

电子电路与系统基础I

理论课第十讲

分段折线法：**BJT**电流源、反相器电路

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BJT电流源、反相器电路 大纲

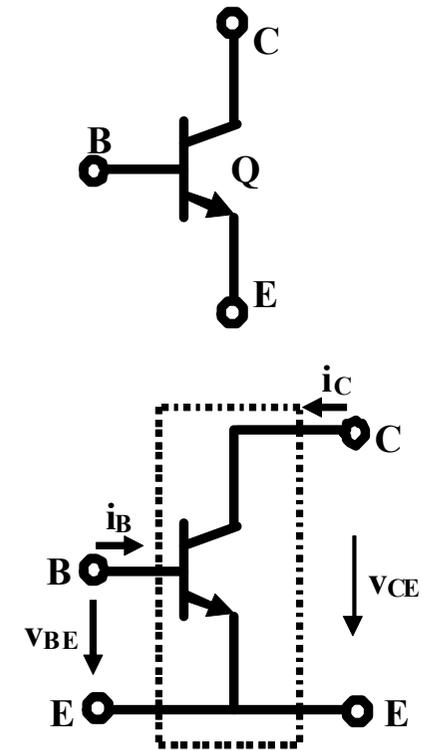
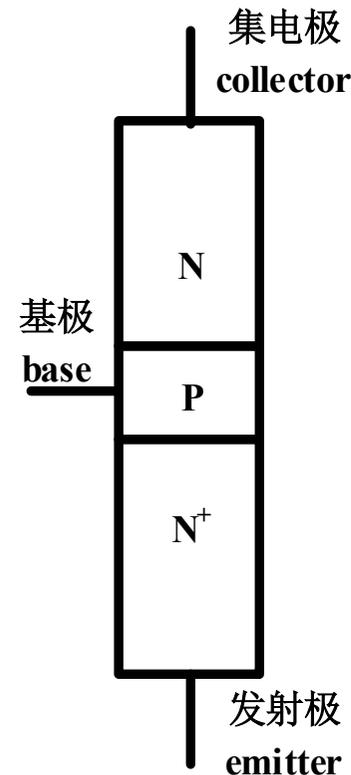
- **BJT的分段折线电路模型**
 - **BJT结构**
 - **BJT伏安特性形成（附录15，不要求掌握）**
 - **伏安特性及其分段折线电路模型**
- **BJT分压偏置电路**
 - **负反馈**
- **BJT电流镜**
- **BJT反相器**

NPN-BJT结构

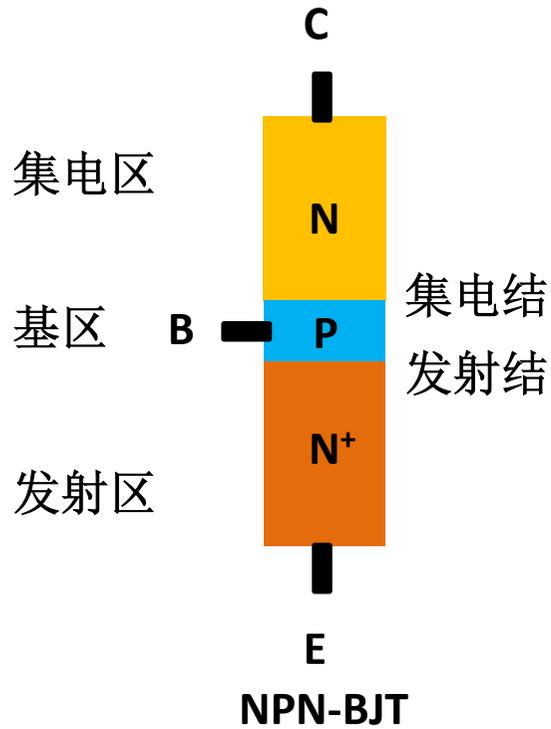
- **Bipolar Junction Transistor**

- 双极结型晶体管
- **Transistor: Transfer Resistor**

- 晶体管，转移电阻器
- **受控的非线性电阻**
 - 通过PN结的导通或截止控制导电特性

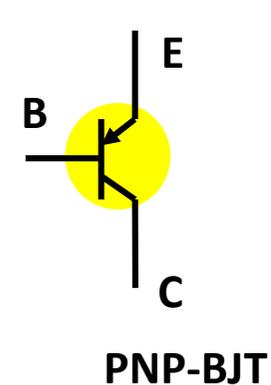
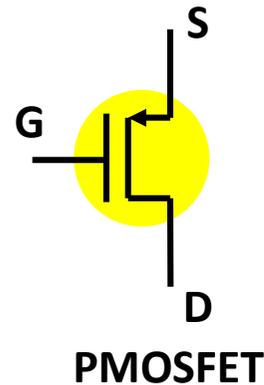
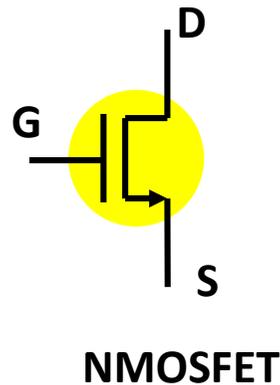
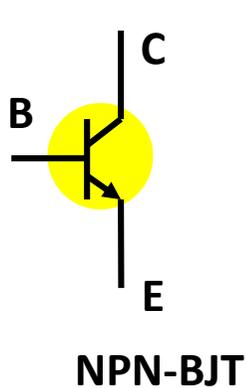
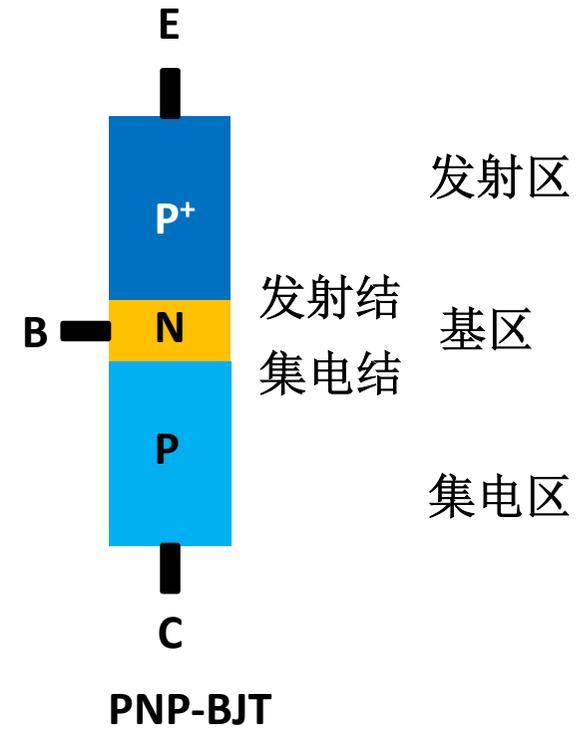


NPN和PNP



E: emitter 发射极: 发射多子
C: collector 集电极: 收集多子
B: base 基极: 少子导电通道
控制端

- (1) 基区很薄
- (2) 发射区掺杂浓度高

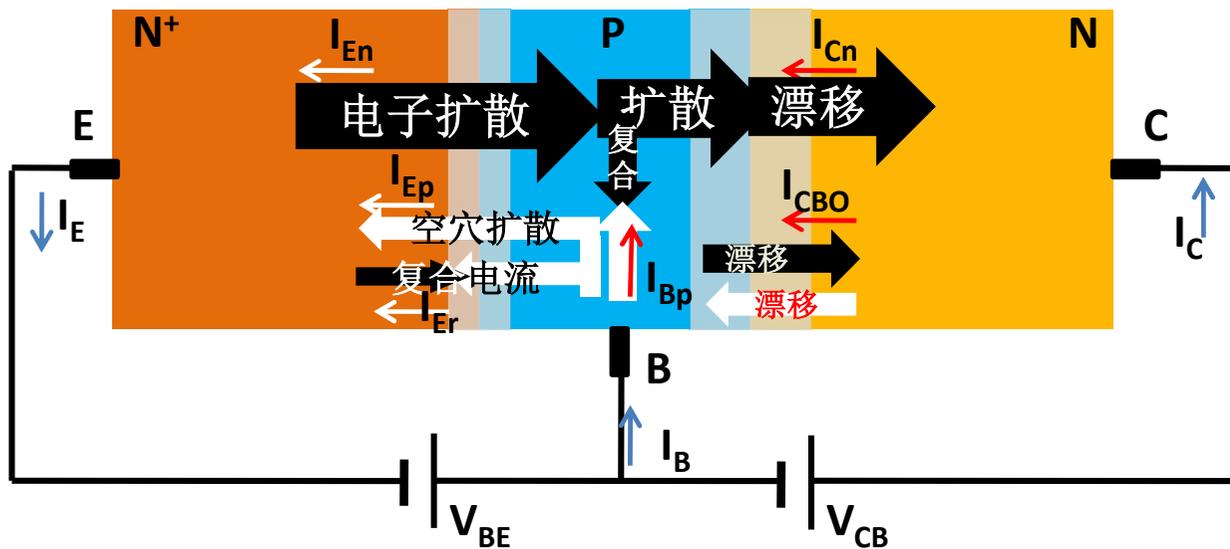


发射结正偏，集电结反偏* 打星号页不做要求

基区很薄，
掺杂浓度低

发射结正偏
耗尽层变薄

集电结反偏
耗尽层变厚



I_E : 发射极总电流
 I_{En} : 电子扩散电流
 I_{Ep} : 空穴扩散电流
 I_{Er} : 耗尽层复合电流
 $I_E = I_{En} + I_{Ep} + I_{Er}$

I_B : 基极总电流
 I_{Bp} : 基区复合电流
 $I_B = I_{Bp} + I_{Ep} + I_{Er} - I_{CBO}$

I_C : 集电极总电流
 I_{Cn} : 电子漂移电流
 I_{CBO} : 反向饱和电流
 $I_C = I_{Cn} + I_{CBO}$

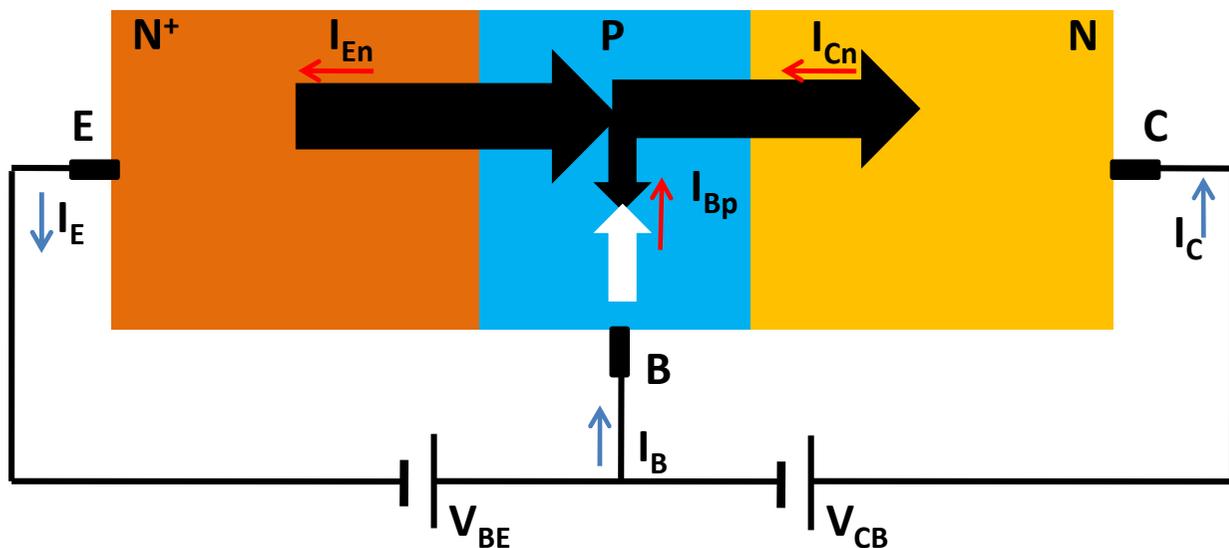
$$I_E = I_C + I_B$$

BJT: Bipolar
MOSFET: Unipolar

电流分配关系

$$I_E = I_C + I_B$$

$$I_C = \beta I_B$$



β : **共发射极** 电流放大倍数: **100**或更大
发射极做为公共地:

BJT是一个电流放大器, 集电极电流由基极电流控制: β 代表了基极电流对集电极电流的控制作用

$$\alpha = \frac{I_C}{I_E}$$

$$I_B = I_E - I_C$$

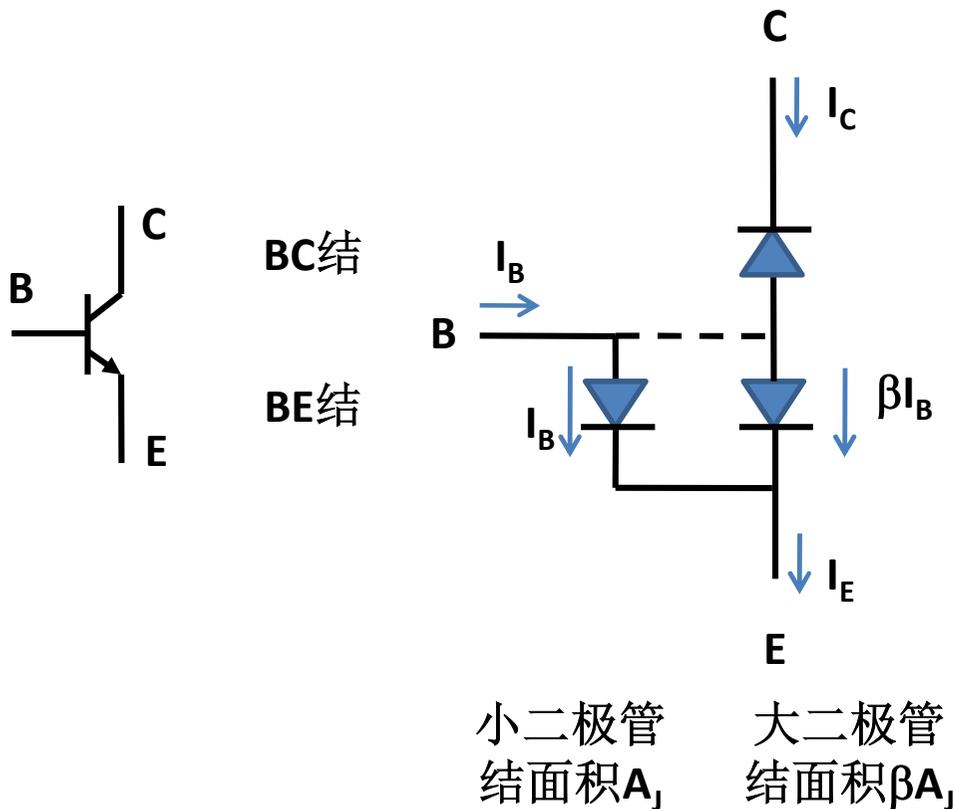
$$\beta = \frac{\alpha}{1 - \alpha}$$

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

α : **共基极** 电流放大倍数: **0.99**左右

基极做为公共地: **BJT**是一个电流缓冲器, 集电极收集电子近似等于发射极发射电子
增大集电极收集能力, 要求基区更薄, 发射区掺杂浓度远高于基区, 大部分载流子通过

如何理解 电流控制关系*

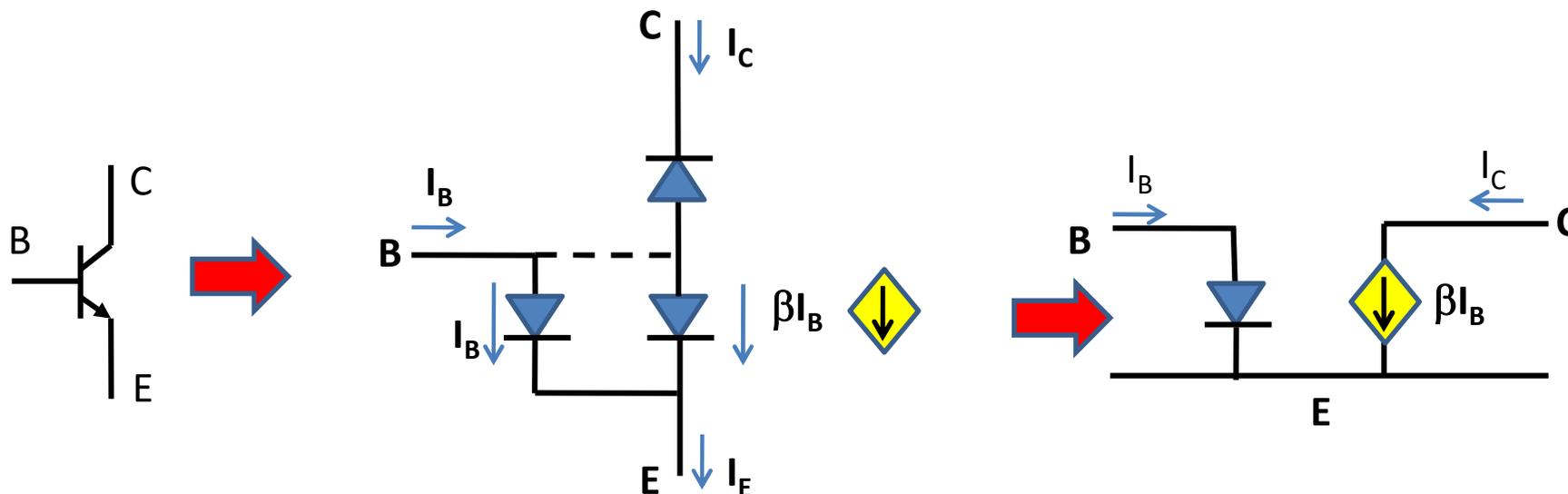


(1) 如果没有集电极，发射极发射电子将全部被基极吸收，BE端口电压、电流满足PN结指数律关系

(2) 现有集电极，形成反偏集电结，且基区很薄，发射极发射电子大部分被集电极收集，少部分在基区和空穴复合：和空穴复合的部分可视为结面积为 A_j 的一个小二极管，电子被集电极收集的部分可视为结面积为 βA_j 的大二极管，这两个二极管电压相等，电流和电压满足相同的二极管指数规律，显然电流比为结面积之比，为 $1: \beta$ ，即集电极电流 $I_C = \beta I_B$ 。

(3) 当基极电流 I_B 改变时，集电极电流 $I_C = \beta I_B$ 将同时改变，两者之间是一个流控流源关系，控制系数 β 近似为一个常数

电路模型*



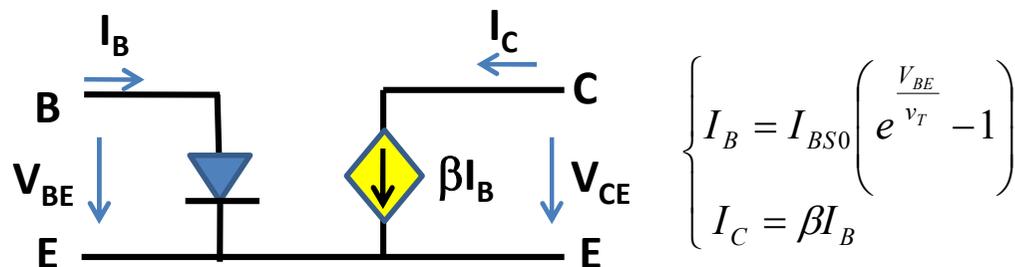
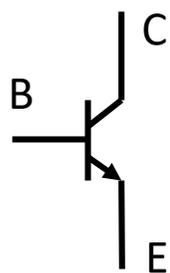
NPN晶体管是特殊连接关系的双二极管结构

其特殊性表现在发射极发射的大部分电子被集电极收集，内在看，**BE**结被等效为两个面积相差 β 倍的二极管的并联

由于两二极管具有相同的**BE**结电压，故而电流之比为结面积之比 β ，从而二端口网络可等效为流控流源

元件约束方程

- 以发射极为公共端点，形成的二端口网络，需要两个元件约束方程以完备描述



$$\begin{cases} I_B = I_{BS0} \left(e^{\frac{V_{BE}}{v_T}} - 1 \right) \\ I_C = \beta I_B \end{cases}$$

$$\begin{cases} V_{BE} = v_T \ln \left(\frac{I_B}{I_{BS0}} + 1 \right) \\ I_C = \beta I_B \end{cases}$$

流控流源
混合控制描述

BE结正偏，BC结反偏

$$\begin{cases} I_B = A_J J_{BS0} \left(e^{\frac{V_{BE}}{v_T}} - 1 \right) \\ I_C = \beta A_J J_{BS0} \left(e^{\frac{V_{BE}}{v_T}} - 1 \right) \end{cases}$$

