Analog Electronic Circuits

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Lecture - 07
Revisiting BJT Characteristic

So, dear students, welcome back to this analog electronic circuits, one of the early modules of the course. Myself Dr. Pradip Mandal from E and ECE department associated with IIT, Kharagpur. So, today’s discussion, it will be on BJT characteristic. From semiconductor device, you may be aware about the BJT, but today what will be discussing is that its basic characteristic, what are the characteristics are necessary for understanding analog electronic circuit.

So, essentially I V characteristic is our main focus, but to appreciate the I V characteristic we need to get little bit into its working principle, and then subsequently will be moving to the equivalent circuit. So, today our main target is to cover the basic working principle along with the characteristic equation.

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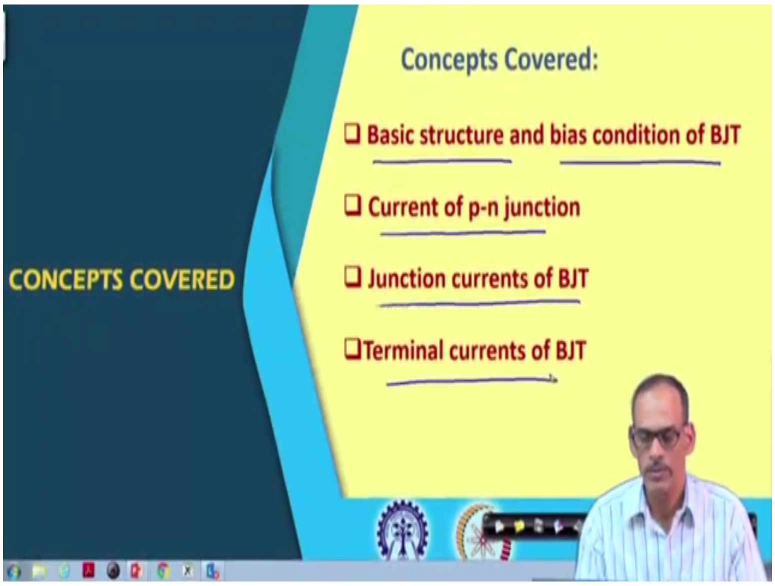

CONCEPTS COVERED

Concepts Covered:

- ❑ Basic structure and bias condition of BJT
- ❑ Current of p-n junction
- ❑ Junction currents of BJT
- ❑ Terminal currents of BJT

So, let us see the plan overall plan. So, today's plan is to cover the basic structure of BJT, and typically what are the bias conditions are followed for BJT particularly in analog operation. And then will be starting with current equation of normal or standard p-n junction it may be silicon or germanium. And we will start with isolated junction then will be gradually moving towards what are the two junctions, and particularly if the two junctions of BJTs are in the near vicinity what are the interactions are happening between the two junctions current. And particularly, if one junction it is forward biased other junction is reverse biased, then what may be the corresponding terminal current.

So, this is the overall plan, the basic structure and bias condition of BJT, then current equation particularly the terminal current equation of BJT.

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Flow of Discussion (Bottom-up) - *Components*

- **System /Sub-systems(*for specific application*)**
  - **Modules (*performing specific tasks*)**
    - **Building blocks (*having specific characteristics*)**
      - ✓ **Components (*devices/circuit elements*)**
- **Week 1:**
  - Introduction and objective of this course;
  - Revisit to pre-requisite topics (Electrical Theory);
  - Starting with simple diode circuit and its analysis.
  - **Revisiting BJT and MOSFET- operating principles, characteristic equations and equivalent circuits**

So, let us see what is our weekly plan and let us see how we are there now. So, this is our weekly plan and as you know that we are in this module particularly components and device characteristics. And so far we already have discussed about the first three items or plan for week 1. And today we are going to BJT; MOS characteristic will be seen in the next class. So, this is the overall plan today and it is well synchronized with our weekly plan.

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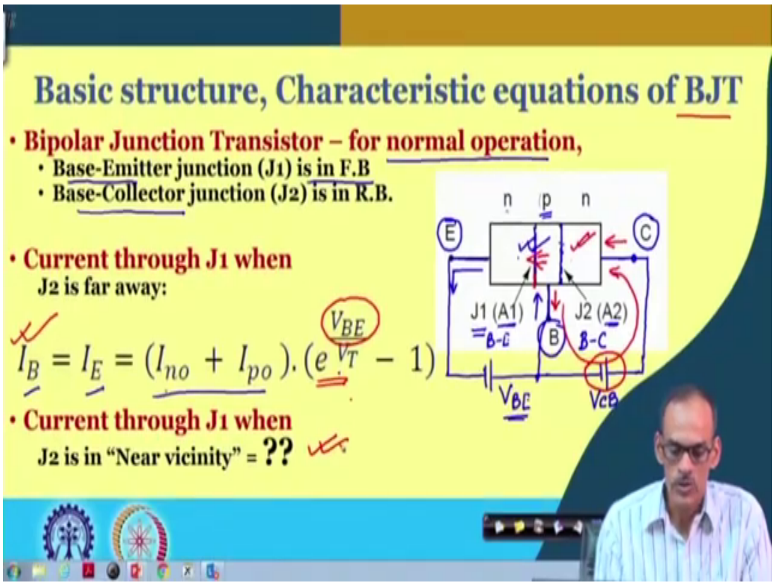

Basic structure, Characteristic equations of BJT

- Bipolar Junction Transistor – for normal operation,
  - Base-Emitter junction (J1) is in F.B
  - Base-Collector junction (J2) is in R.B.
- Current through J1 when J2 is far away:

$$I_B = I_E = (I_{no} + I_{po}).(e^{\frac{V_{BE}}{V_T}} - 1)$$

- Current through J1 when J2 is in "Near vicinity" = ??

