

ĐHBK Tp HCM-Khoa Đ-ĐT  
BMĐT  
GVPT: Hồ Trung Mỹ  
Môn học: Dụng cụ bán dẫn

## Chương 5

# BJT

1

cuu duong than cong . com

### 5.6 Đáp ứng tần số và hoạt động chuyển mạch của BJT

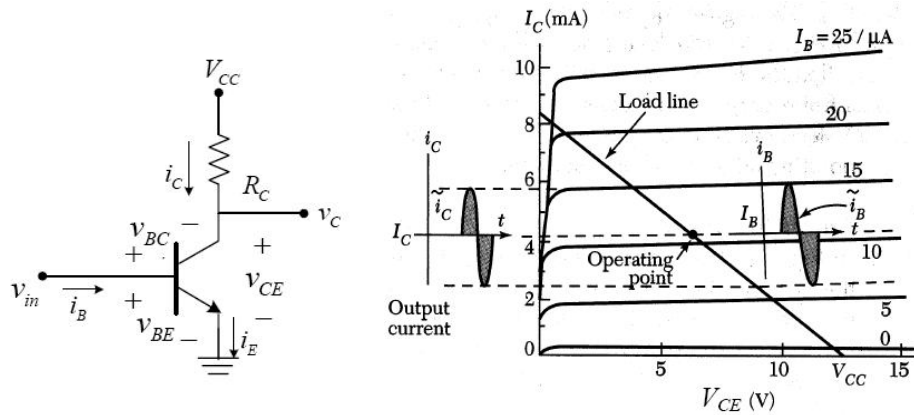
#### 5.6.1 Đáp ứng tần số

- Mạch tương đương tần số cao
- Tần số cắt (cutoff frequency)

cuu duong than cong . com

2

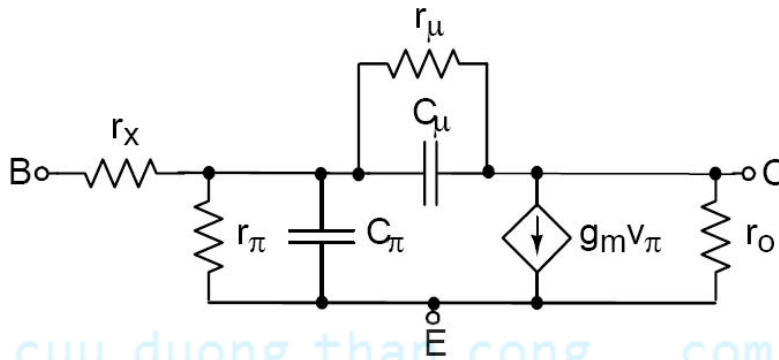
## Mạch KĐ CE – Hoạt động tín hiệu nhỏ



3

cuu duong than cong . com

## Mạch tương đương tần số cao



$r_\mu, C_\mu (=C_{bc})$ : tương đương tín hiệu nhỏ của  $J_C$  phân cực ngược

$r_\pi, C_\pi (=C_{be})$ : tương đương tín hiệu nhỏ của  $J_E$  phân cực thuận

$r_o$ : điện trở của BJT CE

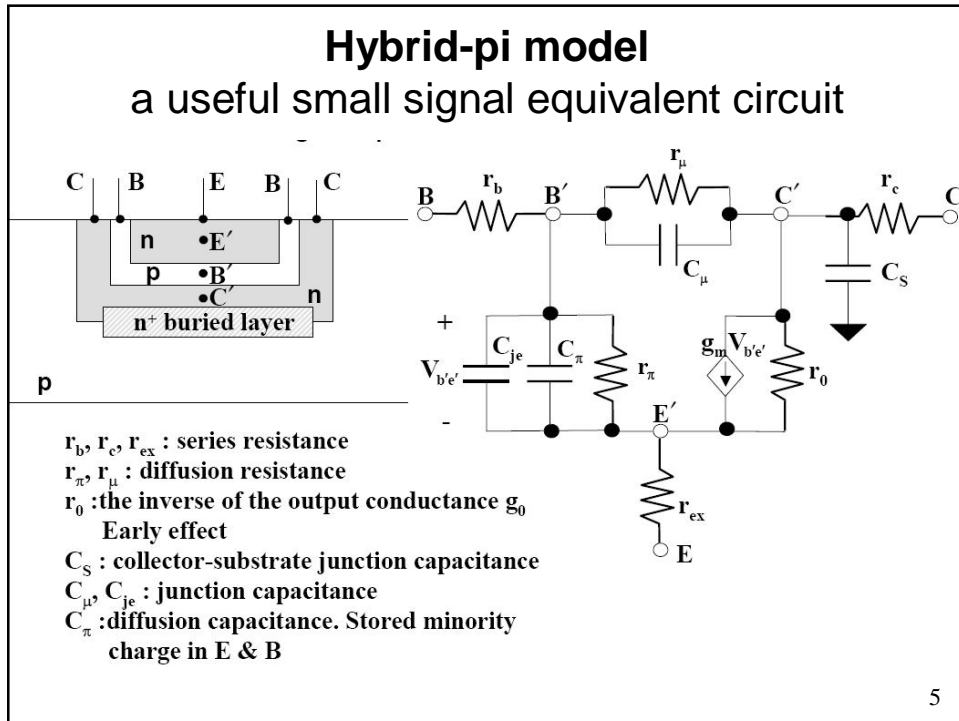
$r_x$ : điện trở tại miền nền trung hòa (bỏ qua trong tần số trung bình)

Các giá trị thực tế của các tham số:  $r_\mu$  rất lớn (có thể xem như hở mạch),

$C_\mu = 1-5\text{pF}$ ,  $C_\pi = 5-50\text{pF}$

4

cuu duong than cong . com



cuu duong than cong . com

## Các giới hạn tần số hoạt động

### (1) Các yếu tố làm trễ

Thời hằng tổng cộng từ E đến C hay thời gian trễ

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

với

$\tau_e$  : thời gian nạp điện dung tiếp xúc  $j_E$

$\tau_b$  : thời gian đi qua miền nền

$\tau_d$  : thời gian đi qua miền nghèo ở miền thu (collector)

$\tau_c$  : thời gian nạp điện dung ở collector

6

(a) Thời gian nạp điện dung tiếp xúc  $j_E$

$$\tau_e = r_e'(C_{je} + C_p)$$

với

$$r_e' = \frac{kT}{e} \frac{1}{I_E} : \text{Điện trở khuếch tán tại tiếp xúc } J_E$$

$C_{je}$  : Điện dung khuếch tán

$C_p$  : Điện dung ký sinh giữa B và E

(b) Thời gian đi qua miền nền

Với transistor NPN, mật độ dòng điện tử ở miền nền:

$$J_n = -en_B(x)v(x)$$

$$v(x) = dx/dt \text{ hay } dt = dx/v(x)$$

$$\tau_b = \int_0^{x_B} dt = \int_0^{x_B} dx/v(x) = \int_0^{x_B} en_B(x)dx/(-J_n) = \frac{|Q_B|}{|J_n|}$$

$$= \frac{x_B^2}{2D_n} \quad \left\{ \begin{array}{l} n_B(x) \cong n_{B0}[\exp(V_{BE}/V_t)](1-x/x_B) \\ J_n = eD_n \frac{dn_B(x)}{dx} \end{array} \right.$$

7

cuuduongthancong.com

(c) Thời gian đi qua miền nghèo ở miền thu (collector)

Điện tử đi qua miền điện tích không gian B-C với tốc độ bão hòa của chúng trong transistor NPN

$$\tau_d = x_{dc} / 2v_s$$

Với  $x_{dc}$  là bề rộng miền điện tích không gian B-C và  $v_s$  là vận tốc bão hòa.

(d) Thời gian nạp điện dung ở collector

$$\tau_c = r_c(C_\mu + C_s)$$

với

$r_c$  : Điện trở nối tiếp ở miền thu

$C_\mu$  : Điện dung ở tiếp xúc  $J_C$

$C_s$  : Điện dung từ miền thu đến đế (substrate) của transistor

8

cuuduongthancong.com

(2) Tần số cắt (cutoff frequency) của transistor

Độ lợi dòng CB

$$\alpha = \frac{\alpha_0}{1 + j \frac{f}{f_\alpha}}$$

$\alpha_0$  : Độ lợi dòng CB tần thấp

$$f_\alpha = \frac{1}{2\pi\tau_{ec}} : \text{Tần số cắt alpha}$$

$$\begin{aligned} \beta &= \frac{\alpha}{1 - \alpha} = \frac{\frac{\alpha_0}{1 + j \frac{f}{f_\alpha}}}{1 - \frac{\alpha_0}{1 + j \frac{f}{f_\alpha}}} \\ &= \frac{\alpha_0}{1 - \alpha_0 + j(f/f_\alpha)} \end{aligned}$$

9

cuuduongthancong.com

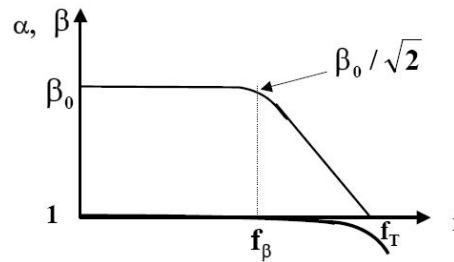
$$\begin{aligned} \beta &= \frac{\alpha_0}{(1 - \alpha_0)[1 + j \frac{f}{(1 - \alpha_0)f_\alpha}]} \\ [\beta_0 &= \frac{\alpha_0}{1 - \alpha_0} \cong \frac{1}{1 - \alpha_0}] \\ &\cong \frac{\beta_0}{1 + j \frac{\beta_0 f}{f_\alpha}} \end{aligned}$$

$$\Rightarrow f_\beta \cong \frac{f_T}{\beta_0} : \text{Tần số cắt beta}$$

Tần số cắt  $f_T$  được định nghĩa là tần số mà ở đó biên độ của độ lợi dòng CE là 1.

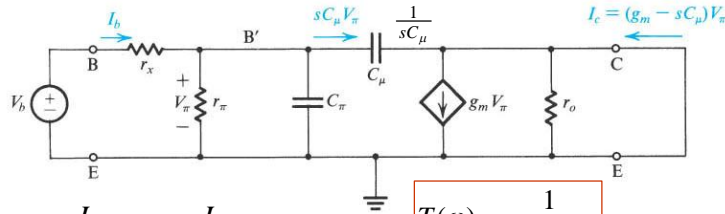
$$f_T = f_\alpha$$

**Chú ý:** Hiện nay BJT có  $f_T \sim 25\text{GHz}$   
HBT có  $f_T \sim 175\text{GHz}$



10

### Tính $f_T$ từ mô hình tương đương tần số cao



$$h_{fe} \equiv \frac{I_c}{I_b} \Leftrightarrow \beta = \frac{I_c}{I_b}$$

$$T(\omega) = \frac{1}{1 + \left(\frac{s}{\omega_0}\right)}$$

$$I_c = g_m V_\pi - \frac{V_\pi}{1/sC_\mu} = (g_m - sC_\mu)V_\pi$$

Tần số -3dB

$$\omega_\beta = \frac{1}{(C_\pi + C_\mu)r_\pi}$$

$$I_b = \frac{V_\pi}{(r_\pi // C_\pi // C_\mu)}$$

Hiện nay BJT có  $f_T \sim 25\text{GHz}$   
HBT có  $f_T \sim 25\text{GHz}$

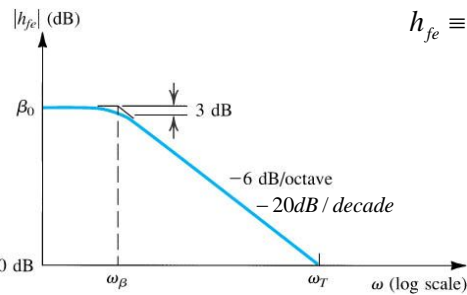
$$h_{fe} \equiv \frac{I_c}{I_b} = \frac{g_m - sC_\mu}{1/r_\pi + s(C_\pi + C_\mu)}$$

