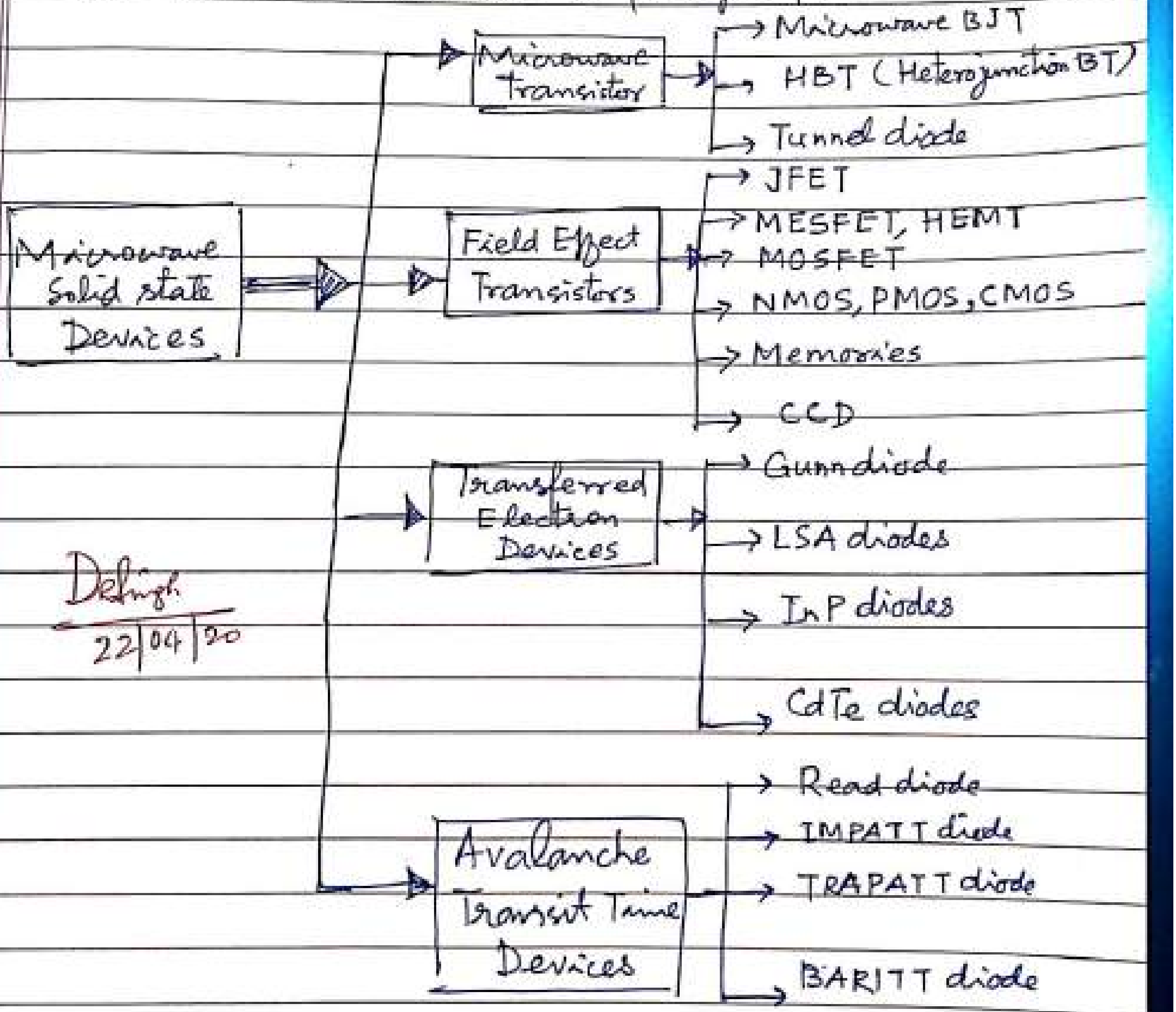
MICROWAVE TRANSISTOR

Prof. Devraj Singh
RBIPSSR, VBSPU, JNP

Microwave solid state devices are becoming increasingly important at microwave frequencies. These devices can be broken into four groups as shown below:



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MICROWAVE BIPOLAR TRANSISTORS

STRUCTURE AND OPERATING PRINCIPLE :

In the lower part of the microwave band (less than 15 GHz) classical bipolar transistors (BT) are used as power amplifiers and generators with low frequency noises.

