Microwave Engineering
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Lecture 21 - Characteristics of Microwave BJT and FET

In the previous module, we have discussed power dividers, directional couplers, and design of filters. In this module, we discuss some of the commonly used microwave semiconductor devices, and in fact in this module we will cover the following contents:

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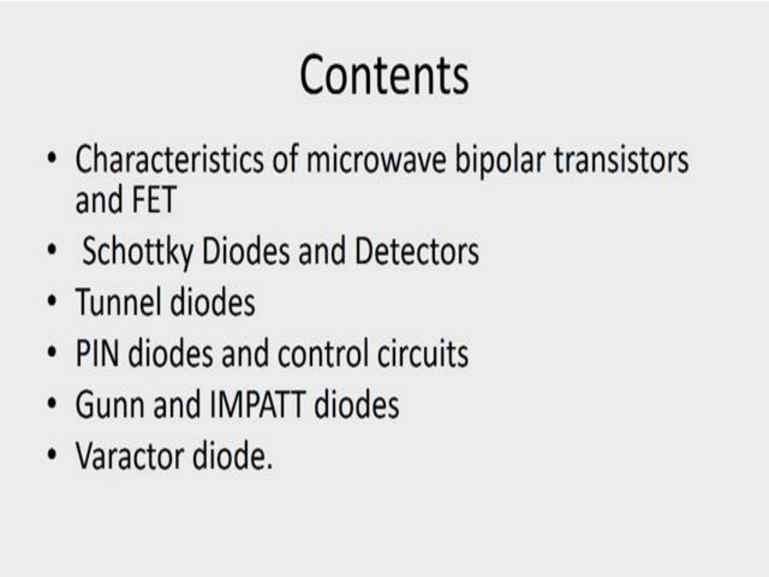

We will study the characteristics of microwave bipolar transistors and Field Effect Transistors or FET. This will be followed by discussion on Schottky diodes and Detectors. Next, we will discuss tunnel diodes. Then we will discuss PIN diodes and control circuits. This will be followed by discussion on Gunn and IMPATT diodes, and we will end this module with the discussion on Varactor diode.

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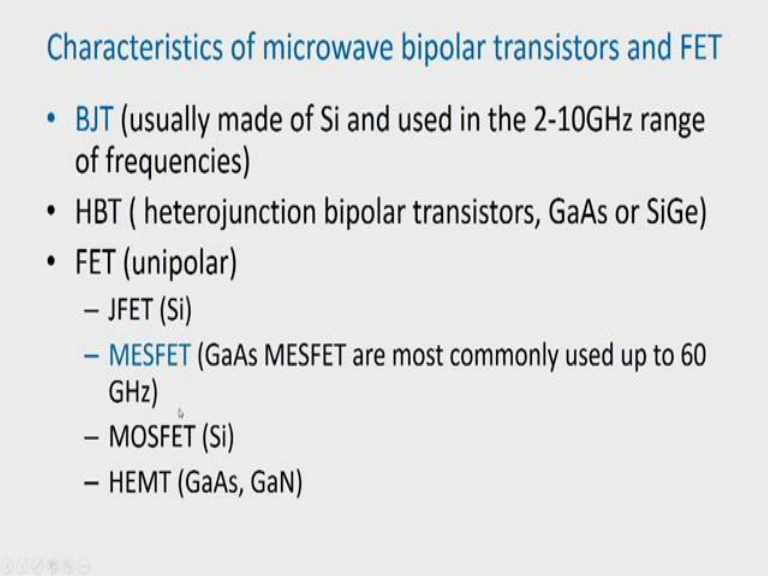

Here we will discuss the device operation in some detail. Without going into the very details of the semiconductor device physics, we start our discussion with the characteristics of microwave bipolar transistors and FET. Bipolar Transistors or BJTs, these are usually made of silicone and used in 2 to 10 gigahertz range of frequencies. Another variant of BJT is HBT heterojunction bipolar transistors, made of gallium arsenide or silicon germanium.

