Optoelectronic Materials and Devices

Prof. Dr. Monica Katiyar
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Lecture - 31
Resistor and diode (p-n junction)

Good morning, today we will start on the last module of this course, basically making devices using electronic materials. So, the in this module we will be covering optoelectronic devices.

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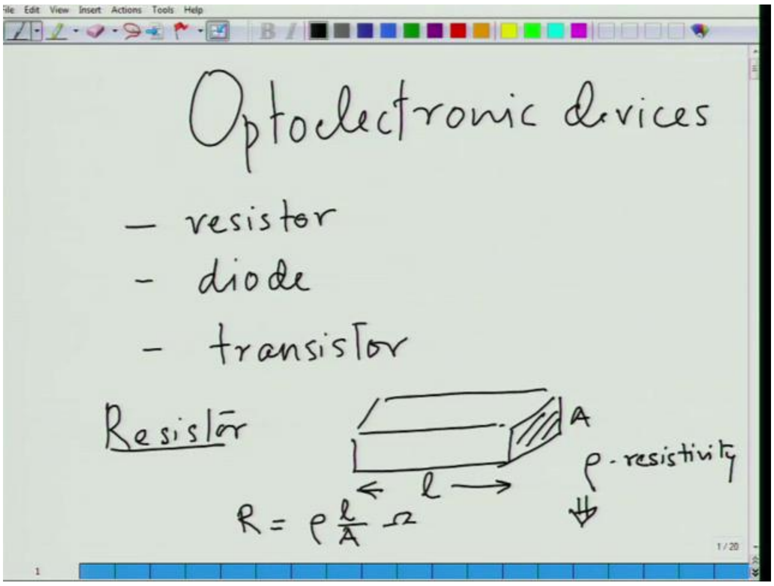

Optoelectronic devices

- resistor
- diode
- transistor

Resistor

$$R = \rho \frac{l}{A} \ \Omega$$

Basically in any electronic circuit, we have three type of basic devices; a resistor a diode and a transistor. Up to now in the last 3 modules, what you have learned? In the first module is how do we visualize the electrons in the materials? How electrons exist in the material? The band gaps, the conduction band, the valence band. In the next module you learnt how to look at materials, which are insulators? Look at their properties. In the third module we learnt how to look at the processes that these electrons and holes in the materials go through. Basically mobility, the absorption of light and emission of light and now we bring all these basic concepts together to make a device. To give an example, I will start with the very simple device resistor.

A resistor is nothing but material of a certain dimension. Let us assume it to be a rectangular piece with the area A and length l and resistivity of rho. In this case the resistance of this material is going to be rho times l over A ohms. Depending on what rho we have and this you have learned earlier in earlier modules that you can have a material which is highly conducting. If you want a conduction property or a semiconducting or a insulator. Hence, one can design a resistor depending on what material one chooses for a particular value of R.

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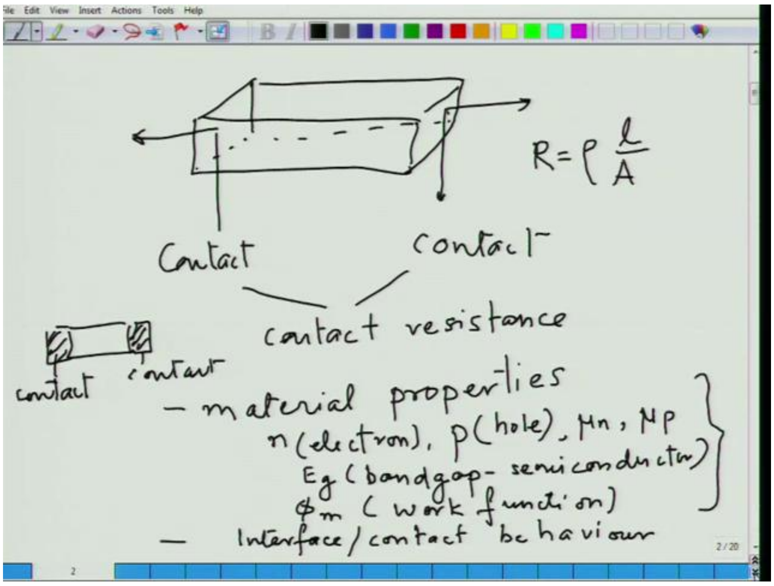

$$R = \rho \frac{l}{A}$$

- material properties
  n (electron), p (hole), μ_n, μ_p
  E_g (bandgap - semiconductor)
  ϕ_m (work function)
- Interface / contact behaviour

Only thing which happens differently in this case in case of materials is when I made a resistor of a certain dimension, I assumed that when I make connection to this device to the outside world through a wire, there is a contact at this point. There is another contact at this point and in writing my earlier equation for resistance, I have assumed that these two contacts are not interfering in the overall resistance, which you have learned is not true. The contacts also have some contact resistance and this comes from the fact that semiconductors the work function of the metals. The semiconductors fermi level may not be the same as learned in the earlier courses.

