Digital Integrated Circuits
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Lecture-4
Diode and BJT Model Parameter Extraction

Today we shall just wind up our discussions on models of diodes and bipolar transistors. That is we have seen some models of diodes and bipolar transistors and the model consists of certain parameters in terms of which the currents are expressed in terms of the terminal voltages. So we have to see how to extract these parameters that is we must know the values of these parameters in order to able to use these models properly. For example the basic idea is that you may use these models to simulate a circuit, to find out how the circuit behaves and there these models are used and the parameter values must be known properly in order to get the proper response of the circuit to understand how the circuit behaves. So how to extract these parameters, so what you have to do is basically you have to take a sample device, do some small experiments and extract these parameters. So we shall just talk about these things because that is important in order to able to use the models properly.

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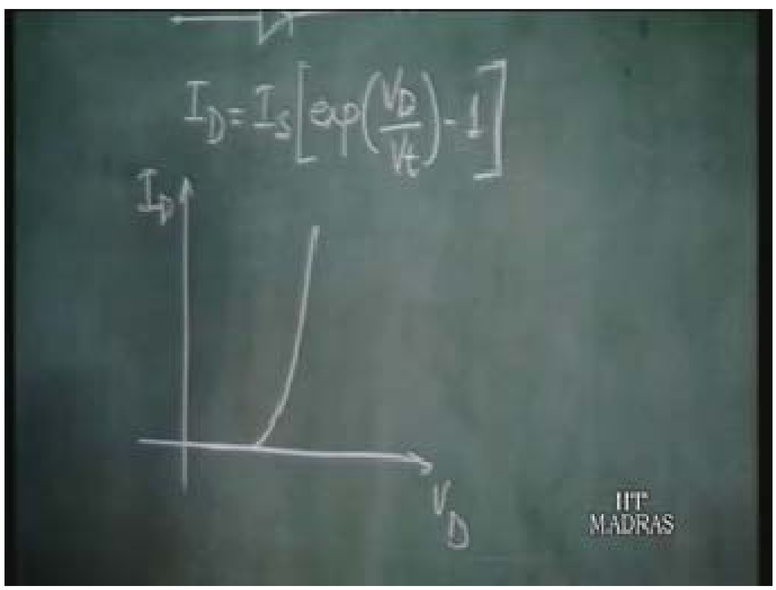

First let us take the diode. In the diode you have the two terminals the anode and the cathode and the current is expressed as this. So here you have the parameter I_S., so if you know the value of I_S you would know how the diode current varies with the applied voltage, V_D is actually the anode to cathode forward voltage. Now so how do you do it? So basically to do that, normally if you plot the current versus voltage in a linear scale, the characteristics is going to be something like this. So the diode current is initially

very small as this is an exponential relationship. So this current is you see is very small but as we increase the value of V.D. it becomes appreciable.
Now in order to extract this, the way to do it, you see that if V.D. is much larger than V.t., V.t. is only about 26 milli volts as we said at room temperature. So if it is say a few hundred milli volts V.D., this term becomes much larger than one so we can neglect this one and so we have an exponential relationship. So if we now plot, if one is neglected you have ln of I.D. is equal to this, now if you plot ln of I.D. you should get a straight line, as we said that you should do the experiment sufficiently higher high values of V.D. compared to V.t. and then this line if you extend it, the value at this point should give you ln of I.S..

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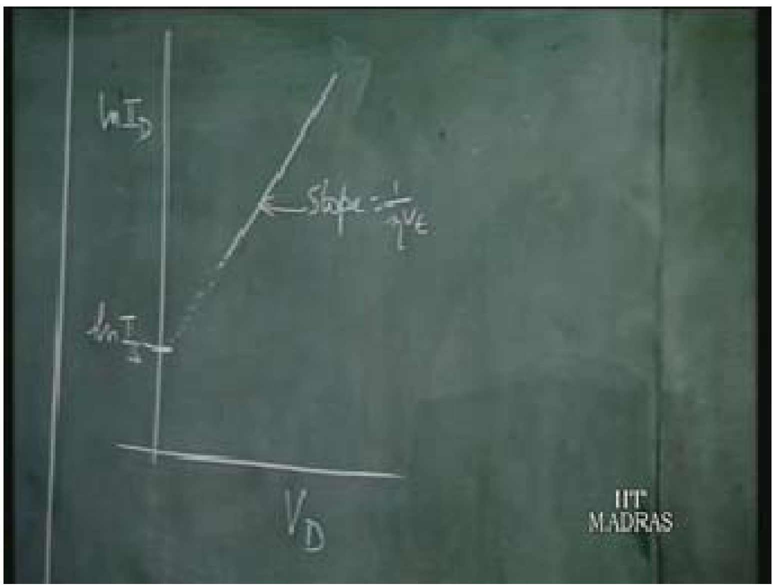

