Lecture 16 – BJT-part1

Chapter 6 from **Microelectronic Circuits** Text by Sedra and Smith

Oxford Publishing

- 8.1 三极管的结构和工作原理
- 8.1.1 重点介绍NPN管的结构和工作原理
- 8.1.2 认识NPN管和PNP管的符号和结构差异
- 8.2 三极管的特性及其等效模型
- 8.2.1 输入特性、输出特性和转移特性
- 8.2.2 π型和T型等效电路（中频）
- 8.3 三极管放大电路的构成及其分析
- 8.3.1 直流偏置电路及其分析
- 8.3.2 三种接法放大电路的分析计算

Introduction

- **IN THIS CHAPTER YOU WILL LEARN**
  - The physical structure of the bipolar transistor and how it works. 三极管的物理结构
  - How the voltage between two terminals of the transistor controls the current that flows through the third terminal, and the equations that describe these current-voltage relationships. 三极管的“电压电流约束关系”
  - How to analyze and design circuits that contain bipolar transistors, resistors, and dc sources. 三极管电路DC分析

Introduction

- This chapter examines another three-terminal device.
  - **bipolar junction transistor**
  - Presentation of this material mirrors chapter 5.
- BJT was invented in 1948 at Bell Telephone Laboratories.
  - Ushered in a new era of solid-state circuits.
  - It was replaced by MOSFET as predominant transistor used in modern electronics.

三极管的结构

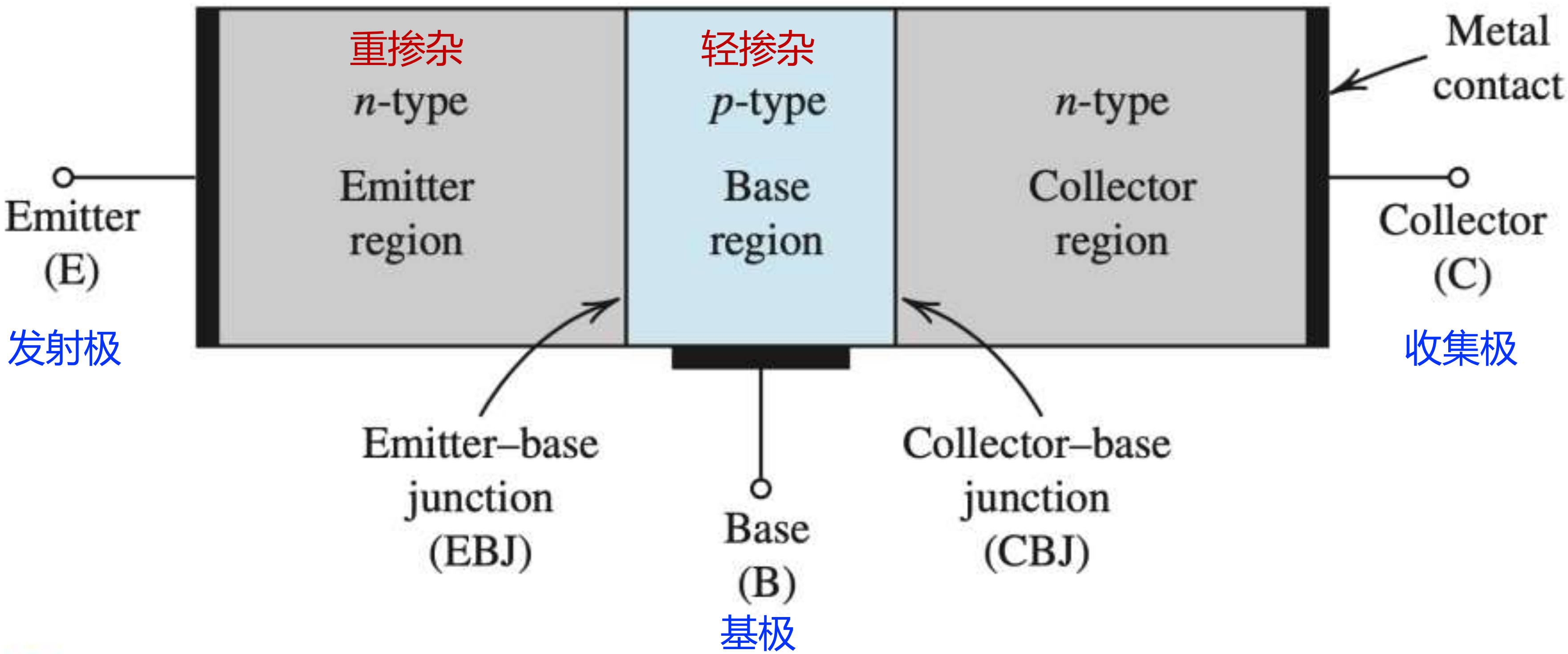
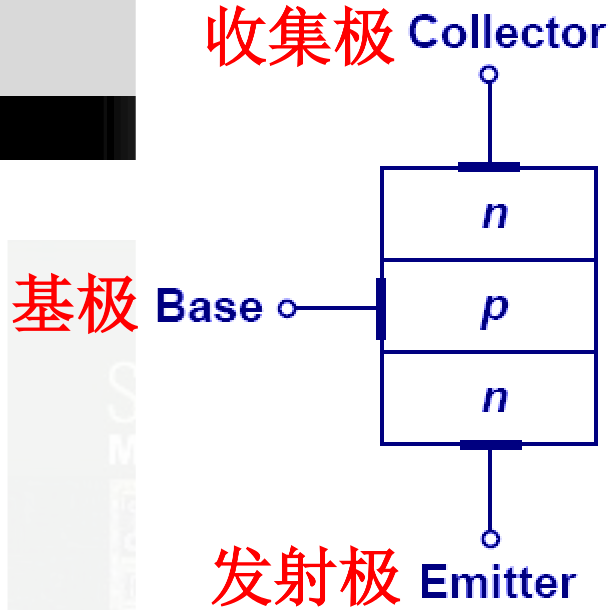


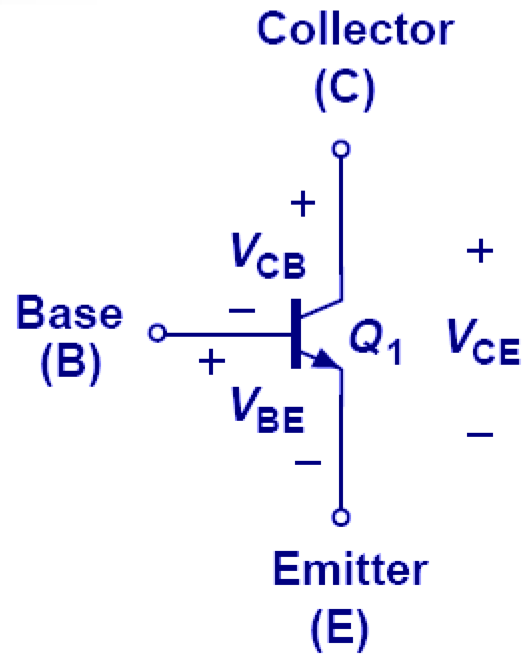
Figure 6.1 A simplified structure of the *npn* transistor.

三极管的结构和符号

三极管的电路符号用“Q”，而MOSFET用“M”，箭头标在发射极，方向表示电流方向



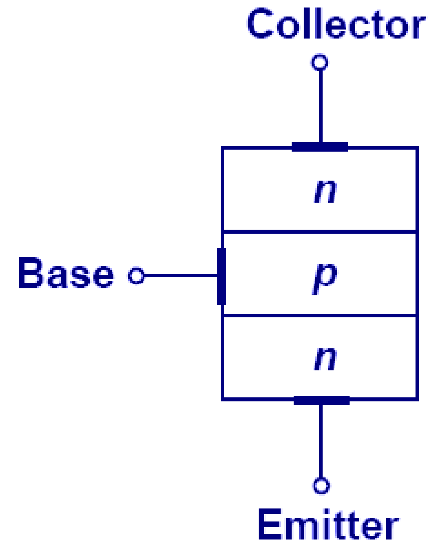
(a)



(b)

- 三极管可看成由不同掺杂半导体构成的三明治结构，如上图所示的npn，另一种可能是pnp；（两侧的掺杂性质一致，并与中间的掺杂性质相反）

注意和MOSFET的区别：
1.MOSFET 能实现放大功能的区域称为“饱和区”
2.Bipolar 能实现放大功能的区域称为“放大区”



(a)

- Transistor consists of two *pn*-junctions:
  - **emitter-base** junction (EBJ)
  - **collector-base** junction (CBJ)
- Operating mode depends on biasing.
  - **active** mode – used for amplification ①放大区
  - **cutoff** and **saturation** modes – used for switching. ②截止区；③饱和区 和Mos管反一下

Table 6.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

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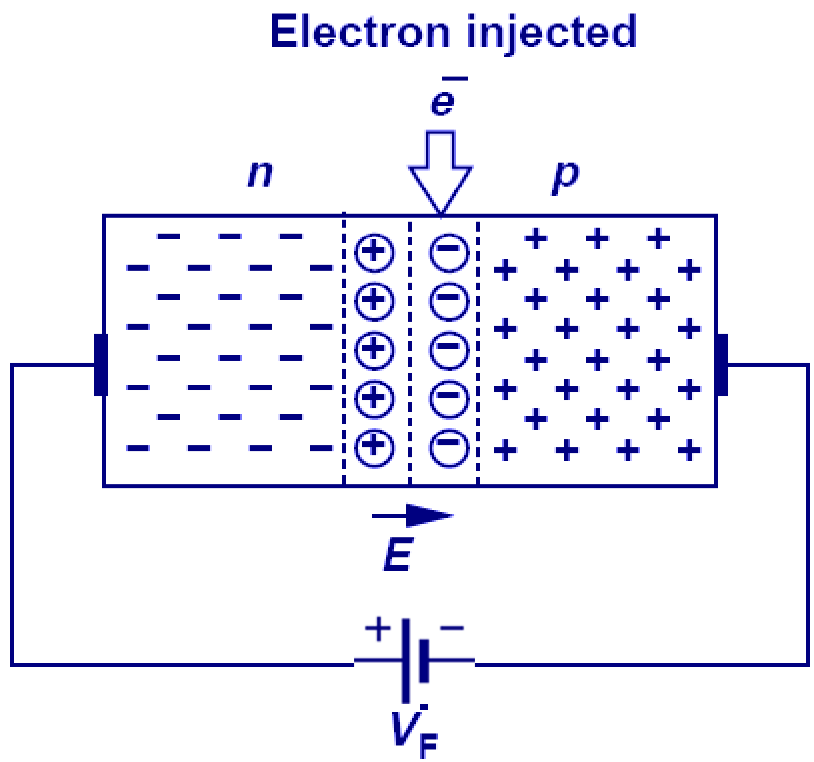
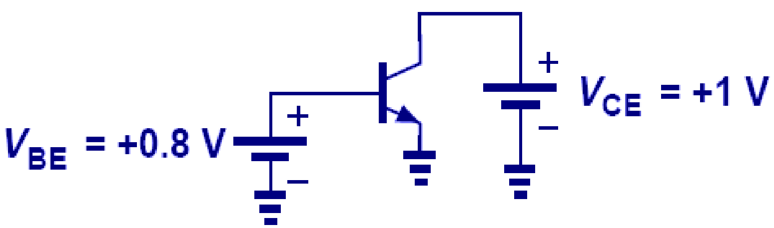
载流子的注入



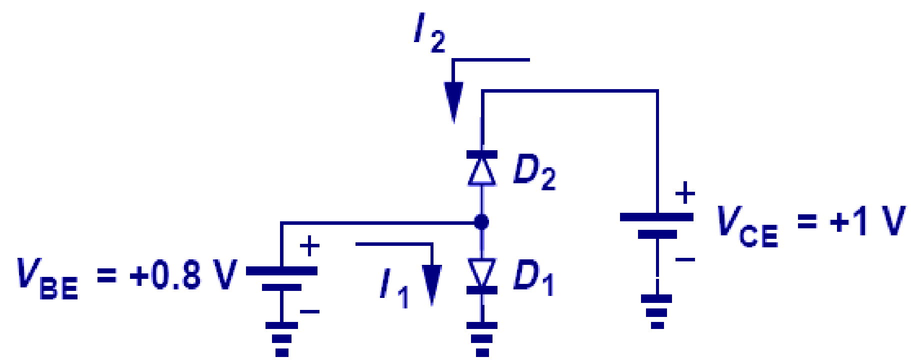
思考：如果有自由电子注入到反偏pn结的耗尽区，会怎样？

- 反偏pn结在耗尽区会形成一个较强的电场，电子若注入到（暂时不考虑如何注入）耗尽区，就会在电场作用下，迅速被扫到左侧n区域；
- 这一现象是三极管工作的基础；

Forward Active Region
（放大区）



(a)



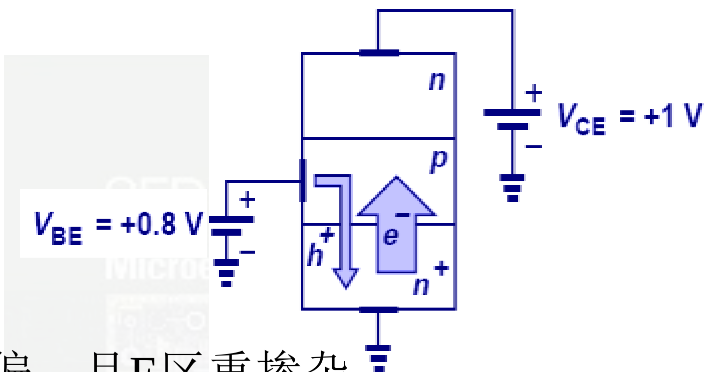
(b)

简单的两个二极管相连不会有放大特性，因此，三极管必有特殊的结构以实现放大性能

- 放大区的定义: BE正偏（ $V_{BE} > 0$ ）,BC反偏（ $V_{BC} < 0$ ）.
- 但三极管并非简单的两个二极管的相连（为何？）

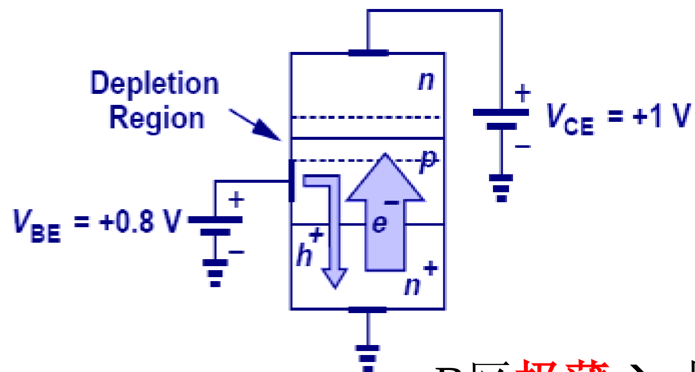
三极管的工作原理（放大区）

特殊性在于：
基区特别薄（约10nm）



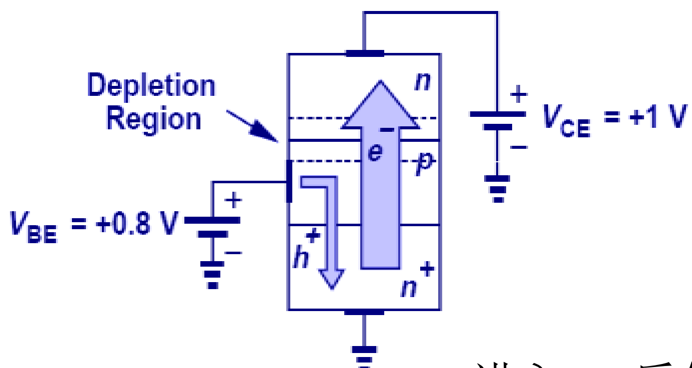
(a)

BE正偏，且E区重掺杂
→ 大量电子从E进入B，
少量空穴从B进入E



(b)

B区极薄→ 大部分电子可以到达BC反偏pn结的耗尽区（即大量电子被注入到反偏pn结的耗尽区）



(c)

进入BC反偏pn结耗尽区的电子被迅速扫到C区

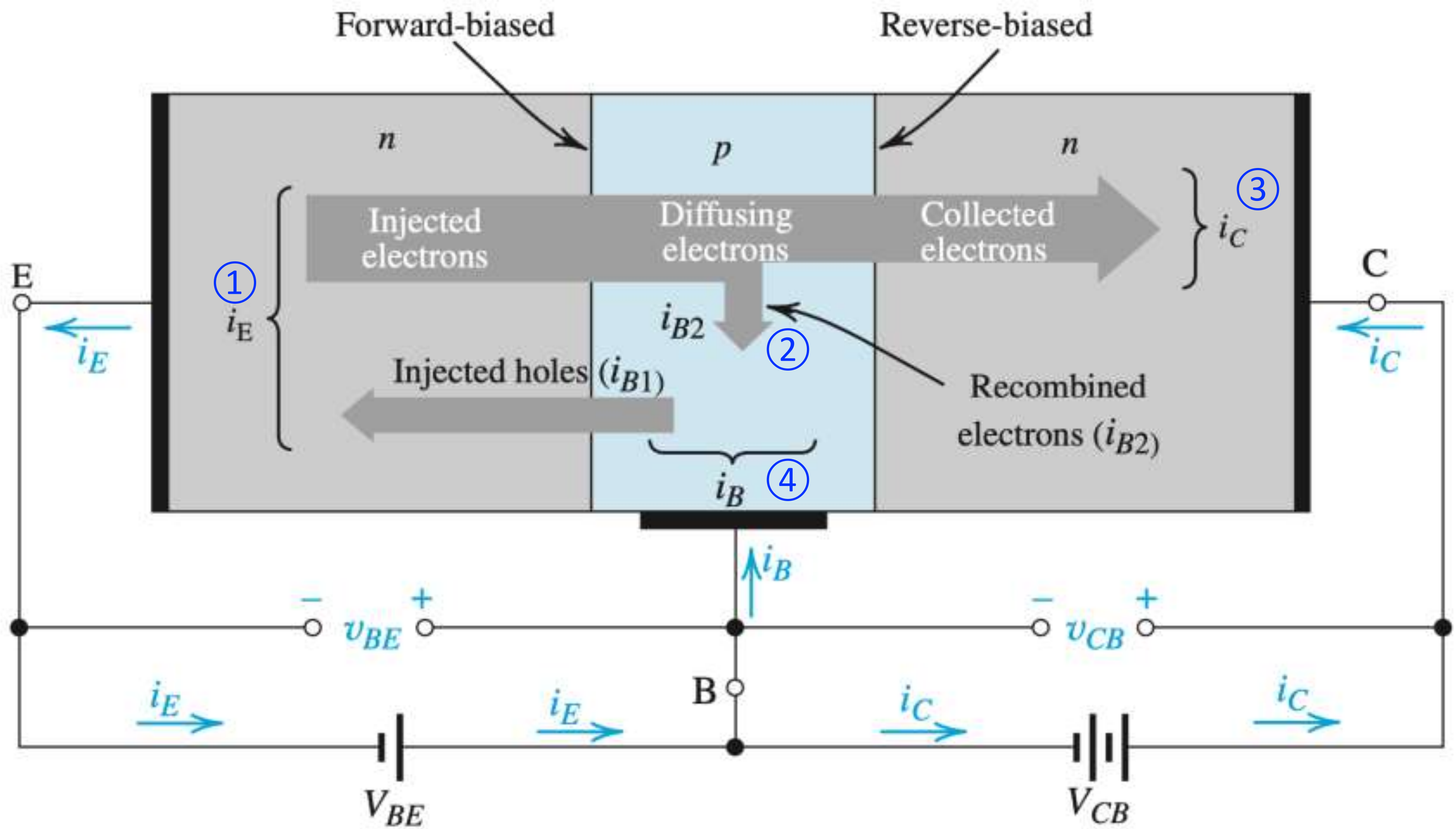


Figure 6.3 Current flow in an *npn* transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)

