Microelectronics Devices to Circuits

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Lecture - 01

Bipolar Junction Transister: Physical Structure of Operation

Hello everybody, welcome to the NPTEL online certification course on Microelectronics: Devices to Circuits. This is basically a 30 hour lecture which is being sponsored by NPTEL and delivered by me. I am Professor S. Dasgupta at IIT Roorkee in the department of Electronics and Communication Engineering.

The prime motivation for this 30 hour lecture which was supposed to be delivered to students and stack holders who are interested in this area is to give you a full knowledge right from devices till circuit level, realization of those devices which means that the first few lectures or the first few weeks will actually carry forward the concept of devices the various devices which are currently used in the area of microelectronics. Starting with bipolar technology and then a short description of MOSFET and CMOS technology after that we will be actually entering into the usage of these devices for both analog and digital applications.

So this course primarily therefore deals with the application area of these devices in analog and digital domain. To understand and to appreciate its usage we need to understand the physics of the devices in a proper fashion and therefore, the first 5 weeks or 4 weeks of this lecture plan or this lecture will primarily deal with the devices and then we will be the understanding therefore the basic device characteristics we will use those device characteristics for realizing certain circuits for all applications.

Now, so the first thing which the first lecture which starts today we will be dealing with bipolar technology which is bipolar junction transistor technology and in this lecture today we will be discussing its physical structure and modes of operation. So today's lecture is termed as bipolar junction transistor or BJT and its physical structure and modes of operation. So we will understand how a bipolar technology or a bipolar transistor looks like and what are the various modes of operation of this device.

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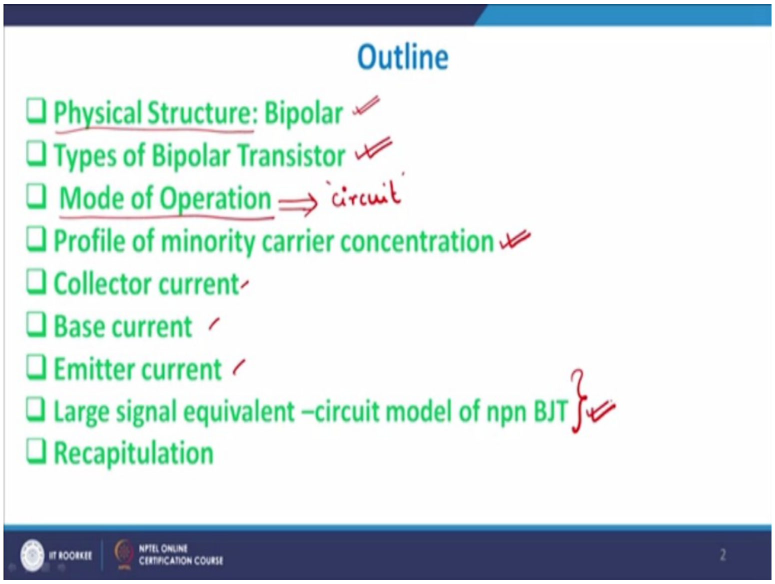

So what we intend to do in the next part of this work is, we will so the outline of my talk is something like this that we will be actually looking into a bipolar technology right. What is a bipolar technology and how is it different from unipolar technologies? We will look into the physical structure of the bipolar technology which means that how does a bipolar transistor looks like physically, various types of bipolar technology or transistors we will be having a look and we will be seeing on what basis the differentiation is done between two bipolar transistors.

We will be then focusing into its mode of operation because this is quite important in the terms of circuit implementation. So when we do a circuit implementation we actually require to know its mode of operation. So we should know under what bias input bias will my transistor work at what stage or at what mode right. So this topic will give you an idea about the working principle with respect to the biases of voltages and currents given to this transistors.

We will be looking into the minority current carrier profiling in this case because that will help us to find out the total current which is there in a bipolar technology. We will be looking into emitter current, base current, and the collector current and its interdependency based on certain rules applied to a bipolar technology we will be also looking at the circuit model for npn transistor which means that if I have an npn BJT or a bipolar and I want to use it in a circuit analysis what modifications or what equivalent circuit models can we have for this BJT so that I can just plug and play in a circuit. So that we will be doing it at the last part of our talk.

So basically large signal equivalent we will be looking into circuit model large signal equivalent which means that once we know what are the currents and voltages of the bipolar transistor is there can I therefore convert that into known devices and known factors so that it is very useful when we want to translate this device into a circuit that we will be doing when we do a last signal equivalent circuit model of BJT. So you should be very careful about the whole flow of this bipolar technology.

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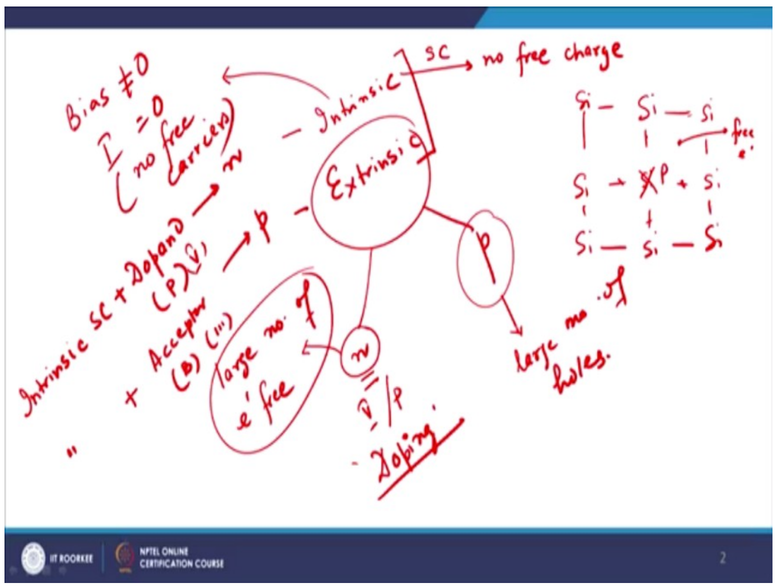

