Fundamentals of Semiconductor Devices
Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science, Bangalore

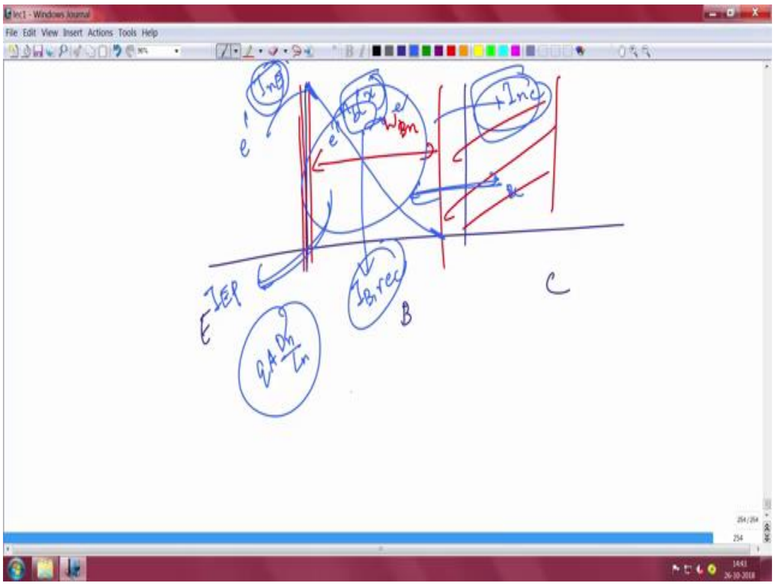
Lecture – 28
Working of BJT (contd)

Welcome. So, if you recall in the last class, we had ended the lecture with telling you how to derive the different expressions of the current. The most important thing is the profile of minority electrons in the base ok. I am talking about n p n, so the base is p-type doped.

When you are injecting electrons from the emitter to the base by forward bias, ok, the electrons will recombine and decay in the base, the base is very short, why? Because then only that will make sure that very few electrons are recombining in the base, so that majority of the electrons reach the collector and come out. Otherwise, most of the electrons will recombine in the base, very few electrons will come out from the collector, you will not get good current out of the device ok.

So, the base, in the base when the electrons are injected, they will decay almost linearly. And we discussed at that profile of the minority carrier electron in the base, is the most crucial ok. So, we will take a recap from there and I will quickly finish up the expression for the base, emitter and the collector current, so that we can understand the transport ratio, the beta, the gain, the base transport factor, all these things can be expressed in terms of proper quantitative definitions ok.

(Refer Slide Time: 01:41)



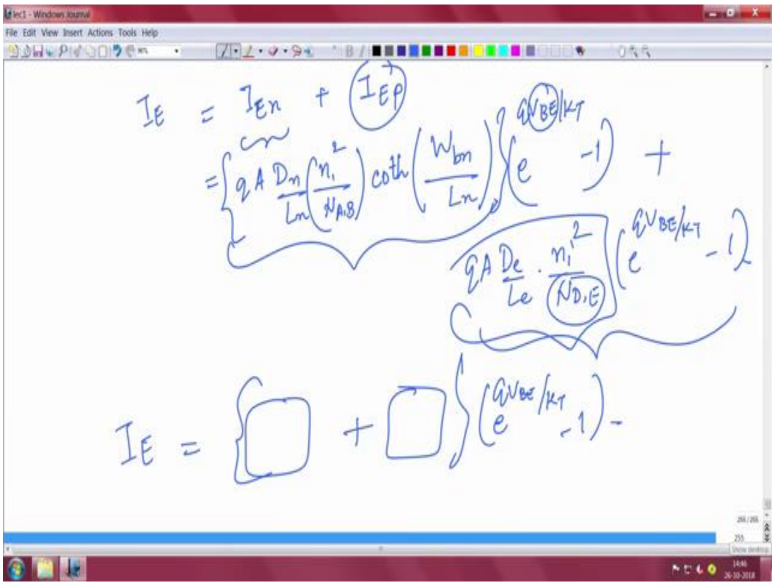
So, we will come to the whiteboard again here. So, if you recall from the last class, I told you, this is your base, this is your emitter, this is your collector, there is a small depletion here, sorry, and then there is a large depletion here, only this matters, which is W_{Bn}. The electrons that are injected from the emitter side will decay almost linearly; almost linearly it will decay and that profile, the minority carrier profile is n b x.