① 发射极电流 i_E 由两部分组成，但主要是电子电流【三极管的工作需要两种载流子参与，所以叫Bipolar】
② 电子电流在经过基区时，一小部分被空穴复合，形成 i_{B2}
③ 电子电流大部分到达收集极，形成i_C
④ i_{B1} 和 i_{B2} 组成 i_B

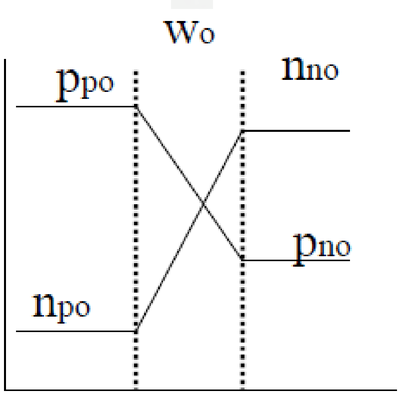
Q： How about MOSFET?
A： 一种，所以MOSFET也叫unipolar

补充：PN结正偏、反偏时少子浓度的分布

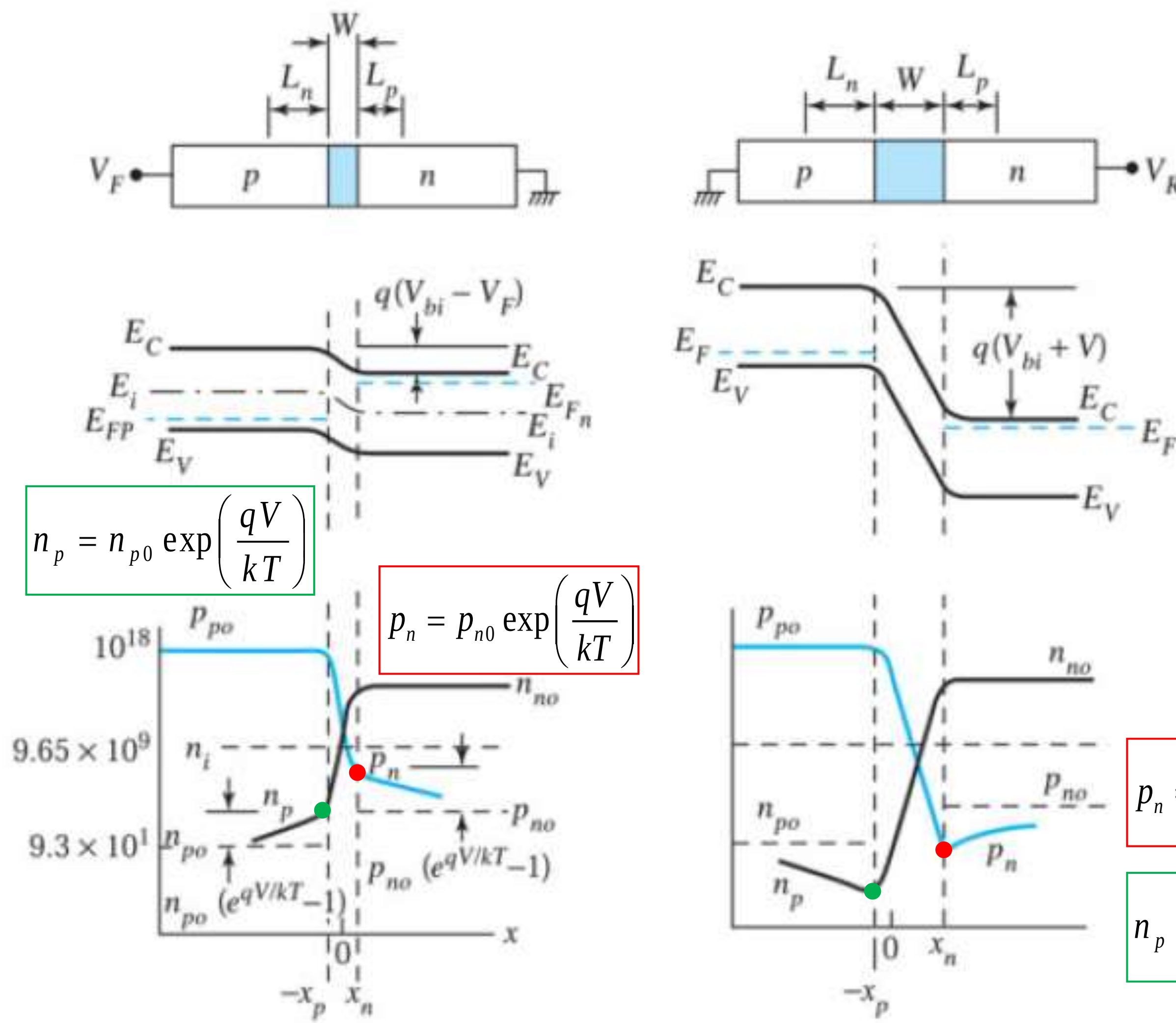
不作要求

重点关注：

耗尽区边界-x_p, x_n的少子浓度



Thermal equilibrium



$$n_p = n_{p0}\exp\left(\frac{qV}{kT}\right)$$

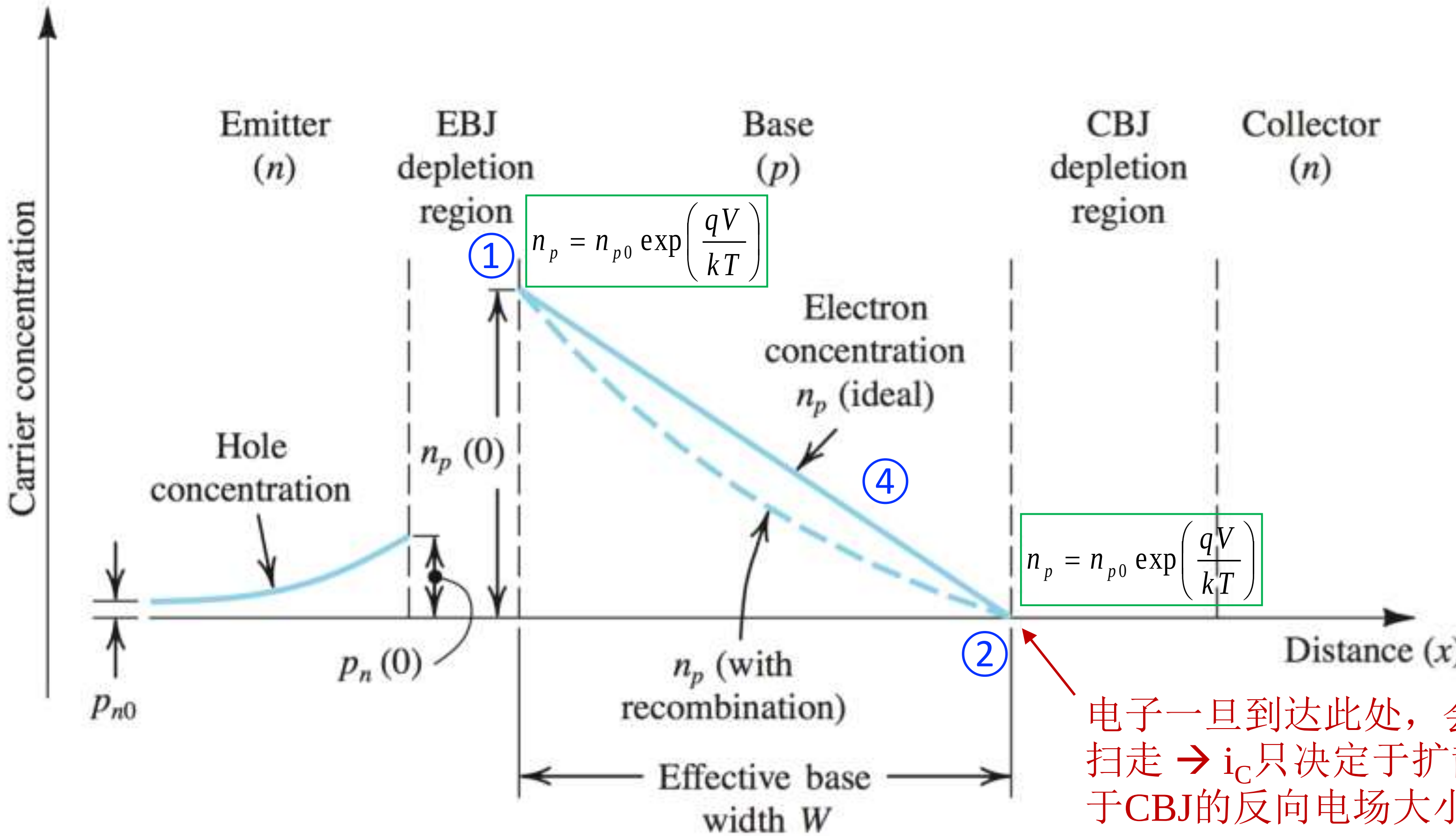
$$p_n = p_{n0}\exp\left(\frac{qV}{kT}\right)$$

$$p_n = p_{n0}\exp\left(\frac{qV}{kT}\right)$$

$$n_p = n_{p0}\exp\left(\frac{qV}{kT}\right)$$

(a)正偏，V>0 (b)反偏，V<0

Depletion region, energy band diagram and carrier distribution. (*a*) Forward bias. (*b*) Reverse bias.



电子一旦到达此处，会被迅速扫走 → i_C只决定于扩散电流，于CBJ的反向电场大小无关

Figure 6.4 Profiles of minority-carrier concentrations in the base and in the emitter of an *npn* transistor operating in the active mode: $v_{BE} > 0$ and $v_{CB} \geq 0$.

①正偏pn结在p侧的电子浓度较高 （V>0）
②反偏pn结在p侧的电子浓度很低 （V<0） ，≈0
③基区电子浓度存在梯度 → 形成扩散电流
④基区很薄 → 电子浓度的分布曲线近似为线性

EBJ的面积

$$I_n = A_E q D_n \frac{dn_p(x)}{dx} = A_E q D_n \left(-\frac{n_p(0)}{W}\right)$$

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

$$I_S = A_E q D_n n_{p0} / W$$

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集电极电流

正偏电压影响很大，BC只需反偏即可

再观察一下：

I_C受V_{BE}影响巨大，但不受V_{CE}的影响 → 理想的压控电流源

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

$$\left.\begin{aligned} I_S &= A_E q D_n n_{p0}/W \\ n_{p0} &= n_i^2/N_A \end{aligned}\right\} \quad I_S = \frac{A_E q D_n n_i^2}{N_A W}$$

基区掺杂浓度

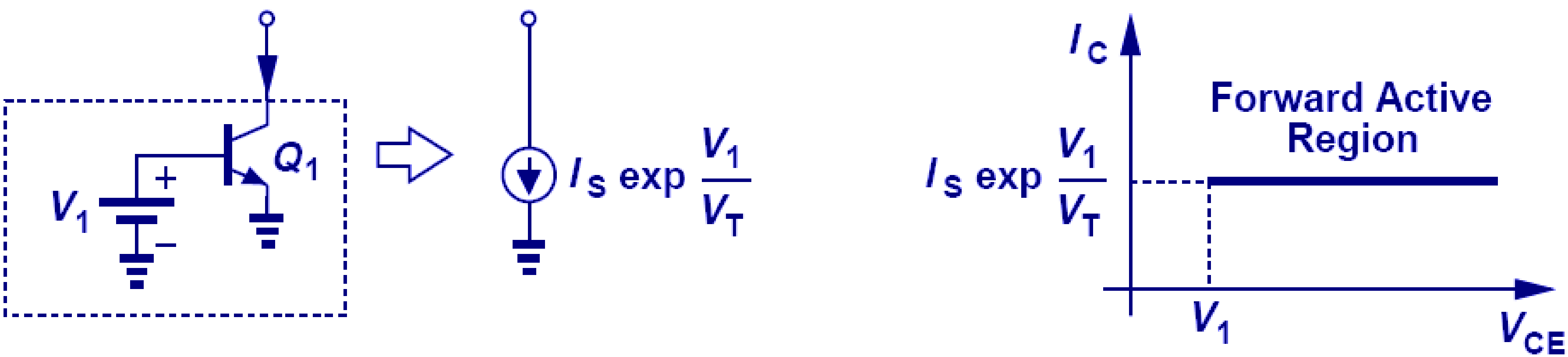
- I_S与基区宽度W成反比
- I_S与发射极结面积A_E成正比
- I_S与n_i^2成正比，强温度相关性

似曾相识？

与二极管的I/V特性一致

不足为奇，因为BE本来就是一个正偏的二极管

恒流源特性（I_C不随V_{CE}变化）

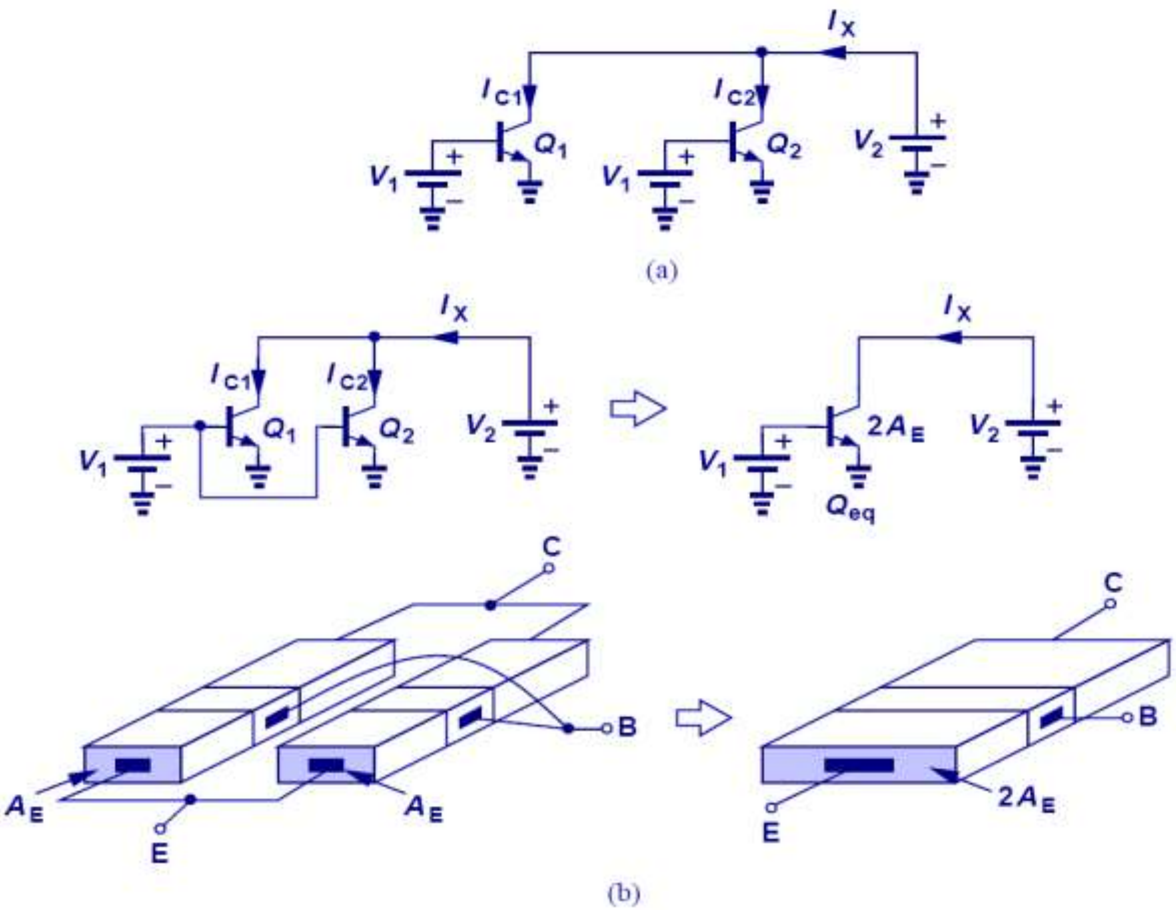


(a) (b)

- 理想情况下，I_C不随V_{CE}变化，只决定于V_{BE} → 当V_{BE}固定时，三极管具有很好的恒流源特性；

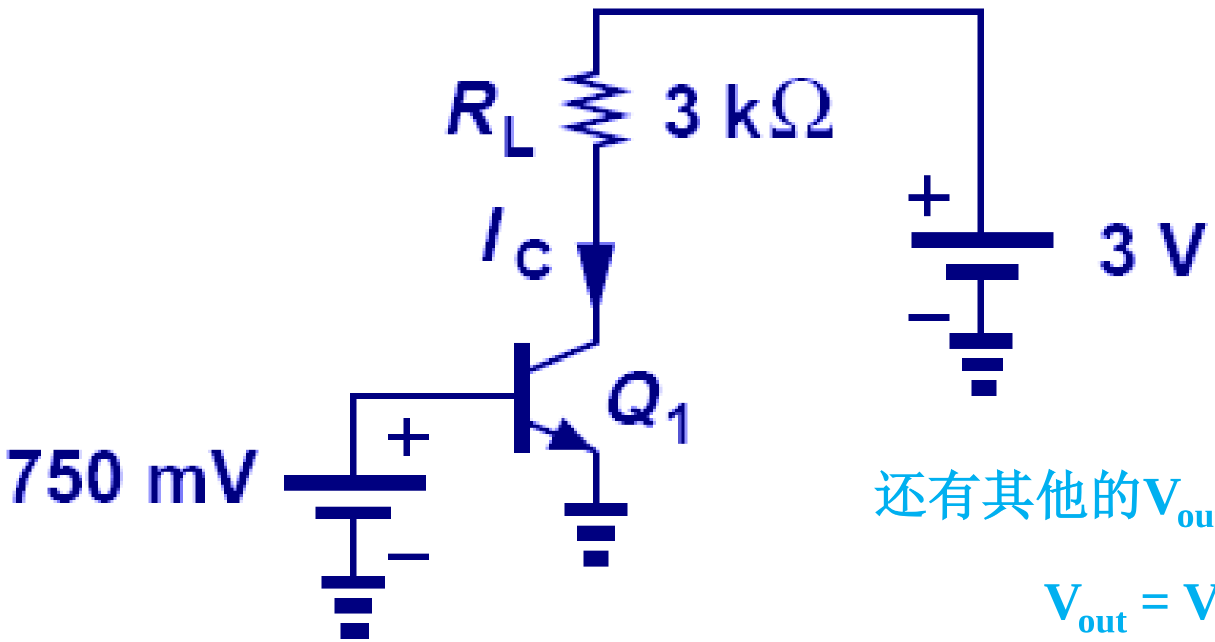
$$I_C = \frac{A_E q D_n n_i^2}{N_E W_B}\left(\exp\frac{V_{BE}}{V_T} - 1\right)$$

并联三极管



- 当两个相同的三极管并联（E、B、C均电位相等）→ 可看做单一的三极管（面积加倍）

简单的三极管电路



还有其他的V_{out}选择吗？

$V_{out} = V_{CE}$

- 晶体管将电压转换成电流，那么如何将电流再转换成电压呢？（实际应用中，一般希望是电压放大成电压，而非电压放大成电流）
- 在C极和V_{CC}之间插入一个负载电阻（load resistor），那么流过负载电阻的电压即是输入电压信号的放大。

例

Example 4.5

Determine the output voltage in Fig. 4.10 if $I_S = 5 \times 10^{-16}$ A.