So, if you see the BJT as you may be aware from semiconductor device, what it is having it is the basic structure it is having two junctions, say for example, n-p junction and then p-n junction. And in this n-region, we do have electrical connection; we may be aware of this called say emitter. So, likewise in the other side of the device the other n-region, it is having a terminal called collector terminal, then the middle portion in between which is p-type. And in this p-region, it is also having one terminal through which you can apply voltage and you can observe the current and this terminal it is referred as base.

And as you as you can see that there are two distinct junctions, metallurgical junction namely junction 1; so, this junction may be referred as base to emitter junction and so this is base to emitter junction. Likewise, the other junction it is base to collector junction. And pictorially though it is shown here the cross sectional area may be same of this junction and this junction, but need not be.

Structurally, if they are different most of the time they are different and this junction may be having a cross sectional area of say A 1; the second junction may be having different cross sectional area say A 2. So, likewise there are some other important characteristic it is having for example, this region even though we call n-region, but actually it is highly doped n-region. So, you may say this is doping concentration why it is higher than whatever the acceptor concentration will be having in the base region.

So, I should say emitter is having the highest doping concentration compared to the other two. So, it is having its own reason, but that detail I may not be getting chance to get into, but let us see what is supposed to be the condition, so we deploy particularly what bias condition we deploy for junction 1 and junction 2 and under that what are the terminal currents.

So, in normal circumstances, particularly for analog operation unless otherwise it is stated, base emitter junction the junction 1 it is forward biased which means that the p-region it is having a positive voltage with respect to the emitter n-region. So, this junction J 1 it will be forward biased by a voltage called base to emitter voltage.

So, on the other hand, base to collector junction again for normal operation, so this junction J 2, it is reverse bias which means that this n-region it is having higher potential than the p-region, ok. So, this is you may say this is V CB. So, this V CB this side is positive that is making the second junction getting reverse bias.

Now, we know that through a p-n junction if this junction is say a forward bias, and if this second junction if it is far away from this junction, then we know that this current it will be having exponential dependency of this forward bias on the forward bias voltage.

So, if I ignore the second junction and if I concentrate only junction 1, and if it is getting forward biased by V BE, the current it will be flowing through this base terminal into the device, the same current it will depart, the emitter terminal. And they are expression of the both base current and emitter current it is given as say some constant we will see that what is the constant involved multiplied by e power the forward bias voltage divided by thermal equivalent voltage minus 1. So, this is nothing but a typical junction current.

In fact, this is true even if the junction it is getting reverse bias. In other words, if I say that if we concentrate only at this junction and if we are biasing this junction by this, and if I say that this is away from this junction, and then again because of this voltage the current may be flowing through this loop. The current it will be entering to the device through this collector terminal and it will depart the base terminal. And this junction again its current, it will be well-defined by the same relationship, similar kind of relationship.

Of course, in that case this will be V CB, ok; so, if it is V CB and if it is large and then this will be negative and typically this part it will be much smaller than 1. So, the current you will be getting whatever you know reverse saturation current multiplied by minus 1. And the polarity of course, it is getting reverse namely, it is the current is not really through p to n-region, it is rather n to p-region.

So, this diode equation which we are already aware of, this may be valid only if these two junctions are apart from each other. However, for transistor action, particularly for this the BJTs action, we need these two junctions should be in the near vicinity. So, it is expected that the current flow through this junction 1 and junction 2, they are going to be interrelated.

So, what may be the corresponding expression of the current if these two junctions are nearby, so that is what the main discussion today will be going through. So, let us see little detail of this structure and let me focus in this junction.

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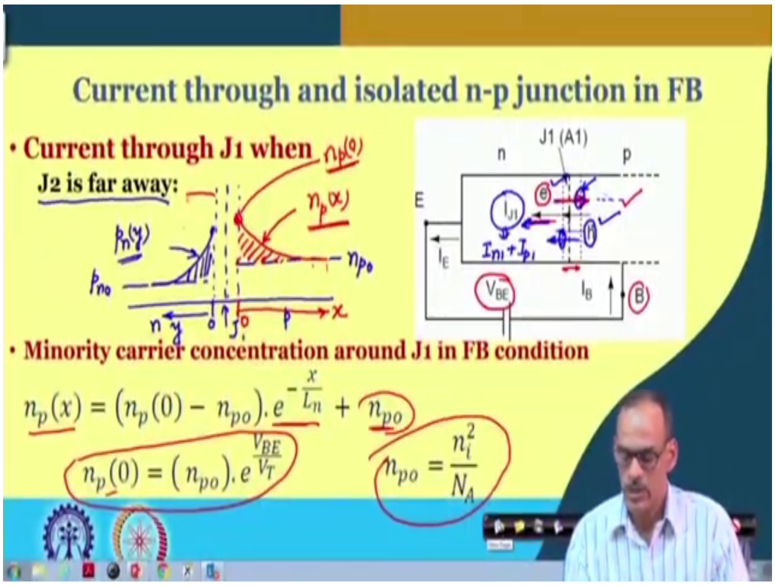

