Power Electronics

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Lecture - 4

Hello, in my last class I told you some of the very important applications of power electronics and some of the significant events in the history of power electronics till 1957, the year in which silicon controlled rectifier or thyristor was invented. As I go long, of course I will tell you the other significant events and we started discussing about the power semiconductor devices. I told you that power semiconductor devices are heart and soul of power electronic equipment. These are used as switches that means when they are on, we need to operate them in saturation and when they are off, we need to operate in: sorry, when they are off, they are in cut off region.

There are three types of switches. One is an uncontrolled switch, uncontrolled because whether a switch is on or off it depends on the circuit operating conditions. Say, diode for example and there is a semi controlled switch. A silicon controlled rectifier or thyristor is a semi controlled switch because it can be turned on by supplying some current to the gate or to the control terminal. But then, having turned on the device, you cannot turn it off using the gate.

Now, the SCR which is conducting, it turns off depending upon the circuit condition. If the current becomes zero in the circuit, thyristor will turn off and third one is a controlled switch. It can either turn it on or off using the control terminal. Say bipolar junction transistor, by supplying a base current, you can turn it on. You make i_b is equal to zero, base current zero, transistor turns off. Now we will study the various devices in detail.

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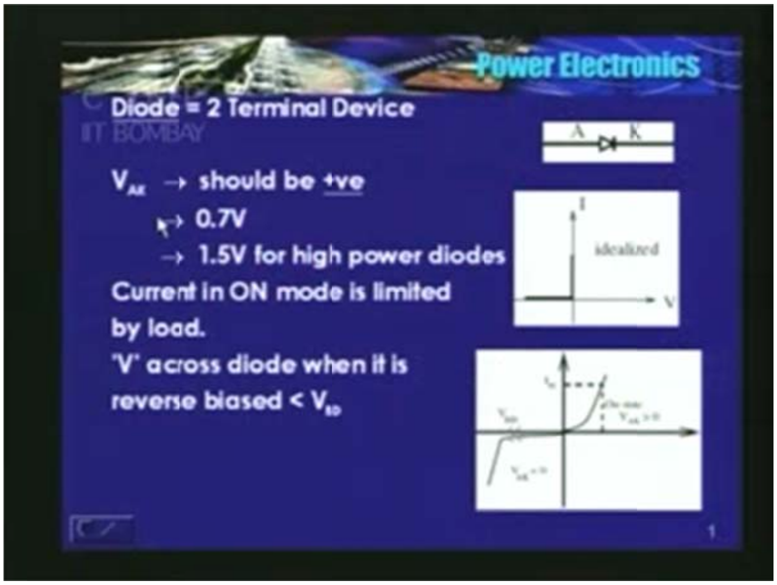

First one is diode, a two terminal device. All of us know, we have been studying may be since the class eleven, anode and cathode. So if V_{AK}, voltage across the diode V_{AK}, should be positive then it is said to be in forward bias mode and diode starts conducting. So for a silicon diode, a low power diode, it could be, V_{AK} could be of the order of 0.7 volts or so and this value increases as the power rating increases. Say, for a power diode it could be of the order of 1.5 volts or so and when the diode is on, all of us know that current in the circuit is limited by the load. See the ideal characteristics are along the y axis. That is, it can carry any current assuming which is less than the rated and it can block a negative voltage, it cannot a block positive voltage. These are the characteristics of a non ideal diode. May be, a cut in voltage somewhere at this point and this the current that is limited by the load. This is forward biased and this is during reverse biased mode, V_{AK} is negative.

Now as long as the applied voltage is less than V_{BD}, see V_{BD} is this point, break down, junction break down, diode will block that voltage. In other words, the maxim reverse voltage that is applied across the diode should be less than V_{BD}, we need to ensure that. Say, the input voltage is 230 volts, so negative peak is going to be 230 into root 2. So, the voltage rating of the diode should be higher than 230 into root 2, if you are using in a single phase circuit assuming that load is a passive one.

But then, if the applied voltage is higher than V_{BD} and if you are not able to control the current that is flowing, then the device will get damaged. Remember, if the applied voltage is higher than V_{BD} and you are not able to control the current that is flowing through the diode, it is going to be destructive. It is going to be destructive. So, during on state, there is a finite voltage drop across the diode. I will call it as V_f and I_a is the current that is flowing through the diode. So, on state loss or the conduction loss is given by V_f into I_a that depending upon V_f and I_a. The magnitude of V_f and I_a say, if it is higher than a certain value, you need to go in for or you need to mount the diode on a heat sink. Invariably power diodes are mounted on a heat sink. A small signal diode, it would not need to or generally is not mounted on a heat sink.

Now, all of us know the on state behavior of the diode. Now, in the power electronics circuit, in the off state, the diode, the way it turns off is a bit important. Why so, I will tell you.