So before we even start with bipolar technology let me give you an idea about what is a basically a brief idea about PN junction because that is where we are starting with. If you remember interestingly in a very basic thing which was being remembering we have two types of transistors or two types of semiconductor devices we have a extrinsic semiconductor and we have got intrinsic semiconductors. I will just go about briefly to give an idea about because this is a starting were with. What is an intrinsic semiconductor? Intrinsic semiconductor is a one in which we do not have any impurity and there are no free charge carriers there are no free charge carriers.

So therefore, in an intrinsic semiconductor for example a silicon if we apply a bias since there are no free charge there will be no current flow and since there are no charge there are no free carrier there will be no current flow. So therefore, in an intrinsic semiconductor for bias equals to even nonzero bias your current will be still equals to 0 as there are no free carriers right.

Now, let us come to extrinsic, extrinsic as you must be knowing from your previous knowledge we have two types of semiconductor, one is known as n type semiconductor and we have a p type semiconductor, what is a n type semiconductor? An n type semiconductor is a one in which we have doped silicon with group five element for example phosphorus and therefore an n type material or n type semiconductor we will have large number of large number of electrons as free carriers.

So what is a extrinsic n type material n type material will a large number of free electrons as free charge carriers from where they are coming they are coming from the donor atoms which are primarily phosphorus in nature, so if I have a silicon here right and I have got silicon here and I have got silicon here right all of must be knowing there are covalently bonded with respect to each other right and so on and so forth, so I have a silicon here I have a silicon here right.

Now if this phosphorus or this silicon is replaced by a phosphorus which is group 5 then all the four electrons of phosphorus will group with this, with this, with this and with this, but its extra electron will be actually free so this will be acting as a free electron right so this what is known as we must be knowing also is basically known as doping, right. So what we do? We take an intrinsic semiconductor we add a dopant to it dopant basically in this case may be phosphorus which is group 5 element and we convert them into n type semiconductor, right.

We similarly take an intrinsic semiconductor add may be accepted type group 3, group 3 element which is for example boron so this group 5 and this is group 3 and we convert this into p type semiconductor available to us so which means that n type semiconductor will have large number of free electrons whereas a p type semiconductor will have large number of large number of holes as a free charge carriers right so this will be large number of holes.

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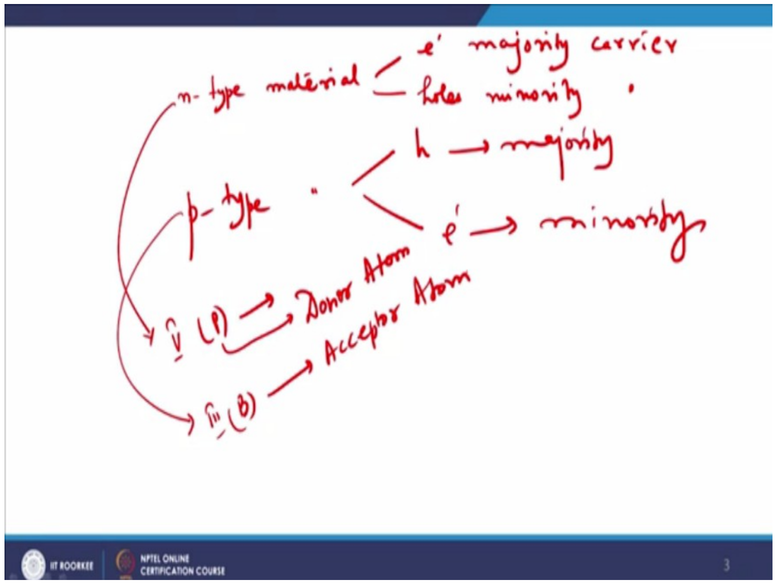

So and therefore let us comeback to an original issue to statement therefore that I have a n type material, I have a p type material, n type will have electrons as very large quantity and therefore electrons will be referred to as. So what we will say is in an n type material, I will be discussing or I will be knowing that electrons will be referred to as a majority carriers a majority carrier right and holes we will see why, holes will be referred to as minority carriers.

Similarly, in a p type material, in a p type material right holes will be referred to as majority current carriers right where as electrons will be considered as minority carriers. Which means that, and we will not discuss this in detail because that will be a part of another course, but what happens actually is in an n type material which is basically an electron having majority carriers you will still have few amount of holes still available to you right.

So maybe there are 100 electrons and may be 3 or 4 holes right may be that will be the ratio. Similarly, for a p type material you might have 100 holes and may be 5 or 6 electrons, but they are still there right there are in small percentage but still there and they make a difference when we are discussing certain issues related to bipolar technology.

So, with this understanding, the basic knowledge which you possibly, already, maybe aware of or if you are then I will refer that you please consult one of the standard books in devices, which will give you an idea about all this things, but for our purposes as far as this course is concerned, this much knowledge will be at this stage sufficient for moving forward, that I have two types of materials, I have a intrinsic silicon, I have extrinsic silicon.