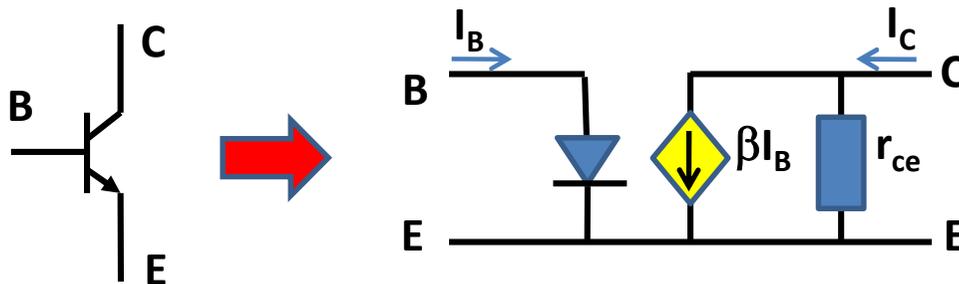
压控流源
压控描述

对元件约束的修正 基区宽度调制效应*

- 当二端口CE电压很大时，意味着CB电压提高，集电结反偏电压的提高导致集电结耗尽层厚度增加，于是基区等效厚度的降低，故而有更多的电子直接穿过基区到达集电区，集电极电流增加

— 基区宽度调制效应

- **Base-Width Modulation**
- 厄利效应：假设集电极电流的增加和 V_{CE} 成正比关系，伏安特性延拓线交于厄利电压 $-V_A$ 位置

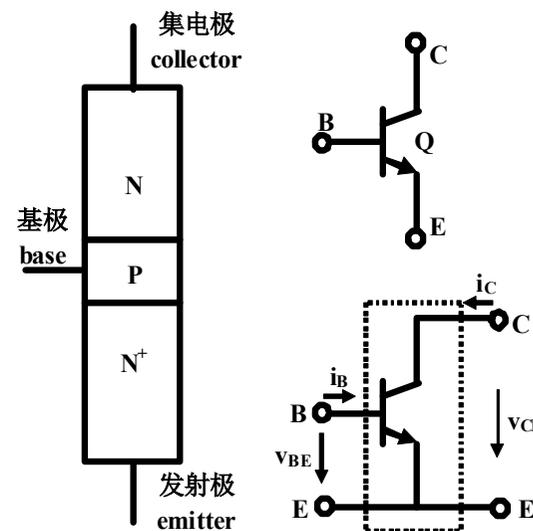
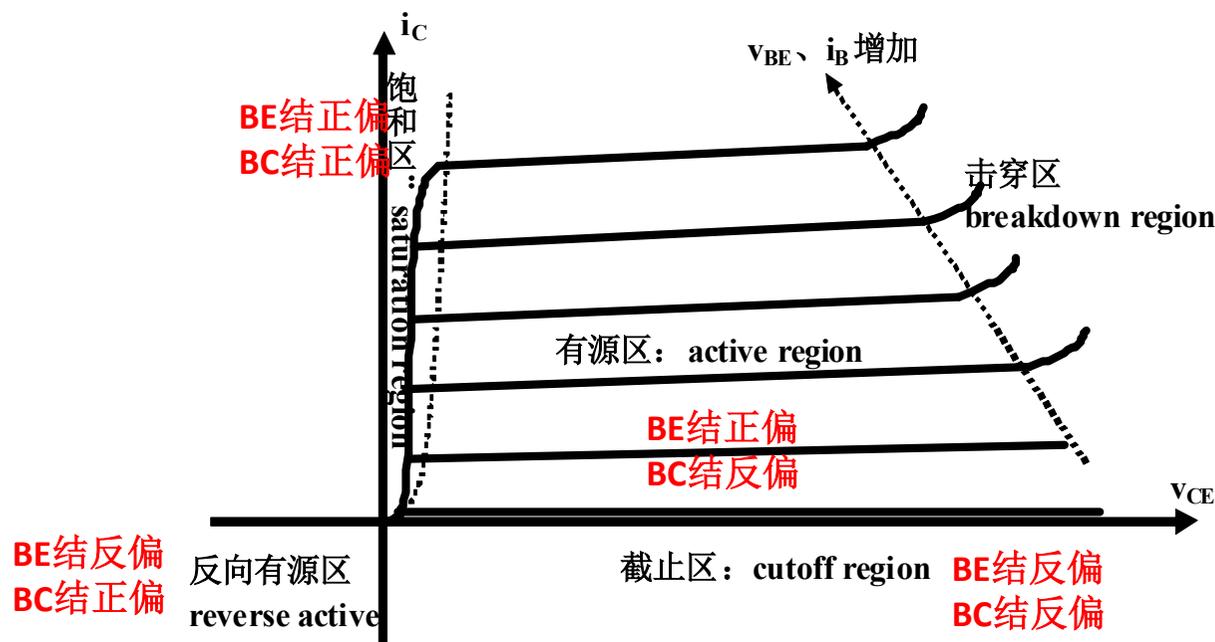


$$r_{ce} = \frac{V_A}{\beta I_B} = \frac{V_A}{I_{C0}}$$

$$\begin{cases} I_B = A_J J_{BS0} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \\ I_C = \beta A_J J_{BS0} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) \end{cases}$$

$$I_C = \beta I_B \left(1 + \frac{V_{CE}}{V_A} \right) = \beta I_B + \frac{V_{CE}}{V_A / \beta I_B} = I_{C0} + \frac{V_{CE}}{r_{ce}}$$

NPN-BJT伏安特性曲线



$$i_B = A_J J_{BS0} \left(e^{\frac{v_{BE}}{v_T}} - 1 \right)$$

$$i_C = \beta A_J J_{BS0} \left(e^{\frac{v_{BE}}{v_T}} - 1 \right) \left(1 + \frac{v_{CE}}{V_A} \right) = \beta i_B \left(1 + \frac{v_{CE}}{V_A} \right)$$

晶体管位于有源区（恒流区）
的元件约束方程

$$v_T = \frac{kT}{q} \quad \text{热电压}$$

$$V_A \quad \text{厄利电压}$$

$$I_{BS0} = A_J J_{BS0} \quad \text{反向饱和电流}$$

$$\beta \quad \text{电流增益}$$

四个分区

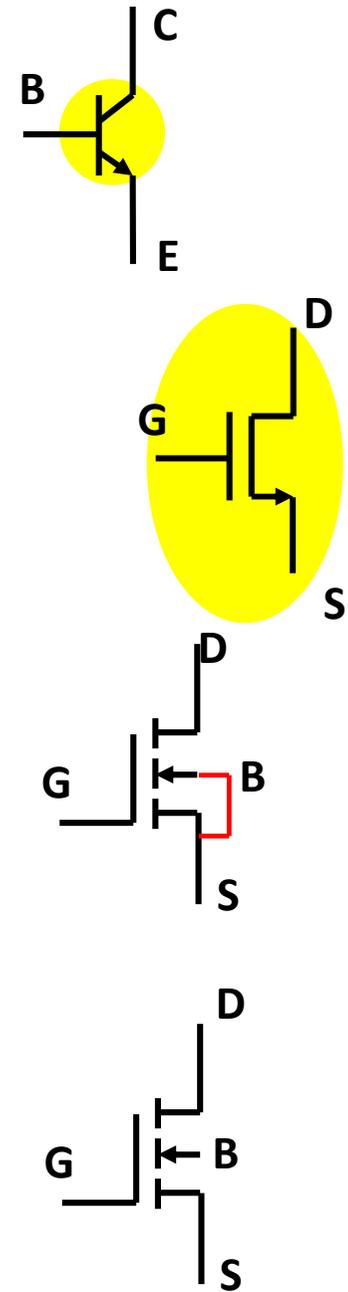
NPN-BJT工作区	BC结反偏	BC结正偏
BE结正偏	有源区	饱和区
BE结反偏	截止区	反向有源区

NMOSFET工作区	$V_{GD} < V_{TH}$	$V_{GD} > V_{TH}$
$V_{GS} > V_{TH}$	有源区、饱和区	欧姆区
$V_{GS} < V_{TH}$	截止区	避免出现这种情况

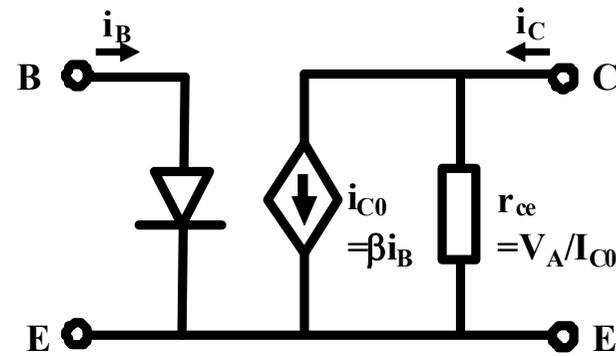
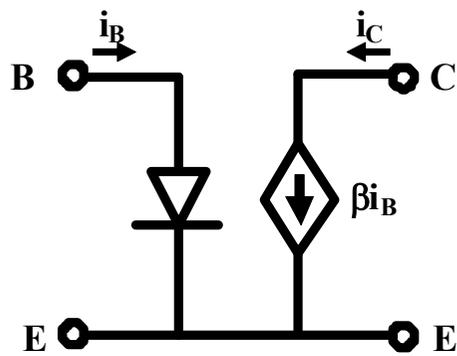
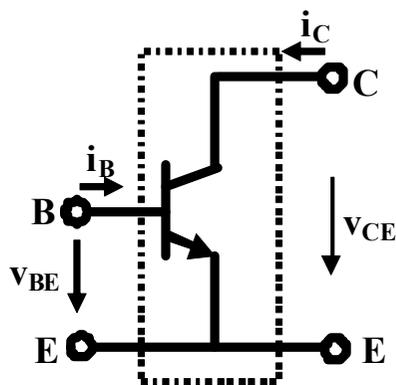
源衬相连，确保PN结反偏，漏极电压只能高于源极电压： $V_{DS} \geq 0$

NMOSFET工作区	$V_{GD} < V_{TH}$	$V_{GD} > V_{TH}$
$V_{GS} > V_{TH}$	有源区、饱和区	欧姆区
$V_{GS} < V_{TH}$	截止区	源漏互换，有源区

衬底电压连接最低电压，源极和漏极对称， V_{DS} 可正可负， V_{DS} 为负时，源漏互换，互换后新的漏源电压仍然满足 $V_{DS} \geq 0$

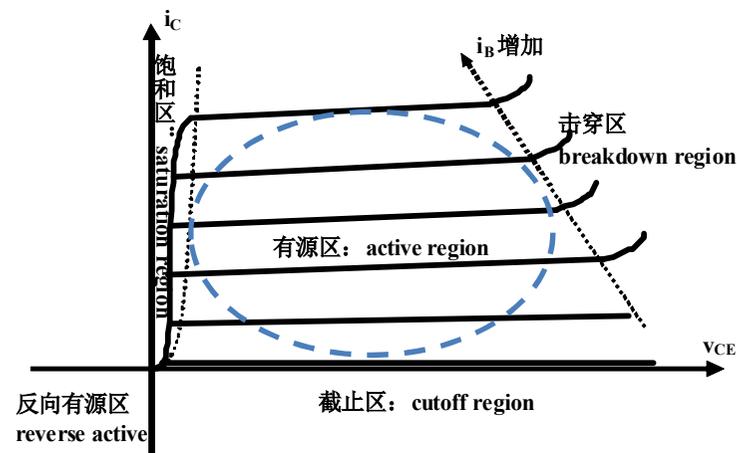


牢记：有源区原理性模型

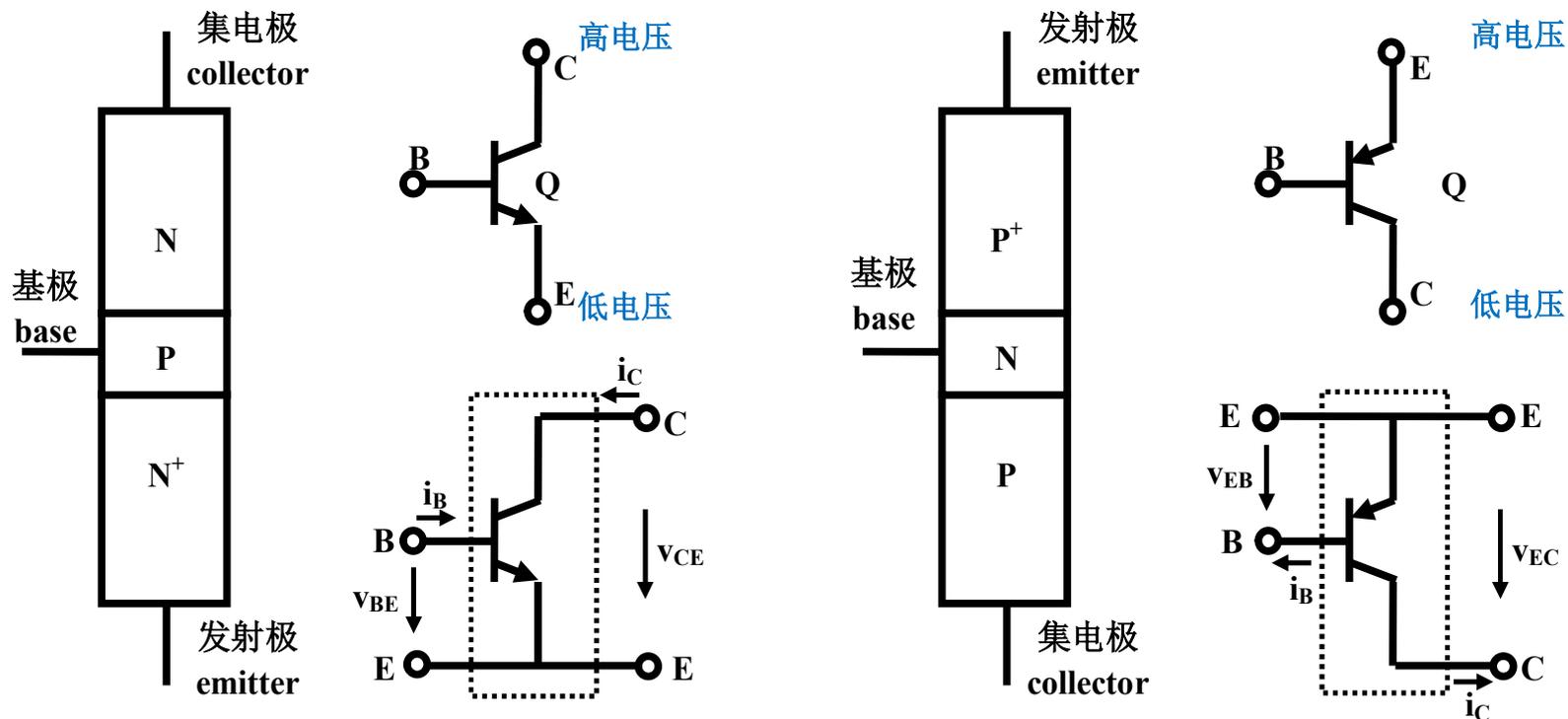


BE端口：看入的是一个BE结正偏二极管
CE端口：是一个流控流源，电流控制系数 β 在数百上千量级

考虑厄利效应，电流源有内阻 r_{ce} ，是恒流区特性曲线斜率的倒数



NPN和PNP：互补结构



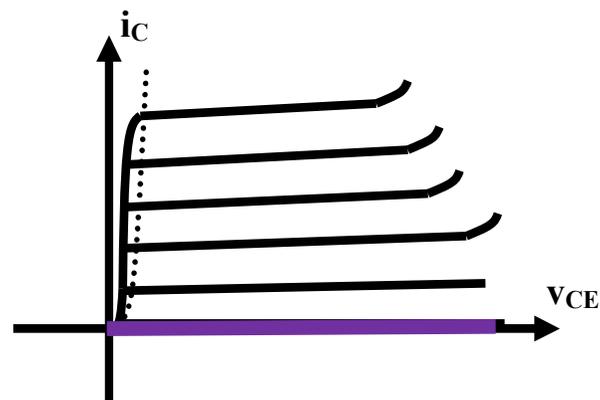
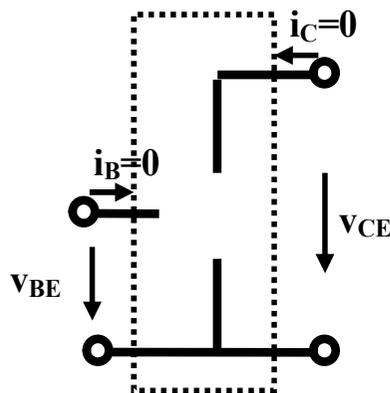
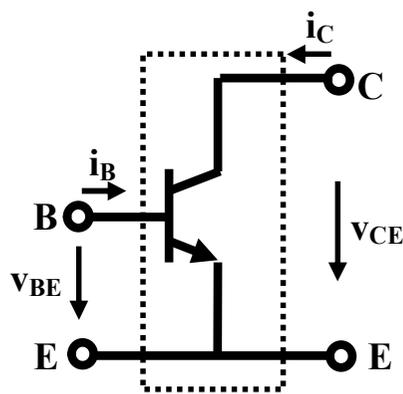
PNP-BJT 的元件约束方程和NPN-BJT的形式一致： PNP方程中，只要将NPN方程中的 v_{BE} 换成 v_{EB} ，将 v_{CE} 换成 v_{EC} ，将 $I_{BS0,n}$ 换成 $I_{BS0,p}$ ，将 β_n 换成 β_p ，将 $V_{A,n}$ 换成 $V_{A,p}$ 后，方程形式没有任何其他变化。

分段线性化电路模型

- 只要元件约束方程有明显的分区特性，原理性分析即可采用分段折线模型
- **BJT**伏安特性曲线在第一象限三个分区有明确的物理含义，可在三个区域分别线性化处理
 - 截止区：发射结和集电结均反偏截止：开路模型
 - 饱和区：发射结和集电结均正偏导通，集电极电流剧烈变化下集射电压几乎保持不变，抽象为恒压源
 - 恒流区：发射结正偏，二极管指数律控制电流，集电结反偏收集发射区发射到基区的载流子，伏安特性曲线几乎平直，抽象为恒流源

以NPN-BJT为例

分段线性化：截止区开路模型



$$v_{BE} < V_{on}$$

$$i_B = 0$$

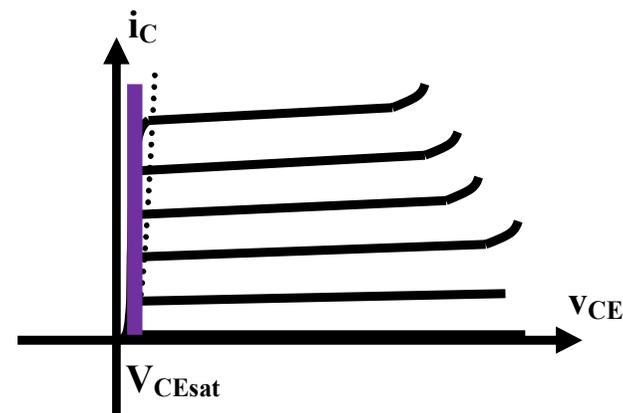
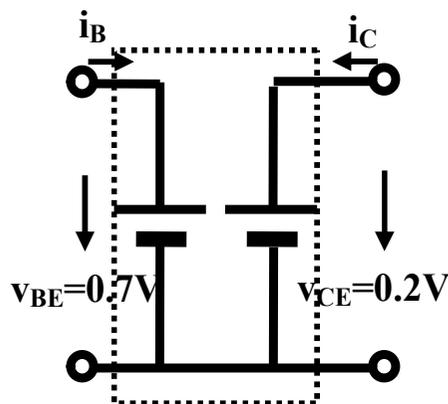
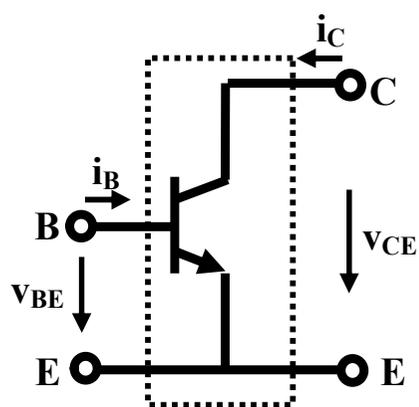
BE结反偏，截止

$$i_C = 0$$

BC结反偏，截止

$$v_{CE} > 0$$

分段线性化：饱和区恒压模型



$$i_B > 0$$

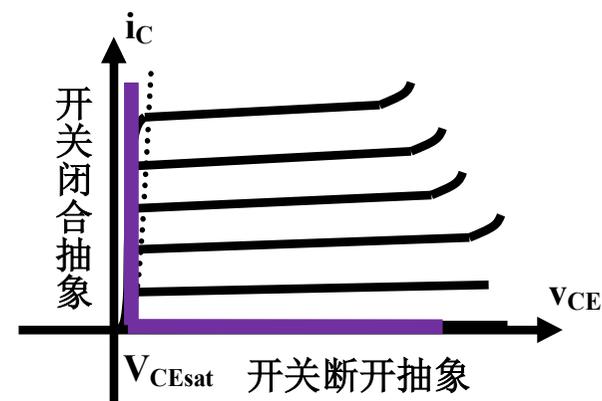
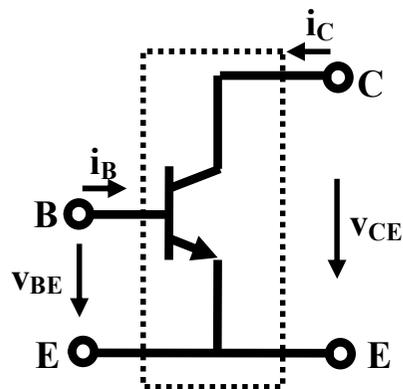
$$i_C < \beta i_B$$

