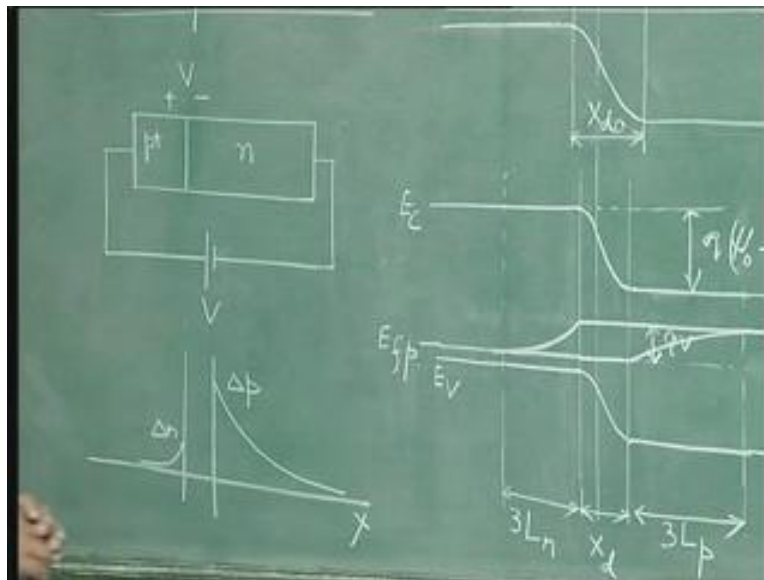


Solid State Devices
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Lecture - 24
PN Junction (Contd...)

In this 24th lecture of this course we will continue with the discussion on the energy band diagram under forward bias. Just to recapitulate, in the last couple of lectures we have seen the forward diode characteristics, we have derived equation for this and then we did a solved example to illustrate some of the practical values of various parameters in the ideal diode equation. We also looked into the deviations of the real characteristics from the ideal characteristics. We drew the energy band diagram under forward bias which looks as something like this. Now we want to explain some features of this energy band diagram.

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Most importantly, this diagram gives you the boundary values of the excess carrier concentrations at the depletion edges. So you recall that the excess carrier concentrations drawn on the linear scale look like this on the p and n-side. This is Δp and this is Δn as a function of x and this is the depletion layer. The boundary value of this excess carrier concentration is the most important result in the entire ideal diode analysis which leads to the exponential characteristics. Now, this equation for excess carrier concentration can be obtained directly from this energy band diagram as follows:

Supposing you want Δp on the n-side, this is the n-side at the depletion edge. In terms of the quasi Fermi-level we can write the equation for p hole concentration at this edge p_n as; $N_v \exp\left(\frac{E_v - E_{fp}}{kT}\right)$ that is quasi Fermi-level for holes by kT so it is minus $(E_v - E_{fp})$ by kT . This is the equation in terms of the quasi Fermi-level for

the hole concentration under applied bias. Now p_{n0} is given by N_v exponential minus (E_v minus E_f by KT) where E_f is the location of the Fermi-level under equilibrium. Here in this diagram we find that the location of E_f is same as location of E_{fn} with respect to E_c . So the quasi Fermi-level for majority carriers are electrons on the n-side is located at the same distance from E_c as the equilibrium Fermi-level which is this therefore these two distances are identical. And therefore we can replace this E_f by E_{fn} under forward bias. Now, dividing these two equations we get p_n is equal to p_{n0} exponential (E_{fn} minus E_{fp} by KT) at the depletion edge. So E_{fn} minus E_{fp} should be measured at the depletion edge on the n-side which is this difference.

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$$p_n = N_v \exp\left(-\frac{E_v - E_{fp}}{KT}\right)$$

$$p_{n0} = N_v \exp\left(-\frac{E_v - E_{fn}}{KT}\right)$$

$$p_n = p_{n0} \exp\left(\frac{E_{fn} - E_{fp}}{KT}\right)$$

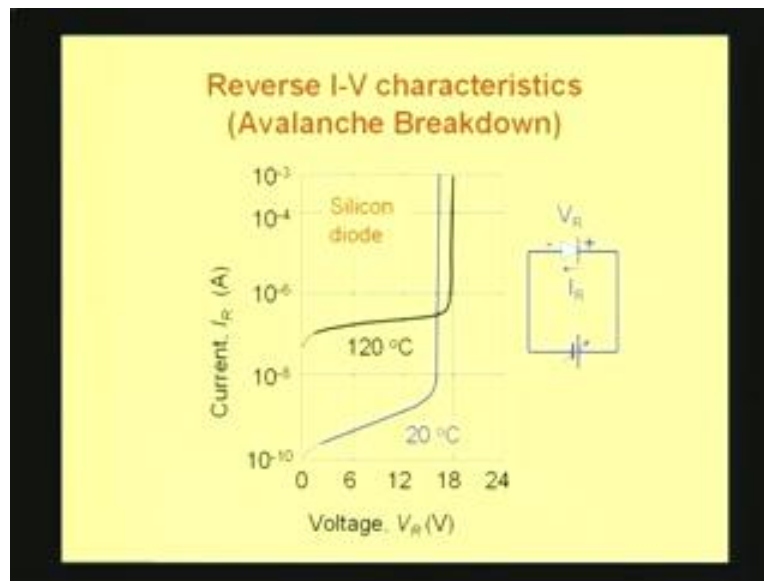
$E_{fn} - E_{fp}$ measured at depletion edge on n-side