The main advantages of such devices are their low cost, low flicker noise and high reliability, determined by debugging of silicon technology.

~~Let us analyze what levels of doping layers, sizes, and materials allow an increase to the boundary frequ~~

Let us consider the features of a bipolar device operating in the microwave band. The improvement of the inertial characteristics of such devices is achieved by reducing the size, especially the length of the base W_b. However, this increases the probability of base punchure i.e., the closing of the depletion layers of the emitter-base and the base-collector. To avoid puncture, it is necessary to increase the level of doping in the base. As a consequance, the emitter efficiency factor falls.

Let us analyze what levels of doping layers, sizes, and materials allow an increase to the boundary frequency of bipolar transistors. To do this, consider the typical structure of the device, the cross-section of which is shown schematically in Fig. 1

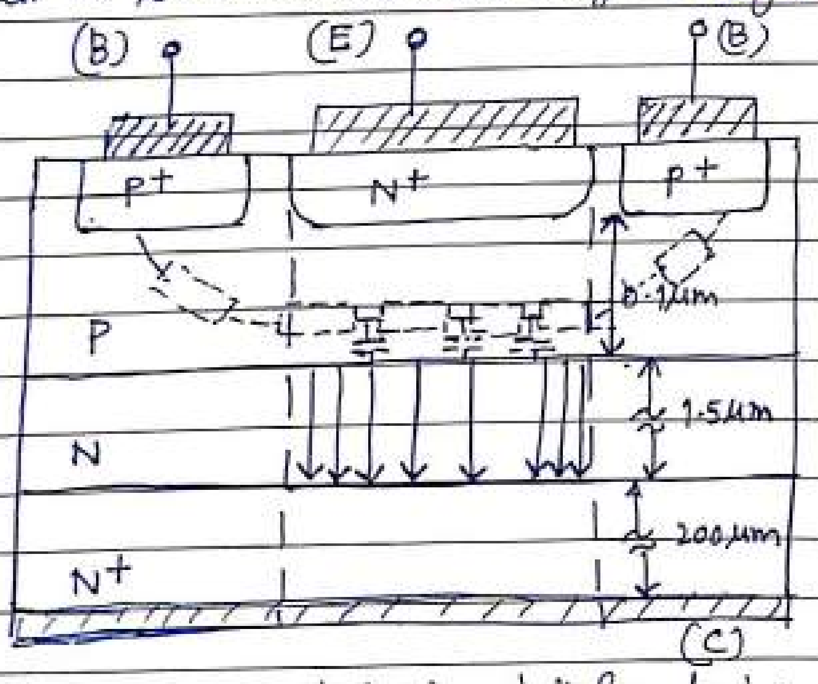

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Fig. 1 Transverse section of a bipolar device

In Fig. 1, resistors and capacitances characterizing the distributed (in space) nature of the current flow between the emitter and collector base are shown in base region. Different parts of the base have different potentials relative to the emitter. The end base regions work more efficiently than the middle ones, because the voltage drop on the resistive elements of the base. That is why the current line in Fig. 1 have a large density along the edges of the base. The effect of current concentration along the edges of the emitter electrode is most noticeable in microwave devices, when the thickness of the base should be reduced, which causes an increase in its resistance. To reduce this effect, the ratio of the area of the emitter electrode to its perimeter is minimized. In this regard, powerful microwave bipolar transistors are built in the form of cellular or comb structures. The width of the emitter electrode in such devices is 1–5 µm. The topology of such a devices is illustrated in Fig. 2.

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This Figs. is attached in separate file

Fig. 2 Cell of a comb-structure transistor.

It shows a photograph of one cell of the transistor. The central electrode (emitter) is surrounded along almost its entire perimeter by the base electrode. A structure consisting of several cells connected in parallel is called the comb structure.

