Fundamentals of Semiconductor Devices
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Lecture – 19
p-n junction under equilibrium

Welcome back to this class now. So, what did you learn in the last class? We had discussed P-N junction in detail about forward bias, about reverse bias. We have derived the expressions for the minority carrier concentration, the current flow right. I told you the how the diode equation looks like eventually that is the increases exponentially in the forward bias and the reverse bias, there is very little current. We call it the reverse saturation current that occurs, when you biasing it reverse in the reverse direction.

And I told you that you know the reverse saturation current depends on the band gap of the material, whether it is a large band gap or a small band gap material. And while it acts as a rectifier, all those things we have learned the different current components on. So, I told you that today's class we shall pause and we shall look back at the different aspects of a P-N junction in contacts of different devices also go into little more details about some other current components that might be there, so that we are equipped to understand further devices as we move along this course ok.

And of course, after a rap up P-N junction and all the discussions associated with it, then we will start looking at breakdown of P-N junction ok. And then capacitance voltage profiling, and then metal semiconductor contact ok. Those is the that is the sequence of the lectures in the next few classes that we will be covering. So, now we shall stop and look back at what are the different aspects of P-N junction that we should be aware of, when we are thinking or designing of different kinds of devices ok.

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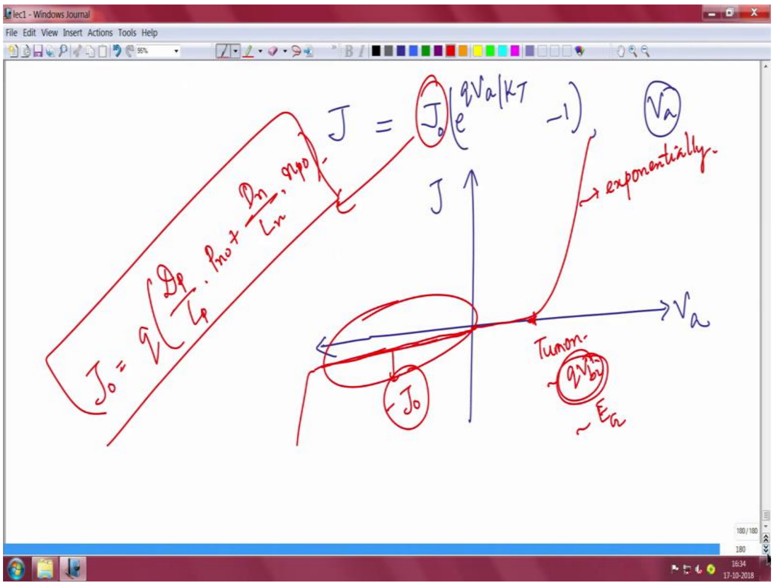

So, we will come through a whiteboard now ok. So, if you recall in the last class, we had told you that the P-N junction you know the P-N junction the total current of a P-N junction can be written as J equal to J_0 exponential of qV_a/k T minus 1, where V_a is the applied voltage.

$$J = J_0(e^{qV_a/_{kT}} - 1)$$

And this if I plot the total current density versus applied voltage, then you have a in the forward bias it will look like this. So, this is a turn on voltage, and the turn on voltage depends on the built-in voltage, is close to built in voltage. And since built in voltage also depends on band gap. So, a larger band gap material will have a larger built in voltage, and hence a larger turn on voltage. It has lot of importance in designing devices, I will tell you very soon ok.

So, this is the turn on voltage, and this rises exponentially; this rises exponentially. Another reverse side the current will be very low ok. The current will be very low eventually will breakdown, that low current is called minus J_0. And it is independent of voltage, because J_0 as I told you J_0 can be written as $q(D_p/ L_p p_{n0} + D_n /L_n n_{p0})$

$$J_0 = q(\frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0})$$

So, this is an independent of voltage. So, this is almost constant current here, and is very small current or at some magnitude. So, it is called a rectifier ok. I told you in forward bias junction the depletion region shrinks, the barrier also reduces, your injecting carriers actively from the n and p side. But, in the reverse bias side, you are not injecting carrier depletion is actually widened, and then the built-in voltage also has widened that way right.

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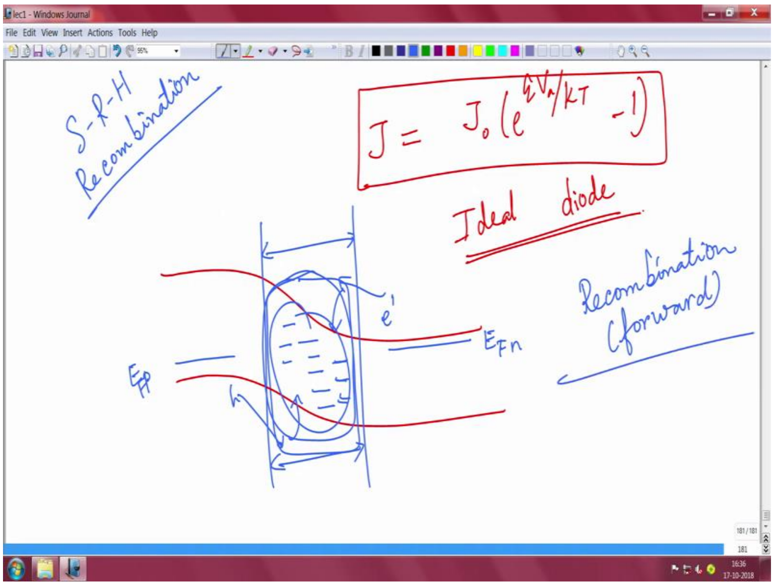

Now, if you look at this equation carefully, J_0 times e to the power qV_a / kT minus 1 ok, this is the diode the ideal diode current right, this is called the ideal diode equation or ideal diode current equation for a P-N junction, but even where are you look at forward bias or reverse bias does not matter.

If you look at the band diagram right, if you look at the band diagram say this is your slightly forward bias. So, this is your E_F Fermi level on the p-side, this is Fermi level on the n-side very small bias that you apply.

There is always a depletion, the depletion maybe narrow, the depletion maybe wide in case of forward and reverse bias respectively. But, in this depletion region in this depletion region when the carriers are crossing over, you know they are you know travelling. The traps, and the defects, and the dislocations and all the things that we have discussed in one of the classes remember recombination and traps.

Shockley-Hall-Read, Shockley-Read-Hall recombination because of defects and traps in the material. This defects and traps always exist in a material. And the defects and traps how do the manifest? They manifest as energy states within the band gap, one of they can either capture electrons or capture hole, they can emit electrons or emit hole by capturing. So, these are like defect states that manifest as energy discrete energy states within the band gap. And that arises because of different defects, dislocations you know interstitial sites defects and so many things in the material.