Now I must tell you that in the actual diode model there is one small correction factor which is introduced here which is called the Etta which is called the ideality factor and this value has in the range of 1:2 because when we develop the model, we did not take into account certain non-idealities like recombination generation in the depletion region certain leakage currents. So these give rise to a factor which is Etta here so if you have Etta here this becomes Etta, you have Etta here. So the slope of this line is one by Etta V.E. and V.t. you know is a constant depending on the temperature. So one can easily evaluate Etta so this is how one can extract the parameters for the diode.

So once you know the value of I.S. for the particular diode you can use the model. In fact all the circuit simulation packages will have some default parameter that is if you don't specify the value of I.S .it will take some value of I.S. and do the simulations but finally what you get may not be what you expect, when you do an actual fabrication because that I.S. value, the default parameter value may not match with the exact values, actual values. So you must in order to get the exact values one must actually do this

experiment, find out I_s and use that value in the circuit simulation. So this is called extraction of parameters so if you have a model there must be a mechanism to extract these parameters, so that you can use them in the circuit simulation. Of course in addition you also have the diode model we have already discussed, we also have the capacitances between the anode and the cathode you have… (Refer Slide Time: 8:42).
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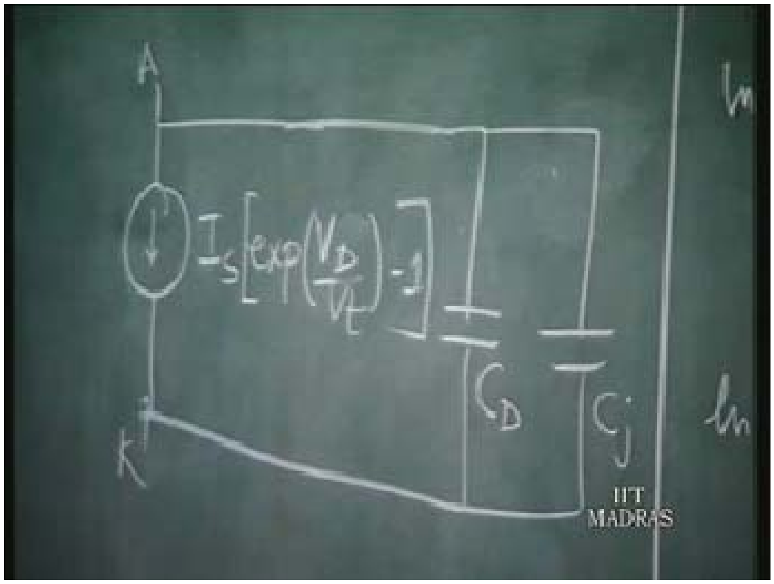

Basically draw this model once again, you have a current force. This is the diode voltage and then you have the two capacitances, one is the diffusion capacitance and one is the junction capacitance. (Student: sir in Etta how do you fix a number, when you say that Etta fixes the non-idealities, how do you fix particular number to that?) Now when you find out the slope of this curve, now this has a particular slope. Now from the slope one can find the value of Etta say suppose if Etta is equal to one then the slope will be 1 by v_t. If the slope is say, if Etta is two it is going to be one by twice v_t so this is done experimentally, it is very difficult actually to model the exact value of Etta from the model because this is due to some non-idealities and one has to really know what are all these non-idealities in the device properly to get the exact value of Etta from a model. So it is usually extracted once by doing the experiment. So this value of Etta usually lies between one and two.

So these are the two capacitances in the device and we have already seen that the diffusion capacitance is equal to the transit time del. Once you substitute this value here you will get almost equal to, we have already seen that and so this diffusion capacitance is proportional to the diode current and the proportionality factor is tou_d by v_t. So this is the transit time, it is the diode transit time. So one has to know this diode transit time in order to know the diffusion capacitance and this diode transit time is usually extracted by the transient experiment which we have already discussed. When you have a transient, the time required for the diode to recover that is once you have the diode in the forward biased region and when you reverse bias that the storage delay time is dependent on this diode transit time. So it can be extracted from that, you also have the junction capacitance which is given by 1 - v.D..

