ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1.1-Transistor Bipolaire

Introduction

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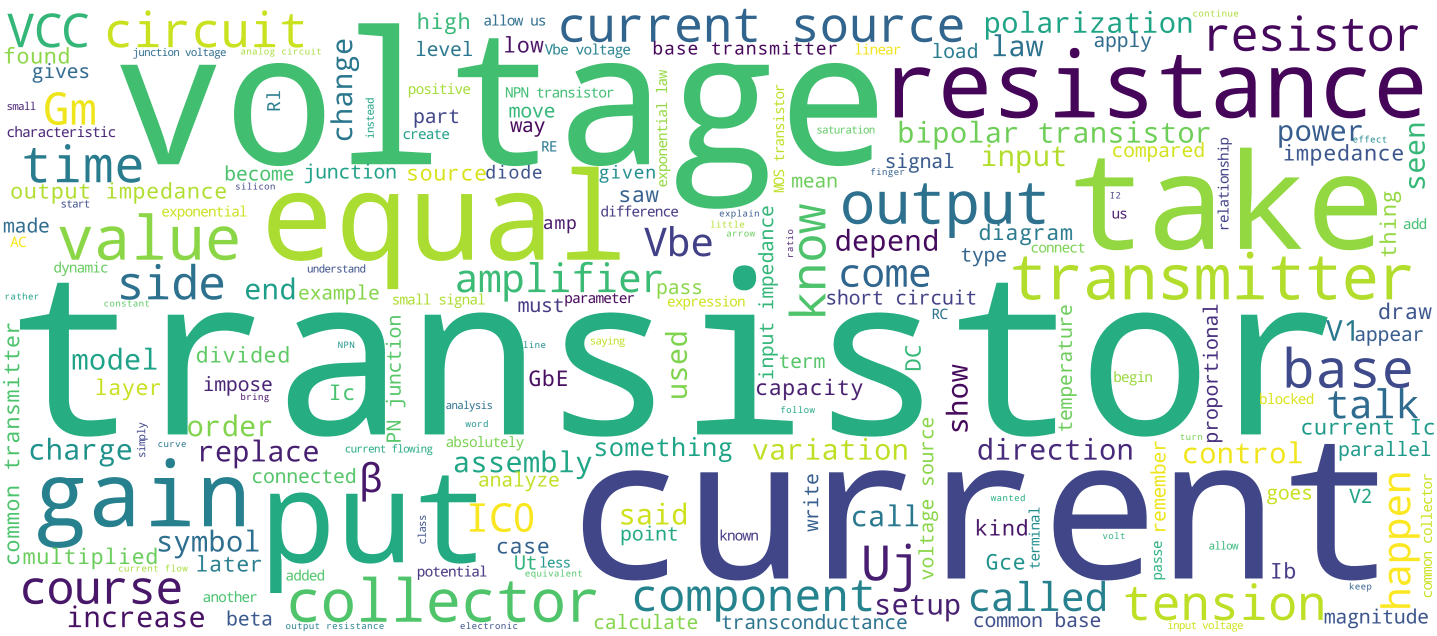
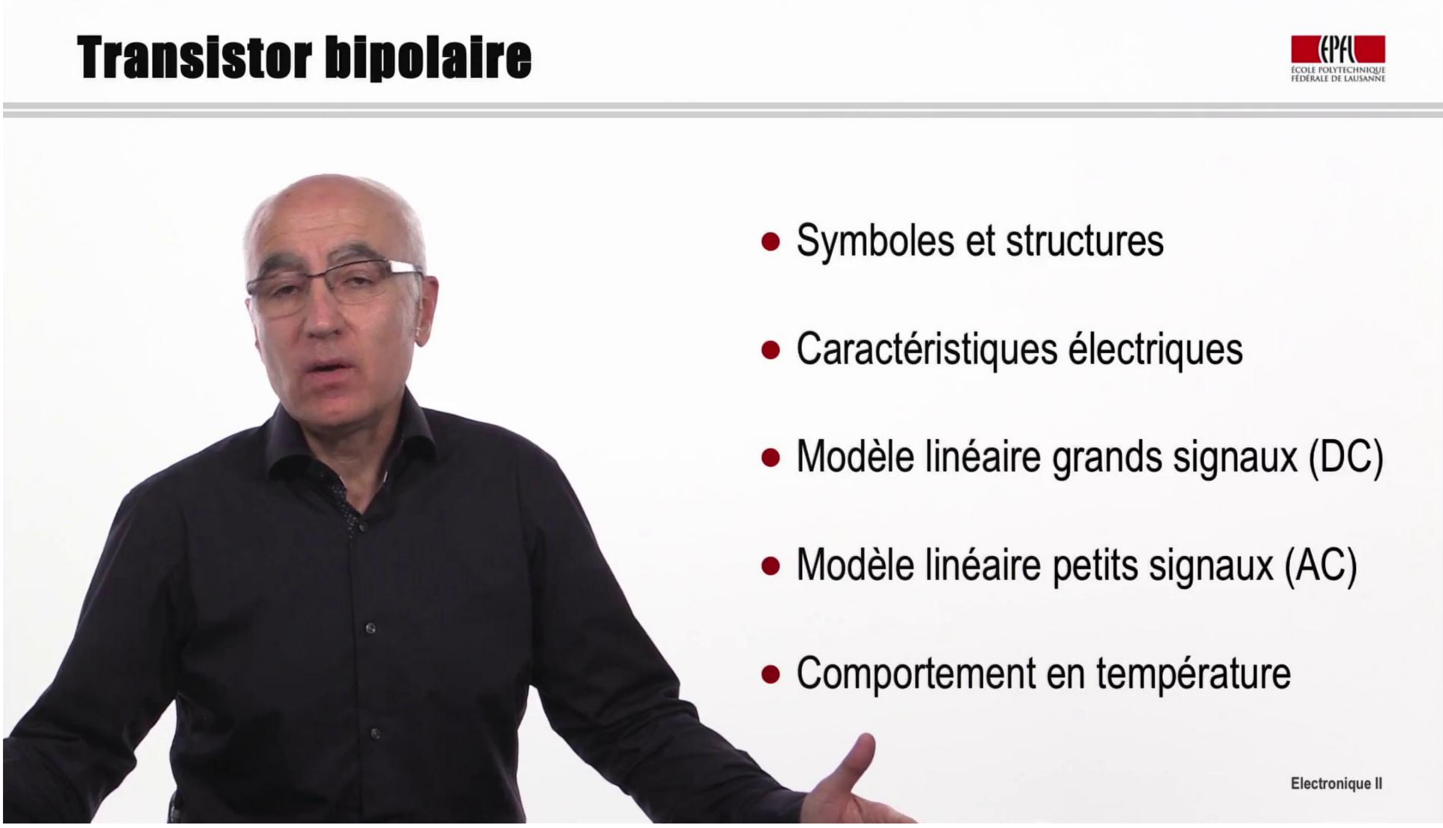


Video

EPFL

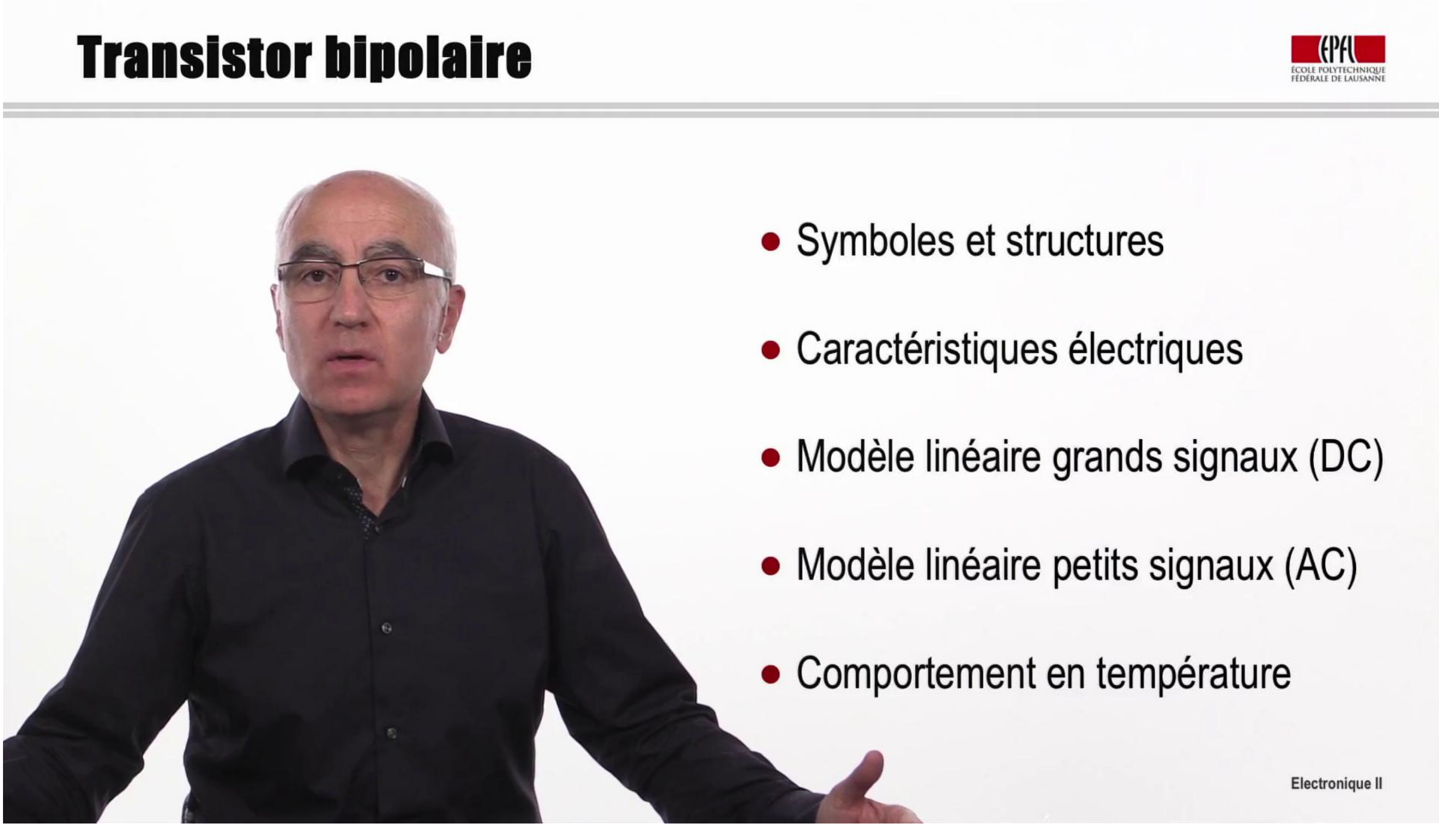


Good morning everyone. We're going to address the study of the transistors. Of course there are different types of transistors and mainly the bipolar transistor and the MOS transistor. The bipolar transistor is absolutety known for its very educational features. We can easily understand how we can put a bipolar transistor in a typically analog circuit. The MOS transistor has very simple qualifications but when it comes to digital circuit it's a bit more complicated than the bipolar transistor when it is in analog circuit. So in this course we will mainly focus on bipolar transistor compared to the MOS transistor, but at the same time we will look at the MOS transistor and analyze it's use in analog circuits also. To begin with bipolar transistor we will first tackle it by analyzing the structure of the transistor, the symbols we use to present it, and then we will move on to its electrical characteristics. It is very important, it is absolutely a very important part in the analysis of all the transistors because this is what will help us to understand later on the true effect called "transistor effect". And then you need to model the transistor.

