**Solid State Devices**
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**Lecture - 20**
**PN Junction (Contd…)**

This is 2nd lecture on the PN junction and 20th lecture of this course.

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In this lecture, we will continue with the analysis of the PN junction. In the last lecture we have outlined the characteristics we seek to explain. Then we saw how a PN junction is fabricated and what the real device structure is. Then we have also shown what are the approximations we make in arriving at the idealist structure based on which the analysis is to be carried out. We also gave a very simple qualitative explanation for the rectifying nature of the current voltage characteristics.

Now, we take up the analysis of the junction in detail. So, as we explained, in our introduction on the PN junction we start with the analysis of the PN junction without any applied bias and that is the starting point. That is, we start with the analysis of the PN junction under equilibrium conditions.

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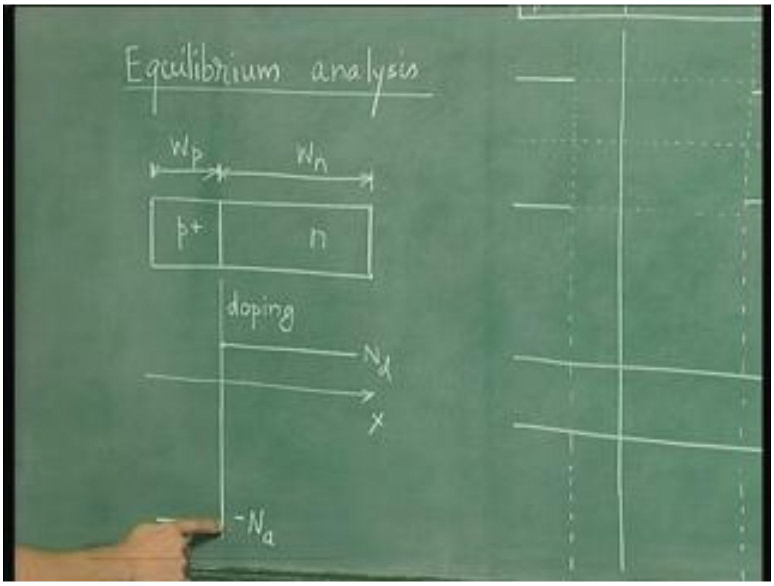


So this is the structure, a P plus N junction. P plus N means the doping on p-side is more than doping on n-side. The widths of this P and N regions are $W_p$ and $W_n$. We assume that these widths are sufficiently long, that is much more than the diffusion length of minority carriers in the respective regions. Then we have made the abrupt junction approximation which means that the doping changes abruptly from the p-side to the n-side. Then we have assumed that these two regions are uniformly doped so the doping is constant in these two regions. So the first step in the analysis will be to get the concentration of electrons and holes as a function of distance. We have said that the purpose of device analysis is to get n, p, $J_n$, $J_p$ and E as the function of x within the device. Once you have this information you can always get terminal characteristics which are of interest to you. So let us start with n and p that is concentration of electrons and holes.

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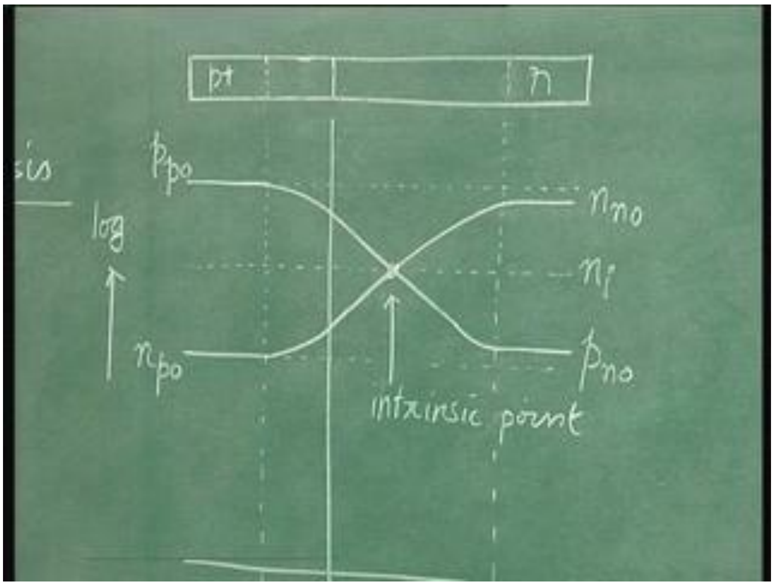

The concentration of holes will be more on the p-side than in the n-side. So let us call this as pp and since we are considering equilibrium conditions this is $p_{p0}$. And this will be similarly $p_{n0}$. Analogously, this is the concentration of electrons on the n-side so this is $n_{n0}$ and this is $n_{p0}$. Notice that these concentrations correspond to the regions which are far away from the junction. This is because we expect some variation in the concentration around the junction because the doping is changing abruptly the concentrations of holes and electrons have to change.

So, far away from the junction however the conditions in the regions are the same which would have been so if these two regions are isolated that is, if the junction was not present. Now, we know that though the doping changes abruptly at the junction the concentration of free electrons and holes cannot change abruptly. This is because if the concentration were to change abruptly for electrons and holes which are free carriers then that would result in infinite diffusion current and this is not physical. So the concentration has to change gradually. So, from $p_{p0}$ to $p_{n0}$ you have a gradual change in concentration. This line should be continuous because any discontinuity would mean infinite diffusion current at the point of discontinuity. Here I want to mention is that we have shown the extent of this region over which the variations occurs on the n-side to be more than on the p-side. The reason for this will become clear as we proceed further.

Similarly, we need to sketch the electron concentration variation from $n_{n0}$ to $n_{p0}$. When we do that we should note that this concentration line should pass through this point. Now what is that point? This is called the intrinsic point. This is because under equilibrium conditions the concentration of electrons and holes the product of these two is $n_i$ square. So when you plot it on a log scale as we are doing, this is log, concentration on the scale. We are plotting a concentration on the log scale because we want to show both the majority and minority carrier concentrations. So when we are doing that as pointed out in an earlier lecture, the $n_i$ point will be exactly in the middle of these two, so this is $n_i$.

On a log scale since $n_{n0}$ into $p_{n0}$ is equal to $n_i$ square the $n_i$ is midway between $n_{n0}$ and $p_{n0}$. Therefore, this point the concentration of the holes is equal to $n_i$. So this is called the intrinsic point. Since the device is under equilibrium, the product of electron and hole concentration should be everywhere equal to $n_i$ square even if they are varying. Since pn is equal to $n_i$ square this $n_{n0}$ to $n_{p0}$ the line describing this variation should pass through this point. So let us draw that. Now what we will explain shortly is that the intrinsic point lies on the lightly doped side. And this statement is related to the fact that the extent of variation is more on the n-side than on the p-side.

Now, if you have to sketch the same variation of holes and electrons on the linear scale, let us see what it would look like. Let us take a typical example, let us say the doping on this side is 10 to the power 16 so $N_a$ is 10 to the power 16.

