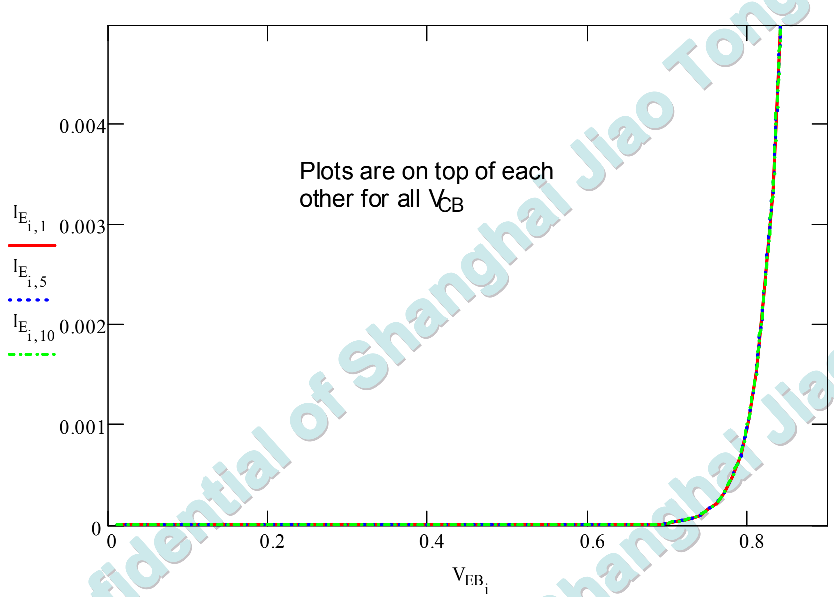
Chater 6 (II)
Dynamic Response of BJT

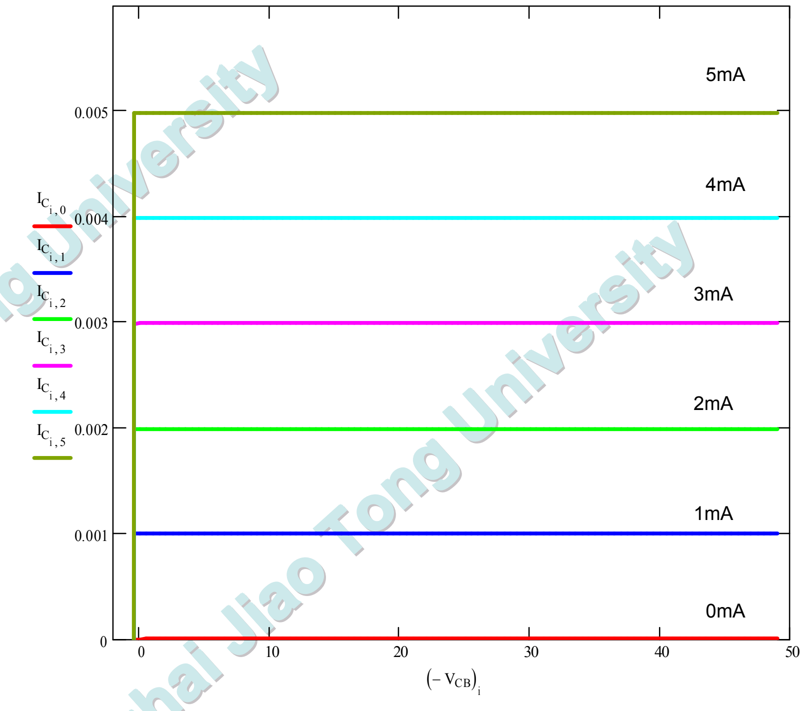
Xiulan Cheng/Shirla Cheng

2012-05-20

Common Base Characteristics

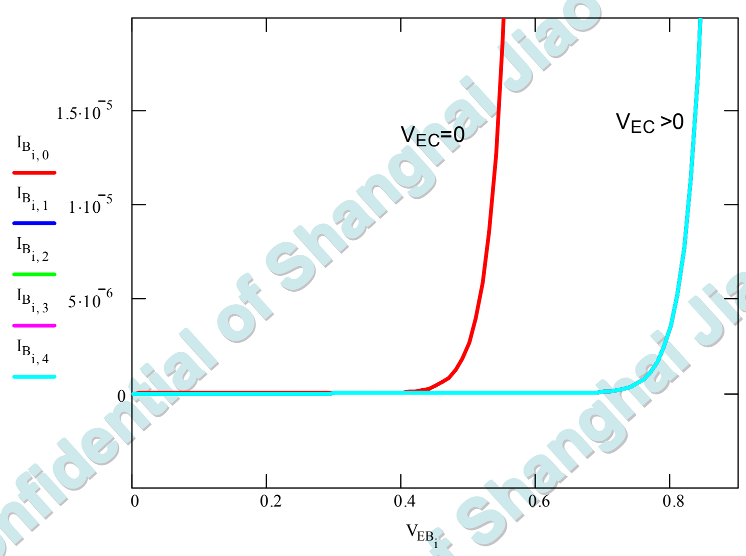


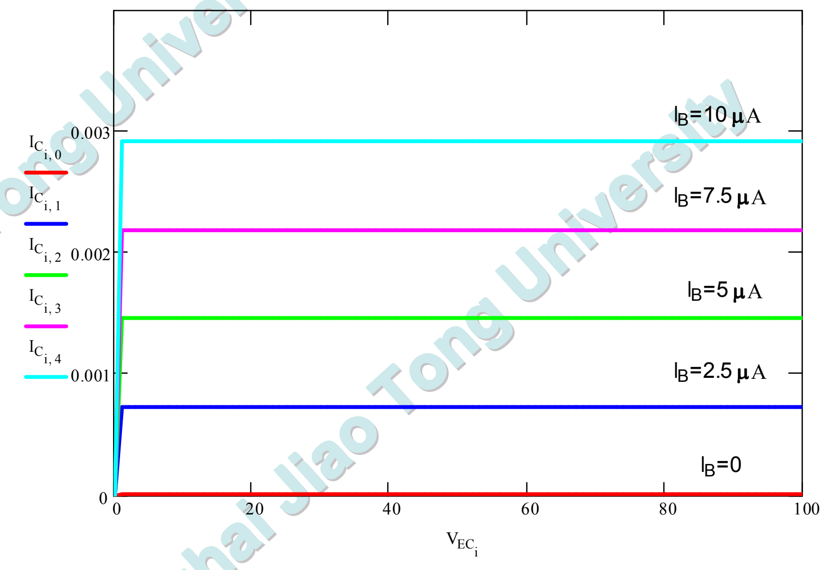
Input



Output

Common Emitter Characteristics



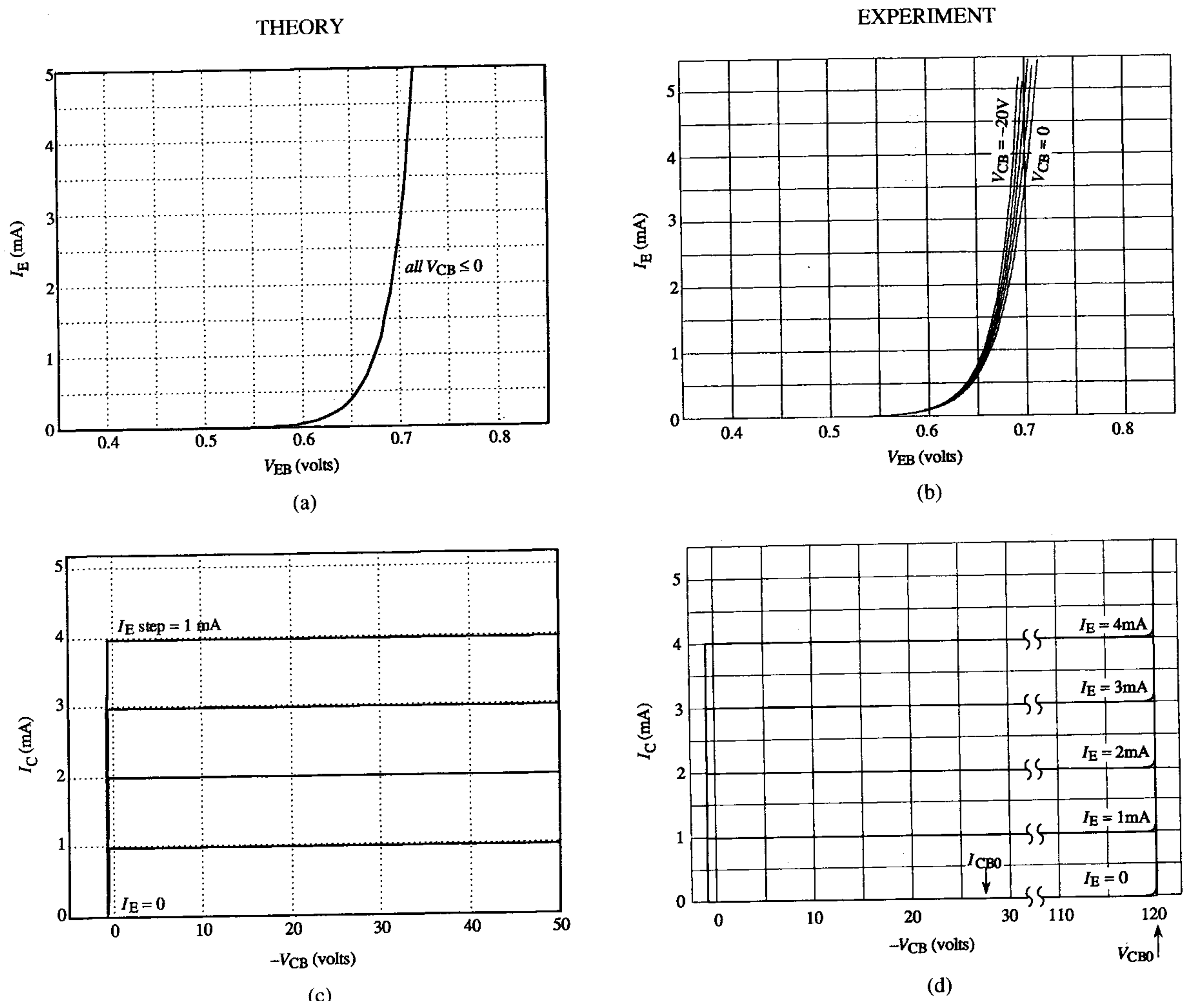


Input
(Forward Biased
PN junction)

Output
(Reverse biased
PN junction ..
I_s controlled by I_B)

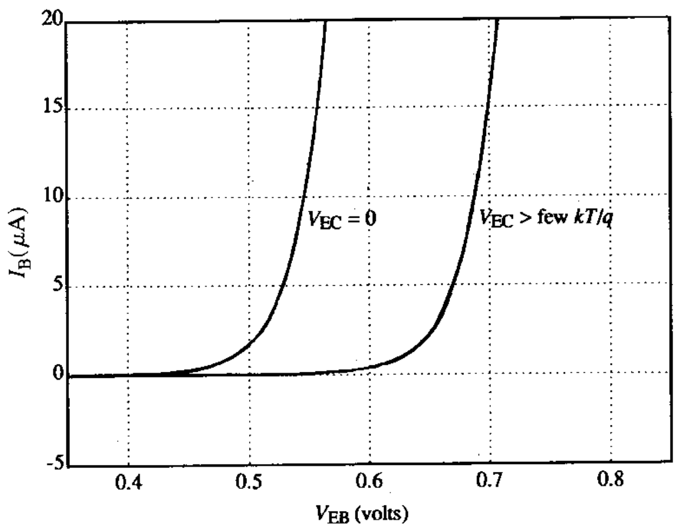
Plans

- How do the computed BJT I-Vs compare with expts?