Current through and isolated n-p junction in FB

- Current through J1 when J2 is far away:
- Minority carrier concentration around J1 in FB condition

$$n_p(x) = (n_p(0) - n_{po}).e^{-\frac{x}{L_n}} + n_{po}$$

$$n_p(0) = (n_{po}).e^{\frac{V_{BE}}{V_T}} \qquad n_{po} = \frac{n_i^2}{N_A}$$

So, here we do have the junction 1 portion we are focusing on. We do have zoomed this part and then again we do have V BE voltage base to emitter voltage we are applying. And since this junction it is getting forward biased of course, it will be having depletion region around the junction. And, then across this junction the electrons it will be going from the n-region to p-region because we do have lot of minority carrier majority carriers here electrons in this n-region, they may be moving to the p-region, and of course, the while they are entering here they will be considered as minority carrier. So, likewise holes are also moving from the p-region where it is majority carrier, but then once it is entering into the n-region they will be working as minority carrier.

Now, beyond this depletion region as we are applying this voltage it is expected that in steady condition, the carrier concentration it will be having exponential fall beyond the depletion region. So, let us look into this profile of this minority carrier concentration particularly around near the junction 1. And the assumption it is that J 2, the second junction we assume that it is very far away from this junction. So, it may not be really influencing this minority carrier concentration.

So, suppose we do have this is the metallurgical junction and it may be having around that significant depletion region, but of course, it depends on the amount of bias you do have around there. And so we do have right side we do have the base region. So, this is the p-region, and so this is the junction 1. And left side, we do have the n-region. Depending on the doping concentration in the n-region, it will be having the minority carrier concentration. In the neutral region, you may say that minority carrier concentration here it is p in the n-region naught.

So, likewise in the p-region, the corresponding minority carrier concentration will be may be denoted as in the neutral region, it may be denoted as n in the p-region in neutral condition. And if it is getting forward bias, so from the p-region, it is expected that a lot of electrons it will be penetrating. And as a result the, so if its concentration beyond particularly beyond the depletion region, it will be having exponential falling this.

So, if you see here this exponential fall, it is coming due to two reasons; one is we do have majority carriers n here, which is getting a junction here, and this junction it is getting forward bias. So, what you can say that compared to its n p 0 in the neutral region whatever the minority carrier concentration we do have, near the junction we do have this excess amount of carrier. So, if I do not say this minority carrier concentration say n in the p-region as function of distance say x. And let us say that x is starting from here, and it is going in this direction. So, x is positive in this direction, it starts from the edge of the junction say 0.

So, whatever the concentration we do have here at this point, we may say that this is n p at x is equal to 0. Of course, this is a strong function of whatever the forward bias we are applying here. And in fact, from Boltzmann equation you may say that n p 0, it is having exponential dependency on this V BE. So, this is what it is given n p 0 which means n p at x is equal to 0 at this point, it is equal to n p naught the neutral region concentration multiplied by e power forward bias divided by thermal equivalent voltage.

And this n p 0 of course, it depends on whatever the acceptor concentration we do have and its expression is given here; so, which is equal to intrinsic carrier concentration square divided by acceptor carrier concentration. So, based on the information available here, probably we can find based on the forward bias, we can find this carrier concentration here.

Now, as you are moving away from this edge of this depletion region towards deep into the base region as I say that it is having exponential fall. And this fall it is you know expression is given here n p x equals to whatever the difference we do have which means n p 0 minus n p naught. So, this is the step and then it is having exponential fall which is indicated by e to the power minus x divided by L n.

So, based on the L n of course, the penetration of the carrier towards the base it may vary. So, of course, it depends on the carrier whether it is electrons or holes. So, you may say that this is a constant in length. And in addition to that we do have this n p 0, so that is why we are writing this part. So, first part is the shaded part and the last part it is whatever the height we do have. These two together it is giving us n p x.

So, likewise if you see the left side, you may say that similar kind of profile we do expect, so but it may be having different levels. So, this is the profile of minority carrier concentration in the n-region, which means that this is p n as function of distance. So, let us say that this is distance is x, where, sorry y. So, y is indicating that it is going from 0 towards the emitter depth. So, you may say that this is y; in this direction it is positive.

So, similar kind of expression similar to n p x, we can find the expression of p and y. We will be finding that soon what will be the corresponding expression, but since these two penetration of the minority carrier whether it is holes or electrons since it is similar, let you focus only one kind of carrier concentration. And since these carriers are moving across this junction of course they are charged particles. So, as a result they will be contributing current flow.

