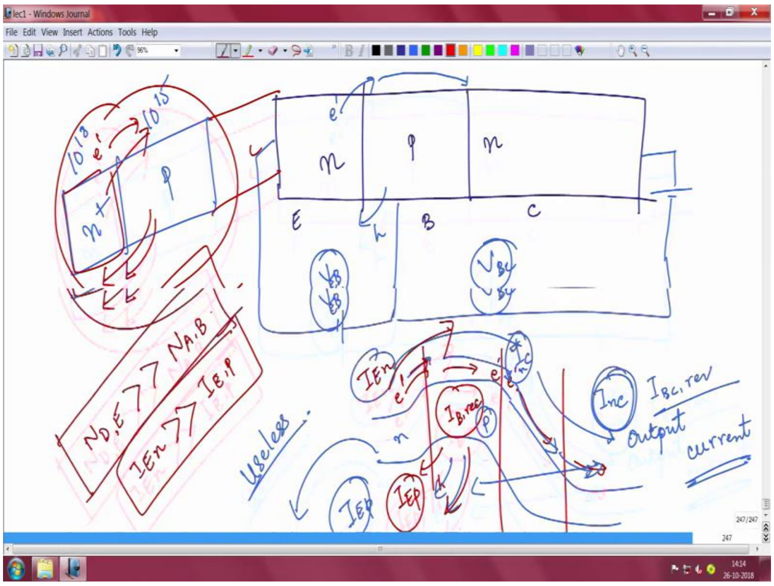
Fundamentals of Semiconductor Devices
Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science, Bangalore

Lecture – 27
Working of BJT

Welcome. So, we shall continue with our last discussion on BJT - bipolar junction transistor. If you recall from the last couple of lectures, we had introduced the concept of BJT, which is essentially 2 back to back p-n junctions. I told you they are called emitter, base, collector. We had taken an example of n-p-n type of BJT. I told you there are various current components and how a BJT works in principle, how you control the current between 2 terminals with the help of a third terminal. That is what we have discussed.

Today we will go ahead, and we will actually give some mathematical or quantitative shape to the equations of current, so that we can derive some very simple expressions of things like gain for example, or how to design a better BJT for example, and there are many effects associated with working of a BJT, there are various aspects of that so, all those things we will take up class by class ok.

(Refer Slide Time: 01:29)



So, let us come to the whiteboard now. If you recall from the last lecture, a BJT is two back to back p-n junctions. So, for example, I have an n and p and an n here. Suppose this is a BJT ok. I told you that this is emitter, this is base and this is collector, and you forward bias the base-emitter junction so that you inject electrons from the n-type to p-type, of course, holes will be back injected from p to n, you want most of these electrons to reach the collector and so, you basically reverse bias the base-collector junction.

So, the band diagrams look something like that, you know, this is forward bias and then this is reverse bias - the base collector right. So, the idea is that, electrons that are injected from here, some of them will recombine in the base and most of them will reach the collector edge here, once they reach the depletion, they will be immediately be swept away by the field to the other side ok. So, electrons are injected from here because it is a forward bias junction, holes are back injected here.

So, this component is called electron current because, the emitter current because of electron, this is emitter current because of hole, this is also a base component by the way because that exists in both cases here and this thing. Some of the current will recombine here, we call that $I_{B,\ rec}$ because the current will also recombine electron-hole. And whatever fraction reaches the other end here contributes to collector current, the electron that comes here will contribute to collector current and goes as the output.

Of course, there is some leakage here, reverse leakage, base-collector reverse leakage current which we essentially ignore, but nevertheless ok. The voltage between base and collector is V_{BC} that you are maintaining and between the base and emitter, you are maintaining V_{EB}, forward-bias ok. I had defined a few terms if you recall, you know about efficiencies for example, emitter injection efficiency and base transfer factor. We will come to that again.

