Solar Photovoltaics :
Fundamental Technology and Applications
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Lecture - 09
p-n Junction Model of Semiconductors

Welcome everyone. In today's lecture we learn about p-n junction diode. You remember in the last class, we have learned the different classes of the semiconductor based on doping, based on the energy band gap, and also based on their positions in the periodic table. So we have seen that based on the doping a semiconductor can be classified either as a p type semiconductor or as an n type semiconductor.

In p type semiconductor hole become the majority charge carrier and in n type semiconductor electron become a majority charge carrier. And both of them are example of extrinsic or impure semiconductor. On the other hand, we can also differentiate semiconductor based on the position of the band gap like direct band gap and indirect band gap.

But as we have mentioned in the last lecture, when we make p type semiconductor and n type semiconductor the next question is that how can we join them together to make a p-n junction. Because for most of the optoelectronic devices, it is the p-n junction which forms the heart of the device. So the question is whether we can simply add the p and n site and make a p-n junction.

And what we have seen that this is not the case. Usually in the engineering aspect what we do first we grow one particular type of semiconductor like n type semiconductor and top up that we dope that with a p type semiconductor. Now what is the reason behind that? What we mentioned that in the depletion region or at the boundary between the p and n junction we form a depletion region which is deployed of any charge carrier.

We will learn in details about that today. Depletion region which is also sometimes called as a space charge region.

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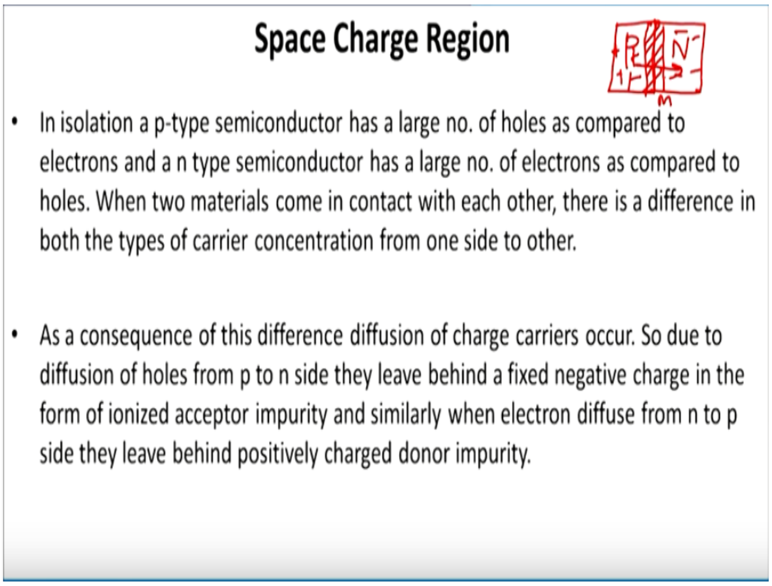

Space Charge Region

- In isolation a p-type semiconductor has a large no. of holes as compared to electrons and a n type semiconductor has a large no. of electrons as compared to holes. When two materials come in contact with each other, there is a difference in both the types of carrier concentration from one side to other.
- As a consequence of this difference diffusion of charge carriers occur. So due to diffusion of holes from p to n side they leave behind a fixed negative charge in the form of ionized acceptor impurity and similarly when electron diffuse from n to p side they leave behind positively charged donor impurity.

In isolation a p type semiconductor has a large number of holes as compared to electrons. An n type semiconductor has a large number of electrons as compared to holes. When two materials come in contact, there is a difference in both the type of the charge carrier concentration from one side to the another side. And when you mix them together at the junction you make a juncture which is called that metallurgical junction.

For example, if this is my P type semiconductor and if this is my N type semiconductor, so at the junction it is called metallurgical junction. And the area around this junction which extends both in the P side and N side the shaded area that is called the space charge region or depletion region. So as a consequence of the difference of the diffusion of the charge carrier, so the accumulation of the charge carrier on both side will be different.

So what we mean here in the P side, since the positive charge carriers are majority charge carrier and on the N side electrons are majority charge carrier, so there is a difference between the charge carrier concentration on both side. So when I combine them together or when I join them together, the positive type of charge carrier will diffuse to the other side and negative charge carrier that is the electron will diffuse from the N side to the P side.

So due to the diffusion of holes from the P side to N side so they leave behind their fixed negative charge in the form of ionized acceptor impurity. And similarly, when electron diffuse from N side to P side they leave behind a positively charged donor impurity atom. Now this impurity atom which they leaves behind they are immobile. So they are deployed of any movable charge carrier.

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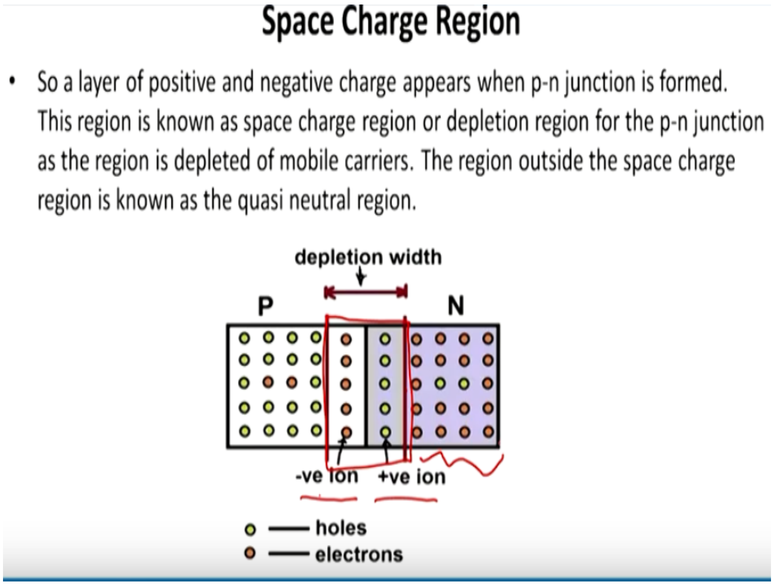

Space Charge Region

- So a layer of positive and negative charge appears when p-n junction is formed. This region is known as space charge region or depletion region for the p-n junction as the region is depleted of mobile carriers. The region outside the space charge region is known as the quasi neutral region.