So, for example, whenever these electrons are coming from the n-region to p-region, so it is going from n-region to p-region, and as it is a charged particle, it is providing a current in this direction. So, likewise when holes are moving from the p-region to the n-region, namely base region to emitter region; and it is charged particle and incidentally this is positive charged particle so it is contributing the current in the same direction as the electrons. So, though the electron and holes movements are opposite, but due to their opposite charges, both of them are contributing the total current.

So, you may say that this junction current it is having two components; one is due to the movement of the electron another one is due to the movement of the holes. And so as the electrons are moving into the base region towards the or at the edge you may say that most of the currents are carried by the nature of the movement of the charge, it is diffusion kind. And as it is progressing inside the p-region, since we do have lot of holes are available these electrons may get recombined.

So, as the electrons are moving inside the base region, the current carried by electrons it may drop as it is getting recombined. And the responsibility of carrying the current of course, it will be, partially it will be done by the majority carrier concentration. And of course, along this across this device at any cross sectional you know area, we can say that the current remains constant.

So, to find the net current what you can do you can find what may be the current at this point coming due to the diffusion of the electron plus whatever the currents are coming at this point due to diffusion of the holes. So, you may say that the total current, it may be obtained just by considering diffusion current at x is equal to 0 plus diffusion current due to the holes at y is equal to 0.

So, you may say that this current is having two component, let me say that this is due to electrons I n 1 plus I p 1. 1 stands for the first junction; n stands for the electrons and the p represents the positive charge or the holes current. So, we understand that because of the diffusion of the minority carriers, there will be a current flow. Let us see what is the equation of that current flow.

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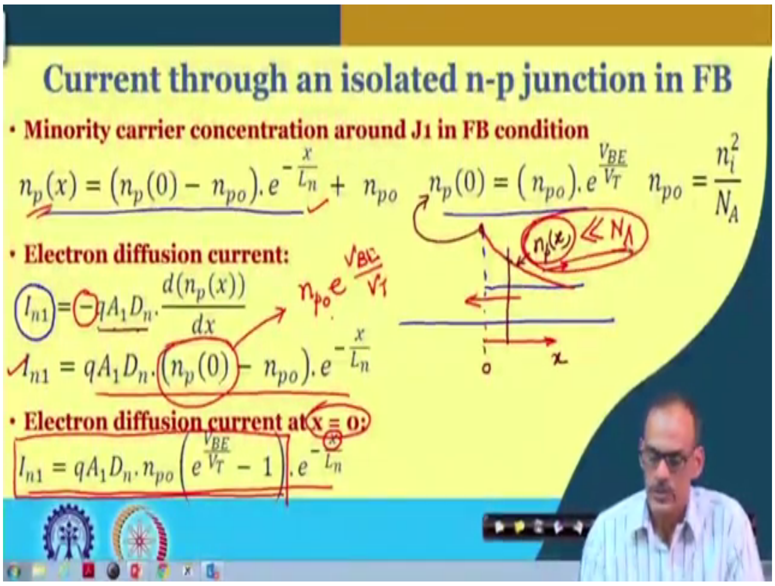

Current through an isolated n-p junction in FB

- **Minority carrier concentration around J1 in FB condition**

$$n_p(x) = (n_p(0) - n_{po}).e^{-\frac{x}{L_n}} + n_{po} \quad n_p(0) = (n_{po}).e^{\frac{V_{BE}}{V_T}} \quad n_{po} = \frac{n_i^2}{N_A}$$

$$n_p(x) \ll N_A$$

- **Electron diffusion current:**

$$I_{n1} = -qA_1D_n.\frac{d(n_p(x))}{dx}$$

$$n_{po}e^{\frac{V_{BE}}{V_T}}$$

$$I_{n1} = qA_1D_n.(n_p(0) - n_{po}).e^{-\frac{x}{L_n}}$$

- **Electron diffusion current at x = 0:**

$$\boxed{I_{n1} = qA_1D_n.n_{po}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)}.e^{-\frac{x}{L_n}}$$

So, you may recall this minority carrier concentration as you have discussed in the previous slide. So, this is what it is given there in the previous slides and the expression of p n naught is given here and p n naught and p n at x is equal to 0s are given here.

Now, electron diffusion current it is whatever you say that I n 1 equals to minus charge of electron, cross sectional area, diffusion constant and then gradients of the carriers. So, if I say you let me redraw here. What we have seen that electrons are getting into the base region and it is having a profile like this. And this profile it is given expression of this profile it is given here. This is x and x is equal to 0 here. And at this point, whatever the concentration it is n p at x is equal to 0, and whatever the concentration at other points it is given by n p at x.

Now, if at any point, if you take the gradient of this n p at any distance at x, then it will be giving us the current the rate at which the electrons are now getting into the, I should say moving from left to right. So, at any point, if you take the gradient here, and then if you multiply charge, cross sectional area and then this diffusion constant, you will be finding the net current carried by electrons. But of course, the since the electrons are moving in this direction, the corresponding current it will be right to left. And that is of course, it is coming due to this the minus sign, because the electrons are having negative charge.

So, if I you say this expression of n p x and then if I take you know derivatives with respect to x, then what you are finding is that I n 1 equals to having this expression. Now, this part, of course, this part it is as I say that it is strong function of V BE. So, we may say that this part it is n p 0 e to the power V BE by V T. So, since I do have n p naught here n p naught here, probably you can take n p naught outside, so we will be having e to the power V BE divided by V T. So, that is how the after rearrangement of this equation or rather using the expression of n p at x is equal to 0, we do find the expression of I n 1 equal to this one.