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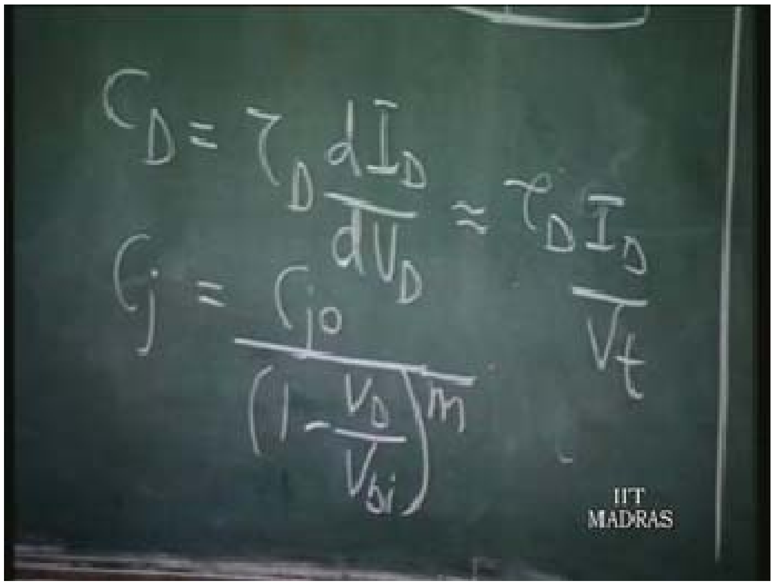

So this is the diode voltage, c.jo. is the junction capacitance for zero bias when v.D. is equal to v.0., c.j. is equal to c.jo.. I have just written this in terms of m when we discussed we have put half, that is for a particular case that is when the p n junction is an abrupt junction that is the doping changes from p to n abruptly but it can have graded junctions when this value changes for linearly graded it becomes one third. Suppose this is half so again we have to extract the values of c.jo. and v.BI., v.BI. is actually the built in potential of the p n junction. So once we know these values, we will know the value of the junction capacitance versus the voltage that is what we want to know and also m.

Now for this suppose m is equal to half that is for an abrupt case then if you plot one by c.j. square and this side if you plot the reverse voltage that is reverse voltage is actually the negative of v.D.. This v.D. is always taken as a forward voltage that is the convention. If you reverse bias the diode and you increase the reverse voltage what happens, this is going to be a straight line and if you extend this straight line, the point of intersection here that is equal to c.jo. that is equal to zero bias junction capacitance and if you extend this point further so that it meets this axis what happens, this is going to give you v.BI. because when v.D. is equal to v.BI., c.j. goes to is infinitely large so 1 by c.j. is zero.

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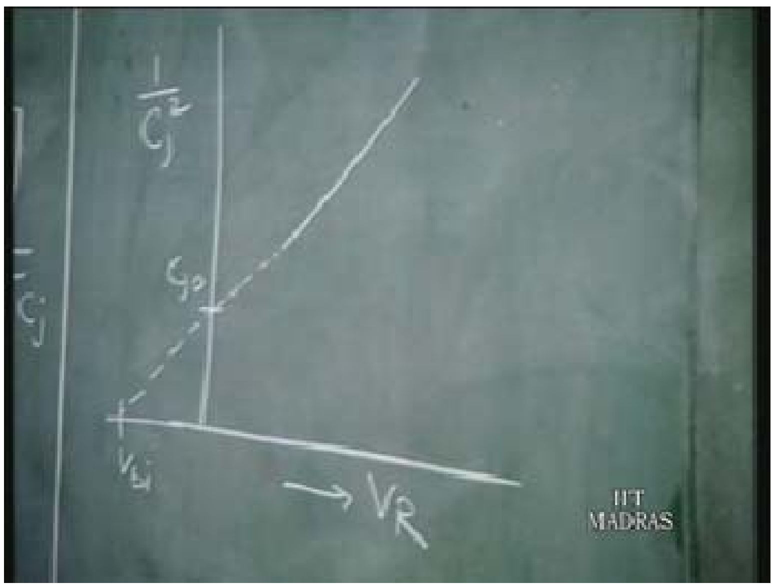

So you can extract both v_{BI} and c_{jo} from this mechanism. The problem is you actually do not know if you are just given a diode whether it is going to behave in a, m is going to be half or one third. So maybe you do this experiment, you may find that this is not a straight line then you have a problem in your hands, it may be one third. So what you have to do in that case? You have to try out different things if it is one third then you have to take one by c_j cube which will be a straight line and then you have to do this experiment and you get the values. So this is how you extract the parameter, so once you know these parameters these diode parameters for example in this case you have I_S and here you have the transit time c_{jo}, v_{BI}, m, you have properly defined the different model parameters. Once you know the different model parameters you can use it properly and get the proper device, you can simulate the device in a proper fashion.