BE结正偏导通
BC结正偏导通

$$v_{BE} = V_{on} = 0.7V$$

$$v_{CE} = V_{CE,sat} = 0.2V$$

分段线性化：开关电路模型



$$i_C = 0$$

BE结反偏，BC结反偏：开关断开

条件：

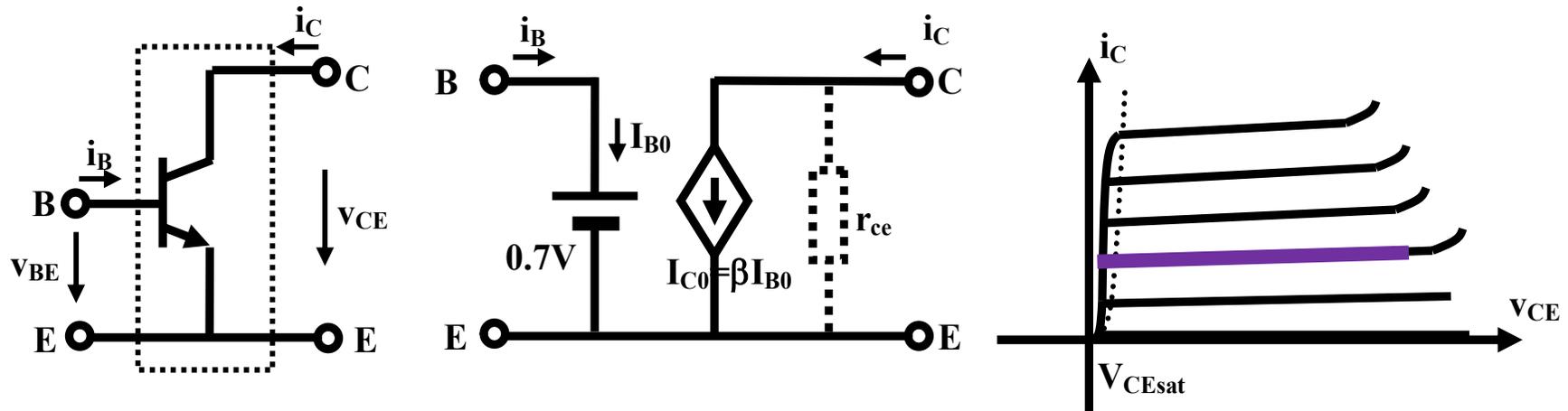
$$i_B = 0$$

$$v_{CE} = 0.2V$$

BE结正偏，BC结正偏：开关闭合

$$i_B \text{ 较大} \quad i_C < \beta i_B$$

分段线性化：恒流区受控源模型



$$i_B > 0$$

$$v_{BE} = 0.7V$$

BE结分段折线模型
正偏0.7V恒压

BE结正偏，BC结反偏

条件: $V_{CE} > V_{CE,sat}$

$$i_C = \beta I_{B0} + \frac{v_{CE}}{r_{ce}} \approx \beta I_{B0}$$

$$r_{ce} = \frac{V_A}{I_{C0}}$$

分段折线化模型中，厄利效应大多被忽略
局部线性化分析中，厄利效应一般会加以考虑

BJT的关键参量

β 不确定性高

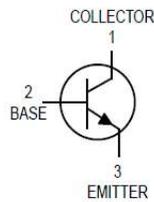
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Low Noise Transistors

NPN Silicon

Motorola BC549



$$\begin{bmatrix} v_{be} \\ i_c \end{bmatrix} = \begin{bmatrix} h_{ie} & h_{re} \\ h_{fe} & h_{oe} \end{bmatrix} \begin{bmatrix} i_b \\ v_{ce} \end{bmatrix} \quad h_{FE} = \frac{I_C}{I_B} \Big|_{V_{CE}=V_{CE0}}$$

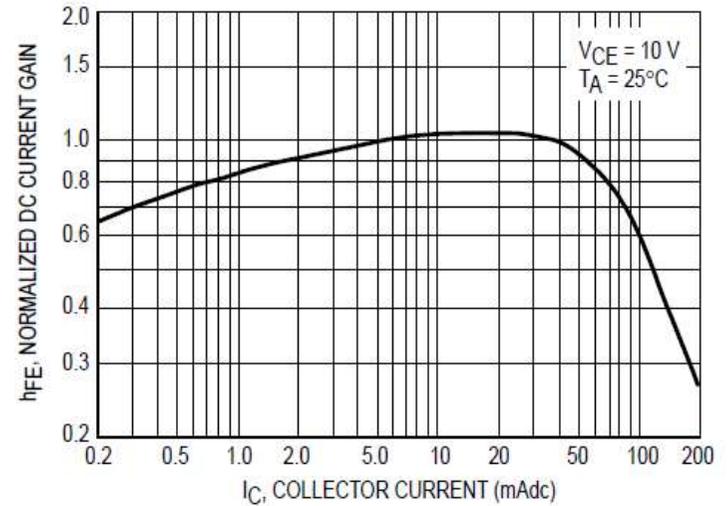


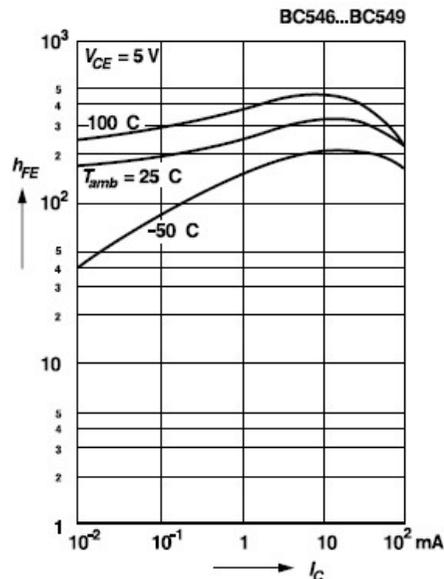
Figure 2. Normalized DC Current Gain

DC current gain
versus collector current

ELECTRICAL CHARACTERISTICS ($T_A = 25^\circ\text{C}$ unless otherwise noted) (Continued)

Characteristic	Symbol	Min	Typ	Max	Unit
ON CHARACTERISTICS					
DC Current Gain ($I_C = 10 \mu\text{Adc}$, $V_{CE} = 5.0 \text{ Vdc}$)	h_{FE}	100	150	—	—
($I_C = 2.0 \text{ mAdc}$, $V_{CE} = 5.0 \text{ Vdc}$)		100	270	—	—
Collector-Emitter Saturation Voltage ($I_C = 10 \text{ mAdc}$, $I_B = 0.5 \text{ mAdc}$) ($I_C = 10 \text{ mAdc}$, $I_B = \text{see note 1}$) ($I_C = 100 \text{ mAdc}$, $I_B = 5.0 \text{ mAdc}$, see note 2)	$V_{CE(\text{sat})}$	—	0.075 0.3 0.25	0.25 0.6 0.6	Vdc
Base-Emitter Saturation Voltage ($I_C = 100 \text{ mAdc}$, $I_B = 5.0 \text{ mAdc}$)	$V_{BE(\text{sat})}$	—	1.1	—	Vdc
Base-Emitter On Voltage ($I_C = 10 \mu\text{Adc}$, $V_{CE} = 5.0 \text{ Vdc}$) ($I_C = 100 \mu\text{Adc}$, $V_{CE} = 5.0 \text{ Vdc}$) ($I_C = 2.0 \text{ mAdc}$, $V_{CE} = 5.0 \text{ Vdc}$)	$V_{BE(\text{on})}$	— — 0.55	0.52 0.55 0.62	— — 0.7	Vdc

General Semiconductor BC549



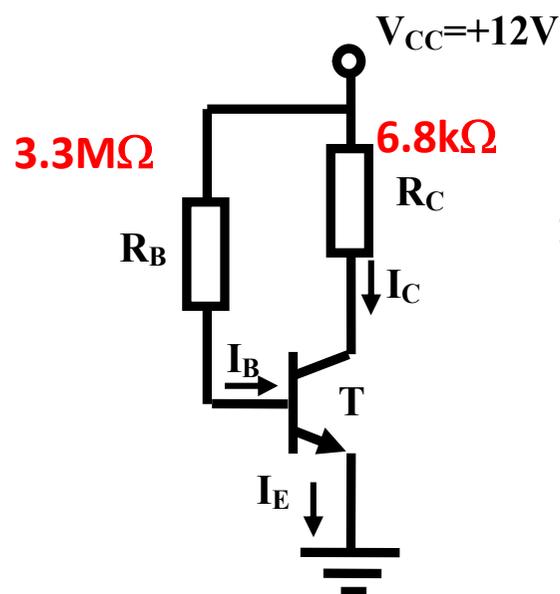
二、BJT分压偏置电路

BJT工作在恒流区则等效为恒流源

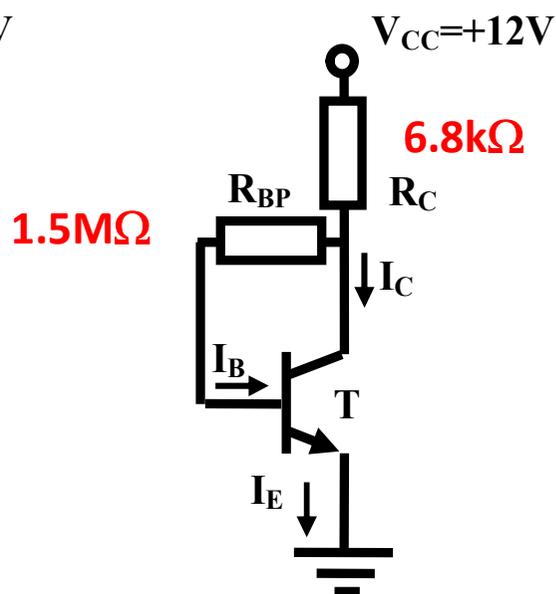
恒流区工作的分立BJT，分压偏置电路是最常见的直流偏置电路

由于负反馈的存在，使得直流工作点很稳定

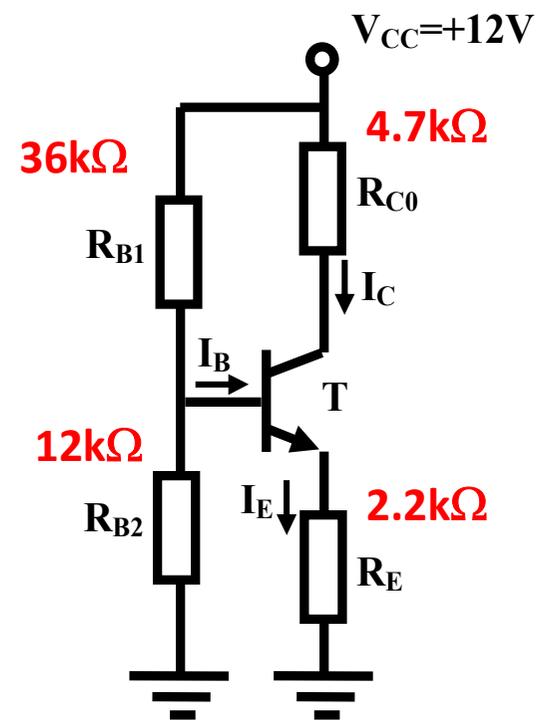
分立BJT: $\beta=200\sim 450$



一般偏置

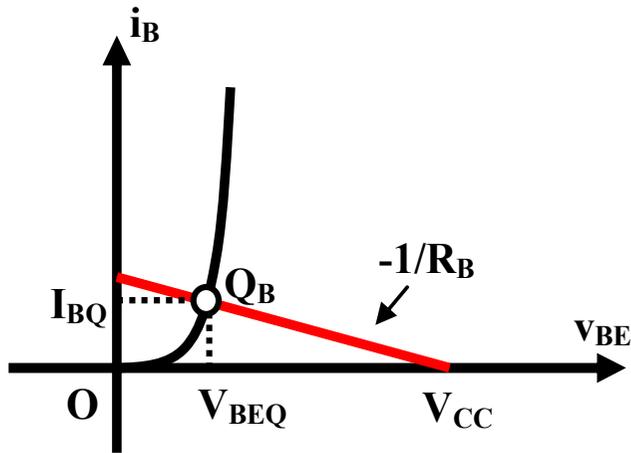
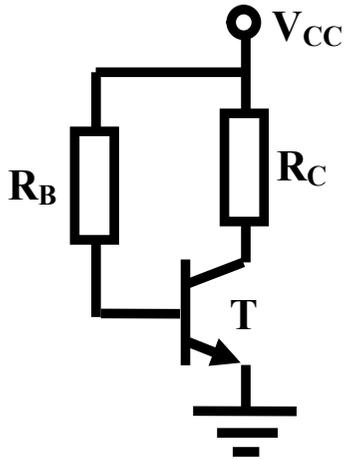
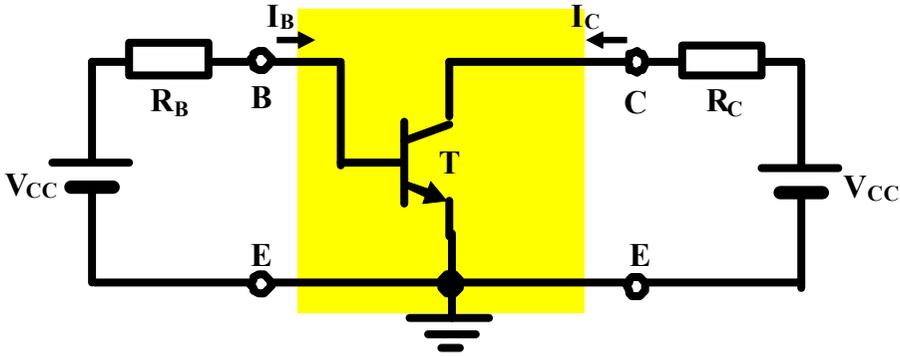


并联负反馈



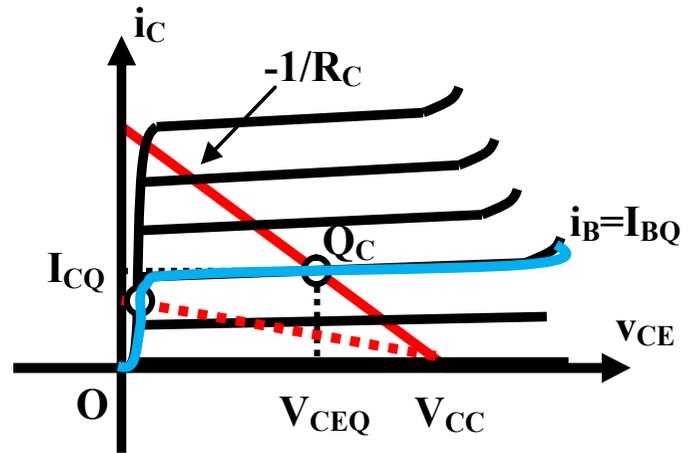
串联负反馈
分压偏置电路

图解法理解



BE端口
BE结与戴维南源对接

输入端口首先确定 I_{BQ}



CE端口
恒流源与戴维南源对接

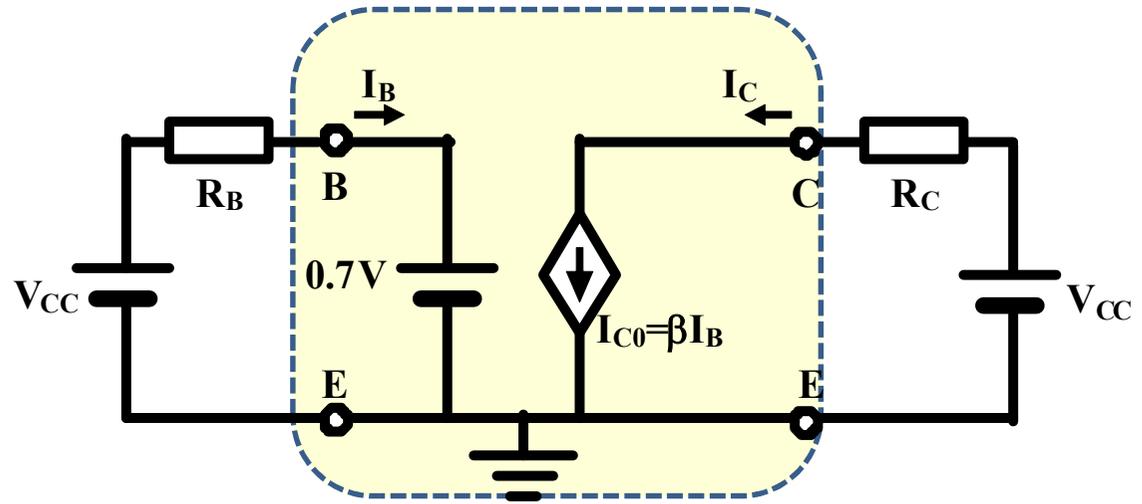
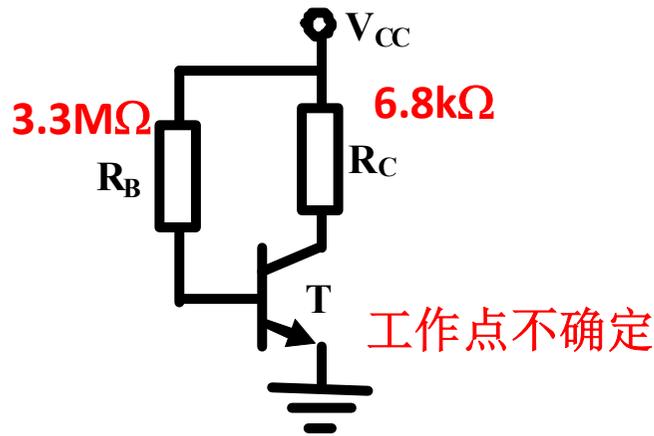
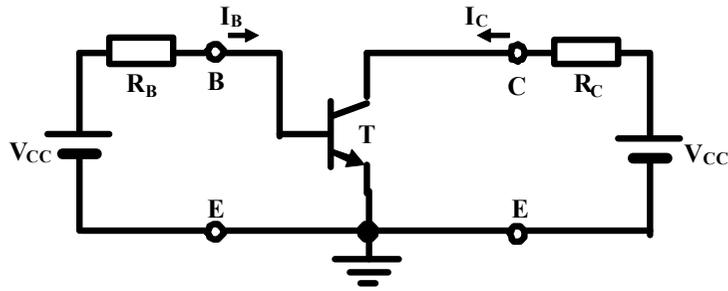
输出端口再确定 $I_{CQ} = \beta \cdot I_{BQ}$
进而确定 V_{CEQ}

R_C 过大，晶体管进入饱和区

工作区假设

- 当我们不知道晶体管工作在哪个区域时，可以先假设它工作在某个区域，然后按这个区域的电路模型进行计算，如果发现计算结果确实落在在这个区域，说明假设正确；如果发现计算结果没有落在假设区域，那么假设就是错误的，需要重新假设工作区域
 - 如果有唯一解，得到合理的解就可以结束
 - 如果有多解，则需每个区域都试试，可能多个假设都成立
- **BJT**电路分析时，可首先假设其工作在恒流区
 - **BJT**电路大多属放大器或电流源应用，都要求工作在恒流区
 - 恒流区电流几乎恒定，可等效为电流源：电流源应用
 - 恒流区又称有源区，工作在该区域的晶体管可等效为受控源，具有将直流能量转换为交流能量的能力：放大器应用

等效电路分析 假设工作在恒流区



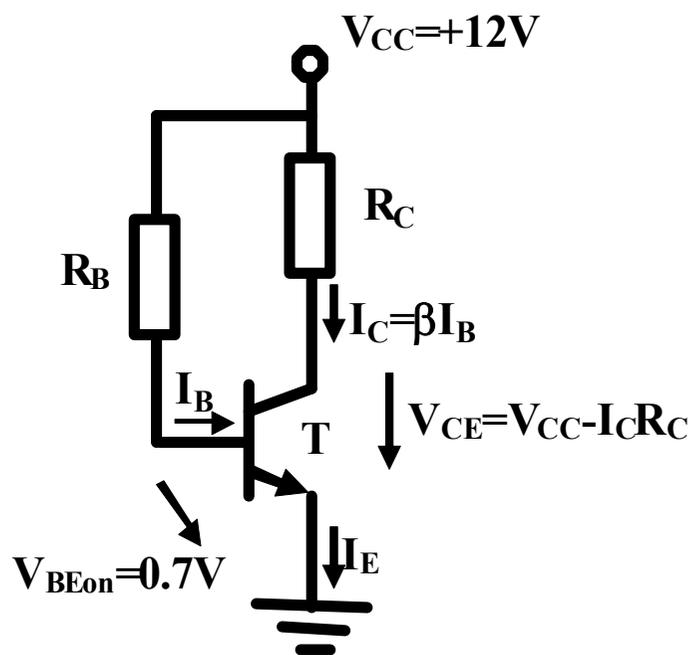
$$I_B = \frac{V_{CC} - V_{BEQ}}{R_B} = \frac{12 - 0.7}{3.3 \times 10^6} = 3.42 \times 10^{-6} = 3.42(\mu A)$$

$$I_C = \beta I_B = (200 \sim 450) \times 3.42 \mu A = 0.685 mA \sim 1.54 mA$$

$$V_{CE} = V_{CC} - I_C R_C = 12 - (0.685 \sim 1.54) \times 6.8 = 7.3V \sim 1.5V > 0.2V = V_{CE,sat}$$