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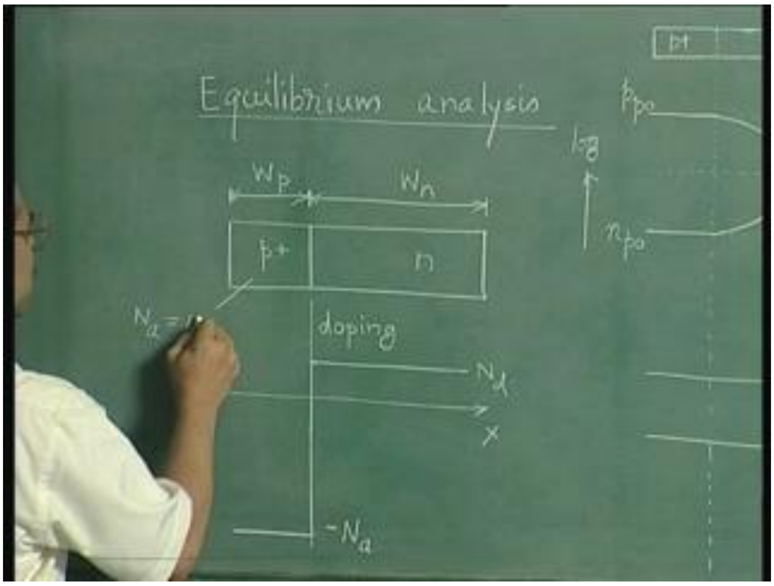


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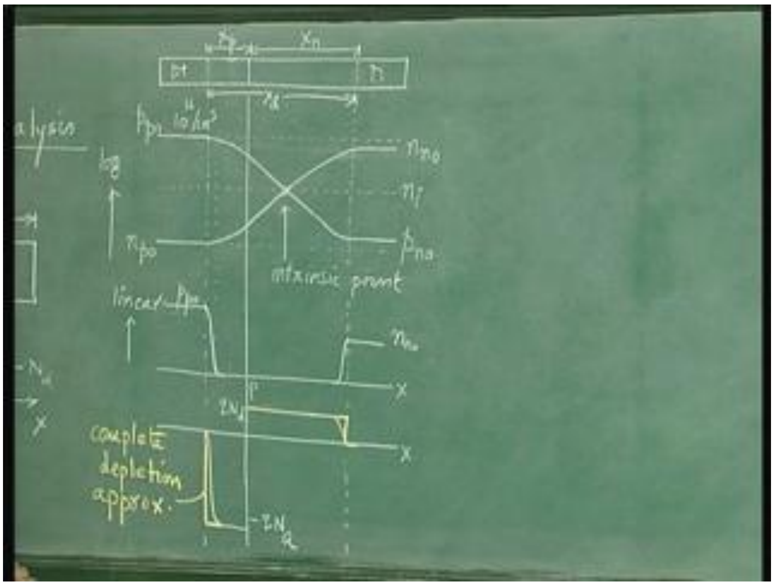


$N_d$ is 10 to the power 15 cm cube then this line is about 10 to the power 16 because we will assume complete ionization and neglect thermal generation and majority carrier concentration is almost equal to the doping level. So this 10 to the power 16 cm cube and this is 10 to the power 15 cm cube. So since $n_i$ is of the order of 10 to the power 10 cm cube, the exact value of $n_i$ is 1.5 into 10 to the power 10 but just we are interested in the order here. So that being the case, the $p_{n0}$ will be of the order of 10 to the power 5 cm cube and this $n_{p0}$ will be of the order of 10 to the power 4 cm cube because 10 to the power 4 into 10 to the power 16 is equal to 10 to the power 20 which is square of 10 to the power 10. So you see that 10 to the power 4 to 10 to the power 16 there is 10 to the power 12 variation. That is, there are twelve orders of magnitude from this point to this point. So if you divide this interval into twelve equal parts then 1 by 12 of this would correspond to the variation in the hole concentration by a factor of 10 which means if you divide this into a six equal parts, these are not equal right now but we assume that they are equal then 1 by 6th of this would correspond to a factor of 10. If this is 10 to the power 16 this point is 10 to the power 15 close to that as shown here. This is not exactly to scale.

So, if you plot this on a linear scale it would look something like this. By this point when it has come down to 1 by 10th of the value it could be 1 by 10th. We are plotting this on a linear scale. So, to avoid confusion I will now remove these numbers, this is linear. Let us do the same exercise on the other side 1 by 10th of variation will occur somewhere over this region. So, if I were to show the same thing on a linear scale then it would be something like this. So this is 10 to the power 15 cm cube and 1 by 10th of this is somewhere here 10 to the power 14. So on the linear scale the variation is much more rapid than on a log scale. I will remove this number to avoid confusion and this is $n_{n0}$. And similarly on this side this is $p_{p0}$. We cannot show $p_{n0}$ and $n_{p0}$ on the linear scale. Further we have used a different scale on these two sides.

Please note that $p_{p0}$ is 10 to the power 16, $n_{n0}$ is 10 to the power 15 in our example. So 10 to the power 15 would be 1 by 10th of this. So strictly speaking this side should be shown 1 by 10th of this so this interval should be 1 by 10th of this. But then it will not be very clear so again we are not drawing with this to scale. So the scale on this is different from scale on this. Now, what this particular plot on the linear scale shows is that these two regions seem to be almost totally depleted of any carriers. You see that the carrier concentration is dropping to almost 0 on a linear scale. That is why the region next to the junction on either side here is referred to as the depletion layer because in this region free carriers are totally missing. That is how we come to the concept of depletion layer.

The width of the depletion layer is this width is $X_p$, this is on the p-side and on this side this width in $X_n$. Depletion layer width is $X_d$ is equal to $X_p$ plus $X_n$. This whole distance is $X_d$, the depletion layer width. Now what is the consequence of the depletion of free carriers on either side? The consequence is that you will have space charge because the space charge rho is equal to q into p minus n plus $N_d$ assuming complete ionization of dopends, this is on the n-side. On the p-side the corresponding equation is q into (p minus n minus $N_a$). This is the equation for space charge in an n region and in a p region.

In a depletion region, p and n are almost negligible; it is zero in this region. There is a rapid fall in n and rapid fall in p. You cannot show n here because their minority carriers are very small and minority carriers here are also very small in number. So, the space charge equation is p and n which we can neglect, so on the n-side this means you have a positive charge of q into $N_d$. And on the p-side, similarly, because we are talking of depletion region, in the depletion region you will have a negative charge q x minus Na. Here we are going to show rho vs x, x is this direction. Then it will look something like this where this is q into $N_d$ and this is minus q into $N_a$. So this is the space charge picture; rho vs x.

Normally what we do is we make what is called a depletion approximation. That is, we assume that this entire region is totally depleted of free carriers though actually it is this region that is depleted of free carriers and there is a region over which the variation occurs gradually. So the space charge is changing to zero gradually here towards the end. But we will ignore this small distance and for simplicity we make the approximation that is called complete depletion approximation. In this approximation the space charge will be shown like this and like this on this other side. This is the so called depletion approximation, complete depletion. So the same applies to this line. This is done to simplify the analysis.

Please note, assumption of a space charge picture like this is equivalent to assuming that the electron concentration changes abruptly at this point to 0 and hole concentration changes abruptly at this point which is obviously not true because if you were to show this on a log scale, if I were to show the complete depletion approximation in a log scale then it would mean that I must assume $n_n$ changes from $n_{n0}$ to $n_{p0}$. That is, electron concentration n changes from $n_{n0}$ to $n_{p0}$ abruptly here something like this and $p_{p0}$ also changes abruptly.

Obviously it would look like a gross approximation if shown on the log scale. That is why it is important to note that both log and linear scales are necessary. You must show the information on both the log scale and the linear scale to get a complete picture. The log scale distorts the real picture;, the linear scale shows the correct picture about the variations. But then we have to use the log scale when our analysis has to show both majority and minority carrier concentrations. So log scale is useful linear scale is also useful and we must use both. But you must use the pictures drawn on these scales judiciously in the given situation. So, to explain the validity of the depletion approximation it is more useful to see the linear scale.

And in fact the log scale may give a wrong picture; it may try to give an idea that the depletion approximation is very crude. But when you see the linear scale then you will know that the depletion approximation is actually quite good. There is another point, sometimes the students have difficulty, that if you use the depletion approximation you are assuming that the free carrier concentrations are changing abruptly at the edge of the space charge layer. How can that be justified because that would imply infinite diffusion currents.

At this point, it is necessary to note that the approximation is used only for a particular situation. You should not try to derive the information from this approximation for other situations. So, in this case the depletion approximation is used to determine this space charge picture and as we will see shortly the electric field based on this space charge. So only for space charge and electric field calculations the depletion approximation has to be used. You cannot use the depletion approximation in trying to find diffusion currents and so on. Depletion approximation makes it easy for us to derive the electric field picture and some of the other parameters under equilibrium conditions. Now let us see, what is the field picture for this particular space charge picture? Now, the field picture is obtained using the Gauss's law. The Gauss's law says that de by dx is equal to rho by epsilon.

