模拟与数字电路

Analog and Digital Circuits

第 十六讲： **基尔霍夫定律与晶体管小信号模型**

Lecture 16: **KCL/KVL, Small Signal Model**

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Instructor : Chixiao Chen

课程主页 扫一扫

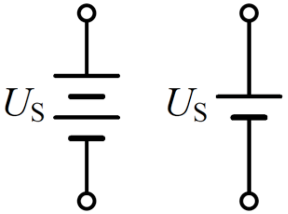
提纲

- 复习
  - 二极管（Diode）与电阻的差别?

- 源与负载
- 基尔霍夫定律
- 晶体管小信号模型

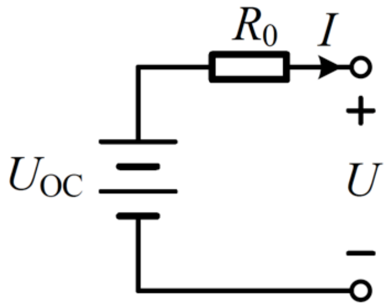
直流源 (DC) 伏安特性曲线

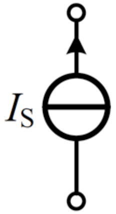
- 直流源



(a) 电压源

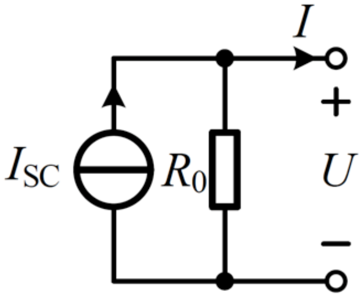
戴维宁等效

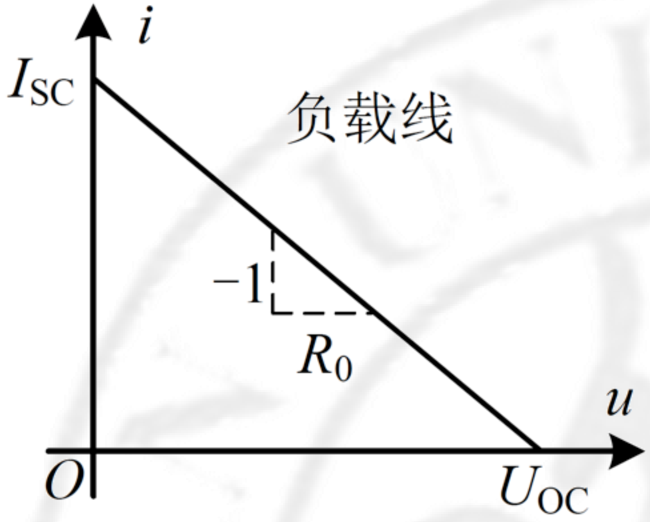




(b) 电流源

诺顿等效

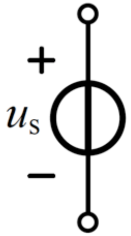




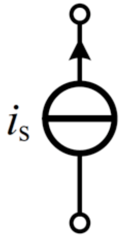
- R_0的物理意义?
- R_0越大越好，还是越小越好?

