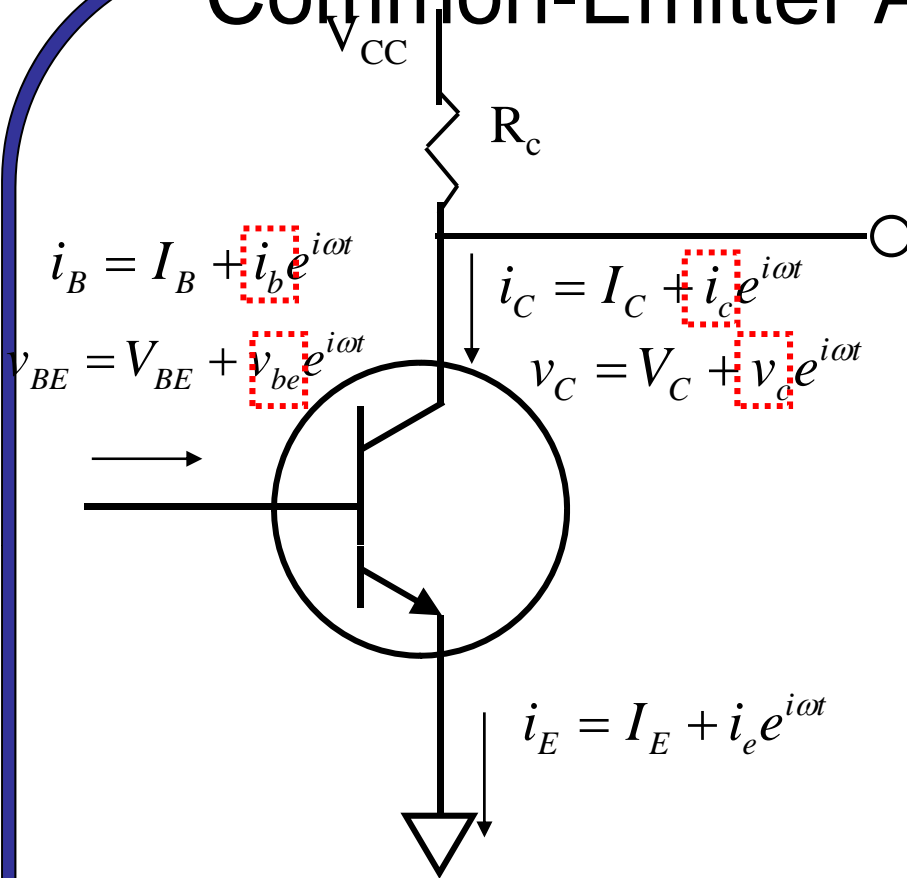
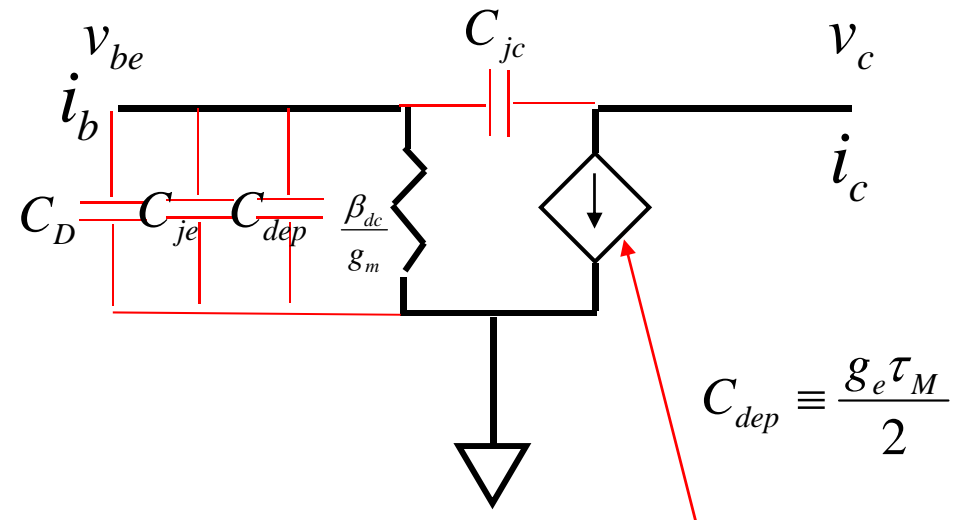


# Lecture 6: HBT parasitics $f_T$ , $f_{max}$

# Common-Emitter AC equivalent circuit:



Hybrid  $\pi$  model:  
 Red is new for ac:

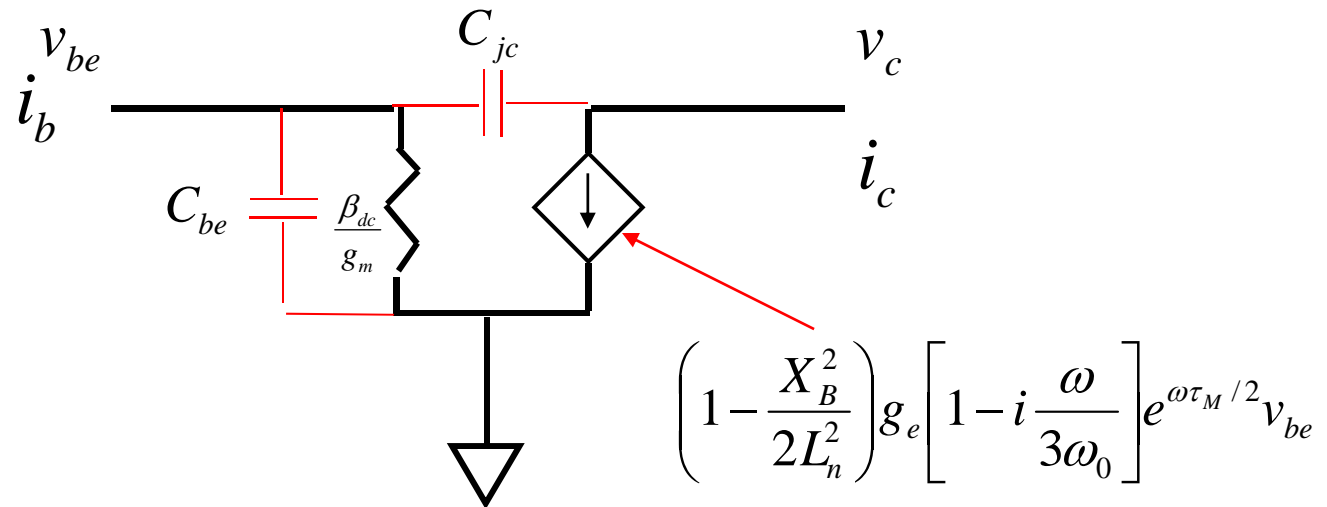


$$\left(1 - \frac{X_B^2}{2L_n^2}\right) g_e \left[1 - i \frac{\omega}{3\omega_0}\right] e^{\omega\tau_M/2} v_{be}$$