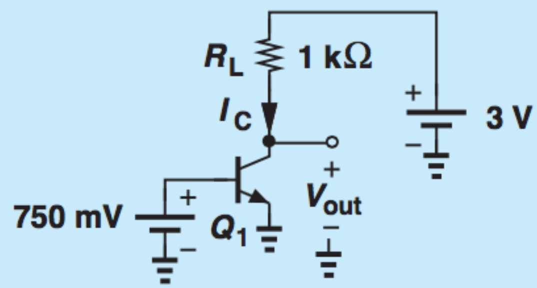


Figure 4.10 Simple stage with biasing.

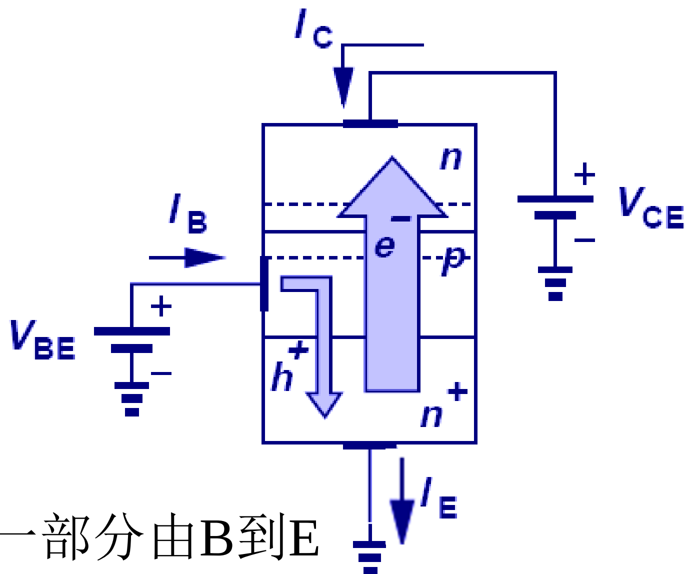
$$I_C = I_S \exp \frac{V_{BE}}{V_T}, \quad (4.9)$$

Solution Using Eq. (4.9), we write $I_C = 1.69$ mA. This current flows through R_L, generating a voltage drop of 1 kΩ × 1.69 mA = 1.69 V. Since $V_{CE} = 3\text{ V} - I_C R_L$, we obtain

$$V_{out} = 1.31\text{ V}. \quad (4.19)$$

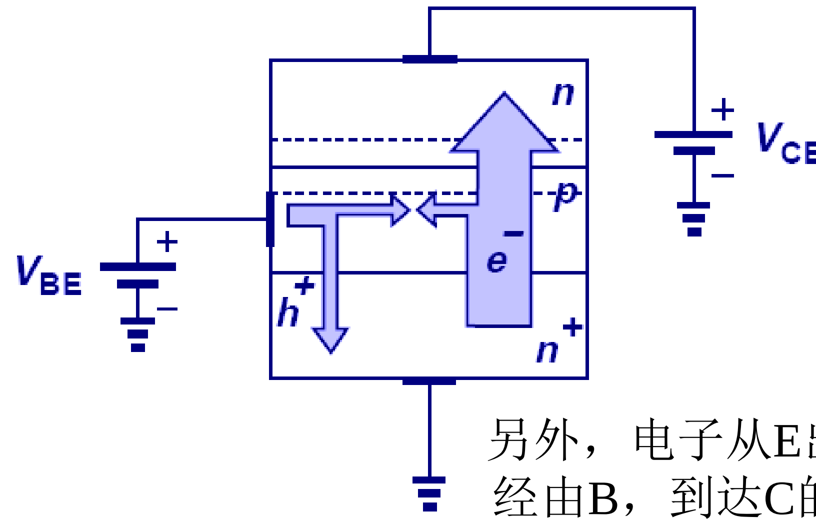
公式（4.9）的前提是三极管工作在“放大区”，即 BE 正偏，BC 反偏

基极电流（i_B）



I_B一部分由B到E的空穴电流组成

(a)



(b)

另外，电子从E出发，经由B，到达C的过程中，会有部分电子牺牲掉（与B区的空穴复合），该空穴电流也是I_B的一部分

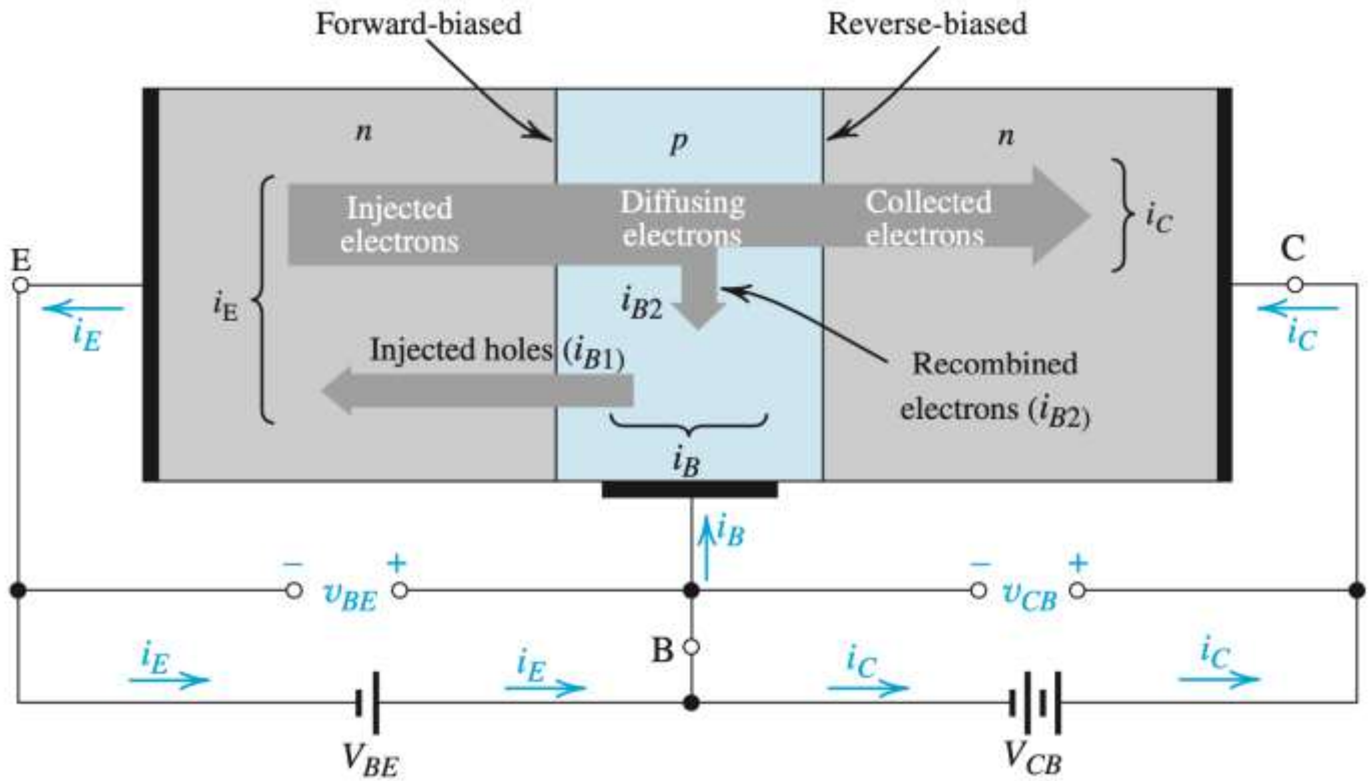
$$i_B = \frac{i_C}{\beta}$$

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

- I_B由上述两部分组成，但总和与i_C成比例，该比例定义为电流增益β

发射极电流i_E

- 应用基尔霍夫电流定律，i_E是i_B和i_C之和



$$\boxed{i_E = i_C + i_B}$$

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

$$i_E = \frac{\beta+1}{\beta} i_C$$

$$i_E = \frac{\beta+1}{\beta} I_S e^{v_{BE}/V_T}$$

定义：$i_C = \alpha i_E$ $\quad \alpha = \frac{\beta}{\beta+1}$

* β很大，所以α接近于1

$$i_E = (I_S/\alpha) e^{v_{BE}/V_T}$$

三极管电流表达式总结

$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$

$$I_B = \frac{1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

$$I_E = \frac{\beta+1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

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

因果，及计算顺序：$V_{BE} \rightarrow I_C \rightarrow I_B \rightarrow I_E$ 即，

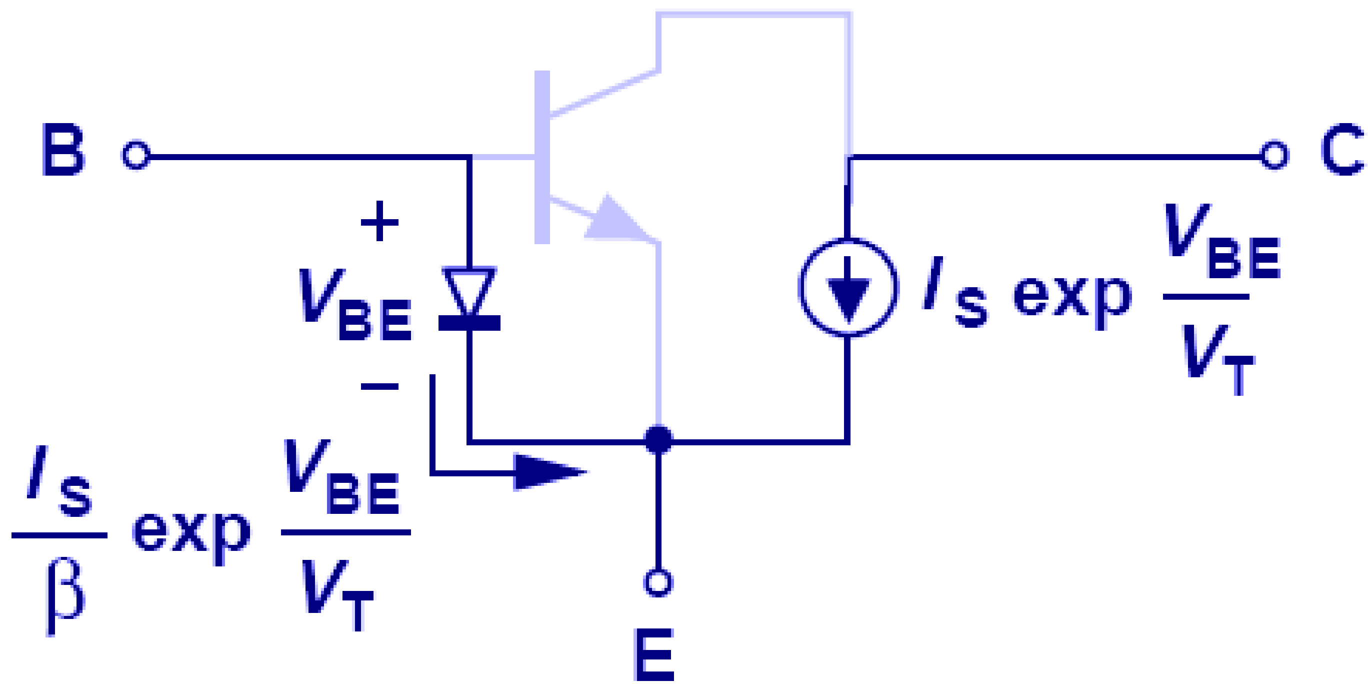
①用公式1从V_{BE}计算出I_C（压控电流源）；

②I_B是I_C的1/β；（工作在放大区时，β较大，也即I_B很小）

③I_E为I_C和I_B之和；（工作在放大区时，因为I_B很小，所以$I_E \approx I_C$；$I_C = \alpha \times I_E$，$\alpha \approx 1$）

三极管放大区的大信号模型（Large Signal Model）

所谓大信号模型，就是对信号的幅度要求没有限制，是普遍适用的电路模型，是器件“电压电流约束关系”的等效电路表述。而“小信号模型”，是大信号模型某一直流工作点附近的线性化近似



- CE之间用压控电流源表示；
- BE之间用正偏二极管表示（注意β）；
- 需注意：始终要确保三极管工作在放大区（即BE正偏，BC反偏）

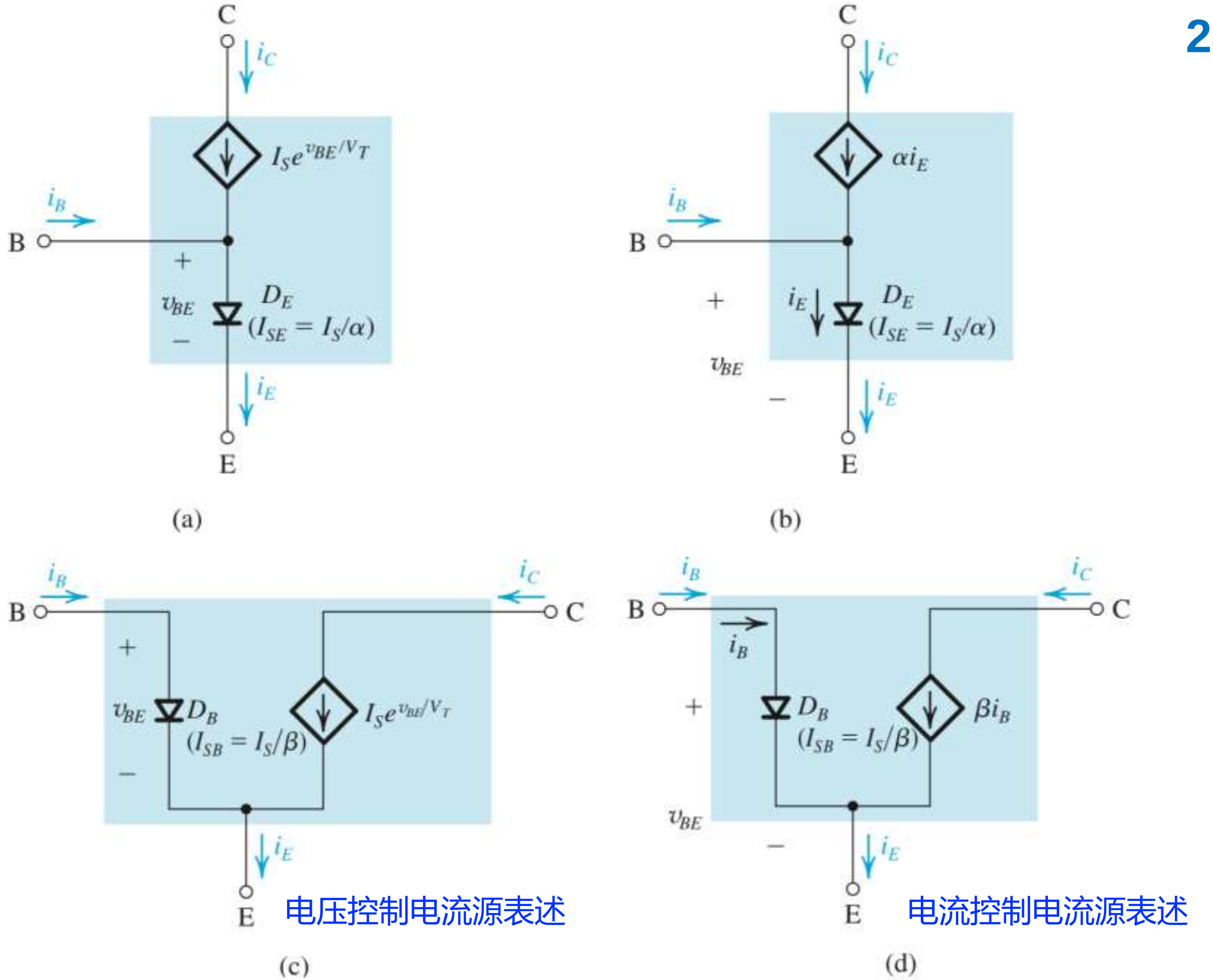
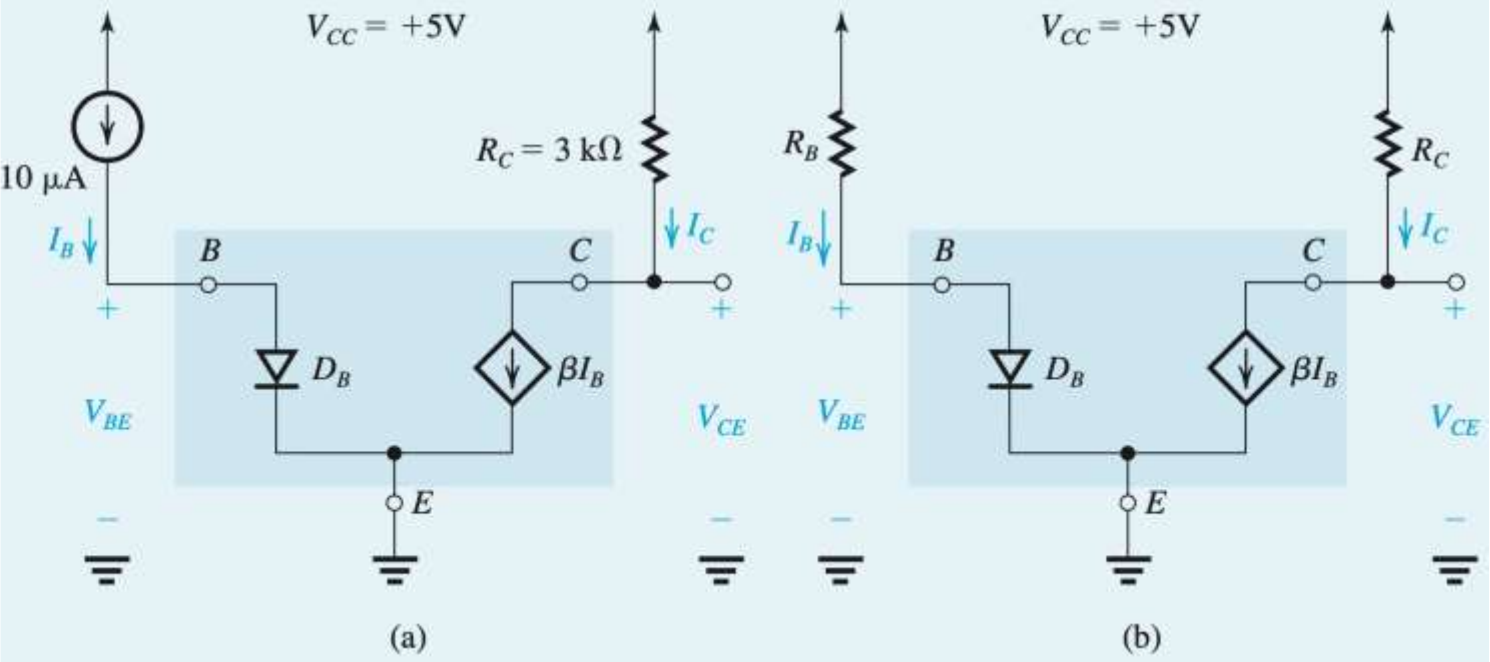


Figure 6.5 Large-signal equivalent-circuit models of the *npn* BJT operating in the forward active mode.

Example 6.1

An *npn* transistor having $I_S = 10^{-15}$ A and $\beta = 100$ is connected as follows: The emitter is grounded, the base is fed with a constant-current source supplying a dc current of 10 µA, and the collector is connected to a 5-V dc supply via a resistance R_C of 3 kΩ. Assuming that the transistor is operating in the active mode, find V_{BE} and V_{CE}. Use these values to verify active-mode operation. Replace the current source with a resistance connected from the base to the 5-V dc supply. What resistance value is needed to result in the same operating conditions?