交变信号源（AC）

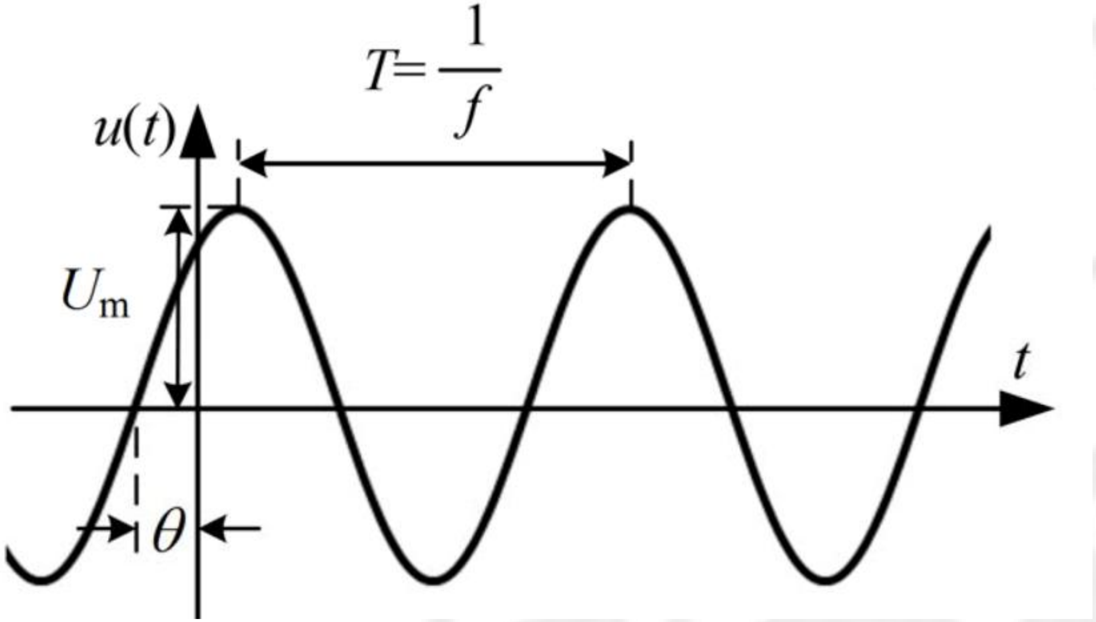
- 信号源



(a) 电压源

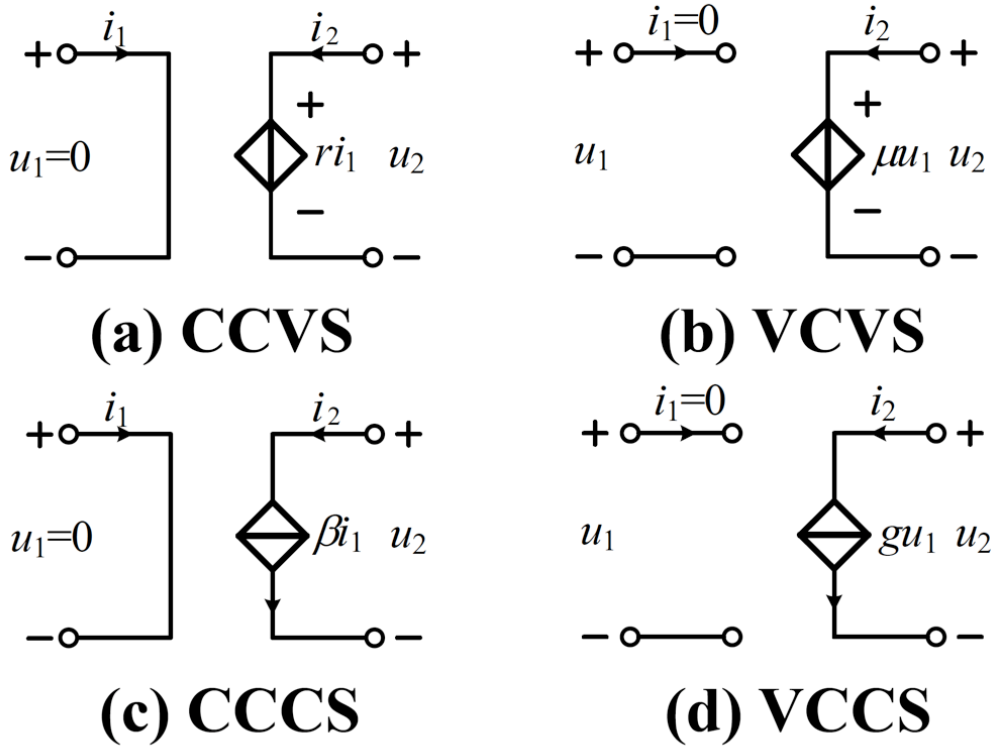


(b) 电流源



- 瞬时表达 $U_m \sin(2\pi f t + \theta)$
- 向量表达 $U_m \angle \theta$

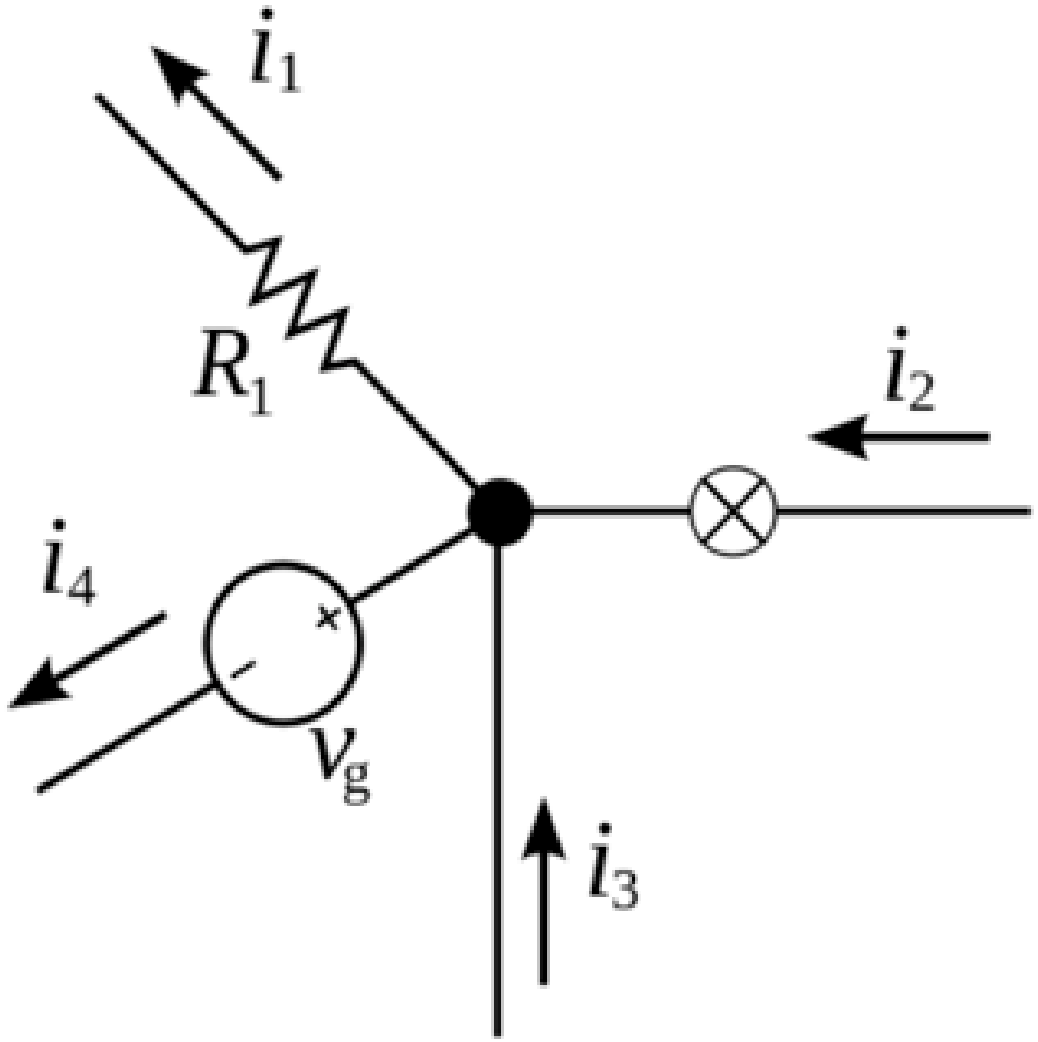
受控源



- CCVS 电流控制电压源
- VCVS 电压控制电压源
- CCCS 电流控制电流源
- VCCS 电压控制电流源

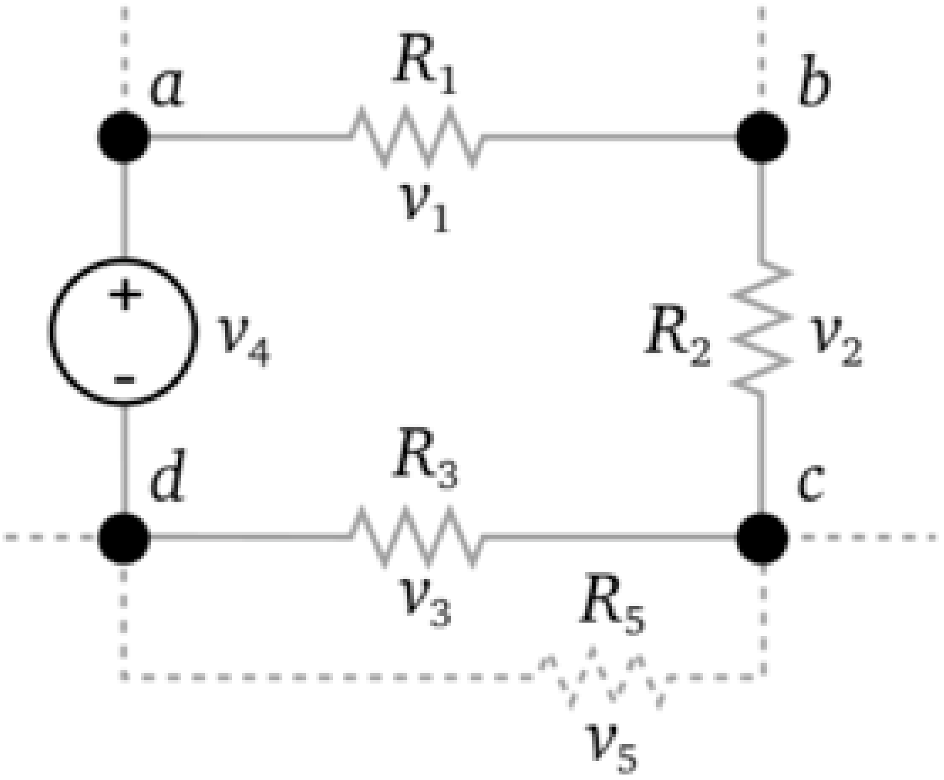
基尔霍夫定律

- 基尔霍夫电流定律 KCL
- The current entering any junction is equal to the current leaving that junction.
- $i_2 + i_3 = i_1 + i_4$

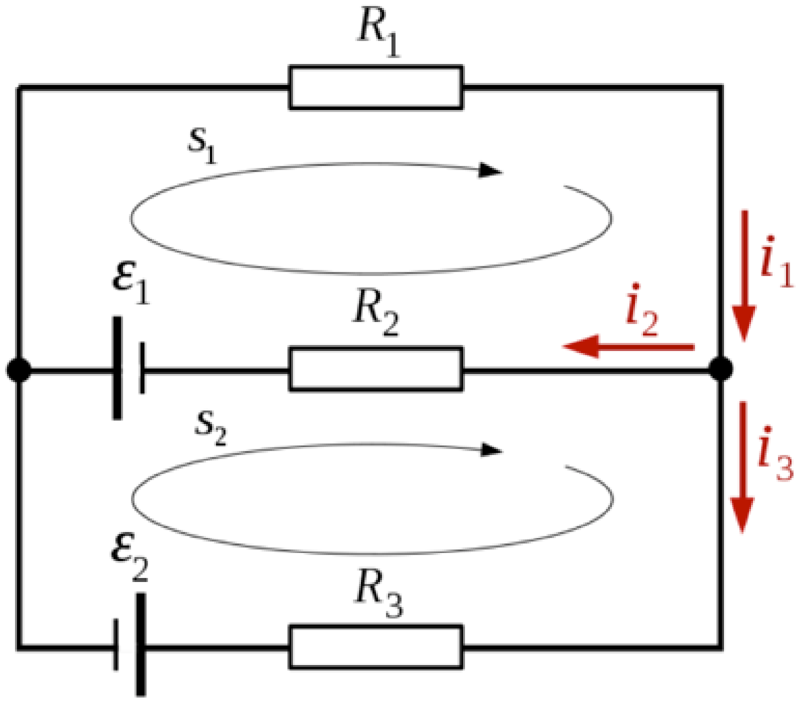


基尔霍夫定律

- 基尔霍夫电压定律 KVL
- The sum of all the voltages around a loop is equal to zero.
- $v_1 + v_2 + v_3 + v_4 = 0$



基尔霍夫定律



- 已知：$R_1 = 100\Omega$， $R_2 = 200\Omega$，$R_3 = 300\Omega$， ε_1 = 3V， ε_2 = 4V
  求 i_1, i_2, i_3?