We have field-effect transistors, which are essentially unipolar devices and a variety of such FETs are there. We have JFET, MESFET metal-semiconductor field-effect transistor. Then we have MOSFET metal oxide semiconductor field-effect transistor. HEMT high electron mobility transistors. So, here in this lecture we will briefly discuss BJT and MESFET.

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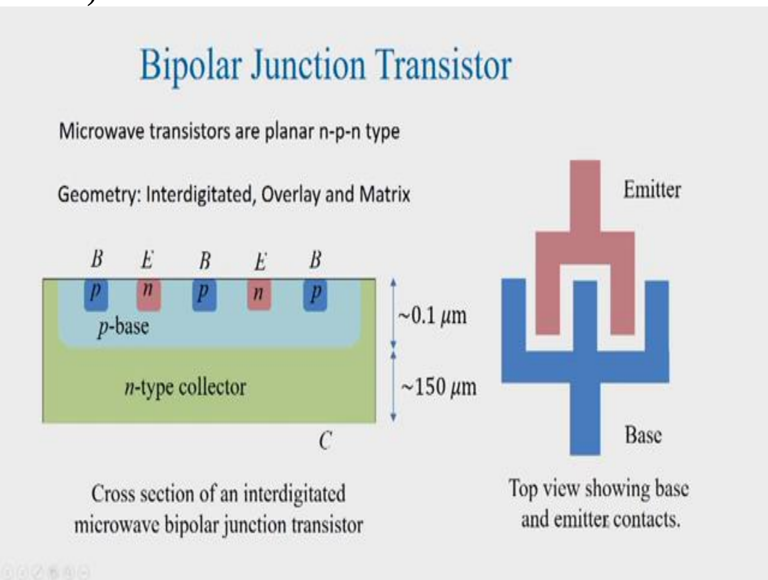

For microwave frequencies are normally n-p-n type transistors are used as the electrons have higher mobility than holes, and the transistors are fabricated using planar technology. Various geometries are used: Interdigitated, Overlay, and Matrix. These are the various geometries used in design of microwave frequency BJTs. Here we are showing the cross-section of an interdigitated microwave BJT. So we have n-type collector, and then you can have this base-emitter. These are interdigitated form which is shown in the top view as in the figure. So you can see the multiple fingers of this base, and this is the emitter.

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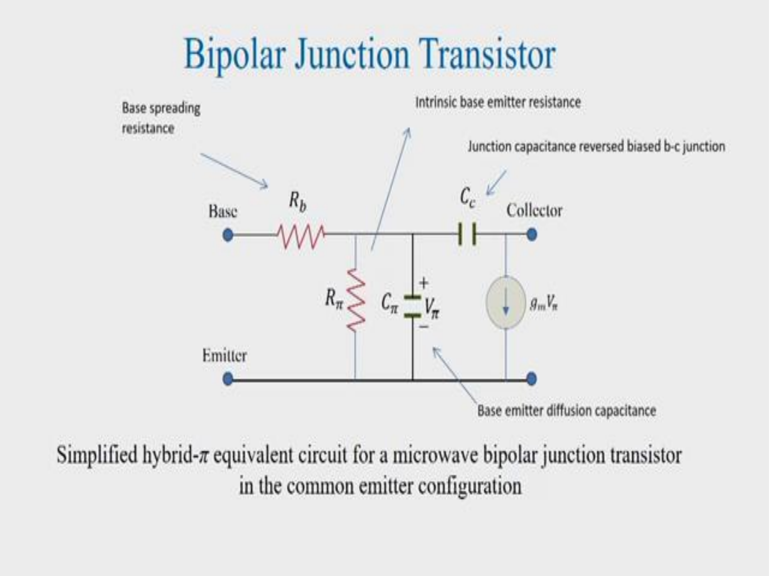

Now since we operate these transistors in the microwave RF and microwave frequency ranges, we use an equivalent circuit model, which is valid at those frequencies and this model is called hybrid pi model, and we are showing here, the simplified hybrid pi model and the transistor, as you know a BJT can operate in different configurations, like common base, common emitter, common collector.

