Solid State Devices
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Lecture - 29
Bipolar Junction Transistor (Contd…)

So we have been discussing the bipolar junction transistor. In the previous lecture we saw how the transistor can be used for small signal amplification. To summarize the discussion of the previous lecture; the bipolar junction transistor can be regarded as a transconductance amplifier. As we will see in today's lecture you can also regard the bipolar transistor as a current amplifier. But fundamentally there are a lot of advantages to be gained if you regard it as a transconductance amplifier.When you regard it as a transconductance amplifier you can compare it with other types of transistors such as field effect transistors. This point will become clear when we discuss the mass field effect transistor.

Now, coming back to this summary what we said is that this is the basic arrangement for deriving small signal amplification from the device. Here the emitter base voltage is applied and a resistance is included in the collector lead in series with power supply. The polarities of these two power supplies are such that emitter base junction is forward bias and the collector junction which is very close to the emitter base junction is reverse bias or utmost it is zero biased. We explained already that you cannot forward bias the collector base junction because then the transistor action is destroyed. Now this is this so-called common base configuration because both the voltages are applied with respect to the base terminal which is the common terminal.

In today's lecture we are going to see the other configurations. So, the bipolar junction transistor's capability to amplify small signals is more easily understood when you want to derive it from first principles when you use the common base configuration and you regard it as a transconductance amplifier. Here if you increment the emitter base voltage the result is an increment in the collector current.

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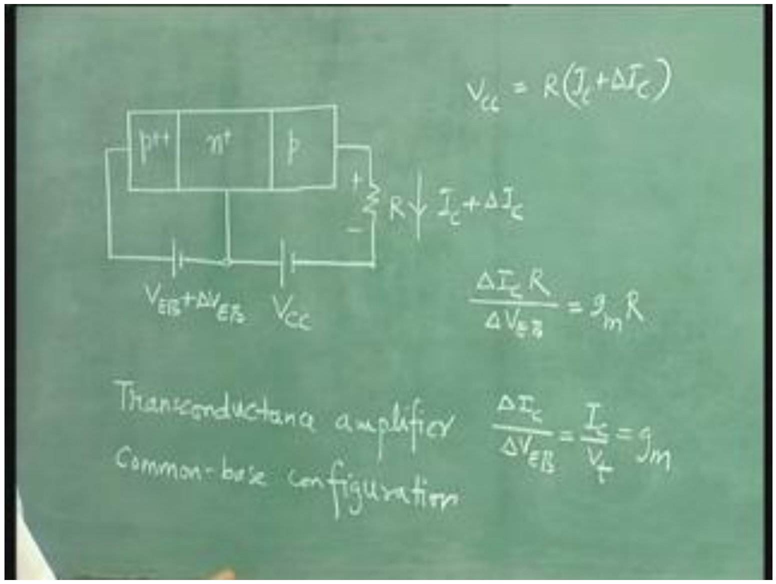

So you have I_C plus delta I_C meaning the current I_C corresponds to the voltage condition V_{EB}. When you increment V_{EB} by delta V_{EB} the I_C increments by delta I_C. The increment delta V_{EB} and delta I_C are related as delta I_C by delta V_{EB} is equal to I_C by V_t. This is what we have shown and this is so called transconductance of the device. Now the voltage amplification is given by delta I_C by delta I_C into R this is the small signal output voltage divided by the input increment that is delta V_{EB} and this is equal to g_m times R this is the voltage amplification.

The power supply V_{cc} should be stored such that V_{cc} is equal to R into I_C plus delta I_C where delta I_C is the maximum possible increment in I_C. So, for this limiting case when the value of delta I_C is such that I_C plus delta I_C into R is V_{cc} this junction will be zero bias because this voltage and this voltage will compensate each other. The polarity of this voltage is like this. For any other value of delta C lower than the value given by this equation this junction will be reverse biased. That is the summary of what we have done in yesterday’s class. Today let us begin by solving an example in which we calculate the values of alpha and beta the two parameters that we have associated with the transistor action.

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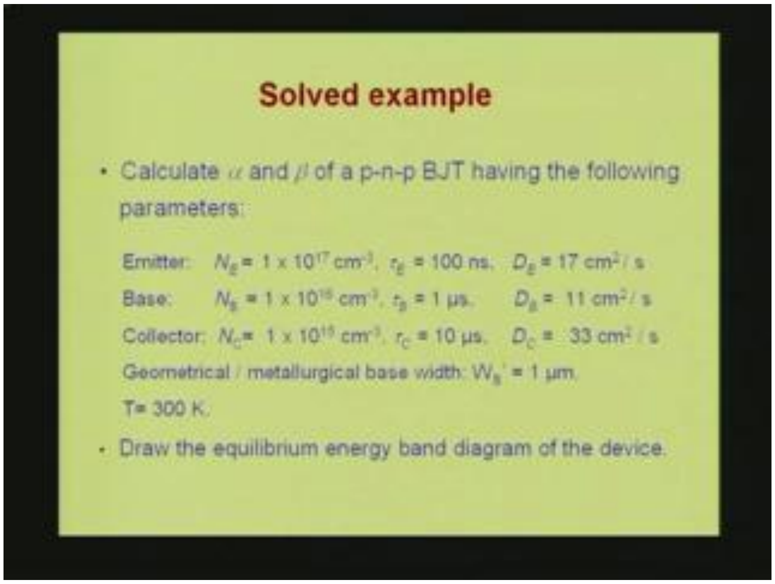

