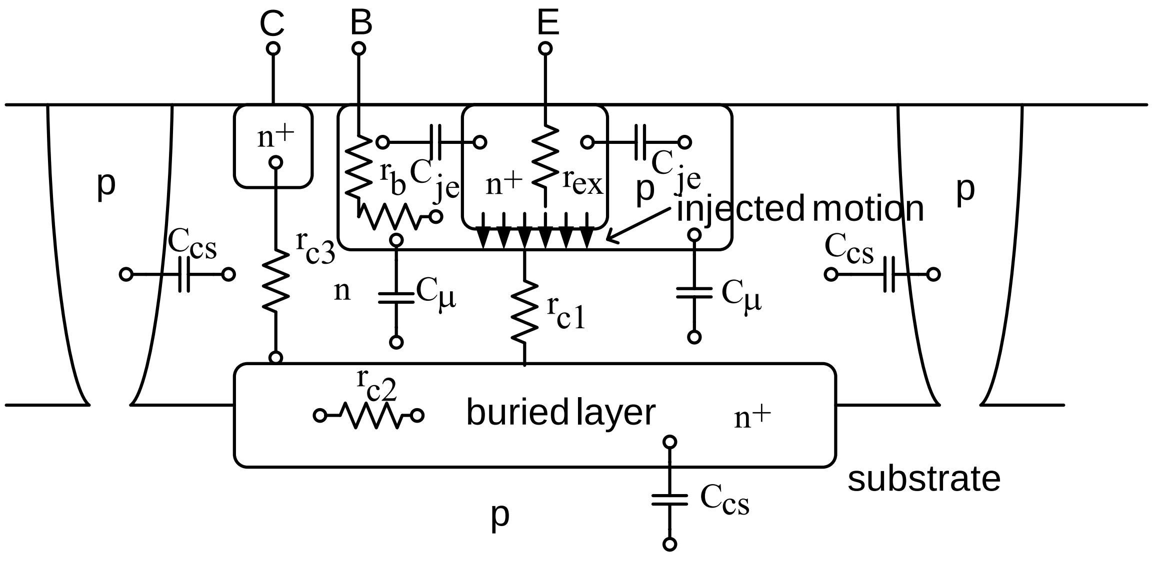
Cross-section of a typical npn transistor:



All pn junctions have a voltage-dependence capacitance associated with the depletion region.

C_{je} = depletion region capacitance at BE junction

C_μ = B-C junction capacitance

C_{cs} = C-substrate junction capacitance

B-E junction approximates abrupt junction due to the steep rise of doping density (E heavily doped). C-B junction behaves like a graded junction.

Since B-E junction closely approximates an abrupt junction:

$$C_{je} = \frac{C_{je0}}{\sqrt{1-\frac{V}{\Psi_0}}}$$

where C_{je0} = value of C_{je} when V = 0, typically 10 fF.

Ψ_0 = built in potential = $V_T \ln(N_A N_D / n_i^2)$

V = biasing voltage at the junction (+ve if fb and –ve if rb)

The C-B junction behaves like a graded junction for small bias voltages since the doping density is a function of distance near the junction. For larger rb values (> 1 V), the junction depletion region spreads into the C, which is uniformly doped, and thus for devices with thick collectors the junction tends to behave like an abrupt junction.