This is E_{fn} minus E_{fp} , E_{fp} is here at the depletion edge and E_{fn} is there. But this difference is nothing but qV as you can see from here. So this clearly shows that you can replace this E_{fn} minus E_{fp} by qV and that is the equation for the carrier concentration on the depletion edge. So p_n is equal to p_{n0} exponential qV by KT which can be written as qV by KT by q and KT by q is nothing but V_t . This is how you get the boundary value of the minority carrier concentration on the n-side. And an exactly similar approach can be used on the p-side and this is how you get the excess carrier concentration as p_{n0} exponential (V by V_t minus 1) so the difference in the quasi Fermi-levels directly gives to the excess carrier concentration at the depletion edges which are the starting point for deriving the equation for current voltage characteristics. This is the significant advantage of the energy band diagram.

The boundary condition is obtained in a very straightforward manner as exponential dependence on the voltage of the carrier concentration. In fact the first analysis of the diode was done using energy band diagram and the boundary value was obtained using the energy band diagram and not using the five basic equations so it was obtained using this diagram. With this we have completed our discussion of the forward current voltage characteristic of a diode where in we have seen how the device is analyzed without the

aid of energy band diagram using the five basic equations. And we can also analyze the device using the energy band diagram which has some advantages. Now we will follow a similar approach and discuss about the reverse current voltage characteristics of the diode. Let us look at the slides which show the reverse characteristics. Here are the characteristics in which the breakdown mechanism is avalanche.

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The current axis here is in a log scale so a wide range of currents have been shown here. The breakdown voltage is of the order of about 16 to 18V. What you find here is that the characteristics change rapidly near the breakdown so for this point here and this point here for two different temperatures the change is quite sharp. In fact if you were to sketch the characteristics on a linear scale if this current was shown on a linear scale these points should appear much sharper. And these points are called knee points. So the characteristics which show a sharp change in this slope near the breakdown are called hard characteristics and these characteristics display the knee point. Under avalanche breakdown we have the hard characteristics which have a knee point.

Now let us look at other features of this particular characteristic. You find here that, as temperature increases the breakdown voltage increases. So, for 20 degree C this is the breakdown voltage which is close to 16V whereas for 120 degree C the breakdown voltage is close to 18V. Therefore this is the temperature coefficient of breakdown as defined by this parameter $\frac{1}{V_{BR}} \frac{dV_{BR}}{dT}$ this is called temperature coefficient of breakdown, and this parameter is more than 0 it is positive for avalanche breakdown.

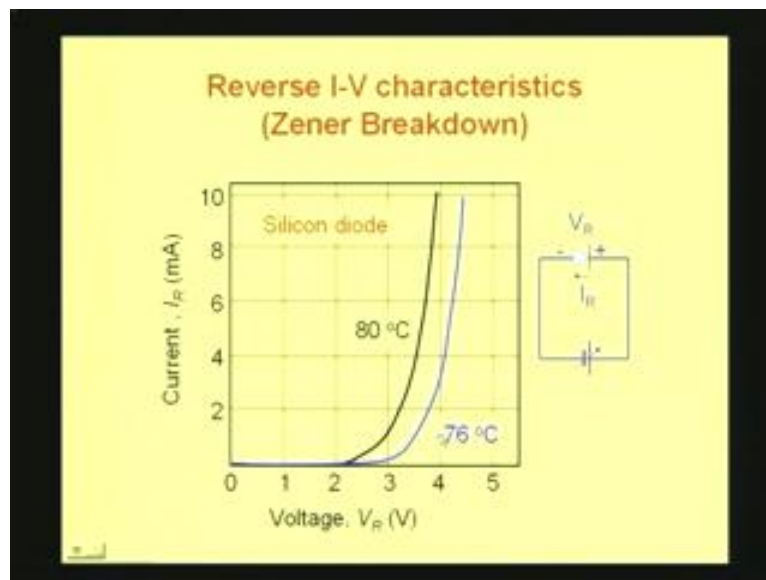
Now it is found that if the breakdown voltage is greater than eight times the energy gap where the energy gap expressed in volts then the mechanism is found to be avalanche. Now exactly what is meant by avalanche mechanism will be discussed shortly. But this kind of mechanism is present if the breakdown voltage is more than eight times energy gap. This means for silicon diodes more than about 9 volts you will have avalanche

breakdown. Let us look at another type of characteristics which corresponds to the Zener breakdown.

An important thing to note is that the current across is linear unlike in avalanche breakdown. This is because the current changes rather gradually near breakdown. In fact these characteristics do not have any knee point, these are called soft breakdown characteristics which do not have any knee point so there is no sharp change in slope therefore the breakdown voltage cannot be identified very easily. There is no precise point you can identify for breakdown. Since the current changes gradually we have shown the characteristics on a linear current axis.

A common practice is to define the Zener breakdown voltage as a voltage at 5 mA. For example, the breakdown voltage here could be 5 mA and this is the breakdown voltage at 80 degree C which is between 3 and 4 which is close to 3.5 volts. In Zener breakdown you have soft characteristics where the current changes gradually or there is no knee point. So the breakdown voltage is defined as the voltage corresponding to 5 mA.

