as a result it takes away one electron from silicon. So, what boron does in energy band gap is, this is E c, this is E v, this is conduction band.

This is valence band. Energetically speaking, boron introduces energy level somewhere close to valence band which is called as acceptor level. So, boron acts as acceptor because it takes the electron away from silicon. So, electrons from here, they are all they join the acceptor level, as a result creating, so you will create electrons here and these will be nothing but then holes. So, essentially, number of so, if this energy level if this E A minus E B is a small enough at R T, then number of holes created in valence band upon boron doping will be same as acceptor concentration.

So, this is acceptor concentration in per metre cube. So, we can say safely that P or n h will be equal to N A. So, in this case, n e will be equal to n i square divided by N A. So, this n i will remain the same, n i will remain the same. So, basically in P-type, you can say n p is n h is much larger than n e. That is why it is called as a p-type semiconductor. So, this is p-type semiconductor.

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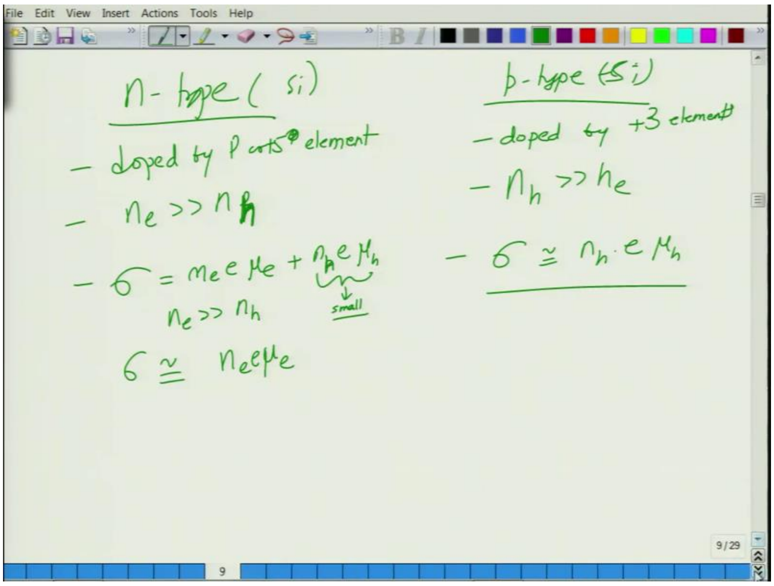

n- type (Si)

- doped by P or 5 element
- $n_e >> n_h$
- $\sigma = m_e e \mu_e + \underbrace{n_h e \mu_h}_{\text{small}}$

$n_e >> n_h$

$\sigma \cong n_e e \mu_e$

p- type (Si)

- doped by +3 element
- $n_h >> h_e$
- $\sigma \cong n_h \cdot e \mu_h$

So, basically in n-type, you can say, doped by phosphorus or 5 plus element, 5 plus 5 element, n e is much larger than n p or n h and sigma as a result will become basically so, sigma is nothing but n e e mu e plus n h e mu h. So, mu e and mu h are, they could be slightly different from each other but if n e is much larger than n h, in that case sigma can be approximated as n e e mu e because this is very small. As a result, it vanishes.

In p-type, what happens is that, it is doped by plus 3 elements. So, basically, we are saying silicon in the context of silicon so, and for other semiconductors, this this would be different. So, n h is much larger than n e and here sigma is basically from the same token it will be n h e mu h. These are the two semiconductors.

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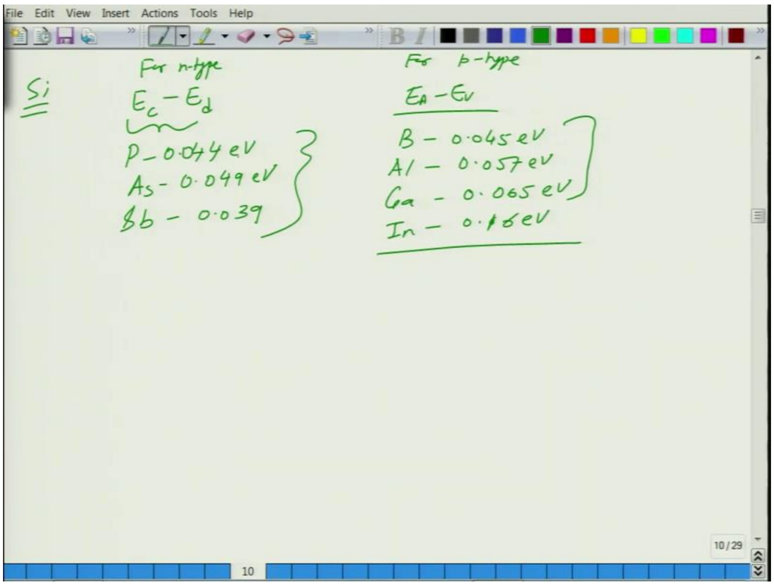

