HBTs: high-frequency attributes

LECTURE 17

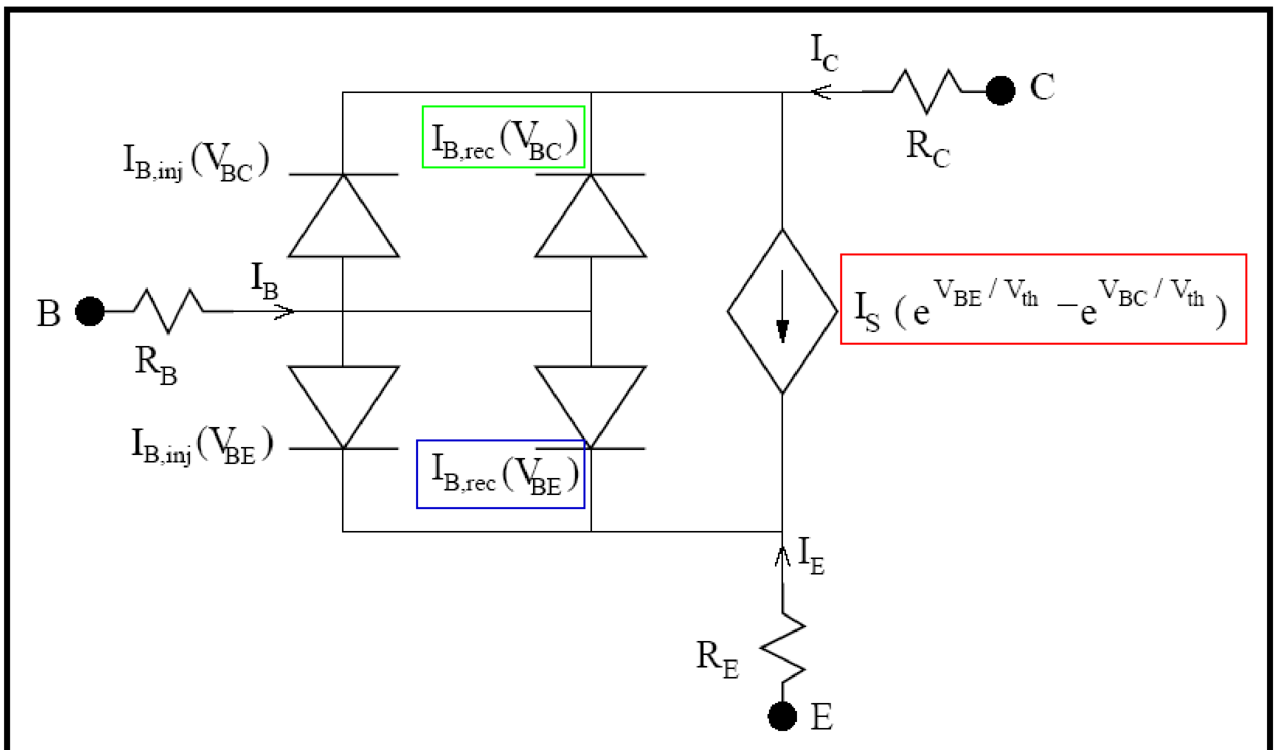
- Recapitulation of equivalent circuits
- Two components of Emitter-Base capacitance
- Figures of merit
- f_T: definition and derivation
- Design for high f_T
- f_{max}: definition and derivation
- Design for high f_{max}

Sec. 9.4

DC Equivalent circuit

$$J_e = -qn_{0B}\left[e^{qV_{BE}/kT} - e^{qV_{BC}/kT}\right]\left[\frac{W_B}{D_e} + \frac{1}{v_R}\right]^{-1}$$

$$I_{B,\text{rec}} = Aqn_{0B}\left[\left(e^{V_{BE}/V_{\text{th}}} - 1\right) + \left(e^{V_{BC}/V_{\text{th}}} - 1\right)\right]\left\{\frac{1}{\frac{2\tau_e}{W_B} + \frac{1}{2v_R}}\right\}$$