The problem goes like this: Calculate alpha and beta of a p-n-p BJT having the following parameters: Emitter: The doping level is 10 to the power 17 per cm cube this is the doping of acceptors because we are considering a p-n-p BJT. The lifetime of minority electrons in emitter tau$_E$ is 100 nanoseconds. And similarly the diffusion coefficient of the minority carriers that is electrons in emitter is 17 cm square by second. The corresponding parameters in the base are doping 10 to the power 16 per cm cube minority carrier lifetime 1 microsecond and diffusion coefficient minority carriers are 11 cm square by second.

In the collector the doping level is 10 to the power 15 per cm cube, the lifetime of minority electrons is 10 microseconds and the diffusion coefficient of this electrons is 33 cm square by second. We shall assume that the device has a geometrical or metrological base width of 1 micrometer, the temperature is 300 K. Now, after calculating the alpha and beta as the problem says we also have to calculate the equilibrium energy band diagram of the device. We have to sketch this diagram. So let us begin the problem.

This doping level is 10 to the power 17 per cm cube and this is 10 to the power 16 per cm cube and this is 10 to the power 15 per cm cube. This width is what we have been given as 1 micrometer up to this point. So this is 1 micrometer. Now we need to understand that the electrical base width that is the base width over which the excess minority carrier concentration is present is smaller than the geometrical base width because the electrical base width is the distance between the depletion edges in the base. So here if these are the depletion regions in the base then this is the electrical base width. So, while this base width is W_B prime this base width is denoted as W_B. So we need to determine W_B.

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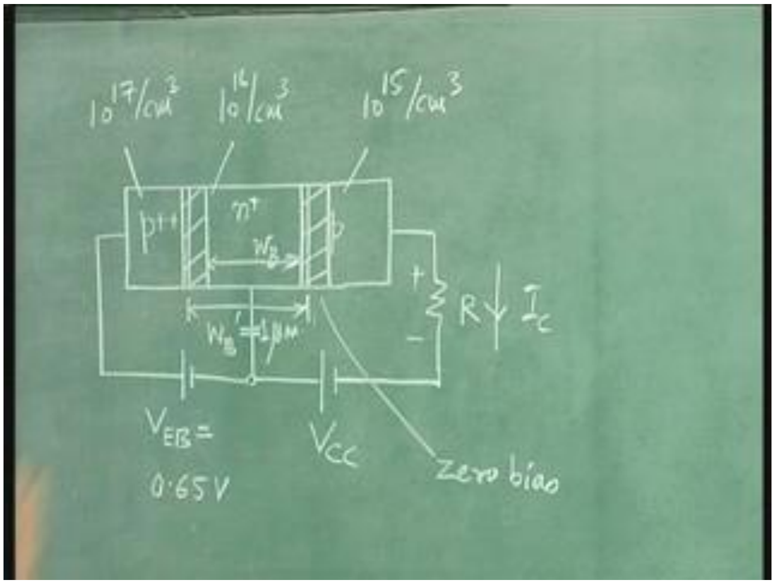

Now evidently this depletion region will depend on the bias V_{EB} and similarly this depletion width will depend on the bias V_{cc}. what we will do is that we will assume that the collector base junction is zero biased. We will find out alpha and beta for this condition. Emitter base junction has to be forward biased because unless there is a forward bias across emitter base junction the device is not really working as a transistor. So, on the emitter base junction we must assume a forward bias. We will assume a forward bias of 0.65 V on the emitter base junction. This we will assume to be zero bias.

So the first step is to determine W_B which requires the determination of the depletion width. So let us calculate the emitter depletion width here. We will redraw this diagram. So this is p to the power plus plus and n power plus base and this is the depletion region. We need this portion and then this portion so this is p so we have exploded the p-n-p transistor to show the depletion regions clearly and this is the junction. Now this distance is given to us as 1 micrometer. This depletion region is X_E that is the depletion region across the emitter junction and this depletion region is X_C across the collector junction. Now X_E is equal to square root of 2 psi_0 of the emitter junction psi_{0E} into epsilon which is the permittivity into the electric constant of this region by q into 1 by doping in the emitter plus 1 by doping in the base.

Now, what is the psi_{0E}? The psi_{0E} that is the contact potential of this junction we can find out as, at 300 degree K the thermal voltage is 0.026 electron V and logarithm of N_E N_B by n_i square so N_E is 10 to the power 17, N_B is 10 to the power 16 and at room temperature this is 10 to the power 10 into 1.5 n_i square so this is the contact potential. Now when you solve this you will end up getting a value of 0.757 V. Therefore, X_E you can evaluate as 2 into 0.757 as we have said we must always include the units also in calculation. So this is V into epsilon you know is 12 for silicon dielectric constant multiplied by 8.854 into 10 to the power minus 14 Farad by cm. This whole thing can be approximated as 10 to the power minus 12 Farad by cm by q is 1.6 into 10 to the power minus 19 Coulomb and the minus 19 we club with this power here, so this is Coulomb. And then 1 by N_E plus 1 by N_B where N_B is 10 to the power 16 and N_E is 10 to the power 17 per cm cube. So, if you take 10 to the power 16 out you will get 10 to the power minus 16 here and this will be cm cube in the numerator. And this bracket will be, if you take 10 to the power 16 out this is 1 by 10 because this is 10 to the power 17 so this will be 1.1 so these are the units. You can see that Farad into volt is Coolum, this cancels and this gives raise to cm square. So square root of cm square is cm. Now, when you solve this you will get this is equal to 0.32 micrometer. Please note that we must collect all the powers of 10 and we must collect all the other numbers here. And by this way you avoid making calculation mistakes.