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Here you can see that as the temperature increases the breakdown voltage reduces. For example, here you can see that for minus 76 degree C the voltage corresponding to 5 mA here is more than 4 volts whereas for 80 degree C it is less than 3.5 so you find that the breakdown voltage reduces with temperature. In other words, this temperature coefficient of breakdown is negative for breakdown which is covered by Zener mechanism.

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	Avalanche breakdown	Zener breakdown
	"Hard" charact, knee point	"Soft" charact., no knee point
$\frac{1}{V_{BR}} \frac{dV_{BR}}{dT}$	> 0	< 0
V_{BR}	$> 8(E_g/q)$	$V_{BR} = V_{I=5\mu A}$

We will also learn about Zener mechanism in detail and know how it is different from the avalanche breakdown mechanism. Now, analysis shows that, for breakdown voltages less than four times energy gap that is four times E_g by q the mechanism is Zener. So what happens for diodes which have breakdown voltage between eight times energy gap and four times energy gap?

Well, for these diodes the Zener and avalanche both mechanisms exist together, they coexist. Now these kinds of diodes which have breakdown voltage between $4 E_g$ and $8 E_g$, that is, if you take silicon diodes this could mean the breakdown voltage between about 4.5 and 9 volts. These kinds of diodes will therefore have temperature coefficient which can be close to 0. So you can adjust the temperature coefficient of breakdown very close to 0 by choosing an appropriate breakdown voltage in this range.

Now returning to the slide showing the reverse current voltage characteristics for avalanche breakdown we would like to explain the behavior of the current below breakdown. More specifically what we find here is that the current is very sensitive to temperature. The current below breakdown is very sensitive temperature. So you can see from 20 degree C here where the current is about 10^{-9} and here it is 10^{-7} so two orders of magnitude change at about 9 volts below breakdown. But why is the current below breakdown very sensitive to temperature?

Another thing is that, at 20 degree C the current seems to change significantly with voltage below breakdown whereas at 120 degree C the current does not change that much. These are the features for a silicon diode. Now, a similar behavior of the reverse current below breakdown also applies in the case of the Zener breakdown. But we are looking at the curves zones on this slide corresponds to avalanche breakdown because as shown in the slides the current is over a large change in order of magnitude, we have plotted the current on a log scale.

If you plot on the linear scale the reverse current below breakdown is not seen very clearly. So the behavior is not shown very clearly unless you plot the current on a log scale on the reverse side. We need to develop some theory to explain these characteristics. So let us start with a theory corresponding to characteristics below breakdown for reverse bias. Now, the approach to derivation of these characteristics will be similar to that followed in the forward bias.

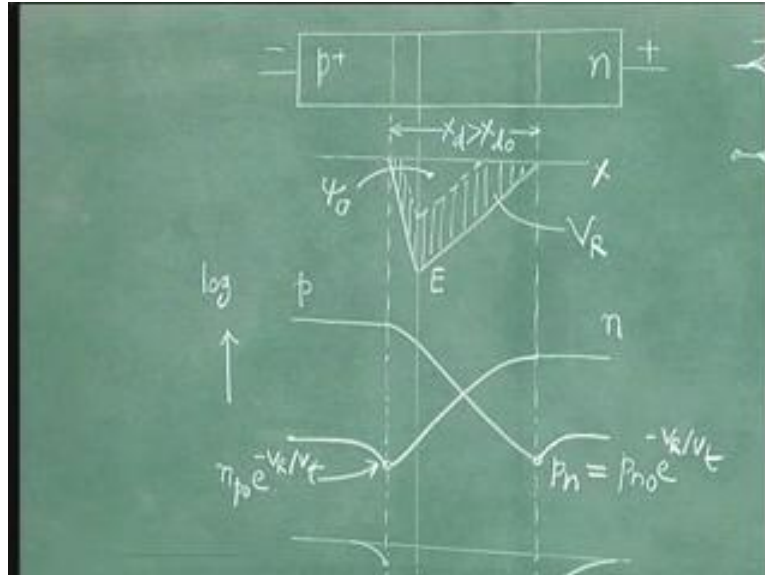
We will first try to derive ideal reverse diode characteristics that are ideal characteristics of diodes which are reverse bias. So proceeding in the same steps as we did for forward bias first we look at the electric field versus distance picture which is the distribution of the electric field. Since this region is depleted you have a triangular distribution. The depletion width has expanded as compared to the equilibrium condition. So X_d is greater than X_{d0} which corresponds to equilibrium.

If you want to show the equilibrium conditions on this graph they would look like something like this. This area would be the applied reverse bias, this is V in magnitude. So we will write V magnitude as V_R because for reverse bias our convention says that the voltage V will be negative because V is assumed positive for forward bias. That is, when P-region is positive with respect to n-region we say the v is positive. So magnitude of reverse voltage will be denoted by V_R . This shaded area is V_R and this area under this triangle is the built-in voltage ψ_0 .

Let us look at the carrier concentrations. Here the concentrations are shown on a log scale. This is the whole concentration and this is the electron concentration, these are majority carrier concentrations. Now applying the same theory that we did for forward bias that is using the Boltzmann relations it can be readily shown that your carrier concentrations for the minority carriers at the depletion edges will be reduced as compared to equilibrium. In forward bias it is increased as compared to equilibrium. In the reverse bias they decrease so the formula is the same as under forward bias.