$\beta$  tần số thấp

$$\Rightarrow h_{fe} \approx \frac{g_m r_\pi}{1 + s(C_\pi + C_\mu)r_\pi} = \frac{\beta_0}{1 + s(C_\pi + C_\mu)r_\pi}$$

11

cuuduongthancong.com



$$h_{fe} \equiv \frac{I_c}{I_b} = \frac{\beta_0}{1 + s(C_\pi + C_\mu)r_\pi} \Leftrightarrow \frac{1}{1 + s/\omega_\beta}$$

$$20 \log \beta - 20 \log \sqrt{1 + (\omega_T/\omega_\beta)^2} = 0$$

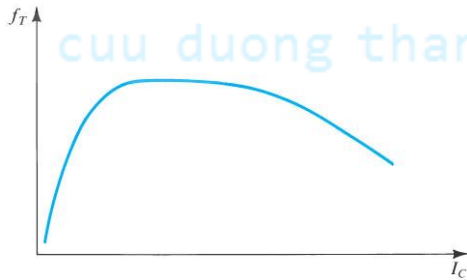
$$\beta = \sqrt{1 + (\omega_T/\omega_\beta)^2}$$

$$\omega_T \approx \omega_\beta \beta \because \beta \gg 1$$

Bảng thông độ lợi đơn vị

$$\omega_T \approx \omega_\beta \beta = \frac{g_m}{C_\pi + C_\mu}$$

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

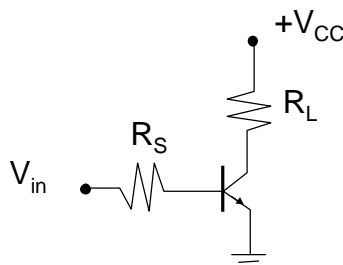


12

cuuduongthancong.com

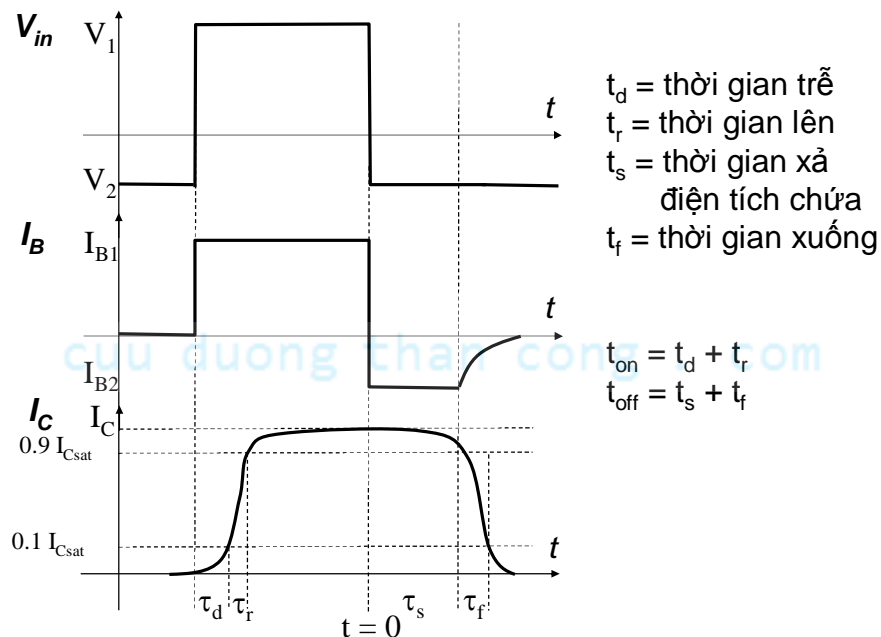
## 5.6.2 Hoạt động chuyển mạch của BJT

- ⊙ BJT có thể hoạt động như một khóa (công tắc) giữa trạng thái dòng thấp-áp cao và trạng thái dòng cao-áp thấp.
- ⊙ Trạng thái tắt (OFF) tương ứng với chế độ tắt của BJT, trái lại trạng thái dẫn (ON) tương ứng với chế độ bão hòa.
- ⊙ Mạch tiêu biểu để đo đặc tính chuyển mạch như sau:



13

cuu duong than cong . com



14

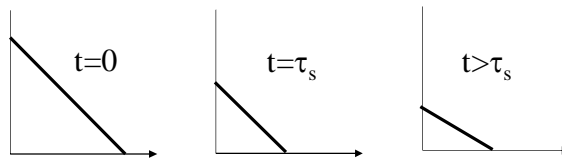
- ⊙ Khi đưa vào điện áp  $V_1$ , dòng nền  $I_{B1}$  được cho bởi:

$$I_{B1} = (V_1 - V_{BEsat}) / R_S$$

- ⊙ Khi xung vào bị chuyển sang tắt và điện áp vào giảm xuống giá trị âm  $V_2$ , dòng nền có trị số mới:

$$I_{B2} = (V_2 - V_{BEsat}) / R_S$$

- ⊙ Dòng nền giữ nguyên giá trị này gần như trong toàn bộ thời gian xả điện tích chứa, nghĩa là, khi phân bố hạt dẫn thiểu số trong miền nền vẫn còn tương ứng với chế độ bão hòa. Sau thời gian xả điện tích chứa, phân bố hạt dẫn thiểu số chuyển sang chế độ tích cực bình thường của nó.



15

cuuduongthancong.com

- ⊙ Sau  $t = \tau_s$ , điện áp emitter bắt đầu giảm và

$$I_B = (V_2 - V_{BE}) / R_S \Rightarrow I_B = 0 \text{ when } V_{BE} = V_2$$

- ⊙ Thời gian xả điện tích chứa là một trong những thời gian quan trọng nhất làm giới hạn tốc độ chuyển mạch của BJT. Để ước lượng thời gian này, ta thấy rằng BJT bị lái vào bão hòa khi

$$I_C = (V_{CC} - V_{CEsat}) / R_L \approx V_{CC} / R_L$$

- ⊙ Từ đó, BJT bị lái vào bão hòa khi

$$I_B \geq I_{ba} \approx \frac{V_{CC}}{R_L h_{fe}}$$

- ⊙ Một khi bão hòa, dòng collector là  $I_C = V_{CC} / R_L$ . Trong lúc xảy ra xả điện tích chứa, dòng collector giữ gần như không đổi cho đến khi BJT vào miền tích cực. Thời gian xả điện tích chứa (storage time) là thời gian cần cho điện tích trong miền nền  $Q_{bs}$  giảm xuống giá trị của điện tích  $Q_{ba}$  tương ứng với chế độ tích cực.

16

cuuduongthancong.com



- ⊙ Khi BJT ở chế độ tích cực,  $I_C$  giảm theo thời gian. Hiệu số của dòng nền ở chế độ bão hòa và tích cực là:

$$\Delta I_{bs} = I_{bs} - I_{ba} = I_{bs} - V_{CC} / (h_{fe} R_L)$$

- ⊙ Từ phương trình điều khiển điện tích

$$I_{bs} = \Delta Q_{bs} / \tau_{sr} + d\Delta Q_{bs} / dt$$

người ta có thể ước lượng thời gian xả điện tích chứa là:

$$\tau_s = \tau_{sr} \ln \left[ \frac{I_{b1} - I_{b2}}{I_{ba} - I_{b2}} \right]$$

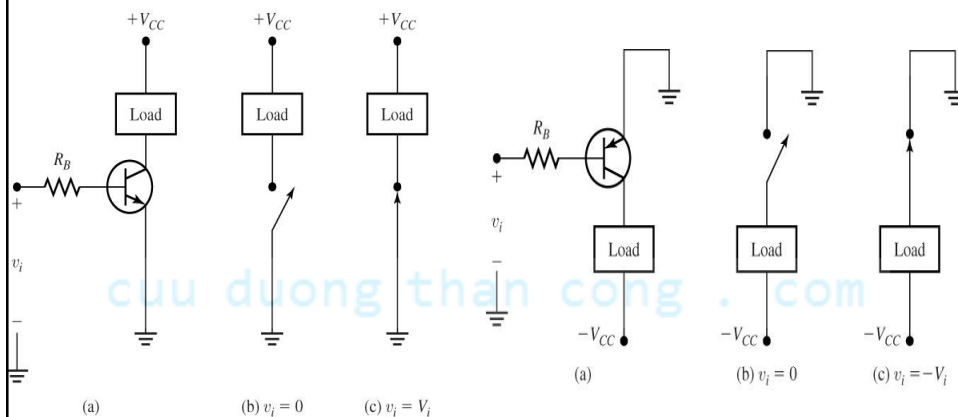
- ⊙ Khi  $t > \tau_s$ , phương trình điều khiển điện tích trở thành:

$$I_b = \frac{Q_b}{\tau_{nl}} + \frac{dQ_b}{dt} \rightarrow Q_b = Aq n_{po} W e^{V_{BE}/V_T} / 2$$

17

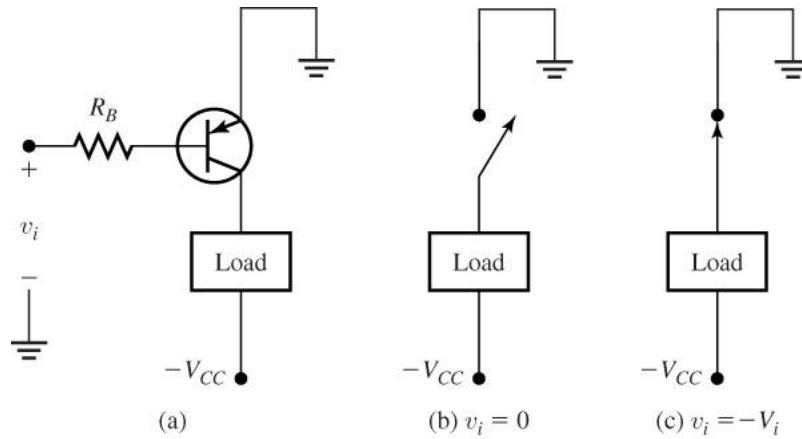
cuuduongthancong.com

## Khóa điện tử dùng BJT



18

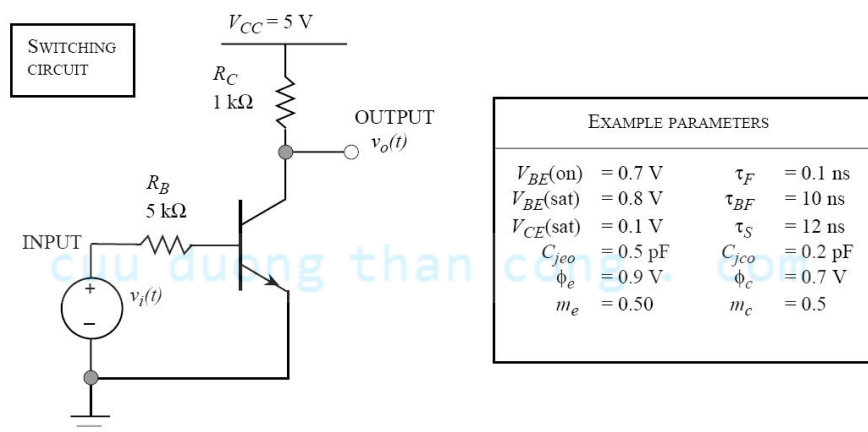
## BJT switch using a PNP transistor.



