Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 16
P-N Junction basics

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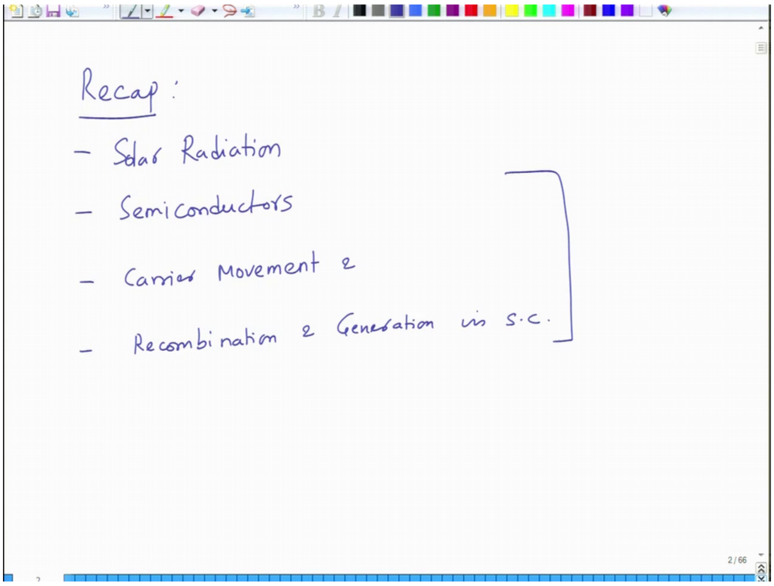

Welcome again to a new lecture. So, today we will start our discussion on P-N junction diode, and look at the characteristics in the context of solar cells. We will first recap last few lectures, and then we will we will move onto the contents of this lecture.

So, just to give you a recap, so far what we have learned is we first learned about the solar radiation, where we knew what kind of radiation is, what kind of geometry sun and earth, how do you measure the intensity, what kind of angular relationships are there to measure the radiation correctly.

And then we learned about the semiconductors, what kind of semiconductors are there, what is the relation of doping with respect to carrier concentration as well as with respect to conductivity, and also the influence of temperature on mobility etcetera. So, we looked at the fundamentals of semiconductors.

And then we looked at the basically you can say carrier movement. And finally, we looked at recombination and generation in semiconductors. So, these three topics lay the foundation of basically how the carriers are how do the carrier concentration changes in a semiconductor under presence of various kind of stimulus or under various conditions of operation.

So, I suggested few books on the course of teaching this part. So, I strongly recommend you to go through these books to brush up your, to get the knowledge in detail, because we did not have time to go through all the derivations and mathematical relations, but it would be useful for you to go through those.

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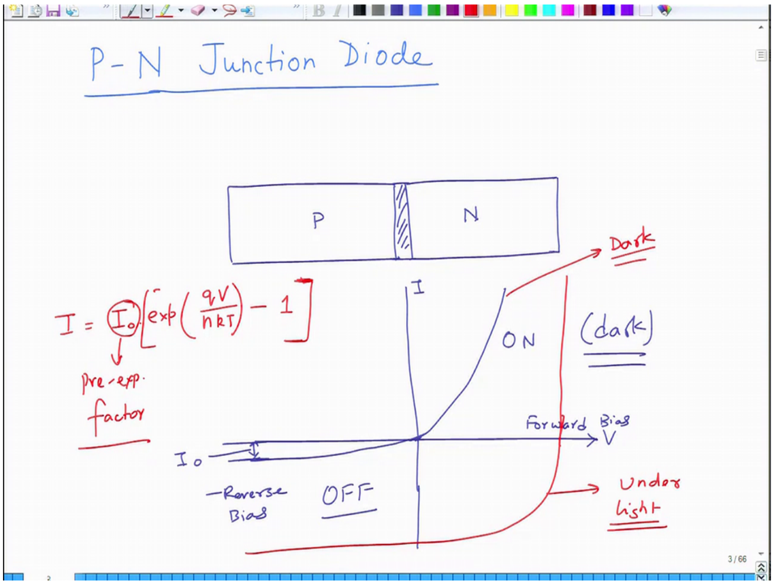

