Elements of Solar Energy Conversion

Prof. Jishnu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture - 31

Hello everybody. Welcome back to the series of lectures on Elements of Solar Energy Conversion. We are looking at the photovoltaic conversion mechanism how these materials work, and we are here at lecture number 31.

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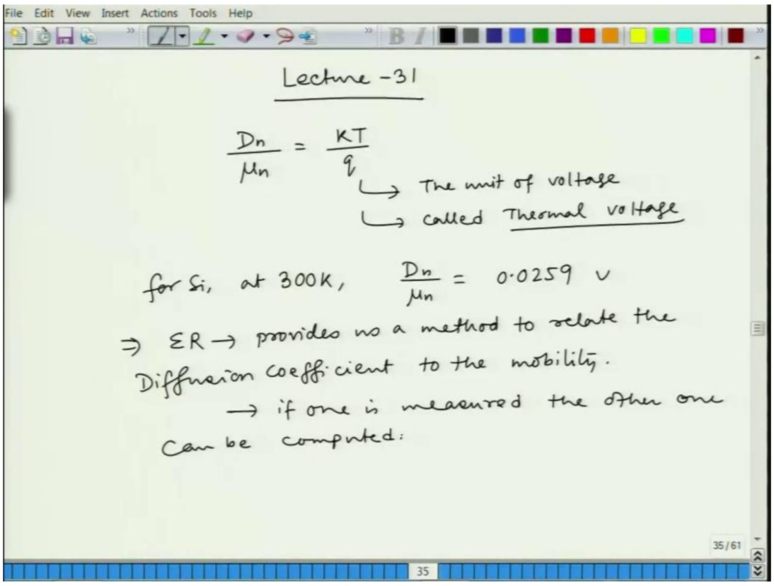

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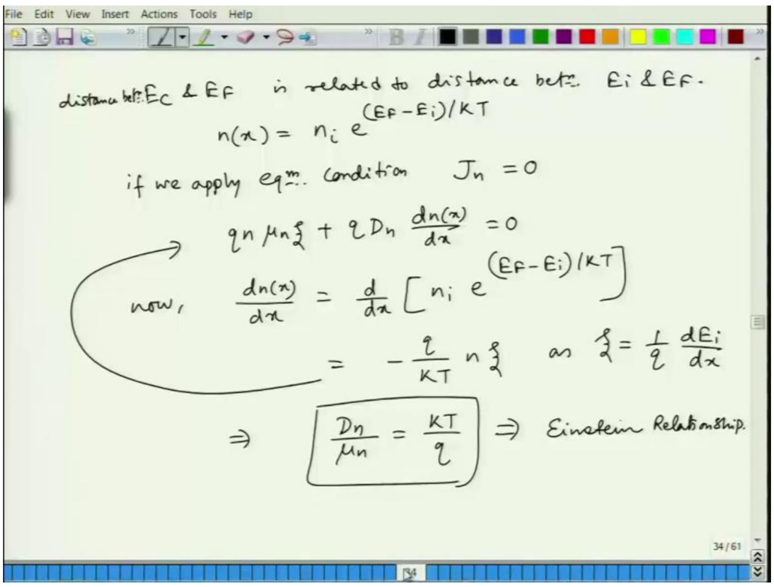

So, in the last class, we stopped here at the Einstein relationship, where we have connected or related the diffusion coefficient for the carriers and the mobility of them. So, for electron, we have seen a relation which is $\frac{D_n}{\mu_n} = \frac{KT}{q}$. And if you look at this particular term carefully, it will have the unit of voltage, and it depends on the temperature.

So, this is called thermal voltage and for silicon at 300 Kelvin. This particular quantity is a tiny voltage of 0.0259 volts. And this Einstein relationship provides us a method to relate the diffusion coefficient to mobility. Similarly, you can write this for holes as well. So, what this relationship gives if one is measured, the other one can be computed right.

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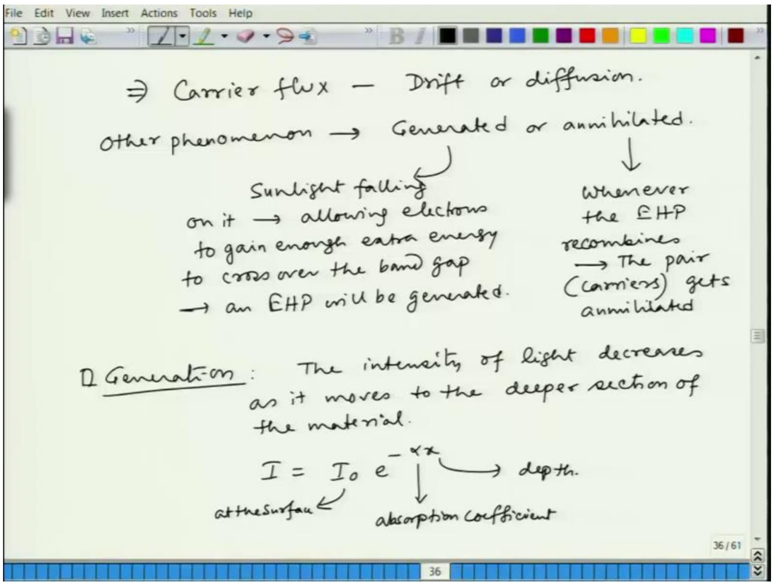