You can use this now to simulate a bigger circuit. Otherwise you have to depend on the default parameters in any simulator which may not be the exact values for your device and so you may not get the proper results for the circuit. So extraction of parameters is very important to know how to extract the parameters. Similarly we can now look at the transistor model, we have already seen that the transistor model, the simple Ebers Moll model of a transistor consists of three current sources.

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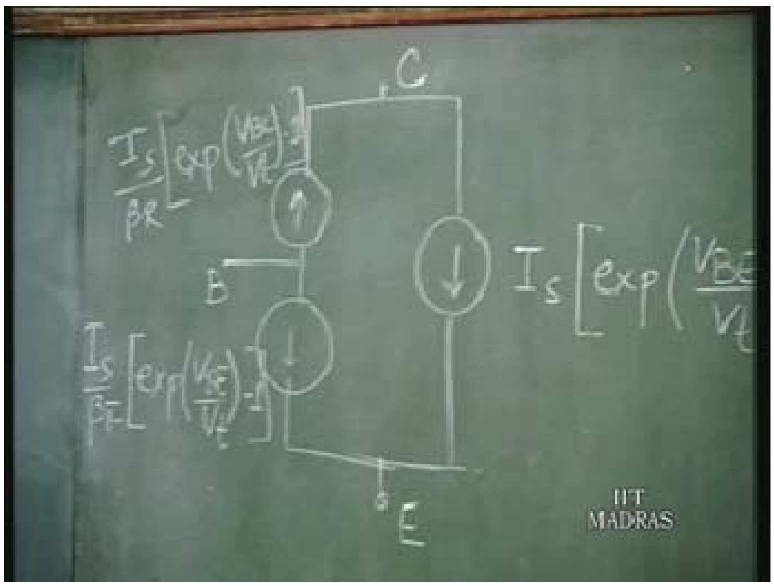

So this is the collector terminal, this is the base terminal and this is the emitter terminal. This current source value is given by I_S exponential, this current source is given by I_S by beta$_R$ exponential v_{BC} by v_t -1 and this current source is given by I_S by beta$_F$ exponential. So you have these three current sources and from that knowing the two terminal voltages, if you know the terminal voltages v_{BE} and v_{BC} you can evaluate the collector current which is the difference of this current source and this one, emitter current sum of these two and base current which is the sum of these two currents. So again you have to know certain parameters. What are these parameters? I_S beta$_F$ and beta$_R$.

So how do you extract these parameters? You do a similar experiment as you have done in the case of a diode to extract I_S. You see that what you have to do is you make for the transistor because v_{BC} is equal to zero. The base collector voltage is made equal to zero and then you plot I_C and I_B versus v_{BE}. Now what is I_C going to be equal to? This current source is zero, V_{BC} is zero so this is zero, so there also exponential V_{BE} becomes I_S, I_C is equal to I_S exponential V_{BE} by V_t -1. So again now just like in a diode if V_{BE} is slightly greater than V_t, few times 4 or 5 times greater than V_t then you can neglect the one and if you plot on a log scale so basically you have to plot on a log scale. This is going to be a straight line, I_C is going to be a straight line. What about I_B? I_B is also going to be a straight line.

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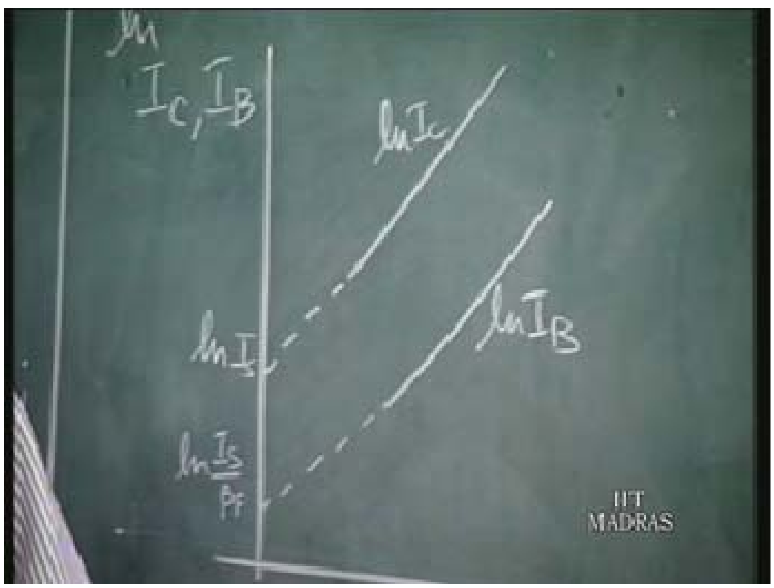