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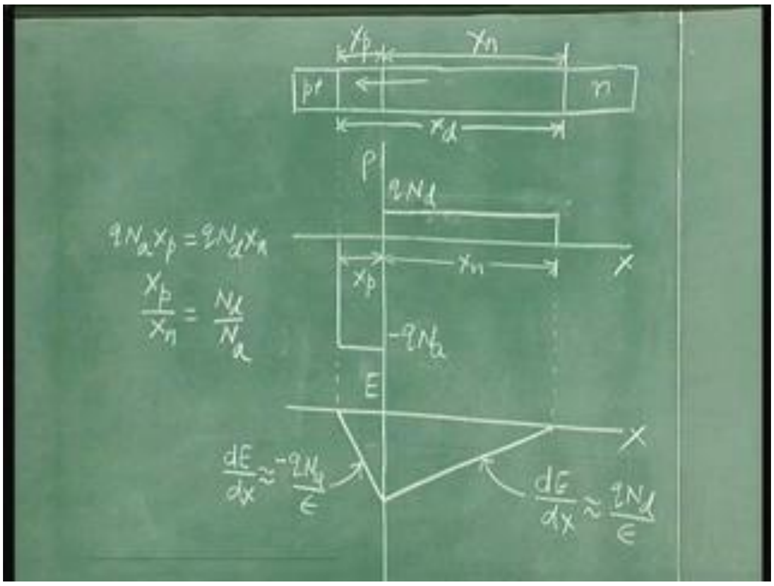


That is $qN_a$ by epsilon with a negative sign approximately equal because this is the depletion approximation we are using. So de by dx is approximately equal to minus $qN_a$ by epsilon on the p-side for this space charge. On this side you have de by dx is approximately equal to $qN_d$ by epsilon that is for this picture. This means if I want to sketch E vs x I know from here that since $qN_d$ by epsilon is constant over this distance, de by dx is constant that means I should have a straight line for electric field as a function of x. So this straight line has a positive slope. This is the way one can draw the straight line on this side. On this side the slope is negative minus $qN_a$ by epsilon so it is something like this.

Notice that I have to start from zero electric field at this depletion edge because the field does not exist beyond the depletion region. All the field lines start from the positive charge on the n-side of the depletion layer and terminate on the p-side of the depletion layer where there is a negative space charge.

You have field line starting here and terminating here. So the total positive charge here, the area under this curve is equal to the total negative charge that is the area under this curve. That is why we are starting from zero electric field at this edge and returning to a zero electric field at this edge here. This is the statement of charge neutrality. Therefore entirely the device is charge neutral. So this de by dx is equal to $qN_d$ by epsilon and this de by dx minus $qN_a$ by epsilon. Now because of this charge neutrality you have $qN_d$ that is this height into this width that is $X_n$ is equal to $qN_a$ that is this height into this width that is $X_p$ $qN_a$ $X_p$ is equal to $qN_d$ $X_n$ is equal to $X_p$ by $X_n$ is equal to $N_d$ by $N_a$. This clearly explains why $X_p$ is less than $X_n$ if $N_d$ is less than $N_a$.

In fact $X_p$ and $X_n$ are in the same ratio as the doping levels. So if you take for example $N_a$ is 10 to the power 16 and $N_d$ is the 10 to the power 15 then $X_p$ would be ten times smaller than $X_n$. That is why we have shown the extent of $X_p$ less than $X_n$ here. This diagram is again not to scale because if we had to draw it to scale we should have shown this as ten times this width.

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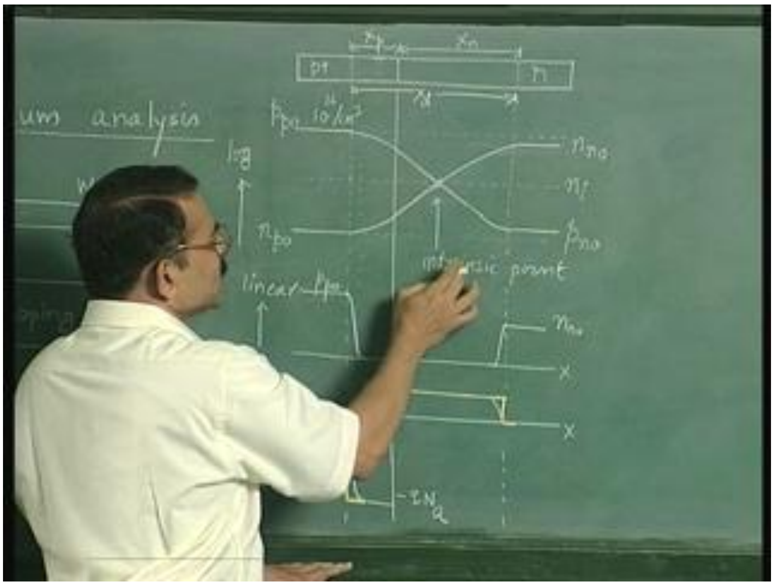


So in fact that is the reason why in this diagram also, here this is much more than this. So most of the variation in the carrier concentration is occurring on the n-side that is the lightly doped side where the width of the depletion region is more. And that is why the in fact the intrinsic point lies on the lightly doped side. This point is on the lightly doped side but most of the variation is taking place here.

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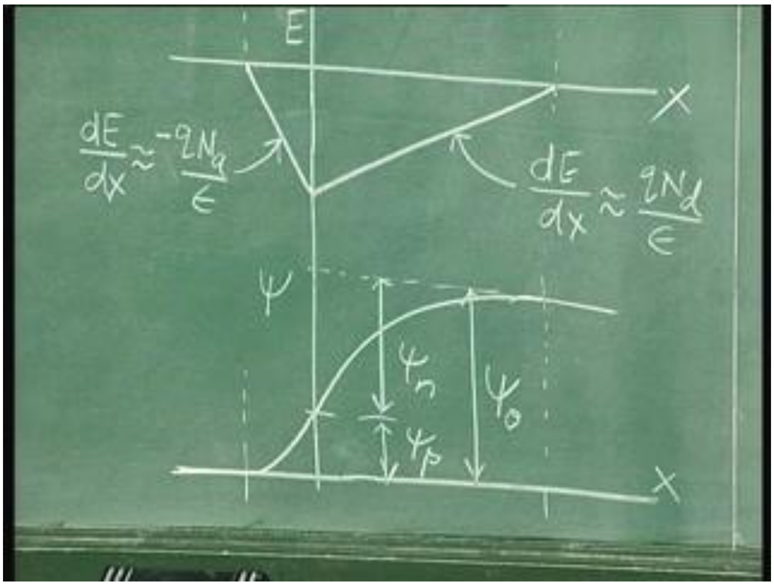


Now returning to this picture of the electric field we can now sketch the potential variation based on this. The potential variation will be integral of the electric field. So I have a reference potential here which is 0 and then the potential is more positive as you move towards the right. This is because the electric field is in this direction which means this is more positive than this in terms of potential. So the potential will be shown more positive on this side. If you integrate these straight line portions you will get a parabola like curve like this and like this and then the potential is again constant. So this is psi potential vs x. Now this is the built-in potential variation.

Notice that most of the potential drop occurs on the lightly doped side or the n-side so this is the potential drop on the p-side and this is the potential drop on the n-side. This is $psi_p$ and that is $psi_n$ and this total potential drop across the depletion layer will refer to as $psi_0$. This is the built-in potential across the PN junction. Now, though there is a potential variation within the device from p to n region please do not think that this potential variation is causing any current.

Students have difficulty understanding this because they feel if there is a potential variation should there not be any current? Now there is a contradiction here. The device is under equilibrium which means there cannot be any net current flow because equilibrium means for every process there is an inverse process going on at the same rate.