If you take the slope of that profile here, and multiply with qAD_n by L_n i.e. $\frac{qAD_n}{L_n}$ that is the diffusion coefficient things and all, you will get and the slope here, you will get the current that is coming from the emitter side because of electron. And if you take the slope here and you multiply with this quantity, you will get the current that is going out there because of electron.

Of course, there is a base-collector reverse leakage current, which I am neglecting here, but there is a small base-collector reverse leakage current here. And that difference of this and this should I ideally give you, the recombination current that is taking place in the base because of the electrons that are going there no, they will recombine in the base, there can be come out from the difference of this and this. Of course, there is a back injected current here, holes that is very easy to explain right.

So, let us write down the equations for the current here, ok, let us write down the equations for the current here. If you recall, the first expression is, you know so let me go to a new page actually.

(Refer Slide Time: 03:03)



So, I_E the total emitter current ok, the total emitter current will have to consist of two quantities. One is the I_{En} that is your electrons that are injected from here ok, which I told the slope here multiplied by this ok. Of course, I did not write down the expression for this profile here, you know, this base profile $n_b(x)$ is the expression depends on sin hyperbolic and other things. It will all be uploaded in the notes, so not a big deal. But, it is close to being linear, but not exactly linear ok.

We know the two boundary conditions by the way. We know the two boundary conditions, the total carrier here and the total carrier here that is the boundary condition you know that. So, you know, so essentially what is going on here is that you have the emitter current, which has two components sorry; one is the electron injected component I_{En} and one is the hole back injected component I_{Ep}.

So, this component is can be written as qA, I told you right, D_n by L_n, this is basically in the base right, n_i^2 by the base doping, this is the minority carrier electron concentration there, into coth hyperbolic, there is a hyperbolic function here of the base width. This is the neutral base width, WBn is the neutral base width remember. This is the base width, not the true base width, but this base width edge of depletion to edge of depletion that is what matters ok. Edge of depletion to edge of depletion by L_n, this is the diffusion length ok. This, of course this times e to the power qV_{BE} by kT minus 1, that is your forward biased voltage that you are applying, of course it depends on the voltage.

$$\frac{qAD_n{n_i}^2}{L_nN_{AB}}\coth(\frac{W_{Bn}}{Ln})(e^{\frac{qV_{BE}}{kT}}-1)$$

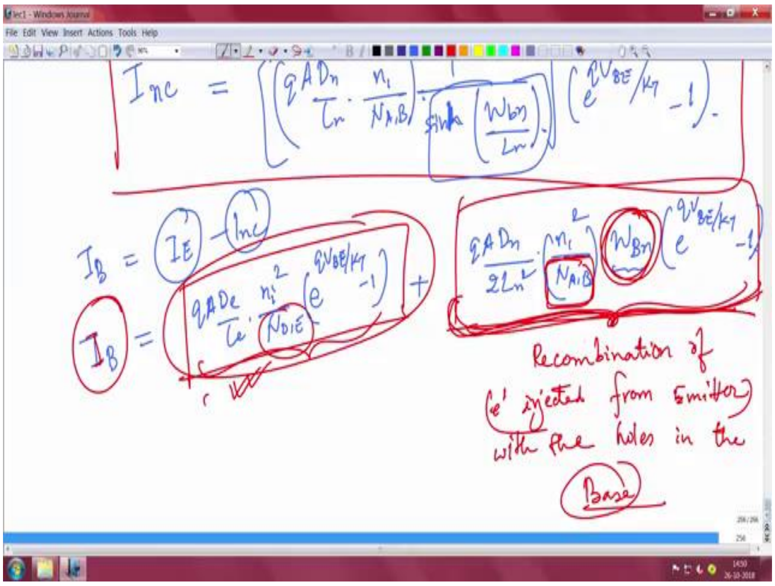
If you do not apply its voltage, you will not get any current plus the this component, which is basically easy, it is an exponential decay qAD_e by L_e, because this is the holes that are decaying in the emitter into n_i^2 by N emitter side doping, that is, you can increase the doping and make this quantity become very small, that is the idea, into e to the power qV_{BE} by kT minus 1.

$$\frac{qAD_e{n_i}^2}{L_eN_{DC}}(e^{\frac{qV_{BE}}{kT}}-1)$$

So, I can write the emitter current as this quantity, that quantity plus this quantity, that quantity, whole thing into exponential of e power qV_{BE} by kT minus 1, that will what will come it to be.

$$I_E = \frac{qAD_n{n_i}^2}{L_nN_{AB}}\coth(\frac{W_{Bn}}{Ln})(e^{\frac{qV_{BE}}{kT}}-1)+\frac{qAD_e{n_i}^2}{L_eN_{DC}}(e^{\frac{qV_{BE}}{kT}}-1)$$

(Refer Slide Time: 05:34)



Similarly, if I take the slope of the minority carrier concentration here and I multiply by this, I get the collector current right, the collector current because of the electrons that are coming out right. So, the collector current because of the emitter the electrons that are reaching there and I am excluding the base-collector reverse leakage current, that is because very it is very small.