Now, so far, we have talked about the carrier flux, either the drift flux or diffusive flux. Now, what other things can happen to these carriers? Another phenomenon that can happen is either they can be generated, or they can be annihilated. So, they can be generated or annihilated. So, the generation when that would happen when you have sunlight or rather any form of energy falling on it and allowing electrons to gain enough energy or gain enough extra energy to cross over the bandgap.

So, when an electron crosses over the bandgap, what happens? An electron-hole pair will be generated. So, an electron-hole pair will be generated. So, that is how the generation will happen and how the annihilation will happen whenever the electron-hole pair recombines that means electron and hole recombine, giving us nothing. So, energy is released, and the electron-hole pair is annihilated. So, the pair or rather both the carriers get annihilated, and annihilation is also called recombination. These are the two possibilities

Now, if we want to quantify this generation part, how can we? First of all, the intensity of light decreases as it moves to the deeper section of the material. So, on top of the material, the intensity will be the highest, and as it moves travels through the material, the energy will be absorbed, and that is how it will be reduced in intensity. So, how we can quantify that intensity reduction is by a simple exponential drop or extinction, also called.

So, this is the value at the surface, and this alpha is called absorption coefficient, and x is the depth; is not it that is how the intensity will decrease. Now, this intensity decrease or this absorption coefficient can also be represented in the form of a length.

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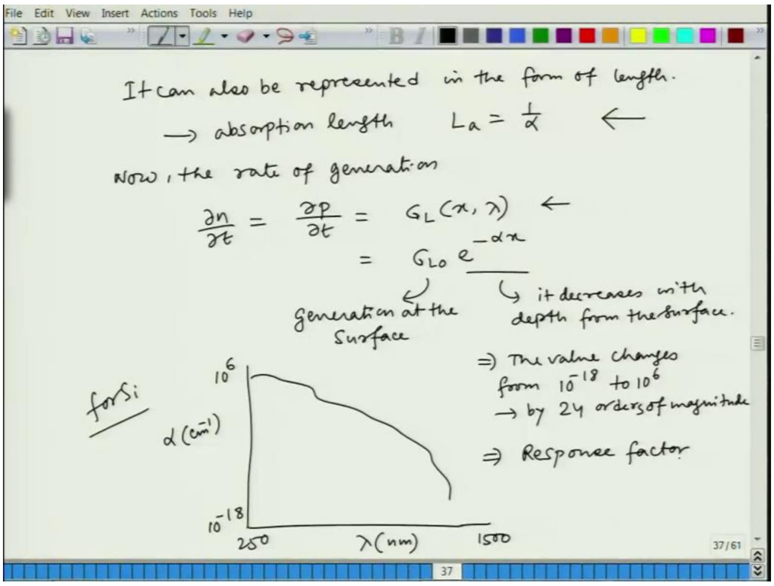

So, it can also be represented in the form of length; what does it mean? And we call that particular thing is absorption length. So, basically, the absorption length L_a, L is the length, and a is the absorption we can write it to be $\frac{1}{\alpha}$.

So, if we do that, we can see that absorption length will be lower when the absorption coefficient is higher. So, the intensity drop will be much faster in the length scale. So, if we can write that, then the rate of generation we can quantify to be $\frac{\partial n}{\partial t}$.

That means the increase of concentration of electron with time, and of course, that will be the same as the concentration of holes with time. Because once there is an electron generated in the sense of a carrier when it moves to the conduction band corresponding hole is generated in the valence band.

So, both the rates will be equal, and we can write the rate of generation, and that will be a function of depth and the wavelength because wavelength gives us the energy content of the wave right. So, how much energy will it absorb to jump from the valence band to the conduction band? It will depend on or how much of that energy is taken will depend on what is the wavelength of the incoming energy.

So, the same thing we can write the as $G_{Lo}e^{-\alpha x}$. So, where this is generation at the surface. So, this absorption length we will use very shortly. So, that is the generation at the surface, and this is how it decreases with depth from the surface right. Now, this alpha this absorption coefficient will be a function of wavelength; that is why this G_L, as you see here, is a function of wavelength lambda.

So, if we look at that for silicon, so, this is alpha with unit centimeter inverse, and this is lambda or wavelength in nanometers. So, for the typical range of solar radiation, which is between 250 to 1500 nanometer, you will see that this is, of course, a schematic value will see that the value changes very significantly. So, so the value changes between 10^{-18} to 10^{-6}. That means so this is for silicon. So, the value changes from 10^{-18} to 10^{-6}.