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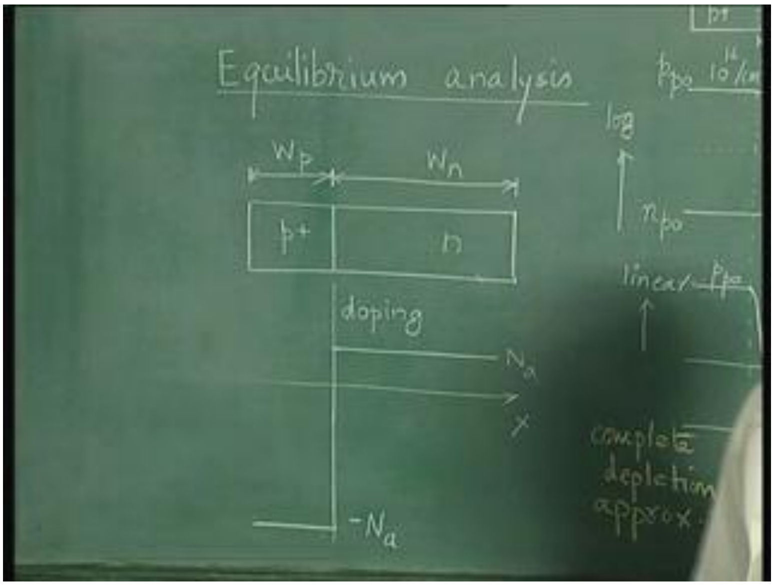


So obviously there cannot be a current flow and also you can look at this structure here there are no terminals connected to any battery. Therefore there cannot be a current flow so the current at every point is 0 either for electrons or for holes. Then how can there be a potential variation within the device?

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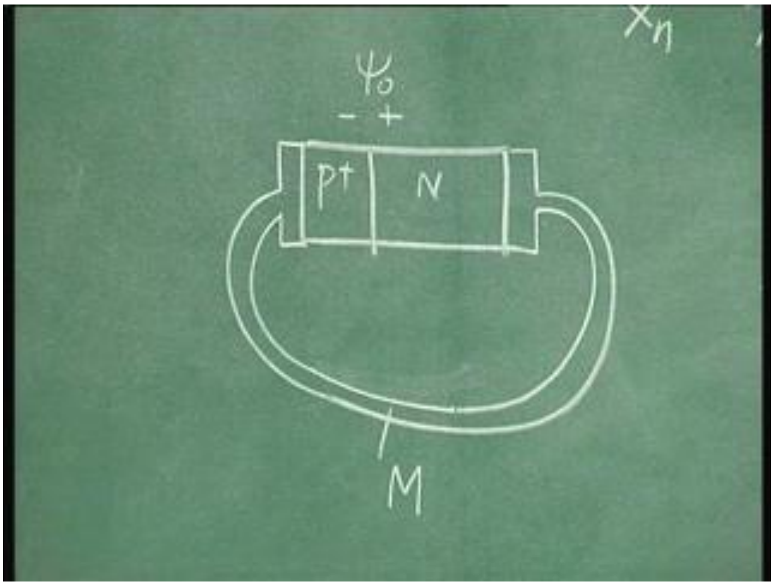


Now, one way to understand this is as follows. This is the device PN junction and there is a build in potential here. The direction of this potential is this, this is positive, this is negative and this is $psi_0$. If you were to join the p and n regions with the wire no current will flow. For example, we use some metal M for connecting this region to the other region a current does not flow because between any two dissimilar regions there will be a built-in potential. Just like we explained how there is a built-in potential between p and n regions using similar arguments we can explain that there will be a built-in potential between metal and p region and between metal and n region. The directions of these built-in potentials will be opposite to that of $psi_0$. The built-in potentials across this contact and this contact, the sum of these two will cancel the $psi_0$. Therefore using Kirchoff's law if you go around you get a 0 change in potential and therefore no current can flow. Now, how is it that there is 0 net current? How can you explain this using this diagram?

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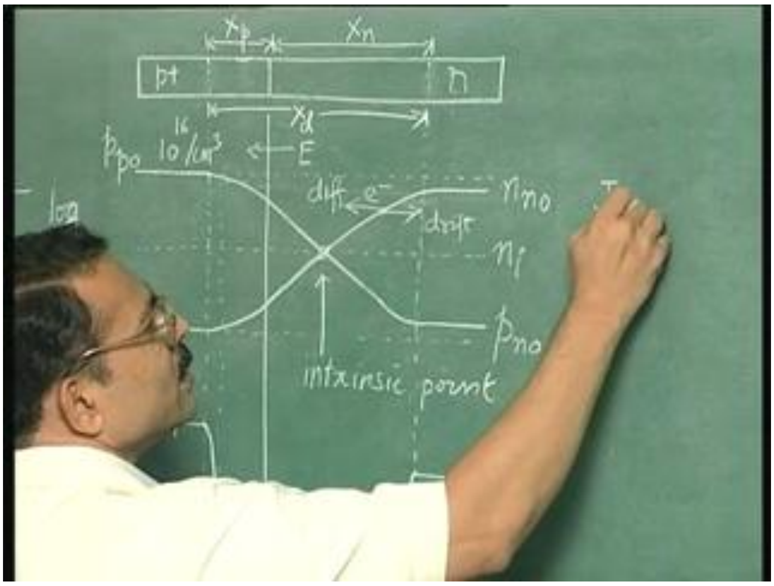

We can explain it as follows:
We have seen how because of this space charge there is an electric field. We can call this as the built-in electric field. Whatever fields, potentials and charges exist under equilibrium they are called built-in potentials charges or electric fields. So because of the built-in space charge there is a built-in electric field and that field is directed in this way from n to p. You have two types of currents drift and diffusion currents. Now, if you take this point there is a gradient of electrons therefore the electrons will tend to move in this direction because of diffusion. I am not showing the current but I am showing the direction of flow of charges.

Electrons move in this direction because of diffusion but then you have an electric field which is this direction. So this electric field will drive the electrons in this direction so you have the drift flow in this direction. Thus the diffusion tendency cancels the drift tendency and because of exact cancellation of drift and diffusion tendencies in the depletion layer you do not have any current flowing which is how it should be because this is the equilibrium condition and it is $J_n$ is equal to 0 everywhere and $J_p$ is equal to 0 everywhere.

Similarly one can show the current flow for holes. At this point the holes tend to move in this direction because of diffusion and this electric field drives them in the opposite direction. Therefore these two tendencies cancel. In fact based on this discussion one can think of a third experiment to explain the formation of the depletion layer.

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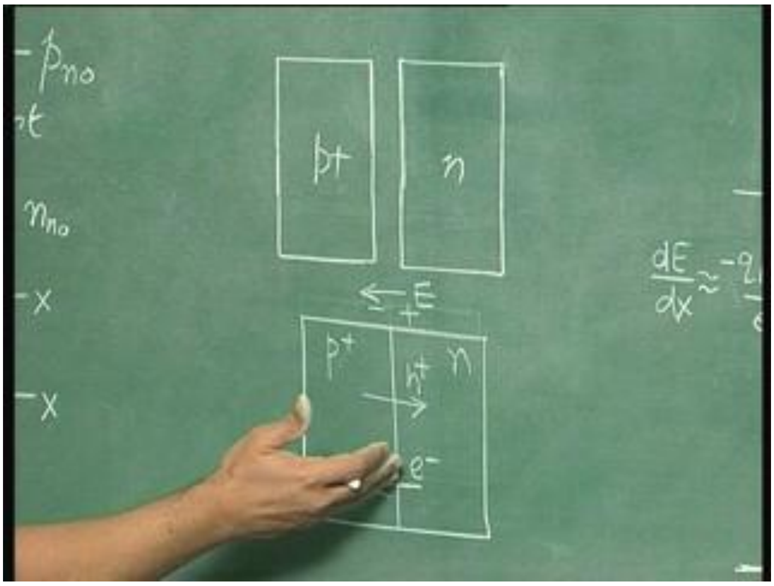


This third experiment is as follows:
You take a p-type silicon and n-type silicon and you join them. At the instant you join the hole concentration is much more on this side than on the other side because holes are minority carriers here and majority carriers here. Therefore that is the diffusion tendency. This causes movement of holes from left to right. Similarly, because of the diffusion tendency of electrons there is a movement of electrons from right to left from n to p region. But this movement causes the build up of an electric field. If p

region loses holes it becomes negatively charged. Also it is gaining electrons which are another reason it is becoming negatively charged.

Similarly, the n region is gaining holes and losing electrons so it becomes positively charged and an electric field is set up in this direction. This electric field opposes the tendency of hole movement and it also opposes the tendency of electron movement. So, once sufficient electric field builds up then these tendencies are opposed exactly or cancellation takes place then this movement stops. That is how the width of the depletion layer will be decided by this condition when the transfer of charges has created an electric field that can exactly cancel the tendency for movement. Let us return to the analysis. Our analysis so far has given qualitative information about the five parameters namely n, p, $J_n$, $J_p$ and E. So n and p variation is sketched here in these two graphs.

