Optoelectronic Materials and Devices
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Module - 04
Optoelectronic Device Physics
Lecture - 33
Fundamentals of p n junction contd

In the last lecture, we had started looking at the I V characteristic of an ideal p n junction, and we stopped at a point in deciding on what happens in the forward bias of p n junction.

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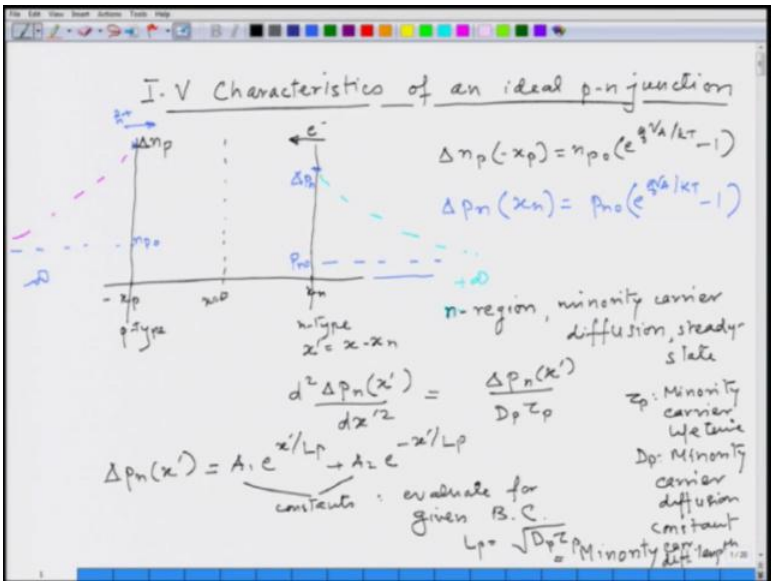

I-V Characteristics of an ideal p-n junction

$\Delta n_p(-x_p) = n_{po}(e^{qV_A/kT} - 1)$

$\Delta p_n(x_n) = p_{no}(e^{qV_A/kT} - 1)$

n-region, minority carrier diffusion, steady-state

$x' = x - x_n$

$$\frac{d^2 \Delta p_n(x')}{dx'^2} = \frac{\Delta p_n(x')}{D_p \tau_p}$$

τ_p: Minority carrier life time

D_p: Minority carrier diffusion constant

$$\Delta p_n(x') = \underbrace{A_1 e^{x'/L_p} + A_2 e^{-x'/L_p}}_{\text{constants}}$$

constants : evaluate for given B.C.

$L_p = \sqrt{D_p \tau_p}$ = Minority carr. diff. length

So, if you recall what we have done so far is that, this is the metallurgical junction at x is equal to zero and we have a depletion width in a depletion approximation, this is the limit for in the n side n p side. So, this is the n type side and this is the p type side and here we have the edge of the depletion width. This should let me assume a equally doped semiconductor on both the sides. So, it is kind of in the centre although it does not matter we have not really put in any values here.

Now, for this for this p n junction, we had shown that when we have it in a forward bias the electrons which are getting injected into the p side. They would be giving rise to an excess electron carrier concentration delta n p here. This we had calculated that delta n p at the point at the edge of the depletion width at minus x p is given by n p o exponential q V applied k T minus 1. Similarly, we had shown that holes which are going to be injected into the n side will be given by delta p n.

We had taken an obtained an expression for that at the value x n, which is edge of the depletion width here. That will be given by p n o exponential q g V V A V A k T minus 1. Now, this basically has now then given us that the electrons which are injected as minority carrier on the p side and holes which are injected as minority carrier on the n side are giving rise to this concentration at the band edge. We know very far from the from the band edge its concentration has to come down to the equilibrium value, which would be the p value at in the on the n side in equilibrium and on this side it will be the n value on the p side in equilibrium.

So, the injected electrons in the p side at the edge it is this concentration far from the edge at point minus infinity, it has to come down here. So, I am drawing some line here and we have to still figure out what this expression is going to be? So, the electron concentration from the edge of the depletion width has to reduce to the equilibrium electron concentration on the p side. Similarly, on the n side the hole concentration from the edge has to somehow reduce to the equilibrium concentration on the n side. This is what we need to solve what this concentration profile is going to be, we know the boundary condition, boundary condition at x n.

