Digital Integrated Circuits

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Lecture-2

Modelling of PN junction Diodes

Today's class we shall continue our discussion on p n junction diodes. Last class we had seen that in a p n junction when you have an applied voltage across the junction, the carrier concentration at the interface of the depletion region and the bulk changes. If you have a forward bias, the carrier concentration increases above the thermal equilibrium value and if you have a reverse bias it decreases and we have also seen that the nature of the variation in the bulk region depends on the length of the material in relation to the diffusion length. If the length of the bulk region is small compared to the diffusion length, the carrier concentration varies in a linear fashion and if it is long compared to the diffusion length the carrier concentration decays exponentially. So based on that we have two types of devices we have said, one is called the long diode and the other is the short diode.

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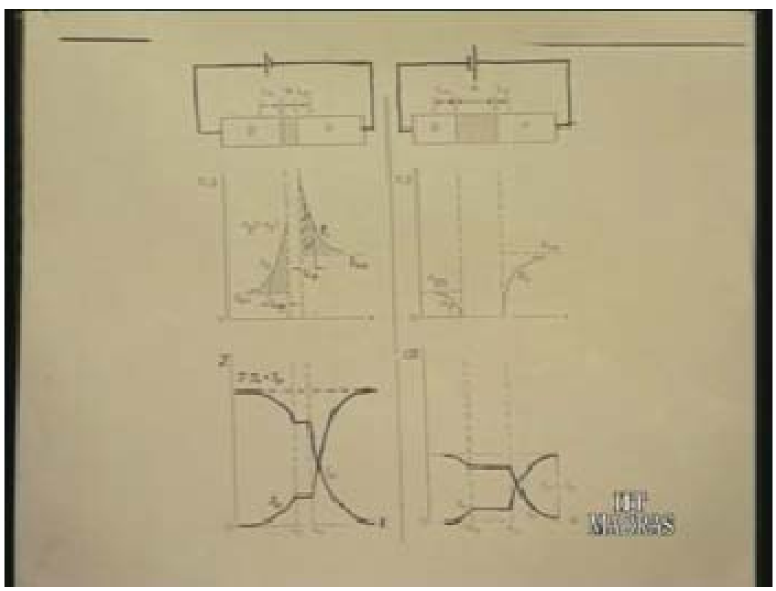

Now today's class we shall go ahead and see how the currents, the nature of the relations for the currents and the capacitances in a p n junction diode. We have this slide here which shows the case for a long diode where the p and n regions are long, that is again in relation to the diffusion length. So we have two cases one is for a forward bias diode and the other one is for a reverse bias diode. Here we see that the carrier concentration on both sides at the depletion width edge is more than the thermal equilibrium value and it falls of exponentially away from the depletion region into the

bulk and one point we note is that the minority carrier concentration on the n side is more than that in the p side. What does it imply?
It implies that the doping concentration on the p side is higher than that in the n side because which means that the minority carrier concentration is less on the p side. Now this slide also shows how the current that is the electron current and the hole current vary in the different regions of the device. For example if you look at the n side, the minority carrier hole concentration decays exponentially and which means that the current also which is proportional to the gradient of the carrier concentration profile also varies exponentially. So as the holes are injected from the p side into the n side and these holes diffuse towards the contact on the n side. Some of them recombine and as the holes recombine the concentration reduces and also the hole current reduces, it falls of exponentially.

Similarly on the p side if you look at the electron concentration profile, it falls of exponentially which also means that the electron current on the p side falls of exponentially. You also see that on the n side the electron current actually increases, if you look at this way that right at the contact on the n side the current which you see is totally electron current and this electrons that means electrons are flowing in and what happens to these electrons the electron current decays that means as the holes are recombining, they will recombine with electrons. So the electron current reduces and similarly on the p side of the contact the current is totally made up of holes and this hole current reduces and as we go from the contact on the p side towards the depletion region.

Now the total current is the sum of the hole current and the electron current which is a constant. Now the way to calculate the total current is to sum up, you can sum up the electron current and the hole current in any region, any point in the device but the easiest way is to sum up at the depletion edges which is the easiest to calculate. So what we do is the total current is the sum of the hole current at the depletion edge on the n side plus the electron current at the depletion edge on the p side. Now how do you calculate these currents? Now one way to calculate it is there could be different ways to calculate it. One way to calculate it is from the charge profile here, we have already seen that the excess carrier concentration, we have already seen a relation for the excess carrier concentration that is equal to the injection that is related to the injection rate and lifetime. What is the injection rate basically? It is the current flowing in. So you can say that the current flowing in that is the hole current which is flowing in the n side is given by the charge stored divided by the lifetime because basically what is the current flowing in.