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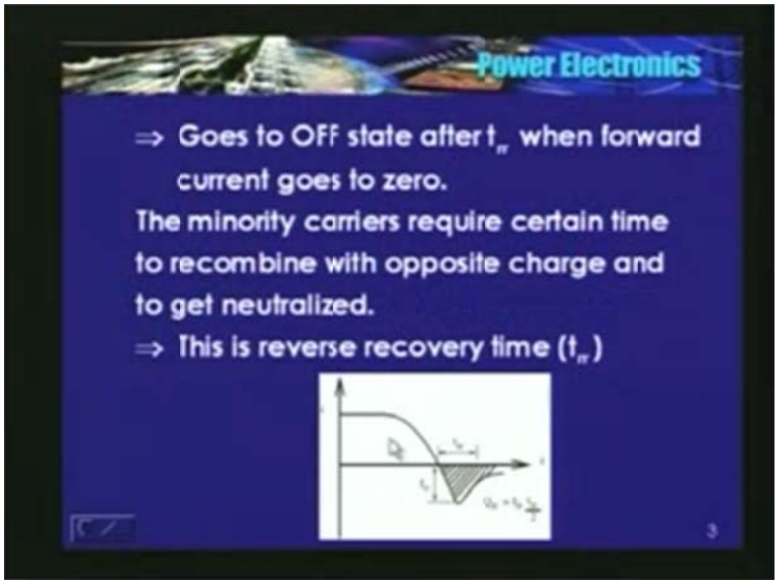

See, when the current in the circuit, of course this is the current that is flowing in the circuit depending upon the input voltage or so current starts following. At this point, current becomes zero but the diode continuous to conduct. A reverse current starts flowing till, say t_{rr}, that is because the minority carriers they require a certain time to recombine with the opposite charge and to get neutralized. I will repeat, the minority carriers which are there they require a certain time to recombine and that takes place in the time t_{rr}. trr is the reverse recovery time. It is a time from this point, the first zero crossing to say 25% of the maximum value of the current that is flowing in the reverse direction. So, the maximum value of current in the reverse direction is i_{rr}.

So, trr is the time from this point to say 0.25 of irr. I am assuming that this point is 0.25 of rr and this current is the leakage current which is very small and this is the charge, reverse recovery charge. Now, what is the reverse recovery charge? It is the area of this plot. I am assuming that this is a linear one. I am just determining the area of the triangle to find out the reverse recovery charge. The area of this shaded part is nothing but i_{rr}, is a peak into t_{rr} divided by 2. I am assuming this to be a triangle one, area of the triangle. So, reverse recovery time and reverse recovery charge, they are very important, two important parameters. Why are they important?

See, even the current has become zero it continuous to conduct for or goes to offset only after $t_{rr.}$ So if the circuit in which the frequency of operation is very high, this t_{rr} will play an important role or in other words t_{rr} will determine the upper frequency of operation and this q_{rr} or the reverse recovery current, it is flowing in the opposite direction, it is flowing from cathode to anode. See this current is flowing from cathode to anode so either it has to flow to the source or it may have to flow through other switches. Those switches have their own current carrying capacity. So, in addition to the load current, that device may have to carry this reverse recovery current.

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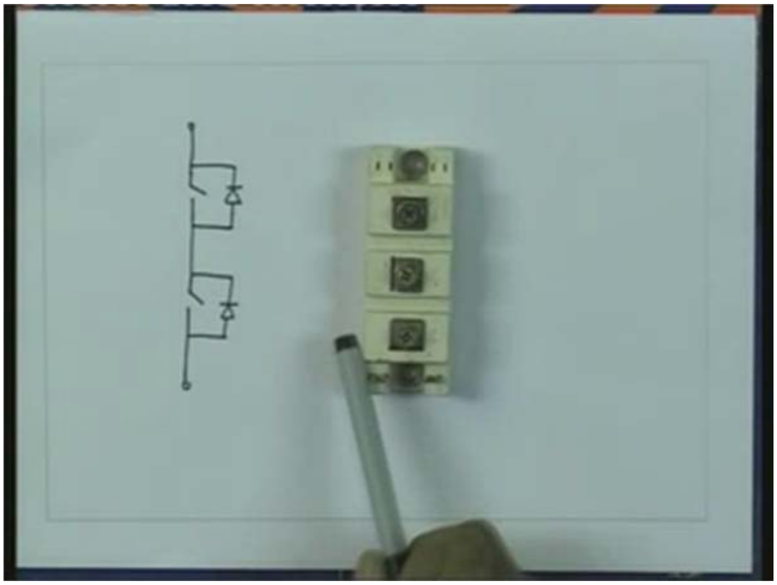

See, yesterday I showed you this power module. I said, there are two control switches. The name of the switches, I will tell you sometime later and in parallel there are two diodes. These are the two diodes, this module has. The current rating of this, each diode is 75 amperes and it can block 1200 volts.

The reverse recovery time of this diode is of the order, say 0.2 micro second. That is what the specifications, the data sheet says. It could be of the order of 0.2micro second and depending upon the junction temperature, q_{rr} the reverse recovery charge is of the order of 1 micro Coulombs. This is all given in the data sheets. So, what about the other ratings? important ratings of the diode. What are the other important specifications of the diode?

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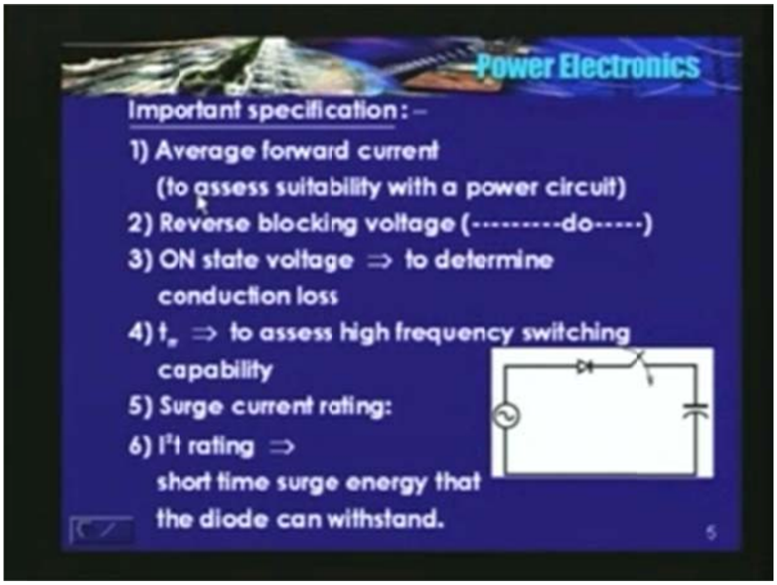