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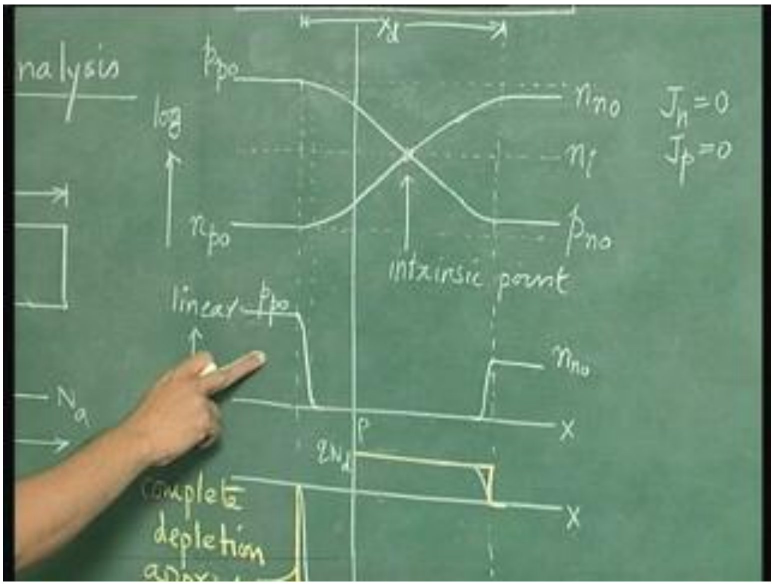


Then $J_n$ and $J_p$ are 0 because for the devices under equilibrium everywhere $J_n$ is 0 and $J_p$ is 0 so we do not have sketch a graph to show this. Then finally we have sketched the electric field E vs X. So the qualitative analysis is complete. Now we need to make a quantitative analysis and get values of the various parameters namely the width of the depletion layer on the p and n-side $X_p$ and $X_n$ and therefore $X_d$, then we would also like to know the value of the peak electric field that is this, the maximum electric field which occurs at the junction.

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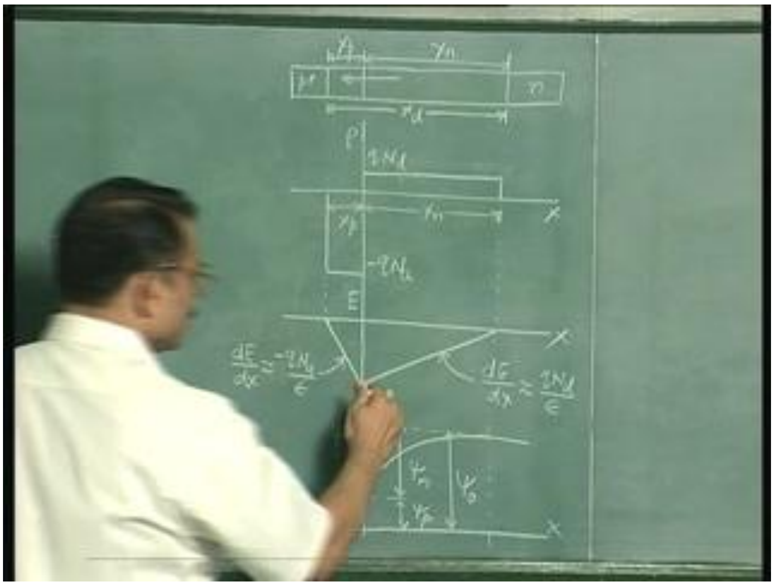

Notice that the maximum electric field occurs at the junction because this is where you have a change from the positive charge to the negative charge. So we need to derive an expression for $E_m$ maximum electric field and then we also want to know the built-in potentials $psi_0$ and the potential $psi_n$ and $psi_p$ on n and p-side. So the parameters to be derived are $X_d$, $X_n$ and $X_p$, $psi_0$, $psi_n$ and $psi_p$ and $E_m$ that is the peak electric field. Now as we have pointed out earlier, analysis of any device is based on the five basic equations. There is nothing beyond the five basic equations.

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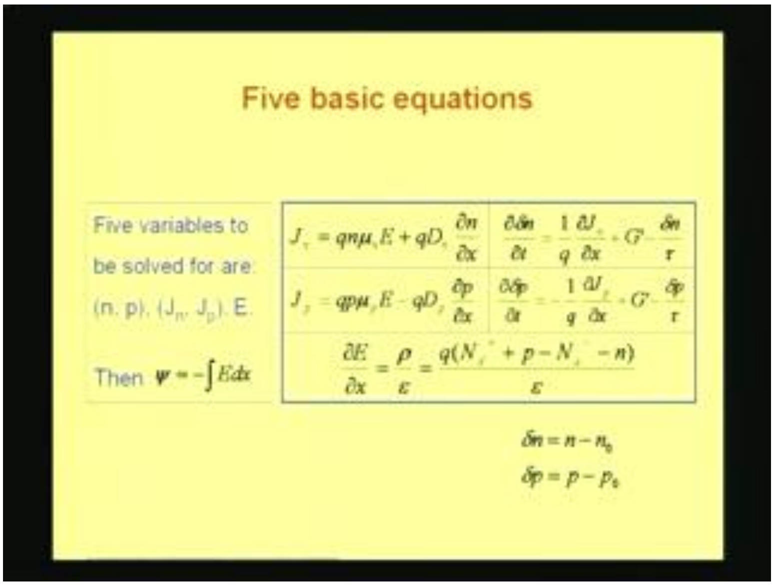


At least in the first course all these analyses for any device are based on the five basic differential equations as follows: the continuity equations, the transport equations, and Gauss's law these are the five basic equations. So, let us see how using these five equations we get the mathematical expressions for the quantities of interest. Let us start with the transport equations $J_n$ is equal to 0 and $J_p$ is equal to 0 because of equilibrium. What information can be derived from here? Let us write the equation for $J_p$ so $J_p$ is drift and diffusion so minus q $D_p$ dp by dx is diffusion plus qp $mu_p$ into E is equal to 0.

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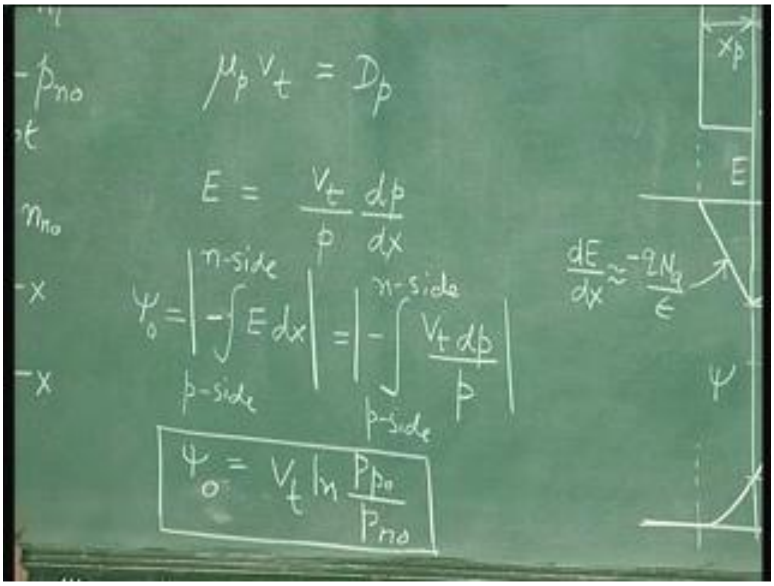


So $J_p$ is given by this formula and this is equal to 0. We will show that we can use this expression and get the built-in potential $psi_0$ which is this value. Let us rearrange this equation. We use the fact that $mu_p$ into $V_t$ is equal to $D_p$ this is the Einstein relation. If you use this fact then you can rewrite this expression as follows: The electric field is given by $V_t$ by p dp by dx. So the q is canceling here and you can cancel $D_p$ with $mu_p$ and you can write $D_p$ as $mu_p$ into $V_t$ so here you w ill be left with Vt when you cancel. That is how $V_t$ into dp by dx is coming here and then you have p which comes in the denominator. So $J_p$ is equal to 0 translates to this particular equation.