19

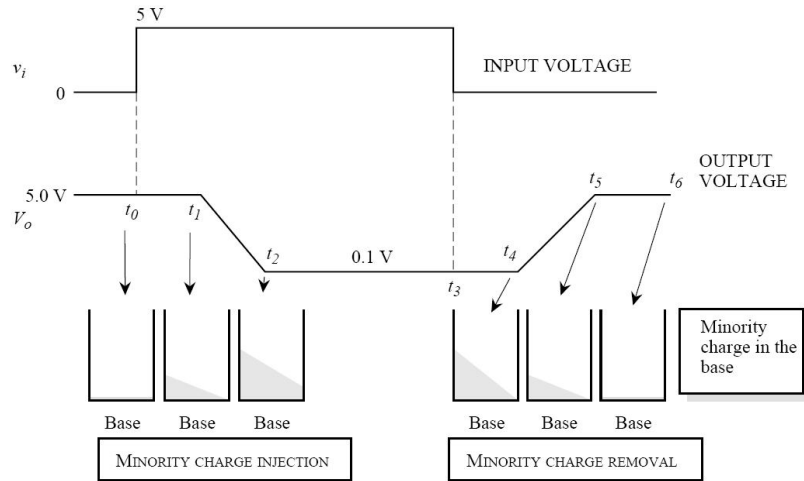
cuu duong than cong . com

## SWITCHING DELAYS IN A BJT (1/2)



20

## SWITCHING DELAYS IN A BJT (2/2)

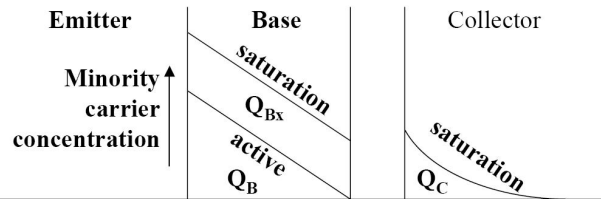


IMPORTANT ISSUE: Avoid going into deep saturation.

21

cuu duong than cong . com

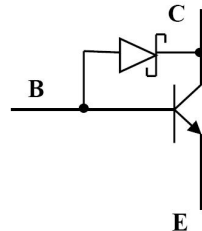
## Large-signal switching



$Q_B$  : excess charge stored in a forward-active transistor

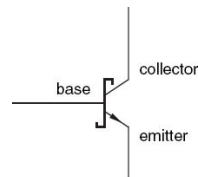
$Q_{Bx}$  &  $Q_C$  : extra charges stored when transistor is biased in saturation

The Schottky clamped transistor



- Reduce the storage time
- Increase the switching speed

Ký hiệu



22

## Schottky transistor

- The Schottky diode is a majority carrier device, which means its transient response is much faster than that of bipolar devices.
- The properties of the Schottky diode are used to speed up the response of the BJT.
- The metal makes an Ohmic contact to the base, but forms a Schottky barrier on the collector.
  - When the transistor is in cutoff (or active) mode, the base collector and the Schottky diode are reverse biased. The Schottky diode thus has no influence on the device.
  - When the transistor starts to go to saturation, the diode becomes forward biased and the voltage across the base-collector is clamped to the forward ON-bias of the diode.

23

[cuu duong than cong . com](http://cuuduongthancong.com)

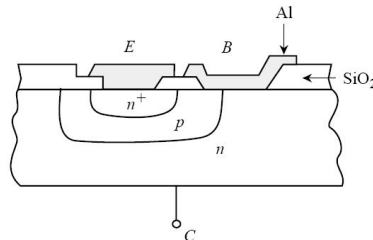
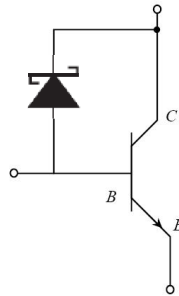
## Schottky transistor

- The turn-ON voltage of the Schottky diode is much smaller than that of the base-collector junction. The diode allows the excess base current to pass through it.
- The device will therefore not go into saturation mode and the extraction of the excess charge becomes fast.
- The device can now be switched in a much shorter time.
- The faster switching of the Schottky-clamped device arises from the time needed to remove saturation charge during device turn-OFF.
- The Schottky transistor is an important component of the non-saturated bipolar logic and is used in applications where speed is important.

24

## Schottky transistor

•MOTIVATION: Do not let the transistor go into deep saturation during switching.

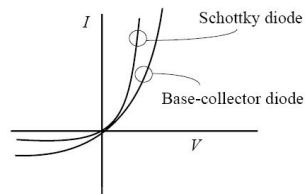


• Collector-Base reverse biased  
Schottky diode is reverse biased

• Collector-Base forward biased  
Schottky diode turns ON  
and collector is bypassed

Schottky diode is turned ON at a voltage smaller than what it takes the CBJ to be in the saturated mode

Al makes an ohmic contact to the *p*-type base and a Schottky contact to the *n*-type collector



25

cuu duong than cong . com

## 5.7 Các mô hình của BJT

### 1. Mô hình tín hiệu lớn

- Mô hình Ebers-Moll
- Mô hình Gummel-Poon

### 2. Mô hình tín hiệu nhỏ (dùng cho chế độ khuếch đại, tín hiệu nhỏ)

26

# Mô hình tín hiệu lớn

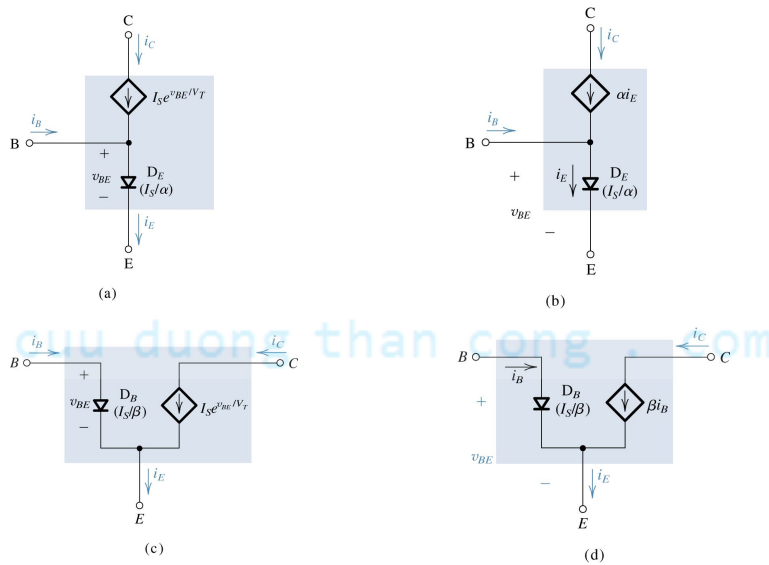
**The Models of NPN Transistor**

NPN	CUT-OFF	FORWARD ACTIVE	SATURATION
BE diode	OFF	ON	ON
BC diode	OFF	OFF	ON
Conditions to be satisfied	$V_{BE} < V_{BE(FA)}$ $V_{BC} < V_{BC(FA)}$	$V_{BC} < V_{BC(FA)}$ $I_B > 0$ ( $I_C > 0; I_E > 0$ )	$\beta_F I_B > I_C$ $\beta_R I_B > I_E$
Model			
	<b>OFF</b>	<b>ON</b>	<b>SAT</b>

27

cuu duong than cong . com

## Mô hình tín hiệu lớn của BJT – NPN (chế độ KĐ)



28

## 2.3 The BJT as an Amplifier

### ➤ Device Operation:

#### Operation in the Active Mode (for Amplifier Application)

Conditions:

1. EBJ Forward Biased

$$v_{BE} > V_{BEon}; V_{BEon} \cong 0.5 \text{ V}$$

$$v_{EB} > V_{EBon}; V_{EBon} \cong 0.5 \text{ V}$$

$$\text{Typically, } v_{BE} = 0.7 \text{ V}$$

$$\text{Typically, } v_{EB} = 0.7 \text{ V}$$

2. CBJ Reversed Biased

$$v_{BC} \leq V_{BCon}; V_{BCon} \cong 0.4 \text{ V}$$

$$v_{CB} \leq V_{CBon}; V_{CBon} \cong 0.4 \text{ V}$$

$$\Rightarrow v_{CE} \geq 0.3 \text{ V}$$

$$\Rightarrow v_{EC} \geq 0.3 \text{ V}$$

Current-Voltage Relationships

$$\blacksquare i_C = I_S e^{v_{BE}/V_T}$$

$$\blacksquare i_C = I_S e^{v_{EB}/V_T}$$

$$\blacksquare i_B = i_C / \beta \Leftrightarrow i_C = \beta i_B$$

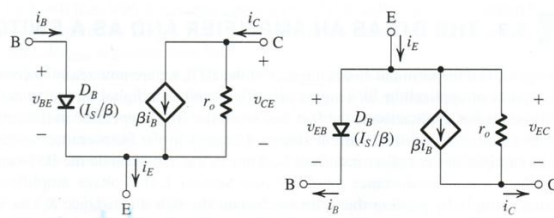
$$\blacksquare i_E = i_C / \alpha \Leftrightarrow i_C = \alpha i_E$$

$$\blacksquare \beta = \frac{\alpha}{1 - \alpha} \Leftrightarrow \alpha = \frac{\beta}{\beta + 1}$$

29

cuu duong than cong . com

Large-Signal Equivalent-Circuit  
Model (Including the Early  
Effect)



$$i_B = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_C = I_S e^{v_{BE}/V_T} \left(1 + \frac{v_{CE}}{V_A}\right)$$

$$r_o = V_A / (I_S e^{v_{BE}/V_T})$$

$$i_B = \left(\frac{I_S}{\beta}\right) e^{v_{EB}/V_T}$$

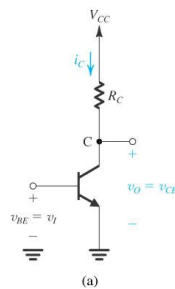
$$i_C = I_S e^{v_{EB}/V_T} \left(1 + \frac{v_{EC}}{|V_A|}\right)$$

$$r_o = |V_A| / (I_S e^{v_{EB}/V_T})$$

30

cuu duong than cong . com

➤ The Common-Emitter Operation:

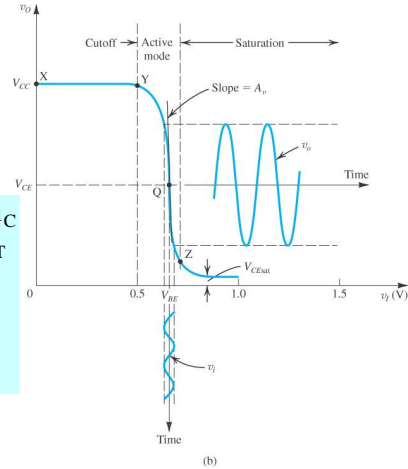


$$v_o = v_{CE} = V_{CC} - R_C i_C$$

$$= V_{CC} - R_C I_S e^{v_{BE}/V_T}$$

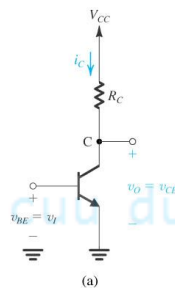
as  $v_{CE} = v_{CE,sat}$

$$I_{C,sat} = \frac{V_{CC} - V_{CE,sat}}{R_C}$$



**Figure 5.26** (a) Basic common-emitter amplifier circuit. (b) Transfer characteristic of the circuit in (a). The amplifier is biased at a point Q, and a small voltage signal  $v_i$  is superimposed on the dc bias voltage  $V_{BE}$ . The resulting output signal  $v_o$  appears superimposed on the dc collector voltage  $V_{CE}$ . The amplitude of  $v_o$  is larger than that of  $v_i$  by the voltage gain  $A_v$ .