确认在恒流区

模型太简单，无需画等效电路



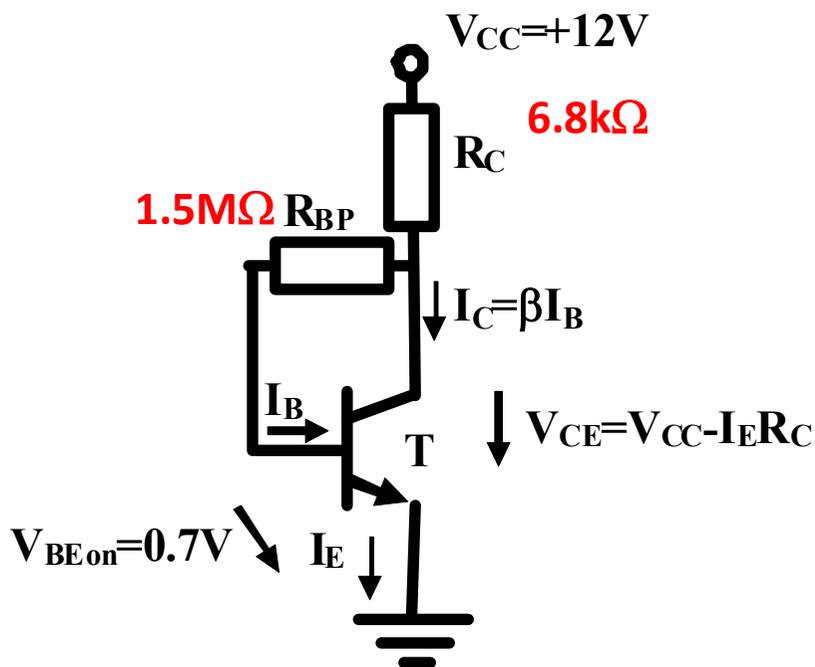
$$V_{BE} = V_{BEon} = 0.7V$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = \beta I_B = \beta \frac{V_{CC} - V_{BE}}{R_B}$$

$$\begin{aligned} V_{CE} &= V_{CC} - I_C R_C \\ &= V_{CC} - (V_{CC} - V_{BE}) \frac{\beta R_C}{R_B} \end{aligned}$$

并联负反馈



$$V_{CE} = V_{CC} - (\beta + 1)I_B R_C$$

$$= 6.6V \sim 4.4V > V_{CE,sat}$$

可确认在恒流区

并联负反馈使得工作点稳定

$$V_{CC} = (\beta + 1)I_B R_C + I_B R_{BP} + V_{BE}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_{BP} + (\beta + 1)R_C}$$

$$= \frac{12 - 0.7}{1.5 \times 10^6 + (201 \sim 451) \times 6.8 \times 10^3}$$

$$= 3.94 \mu A \sim 2.47 \mu A \quad \mathbf{1.37 \sim 3.07 M\Omega}$$

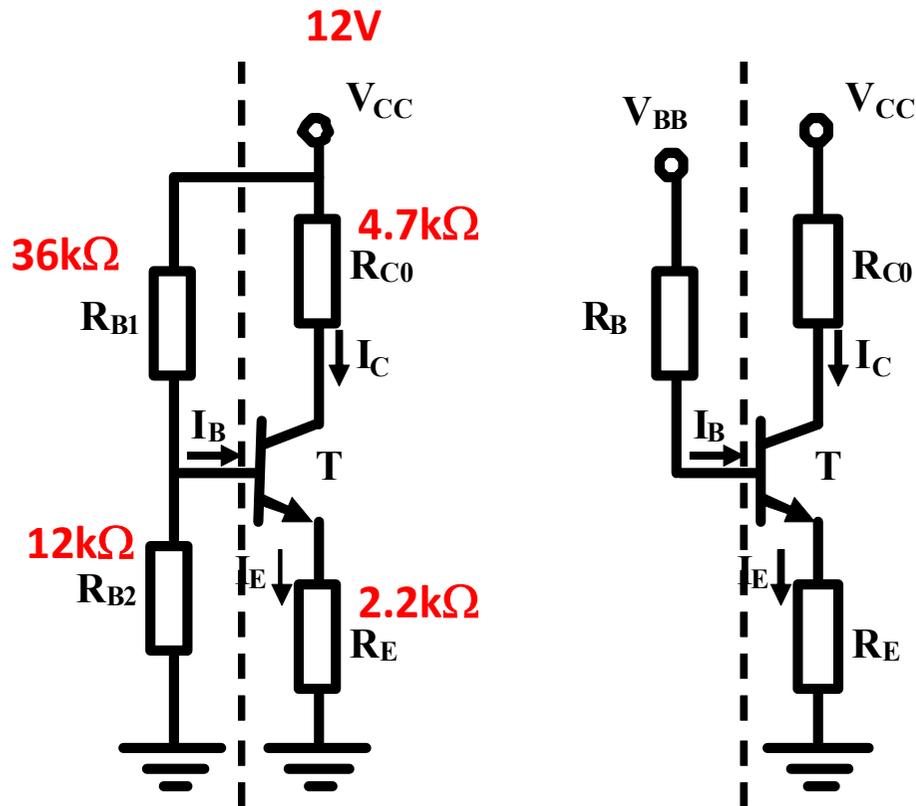
$$I_C = \beta I_B = \beta \frac{V_{CC} - 0.7}{R_{BP} + (\beta + 1)R_C}$$

$$= \frac{V_{CC} - 0.7}{R_C + \frac{R_C + R_{BP}}{\beta}}$$

$$= \frac{12 - 0.7}{6.8 \times 10^3 + \frac{6.8 \times 10^3 + 1.5 \times 10^6}{200 \sim 450}}$$

$$= 0.788 mA \sim 1.11 mA \quad \mathbf{7.5 \sim 3.4 k\Omega}$$

分压偏置的戴维南等效



$$V_{BB} = \frac{R_{B2}}{R_{B1} + R_{B2}} V_{CC}$$

$$= \frac{12}{36 + 12} \times 12 = 3V$$

$$R_B = R_{B1} \parallel R_{B2}$$

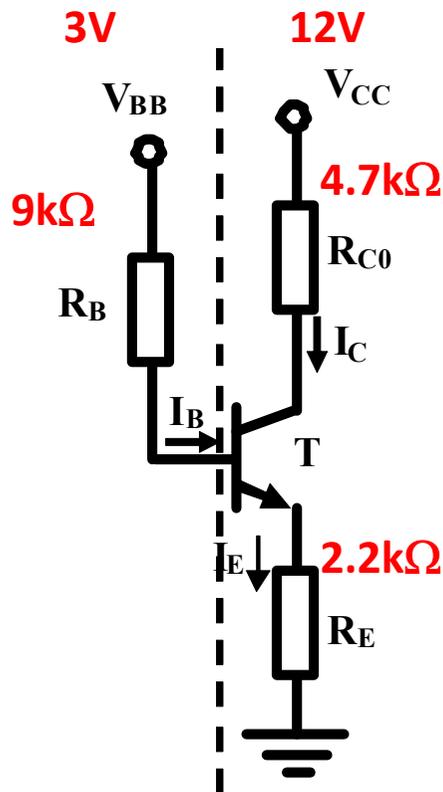
$$= \frac{36 \times 12}{36 + 12} = 9k\Omega$$

串联负反馈

$$V_{BB} = I_B R_B + V_{BE} + (\beta + 1) I_B R_E$$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1) R_E} = \frac{3 - 0.7}{9 \times 10^3 + (201 \sim 451) \times 2.2 \times 10^3} = 5.10 \mu A \sim 2.30 \mu A$$

442~992kΩ



$$I_C = \beta I_B = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B + R_E}{\beta}} = \frac{3 - 0.7}{2.2 \times 10^3 + \frac{9 \times 10^3 + 2.2 \times 10^3}{200 \sim 450}}$$

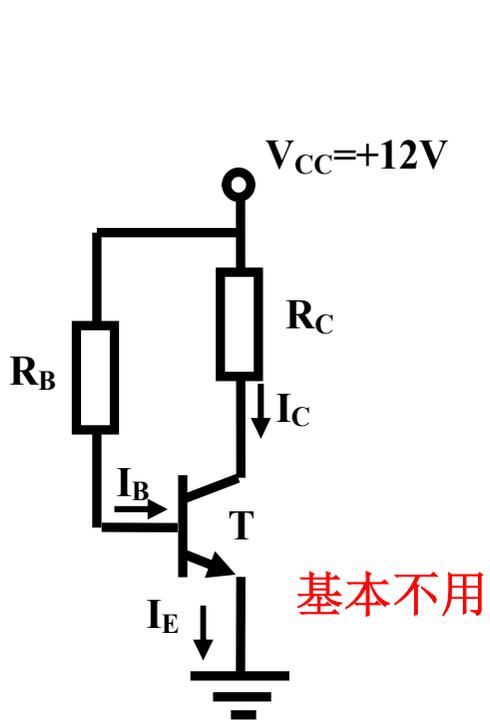
$$= \frac{3 - 0.7}{2.2 \times 10^3 + (0.056 \sim 0.025) \times 10^3} = 1.02 mA \sim 1.03 mA$$

$$V_{CE} = V_{CC} - \beta I_B R_{C0} - (\beta + 1) I_B R_E = 5.0V \sim 4.9V$$

可确认在恒流区

串联负反馈使得工作点十分的稳定

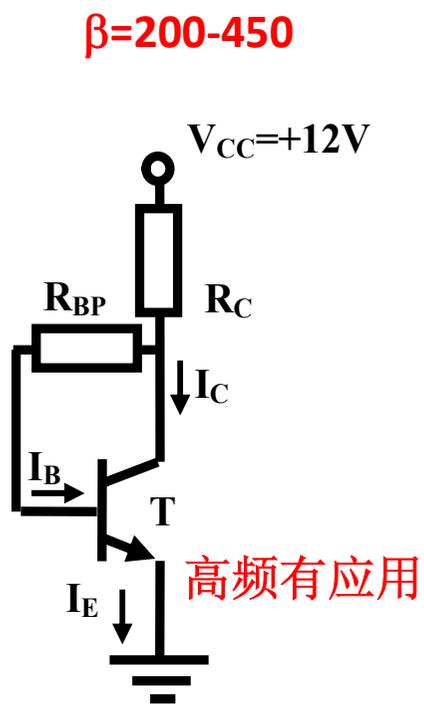
工作点的稳定性差异很大



$$I_C = \beta \frac{V_{CC} - V_{BE}}{R_B}$$

$$= 0.685 \sim 1.54mA$$

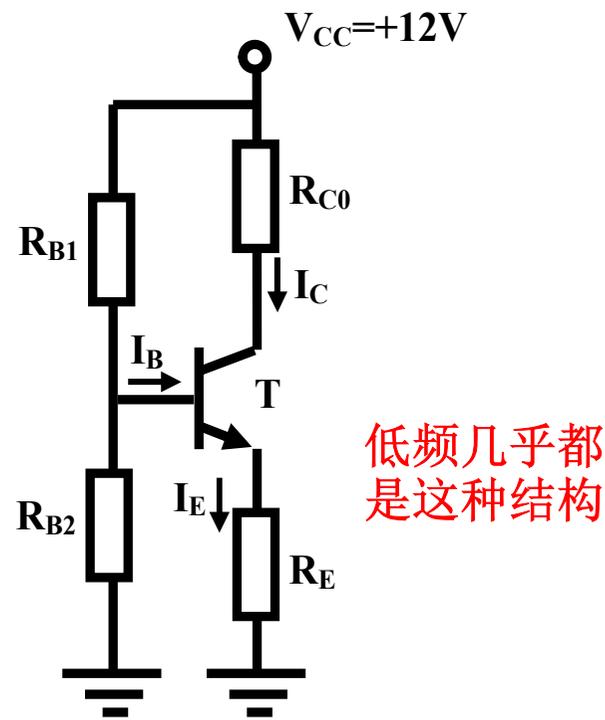
$$V_{CE} = 7.3V \sim 1.5V$$



$$I_C = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_C + R_{BP}}{\beta}}$$

$$= 0.788 \sim 1.11mA$$

$$V_{CE} = 6.6V \sim 4.4V$$

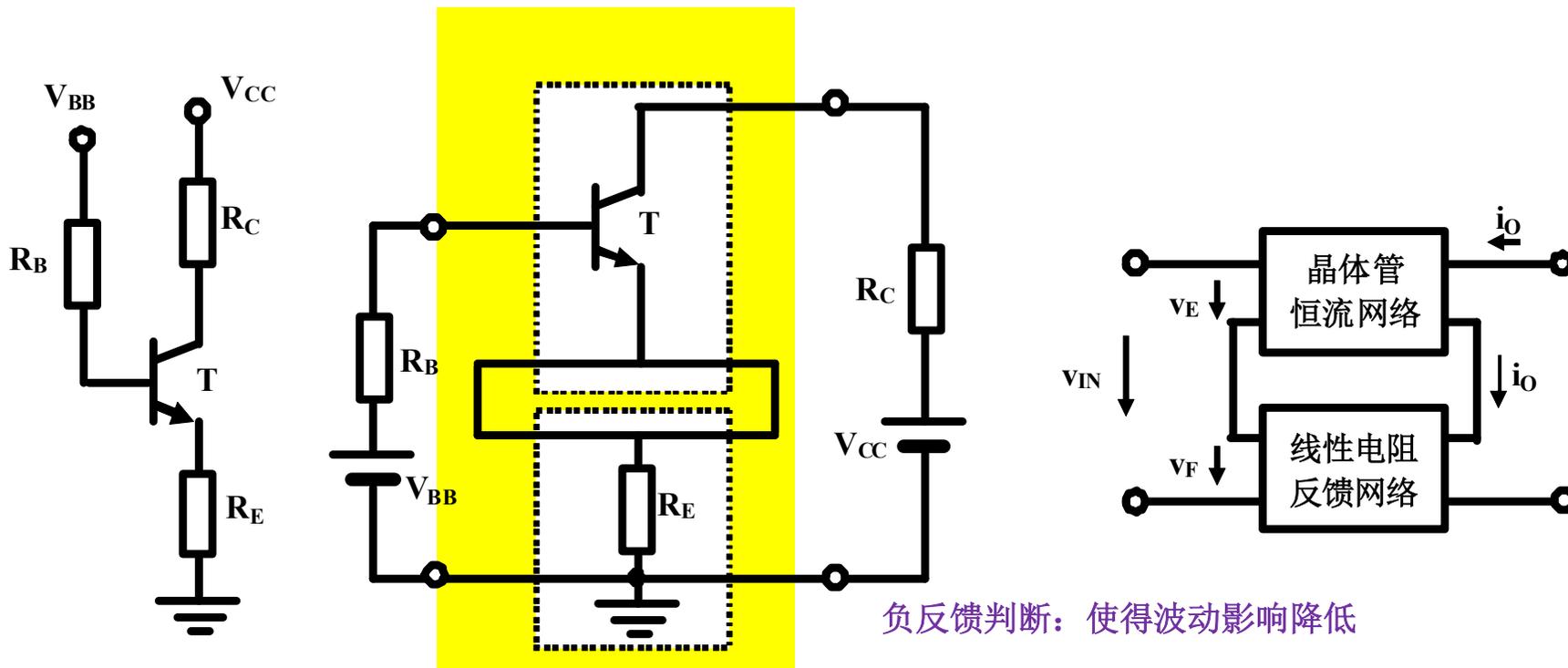


$$I_C = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B + R_E}{\beta}}$$

$$= 1.02 \sim 1.03mA$$

$$V_{CE} = 5.0V \sim 4.9V$$

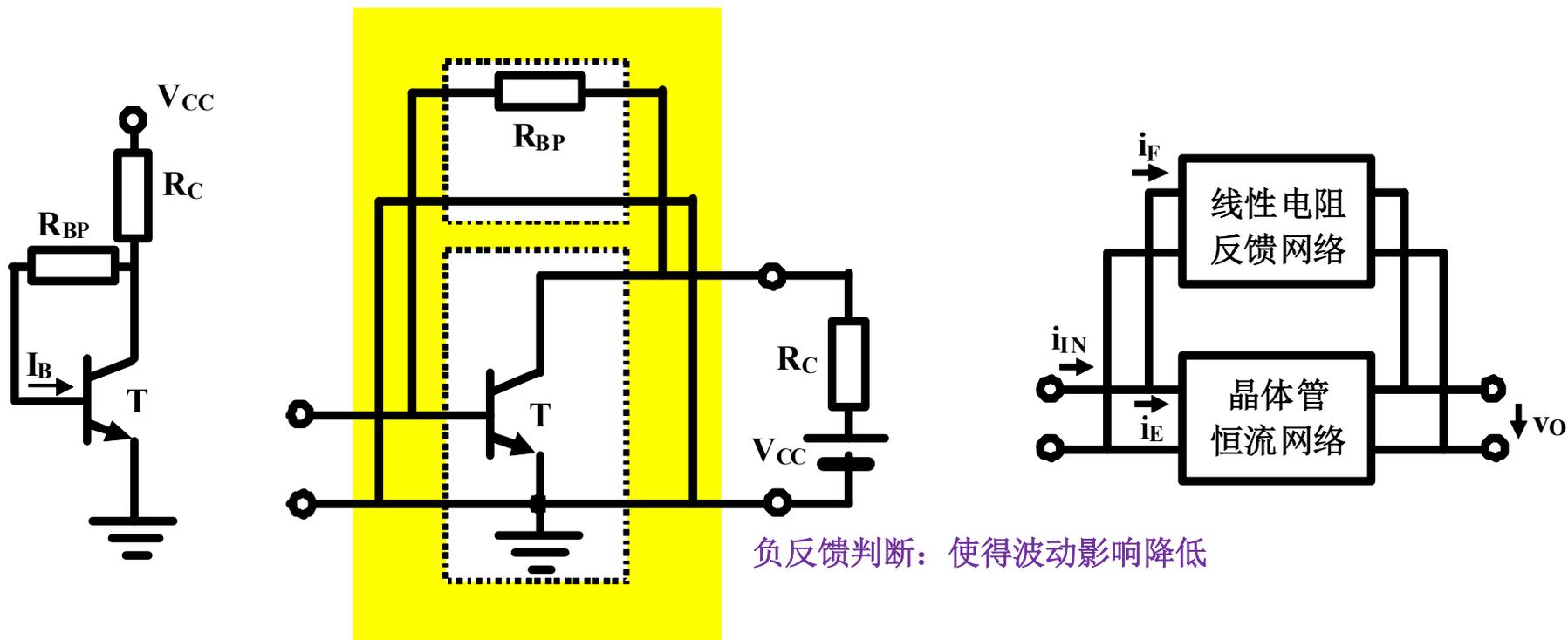
负反馈分析：串联负反馈



串串负反馈，检测输出电流，形成反馈电压
在负反馈电压作用下，使得输出电流波动降低
稳定的电流输出，很高的输入和输出阻抗：接近理想压控流源

恒流区晶体管本身就是压控流源模型，串联负反馈适当其时
使得闭环电路更加接近于理想的压控流源

负反馈分析：并联负反馈



并并负反馈，检测输出电压，形成负反馈电流
在负反馈电流作用下，使得输出电压波动降低
稳定的电压输出，低的输入和输出阻抗：接近理想流控压源

恒流区晶体管本身是压控流源（流控流源）模型，并联负反馈并不十分适当
并并负反馈形成流控压源受控特性，因而稳定性不如串联负反馈

灵敏度分析

灵敏度代表影响力

$$S_{x_i}^y = \frac{\Delta y / y}{\Delta x_i / x_i} \stackrel{\Delta x_i \rightarrow 0}{=} \frac{x_i}{y} \frac{\partial y}{\partial x_i}$$

设计值 实际制作偏离设计值

$$y = f(x_1, x_2, \dots, x_n) = f(x_{10} + \Delta x_1, x_{20} + \Delta x_2, \dots, x_{n0} + \Delta x_n)$$
$$= f(x_{10}, x_{20}, \dots, x_{n0}) + \frac{\partial f}{\partial x_1} \Delta x_1 + \frac{\partial f}{\partial x_2} \Delta x_2 + \dots + \frac{\partial f}{\partial x_n} \Delta x_n + h.o.t$$

$$\Delta y = y - y_0 \approx \frac{\partial f}{\partial x_1} \Delta x_1 + \frac{\partial f}{\partial x_2} \Delta x_2 + \dots + \frac{\partial f}{\partial x_n} \Delta x_n$$