Notes

Summary

0m 04s

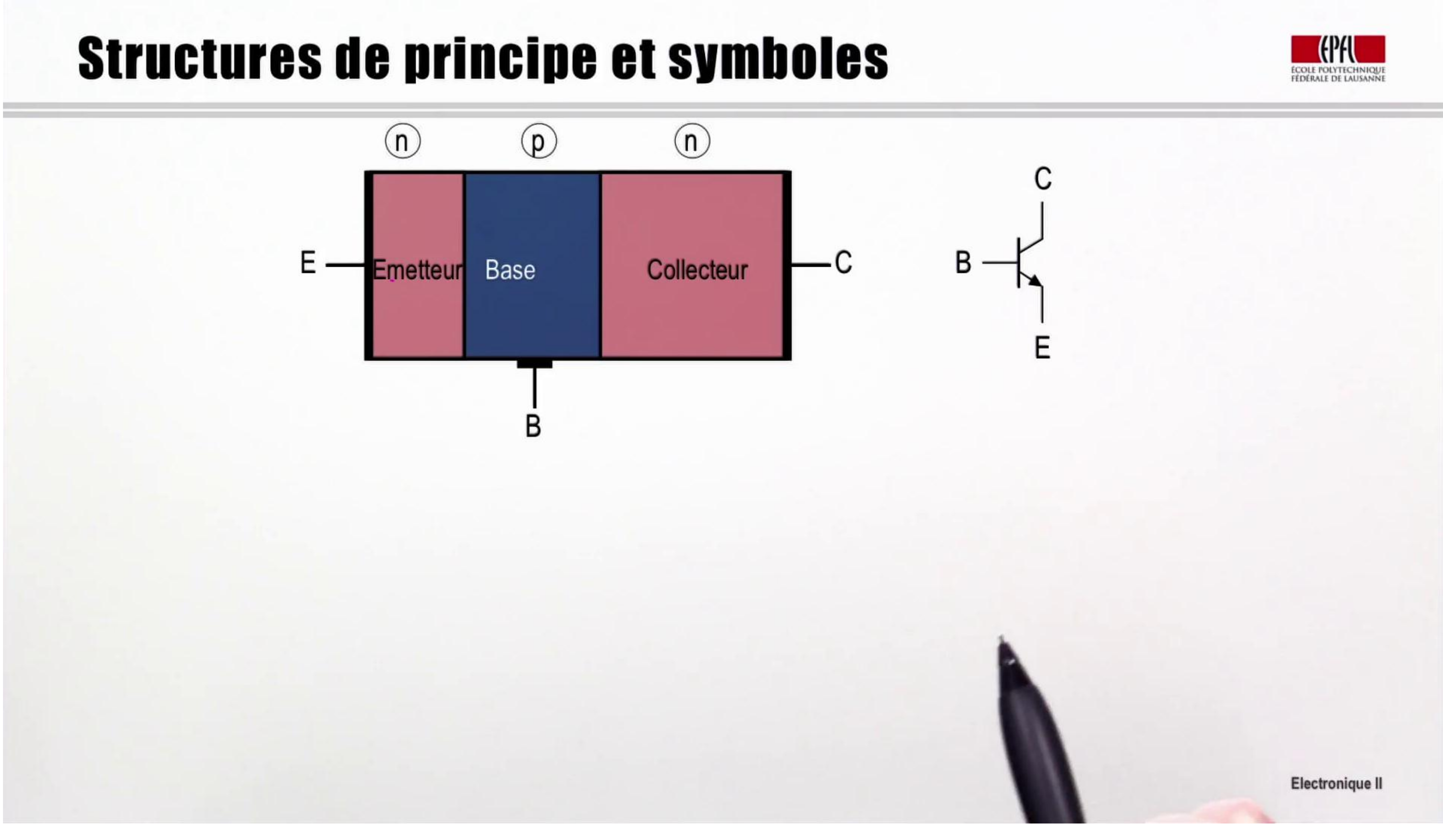


The transistor is made to be used in a circuit where there will be continuous supply, this is what we call the DC model of transistors that will be used in this kind of transistor polarization and continuous supplies, direct currents, direct voltages. And we also have the AC model, it is also known as the increase model or small signals model. This is the case of a signal which varies with time that we'd like to superimpose on a continuous component and both models together will lead us into analyzing a complete transistors circuit. And once we are done and we understand what happens with these two models and we handled them in exercises, we will move to the second order effects with bipolar transistor. And we will see for example the base width modulation effect or end with the thermal behavior of this transistor.

Notes

Summary

1m 29s

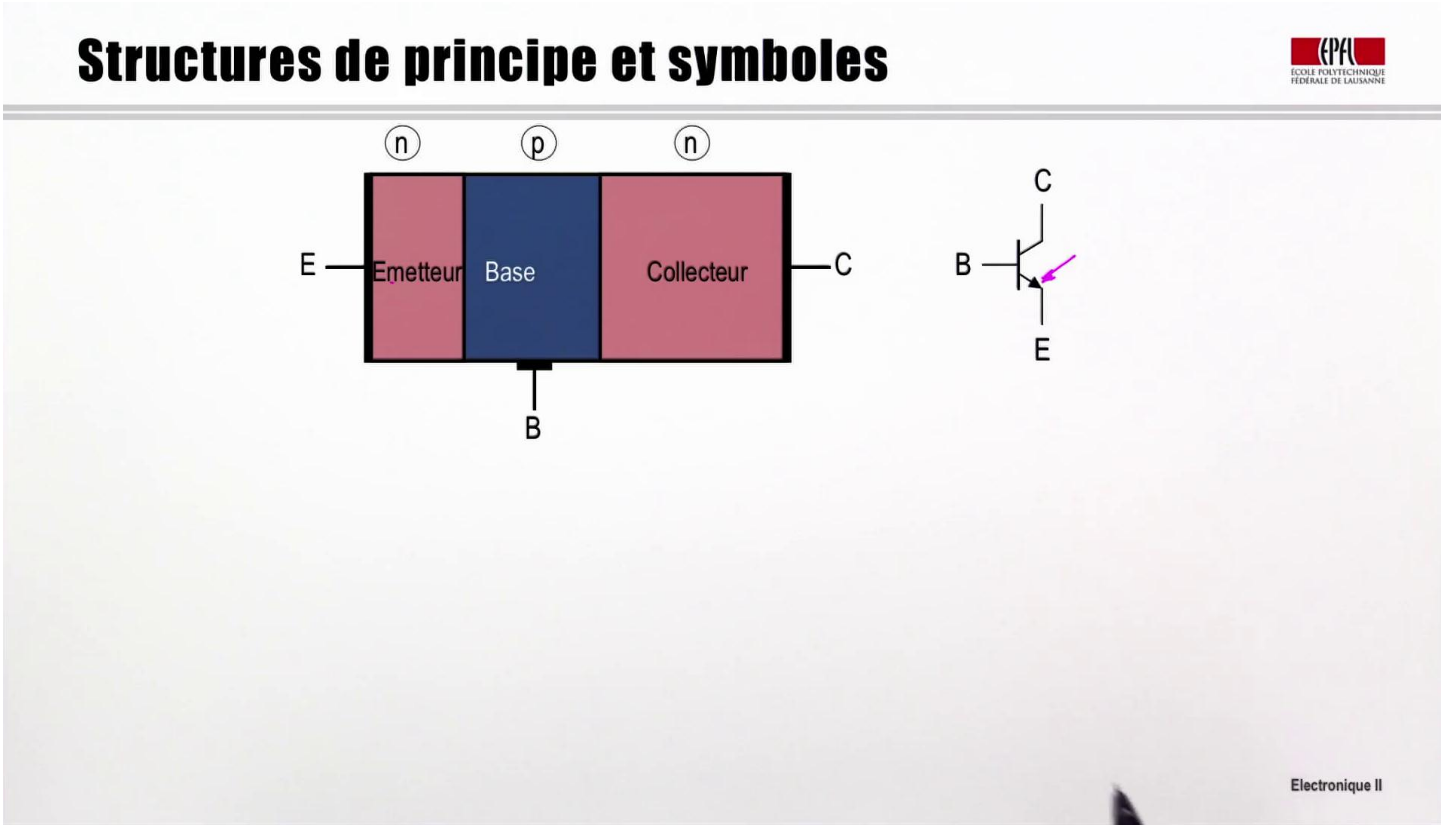


So when you look at this, you'll see that there is NPN. In this course we will not analyze all of the physics of semiconductors and analyze what happens with the PN junction. In other courses of the same nature, you have plenty of courses that are either in physics or in electronics where we will explain what is a PN junction and what happens within a PN junction and what is the transistor effect and how it is made. So the aim of this course is to focus especially on the electronic use and circuiting of transistors, and make especially an analog circuit. So when I take this symbol you see here, this is silicon in which we have created two PN junctions and we talk of an NPN transistor, it looks like a type N silicone sandwich Here, it is type N. So in the middle we put the type P and we end up with a transmitter, a base and a collector and the symbol is this. We will understand what it means, why we called this transmitter, why we called this collector, and why there is a base. First you have to know one thing, if you take the symbol that you see here, it is an arrow, the arrow indicates the direction of current flow.