Practically, $C_\mu = \frac{C_{\mu 0}}{\left(1-\frac{V}{\Psi_0}\right)^n}$

$n = 0.2 \rightarrow 0.5$

$C_{\mu 0} = 10$ fF

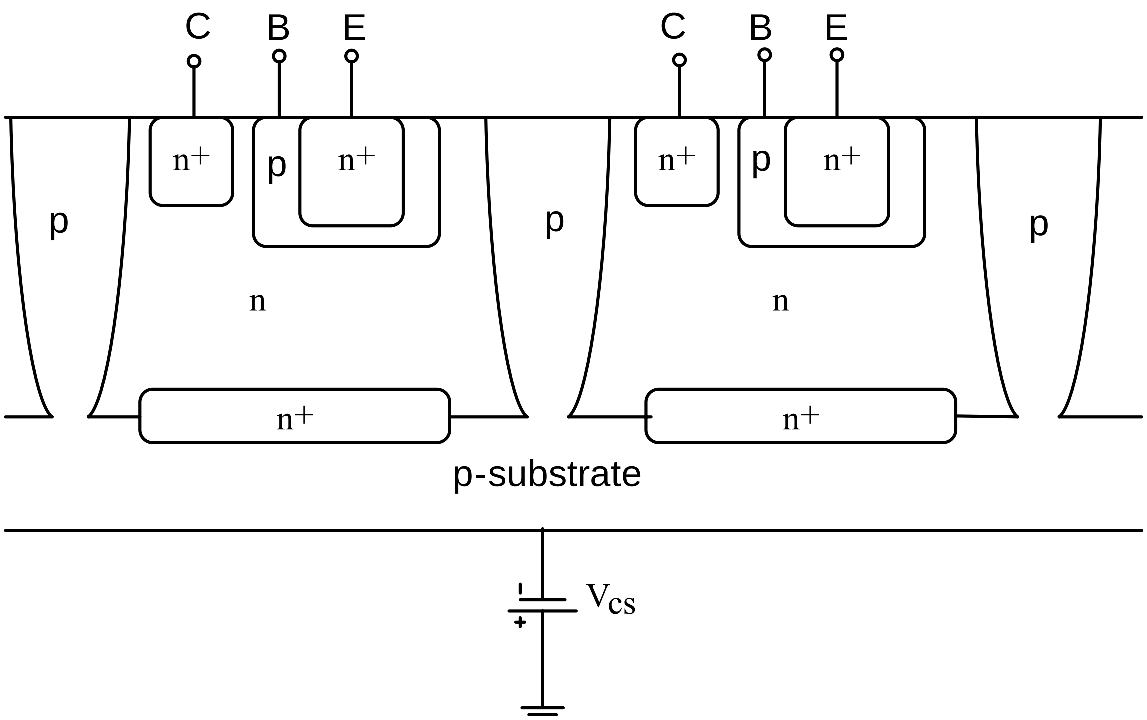
To determine C_{cs}, use the equation for the abrupt junction:

$$C_{cs} = \frac{C_{cs0}}{\sqrt{1 - \frac{V}{\Psi_0}}}$$ for large reverse bias voltage and junction isolated device.

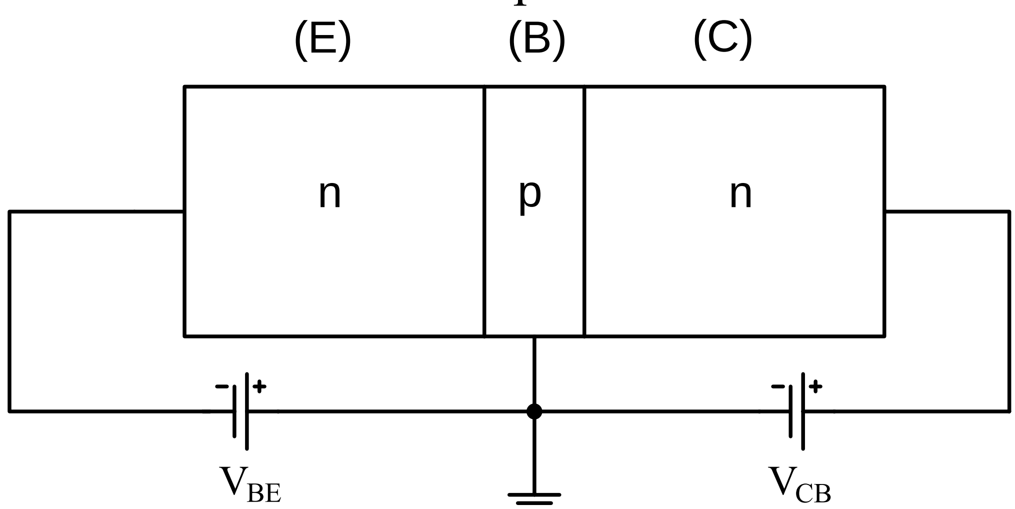
$$C_{cs} = \frac{C_{cs0}}{\left(1 - \frac{V}{\Psi_0}\right)^n}$$ for oxide isolated device, $n < 0.5$.