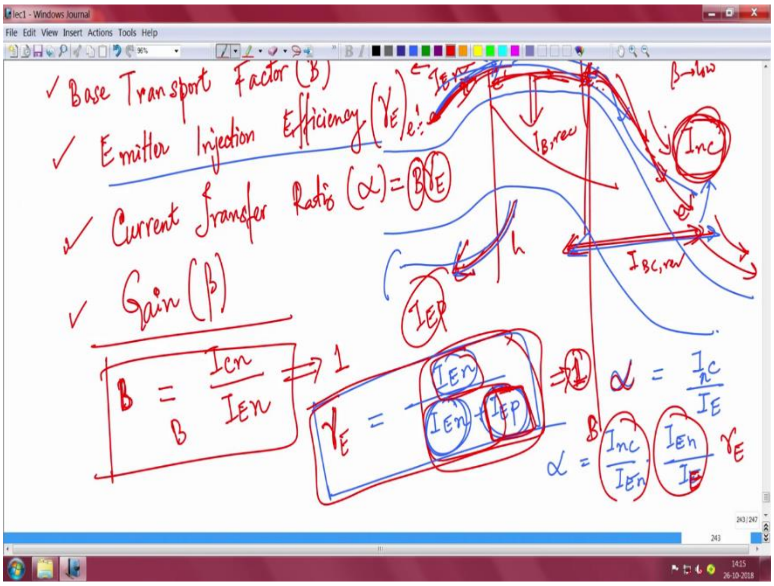
This is how in the end of the last class I told you that this I_{En}, the electrons that are injected from emitter to base, eventually some of them will come out through the collector, most of them will come out through the collector we and this contributes I_{nc} and this is what is important as the output current. This is what is important as the output current, because this matters in amplification and any other thing.

This back injected hole from base to emitter, because remember this is p type, this is n type, the back injected holes that contribute to I_{Ep}, this emitter current because of hole comes out through the emitter only. This is a useless component of current, you want to minimize that and in the last class, that towards the end of the last class, I had mentioned that if you have n+ sort of a p-junction for example, this is 10^{13} doped, this is 10^{15} doped, I have shown you in the equation if you remember, the last slide from last class.

You know the current components that we are injecting from the emitter to base and base to emitter can be dramatically different ok. If you recall these expressions, you will know that the electrons that are injected from here to here will far outnumber holes that will be injected from here to there in terms of the current and so, this junction if you forward bias, predominantly the current will be because of electrons going here and not from because of holes coming here ok.

So, if you dope this emitter very high compared to base, let there be collector, ok, then you can make sure so, if your emitter doping, you remember emitter doping that is emitter doping right and the base doping is N_A in the base. If the emitter doping is much larger than the base doping, then you make sure that your emitter current because of electron which is this is much larger than the back injected current I_{Ep} and this will give rise to a good, you know transfer ratio if you recall. We had discussed many of the terms here, gain we had discussed, base transport factor and you know, we had discussed emitter injection efficiency.

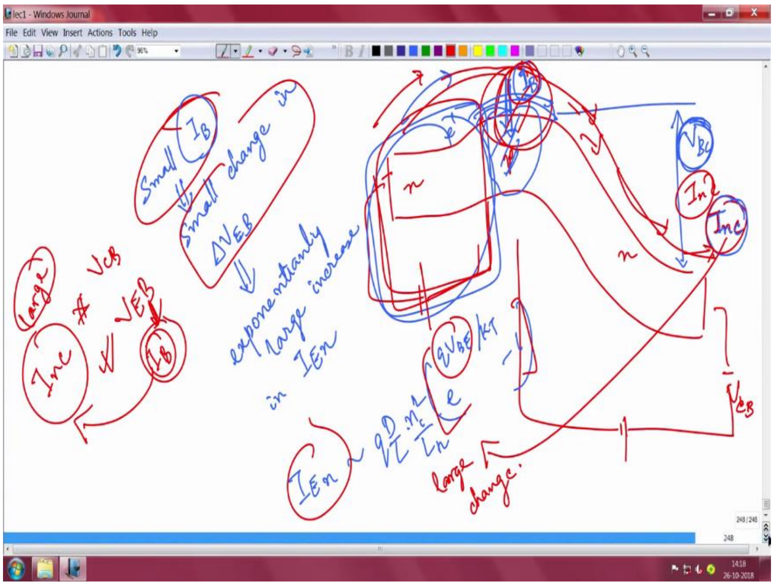
(Refer Slide Time: 05:16)



So, if you recall the emitter injection efficiency was what fraction of the total emitter current is because of electron, if your base component, this the component because of holes coming from base to emitter is reduced, then this component will approach 1 and that as much as it approaches 1, we have a better and better transistor. And if your ɼ (gamma) approaches 1 of course, your you know your α (alpha), the current transfer ratio, which gives you the ratio of the output current to the total input current also will become better, total I mean the emitter current.

So, everything becomes better with making the emitter higher doped than base, to a first extent, but of course, in the way you make basically you know a 3 terminal, I told you a transistor is a BJT is a transistor, the 3-terminal device. Actually, when you have a transistor like a BJT and this is suppose the Band diagram and the operation.