Notes

Summary

2m 33s

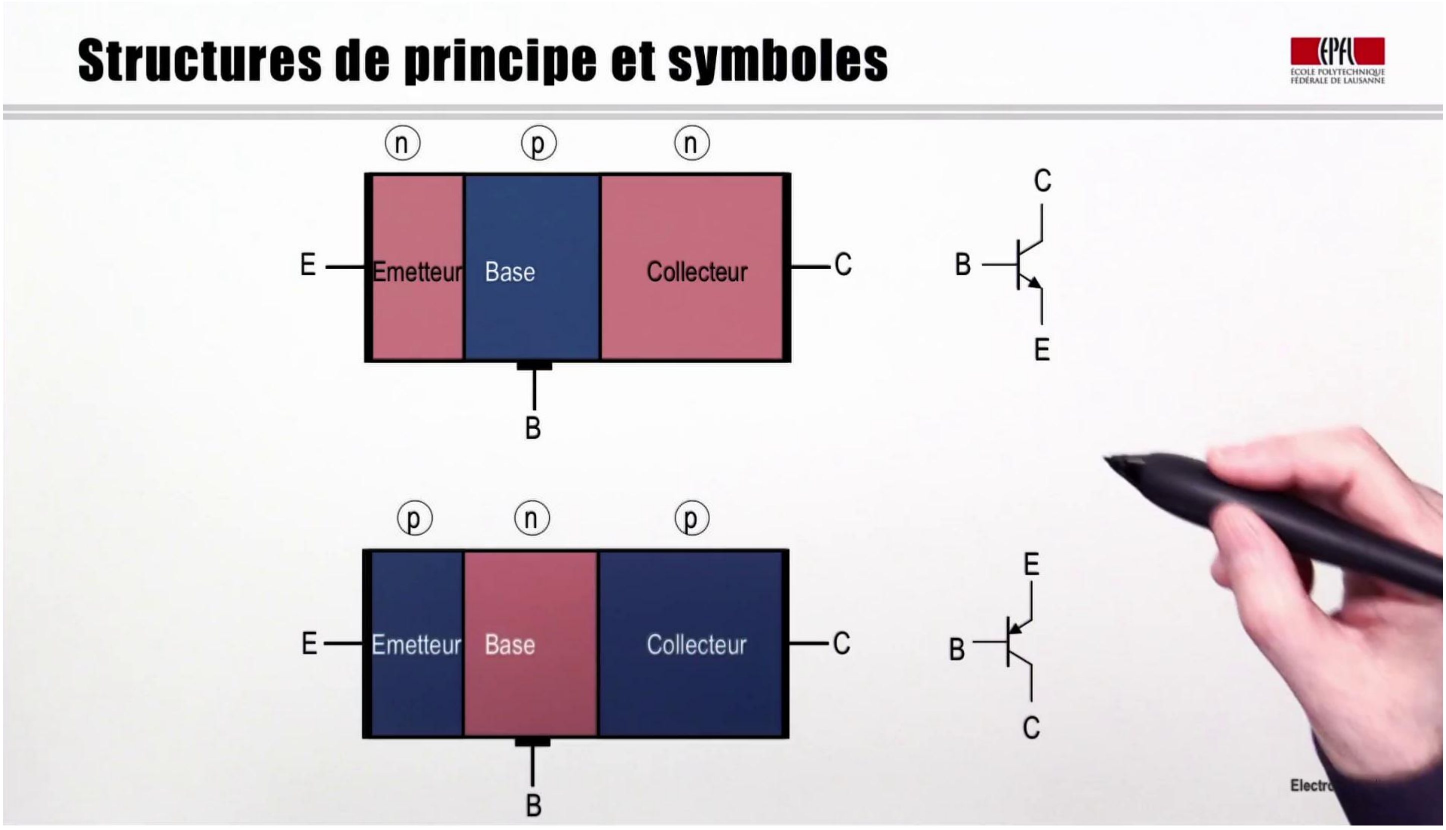


Thus in Switzerland we use an arrow that shows where the current passes and in which direction, and of course in Switzerland we have a convention which shows that the current is latent, the current and the electrons are in opposite directions. In other countries they keep the same direction of the arrows. Here electrons flow from the emitter to the collectors, hence the name transmitter: it transmits electrons which will be collected in the collector. However the arrow here indicates the direction of current flow. The transistor has two accesses that will be used by charges, so it's outlet, it's the collector and the transmitter and the base is the access that allows me to control what will happen in the transistor between the base-transmitter junction or possibly the base-collector junction. So it must be remembered, the collector and the transmitter will be used later as output ports. The base-transmiter junction or the voltage between base transmitter will allow us to control the transistor. This same transistor may be constructed with a PNP structure, that is to say, if you take the same structure instead of putting a P layer between the two N layers, you put two P layers and in the middle you put an N layer, and then you end up with the same transmitter base collector access.

Notes

Summary

3m 57s

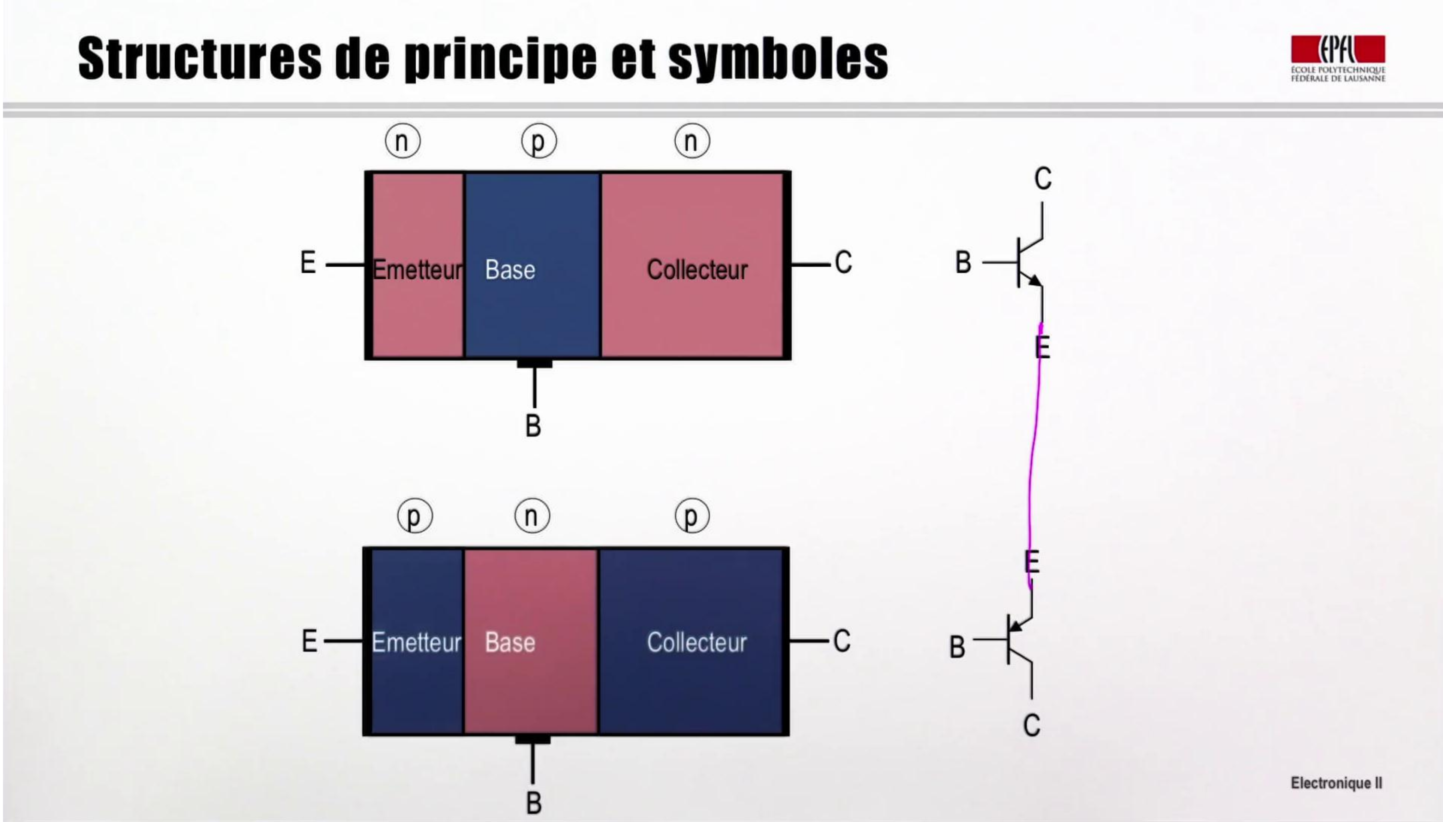


The symbol looks exactly like the one we saw with the NPN and this is the PNP. There is a fundamental difference and it is in the current direction. Look here, the current is going out of the transmitter, here the current enters the transmitter and goes out through the collector, so the arrow always indicates the direction of current flow, so similarly here we will see current entering, and the collector. Otherwise the use of the transistor remains the same. Later you will see, when we'll talk of the collector transmitter that is because the two terminals of the transistor will be used at the output. But you must know one thing that the impedance seen on the transmitter side will be very low, the resistivity seen on the transmitter will be very low, contrary to what we see as resistivity of the collector, on both sides it will be very high. So we have two accesses for output and both accesses behave with output impedances that will be completely different. This is what will allow us later to make set-ups of completely different nature. And later you will see we need to use both transistors because if you see this style of set-ups, they are set-ups in which we may connect both transmitters together.

Notes

Summary

5m 37s



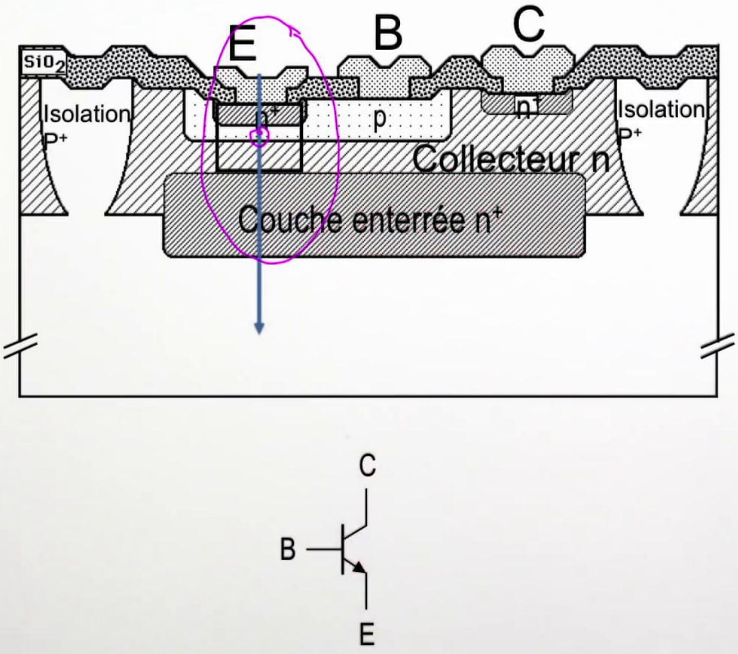
And these two transmitters allow us to take the NPN transistor that will be connected to the PNP transistor. And we will take a current that goes down in this direction, it goes through the transmitter and enters one transmitter, it exits through the collector of the other, so we speak of supplementary set-ups. This is what will enable us make electronic circuits whether in the analog domain or in the digital domain.

Notes

Summary

6m 58s

Transistor Réel



- La base est mince.
- L'émetteur et le collecteur sont différents par leur géométrie et leur dopage.
- L'émetteur bien plus dopé que la base.
- Le collecteur est faiblement dopé.

