Solid State Devices

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Lecture - 26

Bipolar Junction Transistor

In this lecture we will begin a new topic called the bipolar junction transistor. This is the 26th lecture of the course. In the first eighteen lectures of this course we discussed the basics of semiconductors. Then in the next seven lectures we discussed the basis of PN junction and now we are ready to consider the various types of transistors. First we will consider the bipolar junction transistor. Let us see what characteristics we are going to explain for this device. First we will explain the common emitter output characteristics. Let us first understand what is meant by common emitter.

Here we see the biasing arrangement in which the characteristics are measured. As you know, the transistor has three terminals unlike the diode which has two terminals. In fact the transistor contains two PN junctions back to back having a common-region. For example, a p-n-p transistor will consist of an n-region on either side of which you have two p-regions. The n-region will be very thin so the two PN junctions are in very close proximity. The reason for the two junctions to be maintained in close proximity will become clear when we discuss the transistor action.

Now let us look at the symbol of a p-n-p transistor. Here you have the emitter junction showed by this arrow so the p region is emitter and n-region is the base. So it is the PN junction and the arrow shows the emitter junction. Similarly you have the collector, this is the collector, this is again made of p-type material so p-n-p is the arrangement as the p-type collector, n-type base and p-type emitter. Now what we mean by common emitter is that the voltages which are applied (either the voltage or the current) the sources are applied with emitter as the common terminal. You can see here that you are connecting a base current with reference to the emitter. And similarly you are applying a voltage to the collector with reference to the emitter.

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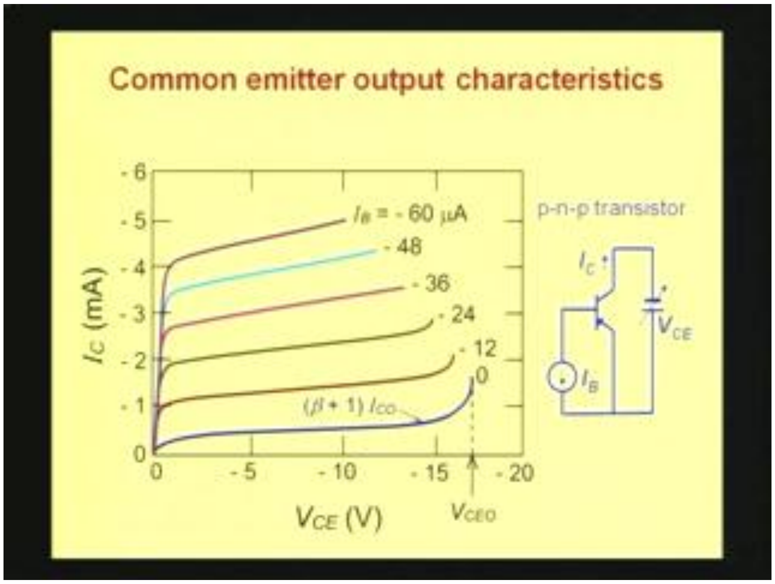

Now what you find is that the collector for a p-n-p transistor is negative as compared to the emitter in this arrangement. Similarly the base current is flowing out of the base terminal. And finally the collector current is flowing out of the collector terminal. The polarities will be reversed for an n-p-n transistor. Now this collector side is referred to as the output side and the base side that is this side is referred to as the input side. So when we talk of output characteristics we are really plotting the collector current as a function of the collector to emitter voltage which is varied.

Now when we plot this kind of characteristics we maintain the base current constant and then we change the base current to a new value and maintaining it constant we vary the collector emitter voltage and see how the collector current varies for the new base current condition. When we do this exercise the resulting characteristics which are called the output characteristics will look something like this. Here you can see the collector current is plotted as a function of collector to emitter voltage. Both the collector current and collector to emitter voltage are negative. Now it is clear that the collector to emitter voltage is negative because collector is negative with respect to emitter. The reason why collector current is also shown in negative quantities is because the convention is that, when the current flows out of a terminal then it is regarded as negative whereas if the current flows into the terminal it is regarded as positive. The collector current as you see from the biasing arrangement here is flowing out of the collector terminal.

Let us also understand the order of magnitudes of the quantities. The base current is small and it is of the order of tens of microamperes. The collector current on the other hand is of the order of mA so the collector current is more than hundred times the base current. For instance, for a base current of 36 microamperes your collector current is of the order of 3.6 mA so there is a factor of hundred which is the difference between the two. Now the collector to emitter voltage is of the order of few tens of volts.

What is happening when you sweep the collector to emitter voltage base current when maintained constant?
Let us take a specific case for example, let us again take this 36 microampere base current case. When we sweep the collector to emitter voltage from 0 we find that in a fraction of a volt the collector current is raising and beyond this point the rate of raise of the current reduces drastically or the characteristics tend to almost saturate. They are not exactly saturating because the current is not constant but they are almost saturating because the current is increasing at a very slow rate with respect to the voltage.

Now let us define the various regions of the transistor operation on this particular graph on the output characteristics. This particular area that is hatched corresponds to the region below the characteristics for zero base current. Note that when the base current is 0 there is still a small collector current. We will explain what is meant by this beta and I_{CO} later when we discuss the characteristics in detail.

The beta is simply the ratio of the collector current to the base current. Here you can see it is of the order of 100. This region which is hatched and which is below the base current equal to zero curve is called the cut off region because the transistor really has almost no current flowing for this particular range of operation. Next, this shaded area, the light blue shaded area where the current raises rapidly with voltage for various base currents is referred to as the saturation-region. This is somewhat misleading because we would like to call the region where the current is increasing slowly as the saturation-region which is this region here because the characteristics tend to saturate.

Unfortunately for bipolar transistors it is this light blue shaded region which is called saturation where the current is increasing rapidly. The reason why it is called saturation will become clear but this is the region where the collector to base terminal is forward bias which we will see this later and will also explain why it is called saturation.

