Fundamentals of electronic materials, devices and fabrication

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Lecture - 12
pn junction breakdown and heterojunctions

Let us start with a brief review of last class.

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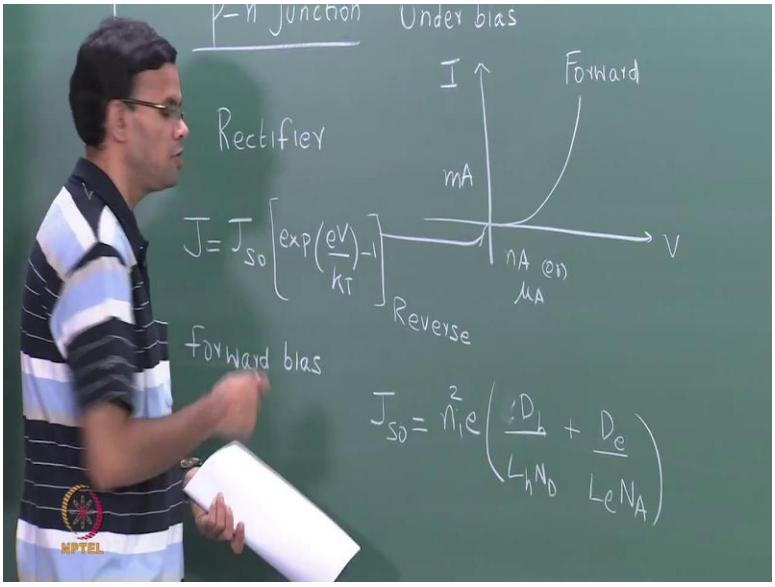

Last class, we looked at a p-n junction, under bias. So, we applied both a Forward and a Reverse bias and looked at the I-V characteristics. We found that a p-n junction is essentially a Rectifier. So that, if you were to plot I versus V, this is I, this is V. The first quadrant is the forward biased, this one is the reverse. We found that, in the case of the Forward bias the current goes exponentially as the voltage, typical value of current is around milli amps. Where if you have a Reverse bias, we have a really small current here is of the order of nano amps or micro amps and that is really a constant. We also wrote down the expression for the current in the case of a p-n junction. So, the expression is J is equal to some constant J_{so}, which is your reverse saturation current times $exp\left[\frac{eV}{kT} - 1\right]$. So, this is in the case of forward bias, J_{so} is the reverse saturation current which is equal to $n_{ie}^2\left[\frac{eD_h}{L_hN_D} + \frac{D_e}{L_eN_A}\right]$. So, D_h and D_e are the diffusion coefficients for the minority carriers within the p and the n region and the L_h and L_e are the diffusion lengths.

So, today we are going to start with an example, in order to calculate some of these values of the current in forward bias and also the reverse saturation current. But, before we do that I want to see how this reverse saturation current will change, if you change the material.

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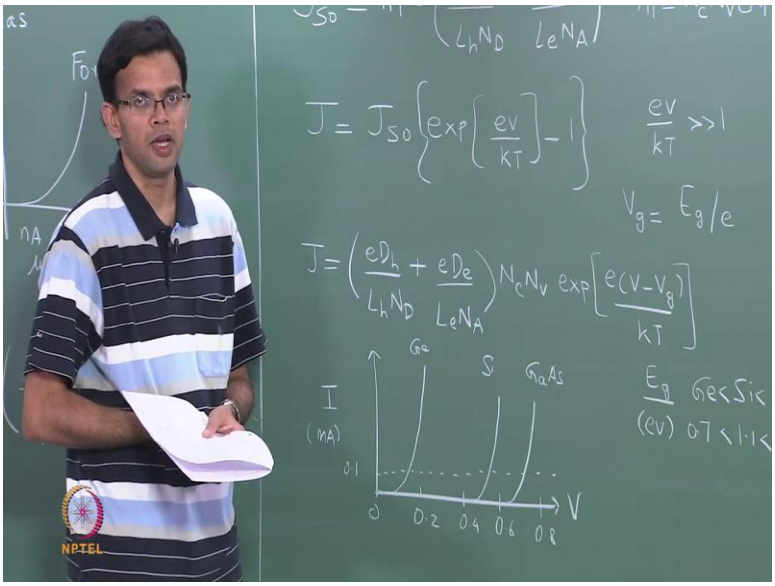