Typical concentration levels of mobile carriers for a microwave N-P-N transistor are shown in Fig. 3. Thin dashed lines show the boundaries of the depletion zones at the emitter-base and collector-base boundaries. Figure 3 also shows the external circuit, which provides height change of the potential barriers formed by the field in the depletion layers.

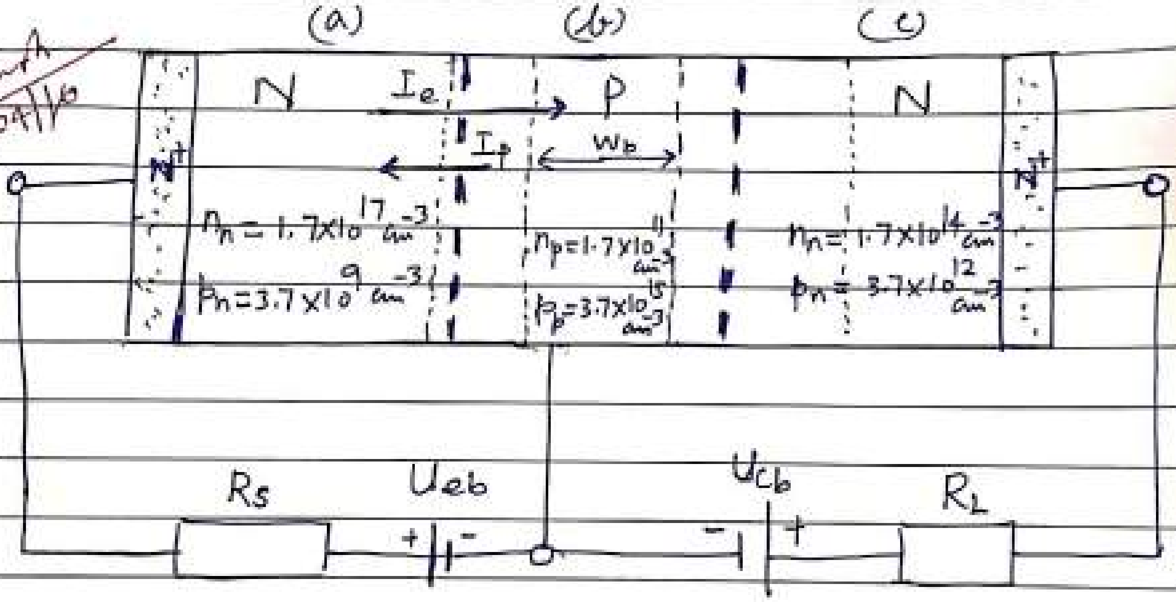


Fig. 3 Typical doping levels of a microwave BJT

In general, a transistor can be represented by a connection of two counter-connected diodes. The main feature of such a ~~concentration~~ connection is a thin neutral base through which the mobile carriers (in this case electrons) can diffuse from the emitter-base region into collector-base depletion layer. An accelerating electric field exists in this layer. As a result, the bulk of the charge carriers from the emitter reaches the collector in time T_{ec}. Thus, for the efficient operation of the bipolar transistor, it is necessary that the diffusion length of the carriers be greater than the length of the base i.e, $l_d > W_b$.

Bipolar transistors have three electrodes and can be included in three different kinds of circuit, as well as vacuum triode valve.