31



As the collector current (neglect the Early effect)

$$I_C = I_S e^{v_{BE}/V_T}$$

then

$$v_o = v_{CE} = V_{CC} - R_C i_C$$

$$= V_{CC} - R_C I_S e^{v_{BE}/V_T}$$

The Amplifier (voltage) gain is

$$A_v \equiv \left. \frac{dv_o}{dv_i} \right|_{v_i = V_{BE}} = -\frac{1}{V_T} (I_S e^{v_{BE}/V_T}) R_C$$

$$= -\frac{I_C R_C}{V_T}$$

That is, the output signal is  $180^\circ$  out of phase relative to the input signal. The maximum available voltage gain is

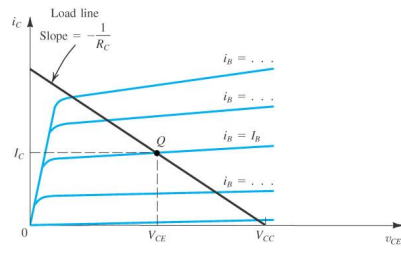
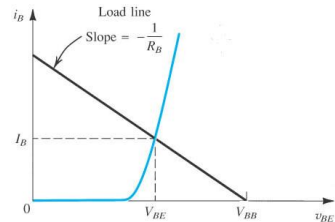
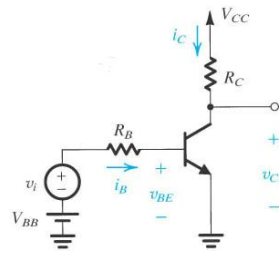
$$A_{v,max} \cong -\frac{V_{CC} - V_{C,sat}}{V_T} \approx -\frac{V_{CC}}{V_T}$$

32



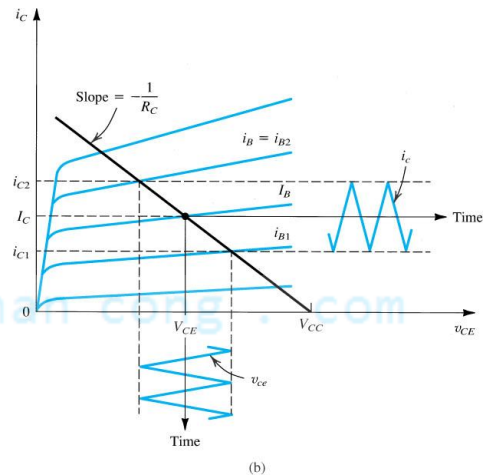
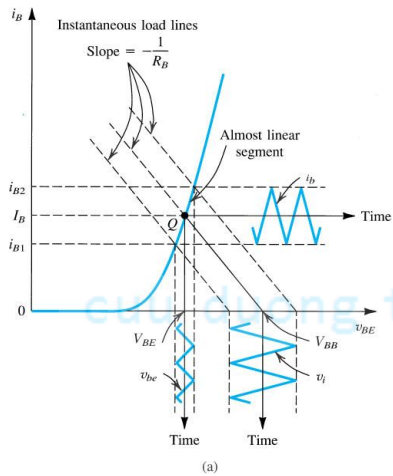
➤ Graphical Analysis of I-V relationships:

• Need both  $i_B - v_{BE}$  and  $i_C - v_{CE}$  plots



33

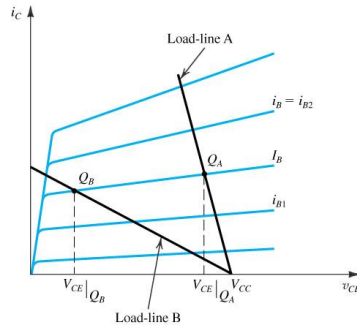
cuuduongthancong.com



**Figure 5.30** Graphical determination of the signal components  $v_{be}$ ,  $i_B$ ,  $i_C$ , and  $v_{ce}$  when a signal component  $v_i$  is superimposed on the dc voltage  $V_{BB}$  (see Fig. 5.27).

34

➤ Operation Point Optimization:  
Voltage Clamping / Distortion / Voltage Swing



**Figure 5.31** Effect of bias-point location on allowable signal swing: Load-line A results in bias point  $Q_A$  with a corresponding  $V_{CE}$  which is too close to  $V_{CC}$  and thus limits the positive swing of  $v_{CE}$ . At the other extreme, load-line B results in an operating point too close to the saturation region, thus limiting the negative swing of  $v_{CE}$ .

35

➤ Small-Signal Model Development:

The above analysis suggests that for small signals

$$v_{be} \ll V_T$$

the transistor behaves as a "voltage controlled current source"

with the transconductance  $g_m$ .

Output Resistance :

Ideally, the output resistance is "infinite".

Due to the Early effect, the output resistance is finite.

The output resistance  $r_o$ , as we know, is

$$r_o = \frac{V_A}{I_C}$$

36

Base current and Input resistance at the base :

The total base current  $i_B = \frac{i_C}{\beta}$ , that is,

$$i_B = \frac{I_C}{\beta} + \frac{1}{\beta} \frac{I_C}{V_T} v_{be} = I_B + i_b$$

Therefore, the small - signal base current is

$$i_b = \frac{1}{\beta} \frac{I_C}{V_T} v_{be} = \frac{g_m}{\beta} v_{be}$$

The small - signal input resistance, denoted as  $r_\pi$ , is

$$r_\pi \equiv \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \frac{\beta}{(I_C/V_T)} = \frac{V_T}{I_B}$$

$$\text{On the other hand, } r_\pi = \left( \frac{\partial i_B}{\partial v_{be}} \right)^{-1} = \frac{V_T}{I_B}.$$

37

cuu duong than cong . com

Emitter current and the Input Resistance at the Emitter :

The total emitter current  $i_E$  is

$$i_E = \frac{i_C}{\alpha} = \frac{I_C}{\alpha} + \frac{i_c}{\alpha} = I_E + i_e$$

That is, the small - signal emitter current is

$$i_e = \frac{i_c}{\alpha} = \frac{I_C}{\alpha V_T} v_{be} = \frac{I_E}{V_T} v_{be}$$

If we denote a small - signal resistance between base and emitter, looking into the emitter, by  $r_e$ , it can be defined by

$$r_e \equiv \frac{v_{be}}{i_e} (= \frac{v_{eb}}{-i_e}) = \frac{V_E}{I_E} = \frac{\alpha}{g_m} \approx \frac{1}{g_m}$$

38

cuu duong than cong . com

Since  $v_{be} = i_b r_\pi = i_e r_e$

thus we have  $r_\pi = \frac{i_e}{i_b} r_e = (\beta + 1) r_e$

Voltage Gain : (small-signal)

The total collector voltage  $v_C$  is

$$\begin{aligned} v_C &= V_{CC} - i_C R_C \\ &= V_{CC} - (I_C + i_c) R_C \\ &= (V_{CC} - I_C R_C) - i_c R_C = V_C - i_c R_C \end{aligned}$$

The small signal voltage  $v_c$  is

$$v_c = -i_c R_C = -(g_m v_{be}) R_C = -(g_m R_C) v_{be}$$

Thus the voltage gain of this amplifier  $A_v$  is

$$A_v \equiv \frac{v_c}{v_{be}} = -g_m R_C = -\frac{I_C R_C}{V_T}$$

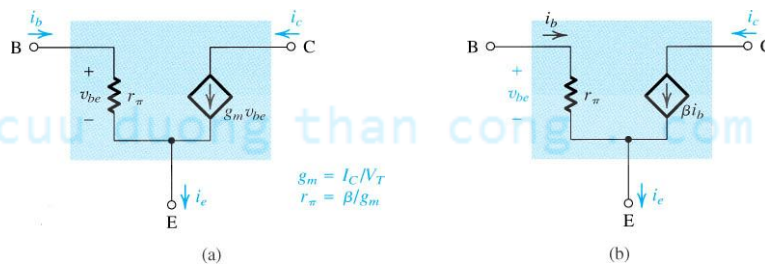
39

cuu duong than cong . com

### ➤ Small-Signal Models: Hybrid- $\pi$ Model and T Model

- From the above analysis, we find that we can separate the signal and the DC quantities to simplify the analysis.

[ Hybrid- $\pi$  Model ]

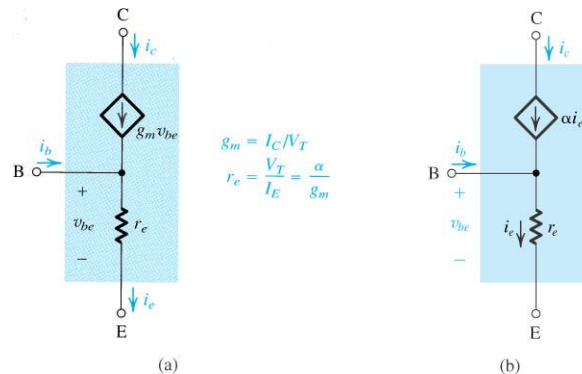


**Figure 5.51** Two slightly different versions of the simplified hybrid- $\pi$  model for the small-signal operation of the BJT. The equivalent circuit in (a) represents the BJT as a voltage-controlled current source (a transconductance amplifier), and that in (b) represents the BJT as a current-controlled current source (a current amplifier).

40

[ T Model ]

Note: both models can be viewed as  
(a) voltage-controlled current source, and  
(b) current-controlled current source types.



$$g_m = I_C / V_T$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$

Figure 5.52 Two slightly different versions of what is known as the *T model* of the BJT. The circuit in (a) is a voltage-controlled current source representation and that in (b) is a current-controlled current source representation. These models explicitly show the emitter resistance  $r_e$  rather than the base resistance  $r_\pi$  featured in the hybrid- $\pi$  model.

41

➤ Steps to doing small-signal analysis:

1. Determine the dc operation point (for a given  $\beta$ ) and get the DC collector current  $I_C$ .

2. Calculate the parameter values of

$$g_m = \frac{I_C}{V_T}; \quad r_\pi = \frac{\beta}{g_m}; \quad r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$

3. Eliminate the DC sources by:

Voltage source  $\Rightarrow$  short circuit

Current source  $\Rightarrow$  open circuit

4. Replace the BJT with one of its small - signal model.

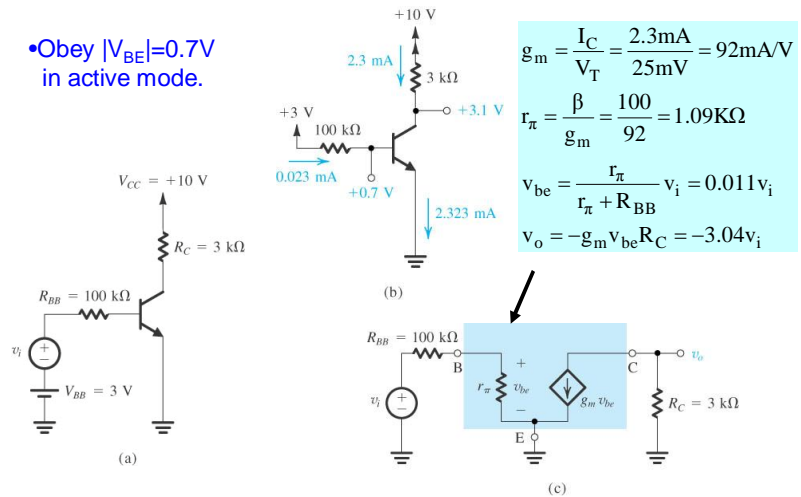
5. Analyze the resulting circuit to determine the required quantities, say, the voltage gain

$$A_v = -g_m R_C$$

42

Ex 5.14: Assume  $\beta=100$ . Find the small-signal voltage gain  $v_o/v_i$ .

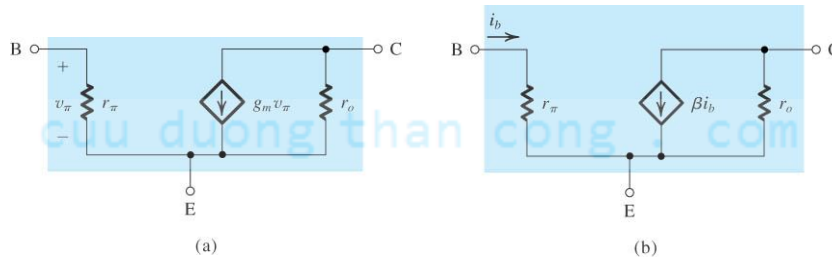
•Obey  $|V_{BE}|=0.7V$  in active mode.