导致输出偏离设计值

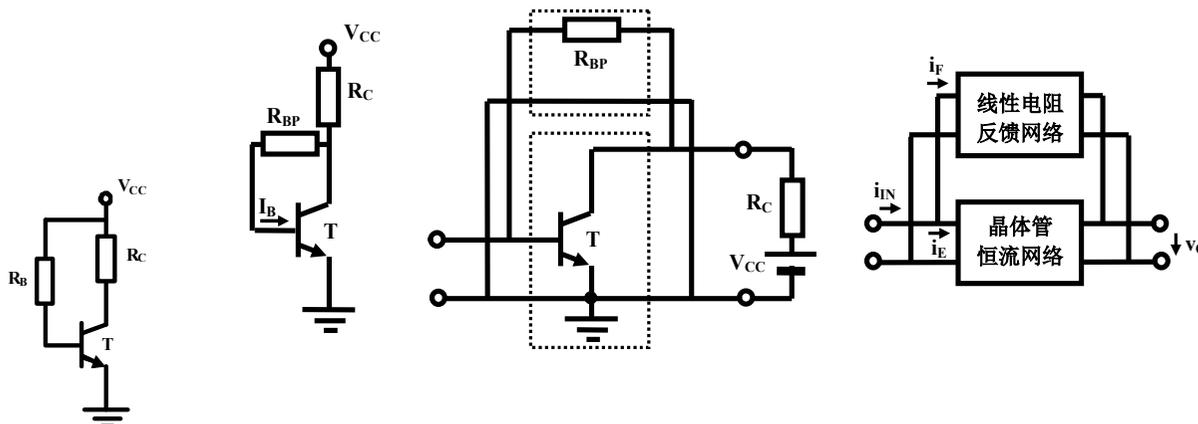
$$\frac{\Delta y}{y_0} \approx \frac{\partial f}{\partial x_1} \frac{x_{10}}{y_0} \frac{\Delta x_1}{x_{10}} + \frac{\partial f}{\partial x_2} \frac{x_{20}}{y_0} \frac{\Delta x_2}{x_{20}} + \dots + \frac{\partial f}{\partial x_n} \frac{x_{n0}}{y_0} \frac{\Delta x_n}{x_{n0}}$$

$$\frac{\Delta y}{y_0} = S_{x_1}^y \frac{\Delta x_1}{x_{10}} + S_{x_2}^y \frac{\Delta x_2}{x_{20}} + \dots + S_{x_n}^y \frac{\Delta x_n}{x_{n0}}$$

对于极度不稳定因素如 β ，电路设计时应确保其灵敏度足够小，从而提高系统稳定性

灵敏度分析

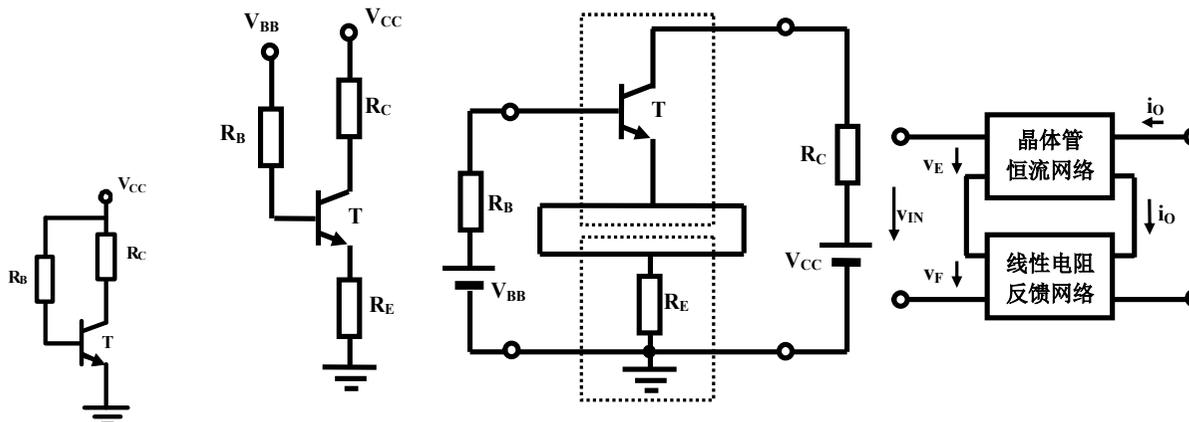
$\beta=300$



	一般偏置	并并负反馈稳定输出电压	并并负反馈
输出电压 V_{CE}	$V_{CE} = V_{CC} - (V_{CC} - V_{BE}) \frac{\beta R_C}{R_B} = 5.01V$	$V_{CE} = \frac{(\beta + 1)R_C V_{BE} + R_{BP} V_{CC}}{(\beta + 1)R_C + R_{BP}} = 5.48V$	
$S_{V_{CC}}^{V_{CE}} = \frac{\partial V_{CE}}{\partial V_{CC}} \frac{V_{CC}}{V_{CE}}$	$= \left(1 - \frac{\beta R_C}{R_B}\right) \frac{V_{CC}}{V_{CE}} = 0.914$	$= \frac{R_{BP}}{(\beta + 1)R_C + R_{BP}} \frac{V_{CC}}{V_{CE}} = 0.926$	
$S_{\beta}^{V_{CE}} = \frac{\partial V_{CE}}{\partial \beta} \frac{\beta}{V_{CE}}$	$= -(V_{CC} - V_{BE}) \frac{R_C}{R_B} \frac{\beta}{V_{CE}} = -1.39$	$= -\frac{V_{CE} - V_{BE}}{\beta + 1 + \frac{R_{BP}}{R_C}} \frac{\beta}{V_{CE}} = -0.502$	
$S_{R_C}^{V_{CE}} = \frac{\partial V_{CE}}{\partial R_C} \frac{R_C}{V_{CE}}$	$= -(V_{CC} - V_{BE}) \frac{\beta}{R_B} \frac{R_C}{V_{CE}} = -1.39$	$= -\frac{V_{CE} - V_{BE}}{R_C + \frac{R_{BP}}{\beta + 1}} \frac{R_C}{V_{CE}} = -0.503$	
$S_{R_B}^{V_{CE}} = \frac{\partial V_{CE}}{\partial R_B} \frac{R_B}{V_{CE}}$	$= (V_{CC} - V_{BE}) \frac{\beta R_C}{R_B^2} \frac{R_B}{V_{CE}} = 1.39$	$= \frac{V_{CC} - V_{CE}}{(\beta + 1)R_C + R_{BP}} \frac{R_{BP}}{V_{CE}} = 0.503$	

负反馈使得 不确定性降低

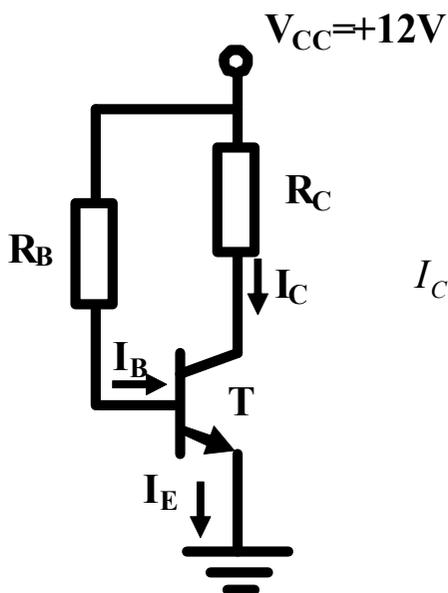
$\beta=300$



	一般偏置	串串负反馈稳定输出电流	串串负反馈
输出电流 I_C	$I_C = \beta \frac{V_{CC} - V_{BE}}{R_B} = 1.03mA$	$I_C = \frac{\eta V_{CC} - V_{BE}}{R_E + (R_{BB} + R_E)/\beta} = 1.03mA$	
$S_{V_{CC}}^{I_C} = \frac{\partial I_C}{\partial V_{CC}} \frac{V_{CC}}{I_C}$	$= \frac{\beta}{R_B} \frac{V_{CC}}{I_C} = 1.06$	$= \frac{\eta}{R_E + (R_{BB} + R_E)/\beta} \frac{V_{CC}}{I_C} = 1.30$	
$S_{\beta}^{I_C} = \frac{\partial I_C}{\partial \beta} \frac{\beta}{I_C}$	$= \frac{V_{CC} - V_{BE}}{R_B} \frac{\beta}{I_C} = 1$	$= \frac{(R_{BB} + R_E)/\beta^2}{R_E + (R_{BB} + R_E)/\beta} I_C \frac{\beta}{I_C} = 0.0167$	
$S_{R_C}^{I_C} = \frac{\partial I_C}{\partial R_C} \frac{R_C}{I_C}$	$= 0$ 未考虑厄利效应	$= 0$ 未考虑厄利效应	
$S_{R_B}^{I_C} = \frac{\partial I_C}{\partial R_B} \frac{R_B}{I_C}$	$= -\beta \frac{V_{CC} - V_{BE}}{R_B^2} \frac{R_B}{I_C} = -1$	$S_{R_{B1}}^{I_C} = \frac{\partial I_C}{\partial R_{B1}} \frac{R_{B1}}{I_C} = -0.982; S_{R_{B2}}^{I_C} = \frac{\partial I_C}{\partial R_{B2}} \frac{R_{B2}}{I_C} = 0.968$	

60倍

低灵敏度代表稳定的系统

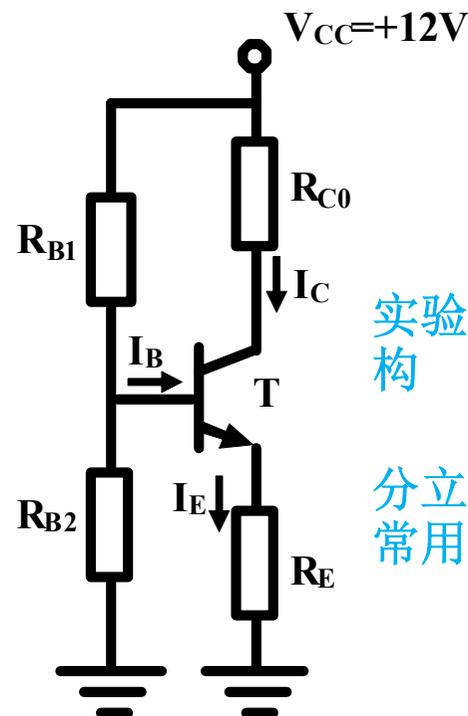


$$S_{x_i}^y = \frac{x_i}{y} \frac{\partial y}{\partial x_i}$$

$$I_C = \beta \frac{V_{CC} - V_{BE}}{R_B} = 1.03mA$$

1.03mA是系统输出的设计值

$$I_C = \frac{\eta V_{CC} - V_{BE}}{R_E + (R_{BB} + R_E)/\beta} = 1.03mA$$



实验常用结构

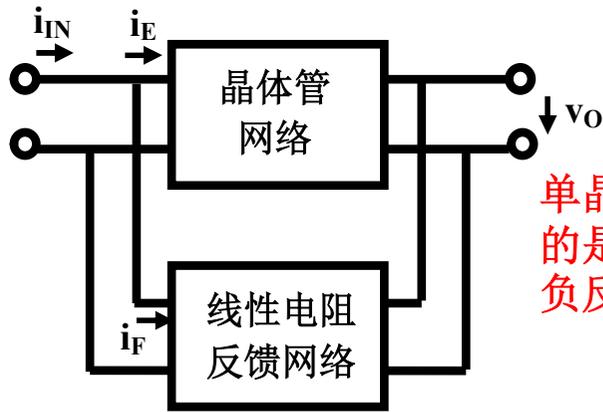
分立放大器常用结构

$$S_{\beta}^{I_C} = \frac{\beta}{I_C} \frac{\partial I_C}{\partial \beta} = 1$$

$$S_{\beta}^{I_C} = \frac{\beta}{I_C} \frac{\partial I_C}{\partial \beta} = \frac{(R_{BB} + R_E)/\beta}{R_E + (R_{BB} + R_E)/\beta} = 0.0167$$

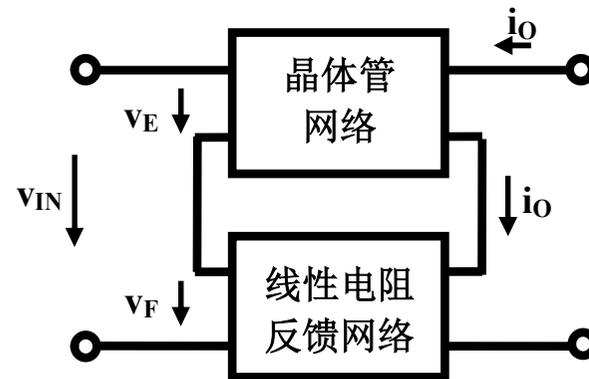
β : 极度不确定, 设计时应确保其灵敏度很小, 则系统稳定
串联负反馈使得晶体管电流增益不确定导致的直流工作点不稳定性大大降低

负反馈连接方式总结

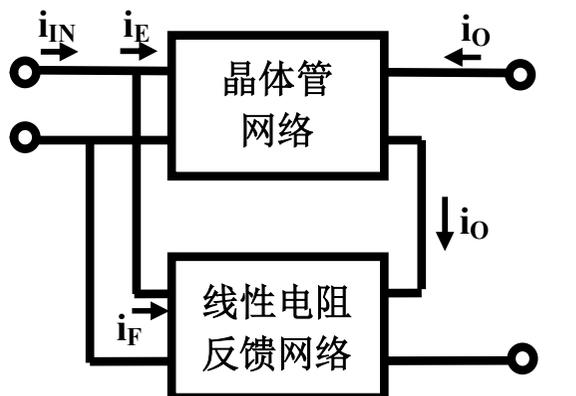


并并负反馈

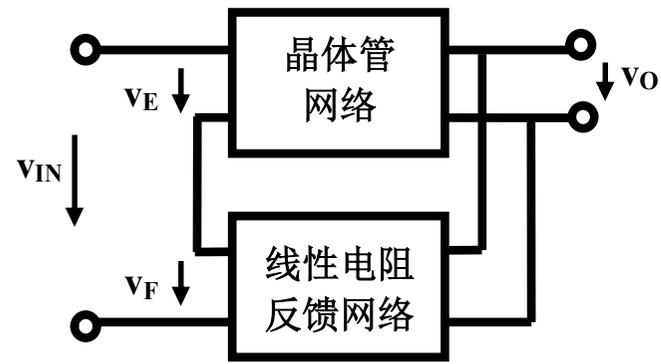
单晶体管：常见的是串串和并并负反馈



串串负反馈



并串负反馈



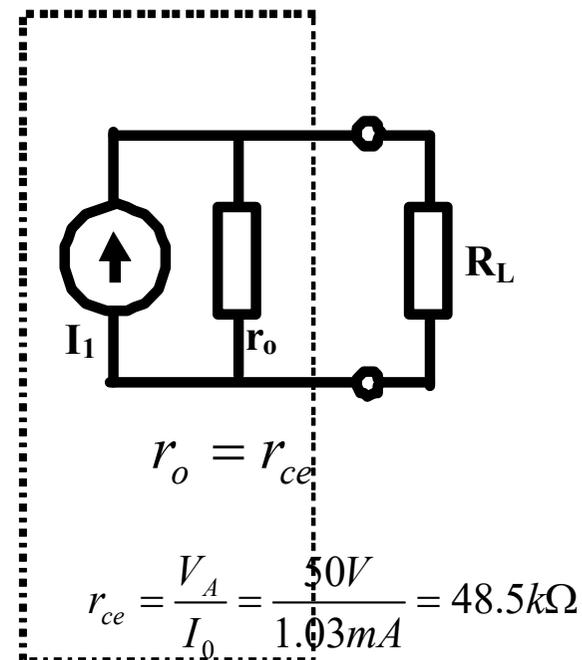
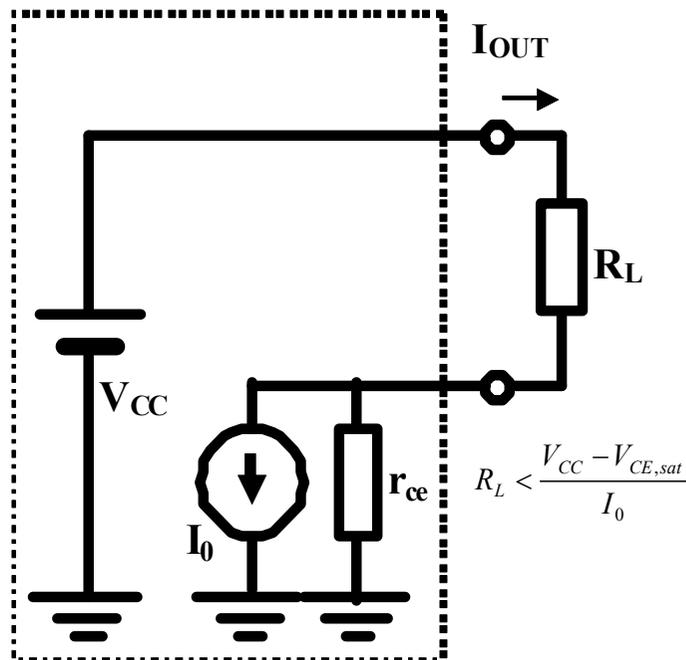
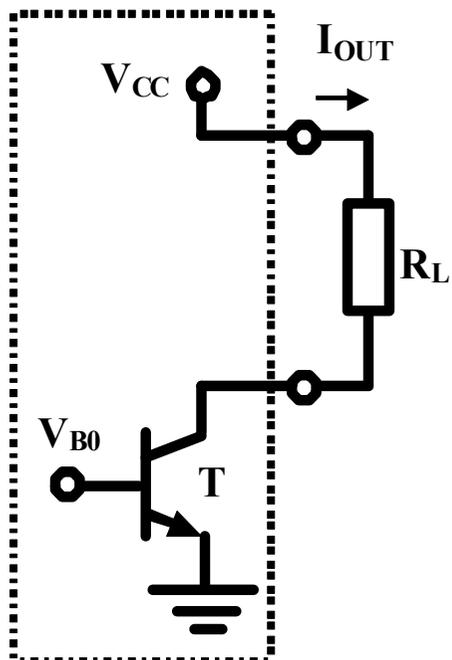
串并负反馈

复杂晶体管网络：四种负反馈都有应用，如运放电路就是复杂晶体管网络：本学期最后两节课讨论运放的4种负反馈连接形成的4种接近理想的受控源

三、BJT电流源

$$I_1 = I_0 + \frac{V_{CC}}{r_{ce}}$$

$$I_{out} = I_1 \frac{r_{ce}}{r_{ce} + R_L} = \frac{r_{ce}}{r_{ce} + R_L} I_0 + \frac{V_{CC}}{r_{ce} + R_L}$$



只要晶体管工作在恒流区，其CE端口对外即可等效为电流源

希望输出电阻越大越好
越接近理想恒流源

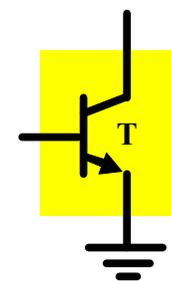
$$I_C = \beta A_J J_{BS0} \cdot \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) = I_0 \left(1 + \frac{V_{CE}}{V_A} \right) = I_0 + \frac{I_0}{V_A} V_{CE} = I_0 + \frac{V_{CE}}{r_{ce}}$$

等效电流源内导

$$I_C = f(V_{BE}, V_{CE}) = I_{CS0} \cdot \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right)$$

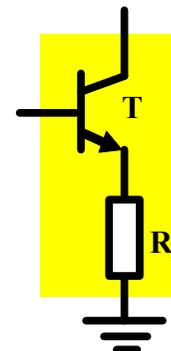
$$g_o = \frac{\partial I_C}{\partial V_{CE}} = \frac{\partial f(V_{BE}, V_{CE})}{\partial V_{CE}} = \frac{\partial f}{\partial V_{CE}} = \frac{I_0}{V_A} = \frac{1}{r_{ce}} = g_{ce}$$

未加负反馈



$$I_C = f(V_{BE}, V_{CE}) = f(V_B - I_C R_E, V_C - I_C R_E)$$

加串联负反馈电阻



$$g_o = \frac{\partial I_C}{\partial V_C} = \frac{\partial f(V_{BE}, V_{CE})}{\partial V_C} = \frac{\partial f}{\partial V_{BE}} \frac{\partial V_{BE}}{\partial V_C} + \frac{\partial f}{\partial V_{CE}} \frac{\partial V_{CE}}{\partial V_C}$$

$$= g_m \cdot \left(-\frac{\partial I_C}{\partial V_C} R_E \right) + g_{ce} \cdot \left(1 - \frac{\partial I_C}{\partial V_C} R_E \right) = -g_m R_E g_o + g_{ce} (1 - g_o R_E)$$

微分跨导增益

$$g_o = \frac{g_{ce}}{1 + (g_m + g_{ce})R_E} \approx \frac{g_{ce}}{1 + g_m R_E}$$

