

电子电路与系统基础(B2)---非线性电路

## 第4讲：BJT

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# B 班课程 内容安排

第一学期：线性	序号	第二学期：非线性
电路定律	1	器件基础
电阻电源	2	二极管
电容电感	3	<b>MOSFET</b>
信号分析	<b>4</b>	<b>BJT</b>
分压分流	5	反相电路
正弦稳态	6	数字门
时频特性	7	放大器
期中复习	8	期中复习
<b>RLC</b> 二阶	9	负反馈
二阶时频	10	差分放大
受控源	11	频率特性
网络参量	12	正反馈
典型网络	13	振荡器
作业选讲	14	作业选讲
期末复习	15	期末复习

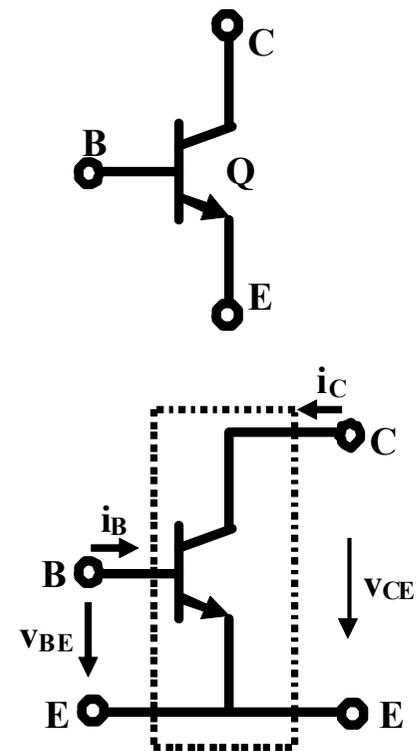
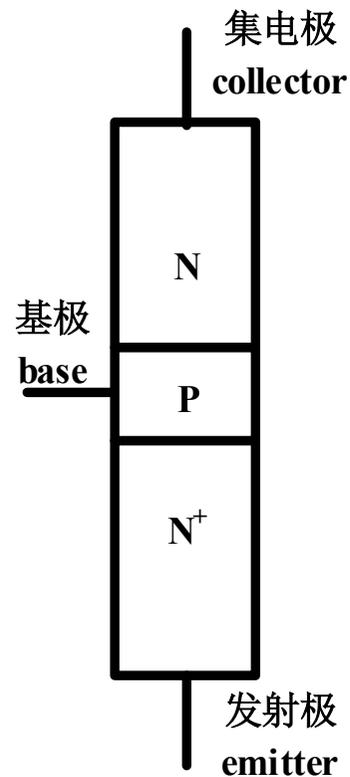
# BJT 内容

- BJT结构及受控原理
  - 解释如此的控制特性是如何形成的
- 分段折线电路模型
- 分压偏置电路
  - 负反馈
- 电流镜
- 作业选讲

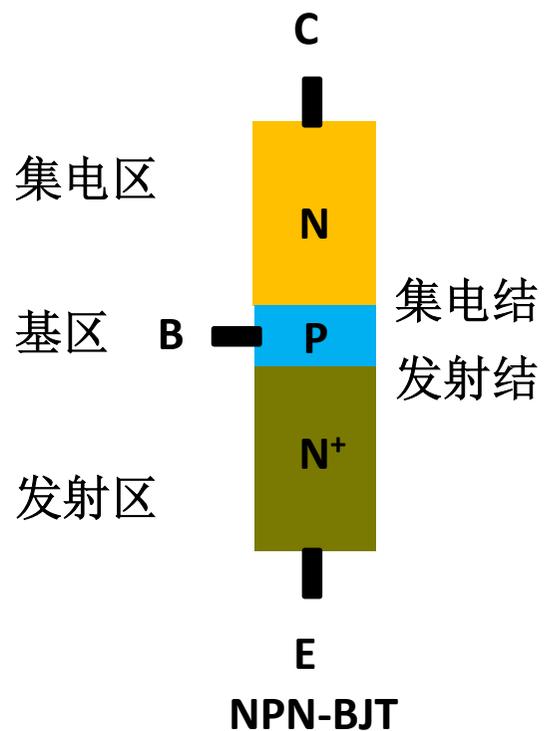
# 一、BJT结构

## ■ 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

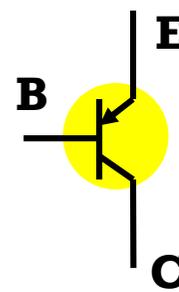
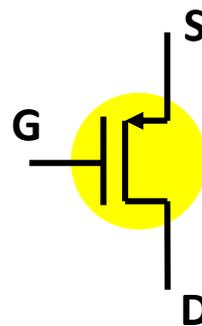
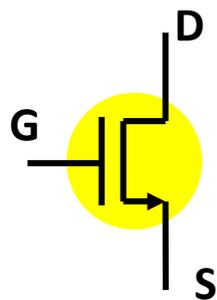
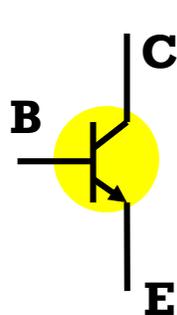
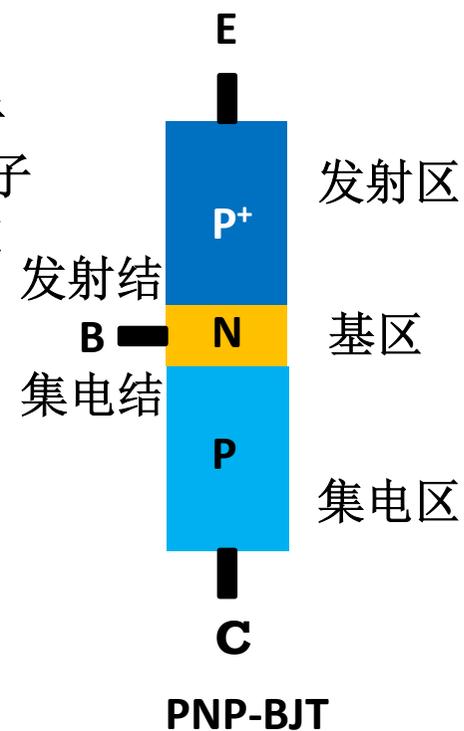


# NPN和PNP



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

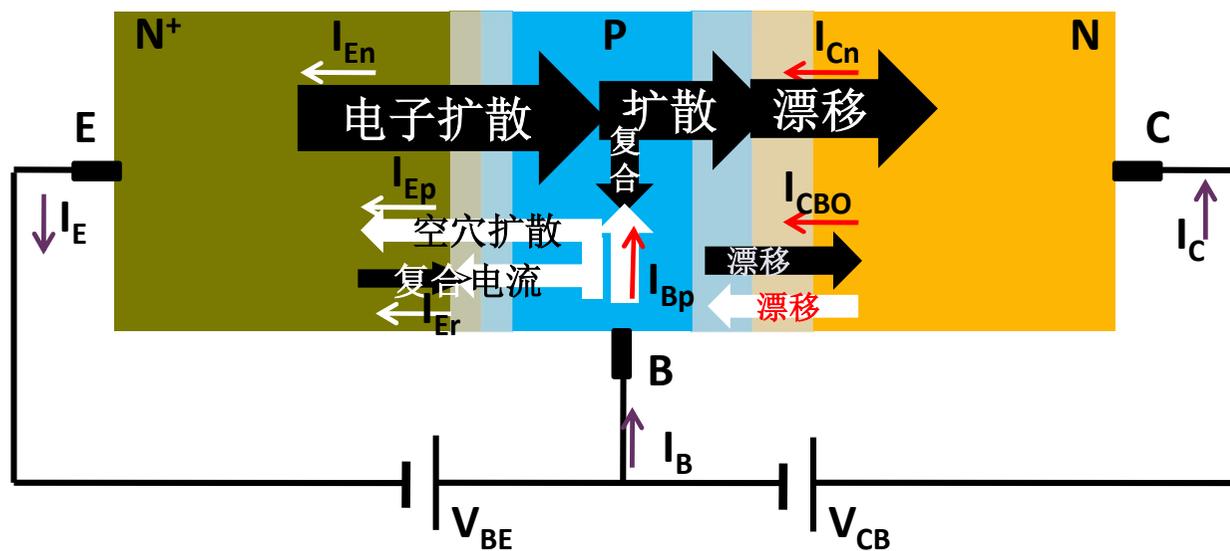


# 发射结正偏，集电结反偏 BJT受控原理

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  
 $I_C = I_{cn} + I_{CBO}$

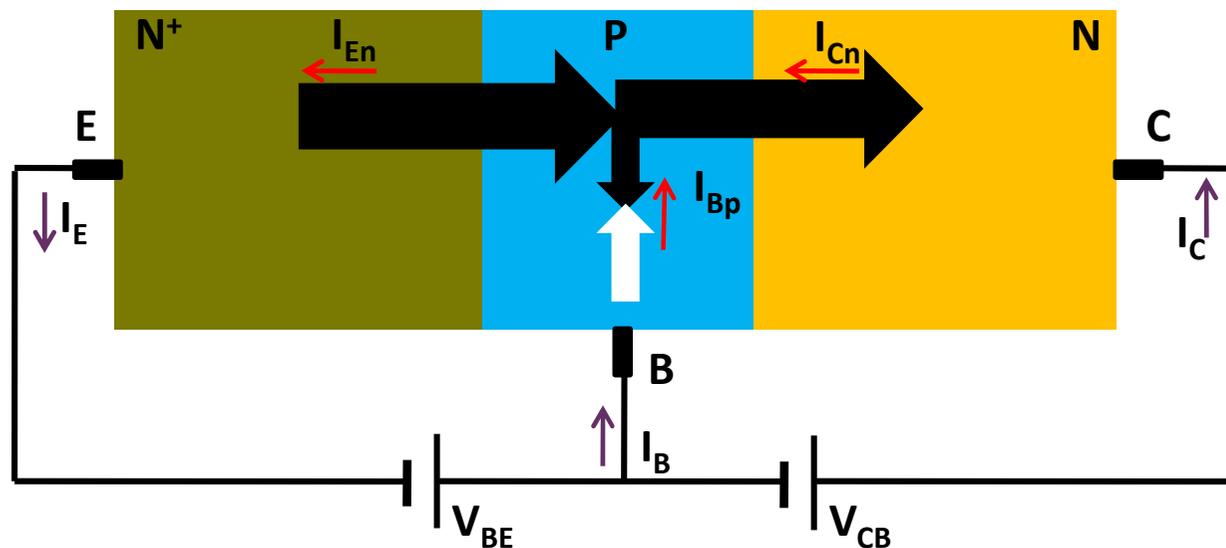
$$I_E = I_C + I_B$$

**BJT: Bipolar**  
**MOSFET: Unipolar**

# 电流分配关系

$$I_E = I_C + I_B$$

$$I_C = \beta I_B$$



$\beta$ : **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:  $\beta$  代表了基极电流对集电极电流的控制作用

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

$$I_B = I_E - I_C$$

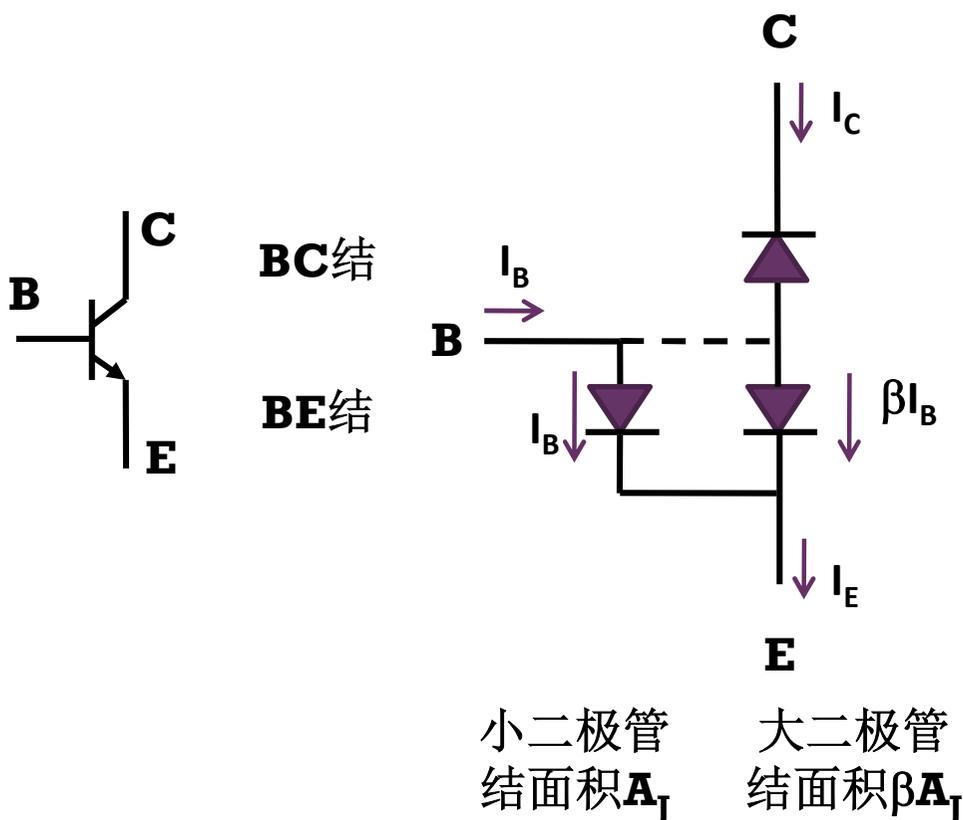
$$\beta = \frac{\alpha}{1 - \alpha}$$

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

$\alpha$ : **共基极** 电流放大倍数: **0.99** 左右

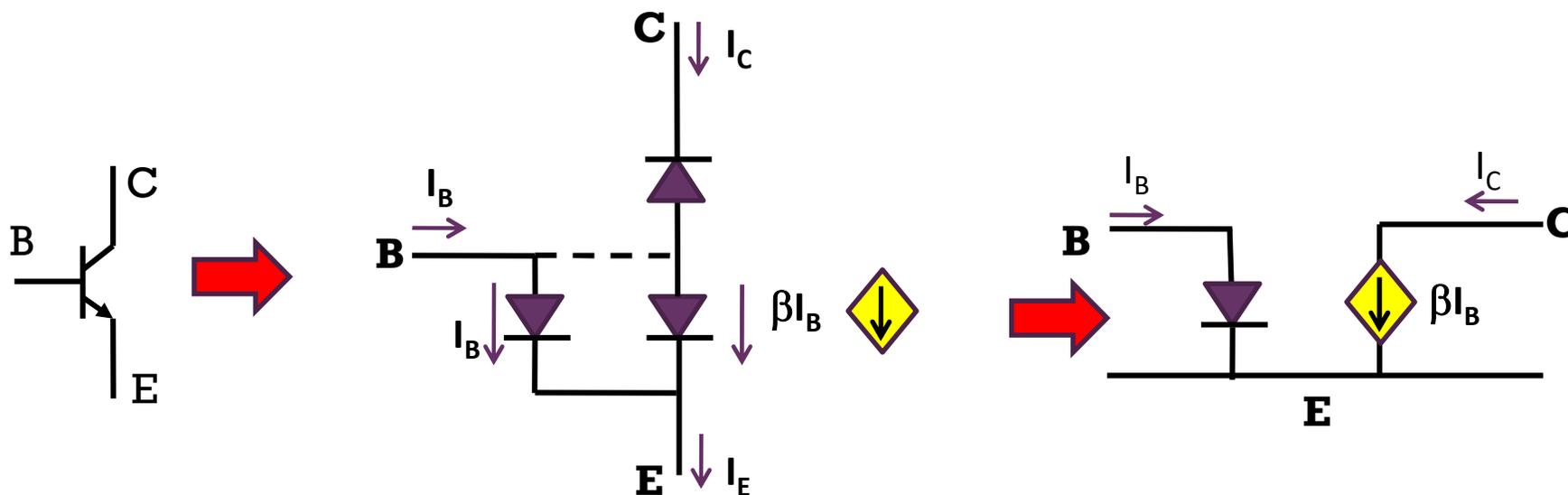
基极做为公共地: **BJT** 是一个电流缓冲器, 集电极收集电子近似等于发射极发射电子  
增大集电极收集能力, 要求基区更薄, 发射区掺杂浓度远高于基区, 大部分载流子通过

# 如何理解控制关系



- 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
- 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  $\beta A_J$  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  $I_C = \beta I_B$ 。
- 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  $\beta$  近似为一个常数

# 电路模型

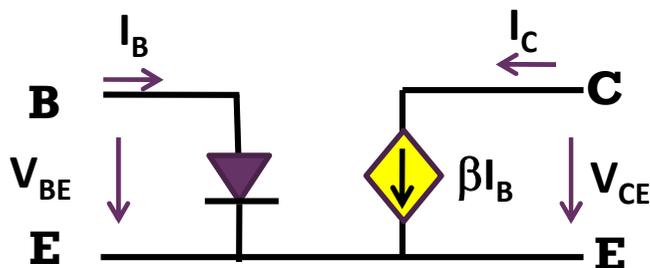
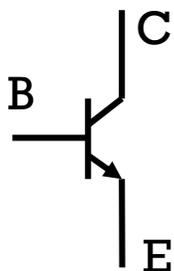


**NPN**晶体管是特殊连接关系的双二极管结构

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 $\beta$ 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 $\beta$ ，从而二端口网络可等效为流控流源

# 器件端口约束关系方程



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

**BE结正偏，BC结反偏**

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

流控流源  
混合控制描述

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

压控流源  
压控描述

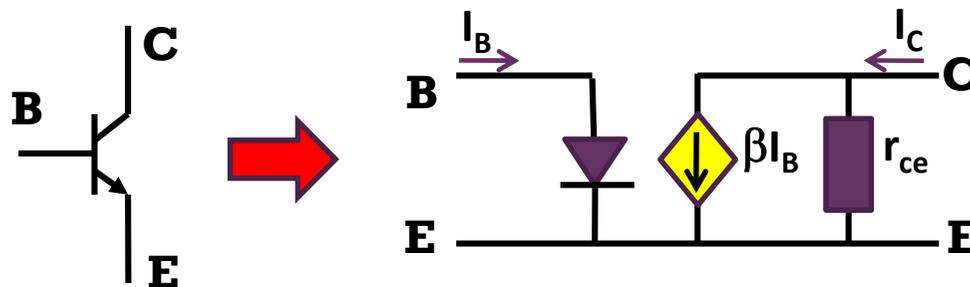
# 厄利效应

- 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

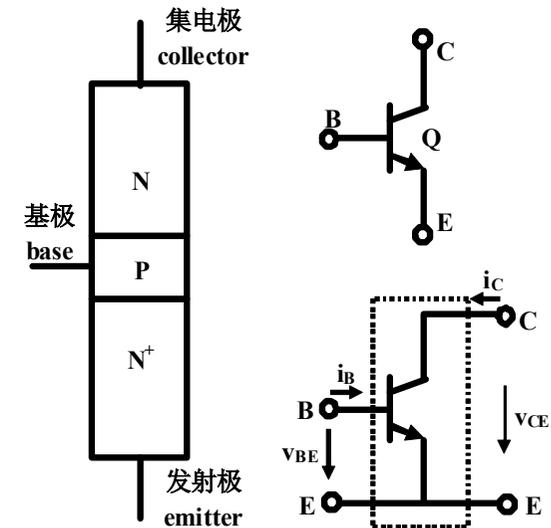
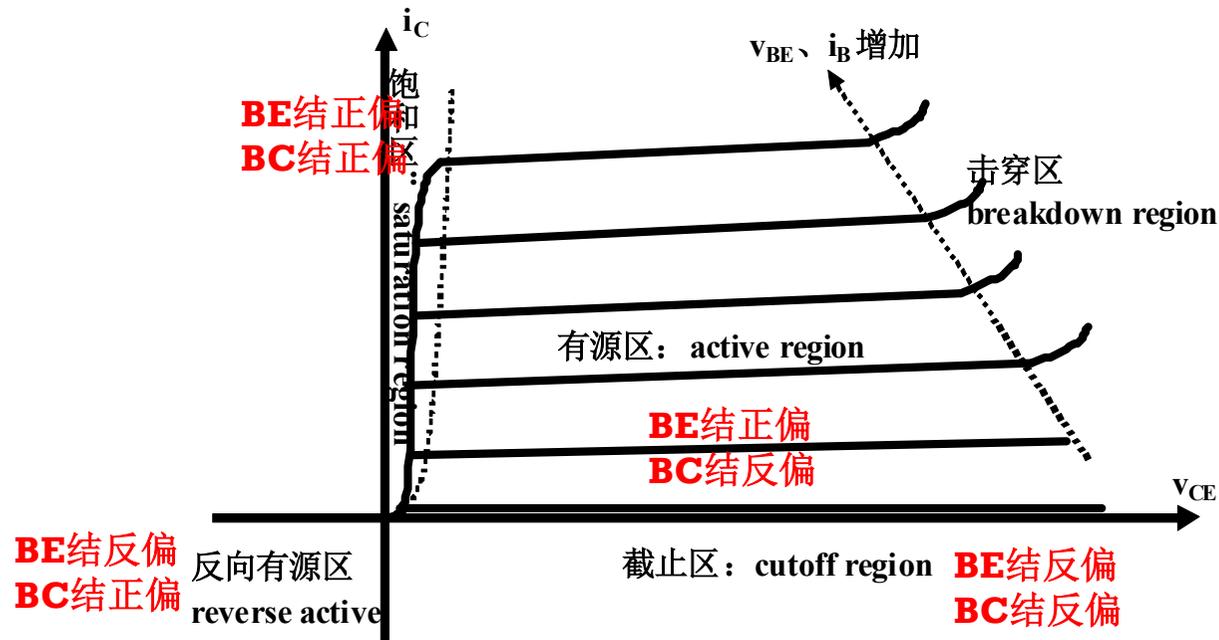


$$r_{ce} = \frac{V_A}{\beta I_B} = \frac{V_A}{I_{C0}}$$

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

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

# NPN-BJT端口伏安特性曲线



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

晶体管位于有源区（恒流区）  
的元件约束方程

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

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

$$V_A \quad \text{厄利电压}$$

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

$$\beta \quad \text{电流增益}$$

# 分区比对

		$V_{BC} < 0$	$V_{BC} > 0$
	<b>NPN-BJT工作区</b>	<b>BC结反偏</b>	<b>BC结正偏</b>
$V_{BE} > 0$	<b>BE结正偏</b>	有源区	饱和区
$V_{BE} < 0$	<b>BE结反偏</b>	截止区	反向有源区

