Solid State Devices
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Lecture - 22
PN Junction (Contd…)

This is the 22nd lecture of this course and the 4th lecture on PN junction.

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So far we have completed the equilibrium analysis of the junction. With this we are ready to explain the static current voltage characteristics. So we will begin by explaining the characteristics shown on this slide.

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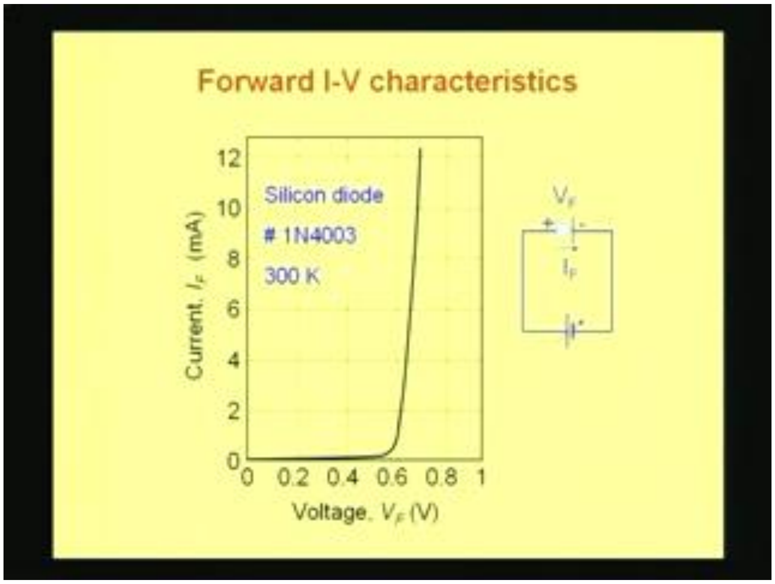

So these are the forward current voltage characteristics. This is what we will try to explain to start with. Now the methodology adopted will be the same as that outlined in the device modeling procedure. Let us look at that procedure, once more, so that we recapitulate the steps involved in device analysis. This is shown on this slide.

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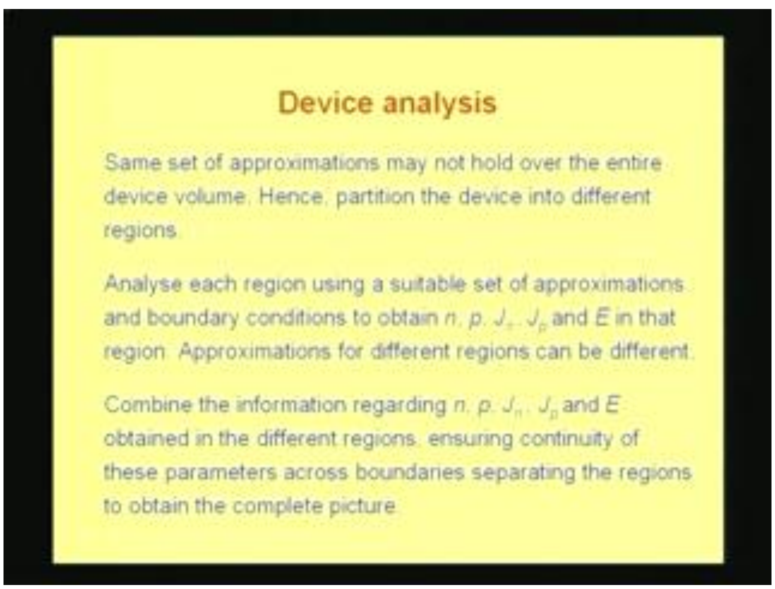

The same set of approximations may not hold over the entire device volume, hence partition the device into different regions. Now, let us see equilibrium analysis: what has it told us about the partitioning of the device?

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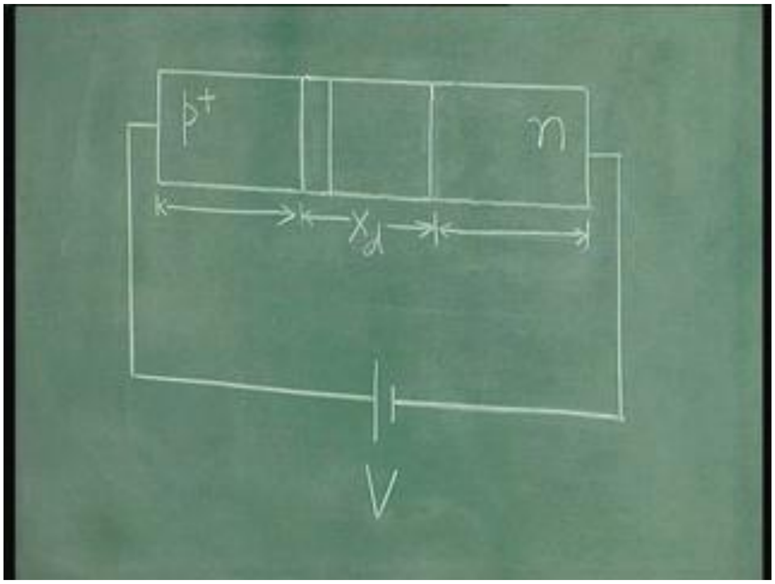

So the device is partitioned into three regions. So this X_d is the space charge region, and these two are the so-called neutral regions. So we are partitioning the device into space charge and neutral regions. So this is the first step in the analysis and this has already been achieved in the equilibrium analysis. What is important to see now is how this region the width of the regions is affected when you apply a forward bias. Let us look at the next step in device analysis as shown on this slide.

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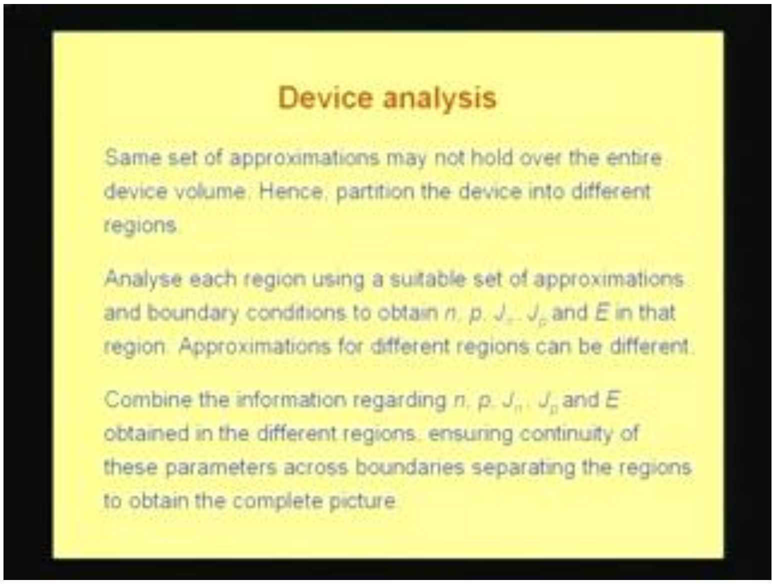

Analyze each region using a suitable set of approximations and boundary conditions to obtain n, p, J_n J_p and E in that region. Approximations for different regions can be different. So the regions that we considered, that is, the space charge and the neutral regions, will be analyzed using different set of approximations.

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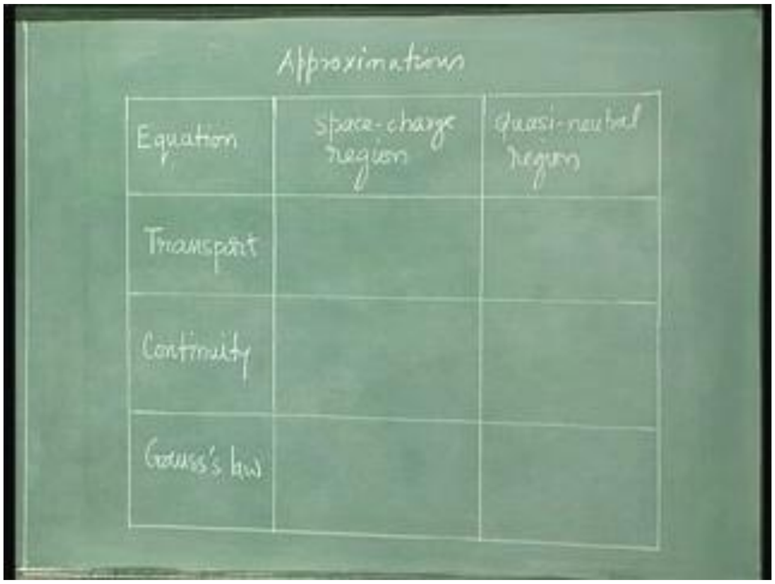

Now, that is why what we do here is that we create a table like this wherein we list the various equations: transport equation, continuity equation, and Gauss's law, and we list the approximations for these equations in the space charge region and in the quasi-neutral region. So these approximations are likely to be different because of the different physical conditions in these regions. So this is the Approximations table.

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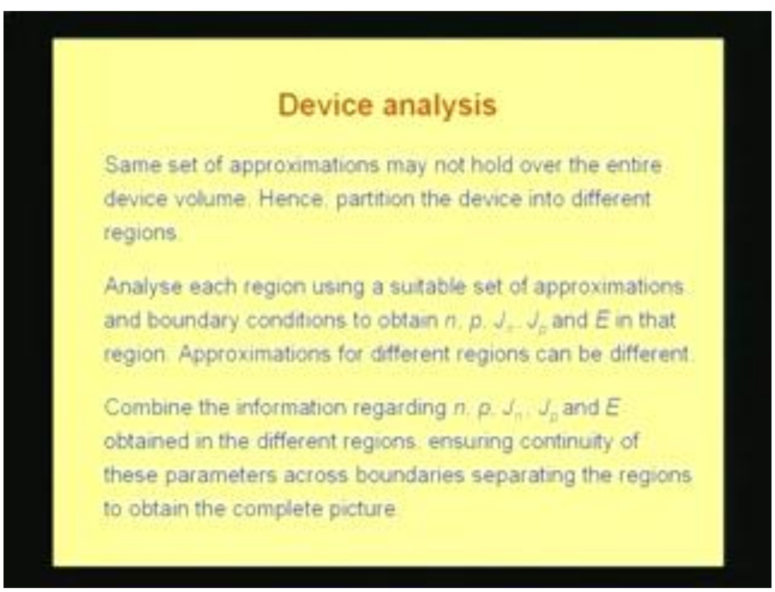

The next step as shown on the slide is: combine the information regarding n, p, J_n, J_p and E obtained in different regions ensuring continuity of these parameters across the boundaries separating the regions to obtain the complete picture. So, that is the outline of the approach that we are going to adopt to derive the current voltage characteristics. Now, I want to emphasis the fact that first we will do the analysis with the help of the five basic equations without using the energy band diagram, and then after completing the analysis, we will discuss the energy band diagram under applied bias conditions. So let us list the assumptions that we are going to make, that is, the simplifying assumptions. The characteristics that are obtained under these set of assumptions are called the Ideal I-V characteristics.