Here, this equivalent circuit, what is being shown is for BJT operating in common emitter configuration. Now, this R_b is the base spreading resistance, so the active base region is inside the base layer, and the metallic connection to this base region, it forms a small resistance, and we are denoting it by R_b. Then we have this R_{pi}. This is the intrinsic base-emitter resistance then C_{pi} is the base-emitter diffusion capacitance. Already in transistor we know that the doping levels of the base-emitter and collectors are different, base is very thin and lightly doped compared to other two and this concentration gradient gives the diffusion of carriers.

Then in the active region, as we know that a transistor can be biased in the cut-off, it can be biased in saturation, or it can be biased in active region. So, in the active region, the collector-base junction is reverse biassed, and we have a junction capacitance C_c and this g_mV_{pi} it is the collector current, g m gives the trance conductance, and V_{pi} is the voltage across this R_{pi} or C_{pi}. So this is the hybrid pi model of the transistor.

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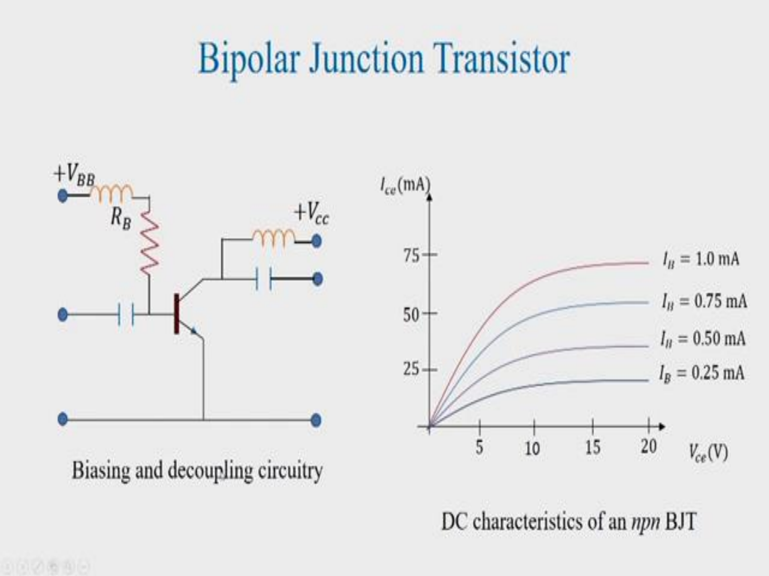

Now for biasing once again, we are showing the common emitter configuration. We find that the collector voltage is connected through an RF choke. Similarly, the base voltage is connected through another RF choke. These chokes are the inductors; they provide very high impedance at the signal frequency and produce the decoupling of the AC signal.

Similarly, these capacitors offer very low impedance for AC, and for DC it becomes open, and therefore, it does not allow the DC sources to load the source or does not allow this DC voltage to appear at the load. So this biasing is very important for proper operation of the transistor, and this is the DC characteristics of an n-p-n BJT, and we can see that, as we change the base current, the collector to emitter current can vary and also this current initially increases with V_{ce} and then it saturates.

So active region is this region where we have set up a DC base current, a DC collector current. The base-emitter junction is forward biased, collector-base junction is reverse biassed, and we apply a signal at the base which gets amplified by the transistor and appears across the load connected at the collector terminal. Now, for AC analysis of this circuit, we consider the hybrid pi equivalent model which we have shown.