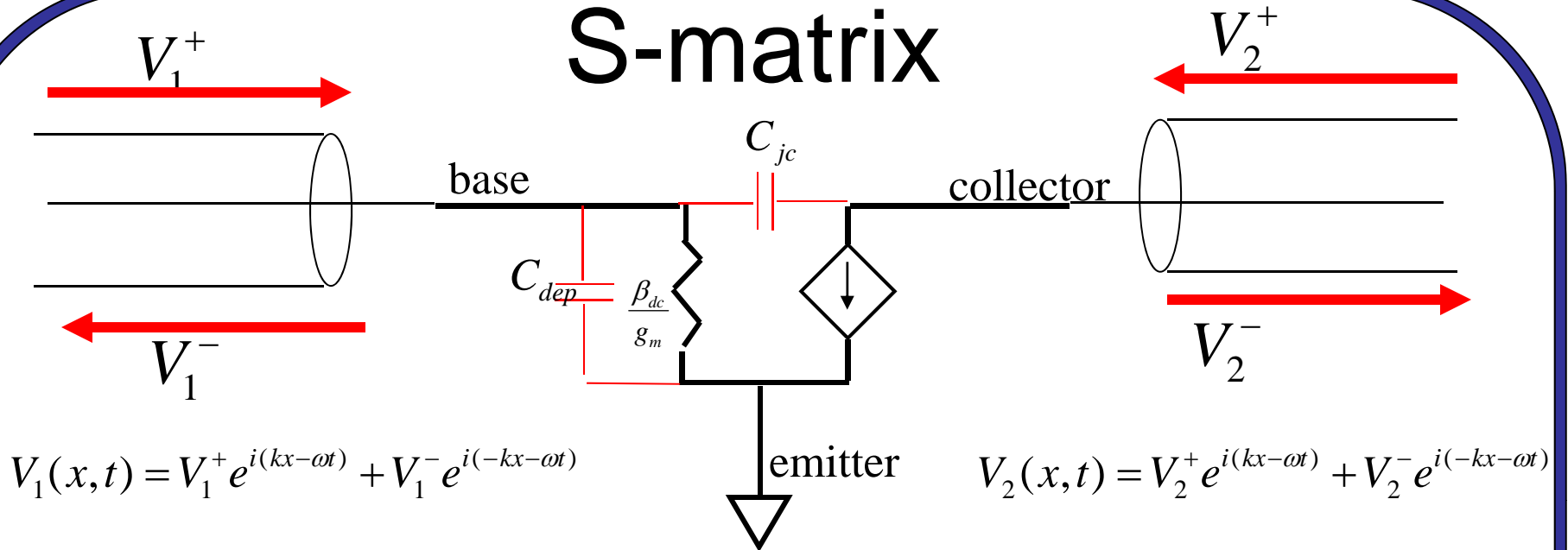
- Circuit model good only for low frequencies
- At high frequencies computer must be used!

# Hybrid $\pi$ model:

simplified:



# S-matrix



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

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

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

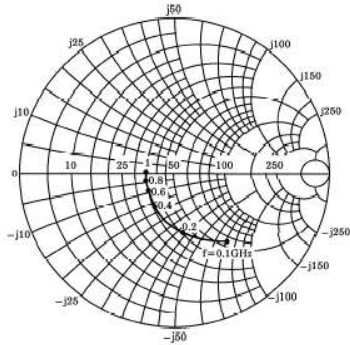
# S-parameters

TOSHIBA

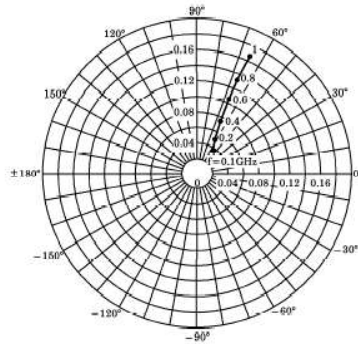
2SA1245

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

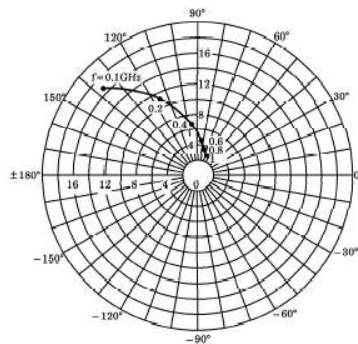
$S_{11e}$   
 $V_{CE} = -5V$   
 $I_C = -10mA$   
 $T_a = 25^\circ C$   
(UNIT :  $\Omega$ )



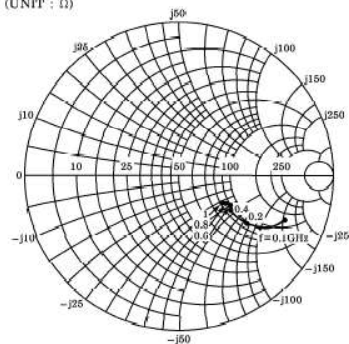
$S_{12e}$   
 $V_{CE} = -5V$   
 $I_C = -10mA$   
 $T_a = 25^\circ C$



$S_{21e}$   
 $V_{CE} = -5V$   
 $I_C = -10mA$   
 $T_a = 25^\circ C$



$S_{22e}$   
 $V_{CE} = -5V$   
 $I_C = -10mA$   
 $T_a = 25^\circ C$   
(UNIT :  $\Omega$ )