The current is flowing in to compensate for the holes which are lost due to recombination because it's in the steady state. So the profile is constant so as the holes recombine you have to make up and that is why the holes are flowing in. So you can do it that way, the other way to do it is from the slope of the concentration profile at the depletion edge. So as you see here that is given by the excess carrier concentration divided by the diffusion length. So we can do it either way, so the total current in the device will be given by j_n plus j_p and what we do is j_n at minus x_p which is the depletion width edge and the p side plus j_p at x_n which is the depletion width edge on the n side.

So this is for a reverse bias diode, here we see that the carrier concentrations at the depletion width edges are in fact are less when compared to the thermal equilibrium value and here it is almost the same argument except that we don't have recombination but you have generation because the carrier concentration in this case the n_p will be less than n_i square.

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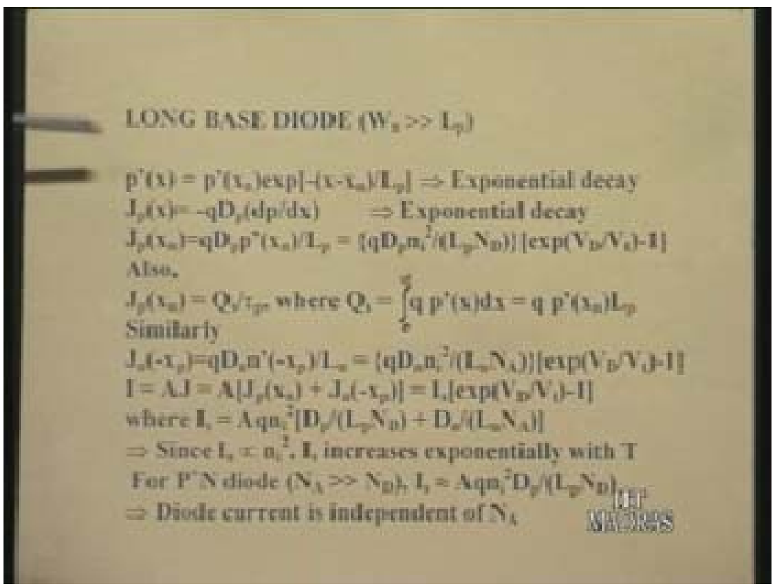

So whatever we have been talking of now just put it in equation form. So you see that the excess carrier concentration profile varies exponentially on the n side this is for the n side in bulk which means the hole current is also going to decay exponentially and this can be calculated this way and you get a relation like this which gives us a constant into v_D by v_t - 1. This can also be calculated as I said by taking the excess charge Q_s by lifetime which excess total charge is calculated by integrating the total charge concentration over the entire region over the entire bulk region.

Similarly if you do the electron current on the p side, you get the similar relation and the total current is given by the sum of these two currents and you get a relation I_s which is called the saturation current exponential v_D by v_t -1 where I_s is given by a relation like this. Now you see that I_s or the saturation current is proportional to the n_i square and what is n_i intrinsic carrier concentration, it depends very much on temperature. So the saturation current also is very much a function of temperature and it increases with temperature this is quite obvious here.

Also if you look back at this relation if you have a p + n diode, what is p + n diode? That in a p + n diode the acceptor concentration on the p side is very much larger than the donor concentration on the n side. So if you look at the relation for I_S, N_A is very much greater than N_D. So this term is going to be very much less than this term. So I_S will be equal to this which is you see that this is independent of N_A.
So it doesn't depend on the acceptor concentration so it depends on the concentration on the lightly doped side and obviously if you want to reduce I_S, what you have to do? You have to increase the concentration on the lightly doped side, when d increases I_S reduces. So this shows a similar case for a short diode, carrier concentration profile in the short diode where the concentration profiles were there is a straight line, linear variation which means that so this is for a forward bias diode this shows the excess charge concentration and which means that the currents here are going to be constants.
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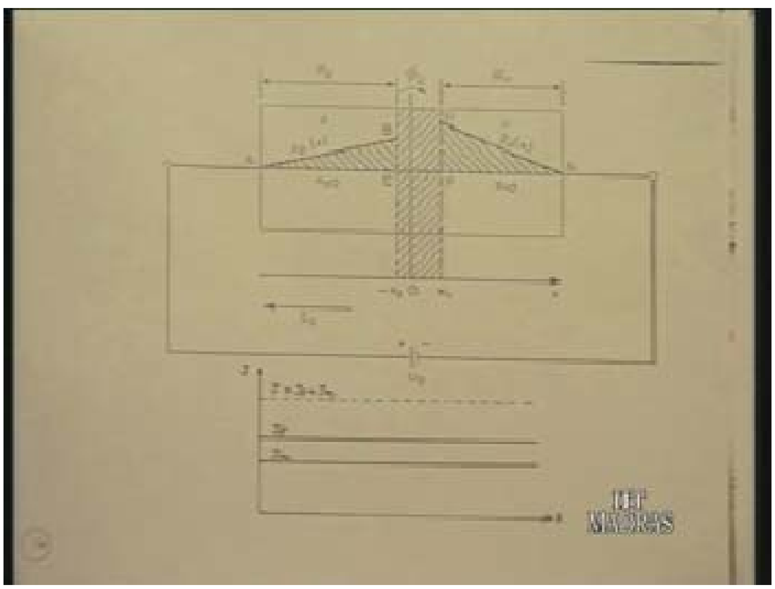

