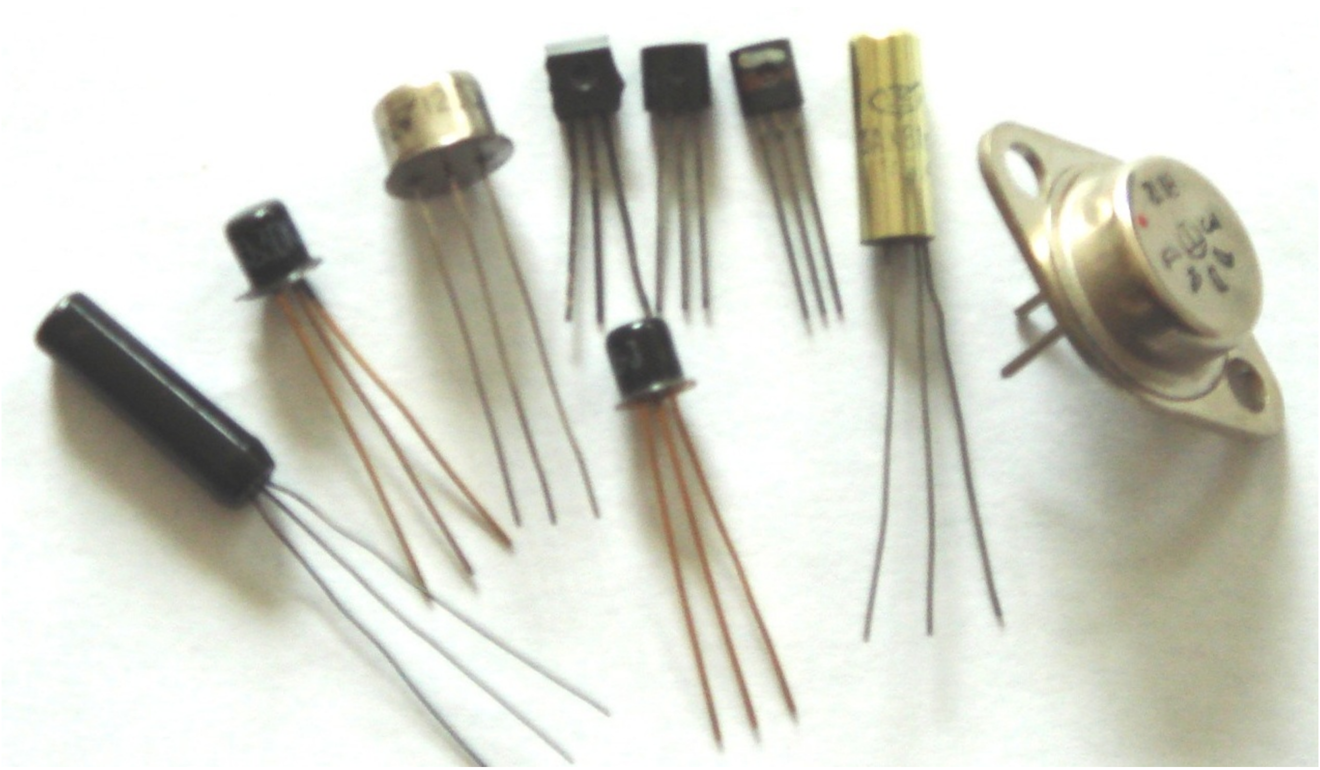
第7章 三极管

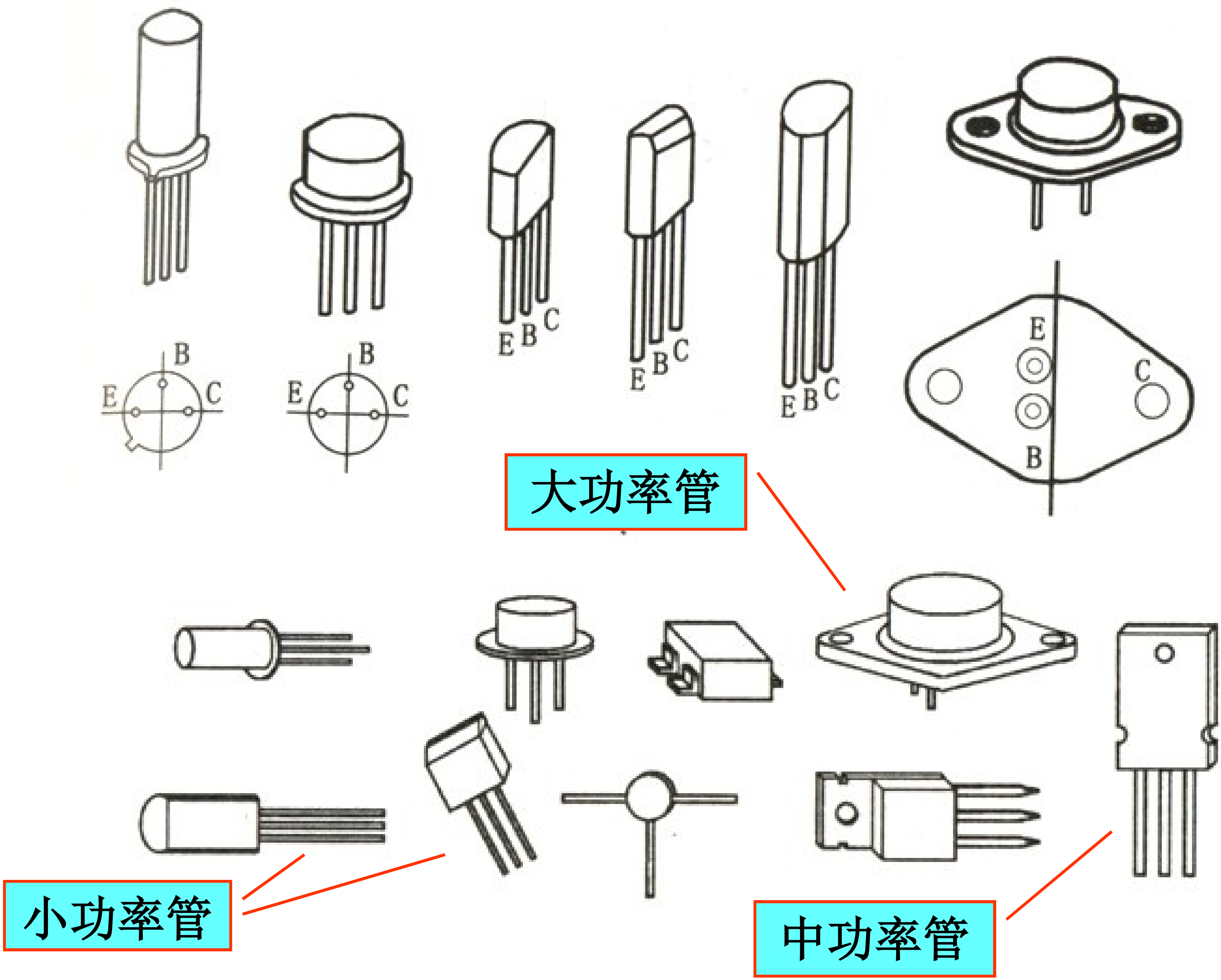
三极管基础

三极管放大电路的构成及其分析

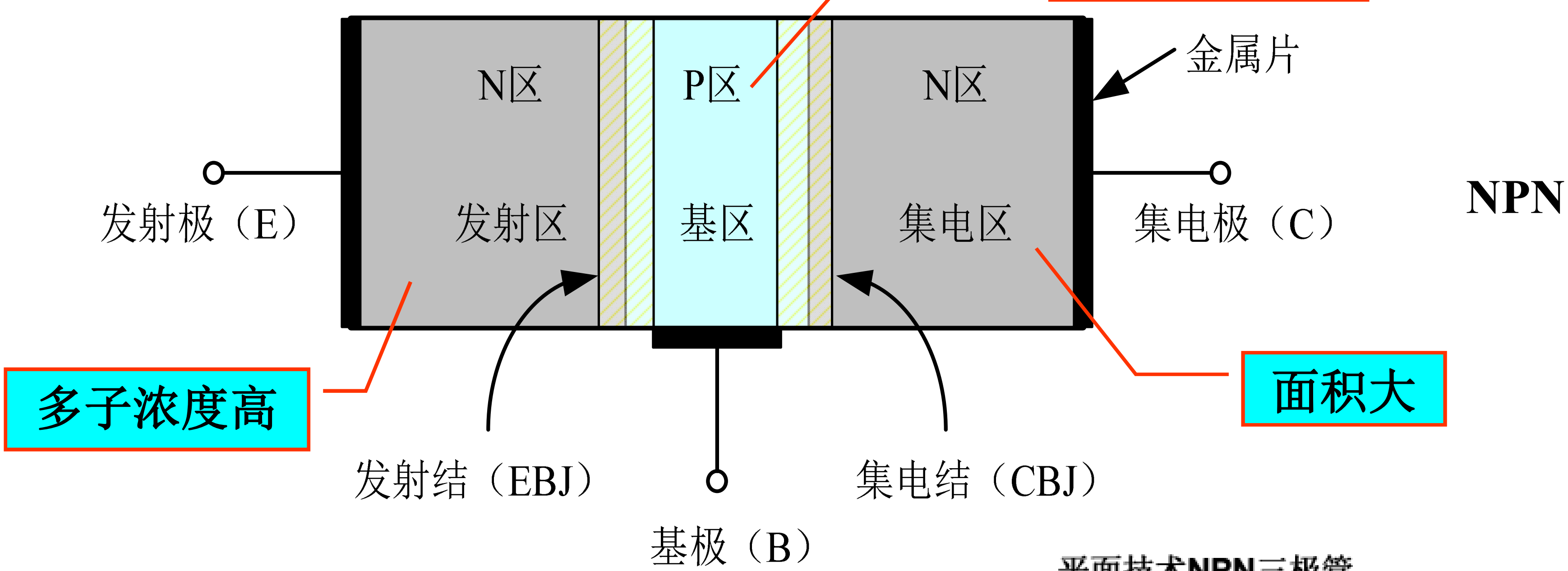
7.1 三极管基础

7.1.1 三极管的结构、工作原理及其电路符号



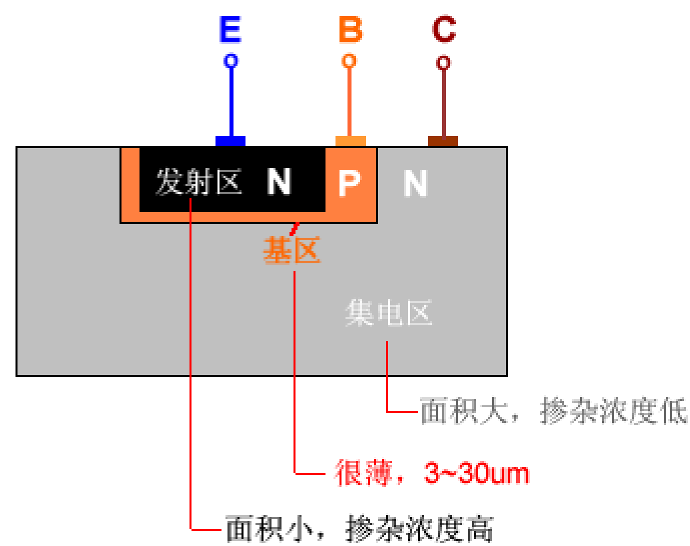

B
E
C
B
E
C
E B C
E B C
E B C
E
C
B
大功率管
小功率管
中功率管

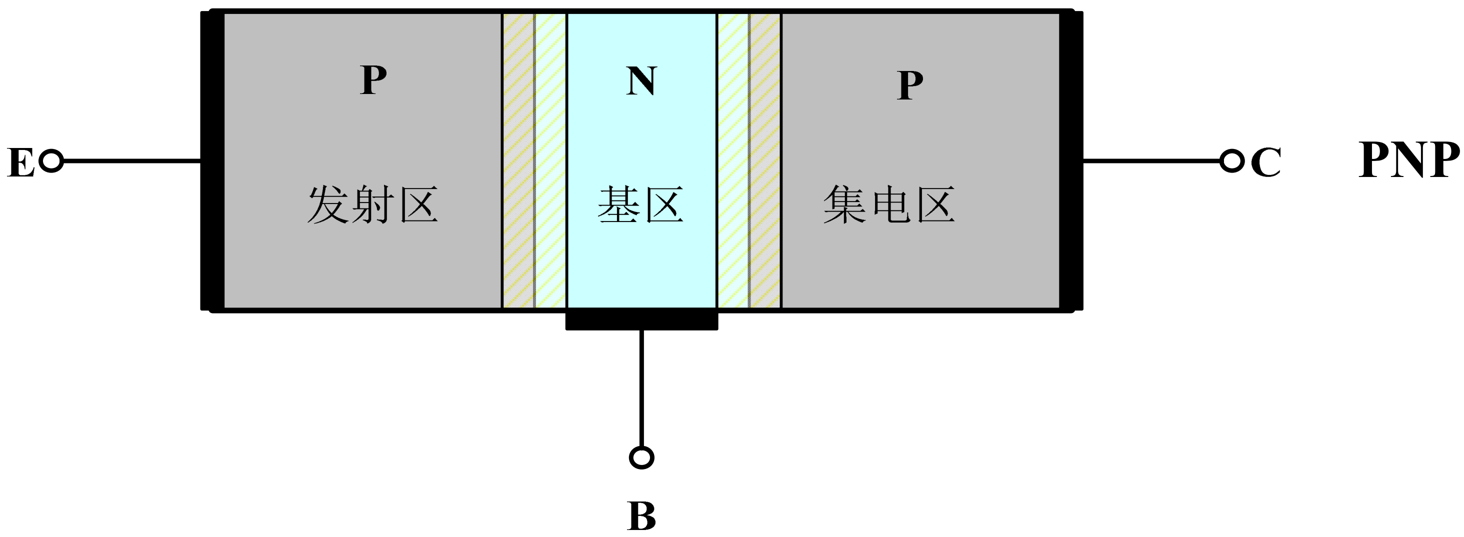
一、三极管的两种结构



(a)

平面技术NPN三极管





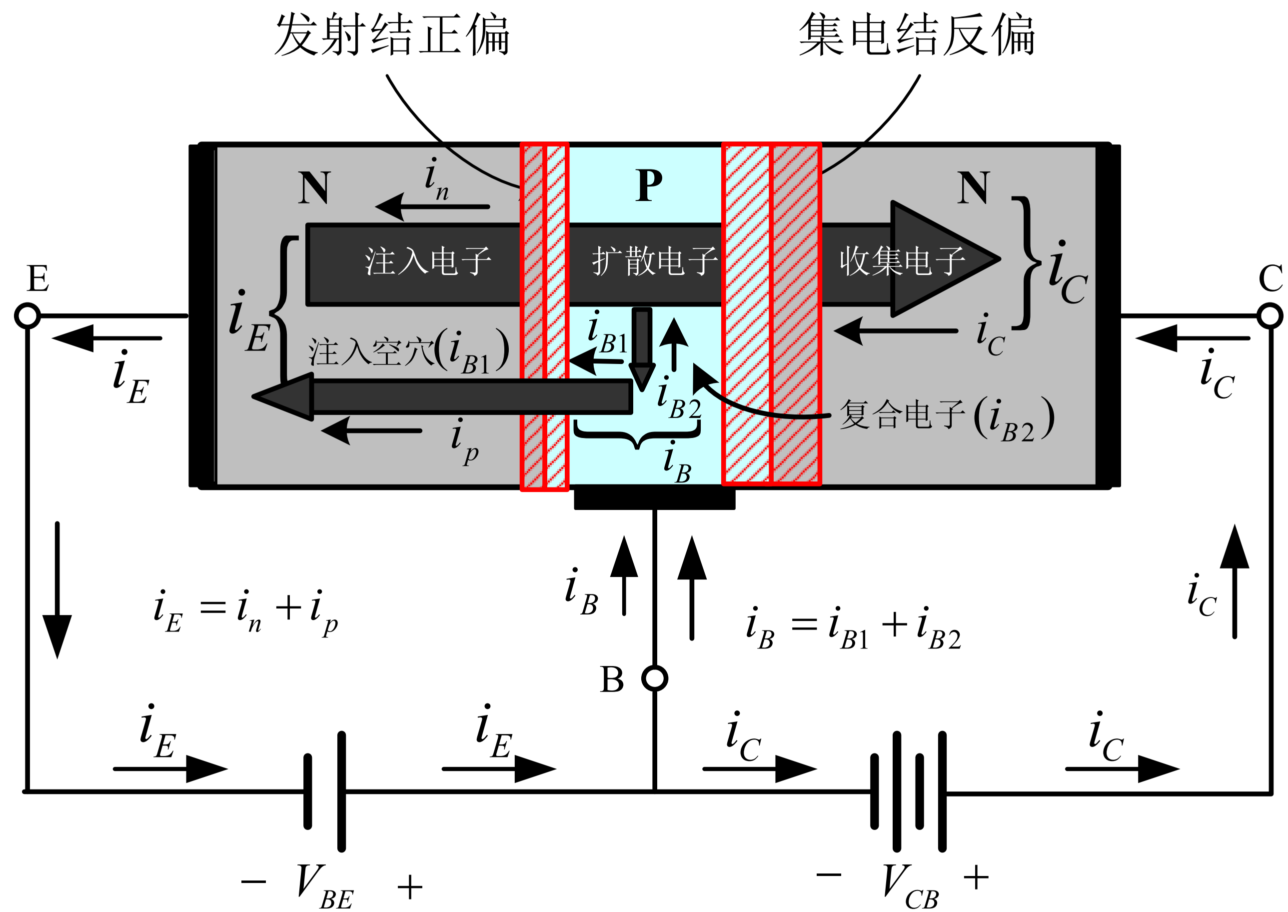
(b)