So, then this component will come out to be the slope of that no, so that will be qAD_n by L_n into minority carrier profile, which is N_A by N_B, this is all P-N junction thing basically, into 1 by sin hyperbolic, because the minority carrier profile has hyperbolic functions, sin hyperbolic into WBn by L_n, ok, and the whole thing of course has to be multiplied by e to the power qV_{BE} by kT minus 1, that is your collector current i.e.

$$I_{nc} = \frac{qAD_n n_i^2}{L_n N_{AB}} \frac{1}{\sinh(\frac{W_{Bn}}{Ln})} (e^{\frac{qV_{BE}}{kT}} - 1)$$

And the base current; the base current will therefore be the difference of the emitter current, the total emitter current minus this collector current, the collector current because of the electrons, I am neglecting the base-collector reverse leakage by the way ok.

So, if you do this, you will get two components of the base current. Of course, one is the back injected hole which is this, you might this is an emitter current, but also this has there are in the base component, you can take think of it, so that component will come, that component is qAD_e by L_e n_i^2 by N_{DE}, right, into e to the power qV_{BE} by kT minus 1, right, plus there is another component and this component comes because of the recombination that is qAD_n by 2 L_n^2.

Because, if we subtract the sin hyperbolic and this coth hyperbolic, their functions will come, the difference of coth hyperbolic and sin hyperbolic function that can be approximated by some Taylor series and that is why the hyperbolic function is gone away. So, two qAD_n by $2L_n{}^2$ into the minority doping n_i^2 by N_{AB} into W_{Bn}, which is your minority carrier. The base neutral base width into e to the power qV the same thing is there actually, qV_{BE} by kT minus 1.

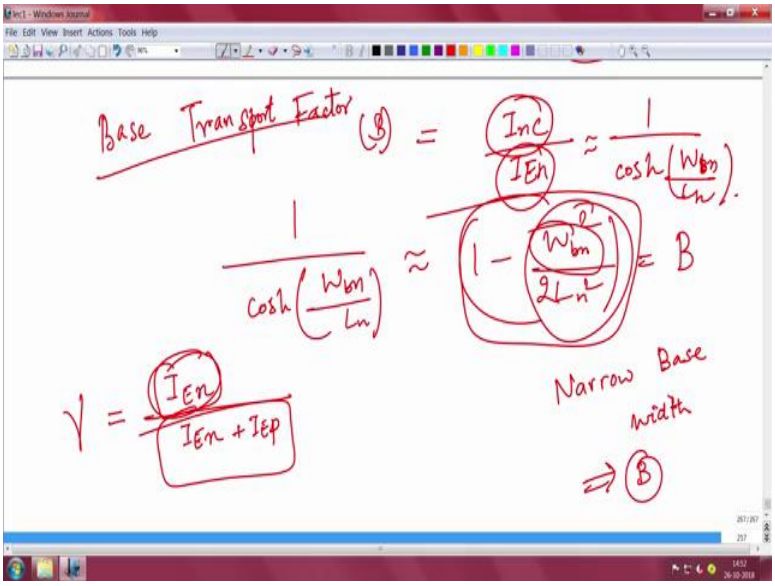
$$I_B = \frac{qAD_e n_i^2}{L_e N_{DE}} (e^{\frac{qV_{BE}}{kT}} - 1) + \frac{qAD_n n_i^2}{2L_n{}^2 N_{AB}} W_{Bn} (e^{\frac{qV_{BE}}{kT}} - 1)$$

So, please recall that this quantity is because purely due to the recombination of electrons in the base, this is because of recombination of electron injected from emitter, ok, this is electron because of recombination of electron injected from emitter with the holes in the base, with the holes in the base. So, electrons that are injected from the emitter will be recombining with the base, holes in the base, so that recombination gives rise to this component of the current.

This is the back injected component, and this can be made very small, you know by basically changing the doping here, this also we want to be very small basically, ok. So, for this to be small, your base width must be small, because the base current should be very tiny. And if the base current this width is small, then also you know you can have a higher gain will come there ok. You also want the, this you know this quantity you cannot make it arbitrarily small now that large or small. Because, if you make because if this quantity is very small, then this might limit your base current.