So, let me write this expression for J_{so} one more time. J_{so} is $n_{ie}^2\left[\frac{eD_h}{L_h N_D} + \frac{D_e}{L_e N_A}\right]$. Now, n_{ie}^2 which is the intrinsic carrier concentration, is a material property. We know that n_{ie}^2 is nothing but, $N_c N_v \exp\left[\frac{-E_g}{kT}\right]$. We can substitute for n_{ie}^2 in this expression. So, that J this is nothing but, $J_{so} \exp\left[\frac{ev}{kT} - 1\right]$. So, I am going to substitute the J_{so} here and instead of n_{ie}^2 I am going to replace it with $N_c N_v \exp\left[\frac{-E_g}{kT}\right]$. Just for the sake of argument and we will find out that it is true, $\left[\frac{ev}{kT}\right]$ is usually much greater than 1. So that, I can ignore this term from -1 is here. I am also going to introduce another term V_g which is nothing but, the band gap divided by e. So, if you do that J becomes equal to $\left[\frac{eD_h}{L_h N_D} + \frac{eD_e}{L_e N_A}\right]$, $N_c N_v \exp\left[\frac{eV - V_g}{kT}\right]$. So, V here is the external potential that you apply during forward bias V_g is nothing but, the band gap divided by e.

So, if you were to plot the current versus voltage for different semiconductors, we find that if you want a given current, the voltage will be higher if the band gap is higher. So, let me plot I versus V, for 3 materials. So, we will look at Germanium, Silicon and

Gallium Arsenide. So, in terms of band gap E_g, Germanium has a smaller band gap than Silicon which is smaller than Gallium Arsenide. Some typical values we know Germanium is around 0.7 electron volts, this is in ev, Silicon is 1.1, Gallium Arsenide is 1.43. So, my current will be in milliamps, this is the voltage 0. So, we find that the curve for Germanium comes first, then you have Silicon and then finally you have Gallium Arsenide; so, Germanium, Silicon, Gallium Arsenide. So that, for a given value of current so, let us say I want the current to be 0.1 milliamps. The voltage is lowest for Germanium, is higher for Silicon and is even more higher for Gallium Arsenide and this is because you have V_g, which is the band gap in that expression.

So, let us now go ahead and look at example of a p-n junction in Silicon and calculate some values for the Reverse saturation current and also the current through the p-n junction in forward bias.

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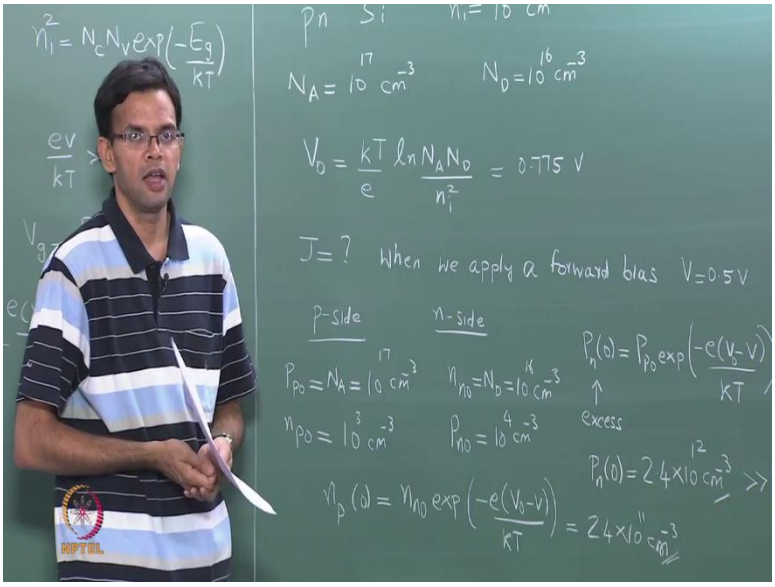

So, we are going to start with the p-n junction that we have looked at before. We have N_A is 10^{17} and we have N_D is 10^{16}, the material is silicon so the intrinsic carrier concentration n_i is 10^{10}. So, we can calculate the contact potential in this p-n junction. Contact potential V_o and we did this last class, is nothing but 0.775 volts. So, we want to know what the current is. So, we want to know the value of J, when we apply a forward bias and let me take the value of voltage to be 0.5 volts.