This is the excess carrier concentration at plus infinity, it is going to come down to p n o. In this on this side boundary condition is delta n p at the edge and at negative infinity it will reduce to n p 0. So, with this boundary condition it is the problem of a continuity problem of a minority carriers, so let us let me solve it for the p region first, for the n region first. For the n region, this is a problem of minority carrier diffusion of holes. We will, we are we are interested in a solution, when I have applied a voltage, so I, we are looking at a steady state solution, what would happen?

So, in a steady state what is going to happen? So, if I look at the minority carrier diffusion equation that we have developed in module 3, I have I basically need to solve in the n region for a equation, since D delta p, T T will be 0. This would reduce to the excess carrier concentration on the n side. I am going to do some change in the reference here. Instead of writing it in x, I am going to write it in x prime and basically what I am doing here is x prime is a new scale, which is x minus x n. So, basically I am shifting the origin from 0 to x n that just helps in writing the solution in a more friendlier form.

So, this would be the new diffusion equation that we need to solve, in order to figure out the current due to this divided by D p tau p. Now, we know what tau p is. If you recall tau p is the minority carrier life time in n side in minority carrier life time. D p is the minority carrier diffusion constant. I had also given that our general expression for this type of differential equation is a general solution for this is given as delta p of n, this we have also covered in the module 3. So, a general expression solution would be of this type a one exponential x prime over L p plus A 2 exponential minus x prime over L p.

The these are the constants that we need to evaluate for given boundary condition. So, when we n what was L p? L p is nothing but a square root of D p tau p. This is also generally given a name this is called minority carrier diffusion length, diffusion length. So, basically what it is saying is L p is a product of the diffusion constant and a life time of the minority carrier, so it is kind of gives you the average distance. The minority carriers can move in a material that is what a L p signify in case of a diffusion problem. So, when I put in the boundary condition, which I have already defined over here. Basically I am going to get a solution for on the in the n region.

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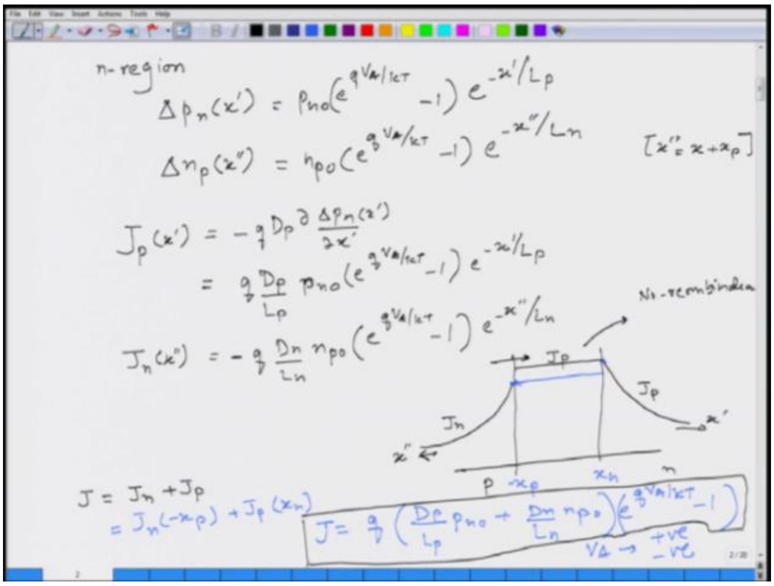

n-region

$$\Delta p_n(x') = p_{no}\left(e^{qV_A/kT} - 1\right) e^{-x'/L_p}$$

$$\Delta n_p(x'') = n_{po}\left(e^{qV_A/kT} - 1\right) e^{-x''/L_n} \qquad [x'' = x + x_p]$$

$$J_p(x') = -q D_p \frac{\partial \Delta p_n(x')}{\partial x'}$$

$$= q \frac{D_p}{L_p} p_{no}\left(e^{qV_A/kT} - 1\right) e^{-x'/L_p}$$

$$J_n(x'') = -q \frac{D_n}{L_n} n_{po}\left(e^{qV_A/kT} - 1\right) e^{-x''/L_n}$$

$$J = J_n + J_p$$

$$= J_n(-x_p) + J_p(x_n)$$

$$\boxed{J = q\left(\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po}\right)\left(e^{qV_A/kT} - 1\right)}$$