So, then you do not want this base doping to be super light, because then your base current will increase, which is not what you want ok. So, these are the two components, and you know depending on the question and the numerical that is asked, either both or one of the components will become predominant in the question, ok. This is a base current, we know the base current, we know the collector current, you know this is the collector current essentially, remember, and this is the emitter current, this is the whole thing is emitter current this plus this.

(Refer Slide Time: 09:36)



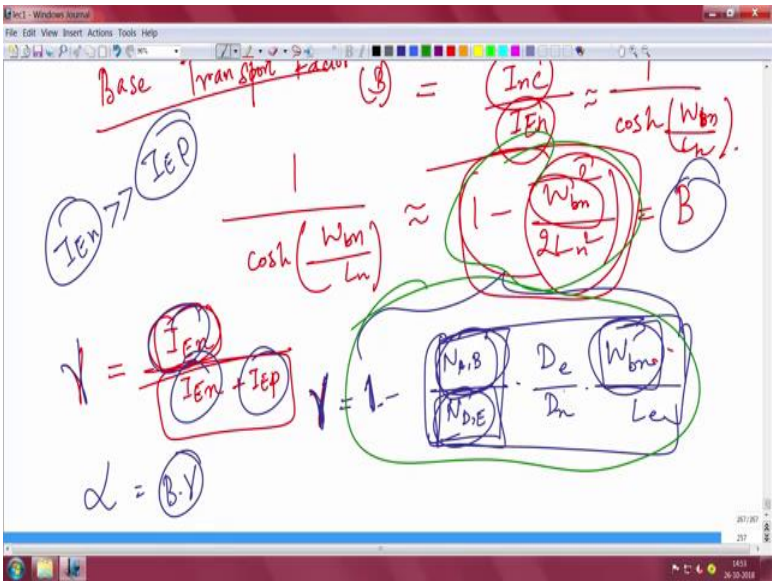
So, what we can do now is that, I can define that you know the, you can define the base transport factor, you know, base transport factor if you remember last to last class probably we had discussed, base transport factor B, essentially tells you what fraction of the collector current because of electron, the electron collector current not the base collector leakage current, what fraction of the collector current actually comes from the electron emitter current, not the total emitter current, the electron emitter current.

So, if you take the expression for the collector current in the emitter current from the two slides before, then this ratio will come out to be $\frac{1}{\cosh(\frac{W_{Bn}}{Ln})}$ ok. So, $\frac{1}{\sinh(\frac{W_{Bn}}{Ln})}$, this whole thing can be approximated as $1 - (\frac{W_{Bn}}{L_n})^2$, ok. So, this is your beta, the B, base transport factor.

So, the base transport factor becomes better or it improves, if this quantity becomes slower, which means this quantity must approach 1, which means the base width has to be narrow. So, a narrow base width also helps, a narrow base width also helps improve your base transport factor, ok.

Similarly, your gamma or the injection emitter injection efficiency is defined as the total fraction of emitter current, which is your electron current. So, this is total fraction of emitter current is $I_{En} + I_{Ep}$. So, if you put down the expression for I_{En} and I_{Ep}, I_{Ep}, there is no base component here by the way, all these things.

(Refer Slide Time: 11:25)



Then you will find out that the emitter injection efficiency, ok, the emitter injection efficiency, gamma, can be written as 1 minus base doping. These expressions I am taking from the previous two slides. Base doping, excuse me, emitter doping, diffusion coefficient in the emitter, diffusion coefficient in the base, base width, neutral base width W bn divided by the emitter efficient, the diffusion length in the emitter.

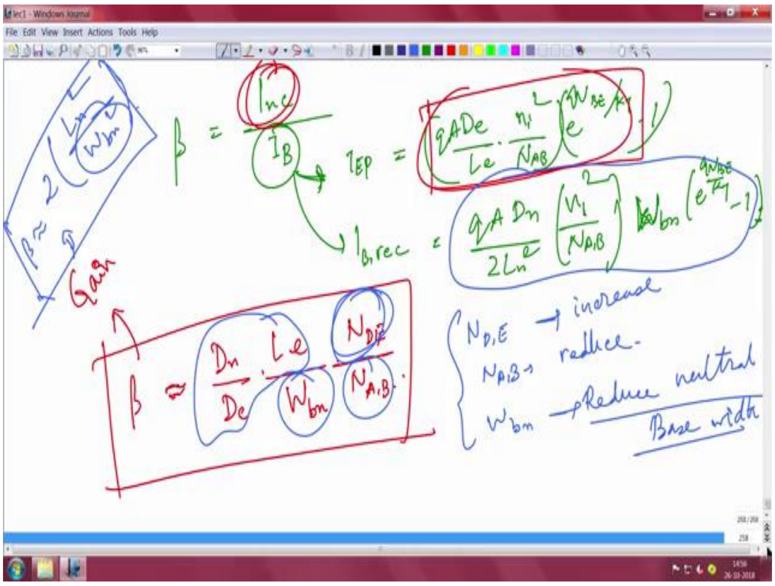
ɼ = 1 - $\frac{N_{AB} D_e W_{Bn}}{N_{DE} D_n L_e}$