Typical C_{cs0} = 20 fF.

The zero-bias values of the parasitic capacitances (i.e. C_{je0}, $C_{\mu 0}$ and C_{cs0}) are for minimum size npn in a modern oxide-isolated process.

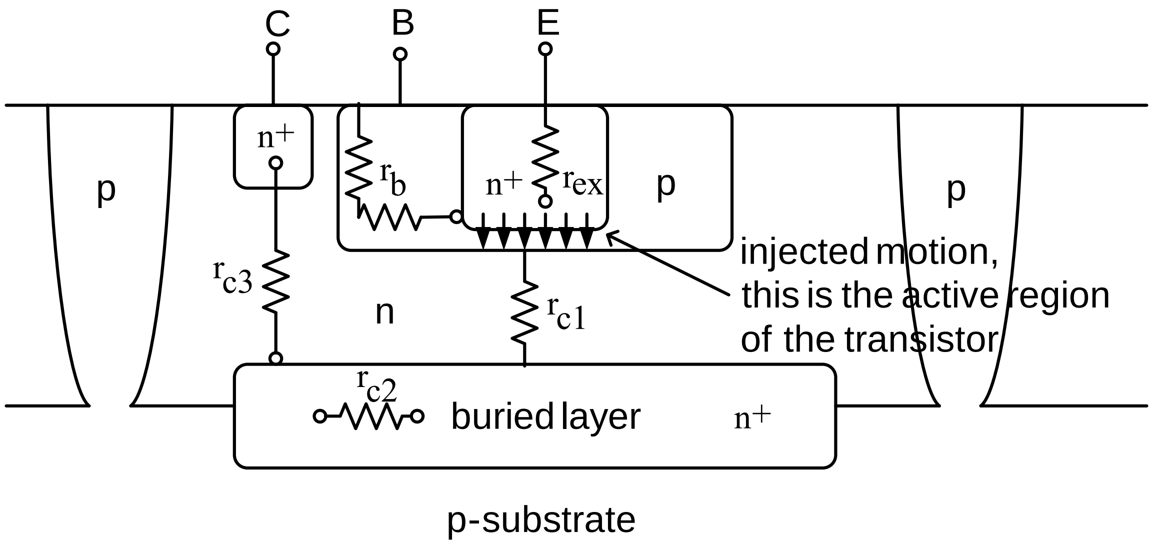


npn in the forward-active operation:



The substrate is always connected to the most negative voltage supply in the circuit in order to ensure that all isolation regions are separated by reverse biased junctions. Thus, the substrate is an ac-gnd, and all parasitic capacitances to the substrate is connected to gnd in the equivalent circuit.

Resistive parasitics



r_b: resistance between B top contact and active region beneath E, typically 50 → 500 Ω