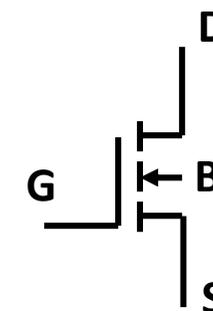
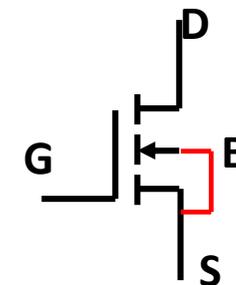
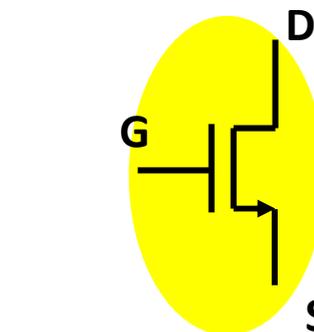
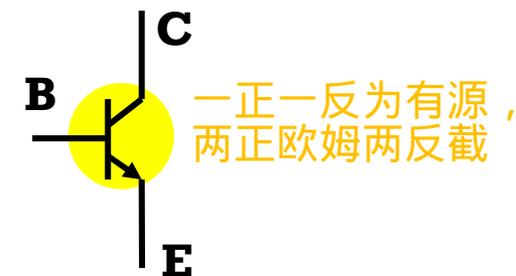
  

	<b>NMOSFET工作区</b>	$V_{GD} < V_{TH}$	$V_{GD} > V_{TH}$
$V_{GS} > V_{TH}$		有源区、饱和区	欧姆区
$V_{GS} < V_{TH}$		截止区	避免出现这种情况

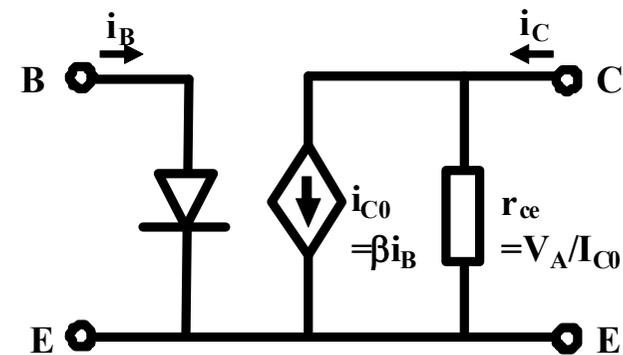
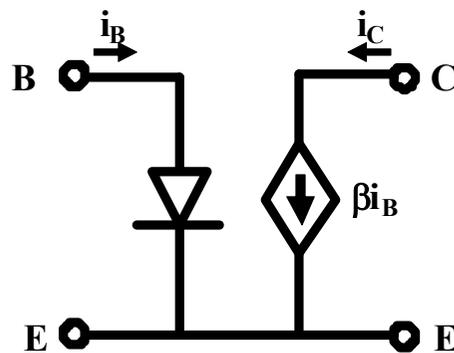
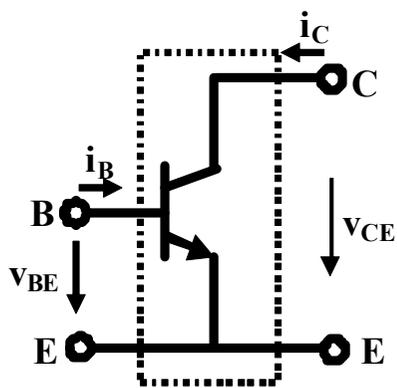
源衬相连，确保**PN**结反偏，漏极电压只能高于源极电压： $V_{DS} \geq 0$

	<b>NMOSFET工作区</b>	$V_{GD} < V_{TH}$	$V_{GD} > V_{TH}$
$V_{GS} > V_{TH}$		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 $V_{DS} \geq 0$

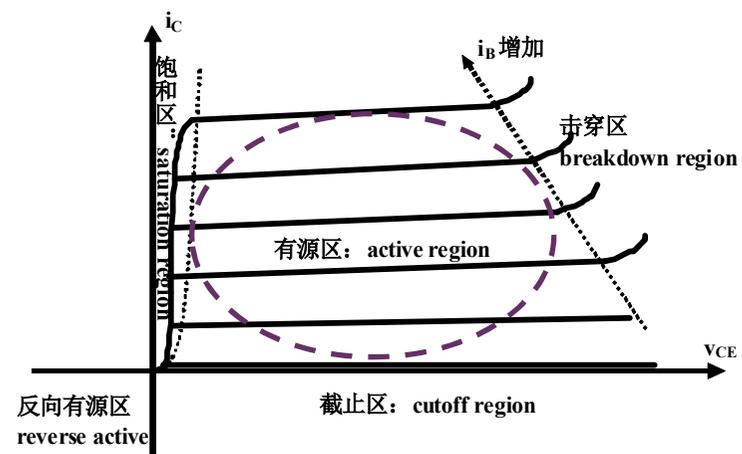


# 牢记有源区电路模型

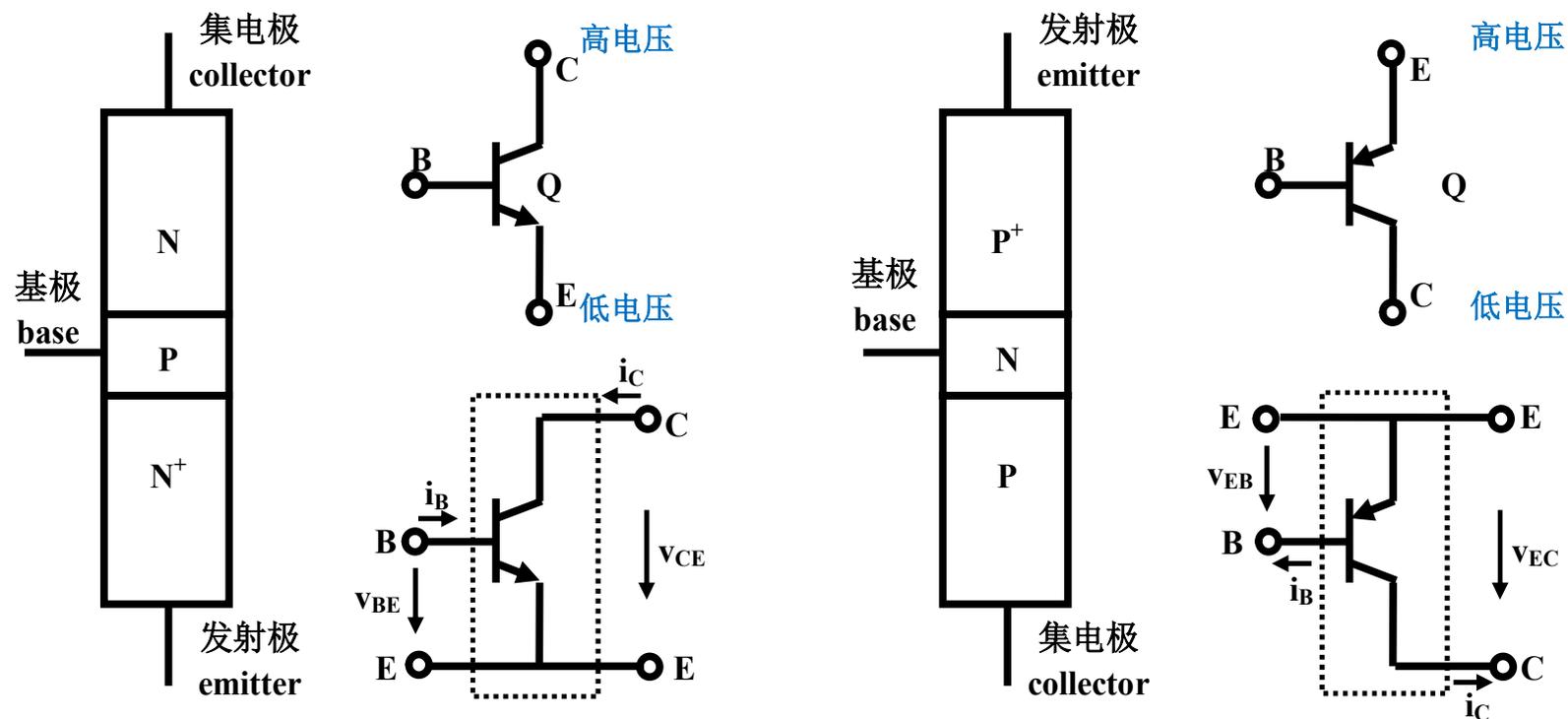


**BE**端口：看入的是一个**BE**结正偏二极管  
**CE**端口：是一个流控流源，电流控制系数 $\beta$ 在数百上千量级

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



# PNP和NPN的互补结构



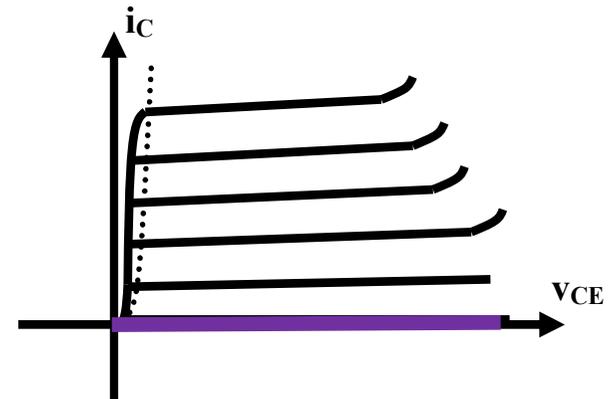
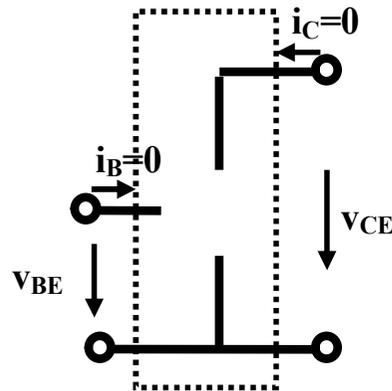
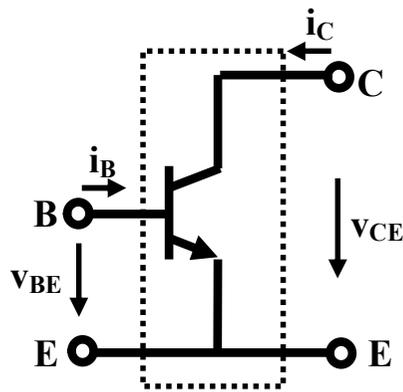
- **PNP-BJT 的元件约束方程和NPN-BJT的形式一致：** PNP方程中，只要将NPN方程中的 $V_{BE}$ 换成 $V_{EB}$ ，将 $V_{CE}$ 换成 $V_{EC}$ ，将 $I_{BS0,n}$ 换成 $I_{BS0,p}$ ，将 $\beta_n$ 换成 $\beta_p$ ，将 $V_{A,n}$ 换成 $V_{A,p}$ 后，方程形式没有任何其他变化。

## 二、分段折线电路模型

- 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

# 截止区：开路模型



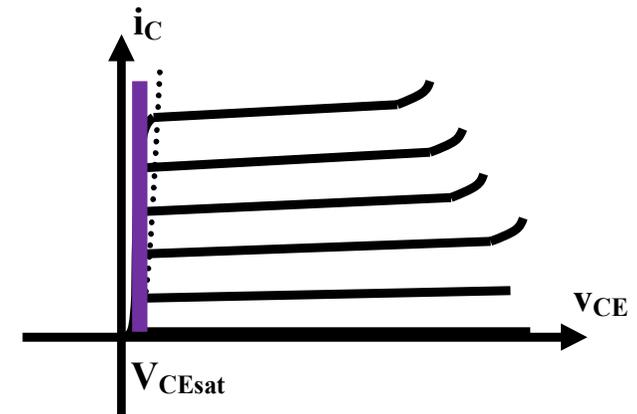
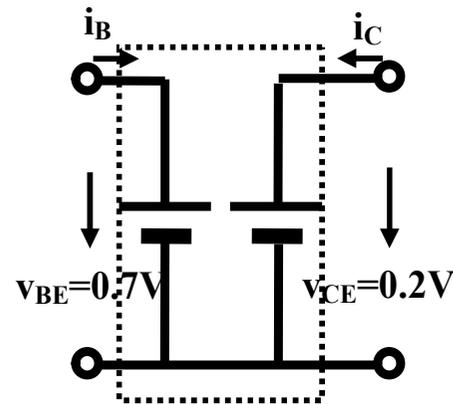
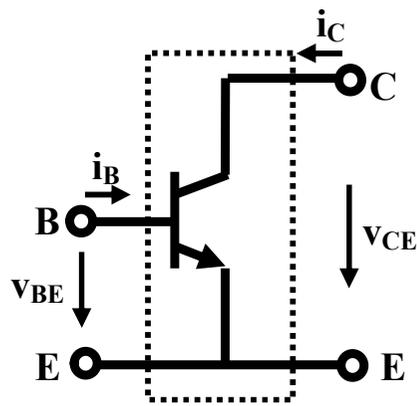
$$v_{BE} < V_{on} \quad i_B = 0$$

$$v_{CE} > 0 \quad i_C = 0$$

**BE**结反偏，截止

**BC**结反偏，截止

# 饱和区：恒压模型



$$i_B > 0$$

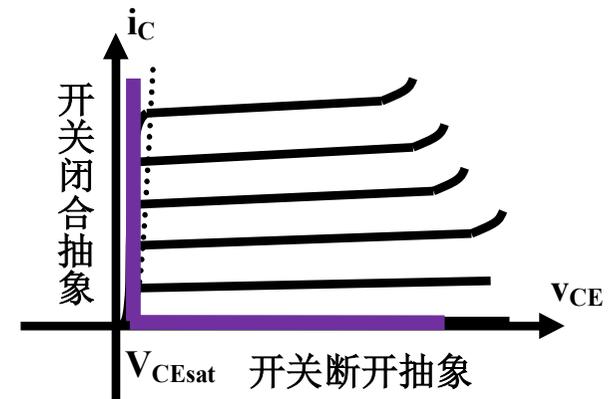
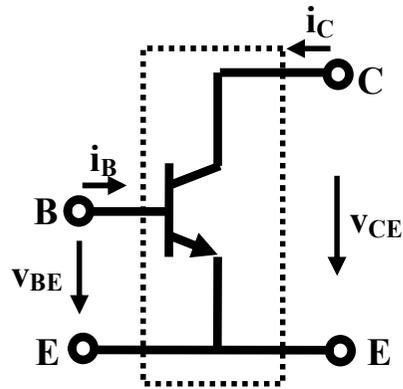
$$i_C < \beta i_B$$

**BE**结正偏导通  
**BC**结正偏导通

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

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

# 截止和饱和：开关模型



$$i_C = 0$$

**BE**结反偏，**BC**结反偏：开关断开

条件：

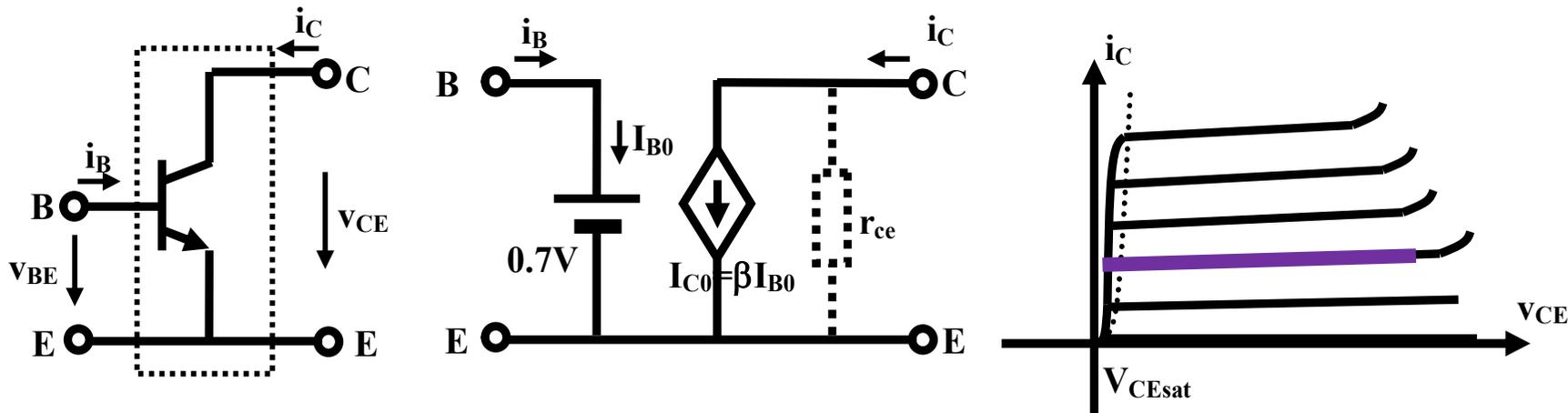
$$i_B = 0$$

$$v_{CE} = 0.2V$$

**BE**结正偏，**BC**结正偏：开关闭合

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

# 有源区：恒流源模型



$$i_B > 0$$

$$v_{BE} = 0.7V$$

**BE**结分段折线模型  
正偏**0.7V**恒压

**BE**结正偏，**BC**结反偏

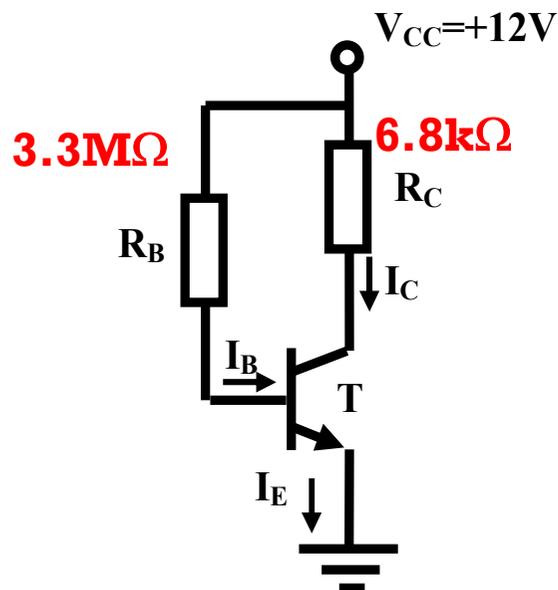
条件:  $V_{CE} > V_{CE,sat}$

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

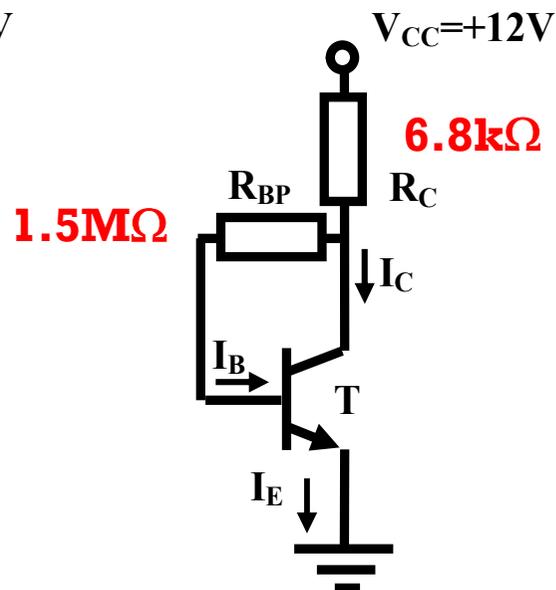
分段折线化模型中，厄利效应大多被忽略  
局部线性化分析中，厄利效应一般会加以考虑

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

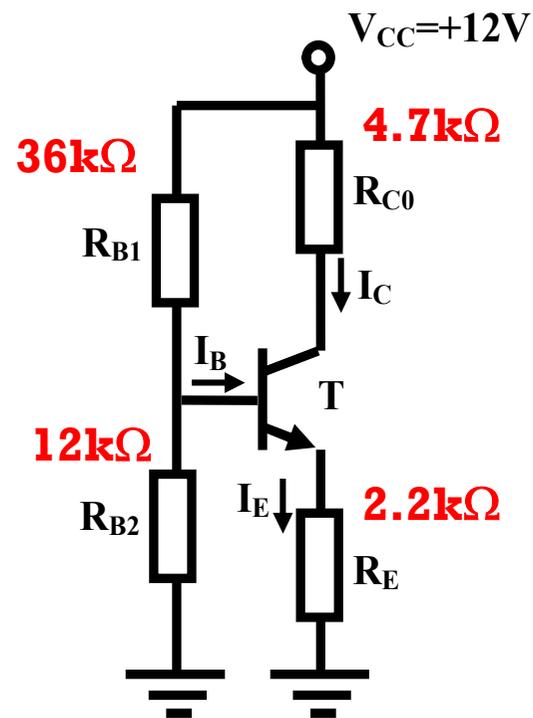
## 三、分压偏置电路分析



一般偏置



并联负反馈



串联负反馈  
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:  $\beta=200\sim 450$

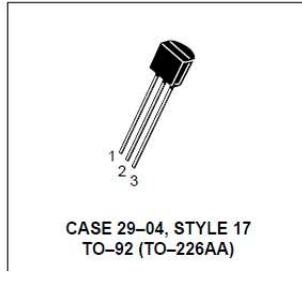
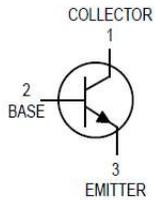
# BJT关键参量β 高度不确定性

