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* Hybrid - Pi Model :

- Eber's-moll model and Gummel - Poon model do not take into account the junction capacitances associated with BJT.
- These models therefore, tend to fail when analysis of BJT is done at high frequencies.
- We consider the various terminals of BJT individually for constructing the model.

Consider npn BJT in CE configuration.

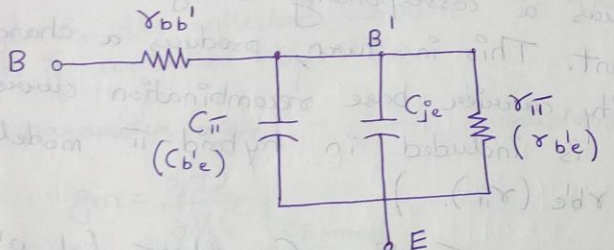

fig a) Components of hybrid-π model between base (B) and emitter (E)

- In figure (a), B represents the external base terminal and B' is the active internal part of the base region.

. <u>Resistance $r_{bb'}$</u> : It is the series resistance in base between external base terminal B and internal base region B'.

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2. Capacitance C_π ($C_{b'e}$):

· B'-E junction is forward-bias, So C_π is the junction diffusion capacitances.

(The excess minority carrier storage in the base region results in the diffusion capacitance C_π between B' and E).

3. Resistance r_π ($r_{b'e}$): It is the junction diffusion resistance.

(Any small change in the B-E forward bias voltage produces a corresponding change in the emitter current. This in turn, produces a change in the minority carrier base recombination current. This effect is included in hybrid-π model as a resistor $r_{b'e}$ (r_π).)

4. Capacitance C_{je} : Junction Capacitances. (of $B'E$ junction)

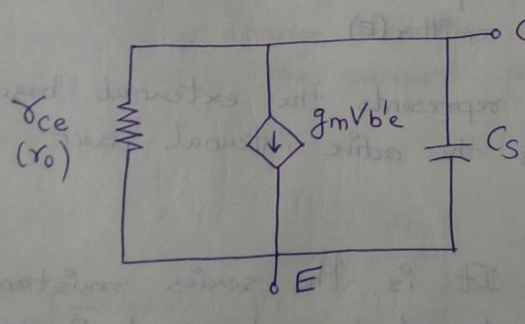


fig (b) Components of hybrid-π model between Collector (c) and emitter (E)

5. Resistance $r_{ce}(r_o)$: The resistance existing between the C and E is represented by $r_{ce}(r_o)$

(r_o is the o/p resistance which is the inverse of o/p conductance and is primarily due to Early effect).

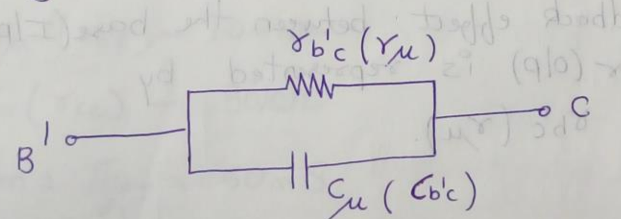
6. Capacitance C_s: It is the junction capacitance of reverse-bias collector substrate junction.

7. $g_m V_{b'e}$ (Dependent current source): It is the collector current in the transistor, which is controlled by $V_{b'e}$.

(The parameter g_m (mutual conductance) ⇒ is

$$g_m = \frac{\partial I_c}{\partial V_{b'e}}\Big|_{CE\text{-mode}}$$

Any small change $V_{b'e}$ in B-E junction produces a corresponding change in the collector current. This results in the current source indicated by $g_m V_{b'e}$.



fig(c) Components of hybrid-π model between Base (B) and collector (C)

8. Capacitance C_{μ} ($C_{b'c}$):

Since B'-C junction is reverse-biased, C_{μ} ($C_{b'c}$) is the reverse-bias junction capacitance.