Now, we start with a new topic today, which is again essential to understand the P-N junction diode. And why we want to understand P-N junction diode is because our solar cell is nothing but a diode ok. And diode is form built on what we call is a P-N junction. So, what we do here is essentially, we have we have a P-type semiconductor, and we have a N-type semiconductor of certain thickness, so this is P, this is N. And they make a diode, when you join them together.

So, essentially a diode so when you join them together, when you create a junction between the two, then when you measure the I V characteristics of such a device, in the I V characteristics this is current, this is voltage, you get a behaviour which is something like this kind of behaviour. So, at the on the positive voltages, which is also called as forward bias. There is a exponential increase in the current, and you get large currents.

And at reverse bias which is at the negative voltage, so this is reverse bias, we get very small current.

So, this is basically you can say reverse current I naught, which is very small in magnitude. And so if you use it, you can use it as a switch. So, in this condition if you use it as a diode as a switch, this is ON condition, this is OFF condition. Now, this is under dark or when it does not work as a solar cell, you use materials which do not make it work as a solar cell. You can use materials and in such a fashion, so that this becomes the solar cell device, and it gives you a IV curve which is so this is for a normal P-N junction diode for a solar cell diode under light you will have this kind of behaviour essentially.

So, our objective is to first see how do we get this kind of curve from a diode, and then how do you get the other kind of curve, when you eliminate a P-N junction diode. So, essentially in the context of solar cell, we can say this is under dark, and this is under light. So, our objective is to understand how do you get these two curves based on whatever background, we have built upon on the basis of semiconductor knowledge basic knowledge.

So, this current is essentially given as I is equal to you can say I naught into exponential of q V divided by n k T minus 1 ok. So, this is at reverse bias, so this is your saturation current in the reverse bias. And as you keep increasing the voltages, the current exponential increases, and you get very large current from the diode. So, this I naught is the pre-exponential factor. So, it is the pre-exponential factor not the (Refer Time: 05:48). So, we will see how do we get to it ok.

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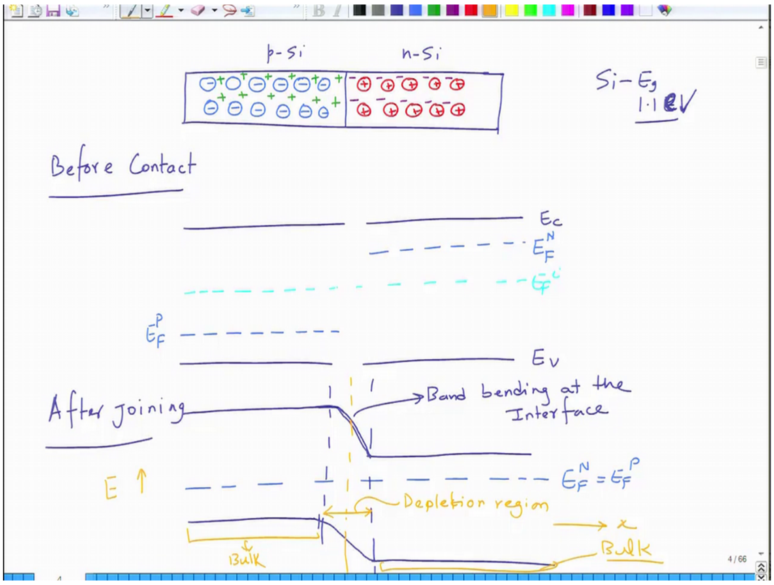

Now, let us see first what are P-N junction is; so P-N junction so if you say that we have a P-N junction like this, so this is before you have made a contact before contact. If you draw the band diagram, this would be your and let us say both of them are silicon, so this is also silicon, this is also silicon, this is p-silicon, this is n-silicon. And the reason you are taking it as because the band gap of both of them will remain same.