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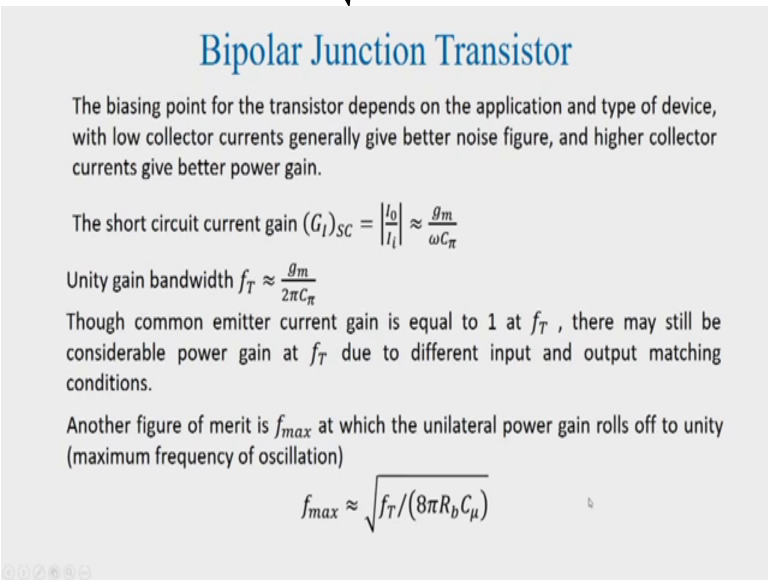
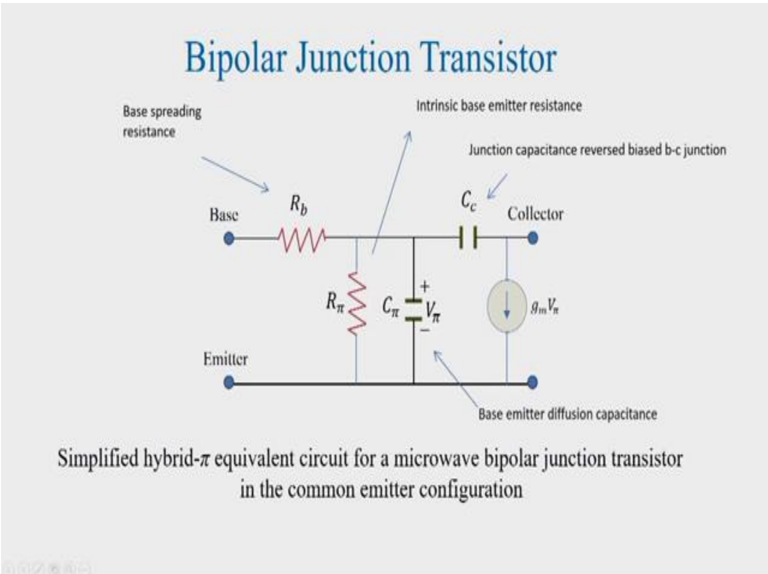
The short circuit current gain $(G_I)_{SC} = \left|\frac{I_0}{I_i}\right| \approx \frac{g_m}{\omega C_\pi}$

Unity gain bandwidth $f_T \approx \frac{g_m}{2\pi C_\pi}$

$$f_{max} \approx \sqrt{f_T/(8\pi R_b C_\mu)}$$





The biasing point, the choice of the biasing point of the transistor depends on the application and also the type of the device. With low collector current, it generally gives better noise figures, and higher collector current gives better power gain.

In the next model, we will see how we design these transistor amplifiers. The amplifier it along with the signal, also amplifies the noise. So noise figure gives essentially a performance measure of the transistor. How much noise signal it adds? Noise figure is a parameter which gives an estimate of the performance of the transistor when noise is present, and later on we will see how we can do low noise design. From the hybrid pi model we have shown, we can find out the short circuit current gain and this is given by mod of output current by input current and can be found as approximately as g m by omega C_{pi}.

Now, when this current gain reaches unity, that frequency is known as unity gain frequency or cut-off frequency and denoted by f_T. So f_T is the frequency, where this short circuit current gain attends a value of unity and if we put 1 here, then we get f_T is approximately equal to g_m by 2 pi C_{pi}.

