Microelectronics: Devices to Circuits
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Module 3
Lecture 13
BJT: Second Order Effects - II

Hello and welcome to the online certification course on Microelectronics: Devices to Circuits. In our previous module we have learnt the second-order effects which are prevalent in a bipolar junction transistor. What are these second-order effects? These are those effects which normally don't show their presence but under certain conditions of electrical parameters or structural parameters, their effects are pronounced and their effects are relatively seen or influence the electrical characteristics of the device. One of the phenomena which we looked closely was basically your, the concept of base width modulation effect also known as early effect and associated with that, we found out a voltage known as early voltage.

This makes the early effect phenomena makes the device behave as a non-ideal current source in the saturation region or in the active region, as we say. And we have also seen that there is a multiplication of charge carriers under effectively large reverse bias near the depletion region which results in a large change in the value of your collector current. We will start from where we have left in the previous term and see what the other second-order effects are and also look into the typical cross-section of a bipolar transistor and then we will recapitulate this whole discussion.

So typically, we would expect to see that this will be the last sort of presentation on bipolar technology. After this, we will move to CMOS technology because that will be the next structure we will see that.

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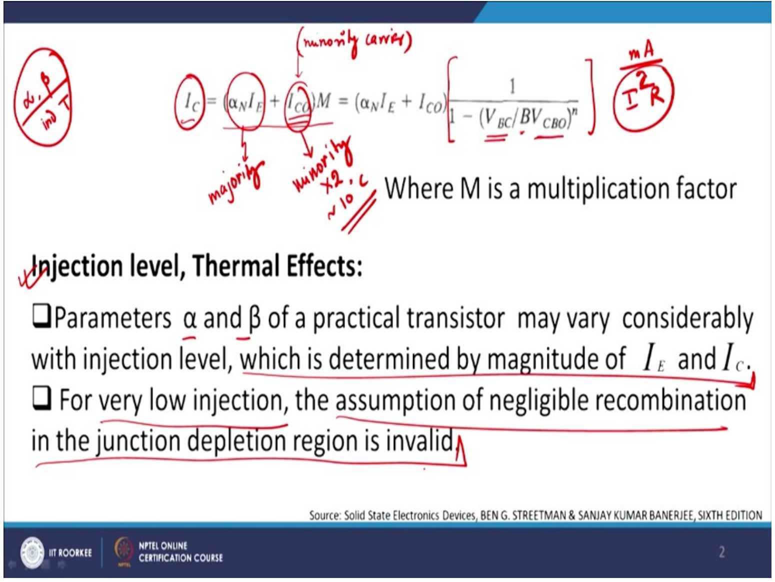

$$I_C = (\alpha_N I_E + I_{CO})M = (\alpha_N I_E + I_{CO})\left[\frac{1}{1 - (V_{BC}/BV_{CBO})^n}\right]$$

Where M is a multiplication factor

Injection level, Thermal Effects:

- ❑ Parameters α and β of a practical transistor may vary considerably with injection level, which is determined by magnitude of I_E and I_C.
- ❑ For very low injection, the assumption of negligible recombination in the junction depletion region is invalid.

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

So as we left the previous discussion, the collector current I_C was equals to given as α N times I_E where I_{CO} is basically my reverse bias sort of a minority current carrier concentration. So this is basically minority carrier concentration, right? And what we are predicting is that the total collector current which is flowing through a circuitry will always be a sum of the majority current carrier contribution plus the minority carrier contribution. And this factor M is given by this term which is 1/1 - BC, base collector junction and... Base collector junction with a capital B to the power N where N is a basically a, an integer value.

Now depending on the value of N which is basically a positive integer, we would expect to see I_C to be large or small right? We also see the fact that there is a contribution, this is basically your majority carrier contribution, right? This is a majority carrier contribution and this is primarily the minority carrier contribution, minority, right? Now please understand that with rise in temperature, you would expect to see minority carrier contribution almost double for every ten degree rise in temperature right?

Or approximately five to ten degree rise in temperature, which means that the collector current doubles itself due to minority current carriers if you raise the temperature. We will come to that when we discuss other effects in our subsequent slides. We have also considered for the time being that α and β which is basically your current gain in common emitter and common base configurations, these are primarily independent of independent of temperature. In reality, not true. And that is where our second issue is coming into picture.