Note that it is function of x and as you can guess that as you are progressing inside the base region, so this side is base region, and then current diffusion current carried by electrons of course it is coming down exponentially. And at this point, we do have the maximum current. So, at x is equal to 0, this part it is getting removed; so, what we have it is at x is equal to 0, the current carried by electron is this one. So, of course, as you are moving as I say that as you are moving away from this point x is equal to 0, the current it will be then carried by partially it will be carried by holes the majority carrier.

It may be noted that this exponential fall it is valid only if I assume that recombination it is primarily dependent on the minority carrier. In other words, if the n p x is much, much lower than the available concentration here in the base region namely N A, then we may say that it is low level of injection.

So, whatever the approximation we have done here, we have assumed that the penetration here it is very low or the minority carrier concentration here it is much lower than whatever the majority carrier concentration we do have in the base region. So, that normally it is assumed that it is valid low level injection.

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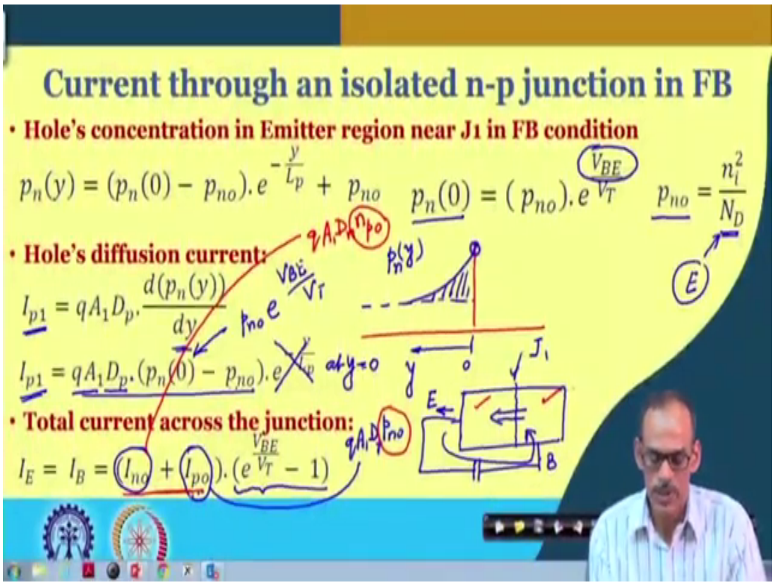

Current through an isolated n-p junction in FB

- Hole's concentration in Emitter region near J1 in FB condition

$p_n(y) = (p_n(0) - p_{no}).e^{-\frac{y}{L_p}} + p_{no}$ $\quad p_n(0) = (p_{no}).e^{\frac{V_{BE}}{V_T}}$ $\quad p_{no} = \frac{n_i^2}{N_D}$

- Hole's diffusion current:

$I_{p1} = qA_1D_p.\frac{d(p_n(y))}{dy}$

$I_{p1} = qA_1D_p.(p_n(0) - p_{no}).e^{\cancel{-\frac{y}{L_p}}}$ at y = 0

- Total current across the junction:

$I_E = I_B = (I_{no} + I_{po}).(e^{\frac{V_{BE}}{V_T}} - 1)$

Now similar to this movement of the electrons as I said that holes are also moving across the junction so, they are also contributing the current. And it is having similar kind of you know expression only difference is that it is the movements of the holes are from right to left. And suppose this is the edge of the depletion region.

So, here also it is exponential change of the minority carrier in the n-region namely p n y, and y is changing from 0 to higher value here. And rest of the things it is similar, only thing I must say that here it is p n 0, it is n i square intrinsic carrier concentration square divided by

N D. So, this N D is donor’s concentration in the emitter region, ok. And rest of the things are it is similar and of course, again this at this point whatever p n 0, it is function of the forward bias, exponential function of the forward bias.

So, I think that it is very clear that now if I take derivative of the p n y in terms of y, we can get the expression of the current carried by holes. In fact, similar to the previous case if you see that you will be finding the expression of I p 1 current carried by holes, it is similar. In fact, this part again you may replace by p n naught e to the power V BE by V T.

And if you do so, then here you can find that p n naught it will be available here, then to get the current at this point which means y is equal to 0, you can drop this part at y is equal to 0. So, the expression of I p 1, it will be q A 1 D p, this is different parameter multiplied by p n naught here and e to the power V BE by V T and then of course, this part it is dropped.

So, the total current across the junction, so you may recall now the junction it is we may say that this is isolated junction. We are not really concentrating on the second junction, we are concentrating only at junction 1 and then we do have the V BE here, we do have the emitter terminal here and the base terminal here.

And whatever the current is flowing through this junction due to this forward bias, of course, we may say that this is also base terminal current and also it is emitter terminal current I b and I e. They are also having the same exponential dependency on V BE multiplied by I n 0 and I p 0. So, what is this I p 0, it represents q A 1 D p and p n 0. So, this part it is essentially q A 1 D p and then p n 0.