An extrinsic silicon can be of two types, n type and p type. n type is a silicon which have got electron as the majority current carrier and hole as the minority current carriers, and p type is semiconductor which is holes as the majority carrier and electrons as the minority current carrier, right. Now please understand, I have still not applied any bias or I have not applied any temperature variation, nothing. So I have just doped it which means my dopant species have been just added, right.

Now in n type material, when we add to this group 5 element for example of a phosphorus, this phosphorus is known as a donor atom, why? Because it is donating one extra electron to the silicon, whereas when we make a p type material, when we add our group 3, for example boron, it is known as an acceptor atom, why? Because it is accepting one electron from the system and a hole is left there and therefore we define it to be an acceptor atom.

So a donor atom will donate electron and make this species intrinsic silicon to an extrinsic silicon n type and the acceptor atom when it is being doped on to intrinsic silicon makes it a p type material, right. So we are clear about these two basic philosophy or basic concept as far as this course is concerned, right.

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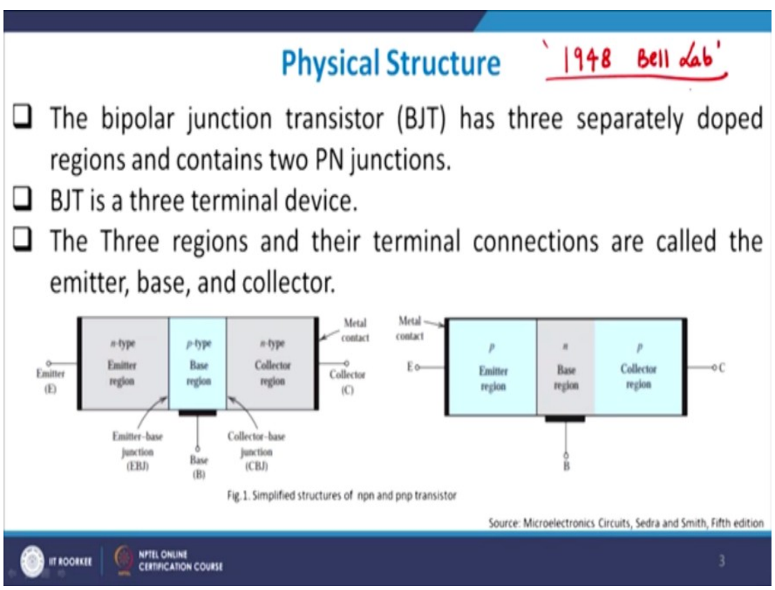

With this understanding, let me come to the first understanding of a bipolar technology. Well, BJT as the name suggest that is the bipolar junction transistor, first came into picture in 1948, right and it was done in Bell Labs at that point of time, so 1948 in Bell Labs in U.S, it was developed and it was very well known to us and the first BJT or bipolar technology which was physically done was by Bardeen and Shockley, they were the first one to propose this concept and 1948 was the time and it was physically available to all of us.

Let us look at the physical structure of the bipolar technology and then see how things move along. Now if you look at the chronological aspects of bipolar technology, in 1950s and 60s, a bipolar technology was the main stay for all your digital and analog applications. So, we had this bipolar technology act as an inverter and also act as an amplifier, this bipolar technology was acting as a logic for all logic. For example TTL, right Transistor Transistor logic, so all your transistor logic used bipolar technology or a BJT for doing all your digital logic design.

Similarly, for the purpose of amplification, voltage amplification, current amplification we use this bipolar technology and in 1950s and 60s and so on and so for. So it was a very standard technology at that point of time, later on MOSFET and CMOS came into picture, this was relegated as a second level device, but still in many applications BJT find still is used, one of the application is BiCMOS technology right. For making rad hard design, for example radiation hardens design we use a BiCMOS technology. So it is known as a BiCMOS technology where we use a bipolar technology, bipolar plus CMOS technology together right. They have been used quite often in all these domain analysis.

I will go in to the physical structure of a bipolar and then we will see why is it known as a bipolar junction transistor right and we will see what is the basic physical reasoning or understand the basic physical working of this bipolar technology. Now, BJT is primarily, if you look very carefully has got all these three regions. So, it is basically a three terminal device.

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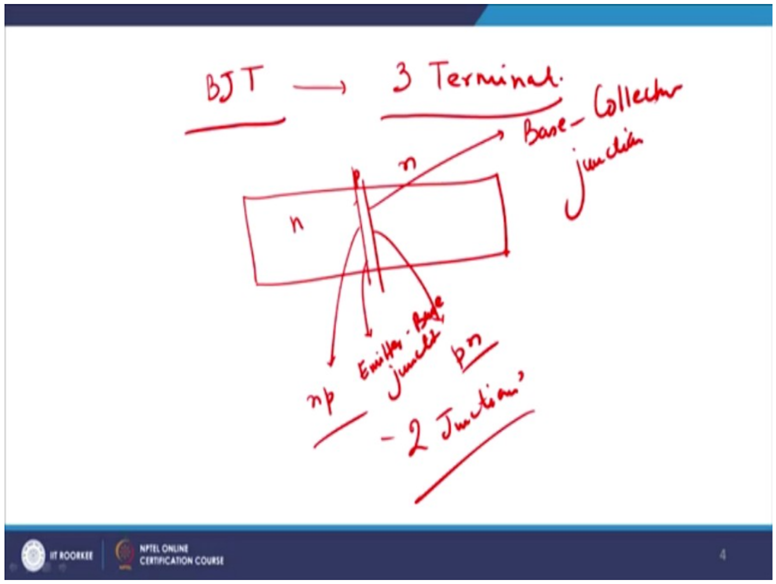