Notice that dimensionally this is correct, this is concentration and this is also concentration so this cancels, this is voltage and this is length so V by M that is the electric field. Now you know that the potential $psi_0$ is nothing but the integral of this electric field with respect to dx and the integration should be carried out from the p-side to the n-side. There should be a negative sign. The potential is integral of electric field with the negative sign but since $psi_0$ is a magnitude it is a positive value.

Notice, that $psi_0$ is simply the magnitude of the built-in potential. Therefore what we need to take is the magnitude of this result. If you do that here integration would look something like this, this is $V_t$ into dp by p. So this dx and when you multiply E dx this dx they will cancel and you are left with $V_t$ into dp by p and you are integrating from p-side to n-side and you have to take a magnitude. So integral dp by p is equal to $l_{np}$. So if you take p on the p-side it is $p_{p0}$ and you take p on the n-side it is $p_{n0}$.

Therefore the result is, this is equal to $V_t$ $l_n$ $p_{p0}$ by $p_{n0}$ is equal to $psi_0$. Here $p_{p0}$ is greater than $p_{n0}$ therefore this is positive. So this is the formula for $psi_0$. This relation is also called the Boltzmann relation which relates the concentration at any two points to the potential difference between the two points under equilibrium conditions. So, in general you can write this equation as follows. So this is the Boltzmann relation.

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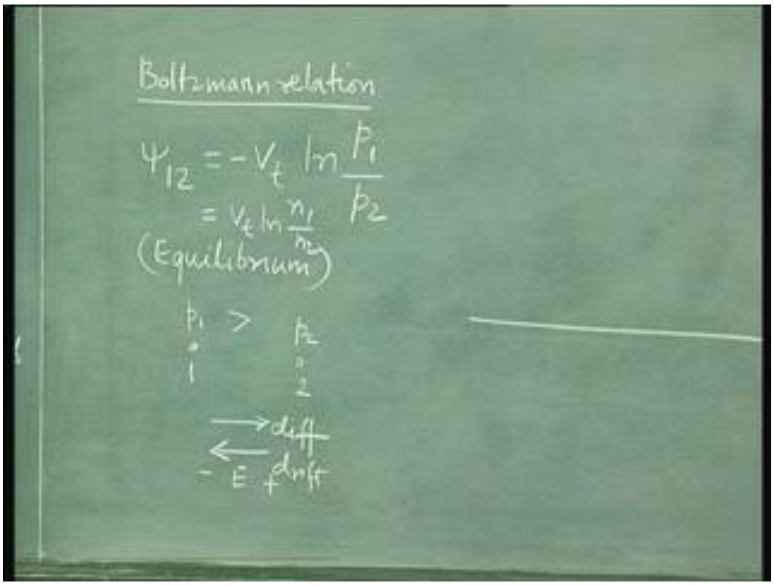


It says $psi_{12}$ the potential difference between 1 and 2 can be related to the concentration difference between the two points; $psi_{12}$ is $V_t$ $l_n$ $p_1$ by $p_2$ under equilibrium. Let us check whether we need a negative or a positive sign here. If this is point 1 and this is point 2 and if $p_1$ is more than $p_2$ then there will be a tendency for holes to move from left to right. This is the tendency for hole movement, it has to be balanced by drift tendency. This is diffusion tendency of holes; it has to be balanced by the drift tendency because this is under equilibrium.

An electric field is created so the electric field should be in this direction which means point 2 should be positive as compared to point 1. If you write $psi_{12}$ as $psi_1$ minus $psi_2$ then point 1 is negative and point 2 is positive. But since p1 is greater than p2 this quantity is positive so you should put a negative sign here. Now one can similarly write Boltzmann relation for electrons. For electrons the relation would be same $psi_{12}$ is equal to $V_t$ $l_n$ $n_1$ by $n_2$. Here there will not be a negative sign, the negative sign will be removed. Now this Boltzmann relation is obtained by considering the equation $J_n$ is equal to 0 instead of $J_p$ is equal to 0.

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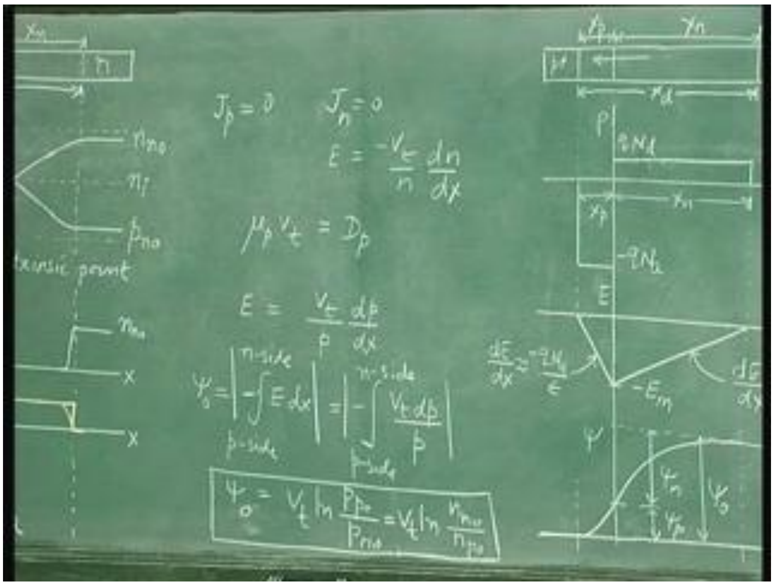


You will proceed in the same way. You will write $J_n$ in terms of drift and diffusion then write the electric field in terms of $V_{tn}$ and dn by dx so you will get the result as E minus $V_t$ by n dn by dx. You will get a negative sign here in this case. Then you can integrate this equation to get the Boltzmann relation. And that being the case you have not just one equation for built-in potential. You could calculate the built-in potential either from the hole concentrations or you could calculate also from the electron concentrations. So I can write the same thing also as $V_t$ $l_n$ $n_{n0}$ by $n_{p0}$. So $J_p$ is equal to 0 and $J_n$ is equal to 0 has given us the built-in potential of the PN junction. Next we need to determine the depletion width. Once we know $psi_0$ how we can determine the depletion width and the peak electric field. For this purpose we need to go to the electric field vs x diagram.

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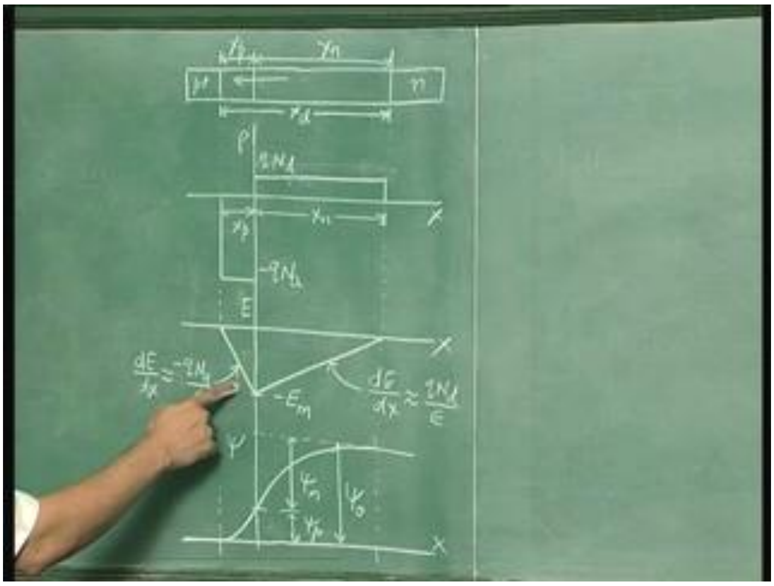

So let us look at this diagram. Area under this electric field picture is the built-in potential $psi_0$. This width is $X_n$ and this width is $X_p$ and this is $E_m$ the magnitude. So we can write, area under the electric field is given by 1 by 2 $E_m$ ($X_p$ plus $X_n$) and this is $psi_0$ for which we have already obtained an expression.