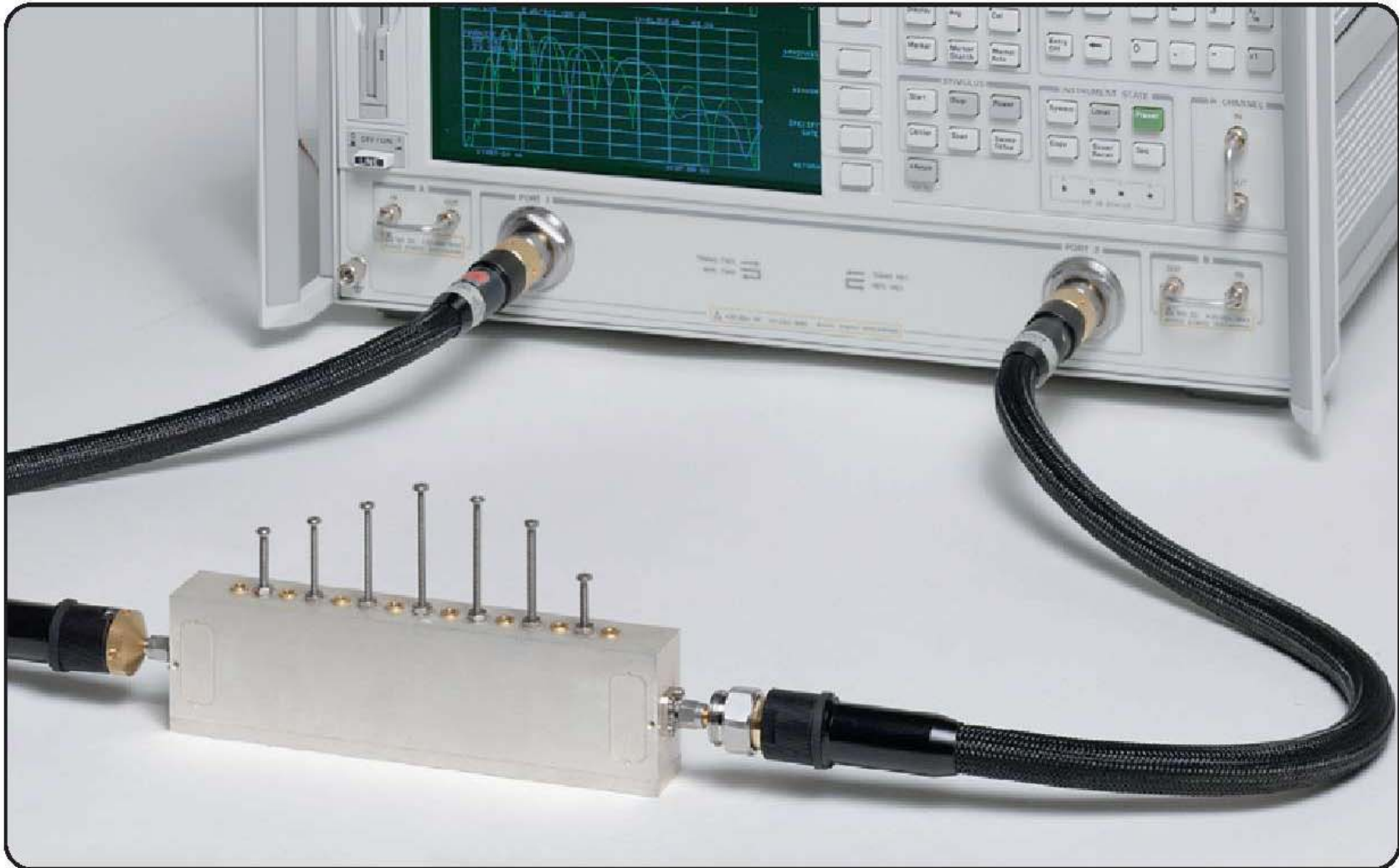


# Summary of parameters

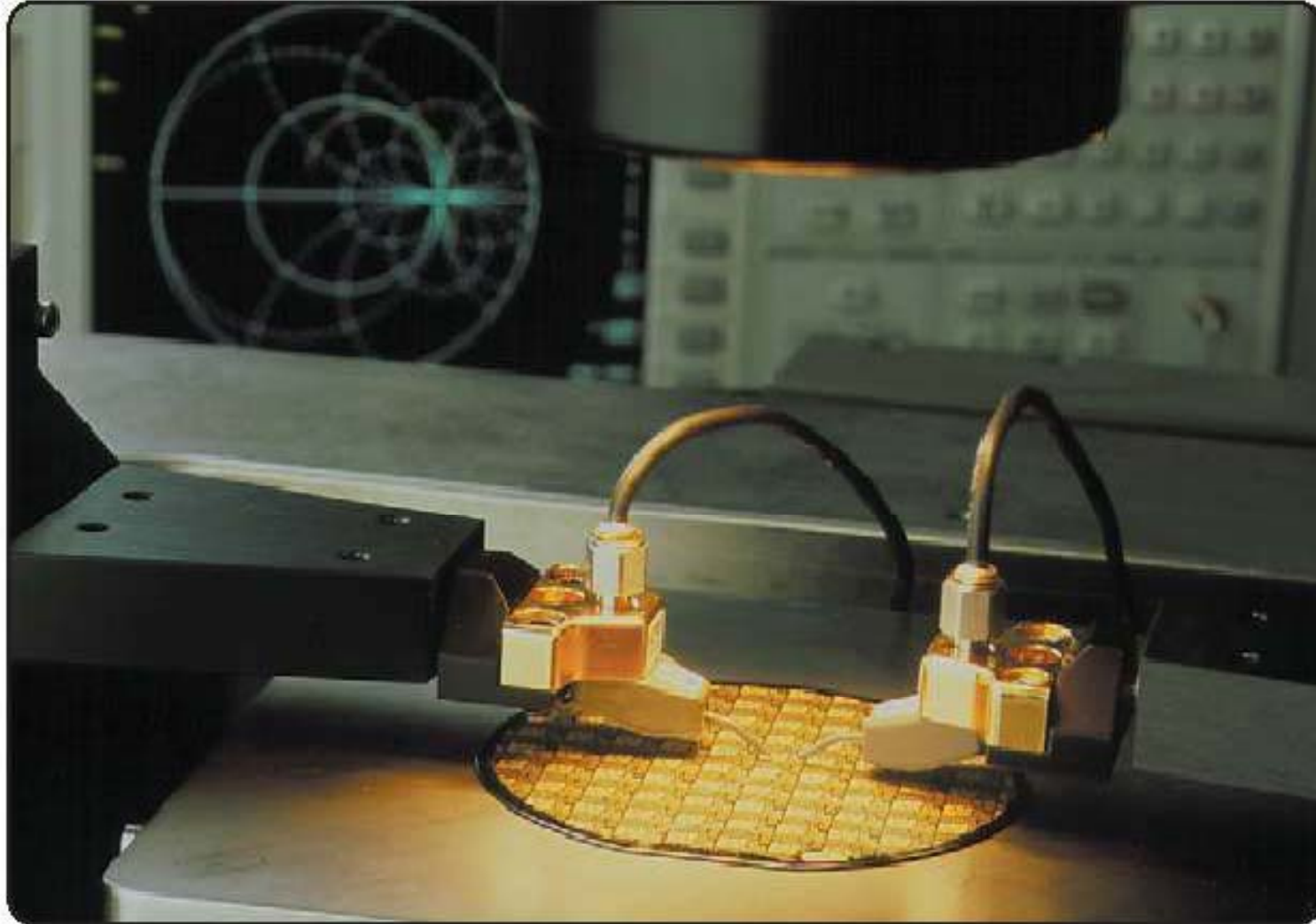
- Impedance matrix ( $V=IR \rightarrow V=IZ$ )
- Admittance matrix ( $I=YV$ )
- h-matrix (combination)
- ABCD matrix (combination)
- S-matrix (microwave reflections and transmissions)

