

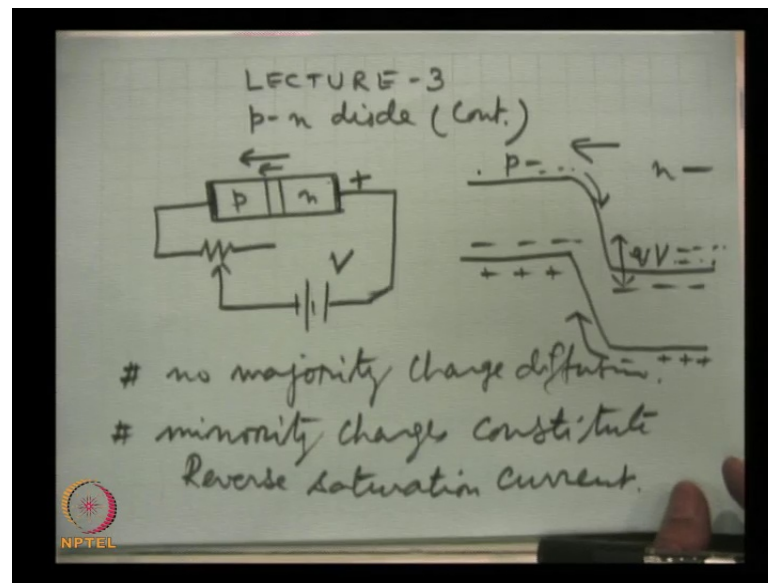
**Video Course on Electronics**  
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**Module No. # 01**  
**p-n Diode**

**Lecture No. # 03**  
**p-n Diode (Contd.)**

We will continue our discussion on p n junction under biased conditions. Biasing means that we apply a external voltage, and as we discussed there are two possibilities for biasing. One is the forward bias in which the a positive terminal of battery is connected to the p type material and n type material is connected to the negative terminal. And we have seen that the field which is applied has a direction, which is reverse of built in field, and as a result the potential height of the barrier falls. The diffusion of majority charge carriers electrons from n side to p side, and holes from p side to n side constitutes. What is known as forward current? Forward current increases exponentially as we increase the forward voltage, and the resistance of the device is extremely small of the order of 10, 20, 30 ohms.

Now, we will discuss about the reverse bias.

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The reverse bias circuit is, this is p type, n type, this is the junction, these are the only contacts and then we apply reverse bias  $V$ . Now look at this was the direction of the built in field and this is now positive, so this is the direction of the applied field, the two fields are in the same direction. As a result the potential barrier height goes up and the diagram becomes this. This is p types p side, this is n side and this is the Fermi level of p side and this is the Fermi level again they are separated. They were align together when there was a no applied field so this separation is equal to the energy equal to the applied voltage  $V$  and that is  $qV$ .

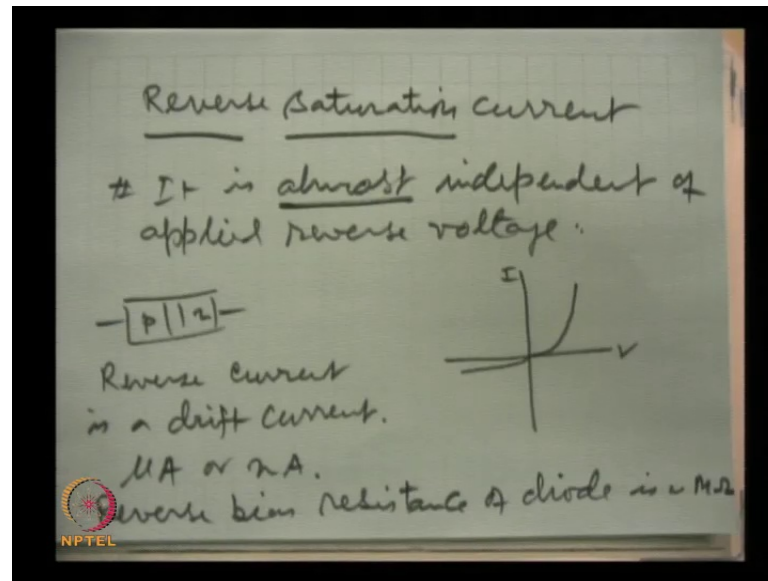
Now as it is evident that the potential height has increased and the majority carriers electrons here and holes here have absolutely no chance to cross over to the other side and so they are unable to diffuse. So, the first point we note that the majority charge carrier diffusion is not possible, no majority charge diffusion and hence the current component does not come from majority charge carriers. However look at what happens because p side the p semiconductor has electrons in minority and holes on the n side are in minority these charges will drift under the applied field mind it, this is the positive side this is the negative side and hence these electrons will drift under the field and as you will remember that this is also a downhill for holes. So, these minority holes from p side will drift under the applied field towards the p side.