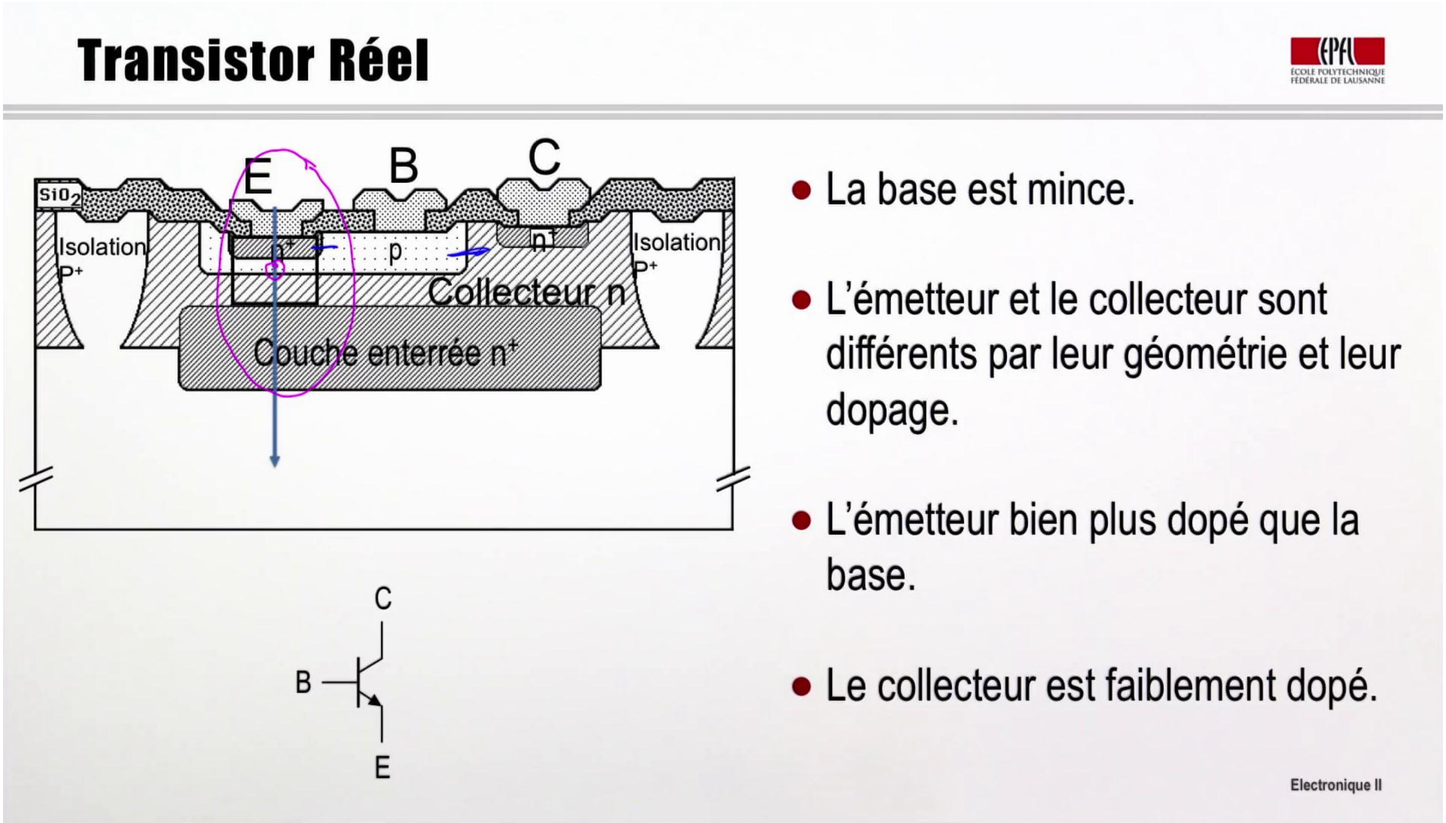
Electronique II

That's the reality. What you have seen before was just a way to explain that there is an NPN transistor and a PNP transistor and the symbols you have seen, so the two symbols, or rather the physical implementation of the transistor do not present the reality. However, this is a diagram of an NPN transistor which is fully integrated and we only see the transistor, we will look at the layers, you have here an N layer, here a P layer and here you have an N layer. But when you look at the access to the transistor, you see it on the surface, that is the transistor is realised according to this vector or this blue arrow, we see the NPN transistor, but when you just connect this transistor to the outside world we see that we take the transmitter from the surface of its various layers formed from a silicon substrate, there you also see the base and the collector despite the transistors production being where I am framing, so we see the NPN. And yet if you look closely, you will realize that the base width, when I pass from the transmitter layer to the collector layer, the base width is in this small part here. And this small part defines the thickness of the base, an extremely important parameter on what we'll later call the current gain, the β of the transistor.

Notes

Summary

7m 23s



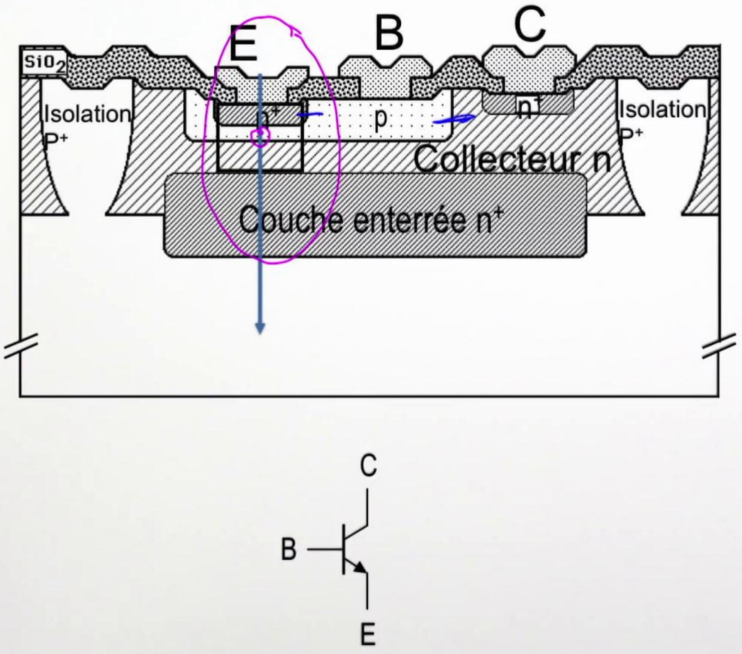
So the more the base is thin the better the current gain of a transistor is. Of course there are other things that degrade with this, but it is not the moment to talk about them. The transmitter and collector are different in geometry and doping that is really in terms of geometry. Just observe, see how small the transmitter is and see how huge the collector is, where the base is set, where we have put the transmitter. This means that this transistor despite it's showing us a PN junction here and another junction seen here, PN, which is on that side, well the two junctions are not symmetrical. And that will be reflected strongly on the symbol you see here. So when I take the base and the transmitter I have a PN junction. When I look at the base and collector I have also a PN junction but the two junctions are geometrically not the same, and the same is for the doping. The doping of the transmitter is much stronger than the doping of the collector, so physically what I wanted to say is that this transistor is absolutely not symmetrical. If you want to use the collector instead of the transmitter you will have a transistor that will be completely degraded and it is a serious mistake.

Notes

Summary

9m 03s

Transistor Réel



- La base est mince.
- L'émetteur et le collecteur sont différents par leur géométrie et leur dopage.
- L'émetteur bien plus dopé que la base.
- Le collecteur est faiblement dopé.

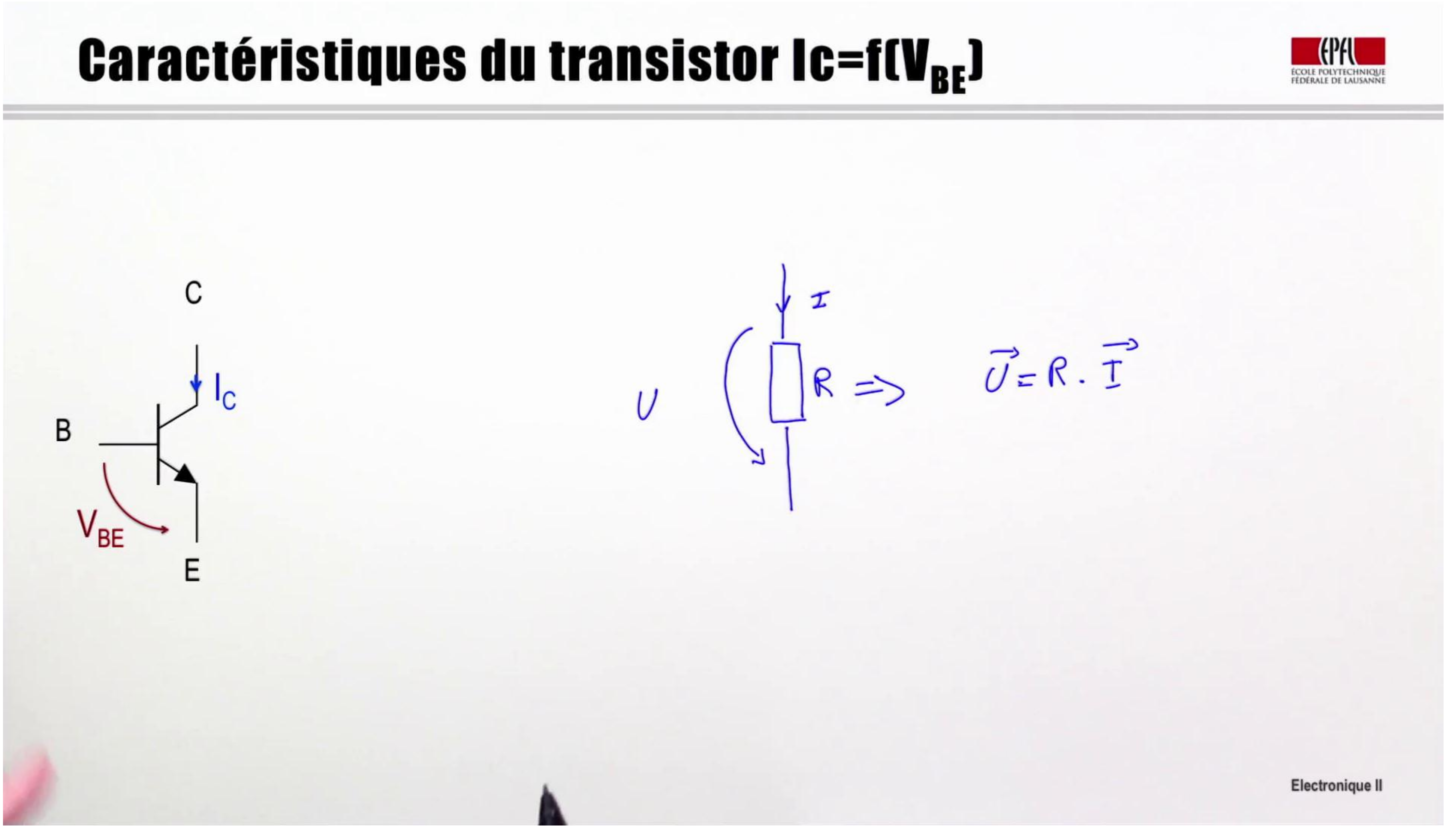
Electronique II

And you need to be careful and manufacturers when they encapsulate it they clearly show us where the transmitter and the collector are. So we cannot turn it in one direction or another, it is essential to respect the different pins or different accesses to the transistor and they are made on the transistor housing.