So, let us write down the p-side and then n-side. So, the first thing we want to know is

how many excess carriers are injected because of the forward bias? So, from last class if you remember, the current in the case of a p-n junction is due to the minority carriers so that you have electrons that are injected in to the p-side, you have holes that are injected in to the n-side that causes the current. If you write down the values P_{po} is nothing but, N_A is 10^{17}. The concentration of electrons will be just $\frac{n_{ie}^2}{N_A}$ so that is 10^3. Same way, we can write for the n-side, the formula for the excess carriers so that, $P_n(0)$ is nothing but, $P_{po} exp \frac{-eV-V}{kT}$. So, V_o here is the contact potential, V is the forward bias potential, that is 0.5. So, P_{no} is the excess carrier. So, if you substitute the numbers and evaluate P_n at 0, turns out be 2.4 x 10^{12} cm^3, So, this number is much greater than the equilibrium concentration of holes on the n-side, which is here. So, this is much greater.

Similarly, we can calculate the excess electrons on the p-side, this is equal to 2.4. So, these are the excess electrons and the excess holes that are injected due to the forward bias. Now, these are still minority carriers. So, ultimately they will diffuse through the material, they will recombine with the majority carriers and get eliminated. So, in order to calculate the diffusion length we need to know the diffusion coefficient.

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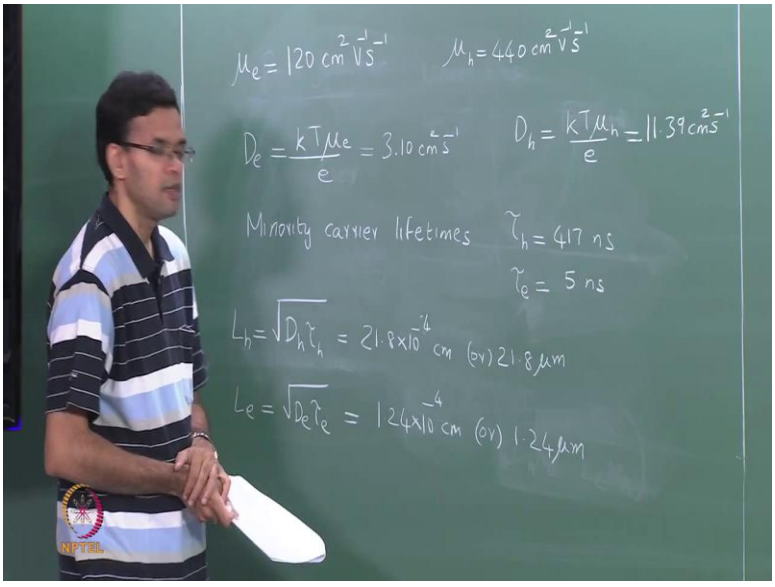

So, let me first write down the mobility, so μ_e that is the mobility of the electron and μ_h which is the mobility of the hole. So, mobility in the case of a semiconductor usually goes down with the increasing doping concentration so, they are standard tables from which we can get these values of μ_e and μ_h as the function of the doping concentration.

So, once we know μ we can calculate the diffusion coefficient nothing but, $\frac{kT\mu_e}{e}$. So, if I substitute the all the values this gives me the diffusion coefficient of the electrons so, 3.1 cm^2. We can also get the diffusion coefficient for the holes, is 0.39.