So, these are the charges which are minority charges they constitute what is known as reverse current actually reverse saturation current. I will discuss. I will tell you that why it is very small and why it is voltage independent and on what factors does it depend now so minority charge carriers, minority charges constitute reverse saturation current. Now which minority charge carriers, the charge the minority charge carriers actually these are all thermally generated. Now the charges far away from the junction here, the electron here this region is p type which has majority of holes so it is very likely that the electrons in the p region when they try to drift under the applied field.

They will recombine there is a high probability of recombination for the electrons in the p region the electrons which are far away from the junction and similarly, the holes which are which are actually in almost uniformly throughout the material. So, the electrons in the n side which are far away from the junction they will again they will recombine in the n region with the electrons and they will not contribute to the reverse current, but within the diffusion within the depletion region or the electrons in the p side very close to the junction they will be able to drift.

Similarly, the holes which are very close to the junction on the n side, they will be able to drift towards the p side. Now the direction of hole movement is the direction of current the holes are move in this way. So, the direction of electric current is in this direction this is reverse saturation current. So, this is clear that the direction of this current is opposite to the current which was flowing in the forward direction in the forward bias case.

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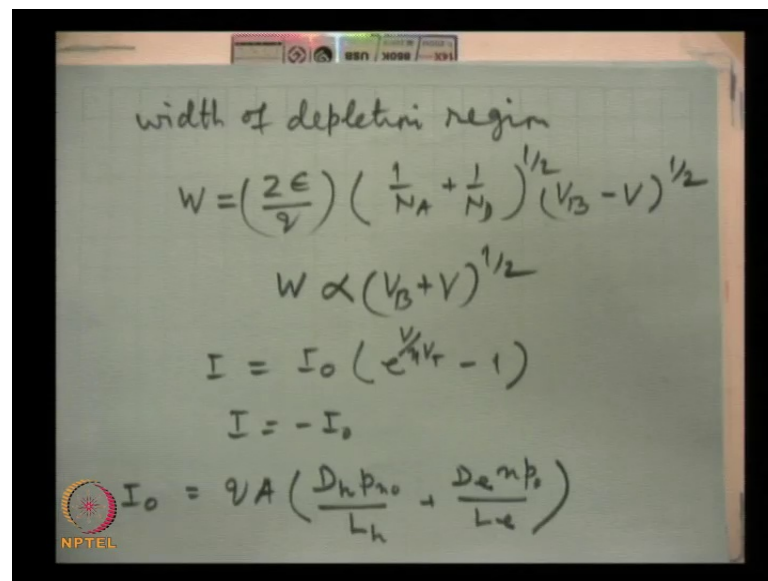
So, this is called reverse saturation current and that comes from the minority charge carriers and the p side the electrons and holes on the n sides which are within the depletion region or around the junction. Now this is we have said it is reverse and I explain that the direction of this current is reverse of the direction which of the current in the forward direction. Why it is saturation current? This is saturation current, because the numbers of this minority charge carriers that simply depend on the temperature. So, if we increase this reverse voltage further then we are simply changing this height more but that will not change the density of minority charge carriers are the number of charge carriers which are closer to the junction.

And hence reverse saturation current is a independent it is almost independent of applied reverse voltage. Why I have written almost that when you draw the actual characteristics I V characteristics in the reverse bias then there is every a small dependence on this voltage. This small dependence comes from the fact that there are defects on the surface of the device, and this gives raise to some movement of a charges and that constitutes that gives rise to this small voltage dependence on the reverse voltage. So, it has it should be now clear that what forms the reverse current, why it is called reverse and why it is saturation current.

So, this is and these are the I V characteristics, forward current was this and this reverse current is a drift current this is not diffusion, drift current and this is n micro amperes or

nano amperes very small, while this is normally in mille amperes this forward current. So, this is about this another very important point which we can derive from these reverse characteristics. That this when we change the voltage significantly there is a insignificant change in the current, that means that the reverse resistance is extremely high. While the forward resistance was just few tens of ohms this is normally in kilo ohms and mega ohms this is around mega ohms so very high resistance.