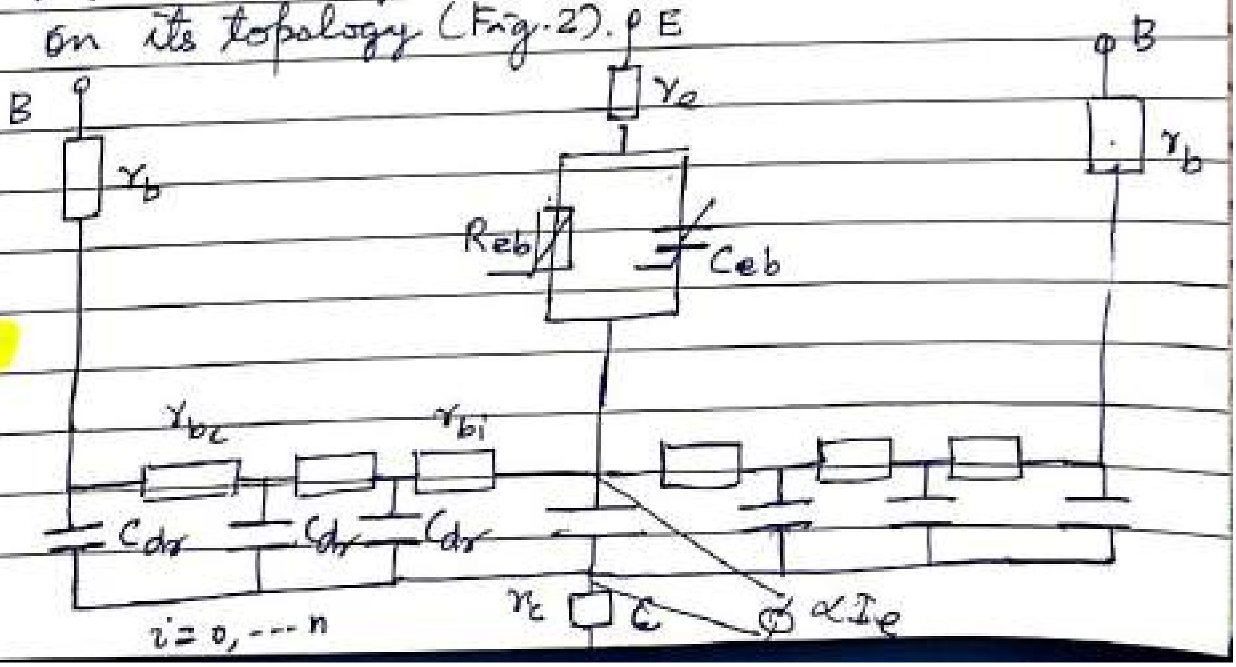
The possible switching circuits are:
with a common emitter (analog with a common cathode)
" " " base (" " " " grid ~~emitter~~)
and " " " collector (" " " " anode)

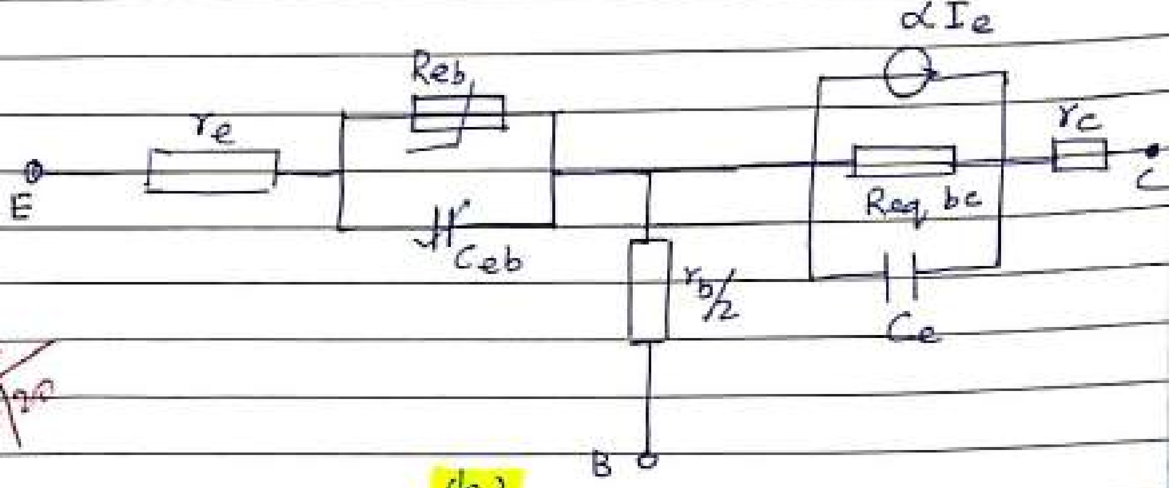
In microwave band, a common emitter circuit is generally used, providing maximum gain.