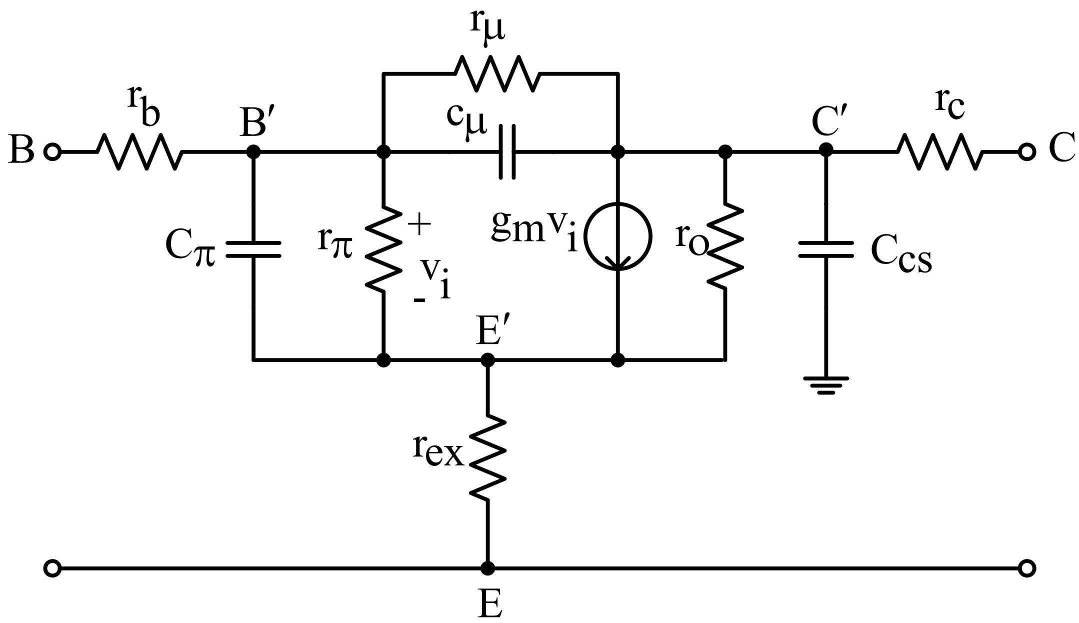
r_{ex}: resistance between E top contact and active region beneath E, typically 1 → 3 Ω

r_c : resistance between C top contact and active region beneath E, typically 20 → 500 Ω
$r_c = r_{c1} + r_{c2} + r_{c3}$

The value of these parasitic resistances can be reduced by changes in the device structure. A large-area transistor with multiple B and E stripes will have a smaller value of r_b. The value of r_c is reduced by the inclusion of the low-resistance buried n^+ layer beneath the C.

Parasitic resistances can be very important at high bias currents or for high-frequency of operation. For low-frequency calculations, especially for $I_C < 1$ mA, they are omitted from the equivalent circuit. (Try example problem on pg. 33).

Complete BJT small-signal equivalent circuit:



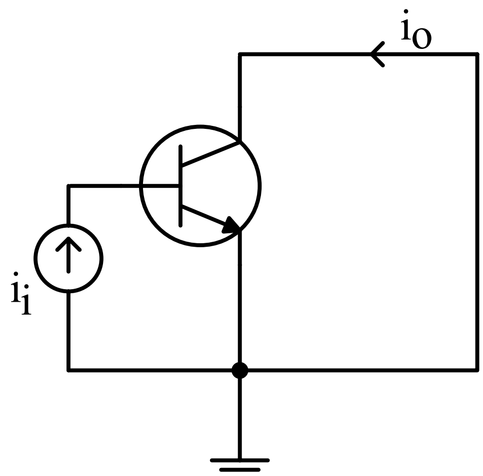
B′ = internal B node, C′ = internal C node, E′ = internal E node.
$C_\pi = C_b + C_{je}$ where C_b is the base charging and C_{je} is the depletion region capacitance at BE junction.
$C_b = \tau_F\, g_m$ where τ_F is the B transit time in the forward direction or the average time per carrier spent in crossing the B. g_m is the transconductance of the transistor.