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width of depletion region

$$W = \left( \frac{2\epsilon}{q} \right) \left( \frac{1}{N_A} + \frac{1}{N_D} \right)^{1/2} (V_B - V)^{1/2}$$

$$W \propto (V_B + V)^{1/2}$$

$$I = I_0 \left( e^{\frac{V}{V_T}} - 1 \right)$$

$$I = -I_0$$

$$I_0 = qA \left( \frac{D_n p_{n0}}{L_n} + \frac{D_p n_{p0}}{L_p} \right)$$

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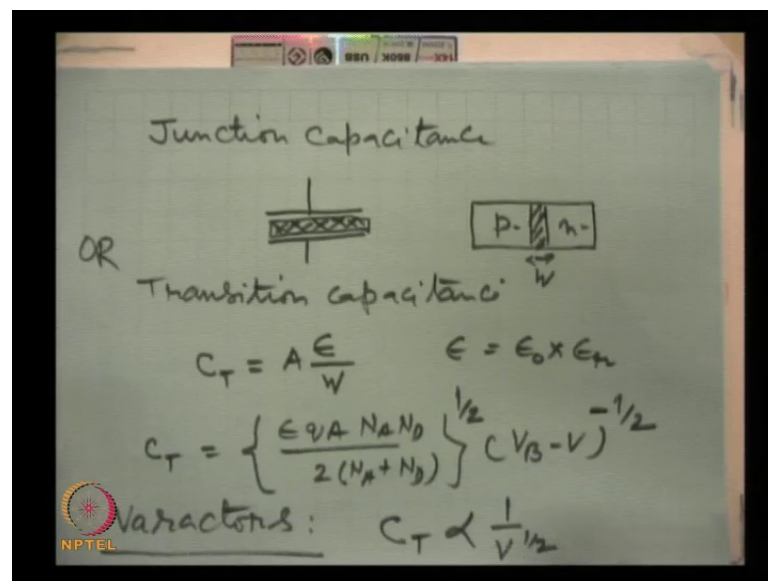
The width of the depletion region it was said earlier that it is a function of the applied voltage and this increases with the reverse bias voltage. As we increase the reverse voltage the depletion width increases the relation is this and we have to substitute voltage with proper sign. When this is negative then this is a this sign becomes plus and hence  $W$  the depletion width gets proportional to the applied voltage in the reverse bias. And physically you can understand that why it should increase because the reverse bias pulls away the majority charge carriers further away from the junction. And hence more ions those impurities ionized ions they will be uncovered and actually they form what is known as depletion region and hence depletion width increases with the reverse bias.

The  $I$  vs  $V$  characteristics as we were discussing earlier. I have given you the expression  $I$  equal to  $I_0 \left( e^{\frac{V}{V_T}} - 1 \right)$  here for reverse bias this voltage  $V$  will be negative and hence exponential term will be approaching 0 very quickly. So, this relation gives you  $I$  equal to minus  $I_0$  this minus sign is the direction of the reverse current

which is opposite to the forward current and if you go in the deeper physics of the device then this reverse saturation current is given by  $q A (D_h p_{n0} L_h + D_e n_{p0} L_e)$  where  $q$  is the charge  $A$  is the area of cross section higher will be the reverse current and  $D_h$  is the whole diffusion constant and  $p_{n0}$  is the whole density whole density on the  $n$  side that is minority density and  $L_h$  is the diffusion length of holes and these are the corresponding parameters for the electron.

So, this is all about the  $I$   $b$  characteristics of  $p$ - $n$  diode and the currents in the forward direction and the reverse direction how the depletion width varies with the applied voltage. It will decrease with the forward bias and it increases with the reverse bias and the resistance of the diode in the forward direction always remember is extremely small just few tens of ohms, but in reverse bias very high impedance of the order of mega ohms is obtained. Now there are several properties associated with the junction some of them we have talked the contact potential and the depletion width and so on.