So, those things within this depletion region can take away some electrons; can give some electrons or holes. So, electrons are going from here to there, some of them might be recombining, holes are coming from here to there some of them might recombine at the traps, so that will give rise to a recombination current that will give rise to a recombination current in forward bias.

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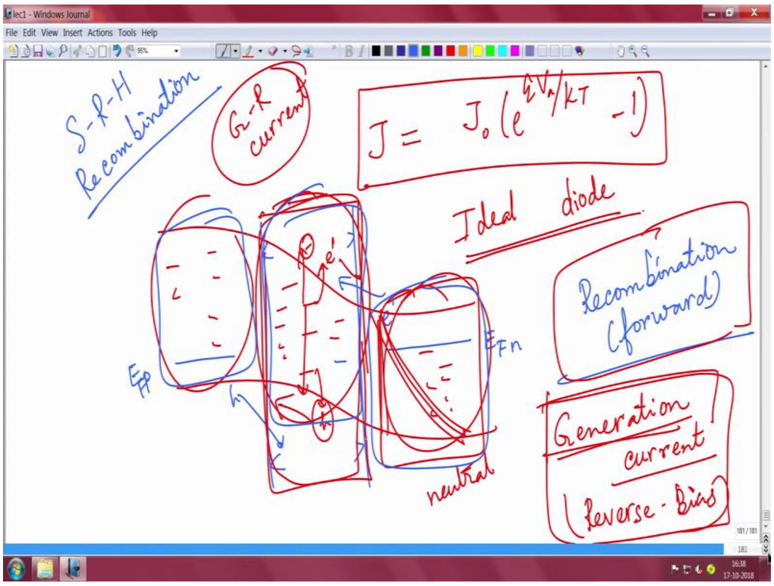

And in the reverse bias, in the reverse bias, when essentially there is very little current that is flowing here right; in the reverse bias, there is very little current that is flowing here in reverse bias, it is almost is completely depleted here. In that case, these traps might emit carriers, and that might be swept away some this trap might capture emit sort of electrons holes that might be swept away that will lead to sort of a generation current. This generation current is not because of light shining.

Of course, if you shine a light, then that is a different generation current that will come. But, this generation current we will occur at reverse bias, and this generation current is because they trap states that are there that might lead to some creation of you know electron hole pair, because they might have captured some electron hole pair earlier, now they are emitting it.

And this excess electron hole pair that might be generated because of this you know traps being there could give rise to a generation current. So, in total this trap induces current that is there is called generation recombination, current generation recombination current in forward and reverse bias, together we call them let us generation recombination current. Recombination current occurs in the forward bias, generation current occurs in the reverse bias, but in generally we call them as recombination generation current that happens here.

The trap states in this region do not matter so much in the neutral region, because these are sort of neutral region right. These are sort of neutral region, and carriers will decay there of course, that excess carrier that we are injecting and the decay that will dominate here. The traps capturing then, and emitting them will not matter much, because these are filled with electrons and holes, whereas this is depletion region right. This region is depletion. So, traps capturing and emitting electron matter more here, but these are filled with carriers you know. So, the traps emitting, and capturing is not very significant that is why, you only talk about generation recombination within the depletion region.

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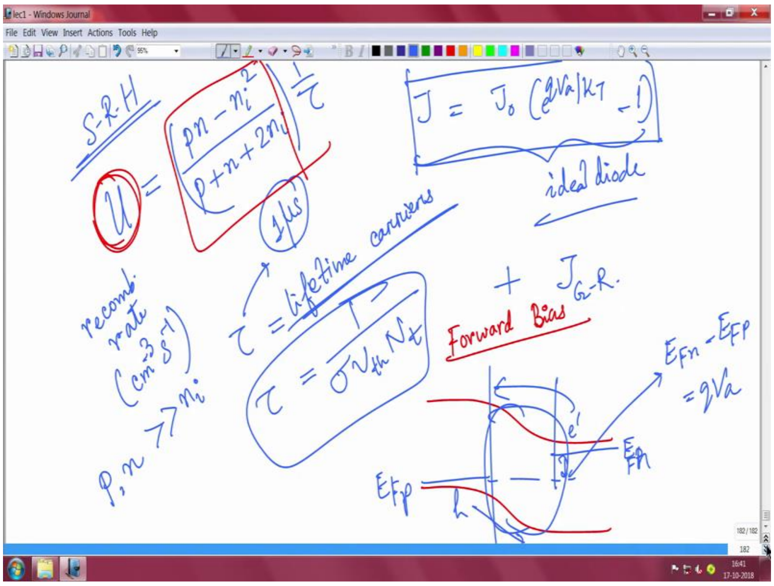

So, what basically this means is that this ideal diode equation that you have J equal to J_0 e to the power qV_a/kT minus 1, this is the ideal diode equation. But, apart from the ideal diode equation, you also have what is call the generation recombination current, the generation recombination current ok, so that current needs to be estimated, and added to this to get the true current.

So, if you recall from your Shockley-Hall-Read statistics that we have discussed, whenever you have you know traps trap cross section is there, and all the things are there, then there is a lifetime a recombination rate that we define, this u is call the net recombination rate. And the net recombination rate has a unit of per centimeter cube per second.

And this net recombination rate is defined as, it is it can be simplified as P times n which is the total electron times the total hole concentration, it is not need not be in equilibrium minus n_i^2/P the total hole plus total electron plus 2 times the intrinsic carrier concentration, this whole thing into 1 by tau. The τ (tau) is called the lifetime of the carriers.

$$U = \frac{pn - n_i^2}{p + n + 2n_i}\frac{1}{\tau}$$

The lifetime of the carrier basically you know when you have traps there is a lifetime, suppose this is 1 microsecond which means excess carriers are recombining after everyone microsecond that is call the that is the lifetime. So, this τ (tau) this lifetime is defined as 1 by the area of the cross-section area (σ) of the trap times the thermal velocity times (v_{th}) the total trap concentration (N_t), that is fine that is given generally in question.

$$\tau = \frac{1}{\sigma v_{th} N_t}$$

So, now you must look at this essentially this term, which is the very important term here. This quantity if it is positive that means, there is a net recombination, like in a forward bias. If this is negative that means, this is a net generation like in a reverse bias. So, if I take the forward bias case, if I take the forward bias case, in forward bias you are injecting a lot of carriers across the depletion region from the n-side to p-side, p-side to n-side.

So, because there is a lot of carriers that you are x that you are injecting you know you have the P-N junction like that the P-N junction like that you know that the hole Fermi level is here. This is quasi Fermi level this is electron Fermi level E_{Fn}. And the difference of these two Fermi levels, this difference of this two Fermi level E_{Fn} minus E_{Fp}. This difference of this two Fermi level is the applied voltage, you are applying ok.