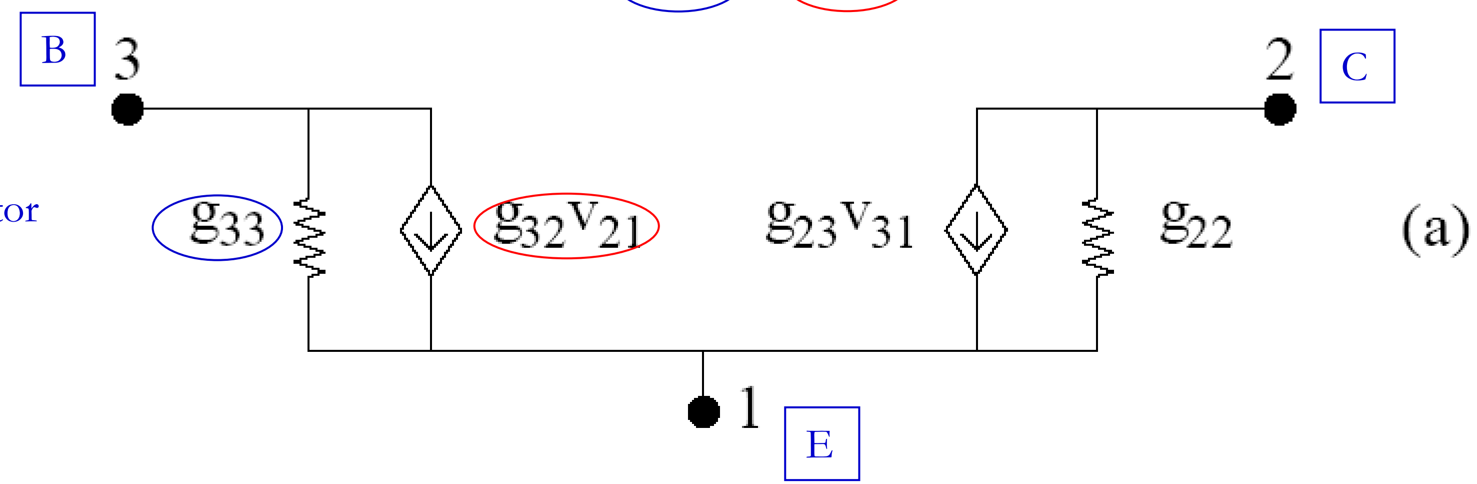
Sec. 14.2

AC small-signal equivalent circuit

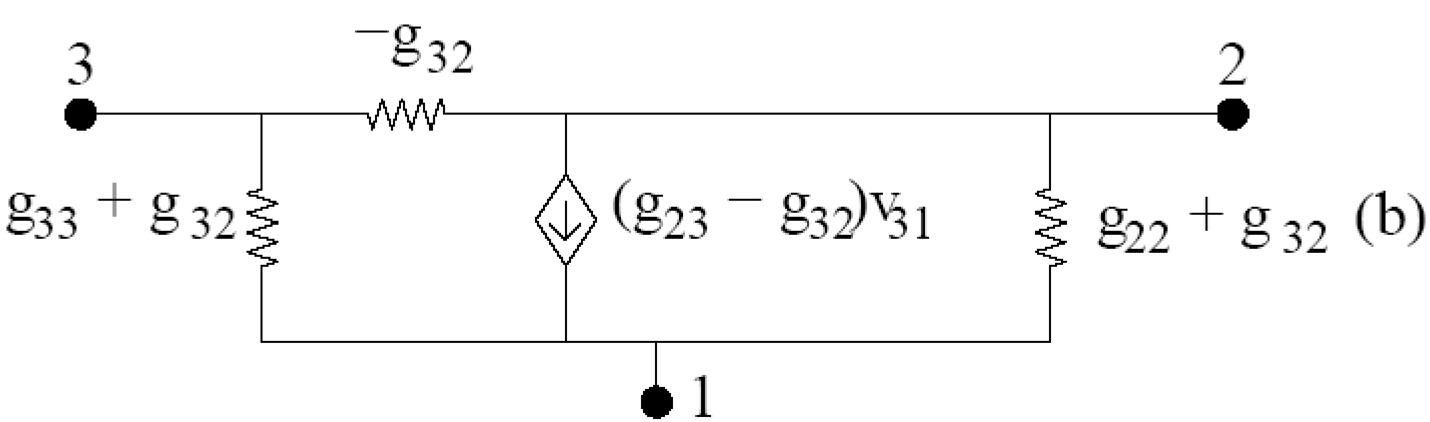
small-signal base current

$$i_3 = \frac{\partial I_3}{\partial V_{31}} v_{31} + \frac{\partial I_3}{\partial V_{21}} v_{21} = g_{33} v_{31} + g_{32} v_{21} \, ,$$