Finally, what it forms? A layer of positive and negative charge which appears in the both side of this metallurgical junction when you fabricate the p-n junction. So this region which is shown in the picture here is called the space charge regions or depletion region. Why it is a depletion region? Because it is depleted of any majority charge carrier.

Once the hole has moved from the p side to n side, it leaves behind the negatively charged ion. When the electron has moved from n side to p side it has left positively charged immobile impurity ions there. So this impurity ion which are negatively charged and positively charged on both side of this junction, they cannot move. They are not mobile charge carriers.

That is why this area is deployed of any movable charge carriers and that is why they are called depletion area. The region outside the space charge region as known as quasi neutral region. So the region outside the depletion region that is known as quasi neutral region, because there are some charge carrier concentration either negative or positive depending upon it is n side or p side exist there.

So that is why it is called a quasi neutral region. Let us take a look at how the band diagrams forms in p-n junction diode.

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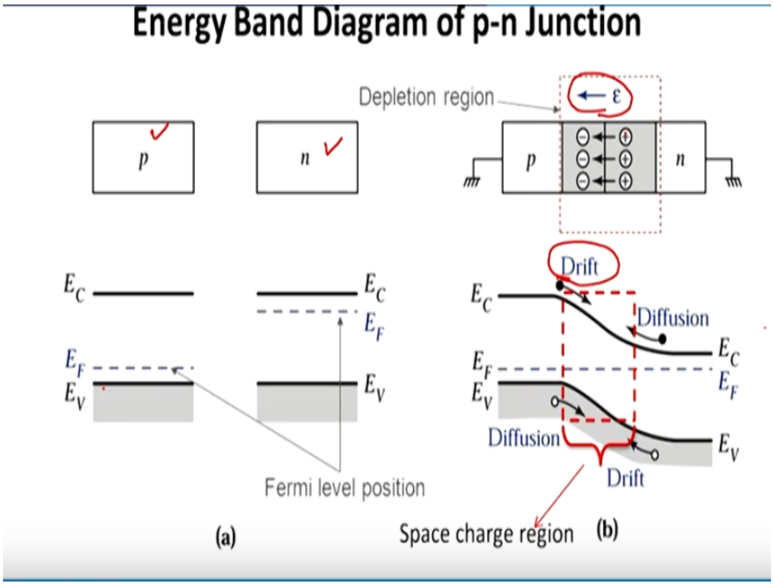

Energy Band Diagram of p-n Junction

We have a piece of p type semiconductor and we have a piece of n type semiconductor on the right side. Now we can draw the band diagram corresponding to this p type semiconductor and n type semiconductor. For a p type semiconductor, this is the valence band and this is the conduction band. And as we know in since in p type semiconductor holes are majority charge carrier, the Fermi level lies close to the valence band.

And in n type semiconductor electrons are the mobile charge carriers or they are the majority charge carriers. So here Fermi level lies close to the conduction band and that is what we have drawn the position of the Fermi level when p and n type semiconductor are isolated. Now in a p-n junction, we combine the p side and n side.

What happens here the electrons they started moving from the n side to the p side and the holes which are positively charged they moves from the p side to n side. And that happens due to the diffusion. That is due to the difference of the charge carrier concentration. This kind of motion is called diffusion. But there is one more types of motion also exist in this semiconductor which is called drift.

And as we have learned that drift is due to the external electric field. Now once this negatively charged electron and positively charged hole moves around on the other side, they leaves behind a negatively charged impurity and positively charged impurity on the other side. Like in the p side you see a negatively charged impurity is there and in the n side there is a positively charged impurity are there.

So because of this charged impurity ions an electric field generates across the depletion regions, which operates from the positive side to the negative side. And because of this electric field or because of this inbuilt electric field, a drift of the charge carrier occurs. So in addition to the diffusion, we have now drift of the charge carrier in semiconductor.

So when we combine the p type and n type semiconductor, we get a band diagram which now bends and it bends in such a way that Fermi level positions itself so that it close to the valence band in p side and it close to the conduction band in n side. So that is the resultant band diagram of an p-n junction diode.

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p - n junction model

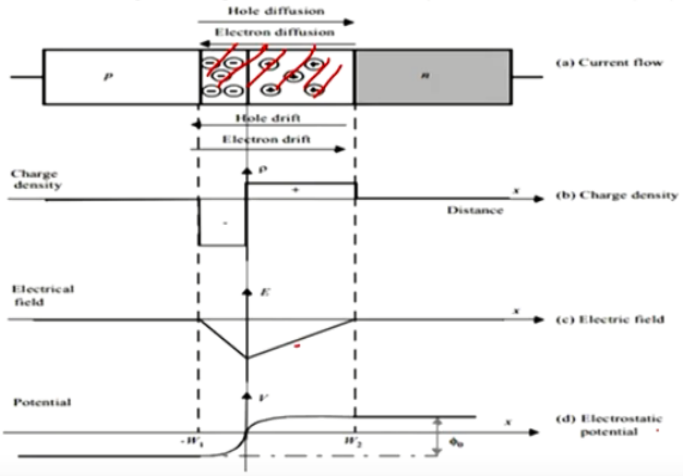

Figure 3.2 The abrupt *pn*-junction under equilibrium bias.

We can also plot how the charge carrier density, how the electric field, and how does the potential looks like in the semiconductor. If this is the p-n junction which has negatively charged immobile ions here and the positively charged immobile ions on the n side near the junction, so because of electron diffusion happens from the n to p side and hole diffusion happens from the p side to n side.

And my depletion regions is in the shaded area so the whole drift is happening from the n side to the p side and the electron drift is happening from the p side to the n side.. And why this drift is happening? This drift is happening due to the inbuilt electric field, which has been generated due to the immobile ions across the junction. Now since there is an electric field, we can also calculate the corresponding charge density.

The corresponding charge density has been plotted in this diagram, which you can see as a state function. So which is negative on the left hand side and positive on the right hand side. The corresponding electric field which is obtained by differentiating the potential with respect to the position has a shape like a triangle as shown in the third diagram.