You want this quantity to be as small as possible, so that the entire, this quantity becomes as close to one as possible. So, the emitter injection efficiency you want to be one, which means you want that most of the electrons, the most of emitter current is because of I mean electron current and not because of the base injected hole current.

Remember a thing, so for that, you want the gamma to be close to 1 and you can get gamma close to 1 when your base doping is much lighter than your emitter doping, that also helps your other things and when your base width also is narrow. So, eventually this all boils down to the fact that base width should be narrow, and the base doping should be much lighter than the emitter doping, in which case, you can improve the gamma, you can also improve the base transport factor, ok.

And of course, the collector transport, that the current transfer ratio alpha is given by B times gamma. So, the product of, you know, the product of essentially this quantity and this quantity will give you alpha. And so, if this improves, then alpha will also improve.

(Refer Slide Time: 12:55)



And finally, we have beta which is your basically the total current in the output by the base current. Now, base current has two components; one is the back injected current component, which is like qAD_e by L_e n_i^2 by N_{AB} into e to the power qV_{BE} by k T minus 1. And another component is the base recombination current, true recombination current, which is qAD_n by 2

L_n^2 n_i^2 by N_{AB}, this is the base doping in the minority base into WBn into e to the power qV_{BE} by kT minus 1, kT minus 1 ok. You can understand that right, this is e to the power qV_{BE} by kT minus 1 ok. So, this is the two components.

$$I_B = \frac{qAD_e n_i^2}{L_e N_{DE}}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) + \frac{qAD_n n_i^2}{2L_n^2 N_{AB}} W_{Bn}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

Now, if I assume that this component dominates, this is the primary component, then your beta will be given by this ratio; by this ratio, if you can plug in this expression from the two slides before, ok, if you take the two slides before, then the ratio will come out to be around the emitter, the base diffusion coefficient by emitter diffusion coefficient, emitter coefficient diffusion into the emitter diffusion length by the base neutral base width into emitter doping by base doping, sorry this is N_{AB}.

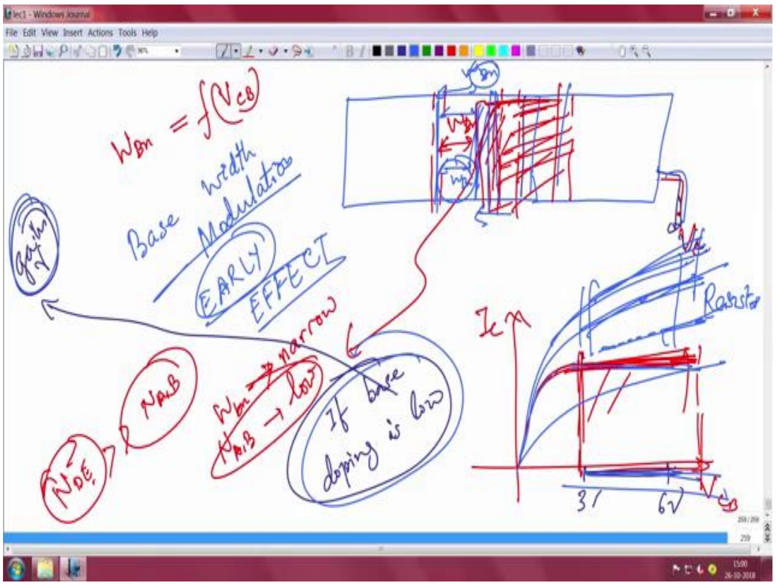
$$ß = \frac{N_{DE} L_e D_n}{N_{AB} D_e W_{Bn}}$$

So, your beta, this is your gain by the way, direct gain, your gain can be increased if your emitter doping is much higher than the base doping, that is what we have been telling you. And if this quantity is very small in the denominator, which is the base width should be narrow, because this other three quantities are constant, you do not change them so much. You increase the emitter doping, increase the emitter doping, which is the same thing right, as we have talked about in the emitter injection efficiency and all.