Si

For n-type
$E_c - E_d$
P – 0.044 eV
As – 0.049 eV
Sb – 0.039

For p-type
$E_A - E_V$
B – 0.045 eV
Al – 0.057 eV
Ga – 0.065 eV
In – 0.16 eV

And if you look at the difference between the donor and acceptor level, so E c minus E d which is basically for n-type. For p-type, we are looking at E A minus E V and if you look at the difference in the ionization energy, the difference for so, if let us say for phosphorus, in silicon so, in silicon we are talking about silicon only. For n-type it is phosphorus has 0.044 eV, arsenic has 0.049 eV and antimony has 0.039 eV. So, these are common dopants that we use.

And if you look at p-type impurity, for boron it is 0.045 eV, for aluminium it is 0.057 eV, and for gallium it is 0.065 eV, for indium it is 0.16 eV. So, you can see that it is easy to ionize and contribute the holes to silicon using boron, aluminium and gallium but indium is difficult but it still work. Whereas for n-type say silicon, we generally use what we call as phosphorus, arsenic and antimony. So, now let us see how does this affect the Fermi level position.

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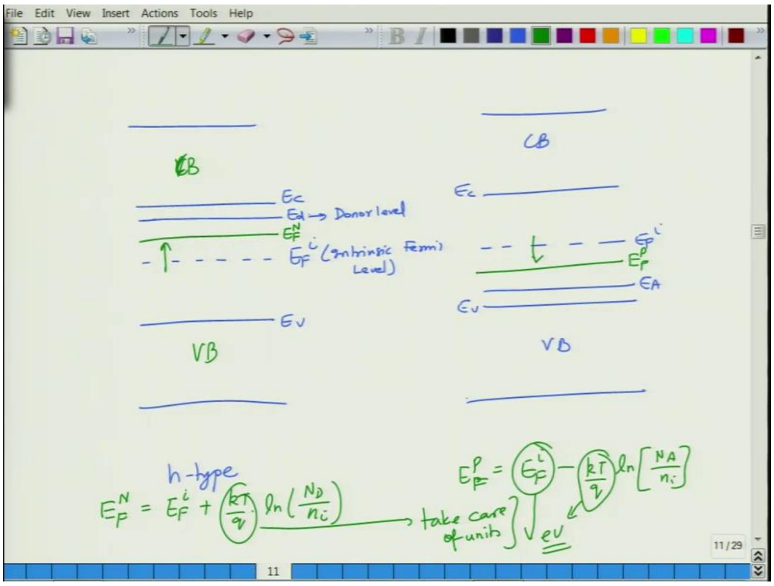

$$E_F^N = E_F^i + \left(\frac{kT}{q}\right) \ln\left(\frac{N_D}{n_i}\right)$$

$$E_F^p = E_F^i - \left(\frac{kT}{q}\right) \ln\left[\frac{N_A}{n_i}\right]$$

So what happens in semiconductors is that when you dope them for a n-type, E c, E v, so this is E F intrinsic. E F i, let us denote it as intrinsic. So, when you dope it, and we are saying that this is my E d. So, this is the donor level and this is intrinsic Fermi level. For the n-type semiconductor, as you dope it, the Fermi level goes up. So, as a result, the Fermi level for a n-type is slightly higher. It is closer to conduction band edge. So, as a result, the Fermi level of n-type semiconductor is approximated as, I can write the expression.

So, for n-type, E F n is equal to E F i plus k T by q into l n of N D by n i. So, as you increase the lower concentration, the Fermi level shifts closer to conduction band as compared to the valence band. So, this is conduction band, this is valence band. For a p-type semiconductor, the situation is like this. Again, we can write E c E v and here we write E A acceptor level and this is the E F i. In this case, the Fermi level goes down.

So, Fermi level for p-type semiconductor will be somewhere here. So, in this case you write E F p as E F i minus of k T l n of N A over n i. So, this k T or k T by q you have to see whether you are writing this in E v or some other energy, so just make sure you take care of units so that this and that both turn out in E v. Otherwise, you will have issues but nevertheless. So, this is how the variation of two values will take place.