“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

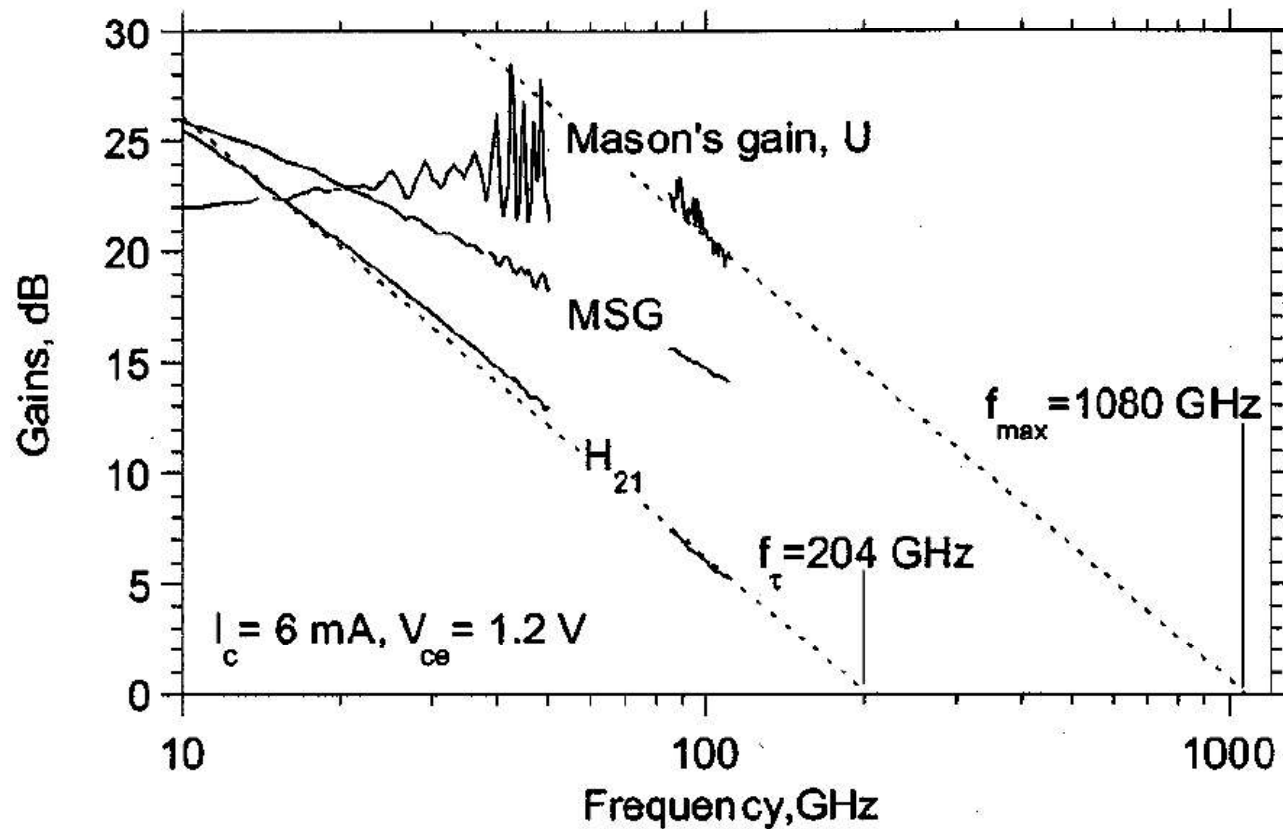
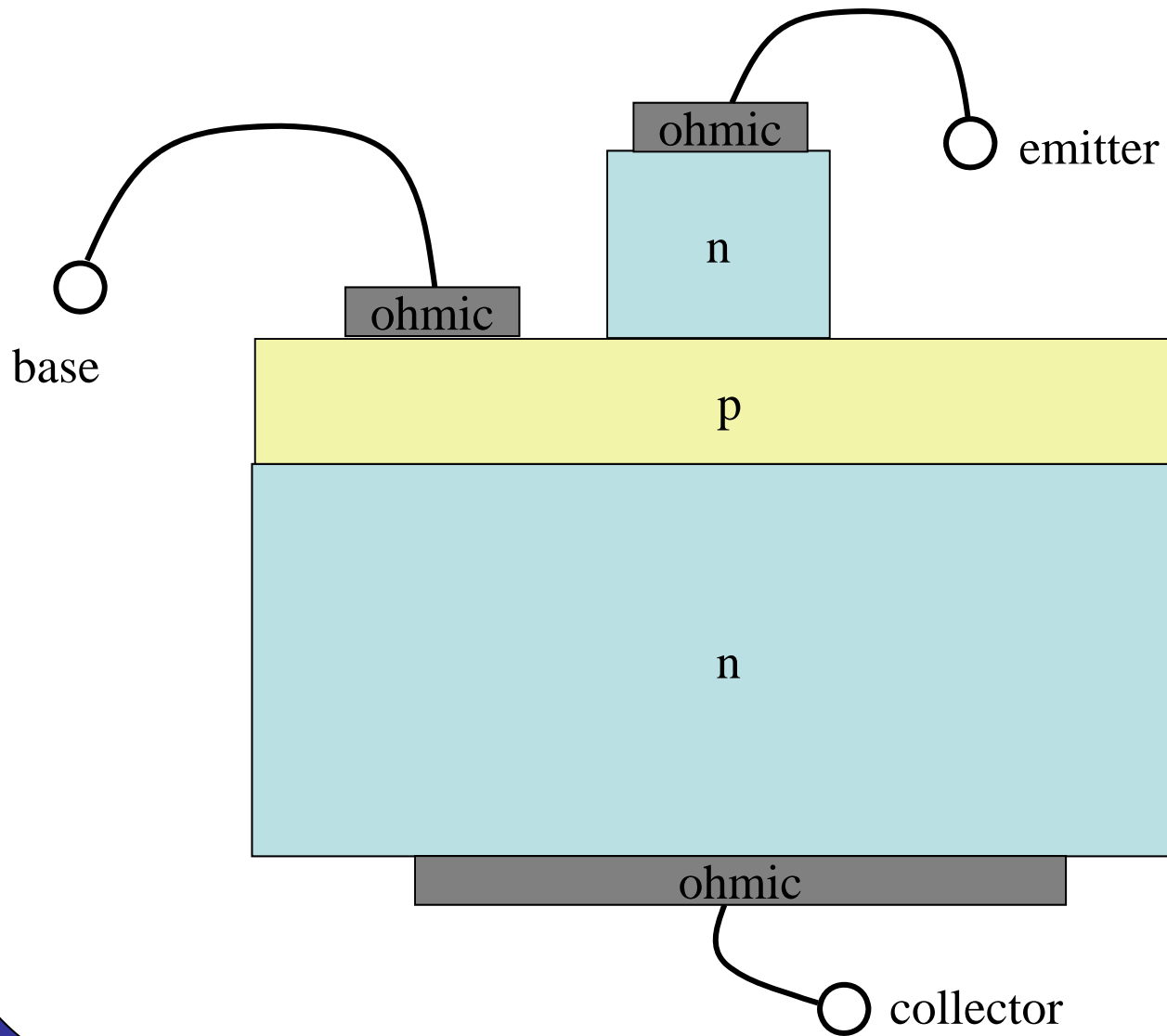