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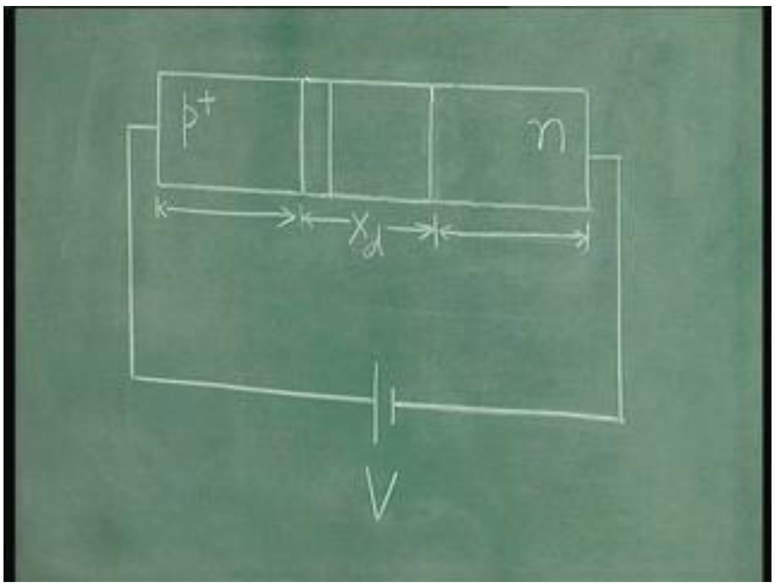

So first we derive ideal I-V characteristics based on a large number of assumptions and then we discuss how some of the assumptions have to be relaxed to get the real characteristics, which where shown on the slide.

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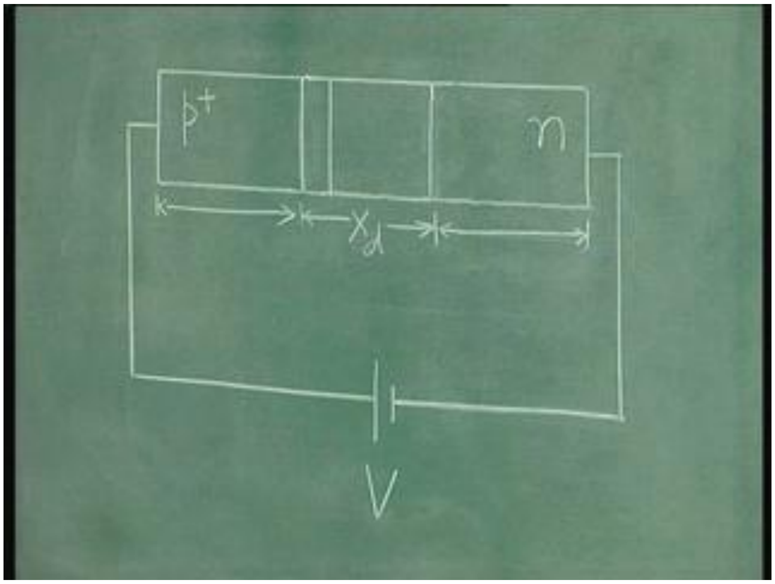

So some of the assumptions which we had already made, let me recapitulate: that the boundary between the space charge and neutral region as shown by these lines is abrupt, the junction itself is abrupt, the p and n-regions are uniformly doped, and the widths of these regions are much more than the diffusion links; that is, this width of the p-region is much greater than the diffusion length of electrons and this width of the n-region is much greater than the diffusion length of holes here. What are the additional assumptions we will make? The one important assumption we will make is that the applied forward bias is really very small, so that the equilibrium conditions are disturbed only to a small extent. This is the so-called important quasi-equilibrium approximation.

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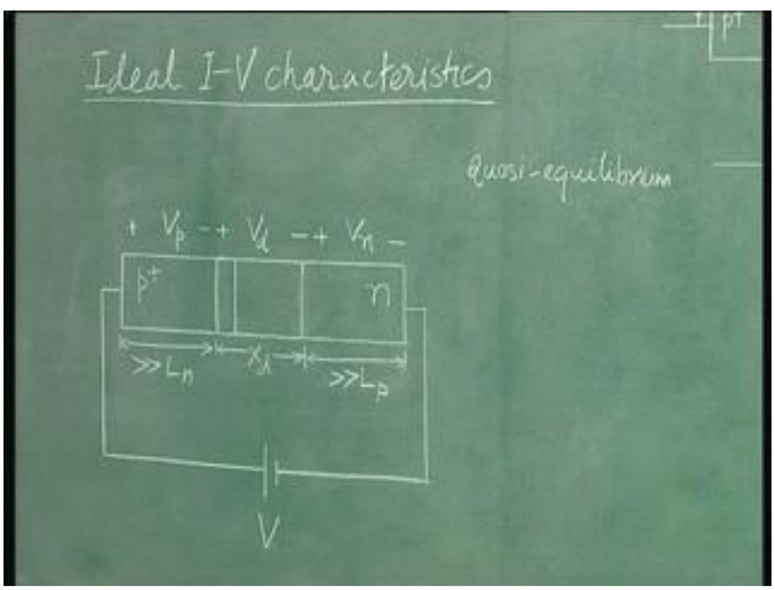

So this is one important approximation that we are going to make: quasi-equilibrium. Next the applied voltage drops across the neutral regions as well as the space charge region. So let us show that this different voltage drops as V_p across the p-region, V_d across the space charge or depletion-region, and V_n across the neutral n-region. Now these two regions, which are neutral under equilibrium, will continue to be approximately so under applied bias; that is why these two regions are referred to as quasi-neutral regions.

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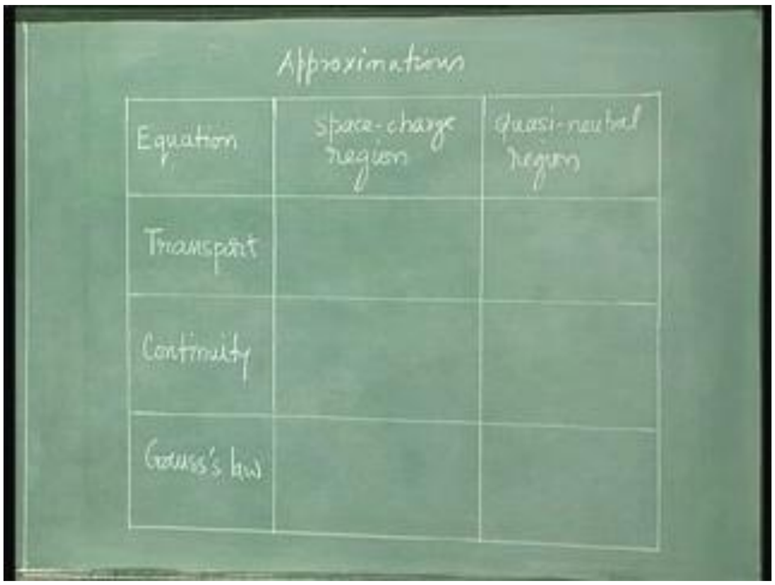

In our table here that is why we have listed the apian indices p and n-regions as quasi-neutral regions.

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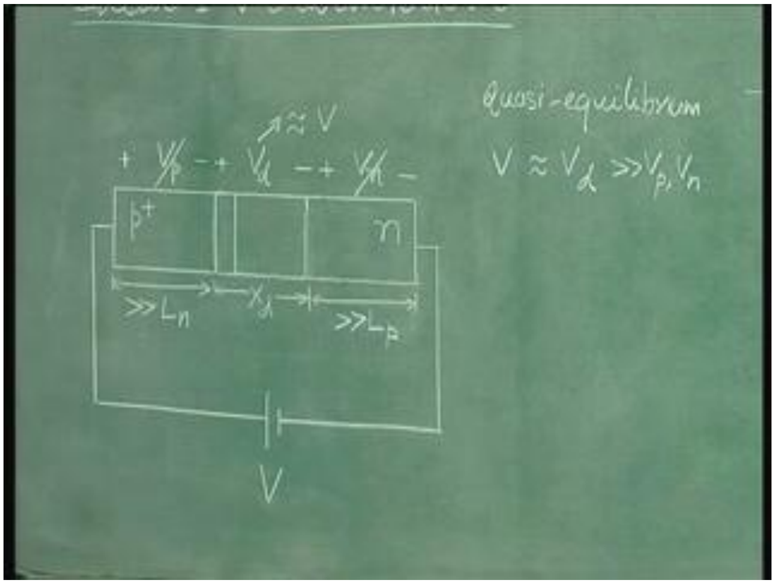

So returning to the voltages here what we will do is we will neglect V_p and V_n and we will assume that they are much less than V_d so that this V_d is approximately equal to the applied voltage. So we are assuming that the entire applied voltage falls across the depletion layer; this is the next important assumption. These approximately equal to V_d, which is much greater than V_p or $V_{n.}$ Now, how do we analyze the diode under these assumptions? So let us look at the space charge region first.

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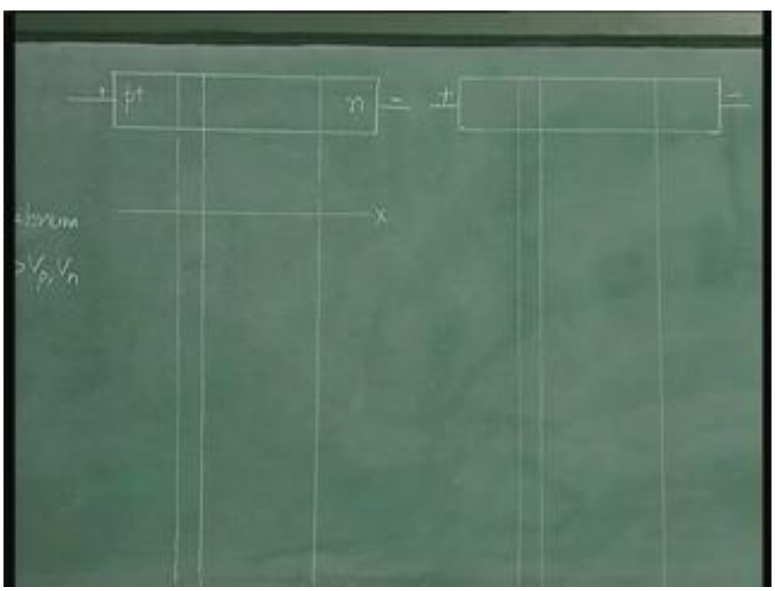

Let us draw the electric field in the space charge region under the applied small forward voltage. For this purpose, we will make the depletion approximation. We have already shown that the depletion approximation is valid under equilibrium conditions. We can easily show that it will continue to be valid under applied bias also.

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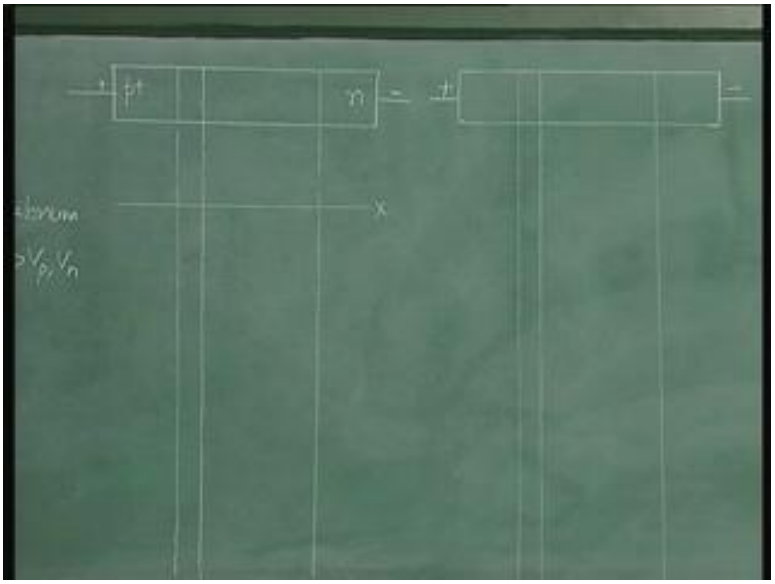

This is because if you write the space charge equation [rho??] is given by p is equal to q(p minus n plus N_d minus N_a).