They are; one is average forward current, see here, it is required to assess the suitability with the power circuit, so depending upon the input voltage, the load and the duty cycle. So average current can be determined, I am saying duty cycle because diode may not conduct for the entire cycle. The second point, reverse blocking voltage, the reverse voltage that is appearing across the diode should be less than the break down voltage. Third, on state voltage drop, it is required to determine the conduction loss and therefore the heat sink size or the cooling requirement. The fourth one, t_{rr} reverse recovery time of the diode is another very important factor in the diode used in high switching applications or it is required to assess the high frequency switching capability.

The fifth one is the surge current rating. To explain this, consider this circuit. What I have done is there is an ac sinusoidal source, diode. I am connecting a switch and a capacitor, the remaining part I have not drawn. Usually that capacitor is completely discharged and I close the switch at omega t is equal to pi by 2. At omega t is equal to pi by 2, input voltage set the positive peak. Capacitor voltage is zero and it cannot change instantaneously. So what happens when I close the switch? There is going to be a large inrush current. Why? Input is at the positive peak and the output voltage is zero and that large inrush current has to flow through the diode and it has to withstand that current and let me tell you that this surge current is much much higher compared to the average forward current.

May be sometime later, I will show you a data sheet wherein as a average forward current, RMS current and surge current ratings are given. Next one is I square t rating, current squared time rating. It is an indication of or it is the short time surge energy that the diode can withstand. This is required to choose a suitable fuse in the diode circuit. When this is important? So take this example, I have a input AC source, a diode and a capacitor. Now I have not drawn the remaining part of the circuit and I have a switch here. Something may be a main switch or so.

Assume that I am closing the switch at omega t is equal to pi by 2 or in the positive peak. Capacitor is totally discharged, in other words there is a short circuit here. Capacitor voltage cannot change instantaneously. Voltage at this point is instantaneous value is at the peak and we have closed the switch at that time. What happens? A large surge current will flow because voltage across the capacitor cannot change instantaneously. It was zero just prior to closing the switch. This is at the peak, you have closed the switch. A large surge current will flow and diode should be able to withstand this surge current which is higher than the average current rating. So that is about the diodes, the so called uncontrolled switch.

Now, what are the various types of diodes? The first one is a rectifier diode or a slow diode. They are suitable for line frequency application, so you want to rectify the input AC which is 50 hertz. So you can use the conventional slow diodes or rectifier diodes. The reverse recovery time is generally is not specified, they are basically slow diodes. So, the maximum rating is of order of 6kv, the diode can block as high as 6kv and current rating is of the order of 4500 amperes are available. I will repeat, diode which can carry say, 4500 amperes of current and can block 6kv, they are available. These are conventional rectifier diodes or slow diodes.

There is second type the one known as the fast recovery diodes. Fast recovery diodes, these are generally used in high frequency application. Sometime later in the course, we will find that fast recovery diode should be used in the circuit. You cannot use the conventional rectifier diodes. So, the rating is of the order of say 6kv and current of the order of 1.1 kilo ampere. They are available in the market, 6kv it can block and current ratings, 1.1 kilo amperes and the reverse recovery time could be of the order of say, 0.1micro second, could be. I am not saying that 6kv 1.1 kilo diode, has a reverse recovery time of 1.1micro second, no. The reverse recovery time of a fast recovery diode could be of the order of say, 0.1micro second. Just now, example which I showed you is of the order of 0.2micro seconds.

The third one is the short key diodes. What are the features? They have a very low on state voltage drop basically these are only majority carriers. Current only due to majority carriers but then the voltage rating is low. Maximum voltage rating is of the order of 100 volts or so and current is of the order of 300 amperes and the last one, the fourth one is what is known as the silicon carbide diode.

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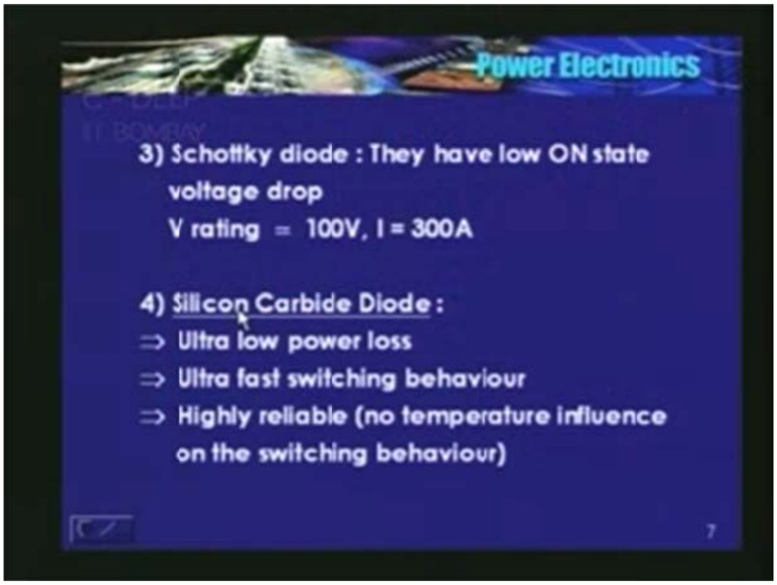

They have ultra low power loss. See, Schottky diode has a very low on state voltage drop. That is what I told you. Therefore on state power loss also is low but silicon carbide diode, it has an ultra low power loss, ultra fast switching behavior, very fast diodes, highly reliable, no temperature influence on the switching behavior, looks like we are etching almost everything in silicon carbide diode. Ultra low power loss, ultra fast switching behavior, highly reliable and what is the problem? Why are they not very popular? You find only silicon diodes not silicon carbide diodes. The limitation is they are very expensive. The process is also very expensive, that summarizes.