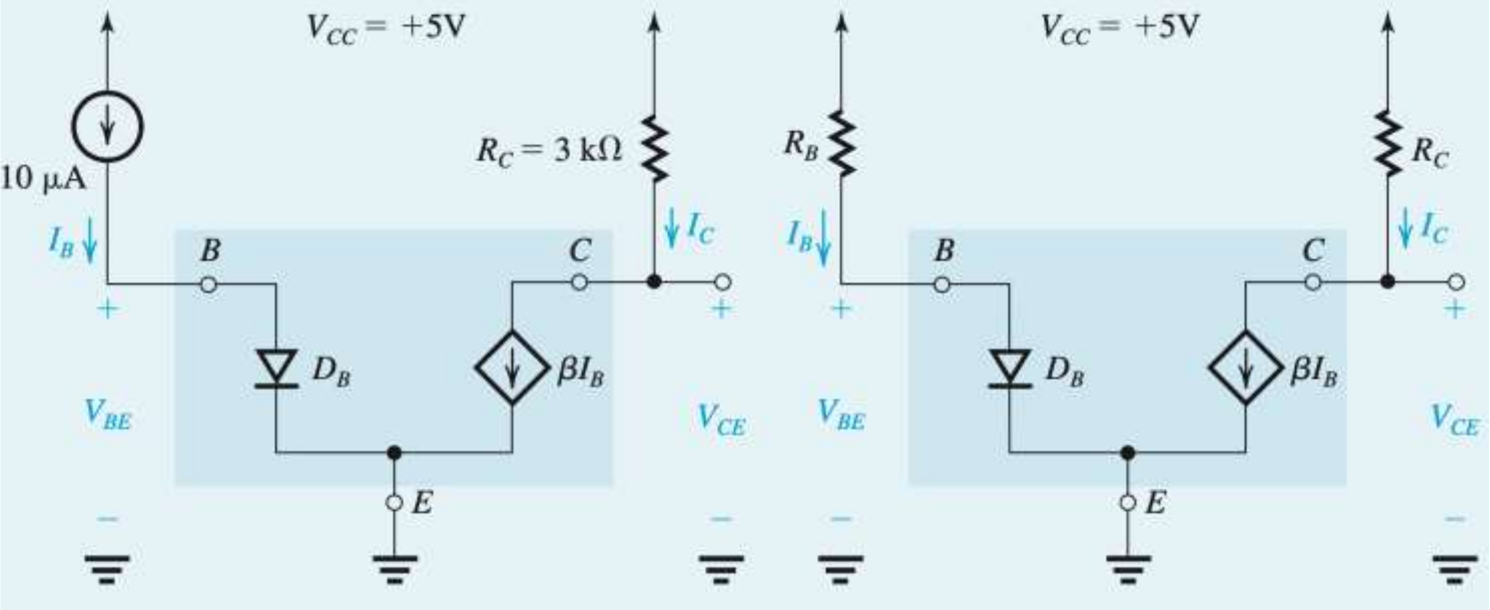
① $$V_{BE} = V_T \ln \frac{I_B}{I_S/\beta} = 690\text{ mV}$$

$$\left.\begin{aligned} V_{CE} &= V_{CC} - R_C I_C \\ I_C &= \beta I_B \end{aligned}\right\} V_{CE} = +2\text{ V}$$

> 0.69 V

Example 6.1

An *npn* transistor having $I_S = 10^{-15}$ A and $\beta = 100$ is connected as follows: The emitter is grounded, the base is fed with a constant-current source supplying a dc current of 10 μA, and the collector is connected to a 5-V dc supply via a resistance R_C of 3 kΩ. Assuming that the transistor is operating in the active mode, find V_{BE} and V_{CE}. Use these values to verify active-mode operation. Replace the current source with a resistance connected from the base to the 5-V dc supply. What resistance value is needed to result in the same operating conditions?



(a) (b)

②

$$R_B = \frac{V_{CC} - V_{BE}}{I_B} = \frac{5 - 0.69}{10\ \mu A} = 431\ k\Omega$$

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实际三极管的结构

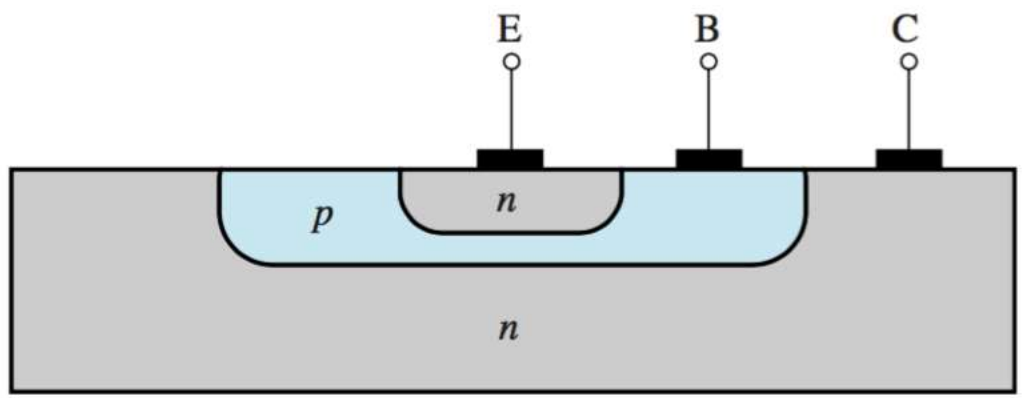
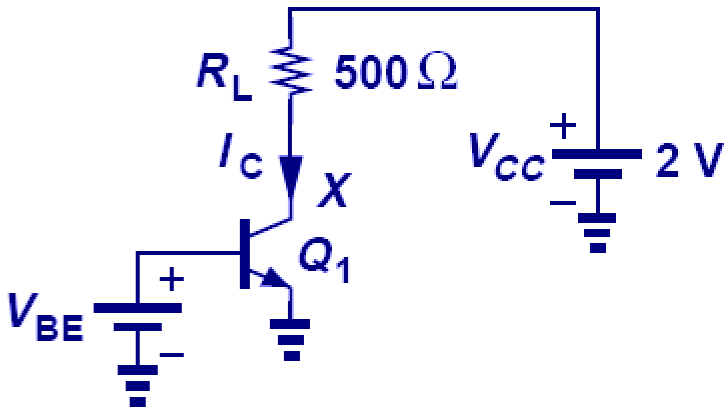


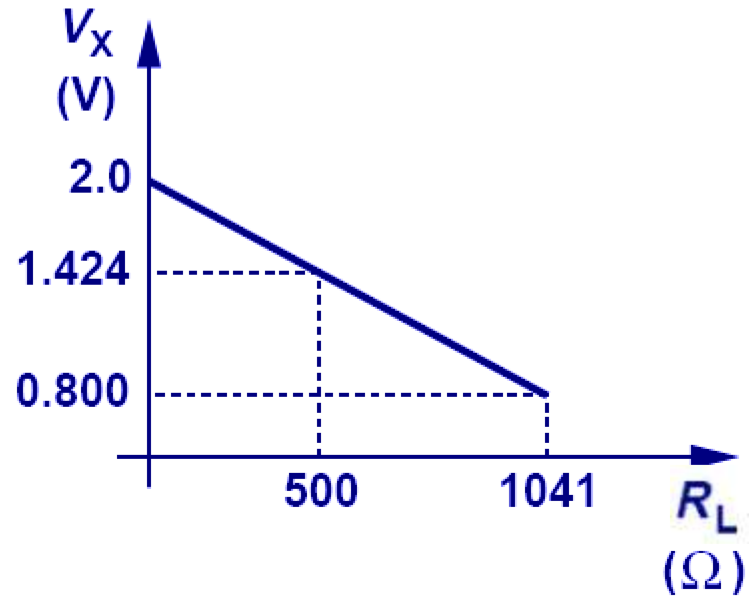
Figure 6.7 Cross-section of an *npn* BJT.

- BC 结面积远远大于 BE 结面积 → BC 的 I_S >> BE 的 I_S
- 结构非对称，与MOSFET比较
- 从E发射出的电子，经过极薄的B区，被C所收集

若要保证三极管工作于放大区，负载电阻 R_L 最大可为多少？

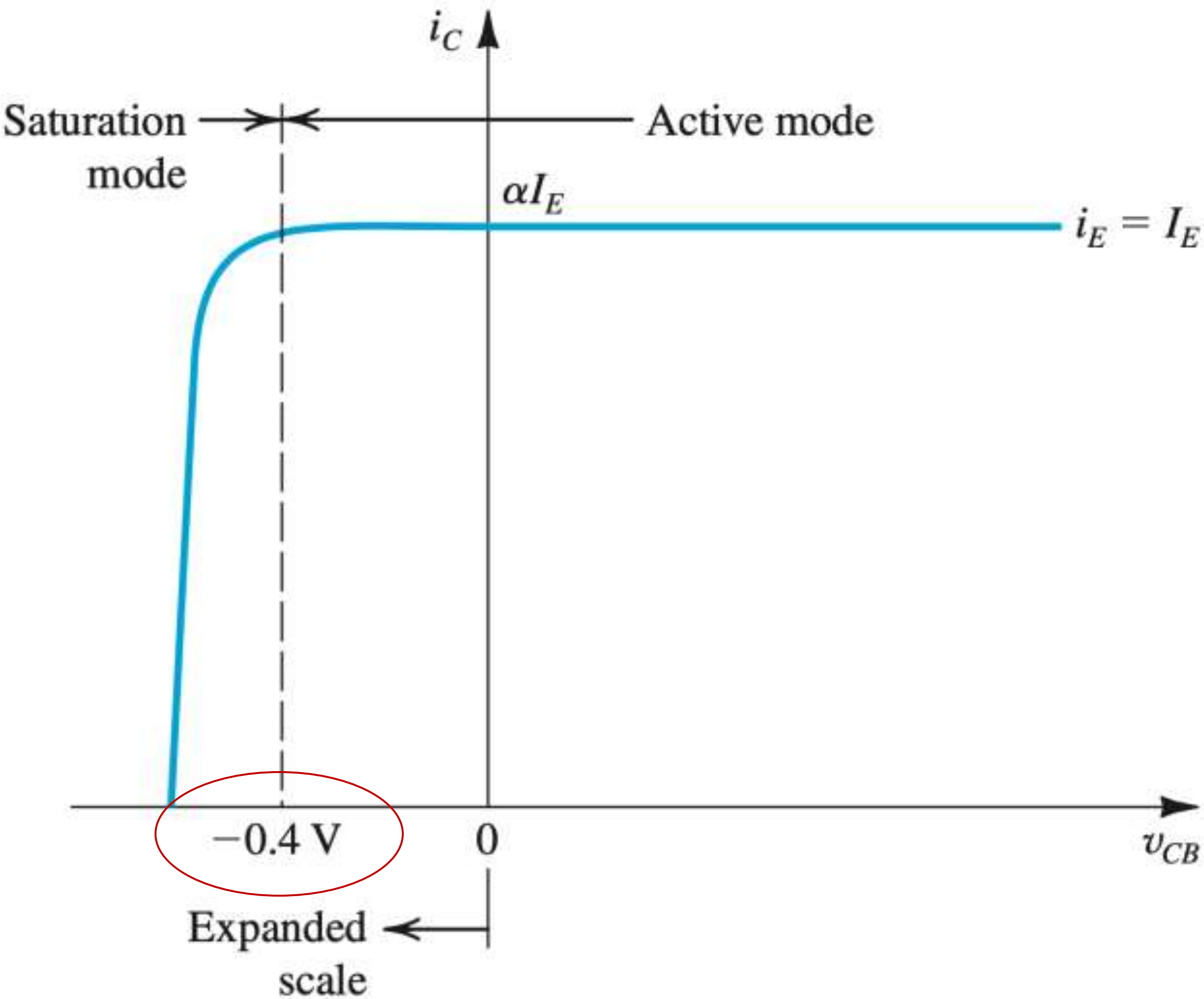


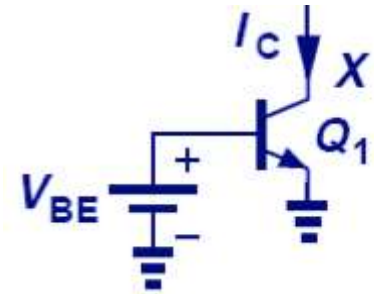
(a)



(b)

- R_L 增加，导致 V_x 下降，若V_x下降到小于一定程度，则 BC pn 结反偏的条件不成立，放大器将不再工作于放大区
- 因此，R_L不能无限制地增加，其存在一个最大的可允许的值，以确保三极管始终工作在放大区





三极管工作于放大区的条件：
V_C最低不得低于V_B-0.4 V

Q：How about MOSFET?

Figure 6.8 The i_C–v_{CB} characteristic of an *npn* transistor fed with a constant emitter current I_E. The transistor enters the saturation mode of operation for $v_{CB} < -0.4$ V, and the collector current diminishes.

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三极管工作于饱和区

Table 6.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

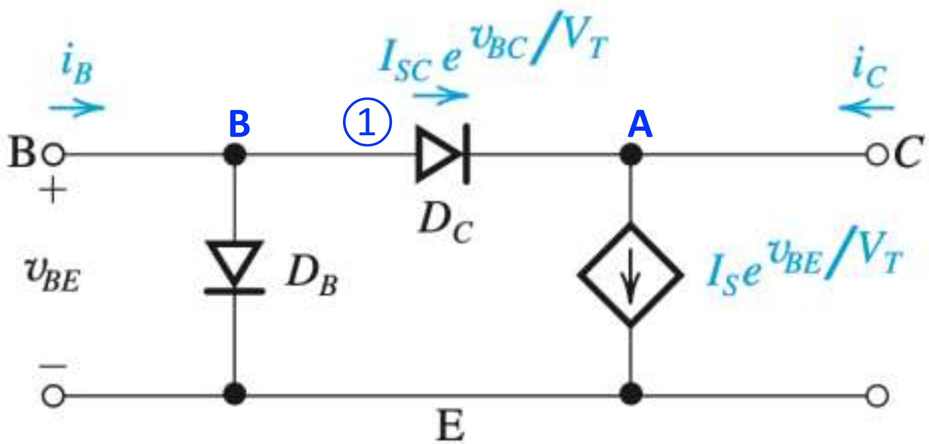

Figure 6.9 Modeling the operation of an *npn* transistor in saturation by augmenting the model of Fig. 6.5(c) with a forward-conducting diode D_C. Note that the current through D_C increases i_B and reduces i_C.

①BC结正偏，用二极管D_C表征
②i_C减小，基于A点KCL
③i_B增加，基于B点KCL
④$\beta = i_C/i_B$减小，可通过控制V_{BC}，来控制β的值
⑤判断三极管工作于饱和区的方法：

$$\beta_{\text{forced}} = \left.\frac{i_C}{i_B}\right|_{\text{saturation}} \le \beta$$

- V_C比V_B低，且相差不小于0.4V $V_{CEsat} = V_{BE} - V_{BC}$

- i_C/i_B 比管子标称的（工作于放大区时的）β要小

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pnp三极管

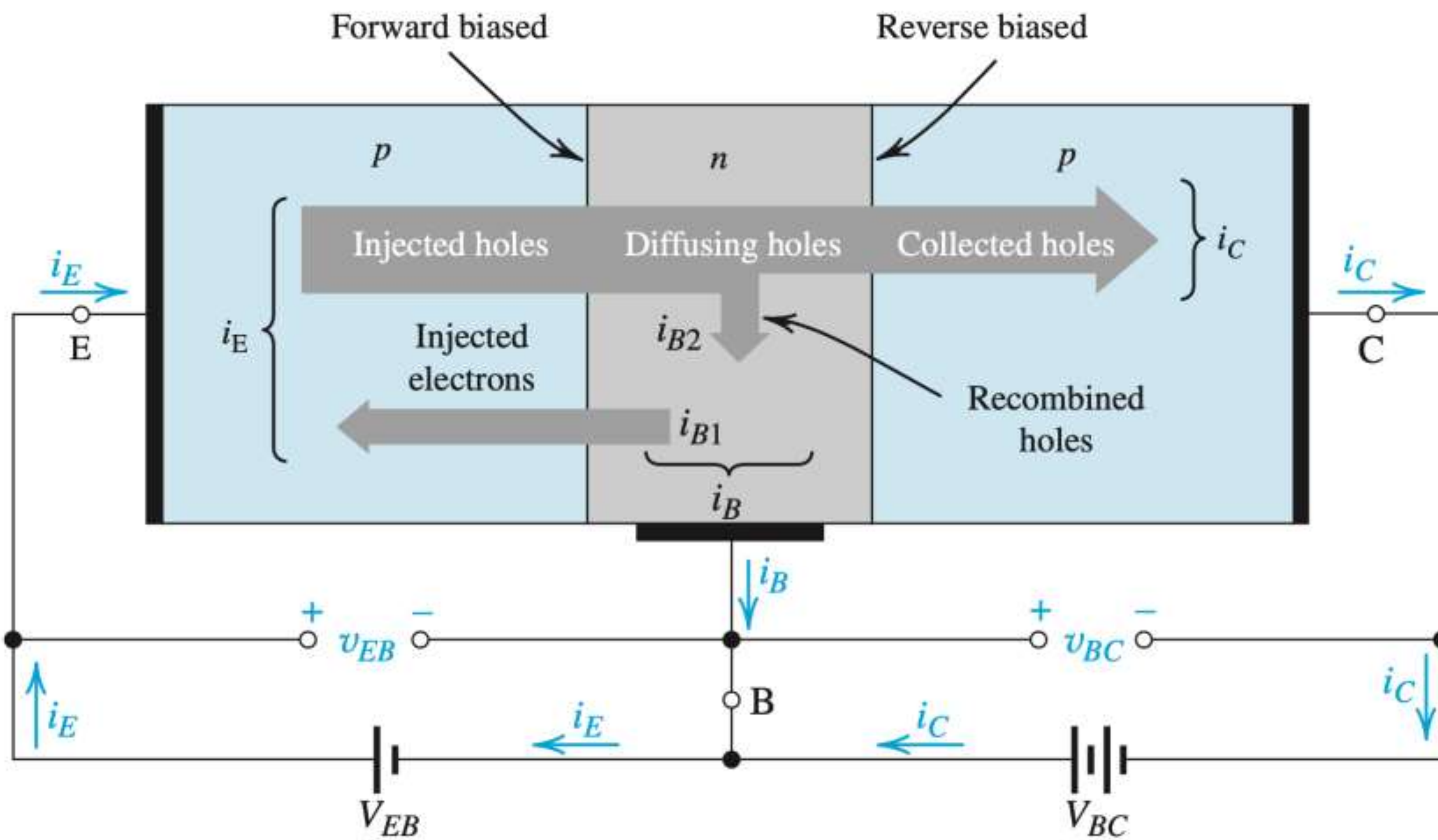


Figure 6.10 Current flow in a *pnp* transistor biased to operate in the active mode.