Whenever you have a situation like this, you are injecting carriers' electrons from this side to that side, holes from this side to that side is a lot of carriers crossing over. So, what happens is that your hole concentration and your electron concentration, because there is a lot of carriers moving around is much larger than your intrinsic carrier concentration, it is much larger than the intrinsic carrier concentration.

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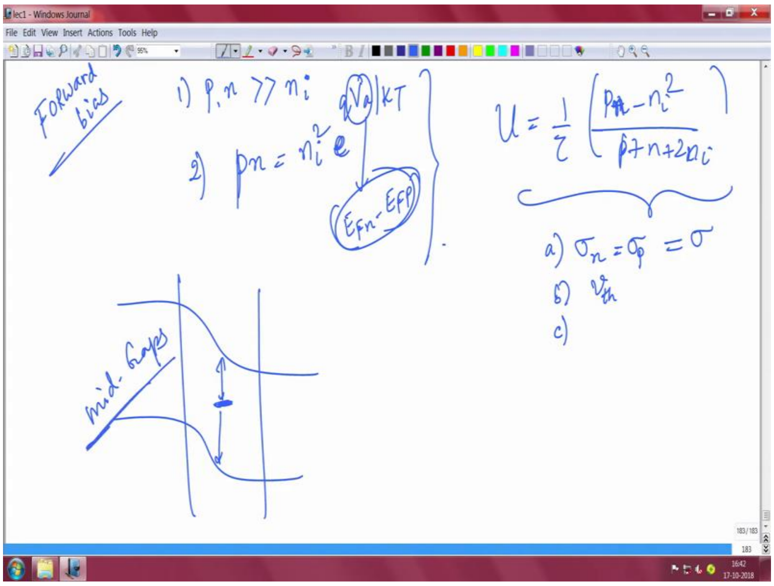

So, the first thing we learn is that the hole concentration, the electron concentration is must much larger than the intrinsic carrier concentration under forward bias ok. In the depletion region, we are talking about ok, they are carrying over so ok.

So, the what is the second thing will learn, I told you that in equilibrium $pn=n_i^2$, but this is not equilibrium, you are applying a bias the pn is equal to n_i^2 times e to the power qV_a/kT.

$$pn = n_i^2 e^{qV_a/kT}$$

Your equilibrium is not distorted, you have the product of $pn = n_i^2$ into e to the power k, because this essentially is the difference of your Fermi level E_{Fn} minus E_{Fp}. So, essentially it, this exponential of the difference of the Fermi level times the n_i^2 is pn.

Now, if you recall that expression, u equal to 1 by tau P n minus n_i^2 by p plus n plus $2n_i$ ($U = \frac{pn - n_i^2}{p + n + 2n_i} \frac{1}{\tau}$). This expression is valid for a few assumptions, one assumption is that the electron cross section was equal to hole cross section, on the electron trap cross section sorry electron trap cross section is equal to hole trap cross section is equal to one constant.

The electron saturation the thermal velocity and hole thermal velocity is the same, we call it v_{th}. And another assumption is that all the traps that are there you know if you draw a P-N junction like this, all the traps at the depletion region are exactly at the mid gap, which means it is a middle of the gap mid gap. Only when because the traps are at mid gap only at the trap at mid-gap, you will get a maximum recombination, so that is why we do that. If you do not take a mid-gap, then you will have a complicated sine hyperbolic function.

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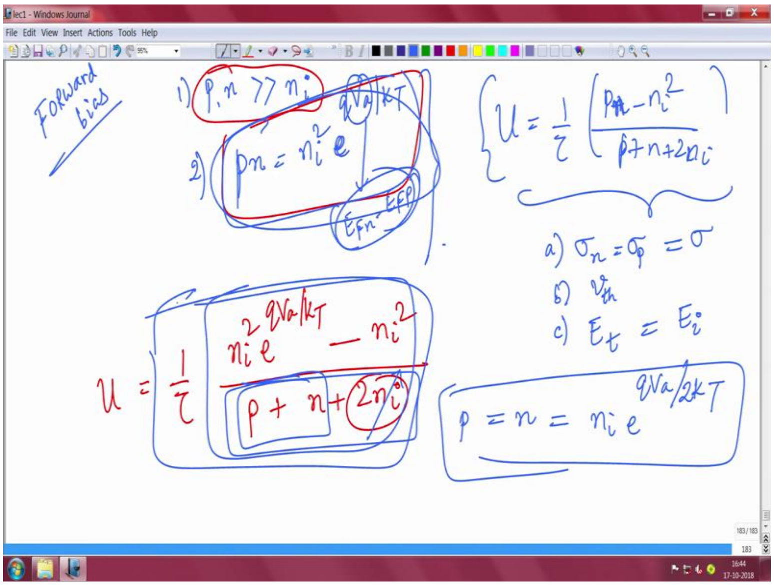

So, all the trap levels E_t there is a trap level is at mid gap, which is the intrinsic level the i level right. So, this is an assumption we have to this is an assumption, which basically lead to this expression that we should not forget. So, now, I will write this expression again u is equal to for forward bias 1 by tau, so p n which can be written as this. So, I will write that as n_i square right, you know what e to the power qV_a/kT minus n_i^2 divided by P plus n plus 2 n_i.

$$U = \frac{n_i^2 e^{qV_a/kT} - n_i^2}{p + n + 2n_i} * \frac{1}{\tau}$$

Now, here there is an interesting thing you must talk about. I told you that p and n are much larger than n i, which means this quantity can be neglected this quantity can be neglected. So, I can just write it as, you can I just I can just ignore this quantity right.

Now, this expression again will be maximum, this expression will be maximum, when this two quantities are equal which means p has to be equal to n I mean and ok, and that will be equal to from this expression, you can write it as n i e to the power qV_a by twice kT you see this is q a V t you know, so that is a so it will be like p times n is equal n_i^2, so p equal to square root of this term, so that will be this that is your term. The under this condition, this denominator will be basically minimum, and hence this quantity will be maximum. The maximum recombination rate that you can get.