In fact the reason is that there is no recombination in the device, very little recombination I should say because the length of the device is very much smaller compared to the diffusion length and almost all the recombination takes place only at the context.
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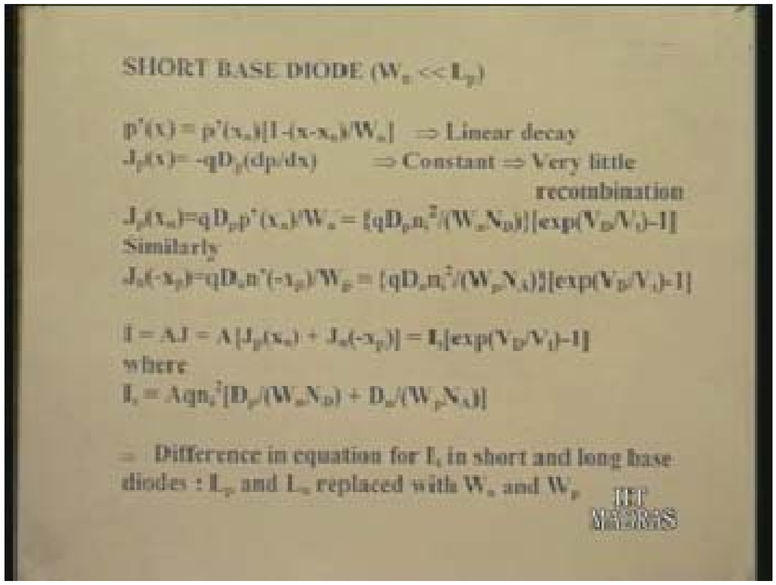

So this is what we have discussed. So the excess carrier concentration there is a linear decay which means that the current is a constant, the minority carrier currents are constant which implies that there is very little recombination in the device and if you look at the current concentrations, if you look at the current relations you will find that you do not have the diffusion lengths coming into picture but you have W_n which is the length of the n bulk region and you have W_p which is the length of the p region. So that the diffusion lengths are actually replaced by the lengths of the devices. So in this case what is important is the length of the devices. So this is the relation for I_s. So difference in equation for I_s in short and long base diodes is that the L_p and L_n are replaced with W_n and W_p. So the diffusion lengths are replaced by actual lengths of the devices.

So the next what we come to is the capacitance voltage relations. There is a lot of stored charge in the p n junction device and when ever you have stored charge and the charge is varying with the applied voltage you have a capacitance and this capacitance have an important role to play in the operation of the devices. There are two types of capacitances one is the stored charge capacitance or the depletion capacitance which is due to the charge stored in the depletion region and this is going to dominate at reverse bias, when the device is reverse biased and you have the other capacitance which is due to the stored charge in the bulk regions that is the minority carriers. So that is going to be more prominent or more important when the device is forward biased.

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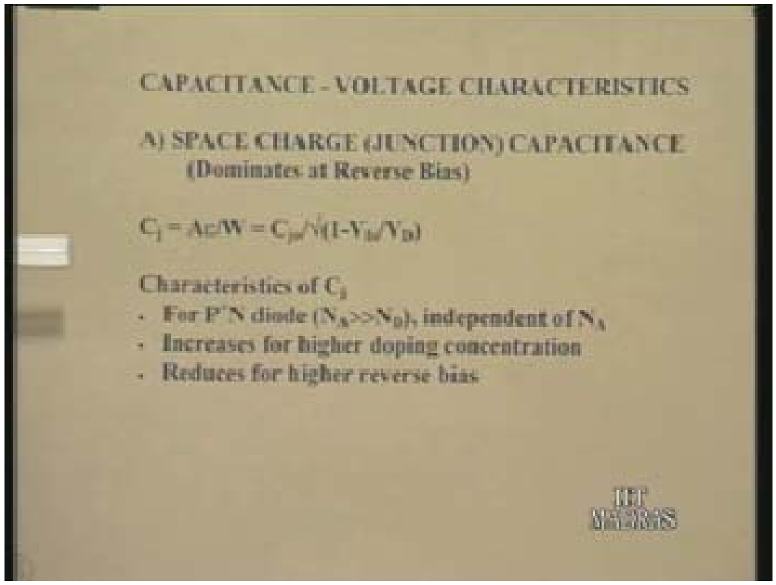

So the space charge capacitance actually it has got a relation that is basically the charge dq dv that is where q charge is stored in the space charge. So you get a relation like this finally when you solve A epsilon by w that is the very well known capacitance relation where A is the area, epsilon is the dielectric constant, w is the depletion width and this gives a relation like this C_{jo} divided by square root of one minus v_{bi} by v_D where C_{jo} is the capacitance for zero bias when v_d is zero and v_d is the applied bias and the important thing to note here is for a p plus n diode