Reduce the base doping; reduce the base doping and reduce the neutral base width, reduce neutral base width, right, neutral base width. So, make the base shorter. So, if you satisfy these three conditions, your beta will go up. And of course, if your beta is dominated by this, then your gain beta will look like 2 into Ln^2/W_{Bn}^2, in which case also modern doping, your base width should be narrow.

In that case, the base will, the base current will become smaller and your ratio your gain will become larger, ok. So, these are the ways in which you can make the transistor have a higher gain and make it a better device, ok. But, there are some price you must pay, you do not get all of these things in free of cost.

(Refer Slide Time: 15:59)



So, one problem is that, one problem is that, what is the one problem. One problem is that, your ideally, ok, I understand that there is a depletion here, there is a small depletion here because of forward bias, there is a large depletion here, this collector whatever collector voltage you are applying.

Like this is your, whatever output characteristics and this is your collector current. The collector current here does not depend so much on the collector voltage, ok. The collector voltage, after it becomes this, you know flat; saturate, the collector voltage does not actually have an effect on the collector bias.

But, if you are, you know for increasing the gain, for increasing the gain or for making emitter injection better, alpha better, B better, if you want to make all this better, ok, then your base width should be narrow, W n should be narrow, that is one thing. And the base doping, the base doping, p-type doping in the base should be low. Remember that emitter base doping should be much higher than the base doping or emitter electron, the n-type doping should be much higher than the base doping; if that is the case, then base doping will be light.

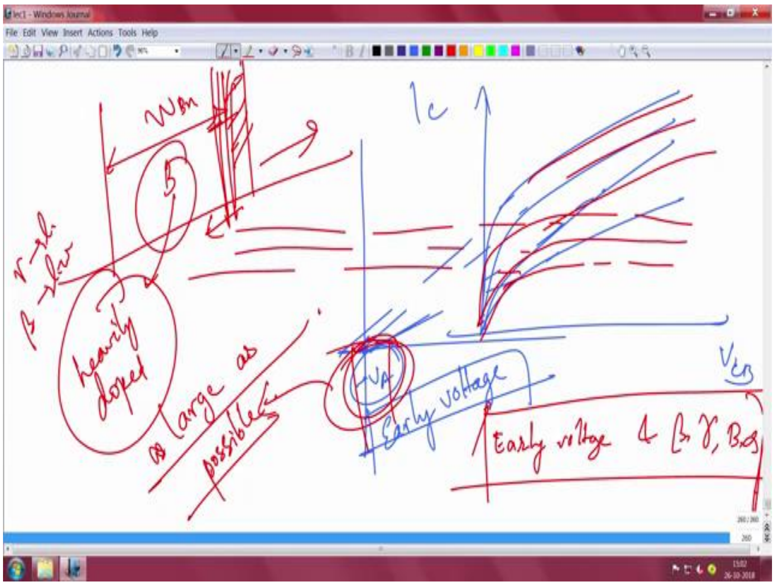
If the base doping is light, ok, so if the base doping is light, if base doping, if the base doping is light, then what will happen; it is low. If the base doping is low, you will get very high gain, nice, very high gain, very high transfer ratio, very good things will come, but there is a price that we have to pay. If the base doping is low, then every time you collector, you increase this collector voltage from say 3 volts to say 6 volts here, if you increase the collector voltage reverse bias voltage, the reverse bias voltage from 3 volts to 6 volts, then this depletion will increase. And this depletion will come more and more towards the lightly doped side if you recall. So, the base side is lightly doped, so the depletion will keep coming more and more, which means this width, the neutral base width W_n, will depend as a function of the output voltage, it is a function of the output voltage. Which means your current here will not be independent of this voltage, but it will increase as we increase the voltage. So, it will be something like that.

Instead of saturating, it will go like that. So, the family of curves will look like that; it will not saturate. Which means the output current will also be a function of the output voltage, why, because if your output voltage increases in reverse bias, then the depletion increases. The depletion extends towards the lightly doped side. If the base is lightly doped to get high gain, then your depletion will extend towards the base.

So, the width, the base width becomes narrow. As the base width becomes narrow, the current becomes higher. So, then it behaves like a resistor, it basically loses the transistor action. It is like a two-terminal device, a resistor, where you are increasing the voltage, also increases the current; it is nothing unusual about this, it is like a metal. You increase the voltage, you increase the current; that is not how a transistor should behave.