Notes

Summary

10m 31s

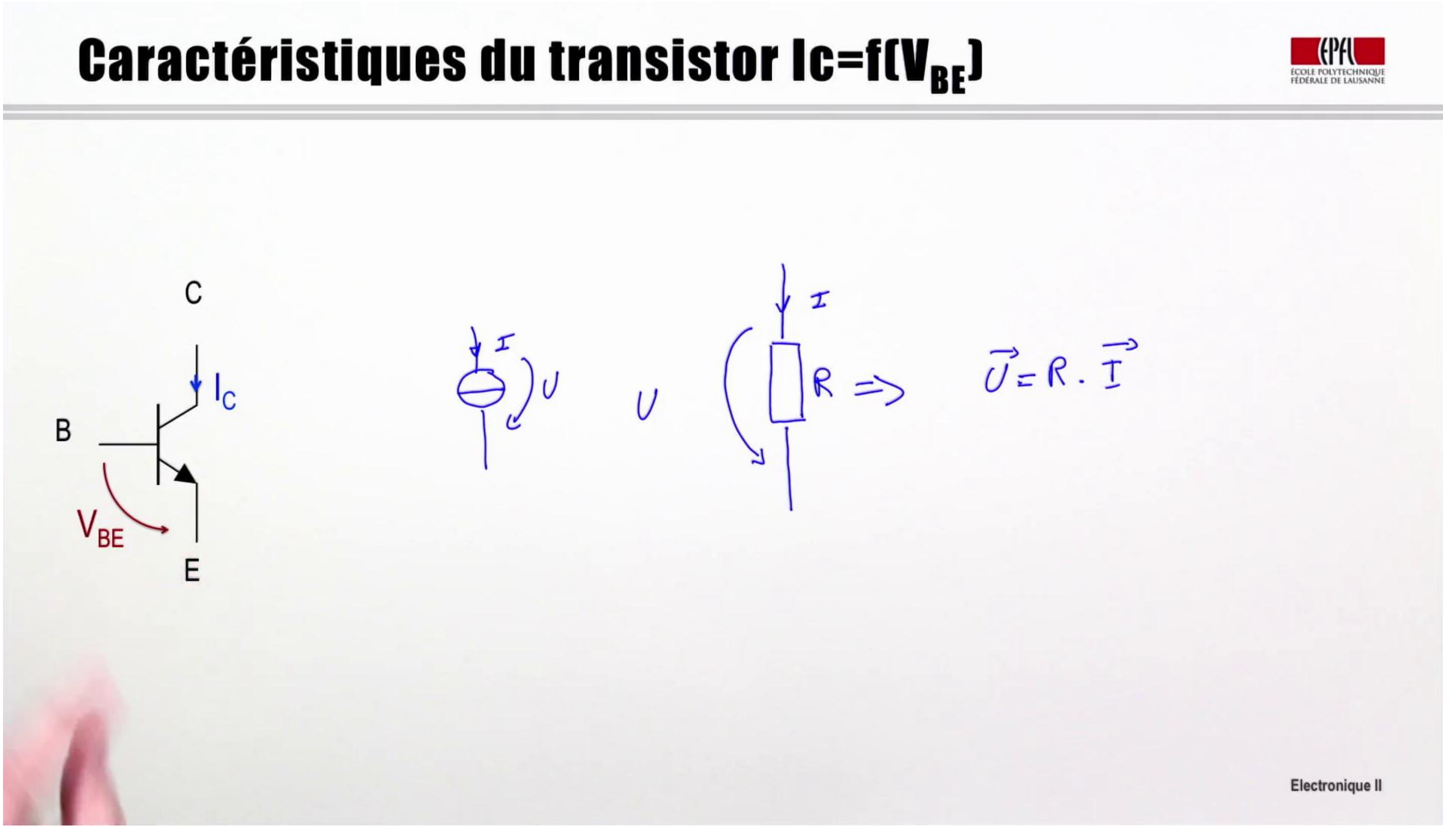


I'll take the transistor as it is and take some time to explain this. I will use this symbol to explain what we wanted to do with a transistor in general. So a transistor when we see it we see a base-transmitter junction and we have the collector on one side we see I drew a current between the base and the transmitter and I have shown that there is a current in the collector. I just want to show you something you know very well, I will draw a resistor. With a resistor, you learned Ohm's law, Ohm's law says that the current you see between this and that is voltage U, and this is current I, and this is a resistor R. You were told, Ohm's law says U equals RI. So if I put my two fingers here, these two fingers show a vector which is the voltage that is proportional to a vector which is the current, and between the two there is a given resistivity and we'll have a link between U and I. So current and voltage are correlated according to the value of resistance. I'll come to the transistor, we'll keep this figure in mind. I want to create a component in which I will be able to control a current as I'm doing here, there I change U,I changes too with it so I have the two linked here, I'll do something else.

Notes

Summary

10m 50s

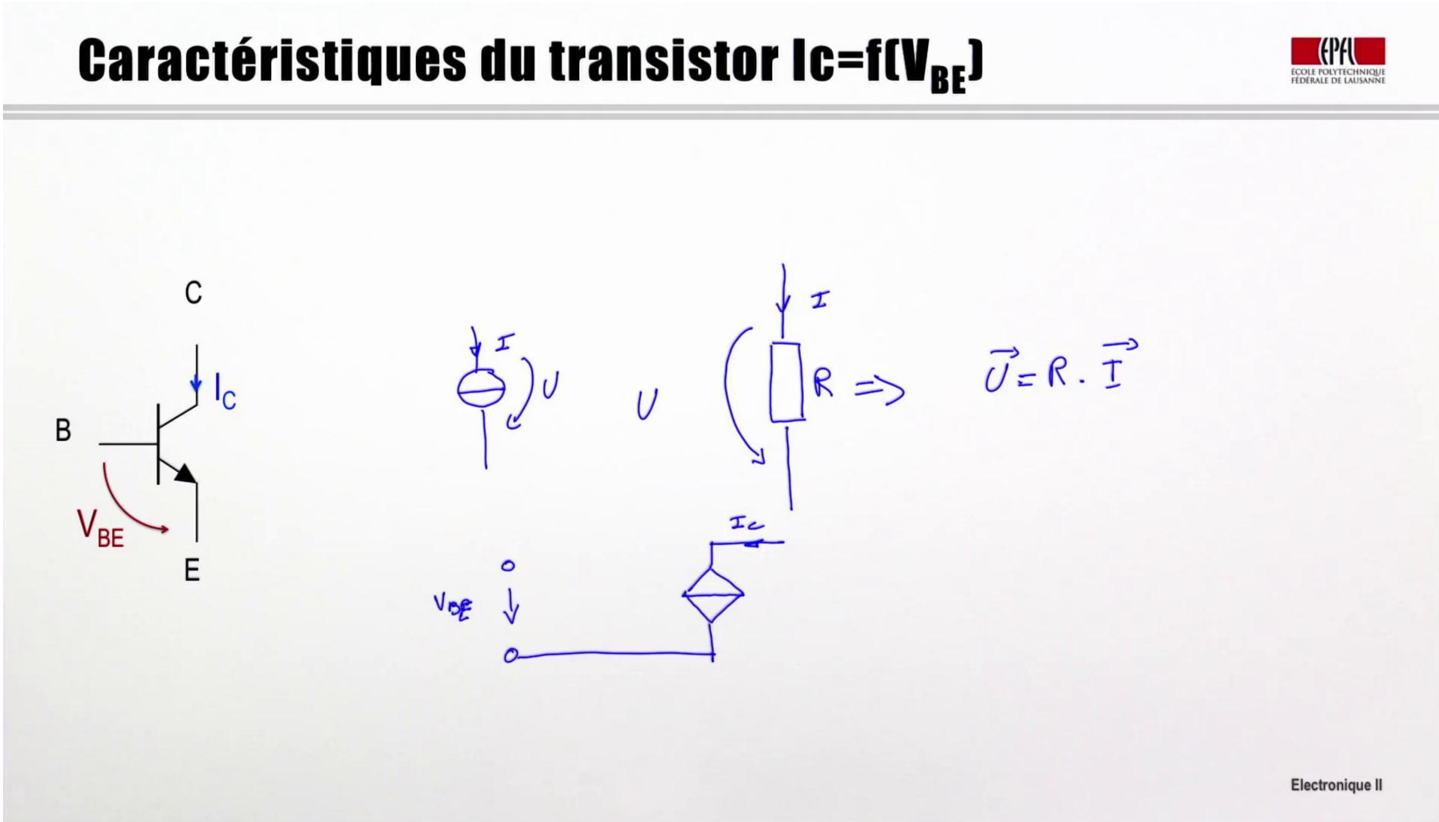


I'd like to put my two fingers here and my other two fingers here and make sure that I control the voltage here between the base and transmitter and there, regardless of what happens between the collector and the transmitter, I would want my current not to be affected by this. So I can move the collector-transmitter voltage but the current Ic is only controlled by Vbe, it is not controlled by the voltage at the terminals, so not like this. So, you know this, this kind of symbols, if I look at the transistor and then I would like to know which component, that when I look at a voltage at its terminals, the voltage can move without affecting the current, you know it is about what we call the current source. So it is a symbol we drew like that, and we said "there will be current in there" when we apply current, you can change this voltage and this voltage will not affect the current and we said it is an infinite resistor, and that's what we wanted do with the transistor, we wanted to create a kind of current tap. I change the Vbe amount and I'll be able to control the Ic current with it, so for each voltage Vbe, I will find a current Ic and they are not linked to the same terminals.