So, this is a very simple example of how to take a material and make a device and what are the characteristics that you need to know. In order to make a good device, so you need to know your material properties namely, you need to know what are the carrier concentrations in your materials? For electron carrier concentration p for hole carrier concentration, their respective mobilities, nu n, nu p, if the material is semiconductor in that case band gap. If it is a metal, you need to know the work function. But in addition to that you also need to know what is the interface or contact behavior?

Once, we put all these things together, we exactly know once he make a device which has material in between and a contact on the two sides. How it will behave once he apply a bias to it? Hence, in addition to the material the contacts become very important. Although, we have ways and means of making sure that the contact resistance is minimal, in that case we the only concentrate on the material properties in deciding, how we make our device? Now, this was a, is a simple device resistor is not very complicated. In this course since we have only 10 lectures to cover the devices, we are going to concentrate only on a diode device which is a p n diode.

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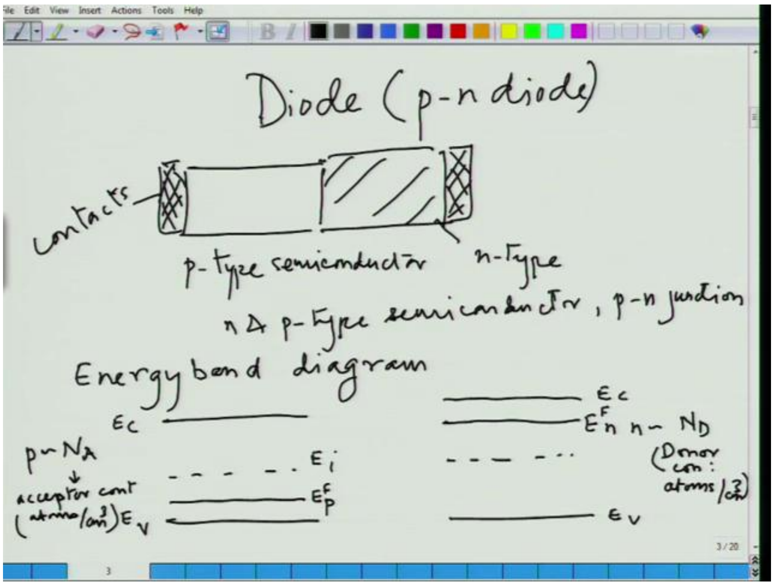

How it can be used as a solar cell or as a photo detector or or even as a light emitting diode? So, this although very simplistic device has many applications optoelectronic device, which are currently very useful and commercially used. So, in a p n diode our picture is basically we start with the p type semiconductor and a n type semiconductor. For the time being although there will be contacts on the two ends, let us let us assume that these contacts are ohmic and there is no intervention in the diode characteristic because of the contacts. Hence, we are only looking at the property of the n and p type semiconductor. The junction, the p n junction to the the junction of importance here is the p n junction between p and n type semiconductor.

Now, you have already learned earlier how to represent this device in terms of the energy band diagram. So, to start with we can plot a energy band diagram of the p type and the n type separately. Then try to bring them together and see how the device will perform? In the p type semiconductor we are going to represent the conduction band edge and the valence band edge and the intrinsic level fermi level, and the fermi level for the p type is going to be more towards towards the valence band. If we have this picture for the p type on the n type, it is going to be changed. For the same semiconductor we can assume that the conduction band and e V are of the same type e I is same, except now fermi level has gone up and this is the fermi level for the n type.

Now, when we bring these two together what is going to happen? First let us look at what is what is the situation about the carriers in these two semiconductors, which we have learned earlier? So, let us assuming in this semiconductor we have number of holes which are approximately equal to number of acceptors to keep the mathematics a little bit simple. In this the number of electrons are equal to number of donors N A and N D are the acceptor concentration in the n type, given in terms of atoms per centimeter cube. N D is the donor concentration given in terms of atoms per centimeter cube. In in this situation if p is equal to N A from the, we can try to now see, what what would be the the situation, if we try to bring these two semiconductors together?

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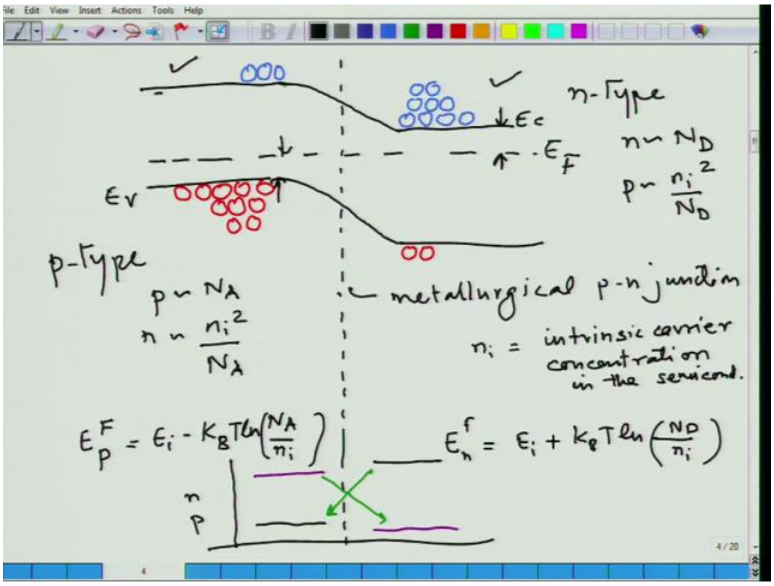