43

➤Small-Signal Model accounting for the Early Effect:

$$r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C} \quad (\Omega)$$

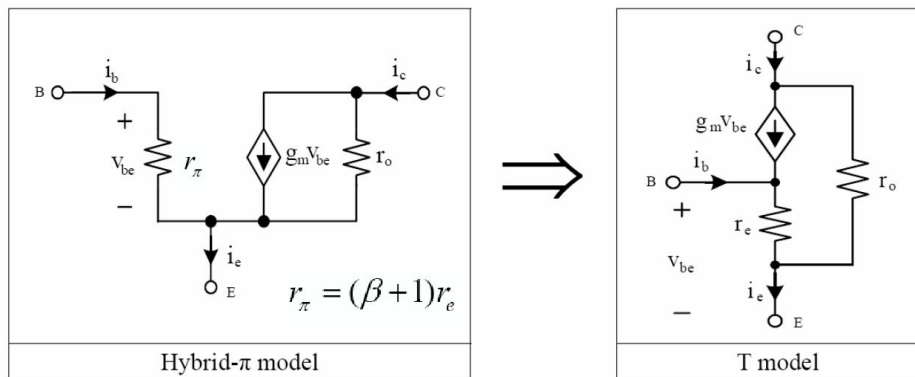


voltage-controlled current source

current-controlled current source

44

## Model transformation



45

## AC Emitter Resistance $r'_e$ or $r_e$

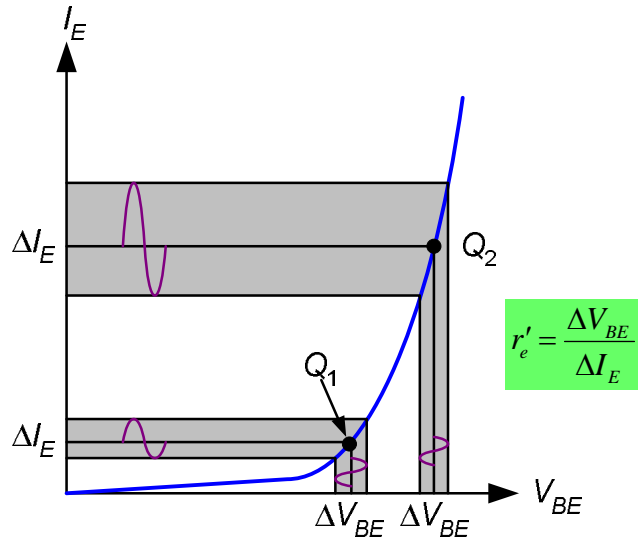
$$r'_e = \frac{25\text{mV}}{I_E}$$

where  $r'_e$  = ac emitter resistance

$I_E$  = the dc emitter current, found as  $V_E / R_E$  for example.

46

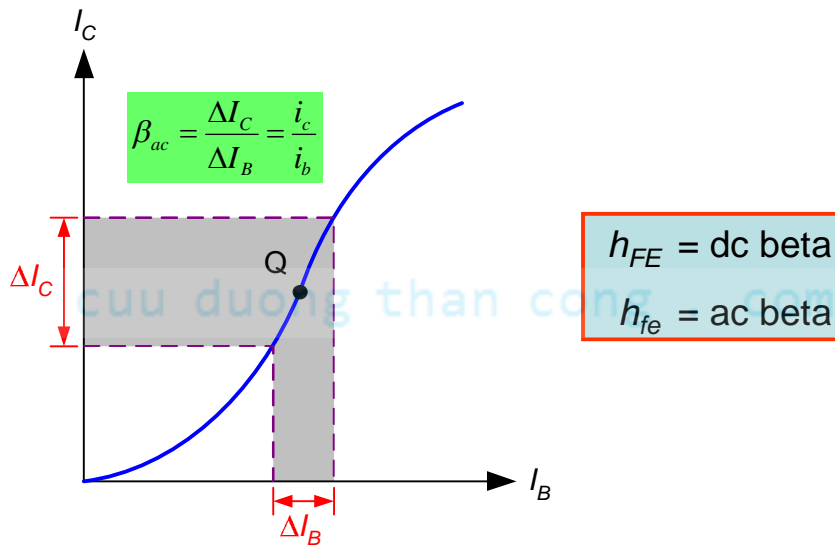
## Graphical determination of ac emitter resistance.



47

cuu duong than cong . com

## The determination of ac beta.



48



## Các đại lượng AC trong bảng dữ liệu

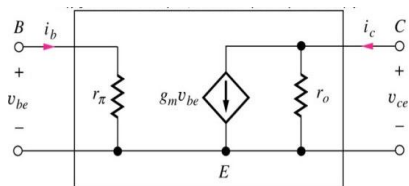
Bốn tham số  $h$  truyền thống:

- $h_{fe}$  là độ lợi dòng AC (mắc CE)
- $h_{ie} = r_{\pi}$  là tổng trở vào (mắc CE)
- $\beta_{ac} = h_{fe}$
- $r_e' = h_{ie}/h_{fe}$
- $h_{re}$  và  $h_{oe}$  không cần cho các thiết kế cơ bản và troubleshooting

49

cuu duong than cong . com

## Mô hình pi hỗn hợp (tín hiệu nhỏ) của BJT



- Mô hình tín hiệu nhỏ pi-hỗn hợp là biểu diễn tần số thấp của BJT.
- Các tham số tín hiệu nhỏ bị điều khiển bởi điểm Q.

Hỗ dẫn:

$$g_m = \frac{I_C}{V_T} \cong 40I_C$$

Điện trở vào (hay  $h_{ie}$ ):

$$r_{\pi} = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m}$$

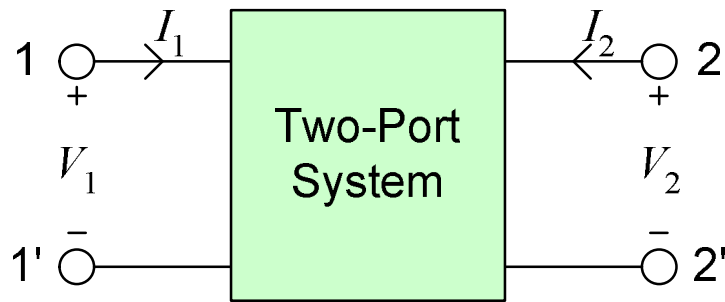
Điện trở ra (hay  $1/h_{oe}$ )

$$r_o = \frac{V_A + V_{CE}}{I_C}$$

với  $V_A$  là điện áp Early

50

## The Hybrid Equivalent Model



Hybrid model is derived from two-port system.

51

cuu duong than cong . com

## Six Circuit-Parameter Models for Two-Port Systems

Independent Variables	Dependent Variables	Circuit Parameters
$I_1, I_2$	$V_1, V_2$	Impedance $Z$
$V_1, V_2$	$I_1, I_2$	Admittance $Y$
$V_1, I_2$	$I_1, V_2$	Inverse Hybrid $g$
<b><math>I_1, V_2</math></b>	<b><math>V_1, I_2</math></b>	<b>Hybrid <math>h</math></b>
$V_2, I_2$	$V_1, I_1$	Transmission $T$
$V_1, I_1$	$V_2, I_2$	Inverse Transmission $T'$

52

## Equations for Hybrid Model

$$V_1 = h_{11}I_1 + h_{12}V_2$$

$$I_2 = h_{21}I_1 + h_{22}V_2$$

Let  $V_1 = V_i$ ,  $I_1 = I_i$ ,  $V_2 = V_o$ , and  $I_2 = I_o$ .  
Then

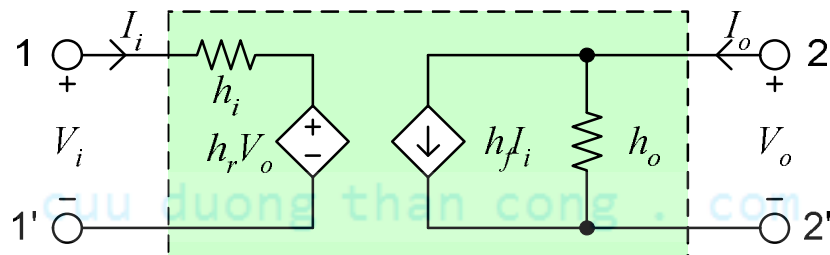
$$V_i = h_{11}I_i + h_{12}V_o$$

$$I_o = h_{21}I_i + h_{22}V_o$$

53

cuu duong than cong . com

## Equivalent Circuit for Hybrid Model



$$V_i = h_{11}I_i + h_{12}V_o = h_i I_i + h_r V_o$$

$$I_o = h_{21}I_i + h_{22}V_o = h_f I_i + h_o V_o$$

54

## ***h*-Parameters**

$$h_{11} = \frac{V_i}{I_i} \left| V_o = 0 \right. \quad h_{12} = \frac{V_i}{V_o} \left| I_i = 0 \right.$$
$$h_{21} = \frac{I_o}{I_i} \left| V_o = 0 \right. \quad h_{22} = \frac{I_o}{V_o} \left| I_i = 0 \right.$$

$h_{11} = h_i =$  Input Resistance

$h_{12} = h_r =$  Reverse Transfer Voltage Ratio

$h_{21} = h_f =$  Forward Transfer Current Ratio

$h_{22} = h_o =$  Output Admittance

55

cuu duong than cong . com

## ***h*-Parameters for CE Amp.**

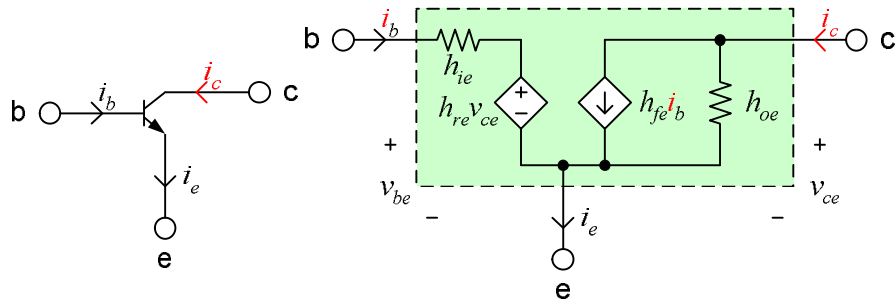
- $h_{ie}$  = the base input impedance
- $h_{fe}$  = the base-to-collector current gain
- $h_{oe}$  = the output admittance
- $h_{re}$  = the reverse voltage feedback ratio

cuu duong than cong . com

$$v_{be} = h_{ie} i_b + h_{re} v_{ce}$$
$$i_c = h_{fe} i_b + h_{oe} v_{ce}$$

56

## Hybrid Model for CE Configuration



$$h_{ie} = \frac{v_{in}}{i_b} \text{ (output shorted)}$$

$$h_{fe} = \frac{i_c}{i_b} \text{ (output shorted)}$$

$$h_{oe} = \frac{i_c}{v_{ce}} \text{ (input open)}$$

$$h_{re} = \frac{v_{be}}{v_{ce}} \text{ (input open)}$$

← May be neglected.