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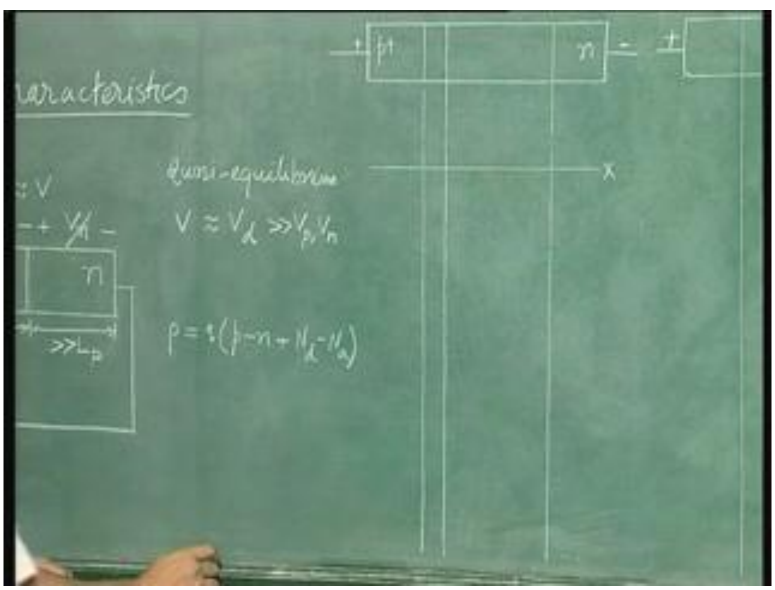

We are assuming complete ionization of the impurities.

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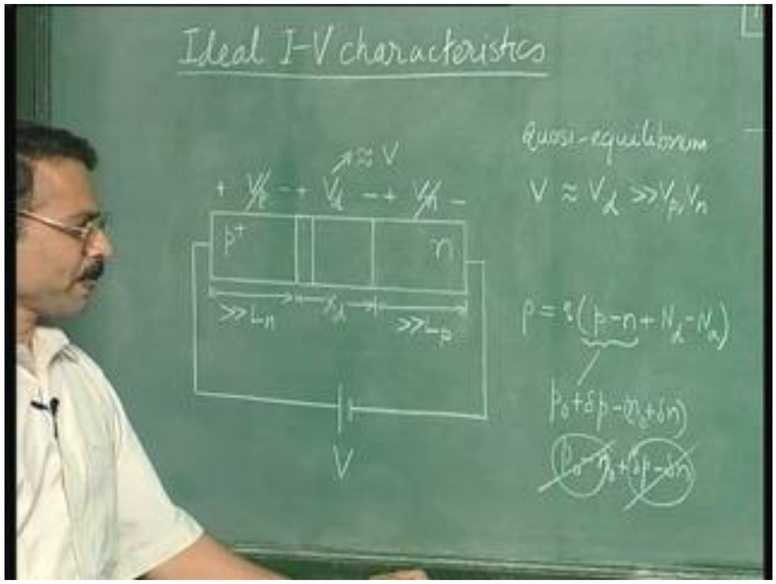

Under equilibrium conditions this p is equal to p_0 and n is equal to n_0 and in the space charge layer this p_0 minus n_0 can be neglected; that is the depletion approximation. Now under non-equilibrium conditions what happens is; this p_0 minus n_0 becomes p minus n which can be written as p_0 plus delta p minus (n_0 plus delta n). That is, under applied bias you have excess carriers delta p and delta n which is nothing but p_0 minus n_0 plus delta p minus delta n. Now we have already shown that this quantity can be neglected because under equilibrium conditions, the depletion approximation is valid. Now under applied bias, since delta p is approximately equal to delta n the electrons and since holes are generated in pairs; therefore, this quantity also will be close to zero and this can be neglected. That is the reason why the depletion approximation is also valid even in the presence of excess carriers in the space charge region.

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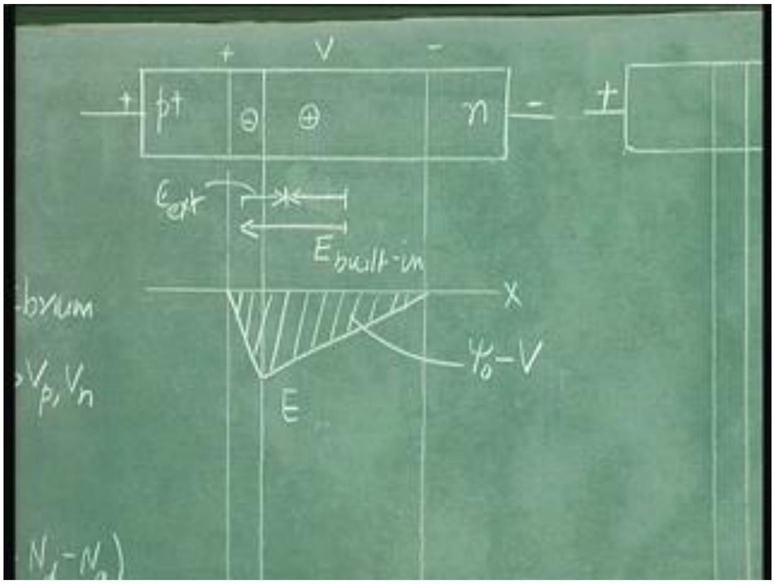

So based on the depletion approximation if you plot the electric field picture then it can be drawn as follows: so you draw two linear segments. Now, what is the width of this space charge region? How do you determine the width under applied bias?
Therefore for this purpose, note that the voltage of V (volts) is coming across the space charge layer. We are assuming that the V (applied voltage) falls entirely across the depletion layer; this is the assumption we are making. That is why the voltage comes across this space charge layer and you can see the electric field here because this voltage is in this direction, from p to n, and this electric field is super posed on the already existing electric field in the depletion layer. That is, the built-in electric field that is in the opposite direction is directed from n to p because you have positive charged donors here and negatively charged acceptors here which are causing the electric field. Now, this is the built-in electric field and this is the externally applied electric field due to the voltage.

Notice that externally applied electric field has been shown by a shorter arrow as compared to the built in electric field. This is because we have shown that the electric field under equilibrium conditions is very high and we also said that we are assuming quasi-equilibrium conditions where in the applied voltage is very small. Now, how small should this applied voltage be? This will become clear by the end of the analysis. So super position of this over this would mean that the electric field will remain in this direction even under applied bias, but it will reduce in magnitude. So if you want to show this by an arrow, if this is the built-in electric field, and this is the external electric field, then this is the electric field under applied bias within the space charge layer.

In other words, the electric field has reduced everywhere. This is logical because now the voltage drop across this space charge layer would be the built-in voltage drop, which was there under equilibrium conditions; that is psi_0, which was directed in this way, minus the externally applied voltage, that is V, so the area under this picture, the field picture, is E versus x, this area is psi_0 minus V. It was psi_0 under equilibrium conditions when you apply an external bias, forward bias, which means the bias's polarity is positive on p-side and negative on n-side. It opposes the equilibrium conditions and therefore it subtracts from the equilibrium voltage or the psi_0. So that is the area under this curve that is the voltage across the space charge layer under forward bias.

Now we can determine the new depletion width assuming this voltage drop and the depletion approximation and the formula for this will be exactly the same as that we have written under equilibrium conditions, except that the built-in voltage psi_0 should be replaced by psi_0 minus V. So if you do that exercise, our depletion width expression would be:

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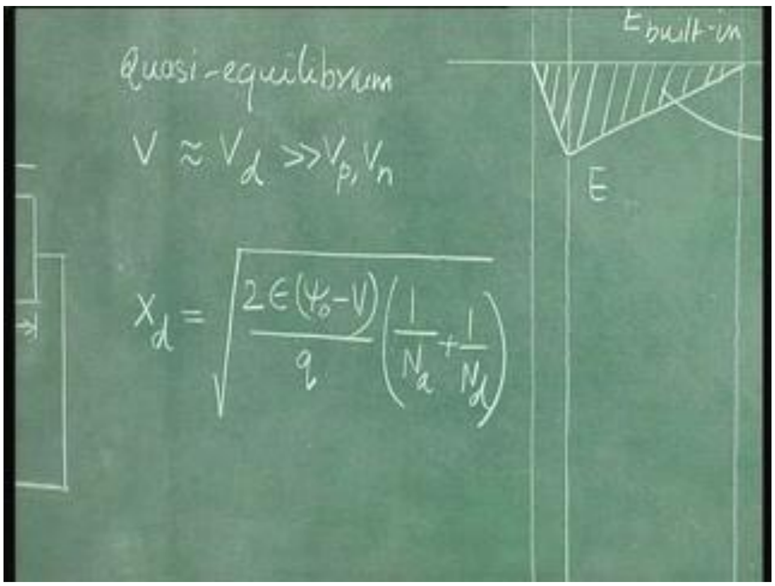

X_d is equal to square root of 2epsilon (psi_0 minus V) divided by q into (1 by N_a plus 1 by N_d). So this clearly shows that because this voltage has reduced by v, your depletion width has reduced. So let us list this approximation that we have made; that is, the depletion approximation in the space charge layer and this approximation will be listed against Gauss's law.

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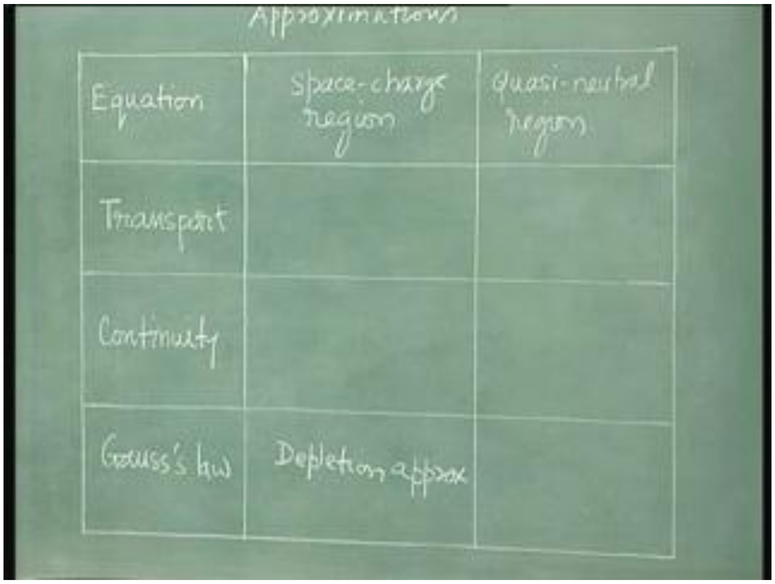

So, for now we have used first the Gauss's law of all these equations to determine the reduction in the space charge region width under forward bias. So here we make the entry depletion approximation.

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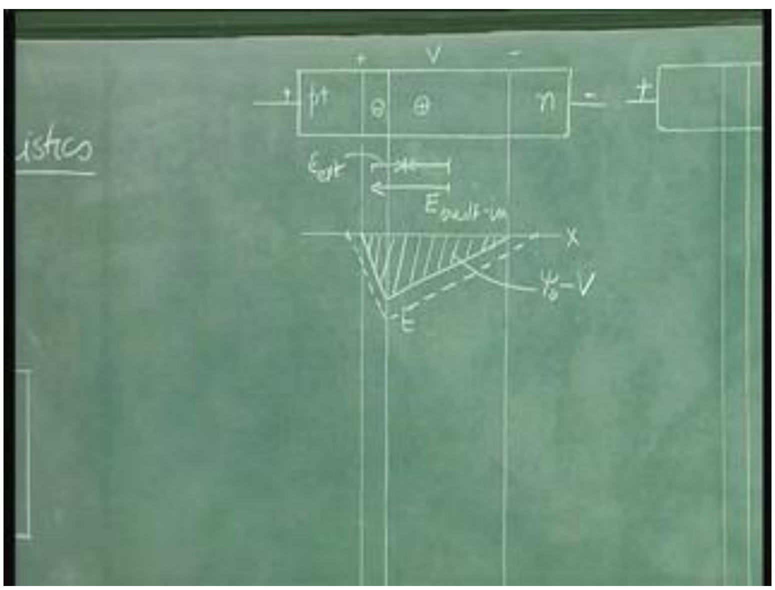

So if we show now on this diagram the equilibrium conditions for comparison, then the equilibrium electric field picture can be shown by this dotted line. So that is your : from this end to the other end is the equilibrium depletion width and this end to the other end here for the solid line is the new electric field, new depletion width; , so that completes the analysis related to the width of the depletion-region.