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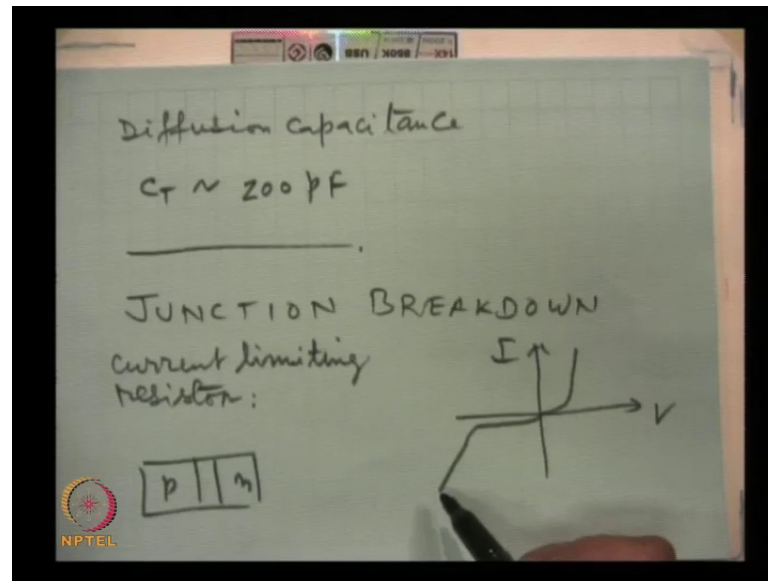
The next is junction capacitance. Junction capacitance here this is the  $p$   $n$  device. Now you will recall that this depletion region is a high resistivity region. It is like a dielectric insulator and the our conductivity or conductivity of  $p$  side and  $n$  side this is relatively several order of magnitude higher than the resistivity of the depletion, of the let us take in terms of conductivity that conductivity of these two regions is much higher than the

depletion region. So, this is almost like a parallel plate capacitor. What happens in a capacitor these are two conducting plates and separated by a dielectric? Dielectric is a high insulator so this is the insulator this is equivalent to the two conducting sides and hence p n junction must have a capacitance. And this capacitance is called transition capacitance junction capacitance or transition capacitance.

The simple parallel plate capacitor expression is  $C = \frac{\epsilon A}{W}$  where  $A$  is the area of cross section of the junction and this is the permittivity of this depletion region of the dielectric divided by the depletion width this permittivity is equal to permittivity of free space into the real part the dielectric constant which is around 11.5 for silicon. Now we actually even from regressive theory as you can find in several books like Milman and Halkias integrated electronics. The regressive theory also gives the relation for the transition capacitance which is this, while we can see that simple analogy of this junction capacitance with the parallel plate capacitor also results in same here  $W$  is the depletion width this is  $W$  and if we substitute the expression of the depletion width then it works out to be  $C = \frac{\epsilon A q N_A N_D}{2 N_A + N_D} \left( \frac{V_B - V}{V_B - V} \right)^{-1/2}$ . This is the expression for the capacitance and this is the function of the applied voltage.

Actually there are especially designed p-n diodes which are known as varactors, which make use of this property of the junction that its transition capacitance depends on the applied voltage. When in reverse bias when we take it with proper sign and because this is minus 1 by 2. So, capacitance you will find inversely proportional to almost 1 by  $V$  to the power half it falls so that especially designed diodes are known as varactors. there is a capacitance in the forward direction also that is known as diffusion capacitance.

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We now understand that when the diode is forward biased lot of majority charge carriers that is holes from the p side are injected to the n side and from the n region the electrons are injected into p side. So, depletion widths falls and have large currents flow, but there is a capacitance which is known as diffusion capacitance. Because depletion width is very small and the forward bias case so diffusion capacitance is actually very large. This is in the reverse bias the capacitance per unit area is of the order of 100 or 200 picofarads. In the forward bias this diffusion capacitance though it is high but, actually because of the heavy currents all effects are actually dominated by the current.

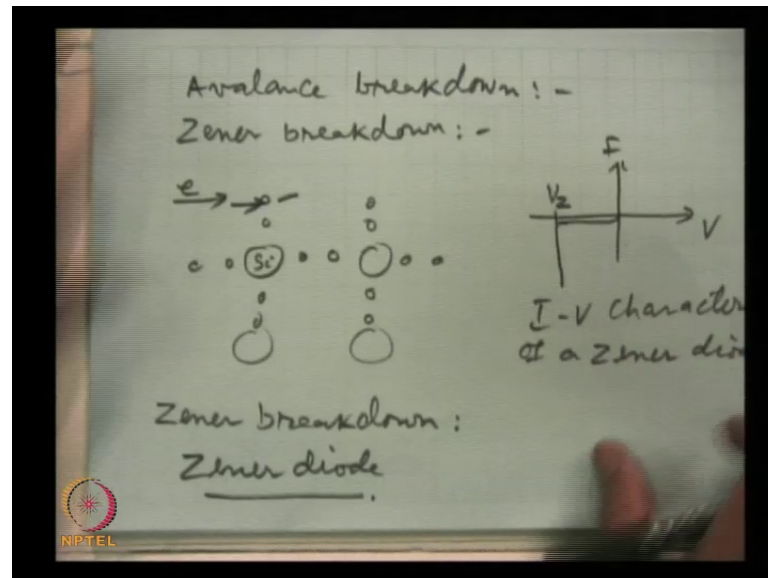
So, the diffusion capacitance does not play that important role as the junction capacitance or transition capacitance. So, this is about the junction capacitance. Now we take another aspect of the I V characteristics and of the device this is junction breakdown. Junction break down if we take a p-n diode and this is I, this is V and forward biased gives exponential rise in current. To limit the current a resistance is used which is known as current limiting resistor that will save the diode from burning because of heavy currents. And in reverse bias as I said the currents are extremely small these are in micro amperes and many times nano amperes.