As you can see, it first increase in the negative direction, then after reaching a particular point, then it again increase. Similarly, one can draw the potential which is drawn in the last diagram, which has a shape which first changes from the negative direction and looks like a IV curve geometry near the junction and then again flattened on the right hand side.

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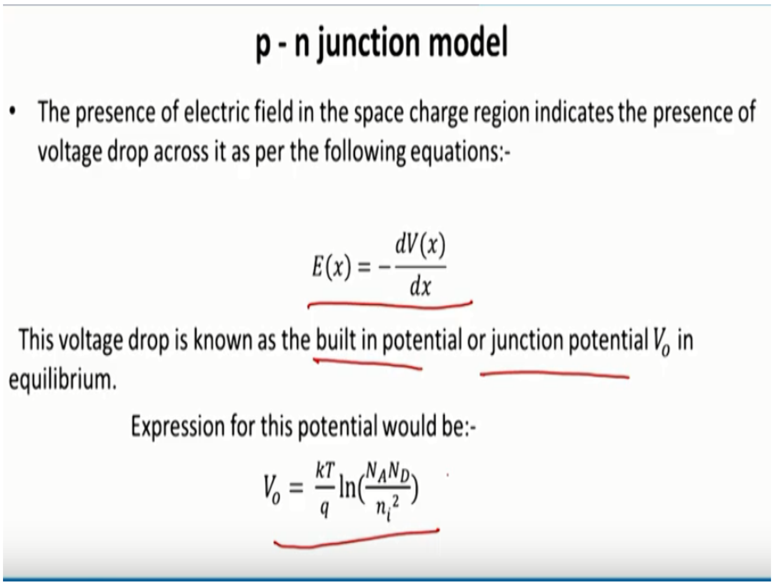

p - n junction model

- The presence of electric field in the space charge region indicates the presence of voltage drop across it as per the following equations:-

$$E(x) = -\frac{dV(x)}{dx}$$

This voltage drop is known as the built in potential or junction potential V_0 in equilibrium.

Expression for this potential would be:-

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

The presence of the electric field in the space charge region indicates the presence of the voltage drop which is given by the following equation electric field E is minus dV dx. It is the first derivative of the potential with respect to the position. The voltage drop known here is sometimes also called built in potential or junction potential V naught.

Expression of this built in potential is given by V naught is equal to kT time by q where T is the temperature, q is the charge, k is a constant, ln this is not the log with respect to 10 but this is ln, remember this. And inside the bracket there is N A which is the concentration of the acceptor impurity times N D which is the concentration of the donor impurity divided by n i square which is the intrinsic carrier concentrations.

When one can derive an expression for this built in potential, but that we will keep it here.

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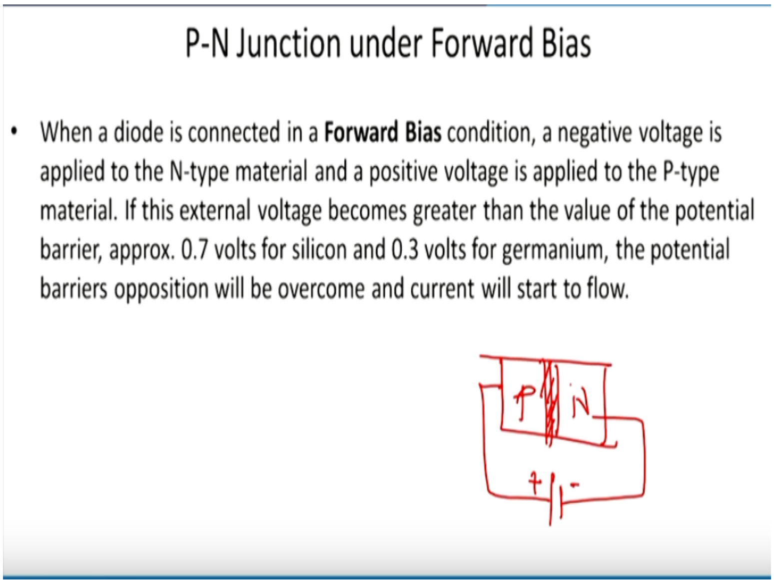

P-N Junction under Forward Bias

- When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.

Now what will happen if we apply some external voltage to this p-n junction. Now I can apply the external voltage to this p-n junction in two different ways. I can either add the positive terminal of the battery to the P side or I can add the negative terminal of the battery to the P side. Depending on that we say that a p-n junction diode can either be a forward biased diode or it can be a reverse bias diode.

When a diode is connected in a forward bias condition a negative voltage is applied to the n type material and a positive voltage is applied to the p type material. So if this is the p-n junction if this is the P side and if this is the N side. So we apply the voltage in such a way that the positive terminal of the battery is connected to the P side and the negative terminal of the battery is connected to the N side and that is called the diode is in a forward bias condition.

If the external voltage become greater than the value of the potential barrier, which is approximately 0.7 volt for silicon and 0.3 volt for germanium, the potential barrier oppositions will overcome and current will start to flow. So there is a depletion region or space charge regions which exist at the junction between p type and n type and the value of this potential near this junction is 0.7 eV for the case of silicon and 0.3 volt for germanium.

Now if the external voltage is higher than this 0.7 volt or 0.3 volt then what will happen? The external field will apply a force so that now the holes and electron can cross the junction and get a current. And those kind of currents will be now responsible for getting the so called forward bias current.