$V_A \to$ +ve, -ve

The solution is going to be delta p of n x prime, this will be given by p n o exponential q V applied over k T minus one exponential minus x prime over L p. So, although I had earlier just drawn it some figure on how this concentration will change, now I have a expression for it which says that this is going to change in x prime as a as in exponential form, which means that I was correct in assuming it this form. The excess carrier concentration is going to exponentially decrease to this value. This what we have obtained.

So, similarly without doing it again I can show that what is going to be the hole concentration. So, del n of p in again may be x double prime, where I would shift it to minus x p. I can show that this is going to be the n p o exponential q V A by k T minus 1 exponential minus x double prime over l n, because now this will be the minority carrier diffusion length for electrons on the p type side. So, this is my electron concentration, I can plot that that is also reducing exponentially from these boundary condition going towards minus infinity.

So, once we have how the minority carrier concentration is changing in an n p region. Now, the problem is reduced to finding out what would be the total current. So, because of diffusion of these minority carriers which are injected on the opposite side, I can calculate the current, the current is going to be let us say first calculate; due to the holes the current in the x prime scale remember x double prime here is going to be x plus x p. So, x prime is going to be negative of the whole current is going to be negative of q diffusion constant the current density, the concentration that I have just calculated n del x.

Because this is the only thing that is existing there is no field in the, in the n region. So, this would be the current that I need to figure out in the n region due to the hole a hole injection taking delta p n x prime. Then taking the differentials this current then comes out to be q D of p over L of p n times sorry p at n o side exponential q V A over k T minus 1 exponential minus x prime over L p. So, this would be the current at any at any parameter x prime, which has been moved from x is equal to 0.

This would be the current due to the holes in the n region. Similarly, the current due to the electrons on the other side is going to can be written as q D of n L of n p o. This term remains the same here for electrons also and this will be x double prime over L n. So, what we are talking about now here is that, I have an expression which is also a exponentially changing current due to the injected hole.

This is expression for J p and then I have a expression for J n in terms of this new scale of x prime and x double prime. So, this is how the currents changing in this region. I have I am interested in finding out what is the total current J which is going to be J n plus J of p, because the electron current is going to add to the hole current this will be given by J n plus J of p and the I do have a negative sign here at minus x p when I calculate that.

So, this is going to be negative current and you evaluate that current, so the total current is going to be the current density due to electron and holes. Because whatever electrons are in holes are injected in the n side, they are being injected from this side. We are assuming there is no recombination in the depletion zone. So, no recombination here which means all the electrons which were which are here they came from this edge. They survived there was no recombination of that so the current inside the depletion region is also J p same thing we are assuming for the electrons, which are injected on the p side.

We are saying that there is no depletion the current remains constant in the in the depletion region. The total current is going to be J n plus J p evaluate J of p J of n at minus x p plus I can evaluate J of p at x n. So, this is in the, this is minus of x p this is at x n, so that is the current that I want to evaluate. If I evaluate the current here that is the total current because inside the depletion zone it remains constant. That is a total current that that is flowing in the device and that is what I need to evaluate.

So, I will take my current expression and put in the values for x prime and x double prime such that; x is x n or minus x p. If I do that, I will get an expression for the total current density and the total current density expression is going to come out to be J is equal to; if I am going to add this and put in the value it is going to be q times D p over L of p n 0 plus D n over L of n and p 0 exponential q V V A k T minus 1. So, this is my current density in a p n diode. Now, it is important to know that so far in all this derivation we have not said whether V A is positive or negative?

Basically, V A can be, it can be both positive or negative. In the positive it is going to be a forward bias case and if I take V A to be negative it is going to be reverse bias case. So, basically then what I am saying is that I have a expression now which is the current density voltage expression for my ideal p n junction. This will give me my J V characteristics for the ideal p n junction. For forward bias I will put the positive voltage for V A and for the reverse bias, I will put the negative voltage for V A. So, let us look at the behaviour of this function, if I plot this function in the general equation, what I am going to get is, I am now going to plot it on J versus V.