So, by order of magnitude or rather by 24 orders of magnitude is not it. So, that is a huge change. So, what it tells us that the absorption or the generation of electron-hole pair is a very sensitive function of the wavelength of the incoming radiation ok. If it is that sensitive, then we will know, or we will have that the wavelength will be or the range of wavelength that will be effective in generating this electron-hole pair will be very narrow for the for a particular material.

So, we define you will come to this term response factor, which tells us in what wavelength region the particular material photovoltaic material is effective.

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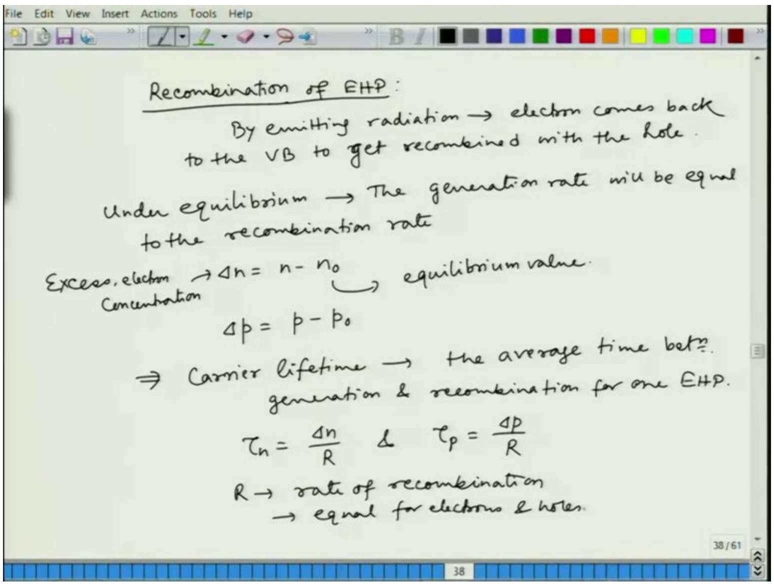

Now, the other thing that will happen is annihilation which is in the form of recombination of electron-hole pair. So, the recombination will happen by emitting radiation, and the electron comes back to the valence band to get recombined with the hole right.

So, now you can think of under equilibrium, the generation rate will be equal to the recombination rate. So, that is why we call it equilibrium; there will be no net generation or net annihilation. So, now, if we say that the excess electron-hole pair that are getting generated, is this.

So, this is the what should I excess electron concentration is this Δn, and this n_o is the equilibrium value. Similarly, you can write for p; $\Delta p = p - p_o$. And we also need to define one more quantity which is called the carrier lifetime, which is basically the average time for generation and average recombination time between generation and recombination for one electron-hole pair.

So, it is getting generated by absorbing some energy, and then by releasing that energy, it is getting recombined, and the average life span of that particular process is called the carrier lifetime. And for electron, we designate it with τ_n; τ stands for time, and that is nothing, but this Δn which is the excess electron concentration divided by the rate of recombination. And similarly, $\tau_p = \frac{\Delta p}{R}$ and R is the rate of recombination, and it has to be equal for electrons and holes.

Now, we are in a position to write the continuity equation or the mass balance of the carrier's electrons and holes.

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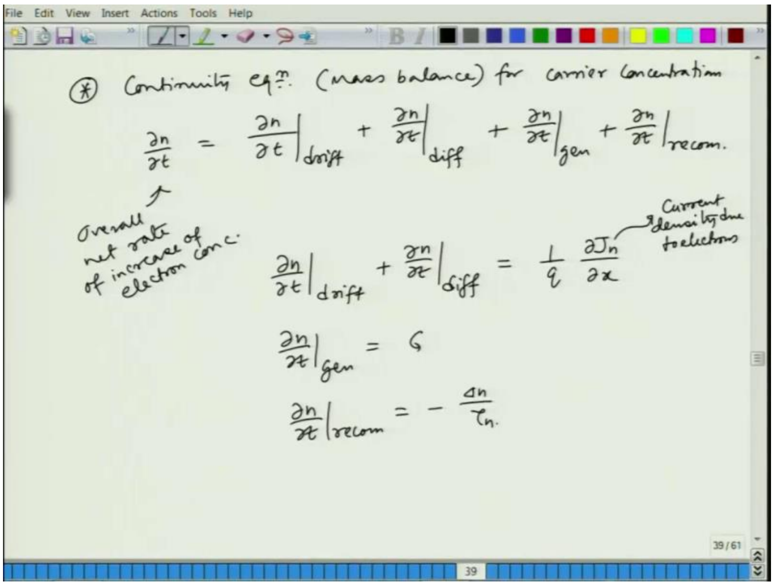

So, if we try to write the continuity equation or the mass balance equation, you can also say the number balance equation for carrier concentration. Then what can we write? The effective rate of generation $\frac{\partial n}{\partial t}$ that has to be equal to few things. The flux terms first are due to drift, and then for the diffusion for any control volume if you take, there will be some flux terms coming in and going out, and there will be some generation and recombination.