So, you lose the transistor action. And this width of the base becoming less and less with this is called base width modulation. This problem is called base width modulation, this base width modulation also is called Early effect. This name is not called Early effect because it is happening earlier or something; the person who discovered this, his name was early actually, ok. So, this is an early effect kind of phenomena, where you basically have a change of base width with the higher doping and that is why your output current never saturates, it is like a resistor, you defeat the transistor action ok.

(Refer Slide Time: 19:39)

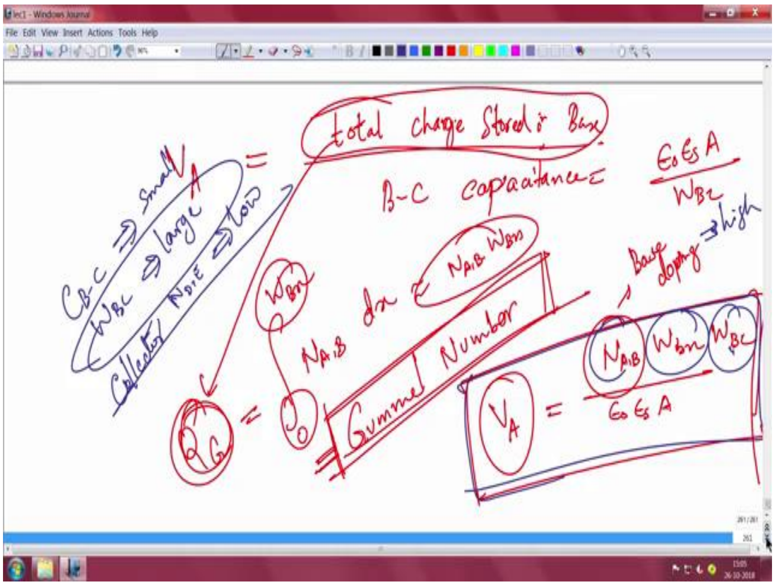


And, if you look into that output characteristics, say I_C and this is V_{CE} for example, it will look something like that, ok. If you actually backtracked all this, they will all meet at one point, they will all meet at one point and that is called some minus V_A, right, some where it will meet, it is called Early voltage. Ideally, we want the Early voltage to be minus infinity because, if this is exactly parallel, the transistor should have the saturated current, exactly parallel. In that case, this will never meet. So, this is infinity.

So, in other words, you want the Early voltage to be as large as possible in terms of negative absolute, may be negative value ok. You want it to be as large as possible, so that will be only possible, when your base is heavily doped. When your base is heavily doped, then the depletion you have here will not extend into the base so much but will extend to the collector. Only if you heavily dope the base, your base width will stay normal, that is the width towards the base will not be so much. But if you dope the base high, then your gain will be low, your emitter injection efficiency will be low.

So, basically you have to make a tradeoff between the Early voltage, you have to make a tradeoff between Early voltage and gain or gamma or beta or alpha whatever. So, everything does not come, you know without any effort. There is a price that we have to pay; either you get high gain or you basically have to sacrifice the output conductance here and you will get a not so good device, ok, you will get not so good device, so that is called a Early voltage.

(Refer Slide Time: 21:34)



And this Early voltage, the V_A that I told you, ok, this V_A has actually a term and that V_A can be mathematically expressed as the total majority charge stored in the base, total majority charge stored in the base. So, what is the total majority charge stored in the base or, divided by the base collector capacitance; base-collector capacitance.

Now, the total charge stored in base, the majority charge stored in base can be called Q_G, and that is basically your doping, the majority doping that you have over the entire base width 0 W_{Bn} ok. And this is called, this is almost equal to N_{AB} into W_{Bn} for uniformly doped base. This is called Gummel number; Gummel number. Gummel number basically tells you, the total amount of positive majority positive charge here in case of n p n. In case of p n p, it will be majority negative charge. The majority positive charge stored here in the base in the neutral base width region, neutral base width region, this is called Gummel number.