Let us identify another important region of these characteristics which is the breakdown-region. The region to the right of this dashed line is the breakdown-region so what you find is that the characteristics for various base currents do not have this same breakdown voltage. As your base current increases the breakdown voltage falls at least in this region where the collector current is of the order of mA. The breakdown voltage corresponding to base current equal to 0 is the maximum breakdown voltage this transistor can have in the particular biasing arrangement. This breakdown voltage is referred to as V_{CEO} that is the maximum collector to emitter voltage and CE stands for Collector to Emitter voltage and O stands for base open.

Since the base current is zero it means that the base terminal is open so this is called the V_{BCEO} rating, the breakdown voltage rating of the transistor in the common emitter biasing arrangement. This is a very important parameter for a bipolar transistor. Now, having identified the saturation cut off and the breakdown-regions we now come to the very important region in which most of the transistors operate. That is the remaining region on this particular graph that is this region in between the cut off saturation and breakdown and this is called the active region of the transistor. The transistor operates in this region in most of the situations. In fact this is the useful region of operation.

Now having seen the output characteristics let us see the input characteristics of the transistor in this arrangement. Since the base side is the input side the input characteristics would mean the variation of the base to emitter voltage. Note that emitter is positive with respect to base so emitter base junction is forward bias. So V_{BE} is negative because base is negative with respective emitter. So variation of V_{BE} with I_B for a given collector to emitter voltage this is the so called input characteristics. They look something like this and these are diode like characteristics. The reason is very simple, since this is a diode the emitter current the current flowing through this diode is the emitter current. The current through this lead will always be exponential related to the voltage across the diode.

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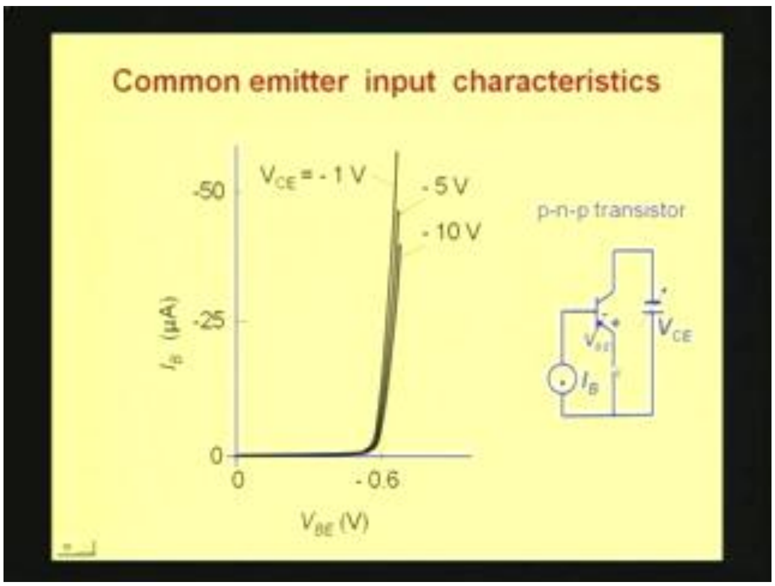

Now, as we have seen in the output characteristics the collector current is much larger than the base current. The collector current was of the order of milliamps whereas the base current was of the order of tens of microamperes. So there is a factor of 100 which is the difference between the collector and base current. So, by Kirchhoff's law, the collector current could be almost equal to the emitter current because the base current is hundred times smaller than this and the sum of all the currents should be 0. That is why there is a constant factor between the base current and the emitter current. So, emitter current is also approximately hundred times more than the base current or the base current is the fraction of the emitter current and which is almost constant when the biasing voltages and currents change. Therefore since base current is almost linearly related to the emitter current and emitter base junction characteristics are exponential, that is the variation of the emitter current with base emitter voltage is exponential therefore the variation of base current with base emitter voltage is also be exponential so that is why on this axis you have the base current which is of the order of tens of micro amps and this is the emitter base voltage access. The characteristics show a small dispersion with respect to the collector emitter voltage. So, for increasing collector emitter voltage the curves start shifting to the right but the shift is very small so these are the input characteristics of the common emitter mode of operation.

Next we will explain the beta versus collector current characteristics. These look something like this so you find the ratio of the collector current to the base current which is the beta is low for low collector currents and it increases and reaches a maximum and again starts dropping for high collector currents. Here since the collector current is shown over a very wide range or orders of magnitude the scale chosen is logarithmic.

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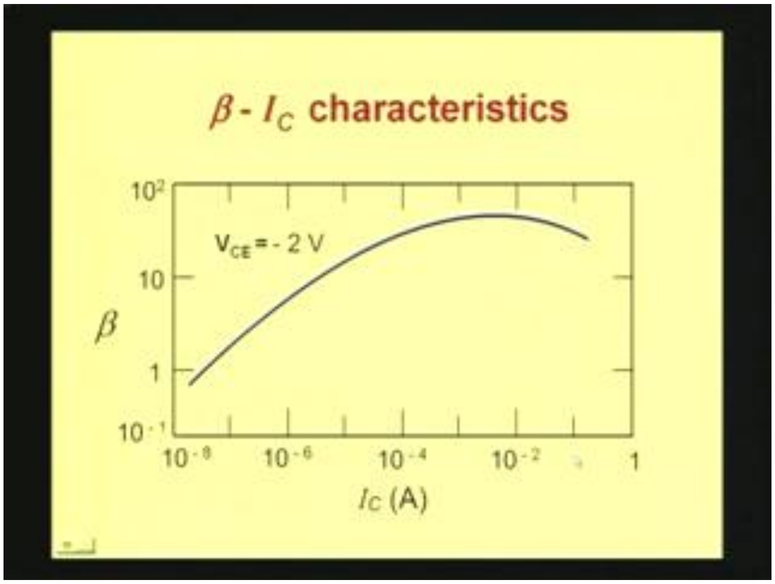

So beta versus I_C characteristics will normally be shown with collector current on the logarithmic axis. Here since the beta also is varying over a wide range over orders of magnitude it is shown on the logarithmic scale. The collector to emitter voltage under which these characteristics are taken is fixed in the particular case at minus 2V. Now, having considered the active region of operation it is also important to know the breakdown characteristics of a transistor. So collector current as a function of collector to emitter voltage shows a breakdown characteristic which is something like this, this is the V_{CEO} which we discussed already. Now if the transistor is operating in common base mode, that is, the collector voltage is applied with respect to the base voltage then your breakdown is higher and this breakdown voltage is referred to as V_{CBO} that is collector to base breakdown with emitter left open.