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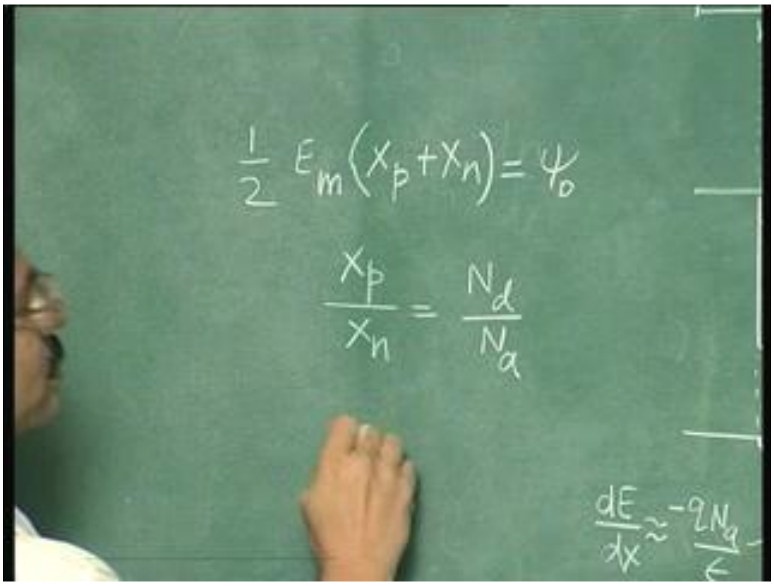


Now we know that $X_p$ by $X_n$ is equal to $N_d$ by $N_a$ because of charge neutrality as shown earlier because this area is equal to that area, the positive charge is equal to negative charge.

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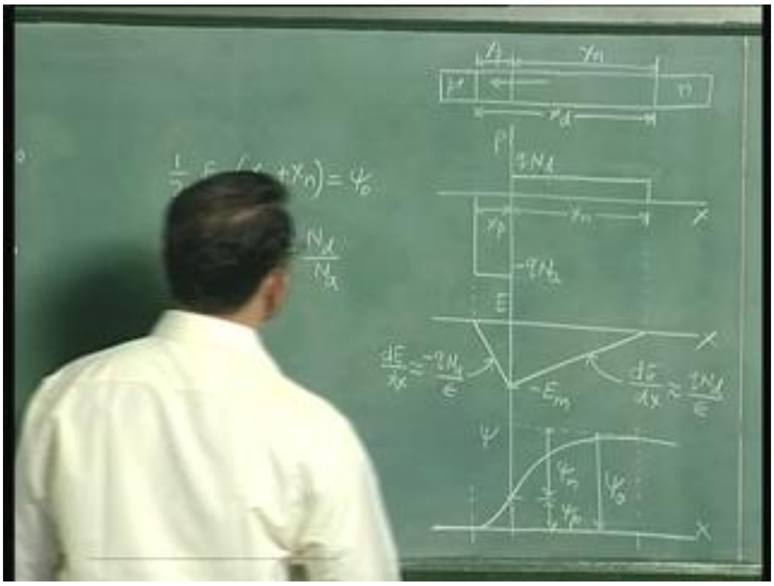

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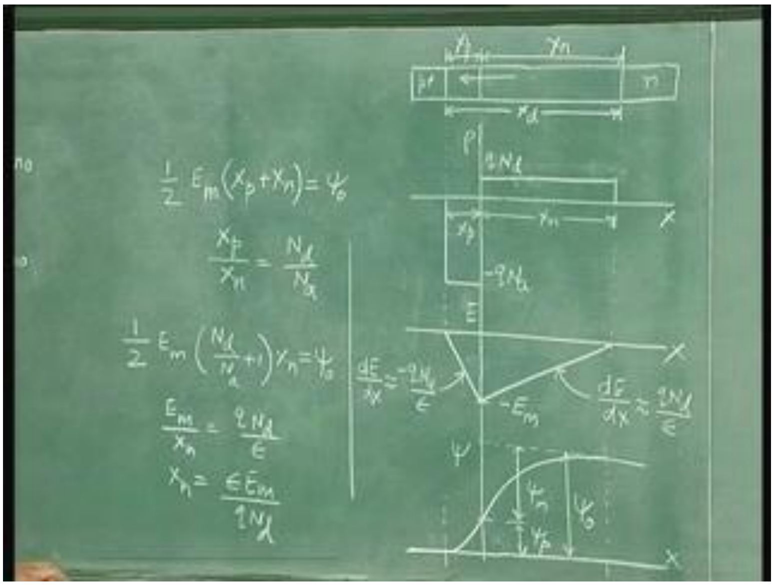

Using this we can replace one of these $X_p$ or $X_n$ in terms of the other. So let us write $X_p$ is equal to $N_d$ by $N_a$ into $X_n$ in this formula then we get 1 by 2 of $E_m$ ($N_d$ by $N_a$ plus 1) $X_n$ is equal to $psi_0$. Now, we have reduced these two widths to one width. Now we need to reduce one more unknown here because you have two $E_m$ and $X_n$. How do we do that? Again using Gauss's law if I take this slope here then I can write $E_m$ by $X_n$ that is the slope of this line; so this is $E_m$, this is $X_n$ and by Gauss's law this is de by dx that is $qN_d$ by epsilon. Therefore using this we can replace $X_n$ in terms of $E_m$ so that this equation will be only a function of $E_m$. Alternately we could also replace $E_m$ in terms of $X_n$ in which case you will get the value for $X_n$. Let us determine $E_m$.

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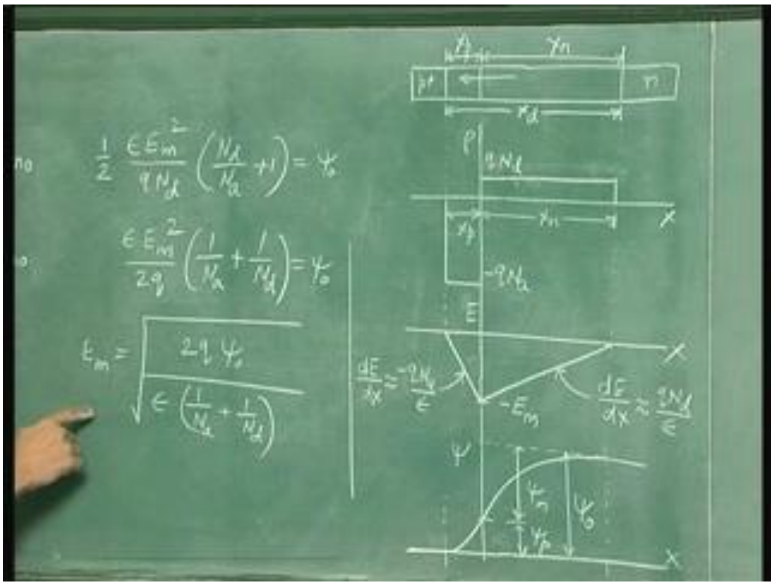

We can write $X_n$ is equal to epsilon $E_m$ by $qN_d$ so we will replace this in this formula and the result would be 1 by 2 epsilon $E_m$ square by $qN_d$ ($N_d$ by $N_a$ plus 1) is equal to $psi_0$. Now if you put this $N_d$ inside then you will get a much better looking expression

1 by 2 epsilon $E_m$ square by 2q (1 by $N_a$ plus 1 by $N_d$) is equal to $psi_0$. So $E_m$ is equal to square root of 2q $psi_0$ by epsilon (1 by $N_a$ plus 1 by $N_d$). So this is the formula for $E_m$. Now let us get a formula for $X_d$. Now this formula can be easily obtained using the equation $psi_0$ is equal to 1 by 2 $E_m$ into $X_d$ that is $psi_0$ is nothing but the area under the electric field picture.