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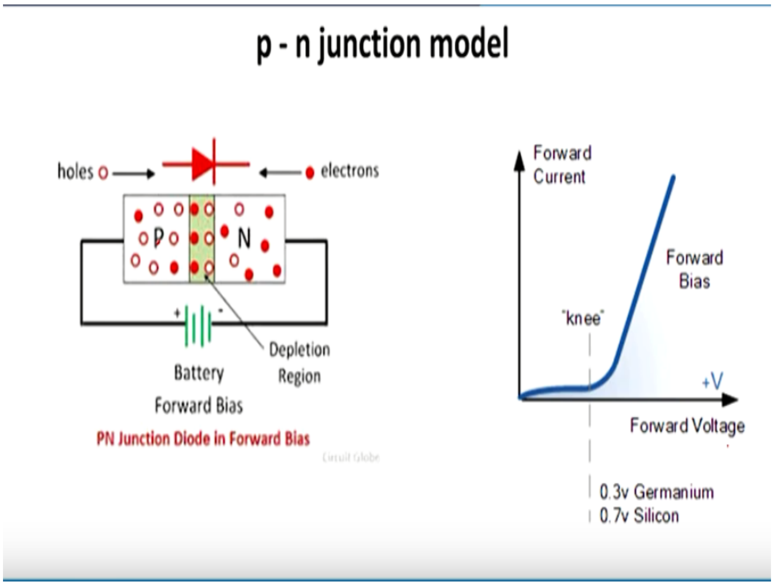

p - n junction model

PN Junction Diode in Forward Bias

We are showing here the p-n junction diode in a forward bias condition. So the P side you see there are both two different types of circles are there. One just solid red circle another is a empty or hollow red circle. The hollow red circles are holes and the solid circles are the electron. If you look at carefully to this diagram, we have more number of hollow cells or hollow circles than the number of the solid circles. So why is that?

Because it is a p type semiconductor, it has more number of holes than the electrons. Whereas in the case of in type, it has more number of electrons than the hole. Now when I diffuse them together or when I combine them together, so what can happens some of the holes has diffused from the left side to the right side which comes near the junction and some of the electrons which can diffuse and comes from the left side to the right side.

Now we have added a battery in such a way that the positive terminal of the battery is connected to the P side and negative terminal of the battery is connected to the n side. And the shaded area or the gray area here is the depreciation regions. The current versus voltage characteristics in a p-n junction diode is shown in the right side diagram under the forward bias condition.

So in the x axis, we have the forward voltage and the y axis we have the forward current. As you can see that as you increase the voltage first the current remains constant until a particular value, 0.3 volt or 0.7 volt. Then all of a sudden it started increasing. So the point where it breaks or where it started increasing that is called the knee point and that is the potential barrier or that is the minimum amount of voltage we need to offer to the p-n junction diode to cross the depletion region.

And that the value is 0.3 volt for the case of germanium and 0.7 volt for the case of silicon. Once we cross the depletion region, then current increase monotonically.

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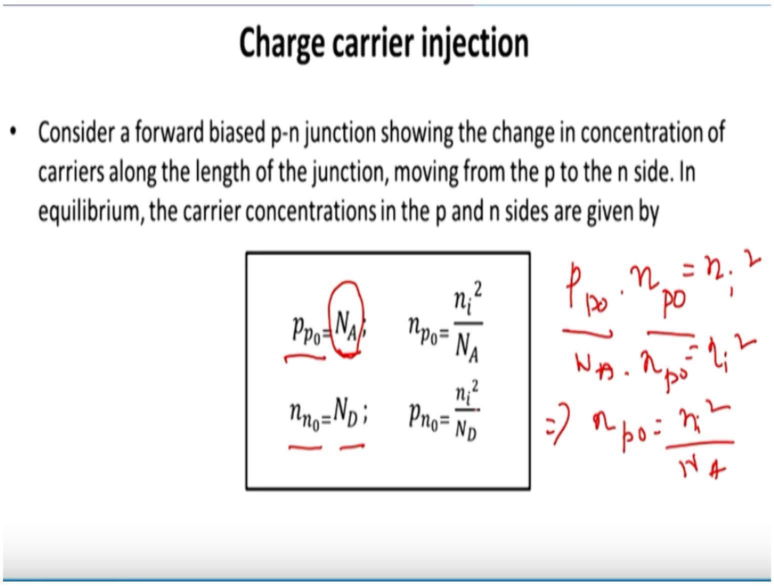

Charge carrier injection

- Consider a forward biased p-n junction showing the change in concentration of carriers along the length of the junction, moving from the p to the n side. In equilibrium, the carrier concentrations in the p and n sides are given by

$$p_{p_0} = N_A; \qquad n_{p_0} = \frac{n_i^2}{N_A}$$

$$n_{n_0} = N_D; \qquad p_{n_0} = \frac{n_i^2}{N_D}$$

$$p_{p0} \cdot n_{p0} = n_i^2$$

$$N_A \cdot n_{p0} = n_i^2$$

$$\Rightarrow n_{p0} = \frac{n_i^2}{N_A}$$

So let us consider a forward bias p-n junction and which shows the change in the concentration of the carrier along the length of the junction moving from the p to n side. In equilibrium, the carrier concentration in p and n side are given by which you have learned earlier p p o is equal to acceptor concentration and n n o that is equal to donor concentration. And n p o is n i square by N A and p n o is n i square by N D.

What does it mean here? P p o that is the hole concentration in the p side. Obviously, the hole concentration coming out from the acceptor impurity. So that is why we put it as a N A and n n o is the electron concentration at the n side and why it is coming from? It is due to the donor impurity. So the electron concentration is basically equal to the donor atom concentrations N D.

So once I know the majority carrier concentration in the corresponding side to get the corresponding minority carrier concentration, I have to divide by the intrinsic carrier concentration square divided by N A. Because the laws of mass action says that n p o and times p p o is equal to n i square. So basically p p o times n p o is equal to n i square where p p o stands for the hole concentration in P side and n p o stands for the electron concentration in P side.

Now remember, holes of the majority carrier in the P side, and electrons are the minority carrier in the P side. Now since holes are the majority carriers and where you are getting these holes? We are getting these holes from the acceptor impurity. That is why the hole concentration we equate to the acceptor impurity concentrations. Now electrons are still there, but their numbers are less.

And since their product is equal to a n i square, and we have already written p p o is N A so we can write N A times n p o is equal to n i square or n p o is equal to n i square divided by N A. That is what we have written here. Similarly in the case of the n side electrons of the majority concentration and where is the electron concentration is coming due to the donor impurity.

That is why we are equate the n n o is equal to donor atom concentration. And to get the hole concentration at the n side we have divided this donor atom concentration by the intrinsic carrier concentration square because the product of n n o times p n o is equal to n i square.