Then what is the effect of thermal effect? So what is thermal effect primarily means that please understand, this BJT is working in an environment where applied voltages are very large. Not only that, your collector current is in the order of millivolts. So if your collector current is in the order of millivolts milliampere sorry, then I square into R which is basically the power dissipation which you expect to see from a device is typically very high, right? As a result, the on chip temperature for a bipolar technology based silicon design will be relatively high. So we cannot neglect the effects of thermal variations or effects of thermal changes onto the device characteristics.

And till now we were assuming that α and β were independent of temperature. But now we will see that the α and β are depending on the value of temperature. Not only that, they also depend on the magnitude of I_E and I_C. Right? We have, this we have already seen, right? Now at very low levels of injection. What does it mean? Low level of injection primarily means that when your bias is so small that even in an NPN transistor, if the number of electrons being injected onto the base side is relatively very small, then we define that to be as a very low level of injection, right? Now the assumption of negligible recombination in the depletion region is invalid. I will explain to you what does it mean.

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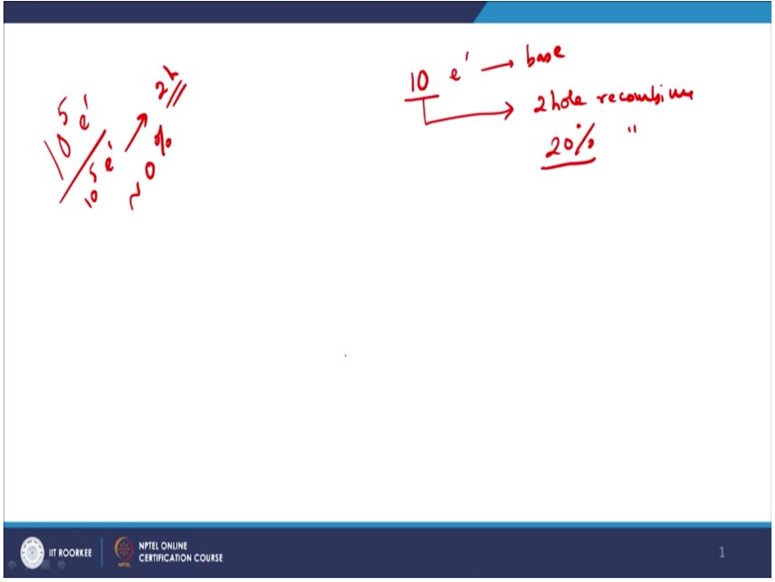

It means that that let us suppose you are injecting, you are injecting let us suppose in one case, which is low level of injection, you are injecting say 10 carriers right? 10 electrons are being injected onto the base side. Right? Whereas for a large injection, we will have let us suppose 10^5 electrons being injected. So if you have 10 electrons, then with respect to 10, even if there are 2 holes in the base side which is recombining right, you still have a 20 % right recombination. Fine?

Whereas if you have 10^5 electrons being inserted and you only have two (elect) two holes being combining more you can understand this negligibly small percentage of recombination, or almost 0 percent recombination. That is what it is written here, the assumption of negligible recombination in the junction depletion region is invalid. And the reason is that we cannot assume that the recombination current is very very low. Right? It will be very very high as compared to your base injection current and that is what is an important issue.

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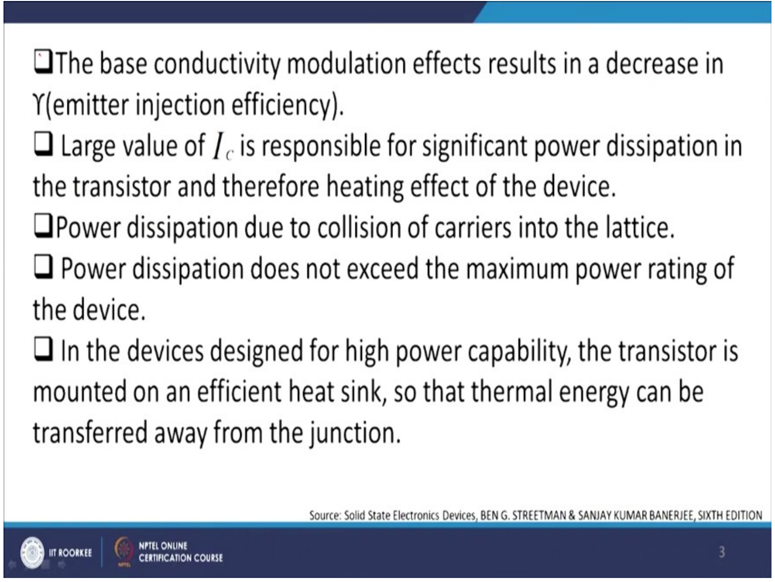