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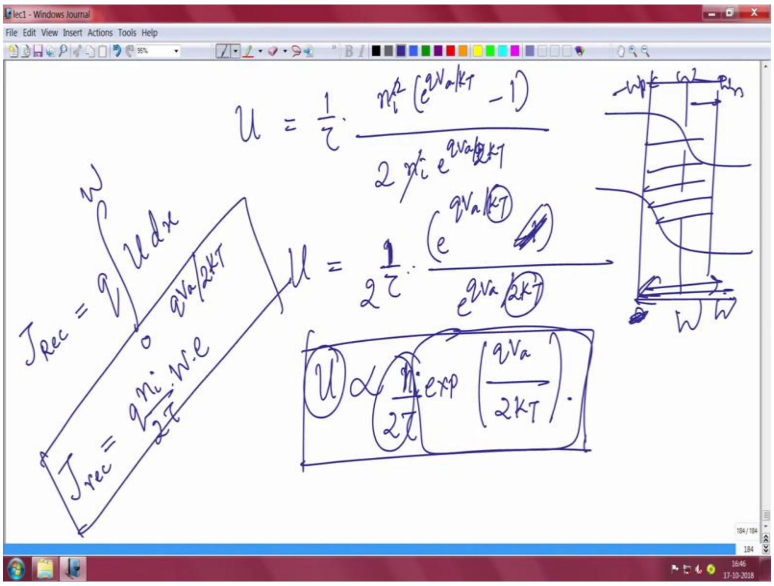

So, let me write down it again. So, the recombination rate, the net recombination rate now. I can write the net recombination rate as u 1 by tau n_i^2 e to the power qV_a by kT minus 1 p plus n plus 2 n, I can ignore 2 n_i. So, I can write p plus n which is equal to same, so that is 2 into n i into exponential of qV_a by 2kT if you recall.

$$U \propto \frac{1}{2\tau}\left(\exp(\frac{qV_a}{2kT})\right)$$

So, this n i, n i will cancel out, what will remain is 1 by tau 1 1 by 2 tau e to the power q a qV_a by k T minus 1 by e to the power qV_a by 2 k T. This is your net recombination rate. And if you are you know this is a net recombination rate, and at larger you know if you talk about little bit larger V a, then this quantity can be ignored. So, approximately this will be proportional to e to the power exponential of qV_a, this is 2, this is 1. So, it will be 2 k T ok. There is a pre factor here, which is 1 by 2 tau n i by 2 tau actually ok.

So, you see the recombination rate, and this is the positive quantity. So, the recombination is taking place, this is the rate.

And the recombination current J recombination can be now calculated as this rate, you must multiply you have to integrate this rate over the depletion region. This is your P-N junction, so over this depletion region the width 0 to W the total width ok. When I say 0 to W, the total width is W the 0 is here, this is W n, this is minus W p, so the total width is W.

So, I must integrate over this entire, so 0 to W we can say you know; q has to be there, because charge times this times dx right. So, of course u is independent of x, so I can take this out and integration of this reacts W will be W only. So, we will come as q n_i by 2 tau into W into exponential of this quantity you know, exponential of e to the power qV_a by 2 k T ok. This is your J recombination.

$$J_{Rec} = \frac{qn_i}{2\tau} W \exp(\frac{qV_a}{2kT})$$

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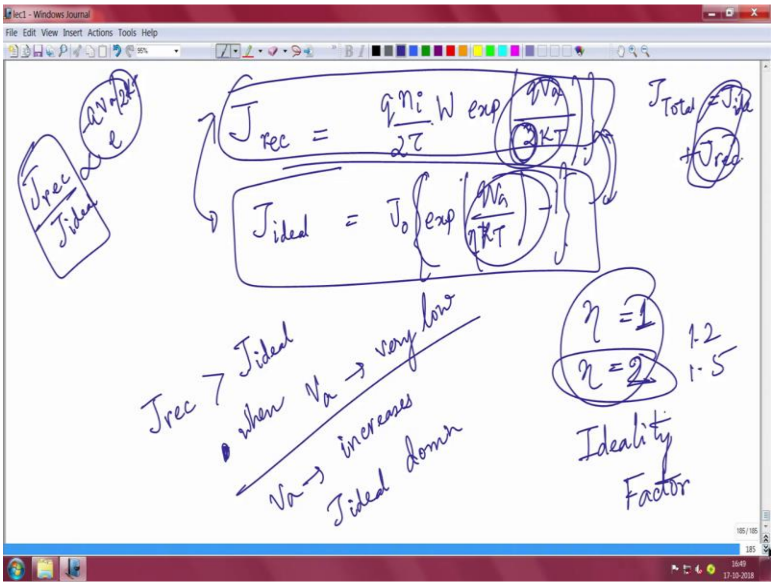

This is your net recombination current, let me come again net recombination current. The net recombination current is q n i by 2 tau into W exponential of q V_a by 2 k T. So, you see in here there is a 2 in the ideal diode equation there is no 2. If you recall the ideal diode equation J ideal that was J_0 exponential of, you know exponential of qV_a by k T minus 1 this is 2 k T, so that quantity that is there. I can say it is those you know eta that quantity is 1 for ideal diode equation, and that quantity is 2 for a recombination current, that quantity is call ideality factor.

$$J = J_0(e^{qV_a/kT} - 1)$$

Ideality factor essentially tells you, how close your diode equation is close to ideal diode equation. If ideality factor is 1, it means it your diode is ideal. If the ideality factor is it can be 1.2, it can be 1.5 ok; that is it is approaching non-ideality. And if it is 2, then that means recombination current strictly dominates. But, since both are there, it is not exactly 2, because this will also be contributed that that will also be contributed this, so it will be between 1 and 2 for example. But more it is closer to 1, it is more and more ideal, more is it is it is closer to two, it means more and more recombination is dominating.

Now, you look into the both of this, the recombination current we will dominate over ideal current, only when you are applied voltage is very low. Once your applied voltage becomes large a little increase, because it is an exponential function you know then J ideally will dominate ok. Because, the ratio of the recombination current by the ideal current, both will add up by the way; the total current the total current will basically be the ideal current plus the recombination current in forward bias I am talking about ok.

In reverse bias also, you will have a generation current which will I will come to that. So, both will add up, which of them is dominate so dominating. So, you take the ratio, the ratio will be proportional to e to the power qV_a by 2 k T, because this is 2 k T this is k T right, so it will be minus 2 k T of course.

