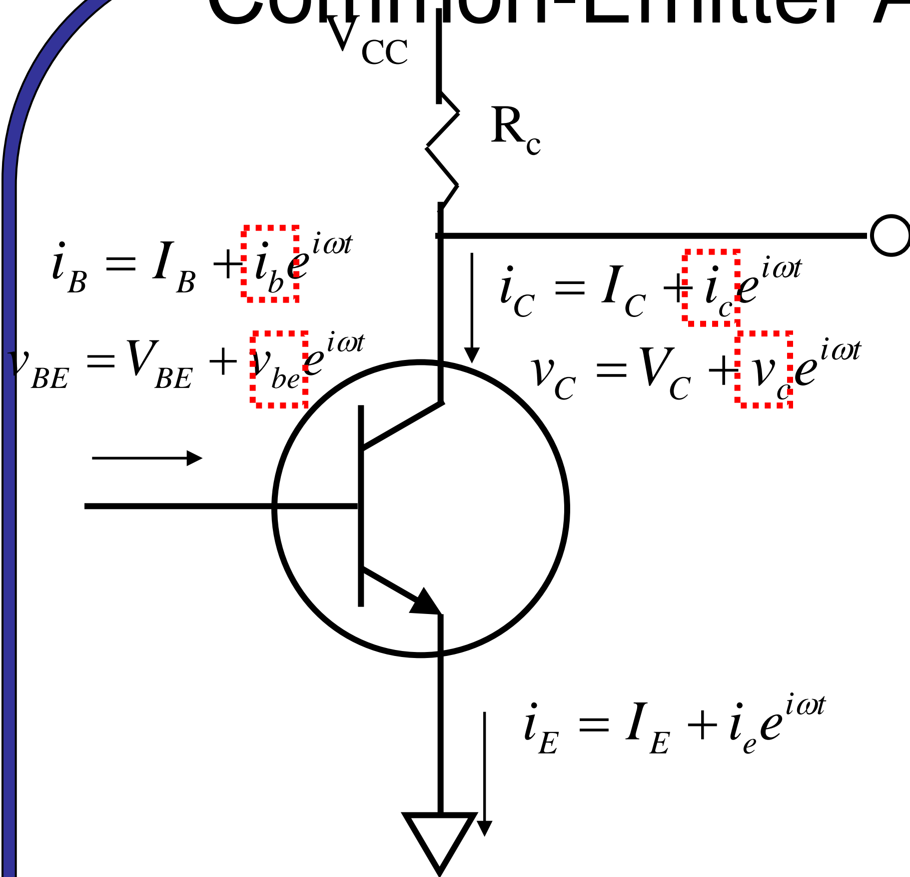
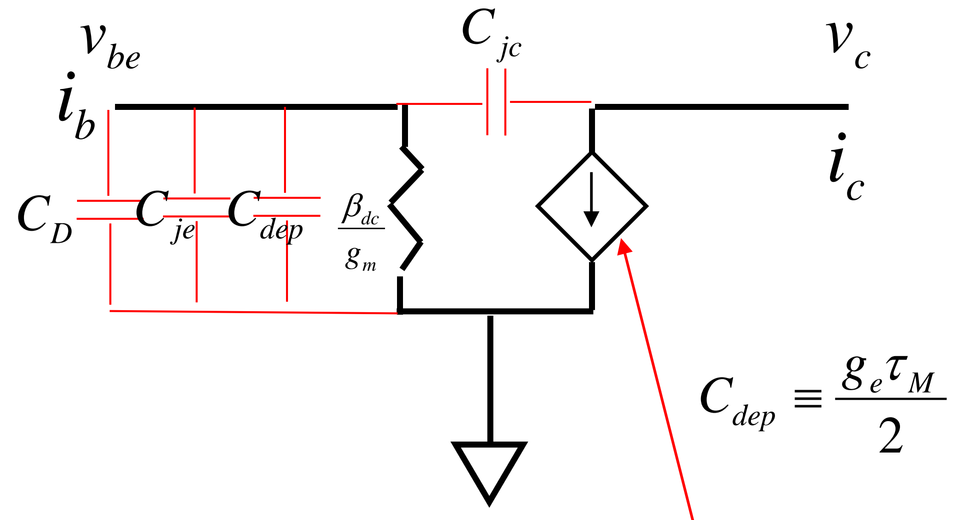
Lecture 6:
HBT parasitics
f_T, f_{max}

Common-Emitter AC equivalent circuit:



Hybrid π model:

Red is new for ac:



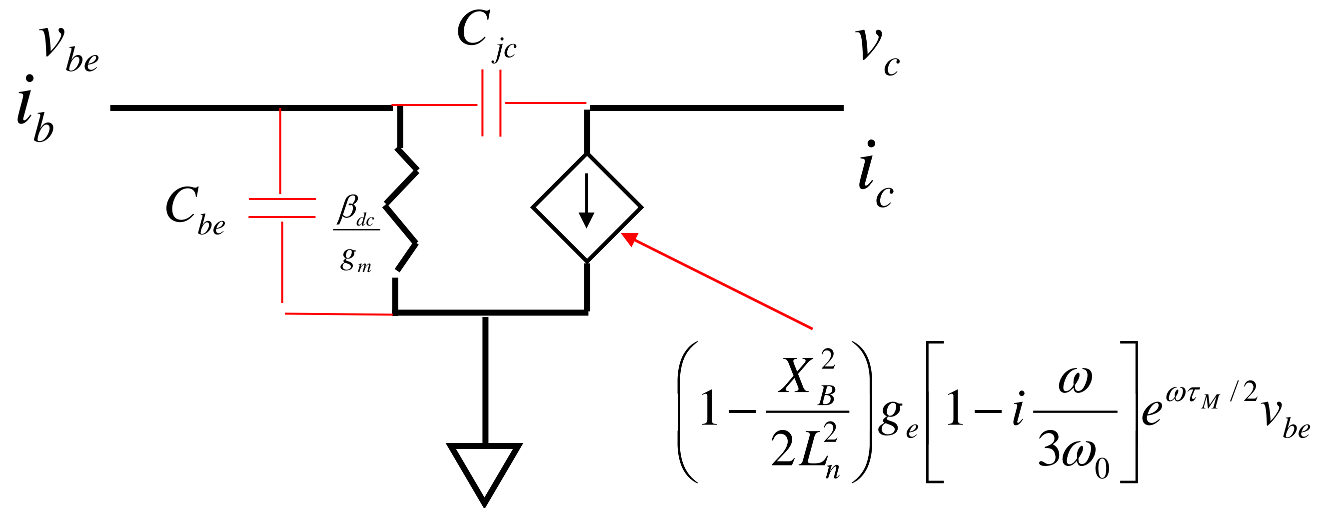
$$C_{dep} \equiv \frac{g_e \tau_M}{2}$$

$$\left(1 - \frac{X_B^2}{2L_n^2}\right) g_e \left[1 - i\frac{\omega}{3\omega_0}\right] e^{\omega\tau_M/2} v_{be}$$