Notes

Summary

12m 31s

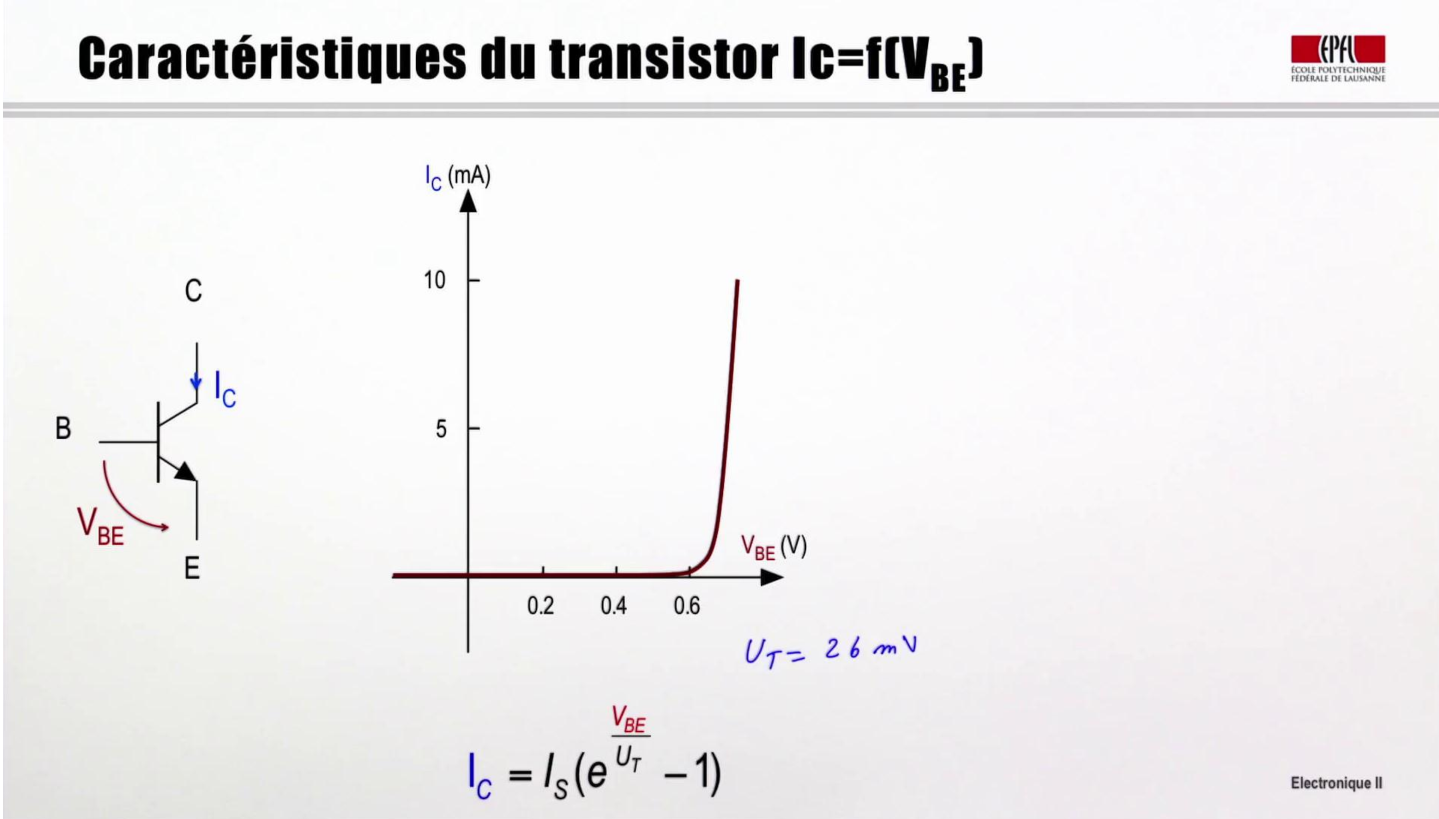


The voltage controls the current here, but this voltage there can move without affecting the current Ic, and that's the aim of those who created the whole transistor phenomenon, so any electronic which is based, either on bipolar or MOS, it is the same principle. Current is controlled by voltage and it is called transconductance. So we will create a component in which there are two accesses and with these two accesses, there is a current source and we draw the symbol of this current source called controlled current source, and this current source, will provide us with a current that passes and this current, will depend on a voltage where the two are not related, here I have the voltage and here I have the current, and the symbol here. So this is what the man wanted to do, to find the three accesses and on one side, I control the current by a voltage and we'll talk later of transconductance.

Notes

Summary

14m 00s

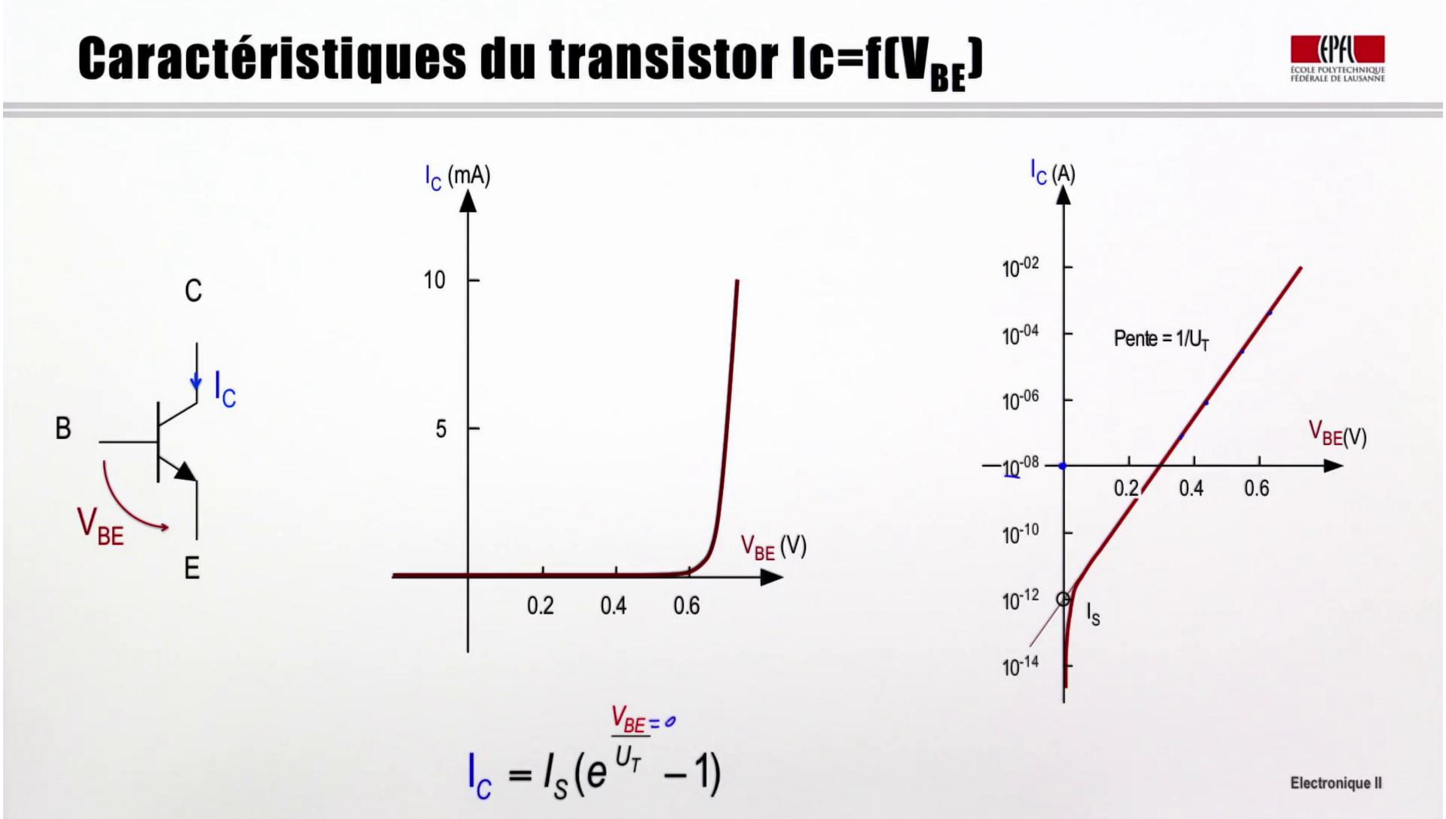


What did we manage to do? So he was able to take this idea I just presented, he found a law through silicon and creating these different layers I showed you earlier, where the relationship between Ic and Vbe, this is the law that you see here. Thus the analytical model corresponds to a current which is exponentially proportional to the voltage Vbe. So he will apply a voltage to Vbe and will see that there is a law which if you draw, you will see suddenly, that from a certain Vbe value, you will have a drastic increase, it is an exponential and it is modeled in this way. There is a parameter inside, Is, Is it is the reverse current in the transistor. Ut is a parameter called thermodynamic voltage that is bonded to silicon and Ut value depends on the temperature, but at room temperature, you have a voltage Ut which is 26 mV at room temperature. However this current Is depends on the geometry. And it changes from one transistor to another, is it a law that we will use oftenly? No, not for the bipolar transistor, you will see why and we will make a very important focus, why this kind of analytic model is hardly used when we want to make a circuit.