So, the first two flux terms and then the generation term and the recombination term right. So, that will give you the overall net rate of increase of electron concentration, is not it? Now earlier, we have seen that these two quantities $\frac{\partial n}{\partial t}$ for drift plus $\frac{\partial n}{\partial t}$ for diffusion. You can write in terms of electron or the current density in the form of current density. So, this will be nothing, but $\frac{1}{q}\frac{\partial J_n}{\partial x}$.

So, this is nothing but current density due to electrons. So, those flux terms you can write in terms of the current density and the other terms for the generation we have used this particular symbol G. And for the recombination part what we have seen that we can write it in terms of this $\frac{\Delta n}{\tau_n}$ which is the lifetime for the carrier.

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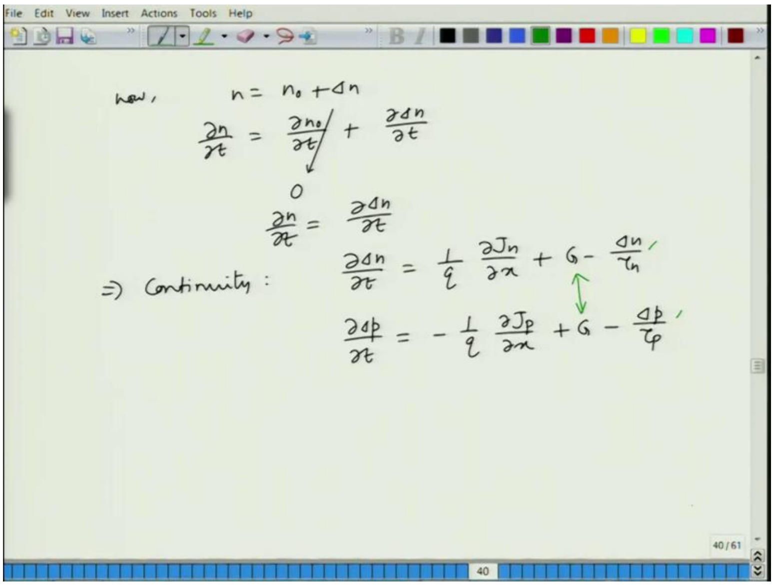

So, now we have seen that $n = n_o + \Delta n$, that is how Δn is defined with equilibrium value plus the excess value.

$$\frac{\partial n}{\partial t} = \frac{\partial n_0}{\partial t} + \frac{\partial \Delta n}{\partial t}$$

This is 0 because it is a constant. So, it is not changing with time. So, del n del t is nothing, but

$$\frac{\partial n}{\partial t} = \frac{\partial \Delta n}{\partial t}$$

So, basically, the continuity now takes the form that

$$\frac{\partial \Delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G - \frac{\Delta n}{\tau_n}$$

And for whole the same way you can find

$$\frac{\partial \Delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G - \frac{\Delta p}{\tau_p}$$

Here you note that these two terms are equal. And again, these two last terms are also equal. But you cannot write them as because this τ_n and τ_p those values can be different.

So, this is the background we have created all the carrier motion generation recombination continuity. So, that we can analyze a complete control volume kind of analysis later, but before that again, we are going back to the conceptual level without trying to quantifying, but qualitatively understanding what is going to happen.

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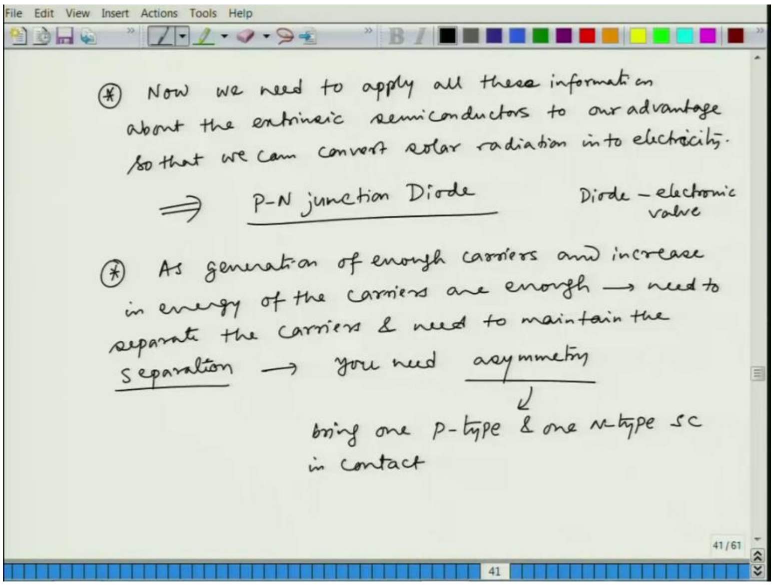

So, now we need to apply all this information about extrinsic semiconductors. Somewhere we have electron concentration dominating, and somewhere you have hole concentration dominating. That means we have these N-type and P-type semiconductors, and both of them are extrinsic. Because otherwise, you will have the same number of electrons and holes. So, for this extrinsic semiconductor to our advantage.