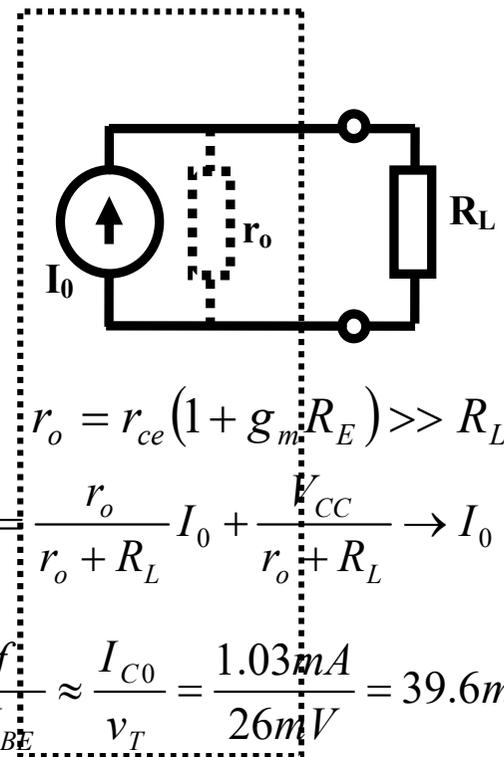
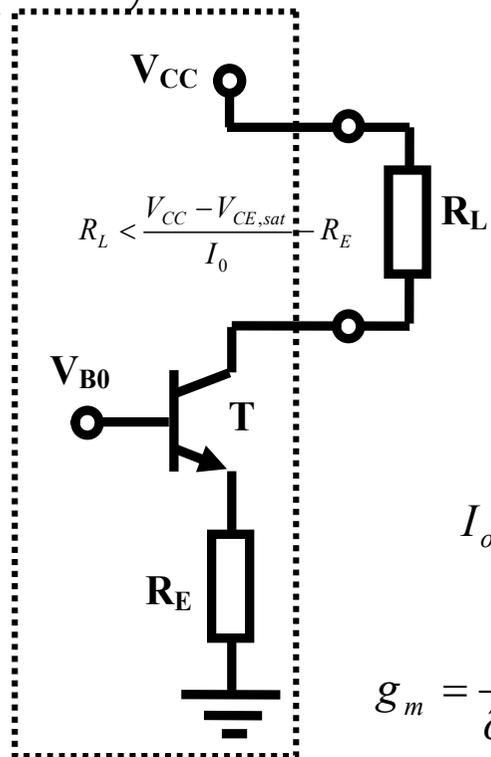
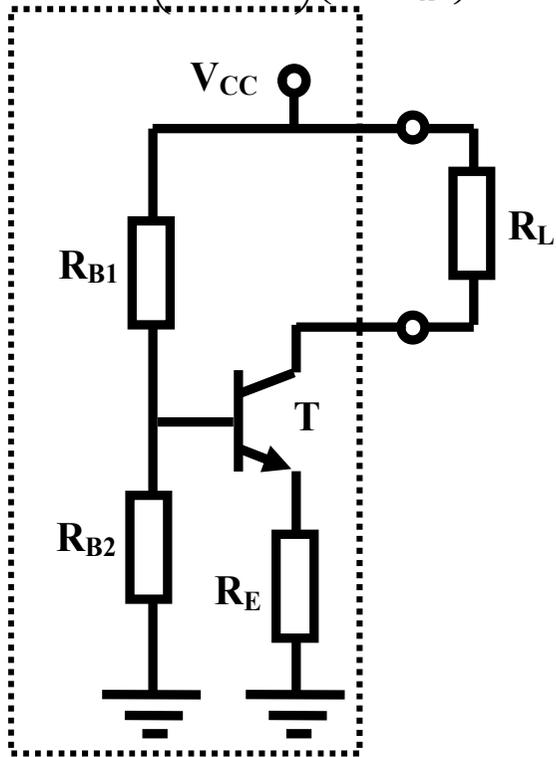
$$r_o \approx r_{ce} (1 + g_m R_E)$$

等效电流源内阻增加，
更加接近于理想恒流源

负反馈使得等效电流源更接近理想

$$i_C = \beta A_J J_{BS0} \left(e^{\frac{v_{BE}}{v_T}} - 1 \right) \left(1 + \frac{v_{CE}}{V_A} \right) \approx I_{CS0} \left(e^{\frac{v_{BE}}{v_T}} - 1 \right)$$

少了2.3V的输出电压空间



$$r_o = r_{ce} (1 + g_m R_E) \gg R_L$$

$$I_{out} = \frac{r_o}{r_o + R_L} I_0 + \frac{V_{CC}}{r_o + R_L} \rightarrow I_0$$

$$g_m = \frac{\partial f}{\partial V_{BE}} \approx \frac{I_{C0}}{v_T} = \frac{1.03mA}{26mV} = 39.6mS$$

$$r_o = (1 + g_m R_E) r_{ce} = (1 + 39.6mS \times 2.2k\Omega) \times 48.5k\Omega = 88 \times 48.5k\Omega = 4.28M\Omega$$

负反馈使得电流源的温度稳定性提高

$$I_C = \beta A_J J_{BS0} \cdot \left(e^{\frac{V_{BE}}{v_T}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) = I_0 \left(1 + \frac{V_{CE}}{V_A} \right) = I_0 + \frac{I_0}{V_A} V_{CE} = I_0 + \frac{V_{CE}}{r_{ce}}$$

$$I_0 = \beta A_J J_{BS0} \cdot \left(e^{\frac{V_{BE}}{v_T}} - 1 \right) \quad v_T = \frac{kT}{q}$$

$$S_T^{I_C} = \frac{\partial I_C}{\partial T} \frac{T}{I_C} \approx -\frac{V_{BE}}{v_T} \approx -27$$

$$V_{BE} = V_{B0}$$

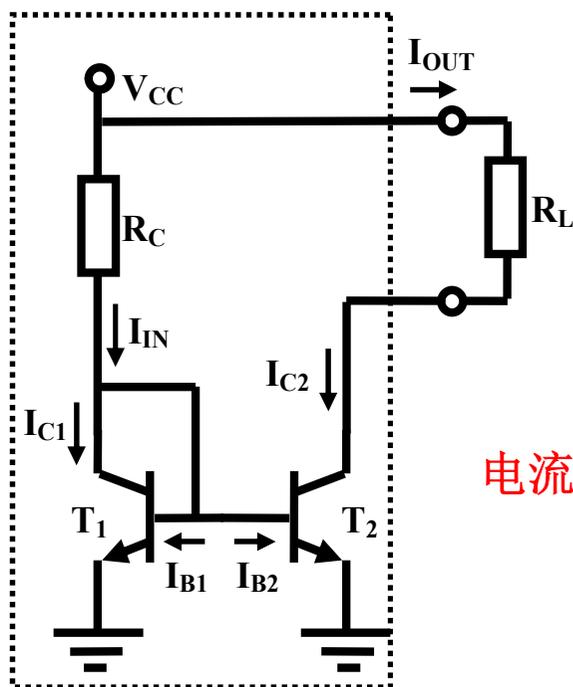
直接偏置温度敏感度极高

$$S_T^{I_C} = \frac{\partial I_C}{\partial T} \frac{T}{I_C} \approx -\frac{V_{BE}/v_T}{1 + g_m R_E} \approx -0.3$$

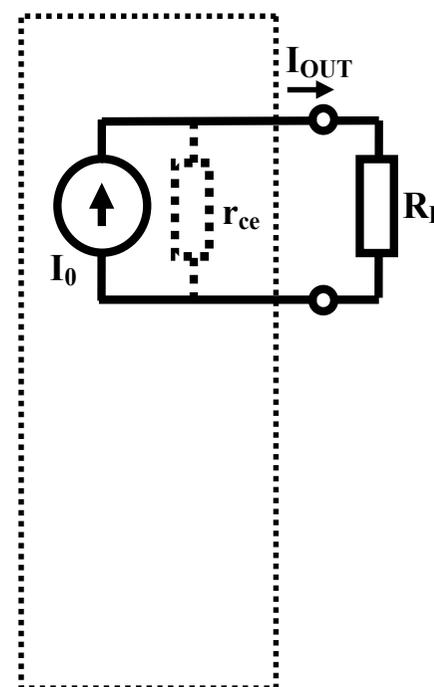
$$V_{BE} = V_B - I_C R_E$$

串串负反馈降低了温度敏感度

电流镜电路：同属性晶体管补偿



电流镜

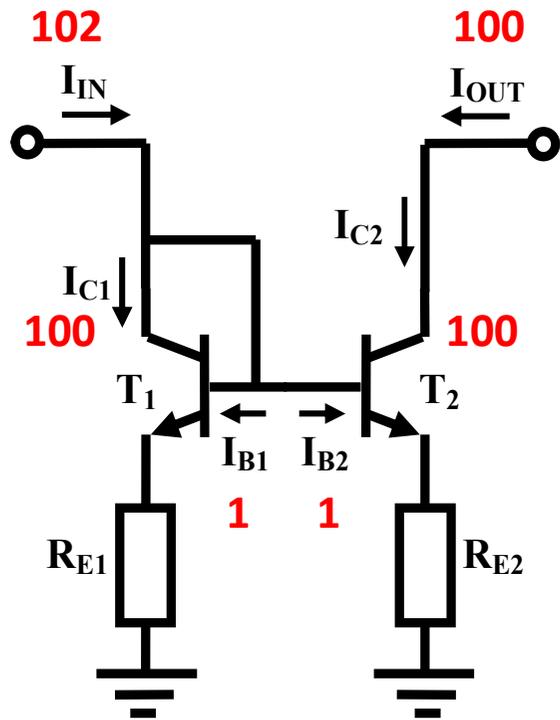


结面积
决定电
流关系

$$G_I = \frac{I_{OUT}}{I_{IN}} = \frac{I_{C2}}{I_{C1} + I_{B1} + I_{B2}} \approx \frac{I_{C2}}{I_{C1}} = \frac{\beta A_{J2} J_{BS0} \cdot \left(e^{\frac{V_{BE2}}{v_T}} - 1 \right) \left(1 + \frac{V_{CE2}}{V_A} \right)}{\beta A_{J1} J_{BS0} \cdot \left(e^{\frac{V_{BE1}}{v_T}} - 1 \right) \left(1 + \frac{V_{CE1}}{V_A} \right)} \approx \frac{A_{J2}}{A_{J1}}$$

提高两条支路的匹配程度

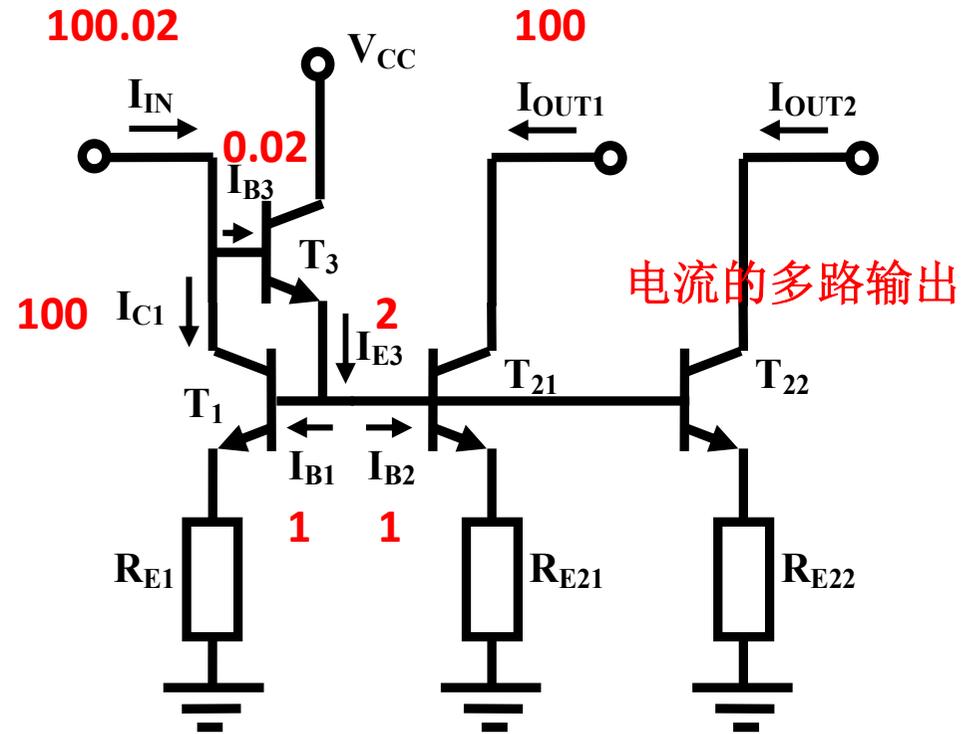
提高电流增益，提高输出电阻（等效厄利电压）



$$I_{OUT} = I_{C2}$$

$$r_o = r_{ce2} (1 + g_{m2} R_{E2})$$

提高了输出电阻

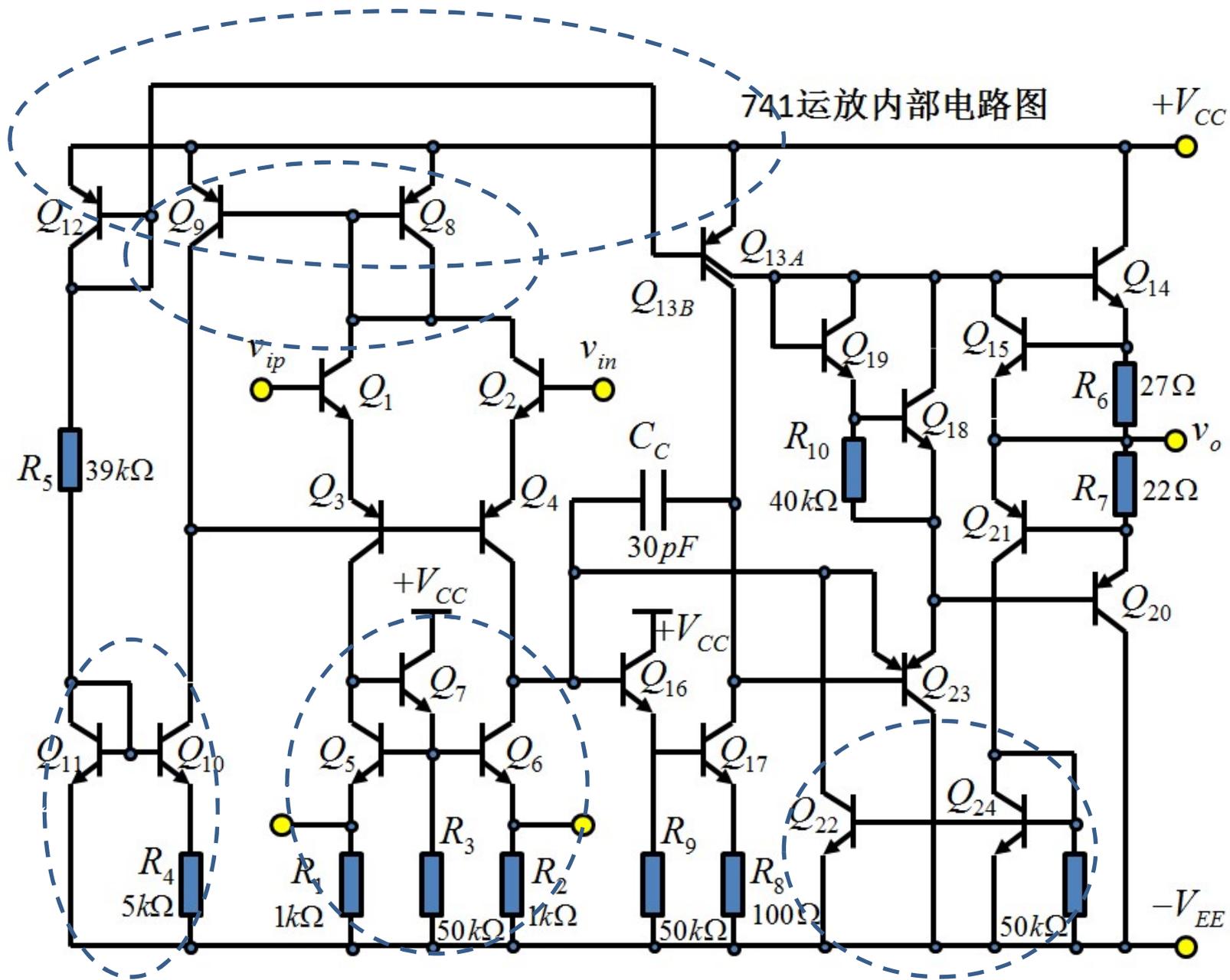


$$I_{IN} = I_{C1} + I_{B3} = I_{C1} + \frac{I_{E3}}{\beta_3 + 1} = I_{C1} + \frac{I_{B1} + I_{B2}}{\beta_3 + 1}$$

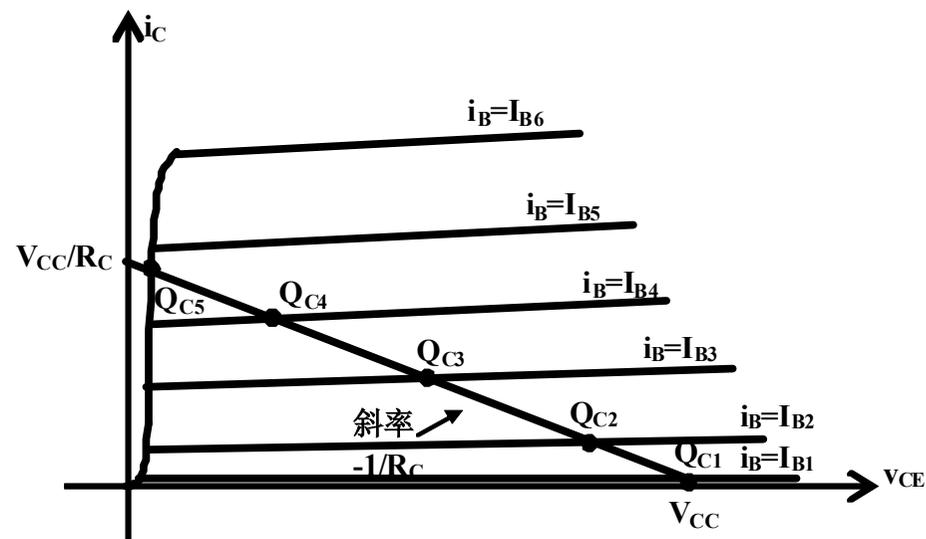
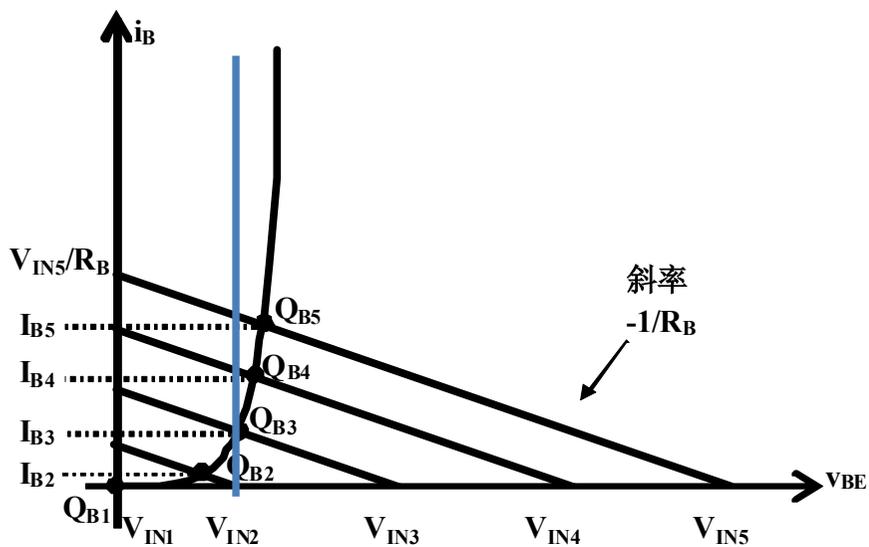
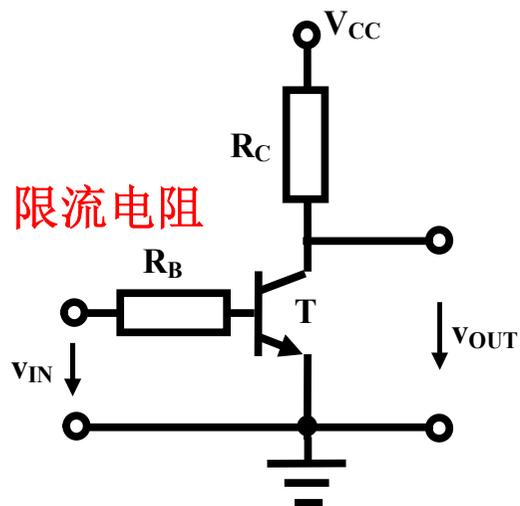
$$= I_{C1} + \frac{1}{\beta_1(\beta_3 + 1)} I_{C1} + \frac{1}{\beta_2(\beta_3 + 1)} I_{C2}$$