Next, let us try to plot the electron and hole concentrations under applied bias conditions. So since we are showing both the electron and the hole concentrations, we must show them on a log scale.

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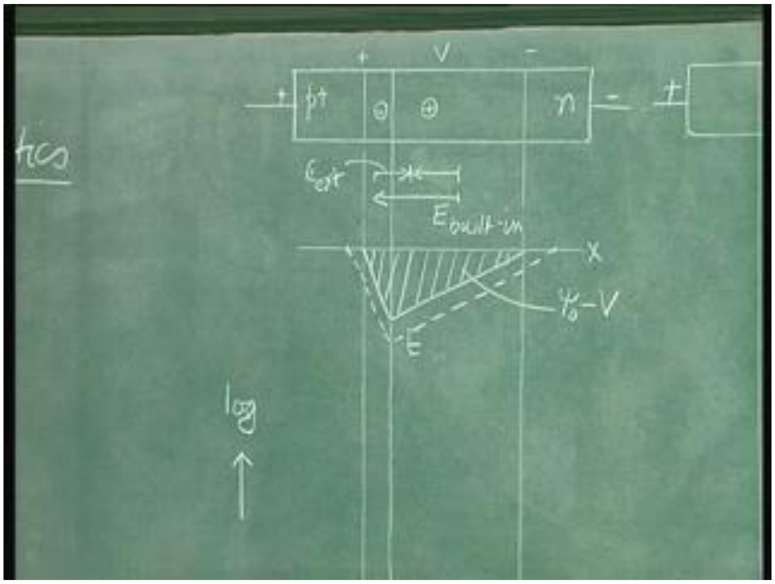

Now, to begin with, let us see how we had sketched the variations of n and p under equilibrium.

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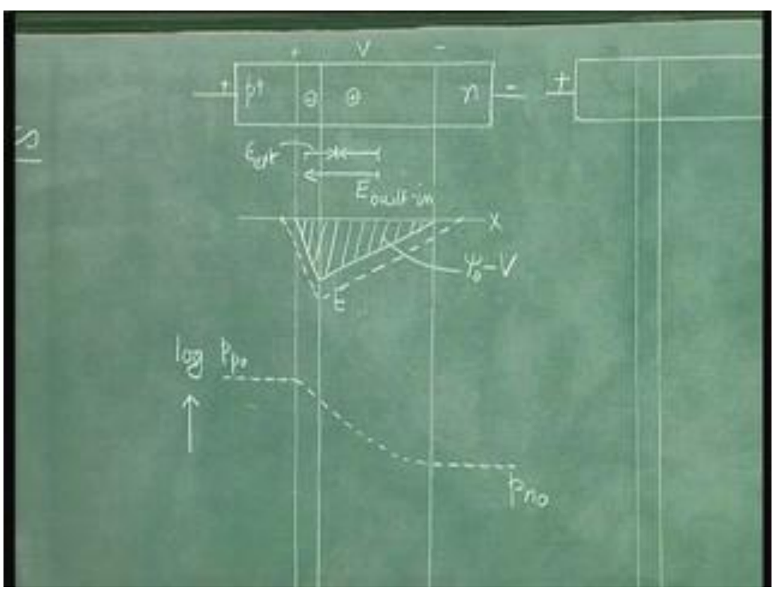

So I am first going to show for the purpose of reference the equilibrium variation of holes and electrons. This will be done by a dotted line. So the hole concentration is majority carrier here and then it becomes, it varies like this and here it is the minority carrier concentration. So this is P_{p0} and this is P_{n0}. To avoid cluttering in the diagram, I am not showing the electron concentration variation. We will show how, starting from this kind of variation of the hole concentration under equilibrium conditions, we can sketch the variation of the hole concentration under applied forward bias and then one can do a similar thing for the electrons also.

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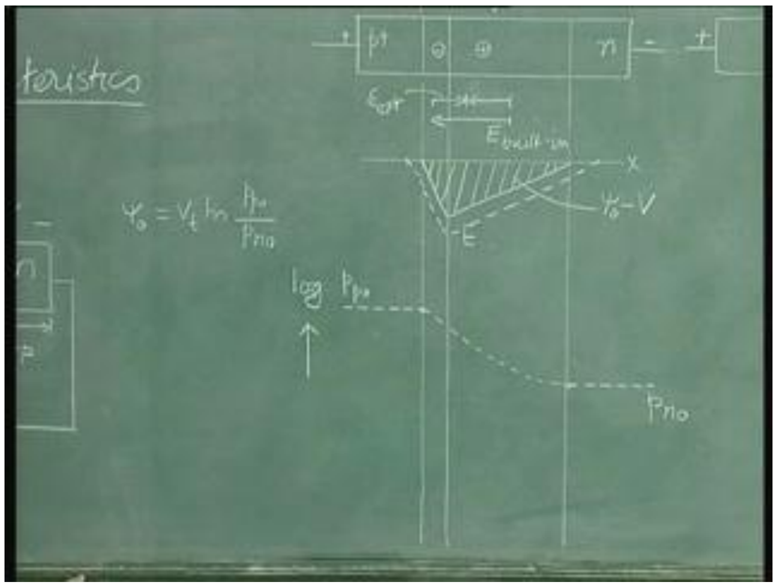

Now, here notice that the concentrations at these two edges of the depletion layer were related to the potential drop between these two points by the Boltzmann relation, which said that the potential drop between the edges of the depletion layer, which is psi_0 is equal to V_t into l_n P_{p0} (hole concentration on p-side) divided by P_{n0} (that is, hole concentration on the n-side). This Boltzmann relation was obtained using the equilibrium condition that J_n is equal to 0 and J_p is equal to 0. That is the reason, the reason for this is that the drift and diffusion currents were in balance.

Now, we have estimated the average values of diffusion currents for holes and electrons and we found that the values were rather large. If you look at the values that we had obtained from the equilibrium analysis for average diffusion current of holes, it was around couple of hundred amperes per centimeter square to the current density and for electrons the diffusion average diffusion current under equilibrium over the space charge region was more than fifty amperes per centimeter square so these are really very large currents.

In practice, if you were to estimate the forward current through a diode under quasi-equilibrium conditions, that is, for small applied voltages, then the current densities would be much lesser than ampere per centimeter square values.

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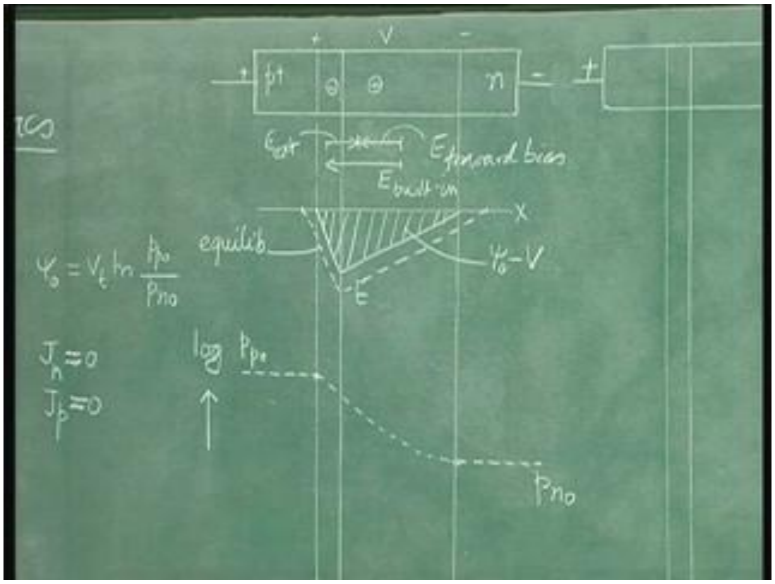

Therefore, what we can say is that under applied bias J_n will continue to be approximately equal to zero, though not exactly equal to zero, and similarly J_p will continue to be approximately equal to zero. This is the statement of quasi-equilibrium. So the statement of equilibrium is that these are exactly equal and the statement of quasi-equilibrium is that these are approximately equal. Now, why is there a small difference between the drift and diffusion components of J_n and similar components of J_p? This is because now you can see that the applied bias is in this direction so the electric field is reduced as compared to equilibrium conditions: this is the built-in electric field and this is the field under applied bias; E under forward bias, for example, in this case, since this electric field has reduced as can be seen from here also.

So this is equilibrium: the dotted line is equilibrium. Therefore, the drift components of the currents would have reduced as compared to equilibrium. So this is why the diffusion component of the currents across this space charge layer would dominate over the drift current; , and that is why the diffusion and drift currents are slightly in imbalance and it is this imbalance that gives rise to the resultant current but since this resultant current, which is the difference of drift and diffusion components is very very small compared to individual drift and diffusion components, the drift and diffusion components can be assumed to be approximately equal.

We have explained this very clearly in the topic on device analysis procedure. So what is the meaning of quasi-equilibrium? When the currents drift and diffusion are very high and they are in approximate balance this has already been explained. So I am only recapitulating for your convenience. So this is the assumption, this is the very important assumption, that we are going to make to get the carrier concentrations for electrons and holes in the depletion layer under applied bias conditions. So let us list that assumption here.

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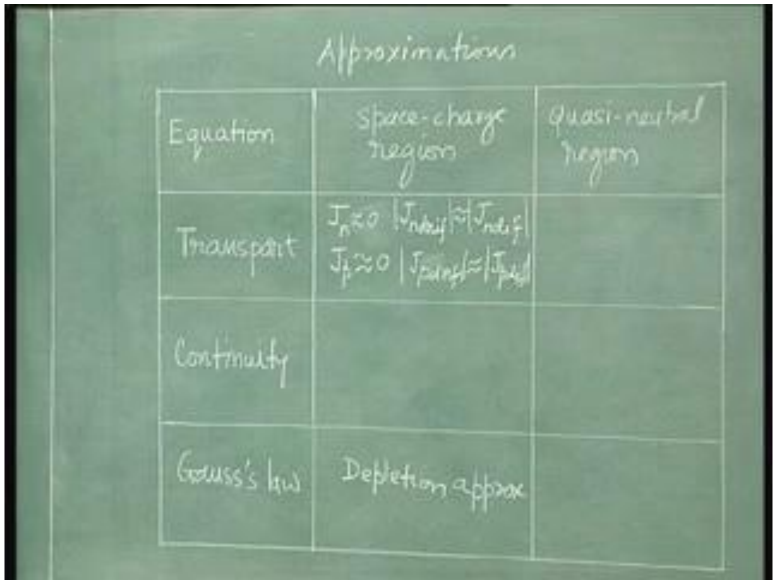

So transport equations, the assumption you are making is J_n is approximately equal to 0. That is to say J_n drift and J_n diffusion are approximately in balance because the difference between these two is very very small and a similar thing follows for J_p. So you can write a similar thing for holes here. Therefore, J_p drift is approximately equal to J_p diffusion.