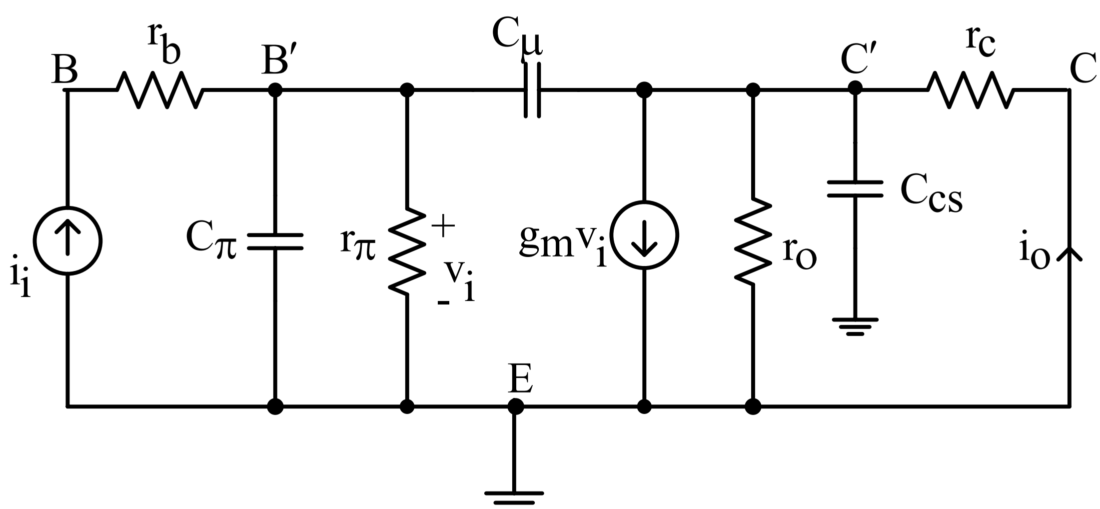
The high-frequency gain of the transistor is controlled by the capacitive elements in the equivalent circuit. The frequency capability of the transistor is most often specified in practice by determining the frequency where the magnitude of the s/c common E current gain falls to unity. This frequency is called the transition frequency, f_T.

1.4.8 Specification of transistor frequency response (pg. 34)

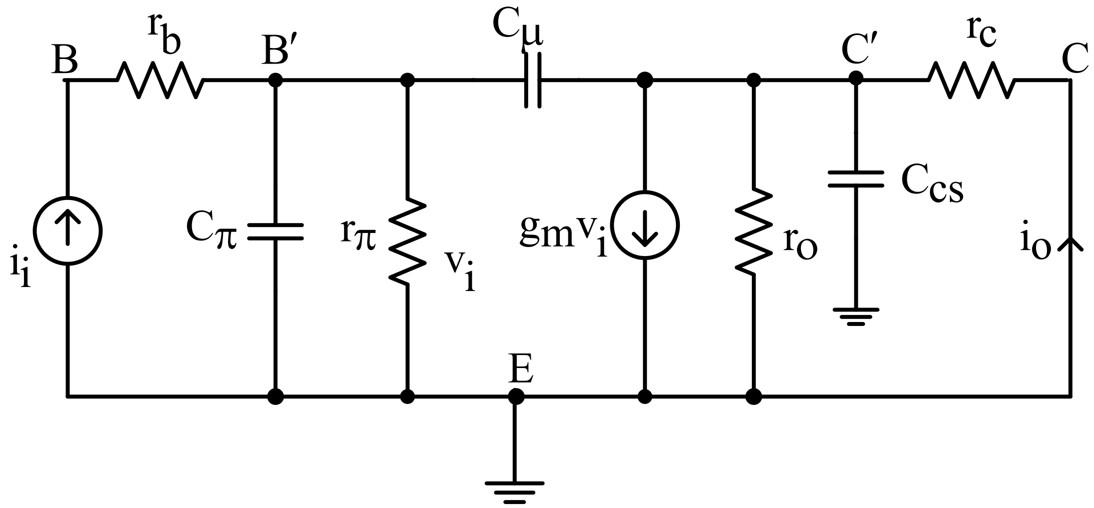
f_T is a measure of the maximum useful frequency of the transistor when it is used as an amplifier.

To measure f_T:

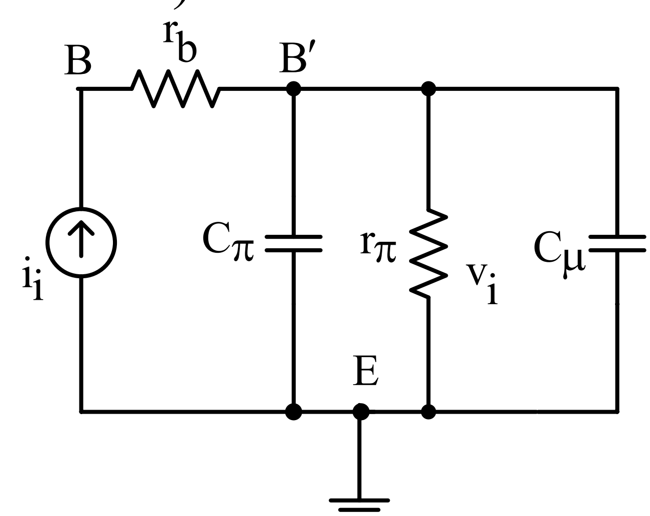




r_π = input resistance
C_μ = B-C capacitance
r_o = output resistance



r_{ex} and C-B resistance, r_μ, are ignored ($r_{ex} \approx 0$ as $r_{ex} = 1 \rightarrow 3\ \Omega$ and $r_\mu \approx \infty$ as $r_\mu = 10\beta_o r_o$). If r_c is assumed small (for simplicity) then r_o and C_{cs} have no influence).

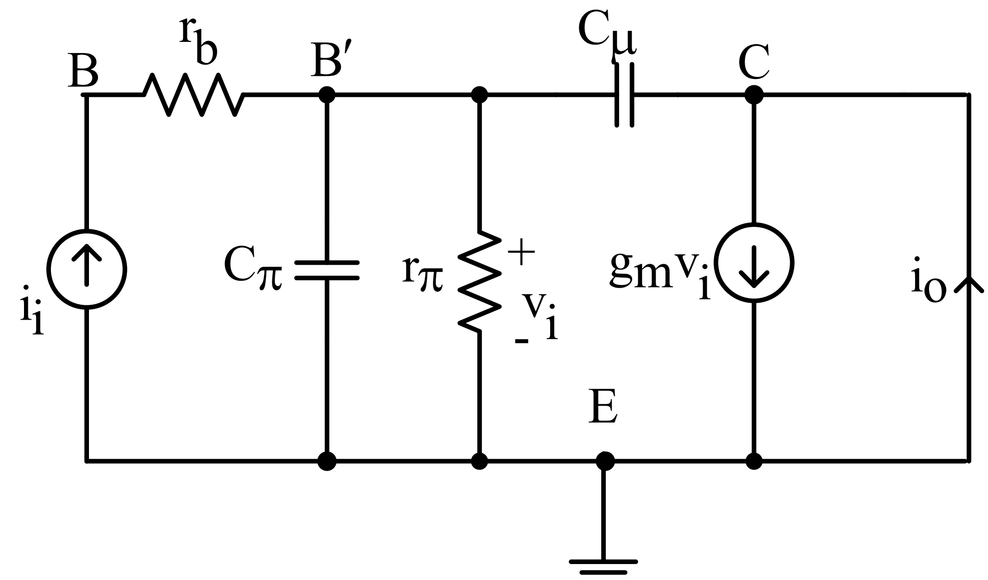


$Z_B{}' = (C_\pi + C_\mu) \,//\, r_\pi$

$C_T = C_\pi + C_\mu$

$$Z_{B'} = \frac{\frac{1}{sC_T} \times r_\pi}{\frac{1}{sC_T} + r_\pi} = \frac{r_\pi}{\left(1 + sC_T r_\pi\right)}, \quad v_i = \frac{r_\pi i_i}{1 + sC_T r_\pi}$$

$$v_i = \frac{r_\pi i_i}{1+sC_T r_\pi} \qquad (1.119)$$



Capacitance, C=Aε/d where A is the plate area, ε is the permittivity of the dielectric material and d is the distance between the plates. For the rb C-B junction, d is ↑. So, C_μ↓. Hence, $X_{C\mu}$ = ↑. Therefore, the current through the B-C junction capacitance C_μ can be neglected (i.e. it acts like an o/c).