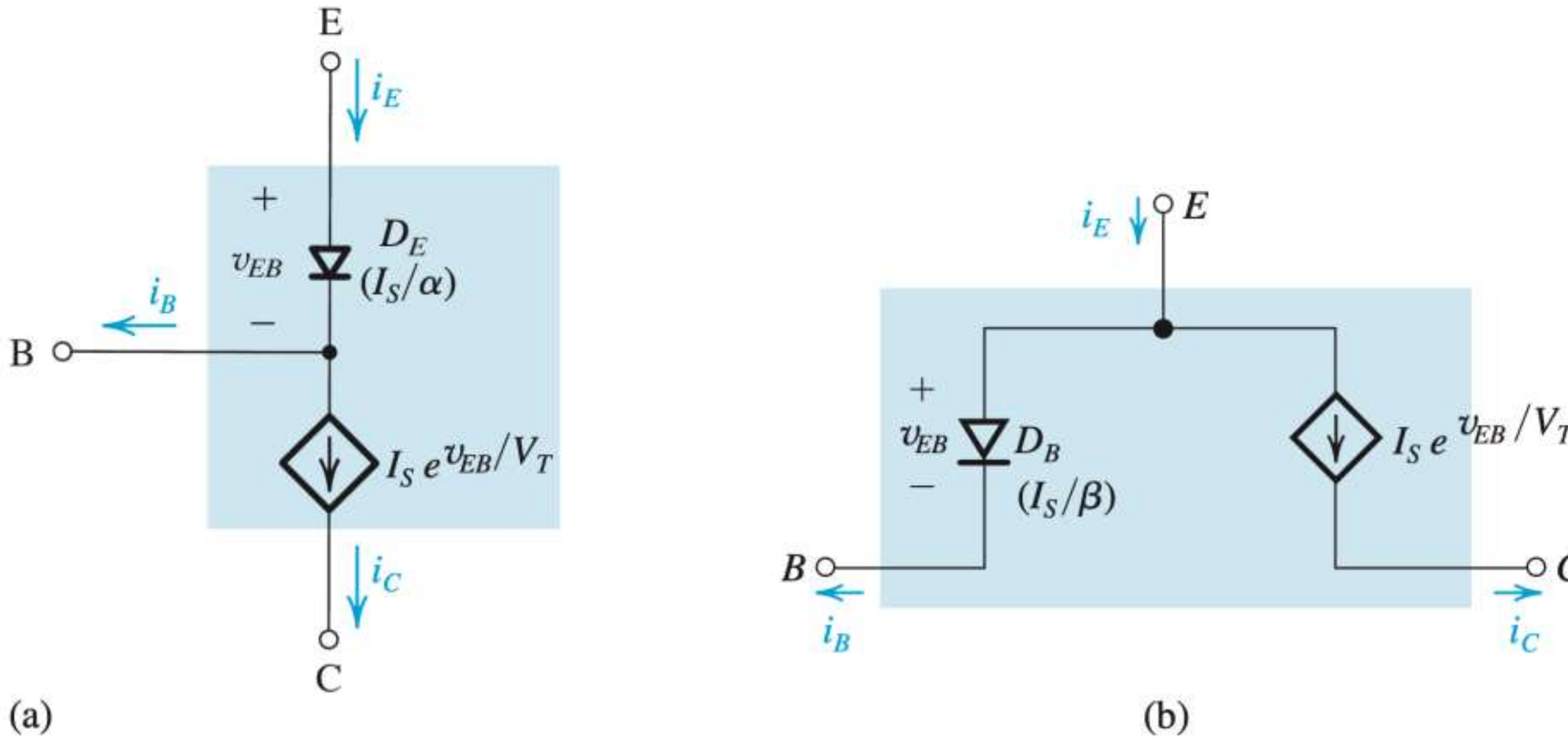


Figure 6.11 Two large-signal models for the *pnp* transistor operating in the active mode.

三极管的I/V特性
“电压电流约束关系”

惯例：

电流从上往下流（电压上面高、下面低）

npn，C在上，E在下，对应NMOS
pnp，C在下，E在上，对应PMOS

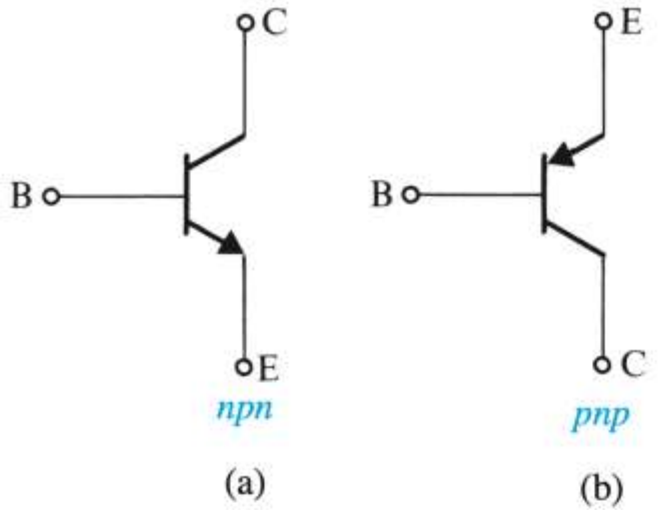


Figure 6.12 Circuit symbols for BJTs.

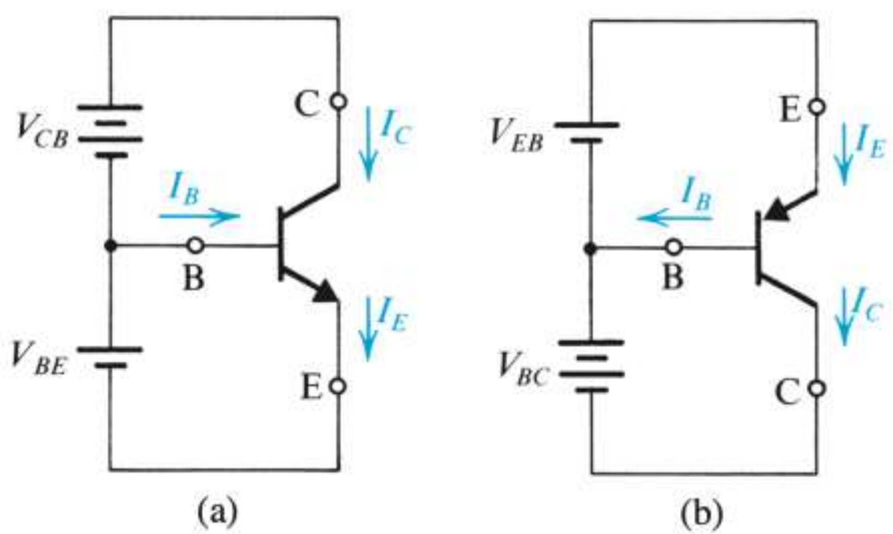
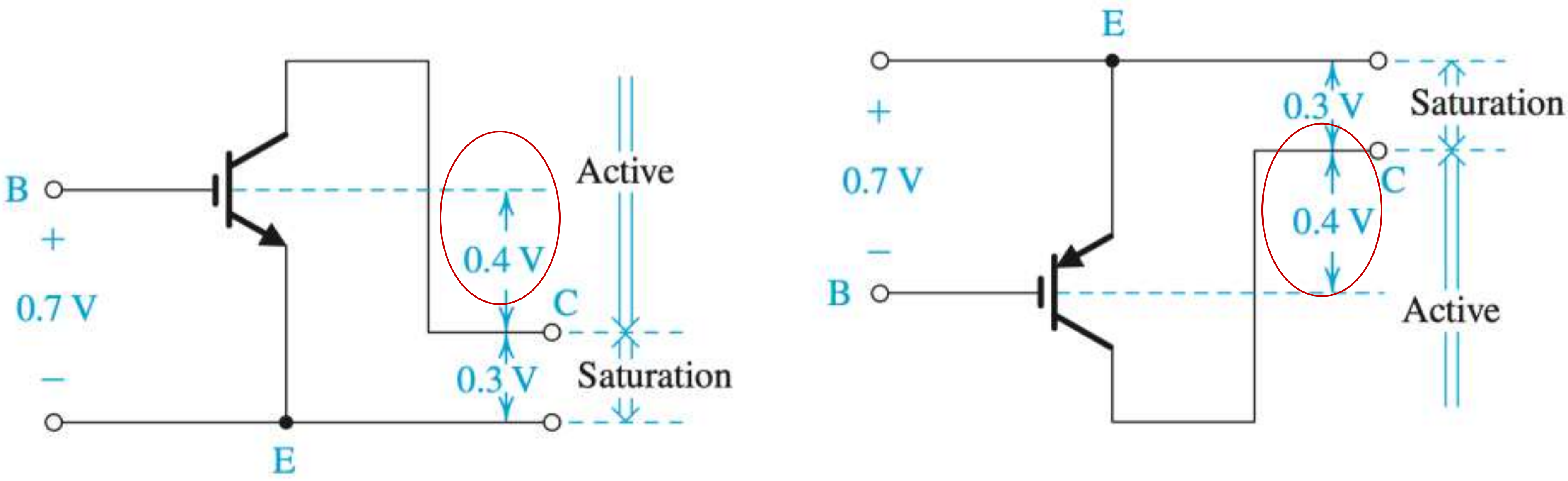


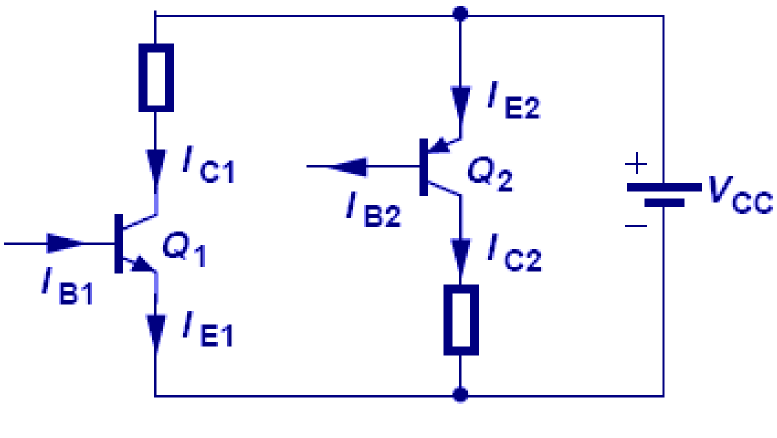
Figure 6.13 Voltage polarities and current flow in transistors operating in the active mode.

三极管工作区域的界限

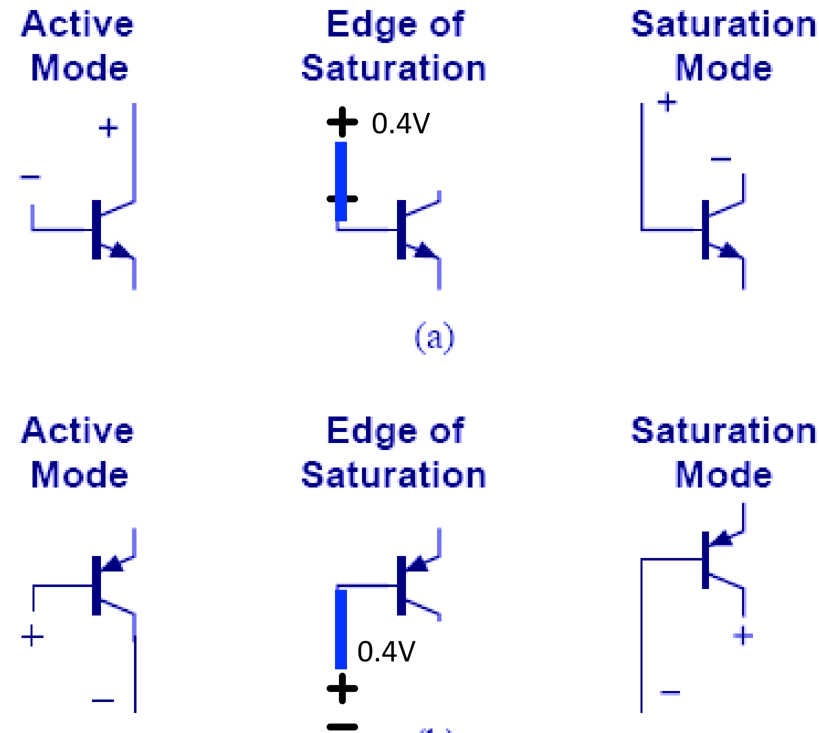


(a) *npn*　　(b) *pnp*

- 三极管工作于放大区的条件，BE结正偏，以及
  - 对于npn，C点电压最低不得低于V_B-0.4
  - 对于pnp，**C点电压最高不得高于V_B+0.4**
- How about MOSFET?



(a)



(a)

(b)

- 注意电流方向以及电位高低

Table 6.2 Summary of the BJT Current–Voltage Relationships in the Active Mode

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

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

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

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

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

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

$$V_T = \text{thermal voltage} = \frac{kT}{q} \simeq 25 \text{ mV at room temperature}$$

Example 6.2

The transistor in the circuit of Fig. 6.15(a) has $\beta = 100$ and exhibits a v_{BE} of 0.7 V at $i_C = 1$ mA. Design the circuit so that a current of 2 mA flows through the collector and a voltage of +5 V appears at the collector.

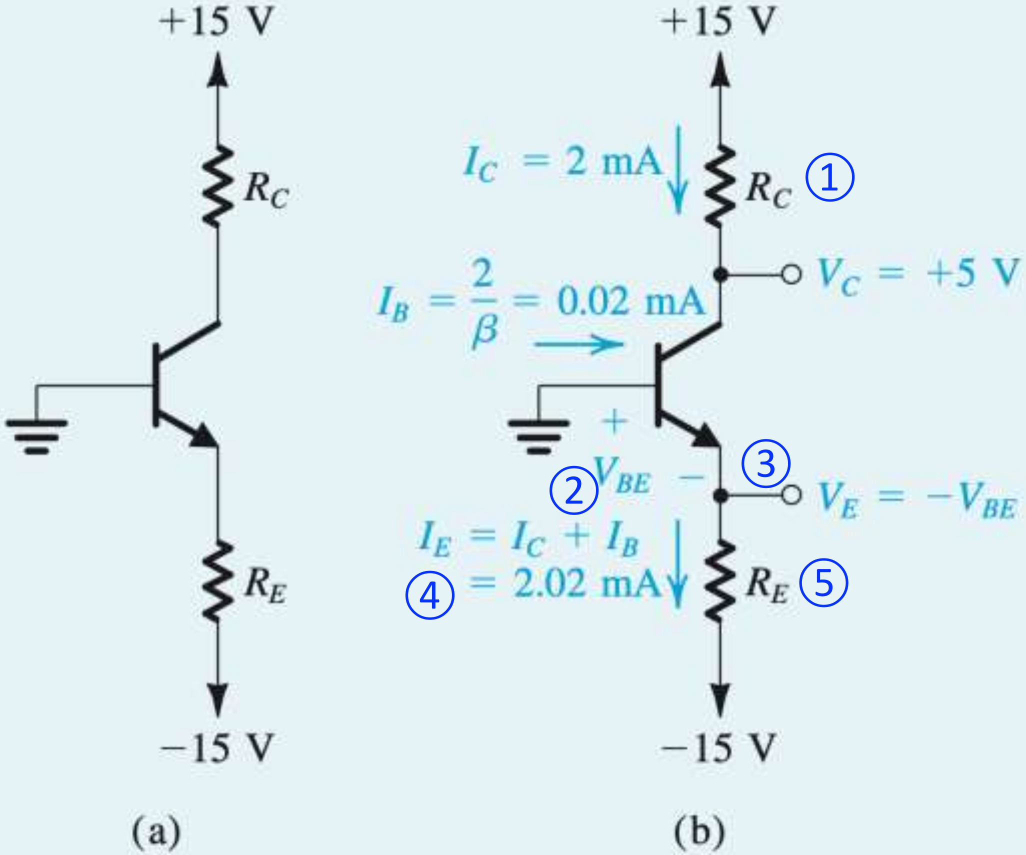


Figure 6.15 Circuit for Example 6.2.

1

$$R_C = \frac{10\text{ V}}{2\text{ mA}} = 5\text{ k}\Omega$$

2

$$V_{BE} = 0.7 + V_T \ln\left(\frac{2}{1}\right) = 0.717\text{ V}$$

3

$$V_E = -0.717\text{ V}$$

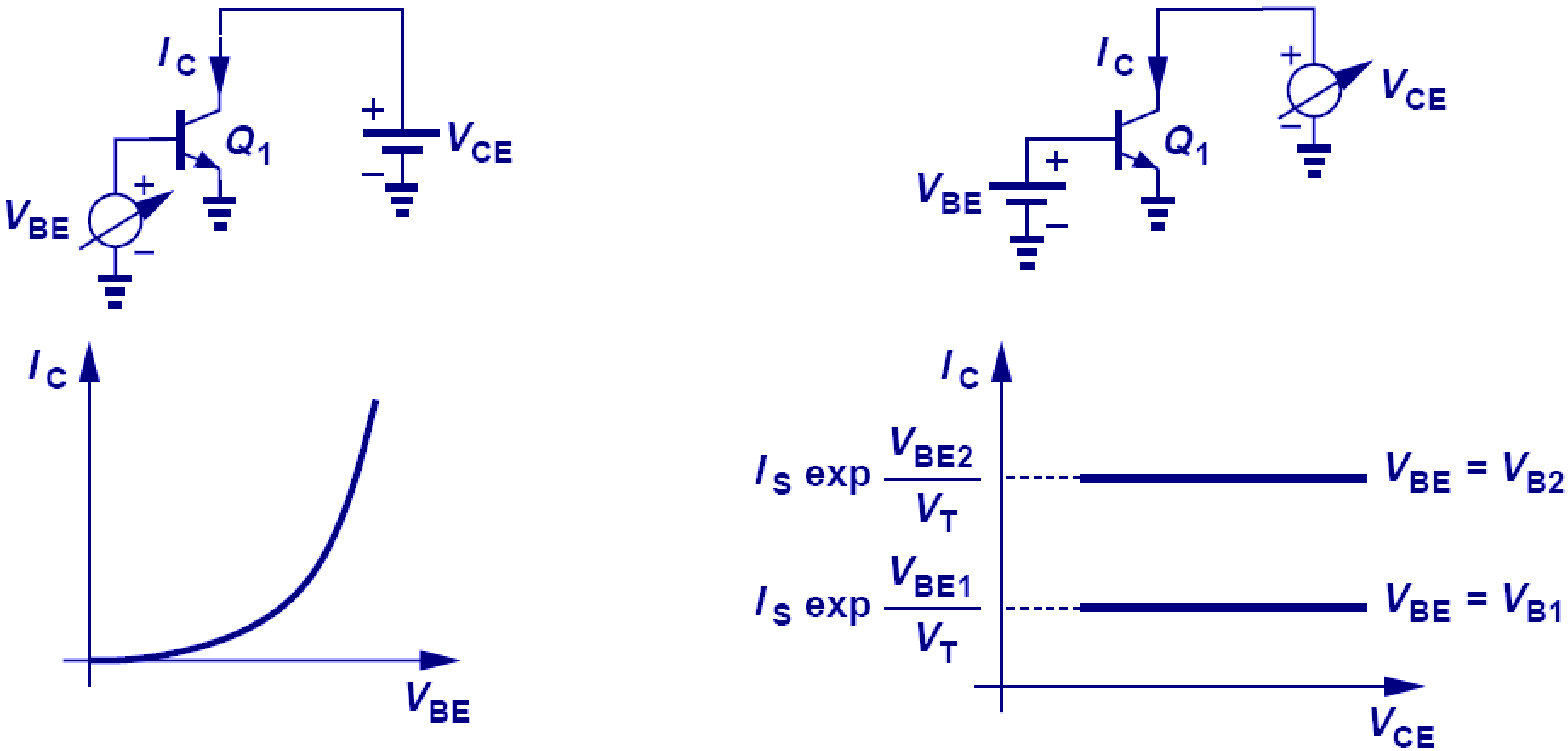
4

$$I_E = \frac{I_C}{\alpha} = \frac{2}{0.99} = 2.02\text{ mA}$$

5

$$R_E = \frac{V_E - (-15)}{I_E} = \frac{-0.717 + 15}{2.02} = 7.07\text{ k}\Omega$$