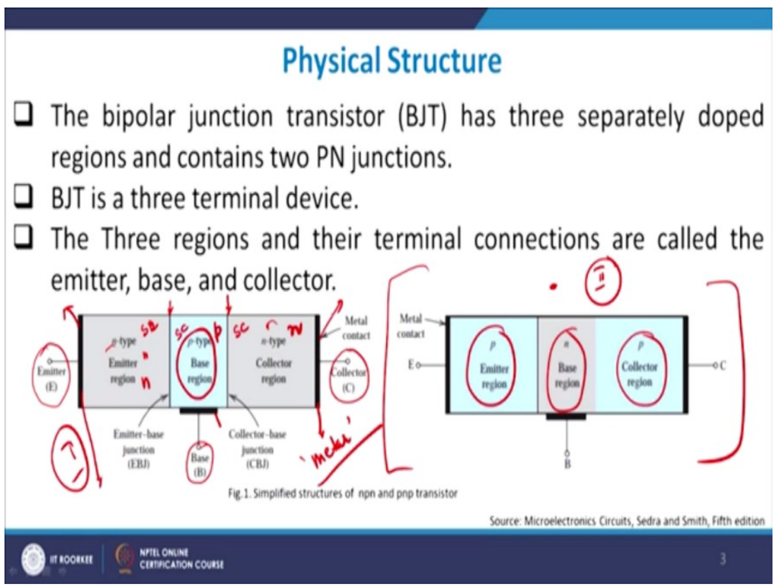

So, a bipolar technology is basically a bipolar, a BJT bipolar transistor is basically a three terminal device which means that there are three terminals associated with bipolar technology, right. What are these three terminals? These three terminals are referred to as, first terminal is known as emitter terminal, this one is known as emitter terminal, we have a second terminal which is known as base terminal right. And then we have a third terminal which is known as collector terminal fine. So, this is basically a semiconductor, this is semiconductor and this is also a semiconductor. But difference is that you have an n type semiconductor for majority current carrier as electrons, the emitter is basically an n type semiconductor and the collector is also an n type semiconductor and sandwich between the two is basically your p type base region, right.

So therefore this is referred to as an npn transistor, right. So I have got npn which means that, so there are three regions emitter, base and collector. Emitter and collector will have the same doping, same type of doping, not necessarily the level of doping, but same type of doping and base will be sandwich between emitter and collector, right, so these are the three separate region are there. Now what we can see is that, therefore if you look very carefully you will have two basically np junction available here, right. What are these two pn junctions? The first one is this junction and the second is this junction, right.

So if you go back to the original diagram of an npn transistor which we are aware of, so there is an npn, this is basically your np junction and this your pn junction. So we have got two junctions, which is there, there are two junctions, right and they play a critical role in determining the properties of this bipolar technology, right. So there are two junctions here, this is known as emitter base junction, right and this is known as base collector junction.

So, I have got two pn junctions, connected back to back, one is known as emitter base junction and other is known as base collector junction. And these two junctions are just auditory pn junction, as we know for sure which is available to us.

Now, the structure is something like this, its dual structure if you see on this side, on the right side of the power point presentation, this side-this side is basically the n type semiconductor which is Emitter, has been replaced by p type, the base which was initially p type has been replaced by n type, the collector which was initially n type has been replaced by a p type, right.

So the p one is basically blue one and the n type is basically shown by brown or light grey. So what we have done is that the second structure you see here is just the dual of the first structure. Which means that structurally exactly the same and doping also is just identically complimentary with respect to each other. I will discuss that later on as we move along.

So, I can have two types of transistor therefore one is known as npn, right The first one which you will see on the left hand side of the screen is npn, right And the second one is pnp . So depending upon where you have sandwiched your base layer, right and what is the doping of the base layer, you can actually make a point whether it is a npn or a pnp transistor. But, we have two types of transistors that is for sure, right.

Please understand also one more important point shown in this diagram, this black material, which you see this, this and this, these are all metal contacts, so these are metal, right. So, I have metal contact, you a need metal contact to form a Schottky barrier between the semiconductor and the metal, right. So there will be Schottky contact here at emitter region here, so there will be Schottky contact here and there will be Schottky contact at this point as well, right. So there will be therefore there are two junctions, three terminals and there are two types of material, p type and n type which you see in front of you.