解： KCL: $i_1 - i_2 - i_3=0$

KVL(1): $-R_2 i_2 + \varepsilon_1 - R_1 i_1=0$

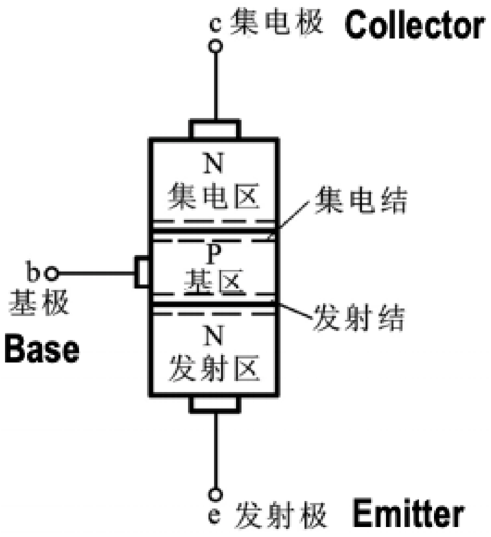
KVL(2): $-R_3 i_3 - \varepsilon_2 - \varepsilon_1 + R_2 i_2=0$

联立方程组求解

$i_1 = \frac{1}{1100}$A， $i_2 = \frac{4}{275}$A， $i_3 = -\frac{3}{220}$A

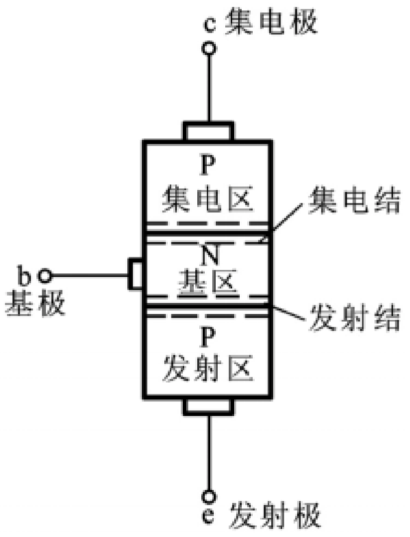
双极性结晶体管回顾 —— BJT

半导体三极管的结构示意图如下图所示。它有两种类型：NPN型和PNP型。



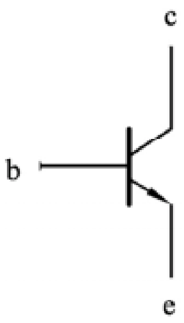
(a)

NPN型管结构示意图



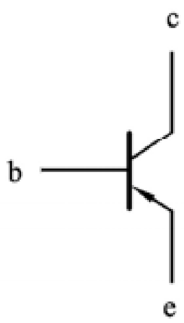
(b)

PNP型管结构示意图



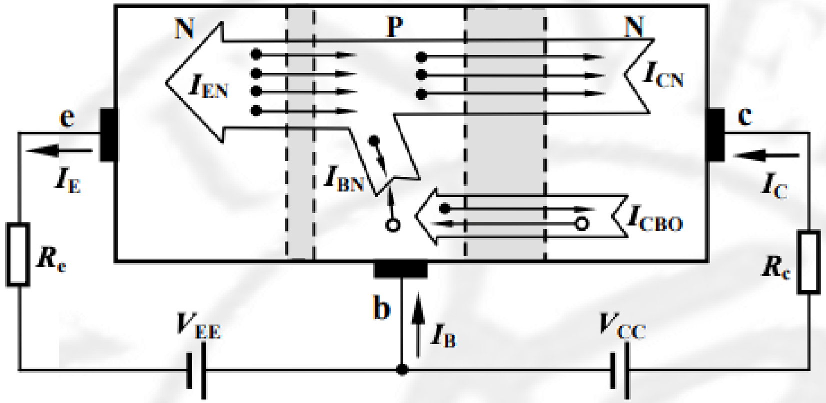
(c)

NPN型管电路符号



(d)

PNP型管电路符号



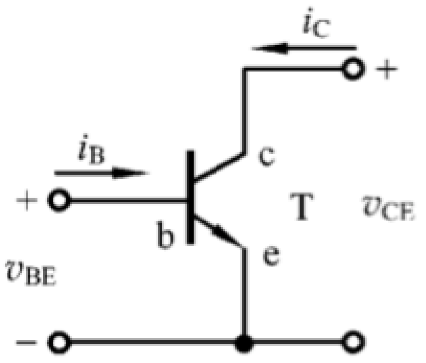
$I_E=I_B+I_C$ $I_C=I_{CN}+I_{CBO}$ $\alpha=\dfrac{I_{nC}}{I_E}$

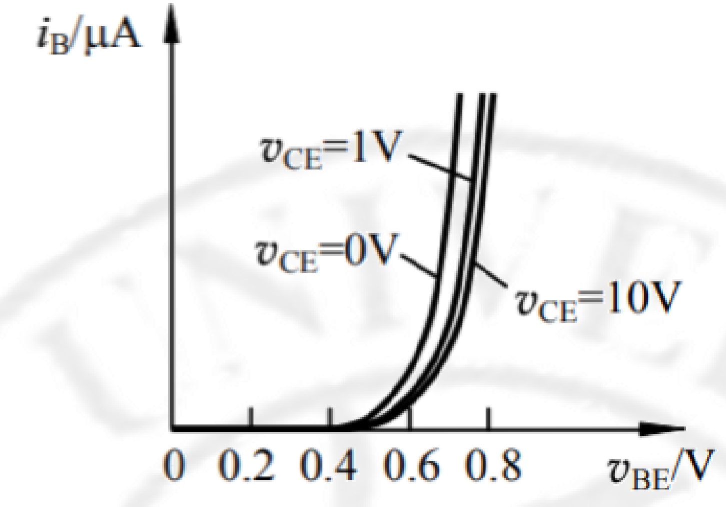
$I_{CEO}=(1+\beta)I_{CBO}$（穿透电流）

$\beta=\dfrac{I_C-I_{CEO}}{I_B}$ 当 $I_C>>I_{CEO}$时，$\beta\approx\dfrac{I_C}{I_B}$