That is again we have seen that the space charge region penetrates more into the lightly doped side. So if you have a p plus n diode the space charge region is almost entirely in the lightly doped side. So it is independent of the doping on the heavy doped side so it is going to be independent of N_A and so it depends on the doping concentration. So the higher doping concentration the space charge width is going to be less which means the capacitance is going to be more. So the capacitance increases for higher doping concentration and in this relation the capacitance so as you apply more and more reverse bias what happens is the space charge region widens. So w is going to become more and so the capacitance reduces. So this capacitance depends on the bias applied, reverse bias and it reduces for a reverse bias. You have the other capacitance that is the stored charge or the diffusion capacitance.

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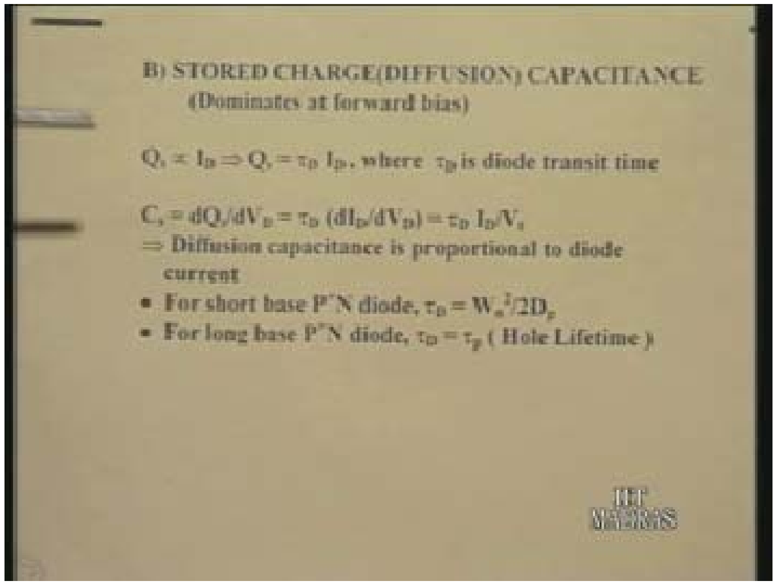

The diffusion capacitance what we have said depends on the stored charge in the semiconductor that is the mobile charges that is electrons and holes and it can be shown that this stored charge is proportional to the diode current because you see that the stored charge is proportional to exponential v_D by v_t minus one. That is you see that the minority carrier concentration on the depletion edges dependent on that, as well as the current is proportional to that same thing. So the stored charge is proportional to I_d and so you can write that Q_s is equal to tou$_d$ into I_d. This proportionality constant tou$_d$ is actually called the diode transit time. So it's a important parameter in a diode, it's called the transit time because it has got the unit of time and if you now obtain the stored charge capacitance c_s which is given by dQ_s by dv and you replace this I_d with the current expression in the diode that is I_s exponential v_D by v_t minus one, you get a relation like this.

So the stored charge capacitance is proportional to the diode transit time is also proportional to the diode current. So these are the two things it is proportional to, now this diode transit time which is related to the stored charge and the current is different for a short base diode and a long base diode.

For a short base diode this diode transit time is actually given by this relation which means that it is dependent on the length of the device that is W_n square by twice D_p. In fact it is proportional to the square of the length of the device and for a long base diode this diode transit time is nothing but the lifetime, the minority carrier lifetime. So this is a very important relation. Next we come to another important aspect of this diode operation which is very important for this course that is digital integrated circuits.

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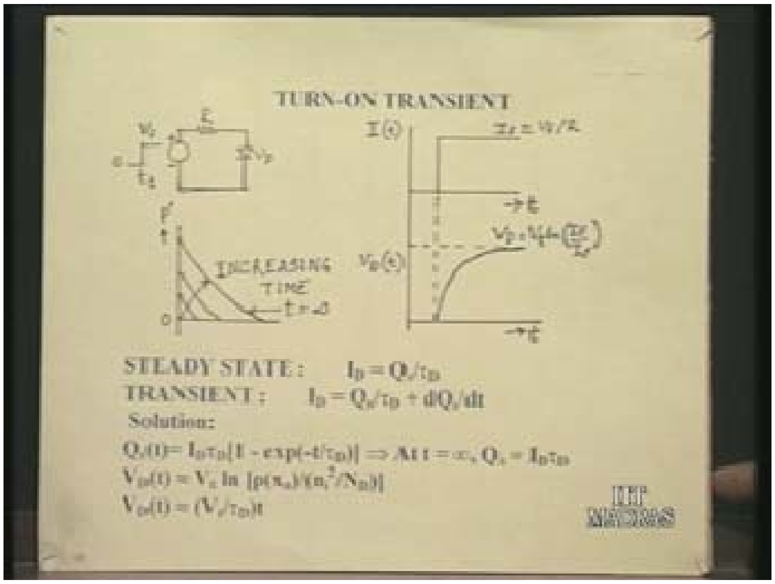