You can take different semiconductors also that is what you do in hetro junction, when you have a P-N junction which is based on two different semiconductor, but we will begin with this identical band gap. So, we take silicon, it has the band gap of about 1.1 electron volt, and we take p-silicon, n-silicon.

So, for a p-silicon, this is for a n-silicon, conduction band edge, valence band edge. Before making a contact, the Fermi level of p-type will lie somewhere here, so this is depending upon the doping level, you will have Fermi level of p. And depending upon the dope doping level of and you will have E F N.

So, essentially you are saying that this material is p-type. So, p type basically means that you have acceptor kind of materials, so acceptor will give you; you have various ions. So, these are let us say some of the ions are negatively charged, let us say these are acceptor impurities, other than you will also have silicon atoms. And on top of this, you will have holes. So, holes will be this positively charged a species inside ok. And here you might have a situation something like this, you will have these donor atoms. So, I am not drawing the silicon atoms, because you will have silicon atoms also ok. And then you will have electrons, so these this will be electron free extra electrons which are caused, this is before you create a contact.

So, what happens, when you and the intrinsic sorry, I need to just draw the intrinsic Fermi level, the intrinsic Fermi level will be identical for both of them, so this is E F i alright. Now, what happens when you join them together, when you join them together the thermodynamic requirement is that the Fermi levels of two semiconductors first align with each other, and they must be constant at the equilibrium.

So, what when that happens is, so when you join them. After joining, we say that Fermi level is so this is now E F N is equal to E F P. If this is the case, deep inside the semiconductor somewhere here, the conduction and valence band are at the same distance. So, this is the position of conduction and valence band, which remains the same.

Here also the conduction and valence band situation remains the same, but at the interface you have a what we called as band bending. So, this is band bending at the interface alright. Now, the region which is at the interface, so this is the original interface let us say, the region up to which bands bend in both the sides is called as we will see it is called as depletion region. And these regions are called as bulk of semiconductors. So, this is bulk, this is also bulk.

Now, what you see here is band bending. Bending of bands mean you have a gradient. And gradient so this is x this is a distance x, and this is energy. If you have a variation in energy as a function of distance, which means you have a built in electric field, because E is proportional to V you can relate energy can be related to potential, you just have to minus and co relate to the electron charge. So, since E can be related to V, V is related to electric field. And since there is a variation in the potential in the device, you have a electric field. So, this is called as built in electric field, we will see what it is.

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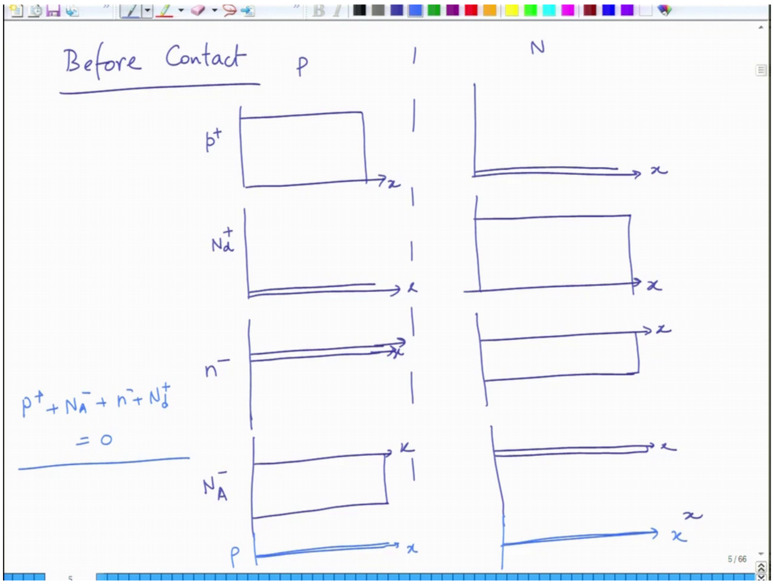