In other words, if you draw for the holes the concentration of holes here would decrease as compared to equilibrium. This is the equilibrium concentration and if you call this point the hole concentration in the n-region at the depletion edge then this p_n is given by p_{n0} equilibrium concentration into exponential of V by V_t where V is the applied voltage. The applied voltage is negative so we will do this explicitly by replacing this by minus V_R . That is how the equilibrium concentration is decreased as compared to the equilibrium because this exponent is negative. One can do a similar thing on the p-side so this would be the electron concentration on the p-side given by n_{p0} exponential of minus V_R by V_t . In the depletion-region you can show some variation like this.

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These relations are obtained from the Boltzmann relation which is a consequence of the assumptions shown here that J_n is approximately equal to 0, J_p is approximately equal to 0 which is the so called quasi equilibrium approximation. The drift and diffusion are approximately in balance in the space charge region and by using that we get these relations. If you were to sketch the excess carrier concentrations now on the linear scale, as we did as a next step in forward bias, then it could look as something like this. Here the carrier concentration is depleted as compared to equilibrium condition.

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Approximations		
Equation	space-charge region	quasi-neutral region
Transport	$J_n \approx 0$ $J_{n0} \approx J_{n0}^{diff}$ $J_{n0} \approx J_{n0}^{diff}$ $J_p \approx 0$ $J_{p0} \approx J_{p0}^{diff}$ $J_{p0} \approx J_{p0}^{diff}$	diffusion approx for minority carriers
Continuity	$\frac{dJ_p}{dx} \cdot \frac{dJ_n}{dx} \approx 0$ (no recombination)	low-level diffusion continuity eqn for minority carriers
Gauss's law	Depletion approx	

So this quantity is δp on the n-side and you similarly have δn on the p-side. Now what is the value of δp ? This value is p_{n0} exponential of minus V_R by V_t minus 1 as we have done in the case of forward bias which means that if V_R is more than $3V_t$ or the reverse bias is more than three times the thermal voltage then this exponent can be taken to be negligible zero. So your result is approximately equal to minus p_{n0} for V_R greater than $3V_t$ or reverse bias more than about 76 mV at room temperature.

You will have the excess carrier concentration to be equal to the minority carrier concentration but with a negative sign which means in absolute terms this quantity can be assumed to be close to 0. It is very small as compared to equilibrium so this is p_{n0} and this is n_{p0} . Now, based on this picture one can easily show that you end up getting the same equation as the forward bias ideal diode equation.

You use the diffusion currents, you use the same approximations that we made in the analysis of forward bias conditions and you get the result as follows. So ideal reverse characteristics I-V characteristics so you get I is equal to I_0 exponential V by V_t minus 1. The V here is negative so for reverse direction V is minus V_R . So the table shown here is the table used for forward bias and exactly the same set of approximations are used for reverse bias also where you get this result.

Now, this equation enables you to give an interpretation to the current I_0 . So what you find is, I is approximately equal to minus I_0 if your V is less than minus $3V_t$ or your V_R is greater than $3V_t$. So, if reverse bias is more than $3V_t$ according to the ideal diode characteristics analysis the current saturates to I_0 in the negative direction. That is why the I_0 is referred to as the reverse saturation current. So the name given to I_0 is the reverse saturation current of the diode.

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Diagram illustrating the ideal reverse I-V characteristics of a diode. The diagram shows a horizontal axis for voltage with a point labeled $-V_R$. A vertical dashed line with arrows at both ends is labeled e^- on the right. Below this, a horizontal axis represents current with a point labeled p_{n0} . A curved arrow points from p_{n0} to the equation $p_n = p_{n0} e^{-V_R/V_t}$. Below this, another equation is shown: $-p_{n0} (e^{-V_R/V_t} - 1) \approx -p_{n0}$ for $V_R > 3V_t$. To the right, a box contains the text "Ideal reverse I-V characteristics" followed by the equation $I = I_0 (e^{V/V_t} - 1)$ and $V = -V_R$.

Now how do you calculate the reverse saturation current I_0 ? You can repeat the formula we derived under forward bias because it is the same formula. And that formula is $q(p_{n0})$ by L_p into D_p this is for the p-side and plus n_{p0} D_n by L_n this is for the n-side and you must multiply this by the area.

Let us multiply by the area here; it is the area of cross section of the diode. So these are the two diffusion currents; one on the n-side and other on the p-side, they are minority carrier currents. And if it is a one-sided junction, that is, the doping on p-side is much more than on n-side then only this quantity which is the whole current will dominate.

We can further write this as follows:

A into q the minority carrier concentration can be written as n_i square product divided by doping so you get the n_i square out and in the bracket you get D_p by $N_d L_p$ plus D_n by $N_a L_n$. It is this n_i square term which makes the I_0 sensitive to temperature. So you know that n_i square can be written as square root of $N_c N_v$ the square root actually goes off because you are taking a square so $N_c N_v$ exponential (minus E_g by KT) this is n_i square product. So this term is responsible for the great sensitivity of I_0 to temperature. Here this quantity is also a function of temperature but this temperature dependence is not that much as compared to the exponential term.

Similarly, D_p and L_p D_n and L_n will also be somewhat sensitive to temperature but that sensitivity is not the dominant sensitivity to temperature. It is mainly this exponential term that is responsible for the sensitivity of I_0 to temperature. This is why the reverse current or the current of a reverse bias diode is very sensitive to temperature below breakdown voltage. The current below breakdown voltage is sensitive to temperature.

Now what kind of sensitivity do we expect?