57

cuuduongthancong.com

## h-parameters of 2N3904

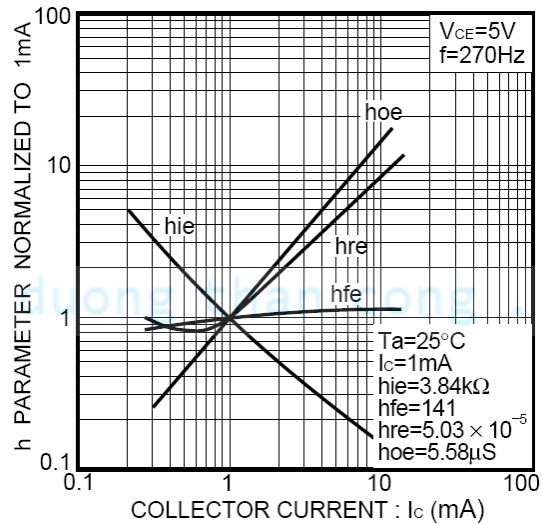
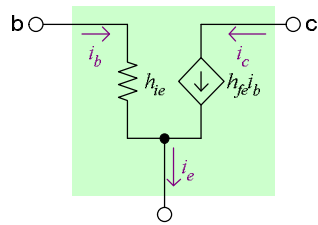


Fig.15 h parameter vs. collector current

58

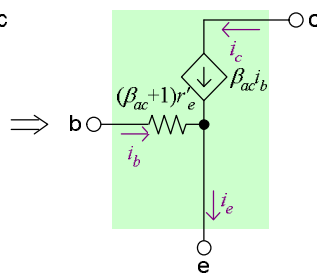
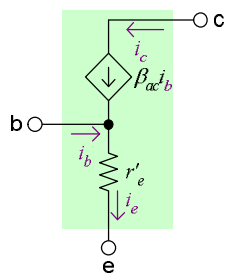
cuuduongthancong.com

## Hybrid Model without $h_{re}$ and $h_{oe}$



$$h_{fe} = \beta_{ac}$$

$$h_{ie} = (h_{fe} + 1)r'_e \cong h_{fe}r'_e = Z_{in(base)}$$



$$A_v = -\frac{h_{fe}r_c}{h_{ie}}$$

$$A_i = -h_{fe} \left( \frac{Z_{in}r_c}{h_{ie}R_L} \right)$$

59

cuu duong than cong . com

## Determining $h$ -Parameter Values

Use geometric means if given max. and min. values.

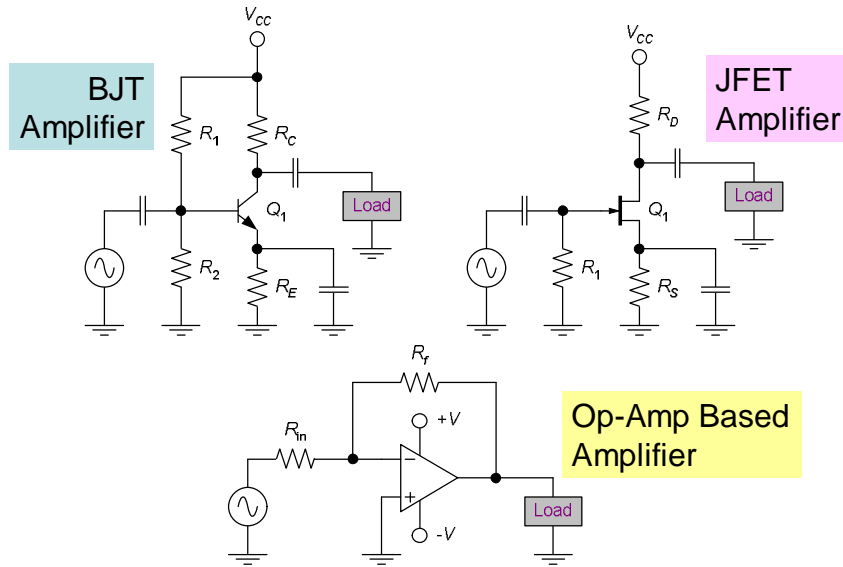
$$h_{ie} = \sqrt{h_{ie(min)} \times h_{ie(max)}}$$

$$h_{fe} = \sqrt{h_{fe(min)} \times h_{fe(max)}}$$

cuu duong than cong . com

60

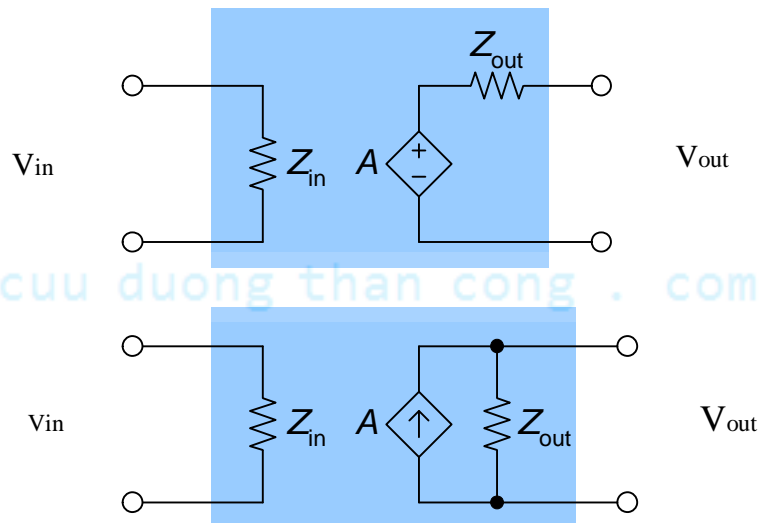
# Typical amplifiers



61

cuu duong than cong . com

# General amplifier models.



62

cuu duong than cong . com

## Gain symbols.

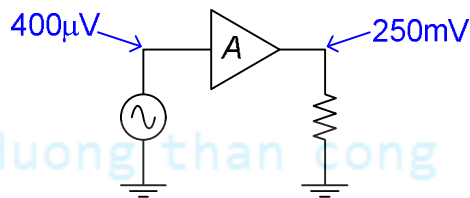
Type of Gain	Symbol	Relation
Voltage	$A_v$	$A_v = \frac{v_{out}}{v_{in}}$
Current	$A_i$	$A_i = \frac{i_{out}}{i_{in}}$
Power	$A_p$	$A_p = \frac{P_{out}}{P_{in}}$

63

cuu duong than cong . com

## Example

The symbol shown in Fig. 8.3 is a generic symbol for an amplifier. Calculate the voltage gain for the amplifier represented in the figure.



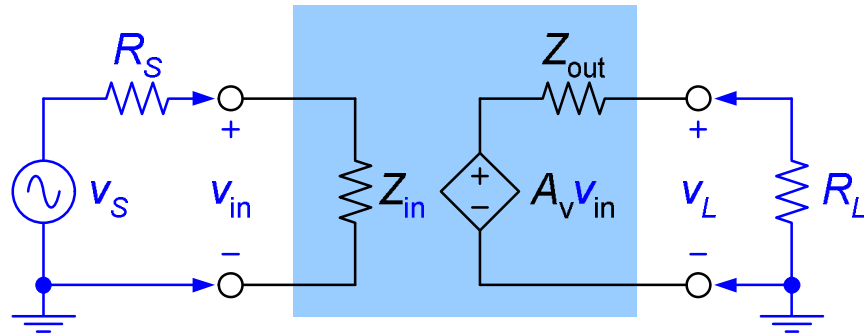
cuu duong than cong . com

$$A_v = \frac{v_{out}}{v_{in}} = \frac{250\text{mV}}{400\mu\text{V}} = 625$$

64



## Voltage amplifier model.



$$v_{in} = v_S \frac{Z_{in}}{R_S + Z_{in}}$$

$$v_{out} = A_v v_{in}$$

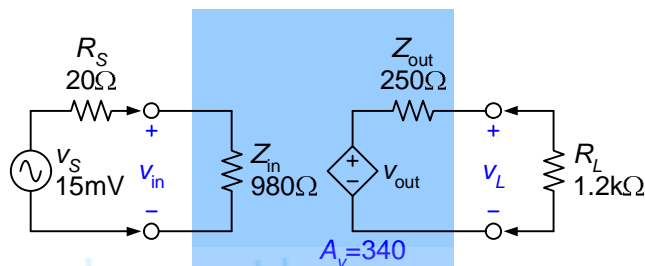
$$v_L = v_{out} \frac{R_L}{Z_{out} + R_L}$$

$$A_{v(\text{eff})} = \frac{v_L}{v_S}$$

65

cuu duong than cong . com

## Combined effects of the input and output circuits



$$v_{in} = v_S \frac{Z_{in}}{R_S + Z_{in}} = (15\text{mV}) \frac{980\Omega}{1\text{k}\Omega} = 14.7\text{mV}$$

$$v_L = v_{out} \frac{R_L}{Z_{out} + R_L} = (5\text{V}) \frac{1.2\text{k}\Omega}{1.45\text{k}\Omega} = 4.14\text{V}$$

$$v_{out} = A_v v_{in} = 340 \times 14.7\text{mV} = 5\text{V}$$

$$A_{v(\text{eff})} = \frac{v_L}{v_S} = \frac{4.14\text{V}}{15\text{mV}} = 276$$

66

## Voltage Amplifier Characteristics

### Ideal:

- Any value of voltage gain (can be infinite if needed)
- Infinite input impedance
- Zero output impedance

### Practical:

- Certain value of gain (cannot reach infinity).
- High input impedance
- Low output impedance

67

cuu duong than cong . com

## BJT Amplifier Configurations

- Common-emitter (CE) amplifier
- Common-collector (CC) amplifier
- Common-base (CB) amplifier

cuu duong than cong . com

68

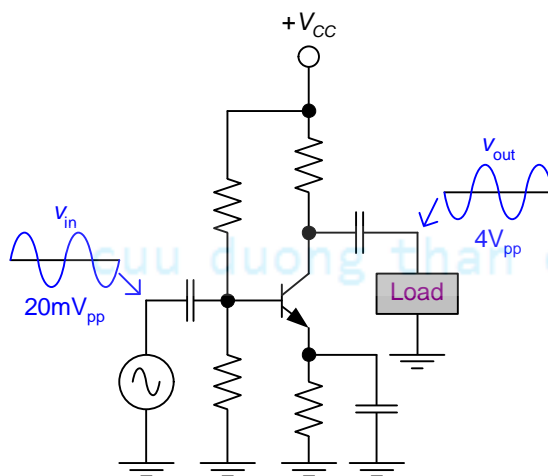
## Property ranges

Property	Low	Midrange	High
Gain	< 100	100-1000	>1000
Impedance	<1k $\Omega$	1k $\Omega$ -10k $\Omega$	>10k $\Omega$

69

cuu duong than cong . com

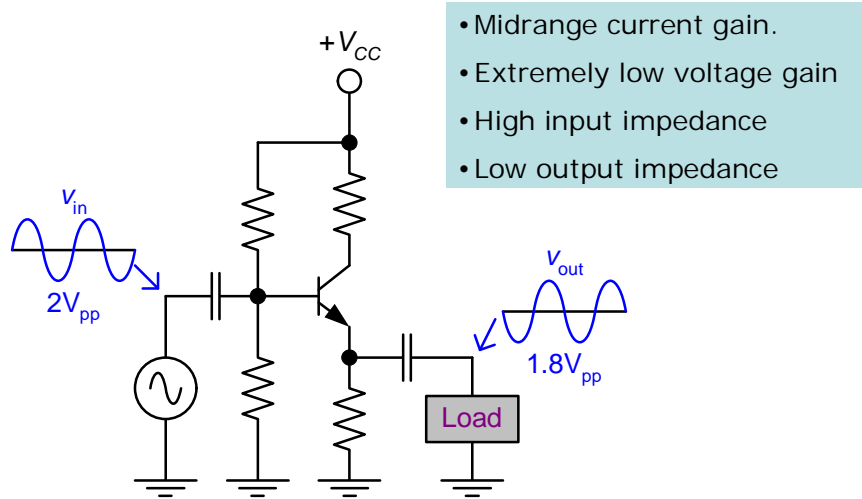
## Common-emitter (CE) amplifier



- Midrange values of voltage and current gain.
- High power gain
- Midrange input impedance
- Midrange output impedance