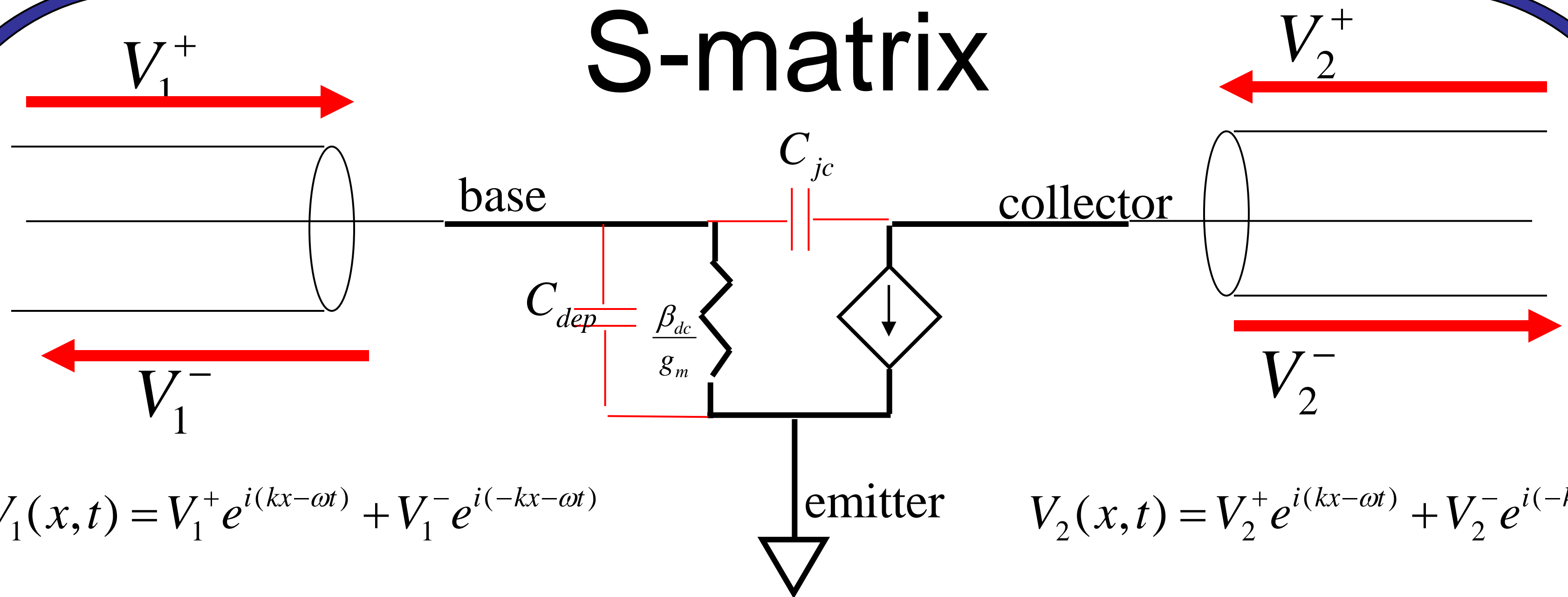
- Circuit model good only for low frequencies
- At high frequencies computer must be used!

Hybrid π model:

simplified:



S-matrix



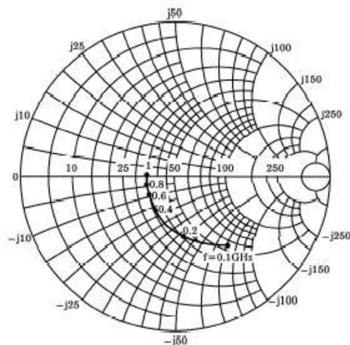
$$\begin{pmatrix} V_1^- \\ V_2^- \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} V_1^+ \\ V_2^+ \end{pmatrix}$$

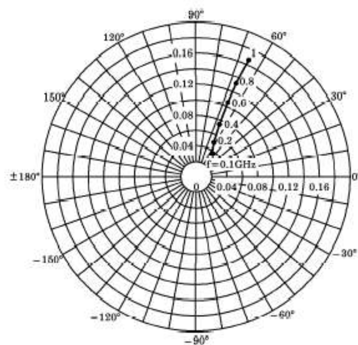
$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+$$

$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+$$

S-parameters

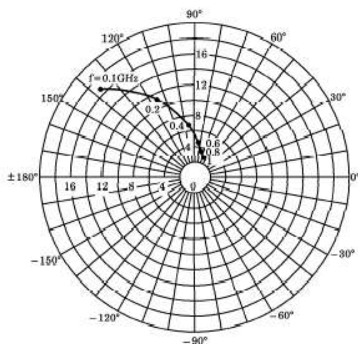
TOSHIBA 2SA1245

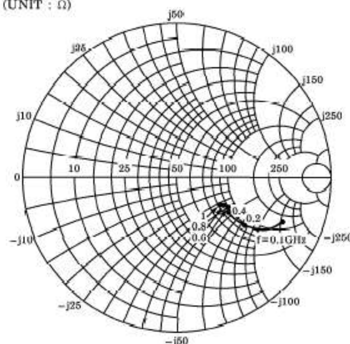




TOSHIBA 2SA1245 (data sheet charts)

This is what you see on data sheets.
Related to input impedance, output impedance and gain vs. frequency.
=> Need to discuss ac performance.