So, that we can convert solar radiation into electricity, so, that is the goal to get a photovoltaic effect you radiate solar radiation, and you get electricity as the output. So, what we need to have is not pure or extrinsic semiconductors but a combination of them. So, we call them a P N junction diode which is the key to getting the photovoltaic effect, and diode means what? The diode is an electronic valve.

So, a diode stands for an electronic valve. What a valve does? It allows flow in one direction but does not allow the flow in the reverse direction; that is the purpose of a valve. Here also, we will see the P N junction diode that we will generate will allow the carriers from one or the current to flow from one direction, not in the other direction, so that is the first thing.

So, a generation of enough carriers and increase in energy of those carriers. So, that they can move that is not enough, what you need to have? You need to separate them separate the carriers and need to maintain that separation somehow. Otherwise, you will get a tiny amount of current quickly, and then it goes to equilibrium, but you have to do it in a sustained manner. So, you have to keep them separated to maintain the separation. So, so you need some asymmetry; otherwise, this separation.

So, this separation will not be generated and maintained. So, this asymmetry is generated when you bring one P-type and one N-type semiconductor in contact. If you bring them to intimate contact, you will generate that asymmetry. Because now you have electron concentration higher on one side and hole concentration higher on the other side. So, that asymmetry we have to generate and maintain is why we call it the P N junction diode.

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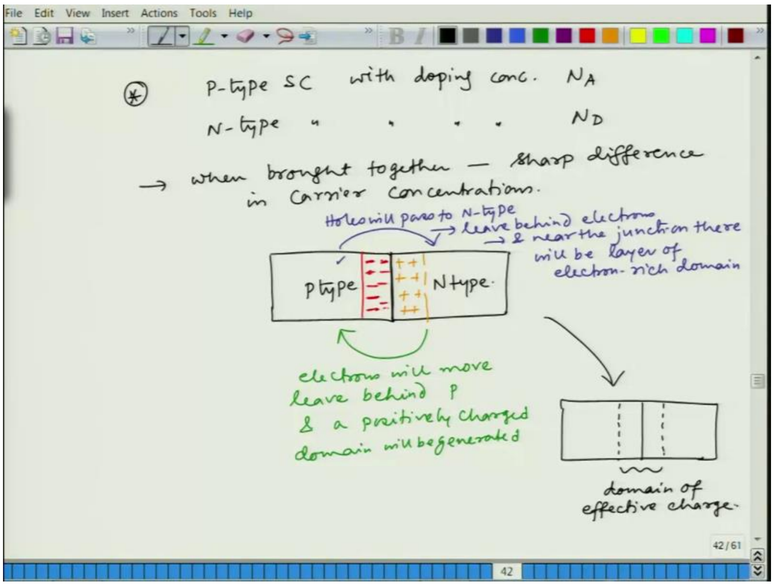

So, let us say that we have one P-type semiconductor with doping concentration N_A. A for acceptor accepted dopant, and we have introduced N_A of that, and we have a P-type semiconductor with doping concentrated of N_D, D stands for a donor. So, N_D is the doping concentration for N-type semiconductors. So, when you bring them together, then there will be a sharp jump or sharp difference in carrier concentrations.

So, you can think that this is the P-type, and this is the N-type you bring them together, you make a junction. So, that the carrier can pass through them, the contact resistance is minimum. So, what will happen? Here the holes are dominant; so, it will try to diffuse to the other side because holes are less in the N-type semiconductor. So, holes will pass to N-type, and by that, it will leave behind electrons right other. I mean, initially, when the junction was not made, it was electro neutral right, even if holes were more in number, but it was electroneutral.

So, when the holes travel to the other side, now it will leave behind those electrons, and that means, near the junction, there will be a layer of electron-rich domain right. So, we can think that this will be an electron-rich or negatively charged domain, and the opposite thing will happen from the N side.

So, from here, the electrons will move, and it will leave behind holes, and a positively charged domain will be generated near the junction right. So, you can think that this will be a positively charged domain that will happen. So, let me use these negative symbols. So, these will be negatively charged domains, and on the other side, they will be positively charged domains.

So, what we can do, what we can see that just by bringing them in contact, what will you generate? We will generate a domain where there will be some effective charge. So, this is the domain of effective charge right. But this process of holes moving to the N-type and electrons moving to the P-type will not continue forever.