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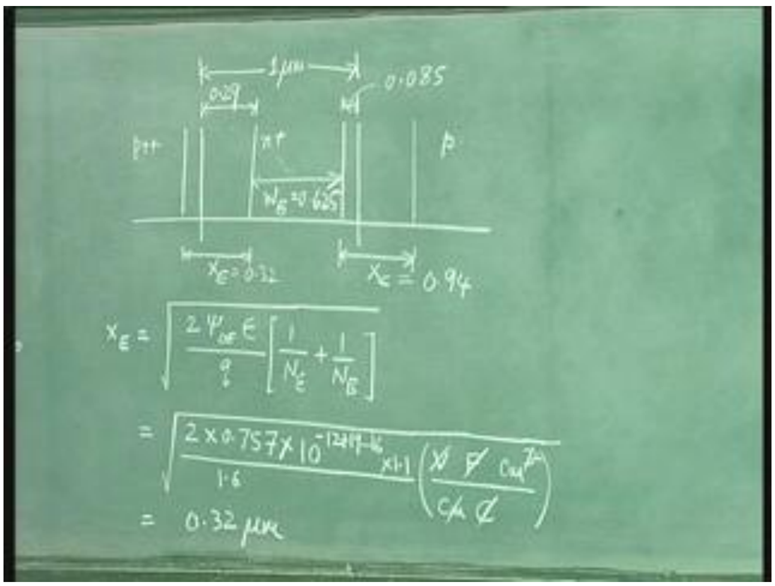

Now this is 0.32 and the values indicated here are in microns. Since this is 10 to the power 16, this is 10 to the power 17 this width is 1 by 10 of this width. Therefore if this is 1 unit this is 0.1 unit. Therefore 0.32 by 1.1 is this particular depletion width and that will turn out to be 0.29 microns. In a similar way we can evaluate X_C and this. It turns out that X_C will turn out to be equal to 0.94 microns. And again following the same approach this is one tenth of this so this distance is 0.94 by 1.1 and this is one tenth of that. Therefore this turns out to be 0.085 microns. We can therefore obtain the base width W_B as 1 minus 0.29 minus 0.085 which is this and that is 0.625 micrometer.

Now these calculations which we have done correspond to zero bias across the emitter base junction. As we said our device will operate with a forward bias across the emitter base junction. So what will happen is because of that this depletion width which we have estimated at zero bias will get reduced. Assuming that the forward bias across emitter base junction is 0.65 V the new depletion width can be estimated as follows: In this formula we replace psi_{0E} by psi_{0E} minus the forward bias. So this formula will get modified to psi_{0E} minus forward bias of 0.65 V. Now when you recalculate the emitter depletion layer parameters using this new value of potential across the emitter base depletion layer finally you will get this value as 0.11 microns. And as a result this base width will get modified to about 0.8 micrometer.

You can calculate the value of X_E for a forward bias of 0.65 V. Ultimately you will find that this X_C will result in the depletion layer on the base side of 0.11 at 0.65 V forward bias. So this is the base width which we must use in our estimation of alpha. Now alpha is equal to the injection efficiency into the base transport factor which is nothing but 1 by 1 plus the injection efficiency term is 1 by 1 plus D_E by D_B because it is I_{En} by I_{Ep}. So, first you have the terms corresponding to the emitter electron current and then the base current. So this is D_E by D_B into W_B by L_E into N_B by N_E and the base transport factor is 1 minus W_B square by $2L_B$ square.

Now we should substitute the various parameters here. For this we need to know what L_B is and what is L_E. Now L_B is square root of D_B into tau_B that is square root of D_B is 11 cm square by second and tau_B 10 to the power minus 6 seconds that is 1 microsecond and the result is 33 micrometer. In a similar way if you calculate L_E you will get square root of diffusion coefficient in the emitter. That is, 17 cm square by second into the lifetime in the emitter which we have taken as 100 nanoseconds or 0.1 microseconds. It is so many centimeters and this turns out to be equal to 13 micrometer. Now we can substitute these values and this can be written as 1 minus ½(0.8 by 33) whole square by 1 plus 17 by 11 as it is D_E by D_B so D_E is 17 and D_B is 11 cm square by second. Thus, each of these terms D_E by D_B W_B by L_E and N_B by N_E are dimensionless. W_B by L_E is 0.8 by 13 both are microns and N_B by N_E is 1 by 10 because emitter doping is ten times the base doping.