Notes

Summary

15m 08s

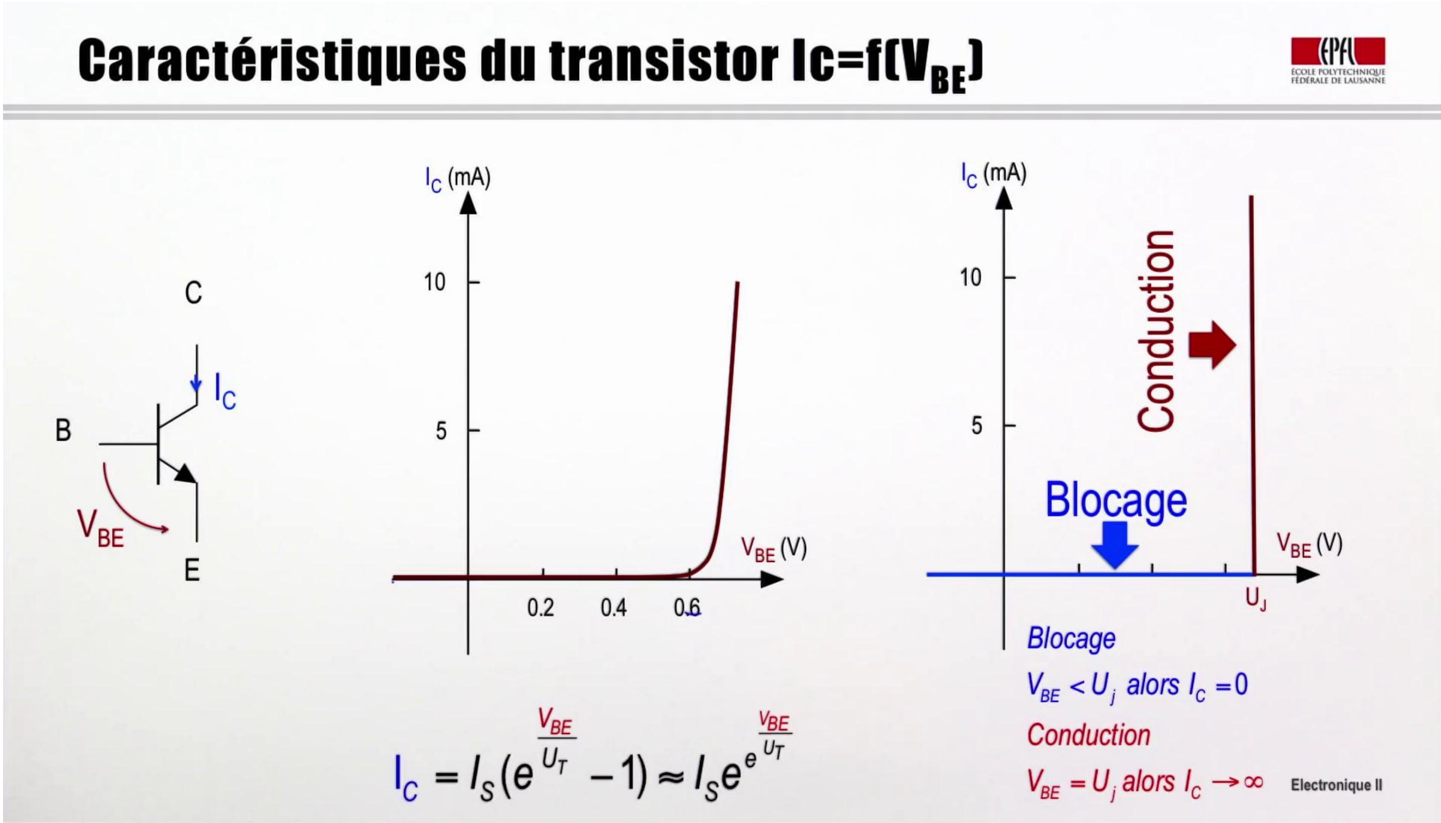


So if you take this exponential law and you now plot the axis here, instead of it being linear, here you replace it with a logarithmic scale and then you will see the following. Here we see the same characteristic Ic equals Is(e^Vbe / Ut-1), when we plot with the scale Ic becomes a logarithmic scale, and we find it is about a law, a line, and this line allows us to easily find the reverse current. So you find this law here, look when Vbe equals 0, so I'm here. Where Vbe is 0, So you replace it with 0 and you will find that the current Ic you are measuring in the transistor will be negative again, which will be equal to -Is. So when you look at a Vbe equals 0, and if you have a very precise micro-ammeter, you are able to measure what is happening with the parameter Is and you can extract the value of Is. Otherwise, if you plot the curve and you plot different points on it and you extrapolate it by the right that we see here on that scale, the intersection of this line here gives you the order of magnitude of current Is, and it is like that in a laboratory that we plot or we extract the value of Is, the slope is 1/Ut so you note that the 26 mV at room temperature, you will also extract this value. That's just to show how we measure a transistor, and we show that this law is a law that fits best with the transistor we saw here.

Notes

Summary

16m 45s



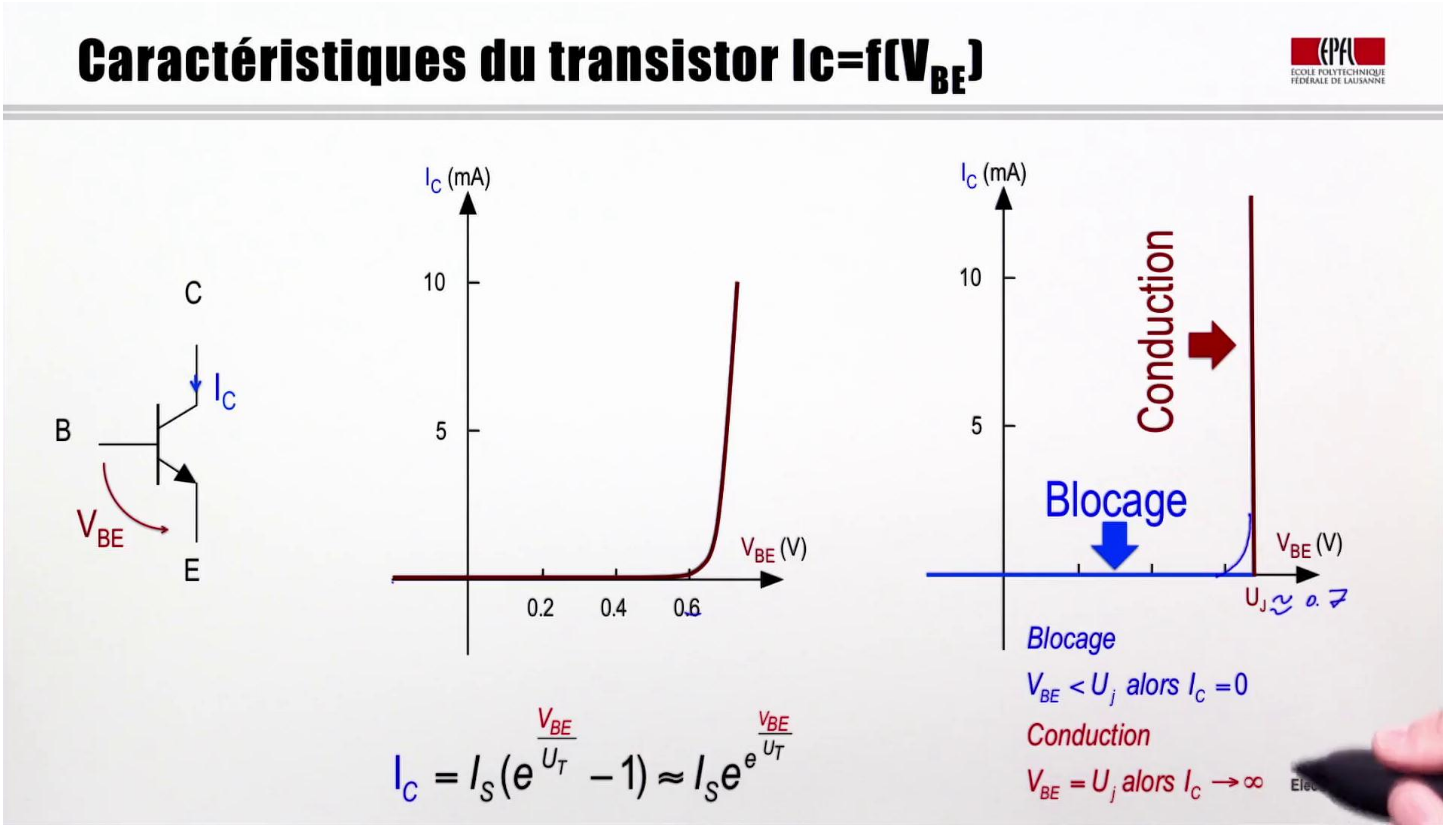
$$I_C = I_S\left(e^{\frac{V_{BE}}{U_T}} - 1\right) \approx I_S e^{\frac{V_{BE}}{U_T}}$$

I would like to take the same thing and take this law, and show that we often approximate it by saying the -1 next to the exponential, I can neglect it, so I can approximate it by this. And now I'll go to an explanation that will help us model the transistor. Look at this graph and look at this one. I think those who have studied the diode before, they understood that every time we have an exponential component, an exponential characteristic, we can replace it with something pretty crude that says the exponential, here I practically have an Ic current equal to 0, and here I have a drastic current increase according to very few Vbe variations. It turns out that in silicon, the voltage junction, the voltage at which we begin to have the sudden current increase, is called the Uj tension and we talk of a junction voltage. So to make things easier, when we're going to make a test model of our transistor, we'll go from this model and we will use this model, it is for this I said earlier, we oftenly do not use the exponential law beacuse we replace it with a linear segments law, so we will say that our transistor will be blocked for a Vbe voltage lower than a threshold voltage called the junction voltage, which is in the order, of 0.7 V, and the current increases sharply, so it can go to infinity when the Vbe voltage is equal to Uj, or is equal to this order of magnitude.

Notes

Summary

18m 42s

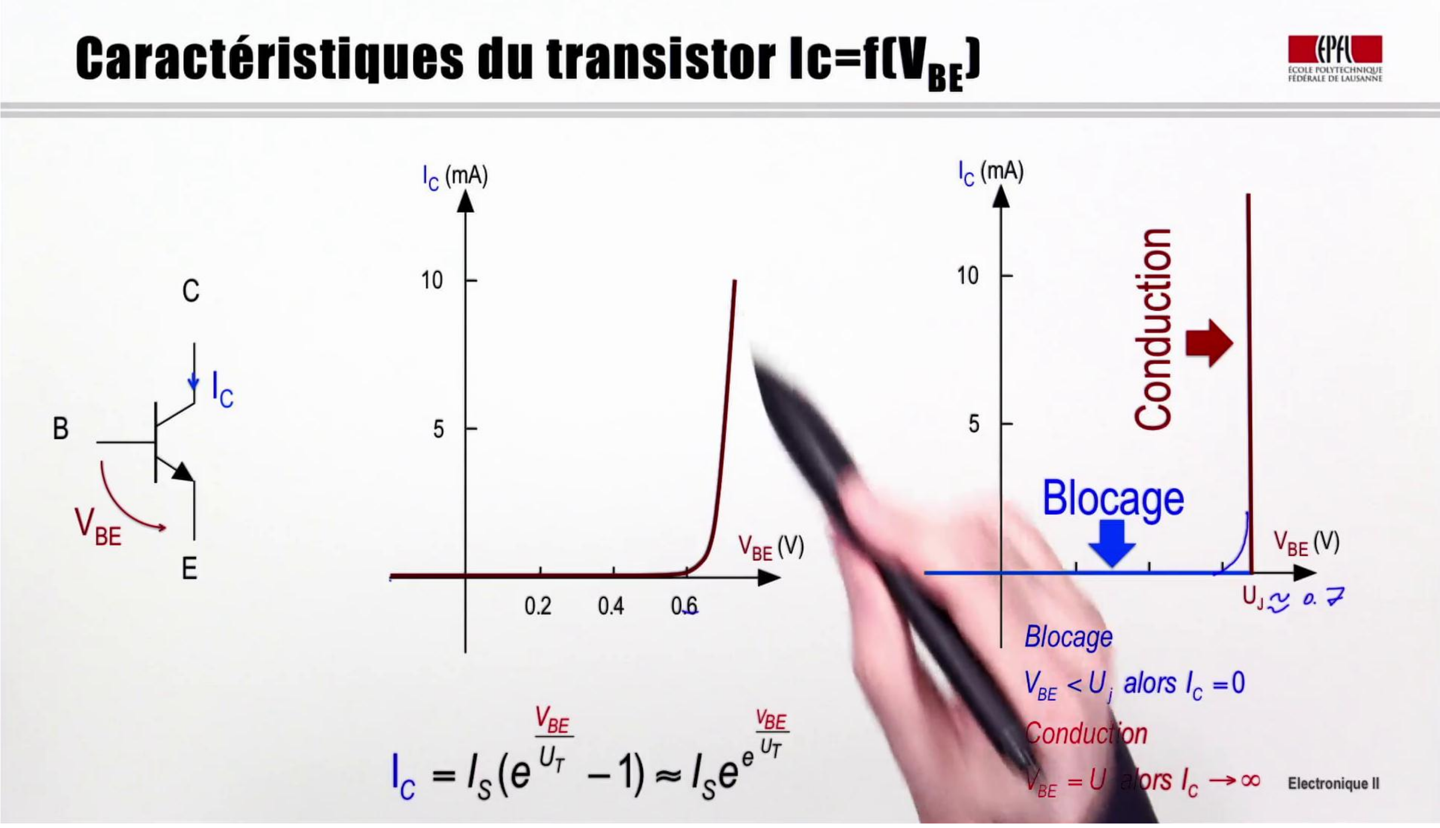


Be careful, this is valid only when we talk of test model and we will strongly insist on it. So I have found a word that I will stick to transistor, and you will retain it, we'll talk of transistor blocking. The transistor blocks when the current Ic is equal to 0, so when I'm here and in a very sudden way, I show that regardless of what happens around this point when I'm in the exponential law I show that the blocking of this transistor corresponds to a value Ic equals 0 and I say suddenly there too, instead of applying very precise analytical law I'm talking here about Vbe less than Uj, so I have a current Ic equals 0, and I will use a second term I call the conducted transistor, and I will say that when Vbe equals to Uj, I have something that is not defined. If you look at this, Ic can be any value here, it can be 5 mA, 10 mA, infinite mA, so in other words, this will depend on the circuit in which I want to put the transistor. But if I do not put or I do not pay attention to the Ic limit, know that your transistors, the current in it can stretch to infinity, the transistor infinity means destruction.