If we try to bring these two semiconductors together, the fermi level as shown earlier for the p type is towards the conduction band and the fermi level for the n type is towards the valence band. In that case what we need to do is we need to align the fermi level because the material when they are brought together is going to be in equilibrium. In the case of p type fermi level is towards the valence band and in case of n type it is towards the conduction band. The band gap is same in both cases. Now, what is happening here is this is the metallurgical junction far away from the junction. This material stays as n type and far away from this junction this is stays as p type.

What does n type mean? n type means that you have more number of electrons here and I am going to denote my electrons in blue colour. p type means you have more number of holes in the p type and I am going to always show my holes in red colour. There are less number of holes here and less number of electrons in the p type. We already know from our statistics of carriers that in this case we have assumed n to be approximately equal to the donor concentration. We have assumed p to be approximately equal to the acceptor concentration.

Now, if we apply the mass law then p can be also written as n i square divided by N D. What is n i? n i if you recall is the intrinsic carrier concentration in the given semiconductor. Similarly, one can write about the whole concentration here and that is electron concentrations for e that is given by this. Further we also know how to write in terms of the the doping or the p type and n type. What would be the fermi level? Basically we know how much is the shift in the fermi level from the intrinsic fermi level?

In both the cases in terms of the carrier concentration and that can be written as in for the for the p type semiconductor. It can be written as the intrinsic concentration times the Boltzmann’s constants time, the temperatures in Kelvin given by similarly, it can be the level energy for the n type can be written as donor concentration divided by n i. Now, this is a situation before we brought both n and p type semiconductor together. Now, you can easily see here what is happening? If I only look at the carrier concentration of electrons, there are more electrons here and less here. So, there is a carrier gradient across it is junction.

So, if I have to plot across this junction what is the n and p concentration? There is there is more n concentration here and less here and p concentration is more here and less here. If the concentration is more in the n type than the p type obviously that the what it means is, there is a concentration gradient and material is going to diffuse electrons are going to diffuse from the n type to the p type. The holes are going to diffuse from the p type to the n type. As a result what will happen is that you are going to get less number of electrons in the n type and less number of holes in the p type. So, let us see if you allow that to happen, then this is going to be in equilibrium eventually. Your junction will have the band banding at the junction of the energy band, because of this exchange of electrons and holes. So, let us look at this exchange of electrons and holes and what will happen eventually, once these are allowed to move?

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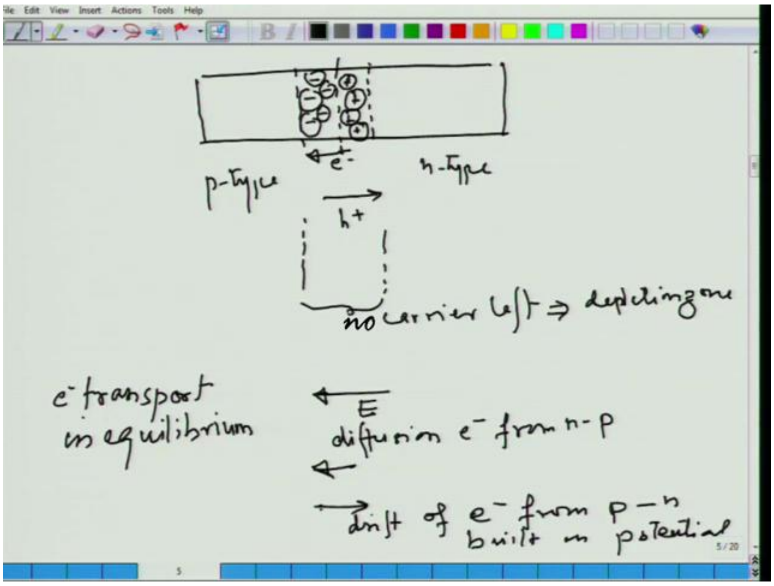

So, because of this motion and this is my junction. Very close to the junction in the n type, the electrons in this part have gone towards the hole. Hence, this is depleted, all is left here is the positive ion core. Same way the holes from here have gone to the other side and what what we have left? Since, the holes have gone from the p to the n type, we are left with the ionized acceptors on this side. In this region which is close to the junction basically there are no carriers left in one approximation. That is then called the depletion zone.

So, if I look at this situation what has happened because of this transfer of high concentration of electrons to the p type and the concentration of hole from the p type to the n type. We have developed a built in potential inside the material and this built in potential leads to a field. So, as you can see there are positive charge here and negative charge here, it is going to lead to a field in this direction. This field is the opposing field to this motion, if the electrons continue to move from the n type to the p type eventually nothing will be left.