Because in digital integrated circuits you have voltages suddenly varying voltages applied to the device and the delays are dependent on how the device reacts to such transient situations. So this gives us the turn on transient of the device. Now suppose you have voltage source here, you have a diode here and you have a resistance here. Now suppose you apply a voltage which is say initially the voltage is zero volts. Suddenly the voltage changes to V_{F} at time t_{1} and this V_{F} is in such a direction that it forward biases the diode. So what happens is at time t_{1} the diode voltage is zero so the current is going to be almost equal to V_{F} by R, it just goes up V_{F} says a large forward voltage. So the current flowing in is V_{F} by R and then what happens is that is the situation which we are going to discuss now. Now in order to understand this transient analysis we have to understand these charge relations. We have seen in a diode, in a steady state the diode current is related to the stored charge by this relation I_{d} is equal to Q_{s} by tou$_{d}$ that is Q_{s} is proportional to I_{d}.

Now what happens in this transient situation that is once you suddenly apply a voltage? Now this relation must be modified by another relation like this I_{d} is equal to Q_{s} by tou$_{d}$ plus dQ_{s} dt. What does it mean? It means that say initially if you look at this initial situation the total charge is zero initially and then what happens is there is a current flowing in. What is current? Current is rate of flow of charge. So what happens to the charge stored in the device so initially I_{d} is equal to dQ_{s} dt that is the current is equal to the rate of increase in charge.

So as the charge is increasing Q_{s} is no longer zero it is also increasing. As this increases this term goes on increasing and what happens to this term dQ_{s} dt, it keeps on reducing because this total current which is the constant, the reason behind this is if you look at it why we put it as a constant is that when you apply a large forward bias the 5 volts and you have a diode like this in the forward direction. The diode voltage in the forward direction it can vary only by a small amount. I think I should have drawn that anyway. So this voltage is always much larger than the diode voltage so we can always say that the current flowing in is almost equal to V_{F} by R is a constant. So if you have a constant current here and the sum of these two components is a constant so as more and more charges are generated, this term goes on increasing and this goes down.

So finally what happens as this keeps going up I_d will be equal to Q_s by tou_d and then you have a steady state dQ_s dt is zero, so charge does not increase. So what happens is if you look at this charge profile again I think in this case we have taken up a p plus n diode. In a p plus n diode the stored charge in p plus side is going to be almost negligible, minority carriers. So we can only concentrate on the n side so initially the charge keeps building up with time and finally you reach a steady state which is what you expect when a current I_f is flowing, you will have a final stored charge and then that you reach finally. So this is the relation one has to take into account which basically says that if a current is flowing in Q_s by tou_d is the normal steady state relation that is when a current flows into a device it is just what is it doing is just for example a long based diode this tou_d is equal to the lifetime.

So the current flowing in compensates for the charge loss due to recombination. So I_d is equal to the charges flowing in compensates for the charge lost due to recombination. So if I_d is greater than Q_s by tou_d what happens to the excess charge it builds up, so it gives rise to an increase in charge. So this is the relation which we will always take into account for a transient situation for diode or transistors, It's a very important relation. So this equation has to be solved so when you solve this equation for Q_s with the initial condition that the charge is zero at time t is equal to zero you get a relation like this which says that at time t is equal to infinity Q_s becomes equal to I_d tou_d. That is what you expect finally, final steady state.

Now if your current I_d flowing the charge is given by this and then the diode voltage you know that this is the well known relation that basically you have written it in different form that the minority carrier concentration at the depletion edge is equal to the value at thermal equilibrium value into exponential v_D by $v_t - 1$. We have neglected the one when v_D is much greater than v_t and then if you substitute it here you get a relation like this which shows that initially it almost increases linearly towards v_D by v_t. Finally it becomes sort of saturates so the important point to note here is that when you apply a forward voltage to the diode, the charge is increasing and the minority carrier concentration at the depletion edge is related to the voltage across the diode.

Since the charge cannot increase instantaneously it will take time to increase the voltage drop across the diode also takes some time to increase because the minority carrier concentration is dependent on the voltage across the diode so the diode voltage goes up to its final value but it takes some time so this time is important it does not react immediately so this gives rise to a delay.