9. Resistance r_{μ} ($r_{b'c}$):

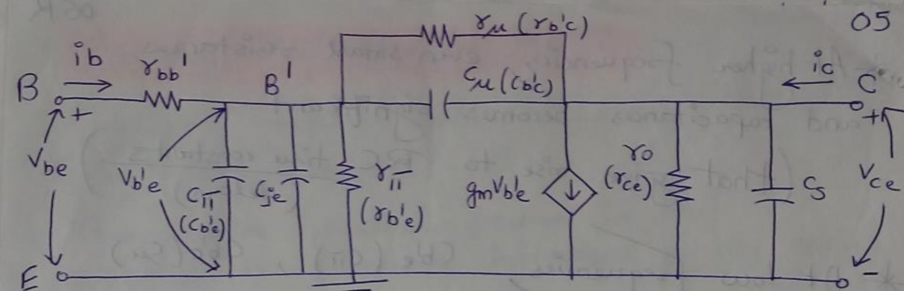
It is the reverse-bias diffusion resistance.

Extra: !!

Any change in B-C reverse-bias voltage produces a corresponding change in depletion width of B-C junction.

- This results in a change in effective base width. The phenomenon that results in a dependence of effective base width on collector voltage is called 'Early effect' or (BWM) → Base-width modulation.
- Any change in the effective base width produces a corresponding change in the emitter and collector currents.
- This is because a change in the base width results in a change in the slope of minority carrier distribution in the base.

→ This feedback effect between the base (I/p) and collector (O/p) is represented by resistance $r_{b'c}$ (r_{μ}).



fig(d) Complete Hybrid-π model for npn BJT in CE configuration

* (Valid for both low frequencies and high frequencies)

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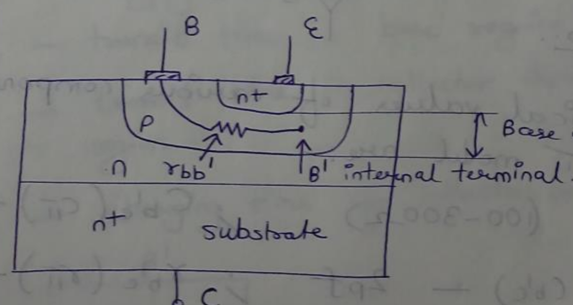
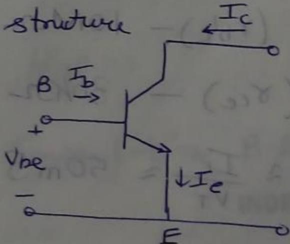
Extra !!



fig(5) npn BJT device structure



* In the model, we have B-E Junction capacitance and B-C junction capacitance shown as [$C_{b'e}$ and $C_{b'c}$]

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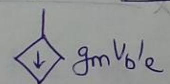
* At higher frequencies, even small resistances and capacitances becomes significant.
  (that give rise to RC time constants (delays))

* At low frequencies, $C_{b'e}$ (C_π), $C_{b'c}$ (C_μ) and $r_{bb'}$ are not significant.

Note: In practise, transistor action transfers only the current in r_π to the o/p, it does not transfer current through C_π to o/p.
∴ Current source is controlled by $V_{b'e}$ only & not i_b..



Some typical values of various components in hybrid-π model are:-

- $r_{bb'}$ — (100–300 Ω) ; $C_{b'e}$ (C_π) ~ 20pf
- C_μ ($C_{b'c}$) — 2pf ; $r_{b'e}$ (r_π) — 1.5KΩ.
- r_μ ($r_{b'c}$) — 10MΩ
- r_o (r_{ce}) — 30KΩ
- $g_m \simeq \frac{I_C}{V_T} \simeq 50mS$

* Frequency Limitation's in BJT:

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- Hybrid - π model introduces frequency effects through R-C elements.
- Thus, various physical factors in BJT contribute to frequency limitations of the device.