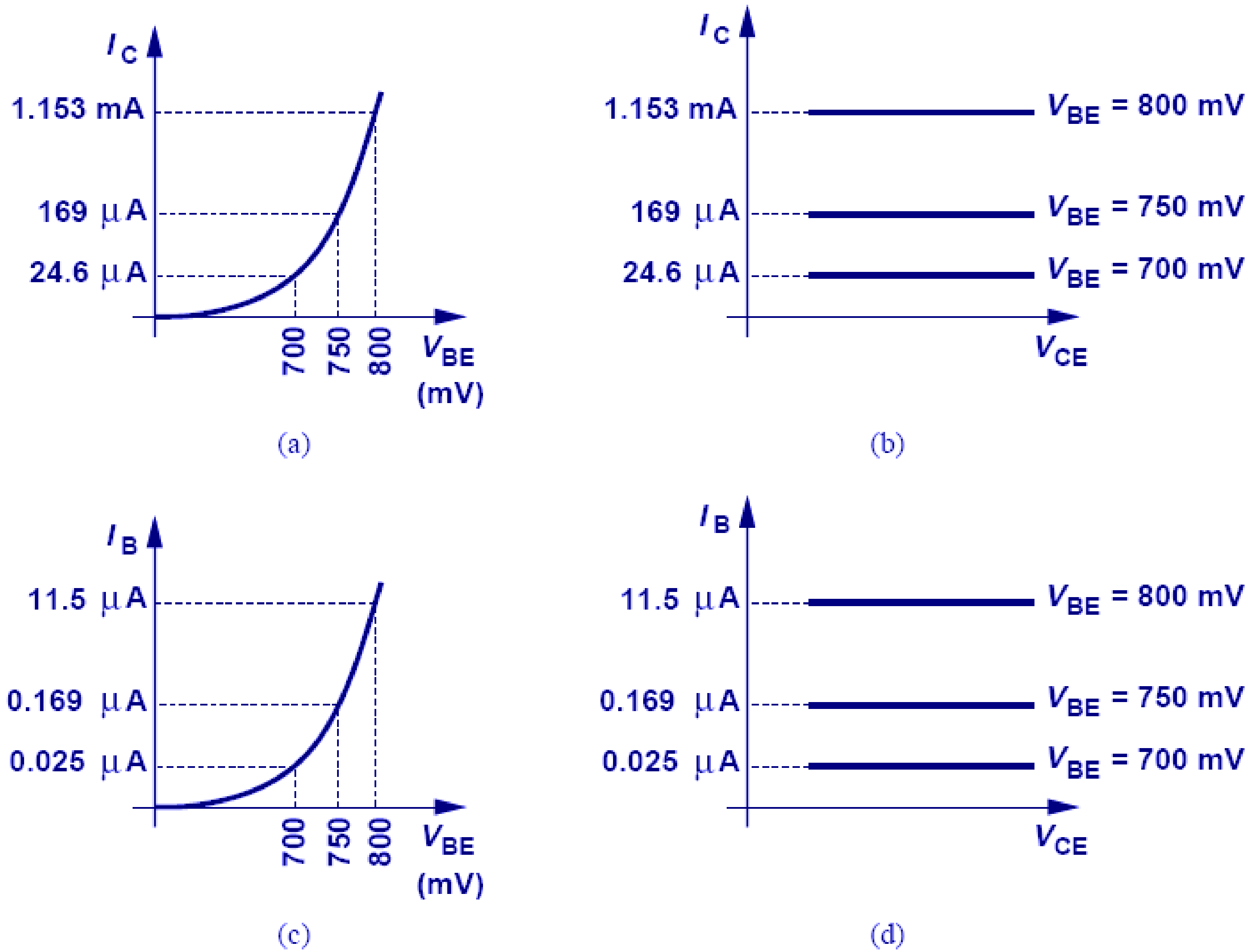
三极管的特性



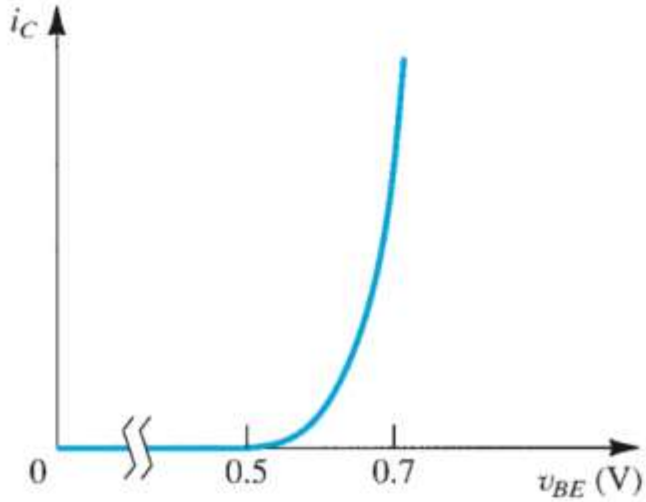
(a) (b)

因是三端器件，分析比较复杂，一般我们不同时变化两个电压量。常规的分析方法是固定V_{CE}，分析I_C随V_{BE}的变化（转移特性）；或固定V_{BE}，分析I_C随V_{CE}的变化（输出特性）

Example: IV 特性



得到I_C后，I_B、I_E可按比例写出



$$i_C = I_S e^{v_{BE}/V_T}$$ 与二极管的特性一样

v_{BE} 每增加 60 mV， 电流 x10

→ 为了快速分析，做近似：$\boxed{V_{BE} \simeq 0.7\text{ V}}$

Figure 6.15 The i_C–v_{BE} characteristic for an *npn* transistor.

Q：MOSFET 直流分析时，V_{GS}并非为一个固定的值，Why?

A: MOSFET 的 I_D 和V_{GS}关系为平方关系，变化比指数关系平缓，所以V_{GS}可变化范围比V_{BE}要大

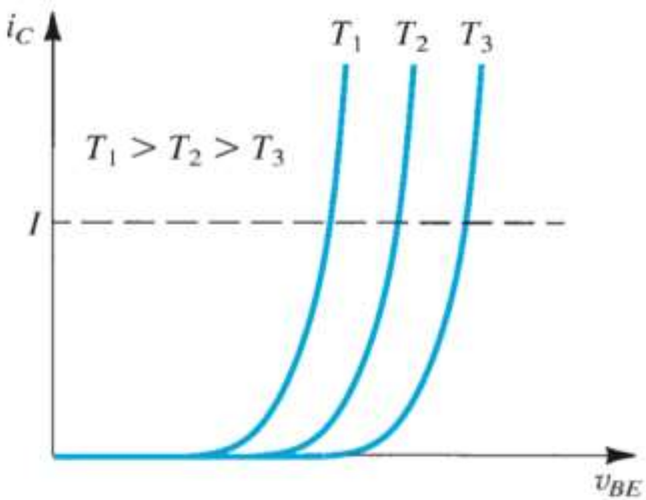
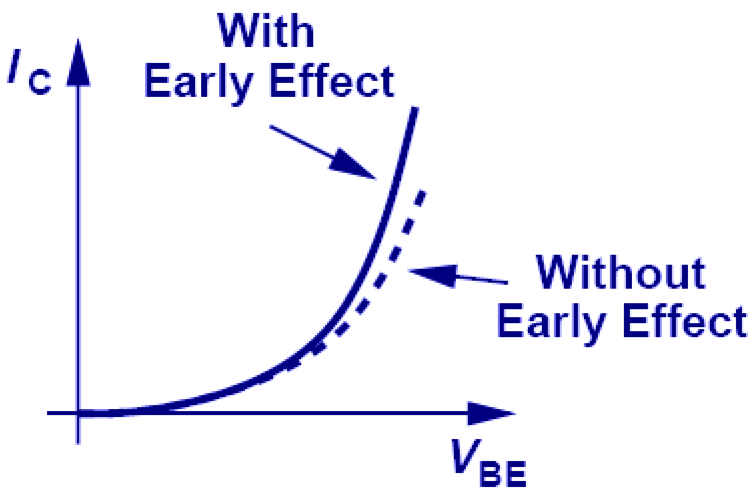
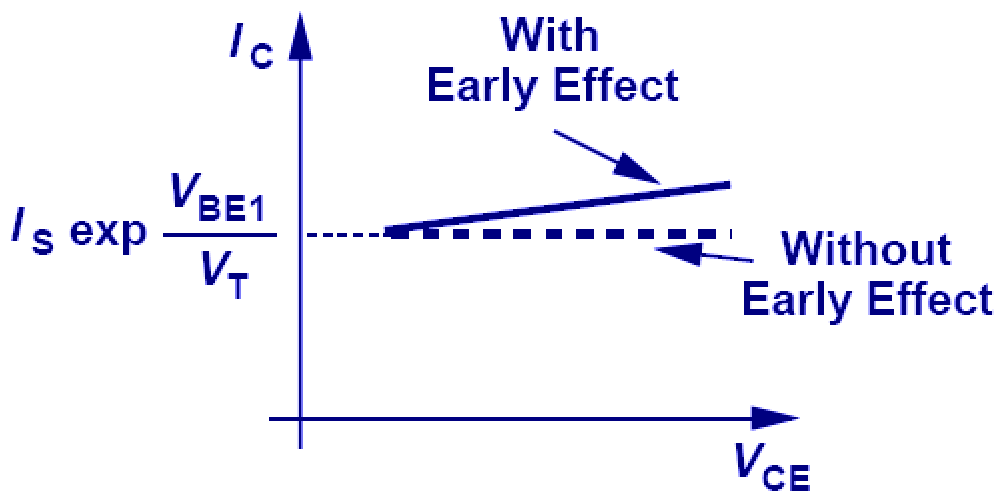


Figure 6.16 Effect of temperature on the i_C–v_{BE} characteristic. At a constant emitter current (broken line), v_{BE} changes by −2 mV/°C.

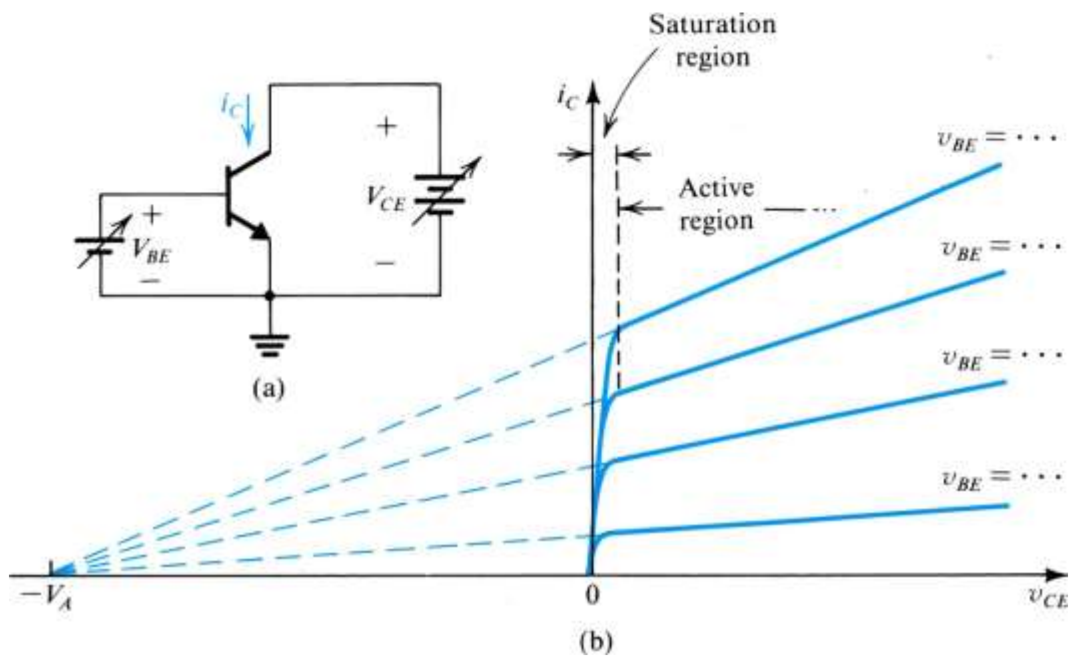
Early Effect （厄雷效应）



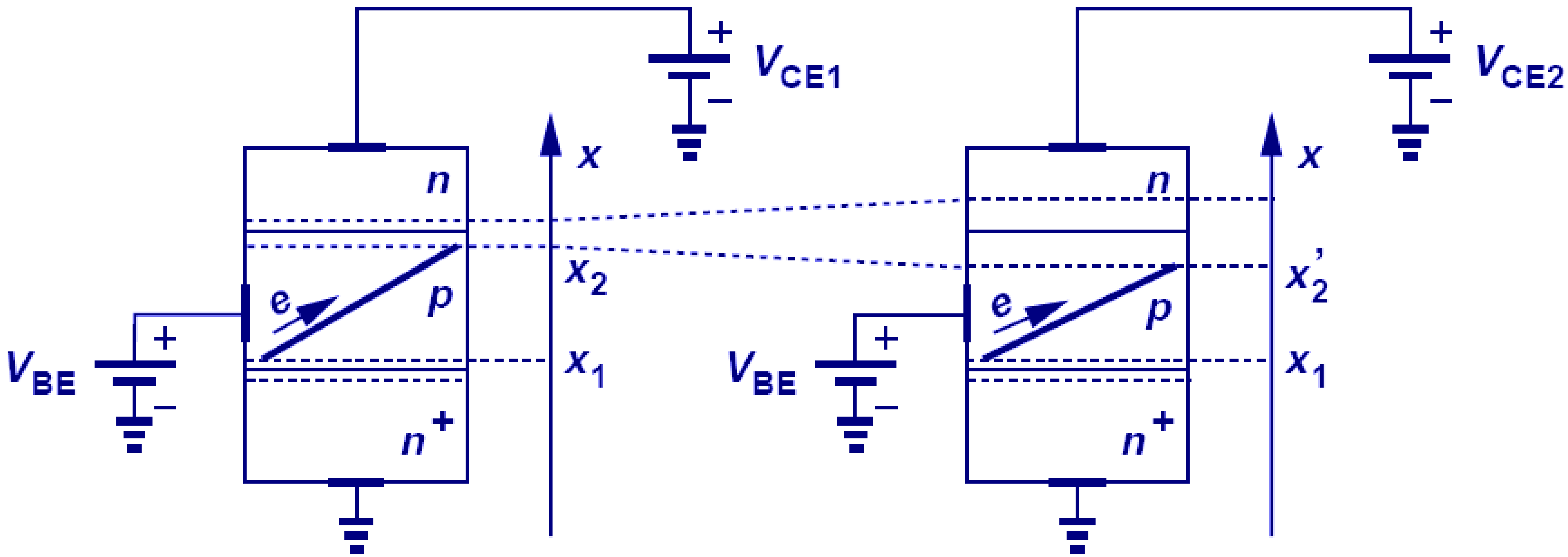
(a)



- 前面所述 I_C 不随 V_{CE} 变化，这在实际情况中是不精确的；
- I_C vs V_{CE} 不是保持水平，而是有轻微上扬；
- 对应于MOSFET中的沟道调制效应

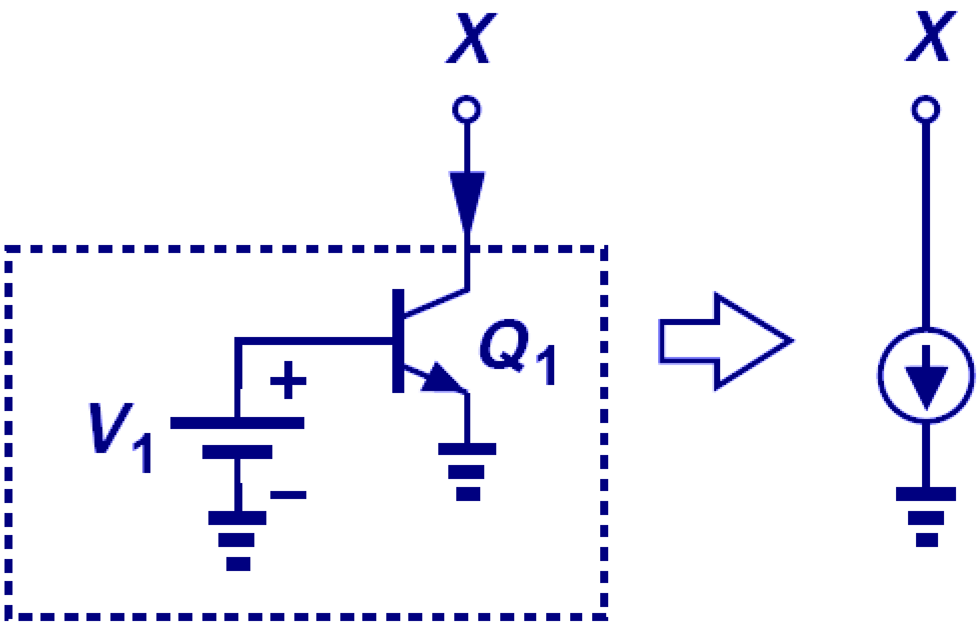


厄雷效应的起因



- 当 V_{CE} 增加时，BC pn结的反偏程度增加 → BC 耗尽区变宽（x_2 → x_2'）→ B区变窄 → 电子浓度的变化加剧（图中直线的斜率变大） → I_C 增加

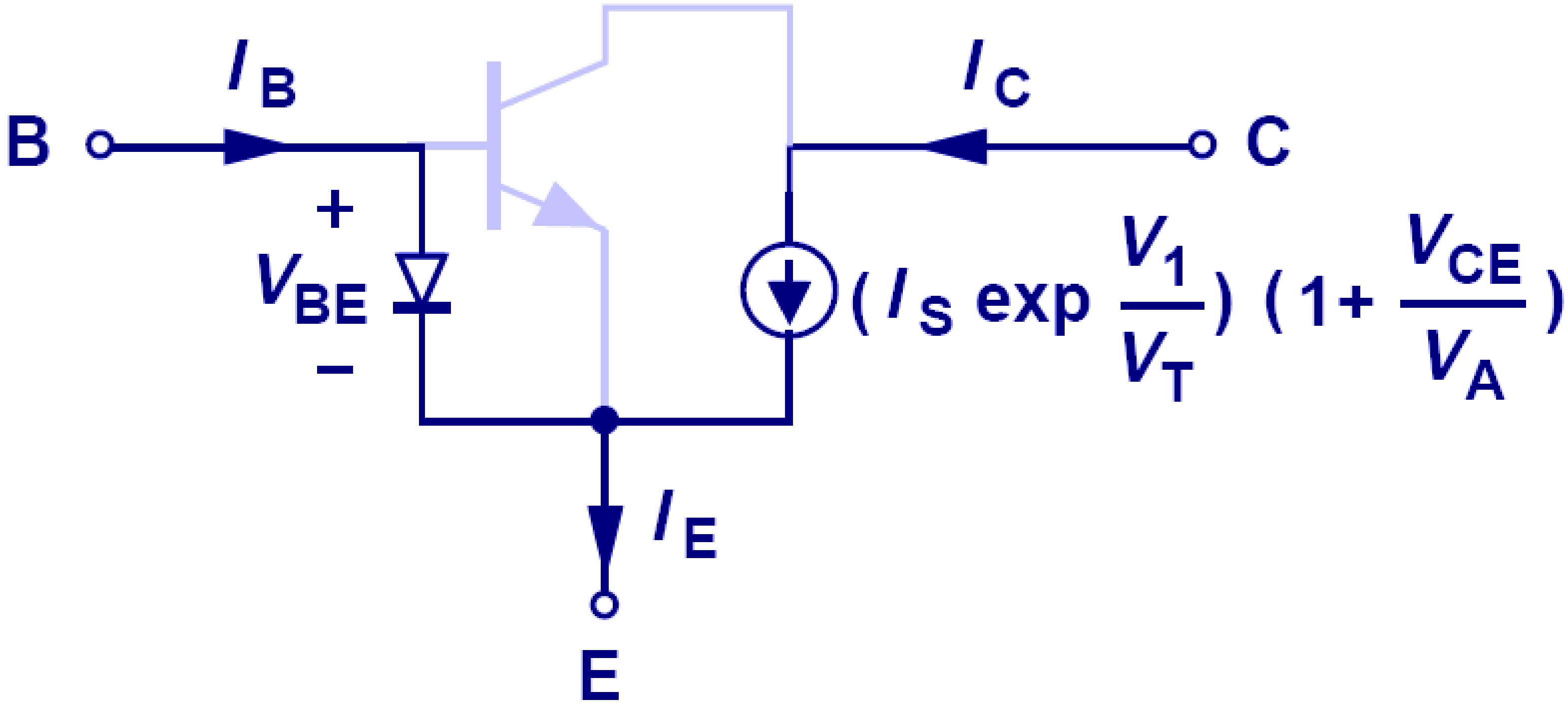
厄雷效应对 I_C 的影响



$$\left(I_S \exp\frac{V_1}{V_T}\right)\underbrace{\left(1+\frac{V_X}{V_A}\right)}_{\text{修正因子}}$$