Now, if you want to find the diffusion length, we should also know how far or how long these minority carriers can travel before they recombine. So, we need to know the carrier lifetimes. So, let me take the values τ_h is 417 nanoseconds, τ_e to be 5 nanoseconds. So, these are again values that are known. Typically, these will also depend upon the dopant concentration. So, τ_h is the lifetime of the holes that are travelling through the n-side of the p-n junction, τ_e is for the electrons that are traveling through the p-side. So, we can then calculate the diffusion length. So, we can substitute the values we have D_h here, you have τ_h is here. So, this is 21.8 x 10^{-3} I am sorry, 10^{-4} cm or 21.8 μm. L_e is nothing but, D_e τ_e τ_e which is 1.24 x 10^{-4} cm or 1.24 μm. So, we have all the values that we need for calculating the reverse saturation current and the current during forward bias.

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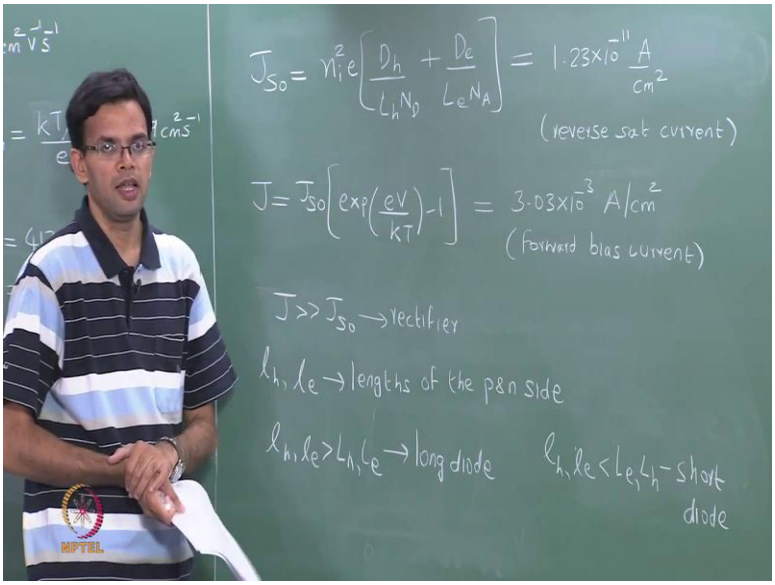

So, J_{so}, we can calculate. So, we have calculated all these values the diffusion coefficients and the diffusion length. So, we can substitute the numbers and evaluate J_{so}. So, J_{so} turns out is 11 A cm^{-2}. So, this is the reverse saturation current. So, this is the current there will be flowing through if I have reverse bias the p-n junction. So, the current during forward bias is nothing but, $J_{so} exp\left[\frac{eV}{kT} - 1\right]$. The voltage that we applied is 0.5 volts, so J comes out be 3.03 x 10^{-3} A cm^{-2}. So, this is the forward bias current.

So, earlier we said that a p-n junction is a Rectifier and we can actually see that it is because, J is much greater than J_{so}. In these calculations we have assumed that the length of the device is larger than the diffusion length. So, let L_h and L_e be the lengths. So, this refers to the physical lengths of the p and n side. So, we have assumed that L_h and L_e are larger than the diffusion lengths. So, this kind of a diode is called a long diode so that, the diffusion lengths are what goes in to this equation. If the physical length is actually shorter, if L_h and L_e are smaller than the diffusion lengths then it is called a short diode. The only difference in the calculation is that, in the equation for the reverse saturation current instead of the diffusion lengths in the case of a short diode, we will put the physical lengths of the p and the n-side.

So, let us again look at the I-V characteristics, but let us look at the reverse bias side.