**MOTOROLA**  
SEMICONDUCTOR TECHNICAL DATA

Order this document  
by BC549B/D

## Low Noise Transistors NPN Silicon

## Motorola BC549



**BC549B,C**  
**BC550B,C**

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

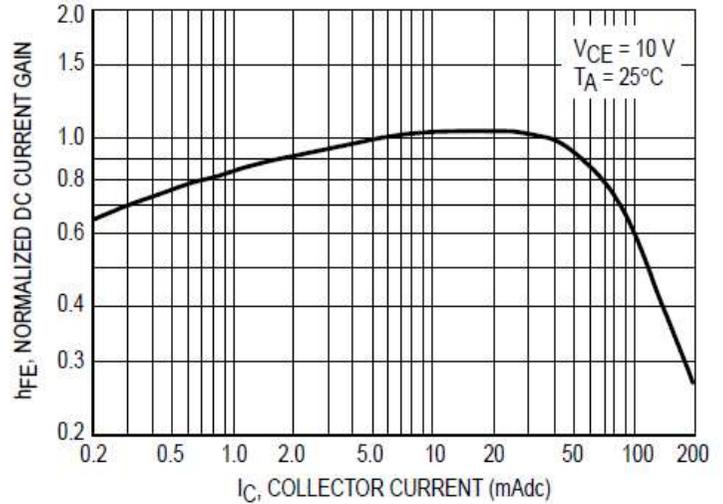
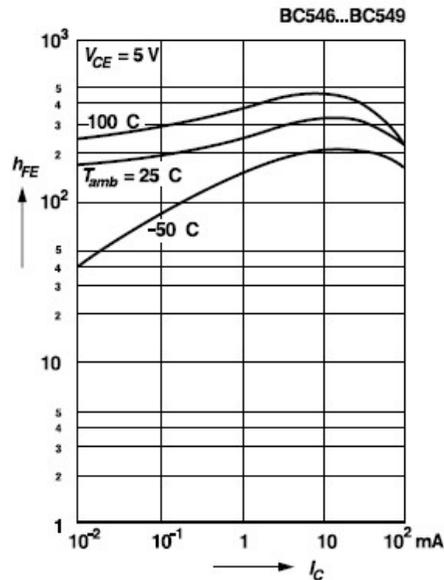


Figure 2. Normalized DC Current Gain

DC current gain  
versus collector current

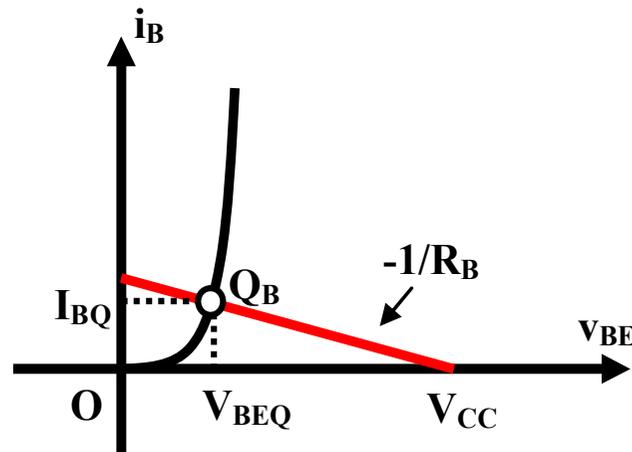
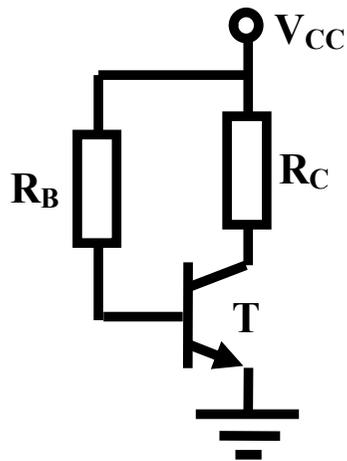
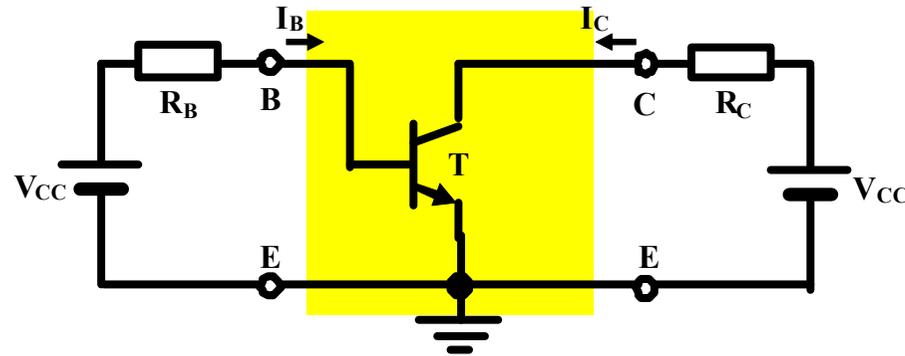


### ELECTRICAL CHARACTERISTICS (TA = 25°C unless otherwise noted) (Continued)

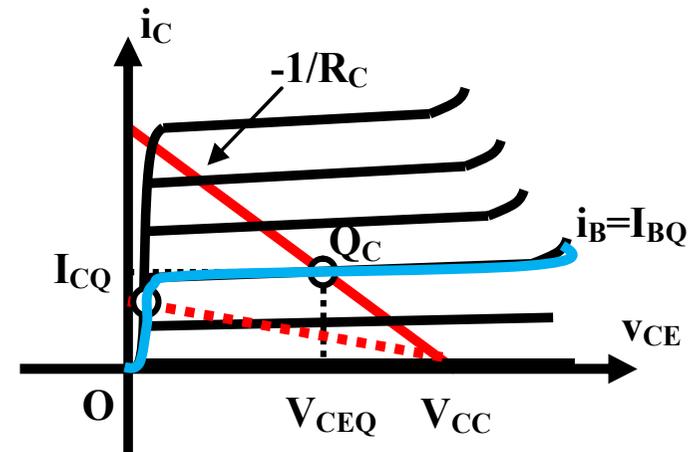
Characteristic	Symbol	Min	Typ	Max	Unit
<b>ON CHARACTERISTICS</b>					
DC Current Gain (IC = 10 μAdc, VCE = 5.0 Vdc)	hFE	100	150	—	—
(IC = 2.0 mAdc, VCE = 5.0 Vdc)		100	270	—	—
Collector–Emitter Saturation Voltage (IC = 10 mAdc, IB = 0.5 mAdc) (IC = 10 mAdc, IB = see note 1) (IC = 100 mAdc, IB = 5.0 mAdc, see note 2)	VCE(sat)	—	0.075 0.3 0.25	0.25 0.6 0.6	Vdc
Base–Emitter Saturation Voltage (IC = 100 mAdc, IB = 5.0 mAdc)	VBE(sat)	—	1.1	—	Vdc
Base–Emitter On Voltage (IC = 10 μAdc, VCE = 5.0 Vdc) (IC = 100 μAdc, VCE = 5.0 Vdc) (IC = 2.0 mAdc, VCE = 5.0 Vdc)	VBE(on)	— — 0.55	0.52 0.55 0.62	— — 0.7	Vdc

General Semiconductor BC549

# 简单偏置图解法分析



**BE端口**  
BE结与戴维南源对接  
输入端口首先确定 $I_{B0}$



**CE端口**  
恒流源与戴维南源对接

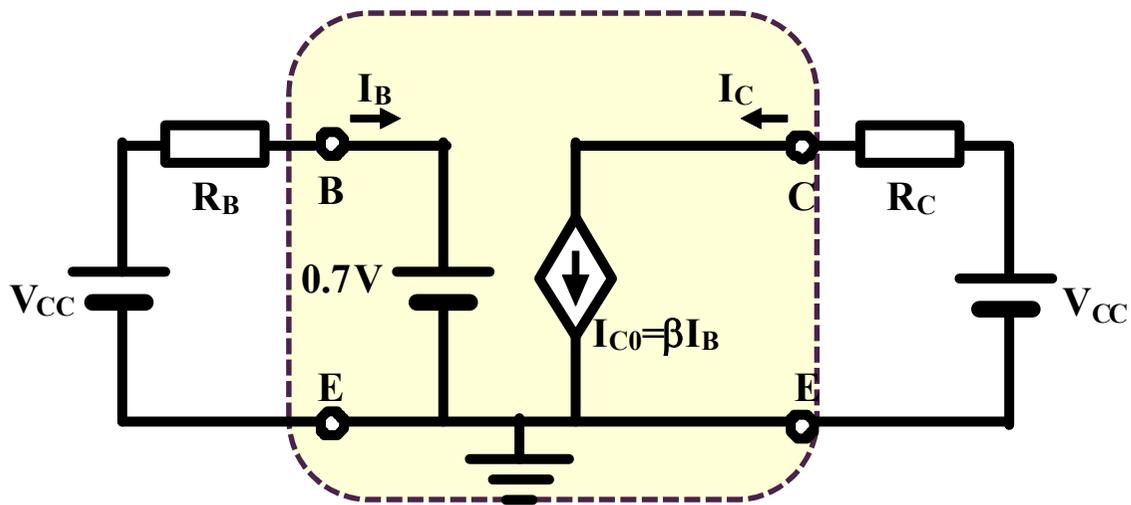
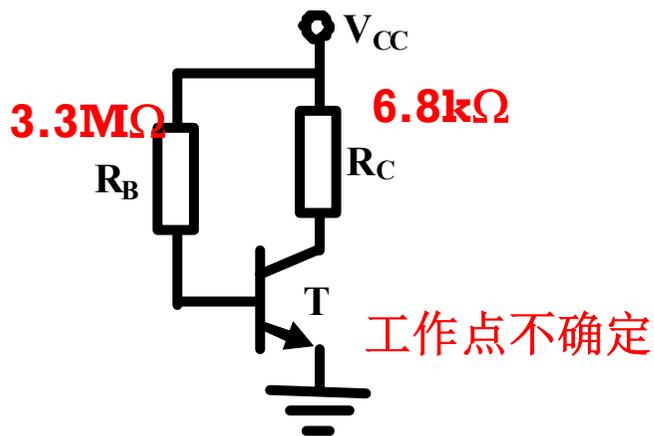
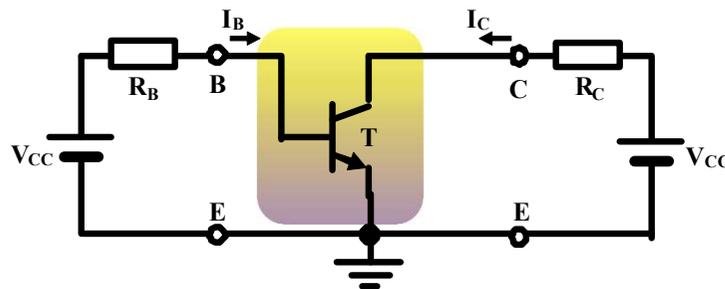
输出端口再确定 $I_{C0} = \beta \cdot I_{B0}$   
进而确定 $V_{CE0}$

# 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

# 假设工作在恒流区 等效电路

检查 $V_{CE} > 0.2V$



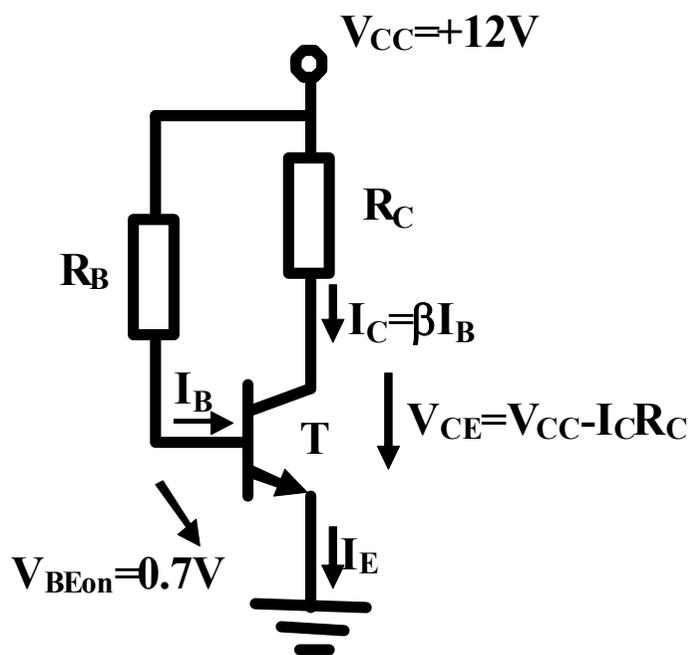
$$I_B = \frac{V_{CC} - V_{BEQ}}{R_B} = \frac{12 - 0.7}{3.3 \times 10^6} = 3.42 \times 10^{-6} = 3.42(\mu A)$$

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

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

# 恒流区模型太简单，无需画等效电路

先看BE再看CE，两条路直接分析



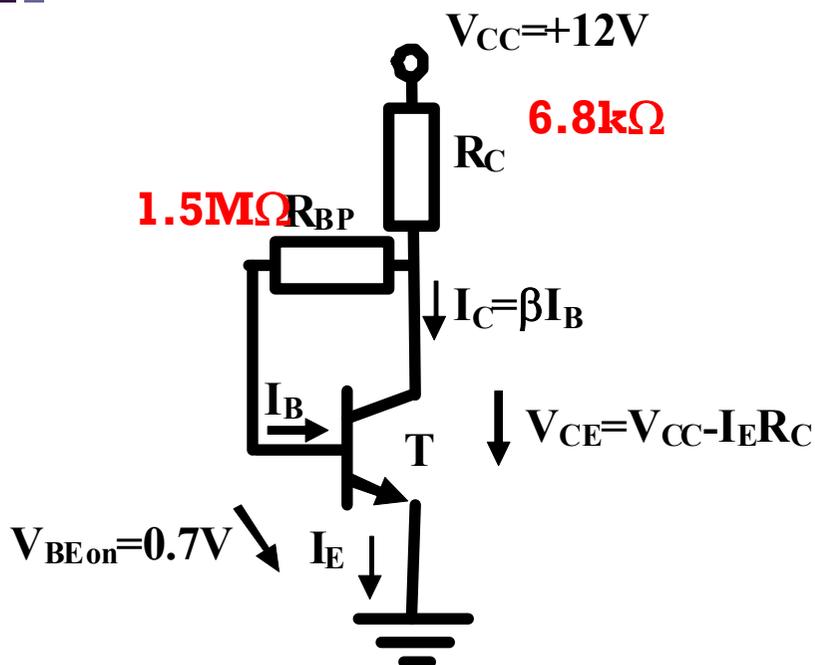
$$V_{BE} = V_{BEon} = 0.7V$$

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

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

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

# 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

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

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

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

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

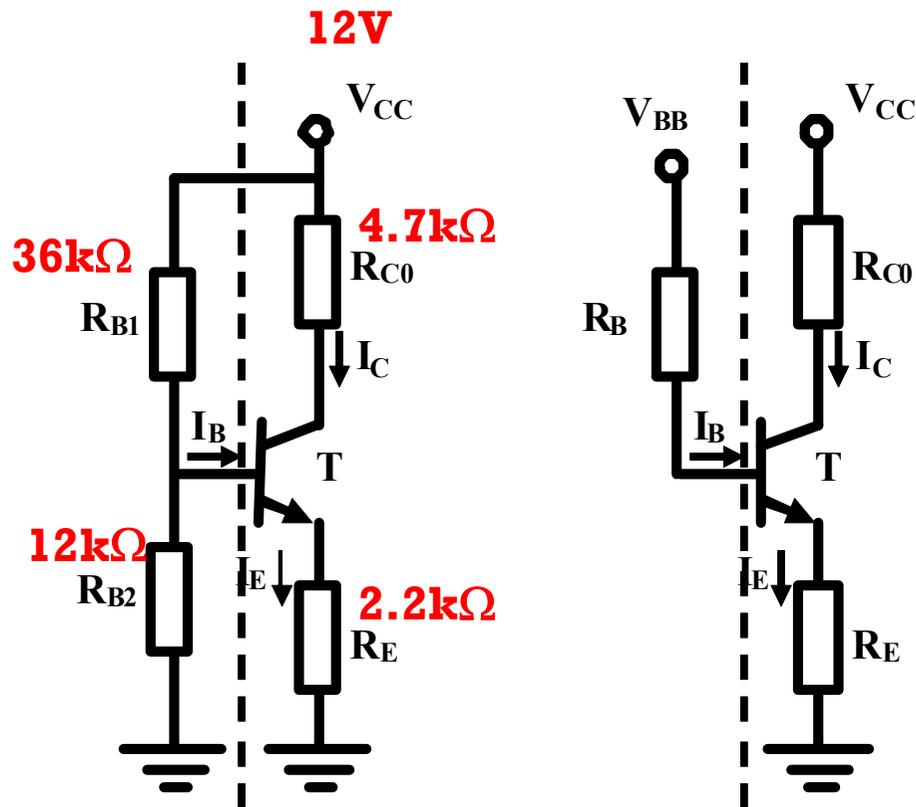
$$I_C = \beta I_B = \beta \frac{V_{CC} - 0.7}{R_{BP} + (\beta + 1)R_C}$$

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

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

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

# 分压偏置电路的戴维南等效



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

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

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

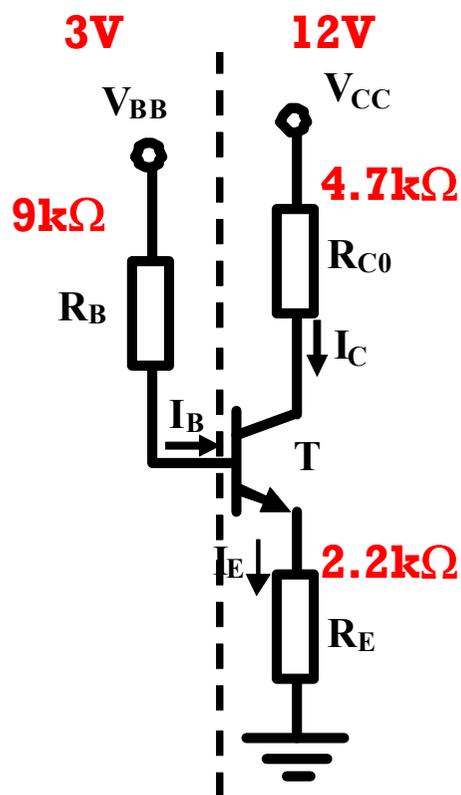
$$= \frac{36 \times 12}{36 + 12} = 9k\Omega$$

# 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**



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

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

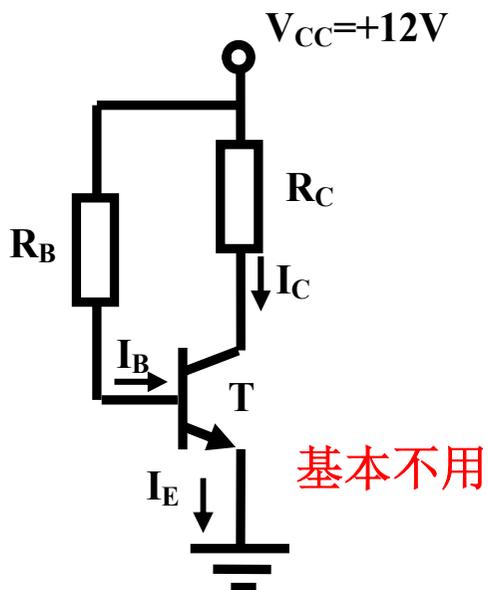
$$V_{CE} = V_{CC} - \beta I_B R_{C0} - (\beta + 1) I_B R_E = 5.0V \sim 4.9V$$

可确认在恒流区

串联负反馈使得工作点十分的稳定

# 工作点稳定性差异巨大

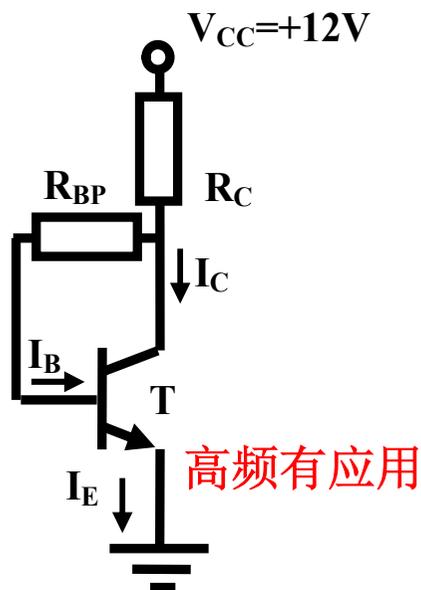
$\beta=200-450$



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

$$= 0.685 \sim 1.54 \text{mA}$$

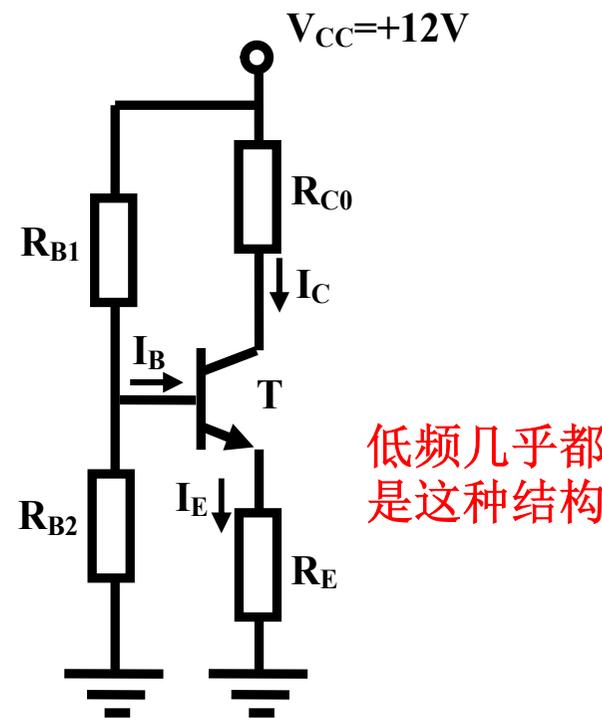
$$V_{CE} = 7.3 \text{V} \sim 1.5 \text{V}$$