❑The base conductivity modulation effects results in a decrease in Υ(emitter injection efficiency).

❑ Large value of I_c is responsible for significant power dissipation in the transistor and therefore heating effect of the device.

❑Power dissipation due to collision of carriers into the lattice.

❑ Power dissipation does not exceed the maximum power rating of the device.

❑ In the devices designed for high power capability, the transistor is mounted on an efficient heat sink, so that thermal energy can be transferred away from the junction.

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

Now, we have also seen that this we have been discussed earlier but we will make it, we will discuss at this point which you see, this point if you see very carefully for the base conductivity modulation effect results in a decrease in the value of γ which is emitter injection efficiency. What does it mean that? I will explain to you what does it mean. It means that let us suppose you did have a base width modulation, which means that you forward biased your base emitter and you reverse bias your base collector and you go on increasing the reverse bias of the base collector.

As a result, the effective base width is decreasing. Now once it is decreasing which means that the effective number of holes available is actually getting reduced and therefore its probability of recombination with electrons is also getting reduced. Right? So what we have learnt from this is that if the base conductivity is there, it will reduce the, it will reduce or decrease the emitter injection efficiency which means that it reduces the efficiency by which the emitter will be able to inject its carrier onto the base side because if it is very small, all the electrons will not be combining with holes, as a result the base the emitter efficiency reduces.

Now we are 100 percent sure that when you are doing common emitter configuration for example, your collector currents are very very high, right? Right? And they are very very high in the sense, they are typically very high. And as a result, there will be significant power dissipation in a transistor, right? And therefore as a result, there will be self-heating of the device itself. The reason is that so large I_C, so I_C square I_C square into R which is basically my power dissipation, this will be typically very high because your I_{Cs} are very very high or collector currents are very very high.

And you see it is basically almost like a parabolic increase in the power dissipation. So even if you double your collector current, you are actually making the power dissipation increase by four times which is quite large power dissipation. Now I will just give you an idea what is known as thermal runaway. Right? Basic thermal runaway, concept of basic thermal runaway. Right?

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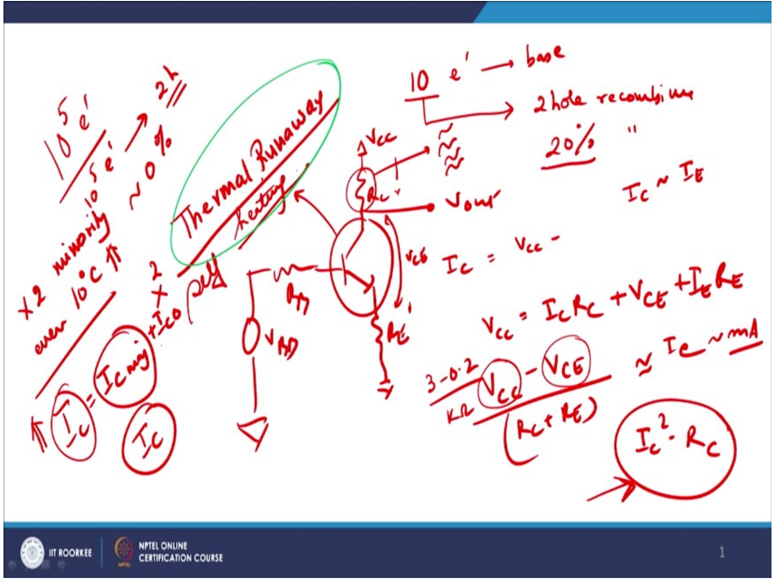