2-generator circuit



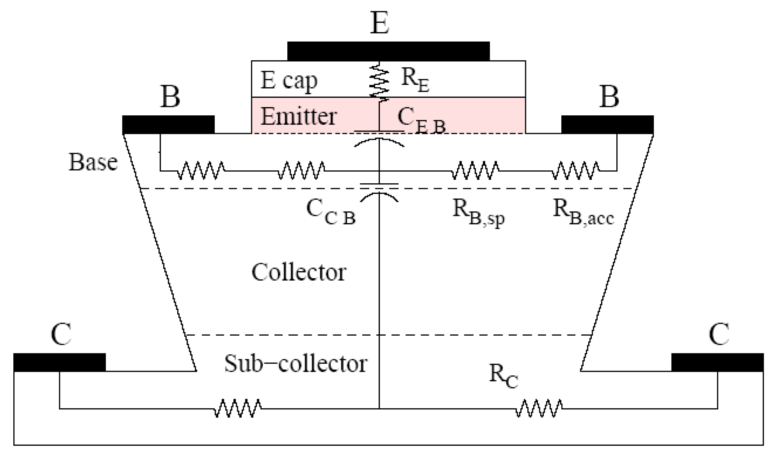
1-generator circuit



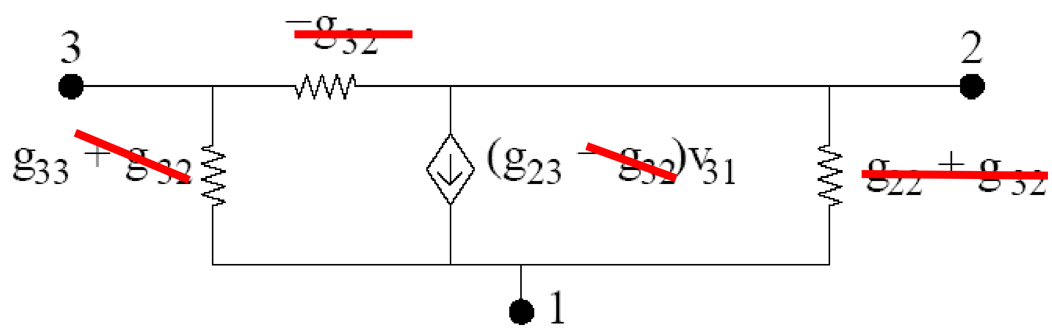
Sec. 14.3

Hybrid-π equivalent circuit

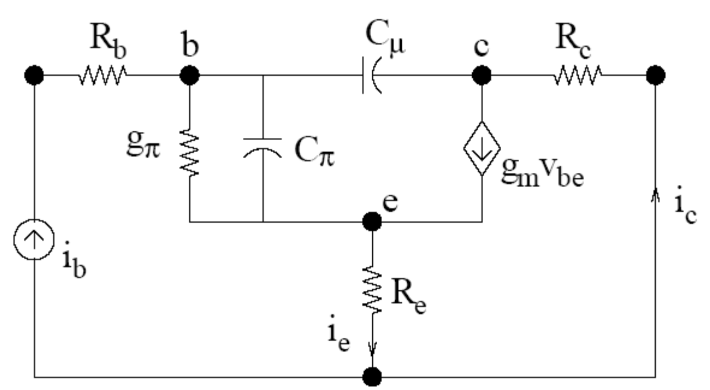
HBT with parasitic R's and C's identified



Omit small-value components



Hybrid-π equivalent circuit under AC short-circuit at the output.



$g_\pi \equiv g_{33}$

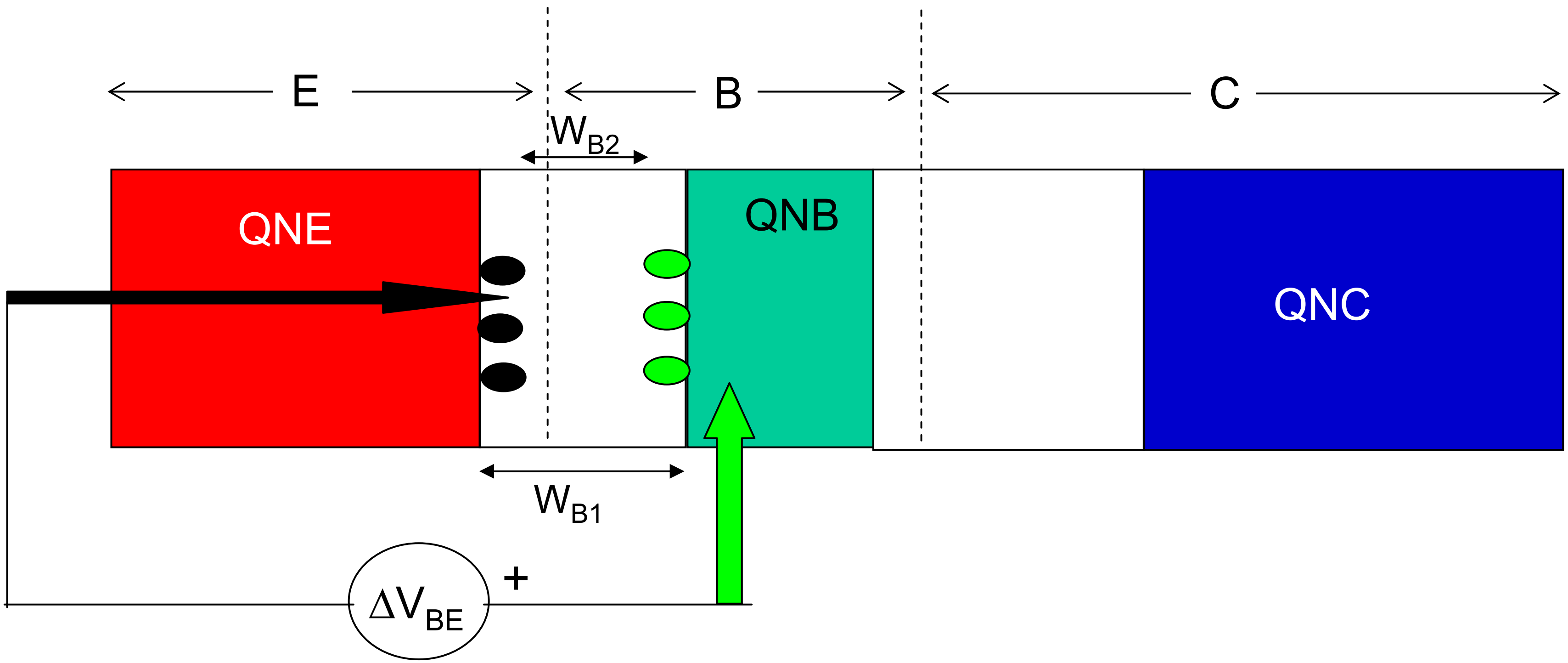
$g_m \equiv g_{23}$

$C_\pi \equiv C_{EB}$

$C_\mu \equiv C_{CB}$

Sec. 12.3.1

Emitter-base junction-storage capacitance



$C_{EB,j} =$ [ ]