BJT的IV特性曲线

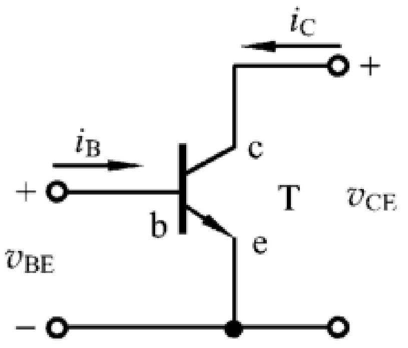
2. 共射极连接时的*I-V*特性曲线

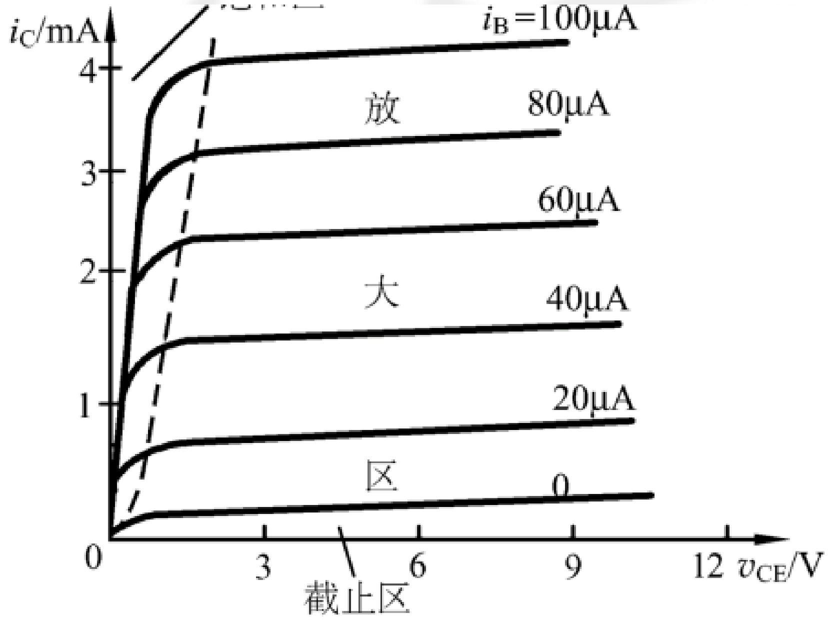




输入特性曲线

$$i_B = f(v_{BE})\big|_{v_{CE}=\text{常数}}$$





输出特性曲线

$$i_C = f(v_{CE})\big|_{i_B=\text{常数}}$$

BJT的IV特性曲线

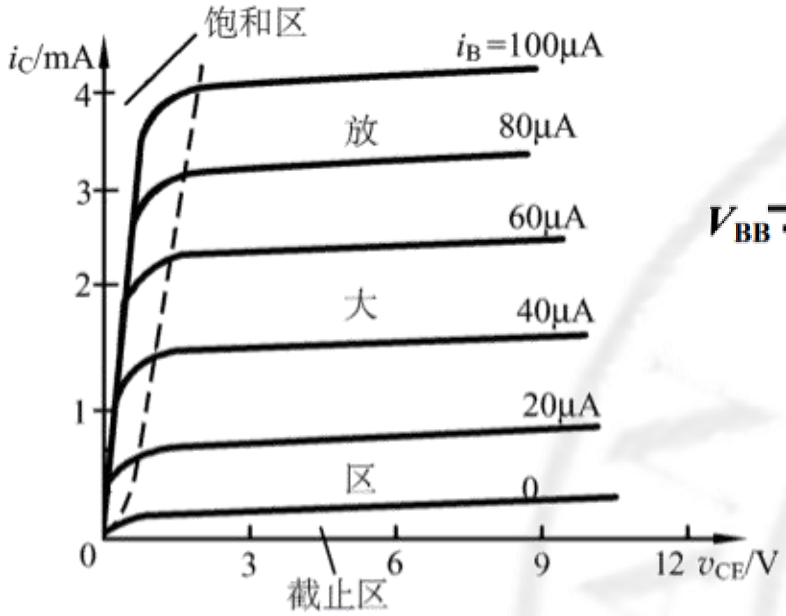
输出特性曲线

$$i_C = f(v_{CE})|_{i_B=常数}$$

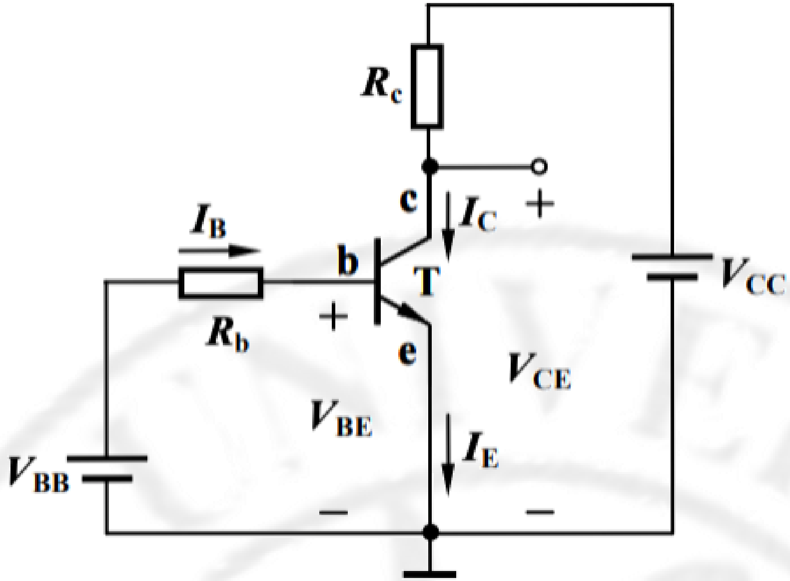
输出特性曲线的三个区域:

饱和区：i_C明显受v_{CE}控制的区域，该区域内，一般v_{CE}<0.7V(硅管)。此时，***发射结正偏，集电结正偏或反偏电压很小。***

截止区：i_C接近零的区域，相当i_B=0的曲线的下方。此时，v_{BE}***小于死区电压。***



放大区：i_C平行于v_{CE}轴的区域，曲线基本平行等距。此时，***发射结正偏，集电结反偏。***



$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_b}$$

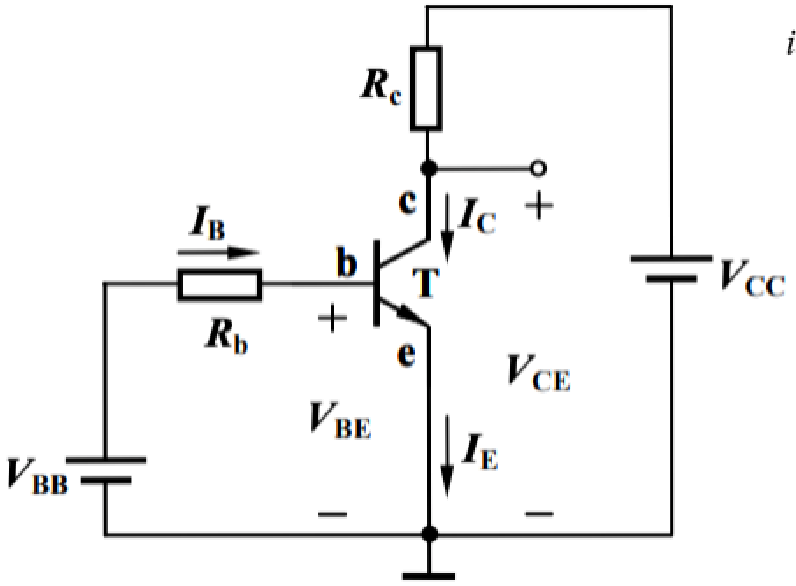
$$I_{CQ} = \beta \cdot I_{BQ}$$

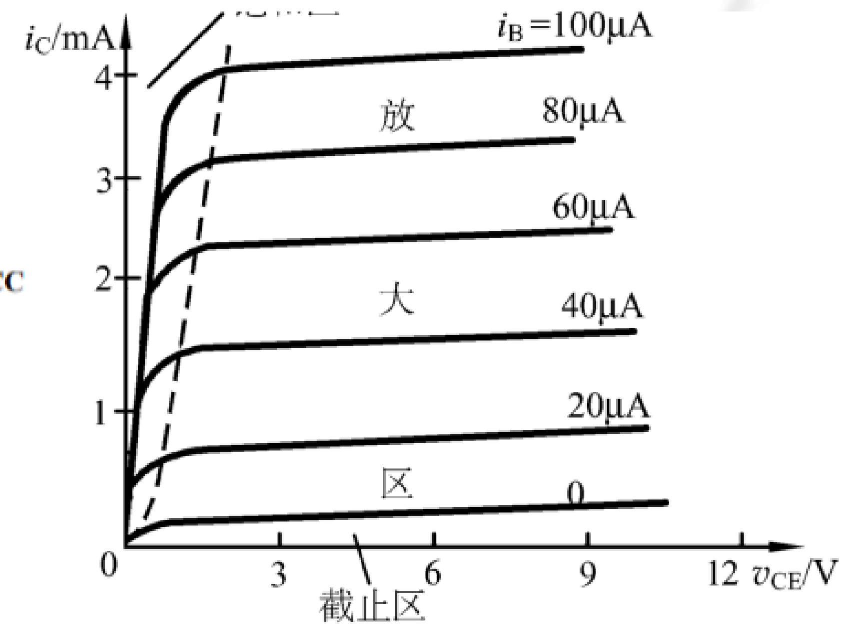
$$V_{CEQ} = V_{CC} - I_{CQ}R_c$$

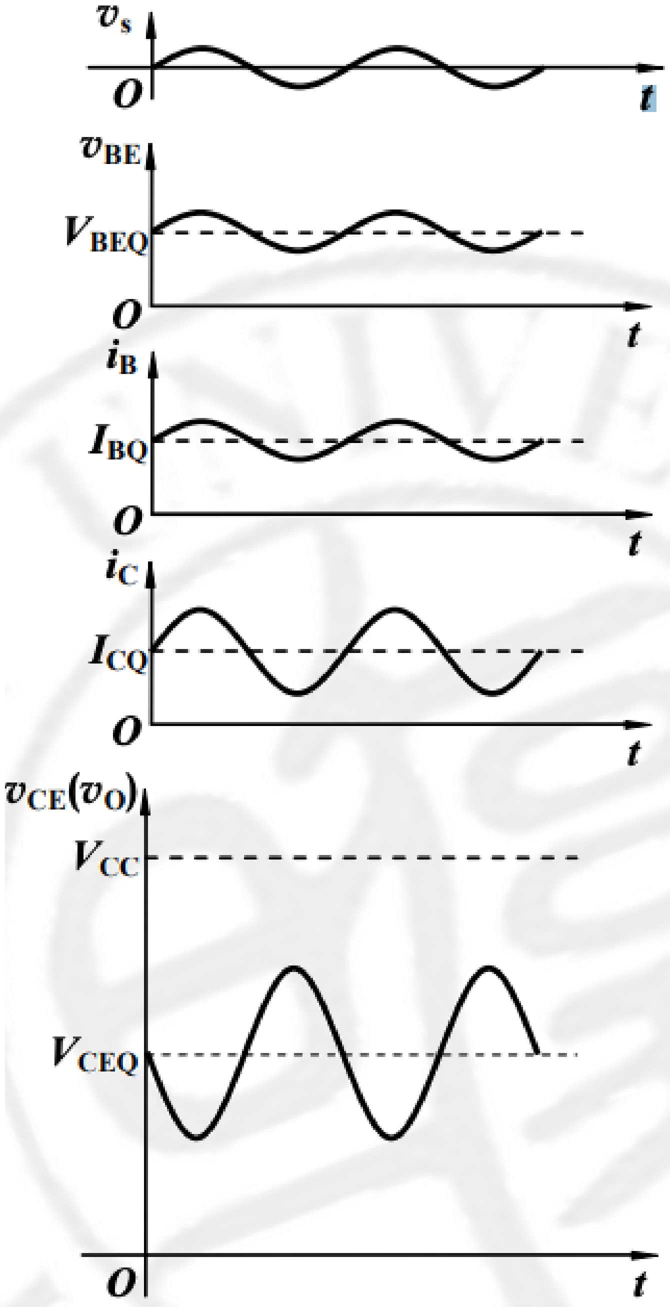
一般硅管V_{BEQ}=0.7V，

图解法分析放大电路

- **合理的静态工作点（Q）保障电路处于放大区**
- IBQ 过大或者过小将导致怎样的情况？

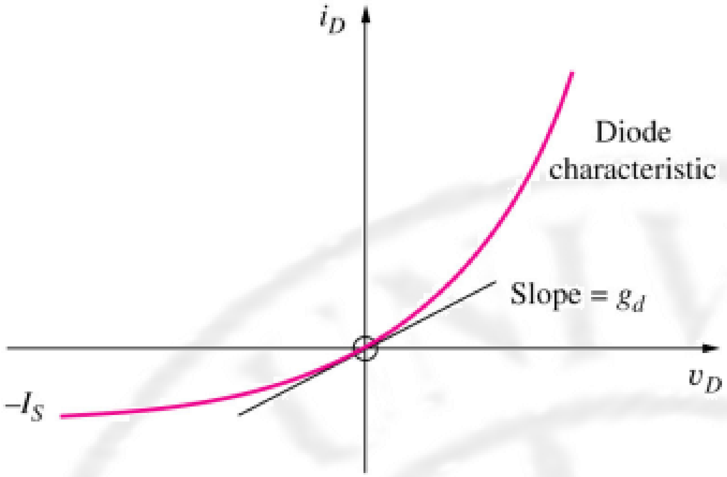


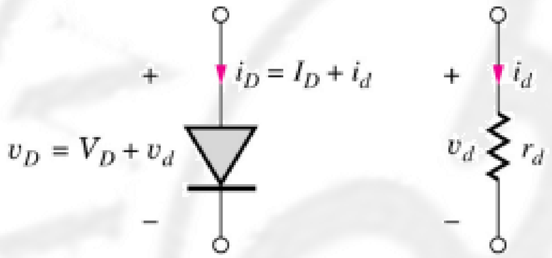


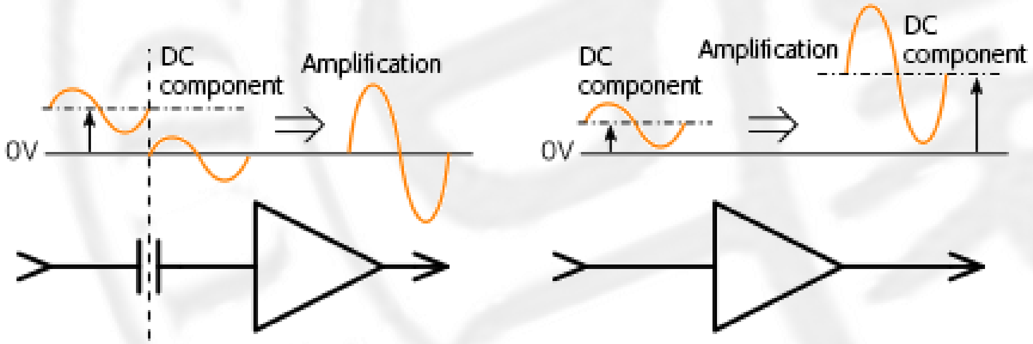


大信号 与 小信号

- 问题：晶体管电路的工作区域均为非线性，如何使用线性电路的量化分析方法?
- - 根据非线性关系推导 直流/静态工作点
- - 将不带直流信息的的交流信号称为交流 **小信号 （AC）**， 小信号由于幅度小，我均视为 线性电路进行分析计算







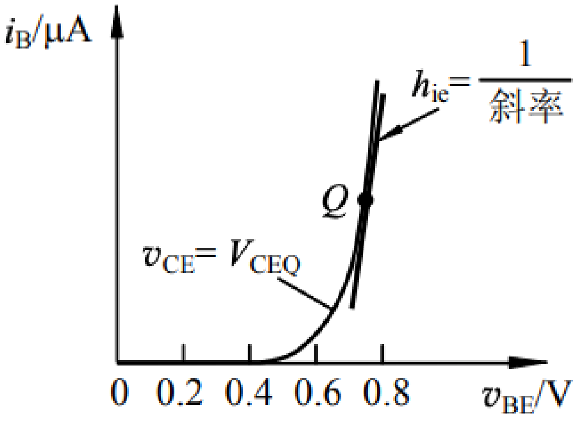
(a) AC coupling

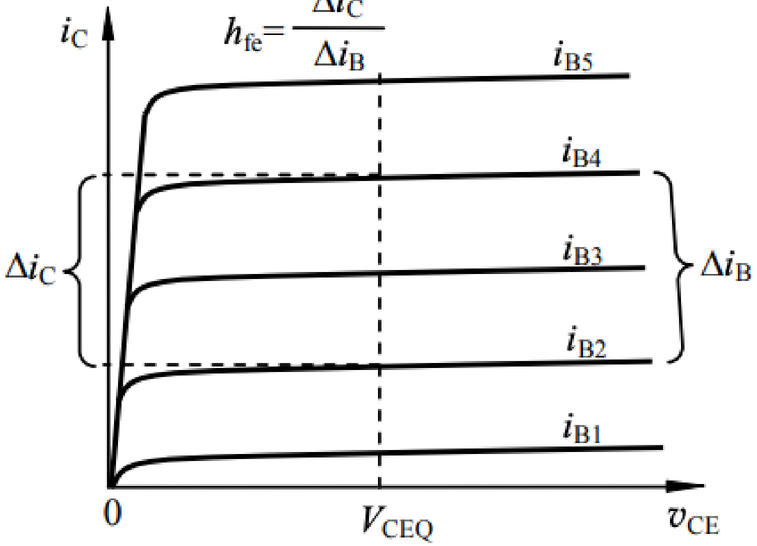
(b) DC coupling

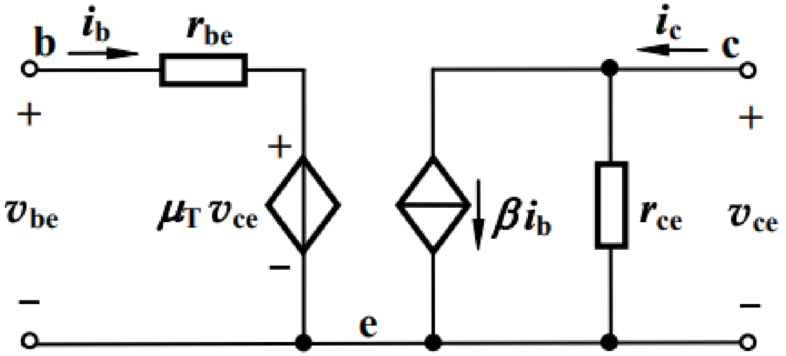
从IV曲线对BJT进行小信号线性建模

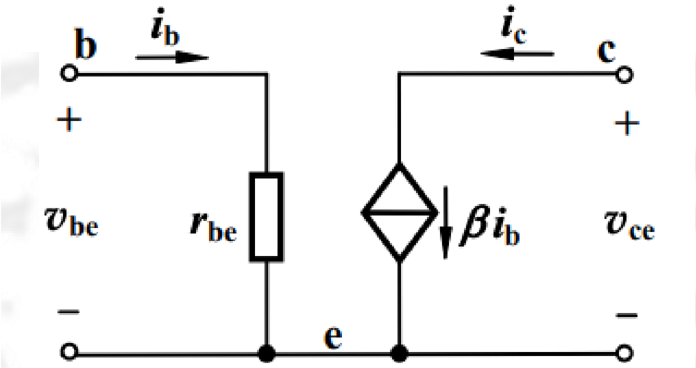
$$h_{ie}=\left.\frac{\partial v_{BE}}{\partial i_B}\right|_{V_{CEQ}}$$ 输出端交流短路时的输入电阻；

$$h_{fe}=\left.\frac{\partial i_c}{\partial i_B}\right|_{V_{CEQ}}$$ 输出端交流短路时的正向电流传输比或电流放大系数；