Just coming to the second type of switches, semi controlled switch, a thyristor or a silicon controlled rectifier. The moment I said semi controlled device, it has to be a three element device; anode, cathode and gate. Anode and cathode, they form the power circuit terminal, they are connected in series in the power circuit and the gate current is supplied with respect to or gate signal is applied with respect to the cathode, say something like this.

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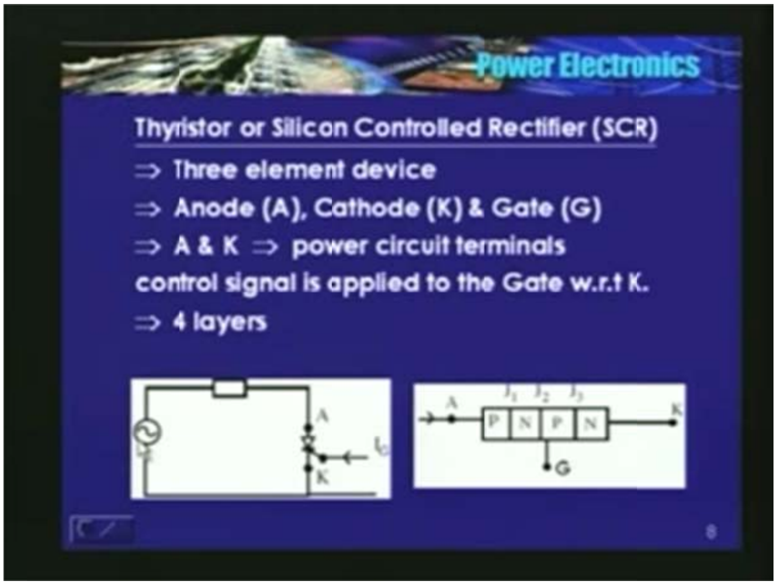

Our source, as I have shown you, a AC source, a load and a thyristor. So, this is the symbol of a thyristor diode with a small gate line here, anode, cathode and gate and can be controlled or can be turned on using positive gate current I_G or control signal is applied with respect to the cathode. There are 4 layers say, P N P N and therefore there are three junctions J_1, J_2 J_3. P N P N; first P is anode, N is cathode and the gate is connected to this P. This is the gate.

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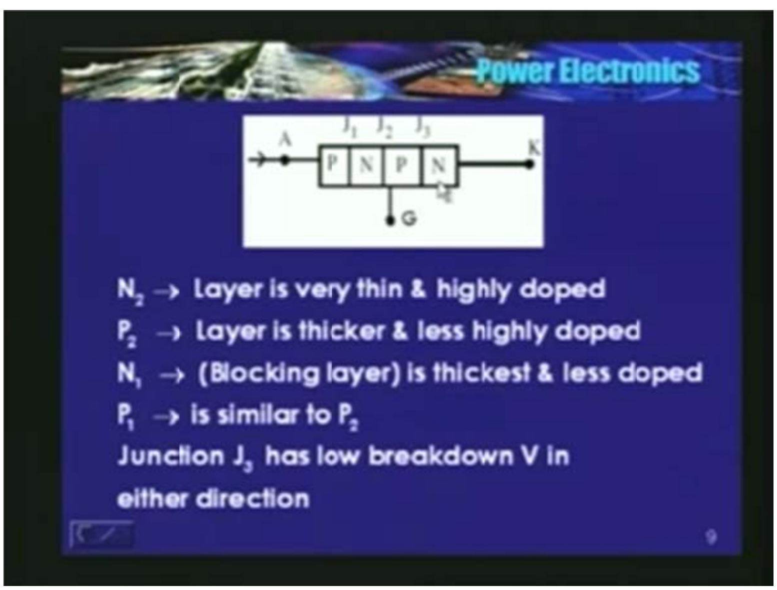

N_2 or this layer is very thin and it is highly doped. This N layer is very thin and it is highly doped. I will call this as P_2, this layer is thicker than this or thicker than N and it is less highly doped. N_1 is the thickest of all, this N is a thickest of all and it is less doped. Highly doped, less highly doped, less doped. Doping level is very low in this and a very thick layer and this P is same as this P, slightly thicker and less highly doped. So, therefore J_3, see N is very highly doped and a very thin layer, this P is relatively highly doped and slightly thicker. So, junction J_3 has a very low breakdown voltage in either direction, something similar to base emitter junction in a transistor.

Base emitter junction in a transistor is lightly low, very highly doped. So, it cannot block a voltage in either direction, in the sense it can block a very low voltage. In the class, may be small signal diode, you need to apply a 0.7volts to the base to turn it on and reverse voltage it can block is very low, very small. It cannot block a very high voltage. So, therefore J_3 cannot support high reverse voltage, cannot support a very high reverse voltage.