One can make a calculation using this formula and find out how sensitive the current is to temperature. Now, based on this theory let us try to explain the experimental observations of the reverse current and try to explain why there are deviations from this theory. So the first thing that we find from here is that this current I_0 predicted according to the ideal diode characteristics is independent of voltage.

Let us look at this formula here, the reverse current I does not change with voltage once your voltage is greater than $3V_t$ so the reverse current is independent of voltage. However, we find in this slide here for 20 degree C the current is quite sensitive to voltage. So you find it is changing by almost an order of magnitude over this range as the voltage is varying. This obviously means that some assumptions which we have made in deriving the ideal diode characteristics are not valid at least for the silicon diode for which we are looking at the characteristics.

Now the reason for this deviation is the following:

If you draw the flow diagram for the ideal characteristics it would look like this. This flow diagram is similar to the one that we have drawn under forward bias conditions except that you can see that recombination have been replaced by generation. Thus, in forward bias the arrows are pointing inwards, both the arrows are pointing inwards

whereas here the arrows are outward because the recombination in forward bias is replaced by generation. And why is there generation instead of recombination?

It is because as shown in this graph you have depletion of carriers so you do not have enhancement in the neutral p and n-regions. Your carrier concentration is less than equilibrium which is shown here also. The excess carrier concentrations are on the negative axis and are not in the positive axis. The carrier concentrations are reduced when compared to equilibrium which means there is a net generation. The generation rate depends on the p_n product and that is why the recombination has been replaced by generation.

So, if you assume only the currents in the neutral p and n-regions then you cannot explain the variation of the current with voltage because these currents saturate with voltage for reverse bias more than $3V_t$. So what we have done is we have neglected this generation current in the depletion layer. To explain the forward characteristics for low voltages again we have to invoke the presence of this recombination current in the depletion layer.

Similarly, for reverse bias below breakdown in many of the diodes particularly silicon diodes this current in the depletion layer is a dominant current at least at room temperature as compared to these two currents. To understand the behavior of this current a simple formula can be derived by noting that the current depends on the generation within the depletion layer so it should depend on the volume of the depletion layer or in other words the width of the depletion layer.

And if you do a rigorous theoretical analysis it is found that the current depends on the intrinsic concentration n_i .

So, if you denote this current to be I_{gr} generation recombination current then we can write I_{gr} as it is proportional to depletion width and also n_i the intrinsic concentration. So, to show that it is proportional to n_i you have to do a rigorous analysis and find out. We are trying to explain the situation for silicon diodes because that is our preference. Since as you increase the reverse voltage the X_d will go on expanding, this X_d is the function of voltage, so X_d increases as V_R is increased. This is what is responsible for the increase of the reverse current with voltage seen at room temperature.

Let us also try to explain why the generation recombination current in the depletion layer under forward bias condition or the generation current in the depletion layer in reverse bias condition dominates at lower temperatures that is at room temperature whereas at high temperatures the other current in the neutral p and n-regions or the diffusion current starts dominating. These can be very well understood using this formula.

You can see that I_{gr} is proportional to n_i whereas the I_0 is proportional to n_i square. This means I_{gr} varies as exponential of minus E_g by $2KT$ because I_{gr} depends on n_i which depends on exponential minus E_g by $2KT$ whereas I_0 the reverse current varies due to diffusion as exponential (minus E_g by KT) as per the ideal diode equation because it varies as n_i square as seen here, so this is I_0 . It is this difference that is responsible for the dominance of the diffusion current at higher temperatures. This current will change much

more rapidly with temperature than this current. So, for low temperatures this dominates over this but for high temperatures this increases so much that this dominates over this.

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Handwritten equations on a chalkboard:

$$I_{gr} \propto X_i \eta_i$$

$$X_i \uparrow \Rightarrow V_A \uparrow$$

$$I_{gr} \propto e^{-E_g/2kT}$$

$$I_0 \propto e^{-E_g/kT}$$

$$I_0 = \text{Reverse Saturation Current}$$

$$= A q \left(\frac{p_n D_p}{L_p} + \frac{n_p D_n}{L_n} \right)$$

$$= A q n_i^2 \left(\frac{D_p}{N_A L_p} + \frac{D_n}{N_D L_n} \right)$$

$$n_i^2 = N_C N_V \exp\left(\frac{-E_g}{kT}\right)$$

On the right side, there is a vertical axis labeled $\log$ and T with an upward arrow.

Since the diffusion current is a dominant mechanism of reverse current flow in diode at higher temperature you will not be able to see much variation of the current as a function of voltage because as the ideal diode equation shows the reverse current is insensitive to voltage beyond a voltage of $3V_t$ under reverse bias conditions. That is why here you can see that for 120 degree C the current does not seem to change much with voltage because diffusion current is dominating. This is how we can explain the behavior of the reverse current to the diode below breakdown.

Now, we will try to explain the mechanism of breakdown itself. Let us start with the Zener breakdown mechanism. For this purpose we need to draw the energy band diagram of a diode under reverse bias. So when you apply reverse bias for a PN junction the energy band diagram looks like this. The quasi Fermi-level for electrons here on the n-side is somewhere here so this is E_{fn} and the quasi Fermi-level for holes are somewhere here. And this difference between the two quasi Fermi-levels indicates the applied voltage.