It is I_C by beta exponential V_{BE} by V_t -1. So you get two straight line so this is, if this is ln I_C this is say ln I_B this when you extend this is going to be ln of I_S and so this one is going to be ln of I_S by beta$_F$. So you have two straight lines and the ratio of these two currents is going to be equal to beta$_F$. So you see when V_{BC} is equal to zero the base current and the collector current are related or the ratio is beta$_F$. So the collector current is beta$_F$ times the base current so that is the forward beta of the transistor. So this is how you can find out I_S and beta$_F$. How do you find out beta$_R$? You have to do exactly a similar experiment but this time you have to make V_{BE} is equal to zero and plot I_E and I_B versus V_{BE} and again you will get two straight lines and the ratio is going to be beta$_R$. So you can evaluate again I_S from that also, as well as beta$_R$. So that is how you can extract these parameters.

So an interesting thing is that you see for yourself here that when v_{BC} is zero the collector current is related to the base current beta$_F$ times the base current. Also if v_{BC} is negative then also you can neglect those terms exponential v_{BC} by v_t terms with respect to exponential v_{BE} by v_t terms and so when v_{BC} is becoming negative it actually means that v_{CE} is increased. So it doesn't really have any effect on the I_C by I_{BE} ratio, it still remains more or less equal to beta$_F$. On the other hand if v_{BC} is made positive which means that v_{CE} is reducing then collector current is going to decrease. At the same time base current goes on increasing because the current is sum of these two. So keeping v_{BE} constant if you increase v_{BC}, make it positive you are going to reduce v_{CE} with the result that the beta of the transistor, I mean you should not call it the beta of the transistor the collector current to the base current ratio reduces. So you can say that the effective forward gain of the transistor has reduced.

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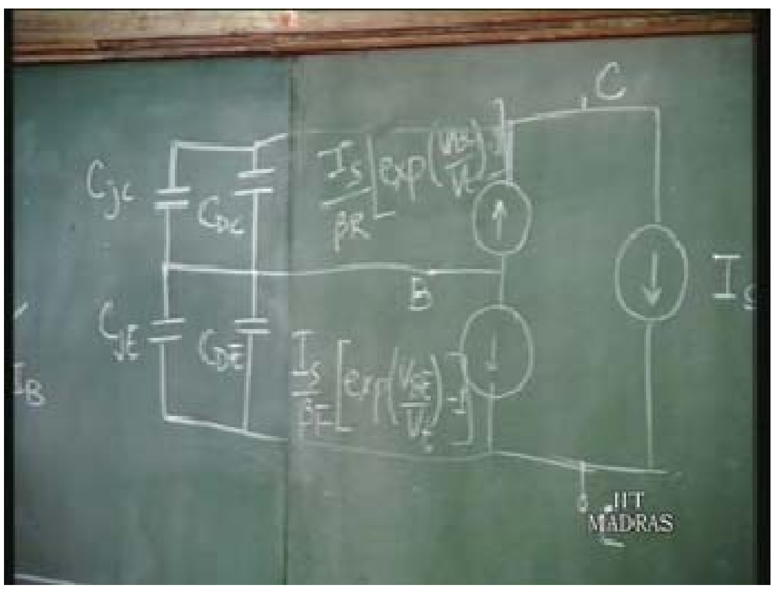

Some other small effects which actually not taken into account for that some base width modulation also takes place which is going to if v_{BC} changes but that is not really taken into account in this. So one has to actually make some corrections to this model, I think what you are talking of is the early effect. So this is the basic model which is used to understand many effects but if you really want to do exact analysis some other corrections taken into account other effects like the early effect has to be done because what she is referring to is if you reverse bias the base collector junction the base collector depletion width is going to change which changes the effective base width.

So all this beta$_{f}$ is dependent on the actual base width so that is going to change so that is not a constant actually but dependent on v_{BC} also to some extent. So this model is just the basic model and so we may have to do some corrections for other effects. Now in this model of course the device also have the capacitances which is just like a p n junction diode. So between each of these junctions you have the junction capacitance as well as the diffusion capacitance. So you will have if I draw it here, the two capacitances here and two capacitances. So this is c_{jc} I can call it, this is c_{DC}, c_{JE}, c_{DE}. So you have the two capacitances again, these are the junction capacitances and they have a similar relation as in the case of a p n junction diode and they can be extracted in a similar fashion by reverse biasing the particular junction and evaluating the capacitances for the diffusion capacitances, they are again related to the transit times. So the device actually in a bipolar junction transistor you have two transit times which are defined, one is called the forward transit time and the other is called the reverse transit time.