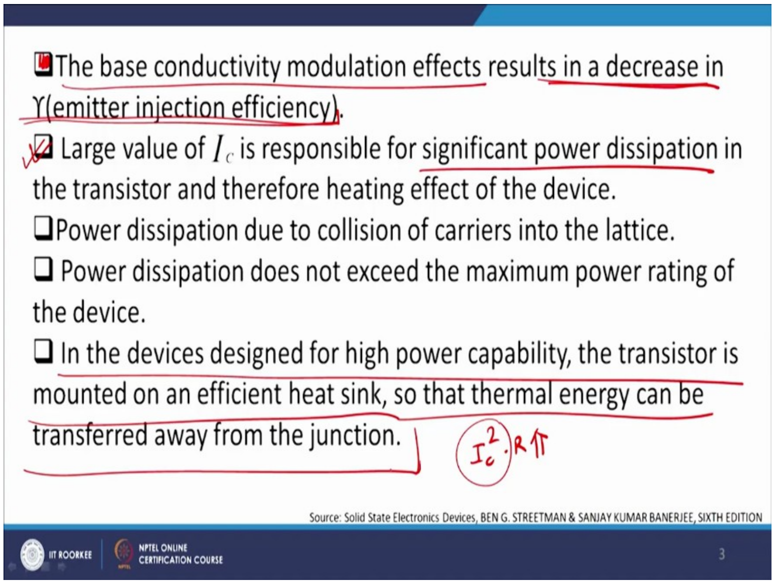

- ☐ The base conductivity modulation effects results in a decrease in γ(emitter injection efficiency).
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- ☐ Power dissipation does not exceed the maximum power rating of the device.
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$I_C^2 \cdot R \Uparrow$

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

So, we will discuss one basic concept which is known as thermal runaway. Now you see that suppose you have a common emitter base configuration, emitter grounded configuration with emitter bias here and you had a base collector junction here and you had a R_C here and R_B and R_E right? And then you appropriately bias it with V_{CC}, this is with V_{BB} and so on and so forth. Right? And you have an NPN transistor, this is your V_{out}. Now you see, in this case your I_C, I_C can be given as, it can be given as V_{CC} -, so if you solve it from this end to this end, I get assuming that I_E is the collector, so V_{CC} will be equals to I_C R_C right + V_{CE}. Which is V_{CE}? This is V_{CE}. Right?

V_{CE} + I_E R_E, right? Assuming that the base current is very small, I can assume simply that I_C is approximately equals to I_E and therefore I can write down V_{CC} - V_{CE}/R_C + R_E is effectively equals to I_C. Right? Approximately equals to I_C. V_{CE} is typically 0.2 or 0.3, this will be around 3 volts. So 3 - 0.2 divided by a few kilo ohms, some kilo ohms. So this will be of the order of a few milliamps right? So it will be of the order of a few milliamps, collector current.

Now what happens is that, this I^2, I_C^2 into R_C will result in power dissipation across this resistance, so there will be a power dissipating, right? As a result this transistor will start get heated away, right? And there will be heating. So what is also known as self-heating. We will explain to you what this self-heating is. So as the temperature rises, please understand, that by my previous discussion just now, my minority current carriers almost doubles for every ten degree rise in temperature. For minority, not for majority, please understand.

For minority carrier doubles for every ten degree centigrade rise in temperature right? So if a (temp), so you have increase in power dissipation which results in increase in temperature. This results, this increase in temperature results in increase in minority carriers. Now I_C overall current will be made up of I_C majority + I_{CO} or I_{CO} minority. Now though this is constant, but this every time doubles itself which primarily means that you're I_C will again increase, with temperature. As I_C increases, I_C^2 into R_C will also increase.

So more heating effect, more temperature and more I_C zero. So this is known as, so a time will come when I_C will be so large that it will destroy the BJT itself. So, there will, this phenomenon is known as thermal runaway, right? So this phenomenon is known as basically known as, known as thermal runaway. So this is thermal runaway or self-heating issues, right? And therefore this thermal runaway gives you a large amount. So in the devices designed for high-power application, the transistor is mounted on an efficient heat sink for the reason I just now discuss with you, so that the thermal energy can be transferred away from the junction right?