What happens is because of this field electrons are going to be be moving from p to n type while because of the concentration gradient, they are going to be moving from the n type to the p type. So, if I only look at the electron motion in equilibrium there is going to be diffusion of electron from n to p, because of concentration gradient. There is going to be drift of electron from p to n, because of the built in potential and when this these two are equal the system is in equilibrium at this point, no more electrons are going from the n to p type. No more holes are going from p to n type the same situation is happening to the holes. That in that situation you have a p n junction which is in equilibrium.

Now, this is very interesting because what we have done now is we have taken two materials. We have not applied any field, but because of the two different properties of the material and the differences in the fermi level when we bring them together, we have a built in potential. This is the key to all the diode devices. we can use this built in potential now to get a diode device or we can also change put a light on to this diode and collect electricity, which is which will be a solar cell. Otherwise we can apply the power and collect light, which will be a light emitting diode. So, in this manner we can use this p n diode.

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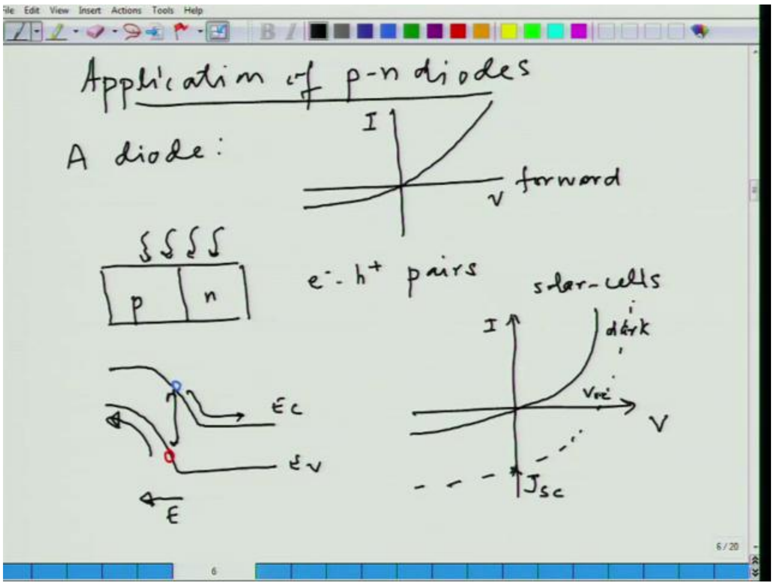

So, let us look at the application of the p-n diode before we go to the more details on how it behaves? Application of p n diodes comes from two parts; first one is just as a diode where it has a very unique current voltage characteristic. The the uniqueness comes from the fact that if I apply voltage in a forward direction, then there is a current flowing through the diode, but if I applied in the reverse direction there is no current flowing through that. That device is used in circuits in many ways.

Now, in the the same diode if I apply a same p and n diode, if I am going to shine light on it, if I shine light on it what we have learned in the third module is that you are going to generate electron hole pairs. When these electron hole pairs are generated, because of the built in potential, which we have just seen how it works? Whatever electrons are being generated in the junction electrons are going to follow the built in potential and go in this direction and hole are going to go in this direction. Remember the field is in this direction and holes follow the field and electron oppose move in the direction opposite to the field.

So, this is a solar cell which is made from a p n diode, so I take two materials make a p n diode, I shine light on it and I would find that. I can generate power through that when I look at the solar cell, I will use the same p n diode with current and voltage. This would be p n diode in the dark and if I shine light on it the current characteristics are going to change because of the additional electron hole generation. You are going to get a short circuit current and a open circuit voltage from such a device and in this third quadrant. If you are operating your device, it will be working as a solar cell and you will be generating the power from whatever light is shining on your p n diode. So, this is a very useful application and very pertinent to today’s time, when we are looking at solar energy.

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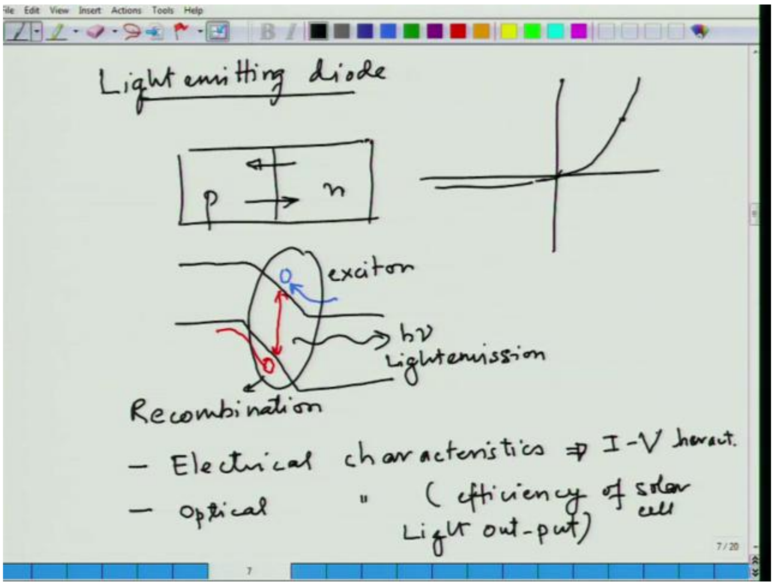