（回忆MOSFET的沟道调制效应）

厄雷效应对大信号模型的影响

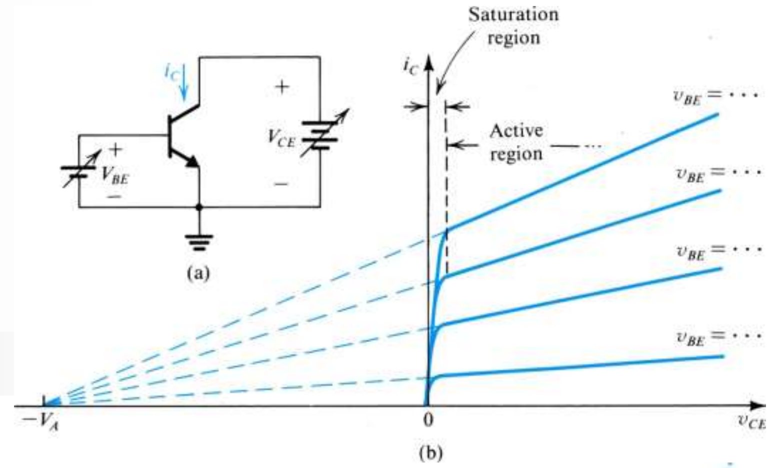


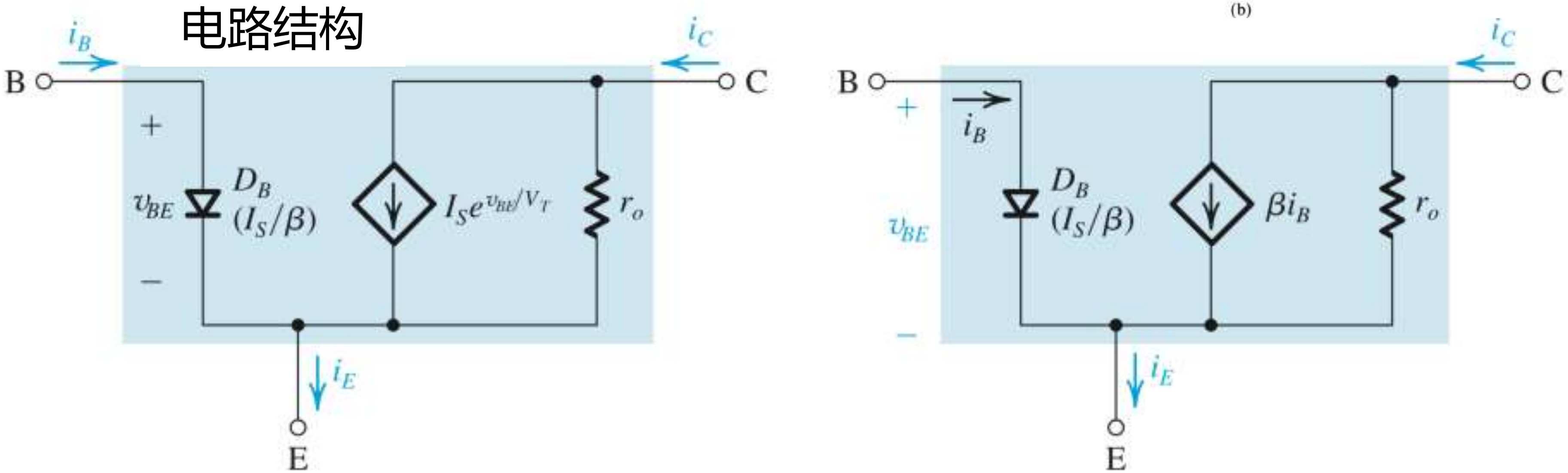
- 只需对 CE 之间的压控恒流源添加一修正因子，该修正因子可用一并联电阻表示（数学表达式→电路结构）
- BE之间不变化

数学表达式

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

电路结构





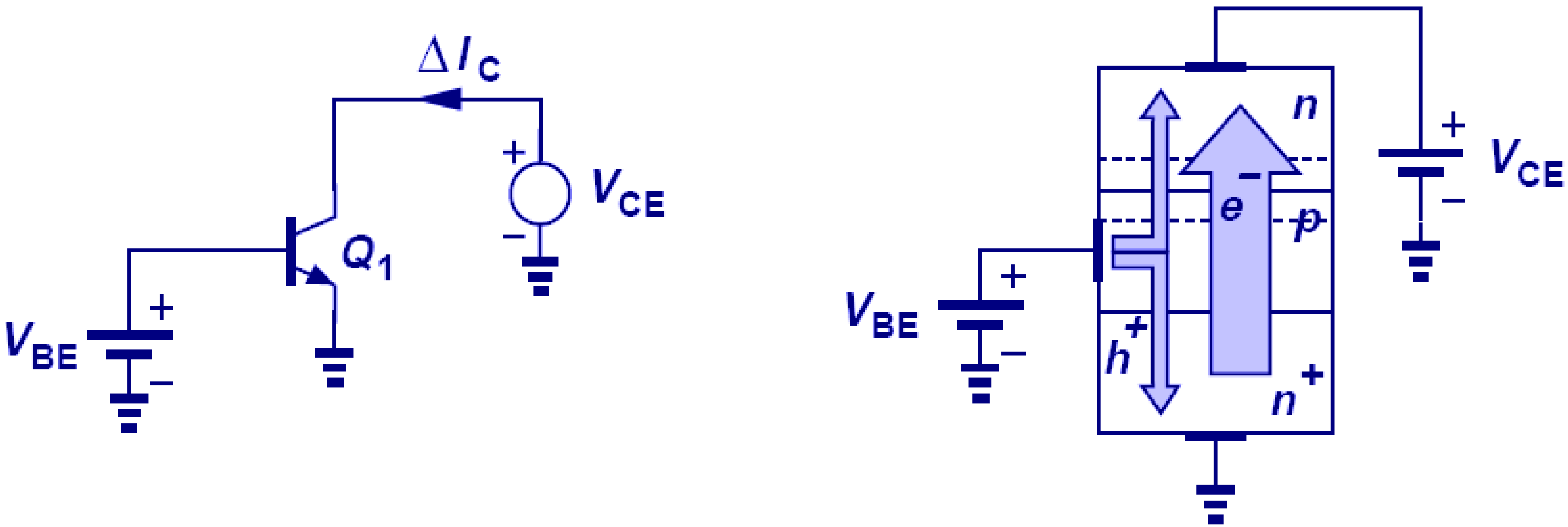
(a) (b)

Figure 6.19 Large-signal, equivalent-circuit models of an *npn* BJT operating in the active mode in the common-emitter configuration with the output resistance r_o included.

$$\boxed{r_o = \frac{V_A}{I'_C}}$$

$$I'_C = I_S e^{V_{BE}/V_T} \longleftarrow \text{不考虑厄雷效应时的 } I_C$$

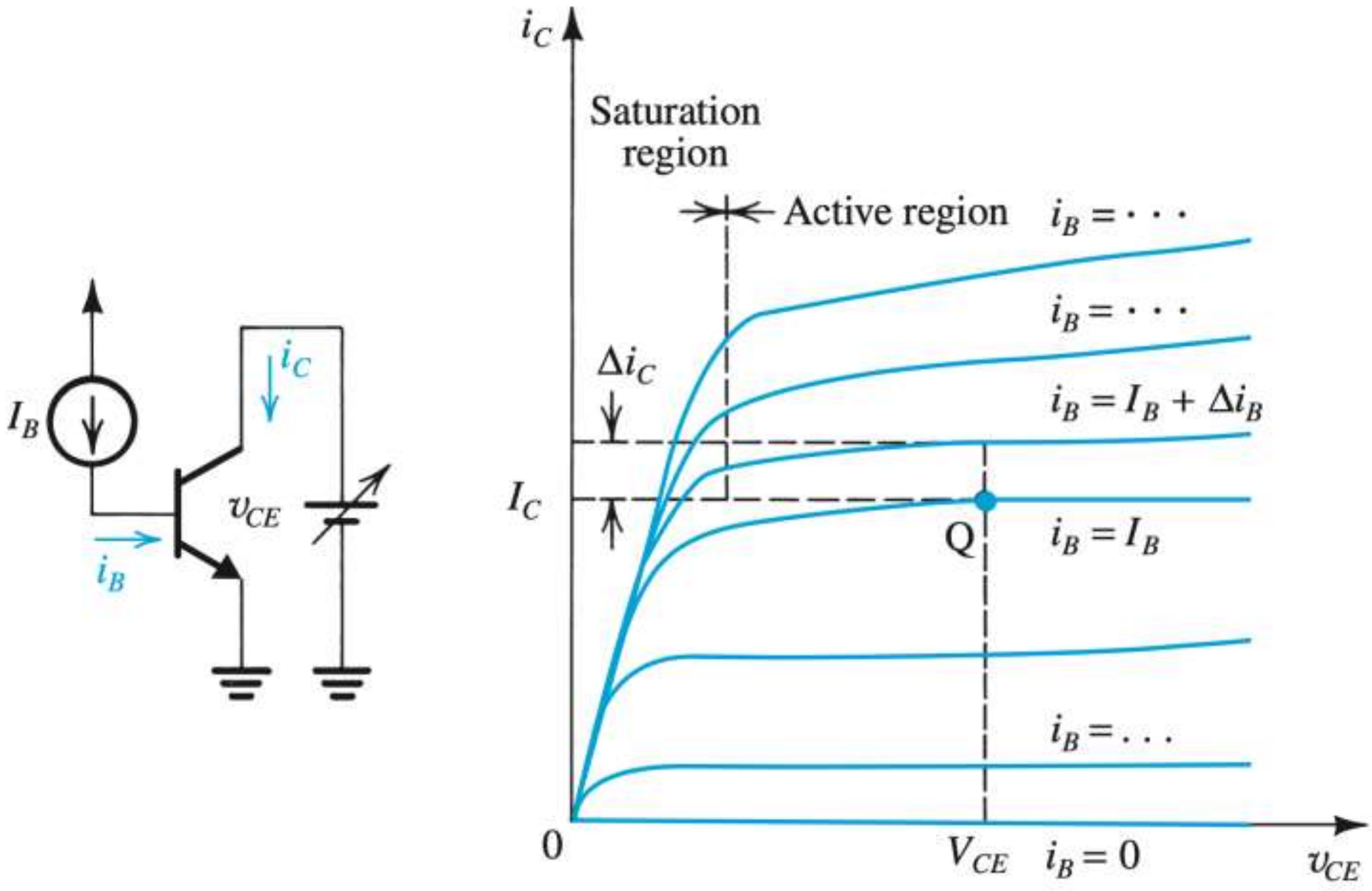
工作于“饱和区”的三极管



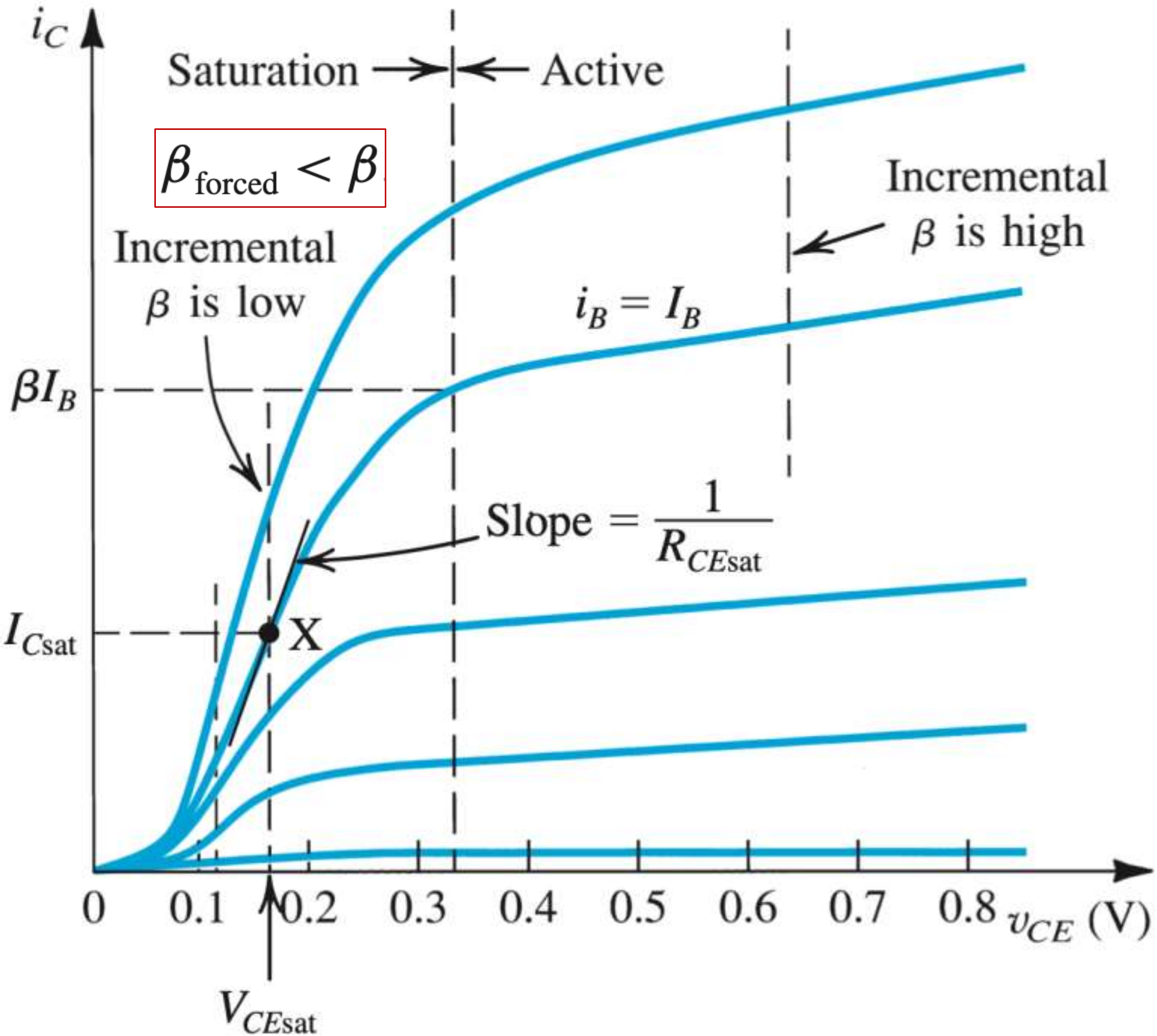
(a) (b)

- 当 C 极电压降低，导致 BC pn 结反偏条件件不成立时，三极管进入“饱和区”
- 进入饱和区后 I_B 增加（BC正偏，新增B到C的空穴电流）→ β减小.

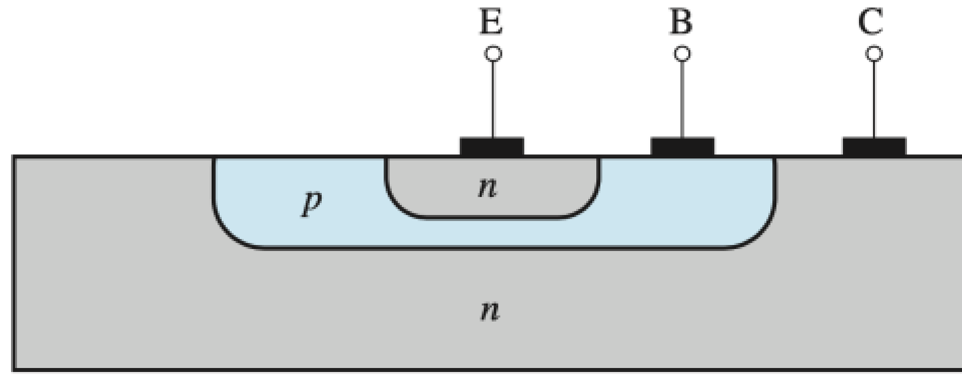
Incremental β

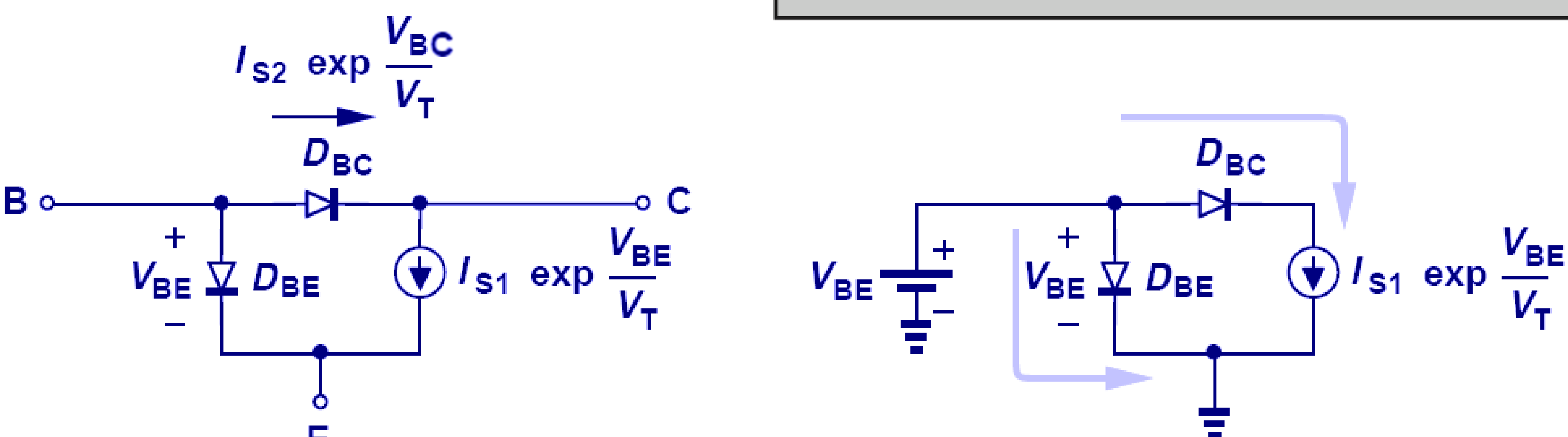


value of β (called *incremental*, or ac, β) is a little different from the dc β (i.e., I_C/I_B). Such a distinction, however, is too subtle for our needs in this book. We shall use β to denote both dc and incremental values.[10]


i_C
Saturation
Active
$\beta_{forced} < \beta$
Incremental β is low
Incremental β is high
$i_B = I_B$
βI_B
Slope $= \frac{1}{R_{CEsat}}$
I_{Csat}
X
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
v_{CE} (V)
V_{CEsat}