三极管
三个极：发射极、基极、集电极
三个区：发射区、基区、集电区
两个PN结：发射结、集电结

二、三极管的工作原理

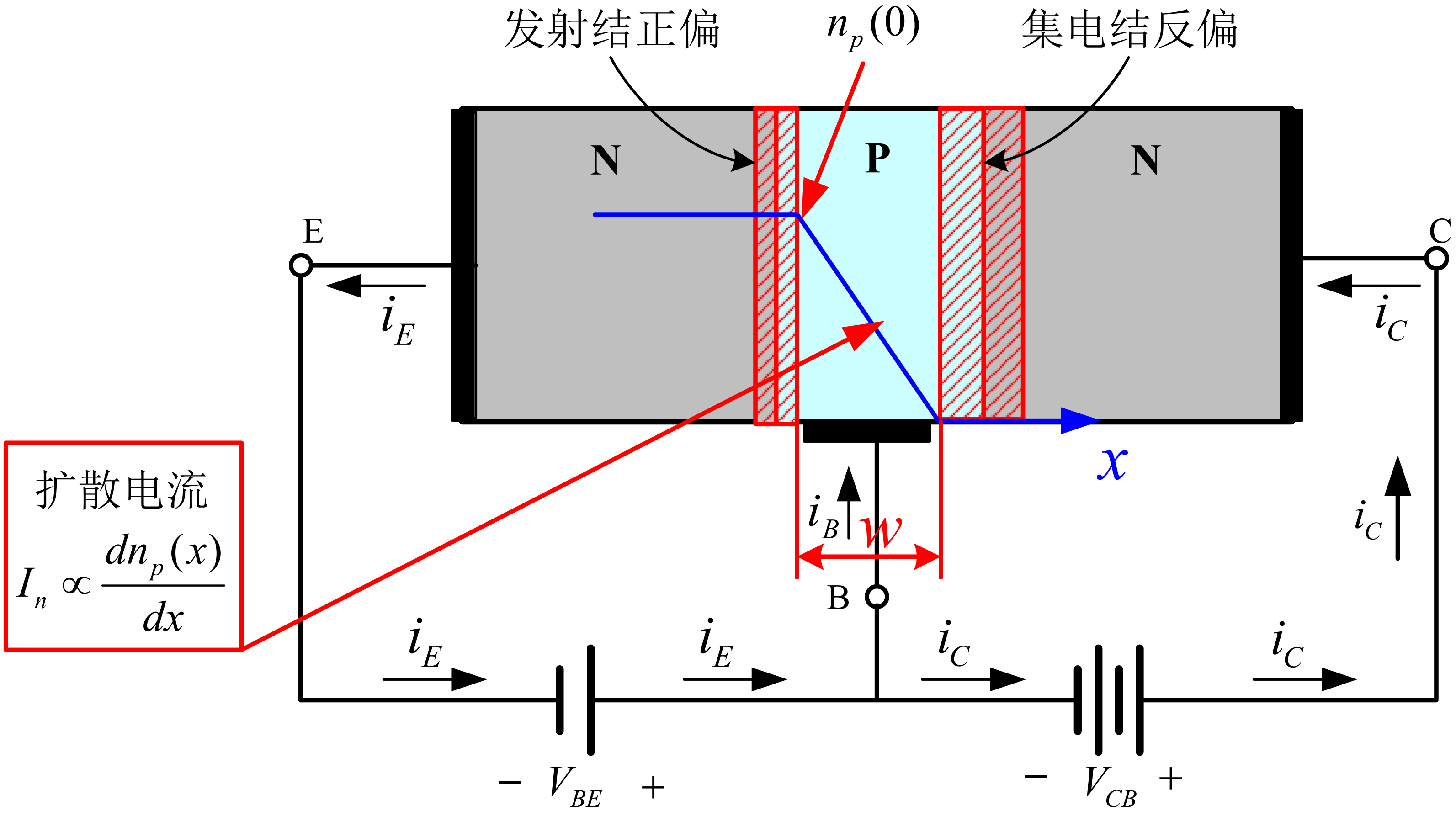
1、三极管内部载流子传输

放大模式下的各电流成分



2、集电极电流

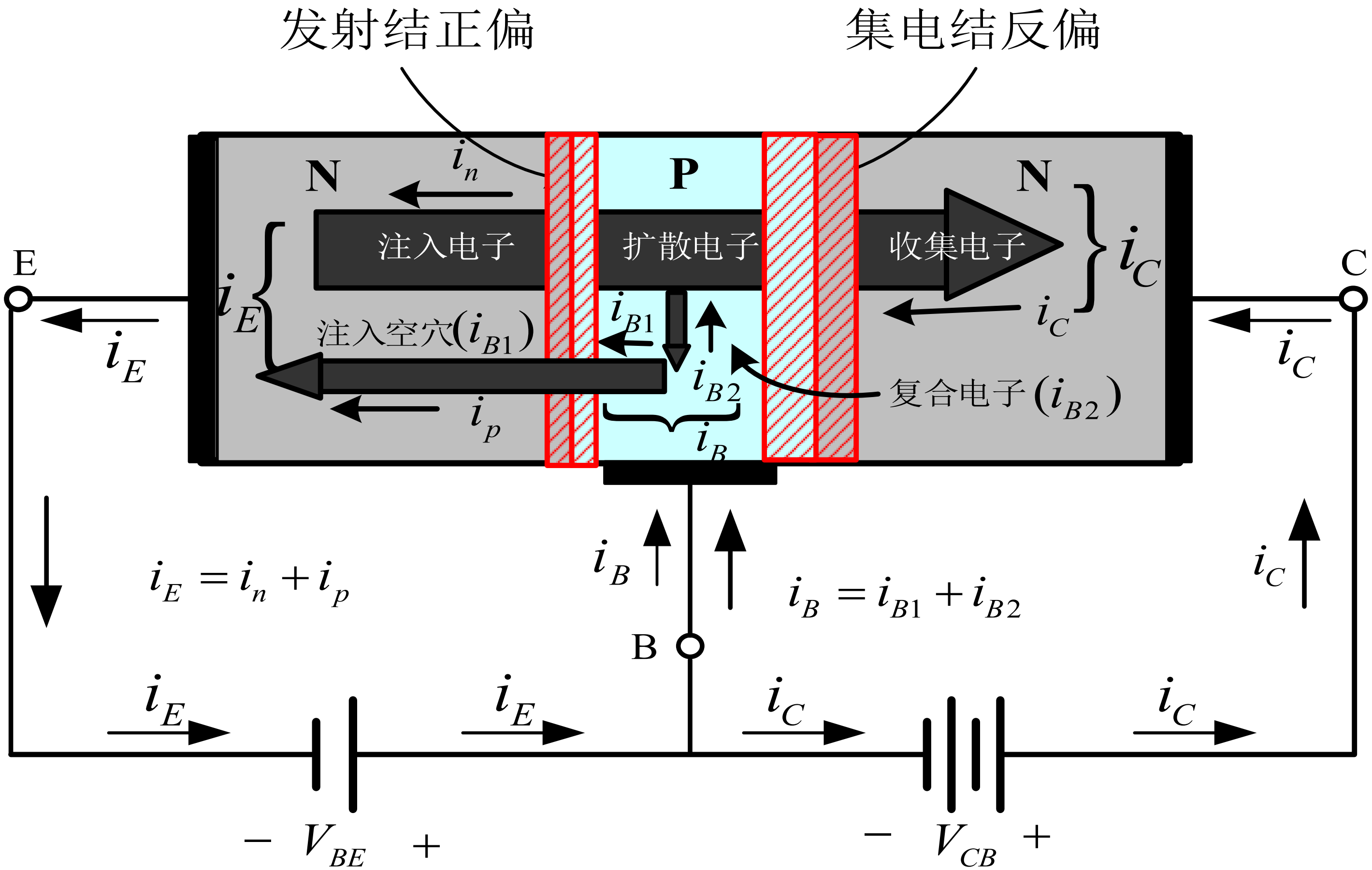
$$i_C = I_S e^{v_{BE}/V_T} \quad (= I_n)$$



3、基极电流

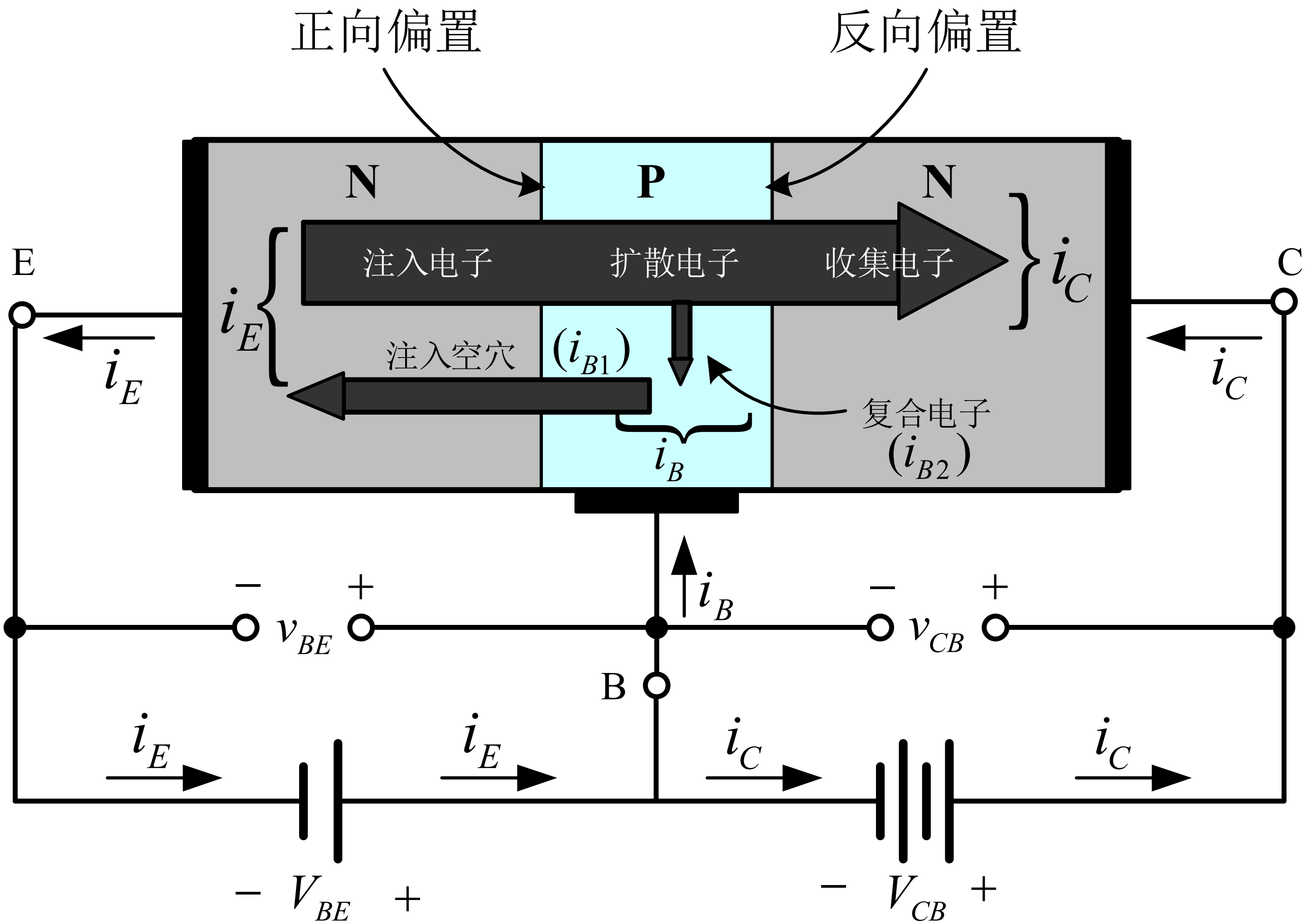
$$i_B = \frac{I_S e^{v_{BE}/V_T}}{\beta} = \frac{i_C}{\beta}$$

β：共发射极电流增益
（common-emitter current gain）



4、发射极电流

$$i_E = i_C + i_B = (1+\beta)i_B = \frac{1+\beta}{\beta}i_C = \frac{i_C}{\alpha}$$



放大模式下重要公式

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

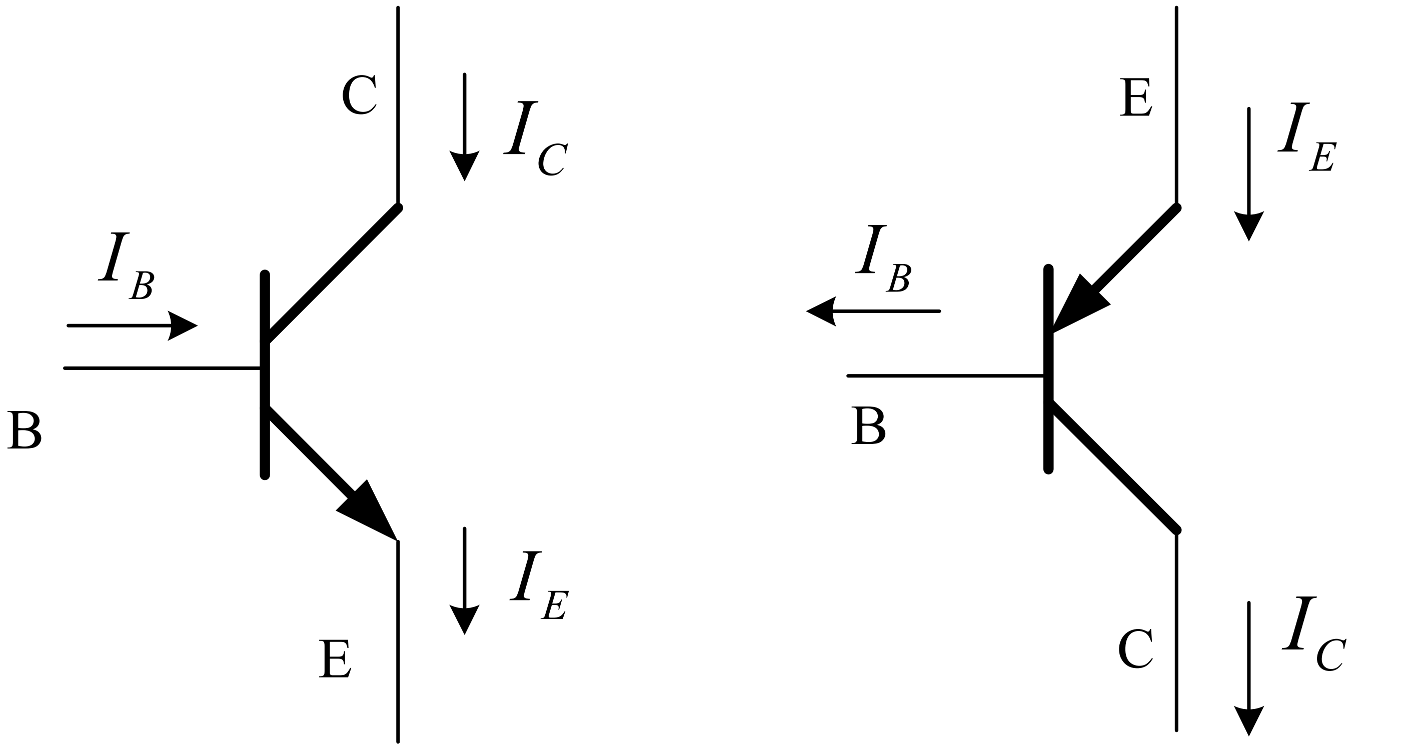
$$i_C = \beta i_B$$

$$i_E = (\beta + 1) i_B$$

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\alpha = \frac{\beta}{1+\beta}$$

三、三极管电路符号



(a) **NPN**

(b) **PNP**

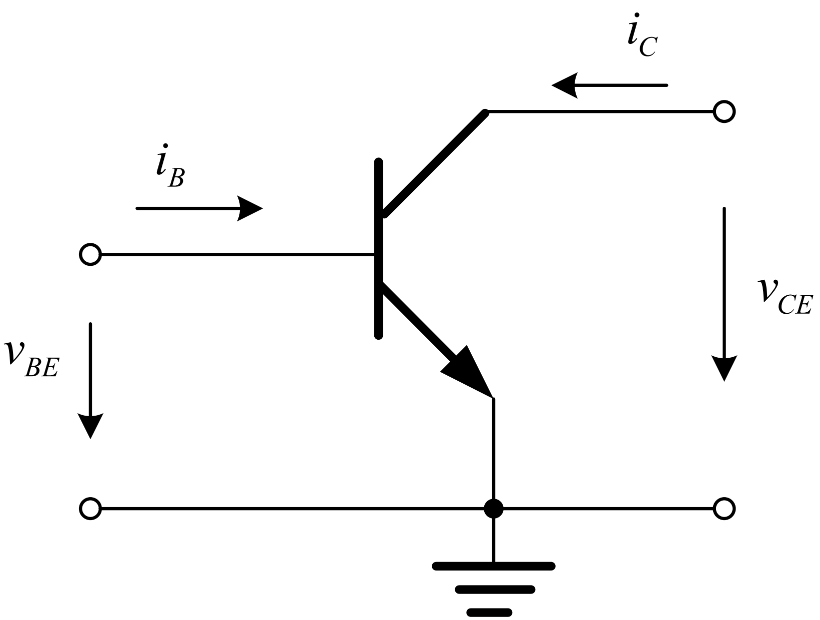
三极管的不同工作状态

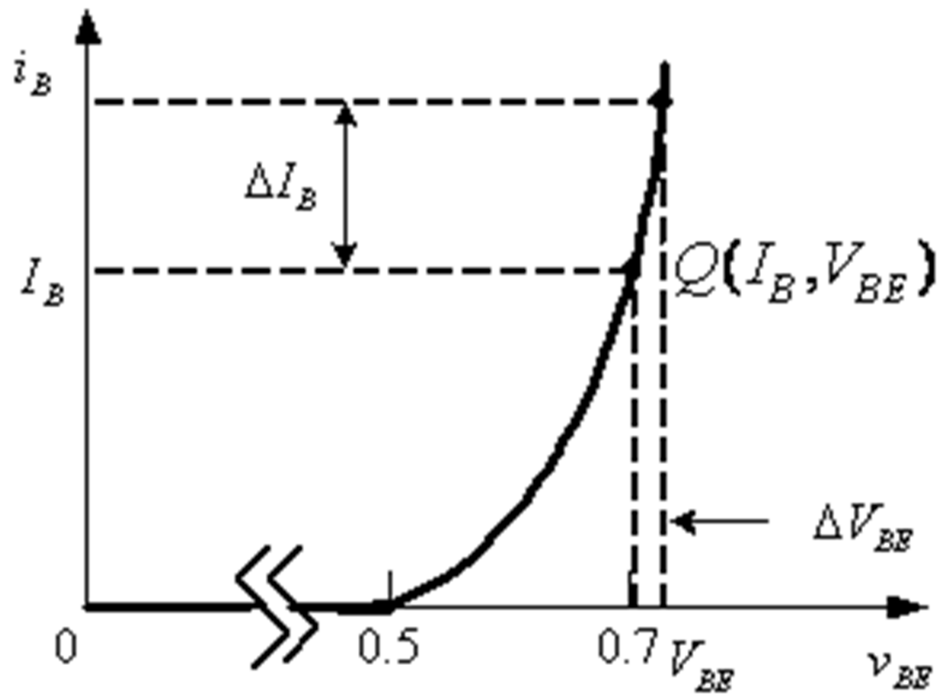
模式	EB 结	CB 结
截止	反向	反向
放大	正向	反向
饱和	正向	正向

7.1.2 三极管的电路特性

一、三极管的输入特性

—— 描述输入电压和输入电流之间的关系。



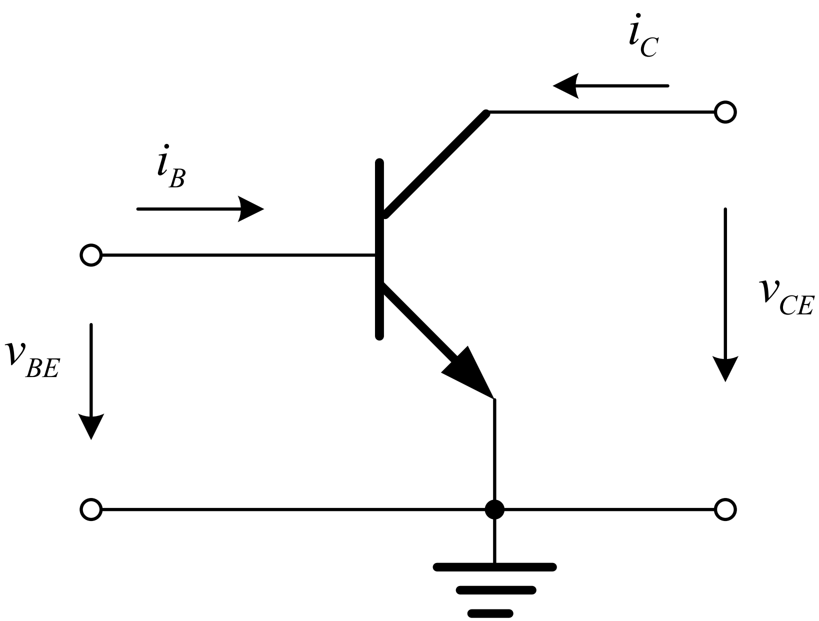


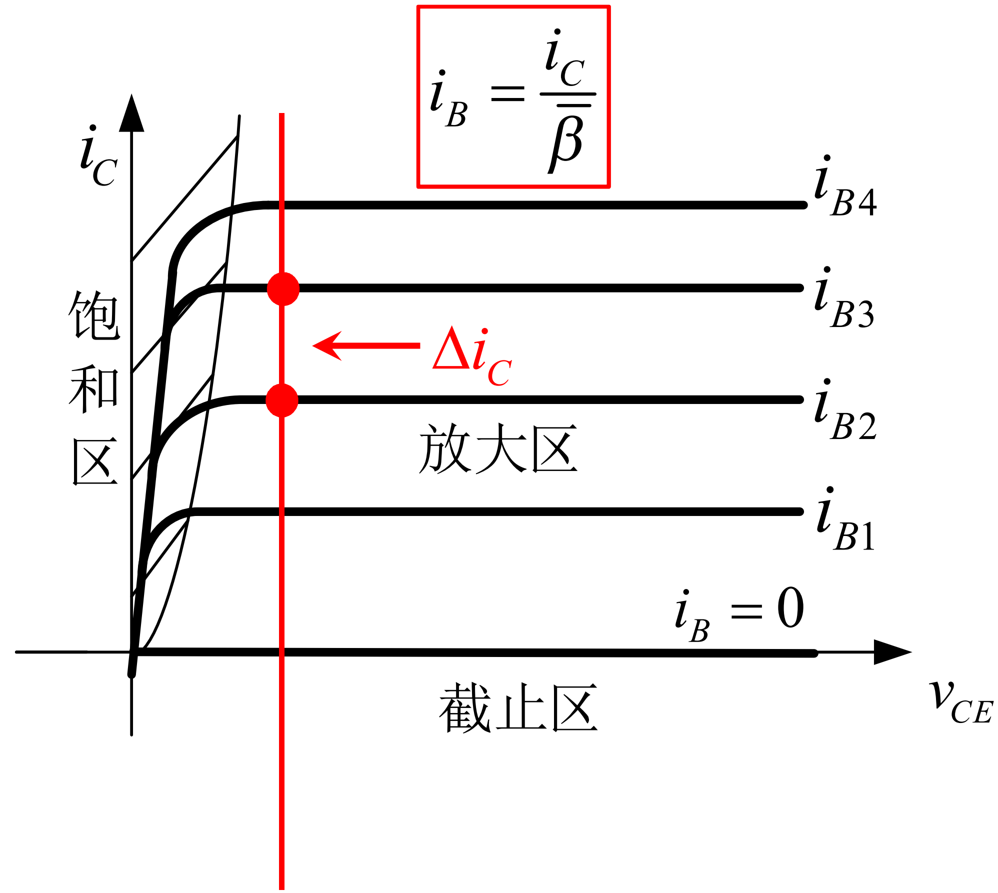
增量电阻 $$r = \frac{\Delta v_{BE}}{\Delta i_B}$$