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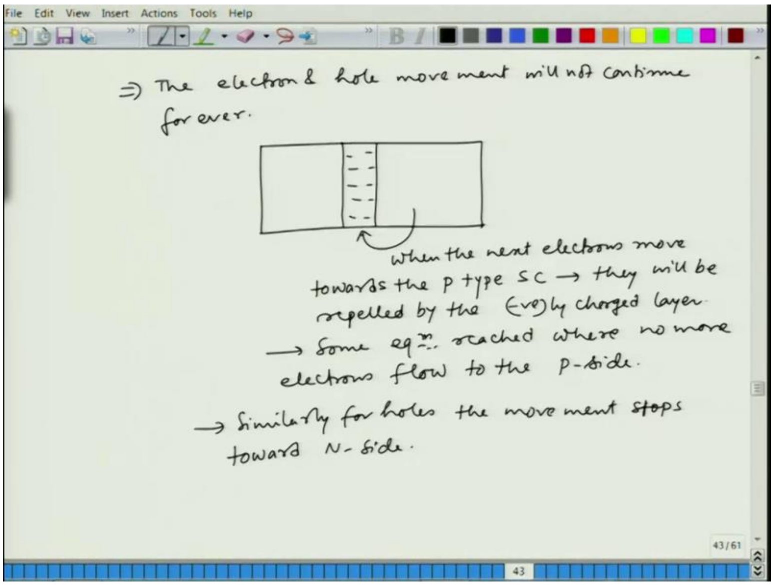

The electron and hole movement will not continue forever; they will come to some equilibrium because as soon as, so we can think of this like if this is the junction. Now, now here we have some negative charge domain. So, when the next electrons move towards the P-type semiconductor, they will be repelled right, repelled by the negatively charged layer, and this repulsion will increase as the process continues.

So, there will be some equilibrium value where it will stop. So, some equilibrium reached where no more electrons flow to the P side right. And similarly, for a hole, the movement stops towards stops toward N side. But effectively, what you get effectively, you get.

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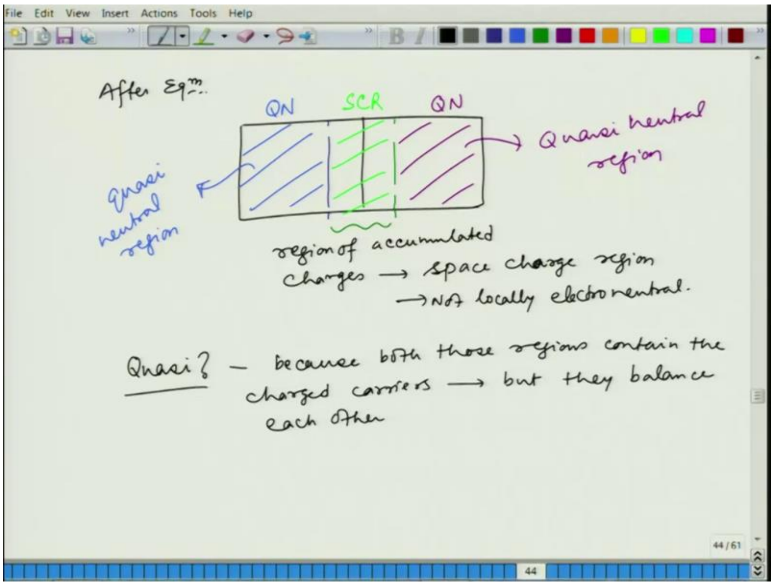

So, after equilibrium is reached effectively, what you get? A domain with positive and negative charges coming together and. So, this region is a region of accumulated charges, and we call it a space charge region where it is not locally electroneutral. It has some accumulated charges, not locally electroneutral, but the other part such as this part is same as the earlier one.

So, this is we call it quasi-neutral region, and for the N-type side, this is also another quasi-neutral region because these sites do not have any accumulated charges; of course, there will be carriers electron and holes in those regions. Because it is part of the P-type and N-type semiconductor, but overall there will be no accumulated charges; only accumulated charge will be here in this space charge region.

So, we have a space charge region here, and here we have one quasi-neutral region and another quasi-neutral region, and the space charge region is sandwiched between these two quasi-neutral regions. And why do you call it quasi-neutral why not neutral? Why quasi because both those regions contain the charged carriers ok, but they balance each other that is why it is overall neutral. But on a smaller scale, you have charged particles. So, that is why it is called a quasi-neutral region.

Now, if you look at this picture of bringing P-type and N-type semiconductors together, forming a junction.