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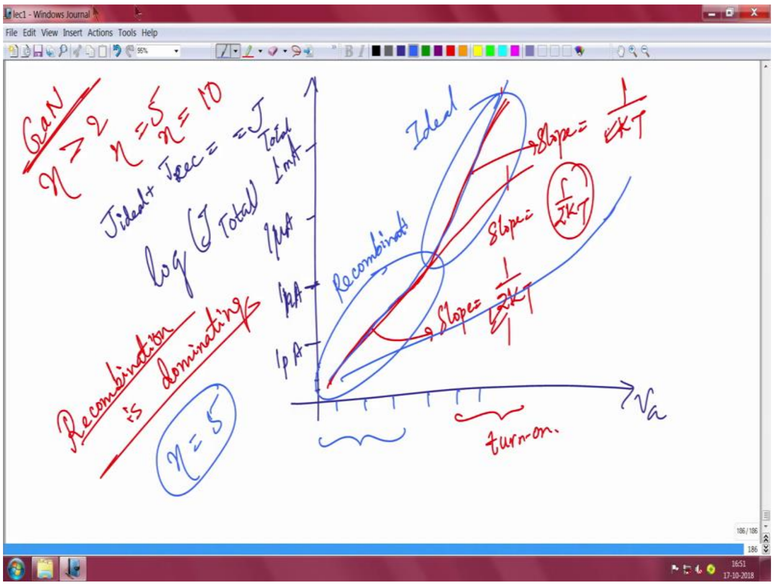

So, essentially this quantity we will dominate only at low V_a. So, what I mean is that if I plot, if I plot J total ok, which is nothing but the ideal current equation plus the recombination current, this is the total current.

So, if I plot total the J current versus V_a, I will plot it in the log scale log of J total, because only in log scale you will see. So, log scale may you have this log scale right, so this is might be 1 Pico, 1 Nano amp, 1 Pico amp, 1 micro amp, 1 milli amp, so it is a log scale. So, we will see that, so essentially you know it is very low voltage as at very low voltage only at very low voltage close to 0, what will happen is that you will have an IV like this. And then the slope will change, it will increase ok. This will in the turn on we will come somewhere here ok, turn on we will come somewhere there ok.

So, the slope of this is low. The slope is 1 by 2 k T, and the slope here is high, the slope is 1 by k T that ideality factor comes in the picture is the ideality factory is 1 here, the ideality factor is 2 here. So, the slope is low 1 by 2, and the slope becomes higher here it increases ok. So, this is your recombination dominated region at low voltage. And this is your ideal diode equation when it is, but sometimes if your current is at a low slope only that means, everywhere the slope is say 1 by 2 k T, it means your diode is not very good. Because, everywhere recombination is dominating, your recommendation is dominating everywhere.

In that case, your ideality factor will be 2. Now, in if the material is not very good. For example, if I take gallium nitride, the material if we do not grow the material well, if you do not deposit the material well. The material might have a lot of traps, it might be very bad quality material, in which case the ideality factor can be much larger than 2 also. The ideality factor can be even 5, now ideality factor can even be 10, which means it will be terrible right, it will be like a sort of thing right.

So, it will be diode only, but the ideality factor will be very high 5 or whatever right, so that is a very bad ideality factor. And that will occur, when your material is not very good. If it is a very good material, initially it will be slope of 1 by kT, this is re-combination than this is your ideal diode equation ok. So, this is an important aspect of your diode equation that we should be aware of.

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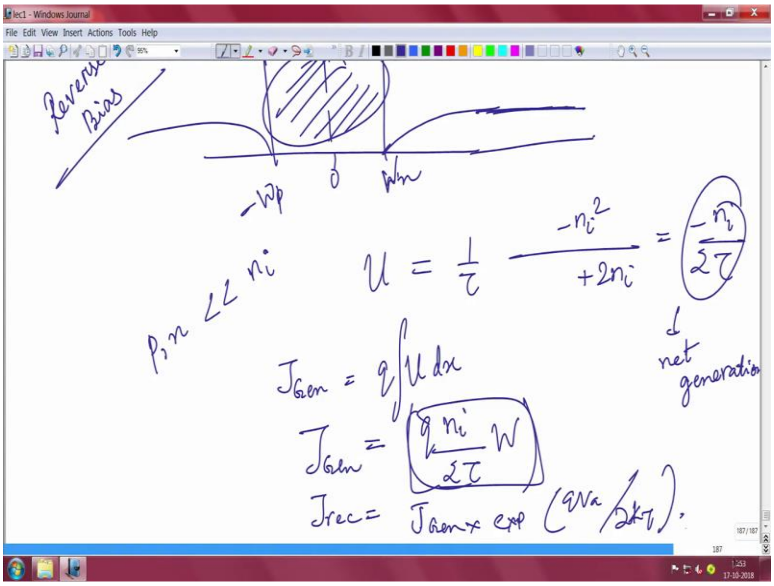

And similarly, for reverse bias; if I take a reverse bias situation ok, if I take a reverse bias situation, then you know if you recall the reverse bias situation, if this is your W n, this is your W minus W p, this is your 0, you know the total carrier concentration is at 0 at this edge. Then it eventually becomes equal to the baseline the background concentration on both side, this is minority I am talking about.

So, within the depletion there is really depletion, there is no current carry and all. So, it is very low you know there is no current base, there is no current also, it is no carriers also here. So, your p and n are much lower, because it is depleted then the n_i. So, if I take this rate that the net combination rate 1 by tau P n minus n i square by P plus n plus $2n_i$.

Then you know this p n and n are so small that you can neglect that. And the product of p n also can be neglected with respect to n i. So, what will remain here is minus n_i by 2τ (tau) and this is negative. So, there is a net generation of carrier. This is not optical generation please keep in mind. This is generation of carrier because of traps in the depletion bulk ok.

So, now if you would find out the generation current J_{gen}, this will basically be qudx. So, it will basically come out to be and I will take the negative sign away, because I am talking about the magnitude here. q n i by 2 tau into W. This is the generation current. And if you recall, the recombination current was, the recombination current was q n_i 2 tau W into exponential of that. This quantity is your generation current you know actually now.

So, essentially this, your recombination current is actually this value, which is the generation current times exponential of qV_a by 2 k T that is was happening ok. So, what is generation current, and recombination current is always in the opposite direction with respect to the diode ideal diode equation.

$$J_{Gen} = q \int U dx$$

$$J_{Gen} = \frac{qn_i}{2\tau} W$$

$$J_{rec} = J_{Gen} * \exp(\frac{qV_a}{2kT})$$

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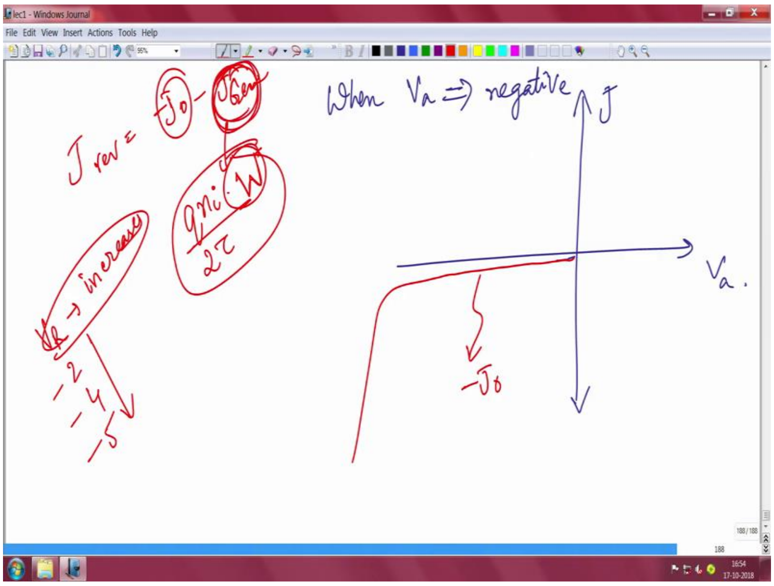

And the generation current has to be added to the reverse saturation current. So, when you are applying a reverse bias, when your V_a is negative, so it is a reverse current. I keep telling you that you know when you have a reverse bias, this is J for example this is you know the V applied voltage.