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What is the transit time? The transit time as we had defined it is the ratio of the charge stored to the current. In this case, the forward transit time is given by so when we define all the forward parameters are defined for v_{BC} equal to zero. So when you define tou$_{F}$ which is the forward transit time it is for v_{BC} equal to zero, so you don't have the reverse the charges due to the base collector junction. So that is given by Q by the collector current, the stored charge so the forward transit time is the stored charge by the collector current whereas the reverse transit time, so this is when v_{BC} is equal to zero. For the reverse transit time it is going to be the stored charge versus I_E with v_{BE} is equal to zero and again the diffusion capacitance for this case c_{DE} will be given in terms of the forward transit time tou_F times just as in the case of a diode del I_Cc del v_{BE} which is almost equal to I_C by v_t.

So this is of course when v_{BC} is equal to zero and for this case c_{DC} will be equal to tou_R. So this is the reverse transit time, so you have the two transit times, each junction as associated with two capacitances one is the diffusion capacitance which is due to the stored charge in the bulk region and the junction capacitance which is due to the charge stored in the depletion region. So this gives the complete model of the transistor. So these again can be extracted so the tou_F and tou_R are again can be extracted from the transient analysis. We shall take up the b_{jt} transient analysis later on and I just wanted to tell you about how the model parameters are extracted.

So once when you discuss a model, it is very important to know because the model is defined in terms of certain parameters and it is important to know how to extract these parameters so that you can use that model in a proper fashion and you are not dependent on the default parameters provided in any simulator because they may be wide of the mark because they may be just some representative values and not the exact values for the given transistor.
So going back to the bipolar transistor as such, we have seen that we look at the current voltage relationship where the output characteristics of the bipolar transistor, we have seen that if we plot I_C versus v_{CE}, now when v_{BC} is equal to zero for example we have seen that I_C and I_B follow a definite relation. That is I_C is beta times I_B and if you go on increasing the reverse bias on the base collector region that is effectively increasing v_{CE} then the relationship doesn't change much, it remains is the same. So for different values of I_B you will get I_C's they are separated almost, if you change I_B by given increments the I_C is like this so these are for constant I_B but when you go to lower values of v_{CE} which means that basically you are tending to make the base collector junction go to forward bias.

What happens to I_C? It reduces, so for the same I_B effectively the ratio between I_B and I_C is going to be reduced. So you have the characteristics something like this, so this is the output characteristics of the bipolar transistor I_C versus v_{CE} and of course we shall be using this characteristics quite a number of times to analyze given circuit. So now from this we move on to an actual circuit, up to now we have been discussing the devices we have been looking at the device. So for the first time we will now draw a circuit and see how this behaves. The circuit which we shall take up is the simplest circuit one can think of but it is very important in the case of especially for digital circuits. So you have a voltage here v_{CC}, this is the collector resistance you have a base resistance and you have an input voltage. Suppose you have a input voltage here and let this be the output voltage so this is the given circuit.

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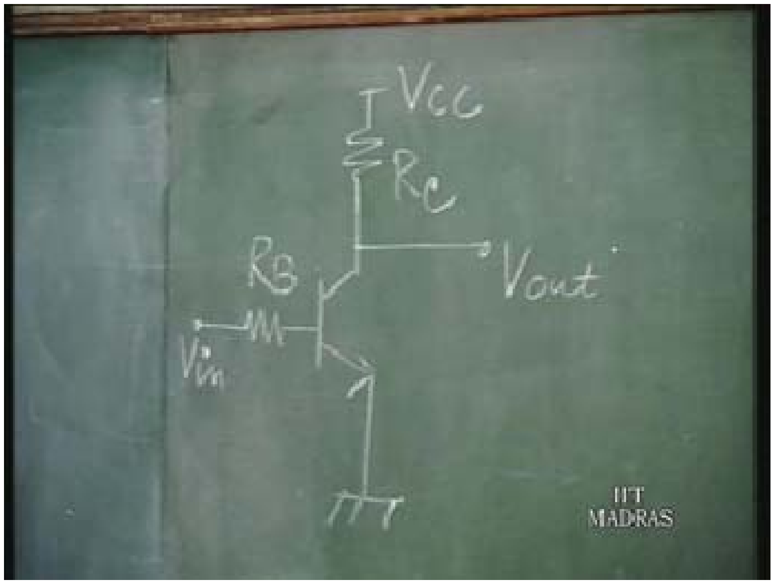

In order to understand the circuit or to find out so this let us come to this output characteristics. So this gives us the collector current for different values of base current versus v_{CE}. Now if you are increasing the base current, the collector current increases. So for a given base current this is how the collector current can vary depending on v_{CE}. Now if you want to find out the exact operating point of the device for a given base current, so suppose we have given a base current what is the exact point in which it operates, it can be operating in any point here. So you have to draw another line which is known as the load line, the equation for the load line is so this is v_{CE} plus I_C r_C is equal to v_{CC}. This equation must also be obeyed, this is v_{CE} plus I_C r_C is equal to v_{CC}, so this equation must also be obeyed. So now let us draw this line here on this output characteristics. So this is obviously an equation of a straight line, let it be like this. So this point when I_C is equal to zero v_{CE} equal to v_{CC} and this point is when v_{CE} is equal to zero from that equation I_C is equal to v_{CC} by r_C. So both these equations must be obeyed.