$$\boxed{i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}}$$

二、三极管的输出特性

—— 描述输出电压和输出电流之间的关系。

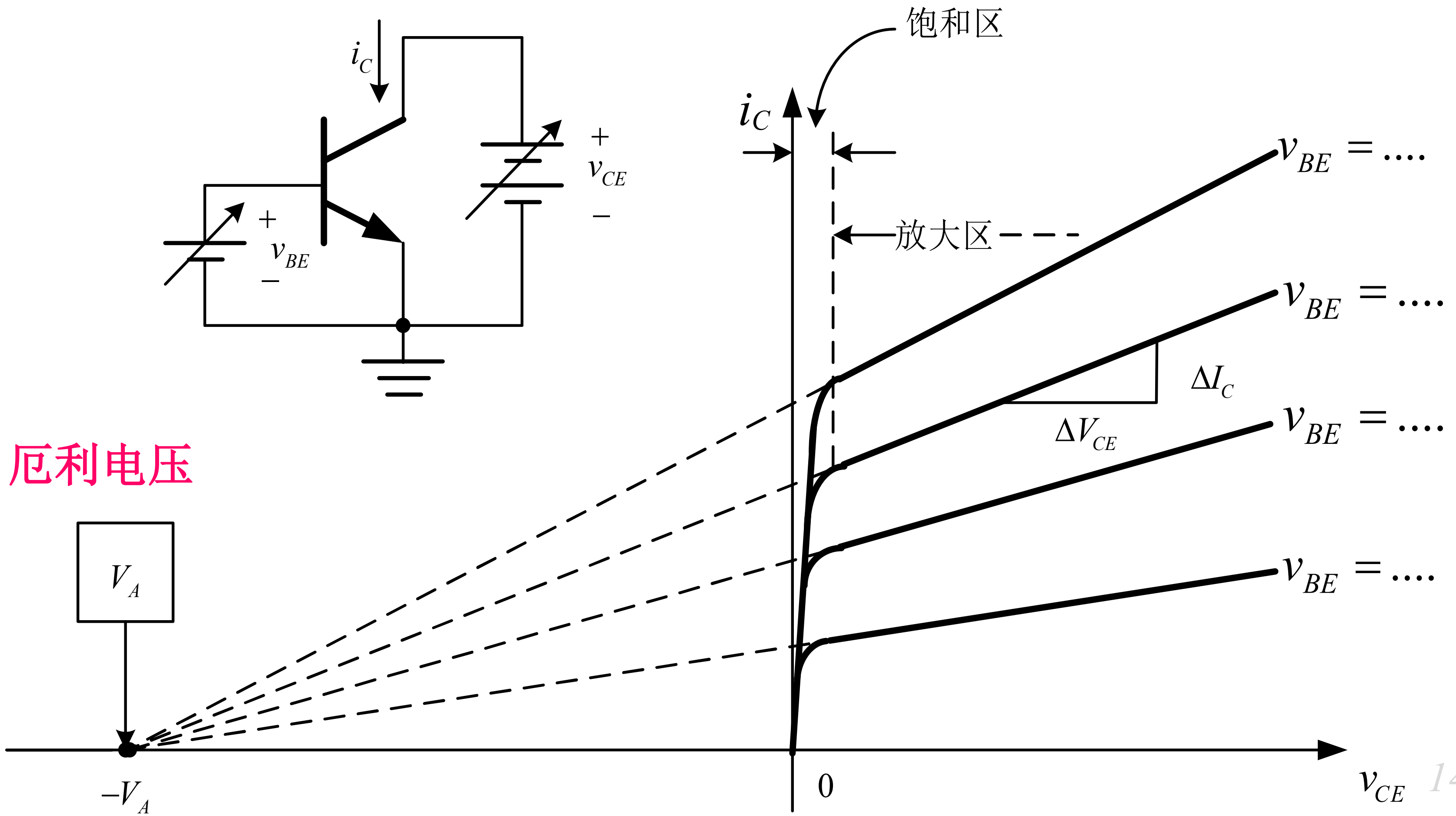




$$\beta = \frac{\Delta i_C}{\Delta i_B}$$

三极管的厄利现象（Early Effect）

给定v_{BE}下， 随着 v_{CE}的上升导致耗尽区宽度增加，使得基区宽度 W 减小，I_n 增大，i_C 增大。



考虑厄利现象后

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

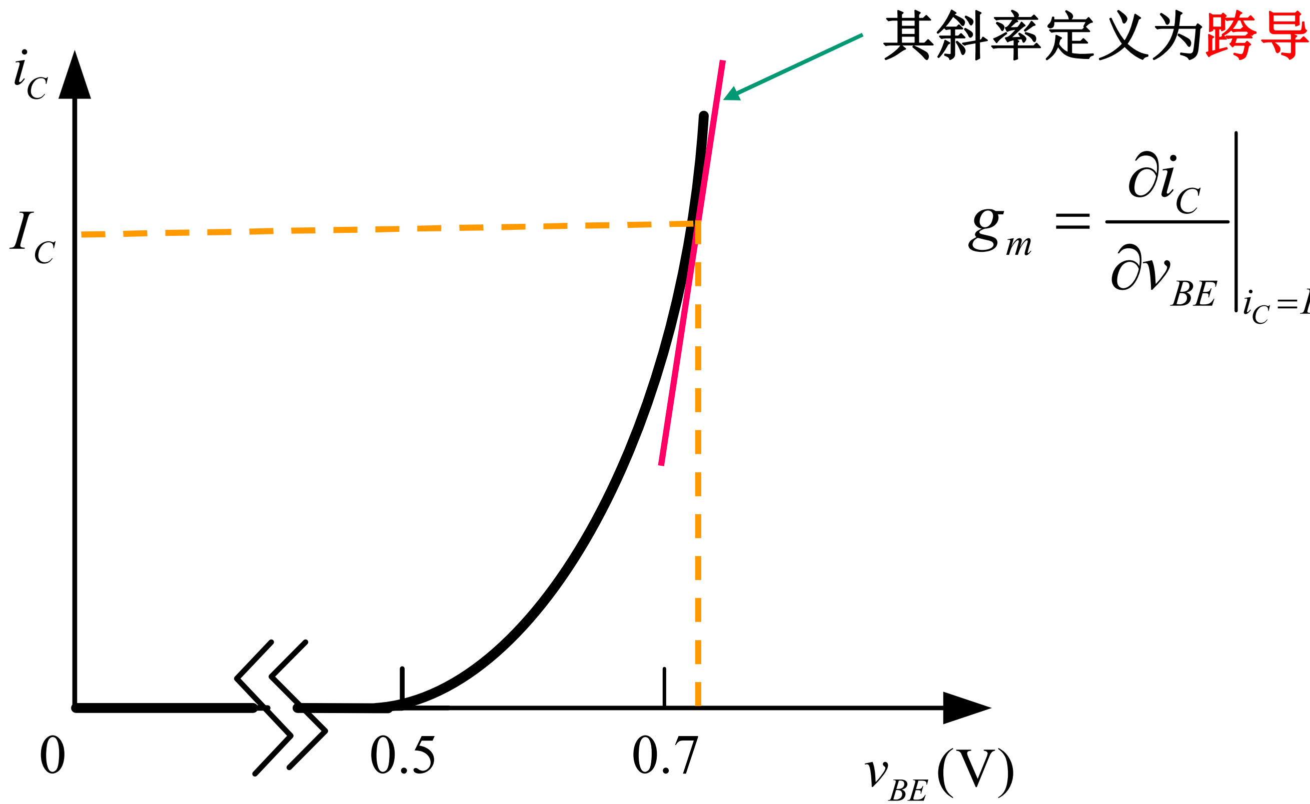
输出电阻

$$r_o = \frac{\Delta v_{CE}}{\Delta i_C} \approx V_A / I_C$$

$$\boxed{r_o = \left.\frac{\partial v_{CE}}{\partial i_C}\right|_{v_{BE}=V_{BE}} = \frac{1}{I_S e^{\frac{V_{BE}}{V_T}} \left(0 + \frac{1}{V_A}\right)} \approx \frac{V_A}{I_C}}$$

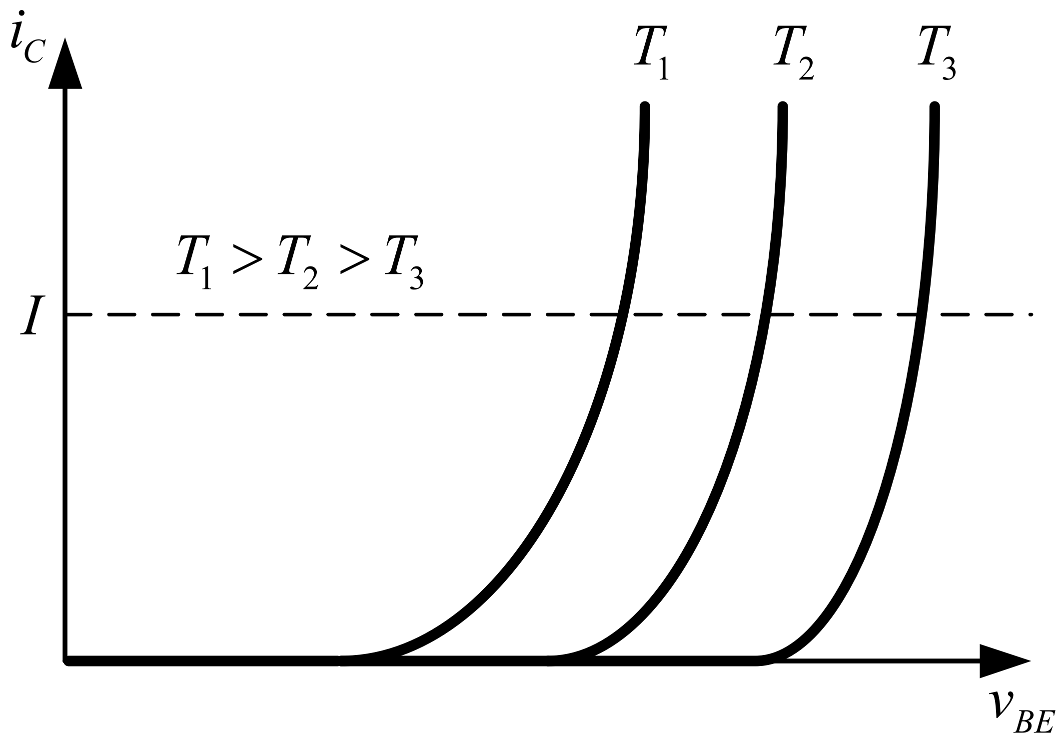
三、三极管的转移特性

—— 描述输入电压 v_{BE}与输出电流 i_C 之间的关系。



$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$$

三极管转移特性随温度变化



四、三极管的参数

- 直流参数：$\overline{\beta}$、$\overline{\alpha}$、I_{CBO}、I_{CEO}、V_{CEsat}

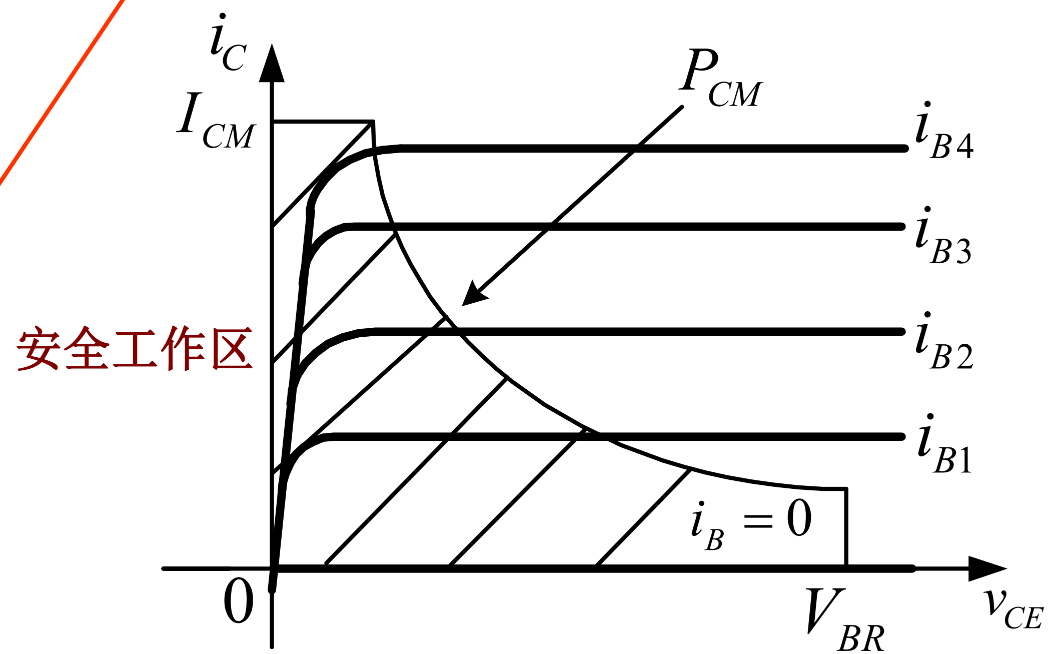
发射极开路，在规定的集电极-基极电压下，流过集电极-基极的反向电流

- 交流参数：β、α、f_{β}、f_{α}
- 极限参数：I_{CM}、P_{CM}、$V_{(BR)CBO}$、$V_{(BR)EBO}$、$V_{(BR)CEO}$

最大集电极电流

最大集电极耗散功率 $P_{CM}=i_C v_{CE}$

发射极开路，C、B间的反向击穿电压



7.1.3 中频等效电路模型

$$v_{BE}=V_{BE}+v_{be}=V_S+v_s$$

$$i_C=I_S e^{v_{BE}/V_T}=I_S e^{(V_S+v_s)/V_T}=I_S e^{V_S/V_T}\cdot e^{v_s/V_T}$$
$$=I_C e^{v_s/V_T}$$

若 $v_s << V_T$

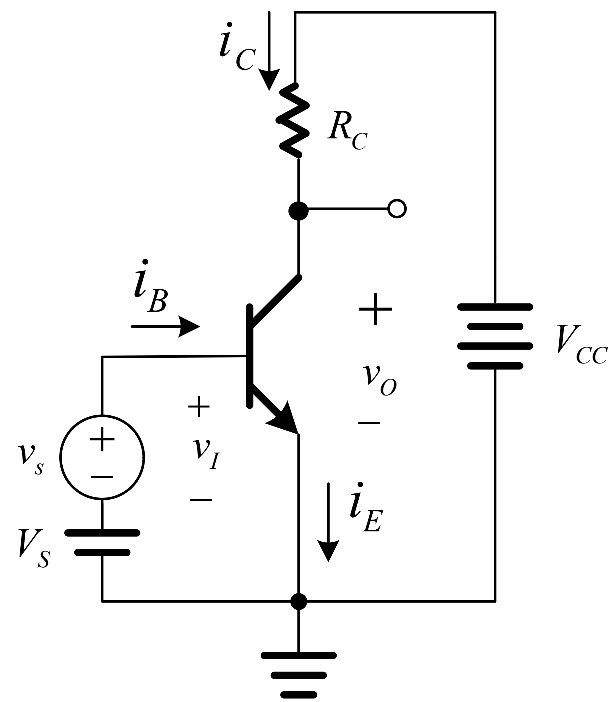
$$i_C \approx I_C+\frac{I_C}{V_T}v_s=I_C+i_c$$

其中 $i_c=\dfrac{I_C}{V_T}v_s$

跨导 $g_m=\left.\dfrac{\partial i_C}{\partial v_{BE}}\right|_{i_C=I_C}=\dfrac{i_c}{v_{be}}=\dfrac{i_c}{v_s}=\dfrac{I_C}{V_T}$

$i_c=g_m v_s=g_m v_{be}$

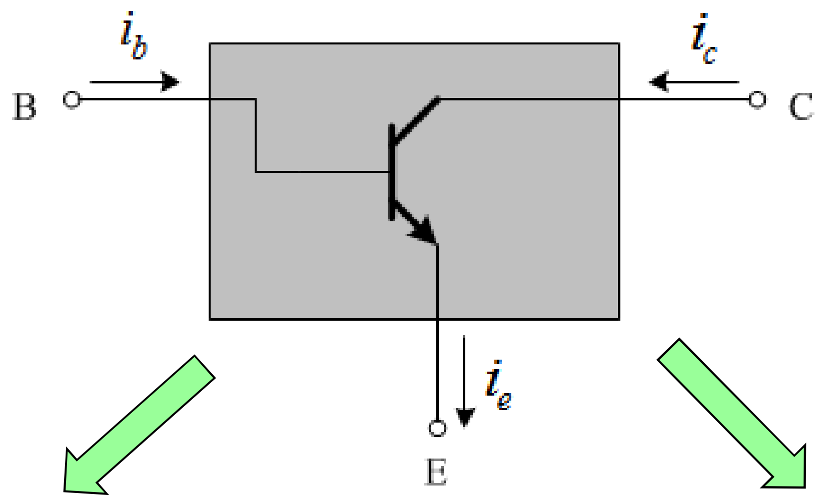
$i_c=\beta i_b$

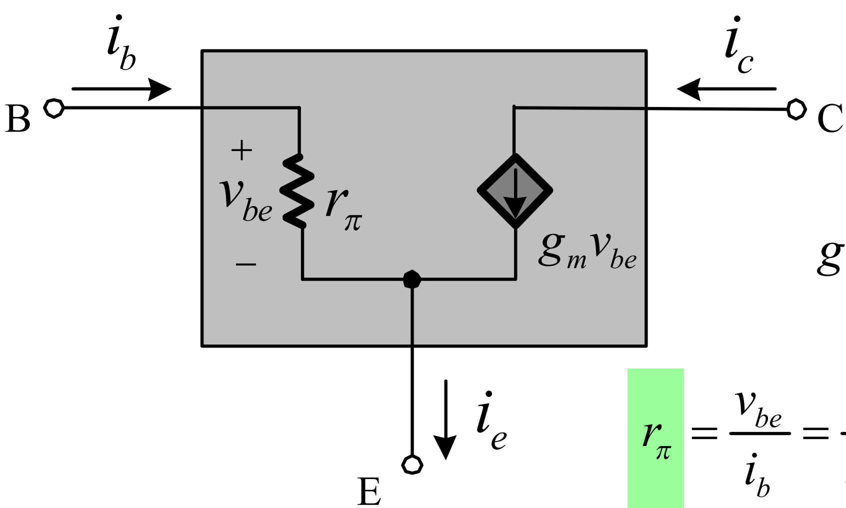


实际电路

一、 小信号模型

1、π型等效电路

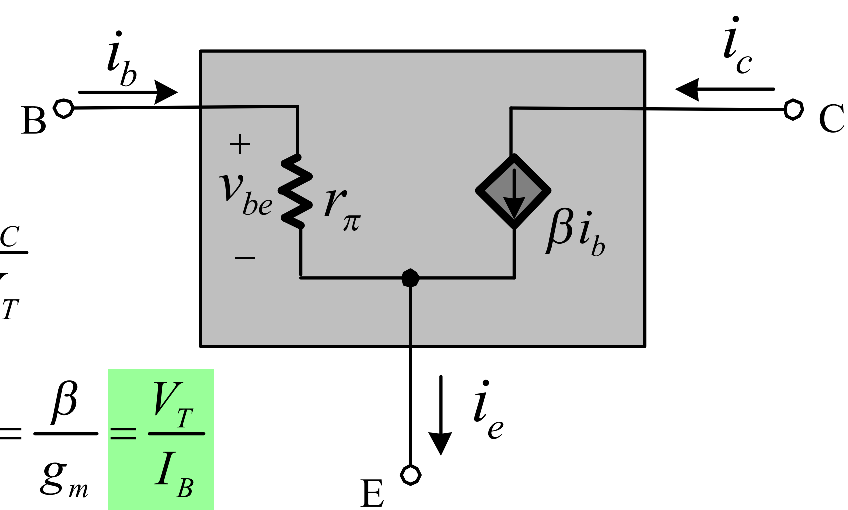




$$g_m = \frac{I_C}{V_T}$$

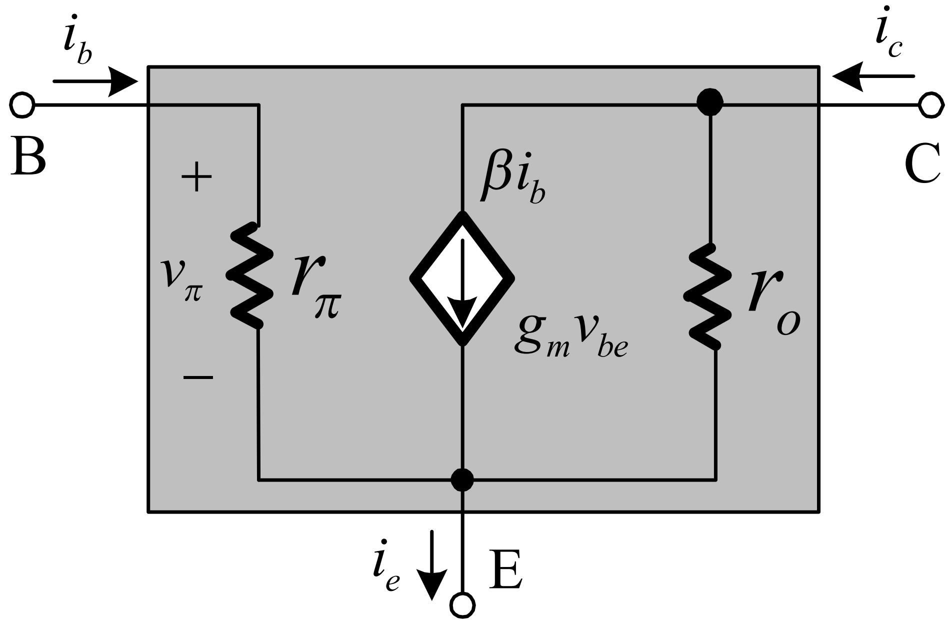
$$r_\pi = \frac{v_{be}}{i_b} = \frac{v_{be}}{i_c/\beta} = \frac{\beta}{g_m} = \frac{V_T}{I_B}$$