So as long as you are able to shift the thermal energy away from the base collector or base emitter junction, we would expect to see no rise in the minority current carriers because of temperature because you are able to shift the important or the major part of our power dissipation or temperature rise away from that. So if you have a heatsink which is working as a very good heatsink, that will help you to remove the power very fast away from the collector, emitter base junction.

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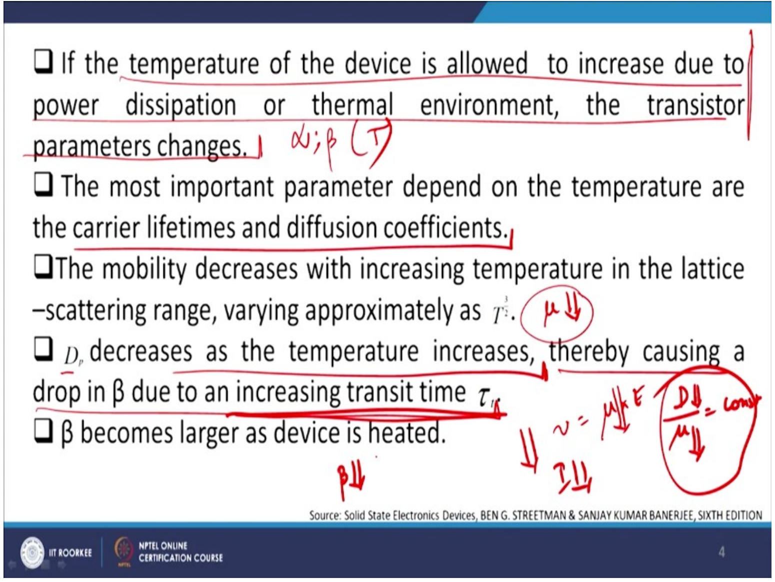

- ☐ If the temperature of the device is allowed to increase due to power dissipation or thermal environment, the transistor parameters changes. $\alpha;\beta\,(T)$
- ☐ The most important parameter depend on the temperature are the carrier lifetimes and diffusion coefficients.
- ☐ The mobility decreases with increasing temperature in the lattice –scattering range, varying approximately as $T^{\frac{3}{2}}$. $\mu\Downarrow$
- ☐ D_p decreases as the temperature increases, thereby causing a drop in β due to an increasing transit time τ_t
- ☐ β becomes larger as device is heated.

$\beta\Downarrow$ $\quad \Downarrow v = \mu\Downarrow E \quad I\Downarrow \quad \frac{D\Downarrow}{\mu\Downarrow} = \text{const}$

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

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Ok, This is what I was saying that if you allow therefore, if the temperature of the device is allowed to increase due to power dissipation of thermal environment, the transistor parameter changes. So your α and β are a function of therefore temperature. Right? And current gain increases. So as we discussed we will not go in the details of it but the most important parameters, the carrier lifetime and diffusion coefficients, also we have seen that as the temperature increases the mobility actually falls down. Right?

And because this is very simple that as the temperature increases, the lattice itself starts to move across its mean position right because of high thermal energy. As a result, electron travelling across the lattice gets scattered by collision with these lattice atoms. As a result, the mobility falls down. So higher the temperature, the mobility starts to fall down and this results in a lower mobility and therefore when you talk of drift, your drift will be equals to, velocity of the carrier will be μ into E. So as a result, when μ falls down, velocity falls down and therefore the current is reduced drastically. Right?

The diffusion coefficient of holes and electrons also decrease as the temperature increases, thereby causing a drop in β due to increasing transit time. I think, I will make it clearer to you what do I mean to say by that. It means that as you as your temperature rises, right, the diffusion coefficients actually starts to fall down. So when that happens, you have because it primarily means that see D/μ is constant, Einstein's relation. So when D starts to drop down, μ also has to go down to make this ratio constant.

So when mobility drops down, it increases the transit time, right? And when it increases the time, the β actually starts to reduce. The β is basically the current gain. Why current gain starts to reduce? Because now, since the transit time is lowered, then within the same amount of time, lesser amount will be (charged) charge will be transferring from emitter to base. So, your overall collector current will reduce and therefore the gain will reduce, right? And therefore, and that is the reason why you have reduction due to increase in transit time as the temperature increases right? And this is one of the problem areas which people face in this thing.