(Refer Slide Time: 05:59)



So, this is collector which is you know you are applying V_{CB} that is the collector voltage between this, you know, the base and the collector this is p-type, this is n-type collector and this is n-type emitter, of course, between the base and the emitter you have a forward bias voltage. The thing is how to the transistor you know the work is that this output current that comes out which is I_{nc}, this is the output current.

It does not depend on what potential difference you have this side, ok, this V_{BC} the base collector voltage. So, you see, the base-collector voltage ideally should not affect the output current. In other words, the output current should be independent of the output voltage, it should depend on input condition and what is the input, you see some electrons that go here, they recombine here know, that when it recombines then, to maintain the equilibrium, you will basically the base will inject some holes here.

Such a very tiny component of current and this base current basically injects holes to replenish the holes that are lost here when the electrons recombine while going to collector ok. So, a small current I_B, a very small current I_B, when you inject, essentially this is a forward-bias junction a very small, this will lead to a very small change in for example, a very small change in your base-emitter voltage. Your base-emitter forward-bias that you have applied can be mildly changed by a small current that you are applying and a small change in this thing leads to an exponentially large change in, exponentially large change in what, large increase or large increase or change in the current that goes here, the current that goes here.

Why? Because this emitter current depends exponentially, if you remember

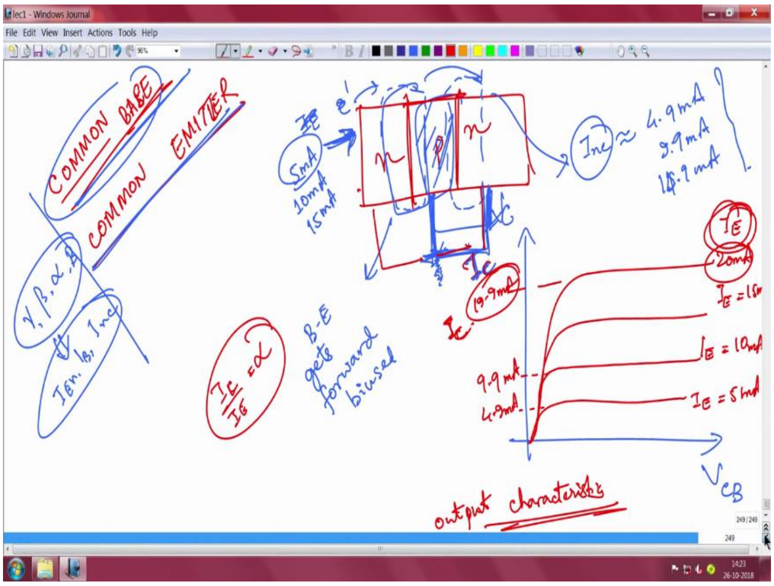
$$I_{En} = \frac{qADn_i^2}{N_A L_n}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

So, if this quantity, the emitter-base voltage is slightly changed, it leads to an exponentially large change of current that you are pushing here and most of this current actually reaches the collector, only few of the electrons will get recombined here, most of them will reach the collector.

So, the collector current I_{nc} this quantity also has a very large change. So, this is the transistor action in a way you can say, a small change in the I_B which changes the delta V you know the potential the difference in a small amount can lead to a large change in current from the emitter which then comes up through collector. And that is how the output current which is I_{nc} does not depend on the output voltage, but it depends on the input voltage, which in turn depends on the input current you can say.

So, essentially by controlling the input current by a very small amount you can make a very large change in the output current ok. So, that is why transistor action is that is why amplification should take place ideally. And so, there are different modes in which we can operate this device of course, I will come to the device equations very soon.

(Refer Slide Time: 09:07)



But suppose you have you know, this is your schematic of the BJT for example, n-p-n right. So, typically there are 2 modes in which you can operate a BJT, one is say common base, common base mode, common base means that the base is grounded and one mode is called the common emitter mode, which means that the emitter is grounded, common base and common emitter.

So, what does common base mode means. First if I take common base mode and we will of course derive the generic expressions for current, of the various components of current very soon, so that we can get a quantitative feel of the things like, you know injection efficiency, beta, alpha, B. If you remember these are the, these are the matrices that will tell you how better, you know how good the transistor is, all this depend on the on the values of the equations of current, like I_{En}, I_B and so on. Just before we come to that, we will just quickly touch base on the modes of operation because to understand a BJT, we need to understand how it is operated.

So, a BJT can be operated in common base or common emitter mode when you want to get you know a forward active kind of operation you want to get some gain and stuff, you do not want to switch it off for example, you want a real you know a working device. So, common base for example, means that the base is grounded, the base is grounded. So, you what you do of course, you know if you remember, this base-emitter junction has to be forward-biased and the base-collector junction has to be reverse-biased, that has to be always holding true if you want to operate in the forward active region, you want to have some gain.