So, now if you look at this device, before you make a contact. First let us plot the so before contact first if I want to plot the charge density as a function of distance, so on P side, on N side this is for N side, this is for P side. So, if I plot p plus density, so my density is like this ok. And in the end p plus is very small, there is very little p plus in this is x, this is x. And somewhere here you have interface right before the contact. So, this is the positive charge carrier density; positive charge carrier density is very high in p-type semiconductor, positive charge density is very small in n-type semiconductor.

Now, when you plot the, so this is N d plus, so p plus is hole density, this is donor density. Donor density is very small in P-type semiconductor, but donor density is very large in N-type semiconductor alright. So, this is something like that depending upon the thickness you will have.

Similarly, you can plot what is the electron density, and you can plot the acceptor density right, so this is acceptor. So, electron density in holes will be in P-type semiconductor will be very small, if you take negative as the connotation. In this case sorry I can draw the line above to make it a little clearer. So, if I draw the line here, so electron density will be very small for N-type for P-type, and it will be very large for ok.

Similarly, for N A now, so this n minus minus and plus are written just to detect the positive and negative charge density. And this is N A minus, N A minus would again be so if I again re-draw these lines, x x sorry x all of them are x ok, so N A minus would again be it is large for this, and very small for this ok. So, P-type has very large hole concentration, and very large acceptor concentration. N-type has very large electron concentration, and donor concentration.

As a result the net charge density if you plot, the net charge density in both P and N type will be equal to 0. So, if you plot rho, rho is the net charge density in both of the semiconductor, it will be 0, because positive and negative charge P plus plus N A minus plus n minus plus N d plus is equal to 0 right in a semiconductor before making a contact. So that is the case then this is before the contact.

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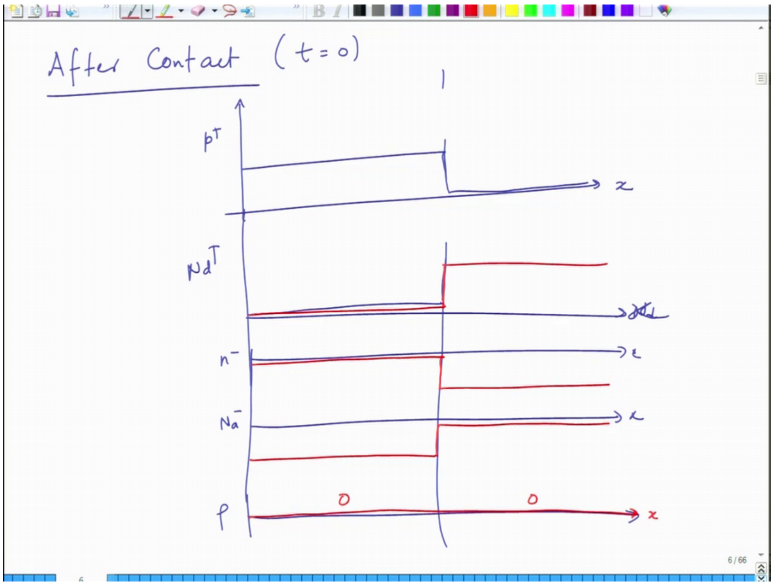

Now, let us see what happens after the contact. When you draw after the contact, then I am not going to draw the whole device here. So, this is let us say p plus. So, at after contact, just at time t is equal to 0 ok, just when they are put together just right, at this time. So, p plus I am going to plot p plus, I am going to plot N d sorry N d plus, then I am going to plot N a so this is going to be n minus, this is going to be n a minus, and then I plot rho ok.