70

## Common-collector (CC) amplifier

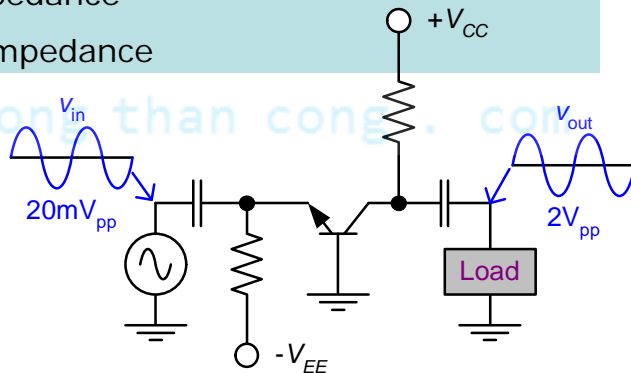


71

cuu duong than cong . com

## Common-base (CB) amplifier

- Midrange voltage gain
- Extremely low current gain (slightly less than 1)
- Low input impedance
- High output impedance



cuu duong than cong . com

## A comparison of CE, CC, and CB circuit characteristics

Type	$A_v$	$A_i$	$A_p$	$Z_{in}$	$Z_{out}$
CE	Midrange	Midrange	High	Midrange	Midrange
CC	$< 1$	Midrange	$\cong A_i$	High	Low
CB	Midrange	$< 1$	$\cong A_v$	Low	High

$$(A_p = A_v A_i)$$

73

cuu duong than cong . com

## BJT Terminal Connections

Type	Emitter	Base	Collector
CE	Common	Input	Output
CC	Output	Input	Common
CB	Input	Common	Output

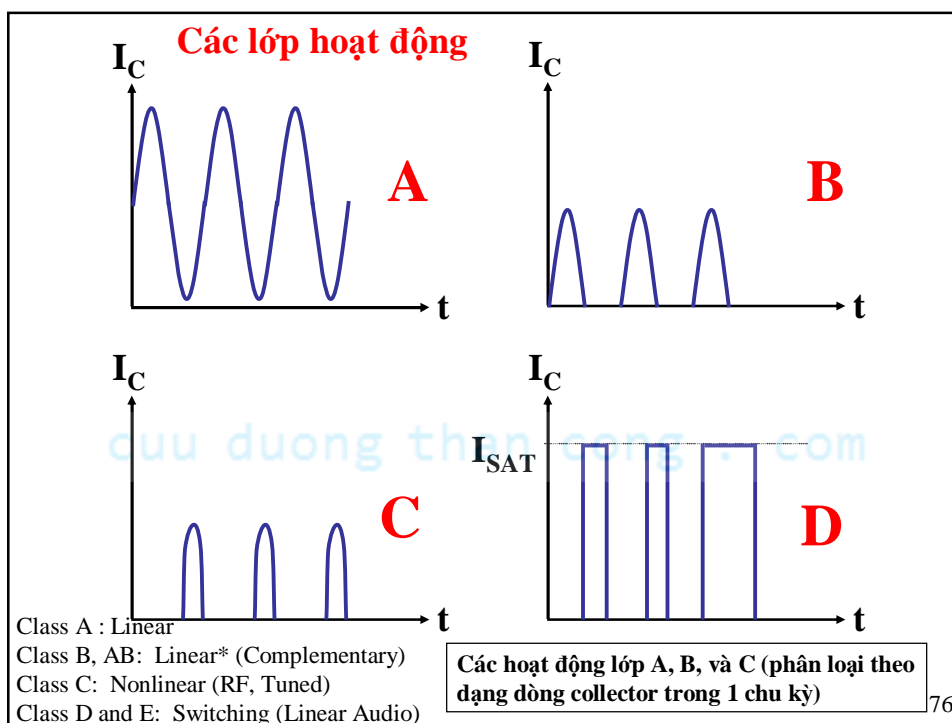
74

## Amplifier Classifications

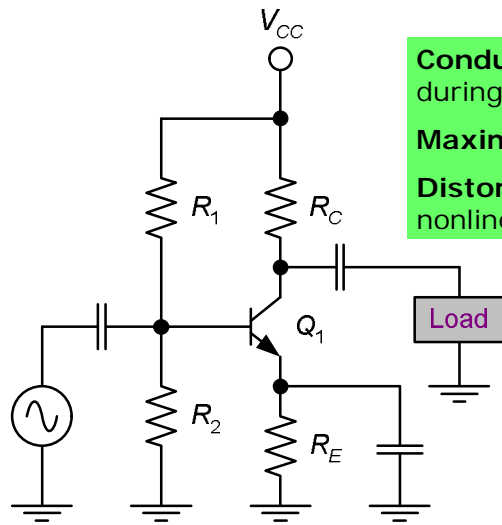
- Class A – low distortion, high loss
- Class B – some distortion, lower loss
- Class C – high distortion, lowest loss
- Others
  - Classes D, E, G, H, T

75

cuu duong than cong . com



## Class A Amplifiers



**Conduction:** Transistor conducts during 360 deg. of ac input.

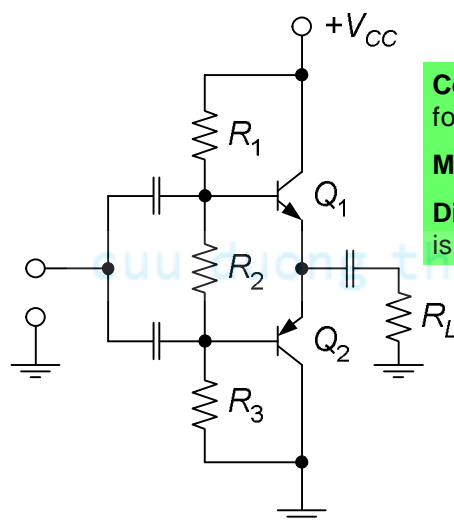
**Maximum theoretical eff.:** 25%

**Distortion:** Little (subject to nonlinear distortion.)

77

[cuduongthancong.com](http://cuduongthancong.com)

## Class B Amplifiers



**Conduction:** Each transistor conducts for 180 deg. of ac input.

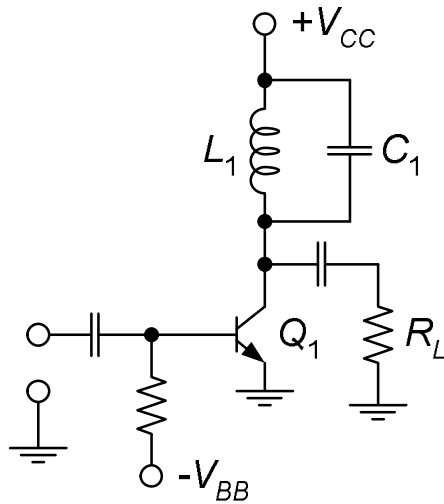
**Maximum theoretical eff.:** 78.5%

**Distortion:** Little. Crossover distortion is most common.

78

[cuduongthancong.com](http://cuduongthancong.com)

## Class C (Tuned) Amplifiers



**Conduction:** Each transistor conducts for less than 180 deg. of ac input.

**Maximum theoretical eff.:** 99%

**Distortion:** Mild to severe.

79

cuu duong than cong . com

## Decibels (dB)

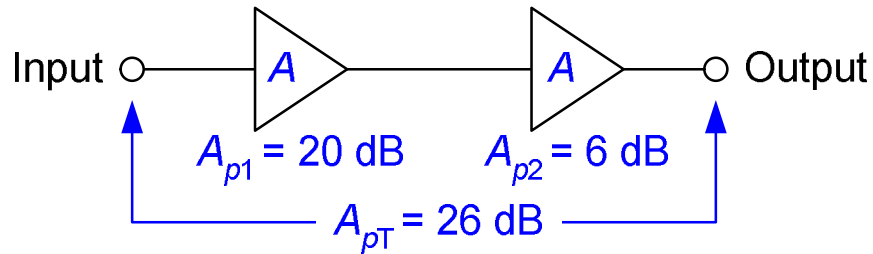
$$A_{p(\text{dB})} = 10 \log A_p = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}} \text{dB}$$

dB Value	$A_p$	dB Value	$A_p$
3	2	-3	1 / 2
6	4	-6	1 / 4
12	16	-12	1 / 16
20	100	-20	1 / 100

80



dB gains are additive



81

cuu duong than cong . com

## The dBm Reference

$$A_{p(\text{dBm})} = 10 \log \frac{P}{1\text{mW}}$$

## dB Voltage Gain

$$A_{p(\text{dB})} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = 10 \log \frac{v_{\text{out}}^2}{R_{\text{out}}} \frac{R_{\text{in}}}{v_{\text{in}}^2} = 20 \log \frac{v_{\text{out}}}{v_{\text{in}}} + 10 \log \frac{R_{\text{in}}}{R_{\text{out}}}$$

$$A_{p(\text{dB})} = A_{v(\text{dB})} = 20 \log A_v = 20 \log \frac{v_{\text{out}}}{v_{\text{in}}} \quad (R_{\text{out}} = R_{\text{in}})$$

82

# Dữ liệu của 1 số BJT thông dụng

**Table 5.9** Bipolar transistor parameters

Parameter	Meaning
$I_C$ max.	The maximum value of collector current
$V_{CEO}$ max.	The maximum value of collector–emitter voltage with the base terminal left open-circuit
$V_{CBO}$ max.	The maximum value of collector–base voltage with the base terminal left open-circuit
$P_t$ max.	The maximum total power dissipation
$h_{FE}$	The large signal (static) common-emitter current gain
$h_{fe}$	The small signal (dynamic) common-emitter current gain
$h_{fe}$ max.	The maximum value of small signal common-emitter current gain
$h_{FE}$ min.	The minimum value of small signal common-emitter current gain
$h_{ie}$	The small signal input resistance (see Chapter 7)
$h_{oe}$	The small signal output conductance (see Chapter 7)
$h_{re}$	The small signal reverse current transfer ratio (see Chapter 7)
$f_t$ typ.	The transition frequency (i.e. the frequency at which the small signal common emitter current gain has fallen to unity)

83

cuu duong than cong . com

**Table 5.10** Characteristic of some common types of bipolar transistor

Device	Type	$I_C$ max.	$V_{CEO}$ max.	$V_{CBO}$ max.	$P_t$ max.	$h_{fe}$	at $I_C$	$f_t$ typ.	Application
BC108	NPN	100 mA	20 V	30 V	300 mW	125	2 mA	250 MHz	General purpose
BCY70	PNP	200 mA	-40 V	-50 V	360 mW	150	2 mA	200 MHz	General purpose
BD131	NPN	3 A	45 V	70 V	15 W	50	250 mA	60 MHz	AF power
BD132	PNP	3 A	-45 V	-45 V	15 W	50	250 mA	60 MHz	AF power
BF180	NPN	20 mA	20 V	20 V	150 mW	100	10 mA	650 MHz	RF amplifier
2N3053	NPN	700 mA	40 V	60 V	800 mW	150	50 mA	100 MHz	Driver
2N3055	NPN	15 A	60 V	100 V	115 W	50	500 mA	1 MHz	LF power
2N3866	NPN	400 mA	30 V	30 V	3 W	105	50 mA	700 MHz	RF driver
2N3904	NPN	200 mA	40 V	60 V	310 mW	150	50 mA	300 MHz	Switching

84

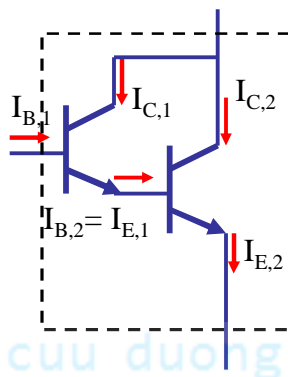
## 5.8 Các BJT khác

- Darling ton Transistor
- Polysilicon emitter Transistor
- Heterojunction bipolar transistor (HBT)=transistor lưỡng cực chuyển tiếp dị thể
- Phototransistor = transistor quang

85

cuu duong than cong . com

### 5.8.1 Cấu hình Darlington



Làm cho độ lợi dòng  $\beta$  rất cao, thường dùng trong các mạch cần dòng  $I_C$  cao (nhiều Amperes), và ta muốn điều khiển nó với dòng nền nhỏ. Và  $\beta$  cũng làm cho điện trở vào cao.