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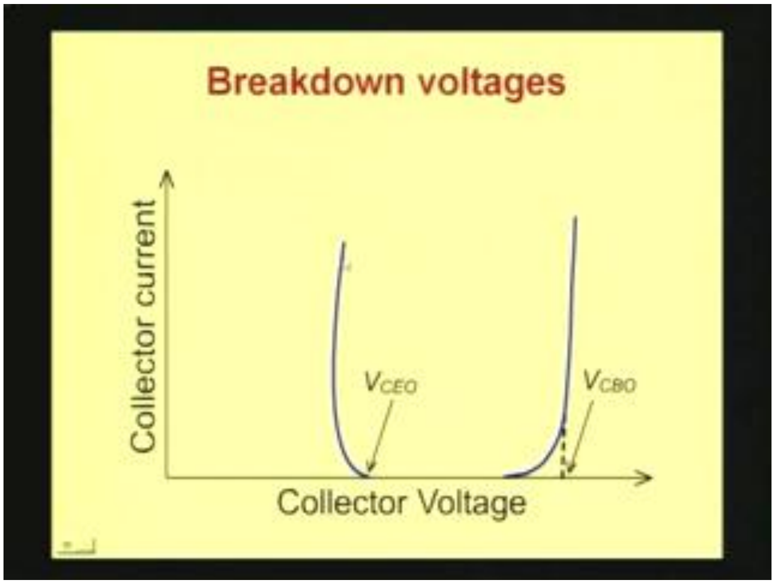

We will also explain why V_{CBO} is much higher than V_{CEO}. We will then explain the E_C characteristics of the bipolar transistor. As in the case of PN junction the A_C characteristics will be represented using an equivalent circuit for the transistor, this is called the small signal equivalent circuit. There are two types of equivalent circuits which are used. One type is called the h-parameter model which is shown here on this particular slide.

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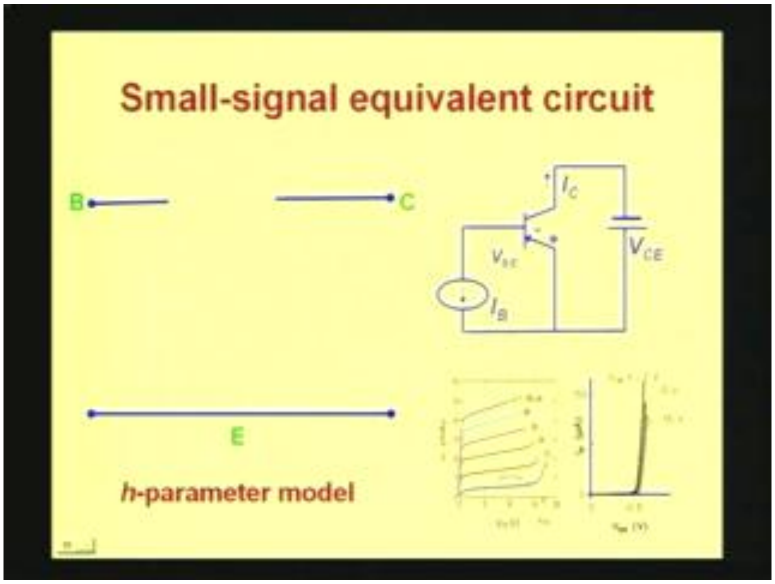

This particular model is directly derived from the DC common emitter characteristics which are shown here as the output and input characteristics which we considered just now. So from these characteristics you can derive the small signal equivalent circuit. Obviously since we are deriving the equivalent circuit from DC characteristics this equivalent circuit is valid for no frequencies. So generally the h-parameter equivalent circuit is used for low frequencies. Some more justification of the use of h-parameter equivalent circuit will be discussed later when we take up the characteristics in detail.

Now let us see what these equivalent circuit components mean. Now, this is the DC biasing arrangement for measuring the common emitter characteristics. So what we do is we superimpose a small base current on the existing DC current, as a consequence of this small signal base current you will have a small signal base emitter voltage and a small signal collector current resulting in the circuit.

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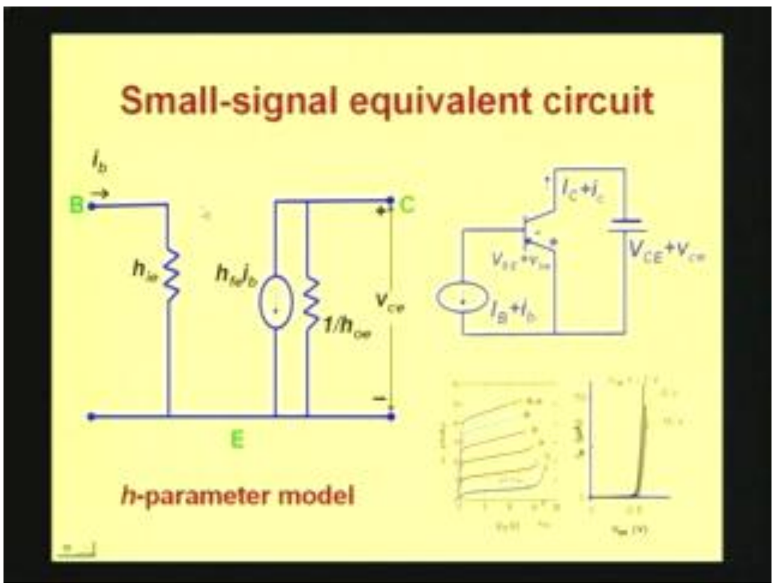

Now these effects, that is, the variation in the base emitter voltage and the variation in the collector current in response to the variation in the base current can be represented as follows. Between the base and emitter you put a resistance so I_B is the base current which flows through this resistance giving rise to a small signal base to emitter voltage that is this voltage. Similarly, the small signal collector current resulting from the base current, that is, a small signal output current because of the small signal input current can be shown as a control current source. So it is the collector current equal to base current into a multiplication factor.