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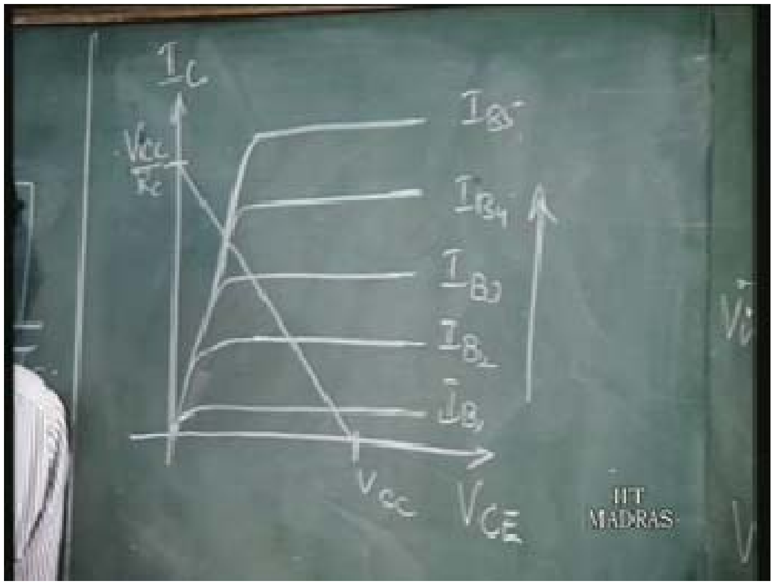

Now suppose I_B is very small, it's almost zero what is the output voltage equal to? So I_B is very small means you have a characteristic curve like this at this point and this is the point of intersection. So it is operating here so V_{CE} is going to be this and actually the V_{CE} is itself the v output, the output voltage is going to be almost equal to V_{CC}. Now if you go on increasing the base current the point of intersection if I_B changes to I_{B1}, the point of intersection is here so V_{CE} is going to be equal to this value here and the remaining part you see that sum of these two is equal to V_{CC}. So the remaining part is the drop across the collector resistance. If I_B is increased to I_{B2} so this is V_{CE} and the remaining part is the drop across the collector resistance.

Basically the collector current is increasing so I_C r_C is increasing, you go on increasing to I_{B3}. So this is the operating point. So what is happening is V_{CE} is reducing that is important and more and more voltage is dropped across the collector resistance. Then you increase it to I_{B4}, this is equal to V_{CE} the output voltage the remaining part is dropped across V_{CC}. Now increase the base current to I_{B5}, what happens? The point of intersection remains almost the same.

So the collector current saturates. Initially as you are increasing I_B, I_C was increasing but once you reach this point here the collector current no longer increases with increase in base current. So you can say that the collector current saturates so that is why in a bipolar transistor, it is this portion of characteristics which is called the saturation region. It is in terms of a circuit it's not, that is once you reach this portion of the characteristics with increase in base current collector current is going to saturate. It is not going to increase any further, so that is why this portion of the characteristics is called the saturation region.

So once you reach here that's it, the collector current becomes fixed. The collector emitter voltage across the transistor also becomes fixed. This is the saturation region and in this region where the collector current increases with increase in base current is called the active region evaporation and where the base current is almost zero is called the cut off portion. So you have the three regions of operation, the cut off region where the collector current is almost zero then you have the active region where the collector current increases with increase in base current and then you have the saturation region where the collector current is fixed, it does not increase with increase in base current. So in a digital circuit we actually operate the device either in the cut off or in the saturation region.