So, likewise this part, it is having similar kind of expression it is q, same A 1 cross sectional area, but of course, it is having D n and n p 0. Note that this n p 0 and p n 0, they are of course, strong function of the doping concentration in this portion and this portion respectively. But if they are remaining constant, so we may fairly say that you may say that this part is remaining constant. Now, similar kind of things it will be obtained for reverse bias condition.

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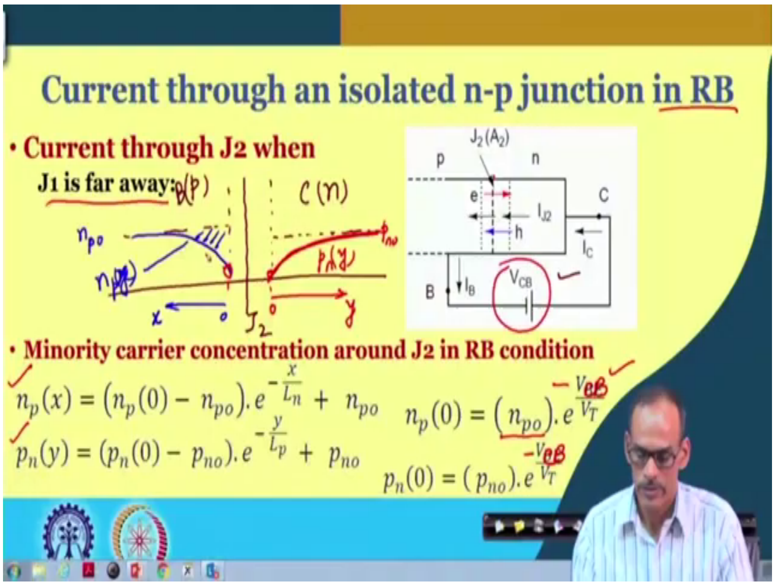

Current through an isolated n-p junction in RB

- Current through J2 when J1 is far away:

- Minority carrier concentration around J2 in RB condition

$$n_p(x) = (n_p(0) - n_{po}).e^{-\frac{x}{L_n}} + n_{po} \qquad n_p(0) = (n_{po}).e^{-\frac{V_{CB}}{V_T}}$$

$$p_n(y) = (p_n(0) - p_{no}).e^{-\frac{y}{L_p}} + p_{no} \qquad p_n(0) = (p_{no}).e^{-\frac{V_{CB}}{V_T}}$$

So, if I consider the other junction namely junction 2 and if I say that this junction it is reverse bias, and then similar kind of expression will be getting assuming that the J 1, it is far away. So, now, we are concentrating at J 2 and J 1 may be somewhere here. So, this J 2 junction now it is reverse bias.

So, under reverse bias condition, in fact, it will be interesting to see that the previous expression, it is valid for this reverse bias condition also. But, interesting information here I like to share here, it is if I consider this is the depletion the metallurgical junction, and then if I say that this is the depletion width around this J 2. So, we do have the collector region; we do have the base region.

So, we may say that this is the collector region n-type, base region p-type. And if we do have 0-bias we know that the minority carrier concentration it will be like this. But if we are applying reverse bias, the influence of the reverse bias here it is interesting to see that it will be approaching towards 0 like this; so, same thing the other side also.

So, this is of course, p-region and you may say that this is n p x or let you call this is y. Now so, I have used x here so, let me call this is x and likewise we may call this is p n y. Now, you may say that x is it is sorry y is this going from say from the edge to dip into the collector region and x is going from 0 to dip into the base region.

So, you may say that now we do have rather deficit with respect to n p naught, and then this side it is p n naught. But then expression here it remains same. In fact, this expression, it will be interesting to see that yeah, I should have given this is V CB, but a minus sign, V CB minus sign reverse bias.

And due to that you can see that this profile, it is going to 0. As this V CB it is going higher and higher with reverse bias compared to V T if it is large, so this part it is going to 0. So, that means, the minority carrier concentration it starts almost at the edge with a 0, and then exponential it is rising like this, so that is the main difference. Otherwise the expression of the current remains the same as whatever we have discussed in the previous slide.

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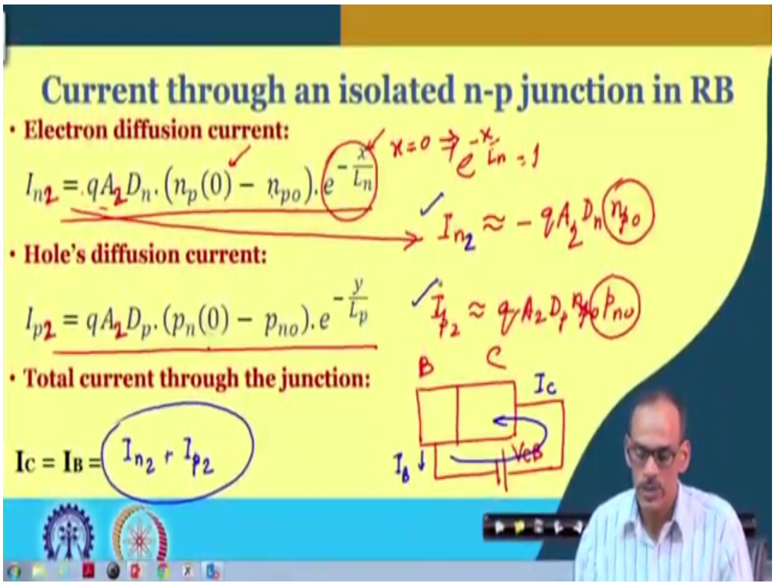