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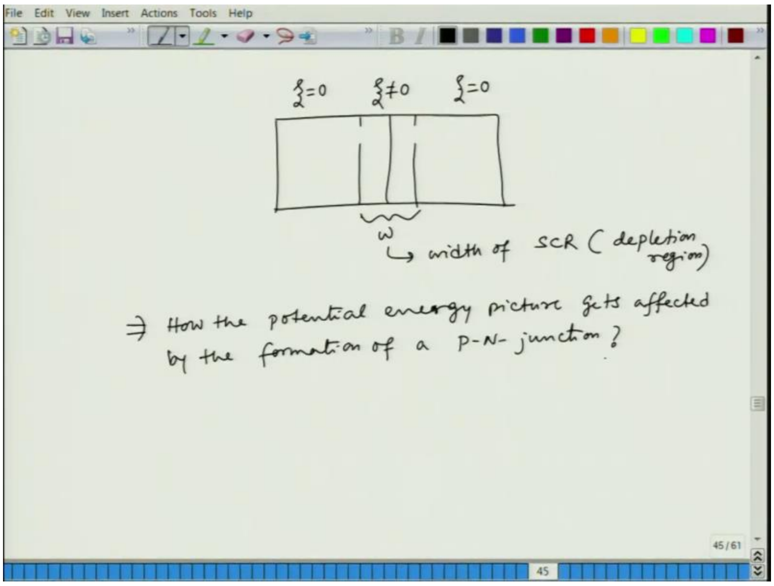

Then you can think of that here in this space charge region, and the field will not be equal to 0 because you have accumulated charges, and for the quasi-neutral region, the field will be 0. And if you say this is the width of the space charge region. So, this is the width of the space charge region, or it is also called which is also called depletion region right depletion; why? Because the electrons or holes do not move further from that space charge region which is coming due to the formation of junction ok.

Now, when we talk about this field now we can think of how the potential energy picture gets affected by the formation of a P N junction; let us look at that. So, far we have talked about, or we have mentioned that we have just brought them together, then what will happen, and that is what we call P N junction.

Now, when we call the P N junction diode, then we have to say that the carriers can move from one direction but not from the other right. So, for that, it has to have has to cross some energy barrier. So, the energy picture is important to understand why P N junction forms a diode.

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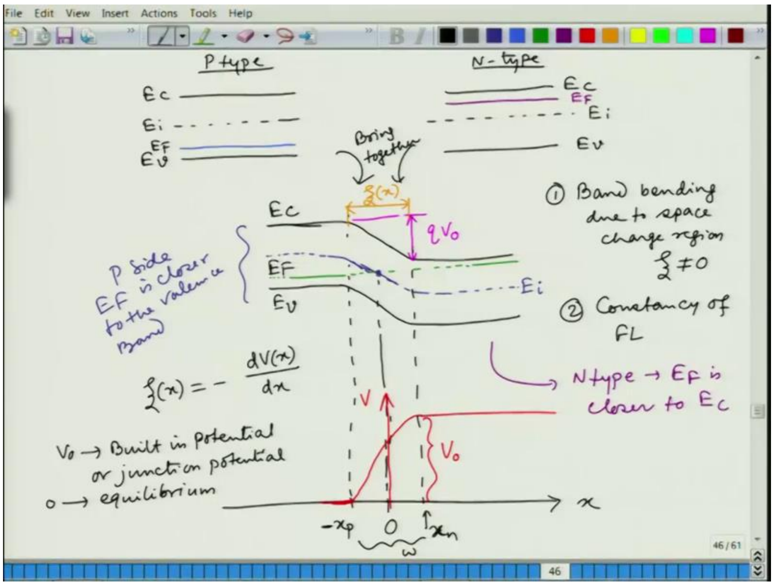

So, when you have a P-type material. So, what is the typical picture we have seen? This is the conduction band, and valance band edges and intrinsic Fermi level is just at the midpoint, which is E_i which is intrinsic Fermi level, but for P-type, we have the actual Fermi level, which is closer to the valence band right, so this is E_F. Now, the same thing we if we have an N-type, then the conduction and valence bands are just like this, and the intrinsic Fermi level is also at the middle.

But it will be easier, and for the N-type, the actual Fermi level will be closer to the conduction band edge. So, this is the actual Fermi level of N-type semiconductors; now, what are you doing? You are bringing them together P-type and N-type; you are making them together.

Now, once you make them together, this band bending will come into the picture because now you have this field not equal to 0, which means the potential energy has to change across the space charge region and the bands have to be bend. And the constancy of the Fermi level principle will also play in play a role. Because now they are in contact, when they are in contact, then the Fermi level has to be constant.

So, this is a very important concept. So, please pay attention now to what you are doing; you are bringing them together. So, the band picture will now look like, let us say that we will have a constant fermi level throughout this thing. So, here you see that band is bending, band bending happening due to space charge region where ξ is not equal to 0 is not it, and also we see this constancy of Fermi level.

And you see that here on the P side, you are still maintaining the P side Fermi level E_F is closer to the valence band, and in N-type, you see the Fermi level is closer to the conduction band. So, here this is your E_c, this is E_F, and this is E_v. So, the Fermi level is not getting bent, and it is the conduction band edge and the valance band edge that are getting bent because those are real energy levels.