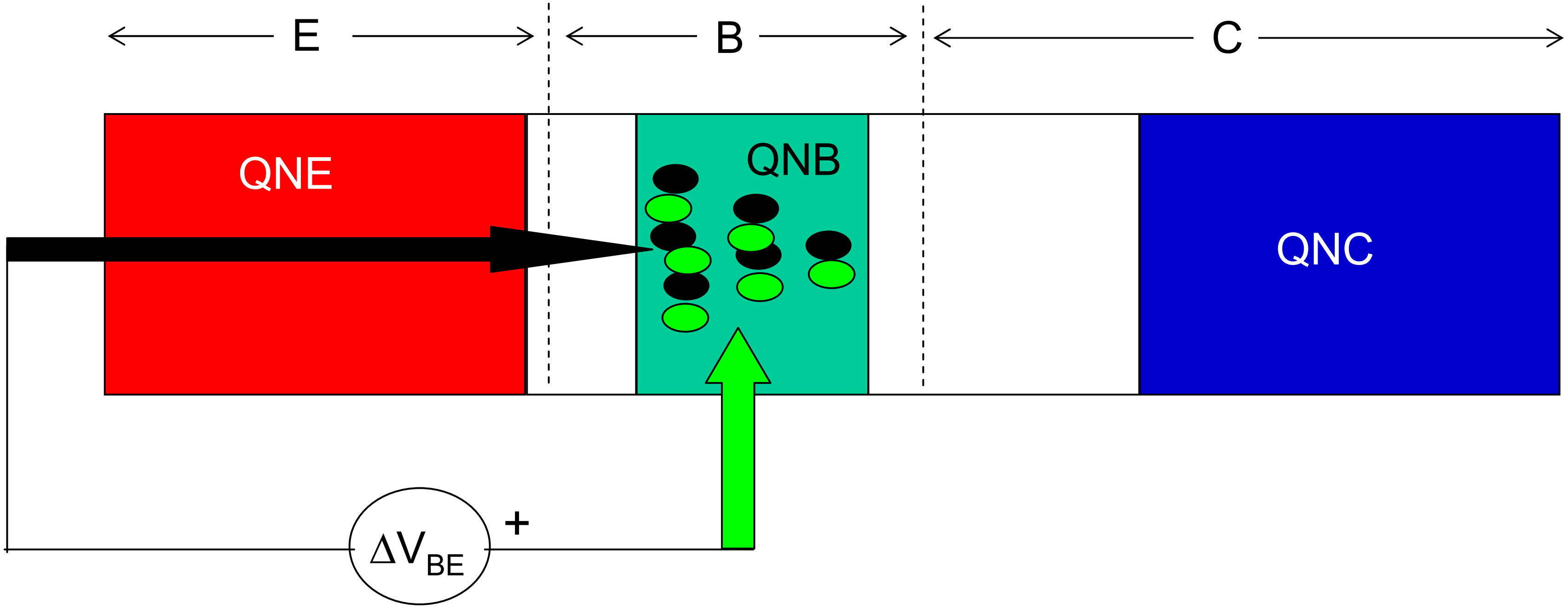
$C_{EB,j} \equiv$ [ ]

- $\Delta Q_{E,j}$ is the change in charge entering the device through the emitter and creating the new width of the depletion layer (narrowing it in this example),
- in response to a change in V_{BE} (with E & C at AC ground).
- It can be regarded as a parallel-plate cap.

What is the voltage dependence of this cap?

Sec. 12.3.2

Emitter-base base-storage capacitance: concept

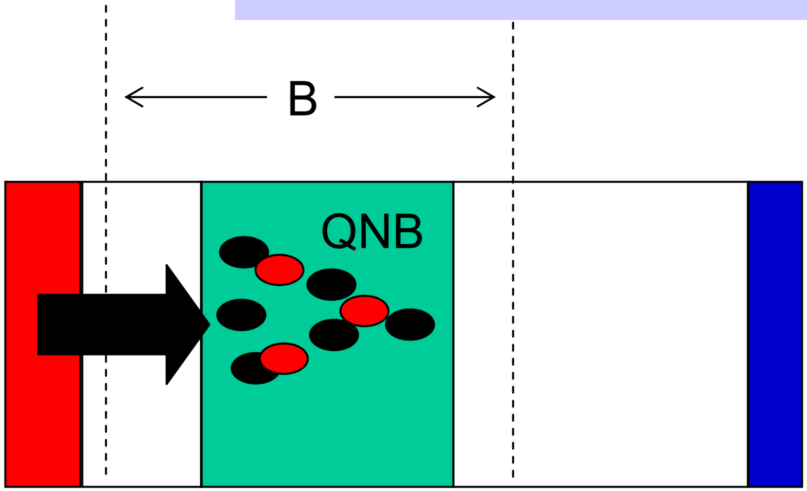


$$C_{EB,b} = -\boxed{}$$

- $\Delta Q_{E,b}$ is the change in charge entering the device through the emitter and resting in the base (the black electrons),
- in response to a change in V_{BE} (with E & C at AC ground).
- It's not a parallel-plate cap, and we only count one carrier.