So, you keep the base grounded and what you do is that, from the emitter side you inject some current I_E. When you say, when I say the base is grounded and I am injecting some current from the emitter, it means the base-emitter, this is the electron current by the way, I mean I am talking about electron. It means automatically that the base-emitter junction gets forward biased, gets forward biased ok. So, basically I am injecting some current from the emitter and emitter current is almost equal to collector current, right if you remember. So, suppose I might you know give 5 milli amp, then I will increase it to 10 milli amp and so on.

I can increase and then 15 milli amp and so on right and of course, this some of them will get recombined here, but most of the electrons will come here and they will collect out through the collector. So, you might want to measure the collector current and collector current will be almost equal to the emitter current that we are putting in. So, instead of 5 amp you might get 4.9 amp milli amp for example, for 10 amp you might get 9.9 milli amp for example, for 15 amp you it might get 14.9 milli amp.

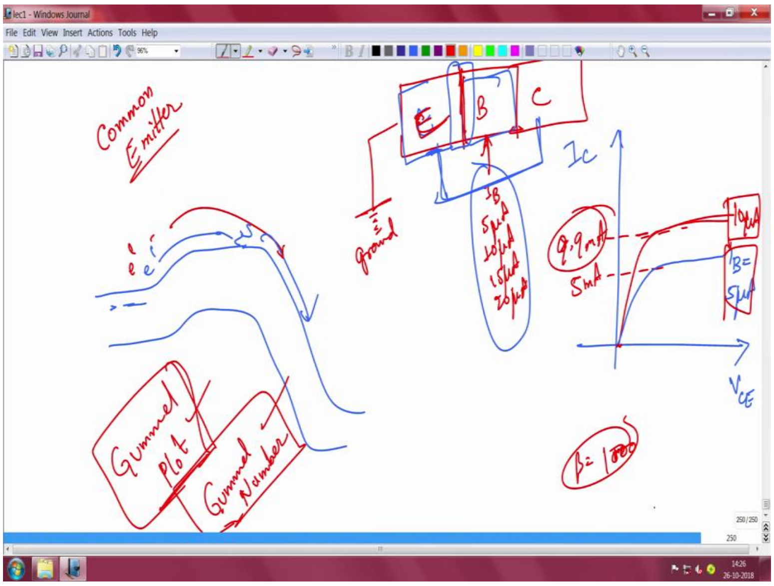
So, almost the entire you know the current is coming there little bit of, little bit of current is dropping here. So, essentially what you do is that you plot the output current which is I_C versus you, this it is voltage, this you know if you keep changing the collector voltage here V_C, nothing will change ideally right. So, I am plotting V_C, but I am plotting V_{CB} because this is grounded. So, with respect to the base I am measuring the collector because base is grounded so collector is measured with respect to base.

So, V_{CB} and this is your, you know I_C that I am putting. So, you know I am putting, say emitter current of you know say 5 milli amp and then you know, in the current of 5 milli amp. So, it will basically be something like that. So, the collector, this is I am plotting collector current, but this will correspond to an emitter current of say 5 milli amp that I am putting and here I will get a collector current of say 4.9 milli amp that I am getting, then you know you might have something like this, the emitter current is 10 milli amp and that corresponds to a collector current of say 9.9 milli amp right.

And this kind of things will come. I_E will be equal to 15 milli amp, you know, I_E will be equal to 20 milli amp. So, this is your output characteristics this is called your output characteristics of the transistor in the common emitter common base mode sorry, the base is grounded here the common base right the base is grounded here. And you have this ratio of this I_E, this is the total current here, the ratio of course, here is 19.9 milli amp, this is your output current I_C, this is your I_E and the ratio of I_C/I_E gives you alpha. So, from this you can find out what is the value of alpha right.

So, one important thing here to notice that you know, when you have the base grounded, when you have the base grounded, then essentially you measure a collector voltage with respect to the base, you also measure the emitter voltage respect to the base. You know this is a common this is I_C for example, this is your common-base configuration and similarly I will come to the common-emitter configuration very quickly.

(Refer Slide Time: 13:42)



A common emitter configuration, common emitter, so as the name suggest in common emitter configuration, you will basically ground the emitter right. So, this is suppose collector, this is base, this is emitter. So here, you will basically ground the emitter, it is grounded. So, what you do is that you inject small amount of base current, very small amount of current say maybe 5 micro amp, maybe 10 micro amp, very small amount of base current 15 micro amp, 20 micro amp, you might be injecting some small base current which essentially make sure that your base emitter junction is forward biased and that small current will lead to a large change and because your base is getting forward biased of course, because you are injecting this current and the collector emitter is 0.