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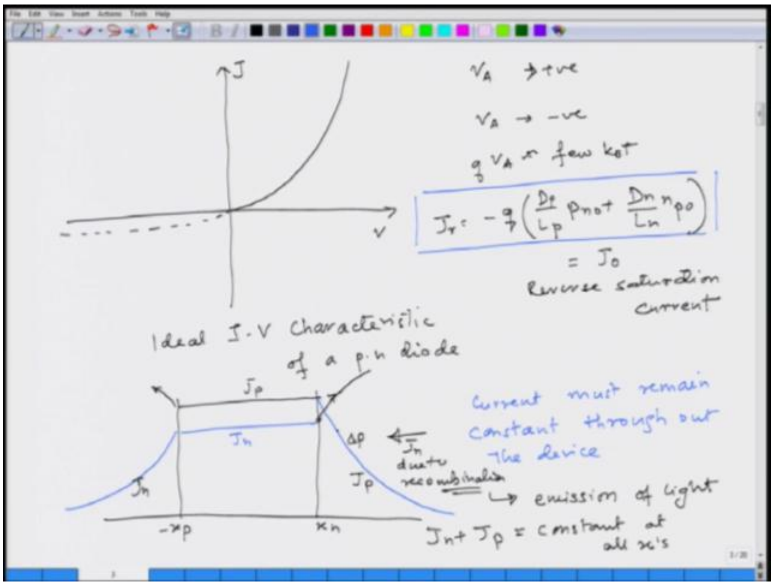

$V_A \rightarrow +ve$

$V_A \rightarrow -ve$

$qV_A \sim$ few k_BT

$$\boxed{J_r = -q\left(\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po}\right)}$$

$= J_0$

Reverse saturation current

Ideal I-V Characteristic of a p-n diode

Current must remain constant through out the device

$J_n + J_p$ = constant at all x's

So, when V A is positive in a forward bias, this is basically giving you an exponential dependence. The current increases exponentially when V A is negative in the reverse bias, then as soon as the V A is V A is or q of V A is approximately few k b T’s k T’s, I will find that the expression here this one becomes goes towards 0, which means that in reverse bias my current density in reverse bias is nothing but negative of q times D p over L p p of n o plus D of n over L of n n of p o.

So, this is my current density in the reverse bias and as you can see it does not depend on the voltage, so in the reverse bias I am going towards constant current, which is given by this. This is also known as the reverse saturation current, this is called the reverse saturation current. So, this is the ideal I V characteristic of a p n diode. It basically gives a behaviour in which in the forward bias you are exponentially increasing current and in the reverse bias you have very small current effectively it is saying it.

This is a device which can work as a rectifier it will allow current to follow in flow in one direction, but in the reverse bias it will not allow it to flow. Hence, many devices can be made from this particular diode. Before we go on to some applications of device, it is good to spend some time in understanding this behaviour on what is happening inside the device? So, if this is the behaviour, how do we see the overall current inside the device? So, we had calculated it we had calculated this behaviour assuming diffusion current, due to the minority carriers in the opposite type of region in for the electrons in the p type and for the holes in the n type.

We evaluated at the point where that there was no recombination in the depletion zone. So, if I look at the current in the inside the device my depletion zone, I am looking at the current inside the device x n minus x p, I know that I have calculated whatever is the hole current and the electron current inside the depletion zone. It is the same because there is no recombination, but I also told you that this current is exponentially decreasing outside, which means this current is decreasing exponentially on this side. It is also decreasing exponentially on this side and almost going to 0 in this side.

Now, this is does not make sense because the current is something which must be current must remain constant throughout the device. So, what is happening? So, in this region of course, it is constant this and this is a still total constant, but here you have J p which is getting reduced in this direction. Here this is a J n which is getting reduced, so that means in order to keep it constant the J n must increase. The, at the rate where it is going down the J n must also increase to compensate to have it all constant, right?

So, as much as it decreases the same amount of J n must increase, so it must increase here. Now, where is this increase coming from this increase is coming from and it will continue on in order to make sure that total J n plus J p will remain constant always. This is coming from because as electrons are diffusing out these sorry, holes these extra holes which are diffusing out they are also getting recombined with the majority carriers. But majority carriers must be getting supplied from outside.