Sec. 12.3.2

Emitter-base base-storage capacitance: evaluation



$$Q_{E,b}(V_{BE}) = -q\frac{1}{2}W_B A\left[n_{0p}\exp(\frac{V_{BE}}{V_{th}}) - n(W_B)\right] - qW_B A n(W_B)$$

Take $\frac{\Delta Q_{E,b}}{\Delta V_{BE}} \rightarrow \frac{dQ_{E,b}}{dV_{BE}}$

Hence $C_{EB,b}$

$$n(0,V_{BE1}) = n_{0p}\exp(V_{BE1}/V_{th})$$

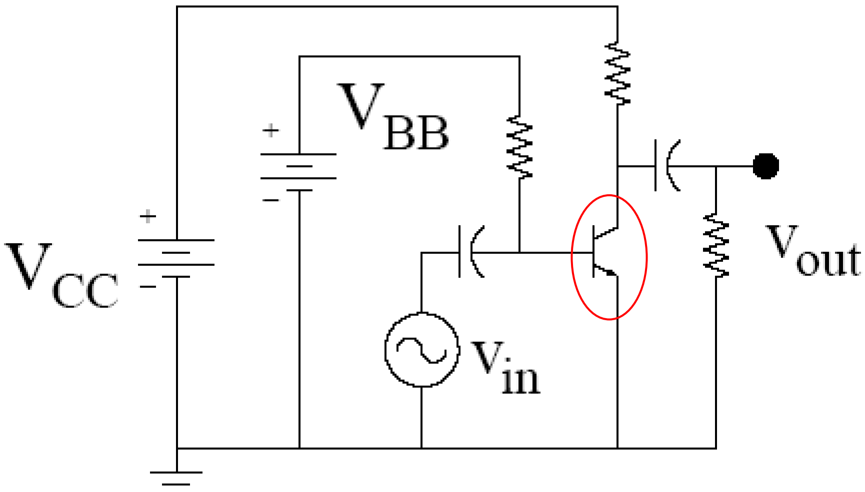
$$n(0,V_{BE,2}) = n_{0p}\exp(V_{BE2}/V_{th})$$

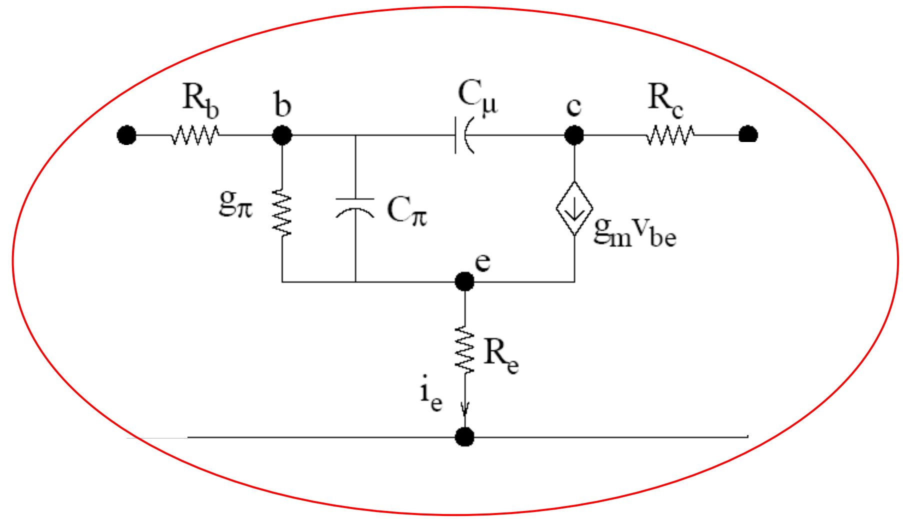
What is the voltage dependence of $C_{EB,b}$?

Sec. 14.2

HF figures of merit

Represent transistor by its small-signal equivalent circuit





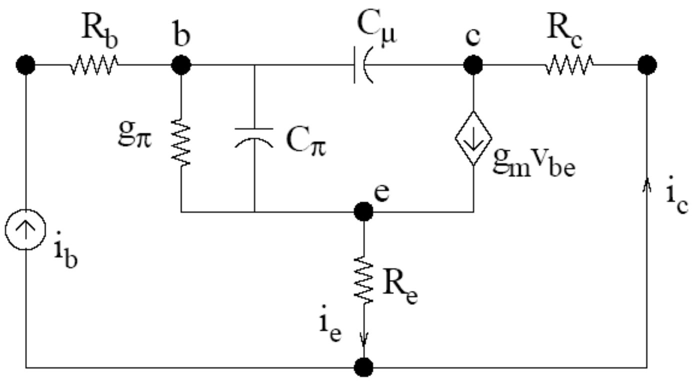
Consider frequency dependence of some current gain

Consider frequency dependence of some power gain

What are the associated figures of merit?