提高了等效电流增益

电流镜是模拟集成电路的特征电路



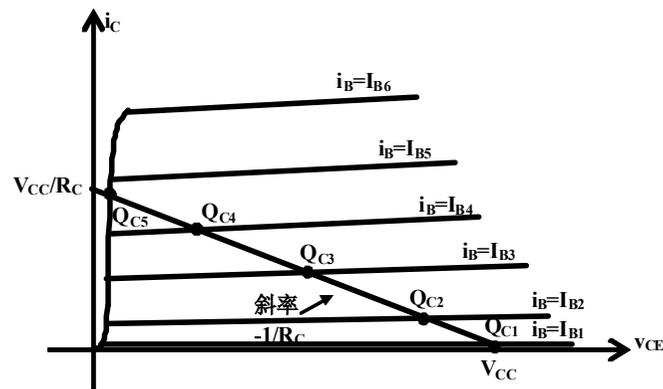
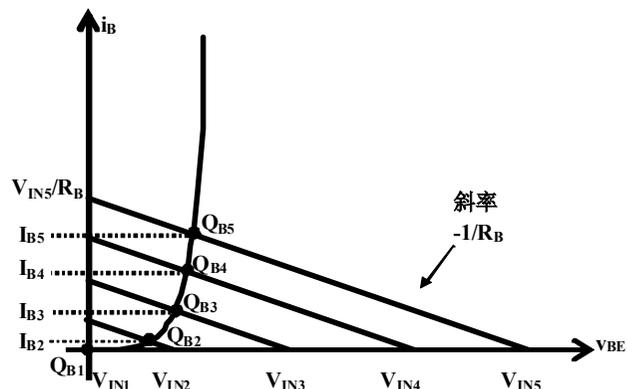
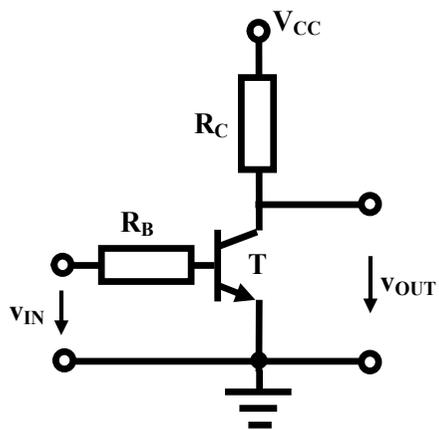
四、BJT反相器



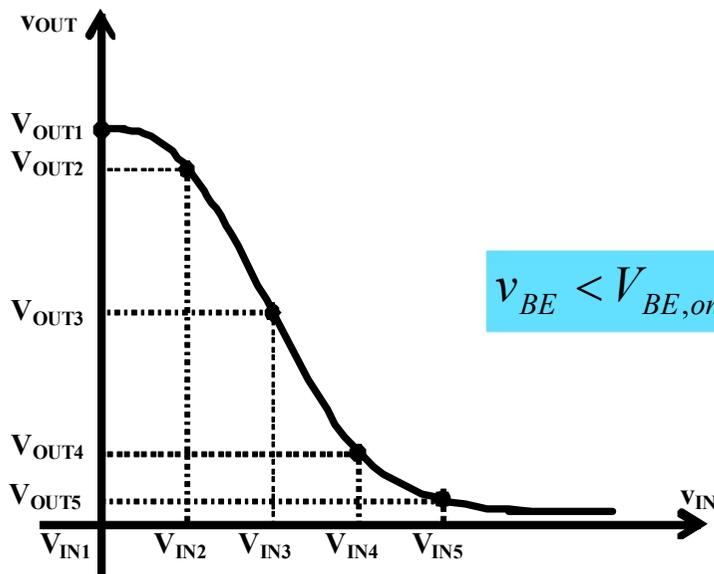
$$i_B = \frac{v_{IN} - v_{BE}}{R_B} \stackrel{\text{启动导通后}}{\approx} \frac{v_{IN} - 0.7}{R_B}$$

负载线方程
戴维南源约束条件

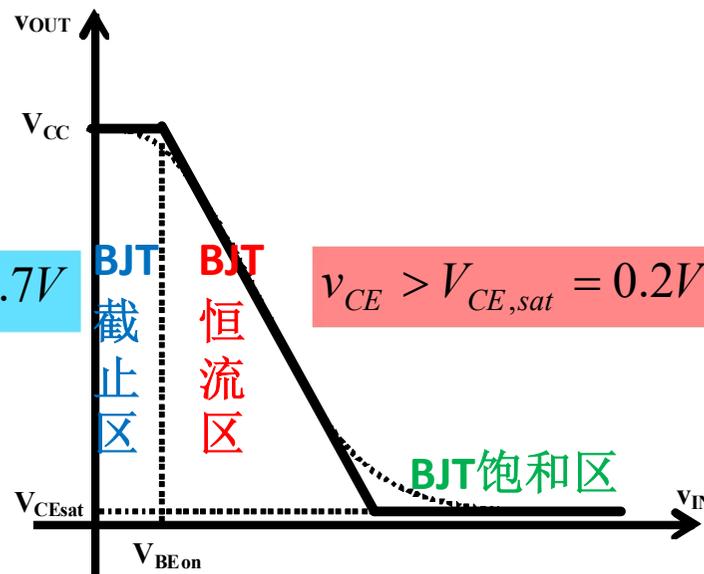
$$i_C = \frac{V_{DD} - v_{CE}}{R_C}$$



反相特性



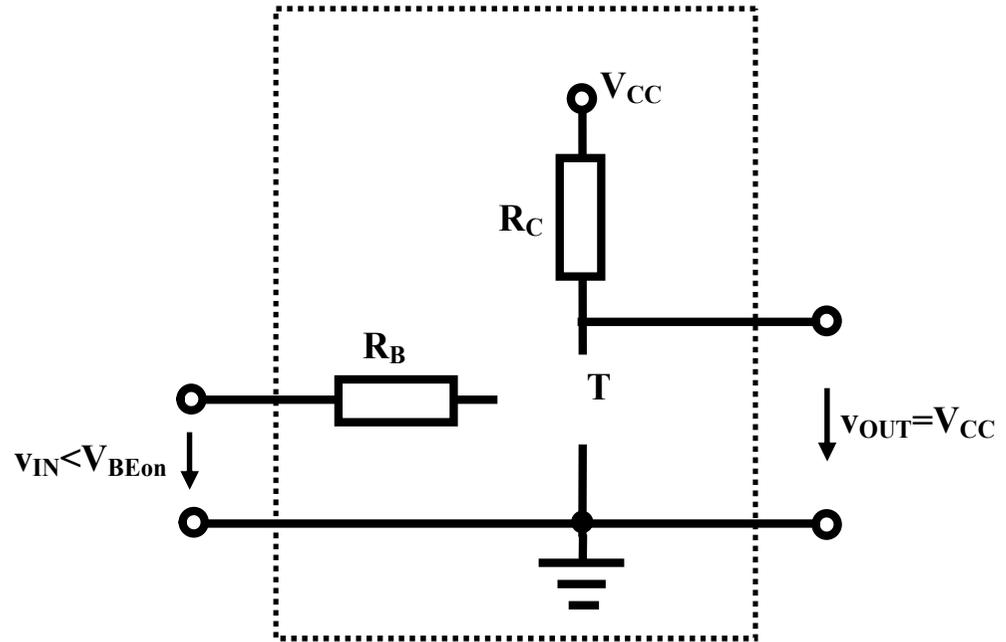
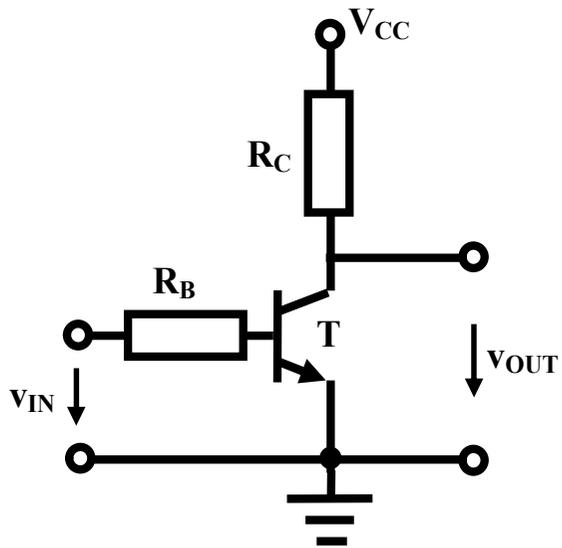
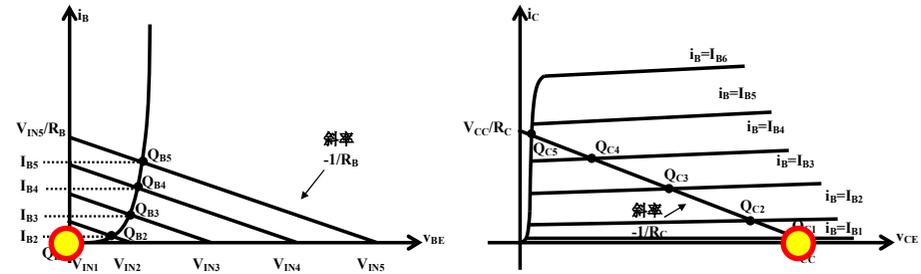
$v_{BE} < V_{BE,on} = 0.7V$



$v_{CE} > V_{CE,sat} = 0.2V$

$v_{CE} = V_{CE,sat} = 0.2V$

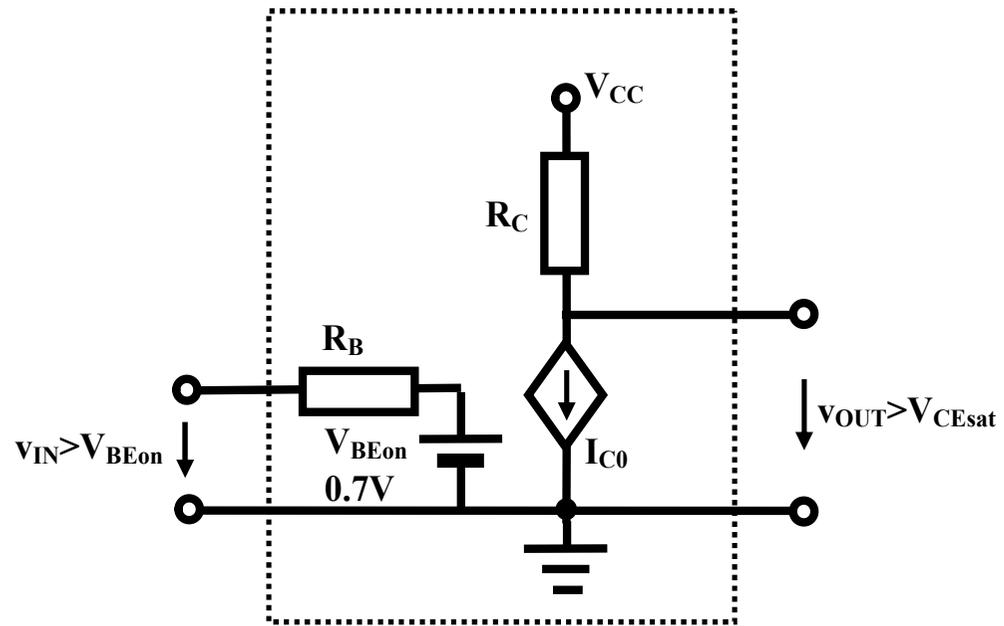
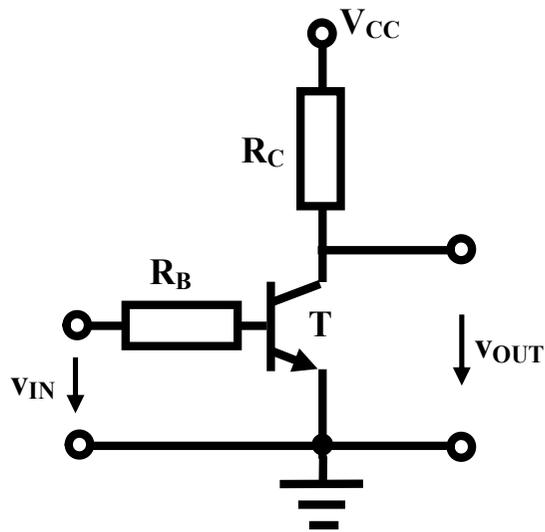
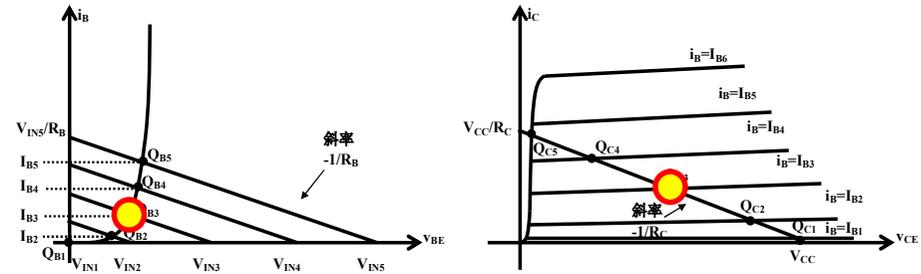
分段折线分析 截止区



$$v_{IN} < V_{BEon} = 0.7V$$

$$v_{OUT} = V_{CC}$$

分段折线分析 恒流区



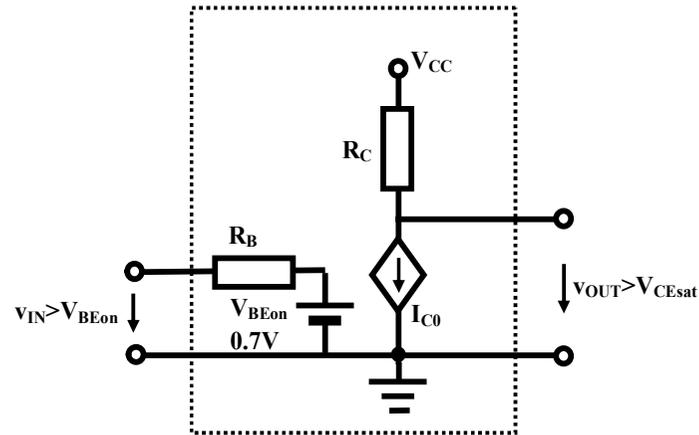
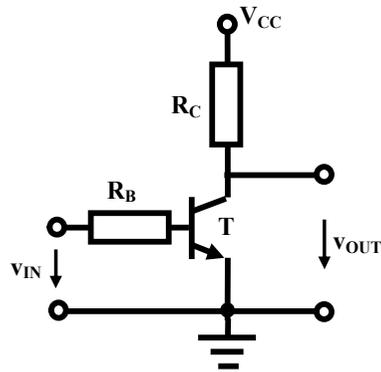
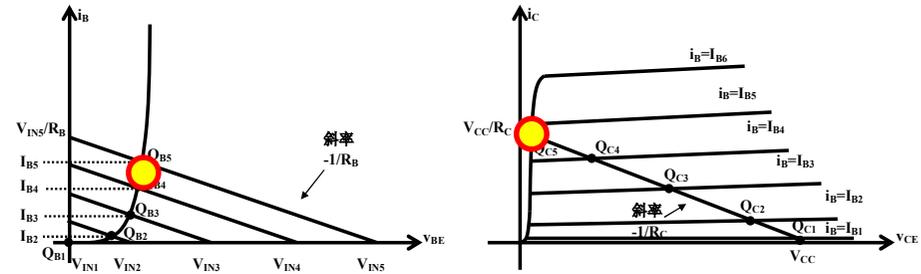
$$v_{IN} > V_{BEon} = 0.7V$$

$$I_{C0} = \beta I_{B0} = \beta \frac{v_{IN} - V_{BEon}}{R_B}$$

$$v_{OUT} = V_{CC} - I_{C0} R_C = V_{CC} - \beta \frac{v_{IN} - V_{BEon}}{R_B} R_C = V_{CC} + \beta \frac{R_C}{R_B} V_{BEon} - \beta \frac{R_C}{R_B} v_{IN}$$

分段折线分析

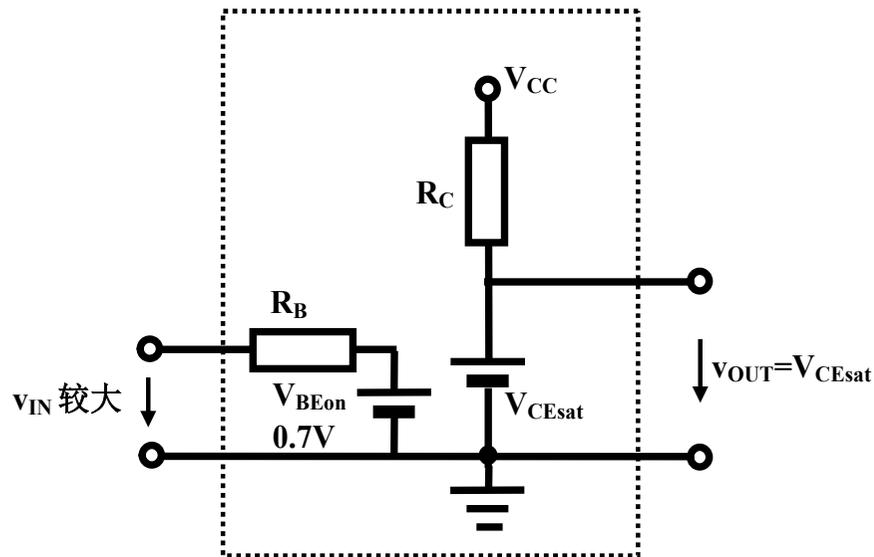
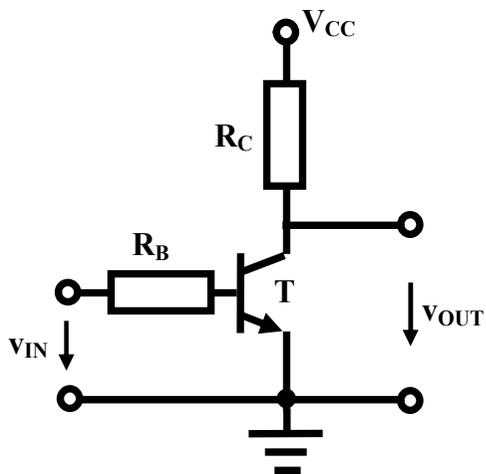
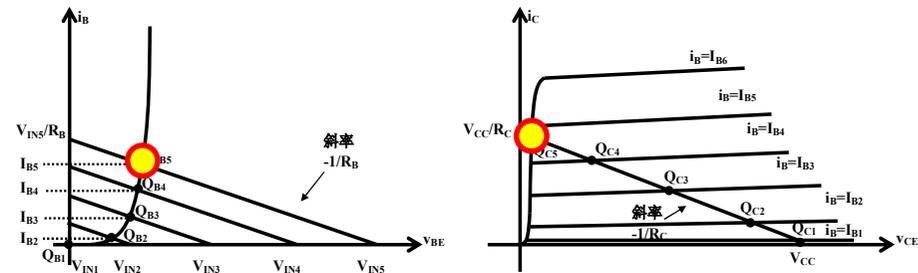
恒流区与饱和区分界



$$v_{OUT} = V_{CC} + \beta \frac{R_C}{R_B} V_{BEon} - \beta \frac{R_C}{R_B} v_{IN,s} = V_{CE,sat}$$

$$v_{IN,s} = \frac{V_{CC} + \beta \frac{R_C}{R_B} V_{BEon} - V_{CE,sat}}{\beta \frac{R_C}{R_B}} = \frac{V_{CC} - V_{CE,sat}}{\beta \frac{R_C}{R_B}} + V_{BEon}$$