So, there must be a J n due to recombination, so there is no recombination here, but here the excess carriers must be recombining with the electrons, which are being supplied from the outer circuit. Hence, this reduction in the diffusion hole current is being made up by that electron current which is coming for the recombination of holes. Now, this is a important part because when we will use the p n diode as a LED, this recombination is what is responsible for the emission of light.

So, if the p n diode is made of a direct semiconductor the recombination in this region is leading to emission of light. Similarly, when the electron current is getting reduced here, which basically means that the hole current must be increasing to make up for the difference in this reduction, such that J n plus J p must remain constant. So, inside the device J n plus J p should be constant at all points, at all x. So, this is what is happening in the device, no recombination here in an ideal device, but recombination must be taking place in the region where your excess carriers.

This recombination is what is the reason for having emission in the forward bias? So in forward bias the carriers are being injected. What is happening in the reverse bias? In the reverse bias see the current that is they are in the reverse bias is about this much. So, in the reverse bias there is no injection of currents, it is actually and it is in the negative direction. So, it is actually rather than pushing minority carriers, the holes in this direction it is pulling the minority carriers. So, the current is going in the opposite direction, this current is in the opposite direction.

So, in the forward bias, the minority carriers are being injected into the n and p side in the reverse bias. The minority carriers are being extracted out of the an n p side. Since, there is a already a built in field those extracted carriers can drift and give you a overall reverse saturation current. So, this is a situation of an ideal p n diode it, where you are using injection of carriers in the forward bias and the thermionic collection of carriers in the reverse bias giving you the I V characteristic of an ideal p n junction. Now, before we close the discussion on ideal characteristic of p n junction, it is also very important to realize another phenomena which happens in ideal p n junctions and that is about reverse breakdown.

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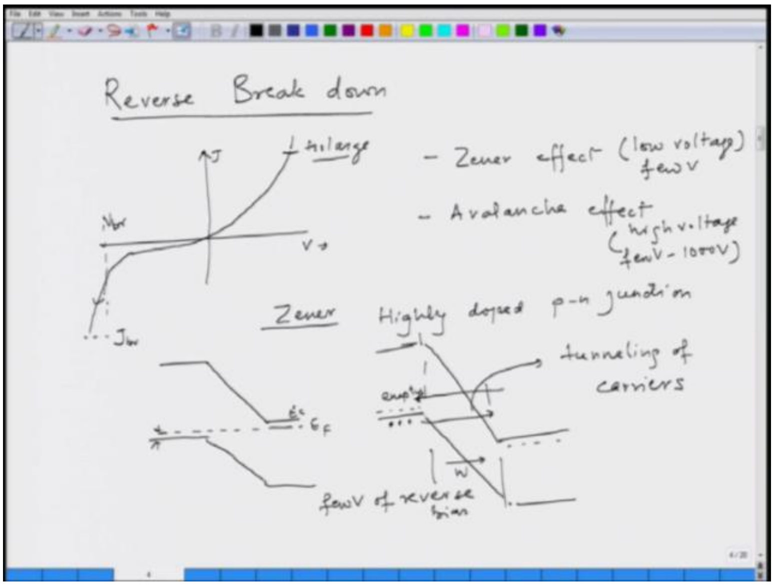

So, we have seen that ideal behaviour should be something like this, but then sometimes when one goes to very large values of reverse field one finds breakdown of the device, which is shown like that. Let me insert a scope here very large increase in the reverse current at a certain value of the voltage, which is known as a breakdown voltage. So, basically what is happening is that the ideal p n junction is deviating at this voltage from its ideal behaviour and it can happen for various reasons.

This breakdown can happen due to two reasons; basically the first one is known as a z zener effect, the second one is known as the avalanche effect. It is important to note that this breakdown necessarily may not be bad, it is not, it is not the breaking down of the device in the sense that it has, it will be permanently damaged. People have used this breakdown region effectively controlled it in order to use a, to even use it as a device. So, one can have a breakdown then go back to the lower voltages and then come back again, so this can be reproduced.

