BJT INTERNAL CAPACITANCES AND HIGH-FREQUENCY MODEL

Figure 23.1: High frequency parasitic elements in a npn transistor.

* This far we have dealt with transistor models which are instantaneous i.e. there is no dependence on the signal frequency.

* Although it's true for certain range of frequencies, at much higher frequencies there are parasitic elements (shown in Fig 23.1) that degrade the performance of the BJT.

* We'll briefly look at the physical nature of these parasitic elements and then create a small-signal model which is valid at higher frequencies.
Base-charging or Diffusion Capacitance (C_b)

This capacitance is the result of change in the minority-carrier charge (\( \Delta q = q_n \)) due to change in the B-E voltage (\( \Delta V_{BE} = \delta V \)).

This capacitance can be written as:

\[
C_b = \frac{q_n}{\delta V}
\]

\[\text{Where,}\quad q_n = \tau_F i_c \quad [i_c = \Delta I_c]
\]

\[\text{Where,} \quad \tau_F \rightarrow \text{has the dimension of time and is called the base transit time. It can be identified as the average time spent per carrier in the base.}\]

\[i_c \rightarrow \text{resultant collector current due to} \ \delta V \ (\text{i.e.} \ \Delta V_{BE})\]

\[C_b = \frac{\tau_F \cdot i_c}{\delta V} = g_m \cdot \tau_F \quad [g_m = \frac{i_c}{\delta V}]
\]

\[\text{or} \quad C_b = \frac{\tau_F \cdot I_{c0}}{V_T} = g_m \cdot \tau_F \left[ V_T = kT/q \right]
\]
The base-emitter junction Capacitance \( (C_{je}) \)

* This capacitance is a depletion capacitance, which is similar in nature to one we have derived in a earlier lecture for a p-n junction.

* Usually, it is expressed as the following:

\[
C_{je} = \frac{C_{je0}}{1 - \frac{V_{BE}}{V_{oe}}}
\]

where,

- \( C_{je0} \) is \( C_{je} \) at \( V_{BE} = 0 \)
- \( V_{oe} \) is the built-in voltage

* Since this is a forward biased junction, \( C_{je} \) happens to be very unpredictable and is usually approximated as:

\[
C_{je} \approx 2C_{je0}
\]
The collector-base junction capacitance \( C_u \)

\* The collector-base junction is reverse biased in forward active region.

\* So the depletion capacitance can be written as:

\[
C_u = \frac{C_{uo}}{1 + \frac{V_{cb}}{V_{oc}}}
\]

Where,

\( C_{uo} \) is \( C_u \) at \( V_{cb} = 0 \) V

\( V_{oc} \) is the built-in voltage (typically 0.75V)

Base resistance \( (r_b) \)

\* Since the base is usually lightly doped, \( r_b \) is the parasitic resistance between the B-E junction and the electrical contact at the base.

\* The value of this resistance is few ohms which can be neglected for low-frequency application but they play a significant role at high frequency.
The High-Frequency Small-Signal Model

![Circuit Diagram]

Figure 23.2

NOTE:
* the dependent current source $g_m V_T$ where $V_T$ is the voltage across $r_x$ * NOT BE junction.

* $C_T = C_b + C_{je}$

* Like the low-frequency small-signal model, the model parameters for the high-frequency have to be determined for the bias point.

* Please review Sec 8.1 in textbook about Bode plots.
Example:

High Frequency Small-Signal model for 2N2222A at \( I_C = 1mA \) & \( V_{CE} = 10V \), \( \beta = 175 \)
Current Gain-Bandwidth Product / transition frequency ($f_t$)

* Usually, data sheets give the number $f_t$ which generally tells you how fast a device can operate.

* For BJTs, it is defined as the frequency ($f_t$) at which $\left| \frac{i_c}{i_b} (j\omega) \right| = 1$ with $i_c$ measured by shorting the collector (in AC sense).

* Let's derive an approximate expression for $f_t$ using the high frequency model just developed.

\[
\begin{align*}
V_x &= i_b \cdot \frac{R_X}{\frac{1}{C_T}} \\
\text{or } V_x &= \frac{i_b \cdot R_X}{1 + \frac{1}{C_T} C_T}
\end{align*}
\]
Assuming the current through $C_u$ is much smaller than $g_m \cdot V_{i_n}$ (i.e. $i_{CB} \ll g_m V_{i_n}$), we can write the KCL at the output to be:

$$i_c = g_m \cdot V_{i_n}$$

Substituting $V_{i_n}$ from (1) we get

$$i_c = i_{bb} \cdot \frac{g_m V_{i_n}}{1 + s \cdot r_a \cdot C_T}$$

Now setting $\left| \frac{i_c}{i_{bb}}(j\omega) \right| = 1$ we get

$$g_m r_a = \sqrt{1 + \omega_T^2 r_a^2 C_T^2}$$

or

$$\omega_T^2 = \frac{g_m^2 r_a^2 - 1}{r_a^2 C_T^2}$$

Usually $g_m^2 r_a^2 >> 1 \quad \Rightarrow \quad W_T \gg 1$$

or

$$\omega_T \approx \frac{g_m}{C_T} = \frac{B}{r_a (C_u + C_n)}$$

$$\Rightarrow \quad C_T = C_u + C_n$$

or

$$\frac{r_a}{C_T} \approx \frac{B}{2\pi r_a (C_u + C_n)}$$