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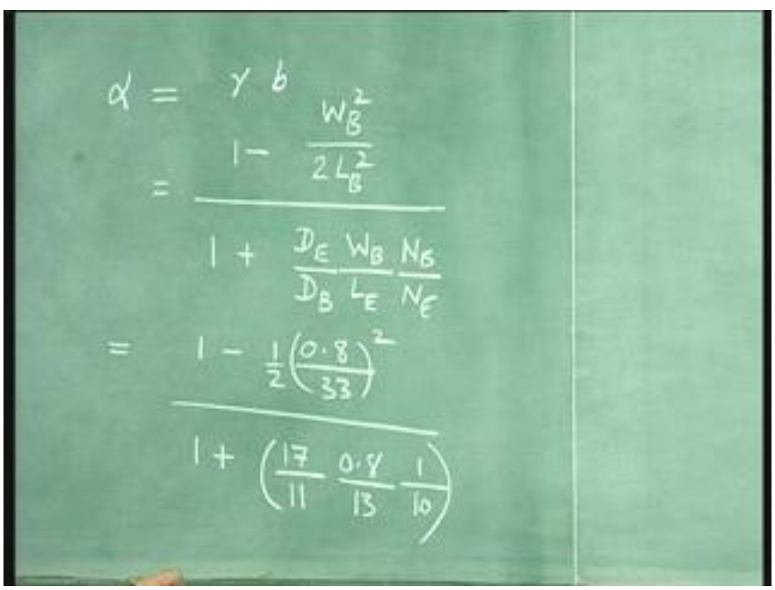

Now this can be simplified and you can write it as follows: First, notice that this quantity is really very small. Similarly this quantity also is much less than 1. It is for this reason that usually this formula in many practical transistors is approximated as 1 minus W_B square by $2L_B$ square minus this term because 1 by 1 plus x is 1 minus x D_E W_B N_B by

D_B L_E N_E so this is the approximation. The first term here is 3 into 10 to the power minus 4 minus the second term is 9.54 into 10 to the power minus 3. So this term is more than this term that is what you can see from here. Thus in modern transistors the base transport factor is not one which controls the alpha, it is this.

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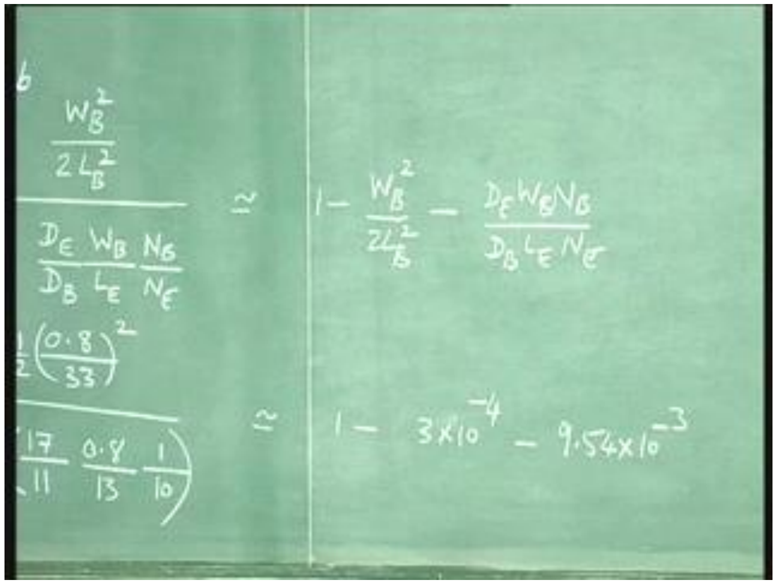

Since this is much less than this and even if you neglect it you still get a very close answer for alpha to the real value or accurate value. This is the value of alpha. Now you can go through the calculations and you will find alpha is equal to 0.99. And if you do the calculations for beta since beta is alpha by 1 minus alpha that would be 0.99 by 1 minus 0.99 so you will find beta is equal to 99. Let us write down these values, so this is equal to 0.99 and beta is 99. So alpha is 0.99 and beta is 99.

Now the next part of the problem was to draw the energy band diagram at zero bias under equilibrium conditions so let us do that exercise. You recall that first we should draw the Fermi-level as a constant line then we locate the junctions. So this is the emitter junction and this is the collector junction. Now, the distance between these two junctions is 1 micron that is what we have been given. When both the emitter base junction and collector base junction are zero bias then you recall that the depletion width here was 0.32 microns out of which 0.29 microns was on the base side. So this is emitter, this is base and this is the collector. So 0.29 microns on this side is somewhere around little less than one third of this distance. So we must draw the diagrams to scale.

Let us say this is 0.29 microns and one tenth of this will be on this side so let us say this about one tenth of that so this distance is 0.29 and this distance the depletion width here is 0.32. Similarly, on this side the depletion width is 0.94 microns out of which 0.085 microns are on this side because collector is lightly doped when compared to the base. So 0.085 is about 0.1 and 0.1 is one tenth of this less than one tenth of this so this is half and divide this into five parts. So this is about one tenth of a micron and even less than that and ten times this on this side so that is about this much. So this distance is 0.94 so this collector depletion width is more than emitter base depletion width out of which here this distance is 0.085 microns. All values are in microns.