Now, in addition, if you now superimpose a small collector emitter voltage these collector currents and the base emitter voltages will be slightly modified. So these modifications can be represented using two additional components, so this is the collector to emitter voltage applied and since the collector current is changing in response to this you put a resistance here. Then, since the emitter base voltage also is changing a little bit in response to V_{CE} this is shown by a dependant voltage source so this voltage source is in series with the resistance because the sum of these two voltages actually represents the voltage between the base emitter terminals when you have changes in the base current and the collector emitter voltage.

Now the symbols for the resistance is 1 by h_{oe} and for the multiplication factor, that is, the relation between this voltage and the collector to emitter voltage the ratio is h_{re}. So this is the small signal equivalent circuit as per the h-parameter model. Generally this voltage source which is present here is negligible and so normally it is neglected. So the h-parameter equivalent circuit used in practice has only three components which is a resistance at the input, a control current source in parallel with the résistance at the output. Another small-signal equivalent circuit which works for both low and high frequencies and which is often used is the so-called hybrid pie model. The reason it is called pie is because of the shape of this particular circuit. This arm together with this arm and this resembles the shape of the symbol pie and that is why it is called hybrid pie equivalent circuit.

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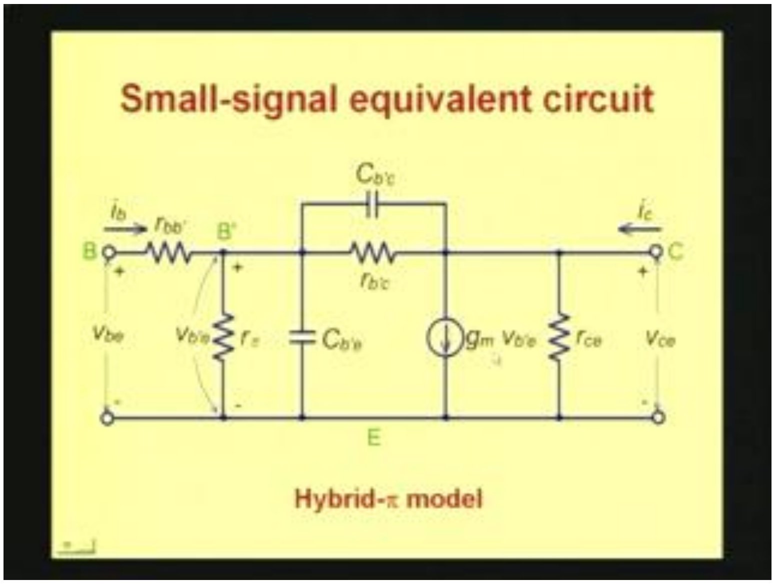

We will also see how this equivalent circuit can be derived. The different between h-parameter equivalent circuit and the hybrid pie circuit is that the current source between the collector and emitter is shown controlled by the base to emitter voltage rather than the base current. So here instead of beta you have the parameter transconductance g_m that is the significant difference between h-parameter equivalent circuit and the hybrid pie equivalent circuit. We will consider the relative advantages and disadvantages of the two when we discuss the characteristics in detail. Now to explain these DC and small-signal characteristics we will proceed as follows.

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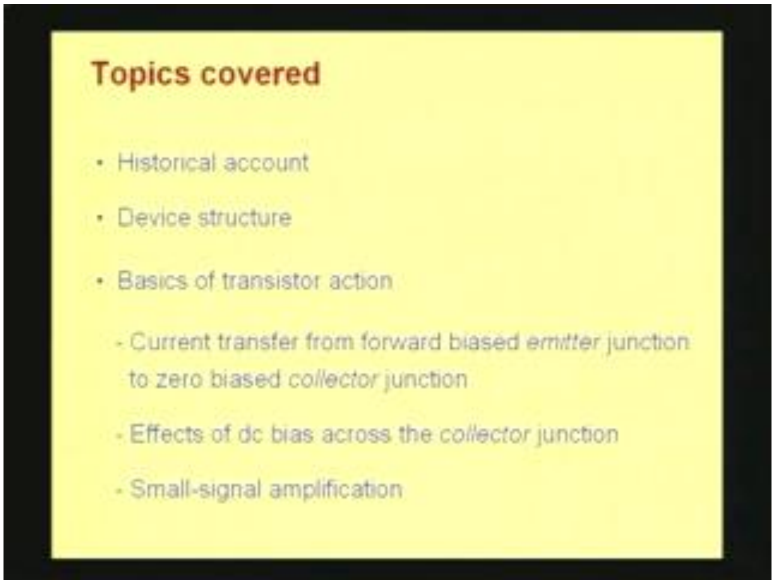

First we will discuss an historical account of how the transistor came into being, how it was invented and under what conditions. Then we will discuss the device structure that is the real structure, and the simplified structure we will use for the purpose of our analysis and then we will discuss the basics of transistor action.

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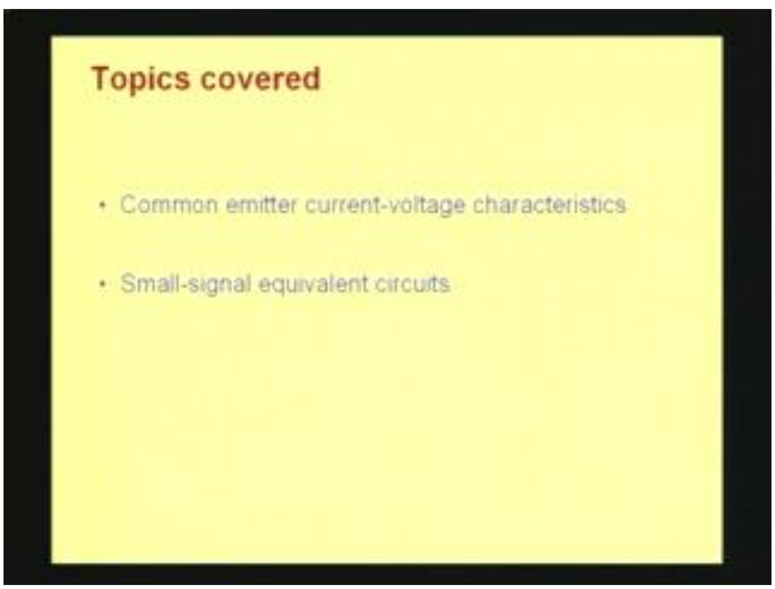

In this first we will consider the current transfer from forward bias emitter junction to zero bias collector junction. So these two junctions are in close proximity, one of them is forward bias and the other is zero bias that is no bias across the other junction and then will see how the current is transferred from forward bias to zero bias junction. Then we will discuss the effects of DC bias across the collector junction. If you change the collector junction from zero bias to DC bias what happens. With this we will be ready to discuss the small-signal amplification using bipolar junction transistor. The small signal amplification is the most important application of this transistor action. Then we will consider the common emitter current voltage characteristics.