Current through an isolated n-p junction in RB

- Electron diffusion current:

$$I_{n2} = qA_2D_n.(n_p(0) - n_{po}).e^{-\frac{x}{L_n}}$$

$x=0 \Rightarrow e^{-\frac{x}{L_n}} = 1$

$I_{n_2} \approx -qA_2D_n n_{po}$

- Hole's diffusion current:

$$I_{p2} = qA_2D_p.(p_n(0) - p_{no}).e^{-\frac{y}{L_p}}$$

$I_{p_2} \approx qA_2D_p p_{no}$

- Total current through the junction:

$$I_C = I_B = I_{n_2} + I_{p_2}$$

So, just to conclude the current here, the reverse bias current it is essentially it is remaining same as the previous one for both electrons as well as holes. And in fact, this part it will be very small. So, you may draw this part and this part. So, we will be having a minus sign and p n 0 and this part. And this part at x is equal to 0, you may say that this is 1; at x is equal to 0, this becomes 1, so e to the power minus x L n becomes 1. So, we do have only this part.

So, under reverse bias condition, I n 1, well approximated by q A 1 D n n p 0. By the way now I should use rather A 2, so we are talking about second junction and this is current is also second one. So, we can use subscript 2. So, likewise I p 2, it is well approximated by the q A 2 D p n p 0. But you have to remember that this n p 0, sorry this is p n 0, it depends on the donor and acceptor concentration in the collector and the base region that you have to keep in mind.

And if you see the whole device, now we do have the base, this is the base region, this is the collector region, and here we are applying V CB. So, the current is actually flowing in this direction. So, you may say that this I C and I B due to this V CB both are equal to I n 2 plus I p 2, where expression of this I n 2 and I p 2s are given here. So, this is what is expected that the two junctions if they are completely isolated, then their currents it may be expressed in terms of a diode current which we are already aware.

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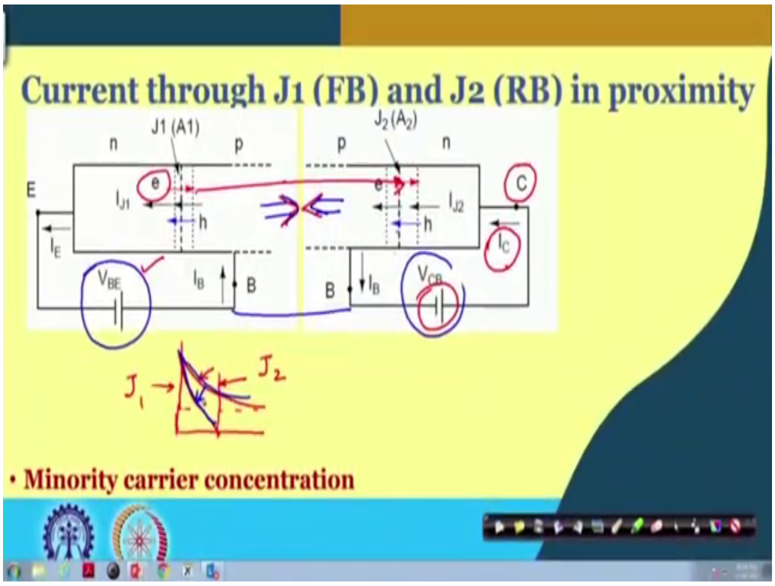

Current through J1 (FB) and J2 (RB) in proximity

- Minority carrier concentration

And so in the next class or next session rather, we will be observing that what will happen if these two junctions they are approaching to each other.

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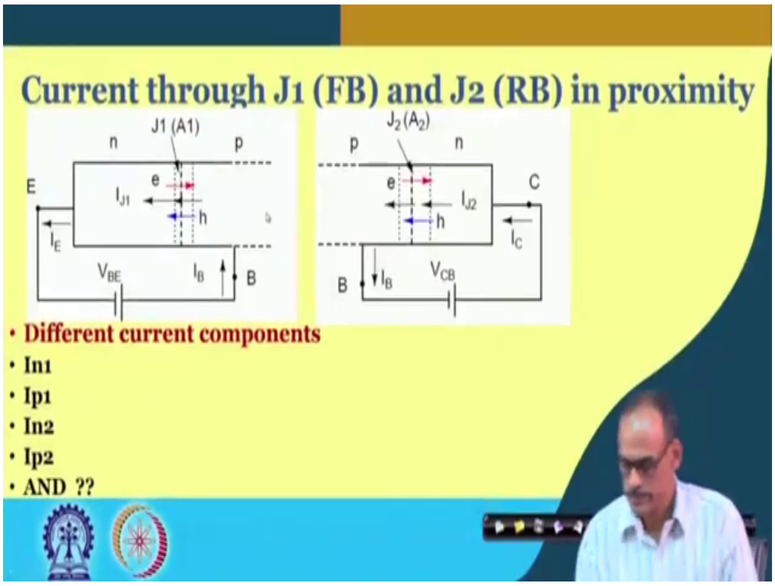

Current through J1 (FB) and J2 (RB) in proximity

- Different current components
- In1
- Ip1
- In2
- Ip2
- AND ??