This breakdown can be reproduced and it does not necessarily mean the damage, the damage can occur because the currents may become too large. The J breakdown may become too large and because of that large current and the heat generation due to that you may the device may get damaged. But otherwise this particular breakdown that we talk about in p n junction can be used a even constructively for making a different kind of device, there is something called zener diode that one can make. This burning of the device can also happen in the forward direction if the current becomes too large.

If the current become too large one can also have damage of the device. So, one has to limit the operating currents of the device, keeping in mind how much heat can be dissipated by the device? That is why thermal management of devices are very important. So, let us talk about what are these two different kind of breakdowns are? The first one zener effect; this occurs normally at low voltage. Something like few volts, this will occur at few volts. This will occur at high voltage, even from few volts to about maybe thousands of volts.

The zener effect is occurring normally when you have highly doped highly doped p n junctions. Now, what happens in the highly doped p n junctions that your p n side is very close to the conduction band, which means in equilibrium a highly doped p n junction in equilibrium will show that it is something like this. Because it is on this side n side it is very close to the conduction band and on the p side it is very close to the valance band of the of the material. So, this is a highly doped p n junction.

Now, if it is in even a small amount of reverse bias, so even few volts of reverse bias, what happens is that the barrier will increase and effectively what one finds is that the electrons here, the electrons that are here are finding empty states over here. So, the barrier has increased and this is the depletion width, call it W earlier a depletion width. So, the empty states here for electrons to come the same way there are holes here. Then there are one would find that there are empty states there would be empty states for holes on this side.

So, this is not drawn really to the scale, it is going it has be the since it is highly doped it has to be a very sharp picture. Let me just redraw draw this at this point, so it should be a picture where the hole of it is like this. So, the electrons are going to be able to inject into directly. They can inject into directly into the empty states available here.

Similarly, holes can inject into the empty the holes can find empty states over here. So, this effect if this thickness if the width depletion width becomes small with the reverse bias and it is highly doped, then this thickness is small enough to initiate a phenomena called tunnelling of carriers. Because of that one finds there will be current because of tunnelling of carriers directly into the other side. That is the overall zener effect.

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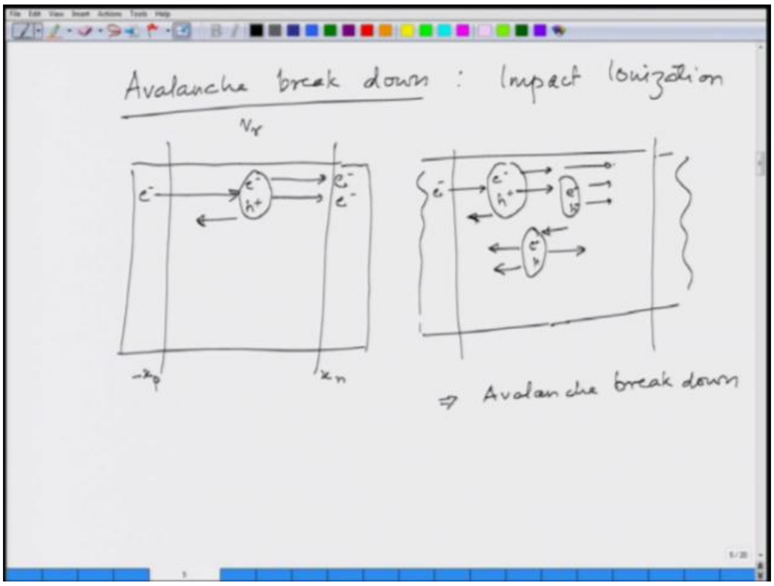

Avalanche break down : Impact Ionization

⇒ Avalanche break down

On the other hand the avalanche effect is something which happens at very large voltages avalanche breakdown. This is taking place due to a process that we discussed in the module 3; that is known as impact ionization, which means that you can create in generation of electron hole pairs. If I am coming with a very high energy electrons, it can it is getting scattered from lattice or from impurities. Its energy is high enough that it can ionize the lattice and create a electron hole pair.