Light emitting diode

- Electrical characteristics ⇒ I-V charact.
- Optical " (efficiency of solar cell Light out-put)

On the other hand, I can also use it as a light emitting diode in this case in the p n junction when I have sufficient forward current at this point. I have large number of carriers going in this direction, more electrons and more holes going in this direction. A electron and hole which is which is moving in this direction comes here on the same time a hole, which is moving in this direction in forward bias, when they come in proximity. They can recombine generate an exciton and bring out light a photon and this is light emission.

So, what you need here is the motion of the electrons and the holes they are recombination and the recombination is leading to the emission of light. So, this is a simple example of how a p n diode a very simple device, which can be a part of our electronic circuit or the same device. You can use as a light emitting diode or as a solar cell so there are two parts. If I am understanding trying to understand this device and also its application and one part is only related to the electrical characteristics of the device, what I mean by electrical characteristics is when I apply a bias. Remember I have already assumed that contacts are not creating any problems.

So, only part I am interested is the p n junction and the p th semiconductor. The n semiconductor and in that case I want to see, I have apply a voltage what would be the current passing through this device? That is understanding that part is the electrical characteristics than if I am trying to use the same p n p n p n diode as a solar cell or as light emitting diode. I need to see when these electrons and holes what they do either to absorb light or emit light? In that time, I also need to know the optical characteristics in terms of solar, this will be the efficiency of the solar cell and in terms of the light emitting diode it would be the amount of light output from the diode.

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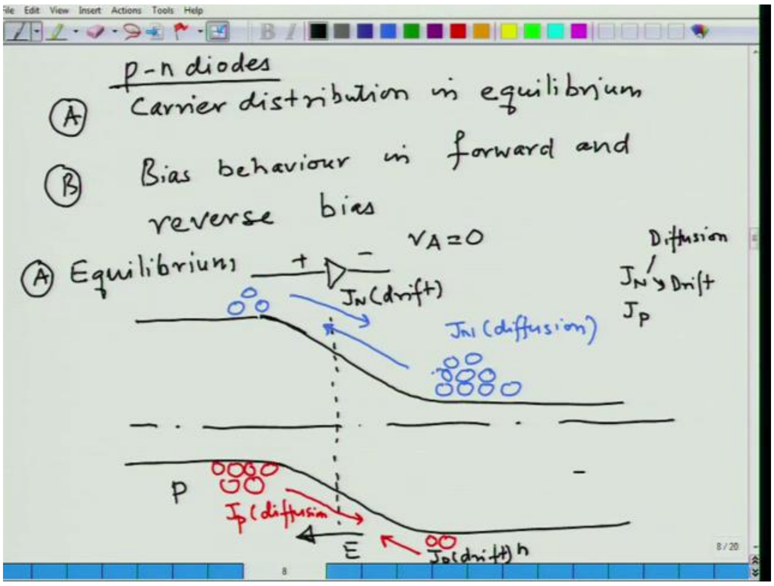

p-n diodes

Ⓐ Carrier distribution in equilibrium

Ⓑ Bias behaviour in forward and reverse bias

Ⓐ Equilibrium

So, I I can break the problem in terms of two problems; first is to understanding only the electrical characteristics of the p n diode which is common, rather you are using it as a solar cell or you are using it as a optical characteristics. The two can then be super imposed on each other to find the final solution. So, let us look at concentrate on only a simple electrical electrical characteristics of a p n diode, where I am only interested in trying to figure out how do I get the I V characteristics that I am getting for a for a p n diode? So, we will start with this part and look at how we get the observed I V characteristics in a p n diode?

So, in case of p n diodes, we can characterize that device in terms of carrier distribution in equilibrium and then we apply bias apply a voltage bias behavior in forward and reverse bias. So, up to now what we have in equilibrium what is happening part a in equilibrium we have alignment of the fermi level. If I want to plot this in terms of a diode sign, then it looks like this in the electronics circuit where my applied bias is 0. So, this is my device in equilibrium and this is a p n junction, metallurgical p n junction and that is the built in potential. If I look at now current for the electrons and the current for the holes, the current for the electron comes from two sources; one is diffusion due to carrier concentration difference in the two sides and the other one is due to the built in field that is due to drift.

So, if I look at the current of the electrons. Electrons are going to be moving in this direction and this is giving rise to J N diffusion. If I look at electrons here which are few they also move in this direction and this is because the field is this field. So, the electrons will follow opposite to the field and this is giving rise to J N drift. Something similar happens to the holes, this is the J P diffusion and this would be the the hole. The holes will follow the field this will be the J P field due to the drift. So, in overall balance in the equilibrium the electron concentration moving due to diffusion from n to p and moving from p to n. Due to drift balances, each other the same thing happens for the holes.