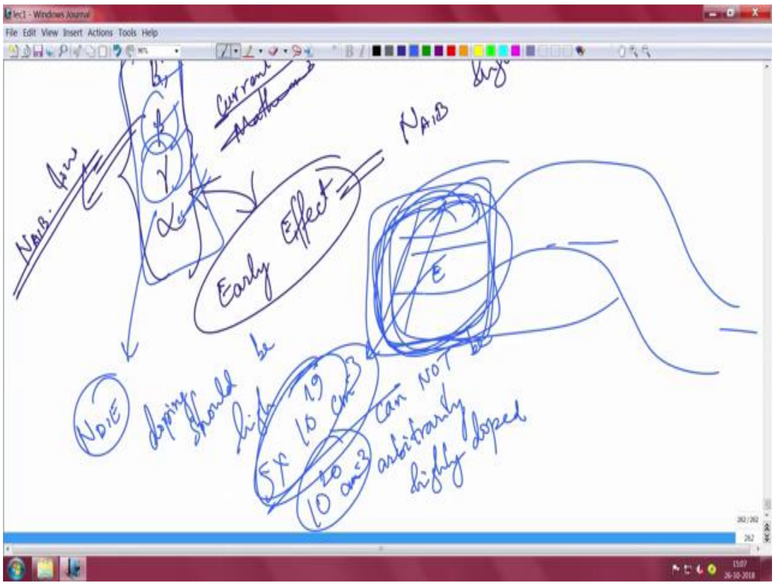
And the base collector capacitance is given by epsilon naught epsilon A, area of course divided by the width of the base collector depletion region. Remember the base collector depletion region width, this width, whatever this width is W_{BC}. In the base collector junction, there will be depletion width is there, that is the ratio, this gives you the voltage, the Early voltage is therefore given by the base doping into the base, neutral base width divided by epsilon naught epsilon S into A divided by W_{BC}, or we can take the W_{BC} upwards, W_{BC} ok.

$$V_A = \frac{N_{AB} W_{BC} W_{Bn}}{\xi_0 \xi_S A}$$

This is roughly your base emitter, sorry, the Early voltage, you want the Early voltage to be as large as possible, only then your output saturation will, you know, be good. So, for having this large, your base doping also should be high, which is in, you know, contradiction to the gain thing. So, I told you already that, the base doping should be high, base width should be high, but let us not touch the base width so much of course.

And the base-collector width should be also large; or in other words, the capacitance should be small. The base-collector capacitance C_{BC} should be small, but which means, the base-collector depletion width should be large and because base doping is high, it means the collector doping should be very light, collector doping should be very light; very low. Only then the base-collector depletion width will be large and, in that case, you will define an Early voltage which is very large ok, so that is an interesting thing that we learned.

(Refer Slide Time: 24:19)



So, what are the things we learned? We have learned the base transport factor, the gain, the emitter injection efficiency, the current transfer ratio, we have expressed that in terms, those in terms of the current. We have given some mathematical expression; we have given some mathematical expression to that. Then I told you about the Early effect; I told you about the Early effect and how this Early effect trades off with the base width, the different parameters for gain and transfer ratio and so on. This needs that the base doping is high, ok, and this needs that the once that the base doping should be low, so this is the problem that we have.

In other words, also if you recall, this also wanted that your emitter doping should be high, emitter doping should be high; Emitter doping should be high. But, there is a problem with emitter doping being high. So, you see, this is a base-collector junction, this is a base, you know, there is a this and this is a this.

So, you see, the base, this emitter cannot be arbitrarily highly doped. You cannot arbitrarily dope, dope it like say 10^{19} or $5X10^{19}/cm^3$. You cannot dope it arbitrarily high, why; because there is a problem that will come very soon. You want to make high gain, high transfer ratio, you want to dope it very high.

But, you cannot, you should not. If you dope it very high like $5X10^{19}$, your beta, your gamma everything will become very small ok. There is a problem because of some twitch, your everything will be sacrificed if your doping is arbitrarily high here. What is the problem, can you think about it? What is the problem that will arise, if your emitter is arbitrarily highly doped like $5X10^{19}$ or $10^{20}/cm^3$? If you dope it ridiculously high, what is that most important problem that will lead to the device having almost no gain. Can you think about it? You should think about it what is now gap that we have.

So, we will end up the class here. Now, in the next class, we will discuss what is that will actually affect the device performance when you dope the emitter extremely high. I will leave you with that question. Think about it, what is the main problem that comes when you dope a material very high. And the moment you know about it, you will understand that, if you dope the emitter very high, all the benefits that you are going to get out of the transistor in BJT will actually be defeated, the purpose will be defeated, you will not get those, ok.

All the discussions that we have had early effect, gain, transport factor, everything will go for a toss, everything will go for basically, you know low, everything will be bad if you dope the emitter extremely high. What is it? So that we will start in the next class.

And we will also finish up more other important things of the base, of the BJT, like some of the non-linear effects perhaps. And also, may we can solve some of the numerical problems of BJT and we will also try to see if we can cover delay in the next class, like what is that what is the speed at which a transistor can operate, what is the fastest speed a transistor can operate, ok. So, we will end the class here today, please think about why emitter cannot be doped extremely high ok. In the next class, the first thing we will begin is to understand why the emitter cannot be doped extremely high, ok.

Thank you for your time.