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

$$= 0.788 \sim 1.11 \text{mA}$$

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

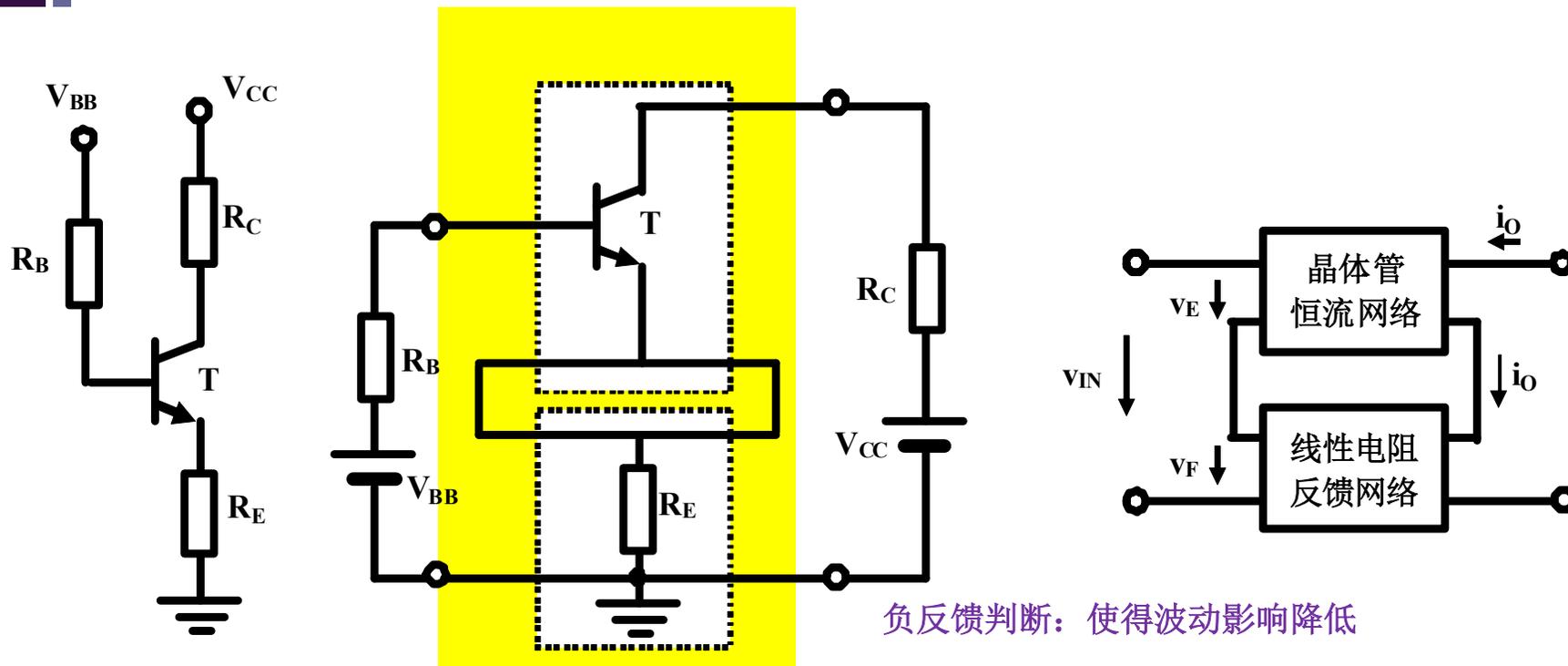


$$I_C = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B + R_E}{\beta}}$$

$$= 1.02 \sim 1.03 \text{mA}$$

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

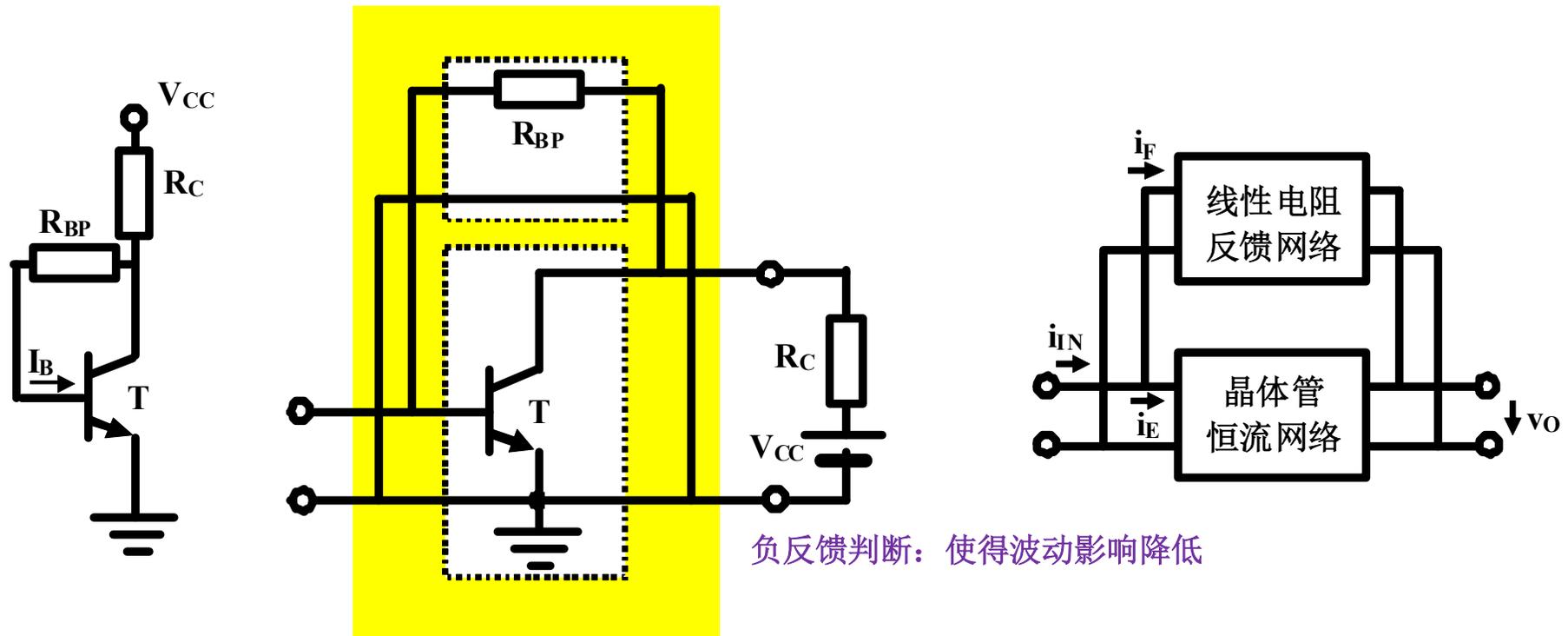
# 串联负反馈连接：稳定输出电流



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

# 并联负反馈：稳定输出电压



并联负反馈，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  
 并联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

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

$$y = f(x_1, x_2, \dots, x_n) = f(\overset{\text{设计值}}{\downarrow} x_{10} + \overset{\text{实际制作偏离设计值}}{\downarrow} \Delta x_1, x_{20} + \Delta x_2, \dots, x_{n0} + \Delta x_n)$$

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

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

导致输出偏离设计值

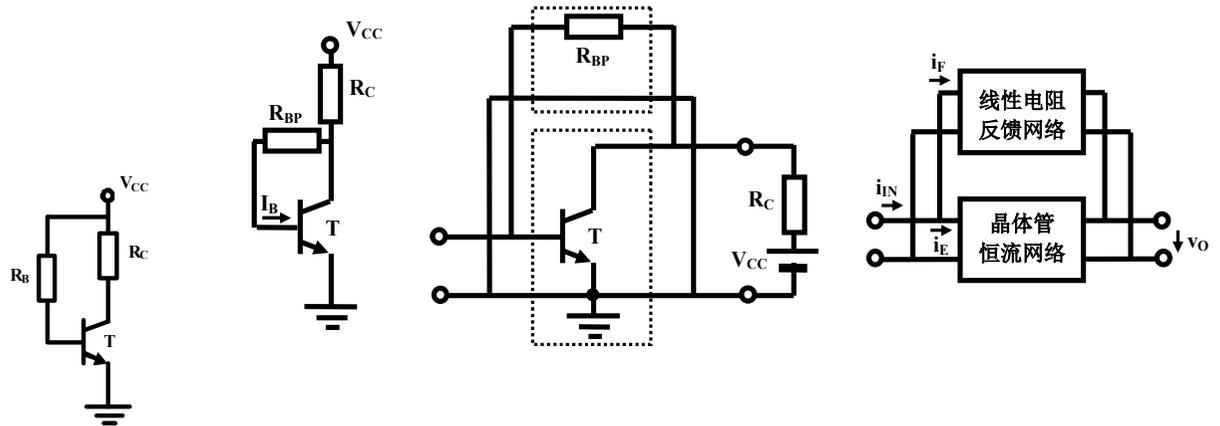
$$\frac{\Delta y}{y_0} \approx \frac{\partial f}{\partial x_1} \frac{x_{10}}{y_0} \frac{\Delta x_1}{x_{10}} + \frac{\partial f}{\partial x_2} \frac{x_{20}}{y_0} \frac{\Delta x_2}{x_{20}} + \dots + \frac{\partial f}{\partial x_n} \frac{x_{n0}}{y_0} \frac{\Delta x_n}{x_{n0}}$$

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

对于极度不稳定因素如 $\beta$ ，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：该因素对最终输出的影响力大小

# 并并负反馈 灵敏度分析

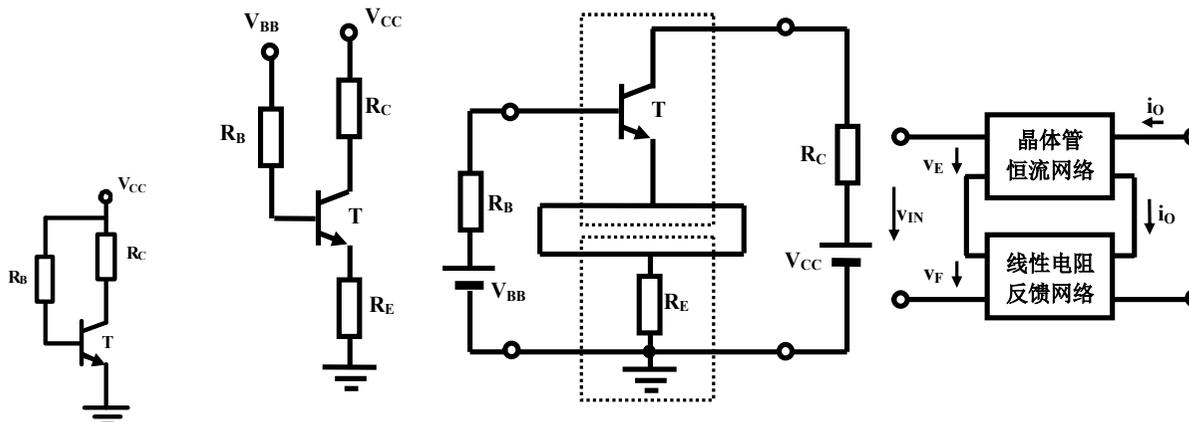


$\beta=300$

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

# 串串负反馈 灵敏度分析

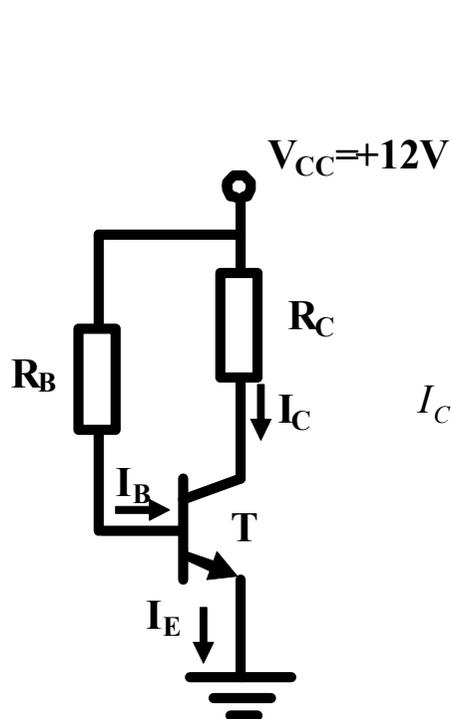
$\beta=300$



	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

# 低灵敏度意味着高稳定性

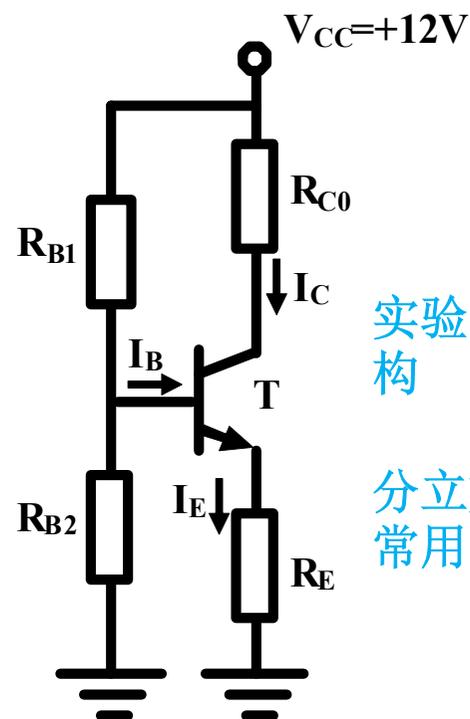


$$S_{x_i}^y = \frac{x_i}{y} \frac{\partial y}{\partial x_i}$$

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

**1.03mA**是系统输出的设计值

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



实验常用结构

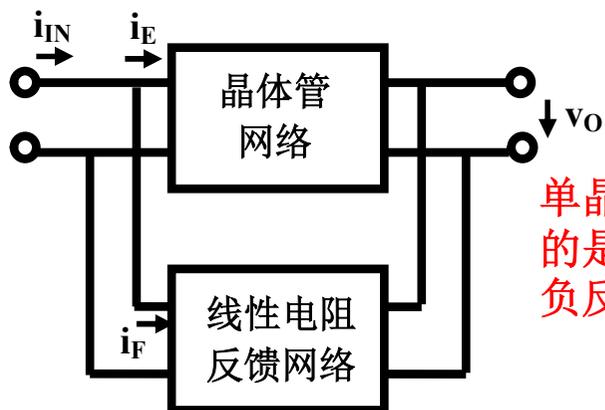
分立放大器常用结构

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

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

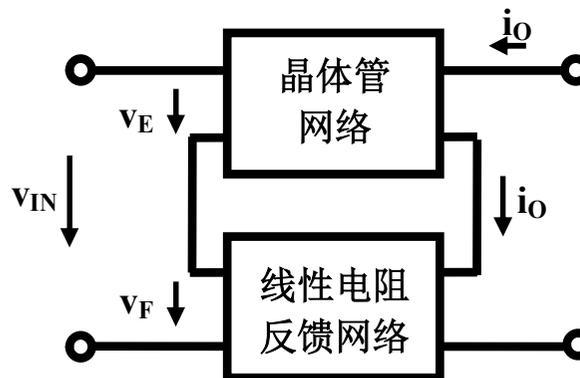
$\beta$ : 极度不确定, 设计时应确保其灵敏度很小, 则系统稳定  
串联负反馈使得晶体管电流增益不确定导致的直流工作点不稳定性大大降低

# 负反馈连接方式汇总

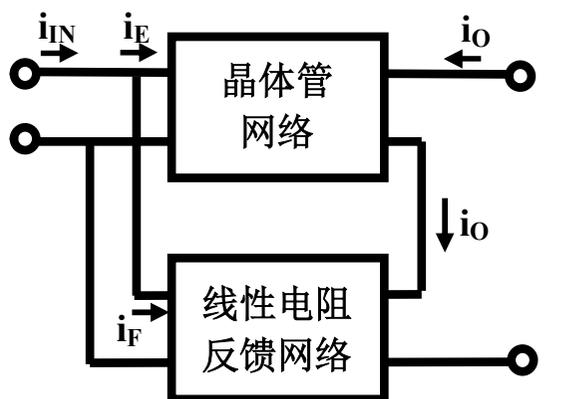


并并负反馈

单晶体管：常见的是串串和并并负反馈

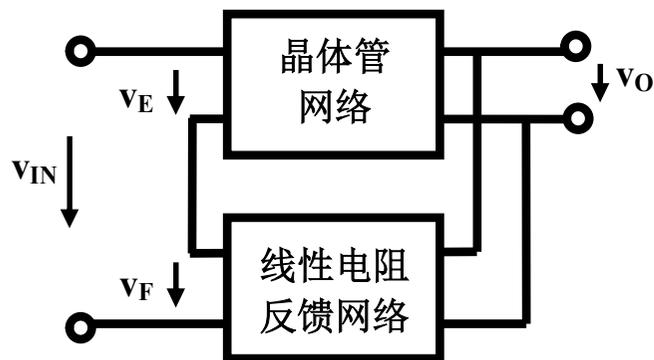


串串负反馈



并串负反馈

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：4种负反馈连接形成的4种接近理想的受控源

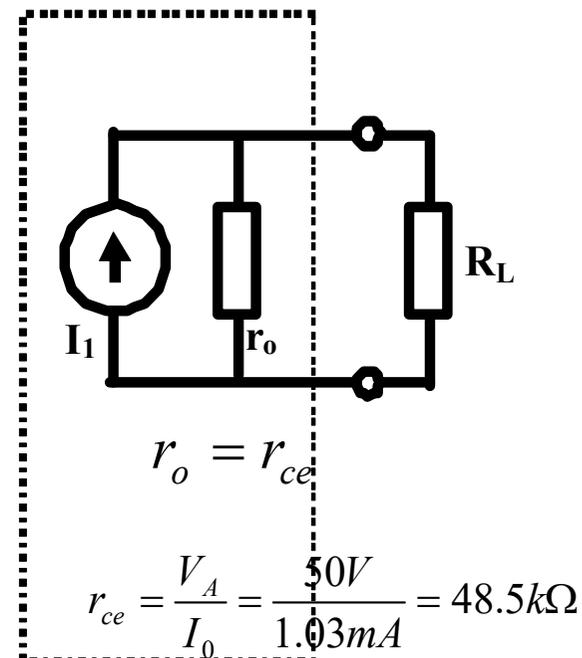
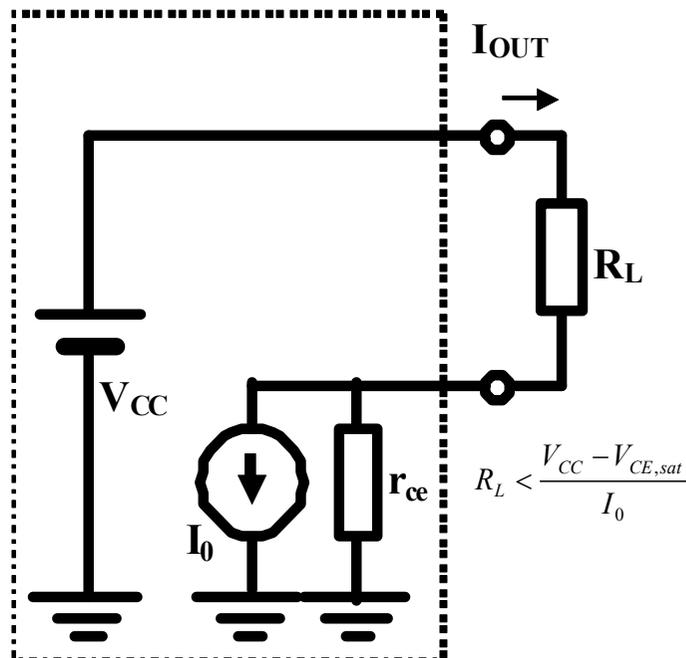
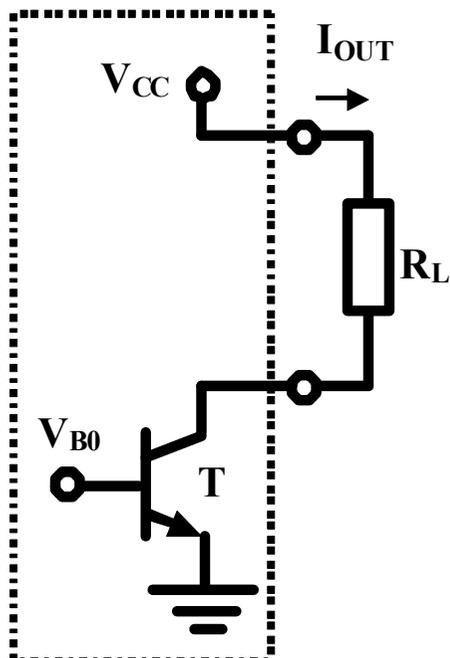


串并负反馈

## 四、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

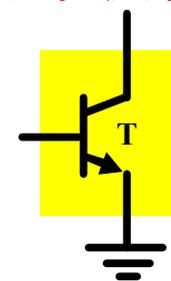
$$I_C = \beta A_J J_{BS0} \cdot \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) = I_0 \left( 1 + \frac{V_{CE}}{V_A} \right) = I_0 + \frac{I_0}{V_A} V_{CE} = I_0 + \frac{V_{CE}}{r_{ce}}$$