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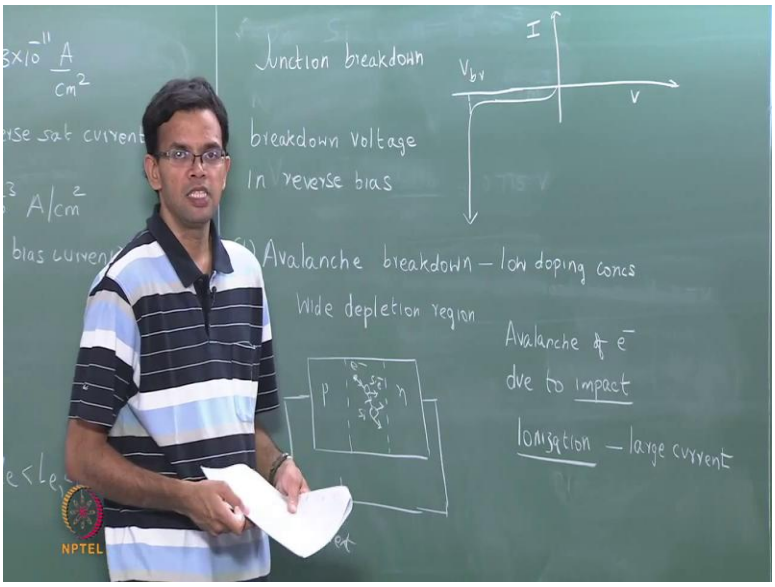

We said that, in the case of a p-n junction in reverse bias, the current is a constant, does not depend upon voltage. So, we said that the current is a constant which is equal to the reverse saturation current, but it turns out at really large voltage values. The diode breaks down so that, you have a large reverse current flowing through the material. So, this voltage where this happens is called your break down voltage this happens in reverse bias. So, when this happens we said that the p-n junction has broken down and there are 2 mechanisms for this. One is your Avalanche breakdown, so this occurs for p-n junction with low doping. So, you have low doping concentrations on the p and the n side. So,

that you have a wide depletion region.

So, if I were to draw this p-side, that is my n-side, this is under reverse bias. So, in this particular case an electron that is being accelerated by the field can essentially interact with a Silicon atom. And, because it has sufficient high energy because of the large external potential that is applied, that electron can ionize the silicon atom and produce more electrons, this in turn can interact with another Silicon atom so that, you have an Avalanche of electrons that are produced. So, this effect where the electron hits a silicon atom and ionizes it is called Impact Ionization and the effect of this is that you that have a large current. So, one mechanism of breakdown is called the Avalanche breakdown, occurs at low doping concentrations, another mechanism of breakdown is called the Zener breakdown.

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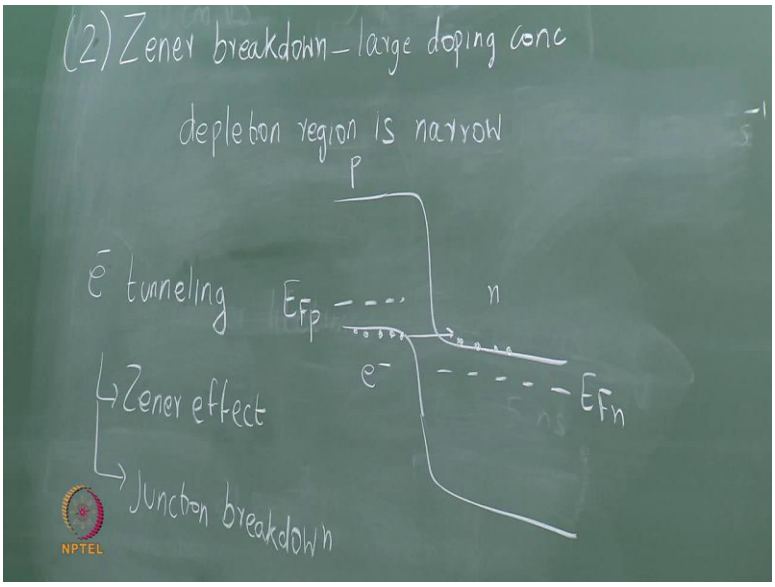

So, the Zener breakdown occurs at large doping values. In this particular case, the depletion region is thin or that is narrow. So, if were to draw the energy diagram for this, we just draw slightly. So, this is my p-side, that is my n-side, these are the Fermi levels. So, we are in the reverse bias, so that there is a large barrier. But, because your depletion width is small we can have electrons tunneling from the p to the n. So, this electrons tunneling is called the Zener effect and because of that, you have a large current. So, you have a breakdown of the junction, this leads to. So, we have looked at a p-n junction, first in equilibrium and then in the case of a bias, both forward and reverse. You have

also looked at the 2 breakdown mechanisms that are possible in reverse bias.