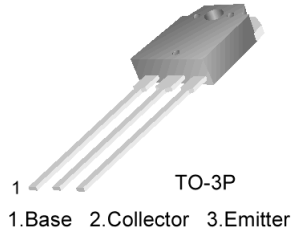
Ta có thể nối 2 BJT rời thành 1 transistor Darlington hay mua loại người ta đã chế tạo sẵn.

Với hình trên ta thấy rằng quan hệ giữa  $I_{B1}$  và  $I_{C2}$  là  $I_{C2} = \beta I_{B1}$  với  $\beta = \beta_1 \beta_2$

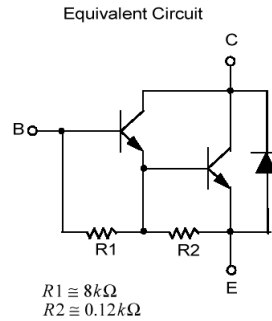
$V_{BE}$  tương đương là  $2xV_{ON}$  ( 1.4V) và  $V_{CEsat}$  lớn hơn (thường thì  $\sim 1$  V).

86

## Cấu hình Darlington (2)



TIP-141



Vì để có tốc độ chuyển nhanh và để bảo vệ BJT, trong đóng gói sẵn của BJT Darlington thường có các điện trở và diode.

Darlington tiêu biểu là TIP140 có thể làm việc với 10A, có độ lợi dòng cao  $\beta$  ít nhất 1000.

Darlington tín hiệu nhỏ có thể có  $\beta$  cỡ hàng 100 000!.

87

cuu duong than cong . com

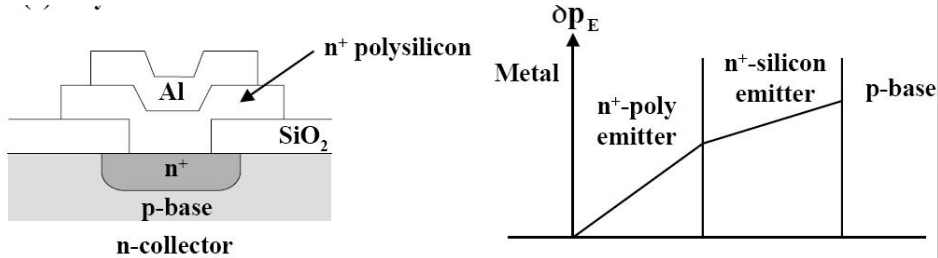
TABLE 6.1. SELECTED BIPOLAR POWER TRANSISTORS

nnp	npn	Pkg <sup>a</sup>	V <sub>CE0</sub> max (V)	I <sub>C</sub> max (A)	h <sub>FE</sub> typ @	I <sub>C</sub> (A)	f <sub>T</sub> min (MHz)	C <sub>cb</sub> <sup>b</sup> typ (pF)	P <sub>diss</sub> (T <sub>C</sub> =25°C) (W)	θ <sub>JC</sub> (°C/W)	T <sub>J</sub> max (°C)	Comments
<b>Regular power:</b> V <sub>CE</sub> (sat) = 0.4V (typ); V <sub>BE</sub> (on) = 0.8V (typ)												
2N5191	2N5194	A	60	4	100	0.2	2	80	40	3.1	150	low cost, gen purp
2N5979	2N5976	B	80	5	50	0.5	2	60	70	1.8	150	
2N3055	MJ2955	TO-3	60	15	50	2	2.5	125	115	1.5	200	metal, indus std
MJE3055	MJE2955	B	60	10	50	2	2.5	125	90	1.4	150	plastic, indus std
2N5886	2N5884	TO-3	80	25	50	10	4	400	200	0.9	200	
2N5686	2N5684	TO-3	80	50	30	25	2	700	300	0.6	200	for real power jobs
2N6338	2N6437	TO-3	100	25	50	8	40	200	200	0.9	200	premium audio
2N6275	2N6379	TO-3	120	50	50	20	30	400	250	0.7	200	premium audio
<b>Darlington power:</b> V <sub>CE</sub> (sat) = 0.8V (typ); V <sub>BE</sub> (on) = 1.4V (typ)												
2N6038	2N6035	A	60	4	2000	2	—	30	40	3.1	150	low cost
2N6044	2N6041	B	80	8	2500	4	4	80	75	1.7	150	
2N6059	2N6052	TO-3	100	12	3500	5	4	100	150	1.2	200	
2N6284	2N6287	TO-3	100	20	3000	10	4	150	160	1.1	200	high current

<sup>(a)</sup> A: small plastic pwr pkg (TO-126). B: large plastic pwr pkg (TO-127) <sup>(b)</sup> C<sub>cb</sub> (nnp) at V<sub>CB</sub>=10V; C<sub>cb</sub> (pnp) = 2C<sub>cb</sub> (nnp).

88

## 5.8.2 Polysilicon emitter BJT



< Simplified cross section of an npn polysilicon emitter BJT >

Diffusion current must be continuous across polysilicon/silicon interface.

$$\Rightarrow eD_{E(\text{poly})} \frac{d(\delta p_{E(\text{poly})})}{dx} = eD_{E(n^+)} \frac{d(\delta p_{E(n^+)})}{dx}$$

$$\text{or } \frac{d(\delta p_{E(\text{poly})})}{dx} = \frac{D_{E(n^+)}}{D_{E(\text{poly})}} \frac{d(\delta p_{E(n^+)})}{dx} \quad (D_{E(n^+)} > D_{E(\text{poly})})$$

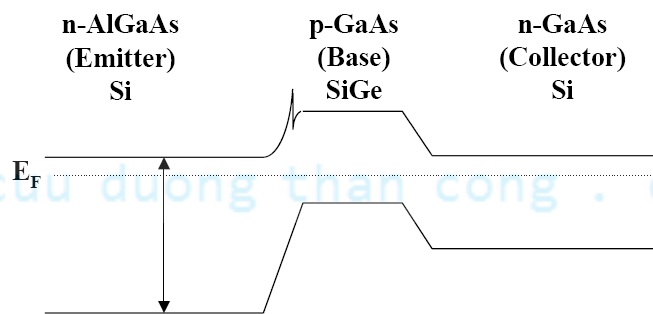
- PET được dùng IC

89

cuuduongthancong.com

## 5.8.3 Heterojunction bipolar transistors

- Higher emitter efficiency
- Decreased base resistance : base can be heavily doped
- Improved frequency response : higher current gain & lower base resistance



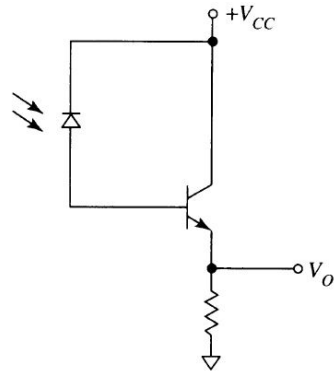
< Energy-band diagram of an npn heterojunction transistor with a wide-bandgap emitter >

Chú ý: HBT được dùng các ứng dụng tốc độ cao/tần số cao

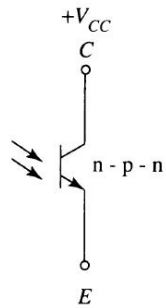
90

cuuduongthancong.com

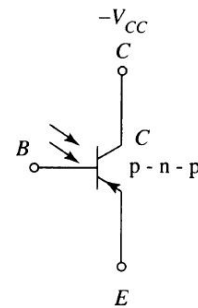
## 5.8.4 Phototransistor (transistor quang)



(a) Photodiode-transistor amplifier



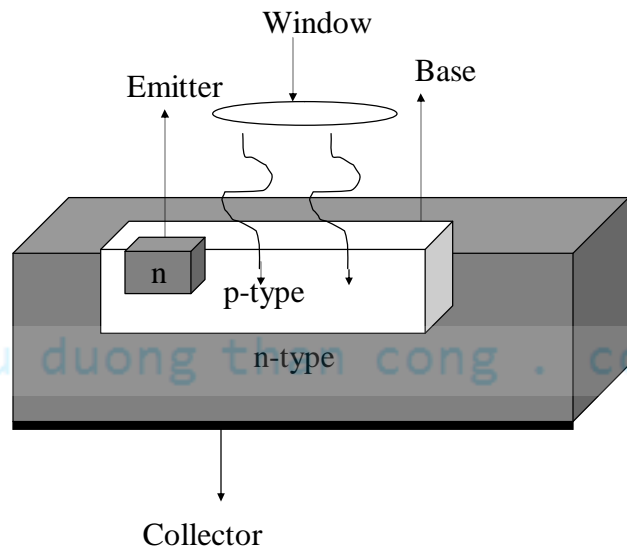
(b) Phototransistor without base connection



(c) Phototransistor with base connection

91

[cuuduongthancong.com](http://cuuduongthancong.com)



92

[cuuduongthancong.com](http://cuuduongthancong.com)

## Phototransistors

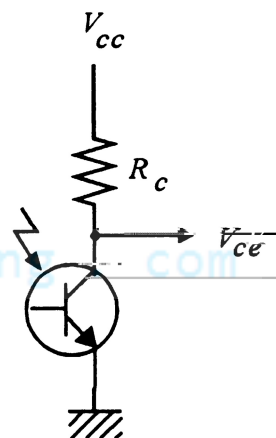
- Photodiode với mạch KĐ (transistor)
- Ánh sáng chiếu vào tiếp xúc B-E ( $J_E$ ).
- Dòng Collector  $I_C$  là hàm tuyến tính của sự tới bức xạ (giả sử  $\beta = \text{const}$ ).
- Dải tuyến tính thì hẹp hơn nhiều so với photodiode hay quang trở.
- Đặc tuyến  $I_C$  theo  $V_{CE}$  được vẽ theo các bước của sự tới bức xạ.
- Độ nhạy của phototransistor (RE) tốt hơn photodiode

93

[cuuduongthancong.com](http://cuuduongthancong.com)

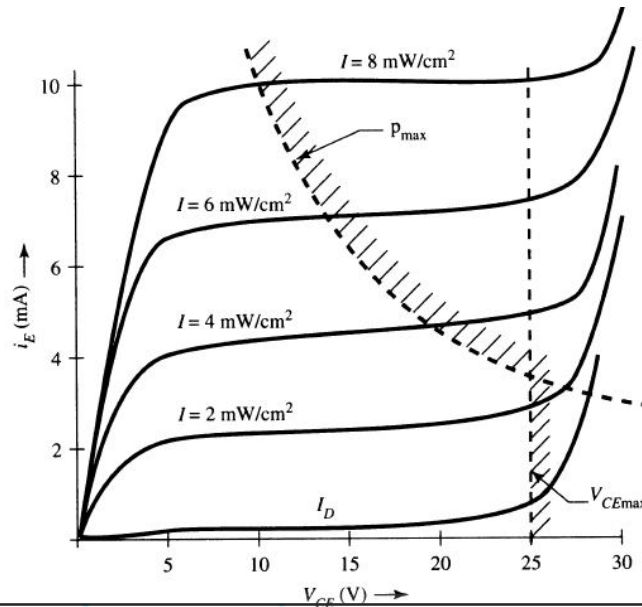
## Phototransistor

- Không nhanh bằng photodiode.
- Sử dụng như transistor, ngoại trừ không cần dòng nền.



94

## TD: Đặc tuyến của phototransistor



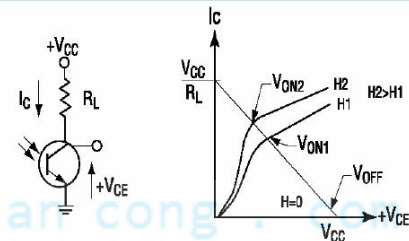
95

cuu duong than cong . com

## Phototransistor

- Intrinsic gain
  - Photocurrent is base current

© PerkinElmer Optoelectronics



Position	Ideal	Actual
"OFF" Position	$V_{CC}$	$(V_{CC} - R_L I_{DARK})$
"ON" Position	0	$V_{CE(SAT)}$

Note that  $V_{CE(SAT)1} > V_{CE(SAT)2}$ .

96