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Charge carrier injection

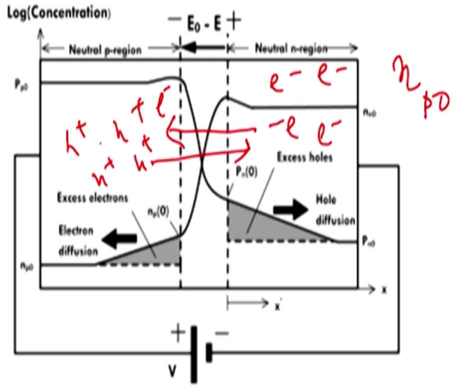

Fig:- Current in a p-n junction is due to injection of minority carriers in forward bias. These excess carriers can diffuse before recombining with the majority carriers. Adapted from Principles of Electronic Materials - S.O. Kasap.

In this diagram, we are showing the charge carrier injection. As you can see here, the current in a p-n junction is due to the injection of the minority carriers in forward bias. This excess carriers can diffuse before recombine with the majority carriers. Now once I apply the forward bias that means I have added the P side to the positive side of the battery and n side to the negative side of the battery.

And I know that in the negative side or in the n side electrons are the majority carrier. So here electrons are the majority carriers and here holes are the majority carriers. Once I have added these things, so the electron diffusions is happening from the left side, from the right hand side to the left hand side or the electron diffusion is happening from the n side to the p side.

But due to the depletion reasons, which prevents the further infusions of the electron from the n side to the p side. Now once I have connected to the external battery, so battery is connected to the negative terminal which gives its excess electron concentration or it decrease the effective width of the depletion regions and that actually helps more and more electron to cross the boundary and comes here.

Now once electron cross this boundary and reaches on the P side in the P side electron is a minority carrier. Similarly, once holes crosses this boundary and reaches to the n side, there it becomes a minority carrier. So that is why it is called that in a forward bias in a semiconductor or in a forward bias p-n junction current is due to the minority carrier.

Because once the electron crosses the boundary and reaches to the p side it becomes a minority carrier and once the hole crosses the boundary and reaches to the n side it also becomes a minority carrier. So the current is due to the minority carrier in forward bias.

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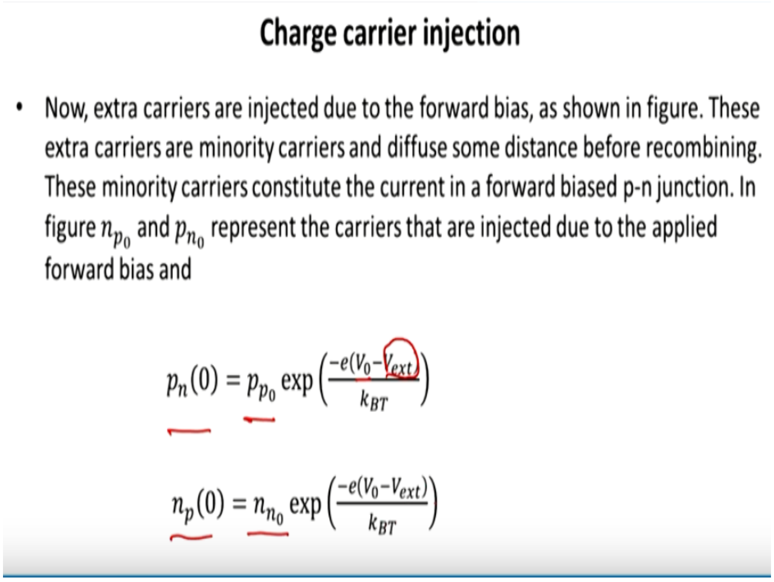

Charge carrier injection

- Now, extra carriers are injected due to the forward bias, as shown in figure. These extra carriers are minority carriers and diffuse some distance before recombining. These minority carriers constitute the current in a forward biased p-n junction. In figure n_{p_0} and p_{n_0} represent the carriers that are injected due to the applied forward bias and

$$p_n(0) = p_{p_0} \exp\left(\frac{-e(V_0 - V_{ext})}{k_{BT}}\right)$$

$$n_p(0) = n_{n_0} \exp\left(\frac{-e(V_0 - V_{ext})}{k_{BT}}\right)$$

Now extra carriers are injected due to the forward bias as shown in the last figure. These extra carriers are minority carriers and diffuse some distance before they combine. This minority carriers constitute the current in a forward bias p-n junction. In our previous figure n p o and p n o they represents the carriers that are injected due to the applied forward bias.

You remember if we look to the previous diagram again n p o that is the electron concentration in the P side. Electron concentration in the P side what does it signify? Hole is the majority carrier in the P side, but where this electron is coming from? From the n regions. But once it reaches to the P side it is no longer a majority carrier. In the P side it becomes a minority carrier.

So n p o is a minority carrier in P side. Similarly p n o is a minority carrier in the n side. So we can find out an expression of the n p o and p n o which is given by p n o is equal to p p 0 exponential minus e V naught minus V external divided by k BT. So you look that the value of this minority carrier concentration that depends upon the external voltage for a given V naught. Similarly, the carrier concentration of the electron in the P side that is given by the carrier concentration of the electron in the n side times exponential minus e V naught minus V external divided by k BT. Here k B is the Boltzmann constant and T is the temperature.