Having located the depletion regions let us extend this E_f a little bit more. Now we must draw the conductance and balance band edges. So this is P side and the doping here is 10 to the power 17. Suppose this is the valance band edge here so this is E_v. So E_f minus E_v here represents 10 to the power 17 doping. The doping in the base is 10 to the power 16 so the distance between conduction band and E_f will be more than the distance between valance band and E_f here because this is n-type so we take little bit more.

Let us say this is E_c. Now coming back to this side this 10 to the power 15 p-type and this distance here will be more than this so let us take this as E_v in the collector. This is the conduction band edge in the collector and now we can locate the conduction band edge and following this we can show the valance band edge in the base somewhere here and then similarly the conduction bandage here. Now we join the conduction and balance band edges as a continuous line. So this is what you have as the energy band diagram. This potential drop is 0.757 V and similarly this is a built-in potential and this potential drop is 0.637 V. This is our energy band diagram under equilibrium. Let us write it down here, this is equilibrium band diagram of the pnp BJT. Now, when the devices are operating as a transistor as we said the voltage across emitter base junction would be such that it is forward bias. For example, we have assumed a forward bias of 0.65 V.

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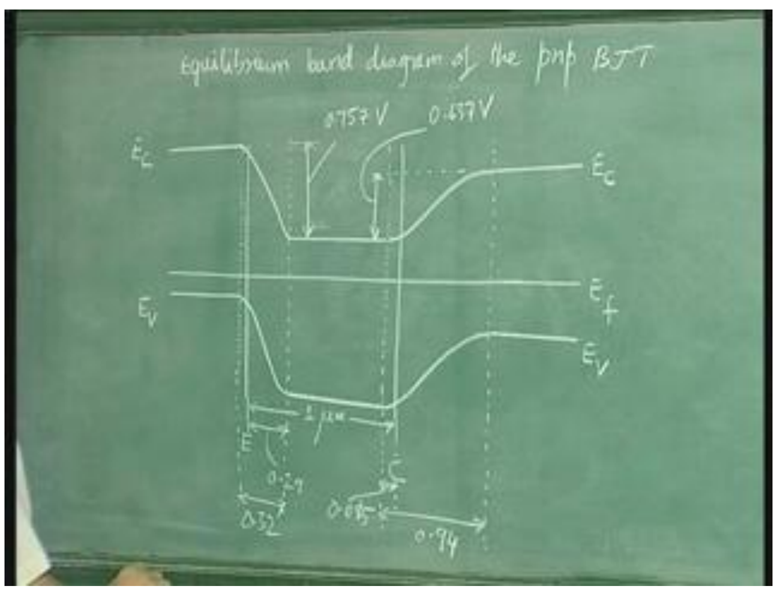

So when you want to draw the energy band diagram under forward bias for the emitter base junction please note that this height will reduce from 0.757 to 0.757 minus 0.65. And similarly the collector base junction maybe reverse biased. So, in practice when the device is operating as a transistor the band diagram will be such that the emitter base junction will have a small variation in the conduction band edge but the collector base junction will have a vary large variation in the conduction band edge. So unlike what has been shown here this height is small when compared to this but when the device is operating most of the operating conditions this will be small because this will be forward bias and this will be large because it will be reverse bias. So, band diagram when it is operating good look something like this. This is the conduction band edge and this is the balance band edge. I have not drawn the Fermi-level here so this is an emitter base junction and here you have the collector base junction something like this. This is a kind of energy band diagram you will see where this height is built-in voltage minus the applied forward bias and this height is built in voltage plus the magnitude of the reverse bias.

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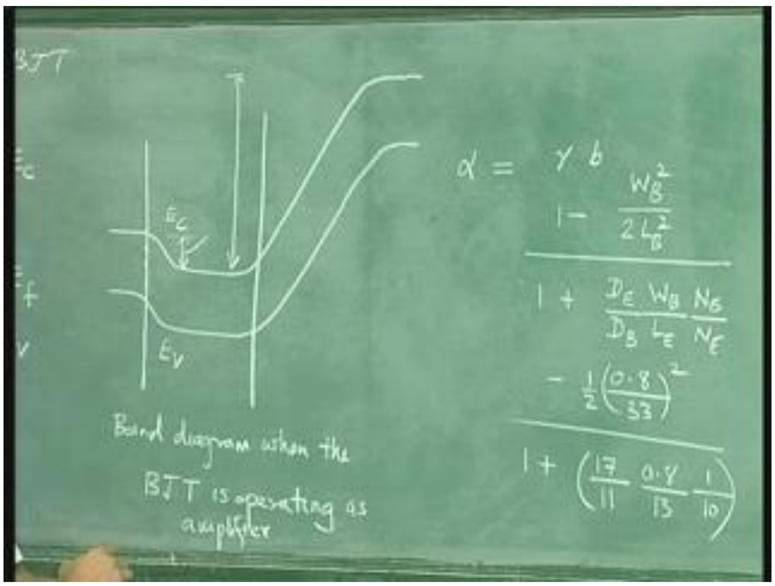

So, this is band diagram when the BJT is operating as amplifier. The collector base voltage keeps changing so this height will keep changing. The emitter base voltage also keeps changing little bit so this height may change a little bit. But here the variation will be large because you can have the collector base bias going from 0 to very high reverse biases. That is the energy band diagram of the bipolar junction transistor.