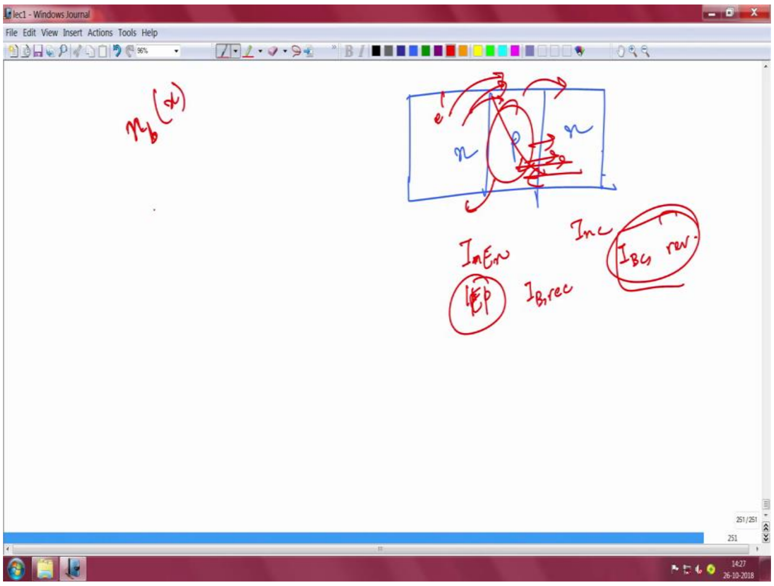
So, it looks like you know so, this is 0 and then the base is getting forward biased here, right and then the collector comes here, collector is reverse biased in here right, collector is reverse biased in here. So, whatever electrons can go here now immediately will get you know swept by the other side. So, if you look at this then you can plot the collector current output versus the, you must plot V_{CE}, because everything is grounded the emitter is grounded. So, you measure the collector potential with respect to E. So, you plot V_{CE} and at this you plot with respect to you know I_B. So, I_B could be very small say 5 micro amp, corresponds to that you have an I_C of say 5 milli amp.

So, the gain is basically beta is 1000, you know 1000, because is 5 microamp this is 5 milli amp. Similarly, you might have 10 milli microamp of base current your injecting you are getting maybe say 9.9 milliamp of say for example, you know, the collector current ok. So, this is your common emitter configuration, common emitter configuration. So, if you look into this carefully, you will see that, here actually your electrons that are moving from the emitter, they go around to the collector side here which is reflecting here.

So, here the step input is basically your base current, in the other case your step input was basically your emitter current, please keep that in mind. So, these are 2 common modes in which you operate and there are many things associated with these operations that we will come to that later. So, this is and you should keep this in mind because when we talk about different, you know, different plots and different kind of matrices are performance in these devices, it is very good to recall how a common mode or a how a common emitter, common base configuration should look like ok.

So, this is all about that. There is also associated something called Gummel plot we will come to that sometime soon after we discuss on the current things, but Gummel plot also will tell you about the gain and many other things that we have to plot, you know and there is also a Gummel number, there is a Gummel number and the Gummel number also will become handy. So, all these things will come, but before that we have to discuss about the current equations actually ok. All the basic components of current, we should know them, their equation should be known only then we can relate properly about the Gummel plot, Gummel number and many of the other things associated with common emitter and common base will become clear only then. We will come to that.

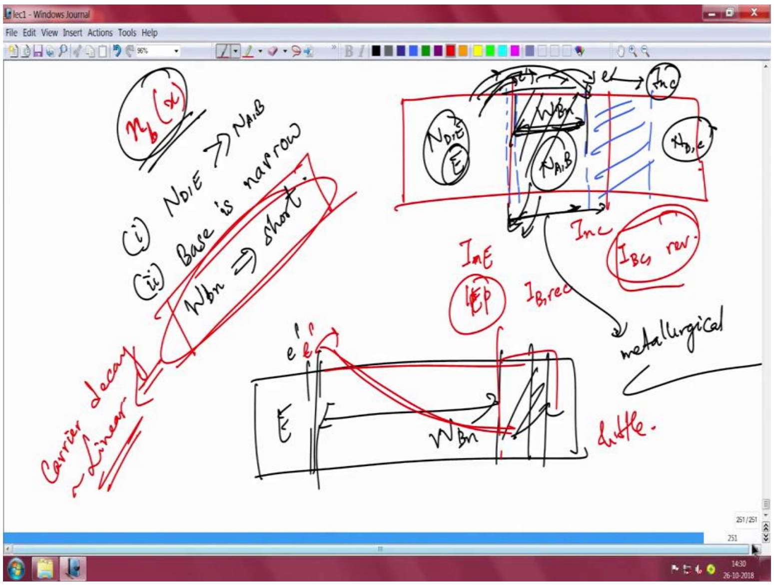
(Refer Slide Time: 16:52)