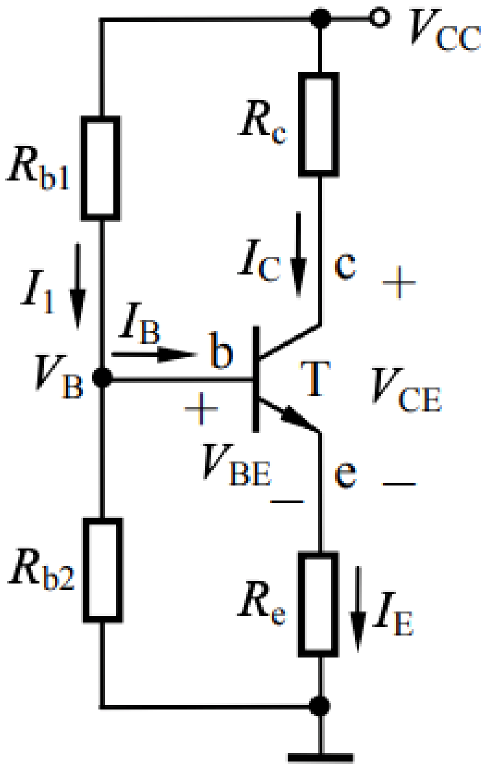


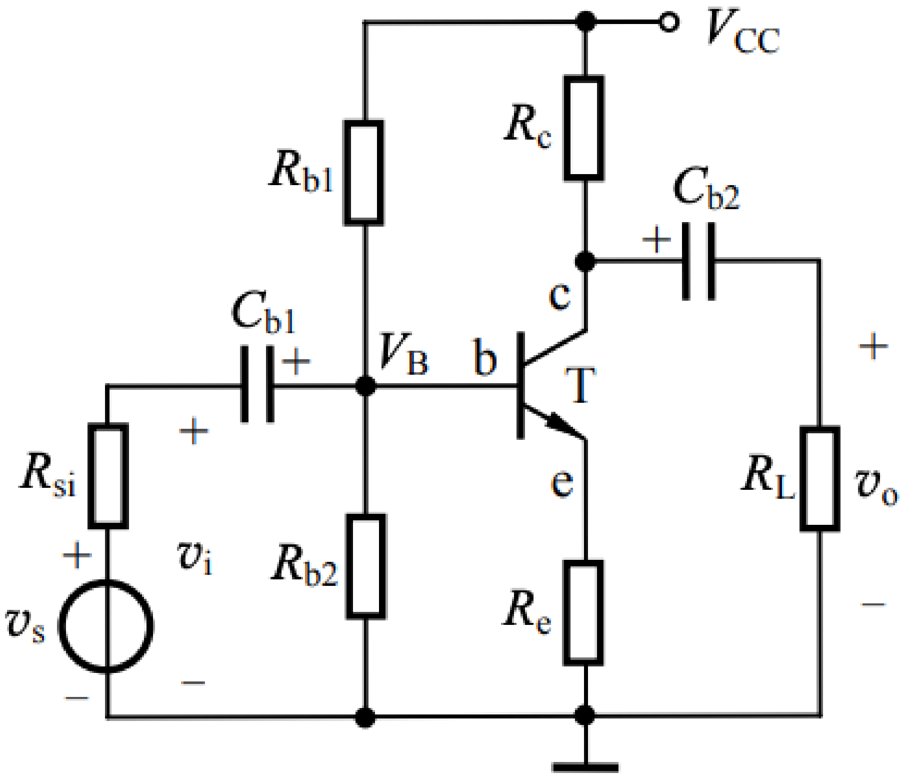
- βi_b 是受控源，且为电流控制电流源(CCCS)；
- 电流方向与i_b的方向是关联的。

例题

例5.4.1 已知图示基极分压式射极偏置共射极放大电路中，V_{CC}=16V，R_{b1} =56kΩ，R_{b2}=20kΩ，R_e=2kΩ，R_c=3.3kΩ，R_L=6.2kΩ，R_{si}=500Ω，BJT的β=80，r_{ce}=100kΩ，V_{BEQ}=0.7V。设电容C_{b1}、C_{b2}对交流信号可视为短路。试计算A_v、R_i、$A_{vs}=v_o/v_s$、R_o。

解： ①由直流通路求静态工作点





例题

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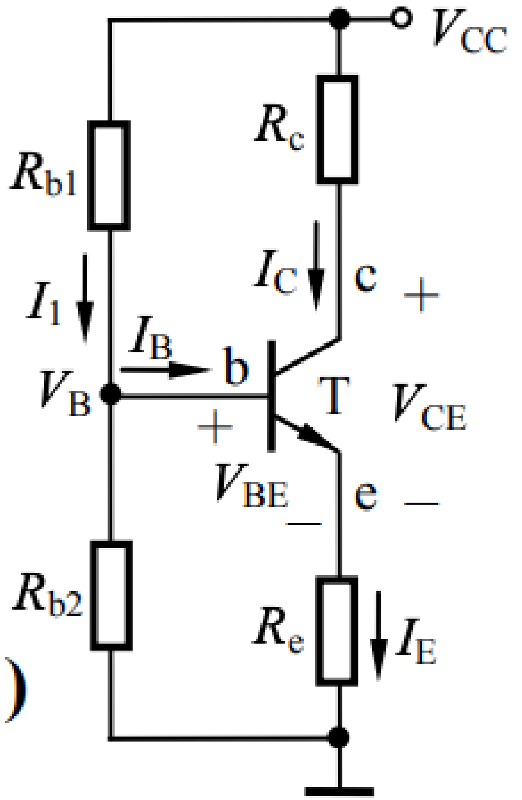
解：①由直流通路求静态工作点



$$V_{BQ} \approx \frac{R_{b2}}{R_{b1}+R_{b2}} \cdot V_{CC}$$

$$I_{CQ} \approx I_{EQ} = \frac{V_{BQ} - V_{BEQ}}{R_e}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_c - I_{EQ}R_e \approx V_{CC} - I_{CQ}(R_c + R_e)$$