So, far in the p-n junctions you have considered, if considered the material to be the same so you have the p and the n-type and they are the both the same materials. So, they could be Silicon or Germanium or Gallium Arsenide, but the material is same. The next thing that we are going to look at briefly is, what happens if you have 2 different materials so that, you have a Hetero structure.

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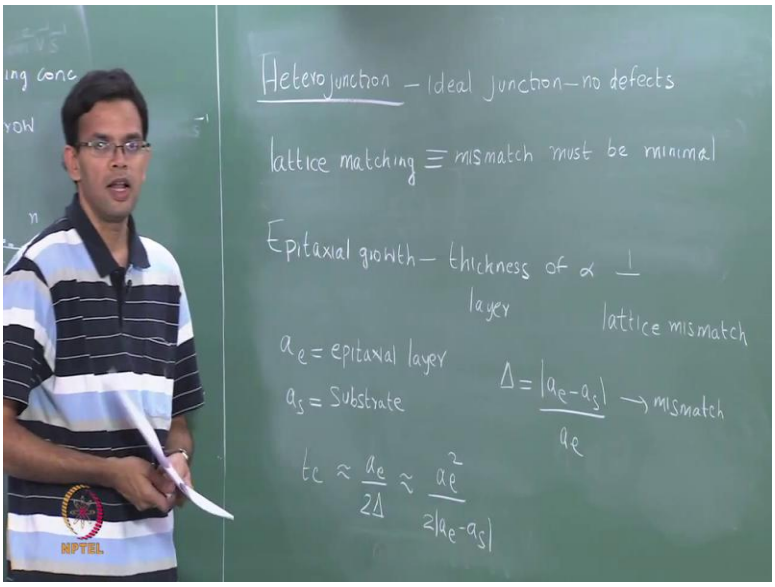

So, now you have a Hetero junction, so that you have a junction formed between p and n-type of different materials. Once again when we have such a Hetero junction, we are going to assume that you have an ideal junction with no defects. So, this imposes a restriction on the types of materials that we can choose. In order to have an ideal junction with no defects, we must have lattice matching between the 2 materials or if you want to put it in another way, the mismatch must be minimal. So, depending upon the degree of mismatch we can control the thickness of the second layer on the first. So, if we look at Epitaxial growth, in the case of Epitaxial growth the layer you are trying to grow has the same lattice constant as that of the substrate. So, that if there is a lattice mismatch, there is inherent strain in the material.

So, the thickness of the layer you are trying to grow is inversely proportional to the lattice mismatch. So, more the mismatch then the thinner the layer you can grow. Ultimately, if your mismatch is large you are just going to have a large number of defects

at the interface. So, if a_e is the lattice constant of the Epitaxial layer and a_s is the lattice constant of the substrate, then we define mismatch $\Delta = \left[\frac{a_e - a_s}{a_e}\right]$. So, this is the mismatch. So, the thickness of the Epitaxial layer that we can grow tc is proportional to $\left[\frac{a_e}{2\Delta}\right]$. So, this is an approximate expression. So, this is equal to $\left[\frac{a_e^2}{2(a_e - a_s)}\right]$. So, let us take an example of Silicon and Germanium