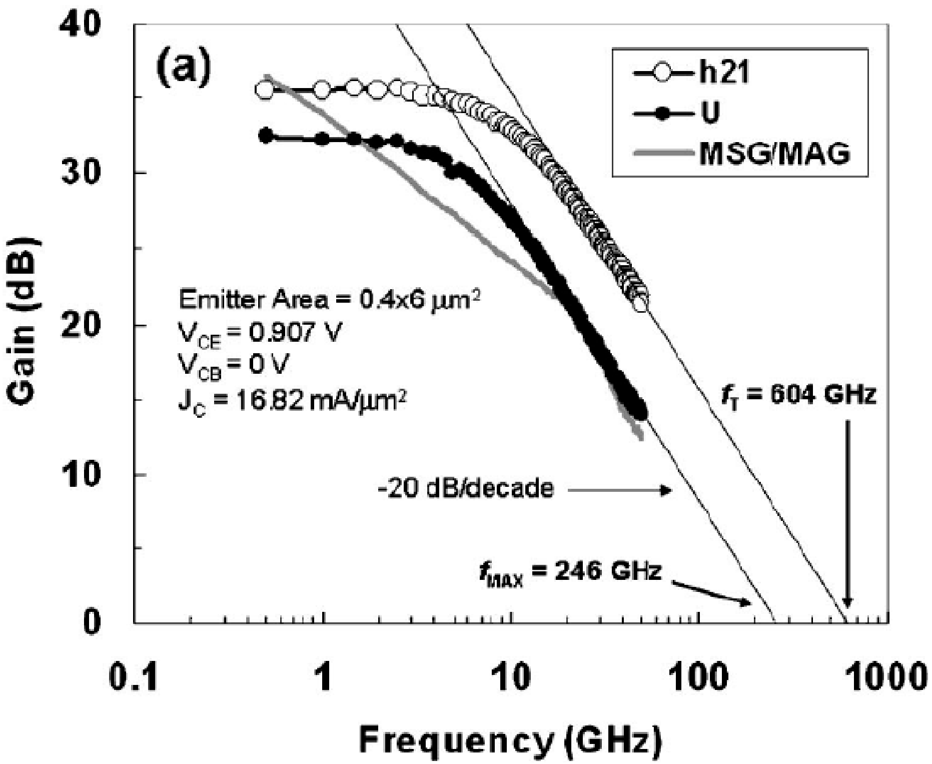
Sec. 14.4

f_T from hybrid-pi equivalent circuit



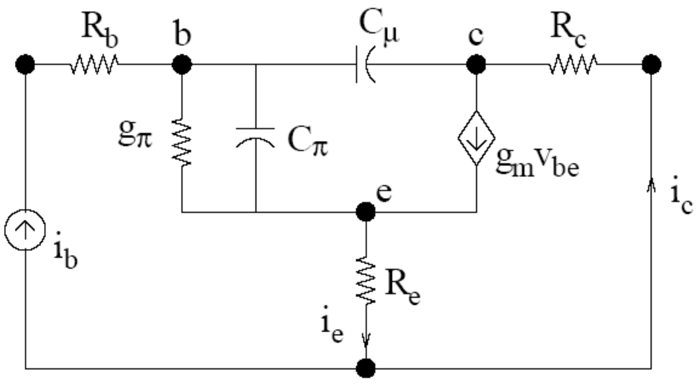
- f_T is measured under AC short-circuit conditions.

- We seek a solution for $|ic/ib|^2$ that has a single-pole roll-off with frequency.
- Why?
- Because we wish to extrapolate at -20 dB/decade to unity gain.



Sec. 14.4

Extrapolated f_T



- Assumption: $$i_b R_e \ll i_c(R_e + R_c)$$

- Conditions: $$\omega^2 \ll \frac{g_m^2}{C_\mu^2}$$

$$\omega^2 \ll \frac{1}{C_\mu^2 R_{ec}^2} \qquad \omega^2 \gg \frac{g_\pi^2}{\left(C_\pi + C_\mu(1 + R_{ec} g_m)\right)^2}$$

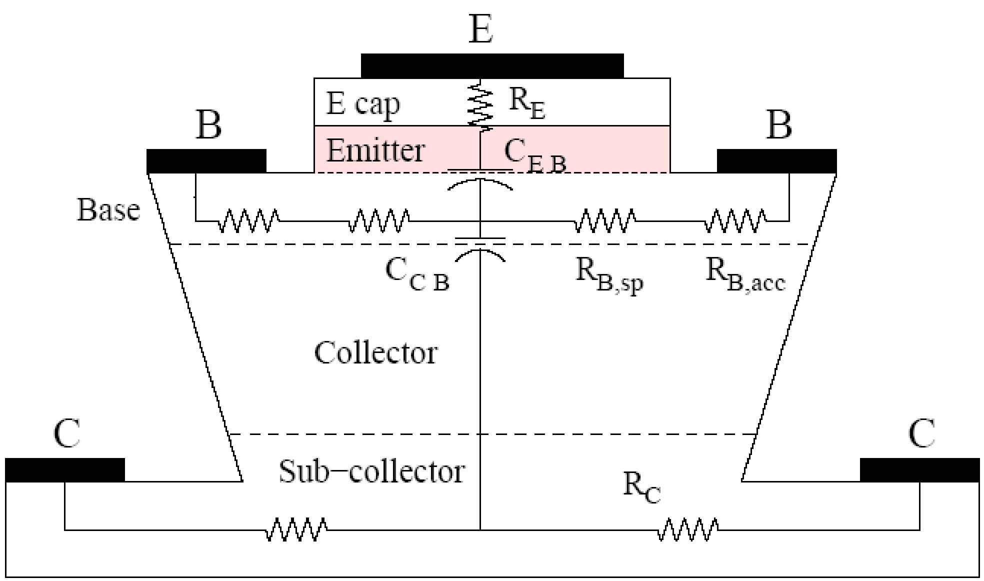
- Current gain: $$\left|\frac{i_c}{i_b}\right|^2 = \frac{g_m^2}{\omega^2 (C_\pi + C_\mu(1 + g_m R_{ec}))^2}$$