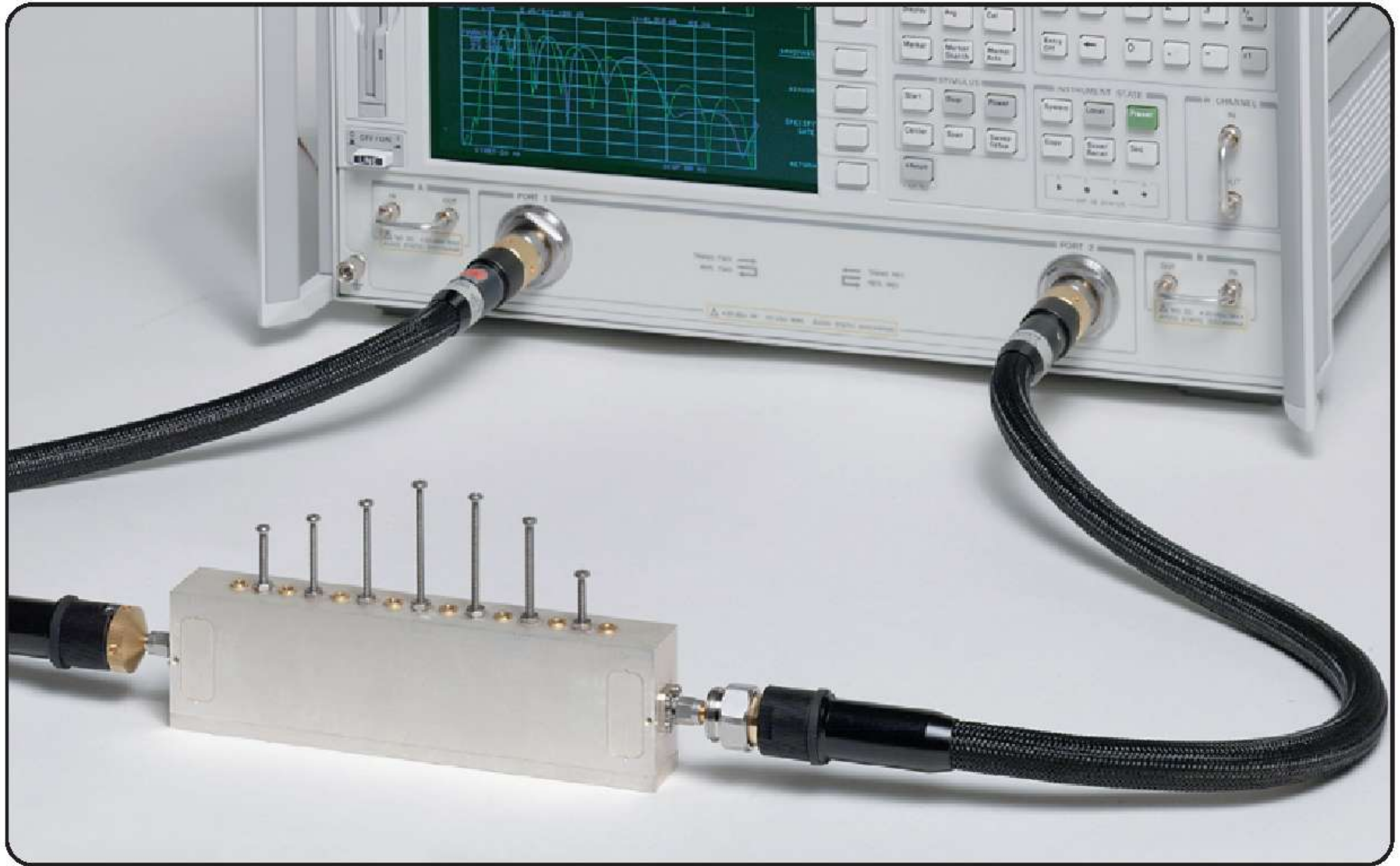


Summary of parameters

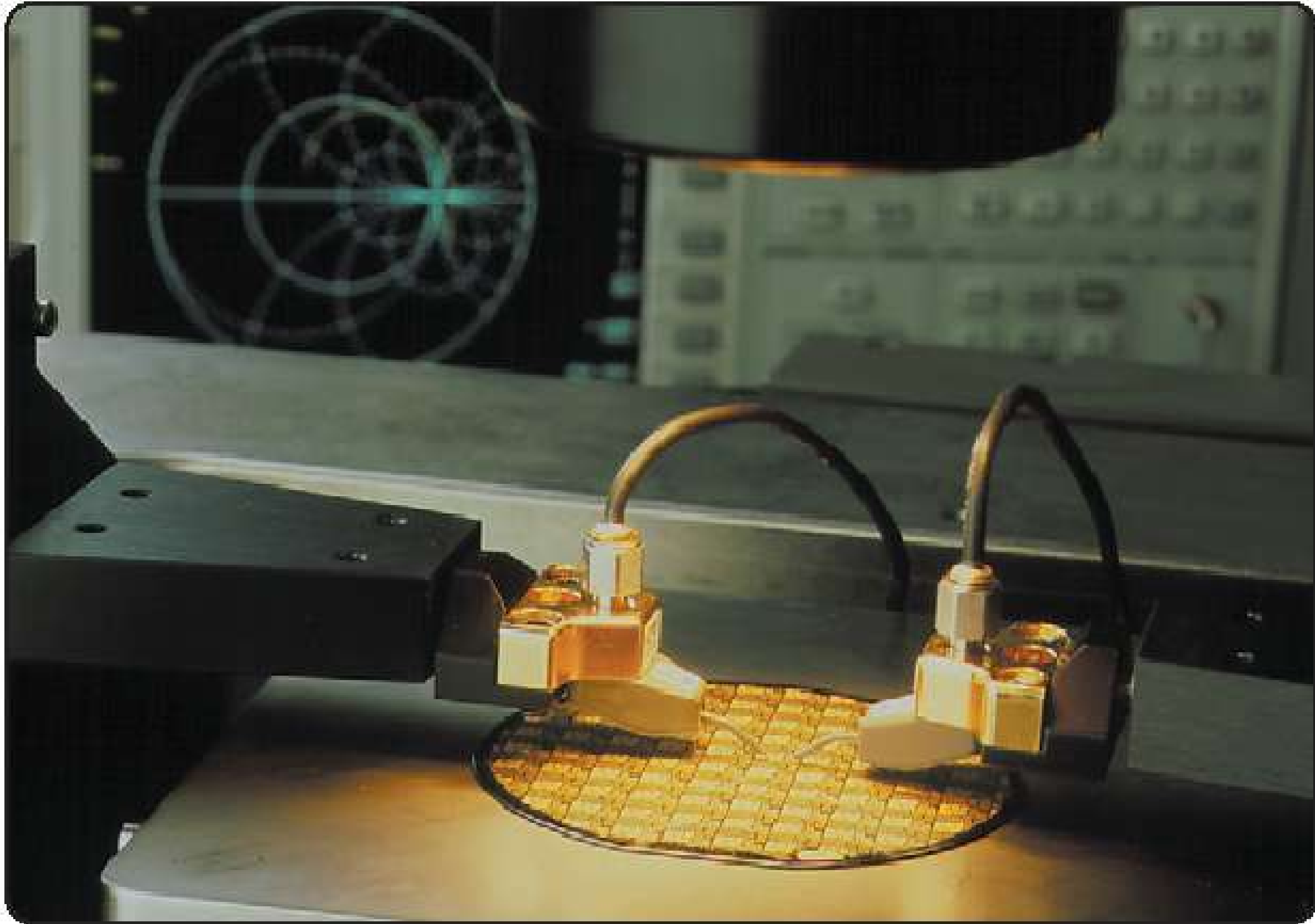
- Impedance matrix (V=IR -> V=IZ)
- Admittance matrix (I=YV)
- h-matrix (combination)
- ABCD matrix (combination)
- S-matrix (microwave reflections and transmissions)

"If you know one, then you know them all…"
See Liu, page 249 for conversions.

Measurement techniques



Measurement techniques



Cost (*rough* estimates)

- 10 GHz: $50,000
- 20 GHz: $70,000
- 40 GHz: $90,000
- 110 GHz: $250,000
- > 110 GHz: very expensive

For cost and difficulty reasons, parameters of transistor not always measure all the way up to f_T, but extrapolated.

These are only estimates. Contact vendor for actual prices.