- Can we understand the discrepancies?
- What does the gain look like?
- AC properties (small signal and transient response)


THEORY
EXPERIMENT
I_E (mA)
all $V_{CB} \le 0$
V_{EB} (volts)
(a)
$V_{CB} = -20V$
$V_{CB} = 0$
(b)
I_C (mA)
I_E step = 1 mA
$I_E = 0$
$-V_{CB}$ (volts)
(c)
I_E = 4mA
I_E = 3mA
I_E = 2mA
I_E = 1mA
I_E = 0
I_{CB0}
V_{CB0}
(d)

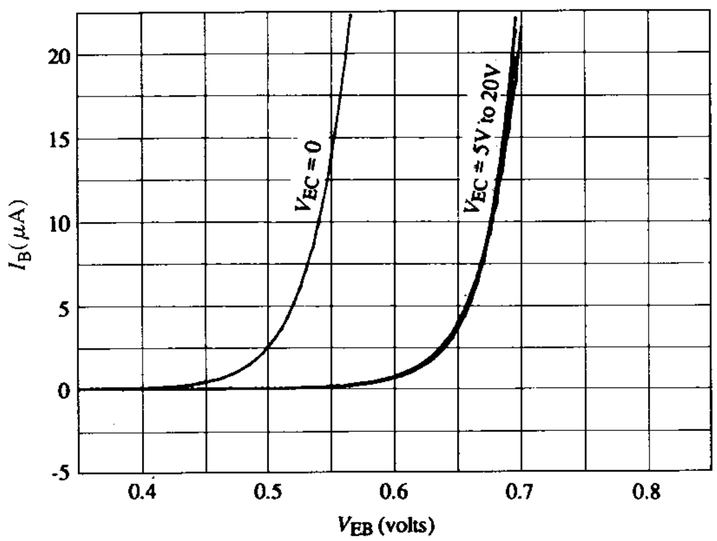
Common Emitter

THEORY

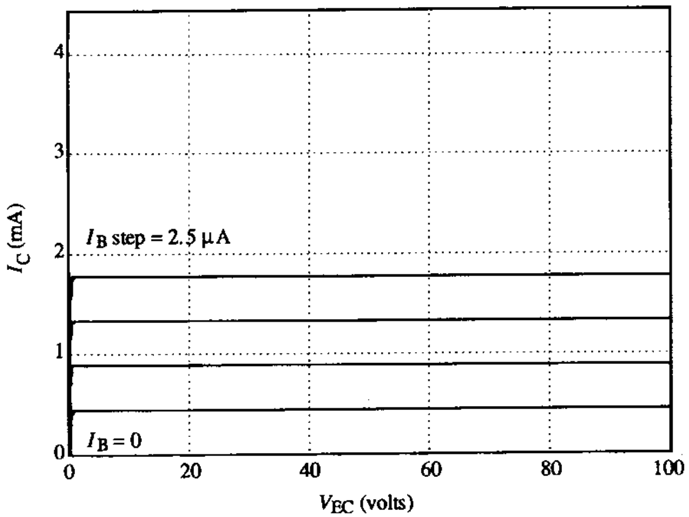


(a)

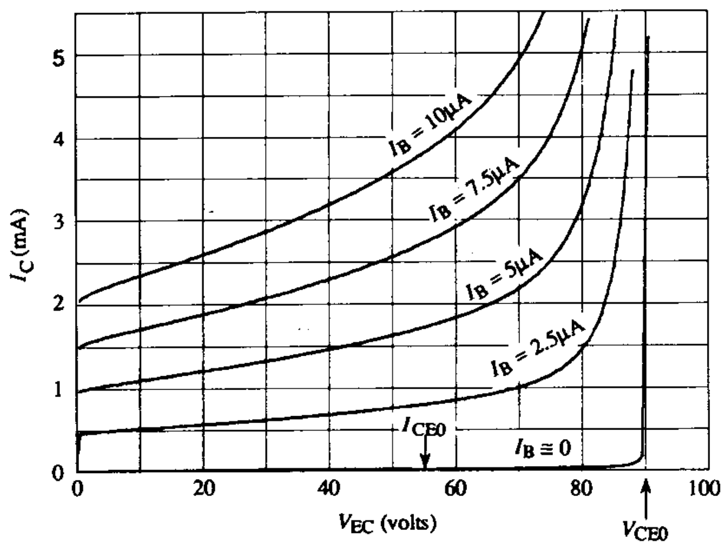
EXPERIMENT



(b)



(c)



(d)