# 负反馈改善电流源内阻特性

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

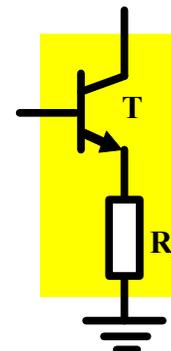
$$g_o = \frac{\partial I_C}{\partial V_{CE}} = \frac{\partial f(V_{BE}, V_{CE})}{\partial V_{CE}} = \frac{\partial f}{\partial V_{CE}} = \frac{I_0}{V_A} = \frac{1}{r_{ce}} = g_{ce}$$

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

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

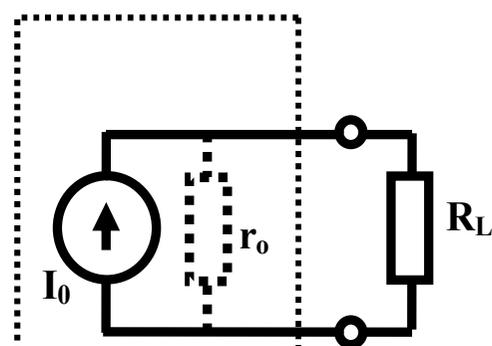
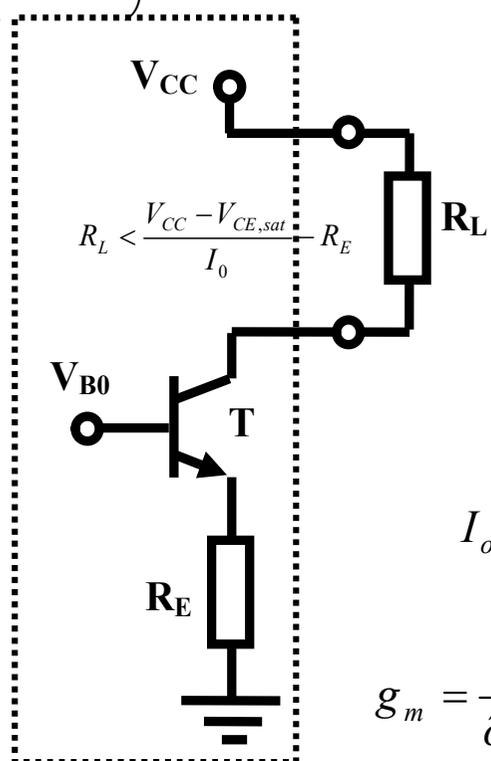
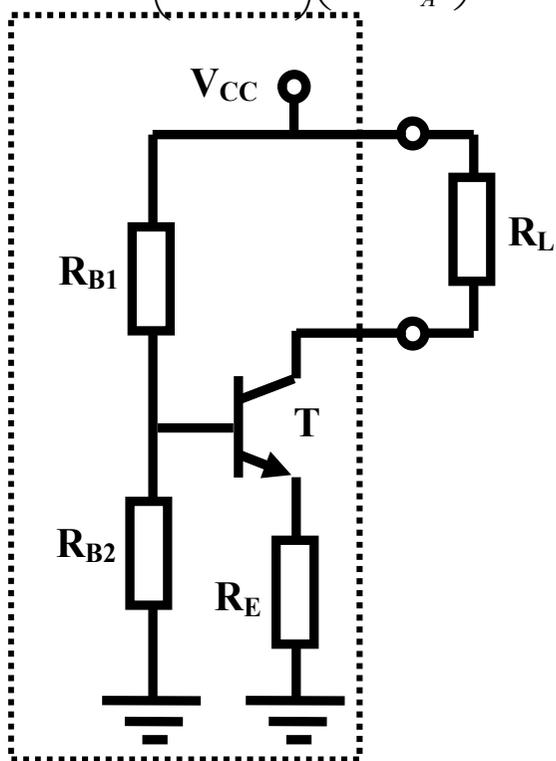
$$r_o \approx r_{ce} (1 + g_m R_E)$$

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



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

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

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

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

# 负反馈使得温度稳定性提高

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

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

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

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

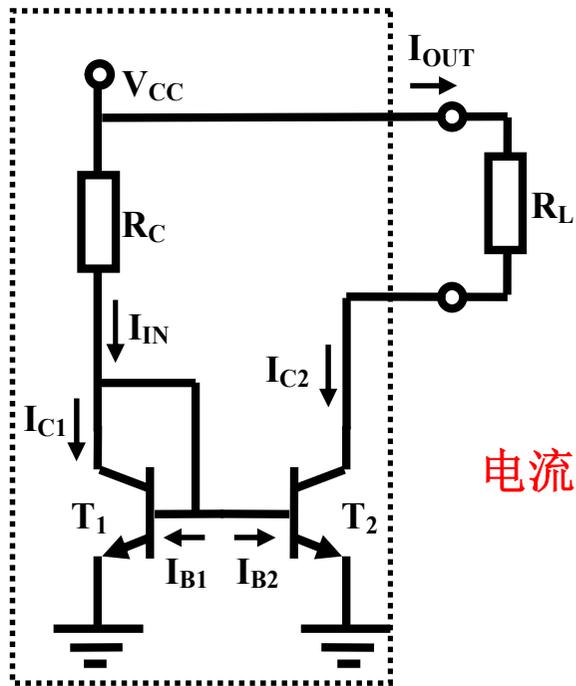
直接偏置温度敏感度极高

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

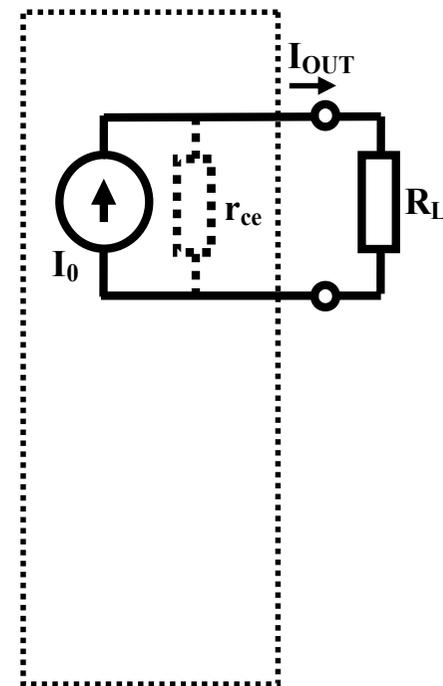
$$V_{BE} = V_B - I_C R_E$$

串串负反馈降低了温度敏感度

# 电流镜结构：同属性抵偿



电流镜



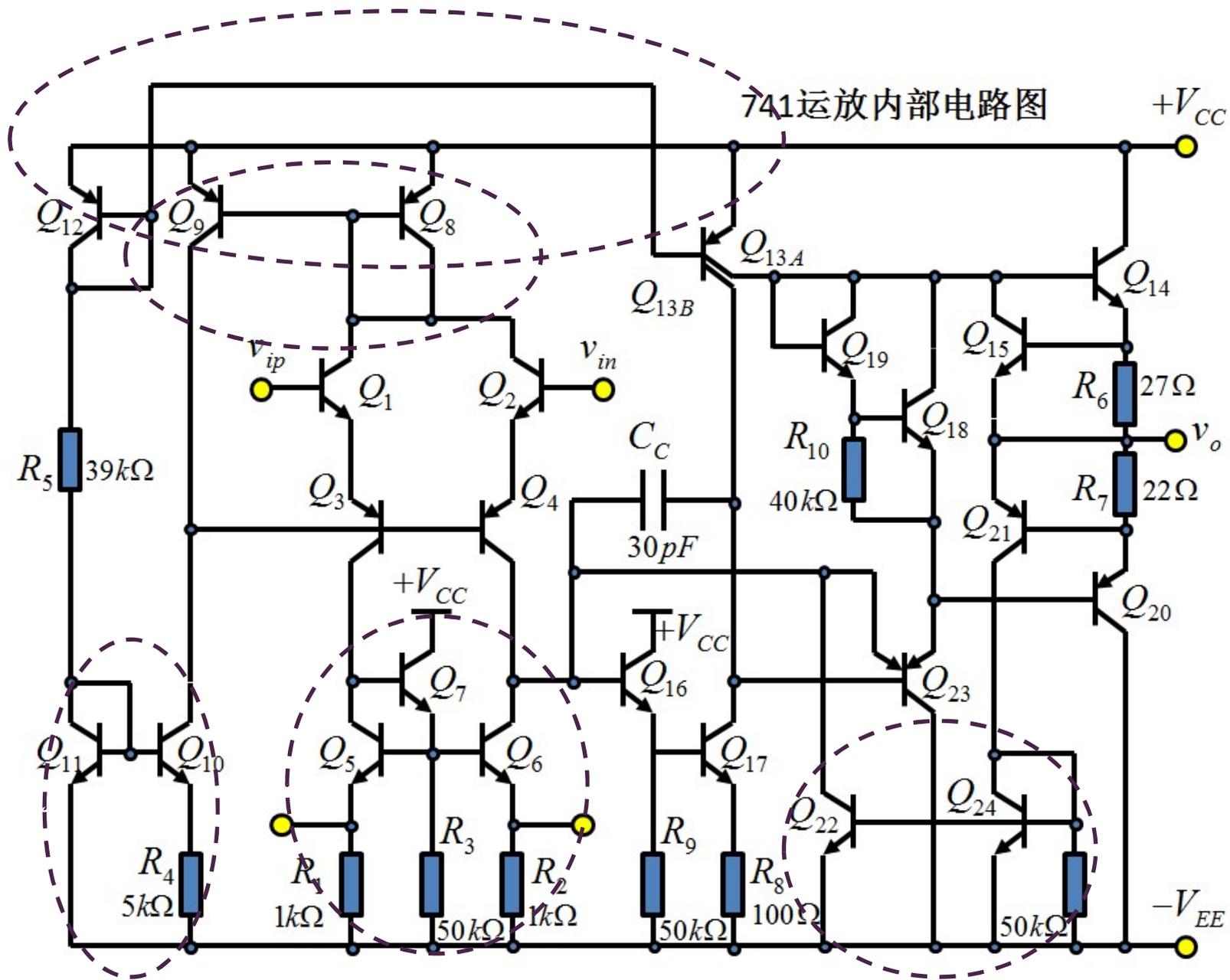
结面积  
决定电  
流关系

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

$\beta$ 越大,  $V_A$ 越大, 匹配程度越高



# 电流镜是模拟集成电路的特征电路



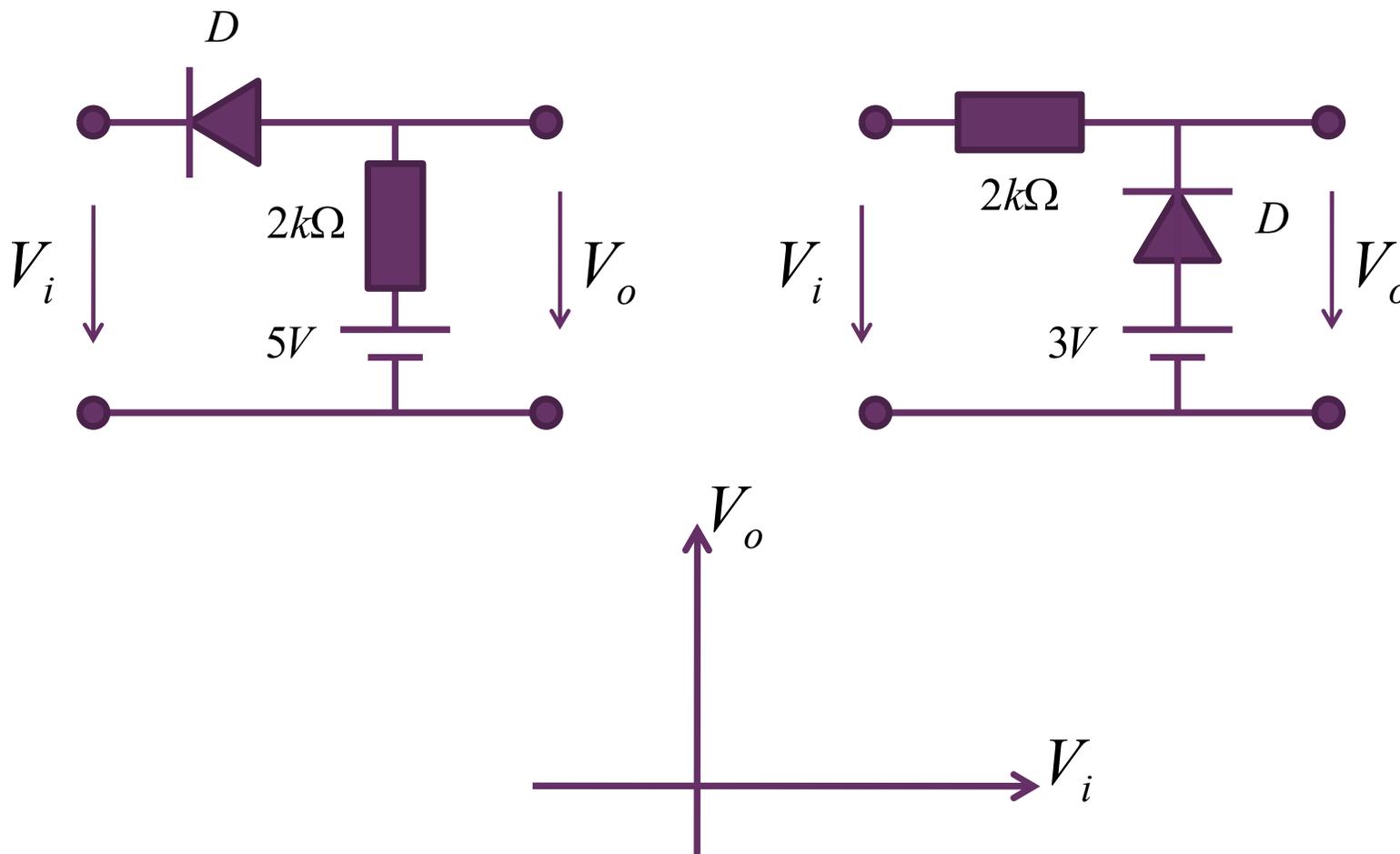
# 小结

- BJT晶体管中由于同时存在两种类型的载流子电流，故称双极型晶体管
- BJT恒流区工作时，CB结反偏
  - 正常的反偏PN结截止（少子漂移电流），但BJT中的反偏CB结可以导电，原因在于基区中有大量的发射极发射过来的少子（对基区属少子）可供漂移
  - BJT结构中的关键点在于发射极重掺杂，基区很薄
- BJT做放大器使用时工作于恒流区，恒流区压控流源模型需要把握
- 分压偏置电路中的串串负反馈电阻可以稳定恒流区工作晶体管的输出电流
- 集成电路中常见的电流镜结构可以确保输出电流和参考电流之间比值由尺寸决定
  - 可以通过负反馈改善输出阻抗
  - 可以通过beta倍增改善两条支路的匹配度

## 五、作业选讲

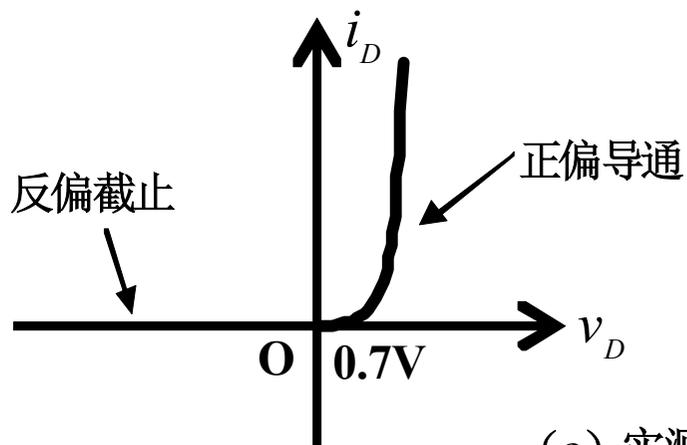
二极管采用“导通**0.7V**恒压、反偏开路”模型

- 作业2.4 画出如图所示电路的电压转移特性曲线

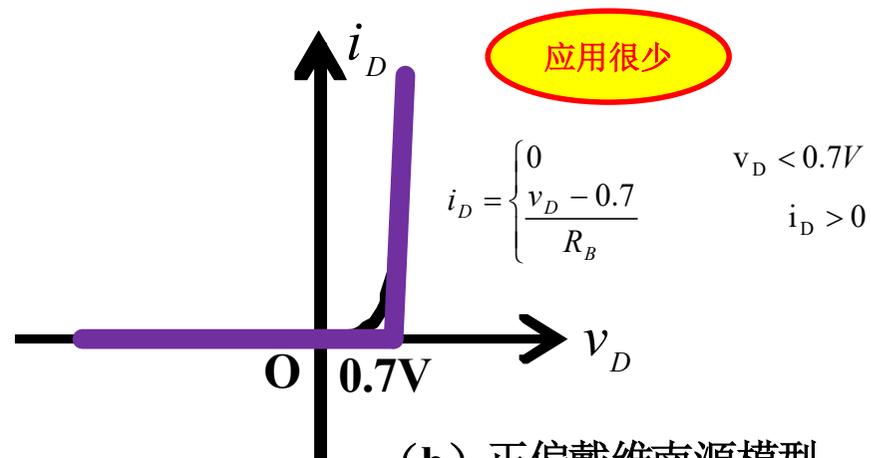


# 二极管分段折线模型

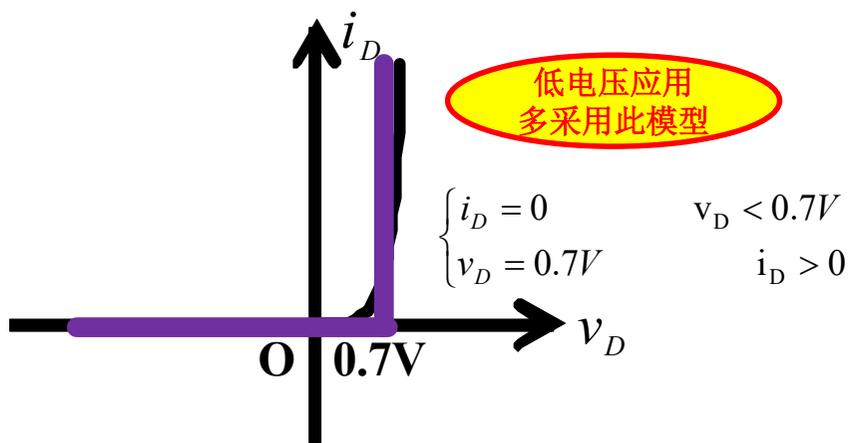
串接负载很小时，戴维南源内阻才会被考虑在内



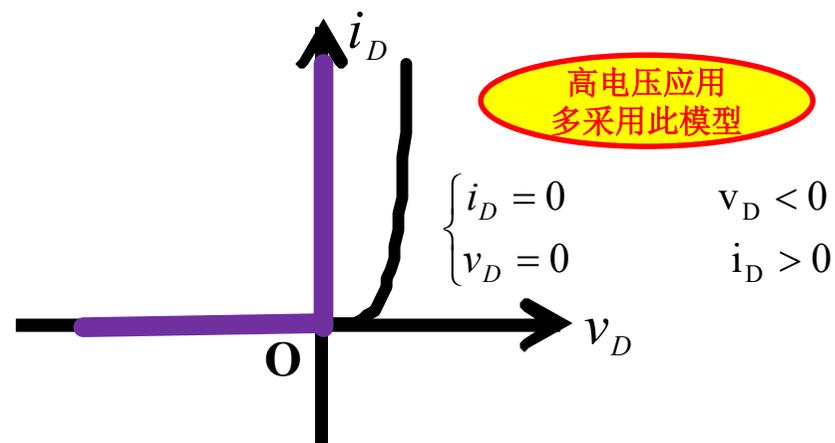
(a) 实测特性



(b) 正偏戴维南源模型



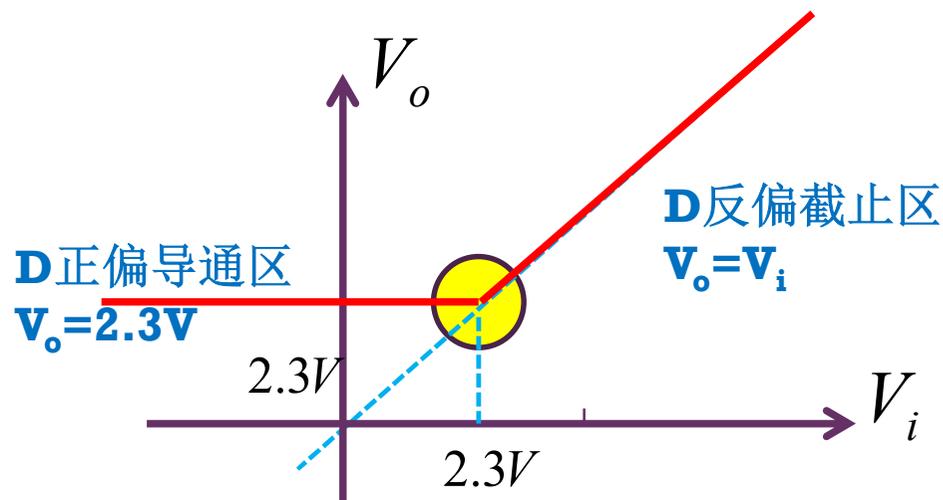
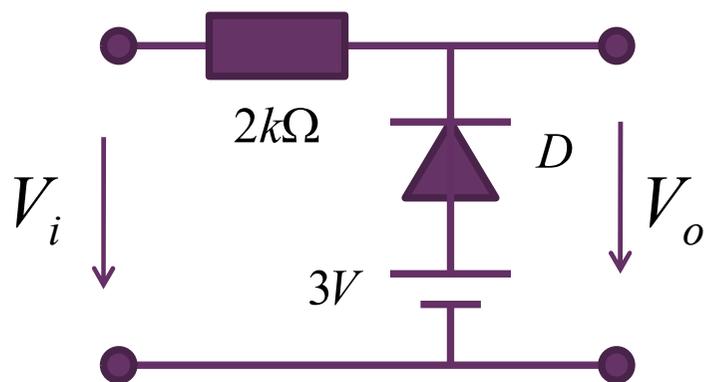
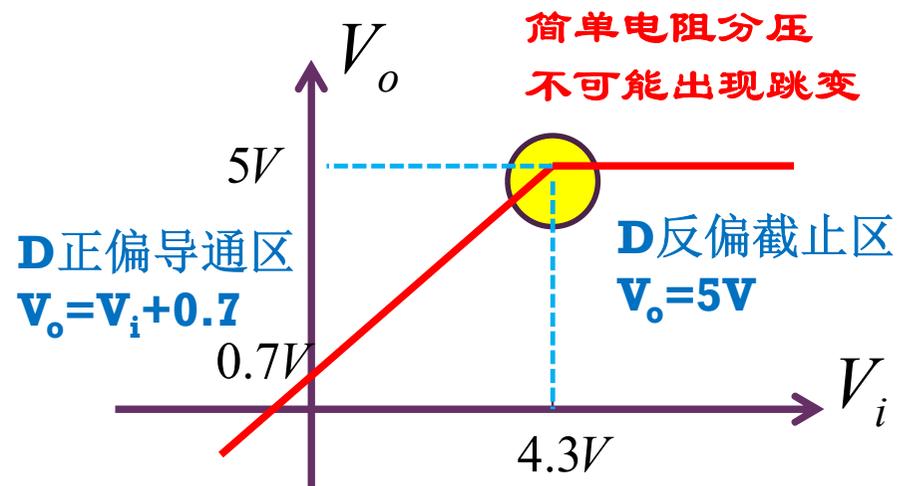
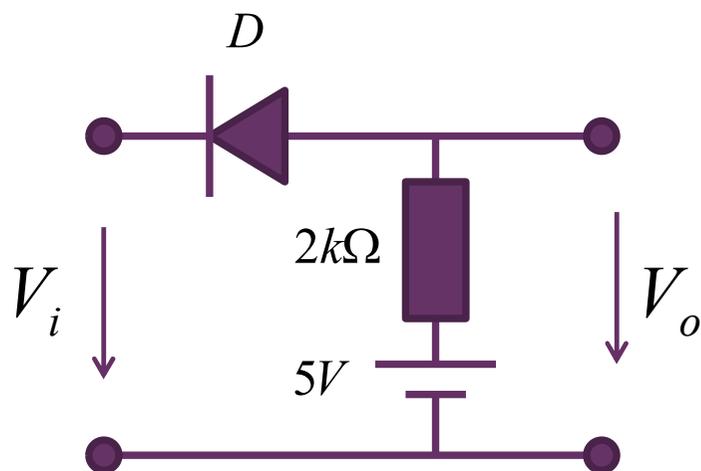
(c) 正偏恒压源模型