So, we can see that if this is the interface, it would be something like this right N d plus would be something like. If I use a different colour, it would be something like this; n minus would be in this case very small in this case, it would be very large. And then N a minus would be in this case it is very large, in this case it would be very small alright. And the net charge density would be equal to 0, this is at time t is equal to 0 ok. So, this is 0, this is 0. So, you can see that now when you put them together, there is a gradient in each of the charge, you can say you can see that there is a gradient in positive charge, there is a gradient in the negative charge.

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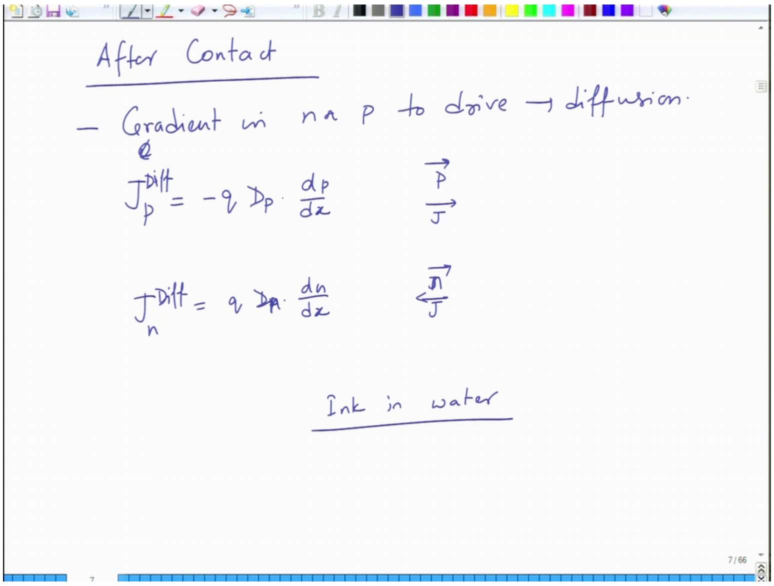

So, what will happen is that when you stick them together, there is a gradient. So, after contact, first you have a gradient in n and p to drive diffusion right. So, we can say that J p diffusion, you have a hole gradient. So, you have hole and electron gradient. So, you can say J p diffusion will be minus of q D p into d p by dx right.

So, holes move in this direction, and current also is in same direction ok. And then you have electron current, which is J n diffusion which is equal to you can say plus q D p into sorry d n into d n by dx. And in this case the electron current is in electron, let us say concentration is on electrons on this side, then current will move to other side ok.

So, you have this so this is very similar to what you do when you mix let us say examples could be, you know you mix ink in water right. You will see slowly the ink diffuses into the water to make a uniform solution right, so this is what it will happen. So, you would assume that when you have a gradient charges will go a long way, but charges do not go a long way away from the interface, because there are columbic forces inside the material which pull them back.

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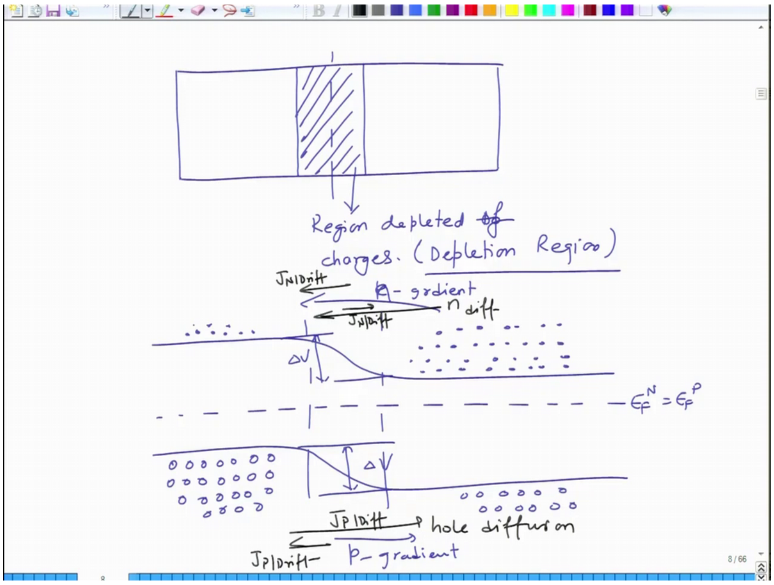