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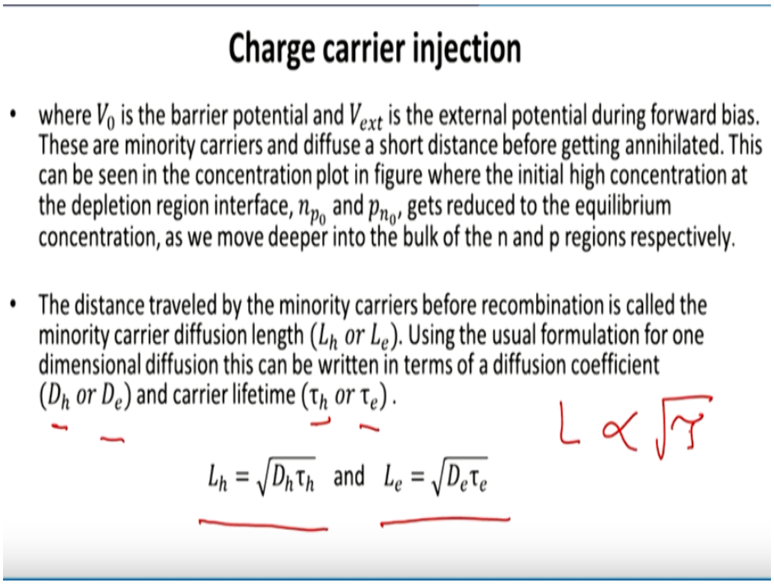

Charge carrier injection

- where V_0 is the barrier potential and V_{ext} is the external potential during forward bias. These are minority carriers and diffuse a short distance before getting annihilated. This can be seen in the concentration plot in figure where the initial high concentration at the depletion region interface, n_{p_0} and p_{n_0}, gets reduced to the equilibrium concentration, as we move deeper into the bulk of the n and p regions respectively.
- The distance traveled by the minority carriers before recombination is called the minority carrier diffusion length (L_h *or* L_e). Using the usual formulation for one dimensional diffusion this can be written in terms of a diffusion coefficient (D_h *or* D_e) and carrier lifetime (τ_h *or* τ_e).

$L \propto \sqrt{\tau}$

$$L_h = \sqrt{D_h \tau_h} \quad \text{and} \quad L_e = \sqrt{D_e \tau_e}$$

Again V naught is the barrier potential and V external is the external potential due to the forward bias. These are minority carriers and diffuse a short distance before getting annihilated. This can be seen in the concentration plot in the figure where the initial high concentration at the depletion region interface n p o and p n o gets reduced to the equilibrium concentration as we move deeper into the bulk of n and p region respectively.

The distance traveled by the minority carriers before it recombine is called the minority carrier diffusion length. Since there are two different kinds of minority carrier namely hole and electron so there are two different types of minority carrier diffusion length. One is called L h, another is called L e.

Using the usual formulation for one dimensional diffusion this can be written in terms of the diffusion coefficient, which is capital D subscript h in the case of hole and capital D subscript e in the case of electron. And the carrier lifetime tau h which gives the lifetime of hole and tau e gives the lifetime of the electron. So we can find out an expression of the diffusion length corresponding to electrons and hole provided we know that diffusion coefficient and the lifetime.

An expression is given here for the hole diffusion length which is L h is equal to square root of D h times tau h. Similarly, the electron diffusion length L e is square root of D e times tau e. So as you can see that the diffusion length L is proportional to the square root of lifetime. So as the diffusion length is higher lifetimes will also be higher. If the diffusion length is lower lifetime is also lower.

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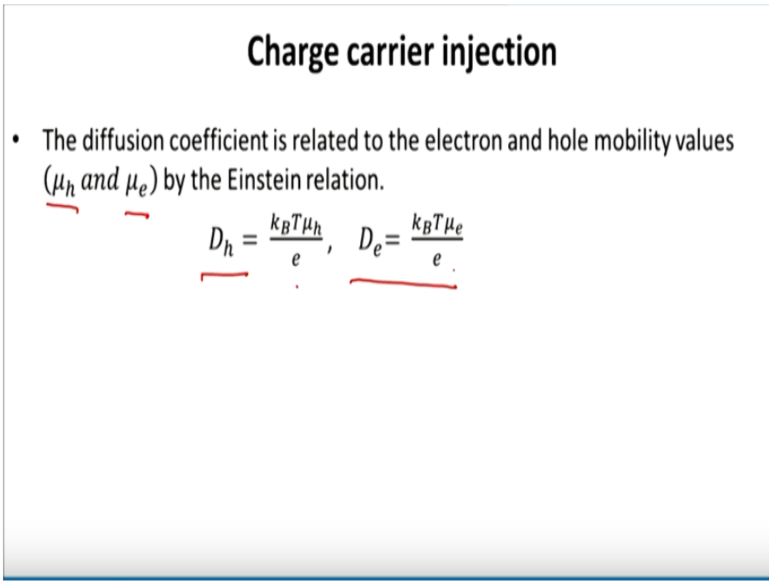

Charge carrier injection

- The diffusion coefficient is related to the electron and hole mobility values (μ_h *and* μ_e) by the Einstein relation.

$$D_h = \frac{k_B T \mu_h}{e}, \quad D_e = \frac{k_B T \mu_e}{e}$$

Now the diffusion coefficient that is related to the electrons and hole mobility. Electrons and hole mobility is usually written by mu subscript h and mu subscript e. So mu h stands for hole mobility and mu e stands for electron mobility. And what is the general expression for the mobility that is given by the Einstein relation.

We can write the diffusion coefficient D h is equal to k B that is the Boltzmann constant times temperature times mobility due to the hole divide by the charge carrier e. Similarly, for the electron D e is equal to Boltzmann constant k B times temperature times the mobility of the electron divide by the electron charge e.

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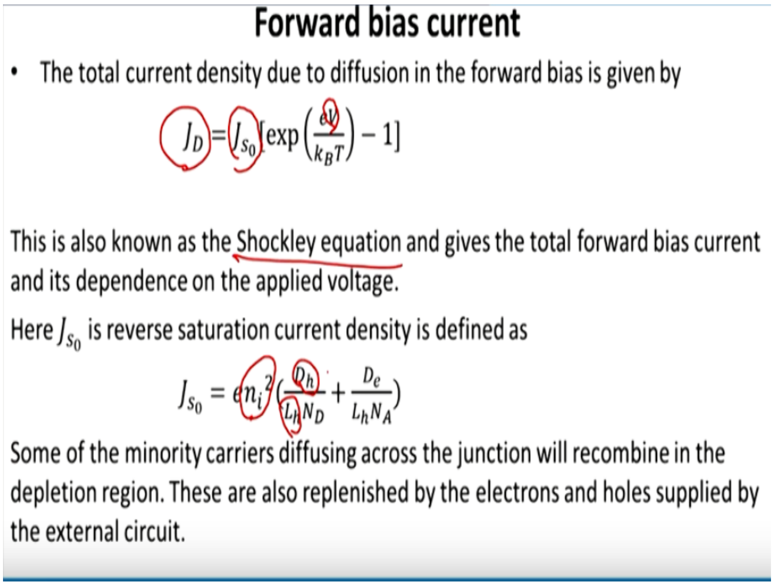

Forward bias current

- The total current density due to diffusion in the forward bias is given by

$$J_D = J_{S_0}\left[\exp\left(\frac{eV}{k_BT}\right) - 1\right]$$

This is also known as the Shockley equation and gives the total forward bias current and its dependence on the applied voltage.