Now what are the various characteristics when V_{AK} is positive? In other words, the device is forward biased and the current is zero, the device current or the current that is flowing from anode to cathode is very small, the device is said to be in forward blocking mode. I will repeat, device should be forward biased, V_{AK} is positive, a very small current equal to the leakage current will flow through the device. So, this mode is known as forward blocking mode. Now, what happens in forward blocking mode? There are three junctions J_1 J_2 J_3.

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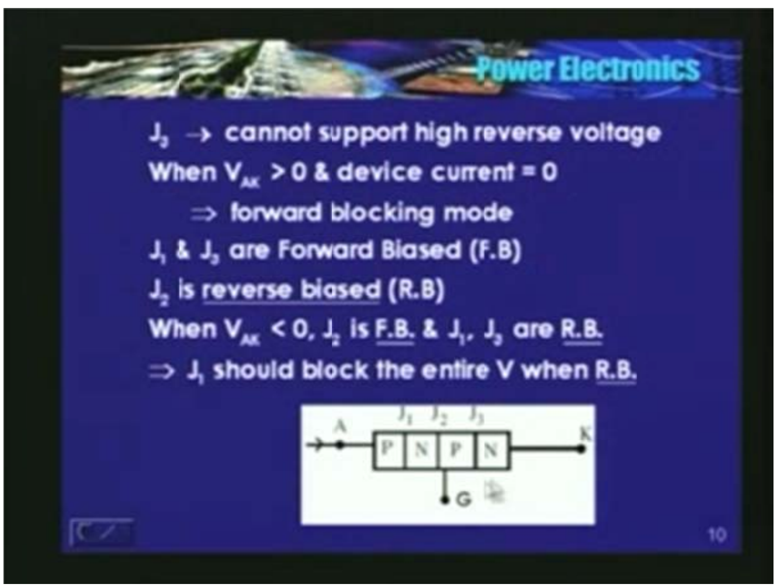

I said V_{AK} is positive, see look here, V_{AK} is positive. So P is connected to, as said, positive of the battery. N is negative, so definitely J_1 is forward biased and J_3 is forward biased. Junction J minus forward biased, J_3 is forward biased and J_2 is reverse biased. So, in the forward blocking mode, junction J_2 is reverse biased. So the entire voltage appears across J_2.

Now, what happens when the devices in reverse biased mode? When the junction is, when the V_{AK} is negative, something similar to the diode, V_{AK} is negative, at that time J_1 and J_3 are reverse biased. See, when V_{AK} is positive, J_1 and J_3 are forward bias and J_2 is reverse biased and when V_{AK} is negative, J_1 and J_3 are reverse biased and J_2 is forward biased.

In the forward blocking mode, since J_1 and J_3 are forward biased, the entire voltage appears across J_2 or J_2 should block the voltage in the forward blocking mode, remember.
Now, when at the device in reverse bias mode, J_1 and J_3 are reversed biased. But I told you that J_3 cannot support a high reverse voltage because N_2 is very thin and it is highly doped. So, therefore when it is reverse biased, entire voltage should be blocked by $J_{1.}$

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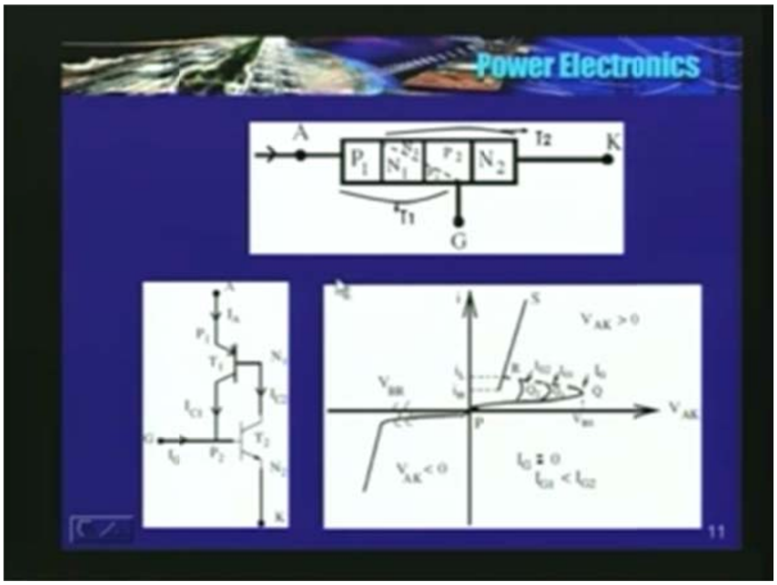

Now I will show you the characteristics. Before that maybe, I will try to show you the two transistor analogy. See, I told you there are 4 layers, P_1 N_1 P_2 $N_{2.}$ Now, what I will do is, I will cut this and this. Say, $N_{1,}$ $N_{1,}$ $P_{2,}$ $P_{2.}$ Now, what is this? Say, here $P_{1,}$ N_1 and $P_{2.}$ Now this forms a PNP transistor. See here, $P_{1,}$ N_1 and $P_{2.}$ This is $P_{2,}$ a PNP transistor and again here I have $N_{1,}$ $P_{2,}$ N_2. It forms a NPN transistor. See here, NPN transistor.