(d) 理想整流模型

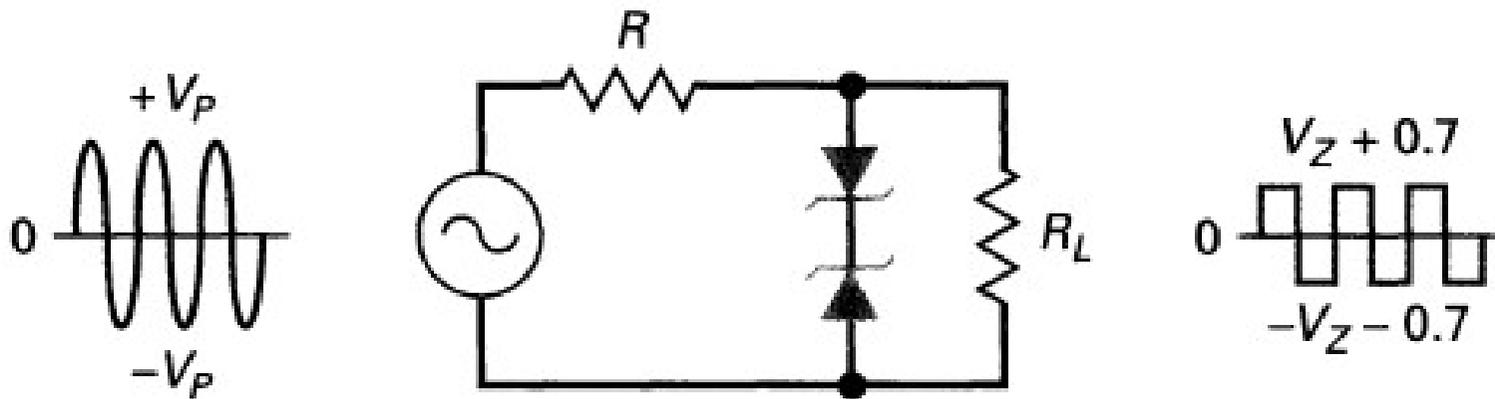
# 一般方法：先抠出二极管，再摁回去

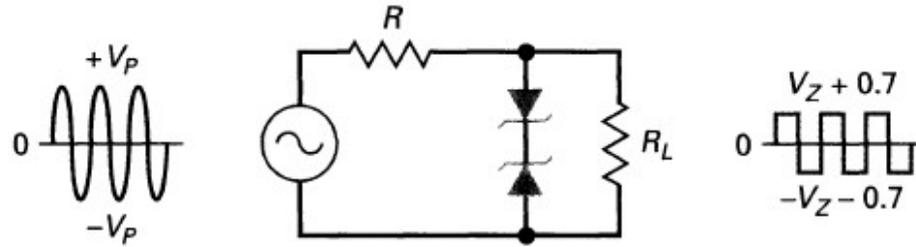
先假设二极管反偏截止，再确认假设是否成立



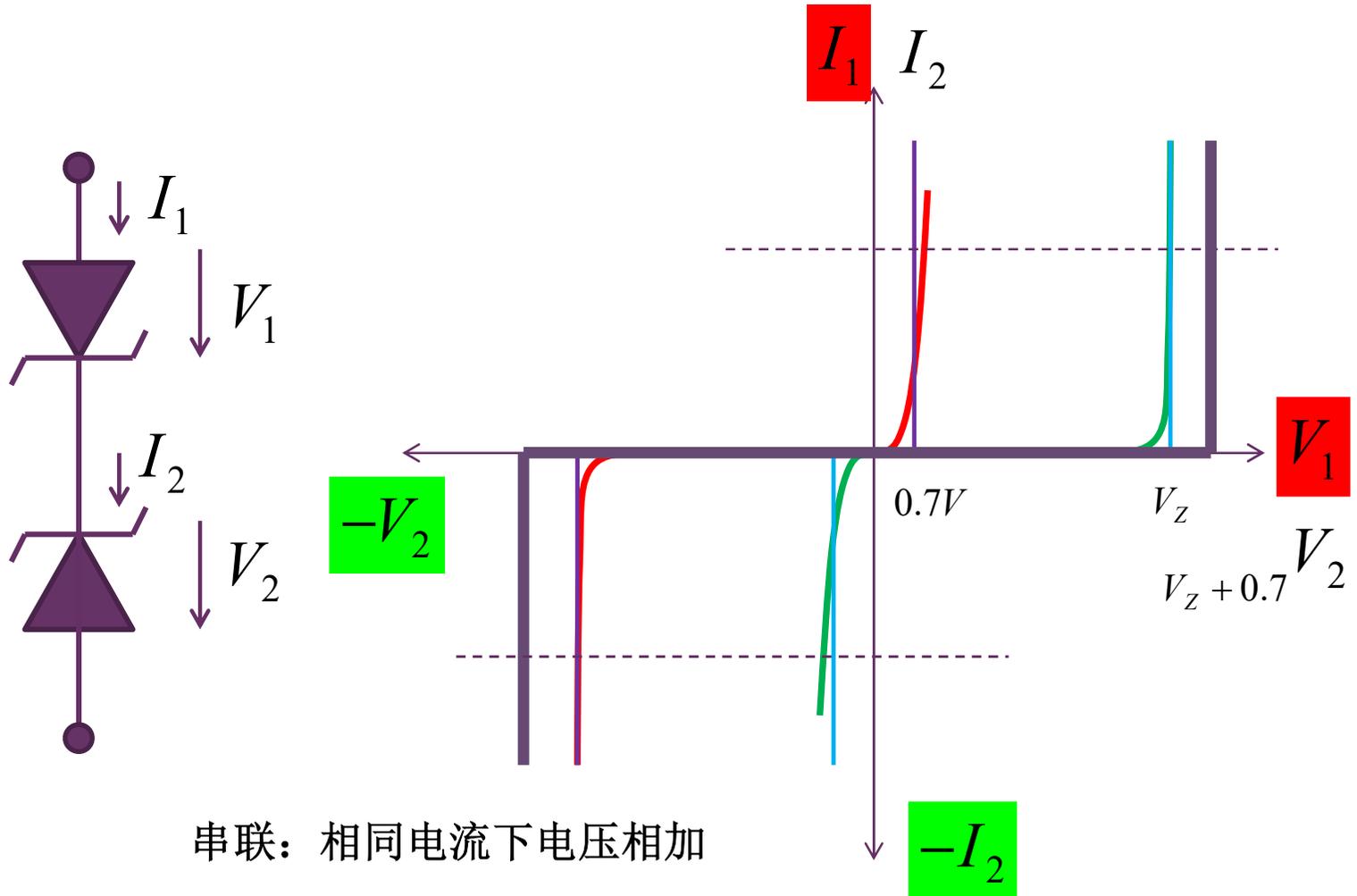
## 作业2.6 限幅电路

- 分析说明图示电路为什么有这样的输出电压波形？

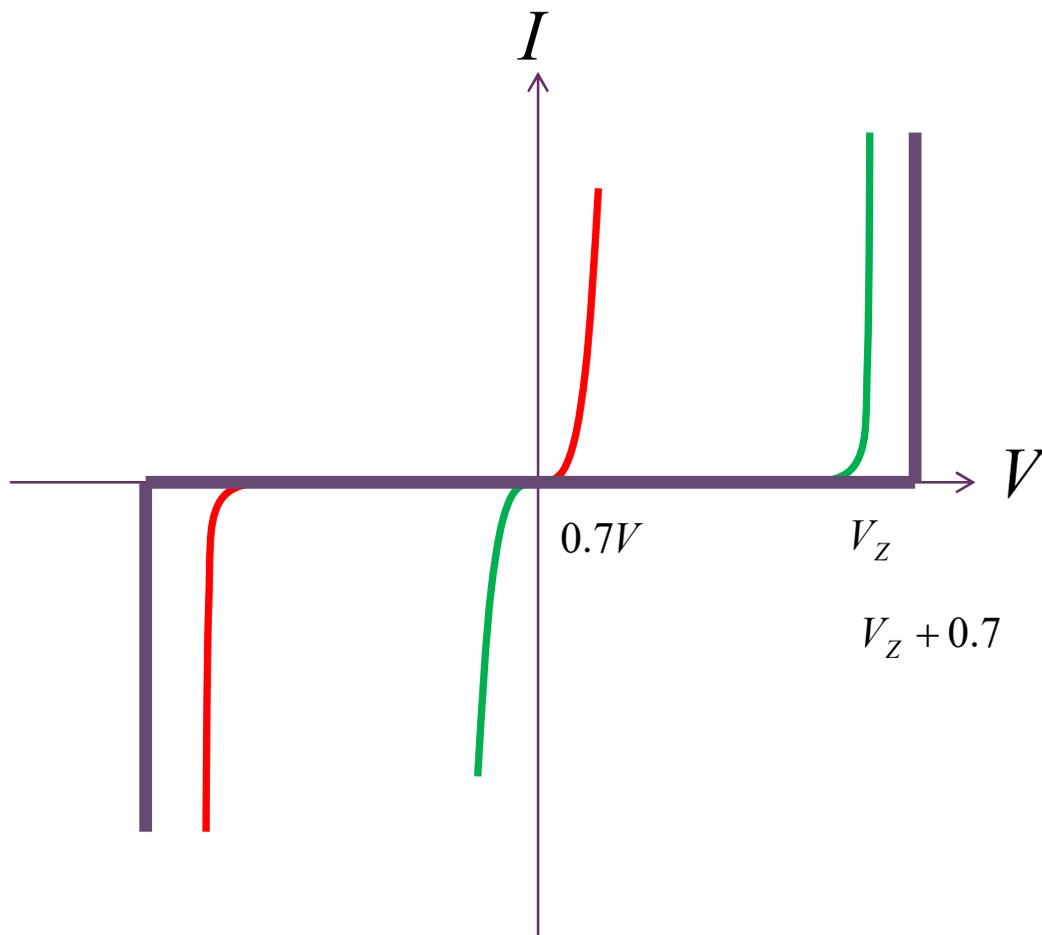
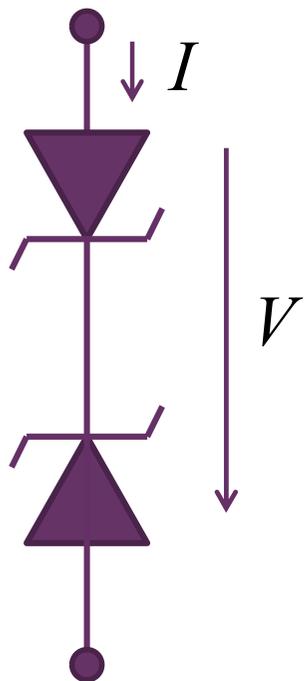




# 稳压二极管串联

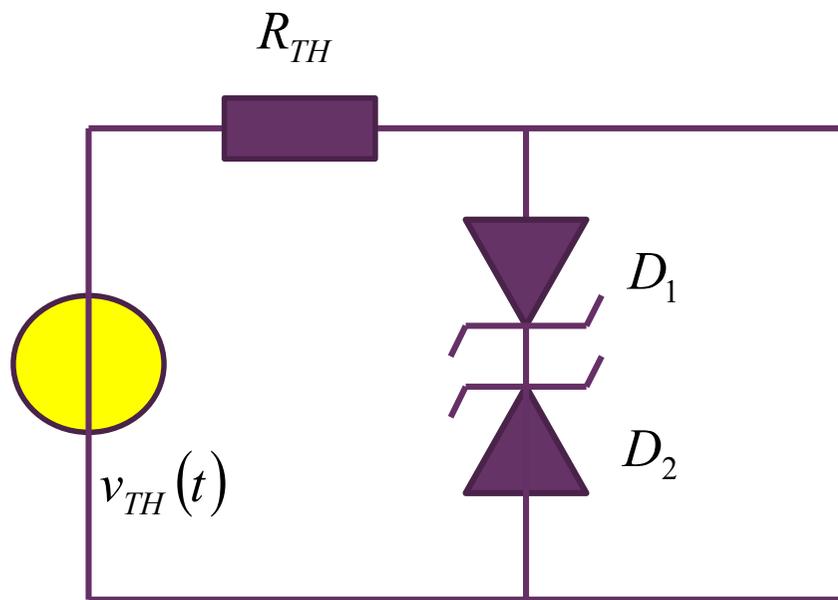
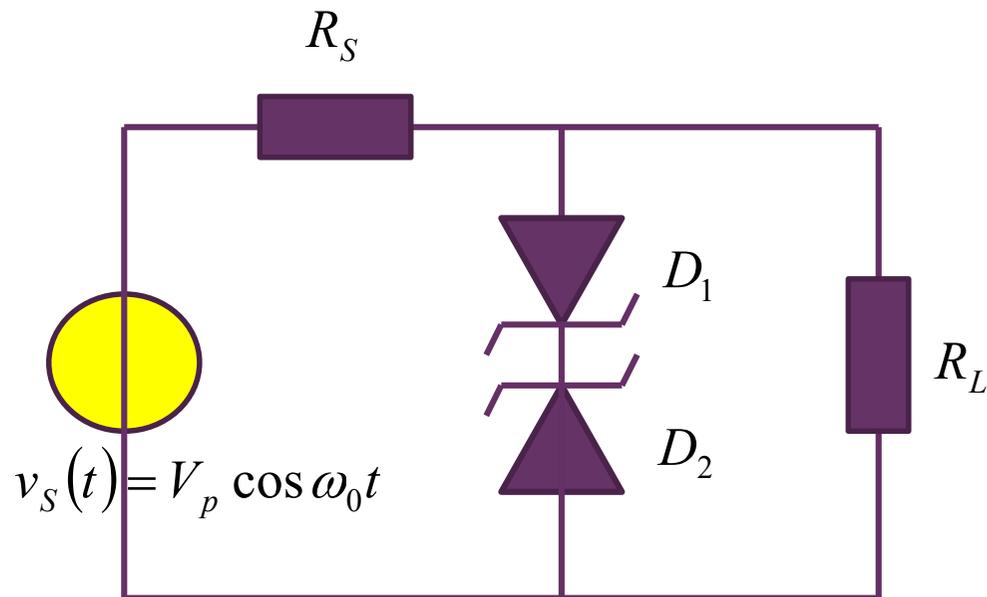


## 分段折线电路模型



$$\begin{cases}
 V = +V_Z + 0.7 & I > 0 & \text{恒压源} \\
 I = 0 & -V_Z - 0.7 < V < +V_Z + 0.7 & \text{开路} \\
 V = -V_Z - 0.7 & I < 0 & \text{恒压源}
 \end{cases}$$

# 线性非线性分离

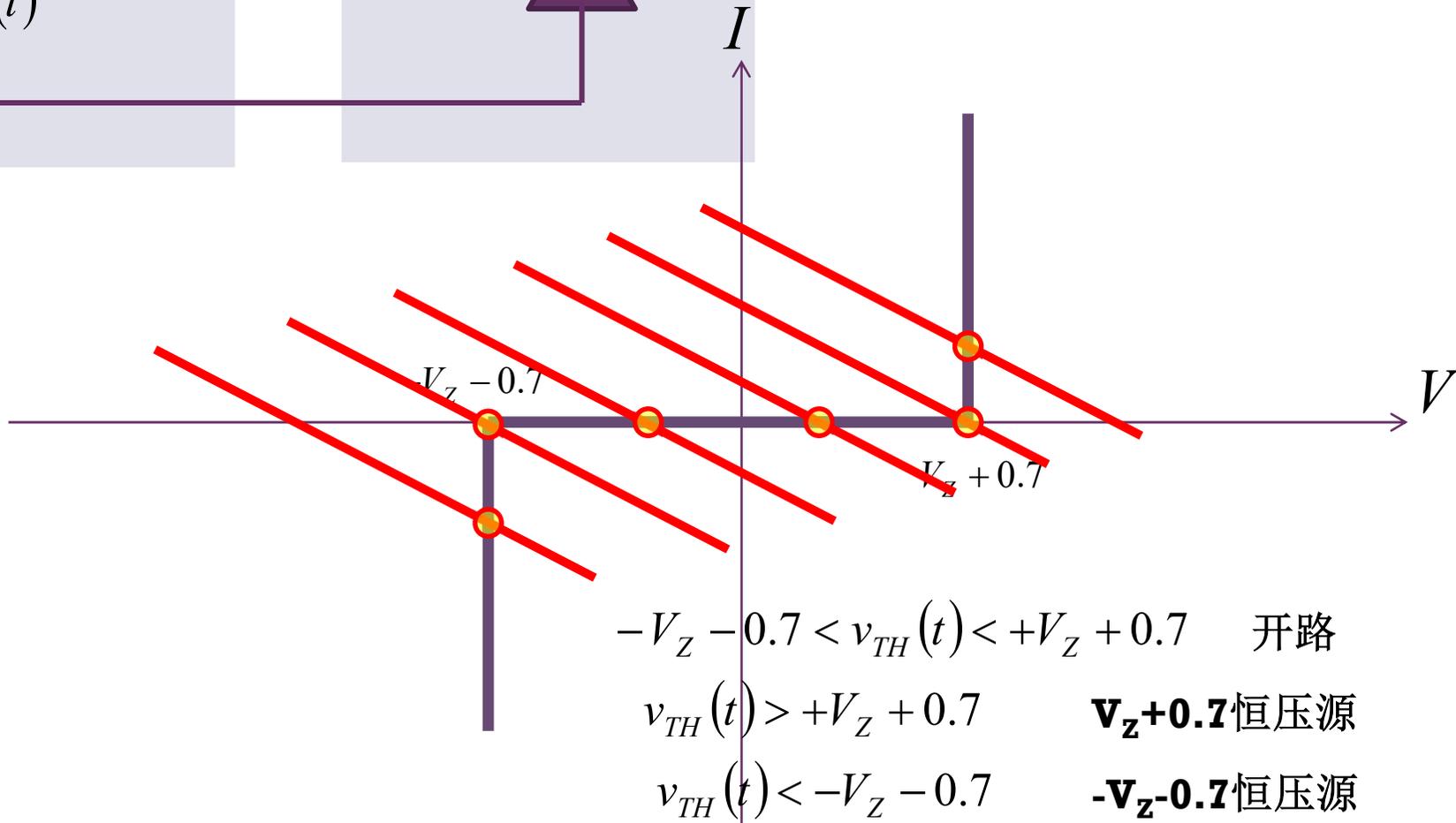
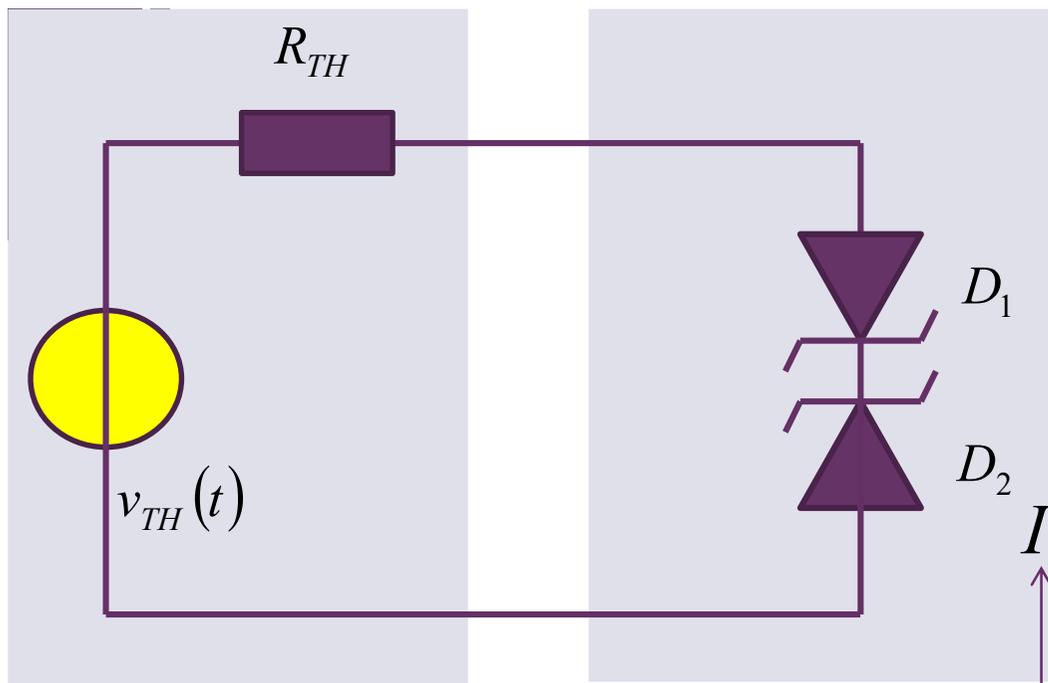