Example

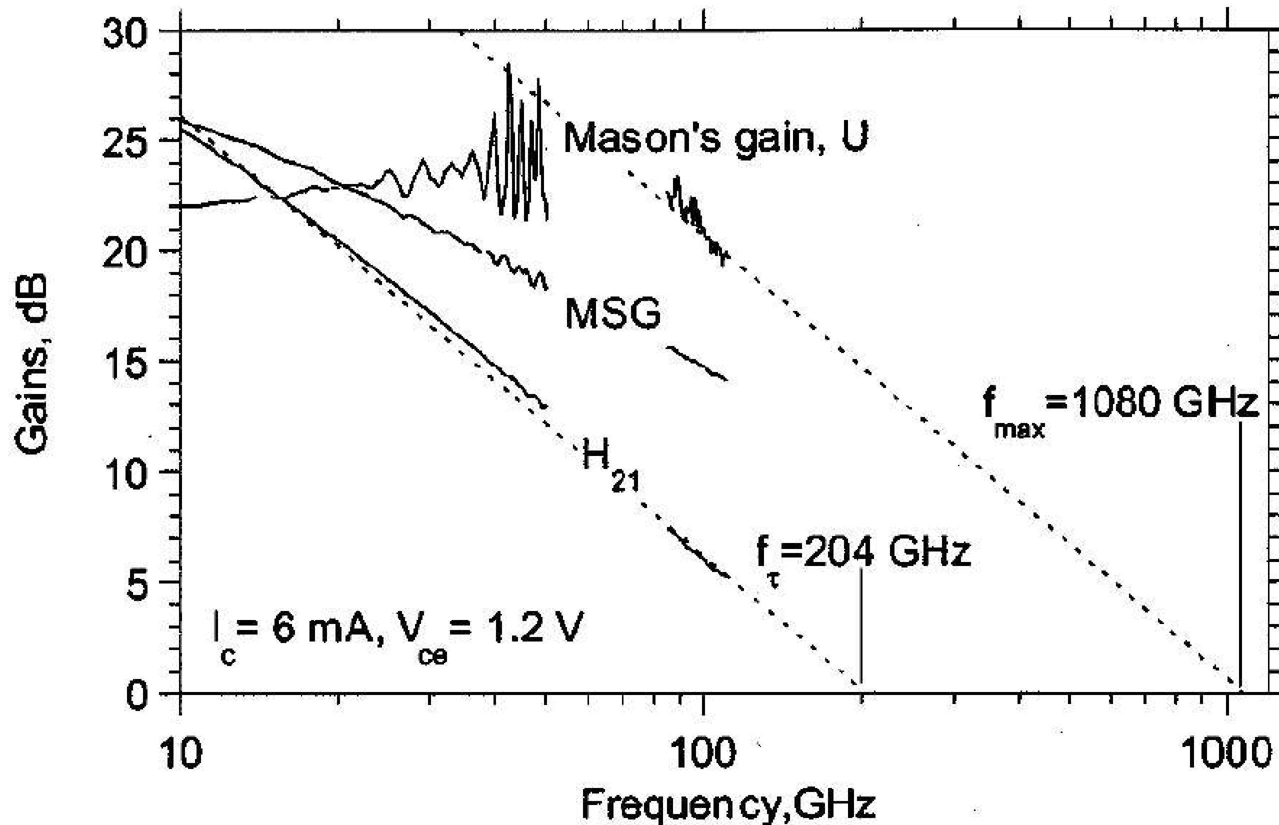
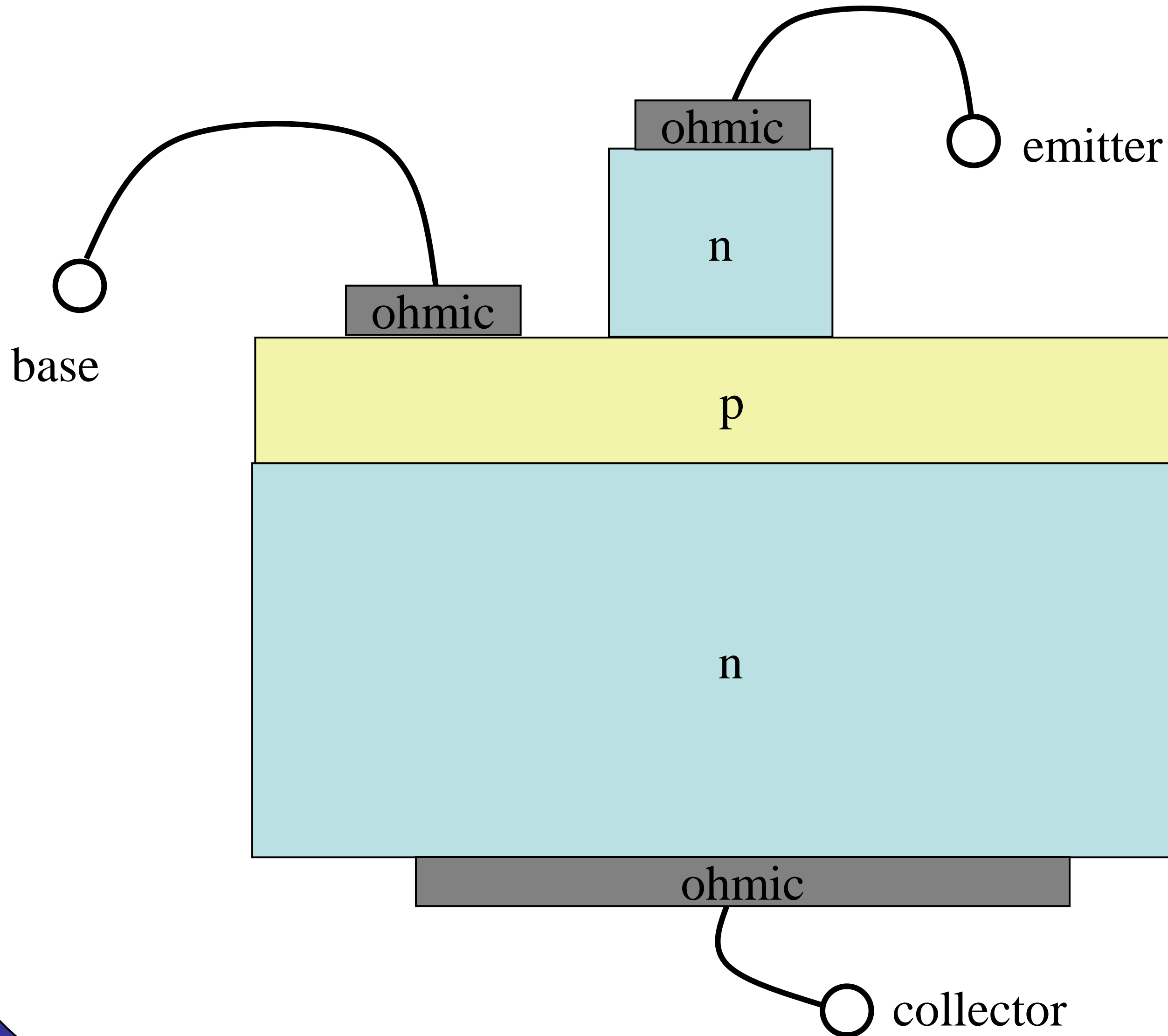