So, now, let us again come back to the main schematic of a the BJT - this is n, this is p, this is n. I told you what are the current components, one component is this emitter is going. So, this is I_{En}, one is back component I_{Ep}, this is I_{En} for example, most of them will reach here. So, there is a collector current, some in the base will get recombine here. So, that is base recombination current. This also is including the base by the way sometimes and a base and collector junction will have some reverse leakage from both this sides and from this side which we are ignoring now, but later on, we can take it out.

So, the most important thing to learn here is the base minority carrier profile, when we are injecting electrons from emitter to base, the electrons become minority in the base. So, they will decay or recombine in the base. So, this $n_b(x)$ tells you the minority carrier decay profile of electrons that are injected in the base ok. So, I will write this as x and if you see carefully here there is a forward bias and there is a reverse bias junction between the emitter base and base collector respectively.

(Refer Slide Time: 17:55)



So, if you draw it little large, this is your emitter-base, this is the base-collector, if you recall the emitter-base is forward bias so, there is a small depletion here, but the base collector is reverse biased so, there is a large depletion here. I told you, the true depletion width, the neutral base width actually is this only, W_{Bn}, all your base current decay and everything will happen here. This red mark to red mark you know, that is called metallurgical, if you remember that is called metallurgical base width and that does not matter now, what matters is the neutral base width, from the depletion edge to the depletion edge ok.

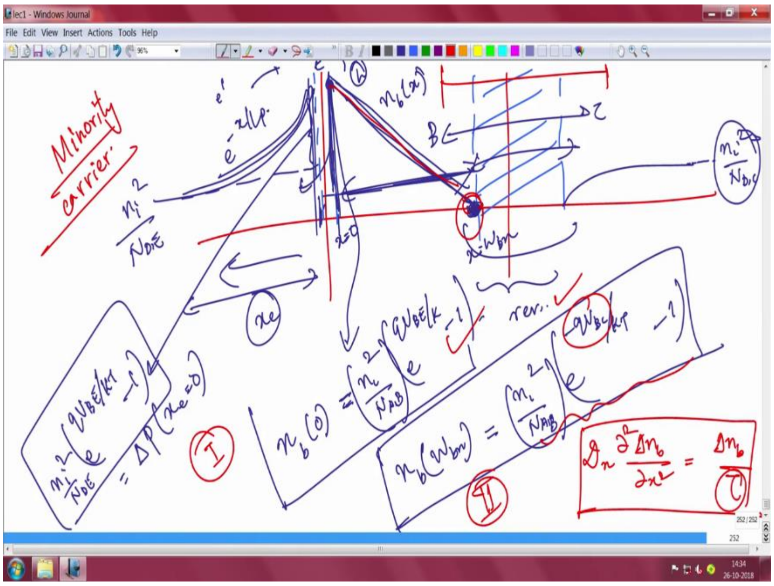
So, this is a minority carrier profile and this is you know if you recall, to have a more component of electrons reach the collector, that is the idea, one thing that we have discussed is that the emitter doping should be much larger than the base doping, that we had learned right. The emitter doping, this is emitter doping, should be much larger than the base doping; base doping is N_{AB}, collector doping is N_{DC} which is not important now. So, the emitter doping should be much larger than the base doping, then most of the electrons will basically be injected, but very few holes will be injected this side.

And another very important thing is that, you want the electrons that are injected here, most of them should reach the collector because if maximum of the electrons decay and recombine in the base region, very few electrons will reach the collector, which means the collector current is low, your gain and your many other things in the transistor will be very poor. You want maximum the electrons injected from emitter to reach there and that is possible only when the base is narrow.

When I say base is narrow, base should be thin, which means this neutral base width W_{Bn} if you recall, W_{Bn}, the neutral base width over which the carriers will decay, has to be very short, what will happen otherwise if the base is very long. For example, I am having emitter, collector and then this is base, there is a small depletion here, there is the large depletion here and then this is the base. If the base is very large, then electrons that your injecting from here, the electrons that your injecting from here, they will get such a large base that they will combine almost or everything.