压控型等效电路

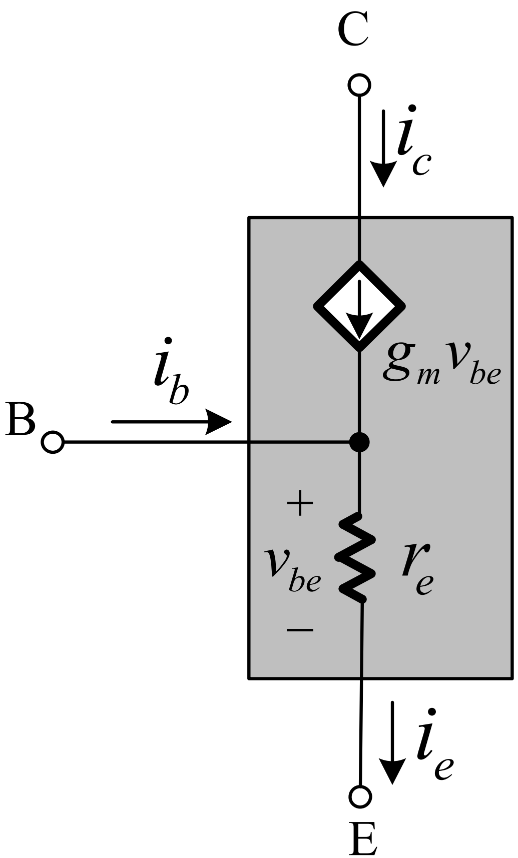


流控型等效电路

考虑厄利效应



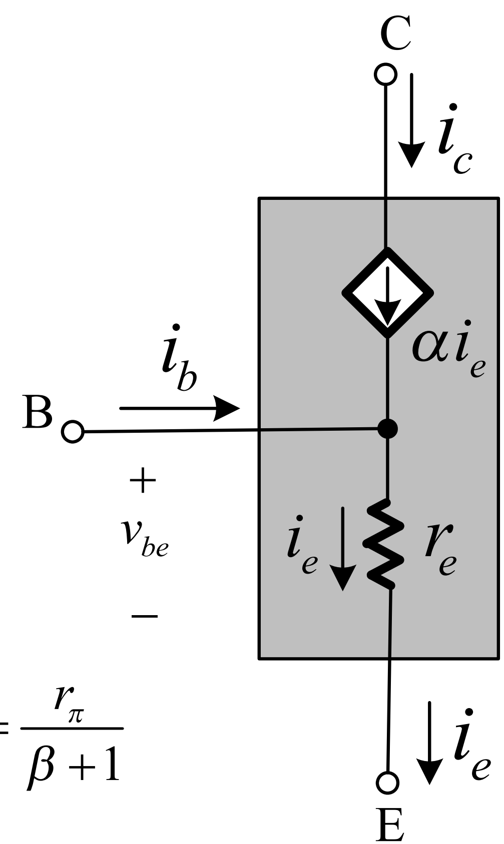
2、T型等效电路



电压控制型

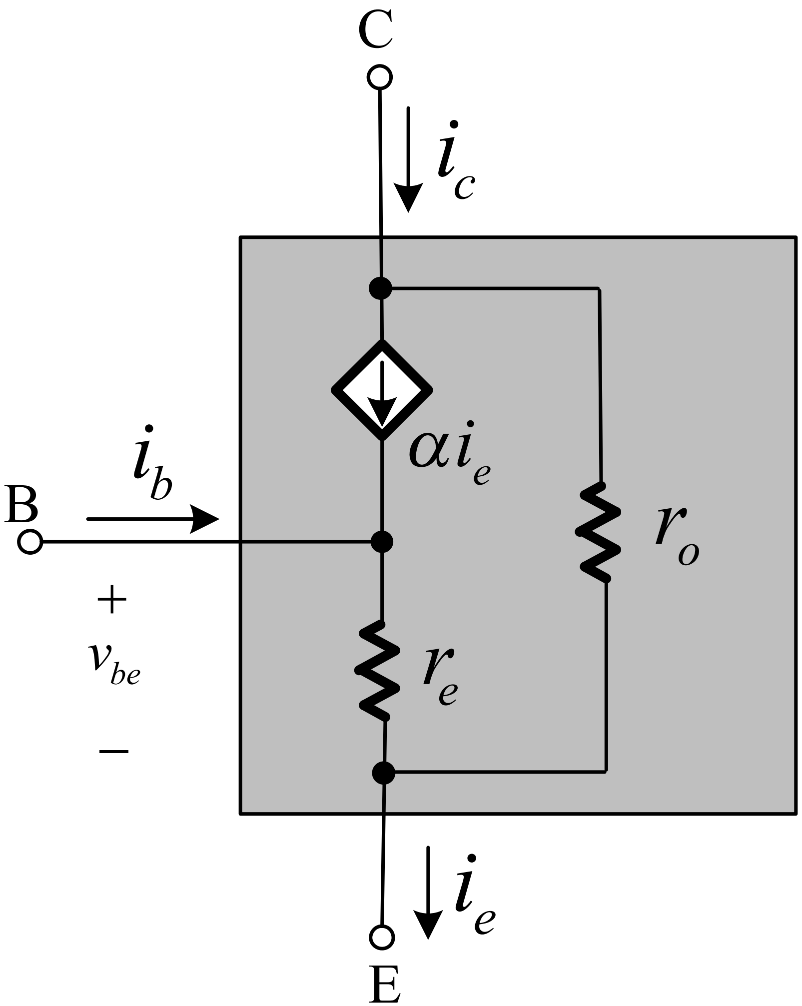
$$g_m = I_C / V_T$$

$$r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m} = \frac{V_T}{I_E} = \frac{r_\pi}{\beta + 1}$$

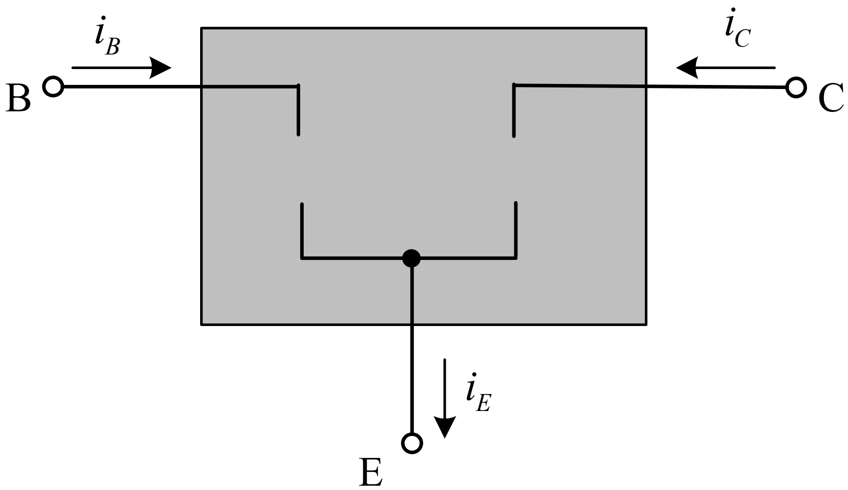


电流控制型

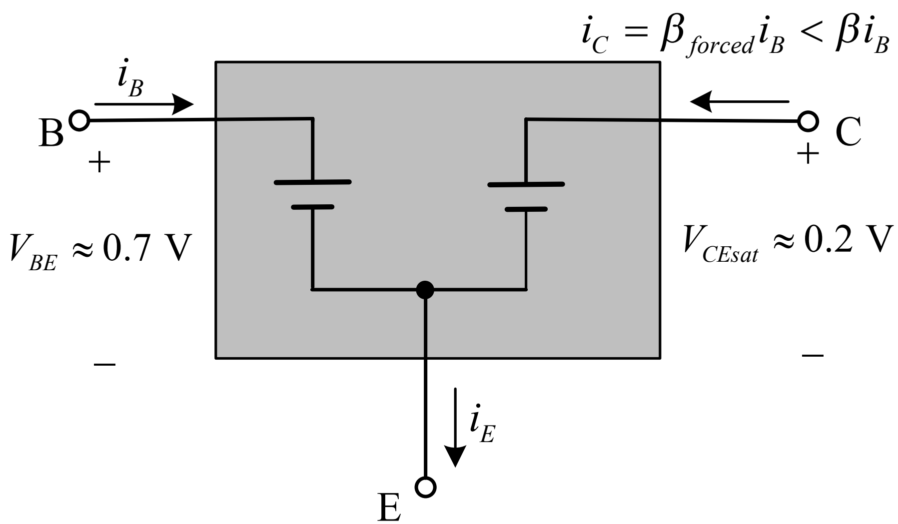
考虑厄利效应



二、截止和饱和时的等效电路



截止时的等效电路

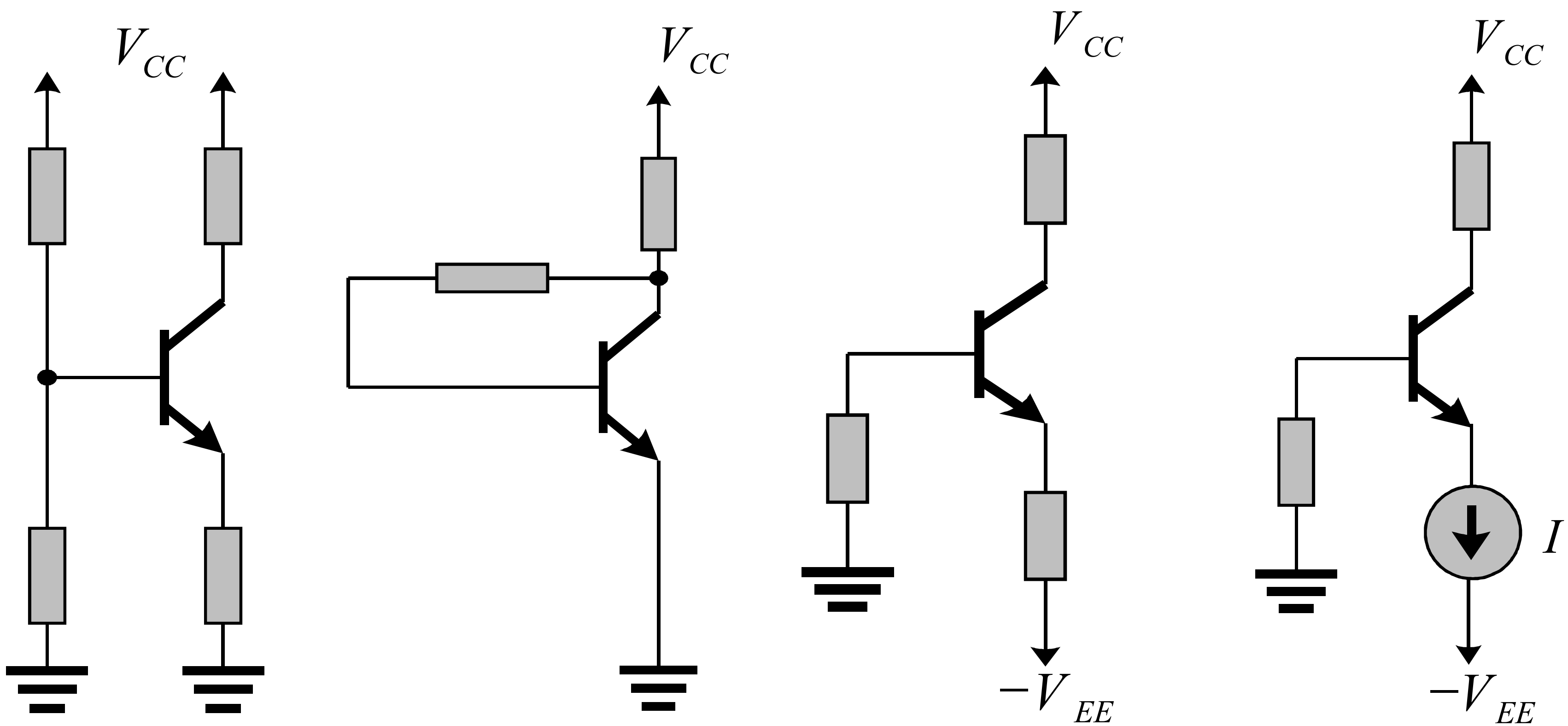


饱和时的等效电路
（NPN）

PNP型三极管饱和时的等效电路相同吗？

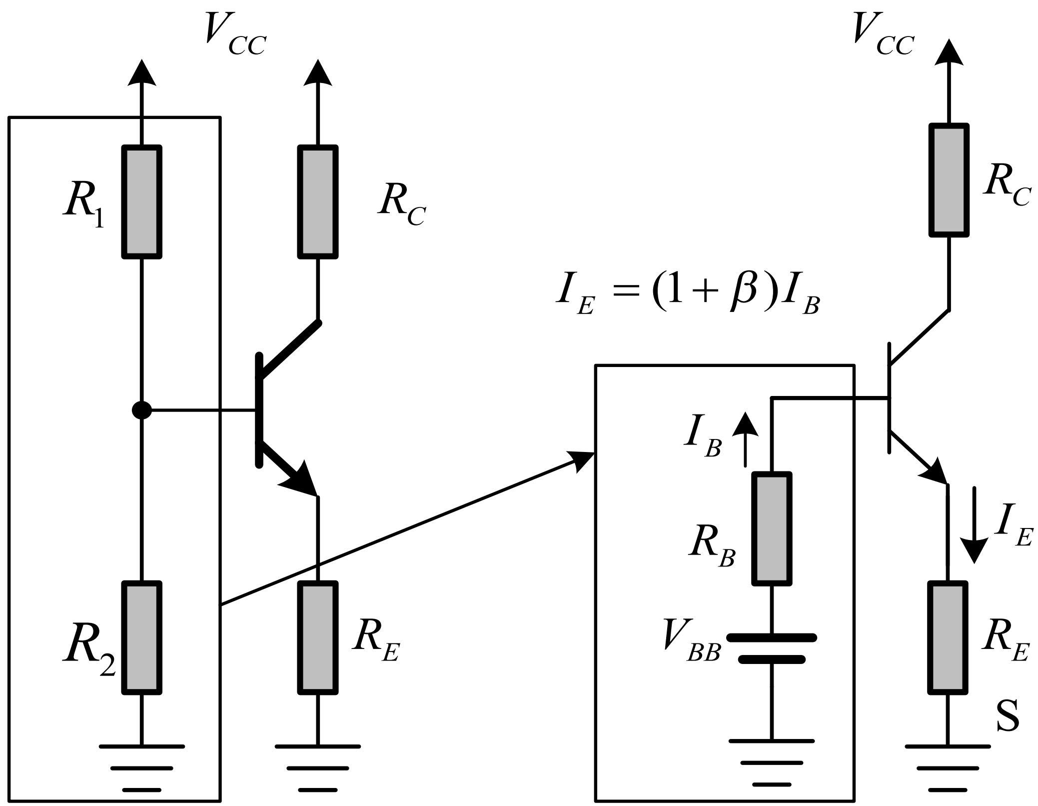
7.2 三极管放大电路的构成及其分析

7.2.1 直流偏置电路及其分析



单电源供电　　可变偏置电路　　双电源供电　　电流源偏置

一、分压式偏置电路（单电源供电）



$I_E = (1+\beta)I_B$

Thevenin等效

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC}$$

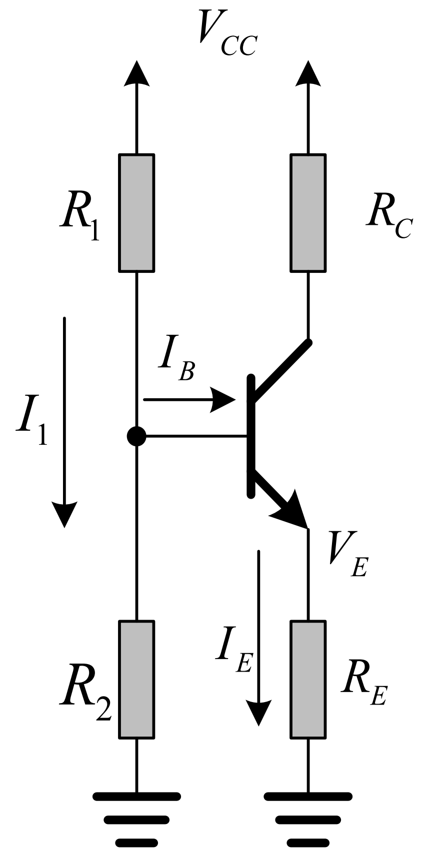
$$R_B = R_1 // R_2$$

$$V_{BB} = I_B R_B + V_{BE} + I_E R_E = \frac{I_E R_B}{1+\beta} + V_{BE} + I_E R_E$$

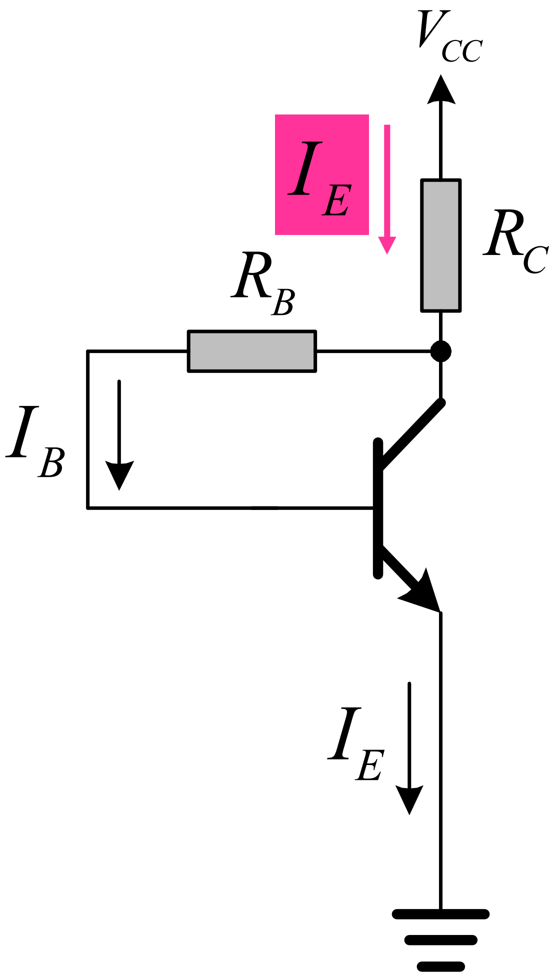
近似计算方法

$$I_1 >> I_B$$

$$V_B \approx \frac{R_2}{R_1 + R_2} V_{CC}$$



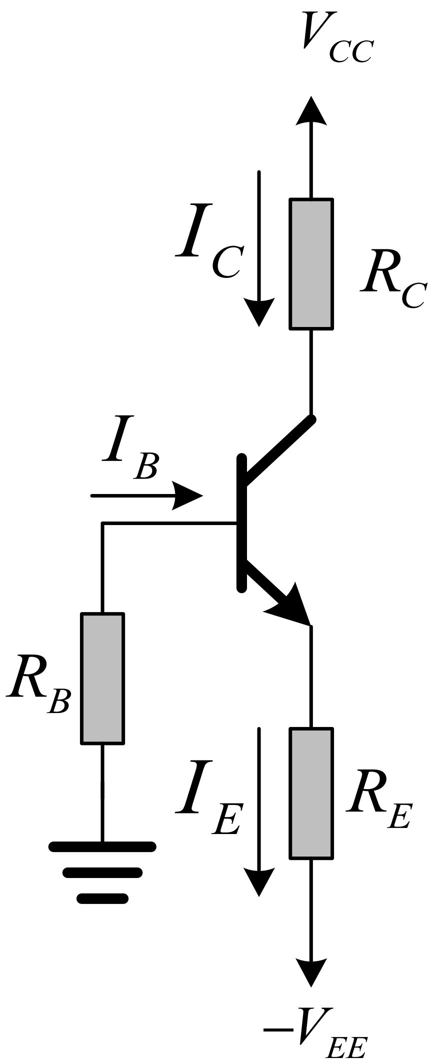
二、可变偏置电路



$$V_{CC} = I_E R_C + I_B R_B + V_{BE}$$

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + R_B / (\beta + 1)}$$

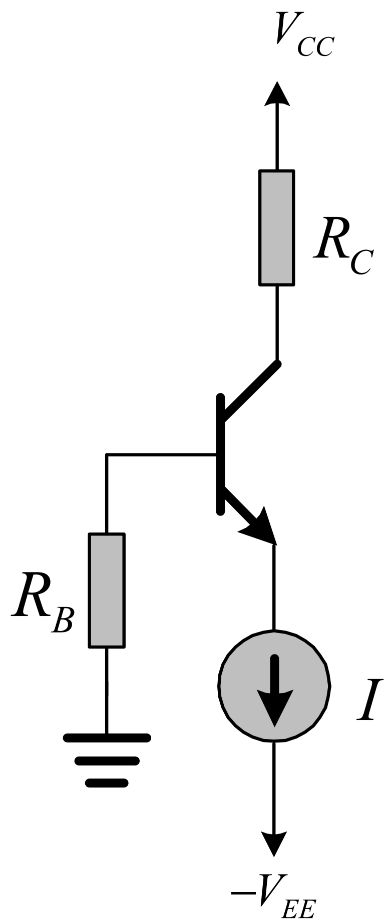
三、带发射极电阻的固定式偏置电路（双电源供电）

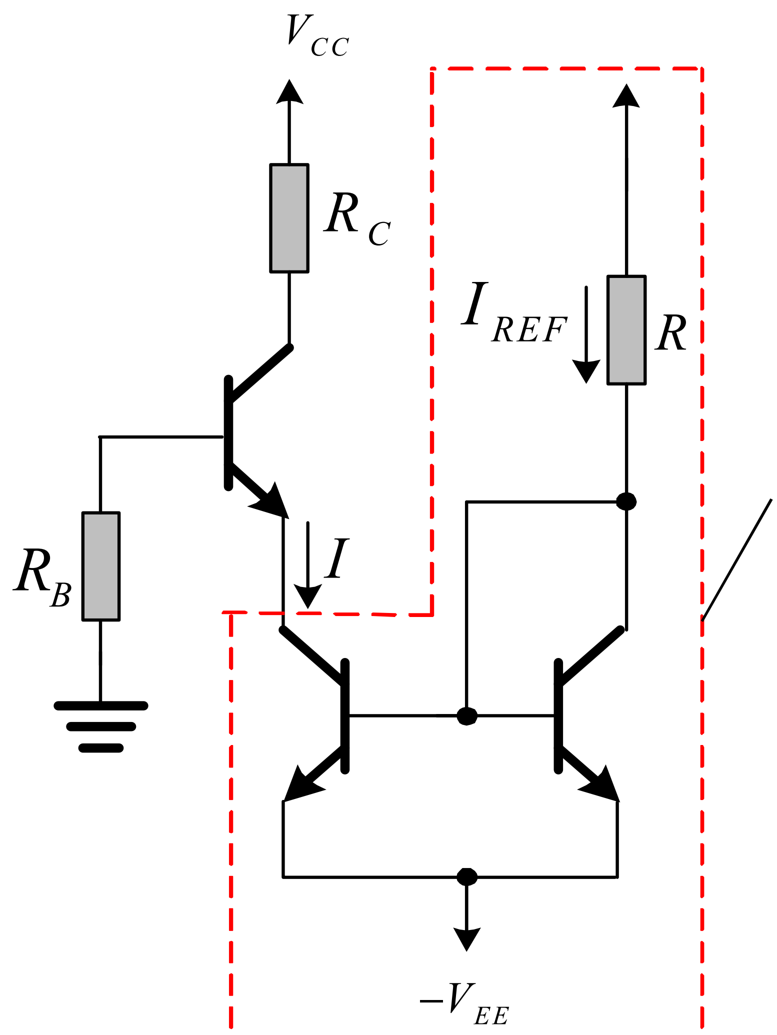


$$I_B R_B + V_{BE} + I_E R_E = V_{EE}$$

四、电流源偏置

$$I_{REF} = \frac{V_{CC} - (-V_{EE}) - V_{BE}}{R} \approx I$$





镜像电流源
电流镜
（Current Mirror）

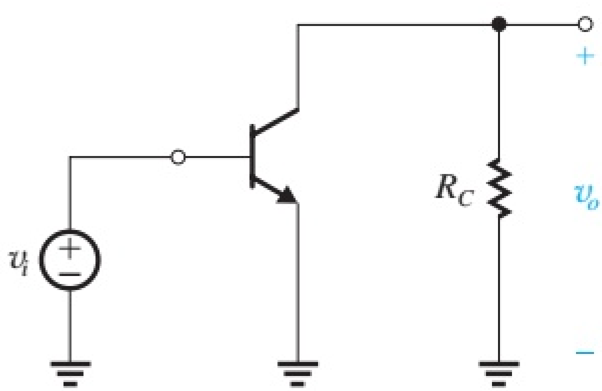
7.2.2 三种接法放大电路的分析计算

一、三种接法

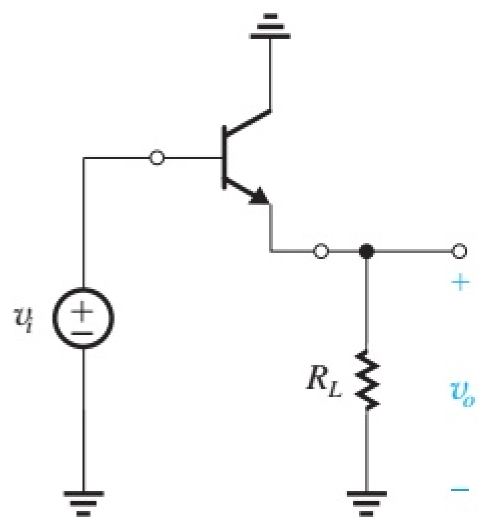
1、共射接法 Common-Emitter (CE)