Here J_{S_0} is reverse saturation current density is defined as

$$J_{S_0} = e n_i^2\left(\frac{D_h}{L_h N_D} + \frac{D_e}{L_h N_A}\right)$$

Some of the minority carriers diffusing across the junction will recombine in the depletion region. These are also replenished by the electrons and holes supplied by the external circuit.

In a forward bias condition, the total current density due to the diffusion is given by J D is equal to J s o exponential e V by k B T minus 1. So the current here change exponentially with respect to the voltage. This is also known as Shockley equations and gives the total forward bias current and its dependence on the applied voltage. So how the current depends on the voltage is driven by the Shockley equations.

Here J s naught the first term is called the reverse saturation current and it is defined as J s naught is equal to e times n i square inside the bracket D h divide by L h into N D plus D e divide by L h into N A. So the reverse saturation current depends on the intrinsic carrier concentrations. It depends upon the diffusion length and it depends upon the diffusion coefficient. So this depends mostly on the materials properties.

For a particular class of material, the diffusion length and diffusion coefficient is constant. For example, if I choose silicon, for silicon I know what is the hole diffusion length or what is electron diffusion length or what is the diffusion coefficient due to the hole and electron. So we can plug in those values and get the terms inside the bracket and then all it depends upon the intrinsic carrier concentration.

Some of the minority carrier diffusing across the junction will recombine in the depletion region also. This is also replenished by the electrons and hole supplied by the external circuit.

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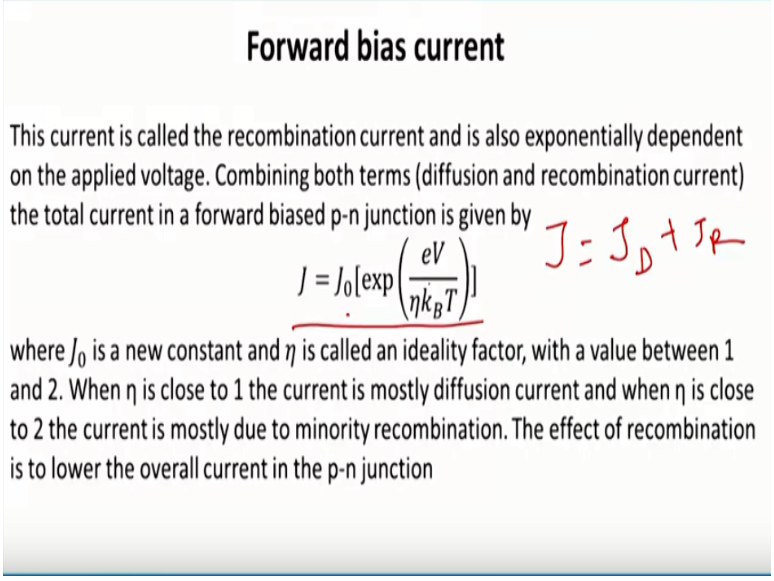

Forward bias current

This current is called the recombination current and is also exponentially dependent on the applied voltage. Combining both terms (diffusion and recombination current) the total current in a forward biased p-n junction is given by

$$\underline{J = J_0[\exp\left(\frac{eV}{\eta k_B T}\right)]} \qquad J = J_D + J_R$$

where J_0 is a new constant and η is called an ideality factor, with a value between 1 and 2. When η is close to 1 the current is mostly diffusion current and when η is close to 2 the current is mostly due to minority recombination. The effect of recombination is to lower the overall current in the p-n junction

In the forward bias the forward bias current is also called the recombination current and is exponentially dependent on the applied voltage as you have just seen. Combining both terms, the diffusion and recombination current, the total current in a forward bias in a p-n junction is given by J is equal to j naught exponential e V by eta k B T and the bracket close.

Where J naught is a new constant and eta is called the ideality factor or diode ideality factor whose values is between 1 and 2. When eta close to 1, the current is mostly diffusion controlled current. And when eta is close to 2 current is mostly due to the minority carrier recombinations. So as you have understood that in this kind of forward bias p-n junction there are two sources of current.

One is coming due to the recombination and another is coming due to the minority carrier concentration. The first one we have learned from the previous equation, which is the Shockley equations and that is given by J D is equal to J s naught exponential eV by k BT minus 1. But in addition to the diffusion part, we have also the recombination current. Because the charge carrier recombine with each other.

When they recombine then we have to add the total current J is equal to current due to the diffusion plus current due to the recombination. And that is given by this expression which depends on the applied voltage. It depends upon the coefficient eta and eta is called it is not the coefficient of viscosity it is an ideality factor. Its values changes with the semiconductor.

Silicon has a different value, germanium has a different value and gallium arsenide has a different value. And usually the values of the eta tells us whether the current is a diffusion controlled or it is a drift controlled or recombination controlled. The effect of recombination is lower than the overall current in the p-n junction. So far we have discussed about the diode in a forward bias condition.

Similarly, the diode can also be connected as a reverse bias condition.