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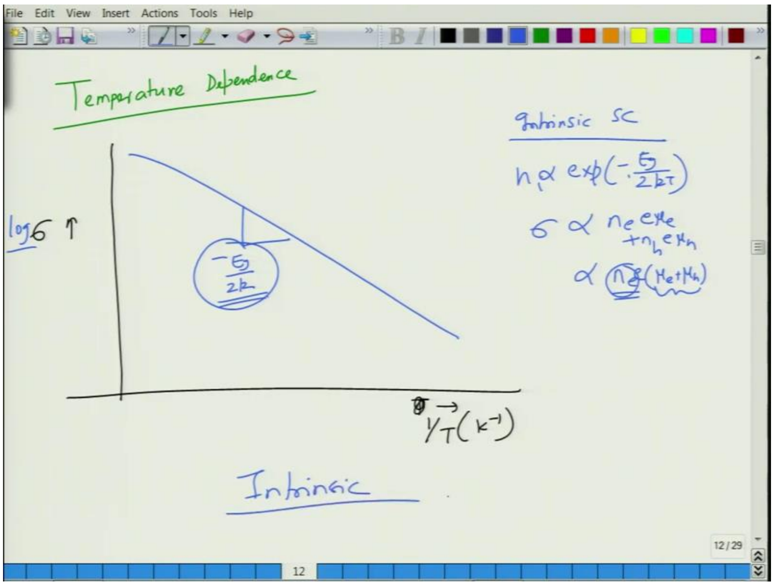

Finally, we look at the temperature dependence of, temperature dependence when we look at, the conductivity of semiconductors in extrinsic semiconductor, so for intrinsic semiconductor so, let us say sigma as a function of temperature, for intrinsic semiconductor basically as you so, we generally plot as 1 over T so Kelvin inverse. So, for intrinsic semiconductor, as temperature increases, the conductivity so, you can say this is log of sigma. This is for intrinsic semiconductor.

So, essentially, we saw that n is proportional to exponential of, n i is proportional to exponential of minus E g by 2 k T and sigma is proportional to n e e mu e plus n h e mu h which is proportional to n e e into mu e plus mu h. So, as we can see as the, of course mu e and mu h go down little bit with temperature. But the stronger effect is seen in n i. So, the slope of this is basically minus E g by 2 k. So, this is for intrinsic semiconductor.

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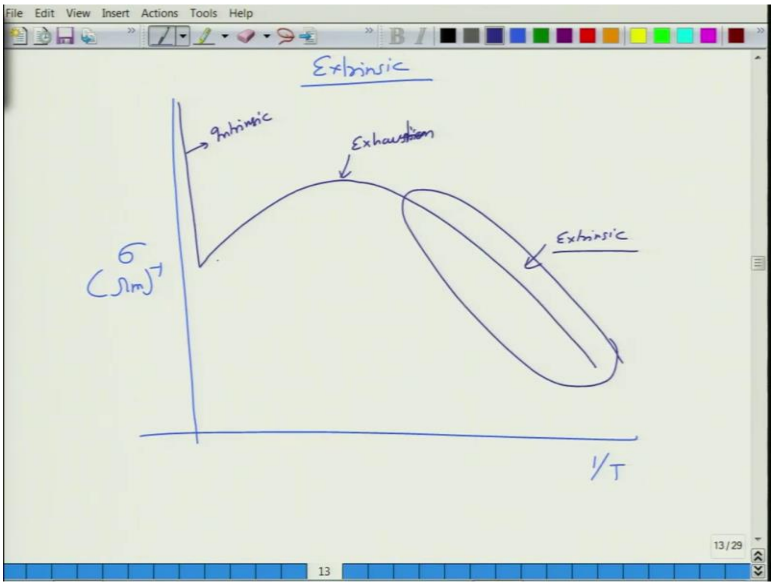

When you do the same for extrinsic semiconductor, for extrinsic semiconductor if you plot sigma n let us say Ohm meter inverse as a function of 1 over T, the plot is slightly different. In the lower region, you follow intrinsic region and then it goes to what we, so this is the region which is higher temperature it becomes intrinsic. And then, sorry, I said lower temperature, it is high temperature and this is exhaustion and this is extrinsic. So, basically, at very low temperature, the material works as extrinsic semiconductor. In between there is exhaustion region, which means it is nearly flat and then at very high temperature it becomes intrinsic.