2、共集接法 Common-Collector (CC)

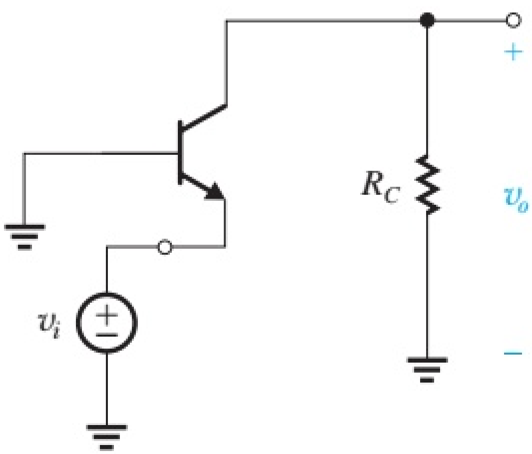
3、共基接法 Common-Base (CB)



(d) Common-Emitter (CE)



(f) Common-Collector (CC) or Emitter Follower



(e) Common-Base (CB)

二、放大器分析方法

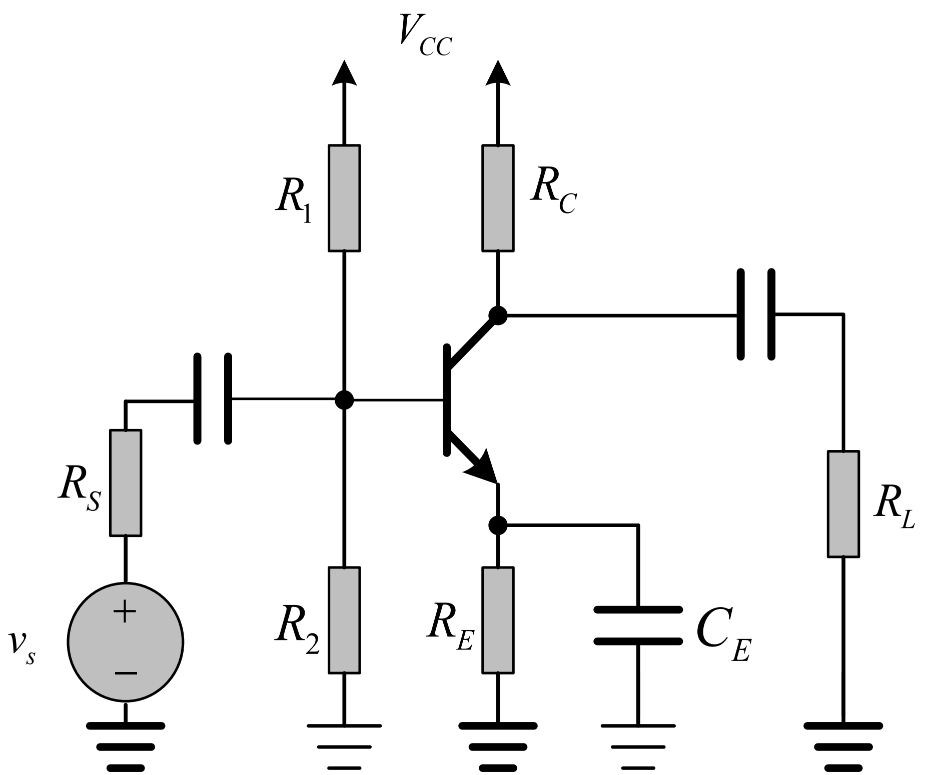
1、分析方法概述

- 分析内容
  - 直流参数（静态工作点）
  - 交流参数
    - 增益
      - 电压增益
      - 电流增益
      - 功率增益
    - 输入阻抗
    - 输出阻抗
    - 通频带

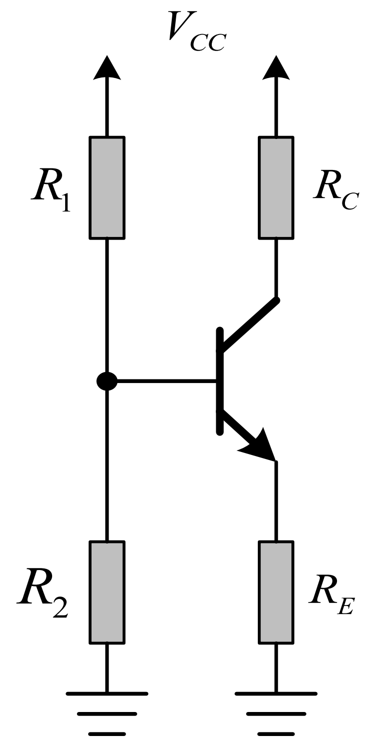
- 分析方法
  - 近似计算法
  - 图解法
  - 等效电路

- 分析途径
  - 直流参数
    直流通路
  - 交流参数
    交流通路

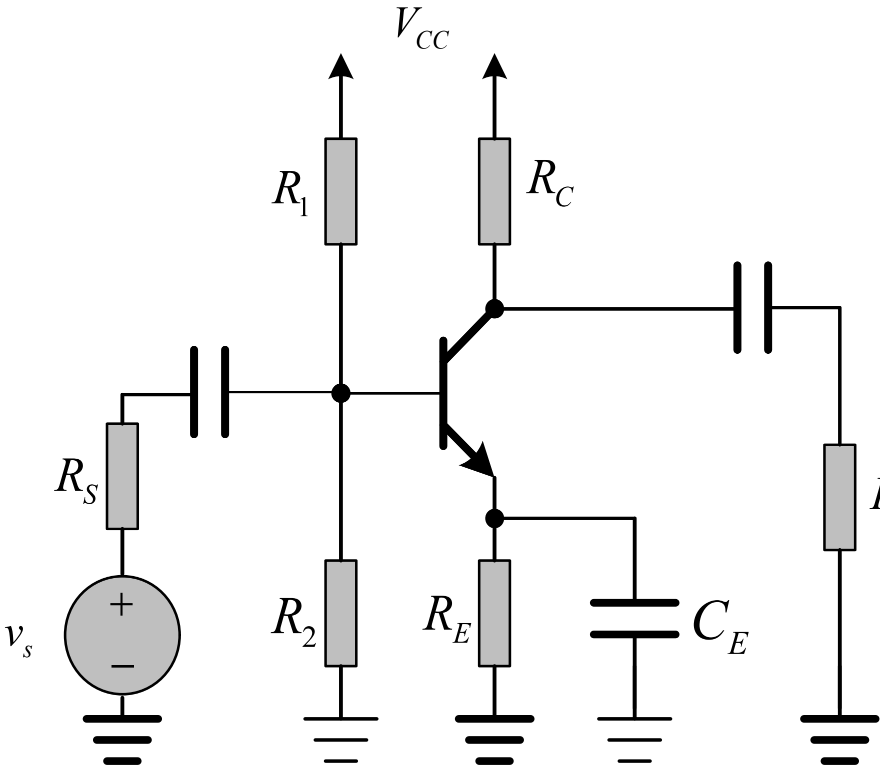
2、直流通路和交流通路



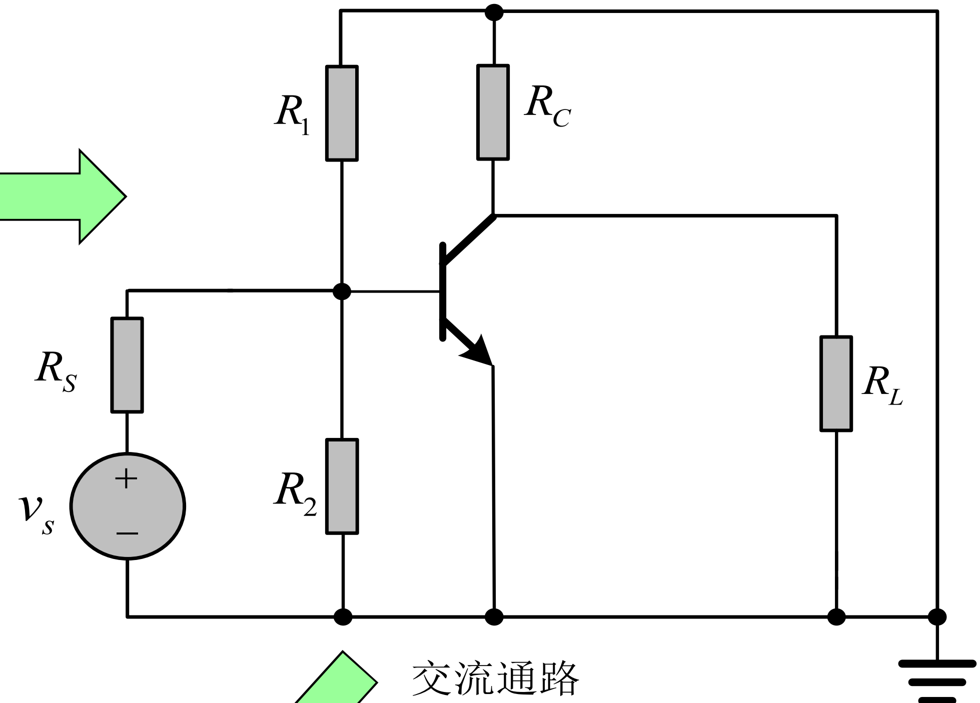
实际电路



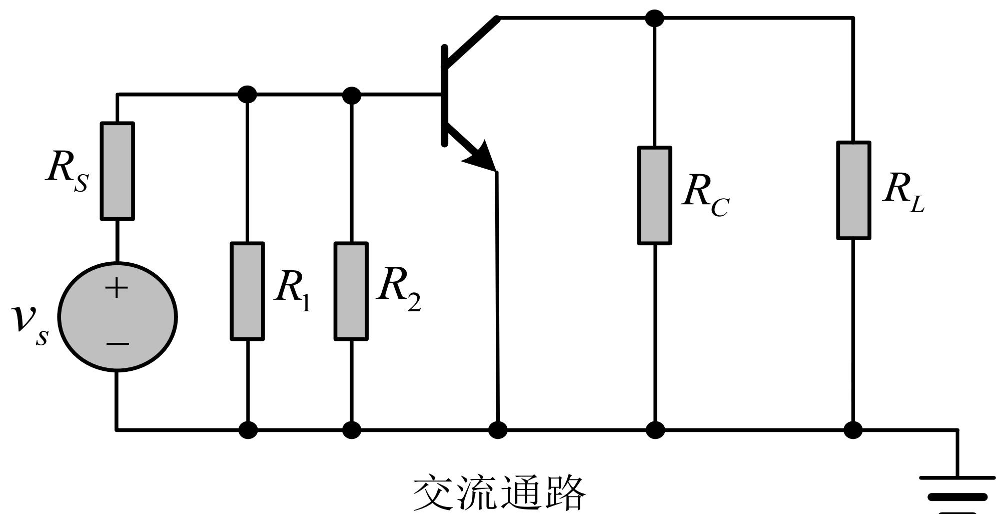
直流通路



实际电路



交流通路

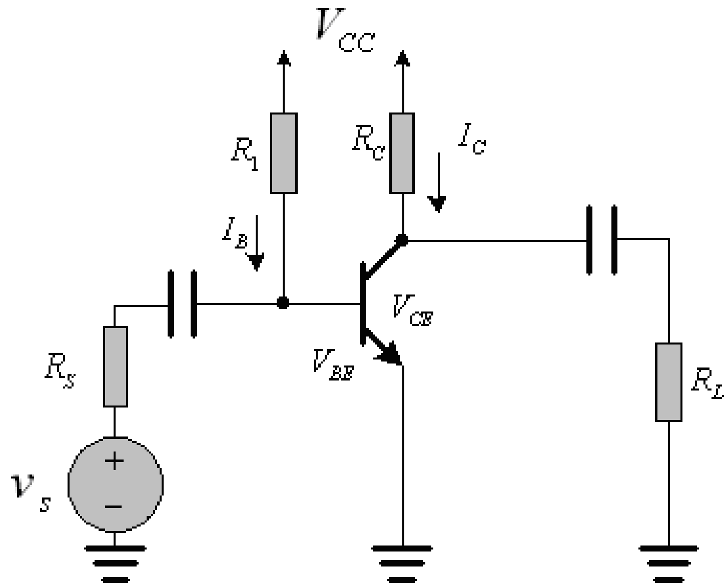


交流通路

3、图解法确定直流工作点

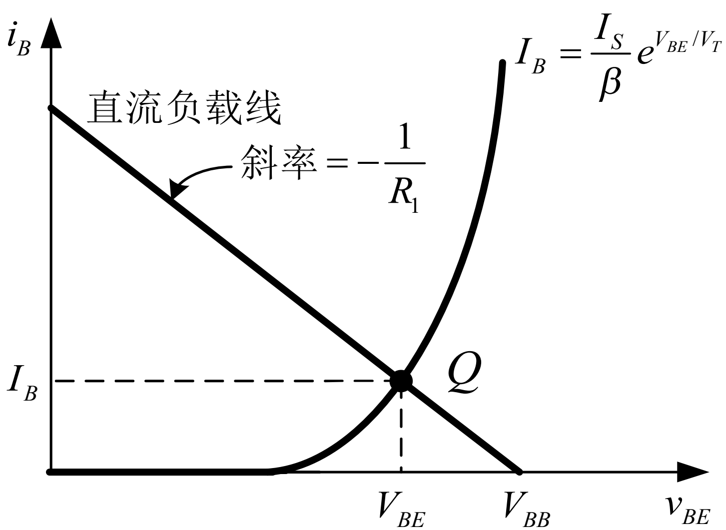
输入特性曲线

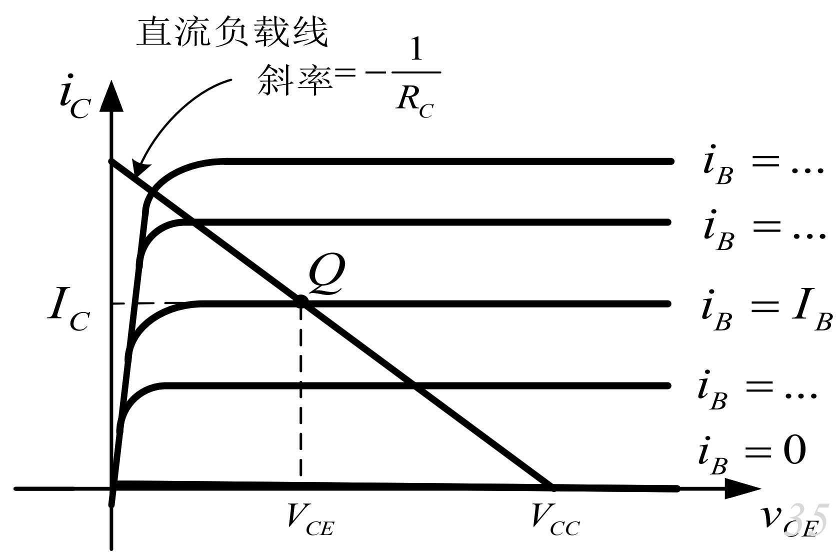
$$V_{CC} = I_B R_1 + V_{BE}$$



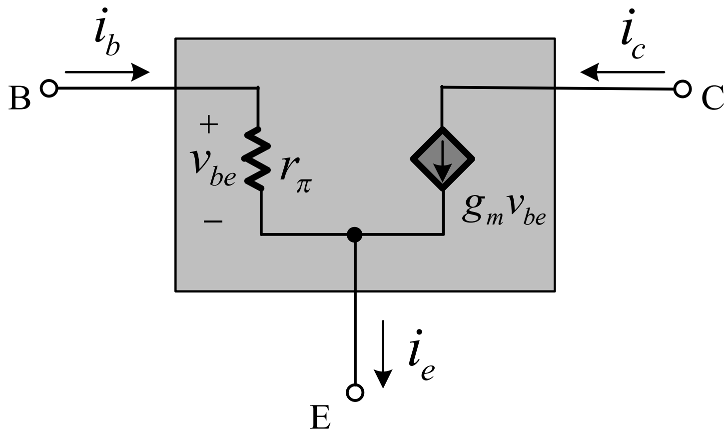
输出特性曲线

$$V_{CE} = V_{CC} - I_C R_C$$

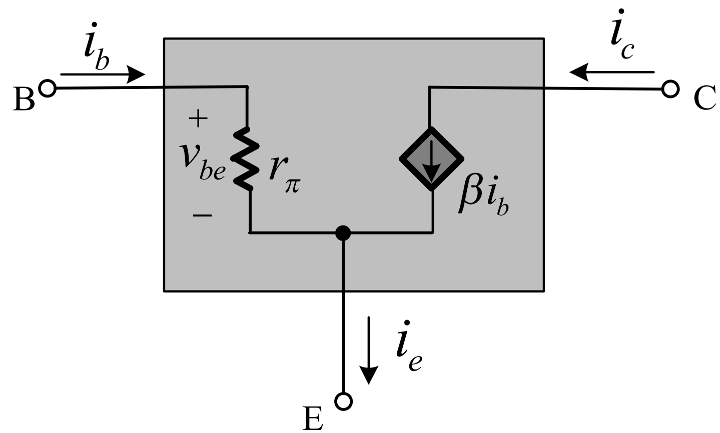




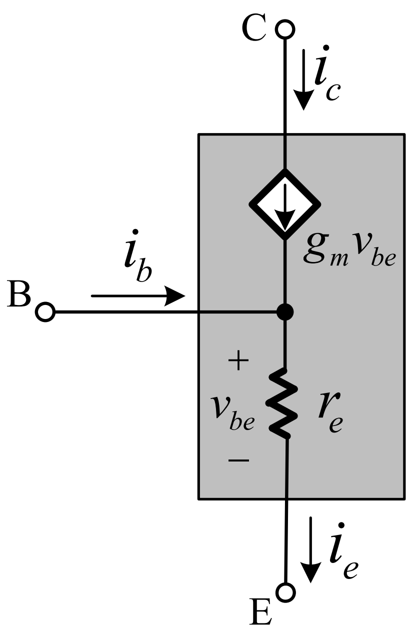
4、等效电路法



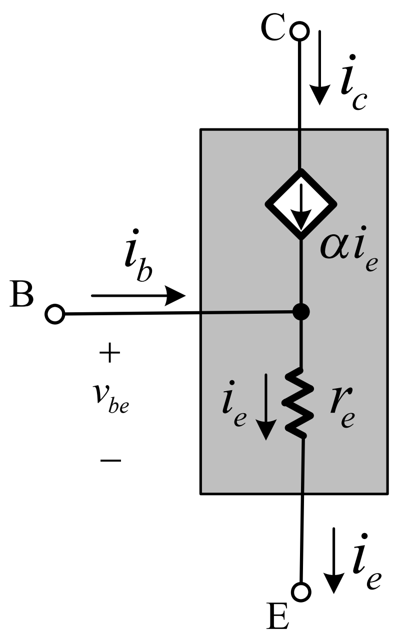
i_b
B
i_c
C
+
v_{be}
r_π
$-$
$g_m v_{be}$
i_e
E



i_b
B
i_c
C
+
v_{be}
r_π
$-$
βi_b
i_e
E



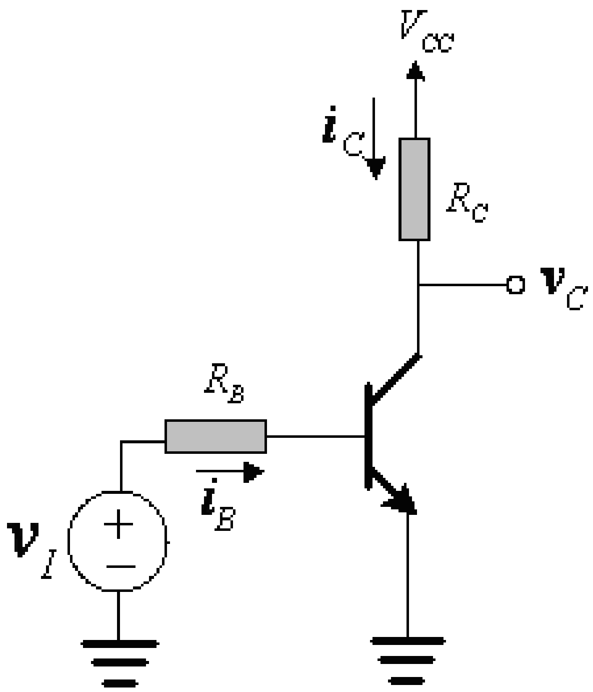
C
i_c
$g_m v_{be}$
i_b
B
+
v_{be}
r_e
$-$
i_e
E