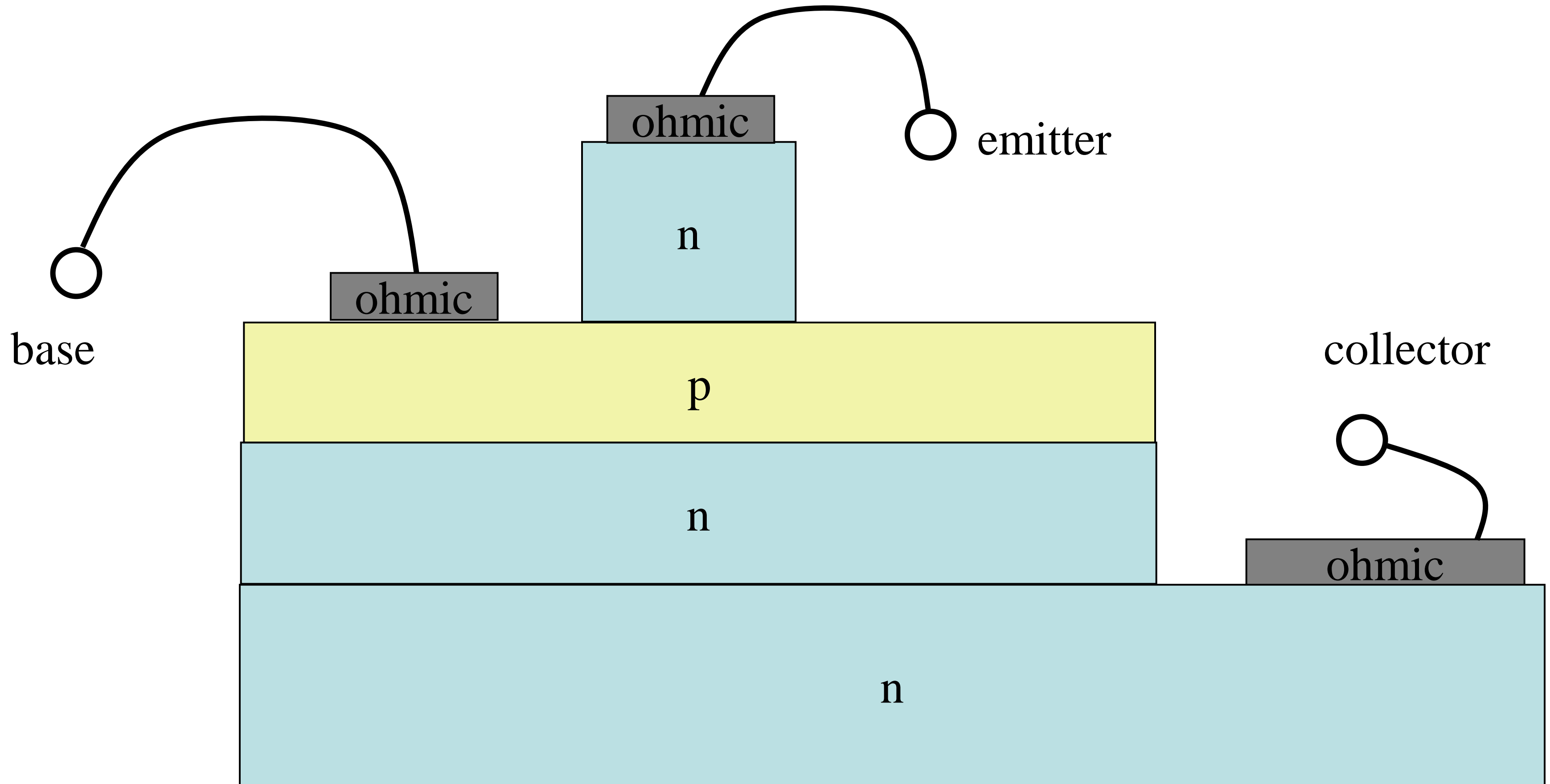
Fig. 14. Gains of a 0.4 μm $\times$ 6 μm emitter and 0.7 μm $\times$ 10 μm collector HBT fabricated using electron-beam lithography. Theoretical −20 dB/decade (H_{21}, U) gain slopes are indicated. The device exhibits an *extrapolated* 1.08 THz f_{max}.

From Rodwell, et al, TRANSACTIONS ON ELECTRON DEVICES 48 (11): 2606-2624 IEEE NOV 2001

Parasitics:



Parasitics:



Ohmic contact

Specific contact resistance typically 10^{-6} ohm-micron^2
(Discuss on board.)

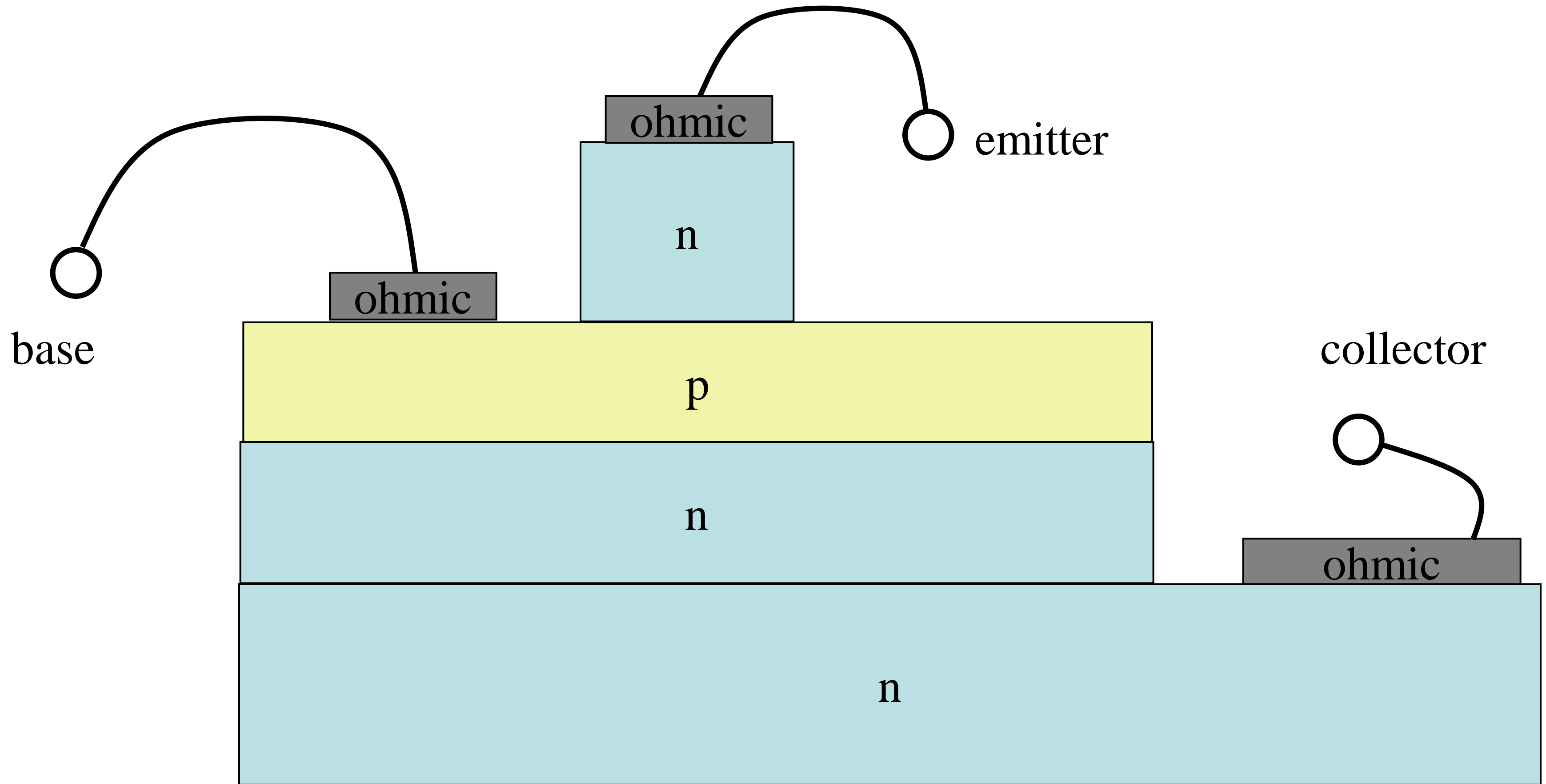
$$R_{EE} = \frac{\rho_{\sigma E}}{A_E} = \frac{\rho_{\sigma E}}{L_E W_E}$$