So, what happens there is so you have you create this region. So, this is the interface, you create this region which is called as a region, which is depleted of charges. So, this is called as depletion region. So, basically what happens is that to counter at the diffusion, since you have a different gradient, but you also have electric field gradient. So, electric field counters the diffusion.

So, as a result you have a, so all the diffusion would allow you to have the charges going all the way into the all the way on both sides into semiconductors, the drift current counter accept because of presence of electric field. You have seen that you have band bending at the interface, and this band bending leads to electric field. And this electric field prevents the opposite basically it is opposite to the diffusion current.

So, basically what happens is that when you form this barrier at the interface, so you can say this is the barrier. So, essentially what you have is you have a Fermi level which is so this is E F N is equal to E F P, you have so this is p side. You have lot of holes on this side, but you have few electrons on this side right. On the other hand you have lot of electrons on this side, but you have four few holes on this side.

So, obviously you have a so this is e-gradient e concentration gradient n you can say n-gradient, this is p-gradient. So, you have a driving force for diffusion to occur. But, you can see also one thing because of band bending at the interface, these electrons now have to overcome energy barrier. And holes on the other side see for electrons positive energy is the barrier, and for holes negative energy is the barrier, for holes also there is a barrier on this side. And this barrier is created by the band bending at the interface, which is manifested in the form of electric field.

So, while you have a electron gradient and hole concentration gradient to drive the diffusion, the counteracting force comes from the electric field. So, basically this delta V whatever is present here this delta V prevents the electron and hole flow from going them further into the device.

So, what happens is that when the diffusion takes place, diffusion does take place in the within this region, the electron and holes which come from each side they recombine. As a result this region becomes completely free or devoid of charges, there are no free charges in this region. And further movement of charges is prevented by this built in electric field which does not allow the charges to crossover on the either side, because you require a energy barrier delta V to be overcome to flow of to allow the flow of carriers to either side.

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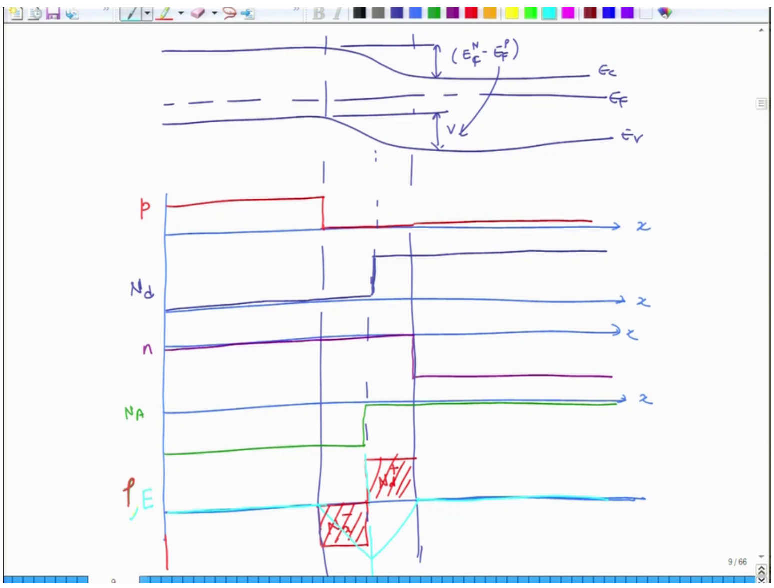

So, now if you plot the various things inside the semiconductor, so you have a energy band diagram something like this. This is E F, this is E C, this is E V, and this is delta V. This delta V is nothing but difference of E C N minus sorry E F N minus E F P because both the Fermi levels were different. Now, they have to align which means the difference is the difference, so this barrier is nothing but same as the Fermi level difference.