C
i_c
αi_e
i_b
B
+
v_{be}
i_e
r_e
$-$
i_e
E

三、三极管放大电路工作区的确定和选择

例



NPN三极管构成的放大电路

截止区

$$v_I \le 0.5\text{V}$$

放大区

$$v_I > 0.7\text{V} \qquad v_{CB} > 0$$

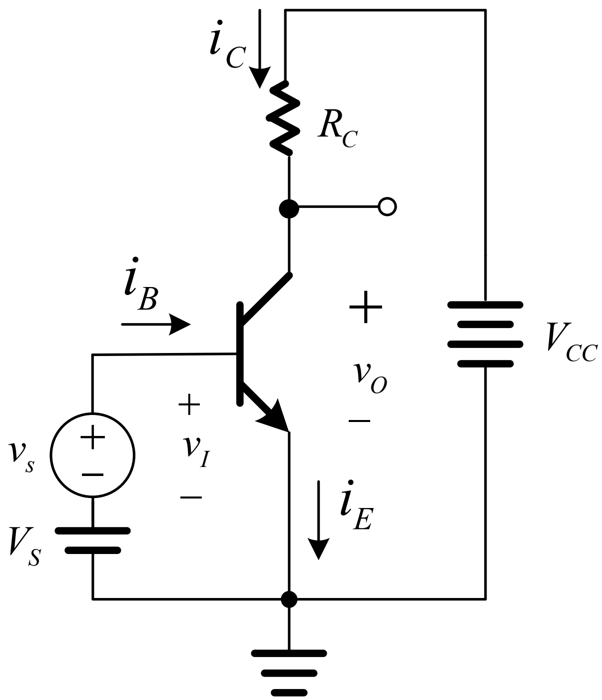
饱和区

$$v_I > 0.7\text{V} \qquad v_{CB} < 0$$

PNP三极管构成的放大电路？

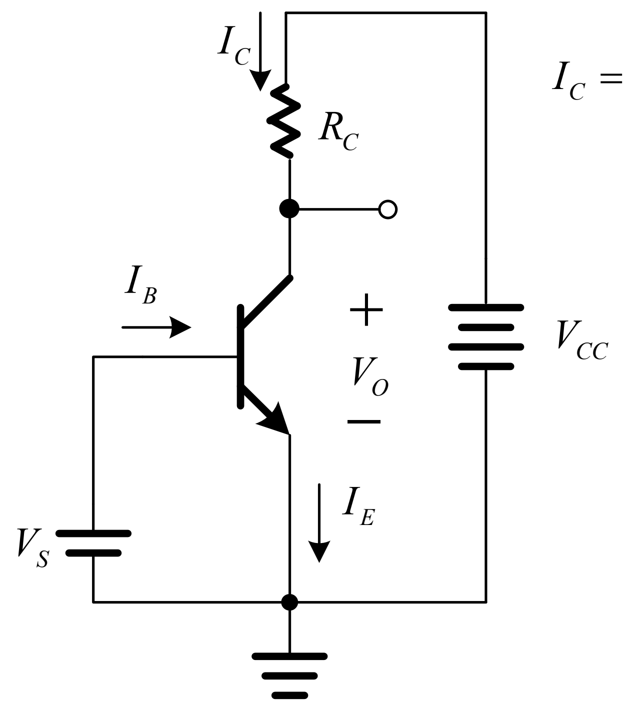
四、三极管放大器分析

共射放大器



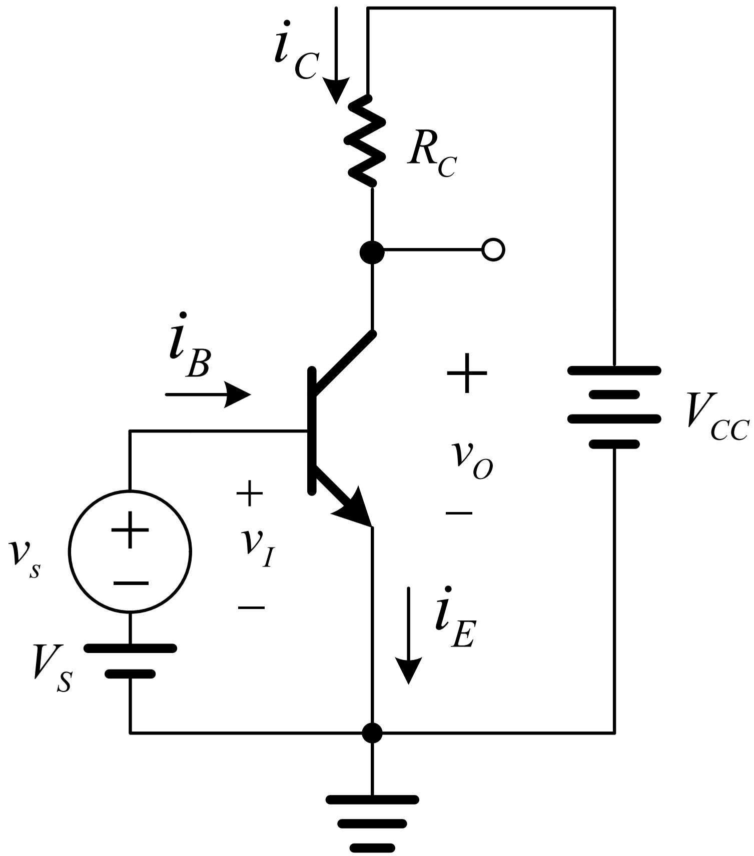
实际电路

1、直流状态



直流通路

2、集电极电流和跨导

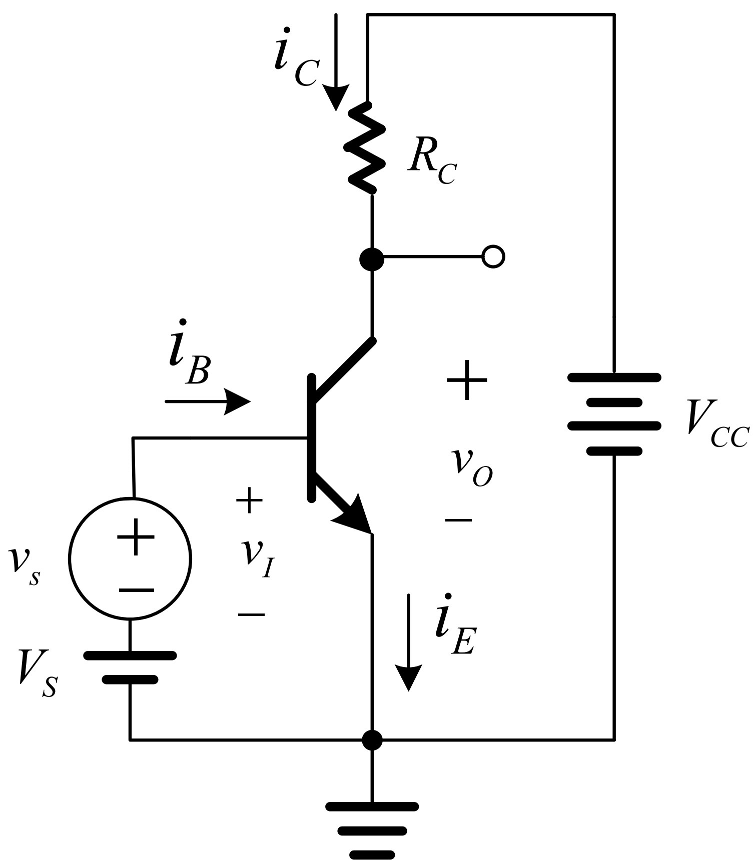


实际电路

$$i_c = g_m v_s$$

$$\text{跨导} \quad g_m = \frac{i_c}{v_{be}} = \frac{I_C}{V_T}$$

3、基极电流和基极输入电阻



实际电路

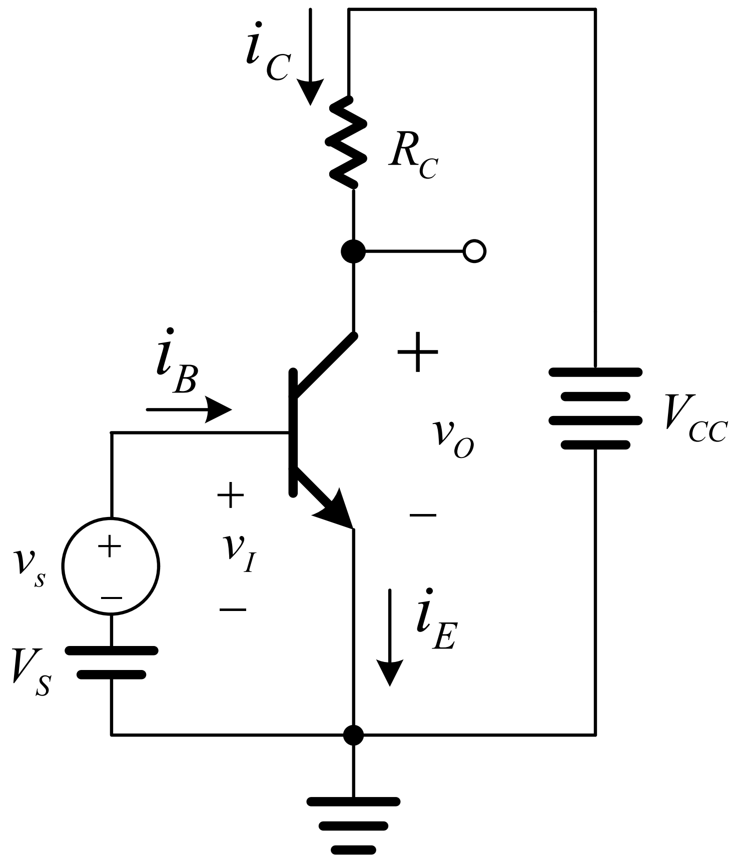
$$i_B = \frac{i_C}{\beta} = \frac{I_C + i_c}{\beta} = I_B + i_b$$

$$i_b = \frac{i_c}{\beta} = \frac{g_m v_{be}}{\beta} = \frac{g_m v_s}{\beta} = \frac{v_s}{\frac{\beta}{g_m}}$$

基极输入电阻

$$r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \frac{V_T}{I_B}$$

4、发射极电流和射极输入电阻



实际电路

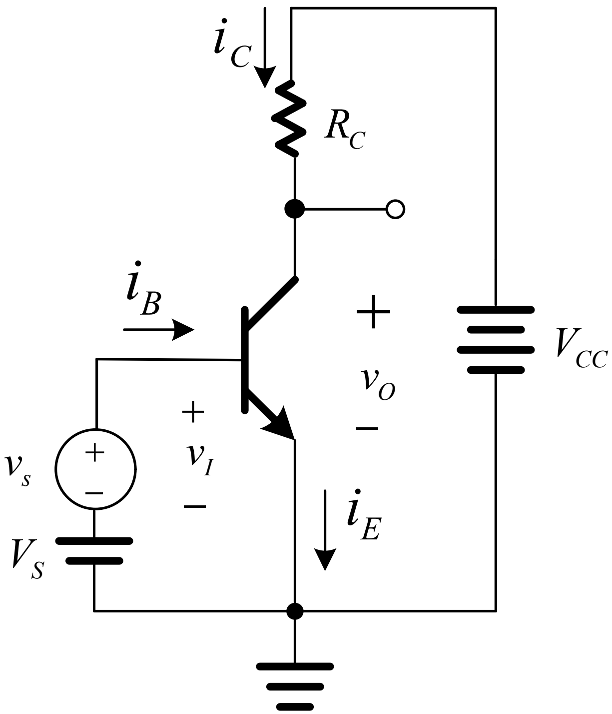
$$i_E = I_E + i_e$$

$$i_e = \frac{i_c}{\alpha} = \frac{g_m v_{be}}{\alpha} = \frac{g_m v_s}{\alpha} = \frac{v_s}{\frac{\alpha}{g_m}}$$

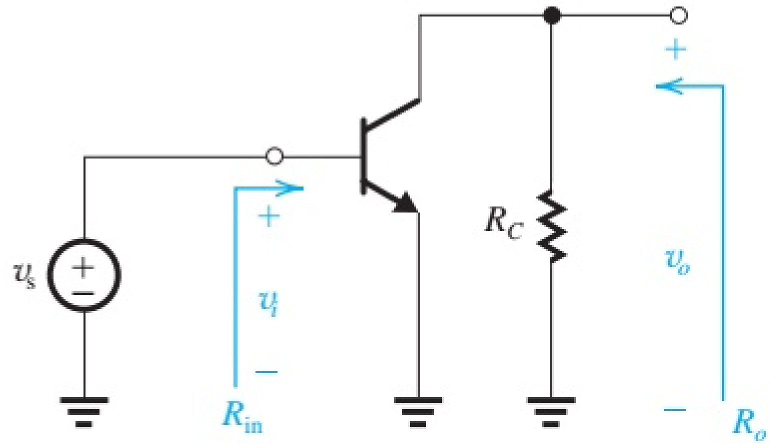
发射极输入电阻

$$r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m} = \frac{V_T}{I_E}$$

5、电压增益

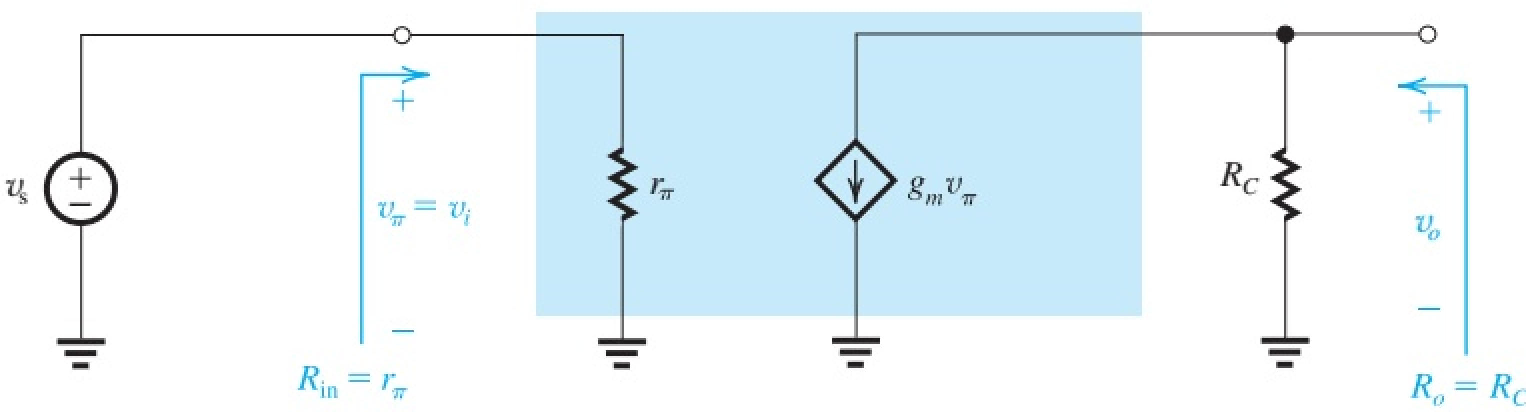


实际电路

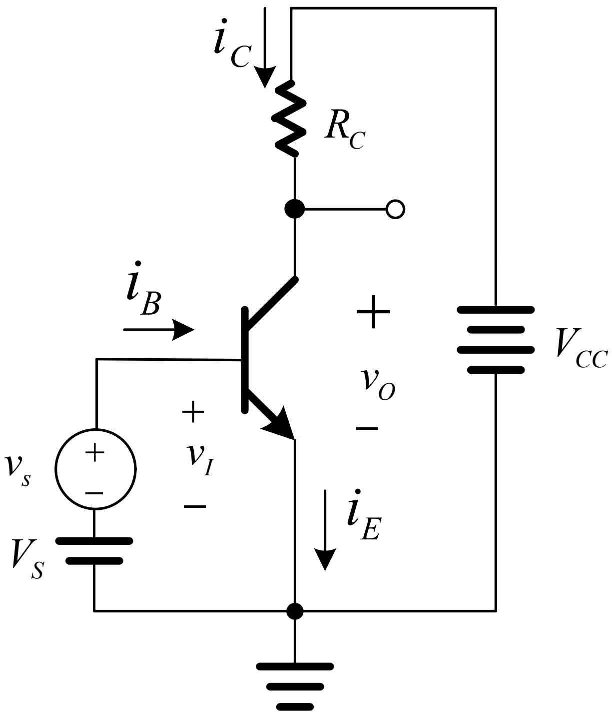


$$A_v = \frac{v_o}{v_i} = \frac{v_{ce}}{v_{be}} = \frac{-i_c R_C}{v_{be}} = \boxed{-g_m R_C}$$