So, common emitter current gain is equal to one at f_T, there may still be considerable power gain at f_T due to different input and output matching condition. So, another parameter which sometimes defines or another figure of merit which is sometimes defined is f_{max} and this is called unilateral power again. We will see later that a unilateral power gain means when the transistor is modelled with S parameters, we will have S12 equal to 0, and f_{max} can be related to f_T by this relation. So, at f_{max} unilateral power gain rolls off to unity.

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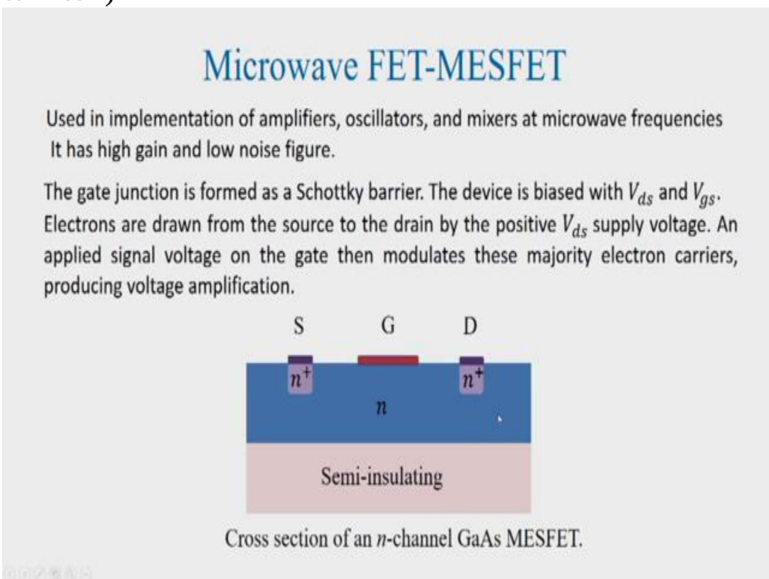

Now, let us briefly discuss the microwave field-effect transistor. We have seen there are variety of field-effect transistors. We will keep our discussion limited to MESFET Metal Semiconductor Field Effects Transistor, and such transistors are used in implementation of the amplifier, oscillators, and mixers at microwave frequencies. It has high gain and low noise figure.

Here we do not have any oxide layer as in MOSFET, so the gate junction is formed as a Schottky barrier. The device is biased with V_{ds} and V_{gs}. The electrons are drawn from source to drain. So this is the source, and this is the drain, and we have the gate terminal. So from source to drain, the electrons are drawn by application of the positive V_{ds}, and a signal is applied at the gate, which modulates this majority electron flow, and thereby, we can produce amplification. So the gate current controls the current from source to drain.

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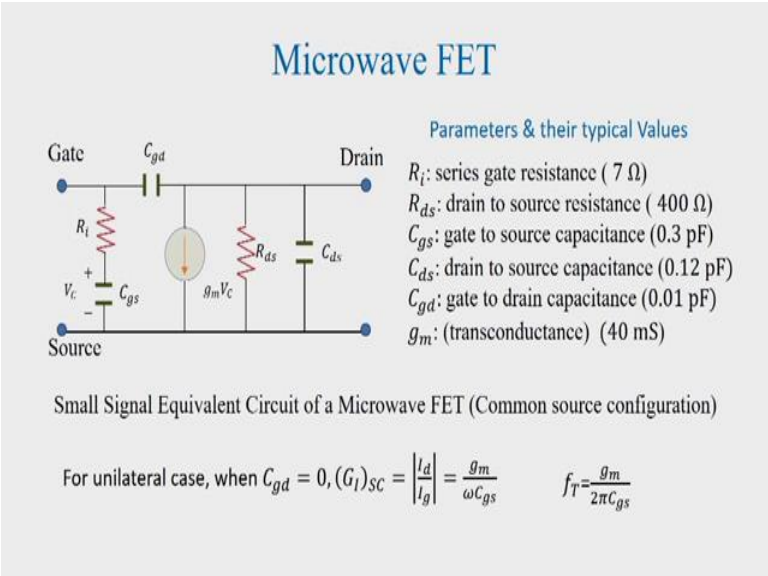
For unilateral case, when $C_{gd} = 0,\ (G_I)_{SC} = \left|\frac{I_d}{I_g}\right| = \frac{g_m}{\omega C_{gs}}$