In a reverse bias current, the current is very small I keep telling you right. The current is very small, it should be constant and then break down. This constant current should be minus J_0 from the ideal diode equation but actually the total reverse current will be minus J_0 of course minus J gen, also generation current. So, this current is basically independent of voltage, but this current as I told you is q n i by 2 tau into W depletion.

Now, as your reverse bias voltage increases more and more, which means suppose you are applying minus 2 V, minus 4 V, minus 5 V and so on. If this reverse bias increases, then your depletion width also increases, you know the depletion width also increases right. And since the depletion width increases, this current also increases your generation current also increases in magnitude slightly.

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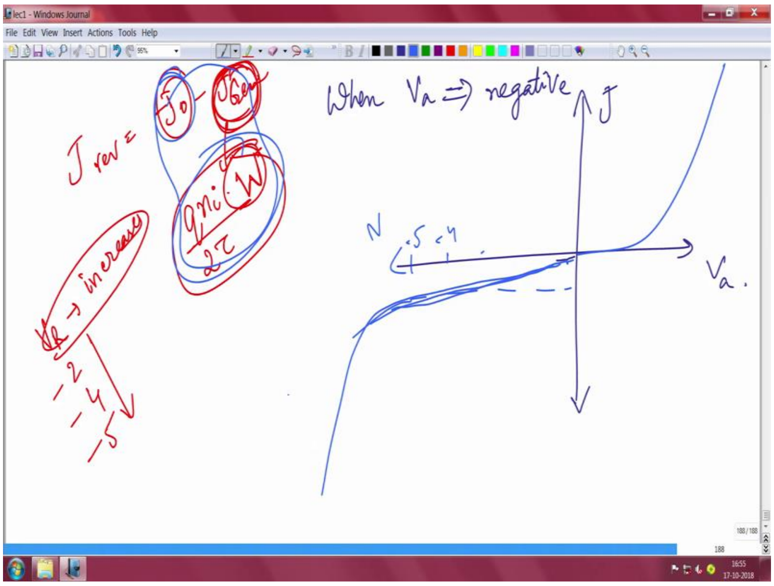

And that is why, this current the reverse bias current is not exactly constant, but it is slightly increasing with bias, this is minus 5 volt, this is minus 4 volt for example, because it biases the generation current increases, this remain constant. So, the addition of both of this keep slightly increasing like this, and that will break ok. This is still very small current Pico amp, femto amp, this is very large current here milli amps and. It is not the same I mean is very small current, but it is slightly gives increasing, so that the generation current then there is a ideal diode current that is coming out alright.

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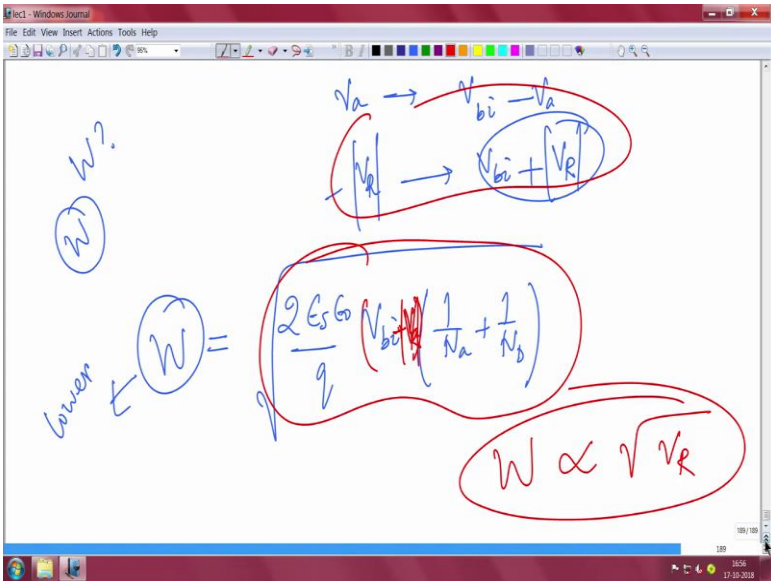

And all this while I have told you that when you apply a forward bias of V_a, your built-in voltage reduces by V_a minus V_b minus V_a. And if you apply a reverse bias voltage of V_R positive, I am talking about so it is you are applying minus this, then your built in voltage increases by V_b plus V_R right.

What about the depletion region? If a ideal depletion region is W, and if you look and the expression of W from the last to last lecture, I think is 2 $\varepsilon_0 \varepsilon_S$ by q into built in voltage by 1 by N_A plus 1 by N_D into their sorry this square root. Now, when you are applying a forward bias, the depletion region becomes lower, it becomes narrower. And that is because this V_a term may you have to apply V_a minus V_b minus V_a, so that quantity become smaller.

And in case of reverse bias uses must add V_R as a magnitude right. So, if you reverse bias increases, this quantity also increases. So, essentially your depletion width scales as the square root of the reverse voltage right sort of ok. So, is you keep increasing the reverse bias, you will basically increase the depletion width, and hence your generation current also we will keep increasing right, so that we should keep in mind.