EQUIVALENT CIRCUITS AND H.F. PARAMETER OF BT

Analysis of the high frequency properties of a bipolar transistor, as in the case of field transistors, is carried out using the equivalent circuit. Fig.4 shows the equivalent circuit of transistor, based on its topology (Fig.2).

(a)





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(b)

Fig-4: Equivalant bipolar transistor circuits:
(a) in depth (b) Simplified.

The physical interpretation of the individual elements of the circuit with this approach is fairly obvious. Non-linear resistance (Reb) and capacitance (Ceb) characterize the properties of the emitter-based barrier. Element r_{bi} and C_{dr} correspond to the previously mentioned distributed character of current transfer in the base.

These elements allow us to take into account the change in the control potential along the base layer. The current source αI_e denotes the injection into the depletion layer of the collector-base emitter current part I_e. The parameter α is called the current transfer coefficient in the common-emitter circuit. Together with this value, we use the value $\beta = \frac{\alpha}{1-\alpha}$, which is called the current amplification factor.

Using electrical engineering methods, a

distributed circuit can be brought to the simplified circuit shown in Fig. 4(b).

Let us analyse what parameters of the structure in question affect the limiting and maximum frequency of the transistor. The total transit time consists of base transit time τ_b, transit time of the emitter-base junction τ_{eb}, transit time of the base-collector junction - τ_{bc} and the transit time of the collector depletion layer τ_c, i.e.,

$$\Sigma_t \tau = \tau_{eb} + \tau_b + \tau_{bc} + \tau_c \longrightarrow ①$$

In a properly constructed transistor, τ_b plays the main role in delay. However, τ_{bc} also plays an important role.

High frequency transistor parameters are usually characterised by the cut-off frequency (critical frequency f_t or $\omega_t = 2\pi f_t$). It is defined as the frequency at which the current gain in the short circuit mode of the common emitter circuit is equal to one. The critical frequency is related to the delay time $\Sigma_t \tau$.

$$f_t = \frac{1}{2\pi \Sigma_t \tau} \longrightarrow ②$$

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Another important parameter is the maximum frequency f_{max} on which the power gain in the circuit with the common emitter is equal to one. To find the f_{max}, we simplify the circuit (Fig 4b) leaving the most important elements: the base resistance r_b at the input, and collector capacitance C_c.

The maximum power in the active load G_L is observed when the currents through the capacitance C_c and through the load are equal. This condition is fulfilled only at one frequency. Suppose that it is satisfied at the critical frequency, that is $G_L = \omega_t C_c$. If the input is matched, the power gain factor will be written in the form.

$$\frac{P_{out}}{P_{in}} = \frac{\left(\frac{\beta I_{in}}{2}\right)^2 / G_L}{I_{in}^2 r_b} = \frac{\beta^2}{4 r_b G_L}$$

$$= \frac{(\omega_t/\omega)^2}{4 r_b C_c \omega_t} = \frac{\omega_t}{4 r_b C_c \omega^2} \rightarrow ③$$

For $\omega = \omega_{max}$, $\frac{P_{out}}{P_{in}} = 1$, then

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$$\frac{\omega_t}{4 r_b C_c \omega_{max}^2} = 1$$

and

$$\omega_{max}^2 = \sqrt{\frac{\omega_t}{4 r_b C_c}} \rightarrow ④$$

If we represent the dependence of the power gain coefficient on frequency on the logarithmic scale, we obtain

$$\log \frac{P_{out}}{P_{in}} = \log \frac{1}{4 r_b C_c \omega_t} + \log \left(\frac{\omega_t}{\omega}\right)^2$$

$$= G_0 + 2 \log \frac{\omega_t}{\omega} \rightarrow ⑤$$

The dependence is shown in Fig. 5. It is characterized by a drop in gain of 6 dB for a frequency octave in the frequency region above f_t.