So, in case if these two junctions are approaching to each other, so then what will happen is this base terminal it will be common terminal, and we do have this voltage to make J 1 forward bias, V CB to make the second junction reverse bias.

But, interestingly what you are expecting is that if this electron it is in the near vicinity of this junction, and we do have strong reverse bias. And this electron may be directly jumping into this one, and it may create abundant availability of the electrons and contributing significantly to this collector current. In other words, based on this voltage the electrons are getting injected into base region, and they are nicely collected by the collector terminal by the virtue of this strong reverse bias voltage, ok.

So, if these two junctions are remaining isolated, we cannot get BJT operation, it will be rather working as two back to back diodes. And this will be getting converted only when these two junctions are moving close to each other in the near vicinity, if I make this reverse bias junction in the near vicinity of whatever the other junction is there. Namely, if the electrons are having profile like this and if this junction it is coming in the near vicinity. So, instead of having an exponential fall of the minority carrier rather it will be having going to drop to 0, because of the reverse bias.

So, if I push the second junction close to this junction 1, then that is what it happens. So, from this profile of the minority carrier, the minority carrier profile, it will be going like this. Anyway we will discuss this one, you please think over and we will continue our discussion in the next class while we will be moving this J 1 and J 2 close to each other keeping J 1 remaining forward biased and J 2 in reverse bias condition.

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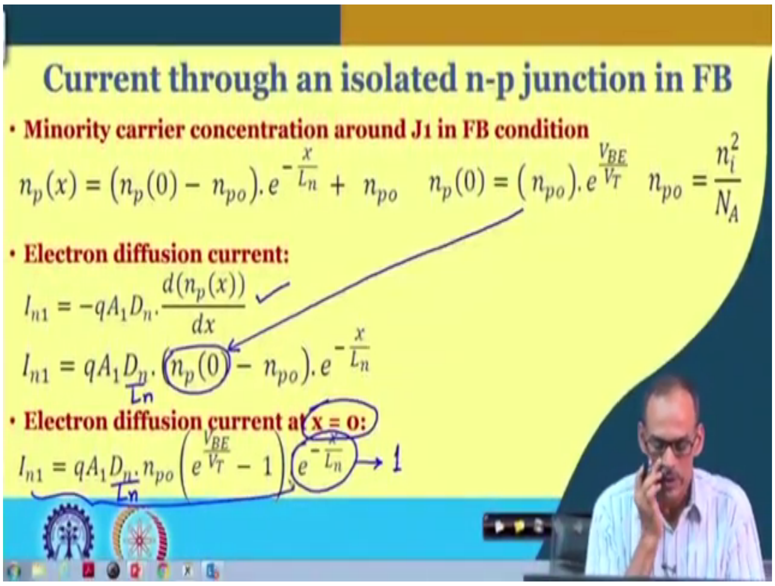

Current through an isolated n-p junction in FB

- **Minority carrier concentration around J1 in FB condition**

$$n_p(x) = \left(n_p(0) - n_{po}\right).e^{-\frac{x}{L_n}} + n_{po} \quad n_p(0) = \left(n_{po}\right).e^{\frac{V_{BE}}{V_T}} \quad n_{po} = \frac{n_i^2}{N_A}$$

- **Electron diffusion current:**

$$I_{n1} = -qA_1D_n.\frac{d(n_p(x))}{dx} \checkmark$$

$$I_{n1} = qA_1\underset{L_n}{\underline{D_n}}.\left(\boxed{n_p(0)} - n_{po}\right).e^{-\frac{x}{L_n}}$$

- **Electron diffusion current at $\boxed{x = 0}$:**

$$I_{n1} = qA_1\underset{L_n}{\underline{D_n}}.n_{po}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)\boxed{e^{-\frac{x}{L_n}}} \rightarrow 1$$

This is where we are talking about the current particularly current carried by electron. I like to mention here a small correction; please make a note of that. Whenever we are taking say derivative of n p x with respect to x, then we do have e to the power minus x by L n, so that L n part it will be coming here. So, this is a correction. And rest of the things it is remaining same, namely this part it will be as we say that it can be replaced by n p 0 e to the power V BE. And so the total current or diffusion current we are getting here and the same mistake it is getting repeated here. So, it should be divided by L n.

So, expression of current carried by electron equals to q A 1 D n divided by L n p naught e to the power V BE by V T minus 1 e to the power minus x by L n, and as I say that if I consider x is equal to 0. So, this part it becomes 1 and hence this is rest of the things it is giving the current flow are carried by electron. If we take the derivative will be getting along with D p will be having L p in the denominator because we do have e to the power minus y divided by L p we do have.

And so, if you replace the p n at x is equal to 0 by its corresponding expression here, what we can get is p n 0. And then p n 0 you can take it out and in this position what will be having it is e to the power V BE by V T.

Thank you.