Notes

Summary

20m 35s



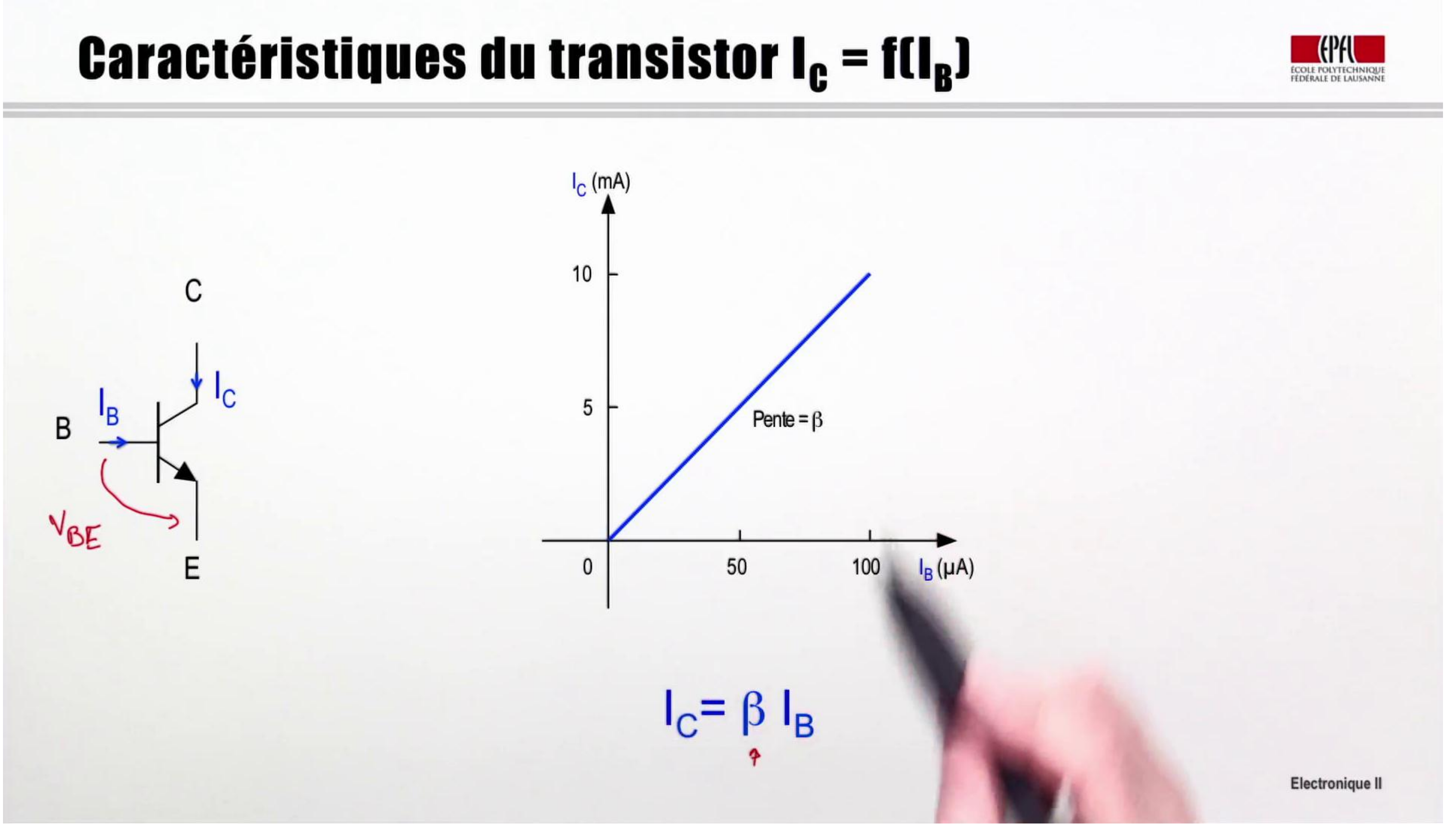
$$I_C = I_S(e^{\frac{V_{BE}}{U_T}} - 1) \approx I_S e^{\frac{V_{BE}}{U_T}}$$

So it is essential to ensure that the current in the collector be limited, and we know very well that the element that will limit this will be a resistor that will surely be inserted in the collector or in the transmitter we will see this later, this is what will limit it to a certain value because of the supply voltage which will also be limited. So in what we have seen on this slide, is simply to show that when it is a DC transistor analysis, then we talk only of the transistor operation when there is a DC current which passes through it or a voltage which will be of the order of of magnitude of Uj, we will use this kind of model, but is it like this all the time ? No. And this I will insist on it a lot, because I know it's a problem when we do not know how to differentiate in our mind the DC model from the AC model, which is most important in the use of transistors, this is a rough approximation of this curve.

Notes

Summary

22m 00s

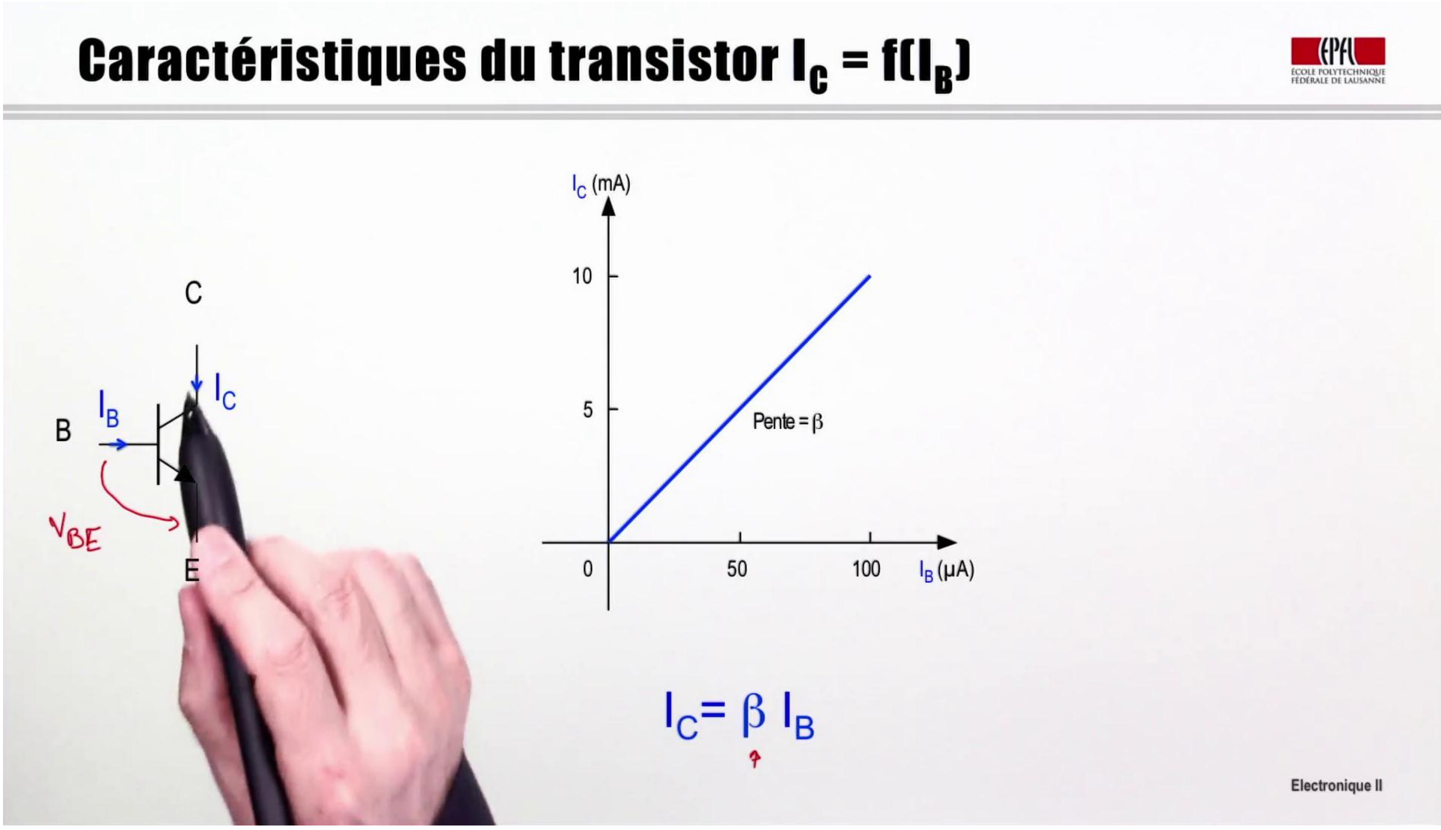


The bipolar transistor has a defect, we do not like this. Remember earlier we were talking about Ube or Vbe voltage, we said the Vbe voltage is the voltage that will allow us to drive or have a proportional current flow between Vbe and Ic, it was found that it is exponential. Will this terminal draw power? Is there a current that will pass into the base? Unfortunately yes, that is what will happen with the bipolar, it would not be the case for an MOS transistor later, in a bipolar transistor, you have a linear relationship between Ib and Ic, so in the first approximation, and it is the line you see here. And the parameter β is a parameter that is given by the manufacturer of your transistors, or if it is you who make the integrated circuits around it, it is the geometry of your transistors that will define the β. Nonetheless, this β is a parameter that will linearly bind Ic and Ib, I'm saying in the first order, and we will find that there is a linearity between the two. The β in transistors, the low power that you will probably use in low power circuits or use in laboratories to learn the use of transistors, you will see that this β is quite high, it is something that varies between 100 and 300, as a ratio, of course it does not have a unit because that is a ratio of amps to amps.

Notes

Summary

23m 00s



So we just found that whenever Ic increases, it is increasing with Ib, and both are bound together in the transistor in the absolute, and we will see that there are conditions of use for this law to be valid when the transistor (inaudible). I would like to stop and summarize a bit what we just saw. We introduced the symbol of the bipolar transistor, we demonstrated that the bipolar transistor is an asymmetric transistor, we can not turn and replace the collector terminals by the transmitter as we want. And we have just seen that there is an exponential law between the output current and input voltage, I just said it. So the input voltage, it is the base-transmitter junction that will allow me to control, and on the output I have a current. Therefore the output variable will be a current and will be the current Ic and I just showed you it has a current flowing through the base and that this current binds it to the collector current so I have a current Ib which is equal to Ic/β, where Ic = β.Ib and β is one of the transistor parameters.

Notes

Summary

24m 36s