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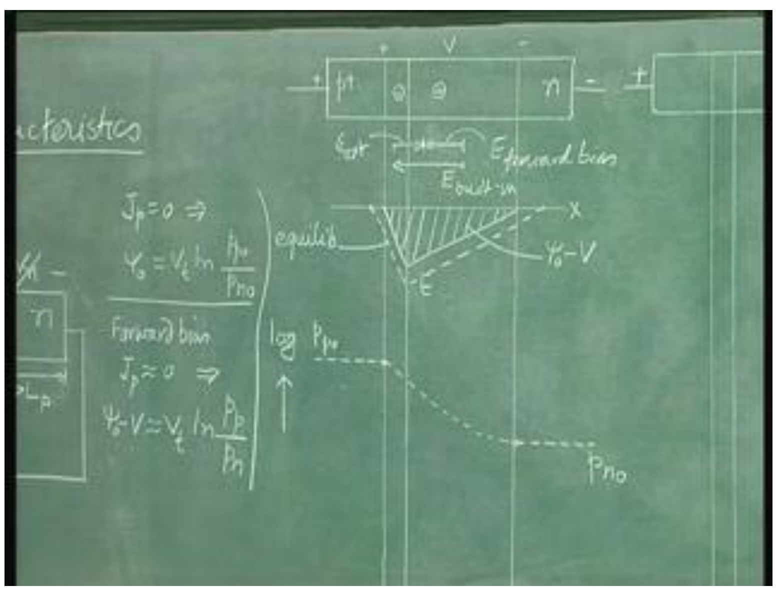

So using these approximations now, if J_p is equal to 0 leads to this condition, then J_p is approximately equal to 0 will lead to a similar condition that now the new voltage drop is psi_0 minus V. Left-hand side is psi_0 minus V under applied bias; so let us write it clearly forward bias J_p is approximately equal to 0, which means the left-hand side is psi_0 minus

V is approximately equal to (to the right-hand side is) V_t l_n, now, P_{p0} will change to P_p and P_{n0} will change to P_n that is the non-equilibrium values.

Now, what is going to happen is that since the ratio is decreasing, this P_p by P_n is decreasing; it definitely means that P_n is increasing. That is, holes are being injected from p to the power plus region to n-region because of this applied forward voltage. This is the polarity of the voltage as we explained in our simple qualitative analysis that the negative terminal will attract holes so the negative terminal will attract holes from here, from p-region, therefore holes are being injected into n-region; therefore, the concentration of holes in the n-region increases. That is why P_n will increase.

Now what about P_p?
It can be shown that P_p will also increase because just as holes are injected from p to n because of this negative potential here, the positive potential here attracts electrons from n-region into p-region so electrons will be injected from n to p. This means the electron concentration increases on the p-region but since these two regions, which are not space charge regions and are quasi-neutral regions, any excess electrons should be counter balanced by excess holes; otherwise the neutrality will not be maintained.

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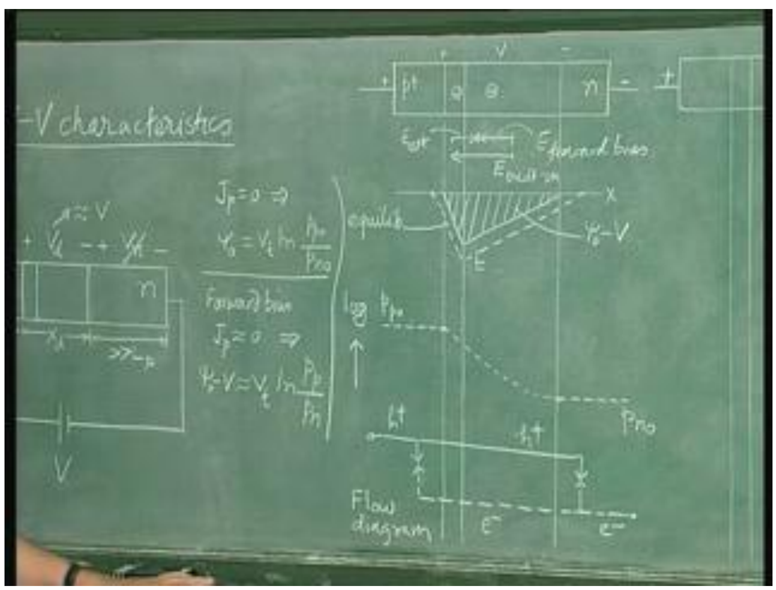

Therefore, if you have excess electrons injected into this region from the n-side, excess holes will also appear here to compensate the excess electrons from the positive contact. So, in fact this can be shown very nicely using a flow diagram. The flow diagram will be that the contact injects holes so the n-region is injecting electrons; let us say the dotted line indicates electrons. Now, because this is a quasi-neutral region, holes are injected from the contact.

We already said that holes are also injected into the n-region because they are attracted to the negative potential here. So this terminal here provides holes to compensate for excess electrons and also for injection into the n-side and similarly, since the excess holes here and this region is quasi-neutral, excess electrons will appear in this region to compensate for charges from the electrons from the negative contact and therefore you have electrons injected from the contact from this terminal. This is how you have e to the power minus injected here. So the terminal injects electrons to compensate for holes here and it also injects electrons into this region, into the p-region. This is the flow diagram. Now the net effect of this flow diagram is that you have excess electrons and holes in both neutral p and neutral n-regions so we can show this picture as follows:

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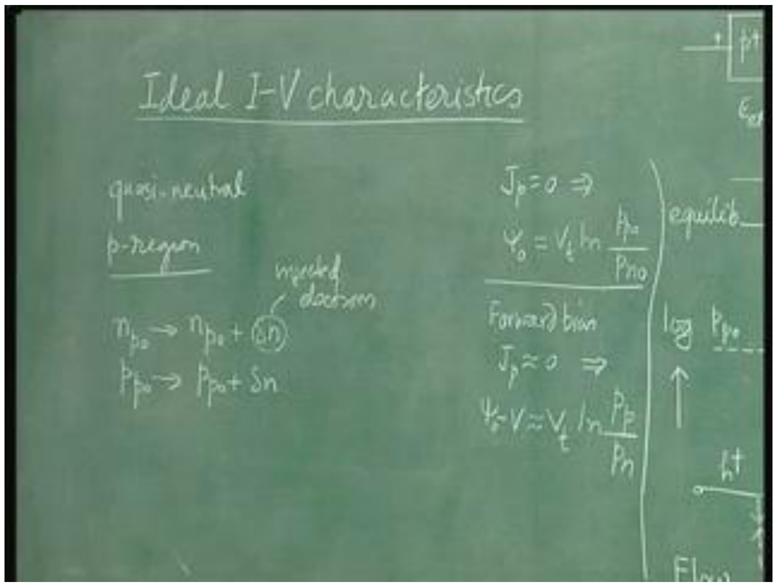

The quasi-neutral p-region, because of injection of electrons N_{p0} changes to N_{p0} plus delta n. To compensate for this delta n, your P_{p0} will also change to P_{p0} plus delta n. So the hole concentration is also increasing in the p-region by the same concentration as the injected electrons. So this delta n injected electrons are these electrons here which are equal to this delta p holes.

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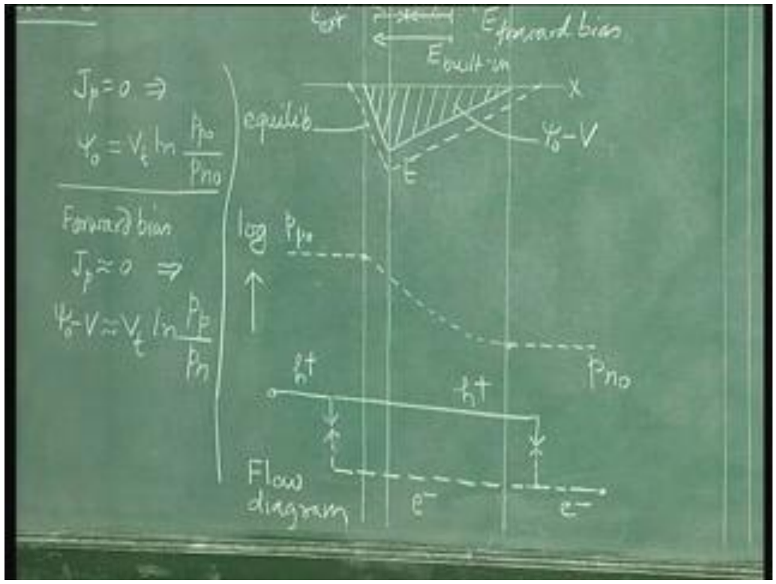

Now what is happening? What does this arrow indicate here? This arrow indicates that the excess holes and electrons are recombining so that they are continuously being replenished by the contacts. When you apply a forward bias, the electrons are continuously injected from n to p-region, the terminal is also injecting holes to compensate for the electrons and the electrons and holes recombine, and of course, holes are also being continuously injected here and these are again compensated by the electrons here, and these are recombining, that is how the current is maintained.

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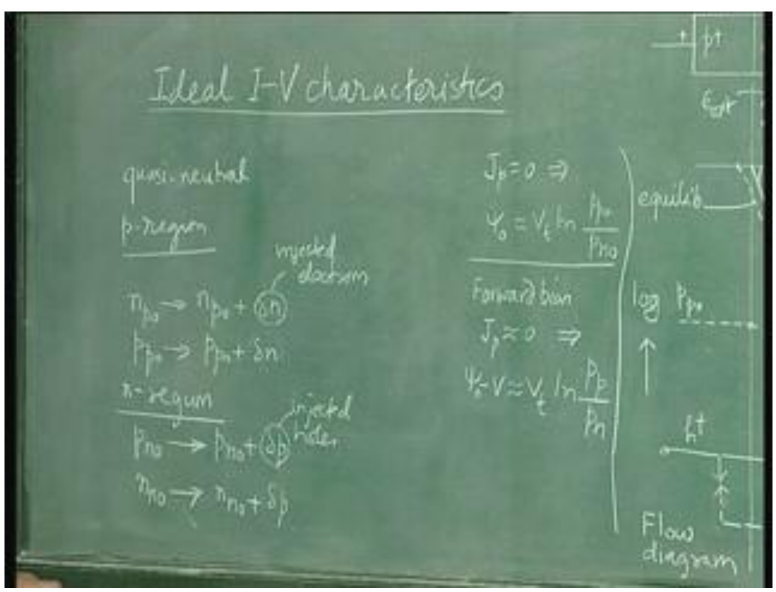

So these are injected electrons and these are the concentrations of holes to compensate for these electrons; so though we write delta n here, it is to be understood that this indicates the excess carrier excess holes, which are compensating for this the magnitude of these excess holes is exactly delta n in this region. So in n-region, similarly, one can write P_{n0}: the minority hole concentration gets changed because of injection of holes from the p-side to P_{n0} plus delta p and to keep charge neutrality the majority electron concentration also changes from N_{n0} to N_{n0} plus and excess electron concentration, which is equal to this injected hole concentration.

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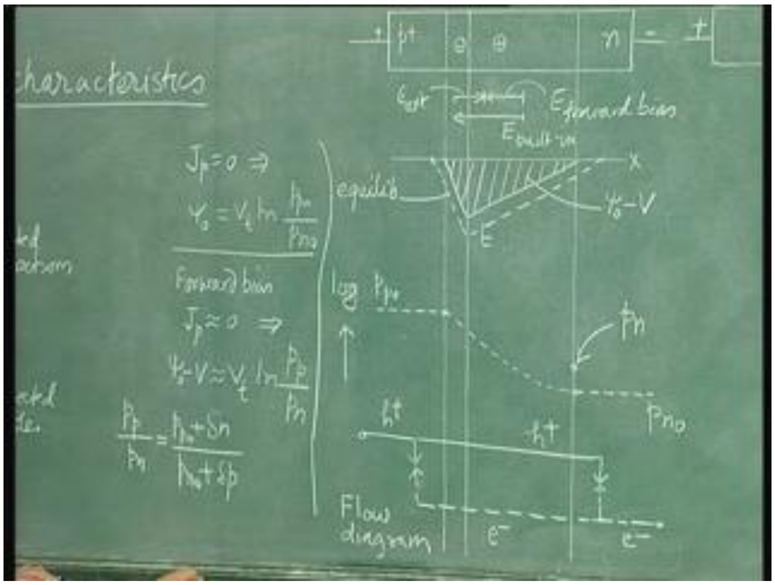

Thus if you want to write this ratio P_p by P_n, we can write it as P_p by P_n is equal to P_{p0} plus delta n by P_{n0} plus delta p. Now it is important to note that this P_p and P_n correspond to the depletion edges, so in other words, P_p is the value of hole concentration here and P_n is the value of hole concentration at this edge. Let us show P_n as some thing like this at the depletion edge. Now what about P_p? P_p is P_{p0} plus delta n. Now this is where we make an important assumption, that is, the low injection level assumption.