Fermi level is what? It gives you the probability distribution right, where the value in half. And you can also draw here the intrinsic Fermi level, which always goes in between the conduction band and valence band just in the middle of it. So, you can write the intrinsic Fermi level as E_i at the middle of it, and it gets bent as well.

So, few things we can draw here; let us say if we just drop a line like this, what we can do we. So, this is the midpoint where it crosses. So, the midpoint is the position of the junction right, and here we have this x_n. So, in this direction, we are plotting the distance from that, and this one is the negative direction and on the P side. So, this we designate at x_p and. So, this is the width of the space charge region.

So, if we draw the potential here, we can draw; the potential will be 0 everywhere and then here also. So, in this direction, what we are drawing is V or voltage or potential. So, due to the space charge region, we are having this particular potential V_o and in terms of the energy height that how much band is bent that you can write is equal to charge into potential. That is the potential energy height, and the field is in between the space charge region, and we can write that it is a function of x.

So, here you, please note that this field strength which is a function of x is nothing but the change in V(x) with x with a negative sign. So, $\frac{dV(x)}{dx}$ with a negative sign, and that is how this V_o you are getting and V_o we call it built-in potential. So, a potential barrier or a potential energy barrier you are creating just by bringing one P and N-type semiconductor together.

By forming a junction, you are producing this built-in potential, or it is called junction potential, and why this V_o; naught stand for equilibrium as always. So, what does it mean? That we have done nothing, we did not apply any voltage or anything; we did not even irradiate light to make some generation recombination nothing is happening.

What are we doing? We have taken two equilibrium materials; one is P-type, another one is N-type, and we just brought them together. So, no equilibrium condition is getting violated. So, it is still under equilibrium, but the junction itself creates a potential barrier, and that is the built-in potential or junction potential.

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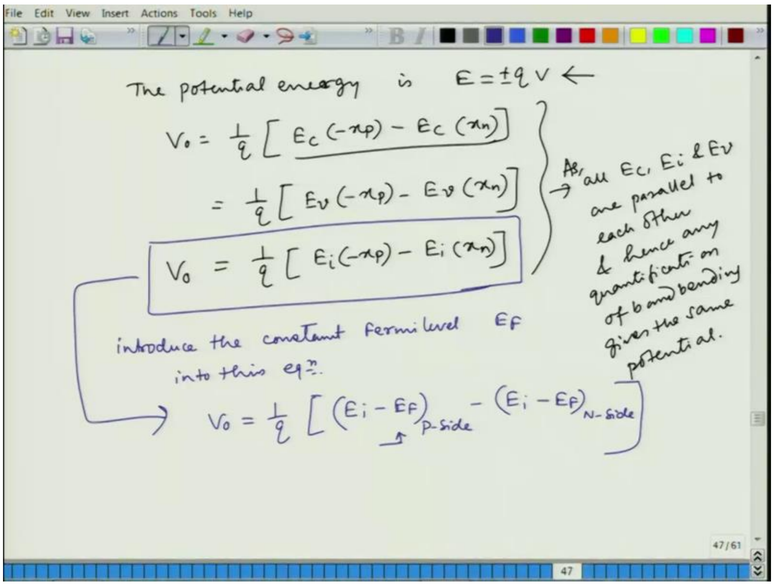

So, what can we write? The potential energy is $E = \pm qV$, and it can be positive or negative depending on the charge. So, here

$$V_o = \frac{1}{q}\left[E_c\left(-x_p\right) - E_c(x_n)\right]$$

So, if you look at the figure here, so, what is V_o you have to find what is the potential energy because this potential is obtained from this equation. So, E_c and E_v, the amount of band bend you have to find by finding this thing.

So, either you have to look at the change in the conduction band, or you can also look at the change in valence band; the thing will be the same, but you can look at it. Similarly, you can also express in terms of the intrinsic Fermi level because all of them are parallel. So, all E_c, E_i, and E_v are parallel to each other, and hence any quantification of band bending gives the same potential; is not it? This is, let me say, as.

So, now what we can do let us take this particular expression, the last one because it is in terms of the intrinsic Fermi level. Now, we are going to introduce the actual Fermi level in the junction, which is basically constant across the junction. Now, introduce the constant Fermi level, which is E_F, into this equation. So that means you add it and subtract it so that the equation does not get altered.

So, V_o you can write

$$V_o = \frac{1}{q}\left[(E_i - E_F)_{p-side} - (E_i - E_F)_{n-side}\right]$$

So, we have separated out the P side and N side, and on the P side, the shift in Fermi level you can quantify it with the amount of doping right and in the N side also the that can be quantified in the amount of doping. So, this we will see in the next class.

Thank you very much for your attention