But, if we go on increasing the reverse bias a situation comes that the current starts rising. This is because of the new phenomenon and that is known as break down junction break down. When we apply the field to a diode? Because they have relatively much



lower resistivity's as compared to the depletion region. So, almost all the field appears along the depletion region and this field as we increase the voltage say 10 volts, 5 volts and if you divide by the width which is of the order of 1 or 2 or 3 micro meters, then the field becomes kilo volts per centimeter which is very high field and that gives rise to what is called junction break down.

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I repeat if we increase, if we go on increasing the reverse bias across the junction is then normally we will absorb very small current, very feeble current in micro amperes or nano amperes which is 3 or 4 magnitudes lower than the forward current. But if we keep on increasing the voltage after a certain voltage the current starts rising and this happens due to another phenomenon which occurs and that is junction breakdown. Now there are two process of junction break down. One is a avalanche breakdown and the other is zener breakdown. What are these two processes? Yes first talk of avalanche breakdown, in the reverse bias mind it breakdown occurs in the reverse bias.

And if we go on increasing the applied voltage then field in the depletion region. As a result the thermally generated charge carriers in the depletion region and around that they get very high energy, they derive very high energy from the applied field and sometimes this energy become so high, that these charge carriers may make a impact on the bound electrons of the crystal and they will knock out those electrons. For example, we can depict like this that this is silicon atom and these are the bound electrons. These are all

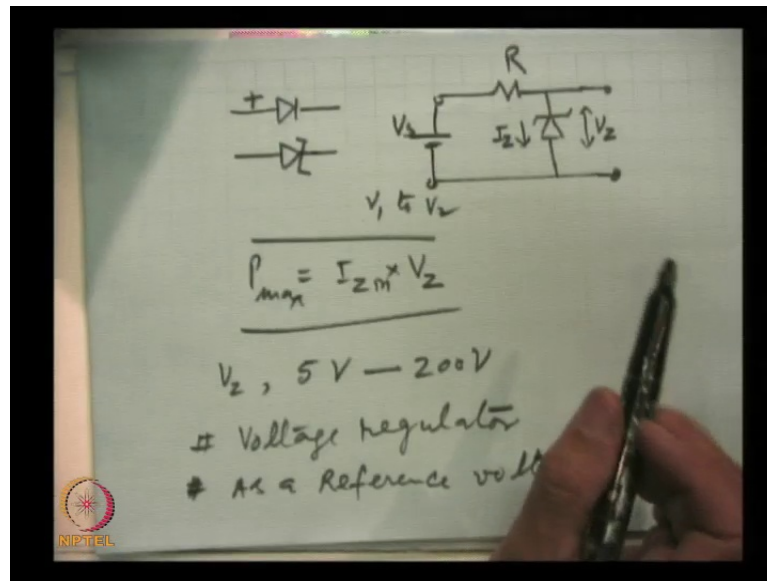
silicon these are the outer most electrons which are avalanche electrons and this is the highly energetic electron. This gains enough energy that it makes impact here and it is able to knock out this electron so that they become too not I mean they get multiplied and in the applied field is very high this continuous and quickly. Quickly means in a say micro second.

For example, we will be multiplied and the current will start increasing rising as we go on increasing the reverse voltage. Now this phenomena of breakdown has been utilized for a very good purpose and we will see that. Normally for a p-n diode this break down is very gradual but, by proper doping proper design of the p n junction we can make it that the breakdown occurs very sharply. So, here this is  $V$ , this is  $I$ , this is that reverse saturation current and then breakdown occurs at a well defined voltage which is known as a zener breakdown voltage.

Now these are the characteristics I V Characteristics of a what we call zener diode. This was the avalanche process which occurs when the thermally generated charge carriers acquire very high energies from the field and they knock down the electrons. In the zener process zener breakdown, in the zener breakdown the field there is no impact there is no collision but the field is so high in the depletion region. That electrons are ruptured they are pulled by the field itself by the influence of the field. The electrons are pulled out of the crystal and this way they are multiplied so this process is known as zener breakdown.