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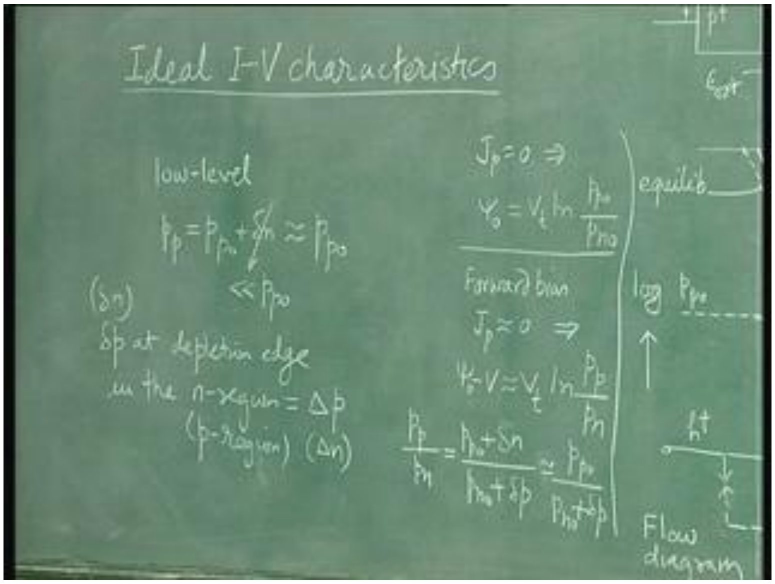

So these are additional assumptions for the ideal I-V characteristics. According to low-level assumption, the majority carrier concentration is not disturbed because of injection of electrons or holes both on the p-side as well as on the n-side. So low-level assumption means that P_p is equal to P_{p0} plus delta n is approximately equal to P_{p0} even under applied bias. So this delta n is much less than P_{p0}; this is the meaning of low level conditions. Similar arguments will apply also to electrons; but since we are considering holes, let us write here the result. This is approximately equal to P_{p0} by P_{n0} plus delta p, where it's important to note that this delta p is a value at the depletion edge. So what we will do is we will use the symbol delta to indicate the values at the depletion edge. So delta p at depletion edge in the n-region is equal to delta p, so that we can retain delta p symbol to show the value of excess hole concentration at any x. Similarly, delta n at the depletion edge in the p-region will be delta n.

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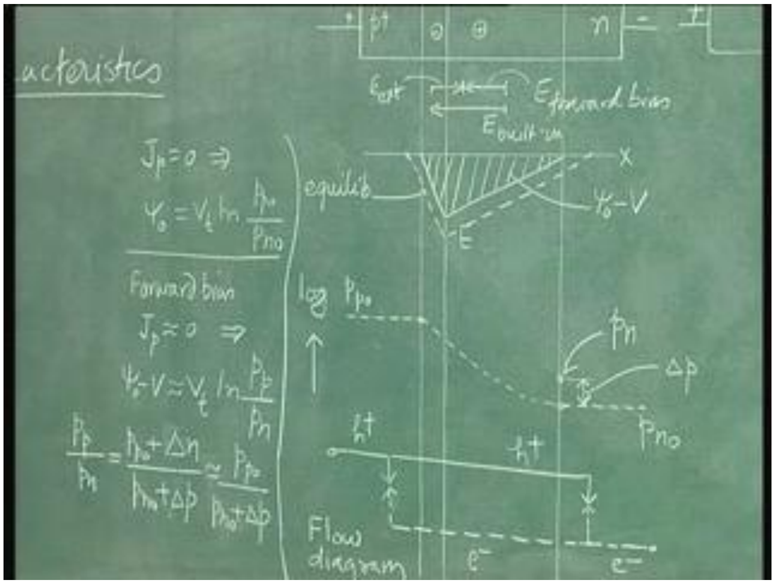

With this symbolism, we can replace this delta n by delta n and this by delta p and this by delta p. So, in other words, this difference here is delta. Now P_{p0} plus delta n is approximately equal to P_{p0}; that is the consequence of low-level assumption, which means that even under applied bias on a log scale, the majority carrier concentration will not be disturbed. This particular fact, we have emphasized in our discussion on excess carriers that low-level conditions means that when you plot majority and minority carrier concentrations on a log scale, the majority carrier concentration appears undisturbed whereas the minority carrier concentration however is definitely disturbed.

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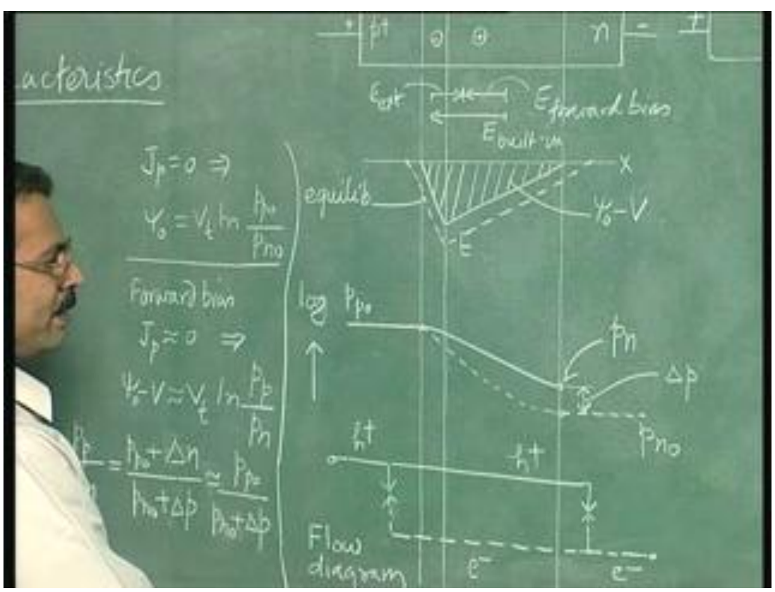

So based on these arguments, one can plot the hole concentration under low level at forward bias as follows: something like this, within the depletion layer and on this side. So we will list the assumptions that we are making.

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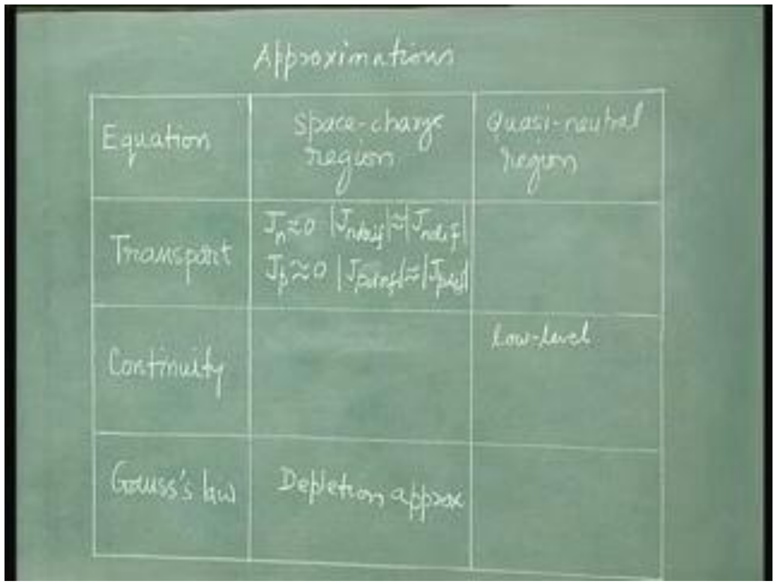

Here in the space charge region we are assuming that low-level assumption prevails. So let us list it here and since we will assume low-level conditions every where, strictly speaking, this low-level assumption should be listed in quasi-neutral region because only there you have high concentration of majority carriers and low concentration of minority carriers in the depletion layer. The carrier concentration really does not exist so we must list it under quasi-neutral region and not under space charge region.

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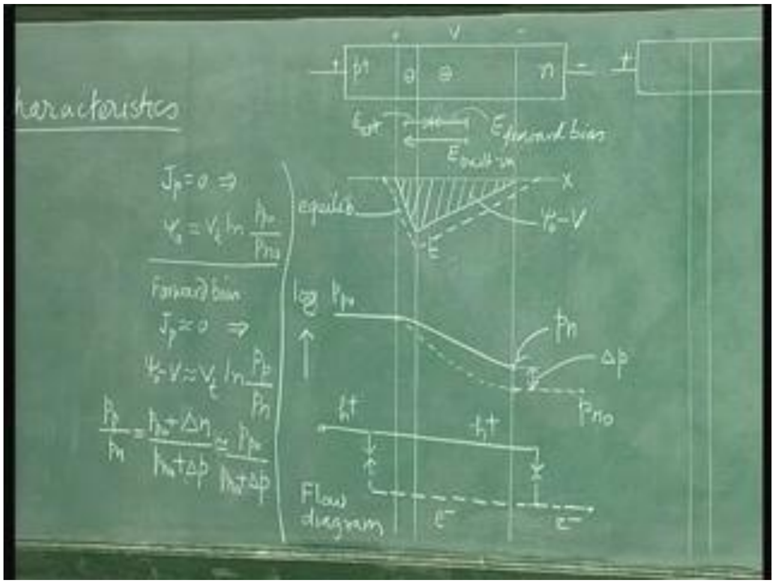

Let us return to this particular equation: what does it tell us about the value of delta p?

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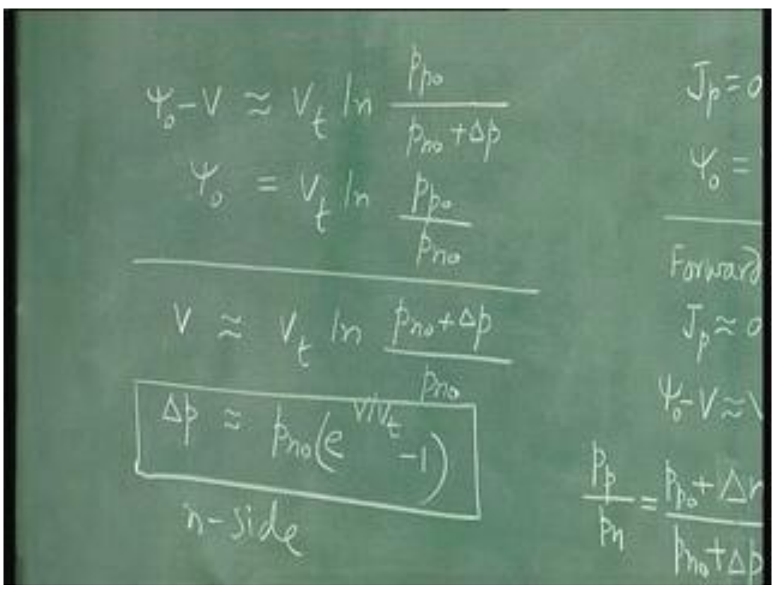

So we write psi$_0$ minus V is approximately equal to V_t l_n P_{p0} by P_{n0} plus delta p. Now we already know that psi$_0$ is equal to V_t l_n P_{p0} by $P_{n0.}$ Therefore, we can subtract this equation from this equation and we can write V is approximately equal to V_t l_n; you are subtracting this from this, so you get P_{n0} plus delta p by P_{n0}. In other words, you can transform this equation and you will get delta p is approximately equal to P_{n0} (e to the power V by V_t minus 1). So this is the important result that we get from the Boltzmann relation under applied forward bias so excess hole concentration on the n-side, this is on the n-side, that is excess minority carrier concentration on the n-side increases exponentially with respect to voltage and in fact, as we will see, it is this exponential increase of the concentration that is responsible for the exponential nature of the current voltage characteristics. You know that current is proportional to the excess carrier concentration. So if excess carrier concentration increases exponentially with voltage, current will also increase exponentially with voltage.