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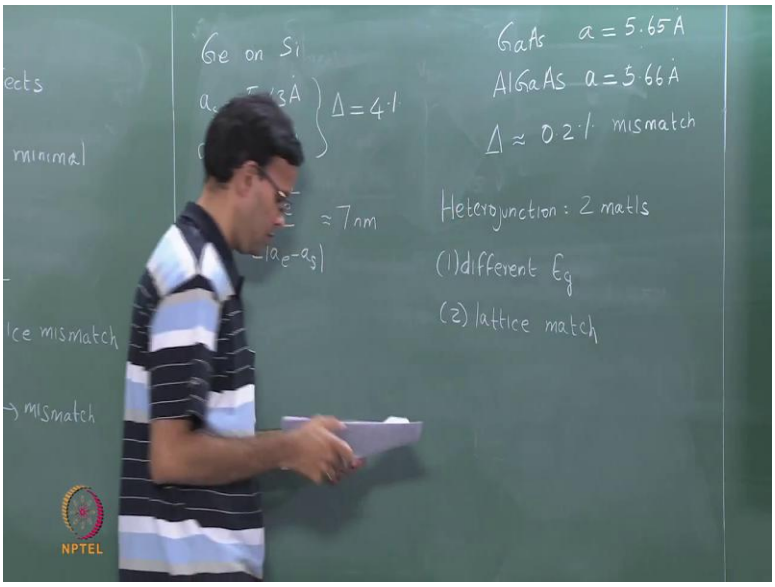

So, let us say I am trying to grow a Germanium layer on Silicon. The lattice constant for Silicon a s is 5.43. For germanium so that is my Epitaxial layer, is 5.66. In this particular case, the mismatch delta if you try to put it in percentage is 4 percent so it is nothing but, $\left[\frac{a_e - a_s}{a_e}\right]$. So, the critical layer that you can grow, the thickness if you use the formula a_e^2 this works out to around 7 nanometers which means, you can grow a layer of germanium on silicon up to 7 nanometers. There will be some inherence strain in the germanium, but if you go beyond that you are going to form defects in the material. In the case of a Germanium and Silicon you actually have (Refer Time: 32:43) ailing formation, this kind of growth is called a Stranski-Krastanov growth.

Instead of Germanium Silicon, let say I have Gallium Arsenide growing on Aluminum Gallium Arsenide or the other way round. In this particular case, the lattice constants are much closer, so this is 5.65, this is 5.66. So, here the lattice mismatch Δ is much smaller, it is typical around 0.2 percent, Silicon germanium it was 4 percentage. So, it is easier to

grow Epitaxial layers here. So, in the case of a Hetero junction we want to choose 2 materials with different band gaps. We want different band gaps because we want to exploit this difference for some interesting electronic properties but, at the same time we want a good lattice match. So, let us now look at a band diagram in the case of a p-n Hetero junction.

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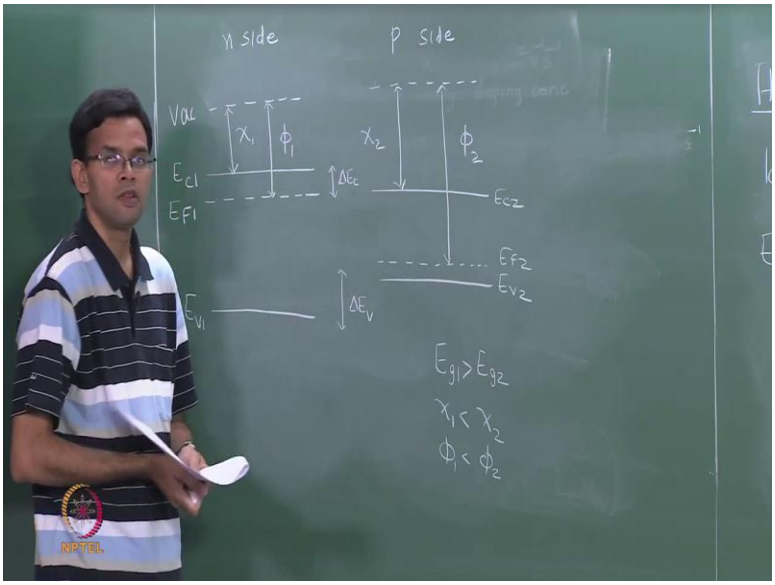

So, I am going to consider a p-n junction. So the first let me draw the n-side and I am going to say that the n-side has a higher band gap than the p-side. This is my n-side, this dotted line represents vacuum, this is the conduction band, that is the valence band and this is the Fermi level. So, I will just call this, put a subscript 1 so that, this is material 1. So, we can define an Electron affinity. Electron affinity is nothing but, the energy from the bottom of the conduction band to the vacuum level. We can also define my work function. This is going to form a junction with a p-type material, which has a smaller band gap. This is the p-side, so this is E_{c2}, E_{v2}, this is E_{F2} and once again we can write down values χ_2 and the work function.