Now, near the breakdown what is happening is that, in the band diagram there is a possibility of electrons from the p-side moving to the n-side from the valance band of p-side to the conduction band of n-side. That is, the generation current we normally talk about can be represented as follows: An electron jumping up, that is, electron whole pair generation within the device volume leaving behind a whole here and electron here and that electron is going down. So, on the energy band diagram the current due to generation either within the depletion layer or in the quasi neutral regions can be shown by the arrows that we have just drawn. This is the path of that particular generation current.

As against this path you can have another path that is electrons from here jumping to the conduction band on the n-side in a manner that is shown by this particular arrow leaving behind a hole here and an electron there. This is also electron hole pair generation but the difference between this electron hole pair generation and this is that here the electron is jumping from the valance band of p-side to the conduction band on the n-side whereas here the electron jumping from the valance band to the conduction band on the same side of the material. This is for generation in the p-layer and you can similarly have generation within the depletion layer by the same process or you could have generation on the n-side by similar process.

In this case what will happen is that the hole will move down in this direction. As against this here this is the generation process that is responsible for breakdown and this is the tunneling process. Now, this is the tunneling process because you can see that electron at certain energy is crossing over to the other side through a barrier, so this reflects a barrier at the same energy. So this is electronic energy and here electron is jumping from a lower energy to the higher energy but here the electronic jumping at the same energy from one side to the other side.

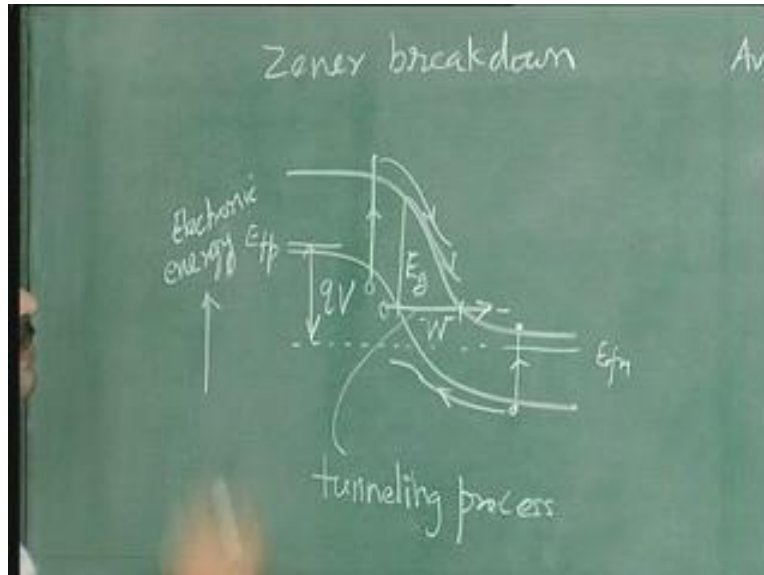
What is common between these two is that both processes lead to electron hole pair generation. But what is the difference between the two? The difference is that this process is at the same energy whereas in this process electrons jump from lower to higher energy. The common thing between these two processes is that in both cases the electrons are jumping from valance band to conduction band because that is how they give rise to electron hole pairs.

When will this kind of process be really significant?

As written here this is a tunneling process because electron from one side of the barrier is going to the other side at the same energy so it is penetrating a barrier and that is why this is a tunneling process. The tunneling process involves electron going from one location to other location through a potential barrier but the two locations are at the same energy. So this kind of process is significant when the barrier width is small and here this represents the width of the barrier.

The height of the barrier is the energy gap, that is, if the electron were to go to this side by an alternate path which does not involve penetrating through the barrier that path would be something like this. It has to jump up and go to the conduction band and then come down. This is the height of the barrier in which it will travel, if does not take this path it has to go up like this and come down. So, height of the barrier is clearly equal to energy gap. The intensity of tunneling depends on the width of the barrier that is this width w and the height depends on the energy gap.

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Now as one can very easily see this width will be small if the depletion width is small because essentially the variation of the bands here represents the width of the depletion-region. So the depletion-region exists wherever the energy bands are varying. So evidently if the depletion width is small this width of tunneling barrier will also be small. When will you have a smaller depletion width? You will have a smaller depletion width when the doping level is high in the diode. That is why this kind of tunneling the Zener mechanism is dominant only when the diode is having a very high doping on both sides. Generally, doping levels more than 10^{18} will lead to this kind of a mechanism of tunneling. Apart from the width it depends on the height of the barrier also. If the height of the barrier is more the tunneling probability will be less. This means that the breakdown voltage because of Zener mechanism is a function of the energy gap of the semiconductor.

Now you know that the energy gap of most semiconductors decrease with temperature. That is why as the temperature increases the height of the tunneling barrier decreases and the breakdown voltage decreases. This is how you can explain the negative temperature coefficient of breakdown voltage associated with Zener mechanism and it also explains why the Zener mechanism is dominant in diodes which have high doping levels. When the doping level is high the depletion width is small and also the width of the barrier is small and only then the tunneling process becomes significant. With this simple explanation we cannot clarify why near the breakdown voltage the current voltage characteristics vary gradually that is the Zener breakdown is soft.

Next we shall look into the avalanche breakdown mechanism in a qualitative manner. Here what is happening is the following: Let us look at the depletion-region. When the doping levels of the diodes are small then the depletion-regions are wide. This is the depletion-region of the diode, on this side you have the p to the power plus n where n is on this side. Let us look at the path of electron which is moving from p to n . Or

alternately you can look at the path of a hole which is moving from n to p through the depletion layer.