Now let us look at the operation of the transistor in little more detail. What do our calculations mean?
So 0.65 V is the forward bias across the emitter base junction and we said that the alpha is 0.99 and beta is 99. What are the kinds of currents that will be flowing in this device for this condition? We can calculate the emitter current I_E as follows: I_E is given by q into n_i square [D_E by N_E L_E plus D_B by N_B W_B] (eV_{EB} by V_t minus 1). Here first we will have the terms for the emitter that would mean emitter doping and emitter diffusion length of minority carriers and in the numerator you will have the diffusion coefficient. Similarly, doing something for the base you will have these terms, for the base you have W_B. This is the relation between emitter current and the emitter base voltage.

We know this from the PN junction theory and we have written it down earlier. Now you can substitute the various quantities here as we have done earlier while finding out the alpha and beta. We are discussing 40 is equal to 300 K. So, if you calculate this you will find incidentally here we must also put the emitter area. Without the emitter area this could be the current density. You can always do a dimension analysis of this and check that right hand side is amperes by cm square. Let us do an exercise here for example.

This is Coulomb, n_i square is equal to cm to the power 6 in the denominator, diffusion coefficient is centimeter square power whole second, doping is per centimeter cube so it goes into the numerator and this is centimeter in the denominator. This quantity also will have the same dimensions as this quantity so we need not consider this. Similarly this is dimensionless. Now here you find this will cancel and here you will get cm square, Coulomb per second is, indecently we made a mistake here we can see that because Coulomb per second is amperes and you are getting this additional volt, this volt should not be there, this was a mistake. The mistake was that the diffusion coefficient we wrote as centimeter square per V second is wrong. Diffusion coefficient is centimeter square per second and mobility centimeter square per V second. So anyway we remove this volt and we find that it is ampere per centimeter square, this is the current density.

If you evaluate this you will find the answer to be 36 ampere by cm square where this V_{EB} is 0.65 V and V_t is 0.026 V. So this is the emitter current density that is the current density flowing here. This means that if your device has an area which is 100 microns by 100 microns. If A_E is 100 microns by 100 microns imagine that the area is in that direction so that area we are talking about is 100 micron by 100 micron. If that is so then the current would turn out to be I_E is equal to A_E into J_E which is nothing but 10 to the power minus 4 cm square that is 36 into 10 to the power minus 4 amperes is equal to 3.6 mA. So we will assume this as the emitter area then the current here would be 3.6 mA. So emitter current of 3.6 mA will be flowing here. And how much is the collector current flowing? Collector current is alpha times the emitter current so 3.6 mA into 0.99 that will give you 3.56 mA.

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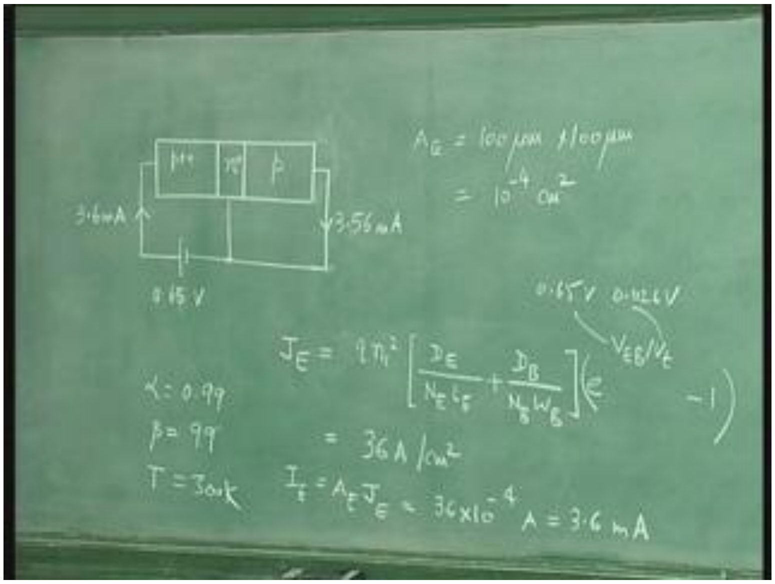

And this base current I_B would be beta times smaller than this or it will be 1 minus alpha times this and 1 minus alpha is 0.01 so hundred times less than this current. So this will be 36 microamperes. Those are the kind of currents flowing in the transistor for this biasing arrangement. Now in practice this will not be zero bias when the device is operating like a transistor, you will have to put a cell here and you will put a load resistance across which you will take the output voltage. And you will make an increment in the input voltage so small signal will be super imposed over this DC and as a result you will have small signal over this DC current.

Now let us understand what is meant by small signal. A small signal current means the current maybe about one tenth in fact one tenth is also a very large value, one tenth of the DC current is not really a small signal but let us for practical purposes assume one tenth of the current. So it is 3.56 mA plus delta I_C which is 0.356 mA. These are the incremental currents. Suppose you want to pump in through this lead what should be the change in emitter base voltage which will produce this change in collector current? We can easily find out as follows: delta V_{EB} is equal to V_t by I_C into delta I_C because delta V_{EB} by delta I_C is V_t by I_C or delta I_C by delta V_{EB} is I_C by V_t.