For a distributed contact, thinks are a little more complicated.
(Draw distributed RC network on board, discuss.)
A solution is:

$$R_{BB} = \frac{\sqrt{R_{SHB}\rho_{\sigma B}}}{L_E} \coth\left(W_B \sqrt{\frac{R_{SHB}}{\rho_{\sigma B}}} \right)$$

R_{SHB} is R per square (discuss)

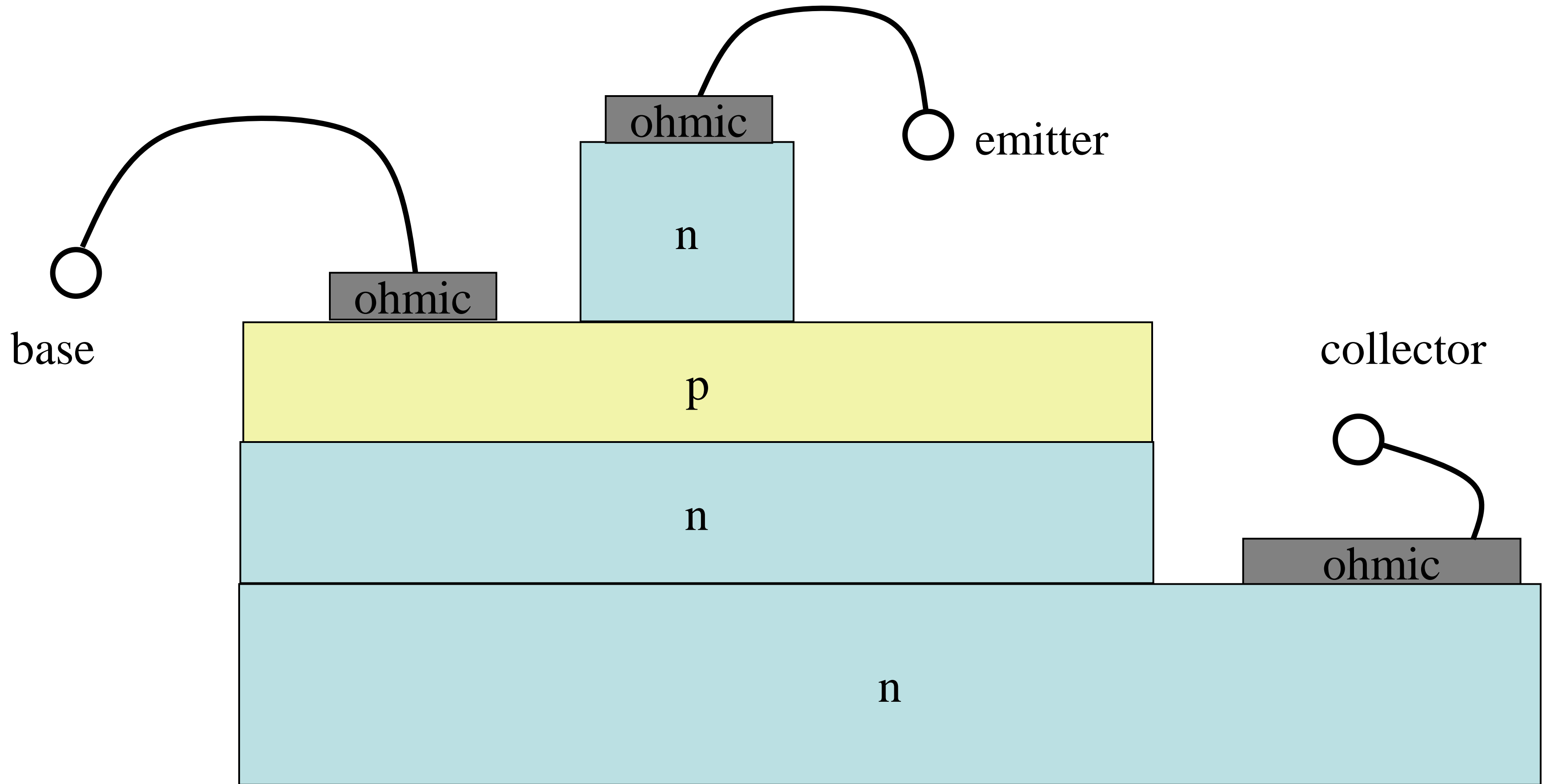
Emitter "epi" resistance:



$$R_{E(epi)} = \rho_{E(epi)} \frac{X_{E(epi)}}{L_E W_E}$$

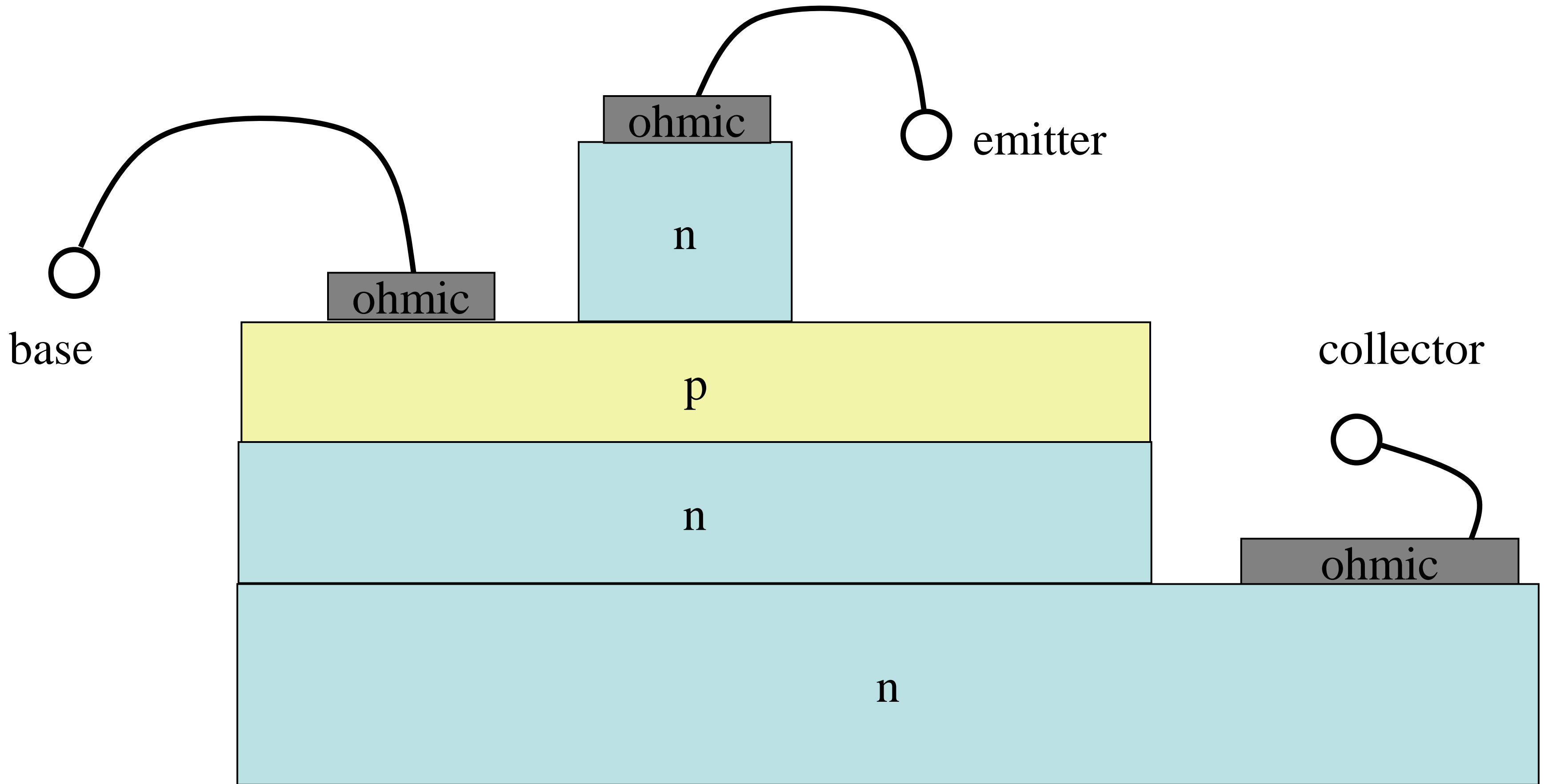
(discuss)

Base "epi" resistance:



$$R_{Bx(epi)}$$ (discuss)

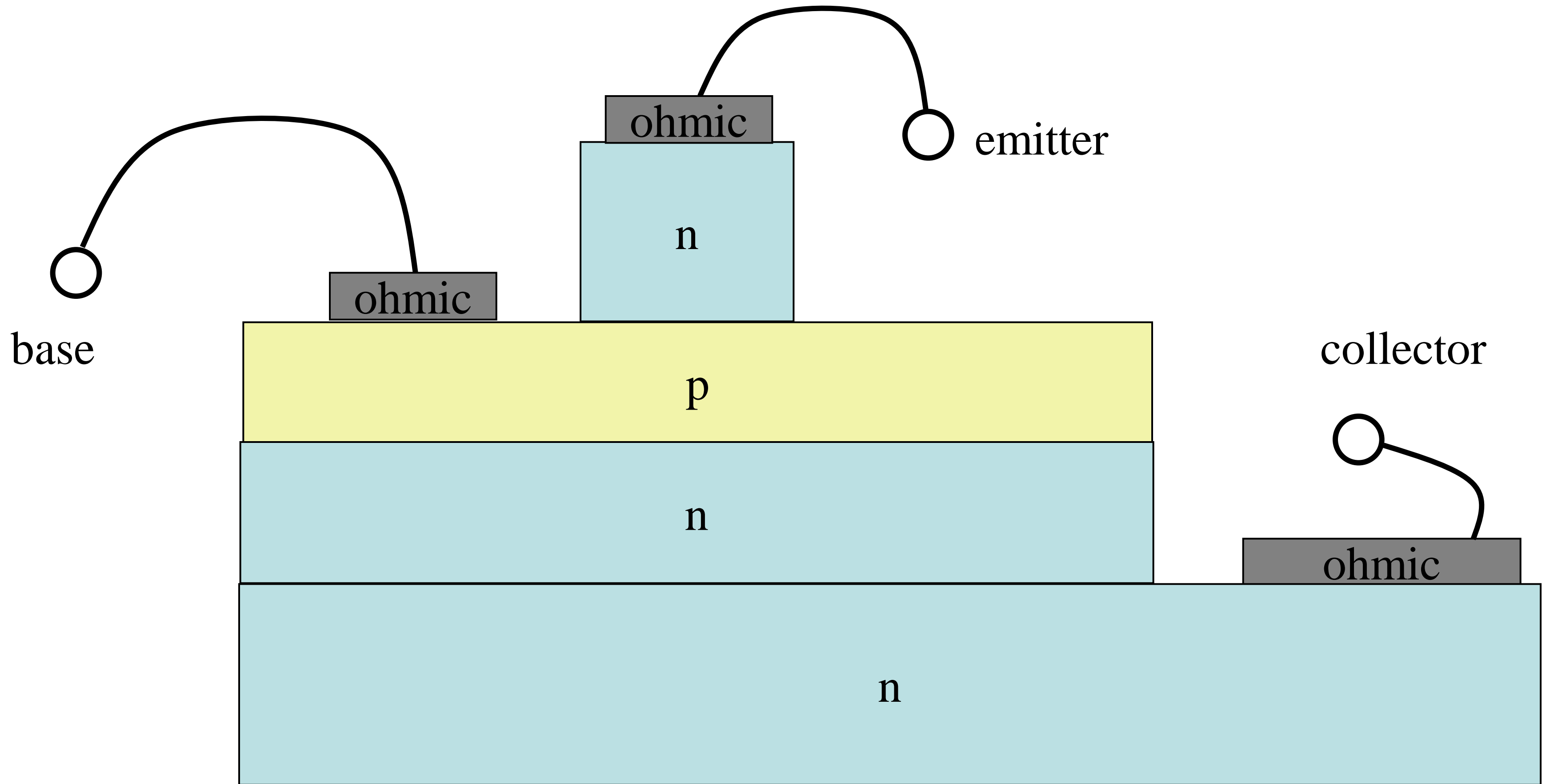
Emitter “epi” resistance:



$$R_{E(epi)} = \rho_{E(epi)} \frac{X_{E(epi)}}{L_E W_E}$$

(discuss)