Now if you look at the expression for the depletion width, then we will see that when the two regions are highly doped p side and n side then depletion width is low. And that means the same voltage will give much higher fields and in the depletion region. So, the zener breakdown occurs in the diodes which are having high level of doping on the p side and n side. While avalanche breakdown occurs when the two sides of the diode are just not too heavily doped. But very important thing whether the process is a avalanche breakdown or the process is zener breakdown the diode is always called zener diode. Zener diode and remember that zener diode will have a well define breakdown voltage which is known as I said zener voltage breakdown voltage, zener voltage.

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Now the circuit symbol of the diode, simple diode the circuit symbol is this. This for ordinary diode and for zener diode this is circuit symbol. So, remember this little difference here that is that gives you that tells you whether the in the circuit design whether this is a zener diode or a simple diode. This is the higher voltage side when this is connected to p battery side, then the ordinary diode is forward bias, in the remember that zener diode is always operated in the reverse bias case. And the voltage has to be higher than the breakdown voltage that means in this region beyond this breakdown region it is operated. Now there are some interesting and useful properties of a zener diode, from this nee this is the current and voltage remains constant equal to the breakdown voltage.

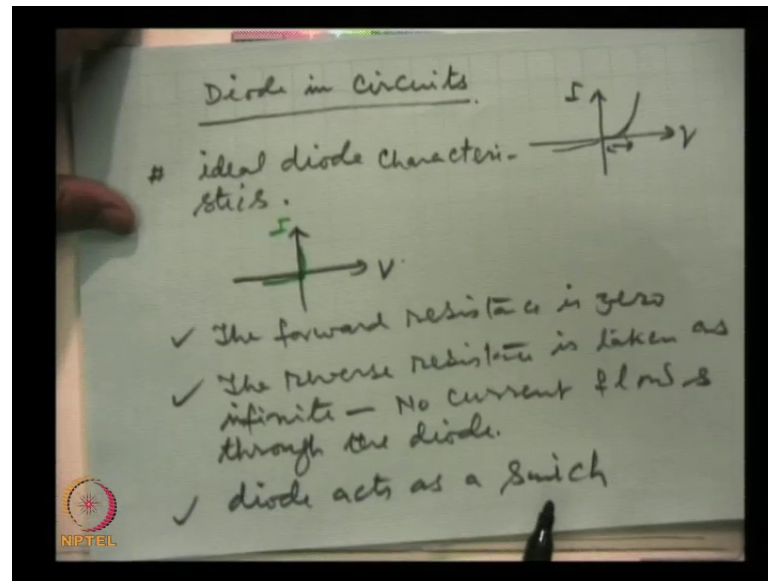
So, this is if we call, let us consider a small circuit. This is a resistance  $R$ , this is the applied battery and here is this current  $I_Z$  now this is a useful property of the zener diode that at through these different amounts of current were flows. But the voltage drop across this will remain same and this will be equal to  $V_Z$  the breakdown voltage. And how much voltage we can apply? If we change the voltage if this voltage change is from  $V_1$  to  $V_2$  both are higher than the breakdown voltage then the drop because the current will change from here to for example, the maximum current here which is  $I_{ZM}$  so much current will vary and hence the drop the extra drop the difference of the two will be across this resistance.

But this voltage across the zener diode remains constant. And this is very important and significant and what is the maximum power, maximum current that will be governed by this expression  $P_{max}$ . The maximum power for which zener can be subjected is  $I_Z m$  that is the maximum current which will flow through the zener diode and this is of course, the voltage is fixed. So, this should not be violated and what is the value of the maximum power which can which is can be applied across the which the diode will with this  $I_Z$  is given by the manufacturer and the data. So, this is about the zener diode always operated in the reverse bias.

And the if we change the input voltage but, this voltage but, the voltage across the diode is a that does not change that means fixed and equal to the breakdown voltage. There are different series, different types of zener diodes which are available ranging in the breakdown voltage from say 5 volts to almost few 100 volts there is a very large range of these voltages. And one of the biggest use applications of the zener diode is as a voltage regulator, that is in or reference as a reference voltage. There are many situations in electronics we required a reference voltage so that other voltages may be compared with the reference voltage and invariably zener diode of appropriate breakdown voltage, that will be the reference voltage and we can use this device conveniently.

Regulation becomes as I explained that if we change the voltage from  $V_1$  to  $V_2$  the currents will change passing through the diode. But the voltage will always remain equal to the breakdown voltage and the extra voltage the potential will apply will appear across the this resistance. Because  $R$  is a function of this various quantities of  $R$  will flow and larger of various currents will flow and higher is the value of current larger will be the voltage drop here, but here the voltage drop remains fixed which is which is equal to  $V_Z$ . This was a about the device and its physics the properties associated with the diode and now we talk of diode in circuits.