$$v_{TH}(t) = \frac{R_L}{R_L + R_S} v_S(t)$$

$$= \eta V_p \cos \omega_0 t$$

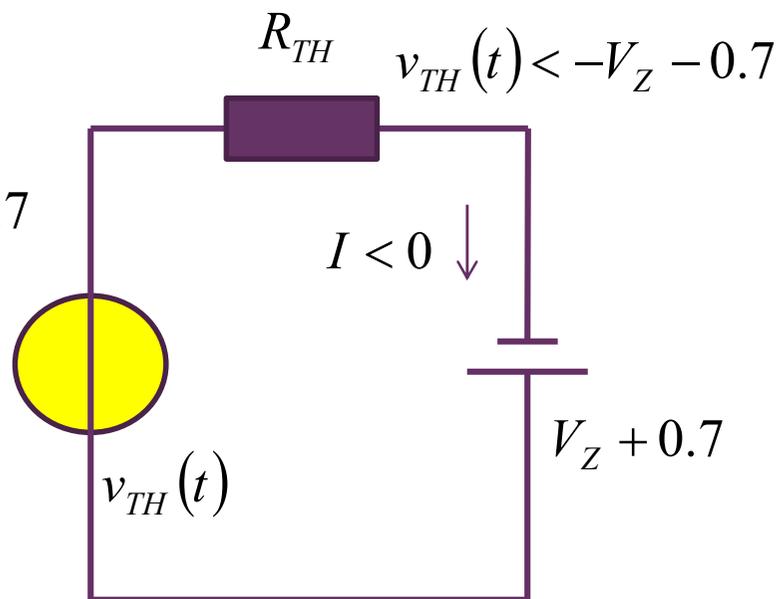
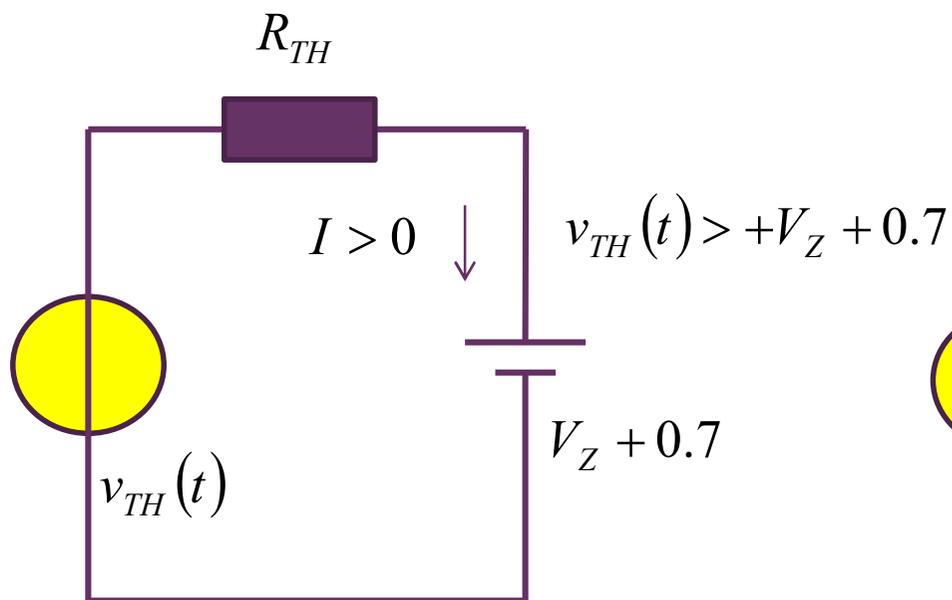
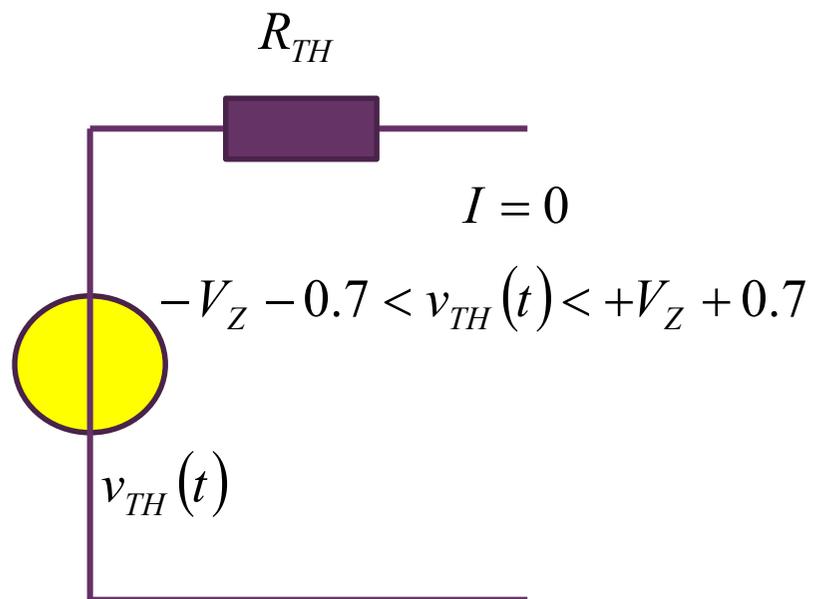
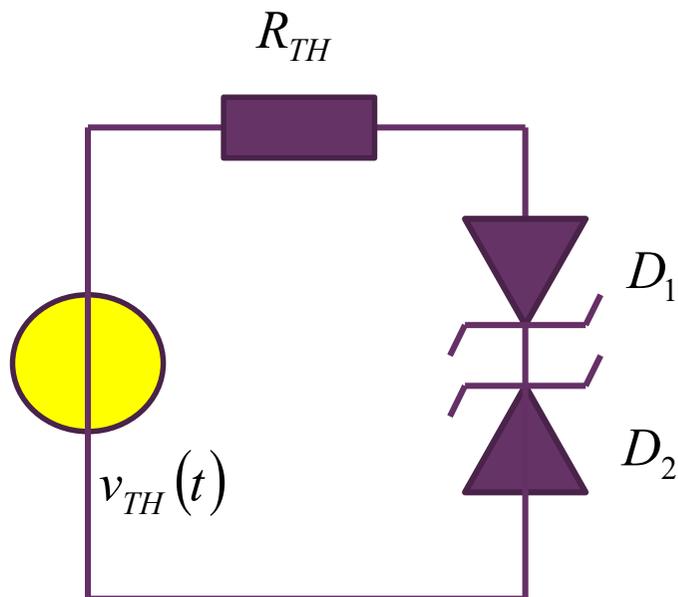
$$R_{TH} = \frac{R_L R_S}{R_L + R_S}$$

# 图解理解

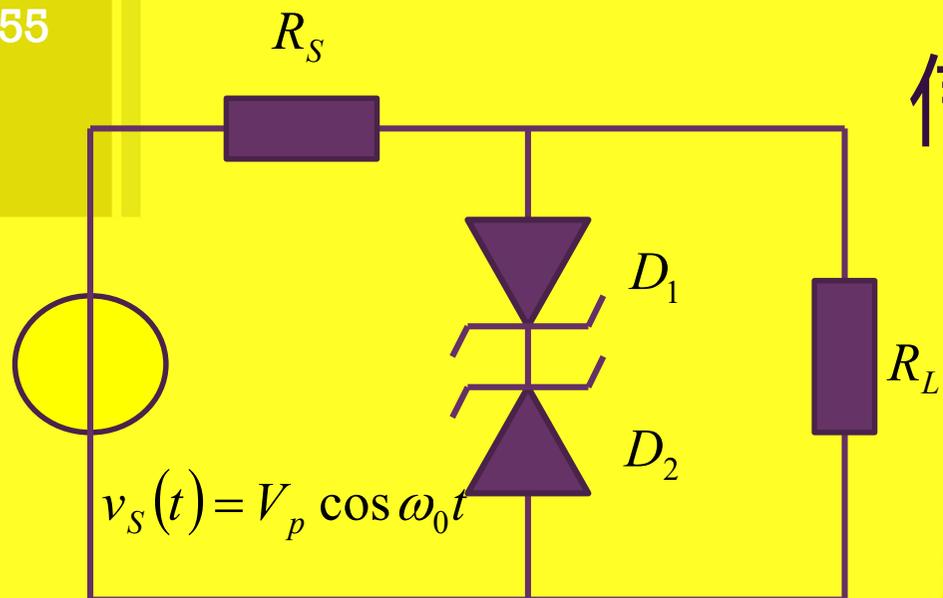


电路理解

不同分区采用不同模型



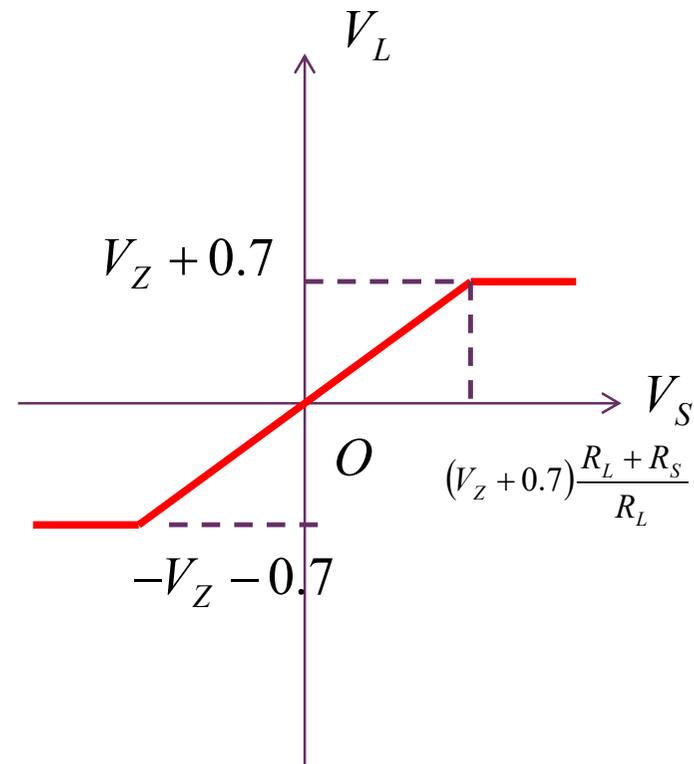
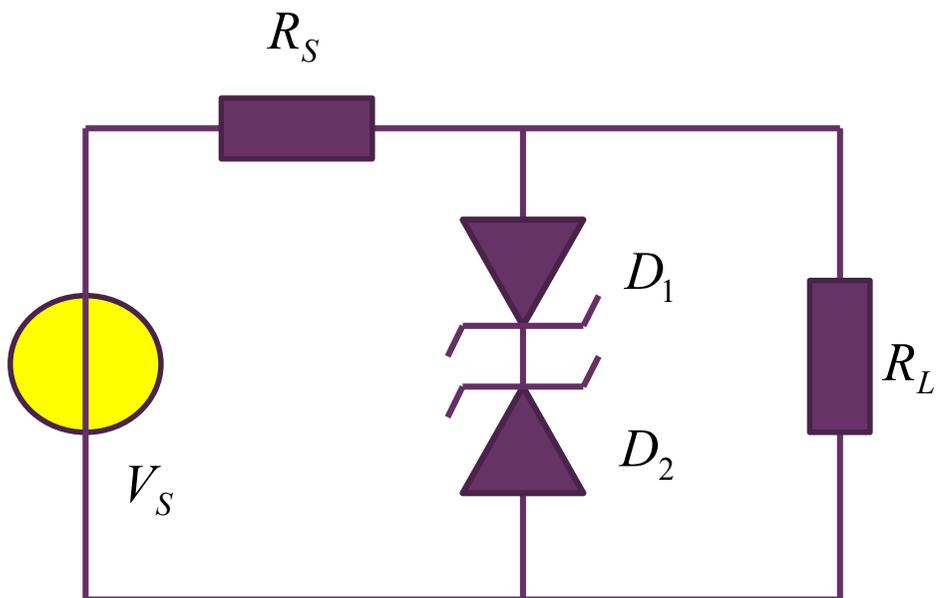
## 信号切顶


 $+V_Z + 0.7$ 
 $-V_Z - 0.7$ 

$v_S$  在某个范围之内，输出和输入为线性关系

幅度超过这个范围，则切顶；输入正弦信号幅度极大，输出切顶近似方波

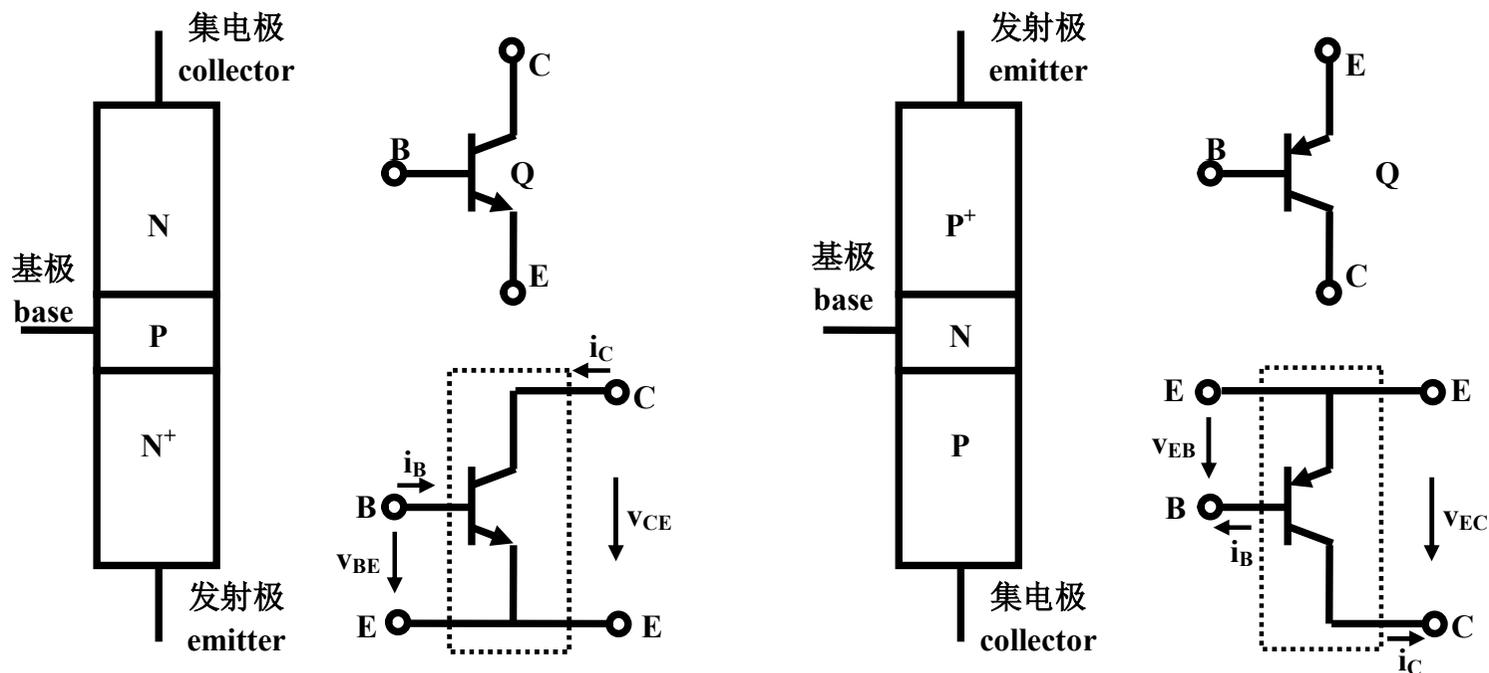
# 输入输出转移特性曲线



$V_S$ 在某个范围之内，输出和输入为线性关系；幅度超过这个范围，则切顶（饱和）

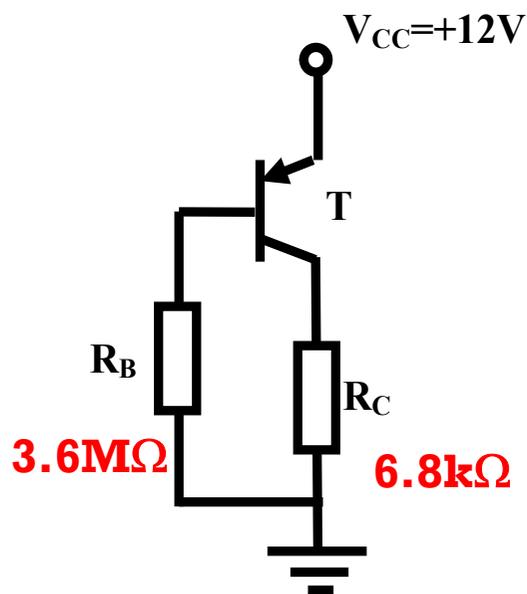
# 作业1 NPN和PNP

- 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

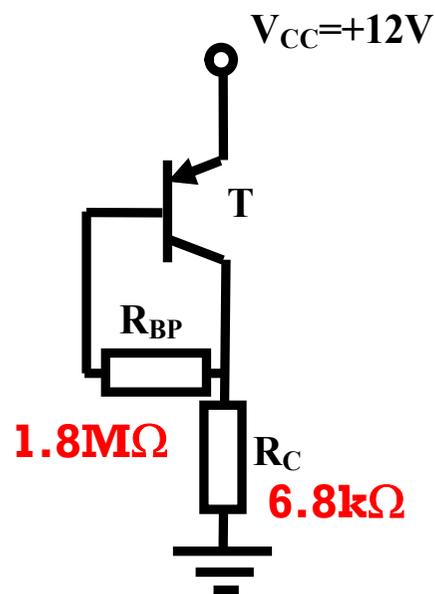


# 作业2 分立PNP-BJT的直流偏置

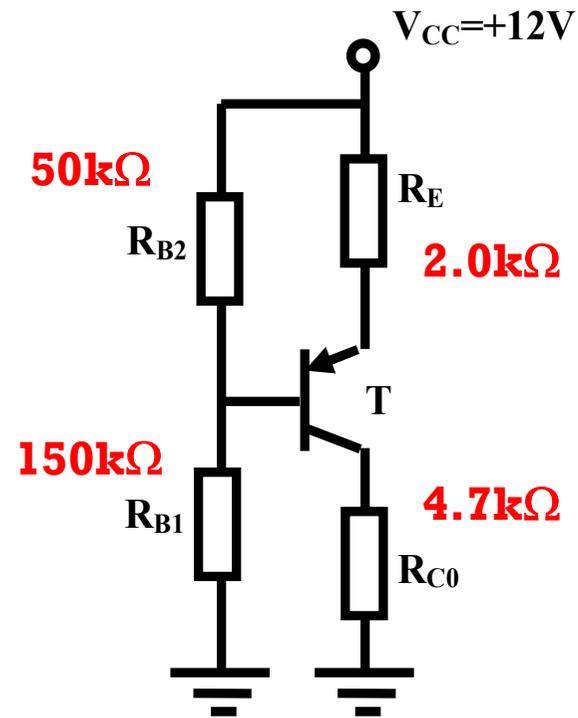
$\beta=150-400$



一般偏置



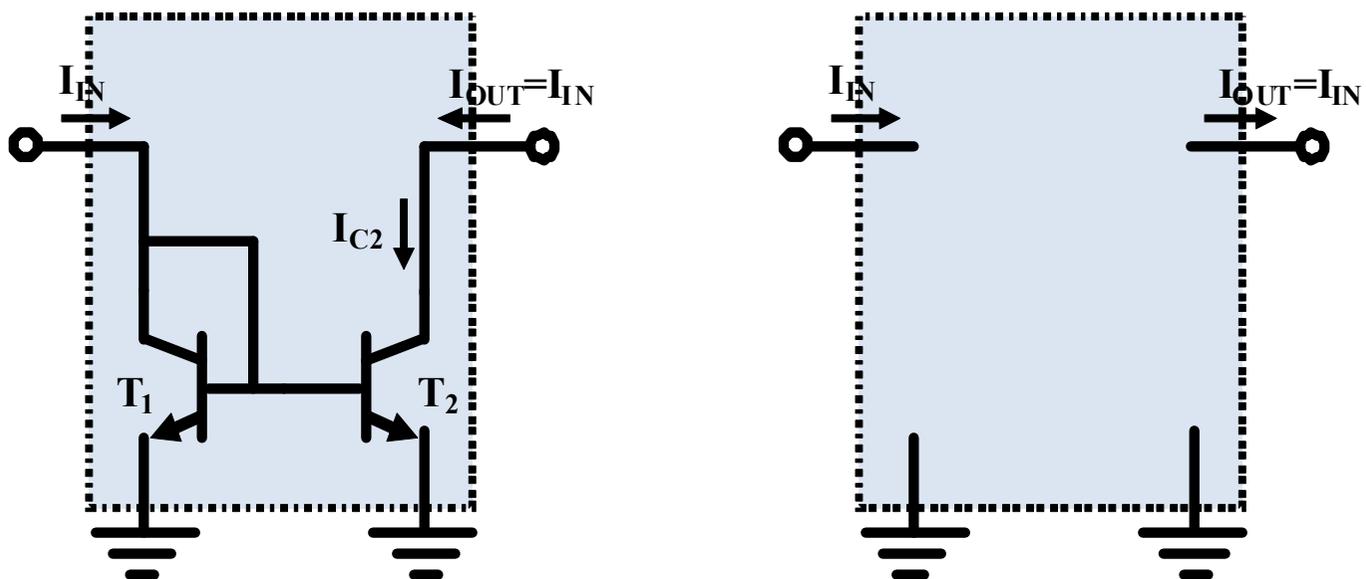
并联负反馈偏置



串联负反馈偏置  
分压偏置

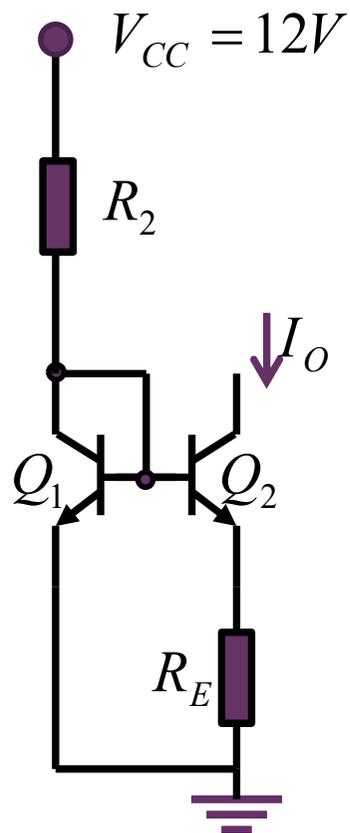
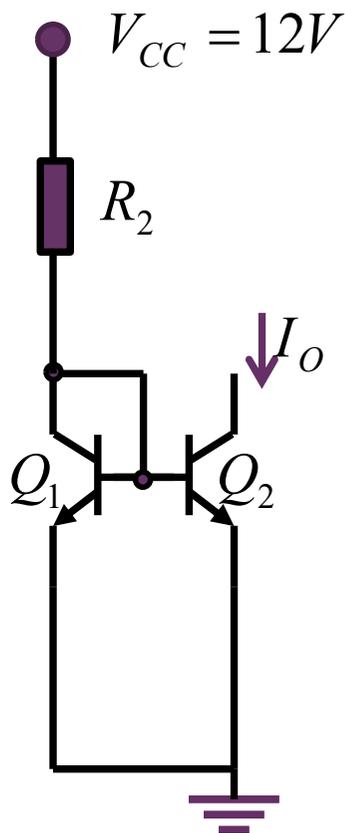
分析上述三个电路的BJT的直流工作点： $I_C=?V_{EC}=?$ 说明负反馈可以稳定直流工作点