The current that comes out here will be very little ok. So, you do not want that, so you want the base to be very short and if you remember for short base, the carrier recombination or decay, carrier decay is almost linear. For a very large diode, it is exponential, but for a very short diode it is linear ok.

(Refer Slide Time: 20:22)



So, you are going to get a linear minority carrier decay profile. So, if I plot the minority carrier profile ok, I am going to plot the minority carrier profile, minority carrier profile is only for the minority that gets injected to that the majority that becomes minority on the other side right. So, for example, I take here you know may be I will be rub this. So, this is your x axis ok, this is your base-emitter junction. So, there is a small depletion here, there is a large depletion here, this is the base-collector junction right.

So, injecting electrons from the emitter side to the base side so, they will decay linearly like this. Because this is a minority carrier this is a depletion region and this is reverse biased, technically, according to depletion approximation, this linear bias should end at 0 here, because of the edge of the depletion region, the total carriers has to be 0 ok, the total carriers has to be 0.

So, this is your $n_b(x)$ this should be a linear function, this is how it is decaying at this point it should become 0, similarly at this point it should become 0 and at and eventually far away, it should become your minority carrier electron which you a holes which is $\frac{{n_i}^2}{N_{DC}}$. Here, similarly you will be injecting holes from the base to the collector emitter side. So, this should be decaying exponentially because the emitter is very long, this should be decaying exponentially far away from the junction, it becomes $\frac{{n_i}^2}{N_{DC}}$ this is your minority carrier.

There is an excess carrier here, if you remember that excess carrier you can find out exactly as $\frac{{n_i}^2}{N_{DC}}$ into x e to the power whatever forward bias you applying by K T minus 1 i.e.

$$\frac{{n_i}^2}{N_{DC}}\left(e^{\frac{qV_{BE}}{kT}}-1\right)$$

gives you the excess carrier which is equal to delta, the hole that your injecting here Δp and this is at x equal to this is at this point which I can say this is at, this is x e this is the you know this direction x equal to 0.

So, at the interface you, will get this kind of excess minority carrier decay that will at the carrier concentration, that will decay exponentially is $e^{\frac{-x}{Lp}}$. But this is a linear decay more or less, but we will come to that again very quickly this is the linear decay more or less, at the edge of the depletion it should come to 0. So, at this point, the total carrier concentration should be not the excess, the total carrier concentration n b at 0. I am talking about this is x = 0, this is $x = W_{Bn}$ because this distance is WBn. So, at x = 0 at this point, at this point your excess the total carrier concentration will be the background minority carrier concentration which is n_0, that is the background minority carrier concentration ok.

Do you know what is background minority carrier concentration, it is equal to $\frac{{n_i}^2}{N_{DC}}$, that is your background minority carrier concentration in the base, times $(e^{\frac{qV_{BE}}{kT}} - 1)$. This is a total carrier here, the total carrier here. The total carrier here should be almost equal to 0, but this is one boundary condition, that the carrier, the total the total carrier here should be this. And the total carrier over here actually, the total carrier at x = WBn, the total carrier at x = WBn should not, it should be very close 0, but it should not be exactly 0, what it should be is that it should depend on the bias between the base and the collector.

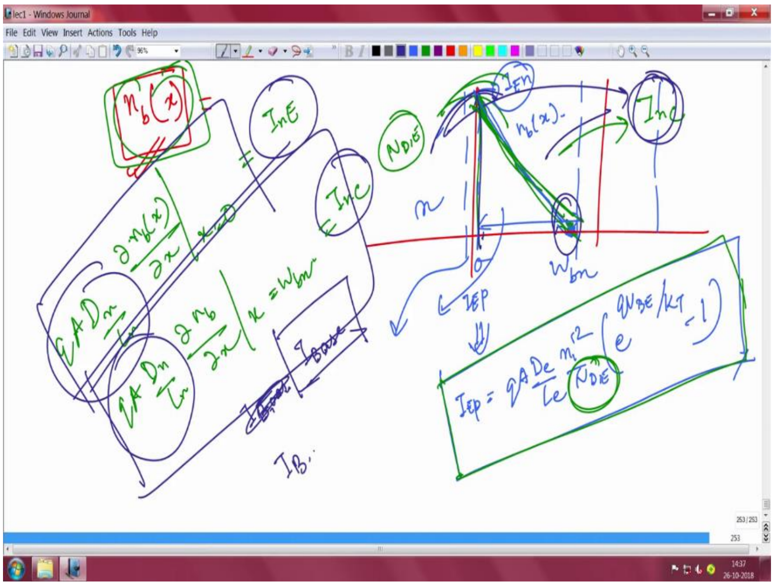
So, it depends on a reverse bias, so what will happen is that it will be the same, $\frac{{n_i}^2}{N_{AB}}$ which is the base line minority carrier here into exponential of the base collector reverse bias voltage which is e to the power minus qV_{BC}, V_{BC} is positive by kT minus no 1 this is not this is not 1 here i.e. $(e^{\frac{qV_{BC}}{kT}})$. This is the net carrier concentration here, the excess carrier concentration of course, will be minus 1 here, similarly the excess carrier concentration here if you want it will be minus here ok.