Now how do I interconnect T_1 and T_2? Base of PNP transistor, say, base of T_1 is same as collector of $T_{2,}$ NPN. Base of T_1 is same as collector of T_2 and collector of T_1 is same as the base of T_2 and this is the gate terminal. So, there is a PNP transistor, PNP, NPN transistor, NPN transistor inter connect them. Base of PNP is same as the collector of NPN, collector of PNP is same as base of NPN. So, this is anode, this is cathode, this is gate and here are the SCR characteristics, I will explain to you now. In the reverse bias mode, characteristics are almost similar to that of a diode, almost similar. $V_{BR,}$ reverse break over voltage, so you should ensure that applied voltage is less than $V_{BR.}$ Same thing, for diode I called as V_{BD} and here I am calling as V_{BR}.

In the forward bias mode, if the current is very small that is equal to the leakage current, I told you the device is in forward blocking mode, again it is stable that corresponds to P to Q or P to Q_1or P to $Q_{2.}$ Assume that you are not supplying any gate current, as of now the gate is open and the device is forward biased. When the device is forward biased J_1 and J_3 are also forward biased. Junction J_1 and J_3 are forward biased and J_2 is reverse biased. So, when it is in forward biased mode the entire voltage J_2 blocks and in case the applied voltage is higher than the break down voltage of the junction $J_{2,}$ device goes into conduction mode.

I will repeat, I assume that gate current is 0 and if the applied voltage is higher than $V_{BO,}$ see here V_{BO} with I_G is equal to 0. V_{BO} that is break over, forward break over, what happens? Device goes into conduction mode. But then how does it go? In what is the path that does it takes? I told you that just prior to device goes into conduction mode, the voltage is may be, approximately equal to $V_{BO.}$ It is high the moment the device goes into conduction mode. The voltage will drop to a very low value. It could be of the order of say 1.5 volts or so 1.5 to 1, 2 volts. Till 0 to $V_{BO,}$ current that is flowing is very small. It is equal to the forward leakage current.

Once the device is in conduction mode, current is limited by the load. Now, what path does it takes? It was blocking a relatively higher voltage, the moment it goes to conduction mode voltage drops to a very low value, the paths taken by this is this. I have shown this is to be dotted one. Why did I show this to be a dotted? Why it is not firm like P to Q? Why it is not firm? This is because this region is an unstable region. Why it is unstable? because it is a negative resistance region.

See, voltage is falling, current is increasing, the slope of this line is negative resistance region. So, it is unstable and it goes to, see, RS is the forward conduction mode, current, the operating point here depends only on the load and now see, there is a third element what is known as a gate and therefore by supplying the gate current it should be able to trigger the device. So, definitely with the finite gate current, the voltage at which it goes to conduction mode should reduce. So see, as the gate current increases, the voltage at which device goes into conduction mode also drops.

$I_{G0,}$ so voltage applied should be higher than V_{BO} forward break over, V_{BO} is forward break over. So, with the finite $I_{G1,}$ device goes into conduction mode at a relatively lower voltage and if I increase I_G further, it goes to conduction mode somewhere at this point, say PQ for 0 $I_{G,}$ P_1Q_1 for some I_{G1} which is less than I_{G2} and for that the path is PQ_2 and once the device current is higher than the latching current, gate has no control. So I will repeat, by supplying a positive gate current, device goes into a conduction mode and by supplying a gate current the voltage at which device goes into conduction mode also reduces.

But then, the gate signal should be present till the current through the device is higher than the latching current. The device should be able to latch, till then gate signal should be present and having gone into conduction mode, the gate has no control. You can withdraw or you can make I_G is equal to 0. In fact, it is advantageous to make I_G is equal to 0. Why? Gate has no control, if there is a constant I_G flowing, definitely there is going to be a dissipation in that junction. So, in a way, it is an advantageous to make I_G is equal to 0. Once the current through the device is higher than the latching, because having gone into conduction mode if the current is higher than the latching, gate has no control and you can withdraw the gate signal.

But then to turn the device off, current through the device should fall to a value which is less than the holding current. Somewhere here, see here, I_H is the holding current. So, to turn off the device, I will repeat, the current that is flowing through the device should fall to a value which is less than the holding current. How does it happen? We will see, whether it happens naturally or do we need to do something different to reduce this current. We will study during appropriate time. So, that is about the SCR characteristics. This is all the explanation that I have given.

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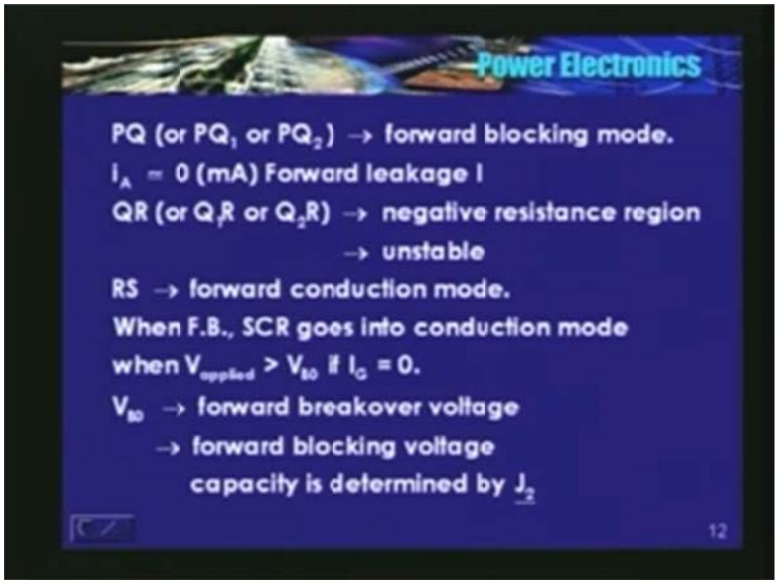

See, V_{BO} is the forward break over voltage and this voltage is determined by, V_{BO} is determined by J_2 because J_1 and J_2 are J_1 and J_3 are, they are forward biased. So, V_{BO} is completely blocked by J_2.