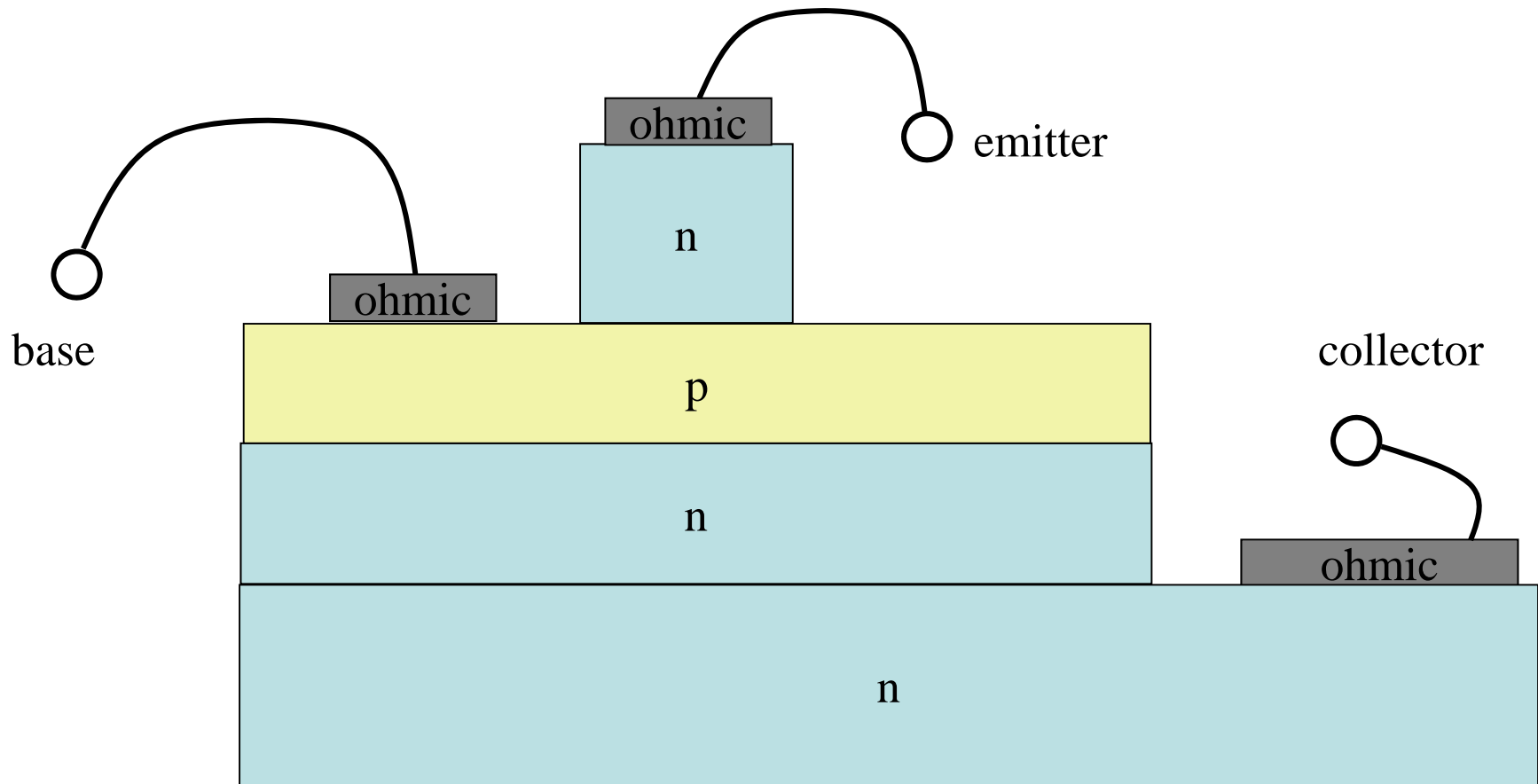
Fig. 14. Gains of a  $0.4 \mu\text{m} \times 6 \mu\text{m}$  emitter and  $0.7 \mu\text{m} \times 10 \mu\text{m}$  collector HBT fabricated using electron-beam lithography. Theoretical  $-20$  dB/decade ( $H_{21}$ ,  $U$ ) gain slopes are indicated. The device exhibits an *extrapolated* 1.08 THz  $f_{\text{max}}$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

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<sup>2</sup>  
(Discuss on board.)