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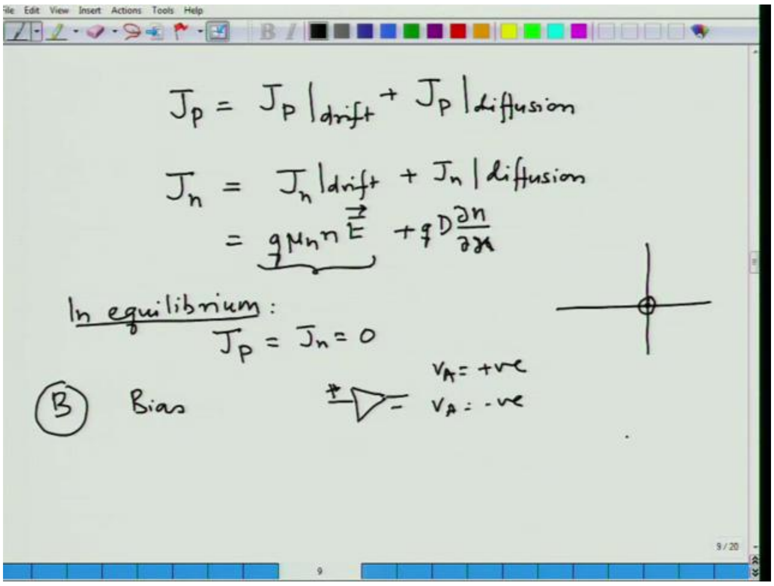

$$J_p = J_p\big|_{drift} + J_p\big|_{diffusion}$$

$$J_n = J_n\big|_{drift} + J_n\big|_{diffusion}$$

$$= \underbrace{q\mu_n n \vec{E}} + qD\frac{\partial n}{\partial x}$$

In equilibrium:

$$J_p = J_n = 0$$

Ⓑ Bias

$V_A = +ve$

$V_A = -ve$

So, writing the hole expression only in mathematical terms I can say that the hole concentration, the hole current, the total hole current is consisting of two part; one is due to drift and the other one is due to diffusion. Similarly, I can write the equation for the electrons and this is also consisting of the two part. Now, we have learned earlier in the second module second or third module. We can write these equation in terms of the material characteristics, if you have a field and the drift equation, then I can write the electron drift current in terms of the charge of the electron, in terms of the mobility of the electron and in terms of the carrier concentration multiplied by the field.

This is the part which is due to the drift and e is the field inside, the inside, the depletion role at the junction. What is the diffusion? Diffusion is obviously due to the concentration gradient of the carriers multiplied by the diffusion constant multiplied by the charge. So, these two equations, similarly I can write for the hole and this equation will give me the overall current due to holes and electrons. Now, in equilibrium what is happening that there is no current. I have not applied any voltage, I am getting no current. This is the point on these I V characteristics, which is at 0. So, it is there is no current which is basically means that J P is equal to J N is equal to 0, which means independently, these two equations can be equated.

If you put it to 0 you would get a equation for a built in potential. You can calculate your built in potential for a given p n junction based on what are the material properties and this exercise can be done? Now, if I move away from equilibrium and that is the second case in which what I will do is, I will apply a bias. Now, I can apply a bias in two ways. Remember my diode is in this manner, I can apply a positive bias and I can apply a negative bias. Now, what happens if I apply a positive bias? Basically what I am saying is my, if I apply a positive bias I am going to give more energy to the electrons to move or the holes to move in the direction to give more current. If I apply a negative bias, it would be obstructing that current.

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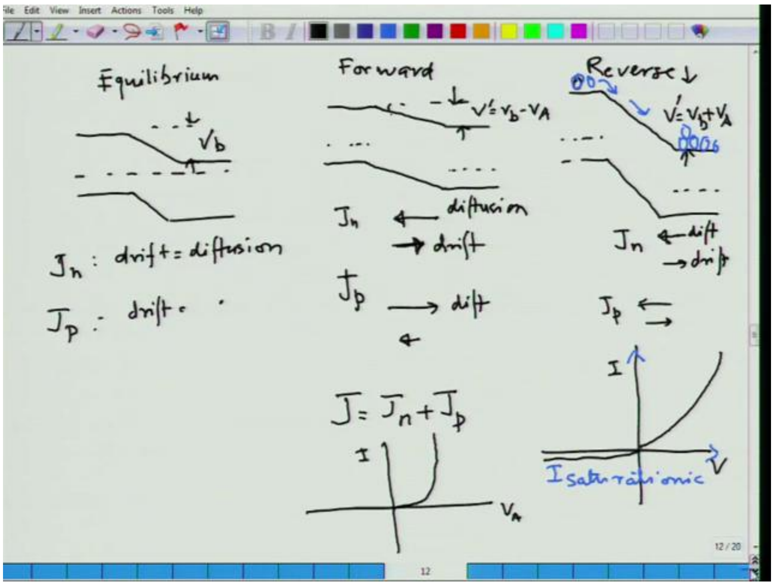

So, if I try to look at this in terms of the band diagram in terms of forward bias I can have a three situation; one is equilibrium, one is forward bias and the other one is the reverse bias. Now, if in equilibrium, I have a built in potential if I forgot biases that potential reduces. Basically what I am saying is that this will then become, I do not have equilibrium anymore. Hence, the fermi level are not aligned but the difference between the two side reduces the V prime becomes equal to V built in minus V A. What does that mean? It means in this situation what we had is for for the electron, for J N, the drift was equal to diffusion. Similarly, for the hole drift was equal to diffusion and hence there was no current and I all I had was a built in potential.