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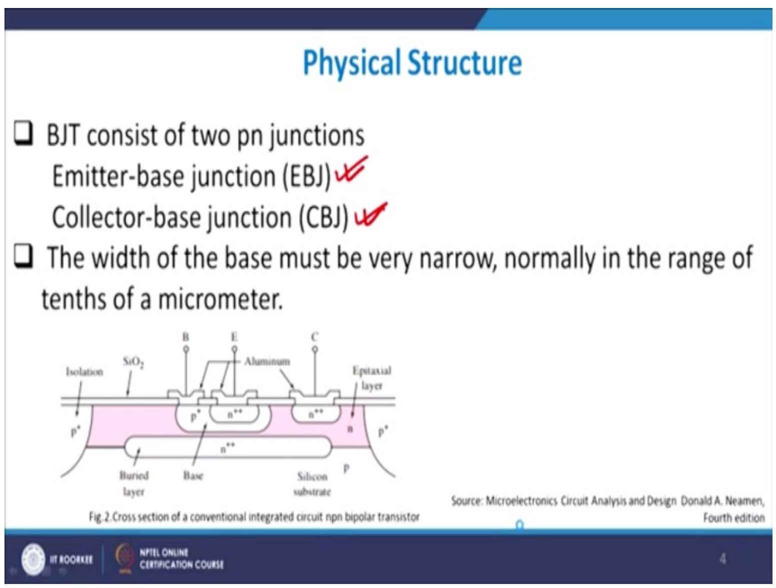

As I discussed with you in the previous slide, we have got two types of junction available one is known as emitter base junction, another is known as collector base junction. Now, what we see is that this is quite interesting that I will discuss it later also that it has been seen or it has been predicted or it has been proposed that the emitter region should have the largest doping concentration among the three regions.

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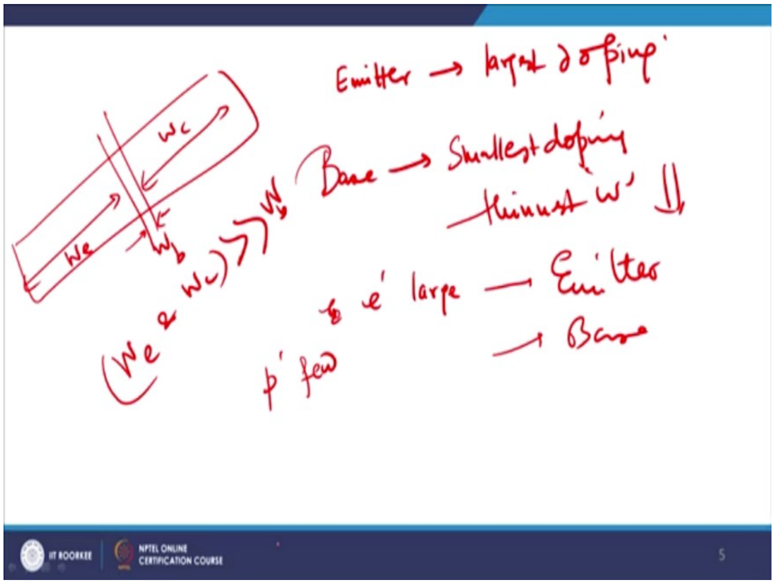

So if you look at the emitter, emitter should have the largest doping and we will discuss it why is it like that, but this is what is there, right, Base will have the smallest doping or the lightest doping, right and will be thinnest so its width is also very low. Width means the disk thickness. So if I have got this I will make this as w has to be very low. So this is your w_e, this is your w_b and this is your w_c.

So what you try to do is that w_e and w_c should be much greater that w_b, this is a general trend which we follow. Which means that, the base should be approximately 1000 of your emitter length, right and it should be very very small and very very lowly doped as compare to the emitter. So if you doped emitter very heavily you will have large number of free electrons available in the emitter side.

Whereas if you doped the base region very lightly as I discussed with you, the number of free holes available in an npn transistor in the base side will be very very low, right. So please get the situation from this point of view, I have still not apply the bias. Please understand once again, but what we are doing here is that my emitter is heavily doped so electrons are very large in number, right and this is for emitter, right and base is basically p type first of all but not only p type it is very lowly doped so there are very few holes available there, right.

Moreover, since the width is very small the overall number of holes in the base region is also very small, fine. So that is the reason why we do this, we will be clearing it off as we move along in this course, but structurally why therefore emitter should be the largest in area, largest in dimension with highest doping, right and base should be very thin or narrow with very very light doping about 100 doping of the emitter side and the collector should be moderately doped, right and these things you have to be very cautious when we are selecting the bipolar technology as far as this study is concerned.

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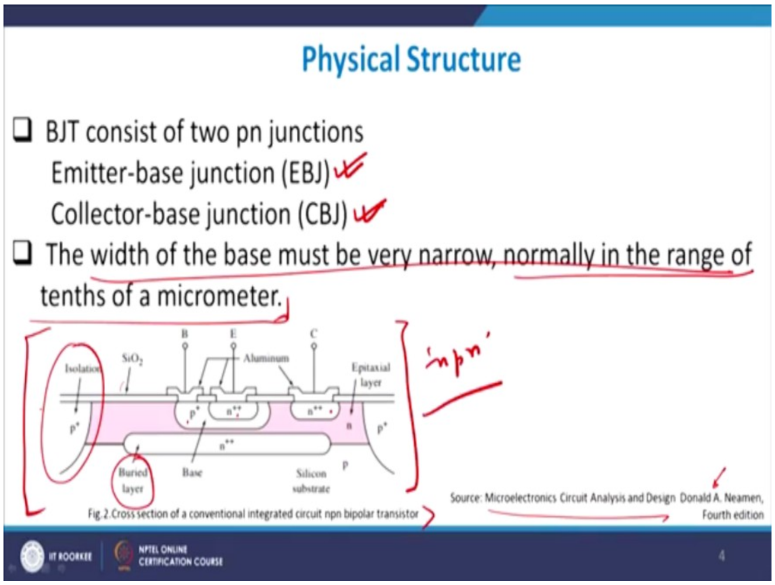

As I discussed with you therefore that the width of the base should be very narrow, right normally in the range of tenths of a micrometre and that is quite important and therefore the width of the base, right determines to what extent you will get the output current right. Just to give you a brief inside into this as we move along, but primarily the width of the base is a deciding factor as far as the total output current is available to you.