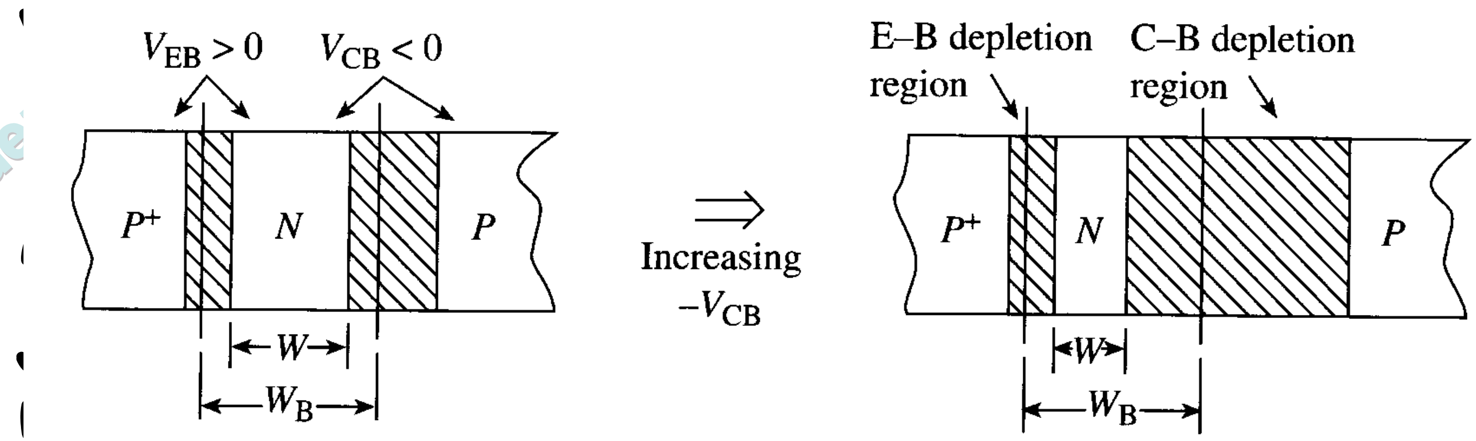
BJT – Real Characteristics

- **What's wrong with these pictures?**
- **Common Base:**
  - Input characteristic shows V_{CB} dependence
  - Output shows breakdown at V_{CBO}
- **Common Emitter**
  - Input characteristic pretty good agreement
  - Output characteristic:
    - Upward slope in I_C – quasilinear V_{EC} dependence
    - Breakdown at V_{CEO}
    - Upturn prior to breakdown

Base Width Modulation: Early Effect

- Base width has been assumed to be constant

- When bias voltages change, depletion widths change and the effective base width will be a function of the bias



- ... s ... junction

Base width gets smaller as applied voltages get larger

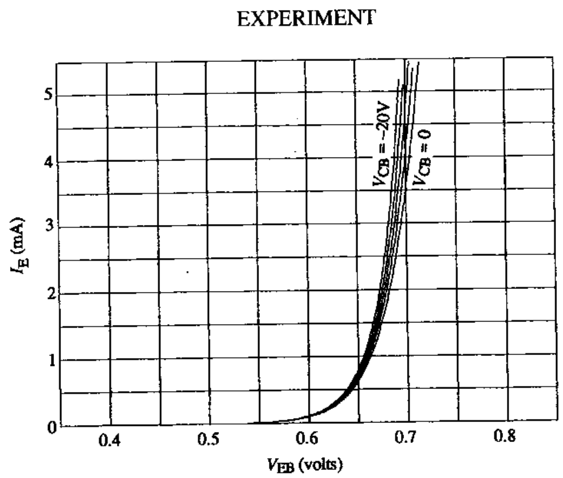
Early Effect: Common Base Input Characteristic

$$I_E = I_{F0}(e^{qV_{EB}/kT} - 1) - \alpha_R I_{R0}(e^{qV_{CB}/kT} - 1)$$ Ebers-Moll

Assuming $-V_{CB}$ > few kT/q and $W/L_B \ll 1$

$$I_{F0} \equiv qA\left(\frac{D_E}{L_E}n_{E0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh\left(\frac{W}{L_B}\right)}{\sinh\left(\frac{W}{L_B}\right)}\right) \cong qA\frac{D_B}{W}p_{B0}$$

$$I_E \cong I_{F0}e^{qV_{EB}/kT} = qA\frac{D_B}{W}p_{B0}e^{qV_{EB}/kT}$$



(b)

- **Exponential prefactor will increase as V_{CB} increases (W decreases)**

Early Effect: Common Emitter Output Characteristic

$$I_C = \beta_{dc} I_B + I_{CE0} \qquad \beta_{dc} = \frac{1}{\dfrac{D_E}{D_B}\dfrac{W}{L_E}\dfrac{N_B}{N_E} + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2}$$

$$W_{eff} = W - W_{EB}\big|_{Base} - W_{CB}\big|_{Base} \cong W - W_{CB}\big|_{Base}$$

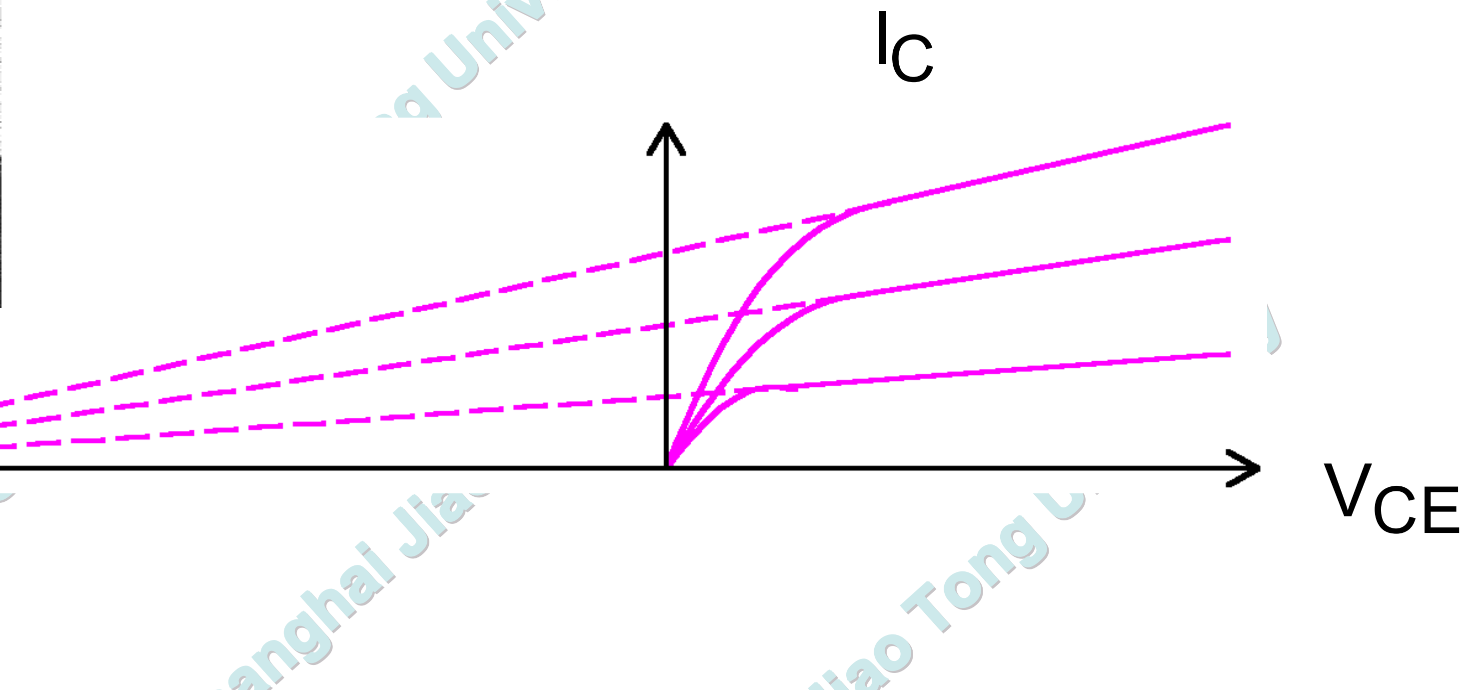
$$W_{CB} = \left[\frac{2K_S\varepsilon_0}{q}\frac{(N_A + N_D)}{N_D N_A}(V_{bi} - V_{CB})\right]^{1/2}$$

$$W_{CB}\big|_{Base} = x_n = W\big|_{Base}\left(\frac{N_C}{N_C + N_B}\right)$$

- If $N_C \ll N_B$ most of the depletion is in the collector and modulation of base width is minimized – reduced Early Effect