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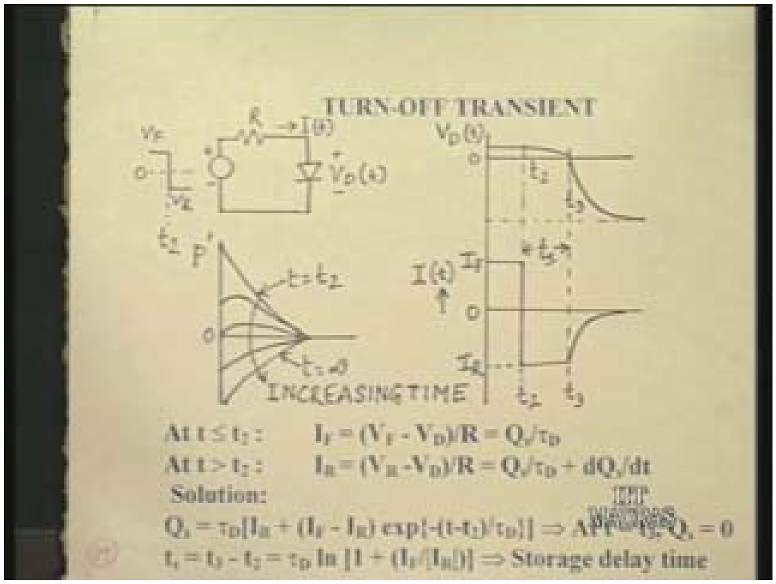

The turn on transient is not so serious but the turn off is more serious we shall see that. So what you have is now we had applied a voltage $v_{s.}$ forward voltage and you had a current flowing forward current flowing in the device and the diode voltage in the steady state it is $v_{D.}$. Then suddenly at time t is equal to $t_{2.}$ we change the direction of the voltage you apply a reverse voltage $v_{R.}$. This reverse voltage what do you expect when you apply a reverse voltage to a diode? The current should go to zero isn't it? In a diode the reverse current is zero but that doesn't happen that is what we are going to see. So again we have the same relations here in the steady state at time t is equal to less than $t_{2.}$. The forward current is given by $v_{F.}$ $-v_{D.}$ that is the diode voltage $v_{F.}$ $-$ $v_{D.}$ by R that is equal to $Q_{s.}$ by tou$_{d.}$. At time t is greater than $t_{2.}$ the reverse current is equal to $v_{R.}$ minus $v_{D.}$ that is the diode voltage divided by R and this is equal to $Q_{s.}$ tou$_{d.}$ plus $dQ_{s.}$ d t.

Now what happens is this $I_{s.}$ is negative, this reverse current is negative so you have the current because $v_{R.}$ is negative. So you have current flowing in the reverse direction so what happens is this $dQ_{s.}$ dt is going to be negative which means that the charges are going to be pulled out, so what ever stored charge is going to reduce. Initially we had this type of profile now as you have $dQ_{s.}$ dt is negative, the charge is going to reduce so it goes like this, with increase in time you see that the charges keep on reducing and as the charges keep on reducing what happens to the diode voltage? At $t_{2.}$ it is forward biased but you see it is going to only keep on reducing slowly because it takes time to remove all this excess stored charge. So again the charge depends on the voltage.
As the charge keeps on reducing the forward voltage keeps on reducing but one must realize that it is not a very fast process. That is you have for example when you forward bias a diode the minority carrier concentration increases by several orders of magnitude. It is proportional to exponential $v_{D.}$ by $v_{t.}$. So to remove a small amount of charge or in other words if you remove even a large amount of charges should say, the voltage drop is very small. The change in voltage is very small, isn't it? So even when

you have removed a large amount of charge the forward voltage has reduced by a small amount. So it takes a long time to remove this excess charge because even if you have 10 to the power 4 here you know the carrier concentration at thermal equilibrium it may go up to 10 to the power 12 or 13 or 14. So many orders of magnitude it can increase depending on the forward voltage at this edge but once you reach this point that is the zero point this shows actually the excess stored charge then the relation v_{D} becomes negative and once it becomes negative there is a small charge to be stored if you remove a small amount of charge, the voltage changes by a large amount. So once you reach this point the voltage is going to reduce very fast so what is happening is the diode voltage drops by small amount and then it falls very fast, we are removing this charge.

So what about the current which is flowing? The current is given by this voltage minus this diode voltage, applied voltage minus diode voltage divided by R. Now from this period t_2 to t_3 you see the diode voltage has been changed only by a small amount. So what about the reverse current? You are having a forward current, at time t_2 you apply a reverse voltage it becomes almost a large reverse current. See if you see that v_{D} is negligible compared to v_{R} you apply a large reverse voltage symbol minus 5 volts or minus 10 volts say, it will be almost equal to v_{R} by R and this is a large reverse current will flow in the device.

So a large reverse current is flowing in a diode. Ina diode when you switch off, you expect it to behave as a rectifier and you do not want any reverse current flow but you see in this case a large reverse current flows until the time t_3 and then of course it switch is off very fast because this voltage across the diode becomes negative, it tends towards v_{R} and as this tends towards v_{R} the drop across this resistance is almost zero. So the current actually falls to zero so finally the diode voltage becomes almost equal to the applied voltage. So this time is called the storage delay time that is the delay due to the stored charge in the device and basically it is the time required to remove the excess stored charge in the device when the diode was forward biased.