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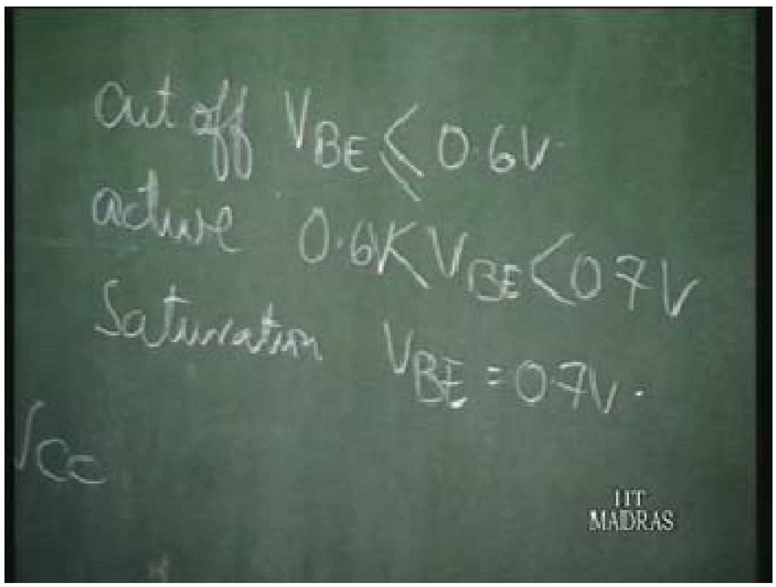

So it is either here or there whereas in an analog circuit usually the transistor is biased in the active region, so that is the difference. So in this active region the transistor behaves as an amplifier whereas here it is not amplifying but it is fixed at two extremes of operation. Now if you come back to this circuit, suppose we will make some assumptions before we go ahead and analyze the circuit. Suppose we say that it is an exponential relation with the base current and the base emitter voltage. So let us say that for cut off v_{BE} is less than 0.6 volts. In the active region so you are increasing the base current, so the base emitter voltage should increase.

So let us say it lies between 0.6 and 0.7 volts and say in the saturation region let us say v_{BE} when it reaches saturation it is equal to 0.7 volts let us say this is just an assumption. Just for the sake of doing some analysis. So when v_{in} is less than 0.6 volts or just up to 0.6 volts what is the base current? Base current is zero. So what is the collector current? Zero, so the output voltage is equal to v_{CC}. So let me draw the input output characteristics here. So output voltage is equal to v_{CC} when v_{in} is zero. Now when you increase v_{in} up to say 0.6 volts it is the same, it is going to be output voltage is going to be equal to v_{CC}. Now once you exceed 0.6 volts, what happens? This base current keeps on increasing so as the base current keeps on increasing, collector current keeps on increasing, V_C is falling so the output voltage keeps reducing. So this characteristic is going to go down like this. Up to what value? Up to here, so this value is called V_{CE} sat that is the V_{CE} at saturation so it is going to go down up to this value.

So this V_{CE} sat in normal cases is around 0.2 volts so we can write it straight away around 0.2 volts. So this goes down to 0.2 volts and after that what happens? If you go on increasing the input voltage output voltage does not change. So this is the characteristics of an inverter because when input voltage is low, output voltage is high. When input voltage is high, output voltage is low. So this is the characteristics of an inverter and this is the basic circuit element in any bipolar digital circuit. So this transistor has an inverter, now you see that using this circuit we have got an inverter characteristics.

Now this circuit here is also in this circuit the transistor is also behaving as a switch. It is also called the transistor as the switch, the reason is what happens when you have a switch? You have say a power supply, a resistance and a switch. When the switch is on, the switch is closed then the current flowing through the switch is equal to V_{CC} by R_C and the voltage drop across the switch is almost zero.

Here also you see when the transistor goes to saturation, the drop here is around 0.2 volts which is very much smaller compared to V_{CC} and you can neglect it. So as if it is a closed switch, the drop across this is zero the current flowing through it is going to be almost equal to V_{CC} by R_C but when the switch is open what happens, you have the power supply all the voltage will be dropped across the switch and current is almost is equal to zero. So that happens when the transistor is in the cut off region. When the transistor is cut off this switch is open and what is happening is, so the switch is open, current is zero and the entire voltage power supply voltage is dropped across this switch.

So basically you see that this is behaving as a switch so either when it is in the saturation region it behaves as an on switch and when it is in the cut off region it behaves as an off switch. So basically you see in initial days the digital circuit began with switches only, you had electromechanical switches like relays which were used to do digital functions. Now the advantage is you have a bipolar transistor which is doing the same thing. What is the difference between a bipolar transistor and say for example an electromagnetic switch?

The advantage is an electromagnetic switch on and off just may be a few times in a second whereas here you can switch it on and off in millions of time per second with the applied voltage is changing. The switch can be turned on and off millions of times of second. So that is the advantage, one derives from a bipolar transistor. So what we shall do later in the course is we shall see how I mean basically you have the different logic families. This is you will find that this circuit is coming over and over again, you have different peripheral circuits which gives rise to different logic families but this is almost an important component of almost all bipolar logic families, the transistor has the switch. So next class we shall actually see the switching performance of these transistors.