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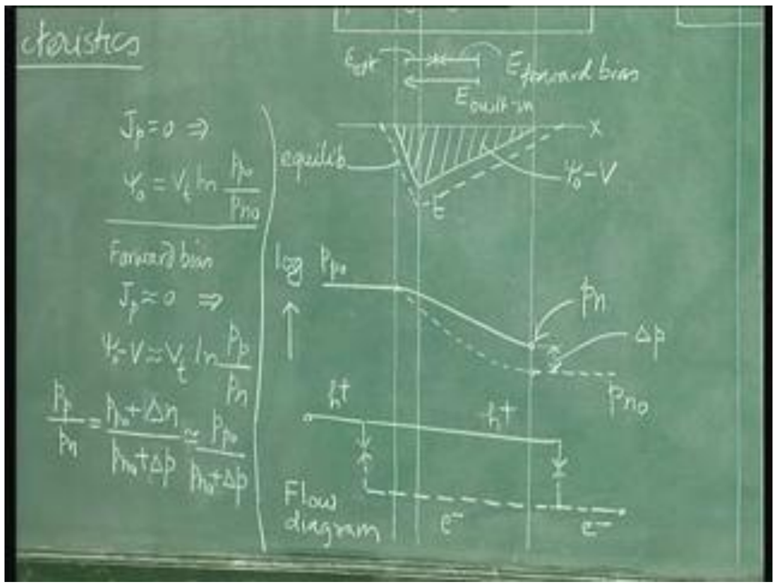

With that we have completed the analysis in the space charge region for the concentrations of holes and electrons; though we have not drawn for electrons, you can draw a similar curve for electrons yourself. Now, what is the next step in the analysis? Now we must move to the quasi-neutral region because you would like to know how this hole concentration, which we have seen up to this point, here, how this will vary in this region and, of course analogously, how the electron concentration would vary in the quasi-neutral p-region.

Now to move here in this region, we need to use an approximation that has been pointed out earlier and that is that we assume that since we are considering minority carriers, note that the hole concentration on n-side here is minority carrier concentration. So these holes, which will move towards the contact in the n-region, they will move by the process of diffusion. So even though electric field may be present, the field would be really very small. It will not cause any significant drift current for minority carriers. So we make the very important diffusion approximation for minority carriers. Let us list this approximation here.

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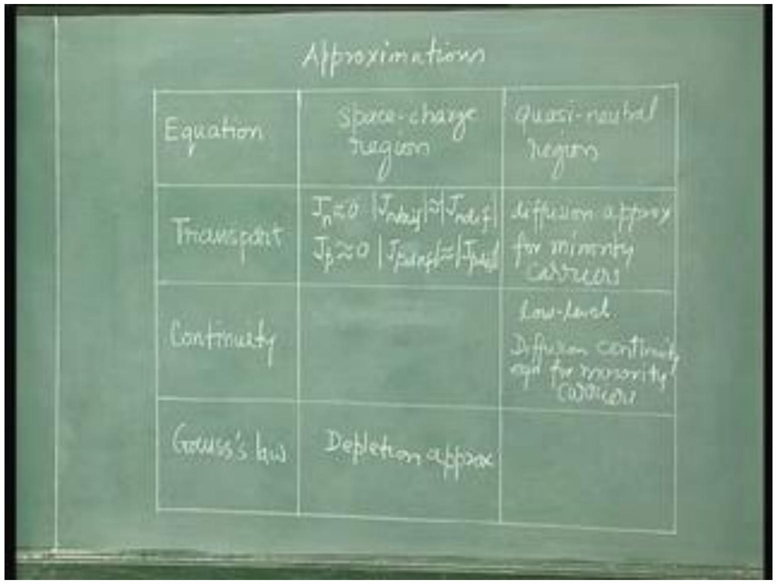

So, for transport equations in quasi-neutral region you have the diffusion approximation for the minority carriers and a consequence of diffusion approximation for minority carriers is that for the continuity equation you can use the diffusion equation, right, diffusion continuity equation for minority carriers and we know that the solution of the diffusion continuity equation is an exponential. So this part also was very clearly pointed out in the procedure for device analysis.

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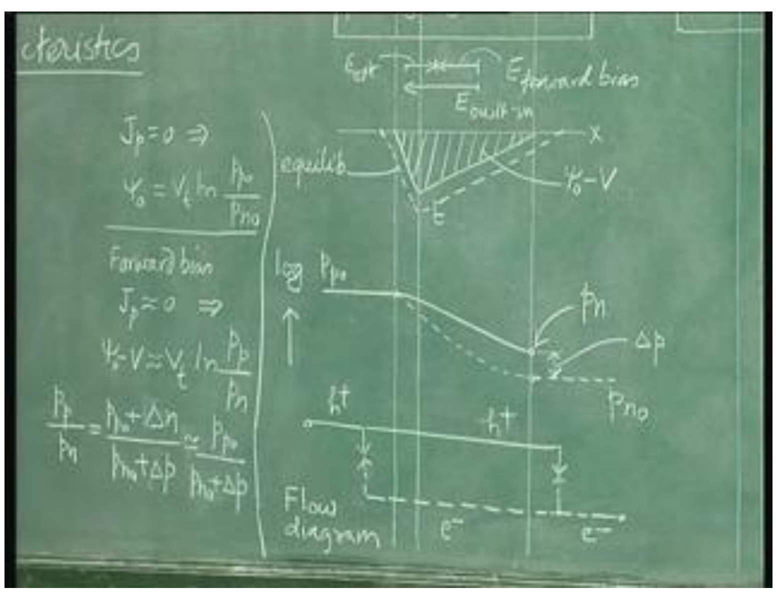

In other words, therefore, we can say that beyond this point the hole concentration would decay exponentially to the equilibrium value. Please note that we have assumed this region to be very long, the n-region to be very long as compared to the minority carrier diffusion length. Now you will appreciate why we assumed the quasi-neutral regions to be very long compared to the minority carrier diffusion lengths in the regions for ideal I-V characteristics, because the minority carriers, are moving by diffusion and therefore, you get an exponential decay and in the exponent[ial?] you have the diffusion length of the minority carriers.

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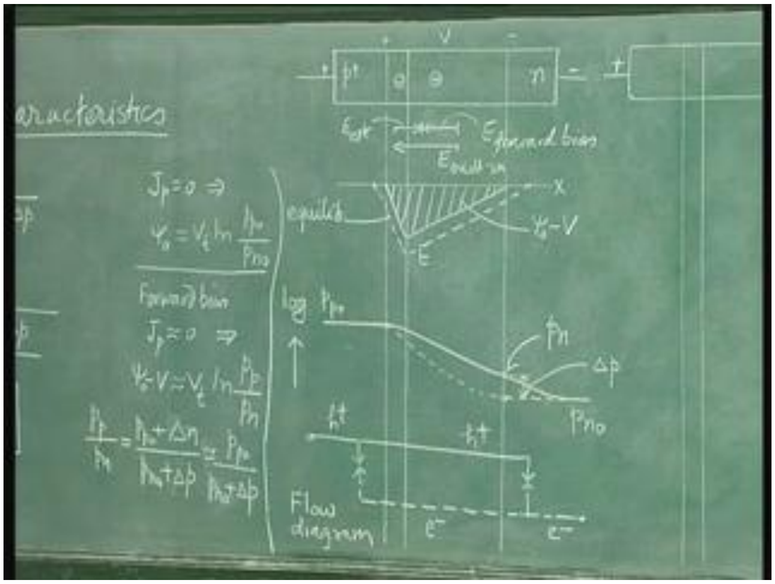

So when you show that here the exponential appears like a straight line but as it approaches this equilibrium concentration, the straight line will saturate. So this is the kind of behavior you have minus so in fact to show this clearly, this behavior here clearly, we must go to the linear scale. Now, on the linear scale, please note that we cannot show both majority carrier concentrations and minority carrier concentrations. But fortunately, since we know that the disturbance in majority carrier concentration is almost equal to the disturbance in minority carrier concentration in their quasi-neutral regions because quasi-neutrality has to be maintained. Therefore, we need not sketch the minority and majority carrier concentrations separately on a linear scale so long as we sketch the excess carrier concentration on the linear scale. We know how the majority carrier concentration would change and how the minority carrier concentration would change. So now we will sketch the excess carrier concentration on the linear scale.

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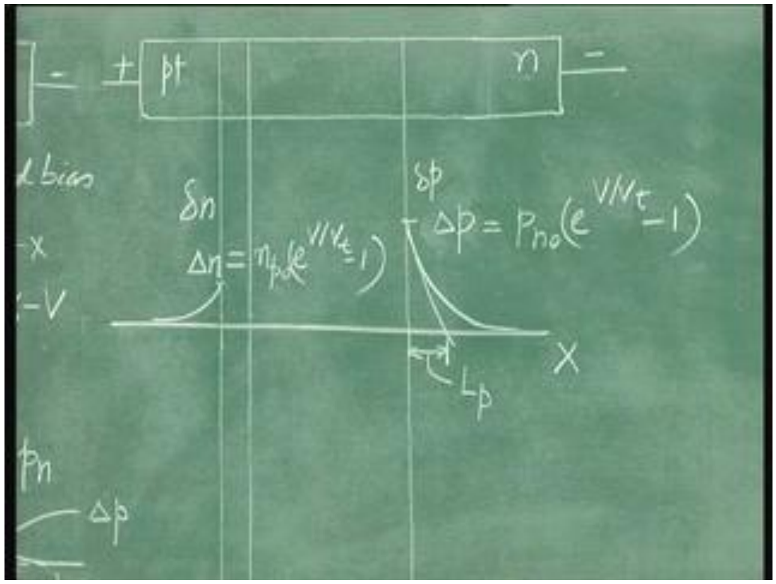

So here although the contact is shown here and this width is small, we must assume that this is sufficiently long. So we will redraw this neatly and this is also assumed to be long enough so what we will call this is delta p. Since this is the n-region, we plot excess minority carrier concentration, excess majority carrier concentration is equal to this, this is an exponential decay.

Note that I am not setting up any coordination system here, because that unnecessarily complicates matters. It is necessary to just realize that this shape is exponential, so this value here in this exponent exponential decay this value is delta p; that is, delta p, which we have shown already is given by P_{n0} (e to the power V by V_t minus 1) and the rate of the exponential is shown by extending this line, the initial slope here. If you extend this then this difference distance on the x axis here is L_p, the minority carrier diffusion length of holes.

One can similarly show excess carrier concentration on the p-side and it would be like this, this is another exponential. Now, notice that this excess electron concentration delta n at the depletion edge is shown less than the excess hole concentration delta p at this edge. This is because of this formula, so if you want to write here this delta n is given by N_{p0} (e to the power V by V_t minus 1).

Since this is p to the power plus, that is, the doping on this side is more than the doping on this side, N_{p0} will be less than P_{n0}. The minority carrier concentration on heavy dope side is less as compared to the light dope side; that is why this is shown less as compared to this. Now, with this we have completed the variation of the electron and hole concentrations with distance. Next what is left is the current densities of electrons and holes. In fact these current densities can now be very readily obtained from the variations of the minority carrier concentrations.