So when you solve this equation and with the initial condition that the initial stored charge is given by this relation Q_{s} initially is given by I_{f} into tou_{d} you get a relation like this and when you put at time t_2 is equal to t_3 the stored charge goes to zero. You can solve for t_s which is nothing but $t_3 - t_2$ which is the storage delay time t_s is equal to $t_3 - t_2$ and you get a relation like this. So it is proportional to tou_{d} which is the diode transit time obviously because the stored charge is actually proportional to tou_{d}. So if tou_{d} is larger you have a larger stored charge so you require more time to remove that charge and also the interesting thing is it depends on $1+ I_{F}$ by I_{R} ln of $1+I_{F}$ by I_{R}. So I_{F} is current when the diode was forward biased initially and I_{R} is the reverse current flowing in the diode this large reverse current which was flowing in the diode.
So if I_{F} was larger storage delay time would be more because initially we had large stored charge and if I_{R} is large, storage delay time would be less because this I_{R} the reverse current is the current which is drawing out the excess stored charge. Isn't it?

This initial you see I_R is equal to minus this dQ_s by dt so it is the current which is drawing out the stored charge. So if I_R was larger it would have removed the stored charge faster, so that delay time would be less. In fact if you see that I_R is then very larger you can neglect this term then stored charge would be zero. It depends on the applied voltages, this depends on the applied voltage say suppose you apply a very large reverse bias voltage. See this I_R is given by $V_R - V_D$ and I_F is given by $V_F - V_D$ now depending on the values of V_F and V_R it depends on that, so if you apply a smaller reverse volt say minus one volt or so this may not be very large whereas I_F, if you apply it depends on the forward diode current.

It could be a very large quantity so the point is you require a large reverse current to remove the charges faster but at the same time you would have to take into account that you would have a large reverse current flowing through the diode which you do not want also because I mean the diode is not supposed to have a reverse current. So it's up to you I mean what do you want, if you want to do it faster you have to have a large reverse current. So this is the turn off transient of a diode. So you see that it is very important aspect of diode switching and we shall also see how this is the same thing you know also manifests itself in a transistor where you have the stored charge delays.

Basically the delays are due to the stored charge in the devices bulk regions where especially it is important when you want to switch off a device because of the excess stored charge in the bulk regions and that excess stored charge has to be removed but there is so much excess stored charge it takes some time and that gives rise to delays. We shall see again, see about this when we go to a transistor how it also becomes very serious. With that we basically come to the end of discussion on diodes and then we shall go into transistors but before that I just want to tell you about another thing. Here what we have discussed is the p n junction diodes and we have seen that the current voltage calculations, the diode current versus the diode voltage if we plot on a linear scale it is something like this.

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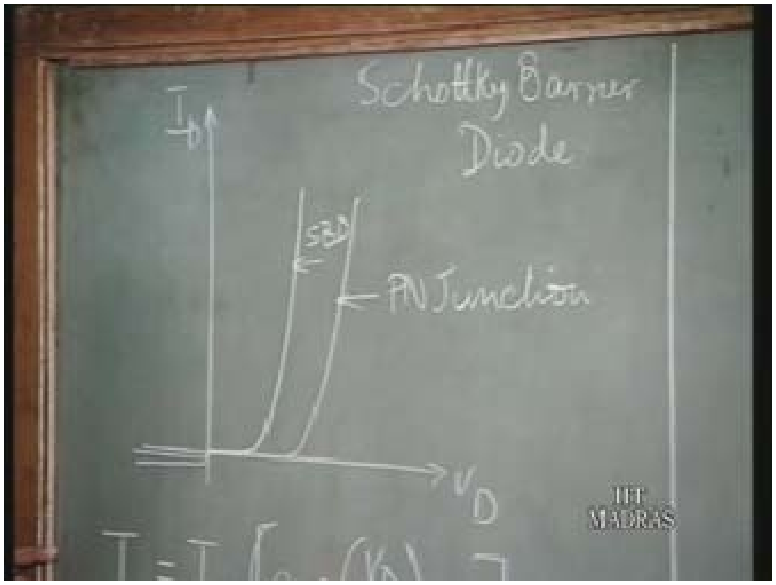

Now you have another type of diodes which is not a p n junction diode as such but it is formed by a junction of metal and the semiconductor. I would just like to introduce that which is called the Schottky barrier diode and which also has a similar relation for current just like a normal diode. Now this but the saturation current are much higher in a Schottky barrier diode compared to a p n junction diode. So in fact they are more than a few orders magnitude higher so how does it manifest itself in the current voltage relationship? So if this is for a p n junction, for a Schottky barrier diode the current voltage relationship is going to be like this. So the cut in voltage is a Schottky barrier diode is much less compared to the p n junction diode and the reverse currents for a Schottky barrier diode is going to be higher compared to the p n junction diode.