Early Voltage

J M Early



Converge ~ at single point called "Early Voltage" (after James Early)

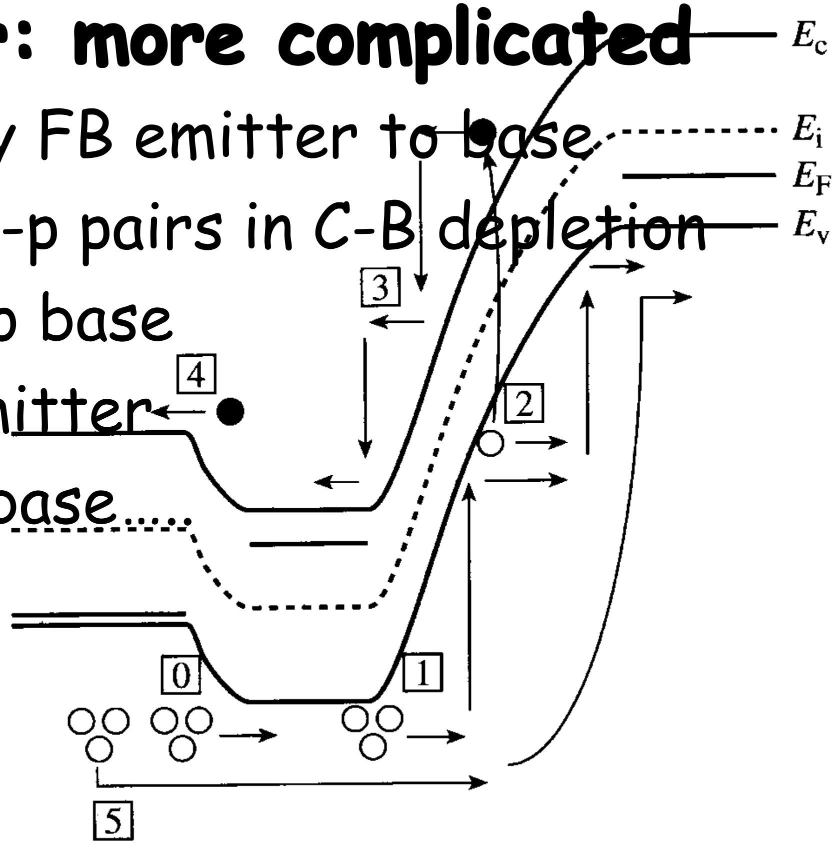
Large "Early Voltage" = Absence of "Base Width Modulation"

= Transistor ~ immune to operating voltage changes

BUT requires wide base => lower gain

Avalanche Multiplication Breakdown

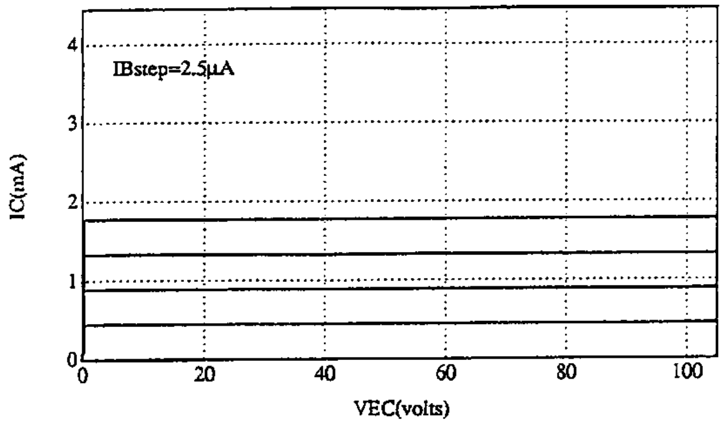
- Common Base: Similar to single p-n junction $V_{CBO} \approx V_{BD}(B\text{-}C)$
- Common Emitter: more complicated
  1. holes injected by FB emitter to base
  2. holes generate e-p pairs in C-B depletion
  3. e- drift back into base
  4. e- injected to emitter
  5. more holes into base.....



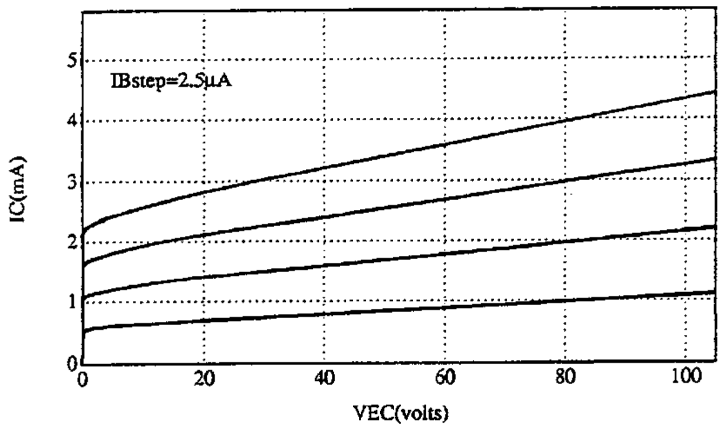
Avalanche Breakdown: Common Emitter

$$I_C = \beta_{dc} I_B + I_{CB0} \rightarrow \frac{M\alpha_{dc}}{1 - M\alpha_{dc}} I_B + \frac{I_{CB0}}{1 - M\alpha_{dc}}$$

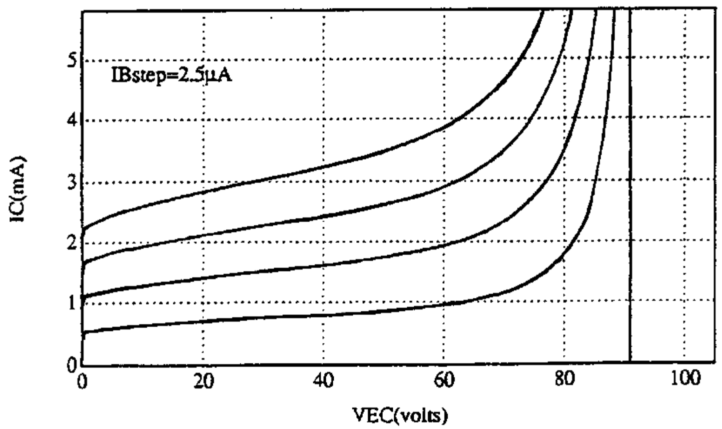
- **$I_C \rightarrow \infty$ when $M \rightarrow 1/\alpha_{dc}$**
- **M only needs to be slightly greater than unity**
- **$V_{CEO} < V_{CB0}$ – Breakdown voltage is lower for common Emitter mode than common**



Ideal



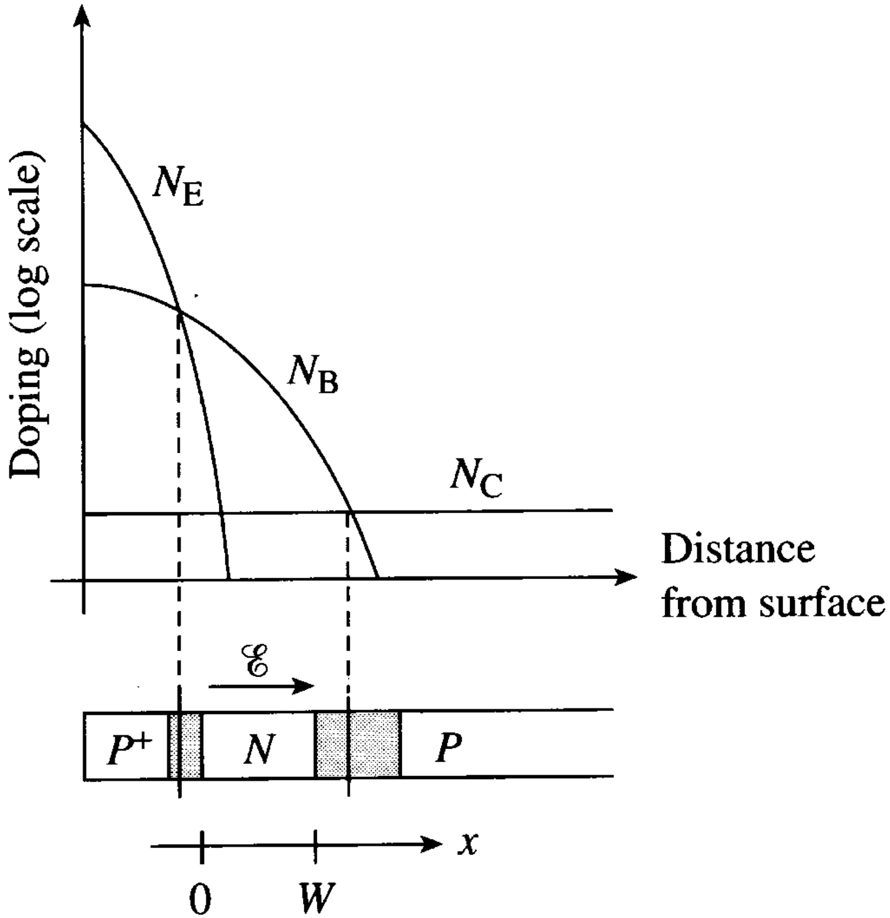
W/base width mod
Early Effect



W/base width mod
& avalanche
multiplication

How can we mitigate these effects?