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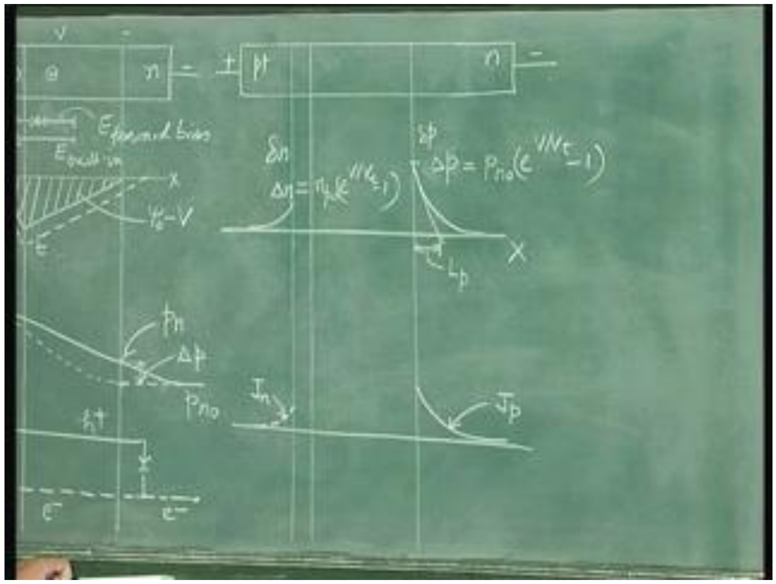

So since we assume the diffusion approximations, we can sketch the concentrations of minority, we can sketch the current densities because of minority carriers from these two graphs. The current density for holes for example in the n-region is simply the slope of this and the current density of electrons in this region is simply given by the slope of this shape of the curve. So let us draw that here. So this is the zero line, now the gradient is zero here and it goes on increasing. So J_p will also be an exponential shape because a gradient of an exponential is an exponential; so this is J_p in the n-region. Similarly, J_n, the electron current, will be shown by a dotted line; this is J_n in the p-region that we have used.

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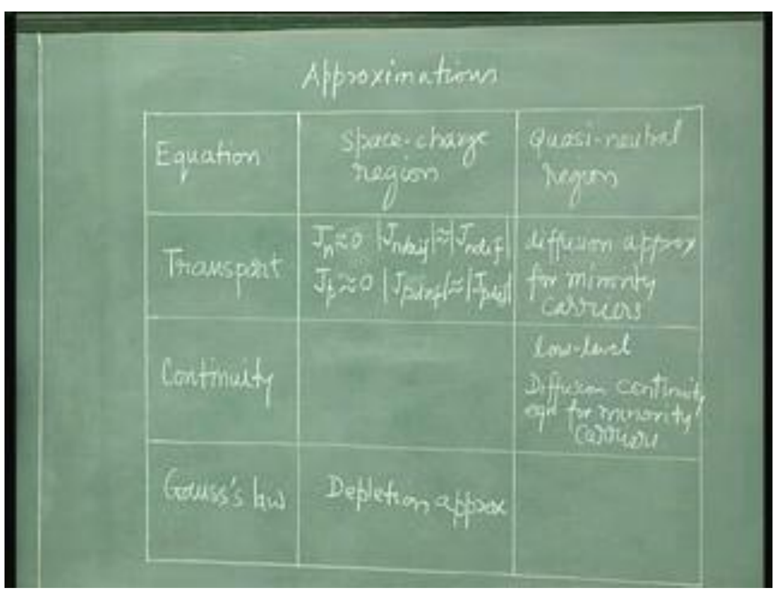

Please note the diffusion approximation for minority carriers, which we have already listed here. Now, how do we complete this picture?

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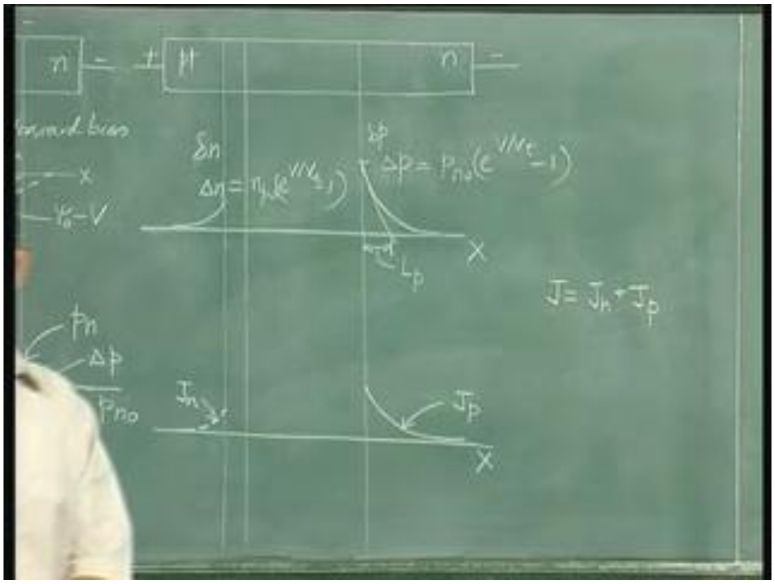

If you want to get the total current you know that J is equal to J_n plus J_p. So if I want to get the total current density then at any point any x if I know J_p and J_n I can get the total current. Unfortunately, with the picture that we have drawn I do not know J_n in this region and I do not know J_p in this region and I do not know either of them as of now in this region. So how do we proceed further?

Now, at this point I must tell you that since this is a steady state condition J is constant with x. This we have shown as a consequence of steady state assumption in the procedure for device analysis, how the total current because of J_n and J_p is constant with x. That is why if you determine the total current at any x, we can determine the current injected at the contacts because J will be drawn as a constant line here.

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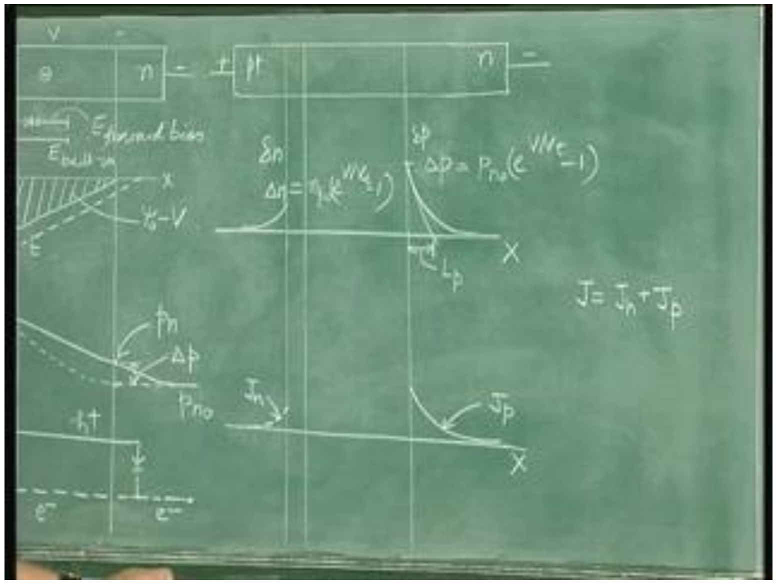

It will be something like this, a constant line. Right now I do not know exactly where to draw. So to draw that we will make an additional assumption and that is that there is no change in the hole or electron currents in the depletion layer, which means there is no recombination of electrons and holes in the depletion layer. This is because the depletion layer is rather thin, we have seen it is only about a micron, so we can assume the recombination to be negligible as an idealization.

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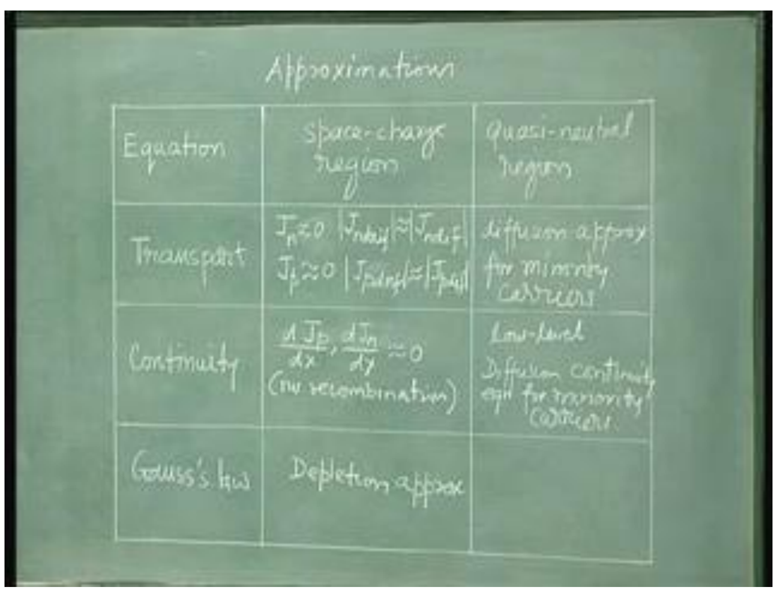

So this is equivalent to putting here the fact that dJ_p by dx and dJ_n by dx the rate of change of the current densities with x is zero is equivalent to saying there is no recombination in the space charge region. So now we draw two constant lines showing the variations of J_p and J_n in this space charge layer.

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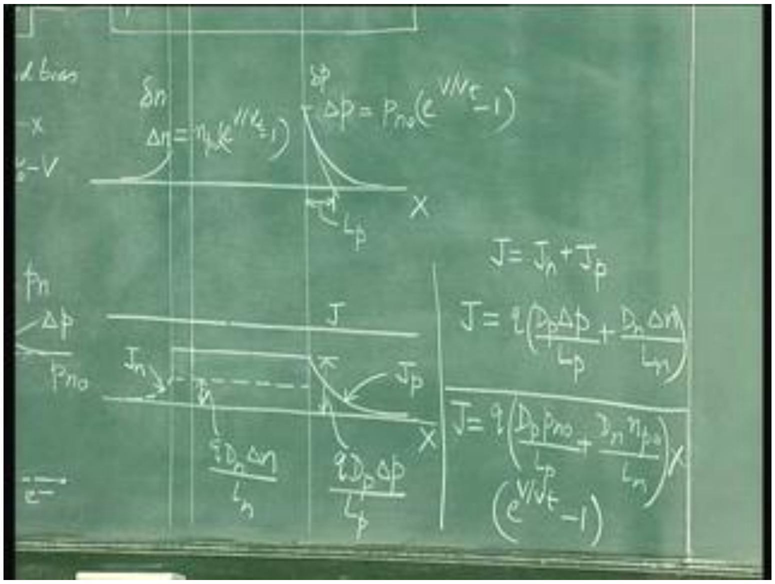

Now, the moment we have done that, you see that we obtain J_n and J_p both at this depletion edge as well as J_p and J_n both at this depletion edge because of extending these lines; and now, therefore, we know the total current. So I must add this and this to get the total current so that is shown here; that will be the total current J everywhere. So this is how I have determined the total current J. I can easily write an expression for J, based on this, because I know what is J_p here and I know what is J_n here. This J_p is, if you write in the terms of this, the diffusion current at this edge.

Please note that these two graphs are on the linear scale that is why we are able to show exponential variation as this shape. So this is qD_p delta p by L_p the diffusion current at the depletion edge that is obtained from this slope and the factor of diffusion approximation. Similarly this current of electrons is qD_n delta n by l_n.

Therefore, obtain the equation for J as q (D_p delta p by L_p plus D_n delta n by l_n) where delta p is already written in terms of this formula. So if you simplify, that is, you substitute this, it is very clearly seen that J is given by q into D_p P_{n0} by L_p plus D_n N_{p0} by l_n (e to the power V by V_t minus 1). So this is the relation for the current, clearly showing the ideal current voltage characteristics given by J is equal to constant (e to the power V by V_t minus 1).

With this we come to the end of the present lecture wherein we have used the five basic equations and stated the various approximations that need to be made in the space charge and neutral regions to arrive at the exponential ideal current voltage characteristics or the ideal current voltage characteristics which are exponential in nature. We will continue with this analysis in the next class.