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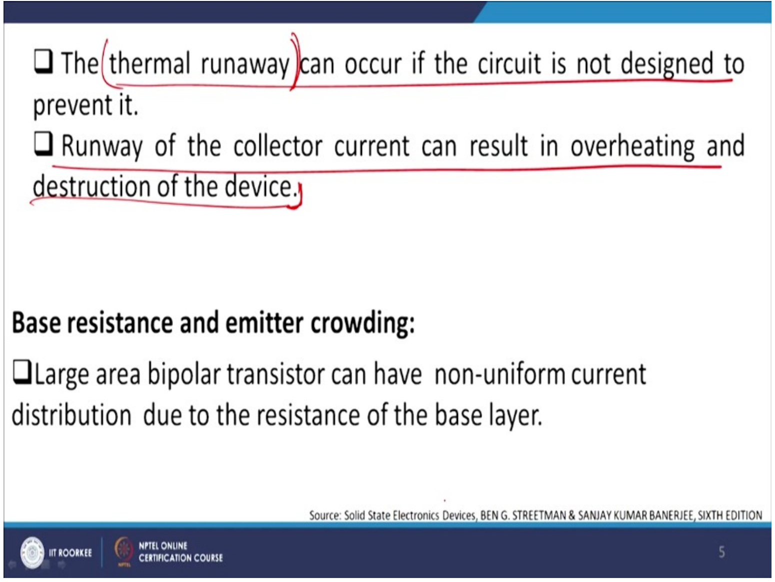

☐ The thermal runaway can occur if the circuit is not designed to prevent it.

☐ Runway of the collector current can result in overheating and destruction of the device.

Base resistance and emitter crowding:

☐ Large area bipolar transistor can have non-uniform current distribution due to the resistance of the base layer.

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

Now, thermal runaway is a standard problem area and if circuit is not designed properly, you will have a thermal runaway which will make the device non-functional and will burn up within a very short period of time. As I discussed with you, runaway of the collector current can be due to overheating and the destruction of the device right. And this is what leads to fatal destruction. Let me come to the third second order effect and that is base resistance, emitter crowding. Now what happens is that we are assuming that the cross-sectional area of the NPN transistor, emitter base and base collector junctions are relatively small, right?

And therefore the flux of electric field is almost constant across that emitter base or base collector junction right? That is true even if you have very small junction areas there. But if the junction areas are relatively large, typically very large, then you do have a non-uniform current density which means that the flux lines are not uniform across the interface. Right? We will not go into details of why is it like that but that is the reality. You don’t get it. And therefore the collector current is not equal across the interface through the base layer.

This is basically known as base resistance or base resistance increases in that case, right? So these are the three major second order effects or second order phenomena which people have seen across the board and its removal is quite important. Early voltage or base width modulation effect can be removed by using the doping concentration on the base side, much much higher, relatively higher as compared to collector, this is one thing.

The second thing is, how do you actually go for thermal runaway removal, well there are standard stabilization techniques by which we can actually have circuit level manipulations to reduce the thermal runaway, or almost remove the thermal runaway. And for the base splitting and emitted following, we require to make the emitting base junction and base collector junction area, cross-sectional area as small as possible.

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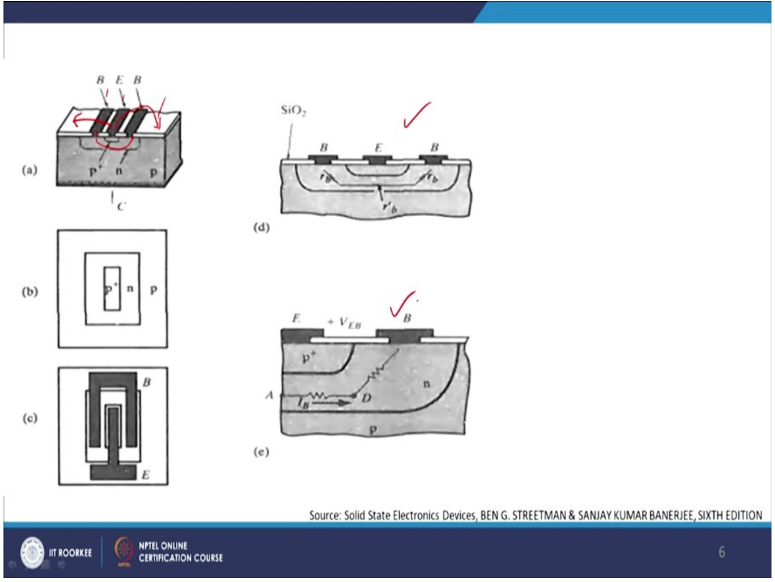