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

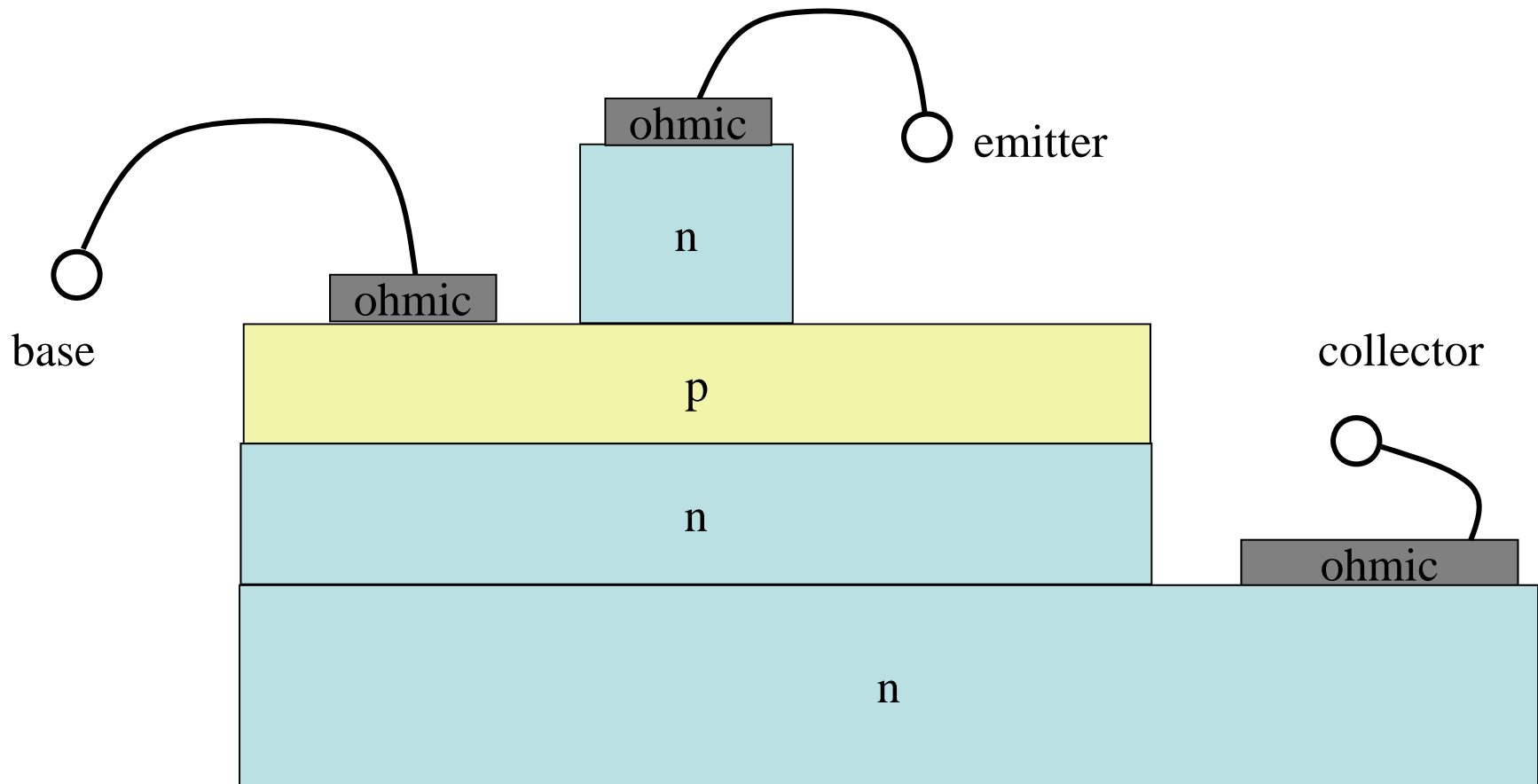
For a distributed contact, things are a little more complicated.  
(Draw distributed RC network on board, discuss.)

A solution is:

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

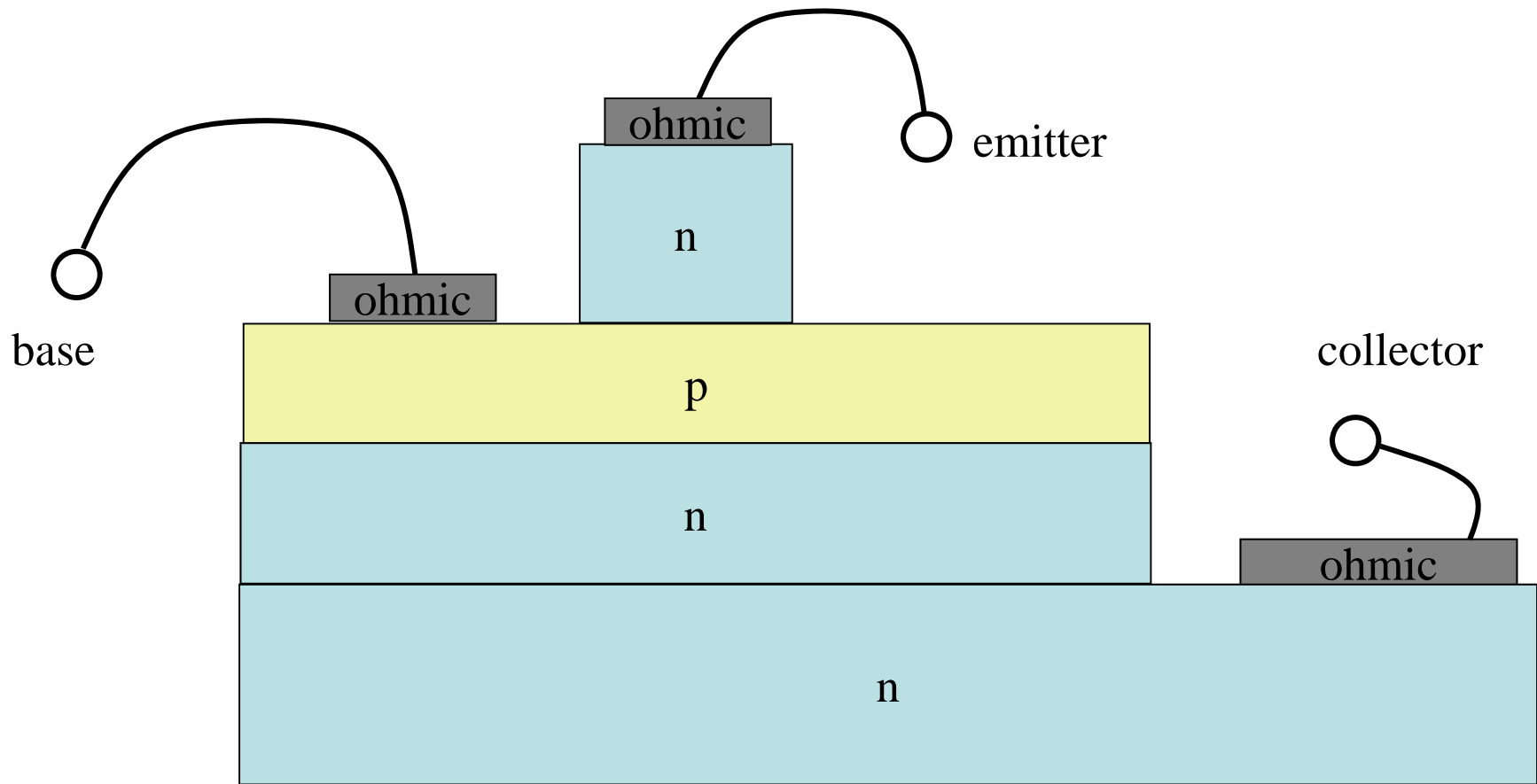
$R_{SHB}$  is R per square (discuss)