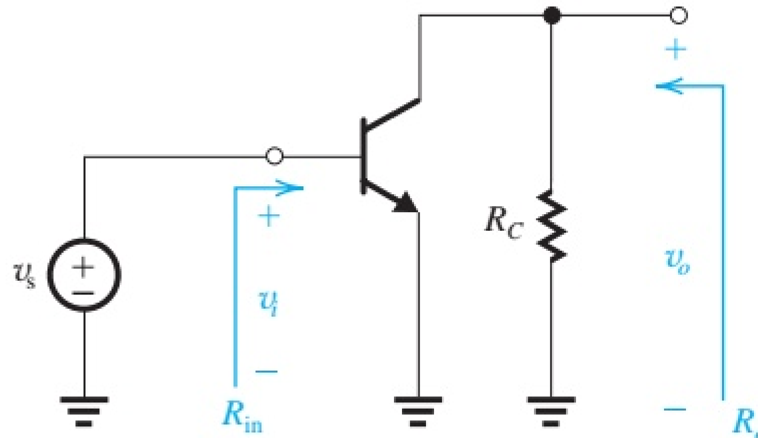
混合π型等效电路适合分析发射极无电阻的共射放大器电路。



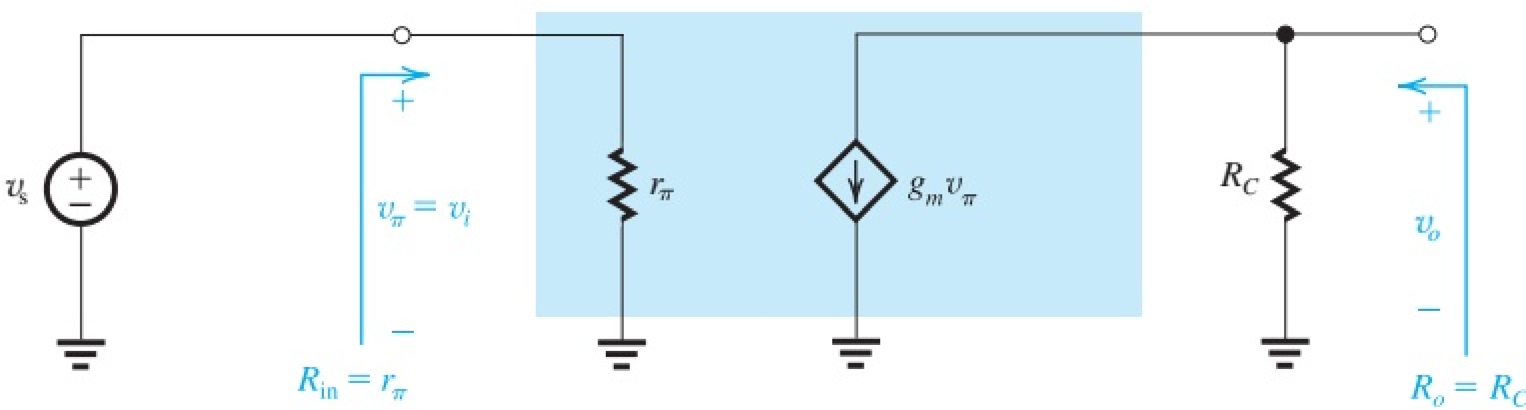
6、输入电阻



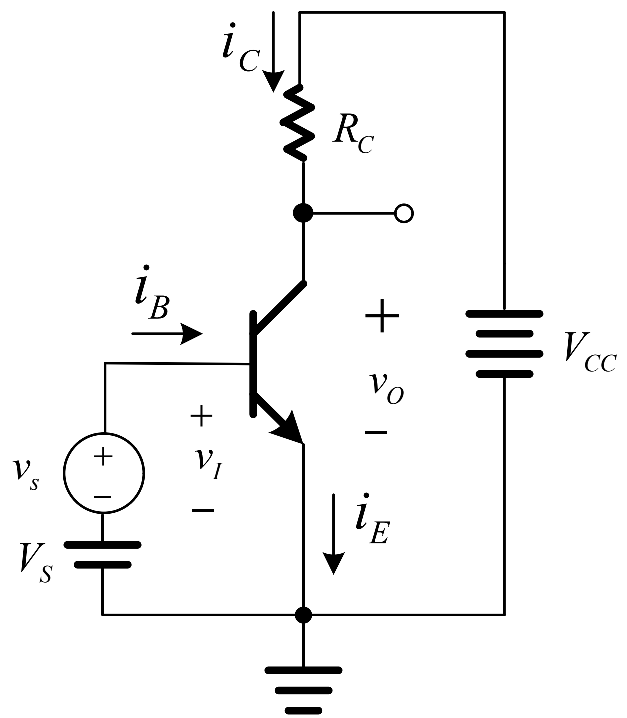
实际电路



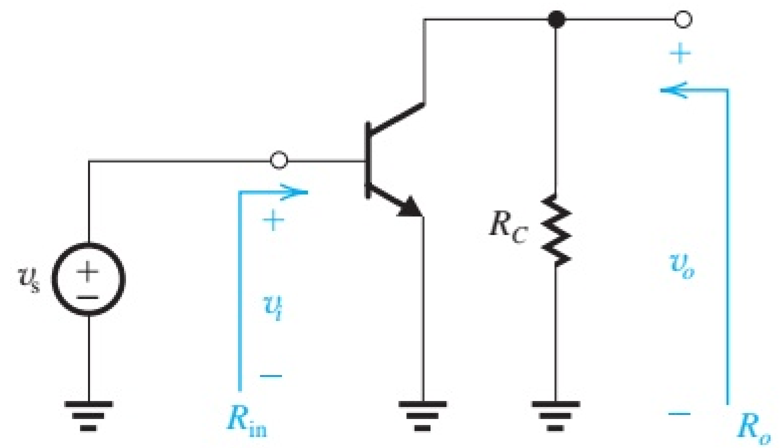
$$R_{in} = \frac{v_i}{i_i} = r_\pi$$



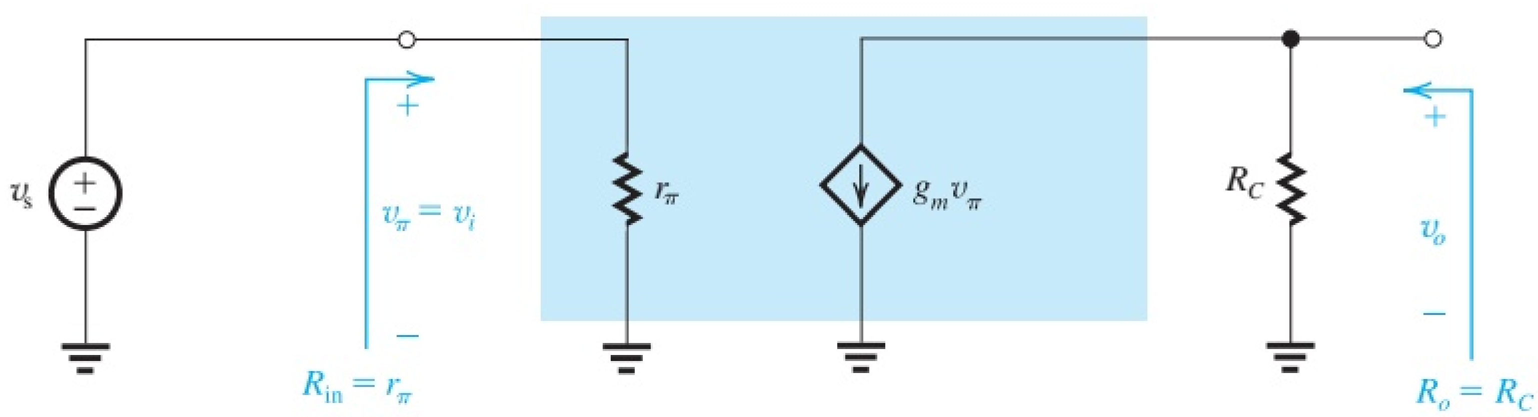
7、输出电阻



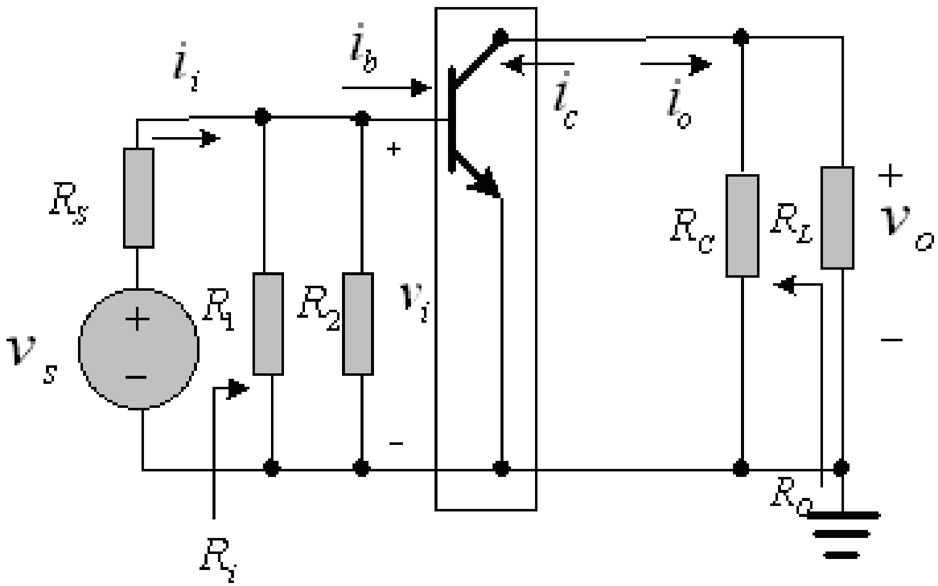
实际电路



$$R_o = R_C$$



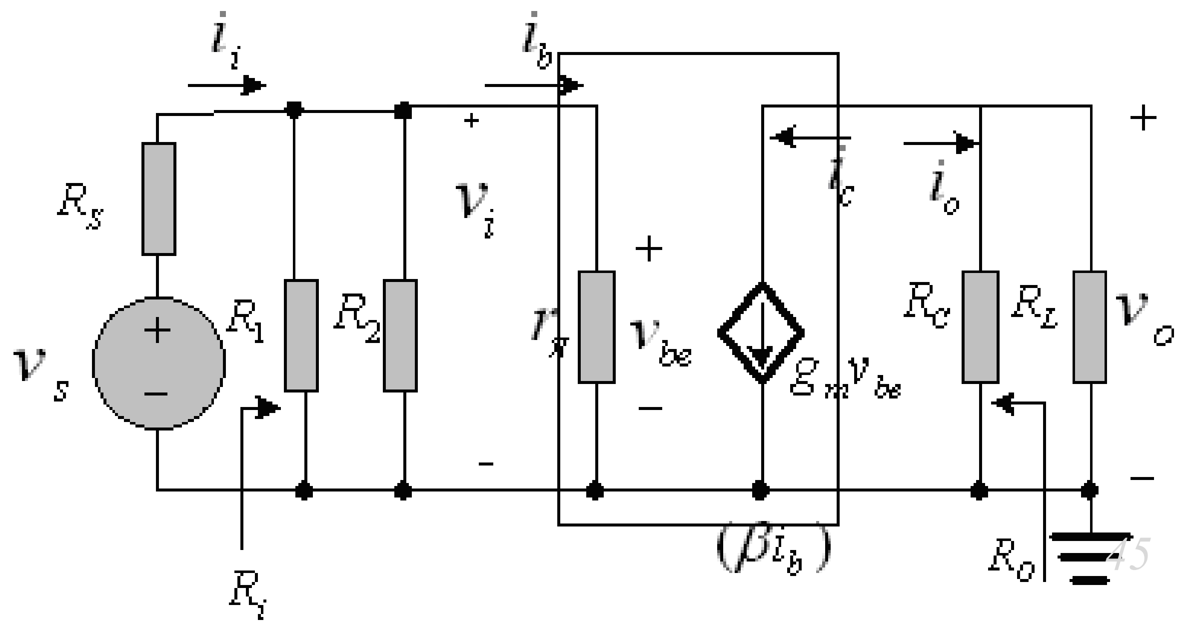
例 若共射放大器连接负载

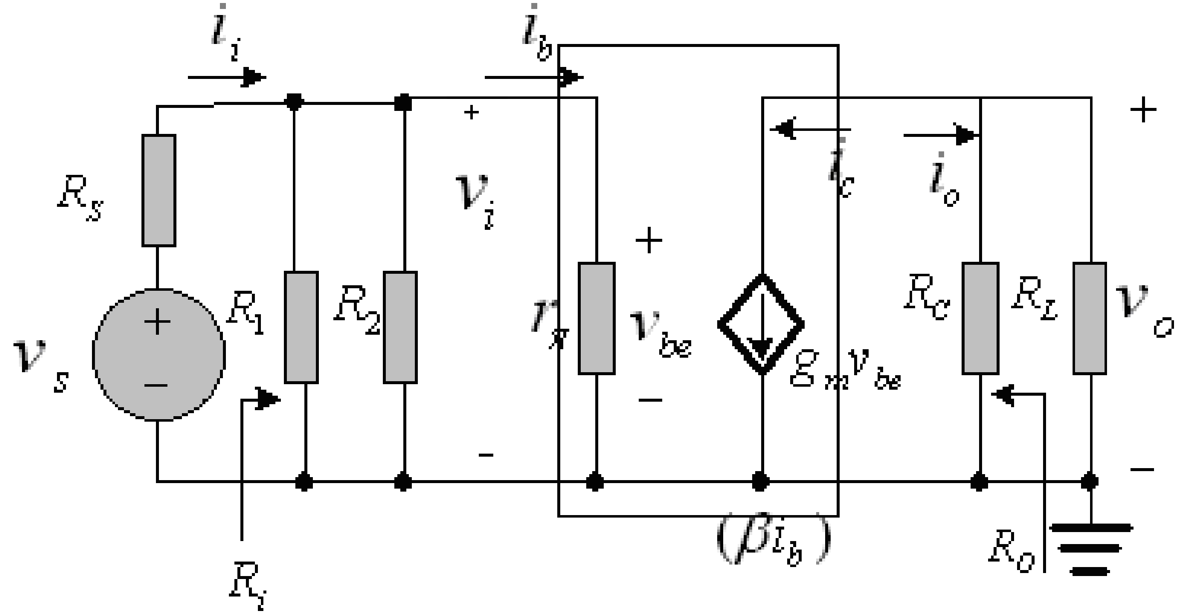


求电压增益 A_v

求输入阻抗 R_i

求输出阻抗 R_o





$$A_v = \frac{v_o}{v_i} = \frac{-g_m v_{be} R_C // R_L}{v_{be}} = -g_m R_C // R_L = -\frac{\beta R_C // R_L}{r_\pi}$$

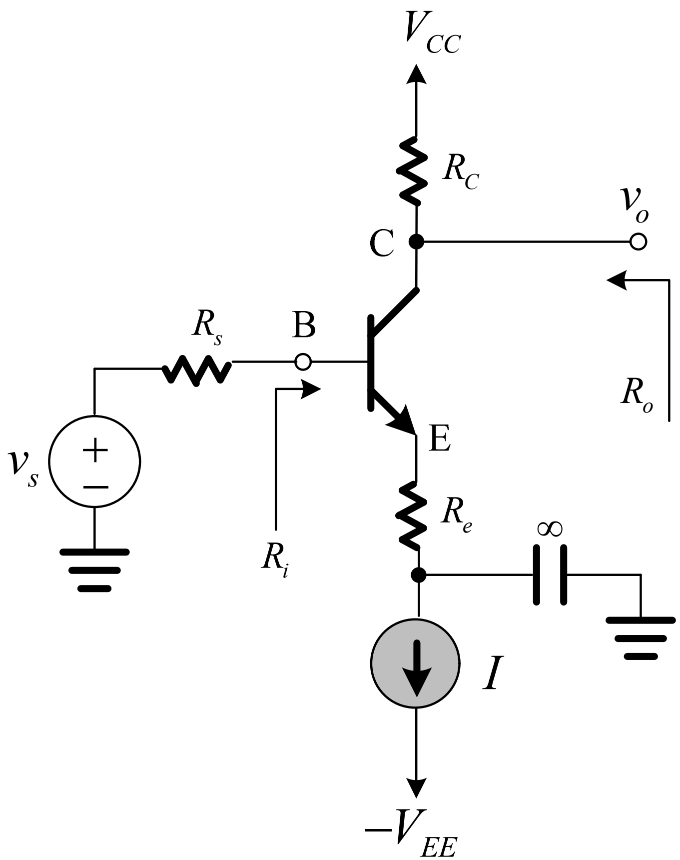
$$R_i = R_1 // R_2 // r_\pi$$

$$R_o = R_C$$

特点：

输入电阻中等，输出电阻大，频带窄！放大电压和电流！

例 发射极接有电阻的共射放大器

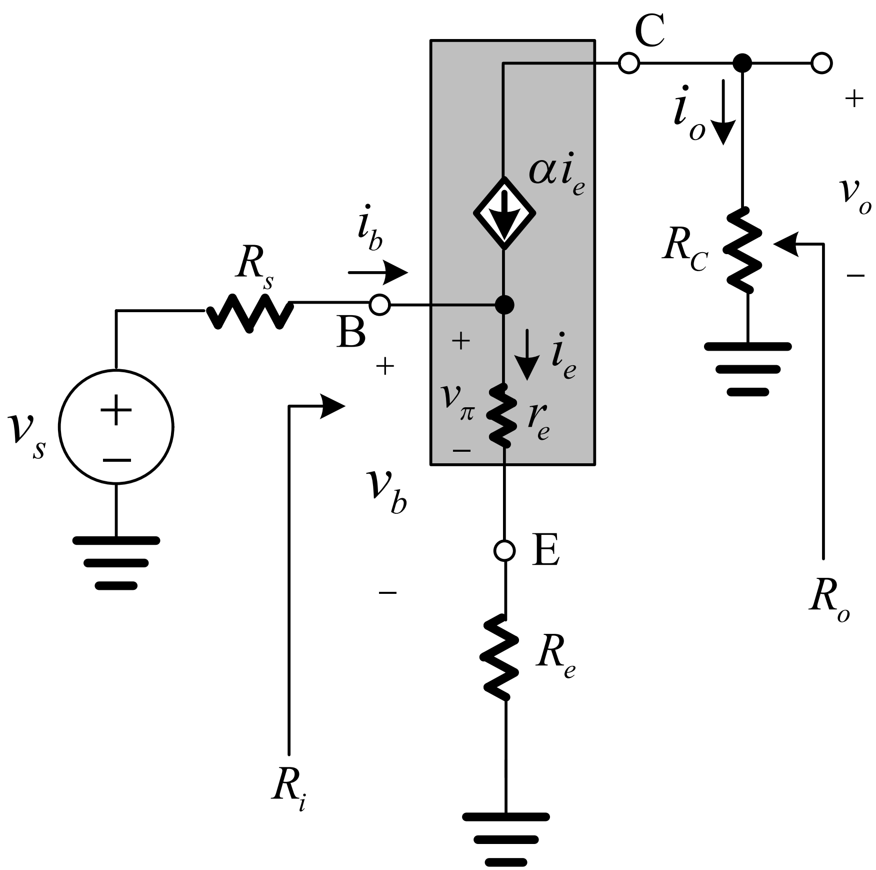


(a)

R_e 的作用

$T\uparrow \rightarrow I_C\uparrow \rightarrow V_E\uparrow \rightarrow V_{BE}\downarrow$（$V_B$基本不变）$\rightarrow I_C\downarrow$

发射极接有电阻的共射放大器适合采用T型等效电路进行分析



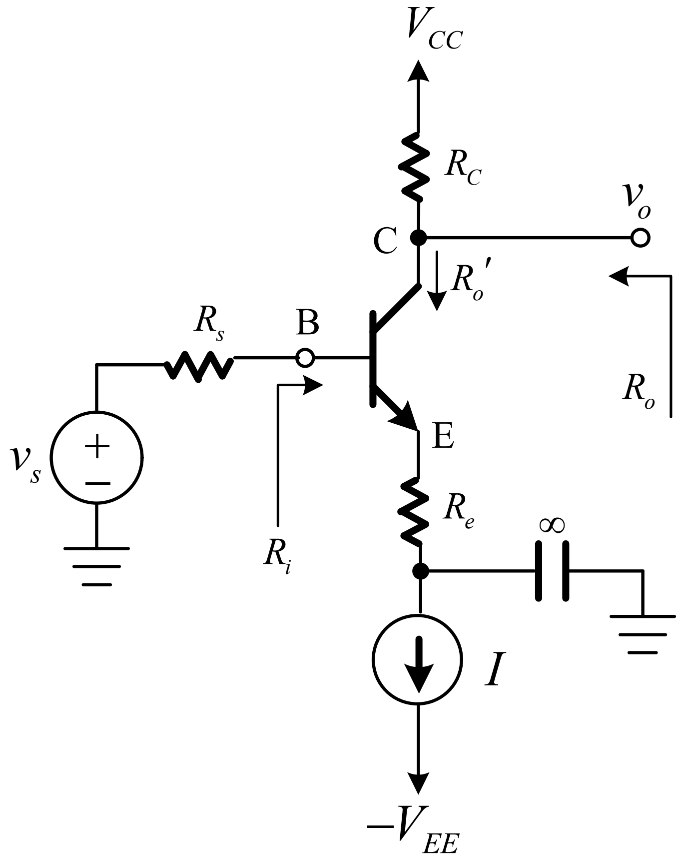
小信号等效电路

$$A_v = \frac{v_o}{v_i} = \frac{-\alpha i_e R_C}{i_e\left(r_e + R_e\right)} = -\alpha \frac{R_C}{r_e + R_e}$$

$$= -\frac{\alpha}{r_e} \frac{R_C}{1 + R_e / r_e}$$

$$\simeq -\frac{g_m R_C}{1 + g_m R_e}$$

$$R_i = \frac{v_i}{i_b} = \frac{i_e\left(r_e + R_e\right)}{i_b} = (\beta + 1)(r_e + R_e)$$

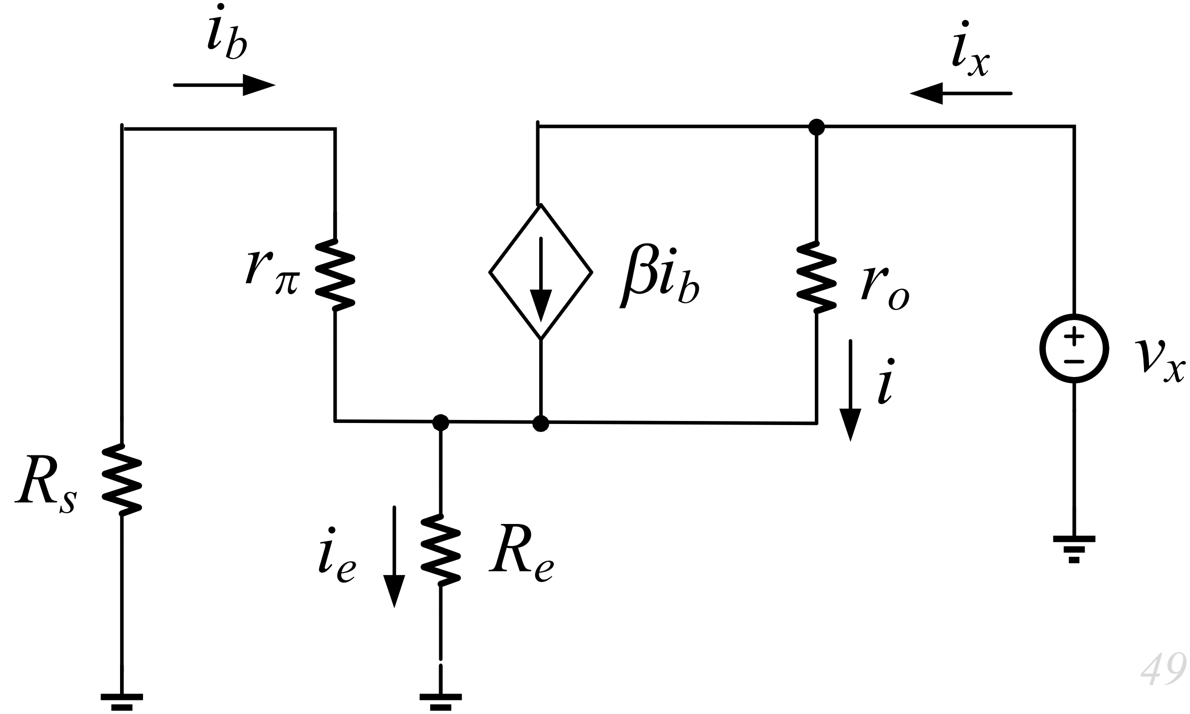


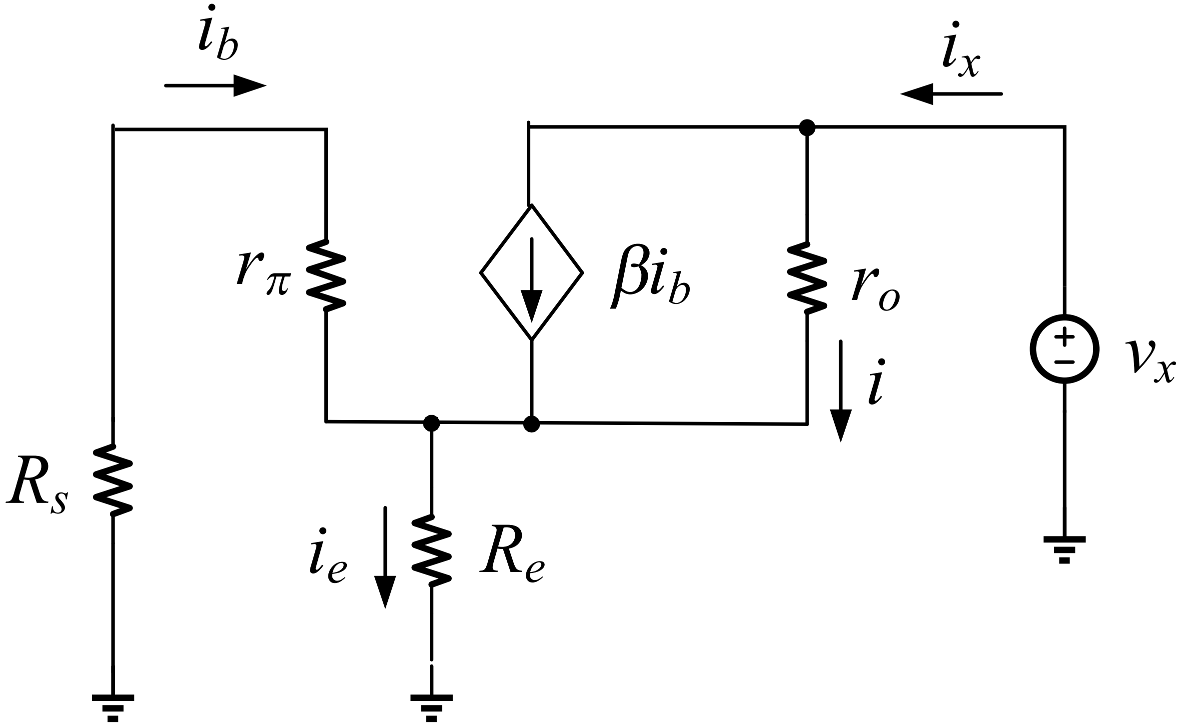
(a)