- Extrapolated f_T: $$2\pi f_T =$$

Sec. 14.5

Improving f_T

$$2\pi f_T = \frac{g_m}{C_\pi + C_\mu(1 + g_m R_{ec})}$$



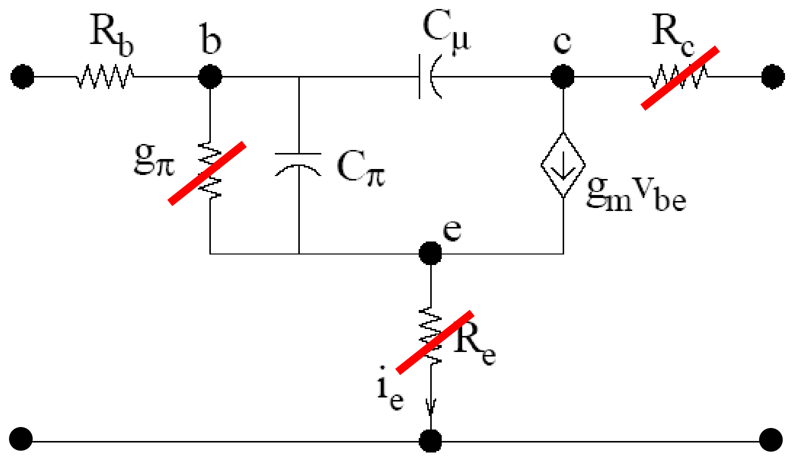
- III-V for high g_m
- Highly doped sub-collector and supra-emitter to reduce R_{ec}
- Dual contacts to reduce R_c and R_B
- Lateral shrinking to reduce C's

What is required to get f_T > 200 GHz ?

Sec. 14.6

Circuit for derivation of f_{max}

Justify these omissions



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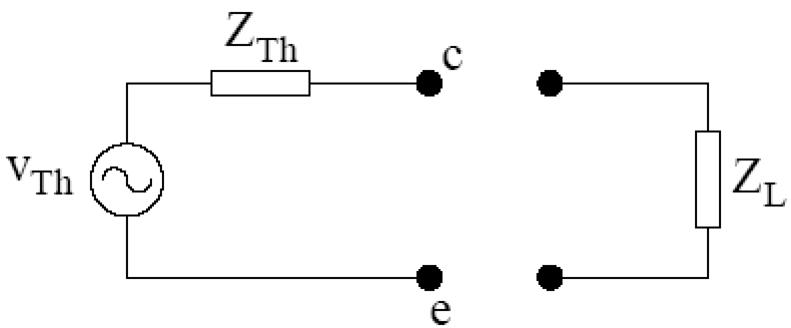
Model with Thévenin equivalent circuit

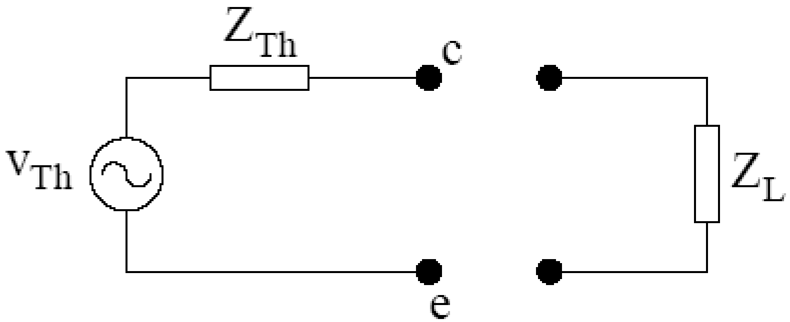


$$v_{\mathrm{Th}} = v_{in} \frac{j\omega C_\mu - g_m}{j\omega C_\mu (1 + g_m R_b) - \omega^2 C_\mu C_\pi R_b}$$

$$Z_{\mathrm{Th}} = \frac{R_b^{-1} + j\omega C_T}{j\omega C_\mu (g_m + R_b^{-1}) - \omega^2 C_\mu C_\pi},$$

Sec. 14.6

Developing an expression for f_{max}



Further conditions:

$$\omega^2 \ll \frac{g_m^2}{C_\mu^2} \qquad \omega^2 \gg \frac{g_\pi^2}{C_\pi^2}$$

$$\omega^2 \ll \frac{g_m^2}{C_\pi^2} \qquad \omega^2 \ll \frac{(g_m + R_b^{-1})^2}{C_\pi^2}$$

Conjugately match at the output

$$\Re(Z_{\rm Th}) \approx \frac{C_T}{C_\mu g_m} \qquad P_{\rm out,max} = \frac{|v_{\rm Th}|^2}{4\Re(Z_L)} \approx \frac{|v_{\rm in}|^2}{4R_b^2}\frac{g_m}{\omega^2 C_\mu C_T}$$