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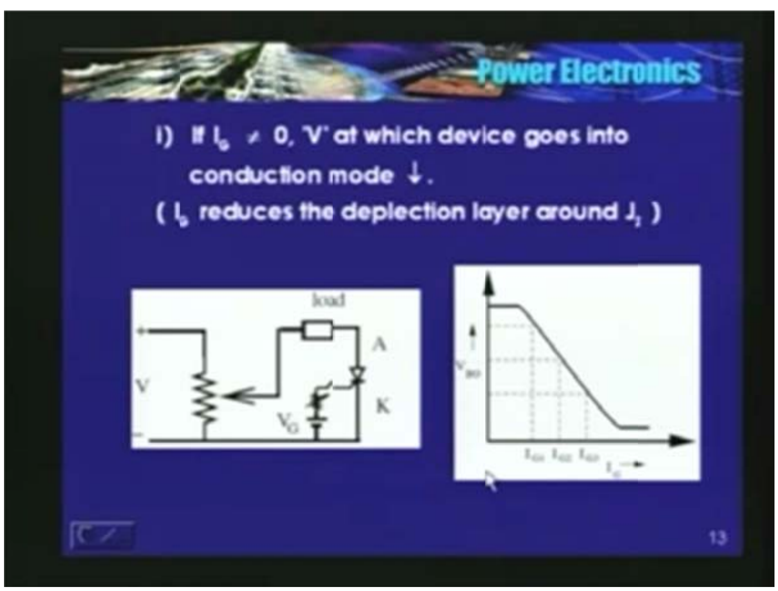

Now here, I have just shown you the plot of the variation of V_{BO} with $I_{G.}$ So, here is a simple circuit, I am just closing the switch till the device goes into conduction motor or till the current through the device, this load current higher than the latching, then I can open the switch and I am varying in this resistor to vary the current that is flowing through the gate circuit.

So, as I_G increases, the voltage at V_{BO} with very low value of I_G is almost the same. This is the voltage, this voltage is determined by junction J_2 itself. Above a certain value, this V_{BO} the voltage at which device goes into conduction mode reduces. So, it goes on reducing, why? It is because $I_{G,}$ the gate current reduces the depletion layer around $J_{2.}$ I will repeat, the gate current it reduces the depletion layer around the junction $J_{2.}$

Now how do we analyze the process by which the device goes into conduction mode using 2 transistor analogy? I just showed you PNPN is equivalent to 2 transistors, there is a PNP transistor and there is an NPN transistor and they are interconnected. Now, using this transistor analogy, can we find out or can we or is it possible to understand the turn on process of the thyristor? Answer is yes, I will explain to you now.

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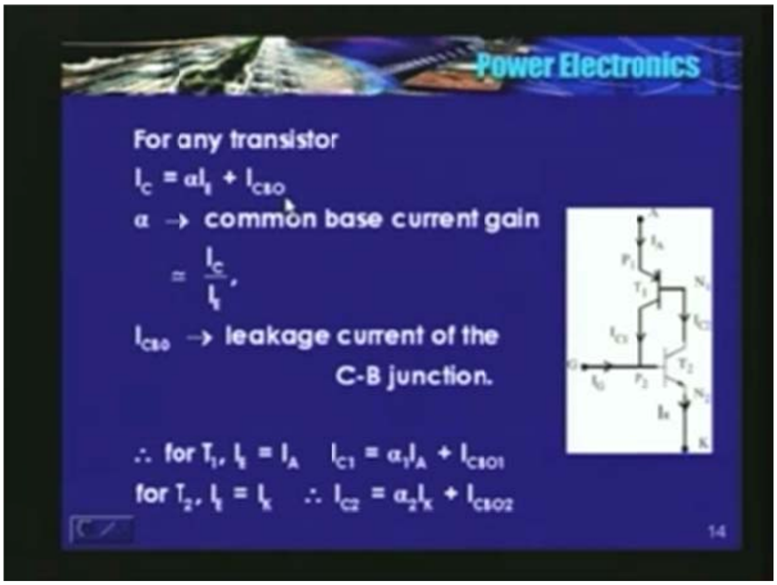

See, for any transistor collector current I_C is given by alpha into I_E plus $I_{CBO.}$ Collector current $I_{C,}$ I_E is the emitter current, alpha is the common base current gain, it is approximately equal to I_C divided by I_E and what is ICBO? It is the leakage current of the collector base junction. So, this is a common equation I_C is equal to alpha into I_E plus $I_{CBO.}$

Now, for this transistor T_1 transistor, what is I_E emitter current? Emitter current is nothing but the anode current $I_{A.}$ So, therefore I_{C1} is equal to alpha into I_A because I_E is equal to I_A, plus $I_{CBO1.}$ I am calling I_{CBO1} is the leakage current of collector to base junction of transistor $T_{1.}$ Now, how about for T_2? Now, for $T_{2,}$ $I_{E,}$ T_2 is a NPN transistor whereas T_1 is a PNP transistor. I_E is equal to $I_{K,}$ the cathode current $I_{K.}$ So, therefore I_{C2} is equal to alpha two, the gain of common base current, gain of T_2 into I_K plus $I_{CBO2.}$