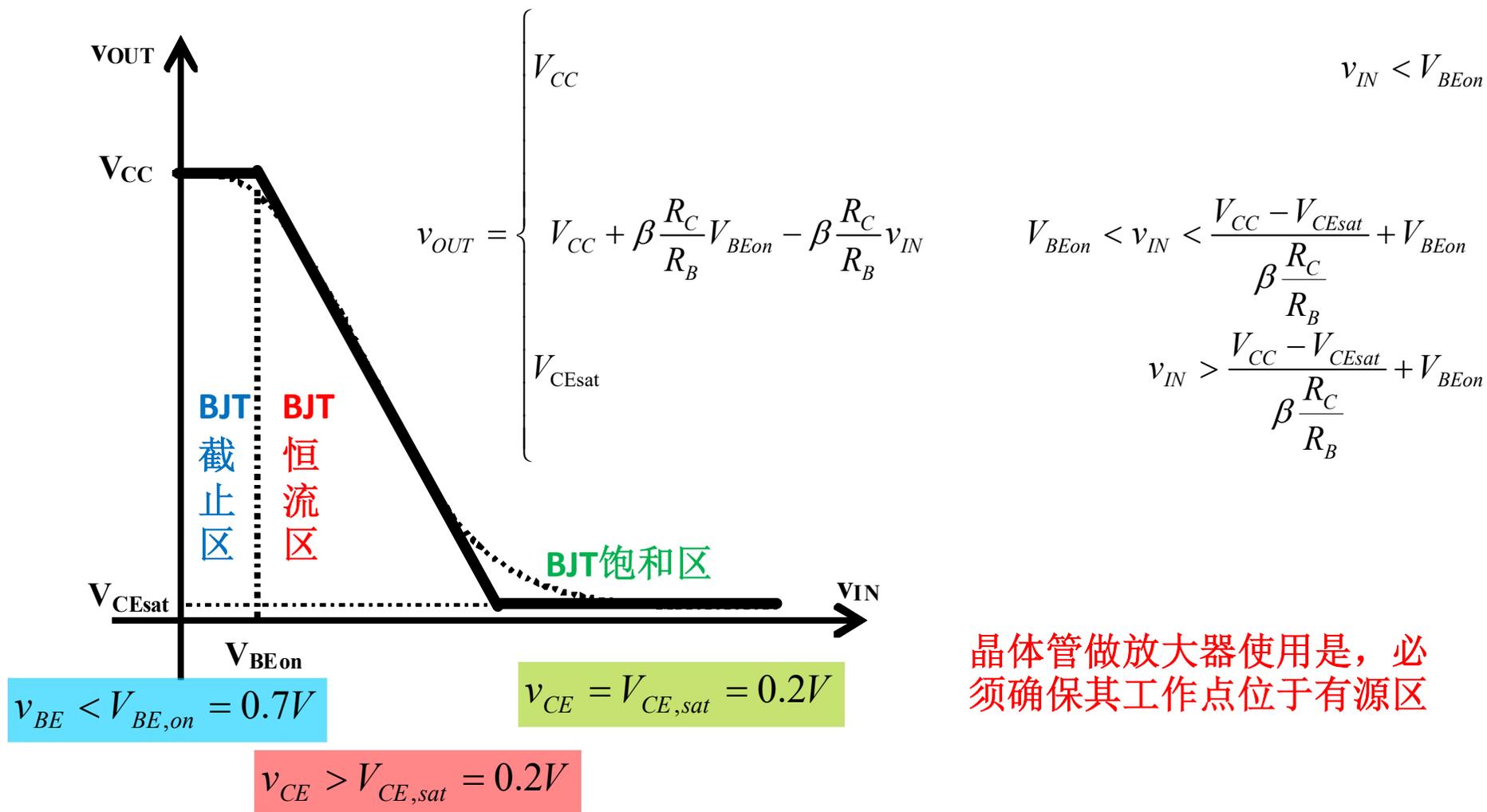
分段折线分析 饱和区



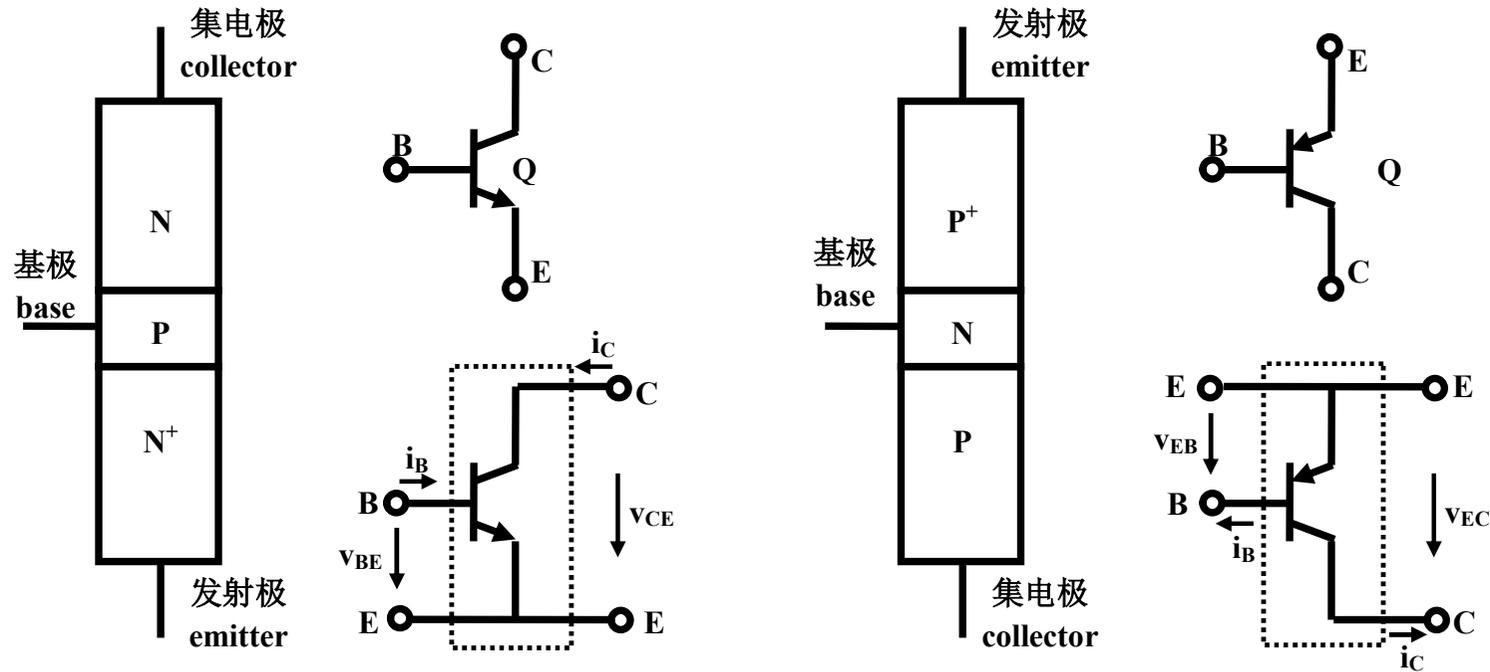
$$v_{IN} > v_{IN,s} = \frac{V_{CC} - V_{CE,sat}}{\beta \frac{R_C}{R_B}} + V_{BEon}$$

$$v_{OUT} = V_{CE,sat}$$

反相特性的分段折线表述



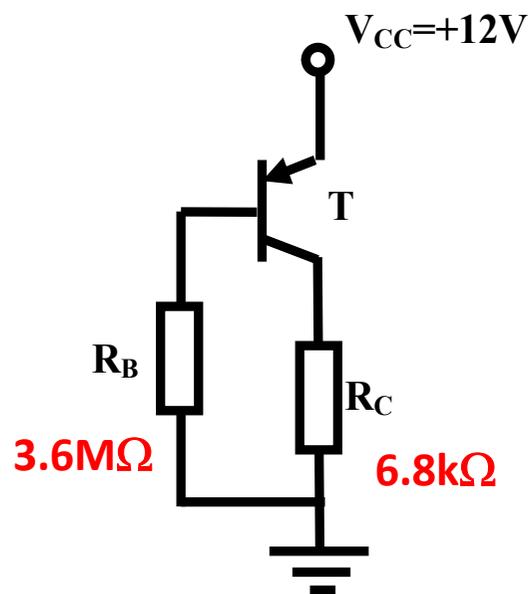
作业1 NPN和PNP



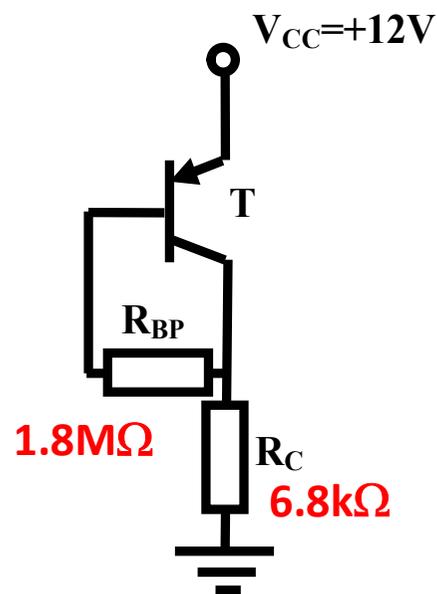
列表对比：（1）结构，（2）电路符号，（3）二端口定义
（4）有源区元件约束，（5）分段线性电路模型

作业2：分立PNP-BJT的直流偏置

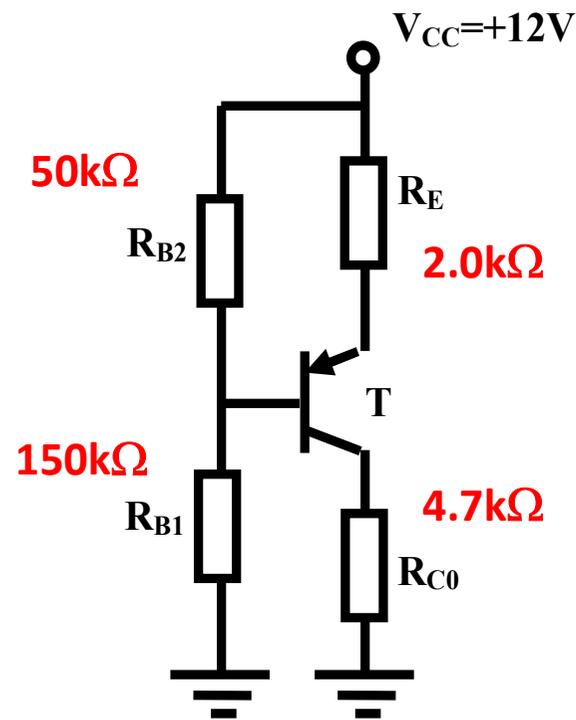
$\beta=150-400$



一般偏置



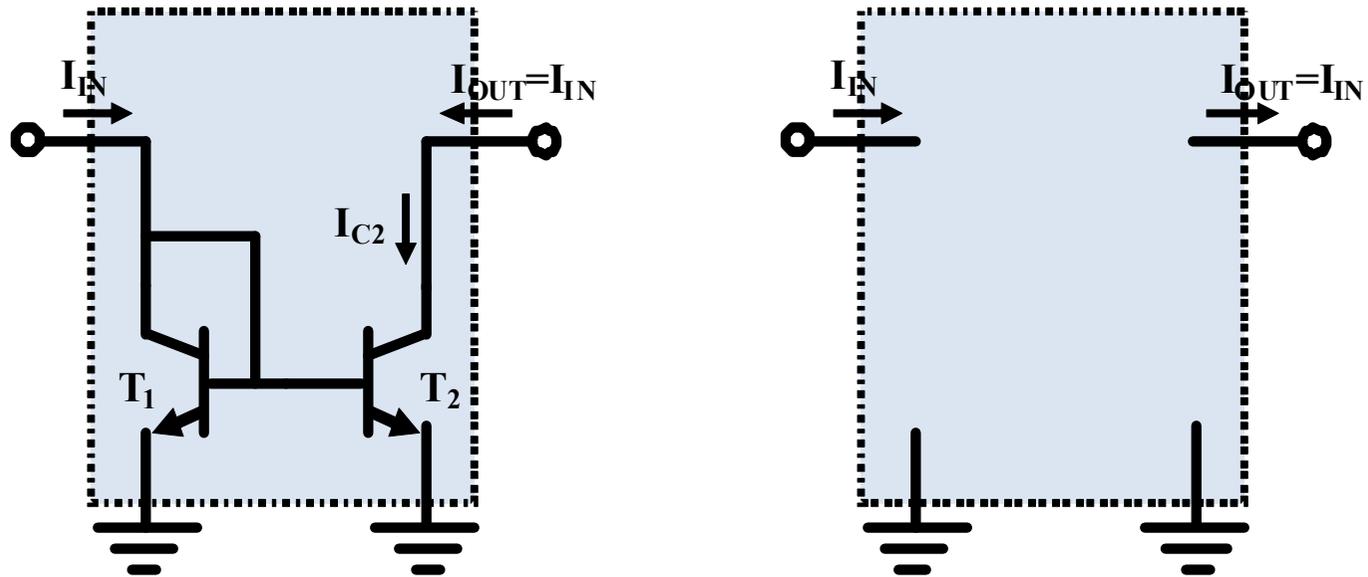
并联负反馈偏置



串联负反馈偏置
分压偏置

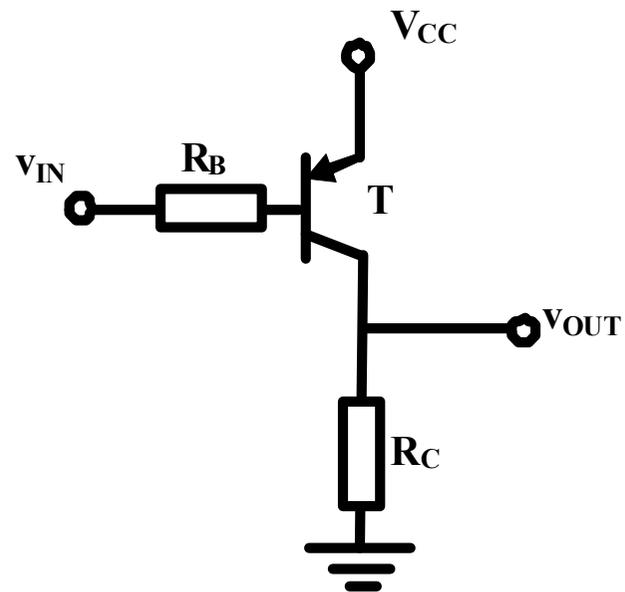
分析上述三个电路的BJT的直流工作点： $I_C=?V_{EC}=?$ 说明负反馈可以稳定直流工作点

作业3： 电流镜电流反向



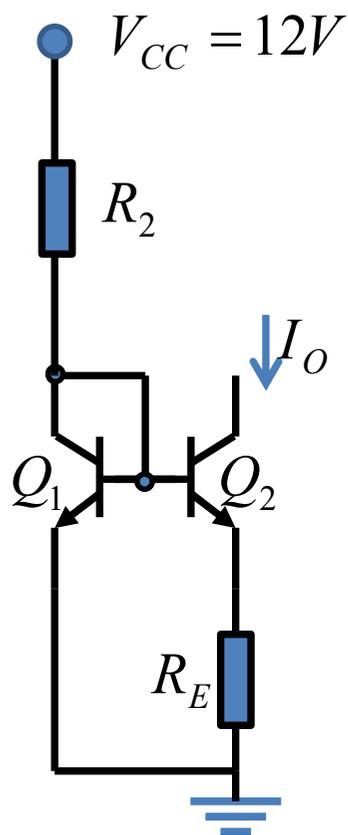
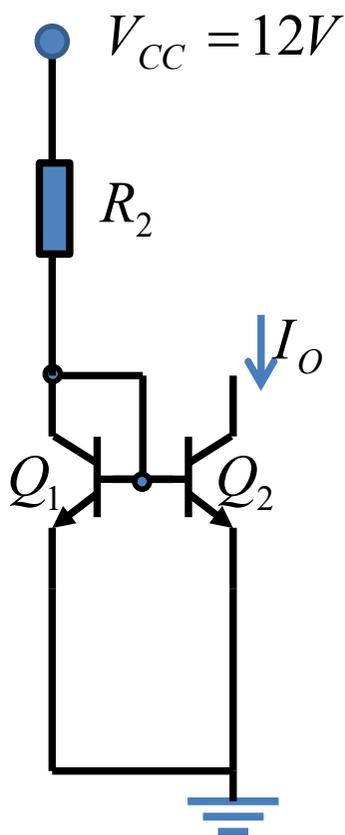
设计电路：使得流出电流等于流入电流

作业4：PNP反相器



用分段折线模型分析，画出其反相特性曲线

习题5 Widlar电流镜

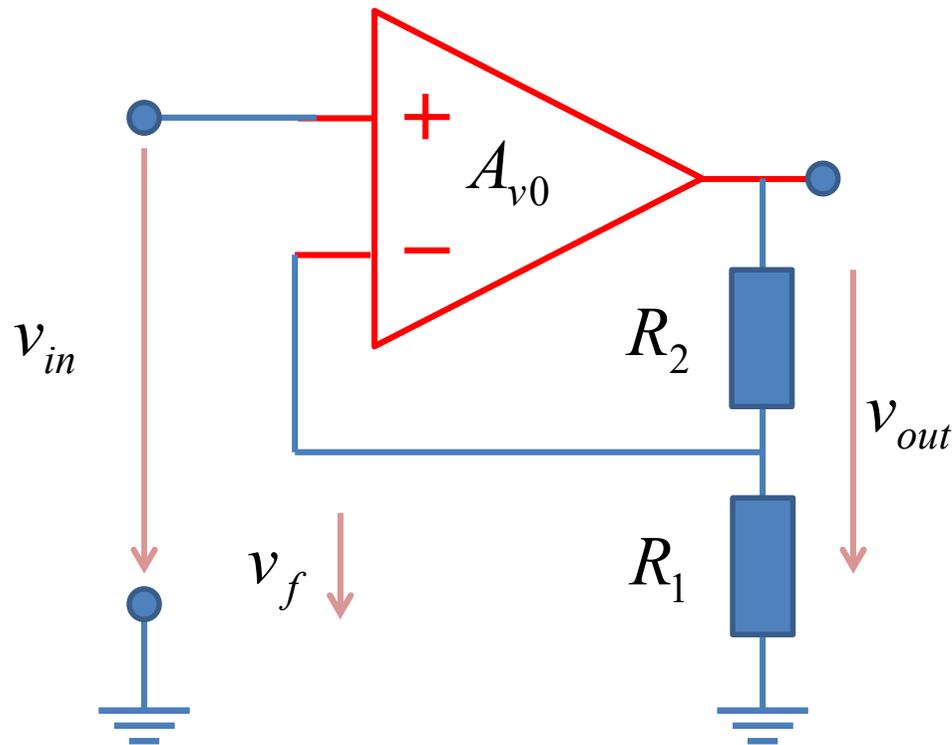


我们希望这两个电流镜都能够产生 $12\mu\text{A}$ 的电流输出，请给出你的设计：给出电阻阻值

假设晶体管在 $I_C=1\text{mA}$ 时的 V_{BE} 压降为 0.7V

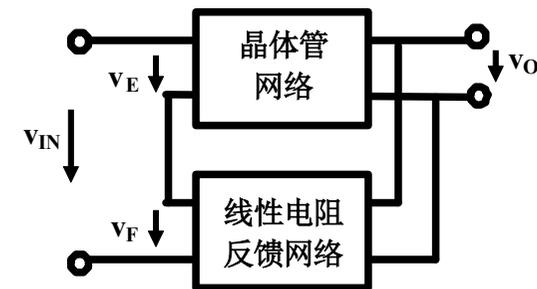
通过研究对比，说明微电流镜在产生微电流时较一般的电流源有哪些优点。

作业6 负反馈 (选作)



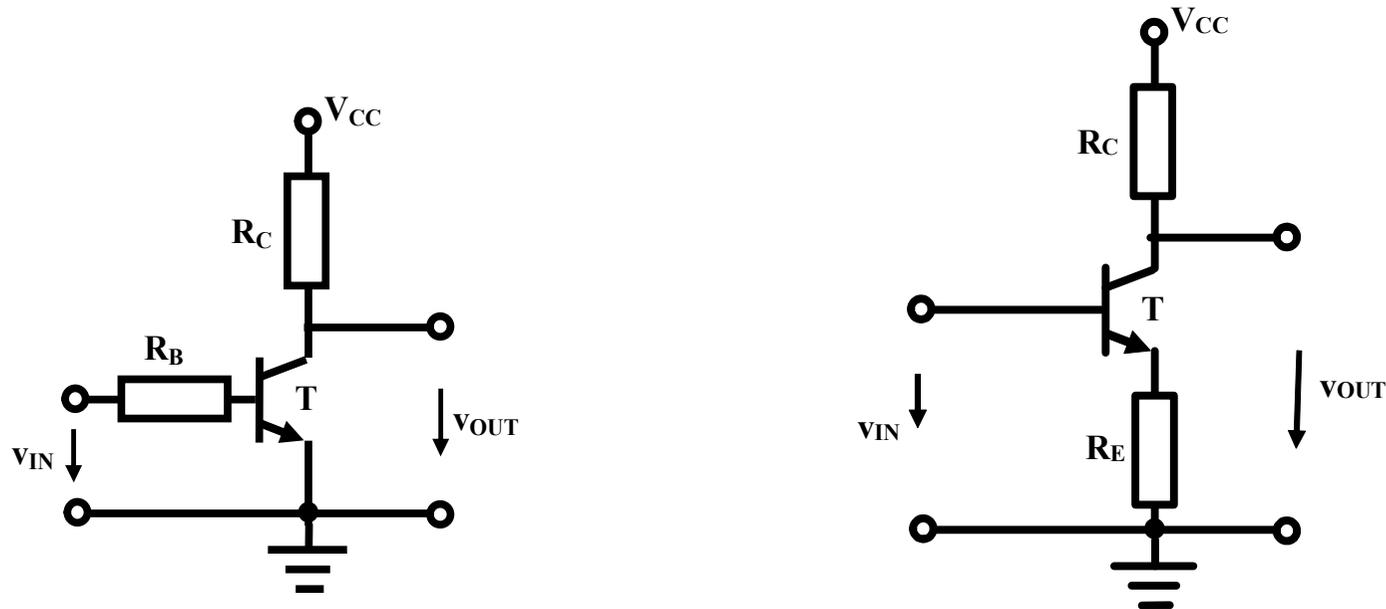
- **选作**: 说明这是一个串并负反馈连接方式, 故而形成的是接近理想的压控压源

- 给出两个网络的二端口网络参量
- 串并连接h相加
- **h求逆得g**
 - 接近理想压控压源; $g_{11}, g_{22}, g_{12} \rightarrow 0$
 - g_{21} 由反馈网络决定



串并负反馈

CAD仿真



1/请设计外围电阻，使得晶体管工作于恒流区时，输入电压输出电压转移特性曲线斜率为-10

2/用分段折线法分析输入电压输出电压转移特性曲线，并仿真确认，你的分析和仿真结果有无差别？