# Emitter “epi” resistance:



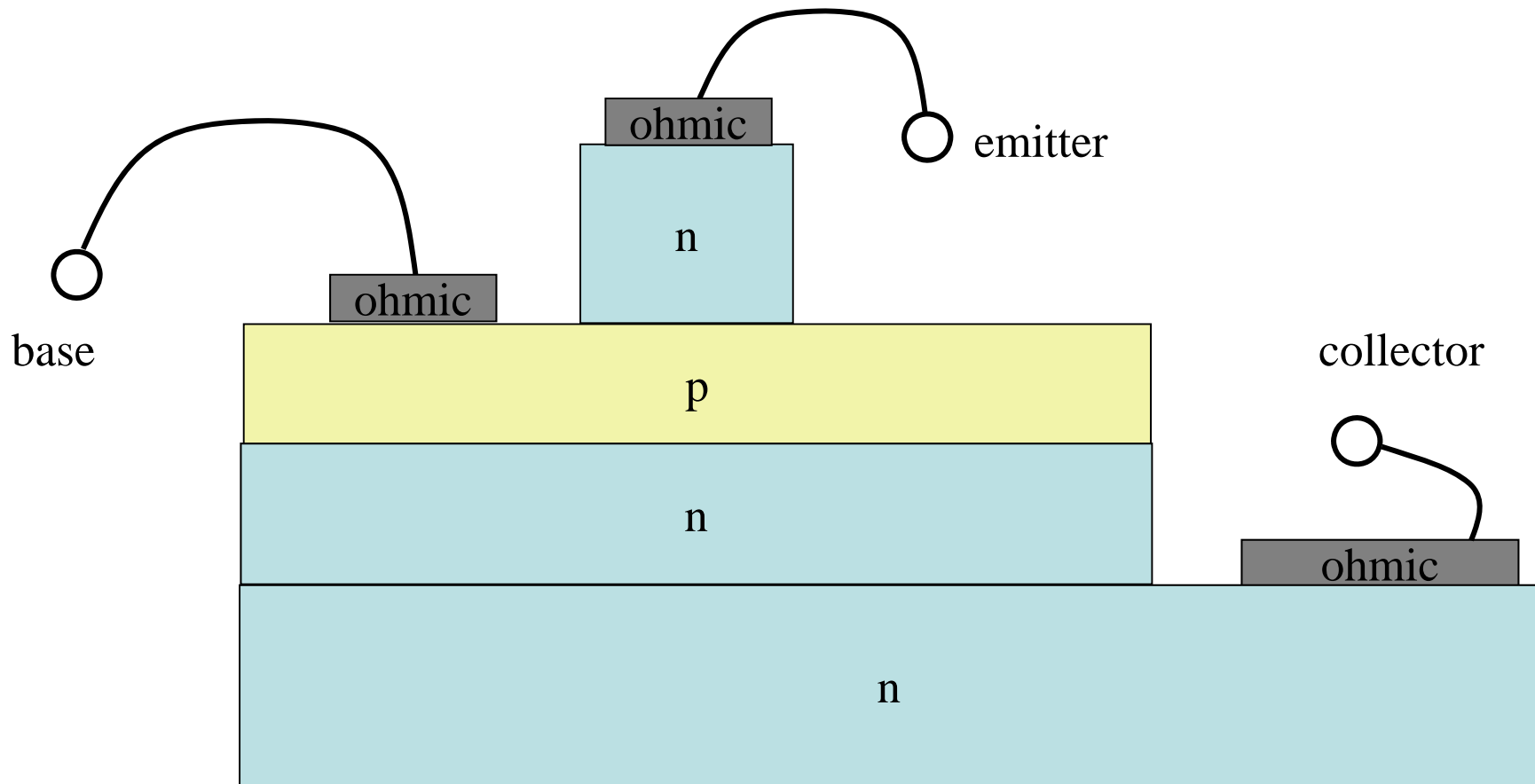
$$R_{E(epi)} = \rho_{E(epi)} \frac{X_{E(epi)}}{L_E W_E} \quad (\text{discuss})$$