We will explain how the various features of the characteristics arise and finally we will consider the small signal equivalent circuits. That is, after considering the DC characteristics current voltage characteristics we will consider the AC characteristics and the result of this will be in the form of an equivalent circuit for the bipolar transistor that we have already shown. So now let us proceed with the history of the device.

During the 1920's when lot of research work was going on for semiconductors an idea was floated. That is, why not we make a vacuum tube triode-like structure in semiconductors. This is the idea of the solid state triode. So the vacuum tube triode was being used for amplification. It was a device made use in vacuum tubes in which there where free terminals. Immediately when people started working on this idea two patents were filed.

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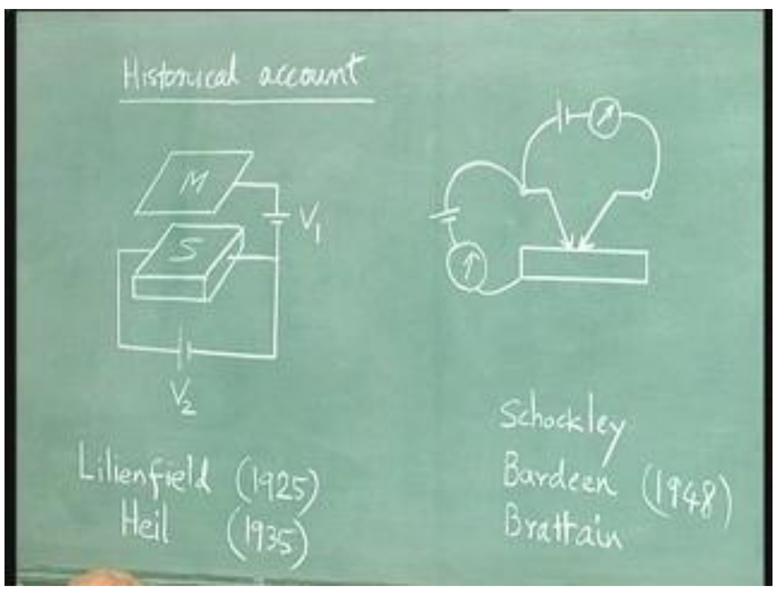

So these are illustrated here. One was by Lilienfield in 1925 and another by Heil in 1935. The basic ideas in these patents were the same and are illustrated using this diagram. So the idea was as follows: You have a semiconductor block whose resistivity is sort to be modulated by a metal electrode which is placed in close proximity to the semiconductor block. But this metal electrode is insulated from the semiconductor electron.

How do you modulate the resistivity of this semiconductor?
You apply a voltage between the metal and this semiconductor as indicated in this diagram. For example, for the polarity of the voltage applied here it is clear that the metal

will be positive and this semiconductor will be negative. So the positive metal electrode will attract electrons to the semiconductor surface. Now, because of this attracted electrons the conductivity of the semiconductor will increase near the surface of the semiconductor. In other words, we can say that the conductivity of the semiconductor itself will get modulated, it will increase. Now notice that these electrons are being given by the negative terminal of the battery.

This is the electric field that is causing the change in the conductivity of the semiconductor so this is the modulating field. If you apply a transfers electric field in this direction using another battery V_2 shown here then a current will start flowing from the positive terminal to the negative terminal. Now this current will depend on the conductivity of the semiconductor. Since the conductivity is being modulated by the metal the current will be modulated by this particular metal electrode. In other words, you have modulation of the current by a transverse electric field which means in a perpendicular direction. This was the concept proposed to implement the vacuum tube triode in the solid state device using a semiconductor.

Now what is happening here? This is the controlling voltage V_1 and this voltage V_1 controls the current I which is created because of voltage V_2 and which is also dependent on voltage V_1 so V_1 controls I. Now this is what happens in a vacuum tube triode also. There is a controlling terminal which controls the current. And now one can always used this particular device for amplifications and so on. How this to be used for amplification is a separate topic but what we want to show here is how a current can be control by a transverse electric filed as it happens in a vacuum tube triode and how a similar concept can be realized in a solid state. Solid state means a semiconductor is solid, that is why this is called a solid state device as against vacuum tube device which is created in a glass tube which has vacuum.

Coming back to the developments people started realizing this device. They found that to make this device you must have an insulating layer between the metal and this semiconductor and this is where they faced difficulty. How do you grow a high quality insulating material which is sufficiently thin so that you can get conductivity modulation in the semiconductor by putting a metal electrode on the insulating layer? So, as they started working on the insulator semiconductor interface they got into more and more difficulties. Specifically what they found is a practical device which was being realized according to this idea at very little current modulation by the control voltage. So, though if you make a simple calculation based on a capacitance model for a certain voltage V_1 or a certain change in voltage V_1 you expect a certain change in the conductivity by the simple capacitance formula. And then using that change in conductivity find out what is the change in current for a given voltage.

Now that was the expected change in current. But practically the device hardly show any change in current and this was the problem. This problem continued to bog the researchers until 1948. So from 1935 to 1948 is about 13 years. So many research workers where putting in all their brains to solve this problem of lack of conductivity modulation.