So, if you now plot various properties, so let us say first we do the hole concentration, let me just plot. So, this is first is this is as the function of x, if I plot the hole concentration, the hole concentration is like this. Of course, it is very small in this region, and it becomes very small in the depletion region or 0 in fact, the depletion region ok, so this is p.

Now, if you plot N d this is N d now, N d is very large in this region, but this is the interface the original interface, it is small up to this region, but then again it goes because N d is the donor ion density, they do not recombine, they do not move its a free carriers which are moving. The donor and acceptor atoms have not moved, they are the atoms they do not move it is the carrier which is moving, so which so you have not moved the donor carrier donor atom which is staying there.

Now, if you do the same thing for hole and for electron, so this electron concentration is like this, whereas the whereas N A concentration is so N A is you can say very large in this region ok. So, now if you plot the charge density, if I plot the charge density now, so you can see that deep inside the semiconductor the charge densities is still 0 right, they still cancel each other.

What you have here is in this region, you have some N d this is the N d, and in this region you have some so this is sorry N a, this is N a, and this is N d. So, this is positive, this is negative. This is what is depletion region, you have only ionic course left there are no free carriers there. And basically this area is equal to so amount of charge which is here is equal to amount of charge which is there alright.

So, if you now since you have now a positive charge and negative charge separated with respect to each other, if you now plot the electric field the electric field goes as so if I now plot electric field with the different colour in this electric field, electric field goes as if this is the interface electric field goes as this is the electric field electric field is 0 everywhere else. So, this is the 0 electric field, but is not 0 within the junction to this electric field prevents further diffusion of carriers into both sides.

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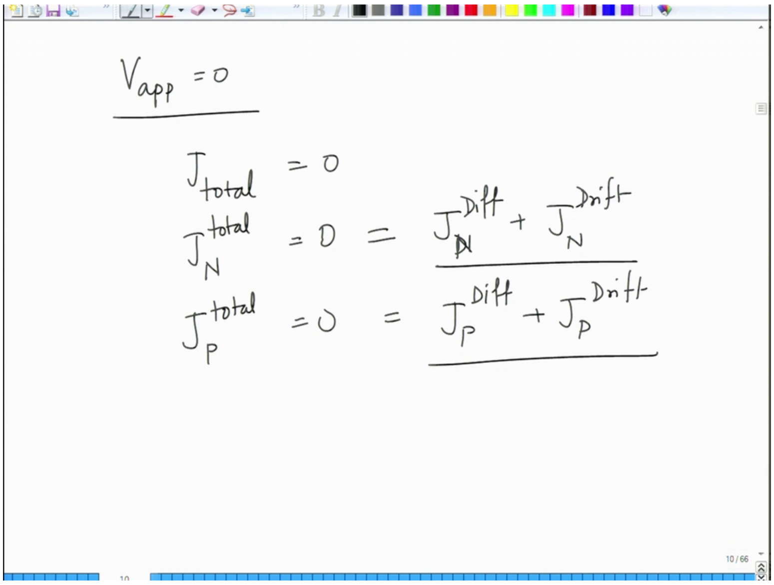

So, you have two counteracting forces. So, you can say when you do not apply electric field, when electric field when external electric field is you can say E external or other I can say when V applied you just connected them ok. Then you can say the overall current is equal to still equal to 0 overall current is equal to 0. J N total is equal to 0, J P total is equal to 0, however J N total is J N diff plus J N drift.

Similarly, here this is equal to J P diff plus J P drift. These two balance each other these two balance each other that is how you get, so these two balance each other. So, you have a counteracting electric field which does not allow the flow of charges, as you can see from the band diagram. There is a diffusion gradient, but that diffusion gradient allows movement of charges right in the beginning, when the recombine, there is no further movement of charge.