Graded Base



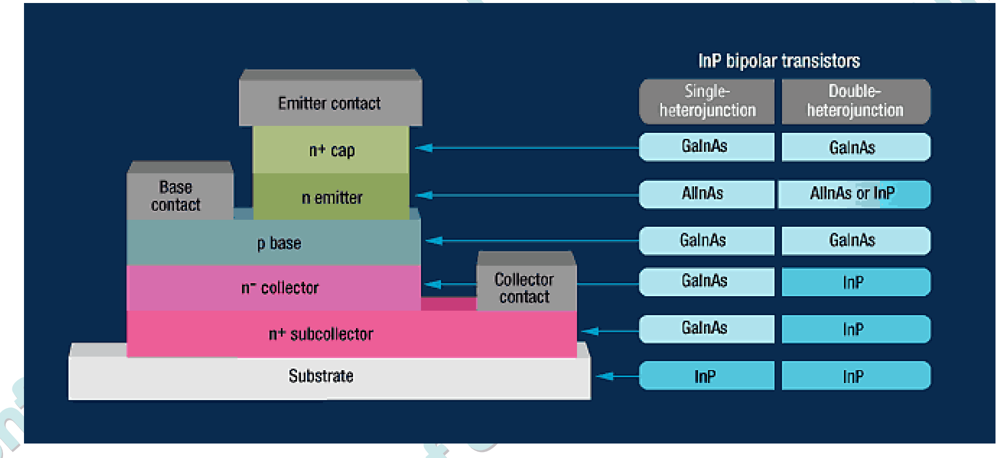
- Implant or diffusion leads to doping profile
- Doping profile leads to E field
- If Emitter is on top layer – E field acts to push carriers toward the collector
- Improved speed if limited by base transport time

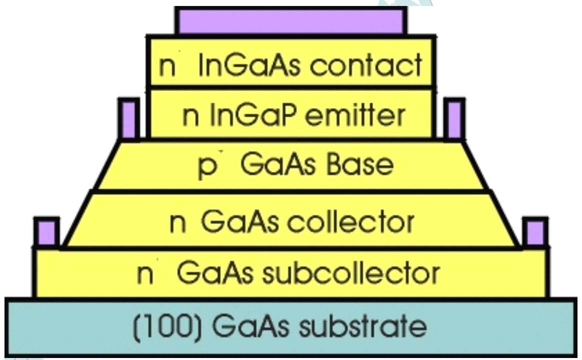
$$\vec{E} = -\frac{kT}{q}\frac{1}{N_B(x)}\frac{dN_B(x)}{dx}$$

Si-Ge HBT's for BiCMOS

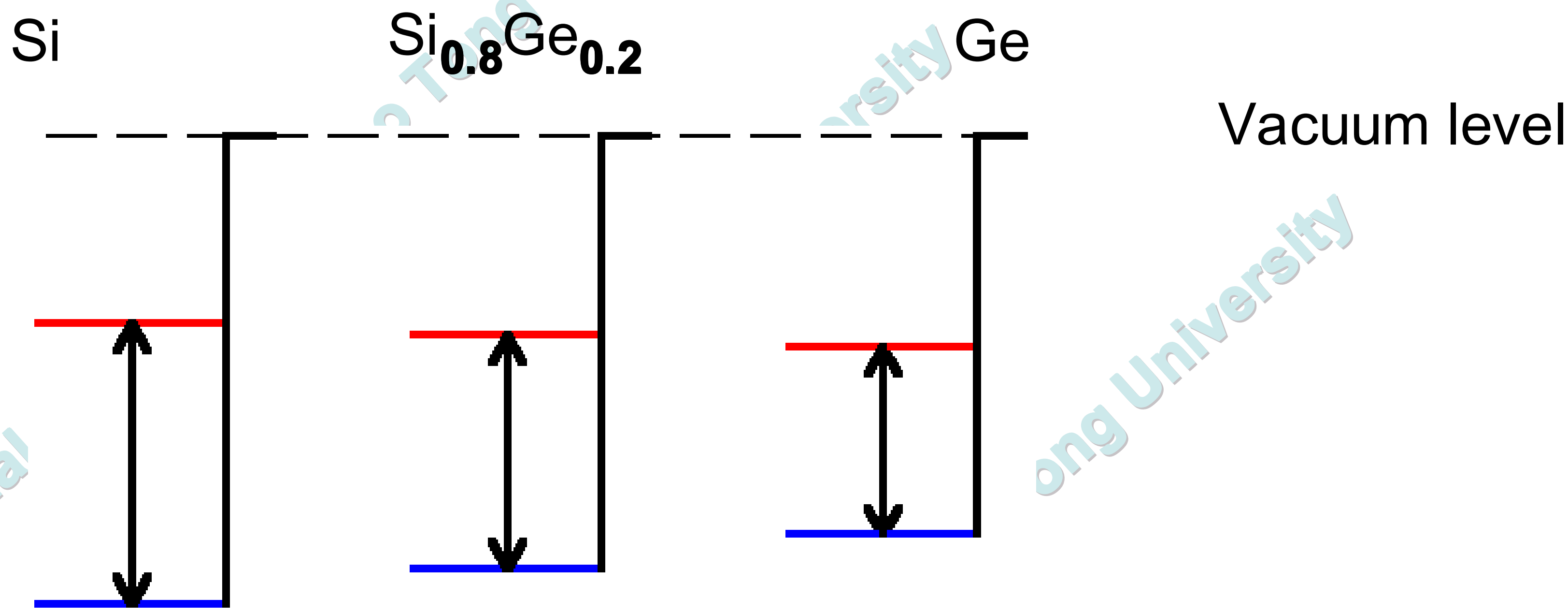
- **Dilemma for bipolar transistors:**
  - For high frequency operation want low base resistance - high base doping
  - For high current gain want to minimize hole injection into emitter (npn) - low base doping
- **Solution HBT - heterojunction bipolar transistors**
- **For CMOS integration use $Si_{1-x}\,Ge_x$ system**
  - Bandgap difference (1.12 eV Si, 1.0 eV, $Si_{0.8}Ge_{0.2}$)
  - 80% ΔE_G in VB

Si-Ge HBT's for BiCMOS





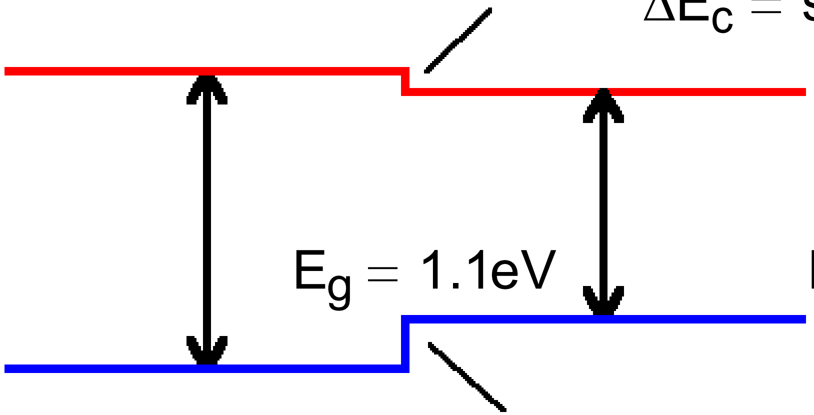
Bandgaps and alignments



Si-Ge Heterostructure

Silicon: $Si_{0.8}Ge_{0.2}$:

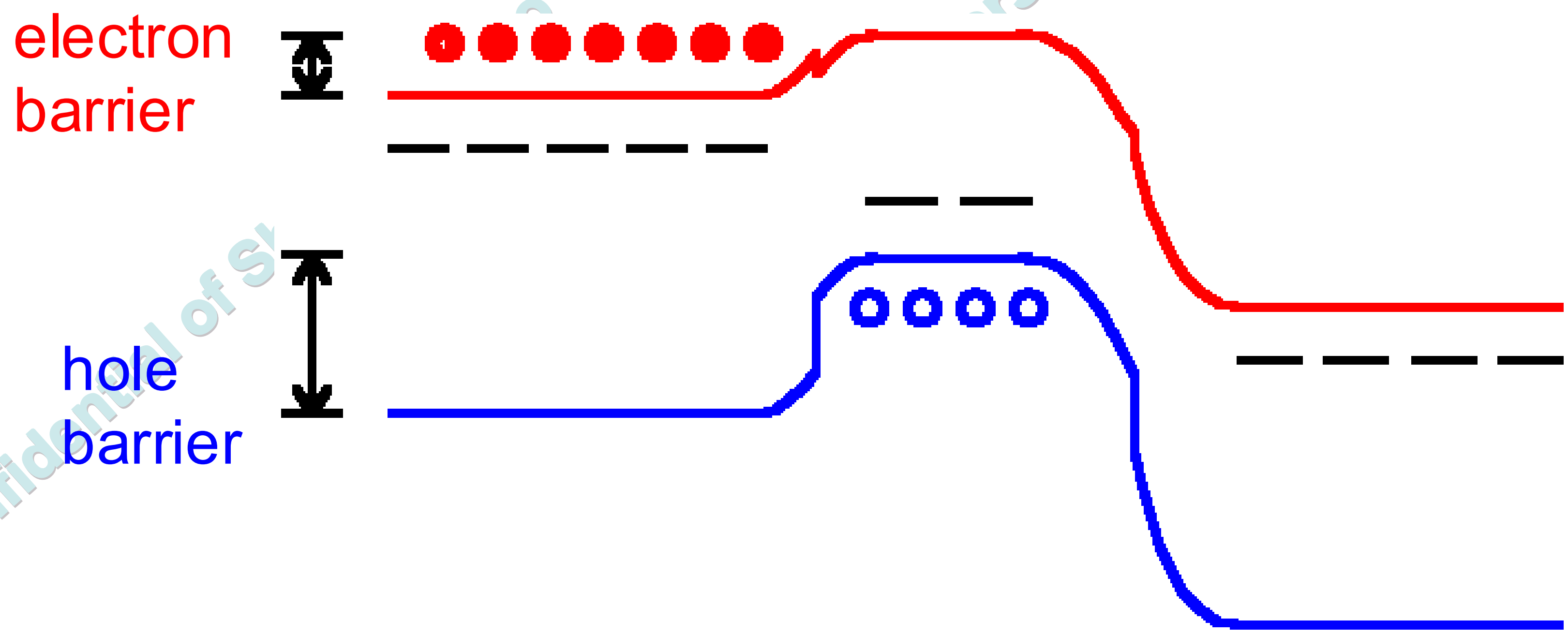
ΔE_C = small = 20% of ΔEg



ΔE_V = large = 80% of ΔEg

- **Most of the bandgap difference shows up in the valence band**

Band Diagram for SiGe HBT



Hole barrier is higher by ~ ΔE_V ~ 0.1 eV!!

Si-Ge HBT's

For $\Delta E_V \sim 0.1$ eV, new exponential multiplier equals:

$$\sim e^{\frac{-\Delta E_V}{k \cdot T}} = e^{\frac{0.1}{0.0259}} = \frac{1}{50}$$

SiGe Heterojunction cuts backward hole injection by ~ 50:

Use higher gain if needed

If more gain not needed, increase BASE DOPING by 50

- Retain gain of previous pure Si transistor

- Reduce "base resistance"

=> more efficient operation

=> FASTER operation (reduced R-C charging time)

Si-Ge HBT's

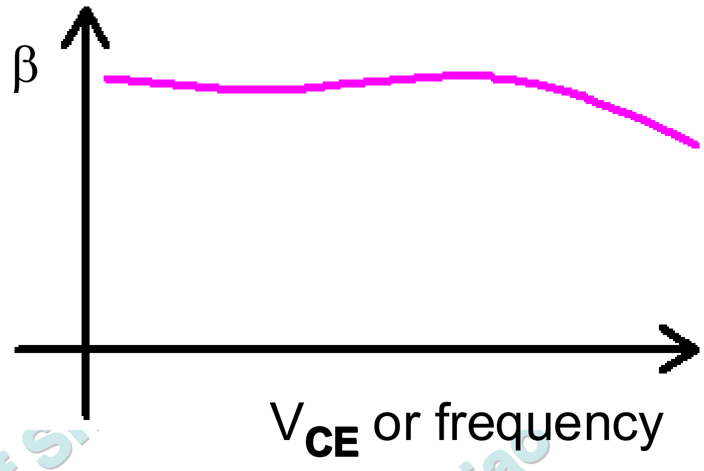
$$\beta_{dc} = D_B L_E N_E / D_E W N_B$$

$$\beta_{dc} = D_B L_E (n_i^2/N_B) / D_E W (n_i^2/N_E)$$

$$\beta^{HBT}_{dc} = \beta_{dc} (n^{Si}_i)^2 / (n^{Ge}_i)^2$$

$$= \beta_{dc}\, e^{(E^{Ge}_G - E^{Si}_G)/2kT}$$

Gain Plots



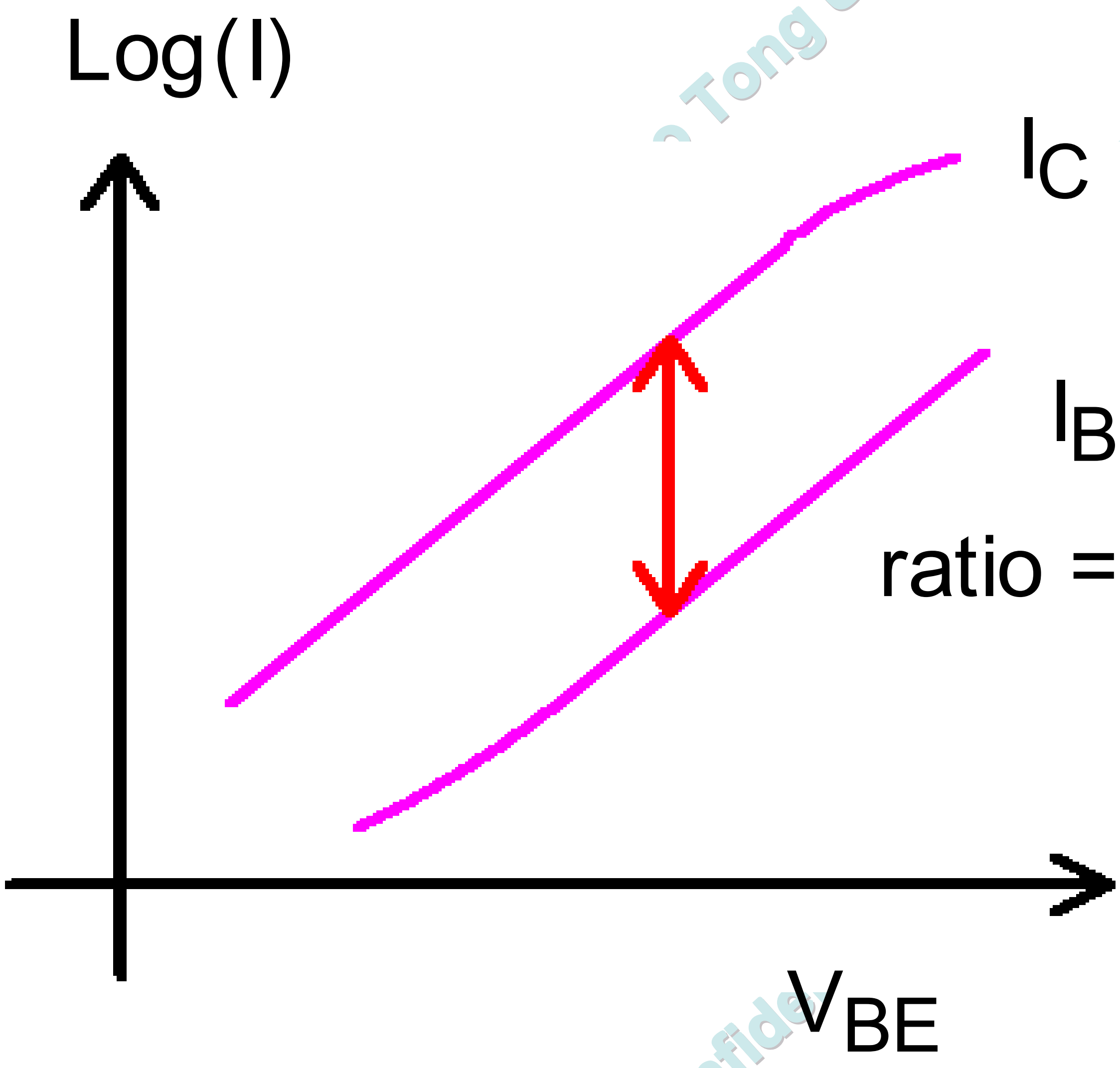
On frequency versions can plot either.