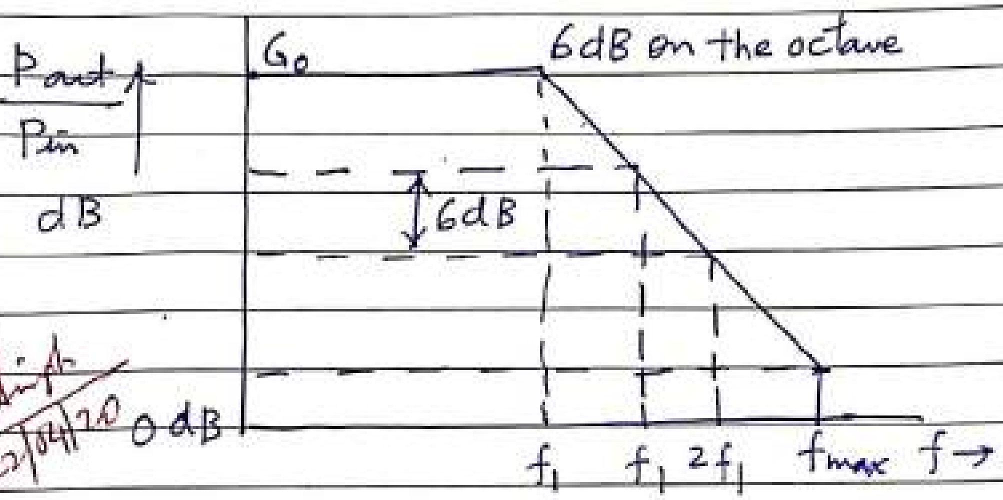

Fig. 5 Typical frequency response of a bipolar device

When describing the high frequency characteristics of bipolar transistors, a so-called hybrid π-circuit is often used in practice (Fig. 6)

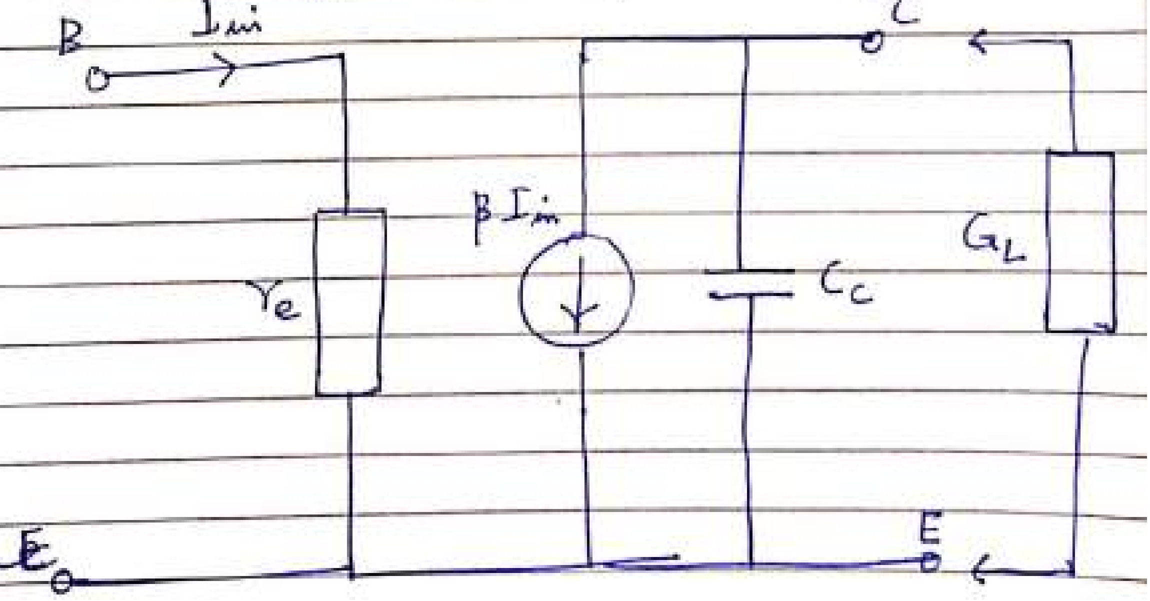

Fig. 6 Hybrid equivalent π-circuit of a BT

Unlike the circuit (Fig. 7), the output source of this circuit is controlled by the emitter-base voltage and not by the base current. In this variant, as in the field transistor, one can apply the concept of transconductivity g_m, defining it by the following expression:

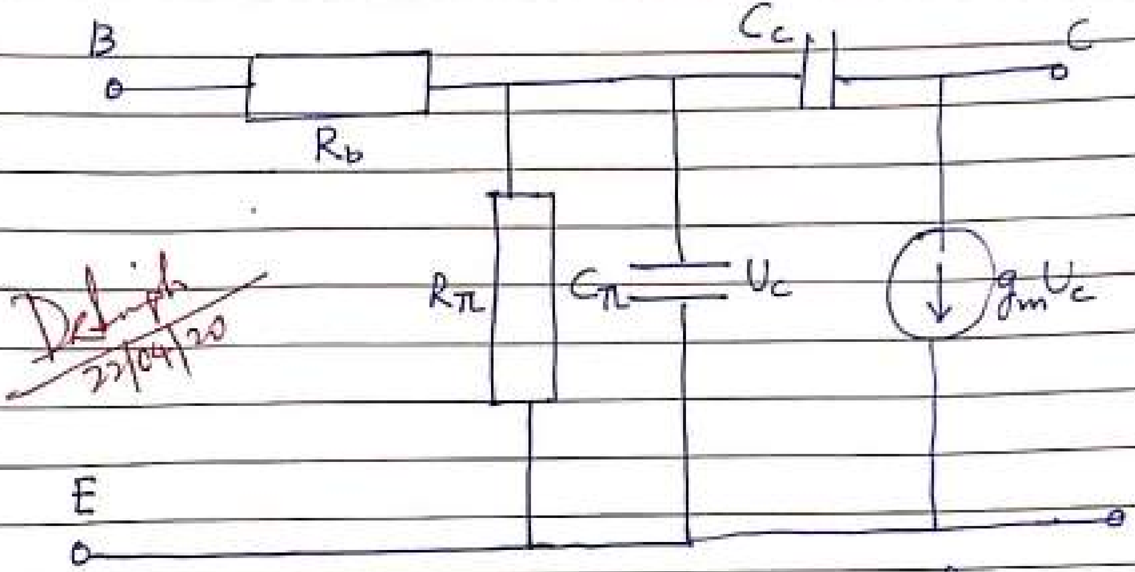

Fig. 7. Calculating the maximum frequency of a transistor

$$g_m = \frac{\partial I_c}{\partial V_{eb}} \longrightarrow (6)$$

The value of g_m is easy to estimate for current I_e through the emitter-base junction

$$I_e = I_s\left[1 - \exp.\frac{eV_{eb}}{k_B T}\right] \longrightarrow ⑦$$

Taking into account the fact that the collector current is approximately equal to emitter current, the expression for steepness (Eq. (6)) leads to the form

$$g_m \approx \frac{e}{k_B T} \exp\left(\frac{eV_{eb}}{k_B T}\right)$$

$$\approx \frac{e}{k_B T} I_e = \frac{I_e(mA)}{26} \longrightarrow (8)$$

Equation (8) is valid for temperature $T = 300K$.

The remaining parameters of the π-circuit can be found from the recalculation of the distributed circuit (Fig. 4(a)) or by using the S-parameters. As an example, the characteristic values for a transistor in the centimeter wave band are presented below:

$R_b = 7\Omega$, $R_\pi = 110\Omega$, $C_\pi = 18\,pF$

$C_c = 18\,pF$, $g_m = 900\,mS$

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Just as for a field transistor, the critical frequency is given by the expression

$$f_t = \frac{g_m}{2\pi C_\pi}$$

For the presented values of the π-circuit parameters

$$f_t = \frac{900 \times 10^{-3}}{2\pi \times 18 \times 10^{-12}} \approx 16\,GHz$$

The equivalent circuits of bipolar transistors, just like the circuits of field transistors, are particularly convenient for analysing non-linear operation modes. In this regard, many firms that manufacture such devices provide along with S-parameters, linear and nonlinear transistor models.

—THE END— Theory