What you see in front of you which is this one is basically a cross section of a conventional npn bipolar transistor, right This discussion can be found in a book which is Microelectronic circuit analysis and design by Donald Neaman in fourth edition but may be later editions are also available and which they are actually giving you the cross section.

So, if you look very carefully this is basically your emitter, this is your base and this happens to be a collector, right and this is a collector which you see in front of you. This is basically an npn transistor, which is there. This buried layers, why do you put this buried layers in silicon dioxide and so on and so forth is that we do not want any leakage current, that means if there are no buried layer or if there are no silicon dioxide which is relatively high dielectric material, I would expect to see some amount of current flowing through this areas as well and therefore the offstate leakage will be large which will effectively means the power dissipation will be large, right.

So, we put this buried material here so on and so forth. We do also isolation here, a p $^+$ isolation to distinguish between two BJTs. So if I draw or if I design two bipolar technologies this isolation will help me to electrically neutralize or electrically isolate these two bipolar transistors, right and this is what we generally grow over here and sort up of twin tub process we use it in this case for the physical structure.

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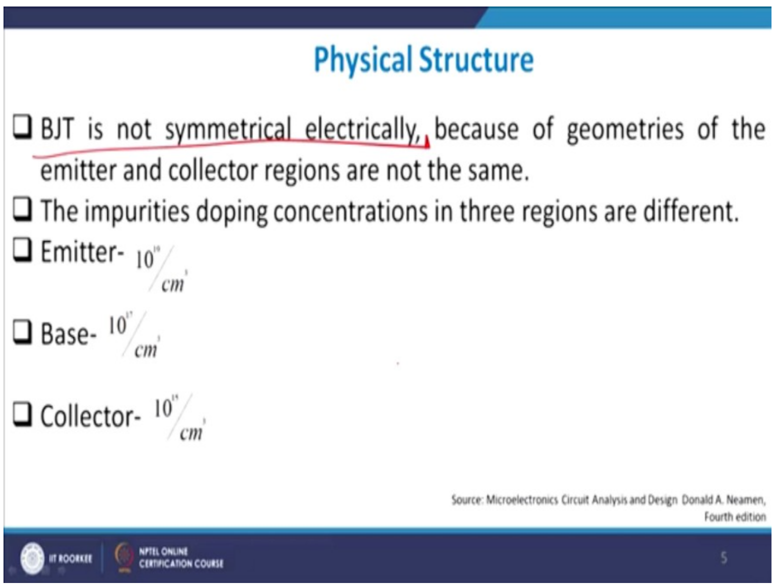

So what we have learned till now is two things, the first thing is that as you can see the first point here that BJT is not symmetrical electrically, why? Because though it looks symmetrical it is not, because your emitter side is having a larger concentration of electron as compared to electron on the collector side, for an npn transistor. Not only that, the emitter and collector regions are also not equal in size, emitter is quite large in dimensions and collector is relatively small in dimension as compared to emitter

As I discussed with you earlier that the doping concentration should be very very low in the base side, it is relatively lower as compared to emitter, one hundred of the thousands of the doping concentration and the collector should be at a much lower concentration of dopant species. So, the dopant species generally if you keep, even if you keep the emitter equal to collector there is no problem.

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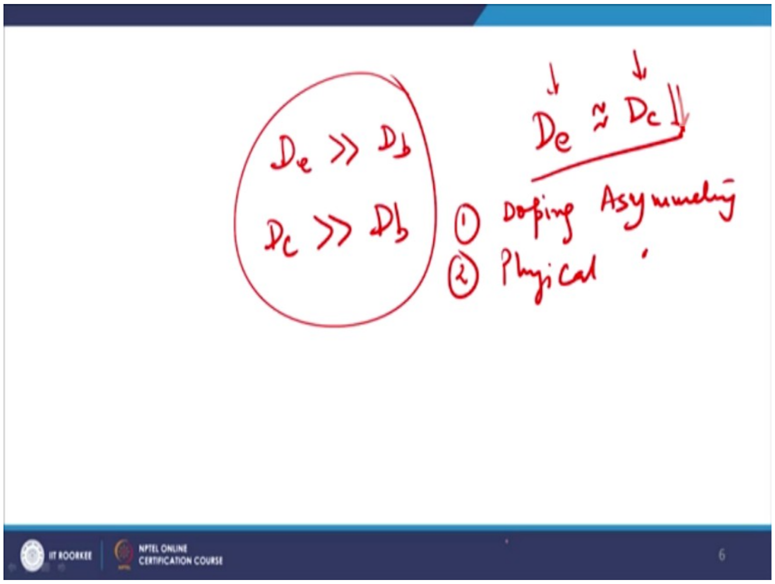

So, in terms of dopant species if you want to look, then typically your doping of your emitter should be much larger as compared to your doping of your base, right and doping of your collector should also be much larger as compared to doping of your base, right. D_e can almost be equal to D_c right. So doping of emitter and Collector can be approximately equal, even if you keep the collector doping slightly lower it does not matter to a larger extent, but this is pretty important, that you need to keep the doping concentration of emitter and collector much larger as compared to base.