# Base “epi” resistance:



$$R_{Bx(epi)} \quad (\text{discuss})$$

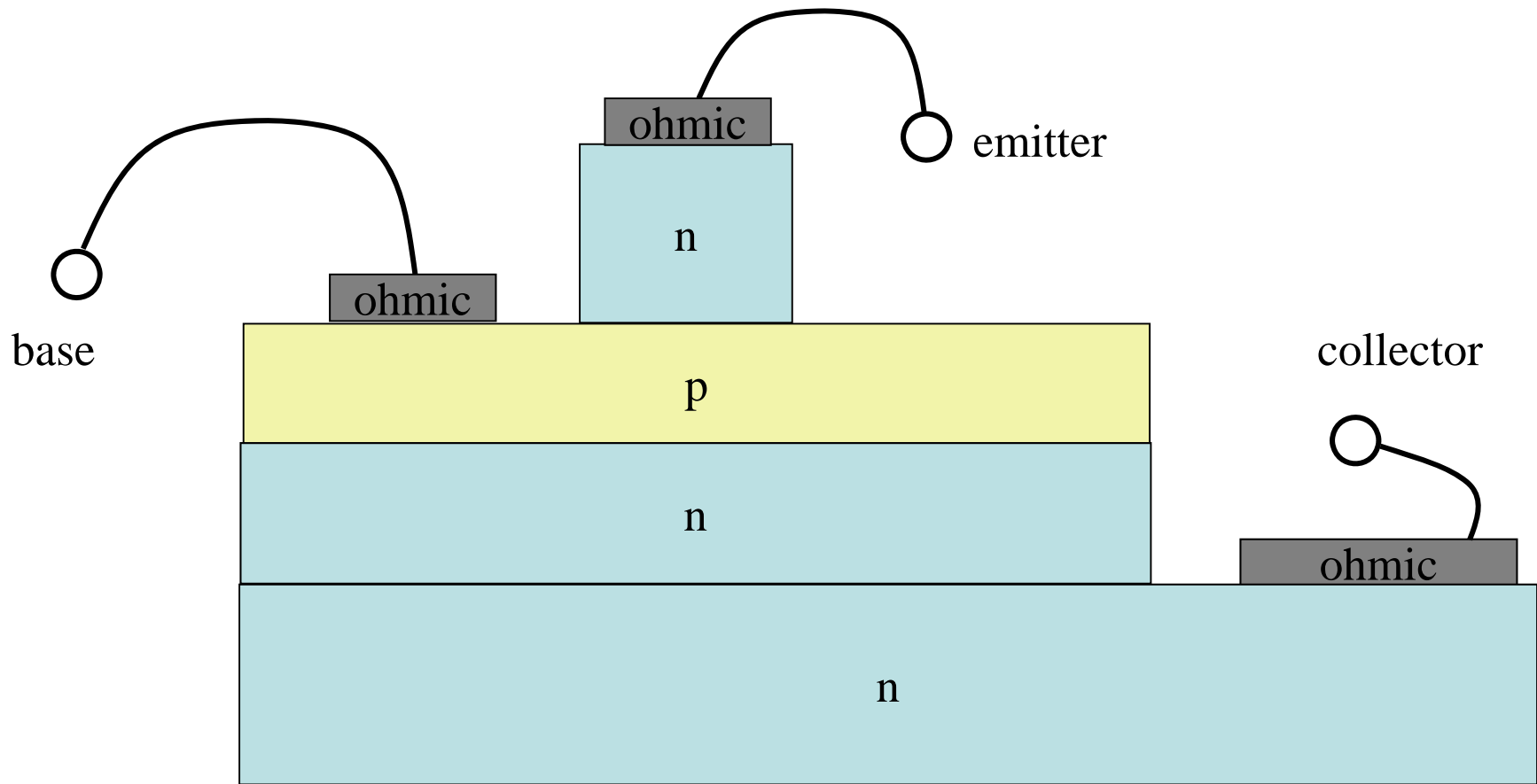
# Emitter “epi” resistance:



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



# Collector “epi” resistance:

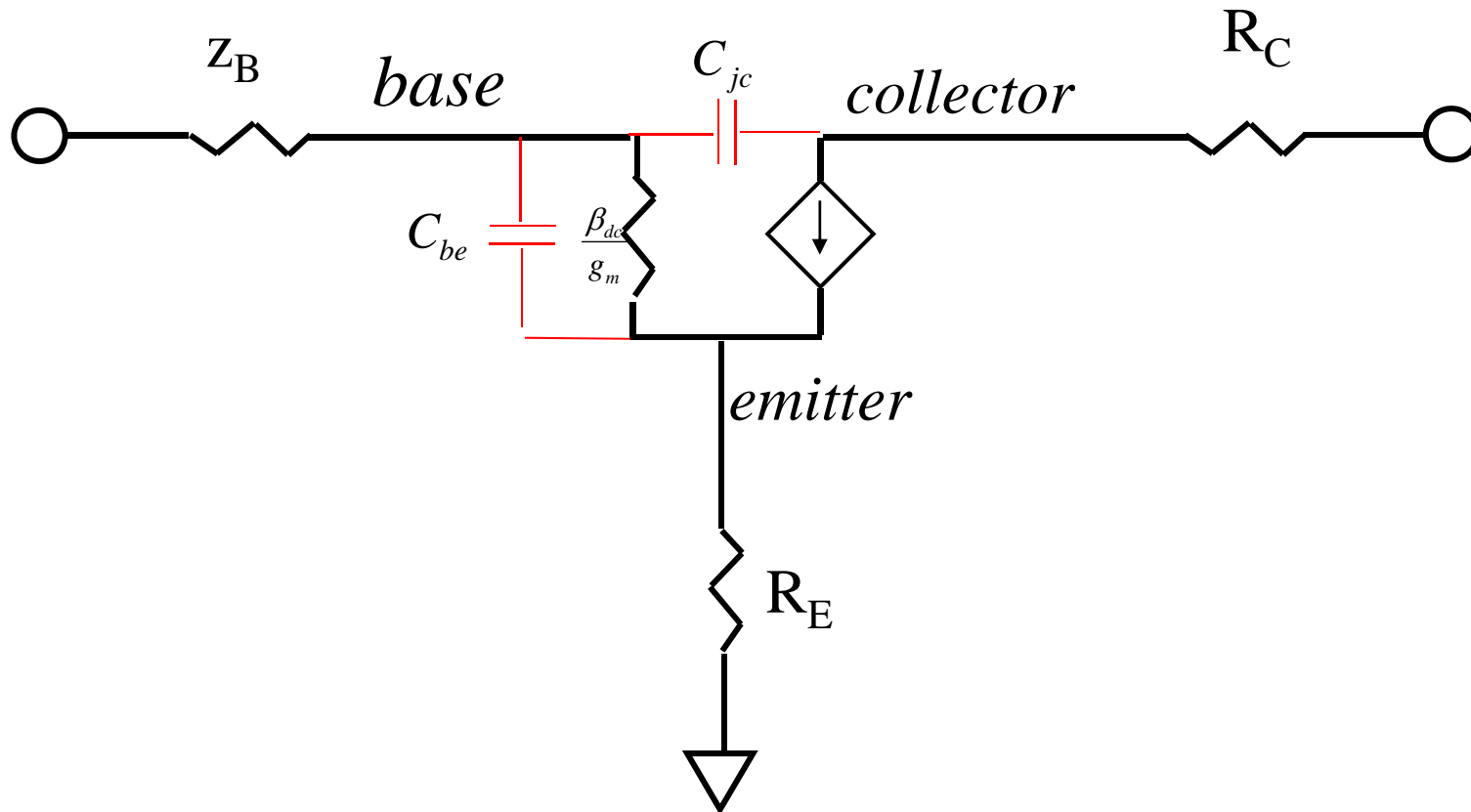


$$R_{C(epi)} = \rho_{C(epi)} \frac{X_{C(epi)}}{L_E W_E}$$

(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 ( $\beta$ ).

- $\beta$  depends on frequency *and* collector voltage.
- How do we define frequency at which  $\beta = 1$ ?
- 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:

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

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

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

# Emitter charging time

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

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...”

$$h_{21e} = \frac{\alpha_{T0}}{(1 - \alpha_{T0}) + i(f / f_T)} \quad \alpha_{T0} \equiv 1 - \frac{X_B^2}{2L_n^2}$$

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...”

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

“It can be shown that...”

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

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

Discuss  $r_b$  dependence,  
want heavily doped base.  
Need for *HBT*.