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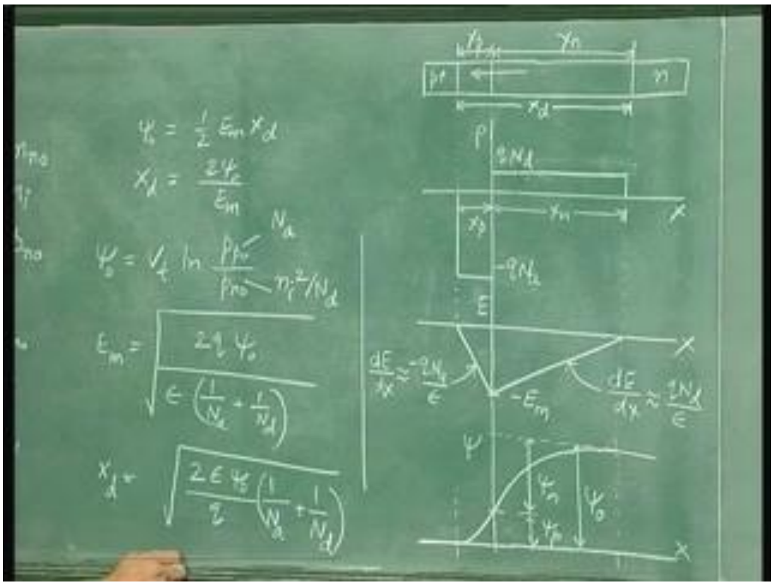


This distance is $X_d$ and this is the triangle. So using this you obtain $X_d$ is equal to 2$psi_0$ by $E_m$. But $E_m$ is already available here so from these two you get $X_d$ is equal to square root of 2 epsilon $psi_0$ by q (1 by $N_a$ plus 1 by $N_d$) where $psi_0$ we have already determined is equal to $V_t$ $l_n$ $p_{p0}$ by $p_{n0}$ or you could write in terms of $n_{n0}$ by $n_{p0}$. Now let us simplify this and get it in terms of doping because everything we want is in terms of doping level in the junction. So $p_{p0}$ is nothing but approximately equal to Na assuming complete ionization and neglecting thermal generation $p_{n0}$ is $n_i$ square by $N_d$ minority carrier concentration on the n-side.

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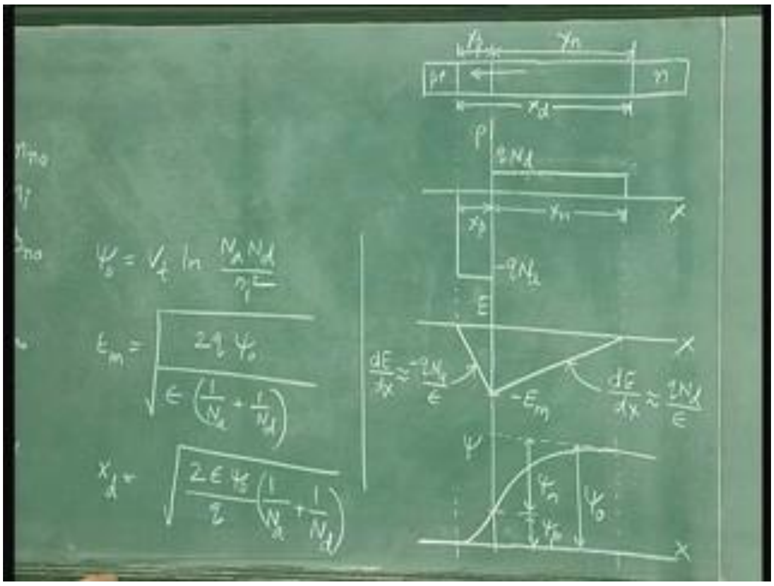

Therefore if you put this you will get the result as; $N_a$ $N_d$ by $n_i$ square which is the formula for $psi_0$.

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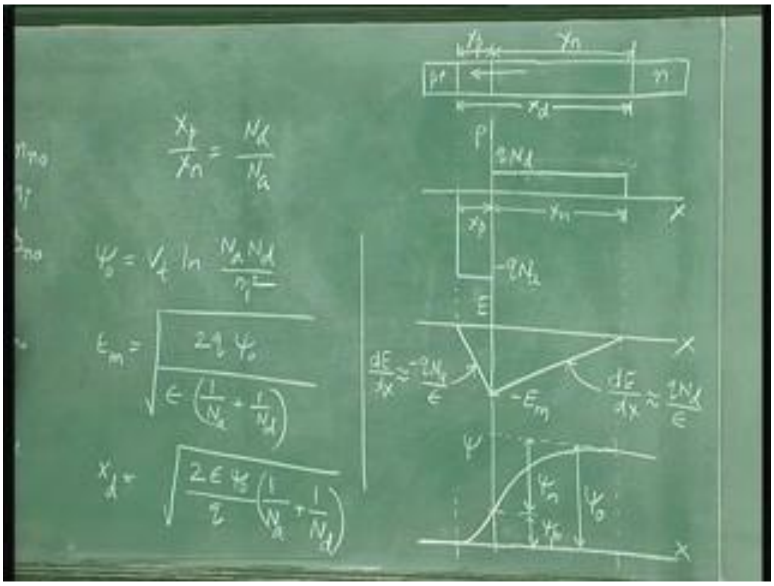

So if you want the parameters namely $X_p$ and $X_n$ once you know $X_d$ you can very easily get these parameters because you know $X_p$ by $X_n$ is equal to $N_d$ by Na. And using the same result you can also get $psi_p$ and $psi_n$ if you like. Let us summarize the results of our equilibrium analysis.

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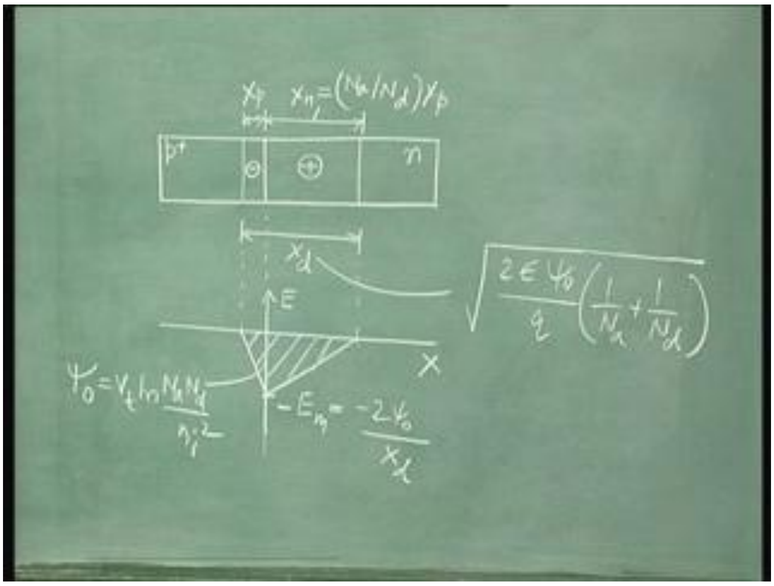


Our analysis has shown that a PN junction like this can be separated into neutral and space charge regions. The width of a space charge region is $X_d$ and of this $X_d$ $X_p$ is on the p-side and $X_n$ is on the n-side where $X_n$ is related to $X_p$ by the formula $X_n$ is equal to $N_a$ by $N_d$ into $X_p$. So this is the neutral region. These are the two neutral regions and this is the space charge region. Further our analysis has also shown that this space charge region can be assumed to be completely depleted of free carriers and therefore a positively charged region here has a space charge given by the ionized donor atoms, and here the space charge is due to ionized acceptor atoms.

Now, based on the depletion approximation which is a very important approximation for equilibrium analysis we have shown that you can sketch the built-in electric field distribution as something like this. The area under this built-in field distribution is the potential $psi_0$ the built-in potential $psi_0$ is given by a $V_t$ $l_n$ ($N_a$ $N_d$ by $n_i$ square).This formula was obtained by using $J_n$ is equal to 0 or the $J_p$ is equal to 0 the transport equations under equilibrium. Then we obtained the width of the depletion region using the Gauss's law square root of 2 epsilon $psi_0$ by q (1 by $N_a$ plus 1 by $N_d$) and using $psi_0$ and $X_d$ one can obtain the peak electric field as minus $2psi_0$ by $X_d$. So this is how starting with the basic equations of transport and continuity and Gauss's law we have derived all the information.

Note that continuity equation was not used because it is trivial in this case because every term of the continuity equation on the left hand side and on the right hand side is 0. There is no rate of change of carrier concentration, there are no excess carriers and there are no currents. Therefore continuity equation was not necessary or not useful at all in this analysis.