When I apply a forward bias, what have I done? I have reduced the built in potential by the amount of the bias. I have applied to the two ends of the p n junction. If I do that what will happen to the diffusion and the drift current? Now, if you would look at only on the in terms of the drift current for for electrons, the diffusion current was in this direction and the drift current was equal in the opposite direction. If I reduce this field what will happen to the drift current of the electron? Now, electrons were falling through this built in potential anyway.

But because of this you are going to have a less amount of drift current, so overall when in this case when drift was equal to diffusion. Now, you have more of diffusion and less of the drift. The drift remains same by with the applied with with the bias applied, but the diffusion increases because of the the concentration gradient being changed. We will see it mathematically a little later, same thing is happening for the holes. The diffusion is in this direction, which increases substantially and the drift remains almost similar. So, when I do the forward bias, I have excess current because earlier these two currents were balancing each other.

The total current through that device is going to be the current due to the electrons plus the current due to the holes. So, when I look at the I V characteristics, I need to see how much increase in the current? I have by applying a bias and that is the reason when I plot the I versus V, when I when I applying applied bias positive, the current increases. We will look at it, how it increases? It increases almost exponentially, this is a forward bias situation when I do the reverse bias. The situation is slightly different, the the the difference between the the two further increases quite a lot.

Now, in this situation the the voltage between the p and n type has changed to whatever was the built in potential in equilibrium. When you had a drift and diffusion equal, this has become V V plus applied potential V A. Now, what does that do? It reduces considerably the diffusion current across the junction. Hence, there is a there is very little change in the this is almost equal to the diffusion remains as such and the drift is almost equal. As a result the same thing happens to the p, both the currents are almost equal. As a result, theoretically when I go to the reverse bias I should have very very small current. This current also is only coming from the fact that because we are at a room temperature some electrons, which are every once in a while, although they are in equilibrium they will wander into the depletion zone.

This thermionic jump leads to a very small current, which is normally called as I saturation and this is due to the thermionic diffusion of electrons into the junction. So, in this sense the we have a simple p n junction. We just used a material and because of the property of the material, it develops a built in potential. Now, we apply a voltage to it, if I apply positive voltage, I get a huge current. This is because we have built in potential gets reduced, if I apply reverse bias I have more bias and the current substantially gets reduced. That is almost a very small amount of saturation current in there and this is basically your diode. So, you see in a very simple manner in a pictorial manner, if I take p n diode I can get the I V characteristics, which are dependent on I would apply the bias. This is how a p n diode then will work.

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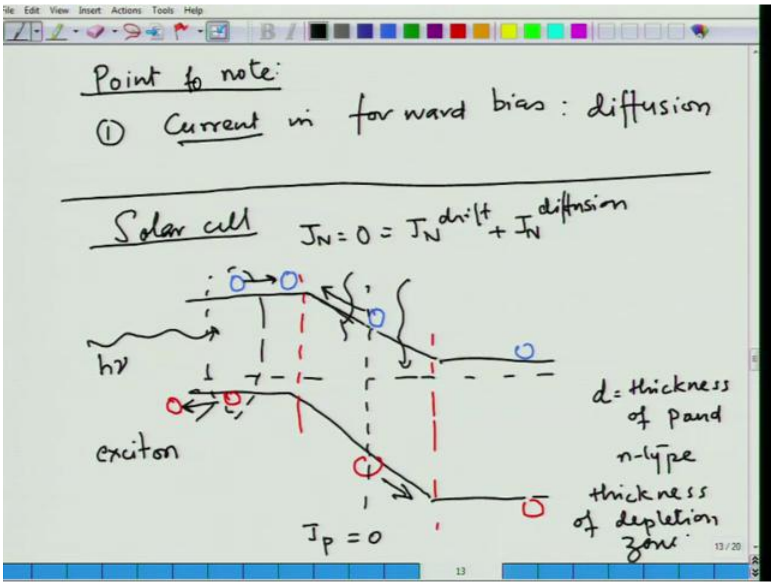

Point to note:

① Current in forward bias : diffusion

Solar cell $J_N = 0 = J_N^{drift} + J_N^{diffusion}$

$J_p = 0$

d = thickness of p and n-type thickness of depletion zone

Now, looking at the overall equations then the the points to note in this whole situation of a diode is that when when you have large current, current in forward bias. It is basically coming from the change in the built in potential, because of applying a forward bias and it is actually a diffusion current, because of the high concentration of the carriers in the n type. The barrier becoming less you have large amount of diffusion and injection of carriers in minority carriers in the p type that leads to the current. So, the current in a diode is a diffusion current of electrons and holes. It is not because of the applied voltage, so that is a considerable shift into in a diode characteristic compared to what you would see in a material.