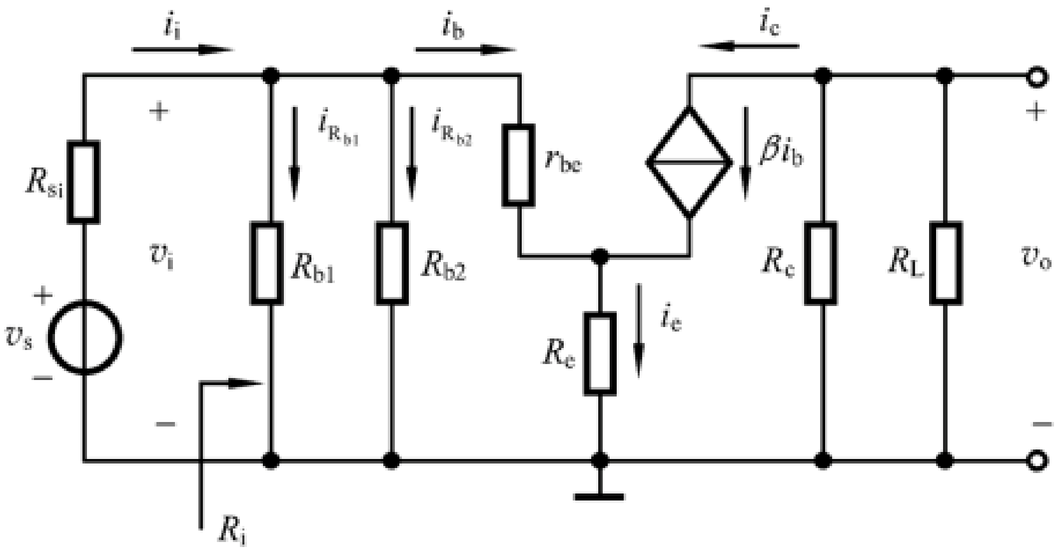
$$I_{BQ} = \frac{I_C}{\beta}$$

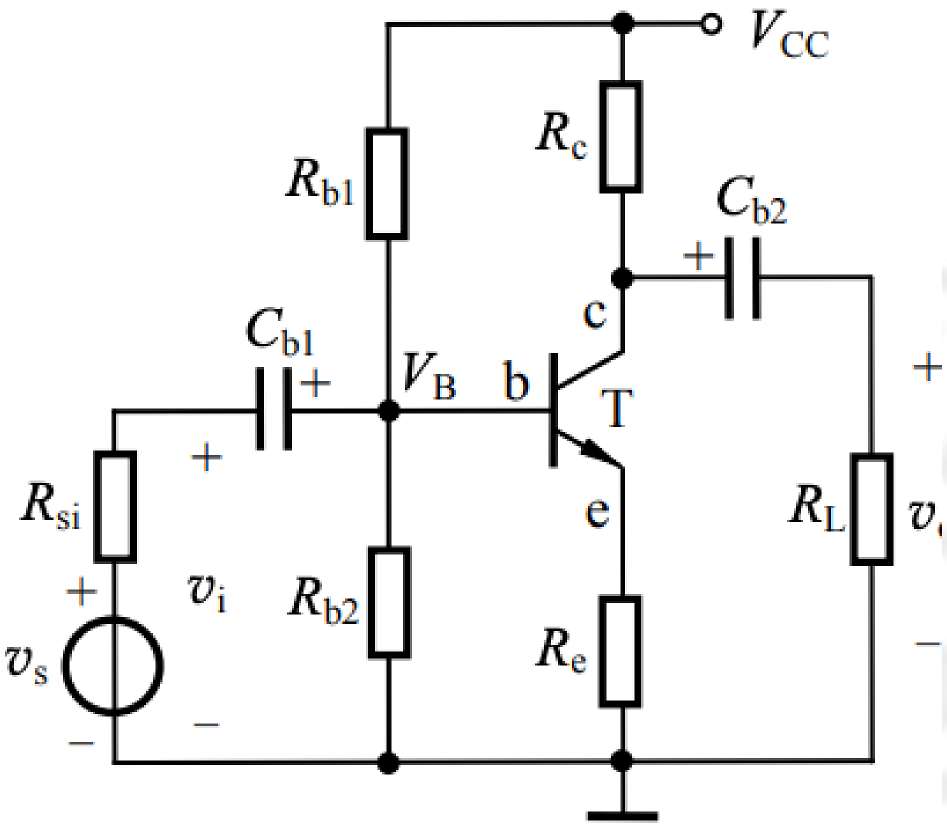
求得 $I_{EQ} \approx 1.76\ \text{mA}$

例题

解：②动态指标分析

画小信号等效电路





H参数 r_{be}

$$r_{be} = 200\Omega + (1+\beta)\frac{26\text{mV}}{I_{EQ}(\text{mA})} = 200\Omega + (1+80)\frac{26\text{mV}}{1.76\text{mA}} \approx 1.4\text{k}\Omega$$

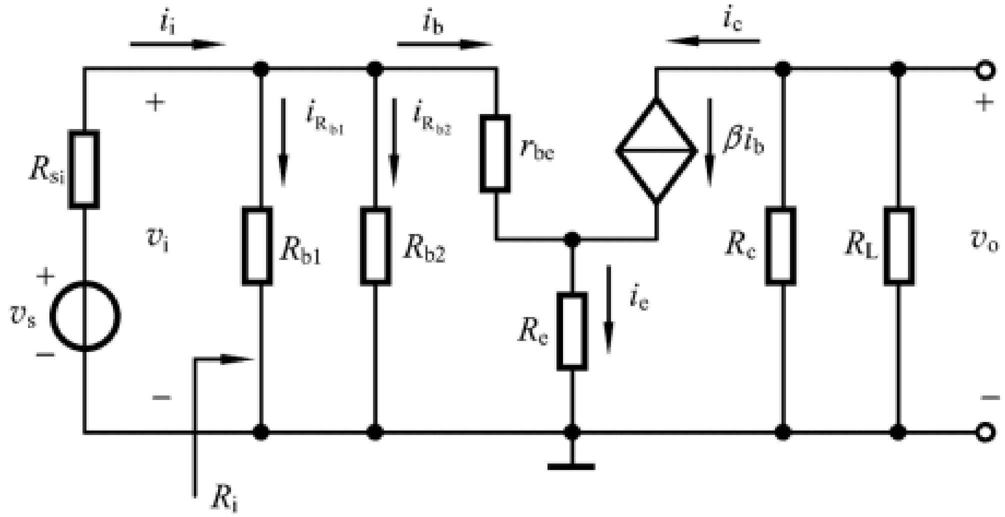
例题

解：②动态指标分析

电压增益A_v

$$v_o = -\beta i_b (R_c // R_L)$$

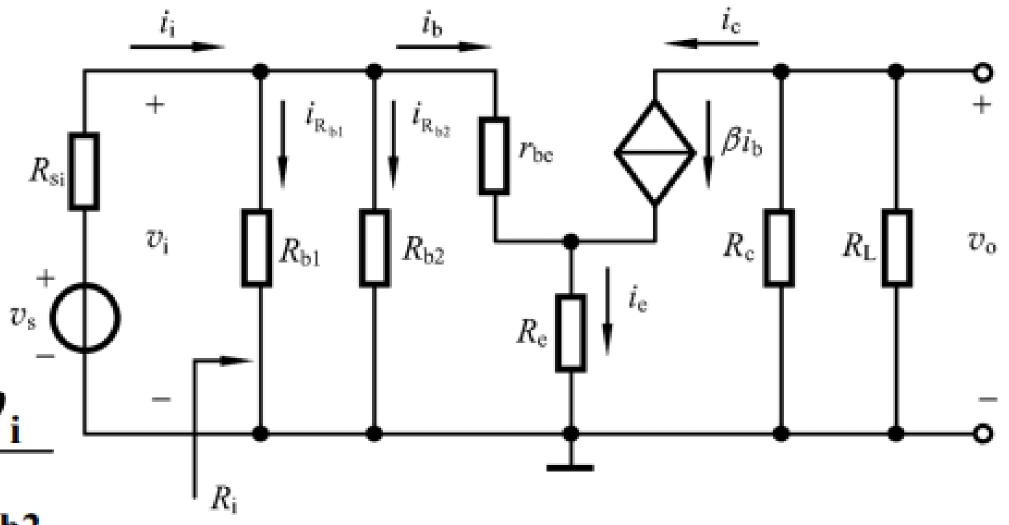
$$v_i = i_b r_{be} + i_e R_e$$
$$= i_b r_{be} + (1+\beta) i_b R_e$$



$$A_v = \frac{v_o}{v_i} = \frac{-\beta(R_c // R_L)}{r_{be} + (1+\beta)R_e} = \frac{-80 \times \dfrac{3.3 \times 6.2}{3.3 + 6.2} \text{k}\Omega}{(1.4 + 81 \times 2)\text{k}\Omega} \approx -1.05$$