Power gain => rolls downward at frequency = " f_{max} "

Current gain => rolls downward at frequency = " f_t "

(Have seen designers ~ come to blows over which more important!)

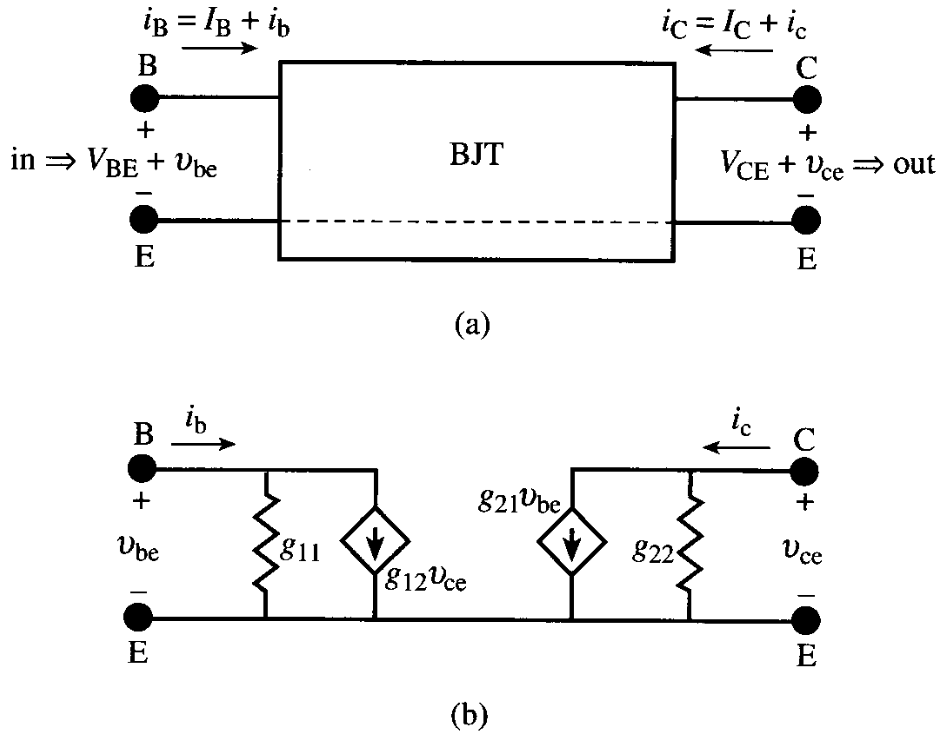
Gummel Plot



Hermann-Gummel

BJT Small Signal Response

- Assume the transistor can follow AC voltages and currents quasistatically (frequency not too high). Also neglect cap ... other par



Common Emitter equivalent circuit model

BJT Small Signal Response

$$I_B = I_B(V_{BE}, V_{CE})$$

$$I_B(V_{BE} + v_{be}, V_{CE} + v_{ce}) = I_B(V_{BE}, V_{CE}) + \left.\frac{\partial I_B}{\partial V_{BE}}\right|_{V_{CE}} v_{be} + \left.\frac{\partial I_B}{\partial V_{CE}}\right|_{V_{BE}} v_{ce}$$

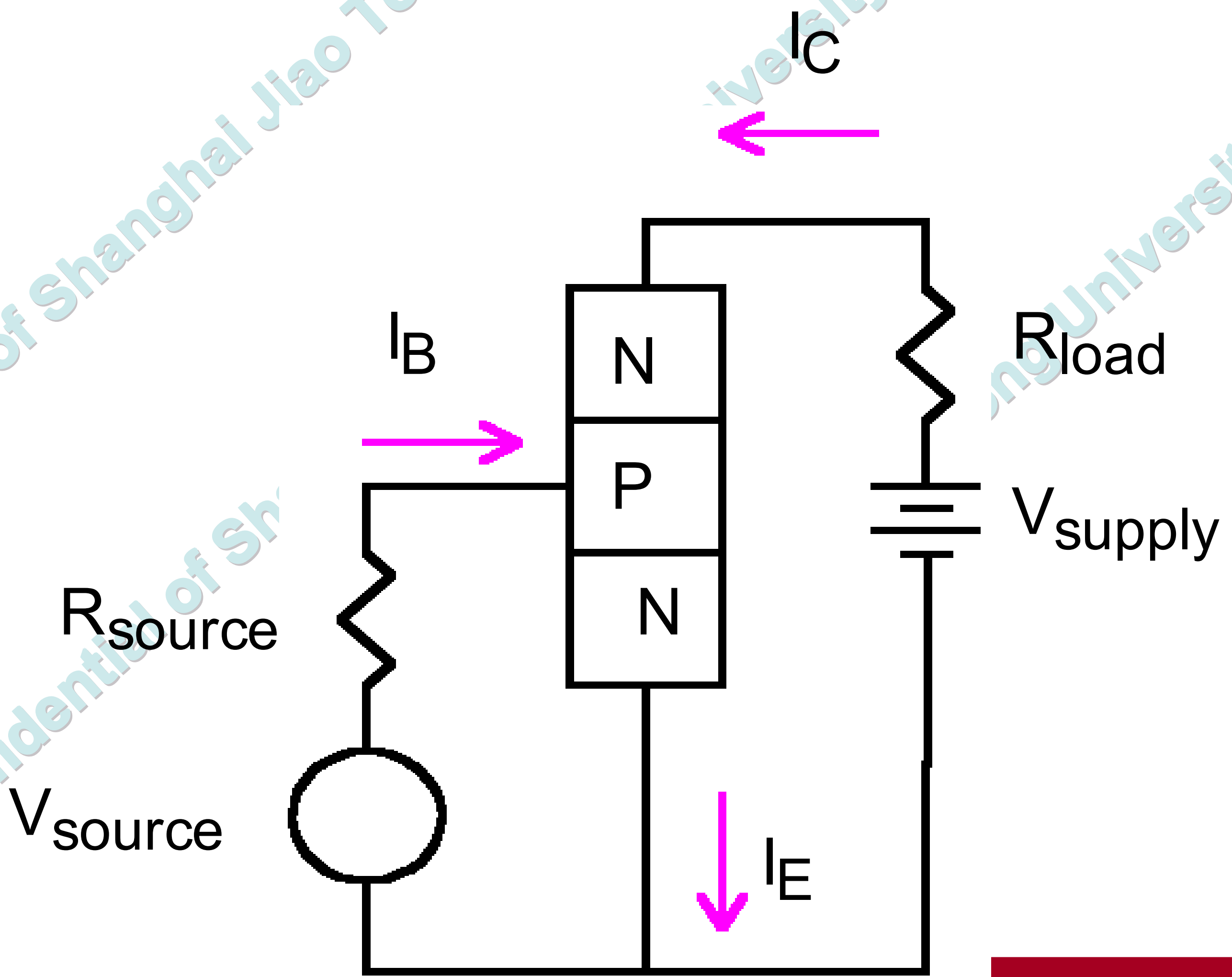
$$I_C = I_C(V_{BE}, V_{CE})$$

$$I_C(V_{BE} + v_{be}, V_{CE} + v_{ce}) = I_C(V_{BE}, V_{CE}) + \left.\frac{\partial I_C}{\partial V_{BE}}\right|_{V_{CE}} v_{be} + \left.\frac{\partial I_C}{\partial V_{CE}}\right|_{V_{BE}} v_{ce}$$