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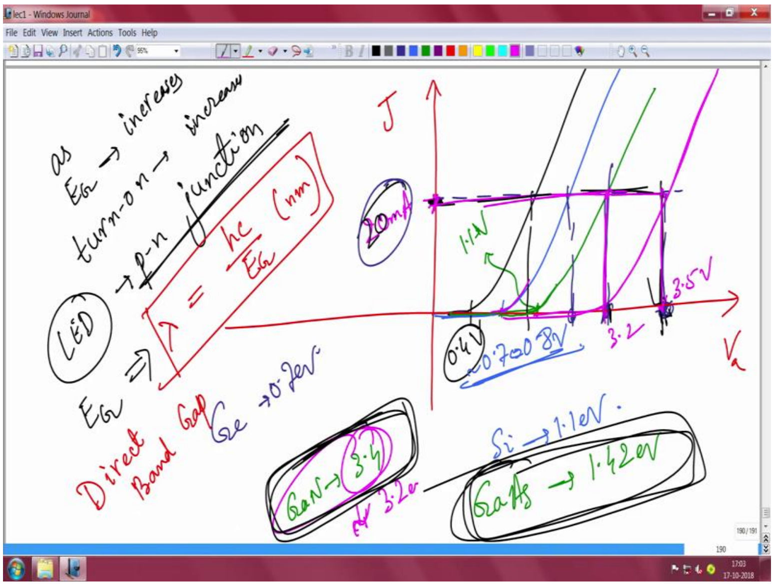

So, now if I investigate that equation J, both everything included this is V. So, I told you that you know for example if I take a silicon diode, it will turn on like that. And the turn on voltage is typically around 0.7 or 0.8 volt in the range maybe 0.7, 0.8 volt. And if I because the silicon has a band gap of 1.1 eV ok, I am not talking about the reverse bias. I mean until point 0.7, 0.8 V the current is very low, then the current increases.

So, suppose I take a material you know I take a material like gallium arsenide, whose band gap is 1.42 eV. So, you know the turn on voltage also will be slightly more, it will come like this it will come like that. So, the turn on voltage might be around say 1 volt or 1.1 volt may be ok. Suppose, I take you know gallium nitride, whose band gap is 3.4 eV ok, whose band gap is 3.4 eV, then you are built in voltage or a turn on voltage would be also large like 3.2 eV may be, so eventually it will be like that this might be 3.2.

So, you see as a wider band gap material, you are turn on voltage also increases in the P-N junction, which means if I want to get a current say, I want to get 20 milli amps of current here, and to get 20 milli amps of current here. For 20 milli amps of current, I must go to a much higher voltage in the gallium nitride, then I have to go in gallium arsenide, then I have to go in silicon.

If I use germanium whose band gap is 0.7 eV, then the turn on will be even low. The turn on might be even here, it might be around 0.4 eV, 0.4 Vwhich means for 20 V, it will be even lower. So, basically as the band gap increases, as it becomes a larger and larger band gap material, your turn on voltage also increases.

And for a given voltage for a given current, if you want to get a fixed current say 20 milli amp or 30 milli amp. The voltage that must apply is also much larger, this is turn on. This will be much larger then that right excuse me, which means to get the same current I must apply higher voltage. So, you know that is a problem, because as I keep going to either band gap material for applying for getting the same current must apply more voltage.

So, if I apply more voltage, it means I am using more power, so the input power will be more. So, you need to go to higher voltages, so that is one. So, for example, if I make a gallium arsenide LED versus if I make a gallium nitride LED, I must apply a more voltage on gallium nitride to get the same brightness as gallium arsenide for example at the same current ok. Because, this is a wider band gap material, so I must go to a higher voltage. This is a narrow band gap, I can at a lower voltage, I can get the turn on I can get a good current alright, so that has lot of you know implications actually lot of effect on a real world devices.

For example, if I talk about LED, and LED is a P-N junction by the way. And LED essentially is a P-N junction only ok, but before talking about the LED I mean, we will talk about LED details in some other lecture. But I am just giving you know a you know a background with respect to the P-N junction. You know that you know if your band gap of a material is E_g, then the wavelength of light that you will emit is λ(lambda) equal to hc/E_g that is the wavelength of light nanometer, you will emit for the band gap. But, for the light to be emitted the material has to be direct band gap, you remember what direct band gap semiconductor is, who have studied reciprocal space and k space and other things.

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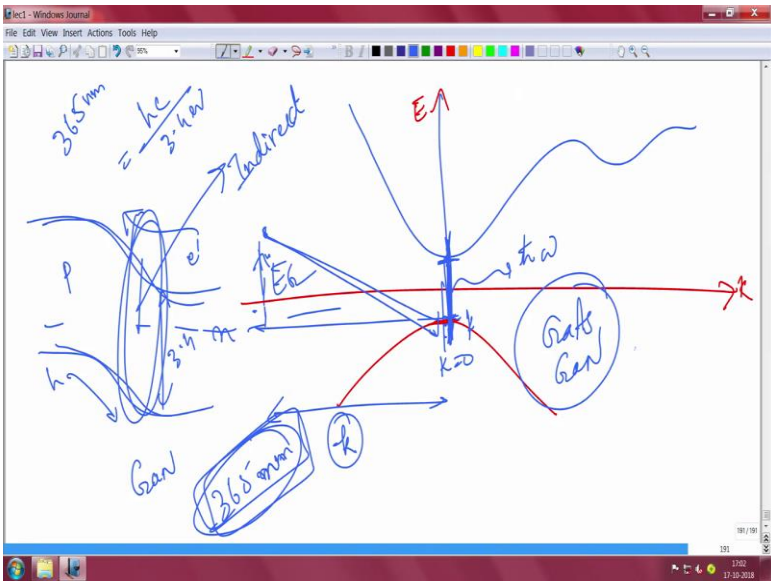

So, I told you E-k diagram if you recall if you recall the E-k diagram E versus k for conduction band, there is this sort of thing you know this different value, and valence band we will come like that. You must look at the thus lowest point in the conduction band is here, the highest point in valence band is here. So, this difference is your band gap, this is your band gap.

And if they are not at the same k point this is k equal to 0, this is k equal to some other point, these are not that the same k point you know. So, electron has to be going from here to here, sorry a electron has to come from here to here by emitting photon that is not going to happen, because it is not the same k, k is very different. So, the momentum is not conserved, you need other particles to help you.

So, this is an indirect band gap semiconductor like silicon or germanium, this cannot emit light. For a direct band gap semiconductor, the lowest point will basically be here only ok. So, the lowest point will be here. So, the lowest point is here at the same k, the k is same. So, by conserving momentum you can actually transit make electrons and holes can transit here. So, the light can be emitted. So, for example gallium arsenide, gallium nitride, these are all direct band material, they can emit light.

So, for example if I make a direct band gap material gallium nitride, and it can LED, this is gallium nitride P-N junction, so this is p, this is n except that the band gap is large now, it is 3.4. Then if I inject electron from this side to that side, if I inject holes from this side to that side, the electrons and holes will recombine in the depletion region, radiatively they must recombine.

So, when they are recombining, they will emit light that emit light will be in the range of hc by band gap is 3.4 eV. So, this comes out to be 365 nanometer 365 nanometer is nearly ultraviolet. So, we cannot exactly see it neutralize, where you can see it like a it is a violet slightly, it is almost invisible now. So, a gallium nitride P-N junction emit alighted 365 nanometer, and it is a P-N junction only by the way it is a P-N junction only.