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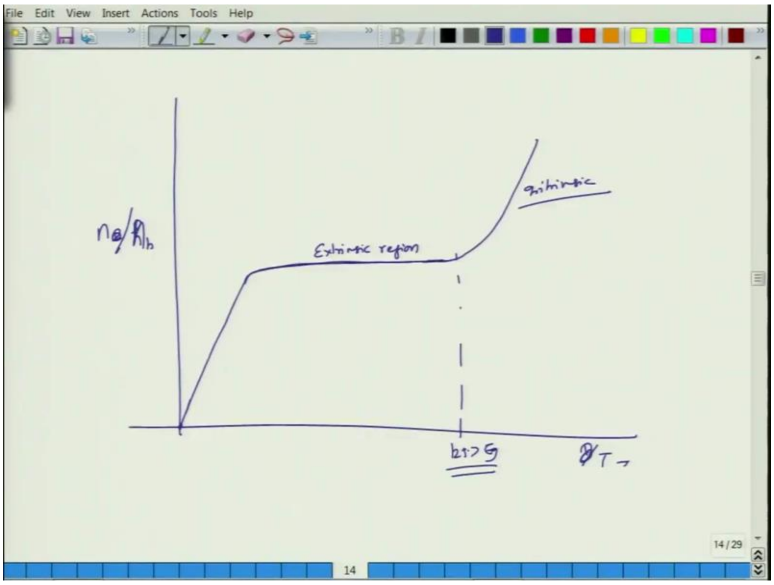

The reason for that is, when you plot n as a function of, number of carriers as a function of 1 over T as a function of temperature what happens is that, at very low temperature there are no carriers in any of the bands. So, as a result, they get excited and they keep increasing until all the donor or acceptor electrons or holes are, so you can say n slash h, n e slash n h. So, this is initial region when so, when temperature 0 nothing can be exited, as a result electron or hole density is 0.

As you keep increasing the temperature, all the donor accepter electrons get excited and get ionized, they contribute electrons and holes and once all of them are saturated then you reach extrinsic region. And then it remains constant.

And once, when you are able to overcome the energy more than the thermal energy or corresponding to the band gap, then you reach the intrinsic region. So, this is what happens that in between you have a saturation region because your number of electrons or holes are similar to number of donor acceptor and until you reach an energy which is corresponding to k T is more than E g, you are remain in the extrinsic region before you enter into the intrinsic region. So, this is the reason why we see such a behaviour in conductivity for semiconductor.

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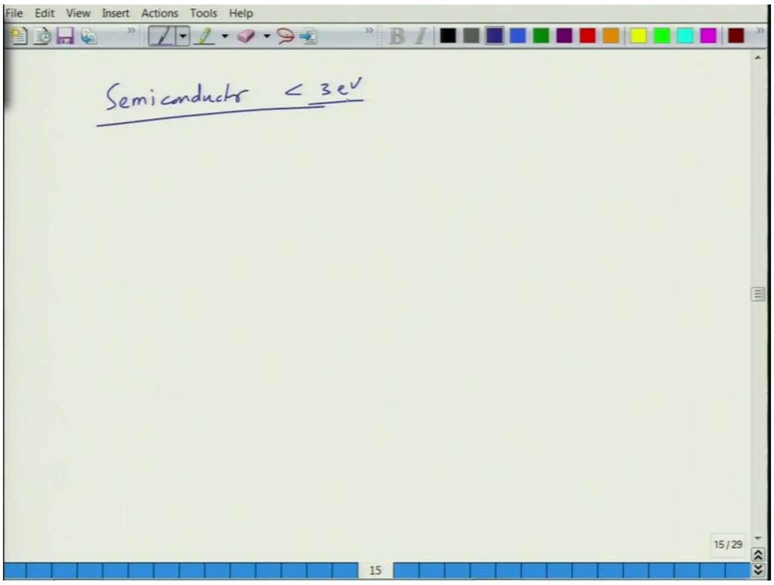

So, what we have seen is semiconductors are the materials which have band gap of so, semiconductor materials with band gap, with a band gap less than 3 eV or let us say 2.5. They are different than metals in the sense that in semiconductor, the carrier concentration increases with temperature whereas in metals and as a result, conductivity increases with temperature, whereas in (semiconduct) metals the conductivity decreases with temperature because of scattering.

So, in this course, what we have done is we have looked at mechanical properties of materials. I talked about elastic properties then plastic properties, stress-strain curve, strengthening mechanism and finally, we looked at basic electrical properties of metals and semiconductors. So, I hope I have been able to give, provide you basic information about these properties. If you have any questions, you can always get back to the portal and ask TAs or myself questions and I wish you good luck with this course and hope you enjoy. Hope you have enjoyed this doing this course. And you can always write to me if you have any queries. And please do read the books.

The lectures are not substitute for any books. These are only so, lectures and books go together to improve your knowledge and ability. So, I would recommend you to go through the books which I have recommended in this course, especially George Dieter and Woolf series for mechanical properties and material science engineering by Raghavan or Woolf series again by Woolf. So please go through the books along with the lectures, then only you will be able to fulfil the objectives of the course. Thank you very much.