Source: Solid State Electronics Devices, BEN G. STREETMAN & SANJAY KUMAR BANERJEE, SIXTH EDITION

Now let me just finish of this bipolar transistor lecture by giving you a effective cross-section of a bipolar device. This is your emitter base junction. If you look very carefully, it is base, emitter and this is also your, so this is your collector, this is your base. So you have got two bases connected back-to-back. So this one base and therefore emitter base collector and emitter base collector, so you have got 2 transistors in series, sort of. And their layout looks something like this and this right? So we will not go into further detail than this, it is available in a standard textbooks for understanding purposes and it gives you a detailed analysis about the BJT as such. Right?

We therefore recapitulate the bipolar technology in a detailed manner which we have already seen. We have seen therefore that the bipolar technology can be used as an inverter to make it saturation, to go to saturation and cut-off.

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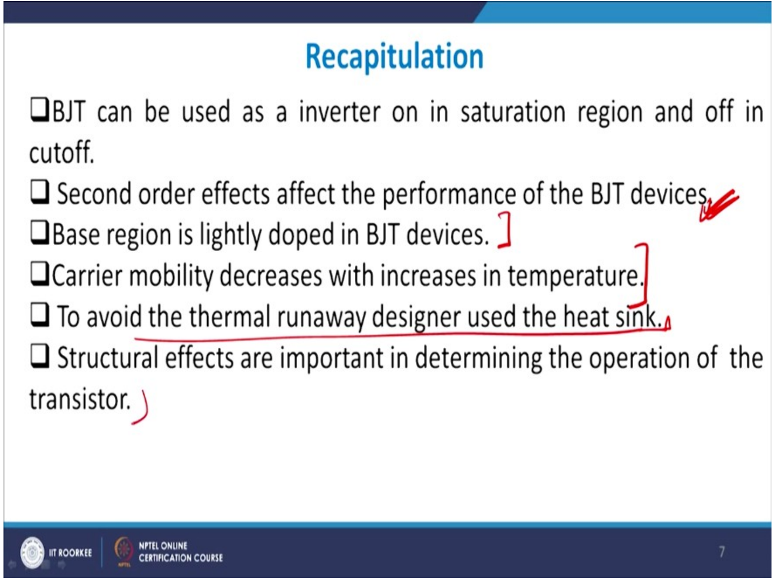

Recapitulation

☐ BJT can be used as a inverter on in saturation region and off in cutoff.

☐ Second order effects affect the performance of the BJT devices.

☐ Base region is lightly doped in BJT devices.

☐ Carrier mobility decreases with increases in temperature.

☐ To avoid the thermal runaway designer used the heat sink.

☐ Structural effects are important in determining the operation of the transistor.

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Second order affects the performance or the behaviour of the device right and it degrades the behaviour of the device. It degrades it, right? Base region is always lightly doped. Carrier mobility decreases with increase in temperature, we have seen that. We, as we discussed earlier that in order to remove thermal runaway, designer has to use heat sink and proper heat sink design is an important one. And structural effects are important in determining the operation of the device. The structural effects primarily mean, how what is the cross-sectional area of the base emitter and base collector junction, right? And these are important.

So this takes care of our understanding of typically the first part of our, of the lecture series. And this was still bipolar transistor, we will and it takes care of basic understanding of bipolar, the parameters of bipolar transistor, various configurations of bipolar transistor, how do you calculate current and therefore what are the second order effects prevalent in a bipolar transistor and that has been discussed in these set of modules. In the next module or the next lecture, we will be going through or going ahead with a CMOS technology or MOSFET technology. Right? With these words let me thank you for your patient hearing. Thank you.