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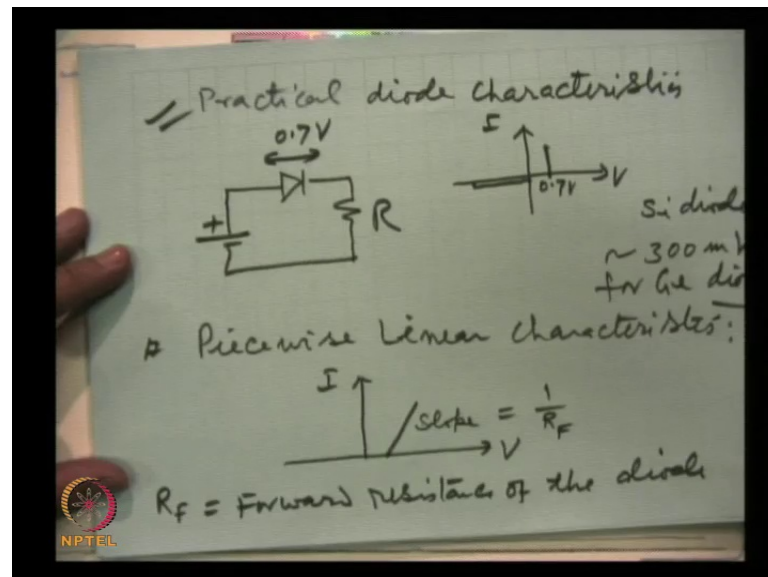
We have talked about I V characteristics and they were in forward bias they were like this. This is exponentially varying current, but when we talk of circuits then we have to approximate these characteristics. And so the simplest approximation is to treat the diode as having ideal characteristics. Now, we are talking of simple p-n junction. The zener thing we are finished that is a special diode used for regulating and as a reference voltage device.

This is the simple p n junction and we will talk about it is a circuit applications and before that we have to talk about the electrical behavior which is described by the I b characteristics. Actual one is this in the forward bias, but this makes analysis very complicated. So, we have to go for certain approximations and that we will see here so one is ideal diode characteristics here this drop of voltage across the device is assumed 0. So, the for ideal behavior the characteristics are these are the characteristics that means the forward resistance is taken 0 and the reverse that means in the reverse biased case.

The reverse resistance is taken as infinite and no current flows in the forward direction, the resistance is taken as 0 and in the reverse direction this is a very feeble current, but we assume because these are idealized characteristics. So, we assume that this current is a 0 and obviously the resistance of the device the impedance that will be infinite. So, these are many times the diode is treated as an ideal diode and we use these characteristics and we remember these things. So, that means when the diode it forward

biased it is almost it is a switch this is one state, the circuit short circuited here 0 current infinite resistances. So, the diode is in the off state here it is in the on state so this is the diode acts as a switch the ideal switch where forward resistance 0 and reverse current 0 like these are the highly idealized characteristics.

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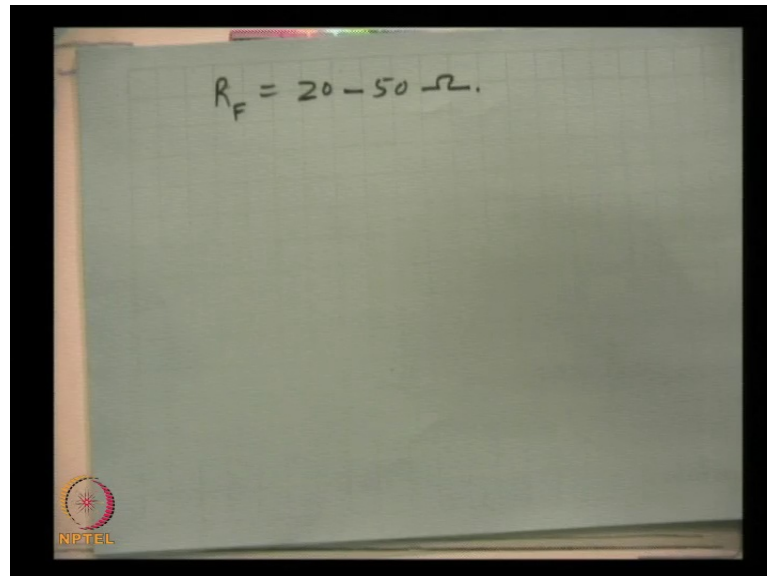


Practical characteristics are practical diode characteristics, these are like this and this is for silicon diode this is taken as 0.7 volts diode drop in the forward direction that means here this is the forward bias diode and when this voltage is above 0.7 or close to 0.7 then drop across this that is the meaning. When the diode is in on state practically we take if it is silicon diode 0.7 volts drops that means 700 mille volts for silicon diode and this is around 300 mille volts for germanium diode so this is these are the practical diode characteristics.