求输出电阻 R_o

$$R_o = R_c // R_o'$$

$$R_o' = \frac{v_x}{i_x}$$





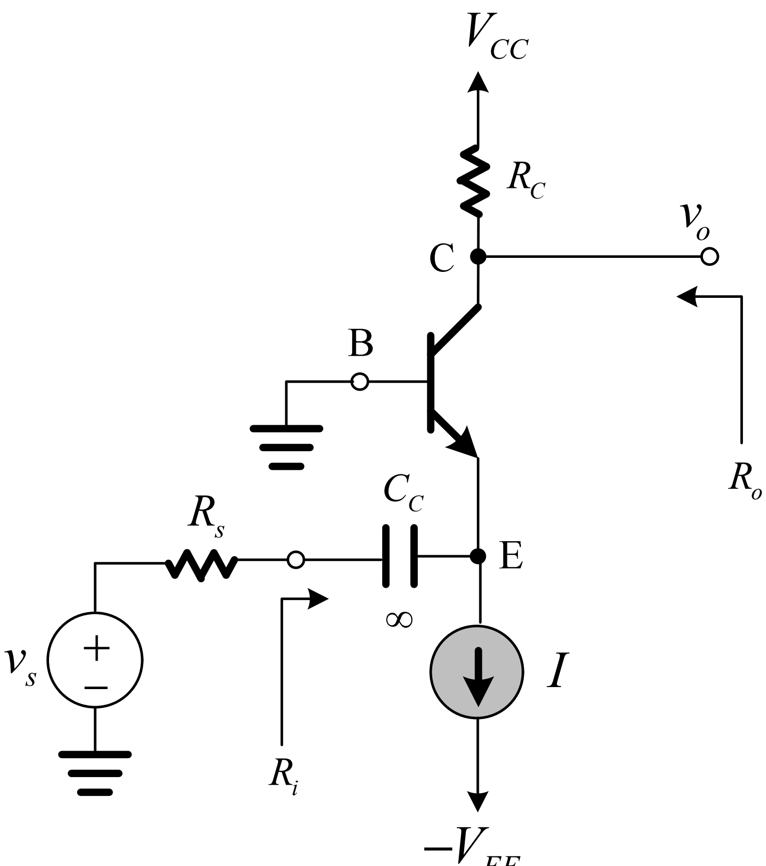
$$R_o' >> R_c$$

$$R_o = R_c // R_o' \approx R_c$$

$$v_x = r_o i + R_e i_e \qquad i_x = i + \beta i_b \qquad i_e = i_x + i_b \qquad (R_S + r_\pi) i_b + i_e R_e = 0$$

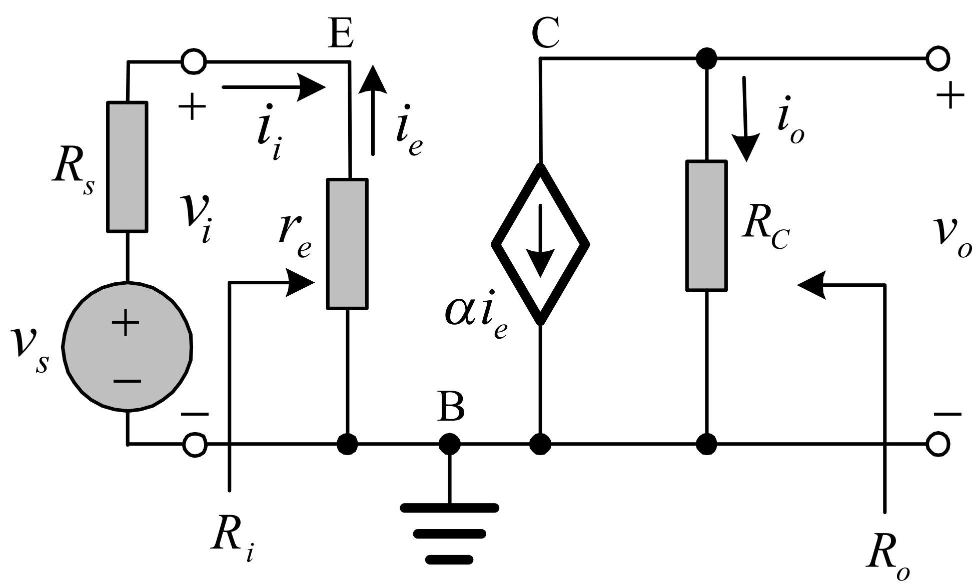
$$R_o' = \frac{v_x}{i_x} = (r_\pi + R_s) // R_e + r_o \left(1 + \frac{\beta R_e}{r_\pi + R_s + R_e} \right)$$

共基放大器



(a)

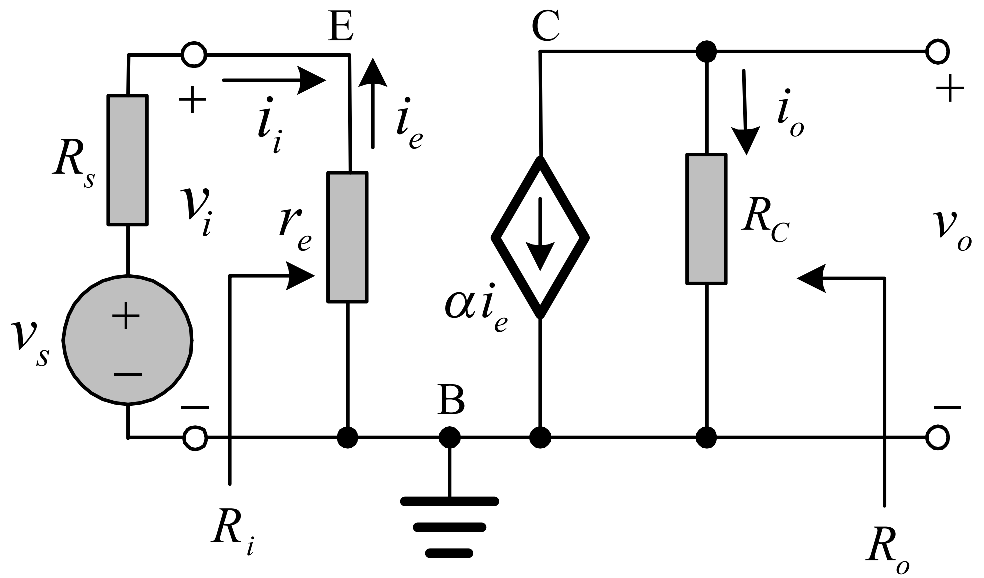
共基放大器适合采用T型等效电路进行分析



T型等效电路

$$A_v = \frac{v_o}{v_i} = \frac{-\alpha i_e R_C}{-i_e r_e} = \frac{\alpha R_C}{r_e} = g_m R_C$$

$$A_i = \frac{i_o}{i_i} = \frac{-i_c}{-i_e} \approx 1$$



T型等效电路

共基放大器又称为电流缓冲器。

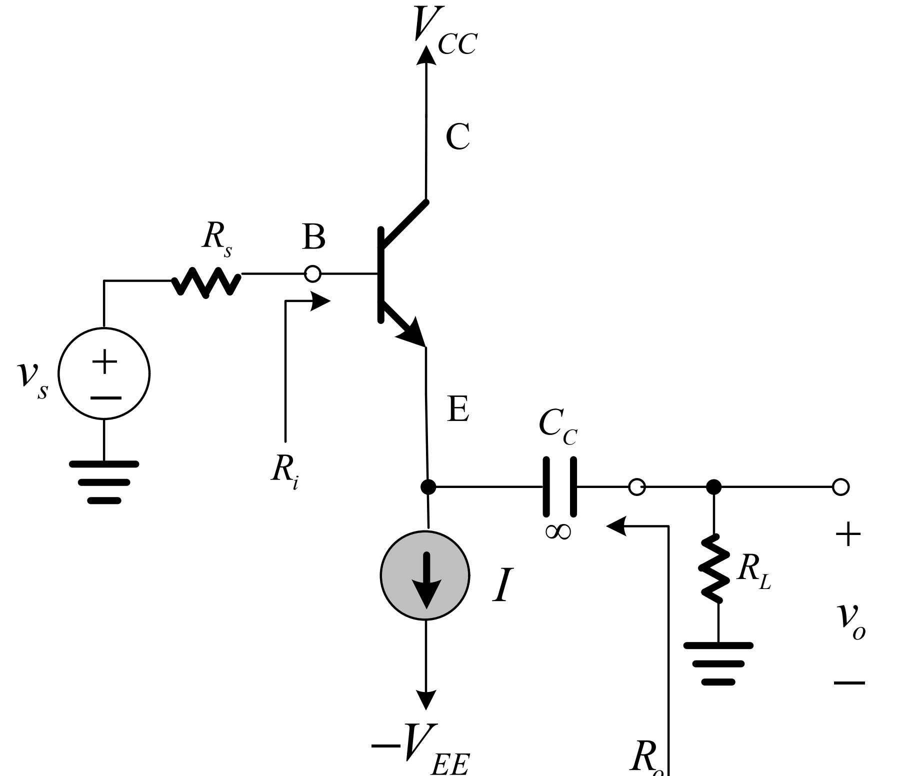
$$R_i = r_e$$

$$R_o = R_C$$

特点：

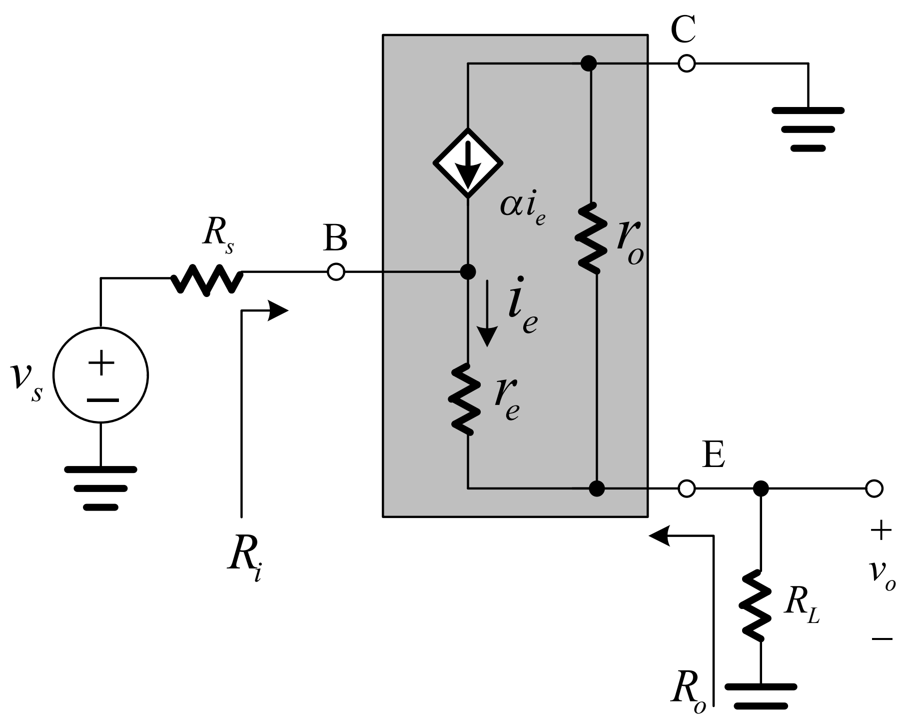
输入电阻小，频带宽！只放大电压，不放大电流！

共集放大器



(a)

共集放大器适合采用T型等效电路进行分析

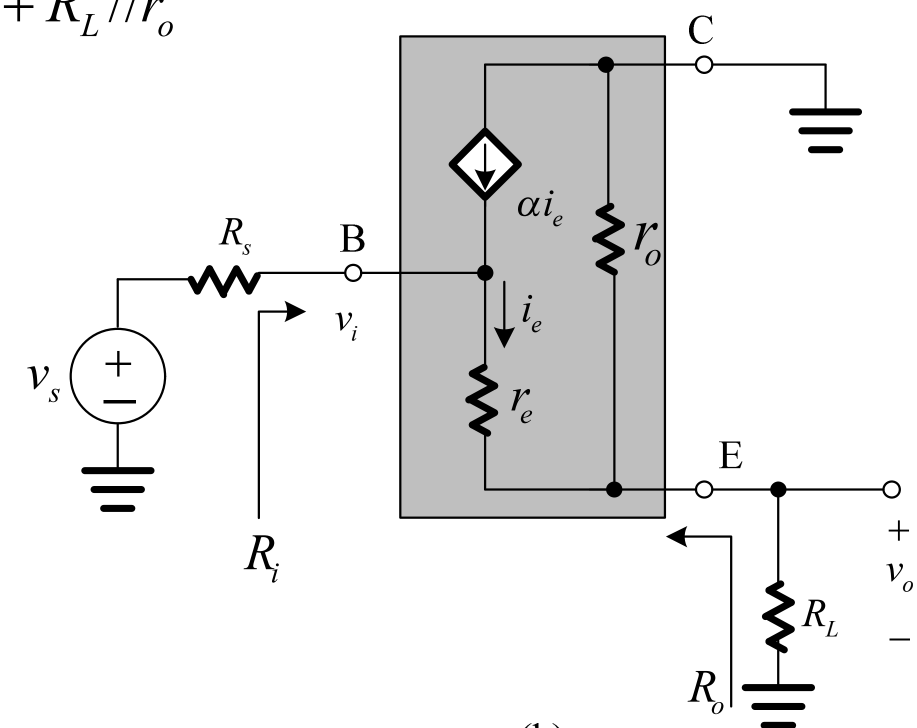


(b)

$$A_v = \frac{v_o}{v_i} = \frac{(R_L//r_o)i_e}{(r_e + R_L//r_o)i_e} = \frac{R_L//r_o}{r_e + R_L//r_o} \approx 1$$

共集放大器又称为

射极跟随器（Emitter Follower）。



(b)

$$R_i = (\beta + 1)(r_e + r_o//R_L)$$

$$R_o = r_o//\left(r_e + \frac{R_s}{\beta + 1}\right)$$

特点：

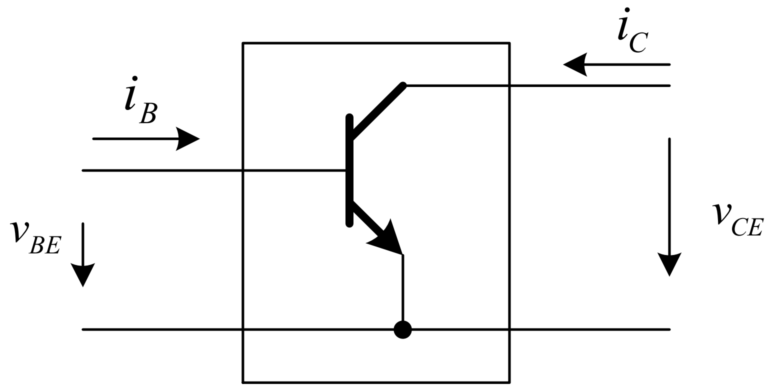
输入电阻大，输出电阻小，频带中等！只放大电流，不放大电压！

三种接法的比较：空载情况下

接法	共射	共集	共基
A_v	大	≈ 1	大
A_i	β	$1+\beta$	α
R_i	中	大	小
R_o	大	小	大
频带	窄	中	宽

8、H 参数等效电路

把晶体管看成是一个二端口的网络 。



$$\begin{cases} v_{BE} = f(i_B, v_{CE}) \\ i_C = F(i_B, v_{CE}) \end{cases} \Rightarrow \begin{cases} dv_{BE} = \left.\dfrac{\partial v_{BE}}{\partial i_B}\right|_{V_{CE}} di_B + \left.\dfrac{\partial v_{BE}}{\partial v_{CE}}\right|_{I_B} dv_{CE} \\ di_C = \left.\dfrac{\partial i_C}{\partial i_B}\right|_{V_{CE}} di_B + \left.\dfrac{\partial i_C}{\partial v_{CE}}\right|_{I_B} dv_{CE} \end{cases}$$

$$\begin{cases} \boxed{v_{be}} = \boxed{h_{11}}\ \boxed{i_b} + \boxed{h_{12}}\ \boxed{v_{ce}} \\ \boxed{i_c} = \boxed{h_{21}}\ \boxed{i_b} + \boxed{h_{22}}\ \boxed{v_{ce}} \end{cases}$$

$$h_{11} = \left.\frac{\partial v_{BE}}{\partial i_B}\right|_{V_{CE}} = h_{ie}$$

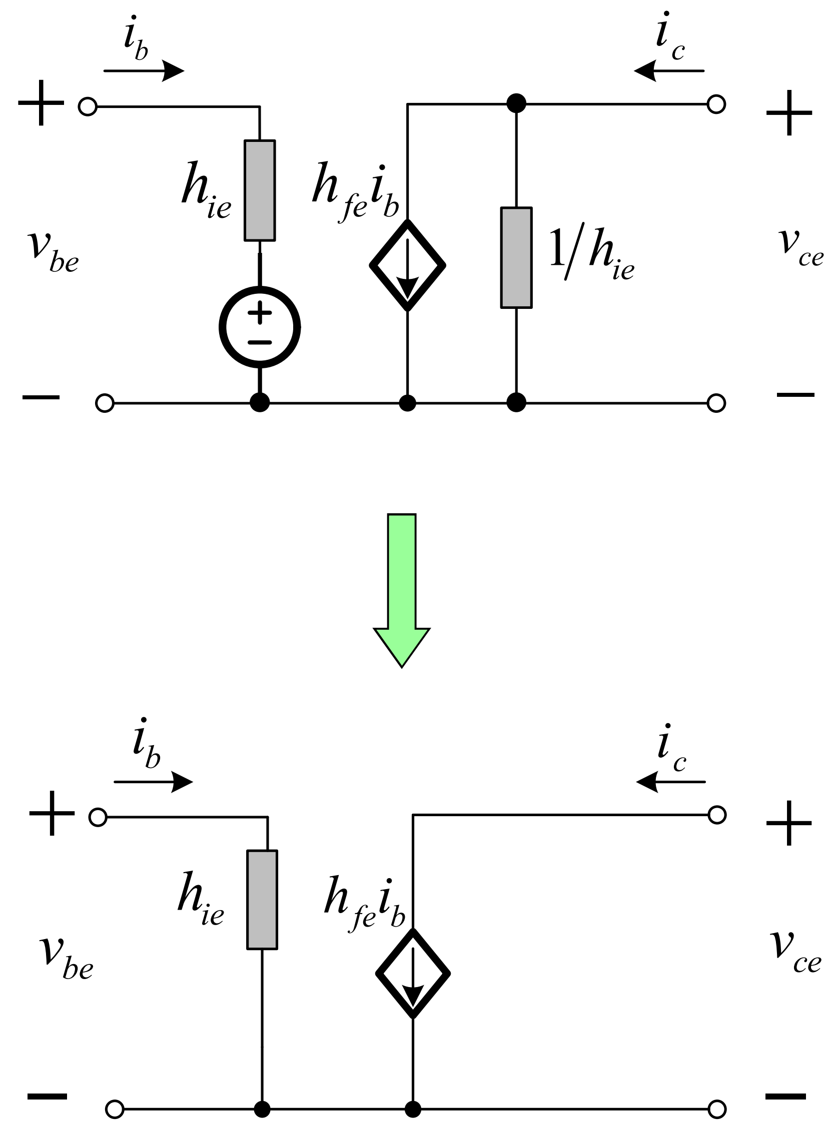
$$h_{12} = \left.\frac{\partial v_{BE}}{\partial v_{CE}}\right|_{I_B} = h_{re}$$

$$h_{21} = \left.\frac{\partial i_C}{\partial i_B}\right|_{V_{BE}} = h_{fe}$$

$$h_{22} = \left.\frac{\partial i_C}{\partial v_{CE}}\right|_{I_B} = h_{oe}$$

根据以下等式可画出对应的等效电路

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



当晶体管工作在放大区时，v_{ce} 对输入特性曲线和 i_c 的影响很小，可以认为 $h_{re} = h_{oe} = 0$ 。