But, as I told you the gallium nitride, you now if you talk about the gallium nitride, which is this you know this pink color, the magenta color for example. To get current in our decent brightness of the light LED, you must apply at some 20 milli Amps of current for example. You have to go to higher voltage, maybe you have to apply like 3.5 volt may be whatever, so that is a large voltage that you have to apply actually to make a bright gallium nitride LED.

But, if I make a gallium arsenide LED for the same sort of thing you know 20 milli amp, I can maybe come to 1.82 V. So, for a wider band gap material, you must apply higher voltage which means to get shorter wavelength, the more UV you go, the higher voltage you have to applied to turn on, because the band gap increases. And so, have to spend more energy to get the same brightness or efficiency sort of thing the brightness actually.

So, narrow band gap material can you know at has smaller voltage you can turn on, but this narrow band gap material only can give you longer wavelength alright, it can give you only longer wavelength not that the sort of the high, the shorter wavelength that we need for blue or other kind of LED’s [FL].

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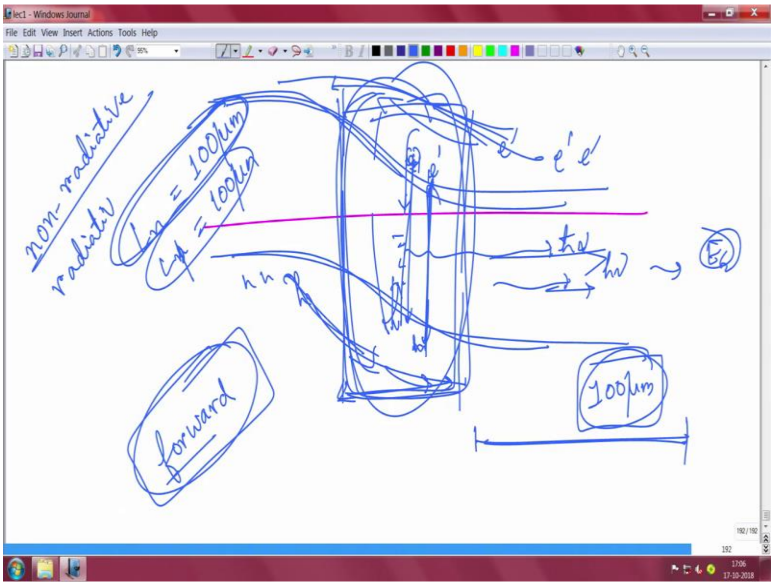

So, this is the, from the so a P-N junction, this is your P-N junction essentially can behave an LED, because this holes that are there will be injected in forward bias. You must do a forward bias, so that holes are injected to this side, and electrons are injected to this side. When electrons and holes are carrying moving there, they might recombine in their depletion region, they might recombine.

And then they will emit light. If they recombine between electron and hole not traps, traps when they recombine it traps that is called non-radiative recombination. Non-radiative as in they do not emit light, if they recombine it traps. But, if the electrons and holes recombine from band to band from this band to that band, then it becomes radiative recombination which means, it can get lost energy that electron is here the hole is there.

Even they recombine that energy is lost know that they will emit their energy as photon h nu that photon, they will emit h nu that is equal to E G the band gap. The gap that is whatever the band gap is there that is the energy that they are losing when they recombine, so that lost energy is emitted as photon that is fine LED works.

So, then your question is doing every p n I mean it has to be direct band gap material if it is silicon, it will not emit, because silicon is indirect band gap material. So, then we have question will be does every material a P-N junction of every material emit light, not exactly it can emit light, but the thing is that if electrons move so fast to the other side. And holes move so fast to the other side that they do not get time to recombine, then the emission will be very low.

So, there are many ways and techniques in which you want to make sure that electrons and holes spend more time in this depletion region, so that they definitely recombine, because the electron might diffuse you know the diffusion length of electron for example is you know long. Suppose, say 100 micron micrometer diffusion length of a holes is also say 100 micrometer. So, this length will not be there, this will be like 100s of nanometer.

So, if the diffusion length is 100 micron that means, every 100 micron every 100-micron one electron and one hole will be combine, but this depletion might be if you 100 Nano meter much lower in this. So, in this depletion less than one electron one hole will be combine, which means less than one photon will come up that is nothing no, you need large number of electron and holes to recombine, so that large number of photons come out as a LED.

So, if you want large number of electron and holes to recombine, then this diffusion length created a problem know. So, you want electrons and holes is spend more time here, so that recombine. So, there are waste to do that, will come in some future classes, we will have compound semi-conductor and other things, right now if do not worry, but other saying is that when you forward bias a P-N junction, it can behave as an LED. There is some slight modification you have to this structure to make sure LED bright, and efficient ok.

So, as forward bias you make in LED, and reverse bias you make in a photo detector that we shall discuss in the next class, because we will end up class today. So, what will be learn today? We have learned P-N junction has different components of current apart from the ideal diode equation, they also have current components like generation and recombination because of the trap states within the depletion region. They also contribute we must carefully take those into to account.

One important thing is that ideality factor, if it is 1 it means, it is close to an ideal diode; if it is 2, it is close to re-combination limited current bad materials can have ideality factor even 5, 10 or even more ok. Next thing that we learned is that the generation current in a reverse current reverse bias depends also on the reverse voltage that is why, the reverse can slowly gives increasing until it breaks down ok.

One important thing is that the band gap of the material defines the built-in voltage, and the built-in voltage defines the turn on voltage. So, a P-N junction diode turn on voltage depends strongly on the band gap of the material. If your band gap of the material is large, then the turn on voltage also will be large that has real implications and importance in designing things like led of photo detectors.

So, in LED for example is a forward bias P-N junction, it must be a direct band gap material, so that electrons and holes can recombine and emit light. In a direct band gap P-N junction, it can behave like an LED. And if it is a wider band gap material, it means you are going to blue UV sort of wavelength, then you must apply a higher turn on voltage. So, you must spend more energy to get the same brightness, compared to a low band gap material, because the turn on voltage will be very small. So, a small voltage is enough to turn on the led ok. So, these are practical things that we should consider, when we design. And P-N junction enables all this.

So, in the next class, we will just again quickly touch base with this LED and photo detector basics. See we will cover is LED photo detectors in details in future classes, but I am just telling them in the context of P-N junction that you are learning now. And then we will quickly move to break down and capacitance voltage profiling ok. Capacitance voltage profiling of a P-N function diode, because that has a lot of importance there ok and after that we will be ready to move into metal semiconductor contacts. So, thank you for your time. And we will meet you next class with taking up the P-N junction away ahead in the discussion.

Thank you.