$$i_o = g_m v_i \qquad (1.120)$$

Substituting (1.120) into (1.119):

$$\frac{i_o}{g_m} = \frac{r_\pi i_i}{1+sC_T r_\pi}$$

$$\frac{i_o}{g_m} = \frac{r_\pi i_i}{1 + sC_T r_\pi}$$

$$\frac{i_o}{i_i} = \frac{g_m r_\pi}{1 + sC_T r_\pi} = \frac{\beta_o}{1 + sC_T r_\pi} \text{ since } \beta_o = g_m r_\pi$$

$$\frac{i_o}{i_i}(j\omega) = \frac{\beta_o}{1 + j\omega C_T \frac{\beta_o}{g_m}}$$

If $\frac{i_o}{i_i} = \beta$, then $\beta(j\omega) = \dfrac{\beta_o}{1 + j\omega\left(C_\pi + C_\mu\right)\frac{\beta_o}{g_m}}$ (1.122)

where $\beta(j\omega)$ = high-frequency small-signal current gain

At high frequencies, the imaginary part of the denominator is dominant,

$$\beta(j\omega) = \frac{\beta_o}{j\omega\left(C_\pi + C_\mu\right)\frac{\beta_o}{g_m}} = \frac{g_m}{j\omega\left(C_\pi + C_\mu\right)} \tag{1.123}$$

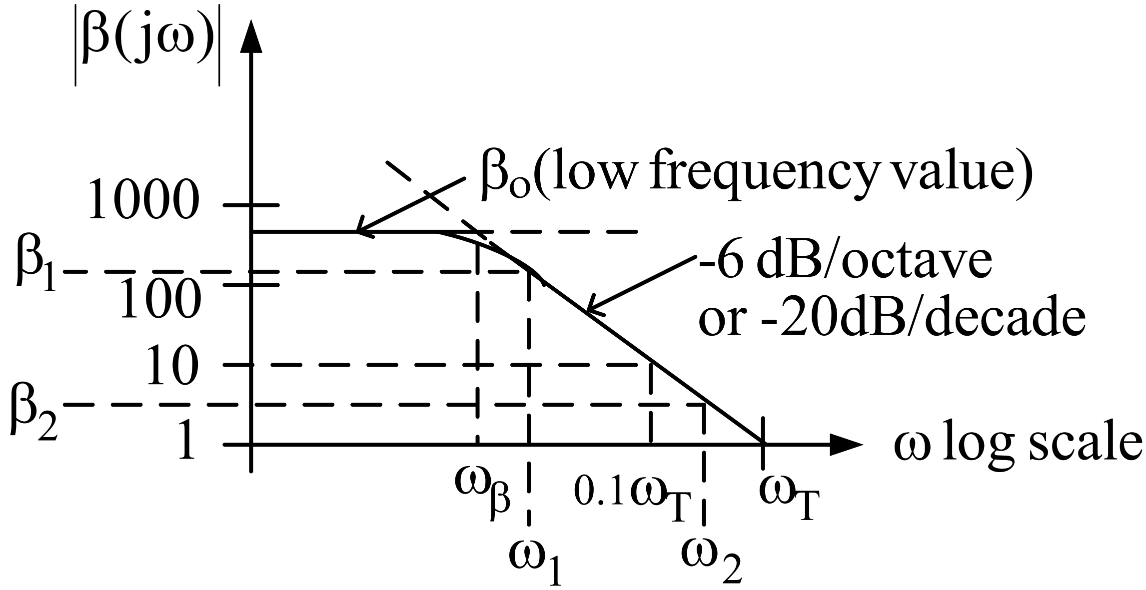
$$\left|\beta(j\omega)\right| = \frac{g_m}{\omega\left(C_\pi + C_\mu\right)}$$

When $\left|\beta(j\omega)\right|=1$ then $\dfrac{g_m}{\omega\left(C_\pi+C_\mu\right)}=1$

$$\omega=\frac{g_m}{\left(C_\pi+C_\mu\right)}=\omega_T$$

Hence, unity-gain frequency f_T :

$$f_T=\frac{g_m}{2\pi\left(C_\pi+C_\mu\right)}$$



ω_β is defined as the frequency where $\left|\beta(j\omega)\right|=\dfrac{\beta_o}{\sqrt{2}}$ or 3 dB down from the low frequency value.