例题

解：②动态指标分析



输入电阻R_i

$$i_i = i_b + i_{R_b}$$

$$= \frac{v_i}{r_{be} + (1+\beta)R_e} + \frac{v_i}{R_{b1}} + \frac{v_i}{R_{b2}}$$

$$R_i = \frac{v_i}{i_i} = \frac{1}{\dfrac{1}{r_{be} + (1+\beta)R_e} + \dfrac{1}{R_{b1}} + \dfrac{1}{R_{b2}}}$$

$$= R_{b1} // R_{b2} //[r_{be} + (1+\beta)R_e] \approx 13.52\text{k}\Omega$$

例题

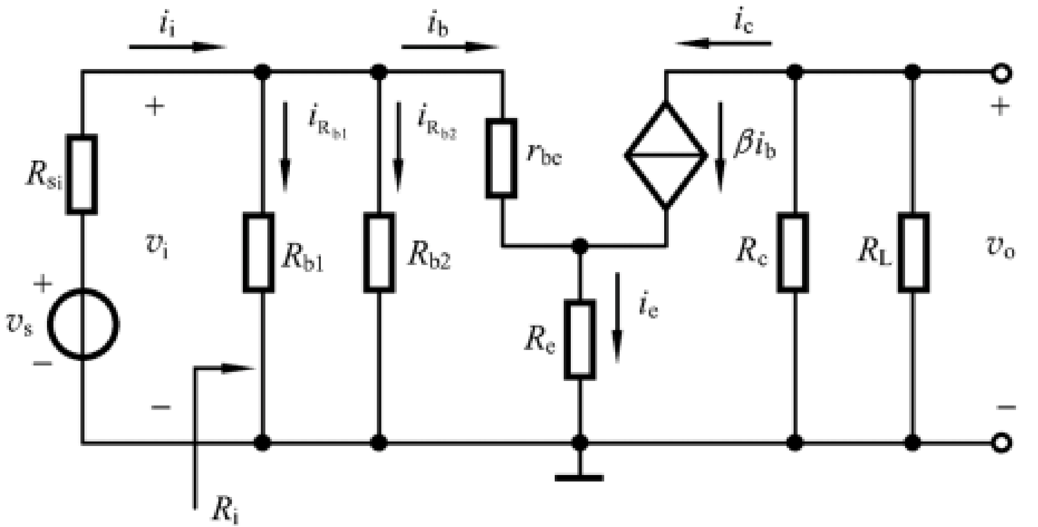
解：②动态指标分析

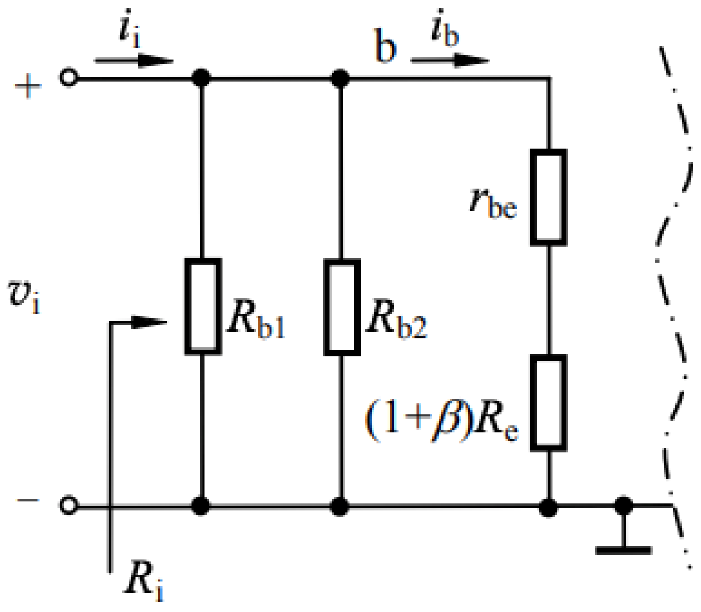
输入电阻R_i

$$R_i = R_{b1} // R_{b2} //[r_{be} + (1+\beta)R_e]$$

式中$(1+\beta)R_e$是发射极支路电阻R_e折算到基极支路时的等效电阻。

发射极支路电阻折算到基极支路需要将电阻扩大$(1+\beta)$倍；反之，基极支路电阻折算到发射极支路需要将电阻缩小$(1+\beta)$倍。





例题

解：②动态指标分析

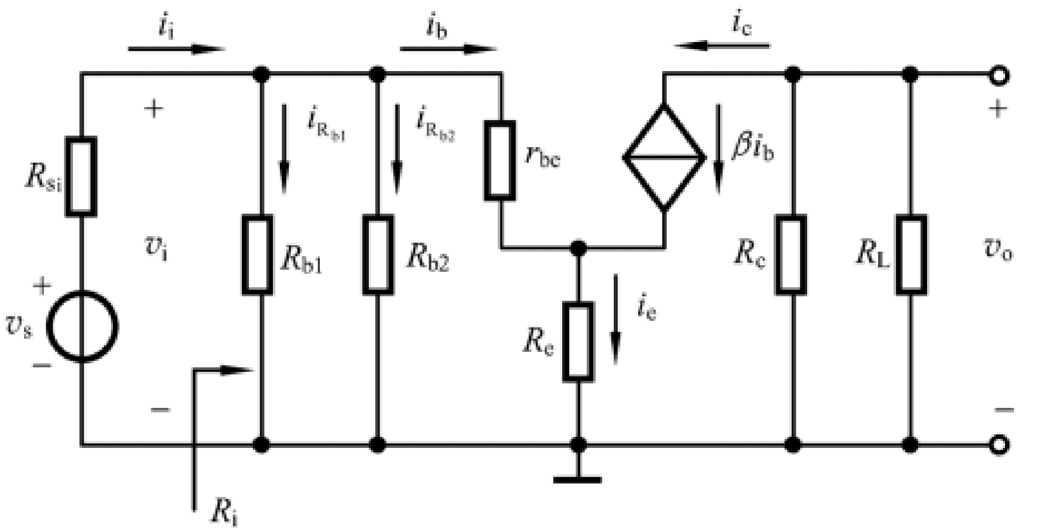
源电压增益A_{vs}

$$A_{vs}=\frac{v_o}{v_s}=\frac{v_o}{v_i}\cdot\frac{v_i}{v_s}$$

$$=A_v\cdot\frac{R_i}{R_{si}+R_i}$$

$$=-1.05\times\frac{13.52\text{k}\Omega}{(0.5+13.52)\text{k}\Omega}$$

$$\approx-1.01$$



思考：若Re减小，那么增益会如何变化？

例题

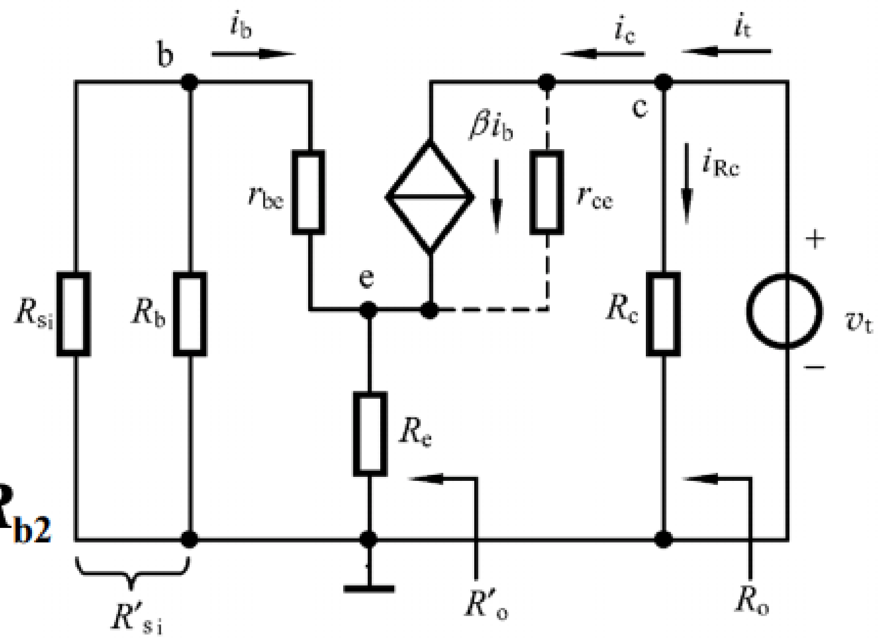
解：②动态指标分析

输出电阻R_o

基极回路根据KVL得：

$$i_b(r_{be}+R'_{si})+(i_b+i_c)R_e=0$$

其中 $R'_{si}=R_{si}\,//\,R_b \quad R_b=R_{b1}\,//\,R_{b2}$



集电极回路根据KVL得：

$$v_t-(i_c-\beta i_b)r_{ce}-(i_b+i_c)R_e=0$$

得 $$v_t=i_c\left[r_{ce}+R_e+\frac{R_e}{r_{be}+R'_{si}+R_e}(\beta r_{ce}-R_e)\right]$$

所以 $$R'_o=\frac{v_t}{i_c}=r_{ce}\left(1+\frac{\beta R_e}{r_{be}+R'_{si}+R_e}\right) \qquad (r_{ce}\gg R_e)$$

通常 $R'_o \gg R_c$

所以 $R_o\approx R_c=3.3\ \text{k}\Omega$