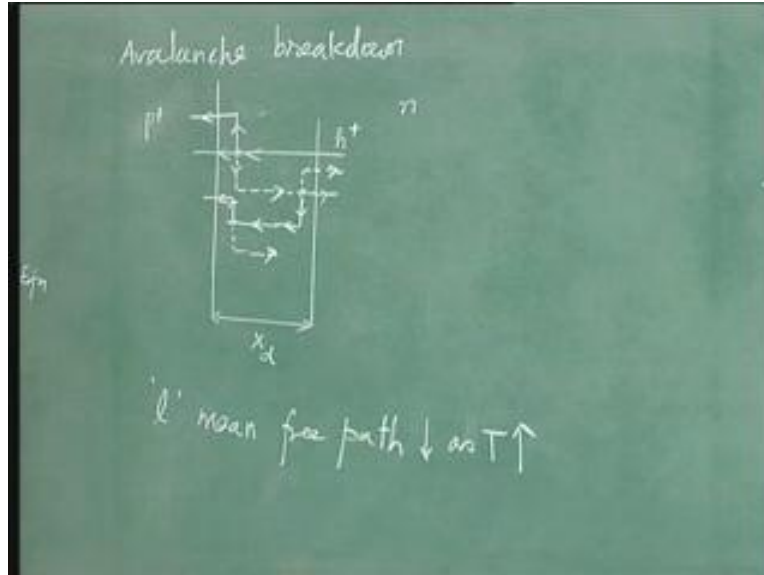
Now, during its motion if the depletion width is sufficiently wide and the electric field is sufficiently large then what can happen is the hole during its motion between any two collisions that is during its travel in the mean free path or over the mean free path it can gain sufficient energy such as the kinetic energy from the electric field. And if this kinetic energy is large and sufficient enough to break a covalent bond that is if this energy is comparable to the energy gap of the semiconductor then next time the hole that is moving here collides with the silicon atom and it can give rise to an electron hole pair thereby generating a hole and an electron. And now the hole is going to move out in this direction whereas the electron which is generated will try to move in this direction.

Now, if the electron is also allowed to travel a sufficient distance within the depletion layer whatever has happened to this hole can happen to the electron as well. That is, this electron may also gain energy which is sufficient enough to break a covalent bond and generate an electron hole pair. So this generates an electron hole pair somewhere here and the generated electron moves out but the hole moves back and the electron hole pair also moves out. Similarly here also there is a hole which was causing the electron hole pair generation that remains and it moves out. Now, this hole has to travel a longer path as compared to this electron. Though this electron may not be able to generate an electron hole pair this hole during its travel may generate an electron hole pair.

This process can go on if the electric field and the depletion width are such that for every electron and hole pair or rather for every hole that is traversing to the depletion layer and electron hole pair is generated. So what will happen is that the electron of this electron hole pair will intern generate another electron hole pair and the hole of this secondary electron hole pair will generate another electron hole pair somewhere here and so you will have a series of electron hole pair generation processes and this will go on till infinity because every electron that is passing through depletion layer is generating electron hole pair and every hole is generating electron hole pair. Thus, the generated electron or hole is also generating an electron hole pair and there is what is called a storm suddenly building up when the current will tend to infinity. So the storm is also called avalanche which is another name for a storm. Since a storm of electron hole pair is generated within the depletion layer the current raises rapidly.

Now, based on this mechanism we can see why this kind of avalanche breakdown mechanism occurs in diodes which are having low doping because you must have a sufficient depletion layer width otherwise the electrons and holes which are traveling in the depletion layer cannot gain sufficient energy. That is why this kind of breakdown occurs in diodes having low doping level. Also, another thing you can see is that, why should the breakdown voltage increase in temperature. This is because the mean free path between collisions l over which an electron or a hole should travel in the depletion layer to create an electron hole pair this mean free path decreases with temperature.

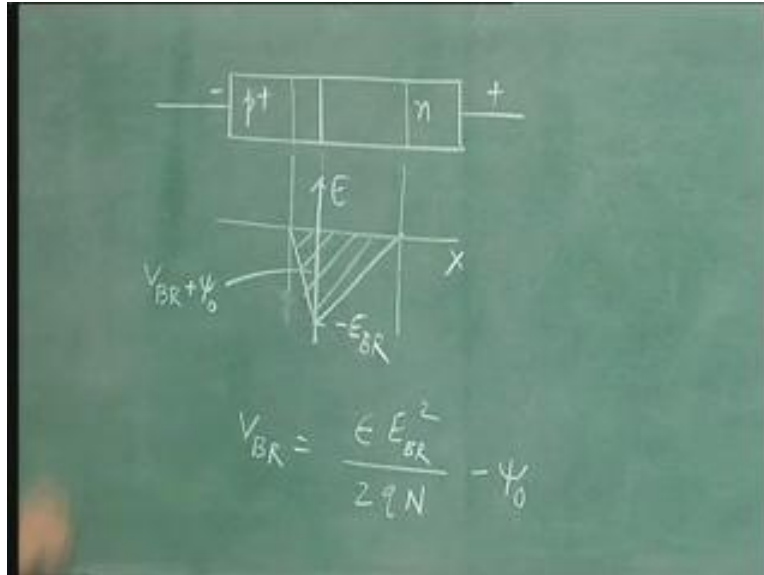
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This is because as discussed in the initial lectures of this course the scattering or collisions increase with temperature. This is the reason why you need to have high electric field to impart the same energy to the electrons or holes moving in the depletion layer as energy gap. So the electrons and holes travel a smaller distance, in the smaller distance they must gain in the same energy but this can only happen if they are subjected to a higher electric field. Now this explains why your breakdown voltage is higher at higher temperatures when the mechanism is avalanche. So this is the end of the qualitative explanation of avalanche breakdown.