The Schottky barrier diode is formed as we said is a junction of a metal and semiconductor but it is all metals in junction with the semiconductor does not give a Schottky barrier diode that is to be remembered. For example aluminum in n type silicon gives a Schottky barrier but aluminum with p type silicon does not give a Schottky barrier diode but it is mode of ohmic nature that is there is no rectifying properties. So it is important to note that you do get Schottky barrier diodes with some metals and semiconductors but not always in all metals and semiconductors, in general when they form a junction they do not have a Schottky barrier.

So I wanted to introduce this so we shall not go into the details or theory of a Schottky barrier diode which is actually quite complicated but externally it is the current voltage relations are almost similar except for this difference the Schottky barrier diodes have a larger saturation current. This is in fact made use of in many circuits as we shall see when we go ahead. The next device which we shall take up quite logically is the bipolar junction transistor which actually consists of two junctions compared to a diode which has just one junction.

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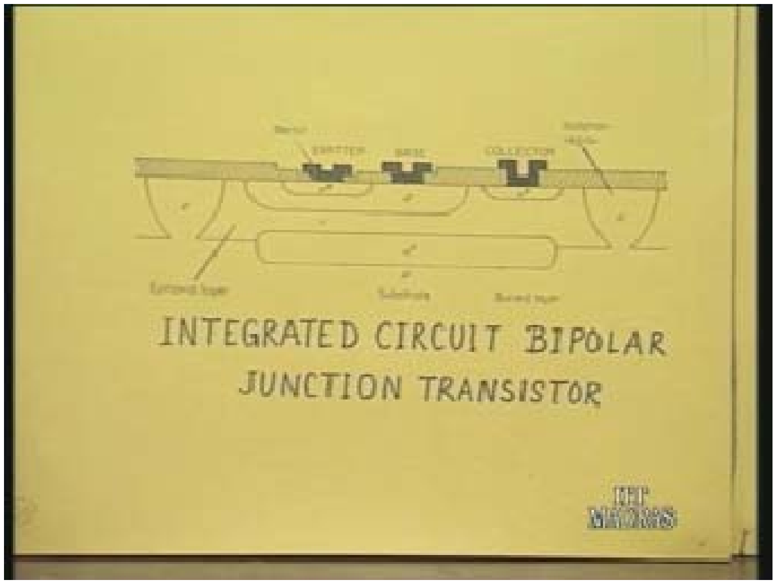

It is a three terminal device we shall actually take up the model of bipolar transistor in the next class but today I would just like to introduce to you the device structure. In this slide we have the device structure of an integrated circuit bipolar junction transistor. Now this integrated circuit bipolar bipolar junction transistor is different from a discrete bipolar junction transistor that means discrete means if you have one single device, it has to be different because in an integrated circuit you are fabricating a large number of devices simultaneously and the individual devices must be isolated. So that makes it structured slightly more complicated. So one must have in mind the actual structure of the transistor in order to understand a lot of things.

So here you see the basic transistor structure n p n, this is the basic transistor structure, you have the n emitter, p base and this n region is the collector from which the contact is taken here. So this is what called as a planar technology that planar technology means all the contacts are taken from the same plane, So which is essential for an integrated circuit. Now there are some other things which you can see here, you have an n plus here at the bottom that is called the buried collector. The purpose of this n plus region is that usually in a bipolar transistor the n region or the collector n region is the most slightly doped region in the device and which means that it is going to have a high resistance and this higher resistance gives rise to a series resistance which is going to affect the operation of a device, especially for digital circuits because in digital circuits when the output voltage should be low any series resistance would mean that the output voltage will not be as low as you expect and also for high frequency transistors this is also important. So this n plus, so the current in this device is actually going to flow down like this through the buried collector which is n plus it is a low resistance region and then into the collector contact.

Here you have an n plus here, the reason for this is because as we just said that a metal with n type semiconductor is a Schottky contact, rectifying contact but we want an ohmic contact so here the n plus the purpose of this n plus is to have an ohmic collector contact over here. Then you have these p regions so you see that the device is this transistor is actually sitting on an island with a p region see this is the p, the substrate is p this is p. So this region is embedded in a region surrounded by p regions. So usually what is done is this p n junction you see always the p n junction on all sides of device, this p n junction is reverse biased and this forms an isolation so this is an island which have a transistor you have similar islands on which you form other transistors and then they are interconnected from the top. So on the silicon these devices, all individual devices are isolated. This is a p n junction isolation which in fact is rather over technology.

Nowadays many other isolation mostly oxide isolation is taken care of is done which has many advantages but anyway the idea is important that you require an isolation and this is the structure of the device and you can see that many things for example one small thing to note is that this is the intrinsic device n p n but you have many other regions. For example you have this p region is essential for taking contact which is called extrinsic part of the device but it gives rise to stored charge in the device but it gives rise when you have stored charge in the base will also have stored charge here which is a parasitic effect. So in order to understand that working of the device one must actually have the idea of the total structure of the device. So we shall take up the modeling of the bipolar transistor in the next class.