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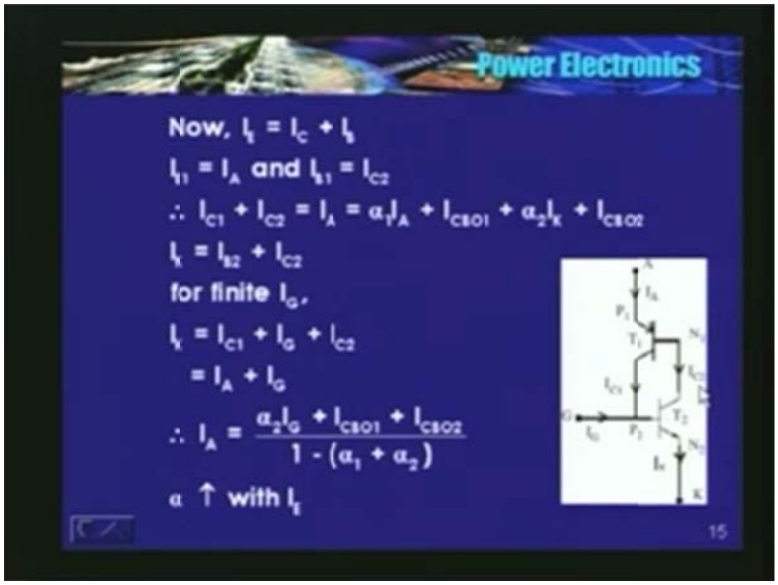

Now, we all know that $I_{E,}$ emitter current is collector current plus $I_{B,}$ base current. Now, what is I_{E1}? I_{E1} is equal to I_A itself, anode current. Emitter current of T_1 is anode current and what is $I_{B1,}$ base current of transistor T_1? Base current of transistor T_1 is same as collector current of $T_{2,}$ $I_{C2.}$ I showed you in the beginning, base of T_1 and collector of $T_{2,}$ they are same, they are tied together. So, I will add up those 2 equations. Which are the 2 equations? These are the two equations, I will add them up. What do I get? I_{C1} plus I_{C2} is equal to alpha one into I_A plus alpha two into I_K plus I_{CBO1} plus $I_{CBO2.}$

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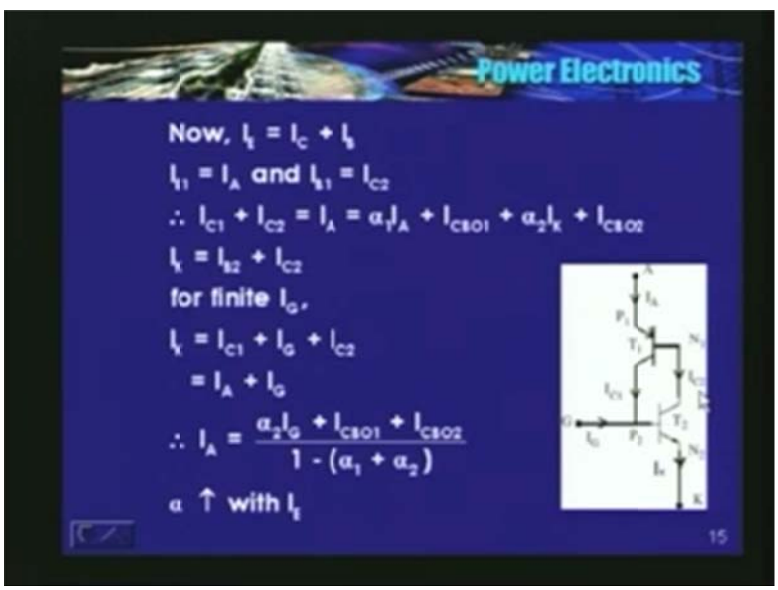

So, here is the equation I have written, as simple as $I_{C2.}$ Now, substitute here, I_C here is I_{C1} itself for transistor $T_{1,}$ I_B is I_B for T_1 is $I_{C2.}$ So, I_{C1} plus I_{C2} is equal to $I_{A.}$ So, these are the 2 current I_{C1} plus I_{C2} should be equal to $I_{A,}$ a PNP transistor that is equal to alpha one into I_A plus whatever that equation we are adding to.

What about for transistor T_2? Listen to me carefully, here what is I_E? That is I_K itself. It is $I_{B2,}$ base current plus $I_{C2.}$This current, I_{B2} plus $I_{C2.}$ Now, if there is finite $I_{G,}$ what is base current? Base current is I_G plus I_{C1} plus I_{C2} is equal to I emitter, I_{E2} that is equal to $I_{K.}$ See, I will repeat, emitter current of T_2 is this current, base current plus collector current. Now what is base current? You apply KCL at this point for finite $I_{G,}$ I_{B2} is equal to I_{C1} plus $I_{G.}$ So, therefore cathode current is I_{C1} plus I_G plus $I_{C2.}$

Now we all ready found that I_{C1} plus I_{C2} is equal to I_A for this transistor. I_{C1} plus I_{C2} is equal to $I_{A.}$ So, therefore I_K is equal to I_A plus $I_{G.}$ Now, you substitute this value in this equation, I_A is equal to alpha one into I_{A1} plus C_{BO1} plus this equation and what do I get? I get this equation, I_A is equal to alpha two into I_G plus I_{CBO1} plus I_{CBO2} divided by 1 minus alpha one plus alpha two. So, I have an expression here for anode current in terms of gate current, the leakage current of collector to base junction and common base current. Now using this expression, how to understand the turn on process of the thyristor? We will do it in our next class.

Thank you.