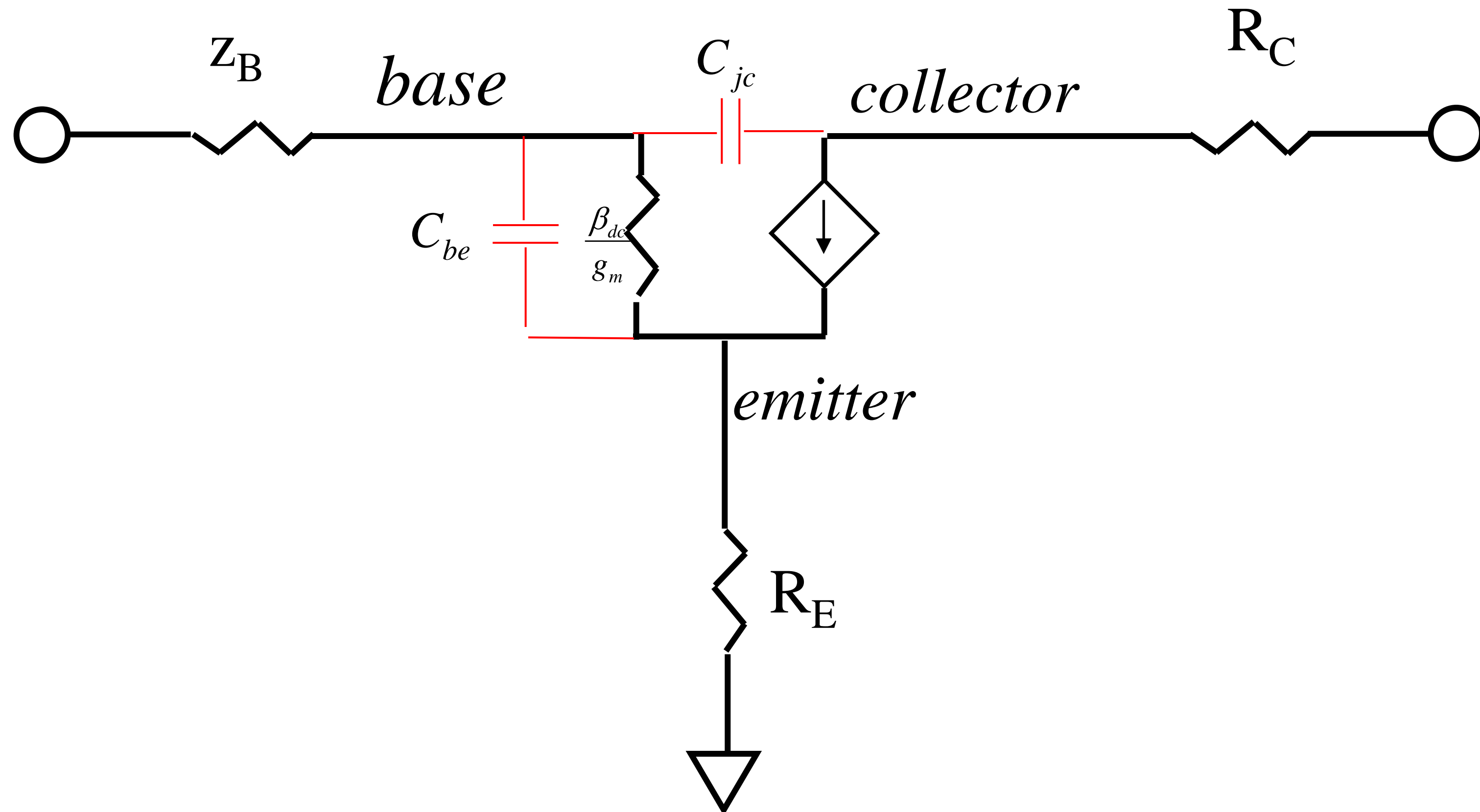
Collector "epi" resistance:



$$R_{C(epi)} = \rho_{C(epi)} \frac{X_{C(epi)}}{L_E W_E}$$

(discuss)
(also discuss spreading effect)

Parasitics: In summary



Total parasitics include contact, epi, and metal layer resistance.
Sometimes inductance also added in.

f_T:

$$\begin{pmatrix} v_b \\ i_c \end{pmatrix} = \begin{pmatrix} h_{11e} & h_{12e} \\ h_{21e} & h_{22e} \end{pmatrix} \begin{pmatrix} i_b \\ v_c \end{pmatrix}$$

- Early effect:
  Collector voltage changes current gain (β).
- β depends on frequency *and* collector voltage.
- How do we define frequency at which β = 1?
- At v_c=0. This *is* h_{21e}

$$i_c = h_{21e} i_b + h_{22e} v_c \rightarrow h_{21e} i_b$$

- We define f_T such that:

$$\left| h_{21e} \right| (f_T) = 1$$

f_T

$$f_T = \frac{1}{2\pi\tau_{ec}}$$

$$\tau_{ec} = \tau_e + \tau_b + \tau_{sc} + \tau_c$$

Emitter charging time

$$\tau_e = \frac{kT}{eI_C}\left(C_{je} + C_{jc}\right)$$

Time to charge up junction capacitors.

Base transit time

$$\tau_e = \frac{X_B^2}{2D_{nB}}$$

Time to charge up base minority carriers.
Or: time to diffuse from emitter to collector.
(Built in field helps a lot here.)

Space-charge transit time

$$\tau_e = \frac{X_{dep}}{2v_{sat}}$$

Or: time to *drift* through space charge of base-collector junction.

Collector charging time

$$\tau_c = (R_E + R_C) \cdot C_{jc}$$

Time to charge collector junction capacitor through parasitic resistors.

f_T:

$$\begin{pmatrix} v_b \\ i_c \end{pmatrix} = \begin{pmatrix} h_{11e} & h_{12e} \\ h_{21e} & h_{22e} \end{pmatrix} \begin{pmatrix} i_b \\ v_c \end{pmatrix}$$

"It can be shown that…"

$$h_{21e} = \frac{\alpha_{T0}}{(1-\alpha_{T0}) + i(f/f_T)}$$

$$\alpha_{T0} \equiv 1 - \frac{X_B^2}{2L_n^2}$$

Discuss rolloff, low frequency value.

f_{max}:

In real circuits, we do not want to short circuit the output!
Unilateral power gain: if impedance matching network is set up so that there is no reverse transmission (S_{12}=0), in that case the power gain is called the *unilateral power gain*.

"It can be shown that…"

$$U = \frac{\left| z_{21} - z_{12} \right|^2}{4\left[\mathrm{Re}(z_{11})\,\mathrm{Re}(z_{22}) - \mathrm{Re}(z_{12})\,\mathrm{Re}(z_{21})\right]}$$

"It can be shown that…"

$$U = \frac{\alpha_{T0}{}^2 \omega_T}{4\,\mathrm{Re}(z_b) C_{jc} \omega^2}$$

$$f_{\max} = \sqrt{\frac{f_T}{8\pi r_b C_{jc}}}$$

Discuss r_b dependence, want heavily doped base. Need for *H*BT.