We have seen this relation: g_m into delta V_{EB} is delta I_C. So substituting the values we can find out delta V_{EB}. So this is equal to 0.1 times V_t because delta I_C by I_C is one tenth is what we have assumed, so 0.1 times V_t means you will have to make a change by writing this as plus 2.6 mV. So, 2.6 mV increment over 0.65 V will produce an increment of 0.356 mA in the collector lead. Obviously this will also produce an increment in the base current as well as the emitter current. So these increments here and here also will be one tenth of the corresponding currents so this will be 3.6 microamps increment in the base current and it will be 0.36 mA increment in the emitter current.

Now, if this is the incremental current present what should be the value of V_{cc}?

The value of V_{cc} should be equal to the resistance R here multiplied by 3.56 plus 0.356 mA. Now let us take an extreme situation where this current delta I_C is exactly equal to 3.56. It is no more a small signal condition but still let us assume that we are trying to operate our device so we can get the maximum change in the collector current and maximum possible output voltage swing. So, if delta I_C is exactly equal to 3.56 mA and if R is 1 kilo ohm, the value of V_{cc} is what you need, so the collector base junction always remains reverse biased or utmost it becomes zero biased.

The value of V_{cc} for that condition to be met would be V_{cc} is equal to 1 kilo ohm into 3.56 that is the DC current the quiescent current plus the incremental current that is another 3.56 mA which is equal to 3.56 into 2 V that is about 7.12 V and that would have to be your V_{cc}. This is the numerical example illustrating the operation of the transistor as a small signal amplifier. Now, as we have said this is the common base configuration because the base is common and this is the emitter which is the input and collector is the output. Instead we can have common emitter configuration where you can not only get the voltage gain that you are getting here from emitter base junction to the collector lead but you can also get a current gain. For example, here the collector current is alpha times emitter current. Actually there is a slight fall in the output current as compared to input current, this is input and this is output so you are not really having a current gain instead a current loss. You are however having a voltage gain or a transconductance gain.

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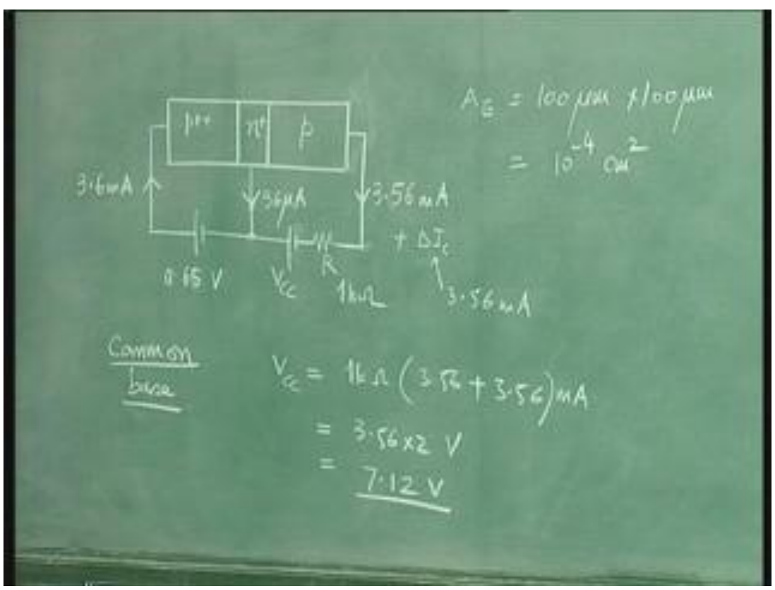

If you use the base lead as the input terminal instead of the emitter lead as a input terminal and continue to use the collector as the output terminal then clearly from base to collector there is a factor of beta increase in the current. So we will be able to get the current gain also in addition to the voltage gain. So the configuration for common emitter would be as follows: Let us modify this same circuit to make it common emitter. If the emitter should be common the collector should be connected to emitter through this so we remove this from here and we put it here.

Now, when we do that this current here will not be 3.6 mA obviously because this is emitter current so this 3.6 mA is actually the current in the emitter lead so that is going to be 3.6 mA and the current in this lead through the cell is 36 microamperes. So these currents are not going to be affected so long as the collector base junction is zero biased or reverse biased, that is the assumption.

Now you may say that when the collector base junction is reverse biased then what about the I_{C0}? Should we not add I_{C0} here because this we have calculated for zero bias condition. When the collector base junction is reverse bias we must add the current because of I_{C0}. In fact the current you will have to add when in the common emitter configuration will be slightly different from the current you need to add in the common base configuration. But since I_{C0} is small we have neglected it but we will justify this approximation later on.

So long as you do not get into the effect of I_{C0} and you maintain zero or reverse bias across the collector base junction you maintain 0.65 V across emitter base junction and your device as an emitter area of hundred microns by hundred microns then for the other doping and lifetime and diffusion coefficient conditions you are going to have the same currents flowing in the device. However, now when you make a change of 2.6 mV here you will get a change of 0.356 mA here and there will be a change of 3.6 microamps here. If you now try to find out the power gain of this then your power gain will be as follows: the input terminal is this and the output terminal is this so delta I_C by delta I_B is a small signal current gain for the common emitter condition. The voltage gain is given by the previous formula that is g_m into R where g_m is a transconductance of the amplifier and R is this resistance.