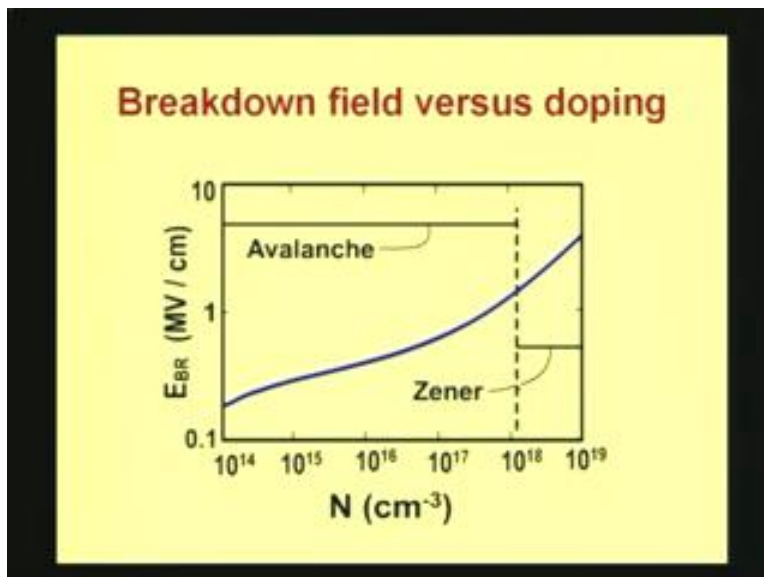
I must emphasize that if you want to explain the sharp change in this slope of the current voltage characteristics at avalanche breakdown or the presence of the knee point then you have to discuss the quantitative theory of this avalanche breakdown which is beyond the scope of this particular course, a word about how one can practically estimate the breakdown voltage of diodes. The approach that is taken is the following: As we have seen the breakdown voltage depends on the peak electric field. This is the electric field picture in a diode so the breakdown voltage depends on the peak electric field. When this peak electric field reaches the breakdown field called E_{BR} then breakdown occurs, this is what we can assume. So using this particular picture we can write the breakdown voltage expression as follows: The area under the electric field is equal to V_{BR} plus ψ_0 where ψ_0 is the built in voltage. So the V_{BR} can be written in terms of the breakdown voltage field E_{BR} as follows:

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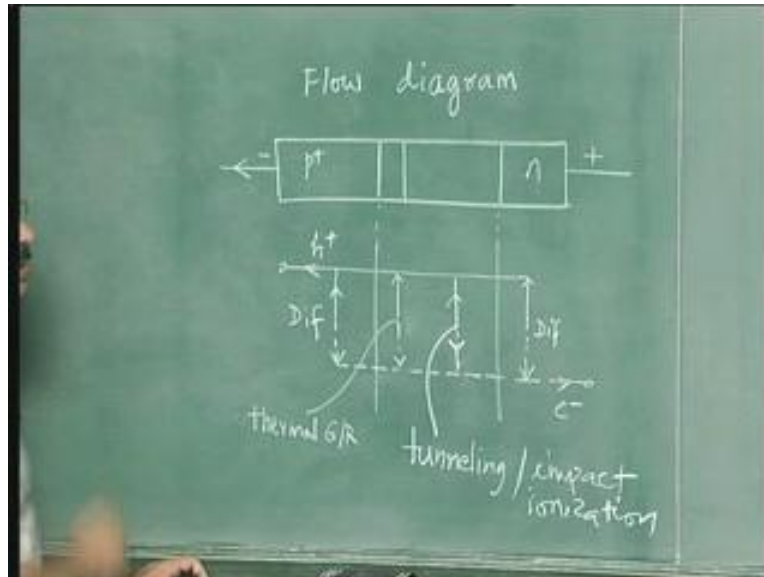
V_{BR} is equal to epsilon into E breakdown voltage square by two times q times the doping level in the likely doped region minus ψ_0 . Here we are assuming a one sided junction. Now the breakdown field calculations have been done and they are available in the form of a graph as shown in this slide. So here the breakdown electric field is shown as a function of the doping level. As you can see from this picture for doping levels higher than about 10^{18} by cm^3 you have Zener breakdown and for low doping levels you have avalanche breakdown.

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So you can take the electric field from this kind of graph and then estimate the breakdown voltage for the given diode. With that we have come to the end of the discussion on the reverse characteristics of diodes. We can summarize our discussion as follows: Let us look at the flow diagram.

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For currents below the breakdown voltage the mechanisms which contribute to current flow are shown here. So you have the diffusion currents in the neutral regions and you have thermal generation recombination current within the depletion layer. This accounts for the reverse current below breakdown. Now, near breakdown an additional generation mechanism is initiated either due to tunneling as in a Zener breakdown or due to impact ionization as in an avalanche breakdown. And this generation increases rapidly with voltage and that is why the current through the device increases rapidly. With this we end our discussion on the reverse characteristics. In the next class we will take up the small signal equivalent circuit of the diode.