In order to study this particular problem Schockley, Bardeen and Brattain these three scientists in one experiment tried to put two contacts on the surface into close proximity of a semiconductor because they knew that something is happening at the surface of the semiconductor which they wanted to understand that is responsible for lack of conductivity modulation. So, to study the surface they created some such arrangement and they were trying to see the currents in these two particular loops as shown here. This is the semiconductor block and these are the two contacts in very close proximity.

Now what they found when they were trying to measure the currents in these two loops is that a change in current in this loop was inducing a large change in current in this loop. Now they realized that this is some kind of a transistor action that they were looking for. This is exactly what is happening or what is rather supposed to happen according to this idea except that here you have a controlling voltage which is modulating this current. In this case you had a current which was modulating another current but of course this current is also set up by voltage. They immediately realized that this is some kind of a solid state triode they were looking for. We will see in a detailed discussion why this device was called the transistor.

We will understand this when we take up a transistor action in detail. But for now let us proceed with the developments. They called this particular device as transistor wherein the current between these two terminals was being modulated by the current between these two terminals. So they called one of these terminals as the emitter and this one as the collector and obviously the third one which was looking like a base on which that put the emitter and collector as the base terminal. That is how you have emitter base and collector in a transistor. Though the action of this particular device was different from this particular device that was proposed in the sense that here the current in this loop was controlling the current in the other loop whereas here the voltage was supposed to control the current here. But otherwise the two devices are similar in that one terminal controls the current through the other two terminals. Therefore, they realized that this device can be used for the particular purpose for which they were doing the experiments to perfect the other device that was the vacuum tube triode given in the patent.

In fact the diagram on the patent looks something very similar to this. Once they found some device which they can use they abandoned the experiment they were doing to perfect a device according to this concept and then they started perfecting this new device which is called the transistor. It is in 1948 that this particular transistor was discovered accidentally while trying to perfect the solid state equivalent of the vacuum tube triode. We can call it the solid state triode. And when they tried to explain the operation of this device they found that it is because of both electrons and holes and that is why they call this as a bipolar device and they call it as a bipolar transistor. That is how the name bipolar junction transistor came into being because the operation of this device could be explained using the theory of PN junctions that had been developed and the operation of this device involved both electrons and holes and that is by you find the word bipolar. This is as far as the history of the bipolar junction transistor is concerned.

We will consider the further developments that took place after bipolar junction transistor in the context of the mass field effect transistor which will be discussed after the bipolar transistor. That is the history of the bipolar transistor which was discovered in 1948.

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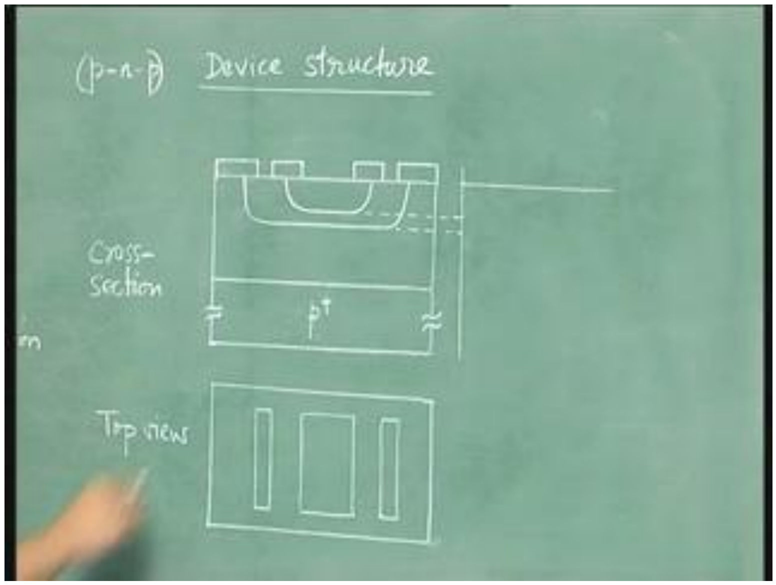

Now let us consider the structure of the device that is there in the modern days and then we will see how we can approximate the structure for the purpose of our analysis. Let us consider a p-n-p transistor and then you can always try to make an n-p-n transistor. You start with a heavily doped p-type substrate that is a p plus substrate and then you grow the subsequent layers. Now the details of the processing of bipolar junction transistor are very similar to those of the PN junction that we considered earlier. The PN junction in modern days is made using a planar process so the same planar process is used to make this bipolar junction transistor. This process involves cyclically going through the steps of deposition of layers then patterning of layers using photolithography and etching and this is repeated again and again until the final structure is realized.

Here you start with a substrate which is heavily doped and then on that you grow a likely doped substrate of required doping level which is a p-type layer. Then through a window you create n-type diffusion and then through another smaller window you create p-type diffusion. Now here it is important to note that the doping of n-type region is more than the doping of the p-type region and doping of the p-type region is even more than the doping of the n-type region. This can be shown by doping profile that can be drawn on this side. So here you have the doping and here you have the distance and we are going to plot this on a log scale. So doping is plotted on a log scale because we wanted to show a wide variation on a single diagram. The doping level varies over orders of magnitude and that is why one must use a log scale to show the doping level.

The doping looks something like this; you have a heavily doped p-type region so this is how it goes and then you have a PN junction at this point and then you have a relatively doped n-type region and then you have a PN junction again here and a much lighter p-type region followed by a heavily doped p-type region which is something like this.