So this g_m is nothing but I_C by V_t so delta I_C by I_B into I_C by V_t into R, so delta I_C by I_B is nothing but beta so this is the power gain in the common emitter mode. Whereas a power gain in the common base mode was alpha times I_C by V_t into R so CE stands for common emitter and CB stands for common base. Now since you get a power gain in the common emitter configuration that is this configuration it is this configuration that is used most often for signal amplification.

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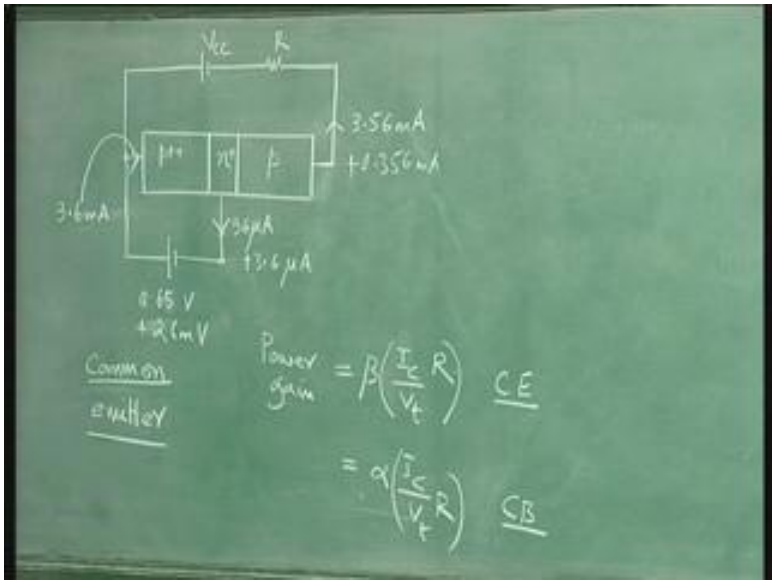

The common emitter is used most often for signal amplification. So it is 3.6 microamperes and here it is 2.356 milliamps so input is 3.6 microamperes output is 0.356 milliamps so current gain is there. In addition, anyway you have voltage gain because when you pass this through the resistance R if it is 1 kilo ohm then it is 0.356 milliamps into 1 kilo ohm that is the output voltage change in response to this input voltage change. Now let us build up from here the normal common emitter amplifiers circuit that we see with many more resistors than this. And that can be a built up very easily from here as follows: We will draw the same circuit using the symbol of the transistor first. So first we convert this into a symbol. Now what we will do is we will turn it to 90 degrees because that is the way we often see it in the books. Here you have the resistor and here you have the power supply.

Now you will have to super impose the AC over this so in equivalent circuits terms putting this as AC source here but in practice doing this is somewhat difficult to put a source in series with another source. There is a better arrangement to do this. For that purpose what we do is we modified this whole circuit a little bit on this side. First for the DC conditions instead of having one power supply here another here and since this power supply is smaller than this power supply we can derive this from here as a resistance divider. So from this power supply we use a resistance divider to get this required voltage and now we use this as the input terminal and we couple the AC voltage to this coupling capacitor. This coupling capacitor provides DC isolation between this point and this point. Similarly the output is then taken from here through another coupling capacitor, this is the output.

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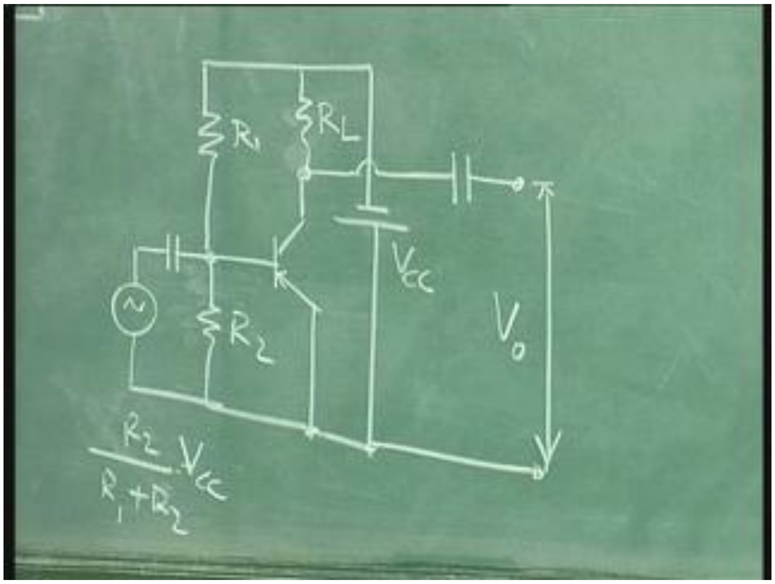

So this is the so called V_{cc}, this is the load resistance R_L, this is R_1 R_2, R_2 by R_1 plus R_2 into V_{cc} is so called V_{EB} here. Now this will not provide you a stable current because you are fixing the voltage here so this is V_{EB}. Try to fix the voltage because if the temperature changes then the current will change rapidly.