$f_T = \frac{g_m}{2\pi C_{gs}}$



The small signal equivalent circuit for a MESFET is shown here. We have a resistance R_i which is the series gate resistance and then in series with gate to source capacitance C_{gs} and then, C_{gd}, it is the gate to drain capacitance. R_{ds} it is the drain to source resistance, and C_{ds} is the drain to source capacitance. As before gm V_c it gives the current. gm is the transconductor and this current source, the current produced by this current source is determined by the voltage V_c across C_{gs}. Now, this small-signal equivalent circuit of the FET is shown for common source configuration, and we have also shown some typical values for these small-signal parameters.

Now, once again when it is unilateral, that means the signal does not this connection between gate and drain is not there, so C_{gd} is zero, and therefore, we have short circuit current gain G_I S_C, which is essentially I_d. So, if we put a short circuit here I_d will be gm V_c and I_g will be essentially V_c into omega C_{gs} and therefore, I_d by I_g mod will be gm divided by omega C_{gs} and as before when this G_I S_C it becomes unity, int that case, we get the f_T or the unity gain frequency and this is given by gm by 2 pi C_{gs}.

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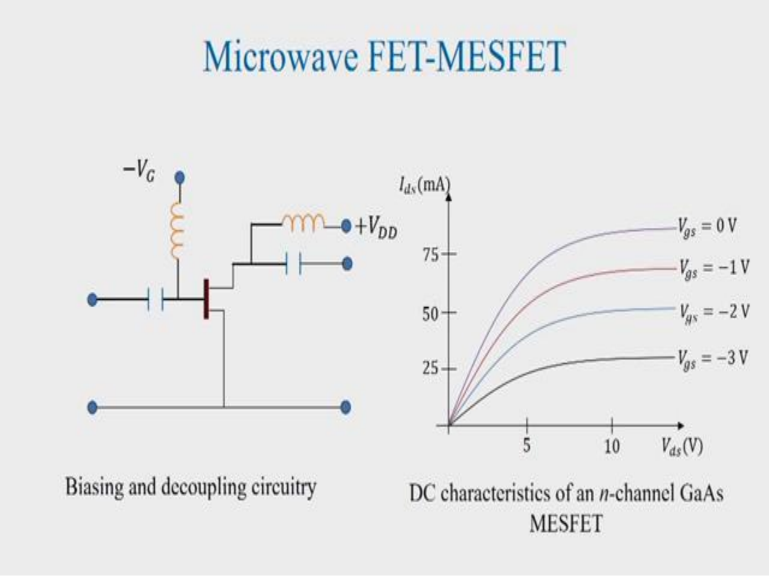

A MESFET also requires to be biased and here we show the characteristics so, we can see that I_{ds} the current from source to drain that changes with the change in V_{ds} and then the current can also be controlled by applying a negative V_g that means the negative voltage at the gate and we have shown the family of I_{ds}, V_{ds} curves, that are obtained for different values of V_{gs}. As in BJT we need to connect the DC source biasing source V_{DD} and V_G through RF chokes, which will provide a short circuit for DC and very high impedance for AC.

And in the same manner, these capacitors will be essentially short-circuited at AC and they will remain open for DC. So, the signal will get coupled to the gate of this FET but this signal will not go to the DC source supplying the gate voltage.

So this is in brief. The operation of the most commonly used transistors at the microwave frequency that is a BJT and the MESFET. We have seen there are many other different varieties of transistors, and some of them are suitable for a higher frequency of operation and used in very high frequencies, such as millimeter waves. Some of these devices are useful for high power applications. So we need to select the transistor type based on the application at hand.