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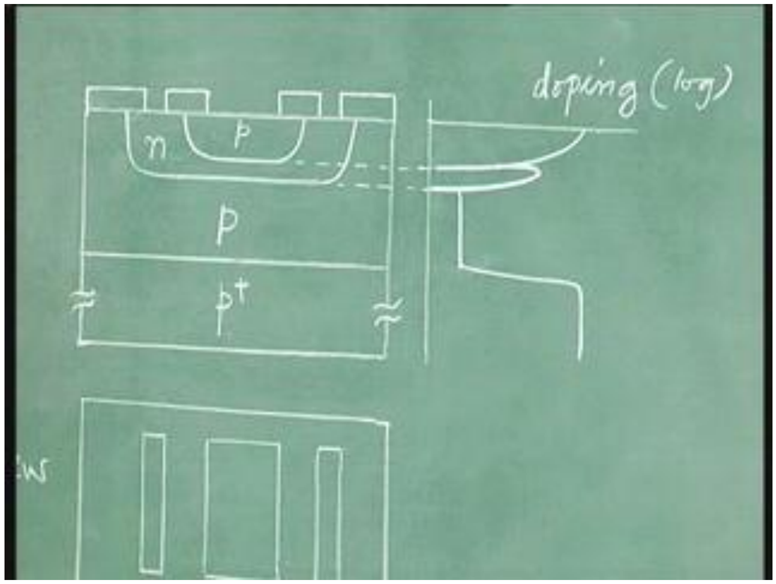

The doping levels would be something like this; at this point the doping level would be of the order of 10 to the power 20 per cm cube. This doping on the other hand could be of the order of 10 to the power 18 per cm cube. And the doping here could be of the order of 10 to the power 16 per cm cube and that here is again 10 to the power 20 per cm cube. These are the rough values and depending on the rating of the transistor these values will change. But definitely this gives you an idea of the order of magnitudes involved.

Now what about the distances?
Taking this as the reference point here this could be about 2 to 3 microns this point and this point if this is 2 microns would be 3 microns or less. The distance here between these two junctions is about a micron. These are the two junctions in close proximity so the PN junction here and this NP junction here are responsible for the transistor action. Here the distance is in microns. Now this point here will depend on the breakdown voltage and other requirements of the transistor just like in a PN junction. So it could be for example about 10 microns, it could be more or even less.

And of course the thickness of this substrate as you know will be more than 100 microns because this thickness is decided by the mechanical handle ability consideration for this device. Now here this is the silicon dioxide layer in which the windows are created to create these PN diffusions. This is the cross section of the device; this is the p-n-p transistor. The top view of this device would look something like this so these three shows the metal contacts. So on this when you want to take the metal contacts the cross section will look something like this and these contacts are shown here. This is the emitter contact and these two are the base contacts because this is the base region and the collector contact for this particular transistor is at the bottom.

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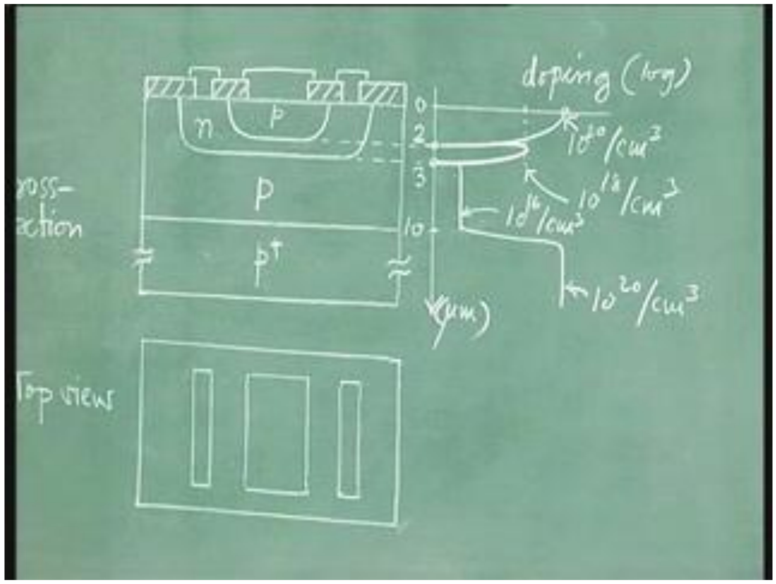

What we are considering here is a discrete transistor. In an integrated circuit, transistor, on the other hand, the collector contact will also beyond the top somewhere here for this particular region. For a discrete transistor it is at the bottom. We will construct the discrete transistor here because its structure is simpler so you have that contact at the bottom, this is the collector.

Let us draw this emitter here. On the top view this is the emitter and these two are the base contacts. This is the real structure of the device. Now, as we have been saying, for the purpose of analysis we need to use a very simplified structure for which simple equations can be derived and the essential phenomena can be very clearly brought out. So, for the purpose of analysis we are going to use a one dimensional structure which looks something like this. We are going to assume a structure that is obtained if you just take this portion of the device.

As you can see here, if I were to separate this portion it would look something like this. I have the p region then I have the n-region which is very thin so this is the so called n-region shown here and then again I have the p and p plus. So if you want to show the relative doping levels then probably this should be called n plus and it should be p plus plus, this doping is more than this and this doping is more than this and this is more than that. So p plus n and this is p and this is p plus. So this is our device, this is the emitter, this is the collector and the base contact we will show on the side.

As you can see here in real life you cannot really connect the base contact here on the side as shown here. This base contact will be in the same plane as emitter contact. But for the purpose of analysis we are showing an idealized structure with the base contact on the side. Further what we will do is we will ignore this p plus layer and we will assume our collector contact is right there. So this will be our idealized structure of the p-n-p transistor. Now in the real transistor the current flows from the emitter to collector so we can show that flow as something like this. But you can see that you also have flow on the sides therefore the current flow is two dimensional in the real transistor.

Further if you see the current into the base contact that current is flowing sideways like this. So this is really a complicated situation which is being simplified here to show that the current is almost entirely in one direction so this is a one dimensional approximation. And you do have a base current flowing from the side but its effect will not be considered in our analysis meaning that we are going to consider the effect of the base current definitely because without base current you cannot have this current flowing. And as we will see the base current controls the current between emitter and collector.