Conjugately match at the input

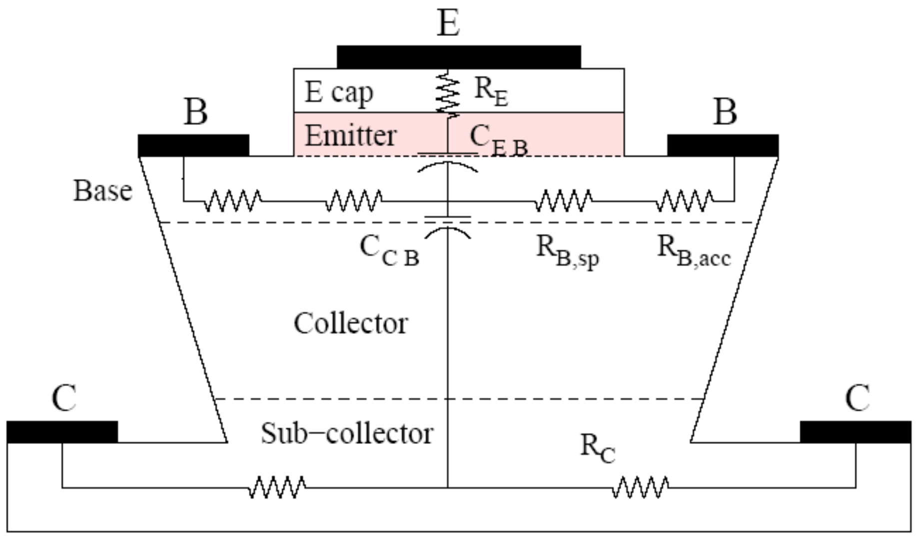
$$P_{\rm in,max} = \frac{|v_S|^2}{4\Re(Z_{\rm in})} = \frac{|v_{\rm in}|^2}{R_b}$$

Sec. 14.6

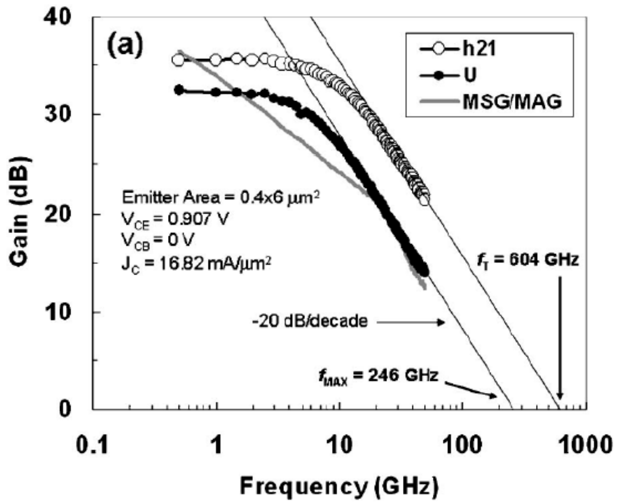
Improving f_{max}

$$\mathrm{MAG} = \frac{P_{\mathrm{out,max}}}{P_{\mathrm{in,max}}} = \frac{g_m}{4\omega^2 C_\mu C_T R_b}$$

$$f_{\max} = \sqrt{\frac{f_{\mathrm{T,i}}}{8\pi C_\mu R_b}}$$

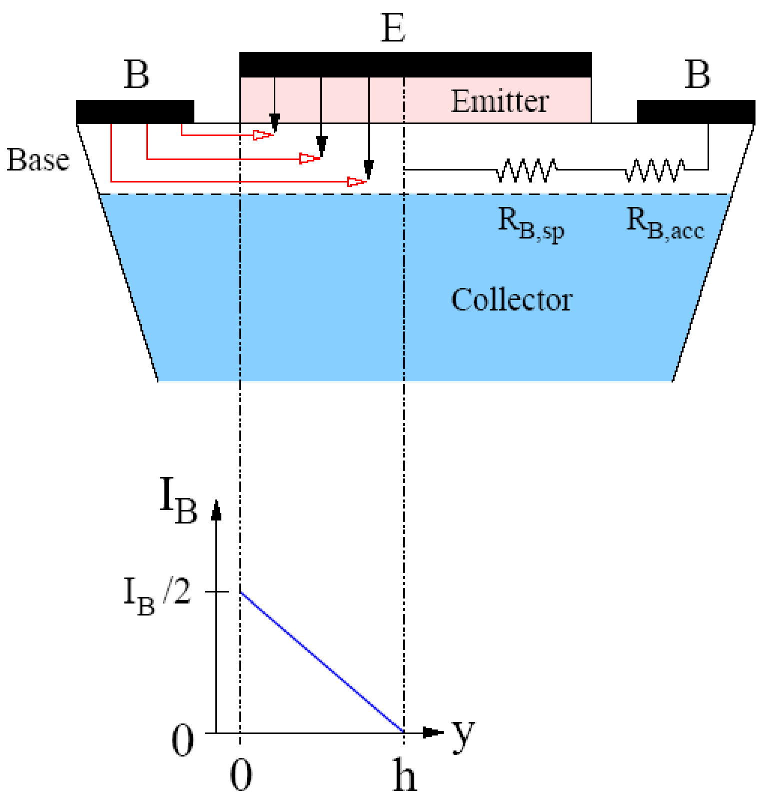


• Pay even more attention to R_b and C_μ



Sec. 14.6.1

Base-spreading resistance



$$P_{\text{left}}(y) = I_B(y)^2 R$$

$$P_{\text{left}} = \int_0^h \frac{I_B^2}{4}\left(1-\frac{y}{h}\right)^2 \frac{\rho\, dy}{A}$$

What is rho?

$$P = \frac{I_B^2}{12} R_{B,QNB} \equiv I_B^2 R_{B,sp}$$

What is $R_{B,QNB}$?

Do you now see why HBTs have helped enable portable wireless products?

What is required to get f_{max} > 300 GHz ?