That was discussed earlier in module 3 and avalanche breakdown is a is a effect of that kind of breakdown. So, in this particular case what we find is because of the impact ionization of the, of the holes. So, if I again look at the region that I have been plotting so far, if I am looking at the depletion region, this is minus of x p and x n, then I know that electrons are getting in the reverse bias electrons are going in this direction. This is in the reverse bias V r. Now, this electron which is going through here can have a scattering event to create a electron and hole pair, because the energy is high enough, it is, it occurs at a very high voltage.

Its energy is high enough it creates a electron and hole pairs and gives some energy that loses some energy. But still its energy is high enough, so that it continues on and you collect two electrons here. The hole which is generated here will go back, so this is one ionization impact event because of highly energetic electrons in the depletion region in the reverse bias you created a electron hole pair, which is due to impact ionization. Now instead of one electron you have two electron.

Now, this may not seem so drastic, but what happens is that if you are having high enough voltage, then the electron created in one impact ionization phenomena can again ionize the lattice. So, one can think of it in actual situation. You can have a p n junction depletion region, a electron which is crossing the depletion region creates one electron hole pair here. Two electrons move in this direction, one holes moves in this direction this electron again creates another electron hole pair.

So, now you have one, two, three going in this direction and a hole going back. This hole can get enough energy to create another electron and hole. There will be two holes going in this direction and another electron going here. So, you can see how this avalanche why we call it avalanche effects starting from a single electron, now the number of electrons which are giving rise to the current is one, two, three, four. This is just showing it in a cartoon form. The number of holes which are generate adding to the current is one, two, three.

So, that is why even a single electron, if impact if the energies can become high enough in the depletion region for the carriers, it can start an avalanche effect and because of this one has the avalanche breakdown. So, this then completes our understanding of a ideal p n junction and what to summarize so far, what we have understood about p n junction.

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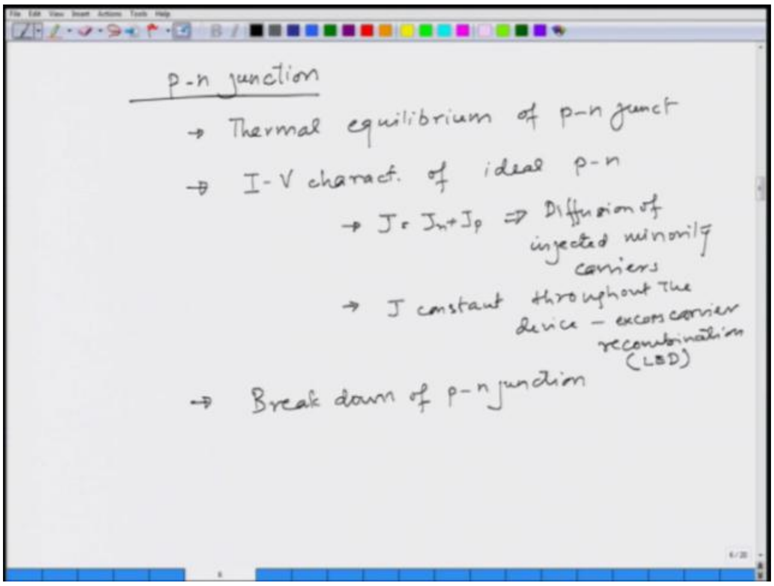

p-n junction

→ Thermal equilibrium of p-n junct

→ I-V charact. of ideal p-n

→ $J = J_n + J_p$ ⇒ Diffusion of injected minority carriers

→ J constant throughout the device – excess carrier recombination (LED)

→ Break down of p-n junction

We started with a qualitative picture of how p n junctions operate? Then we quantified the thermal equilibrium status of what is the charge balance and the fields in the thermal equilibrium of p n junction? Then finally, we looked at how to derive a I V characteristic of a ideal p n junction. The important point there to remember is in the forward bias, what is the total current? The total current is due to the diffusion of minority carriers diffusion of injected minority carriers.

We also looked at how the total current should remains J should be constant throughout the device. This requires excess carrier recombination and this is how one makes LED’s in a direct band gap semiconductor. We also looked at in the ideal characteristics the breakdown of a p n junction and the fact that one can have a controlled breakdown of p n junction. That particular can thing can also used as a device in the next lecture. We will show that how one can fabricate p n junction and that is the real power of semiconductor technology in today’s world.