In a material if you apply more voltage, the carriers are responding to the field and hence you are getting higher current. But in case of a diode because of the interface characteristics, it is a diffusion current that leads to a high current. In case of a diode and this is important because that allows you to make different kind of devices. Now, what we will see is how this equation will get change, when I when I apply a different type of situation. So, if I have a solar cell a solar cell is when you do not apply a voltage and you collect the open circuit voltage, in case of a solar cell looking at the same situation a solar cell in equilibrium. If I look at that is happening to the in the equilibrium J N is equal to 0, which is equal to J N drift plus J N diffusion.

Hence, no current is passing through this when I connect these through same thing is going to be true for the J P. J P is going to be 0. Now, if I bring in light and I am going to create electron and hole pairs and if I create that electron and hole pairs, I can create them in three different region possibly depending on how I bring in light? So, we have seen earlier in the earlier module that when I bring in light of the right photon light energy, then an electron which was in the valence band goes to the conduction band. It leads a hole behind this situation is considered an exciton. These excitons can break and move in either direction, if an exciton is created and it break the electron breaks and and hole breaks out from each, they are bound to each other.

So, if they break open in that case this electron becomes free and this hole becomes free, but if it is created in this region of p or n type p or n type material, then does not have a field in this area. The most of the filed in a p n junction is in this area the field in the p n junction is only around the junction in the depletion width. So, if this electron hole pair is created in either p or n type, it will not be collected by the two ends. On the other hand, if you are in the field area what is happening is this electron is going to because of the field, it is going to be moving up and this hole is going to be moving down. As a result you will generate a field a current in the material. Same thing same thing will be true for the exciton, if it is generated in the n type, it is not going to break open.

We collect it by the two end, so in order to work as a solar cell, it is important for a p n diode device that the electron and holes are generated in the depletion zone. Hence, when we are making the design of the device, it will be important to know what is the dimension of the depletion zone, with respect to the dimension of the area, which is beyond the depletion zone? So, thickness of the p type material is going to be important thickness of the p and n type and thickness of the depletion zone is also, this would be important for the solar cell point of view.

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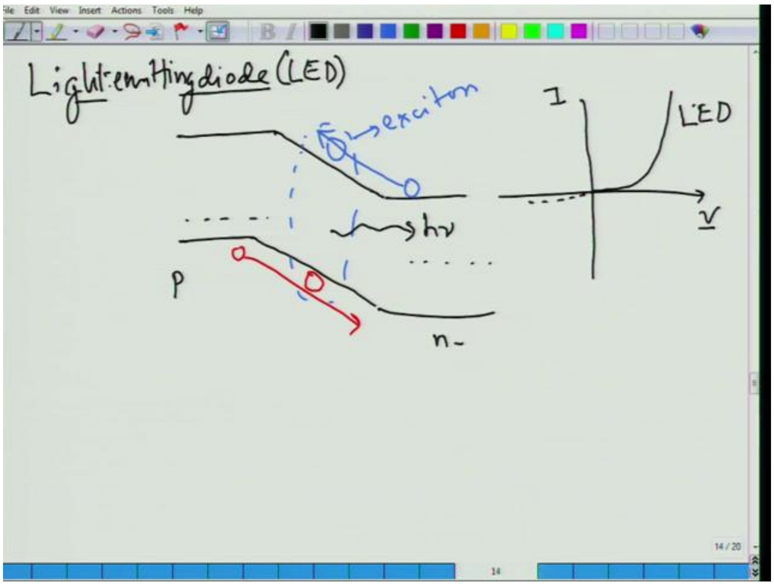

Now, if I look at the photo diode, we have the same situation, but slightly different. You do not have the light shining here, rather we apply a bias forward bias sorry this is a light emitting diode. Now, in the case of the forward bias, what is happening is you are having electrons diffusion of electrons from n type to the p type and of the holes from the p type to the n type. So, this is n type and this is p type and electrons are moving up in this direction, because of the forward bias applied and holes are moving in this direction. Once again the interaction takes place when it is in the depletion zone. If if you have enough electron and holes, especially they will come together at certain point and then they will generate excitons by binding with each other at the end.

What you will end up getting is when they recombine you will get a light out. So, basically light emitting diode works in a different region and the solar cell work in a different region. If I take a diode whose I V characteristics, we have just looked at then light emitting diodes work here. These are LED’s and for for the purpose of the solar cell, it works in the third quadrant, fourth quadrant. This is this is for the solar cell, so this is a very simple device, a p n diode, but a very useful device for making light emitting diode, which I used in many applications today and solar cells which are seen as the next alternative generation of energy.