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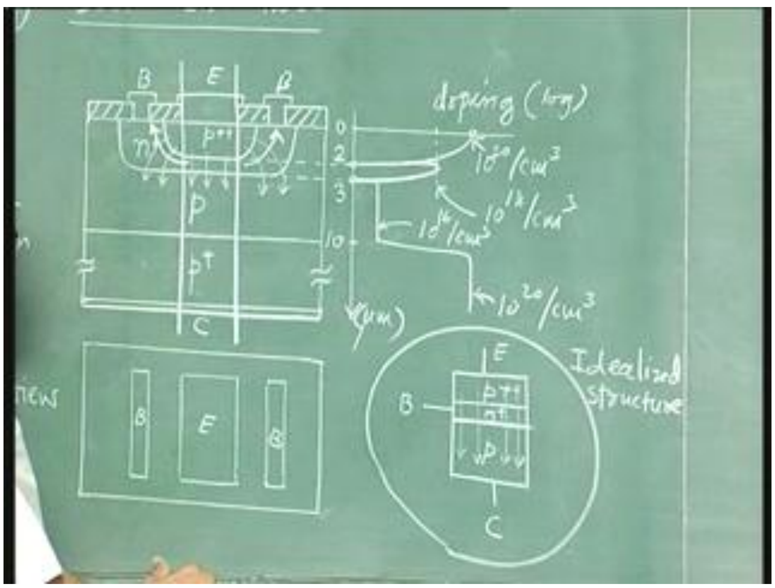

But what we are seeing now is that the lateral flow of the base current, the effect of this, we will not consider in a simple analysis but later on we will show how you can accommodate this effect also. So our analysis will be based on this particular idealized device structure of a p-n-p transistor. This is called the emitter region, this is called the base region and this is called the collector region so doping in the emitter region is more than the doping in the base and doping in the base is more than the doping in the collector. So we could probably show this as follows: p plus plus n plus p or alternately we could also write as p plus n p minus so it all depends on which way you want to represent. Basically we want to emphasize that doping in emitter is more than that in base which is more than that in collector.

Now although the n-p-n transistor is more often used than the p-n-p transistor because the electron mobility is more than the mobility of holes so the n-p-n transistor is faster and it can carry more current for given voltage conditions than p-n-p transistor but still we use a p-n-p transistor to develop the theory. The reason for this is as follows. In a p-n-p transistor the current is because of holes moving from emitter to collector. And you know that for holes the direction of the current is the same as a direction of the movement of the carriers.

Now as we will see, in a bipolar junction transistor the current is because of diffusion. So, if you consider a p-n-p transistor the current direction will be the same as the direction of the hole diffusion and that is the reason why a certain simplification results because the current direction is same as the direction of the movement of holes where the understanding of the transistor action is simplified. Whereas in a n-p-n transistor on the other hand the current will be carried mostly by electrons and the current direction will be opposite to the direction of the flow of electrons and because of that some minor complications arise which can be avoided while developing the theory for the first time and this is why the p-n-p transistor is considered for explaining the theory.

Now, when we discuss the transistor action and other aspects of the transistor we will draw the transistor in the horizontal direction like this where this is the emitter, this is the base and this is the collector. Now, apart from the simplification that we have already considered for the device structure one more thing we will note is that though actually the doping profile is highly non uniform and this non uniformity of the doping profile does have an effect on the bipolar transistor action.

However, the basics of the transistor action are not due to the non uniformity of the doping profile. Therefore in our first analysis we will assume the doping to be uniform in each of the three regions meaning that the junctions are assumed to be abrupt. So, if the doping profile is shown here it would look something like this. We will show the acceptor type doping on the negative side simply because in the space charge region near the junction the acceptor type doping leads to a negative space charge on the p-side. So let us indicate the doping here and call this the emitter doping and represent it as N_E.

Now, the base doping is similarly uniform but it is much less than the emitter doping. From your doping profile we can see that it is at least 50 to 100 times less than the emitter doping. What we need to do is we need to use a different scale for the base doping and for the emitter doping. We can show this by showing a cut here because we are drawing the doping on a linear scale that is we are able to show the polarity.

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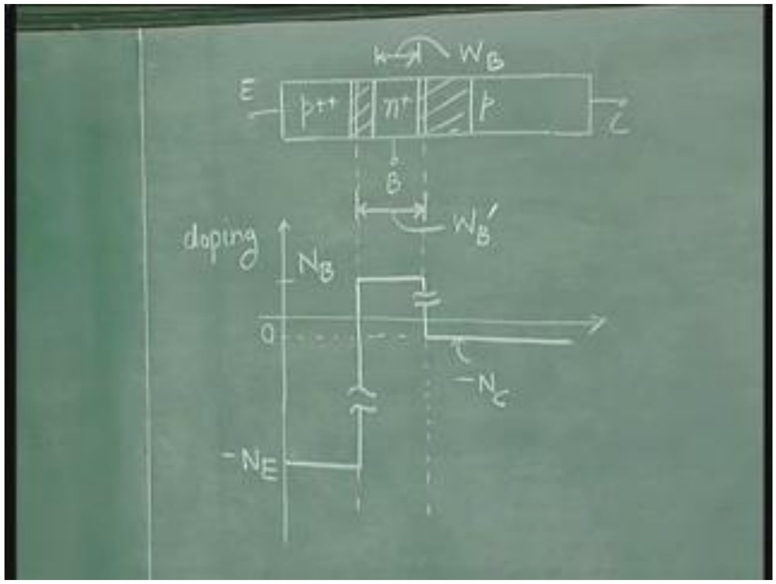

So here it can be shown as something like this and here also we will show a break and this doping is N_B the base doping. It is understood that if it is a p-n-p transistor the emitter doping is acceptor type while the base doping is donor type. Similarly we come to the collector and here the doping is even less than the base doping so this is shown as something like this. So this is this point and this is minus N_c. Now another thing we need to understand is that the p plus plus and p-regions will be assumed to be sufficiently long for the development of our simple theory for the transistor. Similar kind of assumption we had made in the case of PN junctions.

Now one critical distance parameter associated with this particular device is what is called the base width. Now if you show the space charge region here let us assume some bias conditions for this transistor, in the simple case we can assume the equilibrium condition so under equilibrium condition your space charge region can be shown as something like this. Therefore the space charge region is more on the n plus side than on the p plus plus side and similarly it is more on the p side than on the n plus side which is something like this so this is the space charge region. Now the electrical base width is the distance between these two space charge edges called as the base width W_B. And similarly the distance between the metallurgical junctions will be denoted by the symbol W_B prime. As we will see, it is this W_B that is of interest to us for developing the characteristics and W_B is less than W_B prime because of the space charge regions. So that is the device structure we will be using for the purpose of our analyses. In the next lecture we will develop the theory for the transistor action.