Because, then once they recombine in the vicinity of junction, then the ionic course are left alone. When the ionic course are left alone, then you have a positive charge density in one region, negative charge density in one region as a result you have set of electric you have set up an electric field. And this electric field will prevent the charges to move into each region further.

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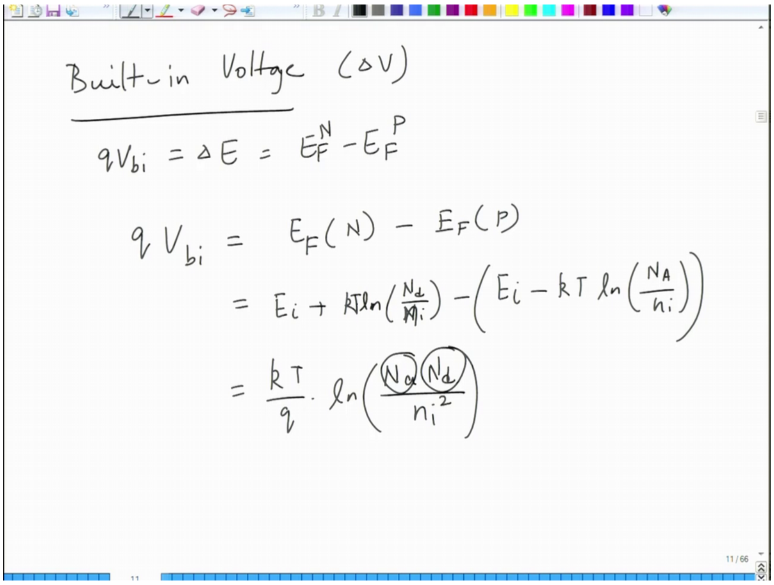

So, from this one can determine, what is the built in voltage built in basically the delta V at the barrier what is that. So, we said that it is because of E is equal to E F N minus E F P right delta E, and this is equal to q V b i ok.

So, this basically you can say q V b i is equal to E F of N minus E F of P side. And this is equal to you can write the value for E F N E F N is equal to E F N is equal to E i plus k T l n N d over N i small n i, and E F is basically E i minus k T of l n, this we saw in the semiconductor fundamentals.

And if we now plug these together, this will become k T divided by q l n of N a N d divided by n i square. So, if your dopant concentration is larger in semiconductor, then your built in field will also be larger. And what is also suggest you as we will see later on, when this happens when the depletion region is also narrow.

So, when the semiconductors are lightly doped, the electric field is a smaller, the magnitude is smaller as a result the field is that the depletion region is wider. But, when the field is when the doping concentration is large the built in field is large, as a result the electric field is large, as a result the region is also narrower, so that we will see in the perhaps in the next class.

So how, so the question is how wide is the depletion region, what is the electric field value inside it, what is the what is the potential inside it, these are the things which can be calculated for a P-N junction easily. And analysis of these things we will do in the next class ok.

So, what we have done? Today is we have just learn the basics of P-N junction, what a P-N junction is what happens to band bending band diagram and the so you can see here again I will just quickly suggest you that. Here you can see that on one hand, we have you can see that this is electron diffusion, this is hole diffusion, so you will have of course a hole current here J P diff, and electron diffusion flow as a result you will have J N diff alright.

Counteracting these you have J N drift, so you will have J N drift, and you have here J P drift, this is because of this electric field which is set up inside at the junction. So, these two cancel each other. As a result you have 0 hole current, and 0 electron current. As a result total 0 current in the semiconductor device, when you do not apply a external field, so because that is external field it has to remain neutral, it has to it cannot give you any current unless you create carriers and move them. So, if you do not apply external field, they do not move, they do not go too far, they just go little bit on each side recombine, and reach the equilibrium ok. So, we will do further analysis in the next few classes ok.

Thank you.