So, now I am forming a p-n junction. So, I have $E_{g1} > E_{g2}$. I have the electronic affinity going the other way and the work function also going in the other way. We can also define an energy gap between the conduction bands of the 2 materials. So that is ΔE_c, we can also define an energy gap between the valence band ΔE_v. So, we want to put together this p-n junction. So, the first rule is at equilibrium, the Fermi levels must line

up.

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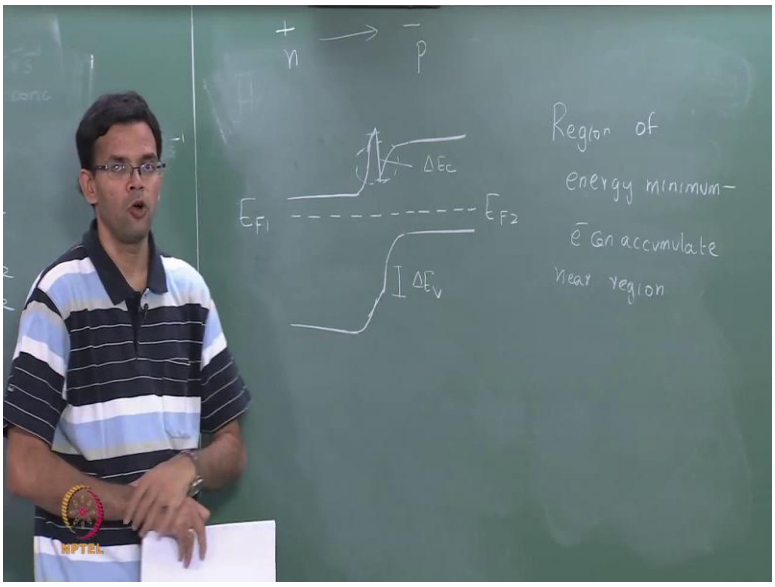

So, let me draw the p-n junction. So, the Fermi levels must line up. So, I have E_{F1} and E_{F2}. So, I have material 1 which is my n-type semiconductor, this is the material with a wider band gap and then I have my p-type material with the smaller band gap. So, if you look at this p-n junction, you see that the electrons go from the n to the p-side. So, that there is a net positive charge on the n-side, there is a net negative charge on the p-side. So, the electronic field goes from n to p. This is a same concept in a regular p-n junction and we know that bands bend up in the direction of the electric field. So, the bands have to bend up on the n-side and the bands have to bend down on the p-side.

So, we also said that there is a difference between the energies of the conduction bands. So, a ΔE_c and a difference in the energies of the valence band ΔE_v. So, when the bands bend we must make sure that, that difference is preserved. So that, this gap is ΔE_v, we just extend this and this gap is ΔE_c. So, now if I join these 2, we just we can get the p-n junction and their equilibrium.

So, if you look at this, this is different from how a p-n junction would look, if you have the same material. Specifically, if you looked at the conduction band there is a region where there is an energy minimum. So that electrons in the p-side can essentially accumulate in a region near the junction. There is the region of energy minimum which means, electrons can accumulate near that region. Also, the energy barriers are different

for the conduction band and the valence band so the barriers are different for the electrons and holes. So, this can again affect the conductivity of the Hetero junction.

So, Hetero junctions have some important properties, when we look at optical properties because of the fact that you can have electron accumulation. If instead of a p-n junction, where the n has a higher band gap, if you choose a p-n junction where p has the higher band gap. You will see accumulation of holes near the junction. So, with this we are done with p-n junctions. So, p-n junctions are an example where we have an interface between 2 semiconductors. So, they could be the p and the n of the same material or they could be the p and the n of the different material.

In next class, we are going to look at devices where we have more than 1 junction. So, an example of such device is a Transistor. So, in the next class we are going to start looking at Transistors.