→ Various <u>time-Delay factors</u> in BJT are :-

Total delay time τ_D (τ_{ec}) between emitter and collector is given as.

$$\tau_D = \tau_e + \tau_b + \tau_d + \tau_c \quad — (1)$$

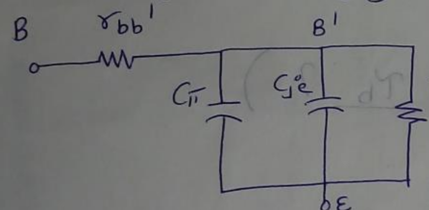
where,

τ_e — charging time of B-E junction capacitance

τ_b — transit time in base region.

τ_d — transit time in collector depletion region

τ_c — charging time of collector capacitance.



fig(1.a)

- The equivalent circuit of forward-bias B-E junction is shown in fig(1.a).

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From the diagram (1.a), capacitance C_{je} is the junction capacitance.

1] Charging time τ_e of B-E junction capacitance is

$$\tau_e = r_e'(C_{je} + C_p) \quad — (2)$$

where, r_e' – diffusion resistance of emitter junction

C_{je} – Emitter junction capacitance.

C_p – represents all the parasitic capacitance between the Base and emitter.

2] The transit time (τ_b) in base region is given by,

$$\tau_b = \frac{W_B^2}{2 D_n} \quad — (3)$$

where, W_B – Width of the base region.

* Base transit time (τ_b) is the time required for minority carriers to diffuse across the neutral base region.

→ Extra! (Expression for τ_b ?)

- For an npn transistor,

$$J_n = -q\, n_B(x)\, v(x)$$

J_n ↓ Electron current density in base.

where, $v(x)$ – average velocity of carriers

$$v(x) = \frac{dx}{dt} \Rightarrow dt = \frac{dx}{v(x)}$$

Transit time can be found by integrating,

$$\tau_b = \int_0^{W_B} dt = \int_0^{W_B} \frac{dx}{v(x)} = \int_0^{W_B} \frac{q\, n_B(x)\, dx}{(-J_n)} \quad -(i)$$

Now,

$$n_B(x) \approx n_{B0} \left[\exp\left(\frac{V_{BE}}{V_T}\right) \left(1 - \frac{x}{W_B}\right) \right] \quad -(ii)$$

Now, $J_n = q\, D_n \frac{dn_B(x)}{dx}$ --- Diffusion current $-(iii)$

Solving (i), (ii) and (iii), we can get

$$\boxed{\tau_b = \frac{W_B^2}{2D_n}}$$

Note: $x_B = W_B$

In textbooks, they have used Base width symbol as x_B

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3] Collector depletion region transit time (τ_d) is

$$\tau_d = \frac{W_{dc} \text{ (or } x_{dc})}{v_s} \quad — (4)$$

Assuming that the electrons in npn device travel across the B-C space charge region with their saturation velocity (v_s).

W_{dc} or (x_{dc}) ÷ is the B-C space-charge width

4] Charging time of collector capacitance (τ_c) is

$$\tau_c = r_c\,(C_\mu + C_s) \quad — (5).$$

where, C_μ – B-C junction capacitance.

r_c – Collector region series resistance.

C_s – Collector to substrate capacitance.

* B-C is reverse-bias so that diffusion resistance in parallel with junction capacitance is very large.

Thus, τ_c is a function of r_c

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How frequency affects the transistor performance!

- BJT is a transit-time device. So any changes in V_{BE} leads to a corresponding change in carrier injected from Emitter into Base region.
- If V_{BE} ↑ses, additional carriers from emitter needs to be injected into the base region.
- These excess carriers then diffuse through base-region, suffers some recombination's there and finally gets collected in the collector region.

→ **Frequency Limitation effect:-**

* As the frequency of input signal applied ↑ses, the transit time of the carriers from E to C becomes comparable to the time period of I/P signal.
* When this happens, the O/P is no more in phase with the I/P signal.
* This leads to a corresponding ↓se in the magnitude of current gain.

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