So this is the first thing, the second thing is as I discussed with you, first thing is doping, right. So this is a doping asymmetry, there is also a physical asymmetry. What is a physical asymmetry? That the length of the dimension of emitter is much larger as compared to that of the collector side, right.

So therefore what I wanted to stress, finally is that emitter has got the largest number of electrons available to it, the collector has got relatively less amount of electrons and base has got a very very small quantity of hole within the small region of operation because of very low doping and very thin width of the doped, right. With these three basic understanding, let me therefore explain to you the various type of transistors which are available here and we will discuss that later on as we move along.

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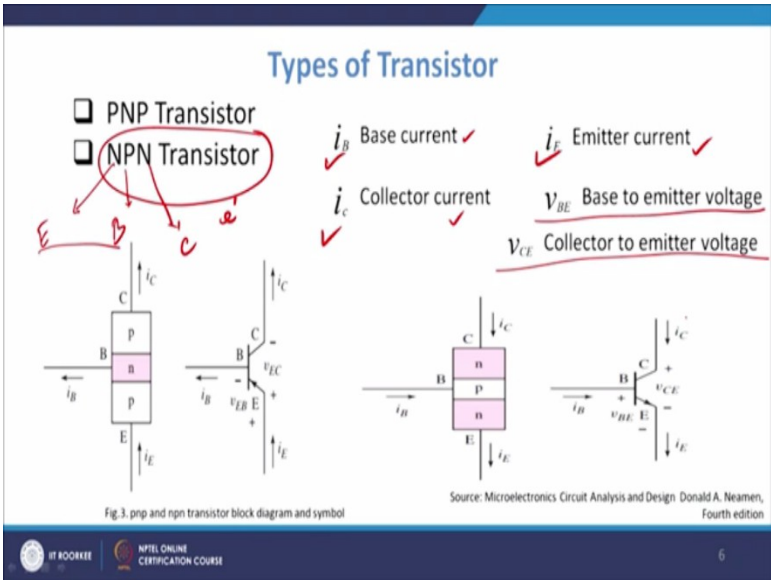

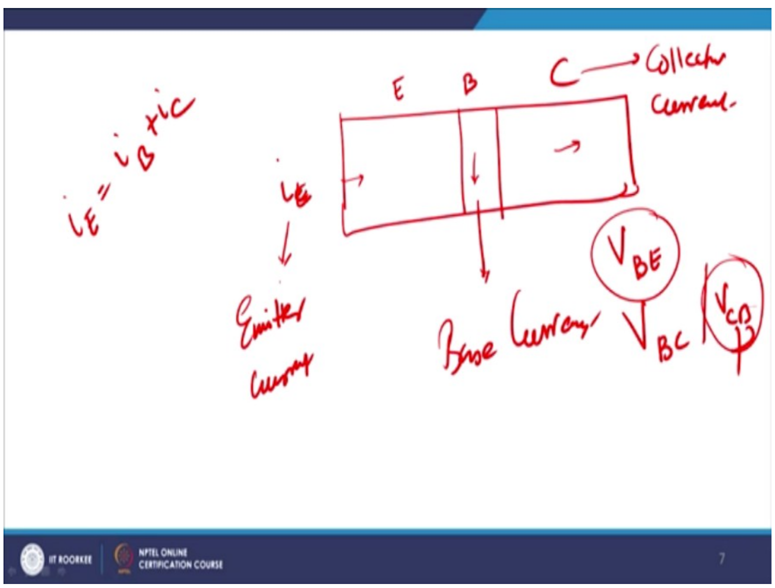

Now we have two types of transistor as I have discussed with you, one is known as the npn transistor, npn as the real name suggest, this is emitter, right this is base, and this is collector, so I have a pn junction emitter base junction. I have got also a base collector pn junction, right and now you see carefully in an npn transistor the majority current carriers are actually electrons, right.

So an npn transistor electrons of the majority current carriers, why? Because the emitter side is basically an n type semiconductor, the n type semiconductor majority current carriers is obviously an electron and therefore electrons are the most largest amount of current carrier here and therefore they result in a larger amount of charge carries and therefore electrons is the majority current carrier here, right.

Similarly, if you just find the dual of npn that is pnp , right. So pnp emitter is having a p type semiconductor, base is basically an n type semiconductor and the collector is a p type semiconductor exactly the same doping profile as we did in the previous case, that emitter of the pnp should be heavily dope so we have a large number of holes are available on the emitter side right.

You have very very small amount of electron are available on the base side and you have negligibly small amount of holes relatively large amount of holes, but on the p side, collector side right. So I have an npn and pnp transistor which is which is there with me on in all practical purposes right and now since its a three terminal device what we do is, since it's a three terminal device which I have just shown here right.

May be this one so I have an emitter, base, and a collector right .We have three currents and two voltage associated with this three terminal device, what are the three currents? One is known as the emitter current i_e right known as emitter current, we have got the another current known as the base current and we have third current which is known as the collector current.

So there are three currents, emitter current, base current and collector current and there are two voltages, voltage between base and emitter, and voltage between base and collector and all we can V_{CB} as well right. So we have two voltages V_{CB} and V_{BE}, V_{BE} is also determined as base emitter voltage this one is known as base emitter voltage and V_{CB} is collector to base voltage and there two three currents emitter current, right, base current and we have got collector current right and of course need not to say by Kirchhoff law this will always hold good that emitter current will be always equal to base plus collector current right this will always hold good for practical purposes right.