So, this is another boundary condition that I know because at this point, at this point, please remember at this point, the excess carrier concentration will depend on the voltage difference between the base and the collector, this quantity is very small. So, this quantity actually goes to almost 0, but it is exactly not 0, but these are the 2 boundary conditions. This boundary condition 1, this boundary condition 2, with these 2 boundary conditions, you solved the continuity equation here which is D n d square by delta n b by d x square is almost equal to delta n b by tau that the recombination time there ok.

$$D_n \frac{d^2 \Delta n_b}{dx^2} = \frac{\Delta n_b}{\tau}$$

So, this is approximately the relation that will hold, this is the continuity equation in which we apply is boundary condition for a sufficiently short diode we can assume it to be a linear equation.

(Refer Slide Time: 24:57)



But if you solve it exactly if you solve it exactly, then you will get a minority carrier profile $n_b(x)$ which will have some hyperbolic functions and so on, but this is the expression that you will get and this will have a hyperbolic function here ok. The boundary conditions are written here, one boundary condition is that at x = 0, this is your carrier concentration, at $x = W_n$, this is the carrier concentration. You solve the continuity equation with those the boundary condition so, you will get that.

So, now, if you look again, this is your small diffusion here depletion and this is your large depletion, this is your x, this is your WBn. So, this distance is WBn. Your minority carrier profile should decay linearly, but it is almost it is very linear, but slightly non-linear may be, slightly you cannot this quickly ok. So, the minority carrier profile is $n_b(x)$ ok. So, the current that you are injecting here, I_{En}, the electron current because of emitter, I am not taking the hole current here, this hole current is easy. You are injecting holes to the n side know. So, that will come out to be I_{Ep} is a p n junction basically

$$I_{Ep} = \frac{qAD_E n_i^2}{N_{DE} L_E}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

this is your backs back injected hole current and you, this component is useless because it comes after the emitter.

And one way to actually minimize this current is to make the emitter doping here very high, if you make the emitter doping very high then this quantity goes to very small, because and the denominator ok. So, that is one thing that is ok, but this point, this you know the carrier profile here can be actually obtain from the boundary condition and if you take a derivative of that this, if you take a derivative of this and you multiplied by q A the electron that is going there right. So, D_n/L_n sort of thing at x = 0, if you take this; if you take the slope here, if you take the slope here and you multiply by this whole thing, you actually get I_{En}, the electron current that you are emitting - injecting here.

And if you take the same expression this profile here, if you take the same expression here, but you take the derivative of this it is not slightly non-linear right you take the derivative of this at x = WBn, which is this point, if you take the slope at this point and you multiply by this, then you actually get how many how much current is coming out there, in the collector from the I_{nc} ok.

All the electron that you have actually injected from here what is the fraction that is coming out here is obtained by the slope here times qAD_n, how much electrons you are putting here, I mean what is the current here, depends on the constant here and the slope here ok. So, this is your I_{En}, this is your I_{ce} and if you subtract this two, you are supposed to get the base current there you are supposed to get the total the total base current ok, you are supposed to get the total base current. So, that will give you an idea of you know and we will actually exactly we will exactly do this also, we will exactly find out what is the expression here, we will exactly find out the expression here, we will subtract them out and we will find the base current ok.

So, let us do that in the next class. So, we will wrap up the class here for today's here. So, we have basically now in the flow of essentially deriving the expressions for current. I told you that the emitter current and collector ,this collector current can be expressed from the slope of the minority carrier profile in the base. It is a very almost linear like profile, but exactly not linear, you and you obtain that expression from basically solving the continuity equation in the base with minority electrons that are injected, with the two boundary condition that we know which I have written down here.

So, we have now the expression for emitter current and collector current and we will also extract the expression for the base current. So, all of these things we will do in the next class. So, we will meet you then and then we will take the current expression forward ok.

Thank you