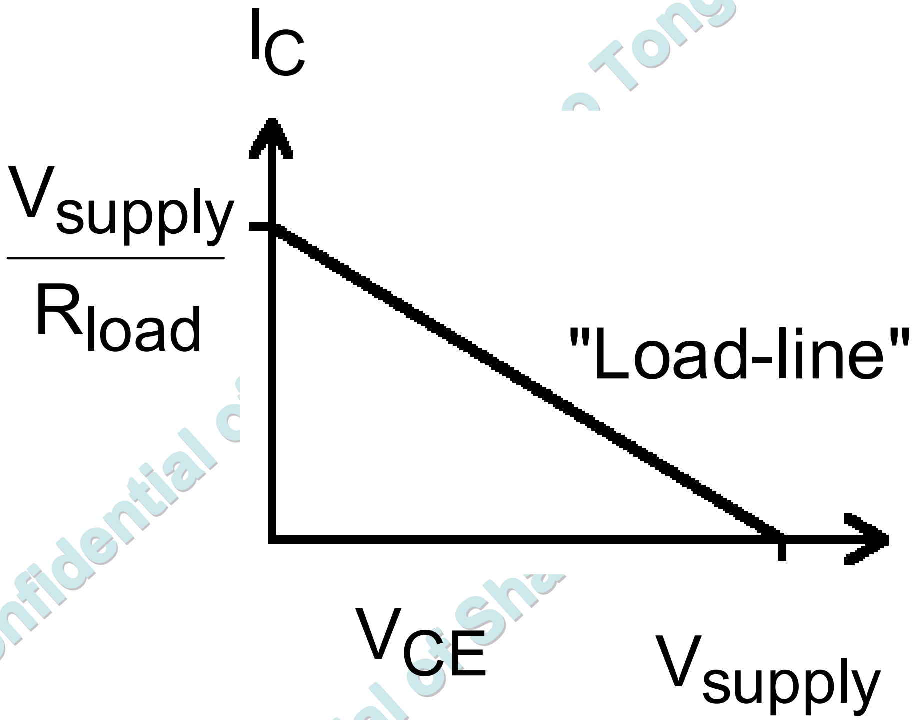
$$i_b = g_{11} v_{be} + g_{12} v_{ce}$$
$$i_c = g_{21} v_{be} + g_{22} v_{ce}$$

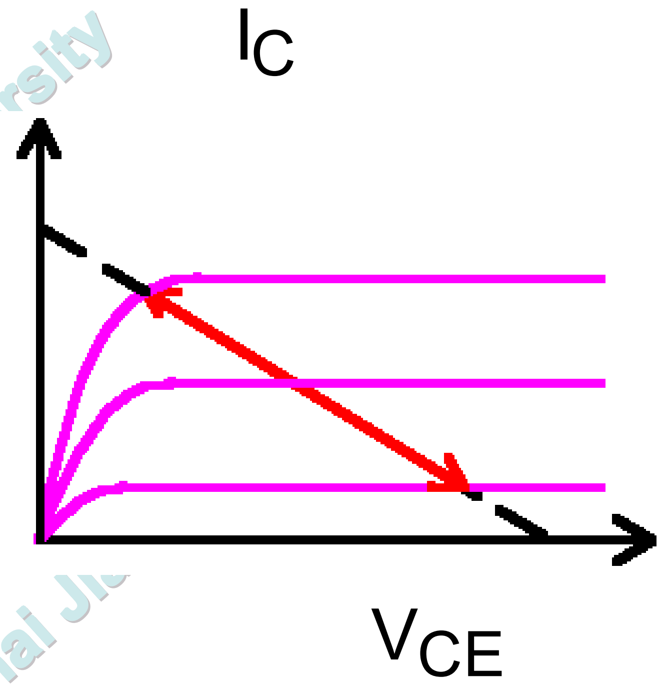
BJT Transient Behavior

As with diodes, switching often limited by external circuit:

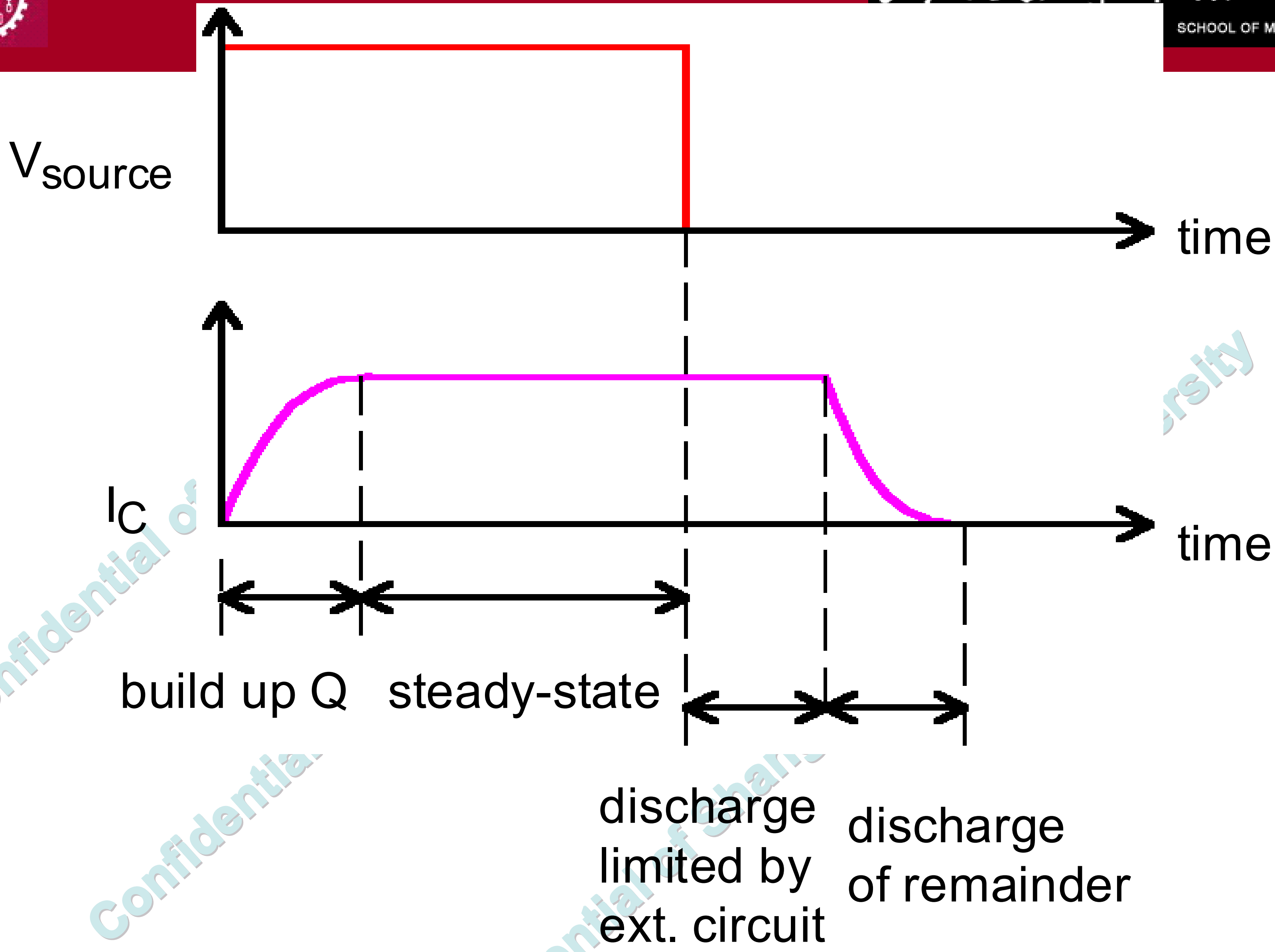


Right Circuit Loop:





Transistor is constrained by load-line:


Vsource
time
IC
time
build up Q
steady-state
discharge
limited by
ext. circuit
discharge
of remainder