So that is what I was say that we have got i_b, i_c, i_e right i_b is the base current, i_c is the collector current and i_e is the emitter current V_{BE} is base to emitter voltage and V_{CE} is collector to emitter voltage, what is the collector emitter voltage? We will see that later on, but V_{BE} and V_{CB} collector to base right. Now you see if you look quite interestingly here and this what the type of transistors and how we show its functionality, we will just show it to you.

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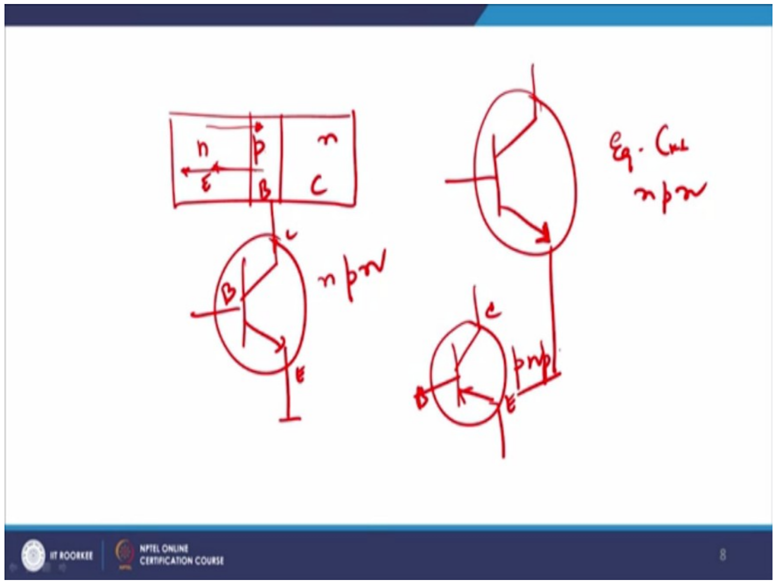

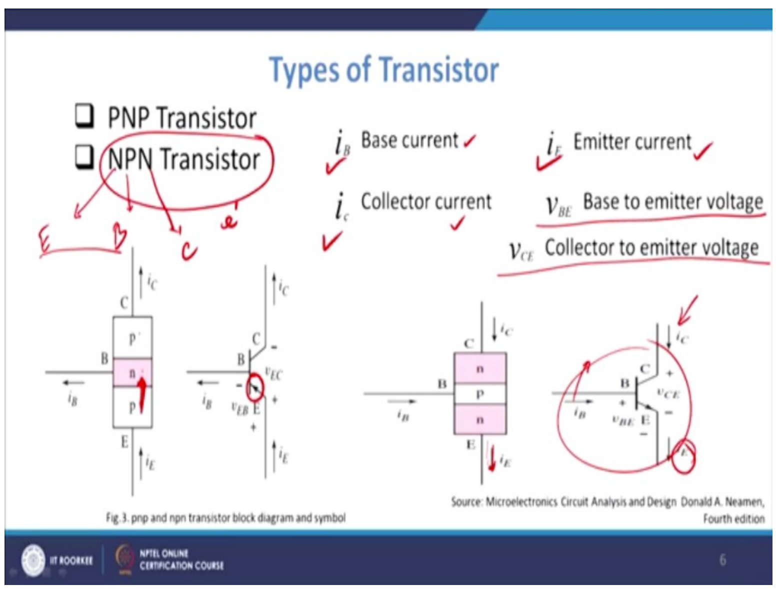

Say for example you have got a npn transistor, npn, so this is your emitter, this is your base, this is your collector. How we show it in circuit or how we represent it in circuit in this manner. Base is always shown by a straight line, right? And then we write down like this as the two edges right. If you want to show the lower one as the emitter so, you define from electron from holes point of view right.

So, if you look very carefully here for example in this case for example in this it will be easier to handle it. Since, electrons are moving from base to emitter, sorry, from emitter to base right? So the conventional current will flow from base to emitter right. Is it okay? So you see what I am trying to say is that you have an npn right.

Electrons will be moving in this direction right? Which is the majority current carrier. Which means that the holes will be moving in base to emitter side. So, we always measure the hole current or the conventional current and therefore the arrow head is always away from the base. So, you see because the holes are moving in this direction therefore I will always get an arrow head like this. So this the equivalent diagram or equivalent circuit diagram of an npn transistor.

As you can see here for an npn transistor this how it looks like. So in npn transistor I will have emitter current right. Flowing outwards just flowing outwards base current and collector current. So i_e will be equals to $i_b + i_c$ right. So there is no violation of Kirchhoff's law as such and we are able to obtain this variations in a much better manner right and we are able to achieve this profiling in much better.

Now if you want to convert this into an npn to pnp then you see pnp and on the left hand side of your this you have. Then you see what we will do the emitter will blow holes into the electrons right into base side.

So, the direction of holes or the direction of movement of holes is from emitter to base and that is the reason the direction of arrow is from emitter to base so base is a straight line collector and emitter are shown by straight lines, curved lines the direction of the arrow in the emitter is actually the direction of the holes flowing in the emitter and you should be able to handle the separation.

So therefore if I want to make an npn transistor like npn transistor then this is the this is my NPN right. This is my emitter, base and collector. If I want to make a pnp transistor right. Then, this is my emitter, base and collector so this is a pnp, so there is a two transistor pnp and npn this gives you an idea about the basic structure of an npn transistor and pnp transistors right. We will take care of the next section in the next class. Thank you very much!