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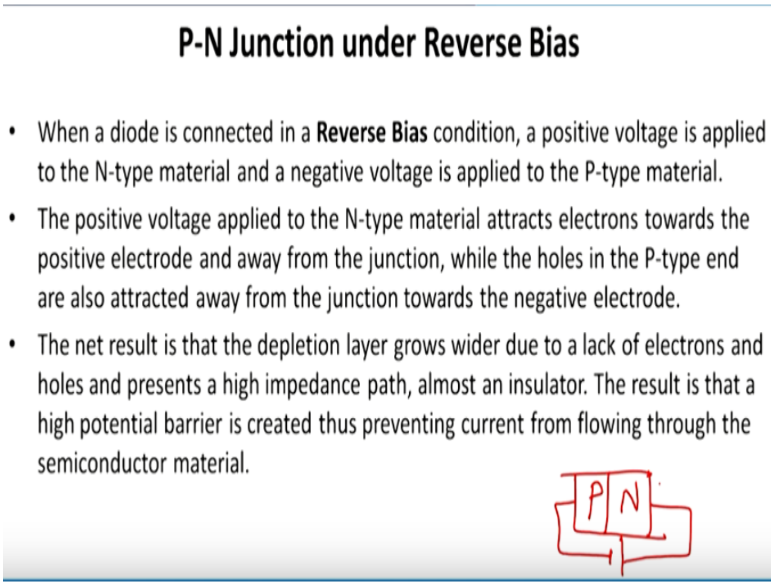

P-N Junction under Reverse Bias

- When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.
- The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.
- The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

For example, if we have a p-n junction diode like this and I add the battery in such a way, the negative terminal of the battery connects to the P side and positive terminal of the battery connects to that N side. In this case the diode will be called a reverse biased diode. When a diode is connected in the reverse bias condition a positive voltage is applied to the N-type material and negative voltage is applied to the P-type material.

The positive volt is applied to the N-type material that attracts the electron towards the positive electrode and away from the junction. While the holes in the P-type end are also attracted away from the junction towards the negative electrode. So what is the resultant effect? The width of the depletion region increase.

The net result is that depletion layer grows wider due to the lack of mobile charge carriers electrons and holes, due to a lack of electrons and holes and presents a high impedance path. So almost like an insulator. The result is that a high potential barrier is created thus preventing further current flowing through the semiconducting material.

So once the width of the depletion region increase so it provides actually a high impedance path, almost an insulator. And if the high impedance path is there so that prevents the further charge carriers to move across the junctions. That is why the current is very **very** low in this kind of reverse bias junctions. So we have learned two different kind of bias junctions. One is forward bias and another is reverse bias.

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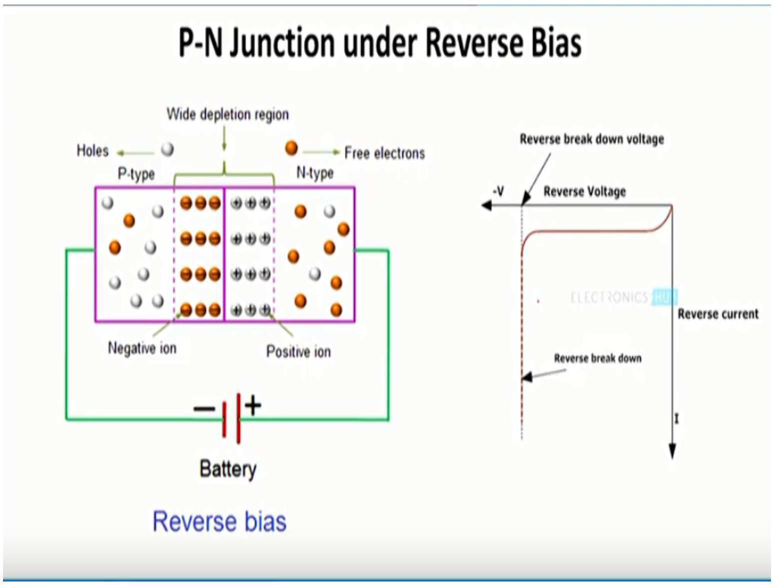

P-N Junction under Reverse Bias

If we draw this diagram, in this case, P-type is connected to the negative terminal and N-type is connected to the positive terminal. And you see that in this case the depletion regions become wider here and the current versus voltage characteristics in a reverse bias diode looks like this where if I increase the reverse voltage first it increase then at a certain point all of a sudden currents become saturates and increase and that is called a break down regions.

And the current under reverse bias is called reverse saturation current. So in our today's class we have discussed two different kind of currents, reverse saturation current and the forward bias current in a diode. In a more precisely in a p-n junction semiconductor diode.

Later on we will see that when we construct a photovoltaic devices, which is nothing but a p-n junction, where n side is narrow and heavily doped and p side is wider we can also control the current flow either in a forward bias condition or in a reverse bias condition.

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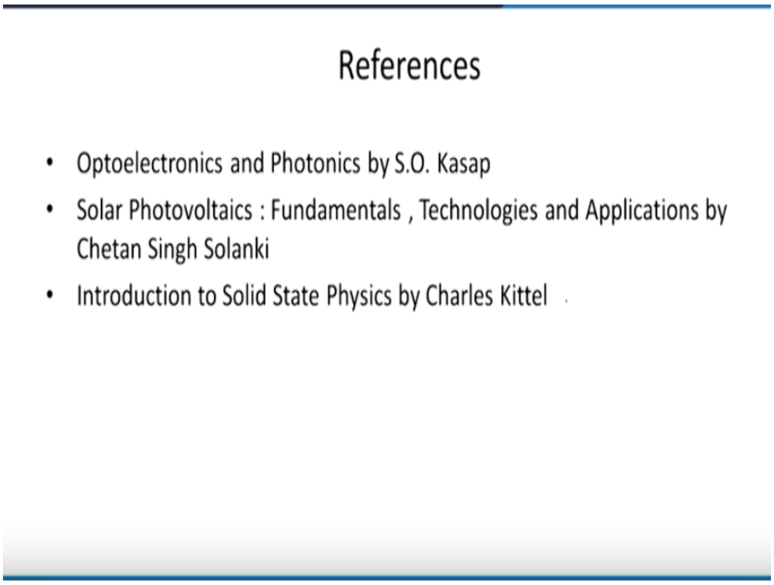

References

- Optoelectronics and Photonics by S.O. Kasap
- Solar Photovoltaics : Fundamentals , Technologies and Applications by Chetan Singh Solanki
- Introduction to Solid State Physics by Charles Kittel

For the corresponding reference you can look this book, Optoelectronics and Photonics by S. O. Kasap or Solar Photovoltaics: Fundamentals, Technology and Application by Chetan Solanki and Introduction to Solid State Physics by Charles Kittel. Thank you.