# 作业3 电流反向



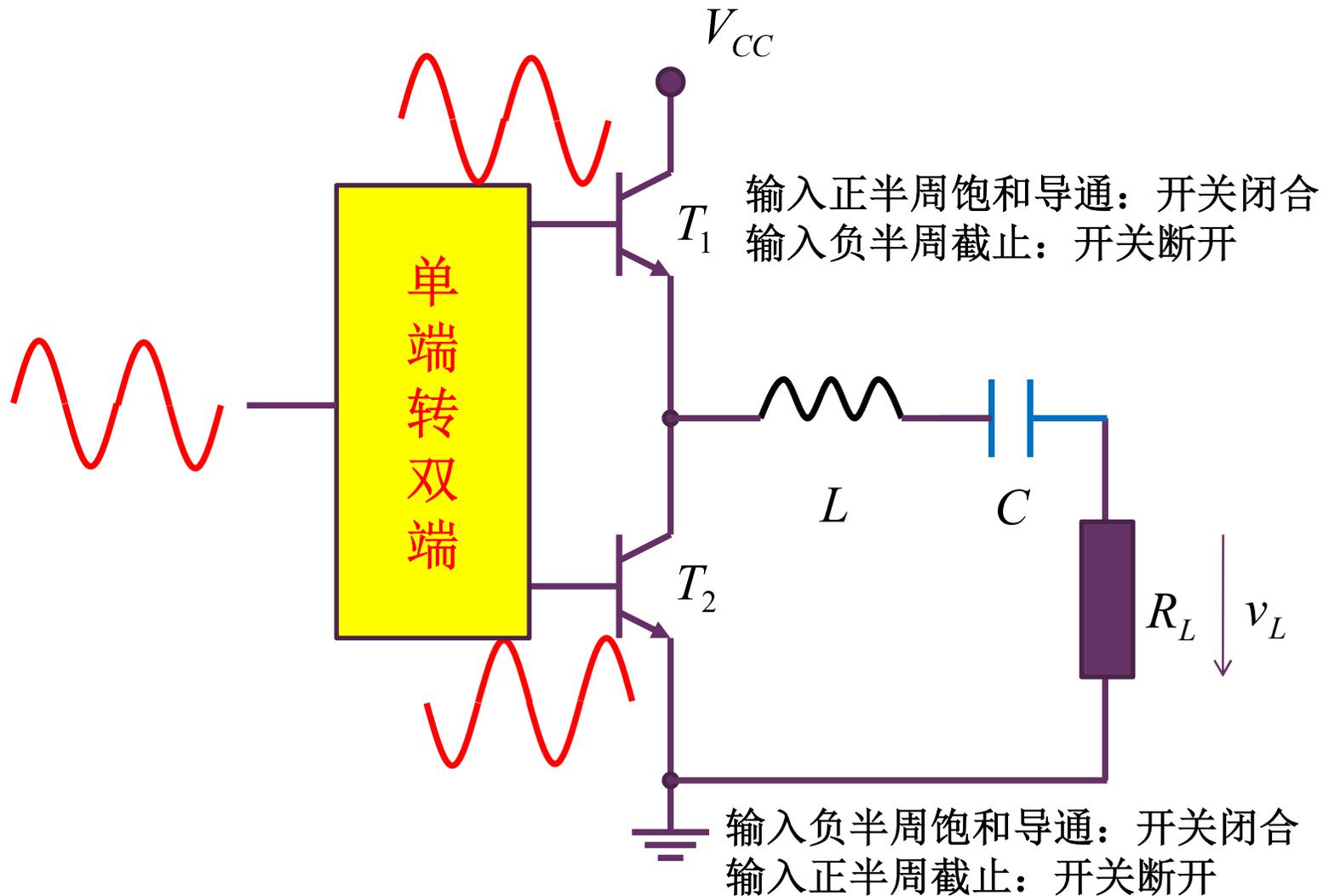
设计电路：使得流出电流等于流入电流

# 作业4 Widlar电流镜

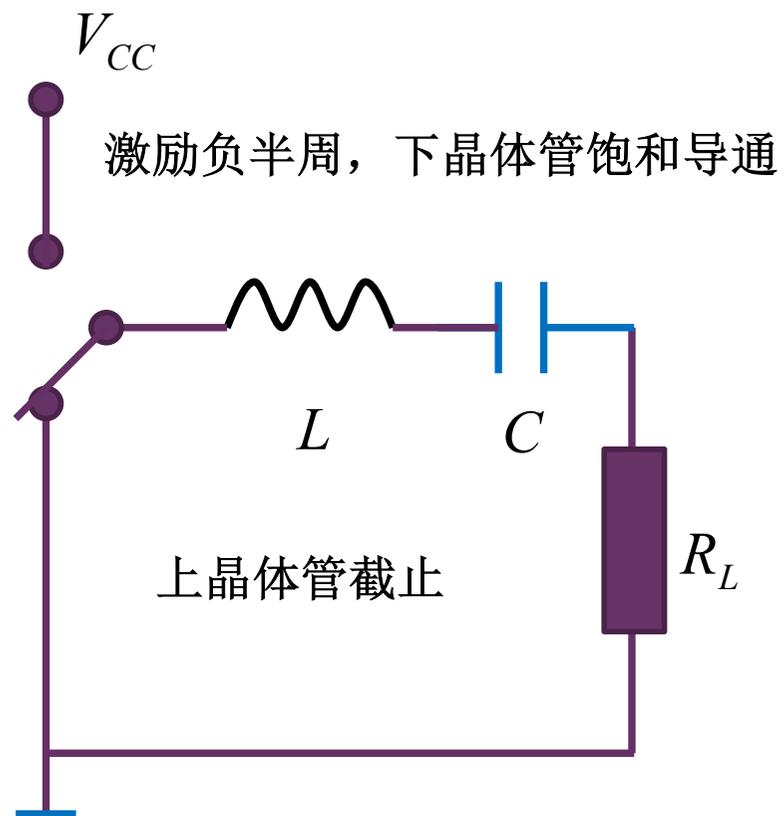
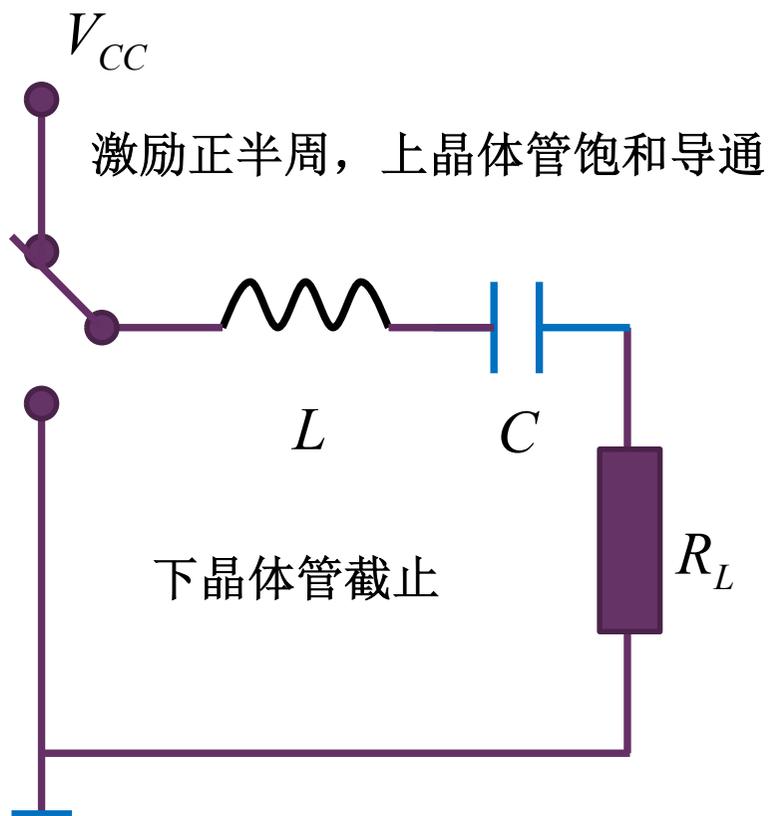


- 我们希望这两个电流镜都能够产生 $12\mu\text{A}$ 的电流输出，请给出你的设计：给出电阻阻值
- 假设晶体管在 $I_C=1\text{mA}$ 时的 $V_{BE}$ 压降为 $0.7\text{V}$
- （选作）说明微电流镜在产生微电流时较一般的电流源有哪些优点。

# 作业5 晶体管做开关

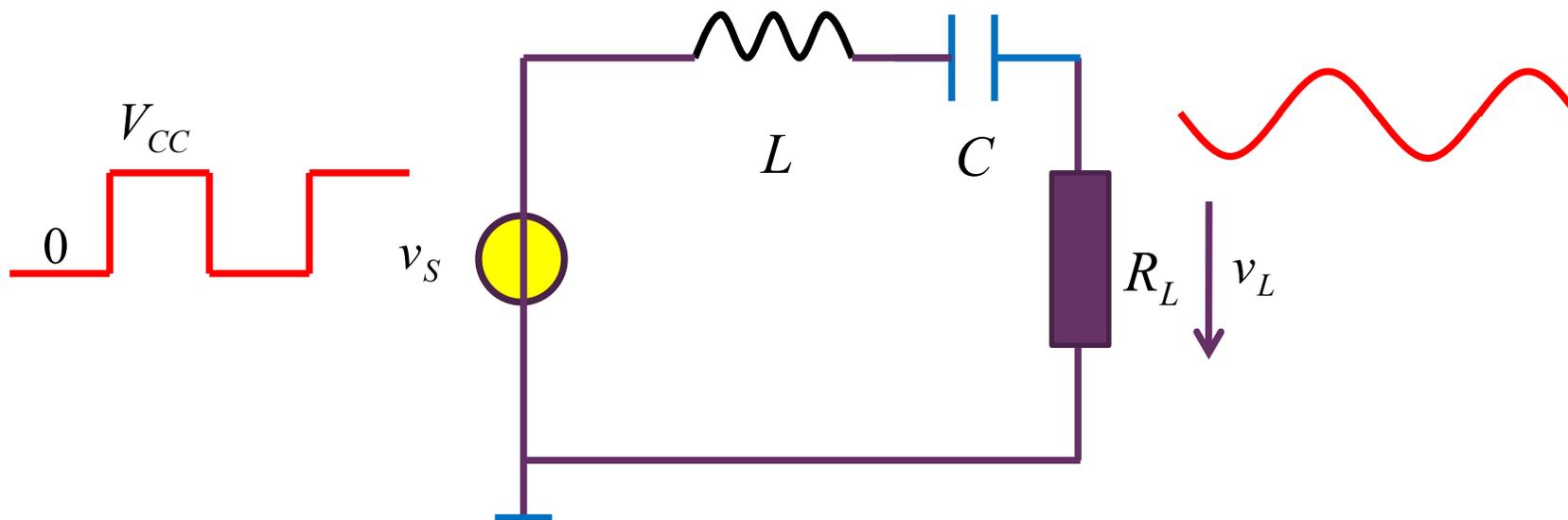
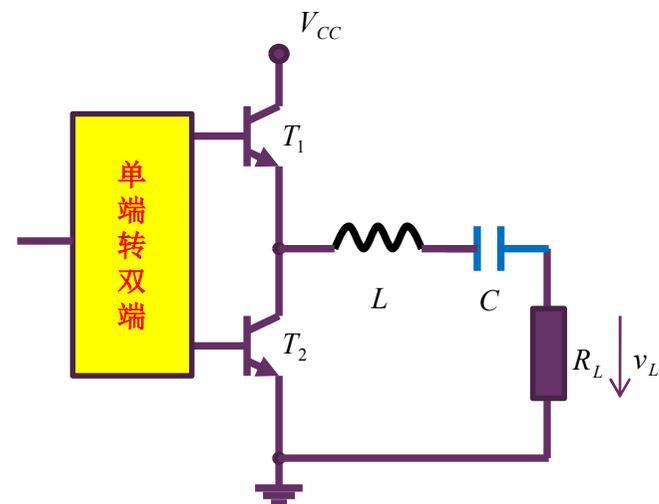


# 开关等效

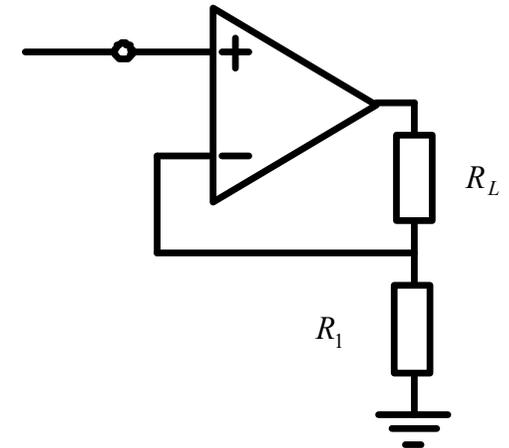
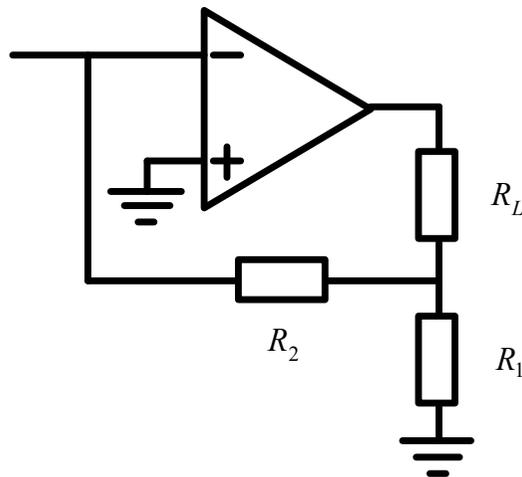
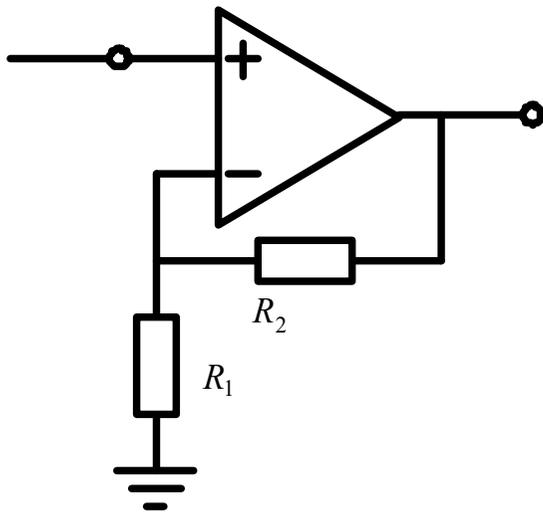
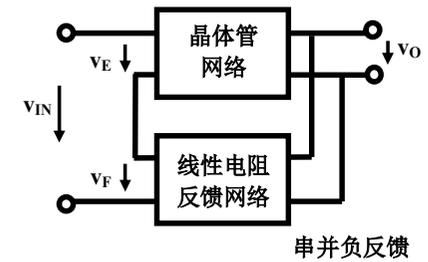
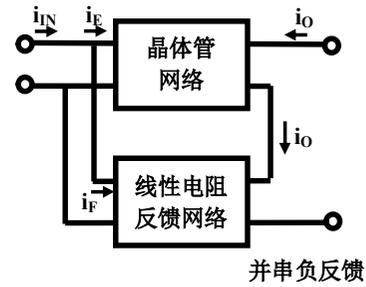
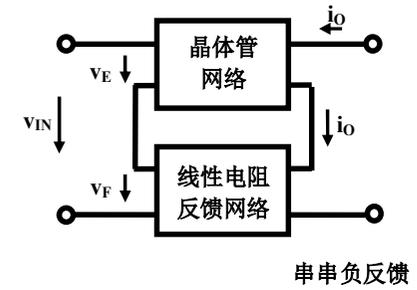
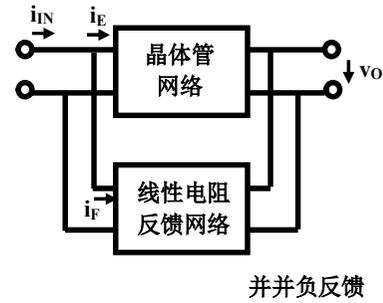
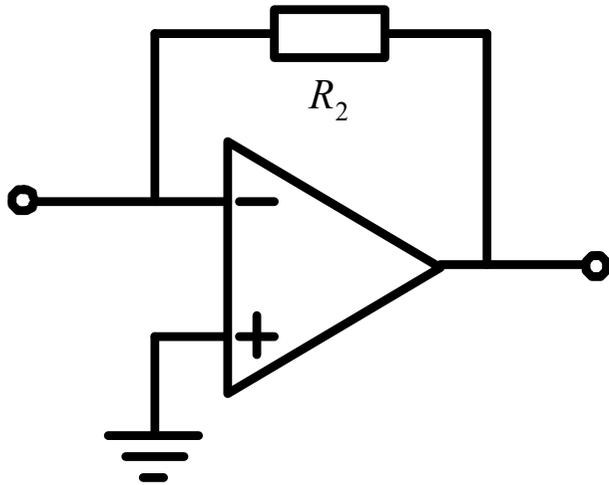


# D类逆变器 D类放大器

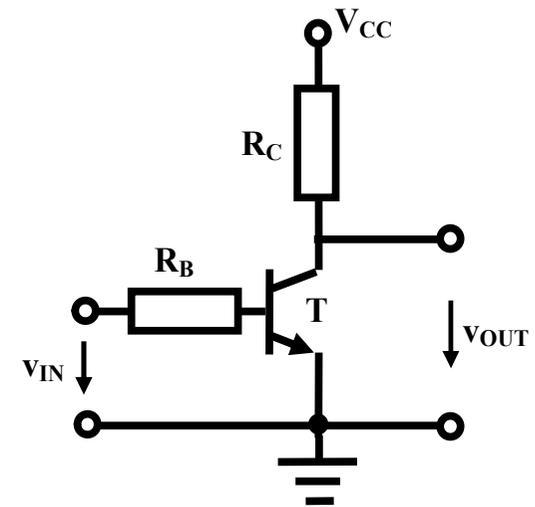
- 要想三次谐波分量低于基波分量40dB以上，谐振回路的Q值应取多大？



# 作业6 负反馈连接类型判定 (选作)



- 对于图示电路，可取 $R_B=1k\Omega$ ， $R_C=10k\Omega$ ， $V_{CC}=5V$ ，请仿真确认输入输出转移特性曲线
  - 对仿真出来的特性曲线进行分析，说明该曲线的哪个分段，晶体管位于哪个工作区？
  - 由晶体管分区电路模型分析输入输出转移特性曲线，和仿真曲线对比，偏差有多大？
  - $R_B$ 的作用是什么？可否不要 $R_B$ 电阻？



# 本节课内容在教材中的章节对应

- P1001-1008: A13 BJT晶体管受控机制
- P302-321: 4.3.3 BJT分段线性化