They remain the same that means in the reverse bias the current is 0. This is most widely used for any precise analysis of any diode circuit, these are the characteristics which are used of course, and for many applications even idealized characteristics are good enough. Now there is third characteristics which are called piece wise linear characteristics. And these are this where the slope, because you know there is a large variety of diodes having different characteristics. So, the forward resistance is also different for different type of diodes and so the slope of this slope is equal to 1 by  $R_F$

where  $R_F$  is the forward resistance of the diode and this is very low as it was said in the beginning. So,  $R_F$  is of the order of is varies from diode to diode from 20 to 50 ohms.

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So, these are the three kinds of a  $I-V$  characteristics which we take we make use in circuit analysis. And then before going for few other applications of the diode let us see that what we have said so far. When we bias the diode in the forward direction the current increases exponentially and the current should not exceed the maximum current, maximum rating as we call it as prescribed by the manufacturer for each number of the diode. We put a series resistance with the diode which is known as current limiting register and that will prevent the diode from damage.

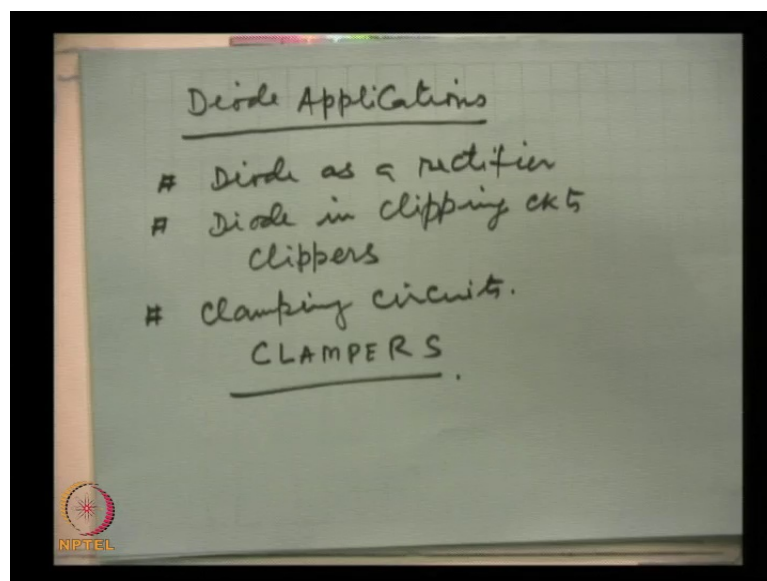
And when we reverse bias it then actually this the resistance of the device is very high. A reverse bias  $p-n$  junction will have very high resistance very high impedance and which is of the tune of 5 few mega ohms, and there are depending on the fact that how much precision we require in our analysis. I have given three different sets of characteristics. And the ideal characteristics these were the real  $I-V$  characteristics and these are the idealized diode and so the forward current was taken as a very high and the forward resistance was taken as 0.

While the reverse resistance was taken as infinity and in the practical diode characteristics these are the practical diode and forward bias, we take this exponential rise as a straight line and the voltage drop for silicon diode as a 700 mille volts or 0.7

volts and for germanium around 300 volts. There are three characteristics which are now called piece wise linear characteristics, for very precise value of for precisely analyzing any circuit we have to adopt for this third type of characteristics and here the slope will vary from diode to diode.

So, this resistance of this is we can find out from the slope, if we have the characteristics we can draw a tangent at the operating point and from that slope we can find the forward resistance. If we drop this tangent at different points of these characteristics slope will vary and hence the forward resistance will vary. And this will be high in this region here if we draw a tangent then if we draw a tangent here. So, actually the tangent is to be drawn at the operating point what is the range of voltages on for which we are operating the diode so actually these characteristics prove useful in that case.

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So, the slope is equal to  $1/R_F$  we will continue now with the diode applications in circuits, these diodes diode applications different kind of circuits are there which make use of these diode properties, and we will be discussing them one by one. So, some of the applications which we will cover these are diode as a rectifier, diode in clipping circuits which are known as clippers and clammers. Clamping circuits are simply clammers. And these we will be studying one by one and then we will start the next unit which will be on transistor and our knowledge will this diode knowledge will be very useful in that case also.