处于饱和区三极管的大信号模型





Vb-0.4和Vb-0.5注意，中间为过渡区

(a) (b)

BC 结的面积 > BE 结的面积 → $I_{S,\ BC} > I_{S,\ BE}$

→ $V_{D\_BC,on} < V_{D\_BE,\ on}$ → $V_{D\_BE,\ on} \approx 0.7V$； $V_{D\_BC,\ on} \approx 0.5V$

饱和区大信号模型

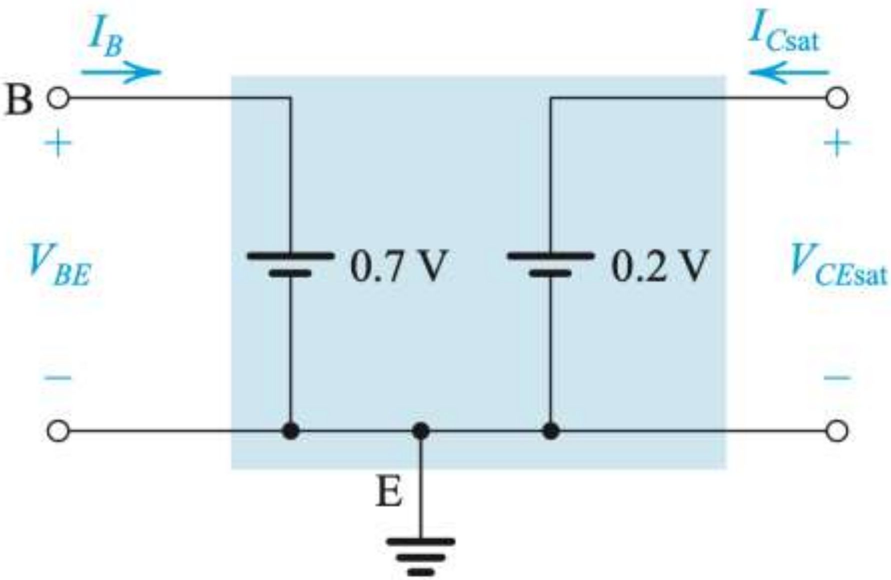
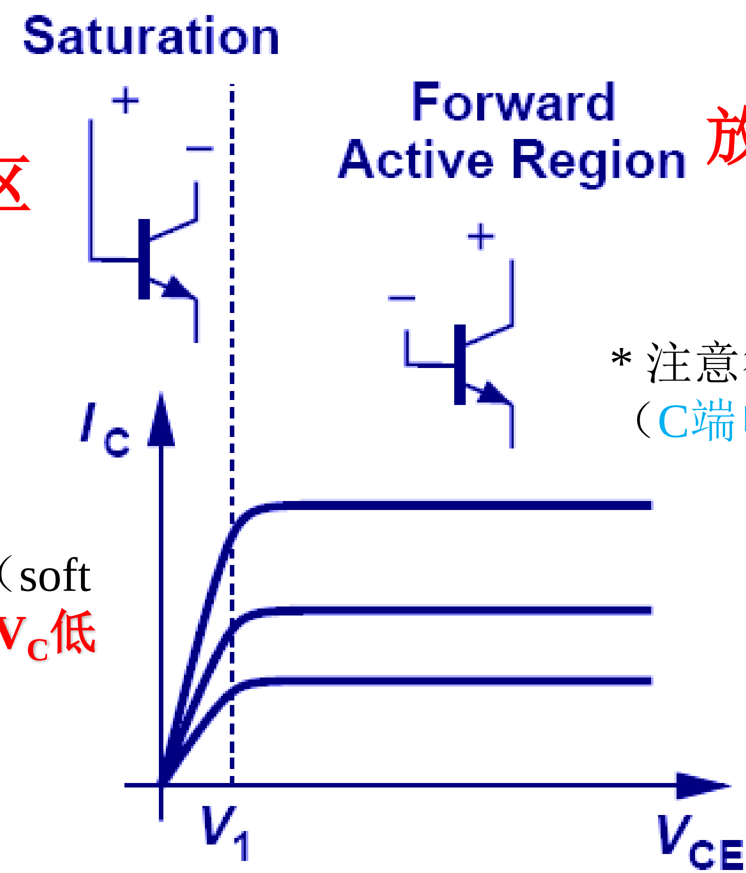


Figure 6.21 A simplified equivalent-circuit model of the saturated transistor.

- 为了快速估算，特别是对于手算，采用上图所示的**简单**模型

饱和区

放大区



* 注意符号图示
（C端电压高于B端电压）

临界处为弱饱和区（soft saturation, 最大**允许V_C低于V_B 400 mV**）

放大区到饱和区不是突变的，一般把临界处（$V_C = V_B - 0.4V$）的饱和区域称为**弱饱和区**；相应地当V_{CE}继续降低时，称为**深饱和区**（V_{CE}=0.2V近似）

Example 6.3

For the circuit in Fig. 6.21, it is required to determine the value of the voltage V_{BB} that results in the transistor operating

(a) in the active mode with $V_{CE} = 5$ V
(b) at the edge of saturation
(c) deep in saturation with $\beta_{forced} = 10$

For simplicity, assume that V_{BE} remains constant at 0.7 V. The transistor β is specified to be 50.

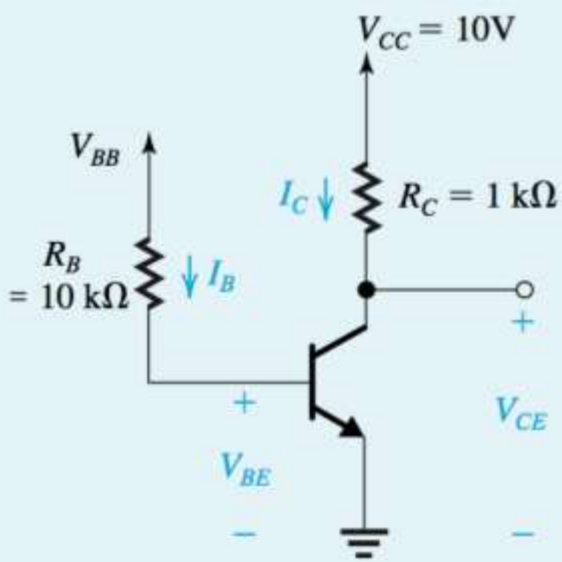


Figure 6.21 Circuit for Example 6.3.

(a) $I_C = \dfrac{V_{CC} - V_{CE}}{R_C} = \dfrac{10-5}{1\text{ k}\Omega} = 5\text{ mA}$

$I_B = \dfrac{I_C}{\beta} = \dfrac{5}{50} = 0.1\text{ mA}$

$V_{BB} = I_B R_B + V_{BE} = 0.1 \times 10 + 0.7 = 1.7\text{ V}$

(b) $V_{CE} = 0.3$ V. $I_C = \dfrac{10-0.3}{1} = 9.7\text{ mA}$

$I_B = \dfrac{9.7}{50} = 0.194\text{ mA}$ $\quad V_{BB} = 0.194 \times 10 + 0.7 = 2.64\text{ V}$

(c) $V_{CE} = V_{CEsat} \simeq 0.2\text{ V}$ $\quad I_C = \dfrac{10-0.2}{1} = 9.8\text{ mA}$

$I_B = \dfrac{I_C}{\beta_{forced}} = \dfrac{9.8}{10} = 0.98\text{ mA}$ $\quad V_{BB} = 0.98 \times 10 + 0.7 = 10.5\text{ V}$

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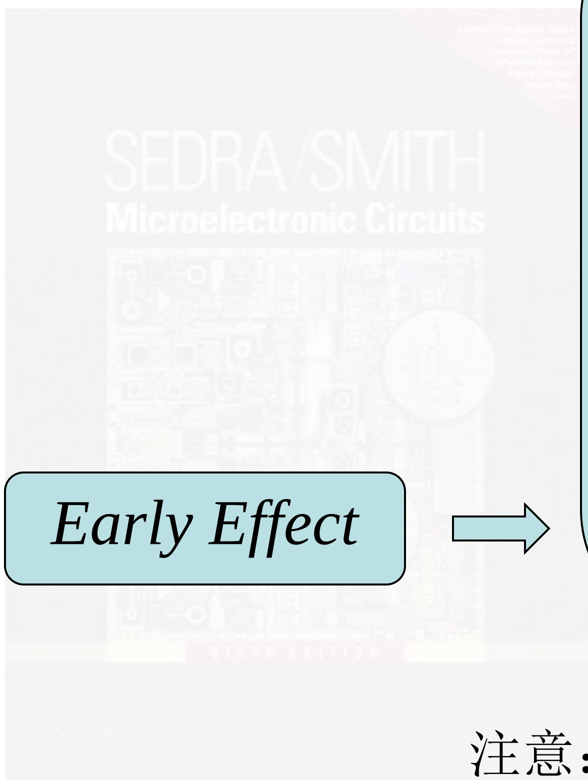
PNP 晶体管的方程



Early Effect

$$I_C = I_S \exp\frac{V_{EB}}{V_T}$$

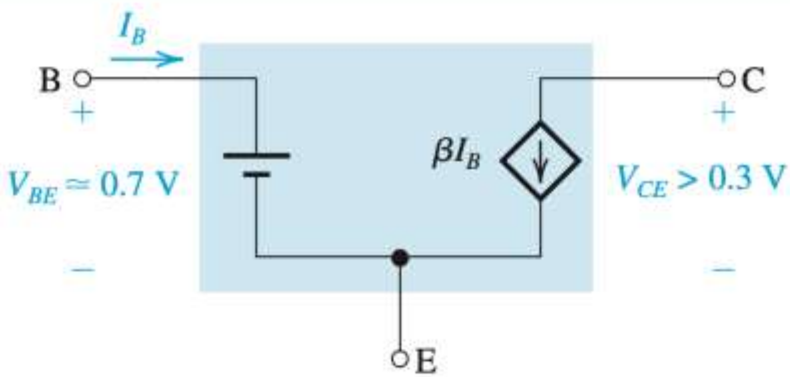
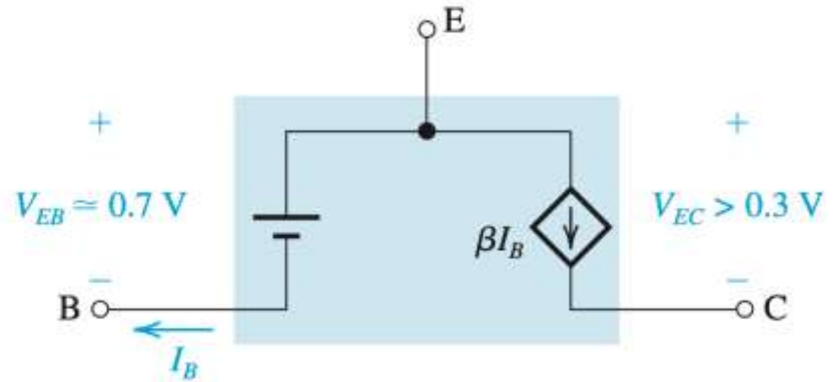
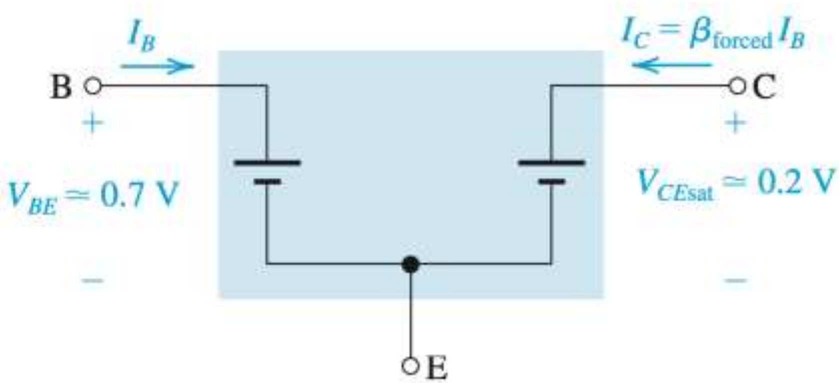
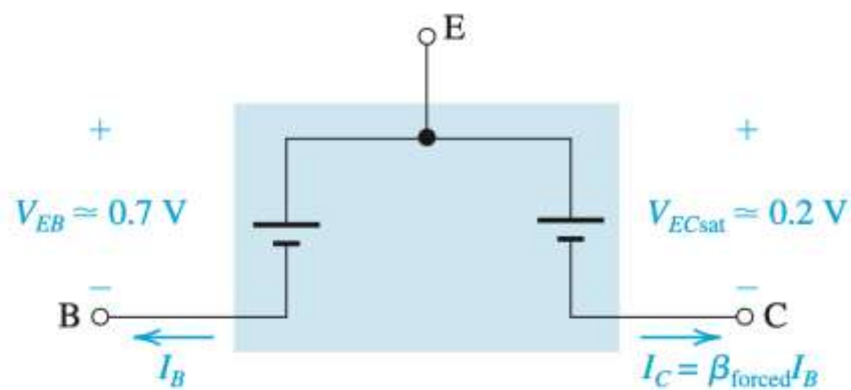
$$I_B = \frac{I_S}{\beta}\exp\frac{V_{EB}}{V_T}$$

$$I_E = \frac{\beta+1}{\beta} I_S \exp\frac{V_{EB}}{V_T}$$

$$I_C = \left(I_S \exp\frac{V_{EB}}{V_T}\right)\left(1+\frac{V_{EC}}{V_A}\right)$$

注意：PNP使用V_{EB}、V_{EC}，NPN使用V_{BE}、V_{CE}
（电压高的字母在前面，或者使用绝对值）

Table 6.3 Simplified Models for the Operation of the BJT in DC Circuits

	npn	*pnp*
Active EBJ: Forward Biased CBJ: Reverse Biased		
Saturation EBJ: Forward Biased CBJ: Forward Biased		

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小结

Table 6.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

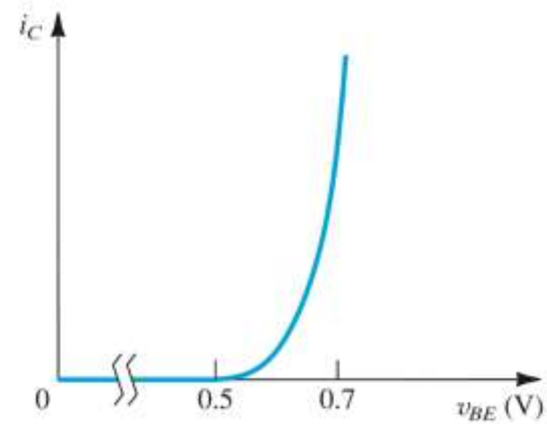
- 三极管的工作区域及其特性
  - 放大区

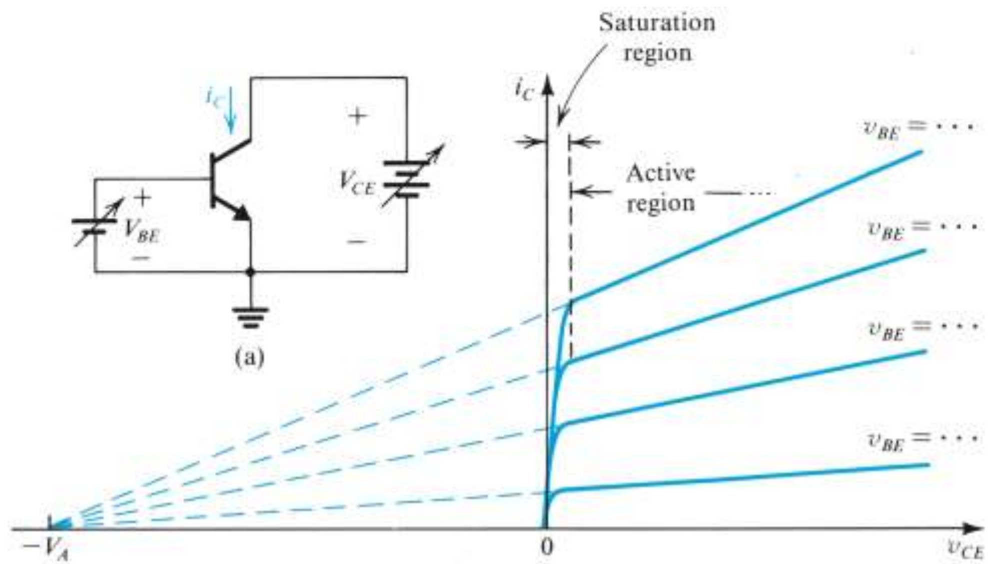
$$i_C = I_S e^{v_{BE}/V_T} \quad i_B = \frac{i_C}{\beta}$$

$$i_E = i_C + i_B$$

$$i_C = \alpha i_E \quad \alpha = \frac{\beta}{\beta+1}$$

  - 工作在放大区的条件
    - 看V_C和V_B之间的关系
- 熟练掌握转移特性和输出特性的曲线及关键坐标点
- Table 6.3 大信号模型

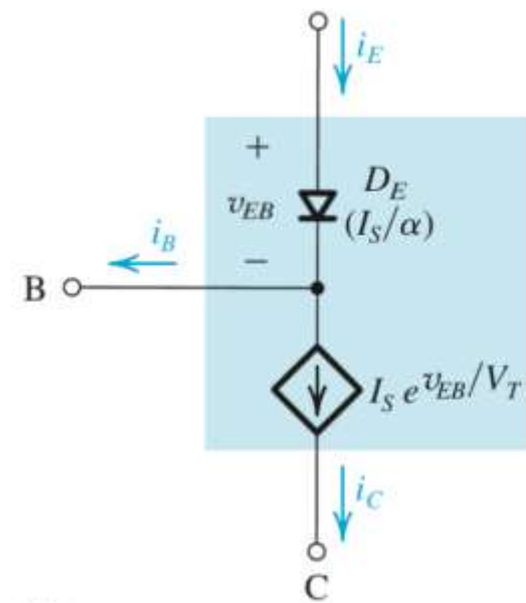




作业

6.5 A transistor for which $I_S = 10^{-16}$ A and $\beta = 100$ is conducting a collector current of 1 mA. Find v_{BE}. Also, find I_{SE} and I_{SB} for this transistor.
Ans. 747.5 mV; 1.01×10^{-16} A; 10^{-18} A

6.10 Consider the model in Fig. 6.11(a) applied in the case of a *pnp* transistor whose base is grounded, whose emitter is fed by a constant-current source of 2 mA, and whose collector is connected to a –10-V dc supply. Find the emitter voltage, the base current, and the collector current if $\beta = 50$ and $I_S = 10^{-14}$ A.
Ans. 0.650 V; 39.2 μA; 1.96 mA



(a)

6.13 In the circuit shown in Fig. E6.13, the voltage at the emitter was measured and found to be –0.7 V. If $\beta = 50$, find I_E, I_B, I_C, and V_C.

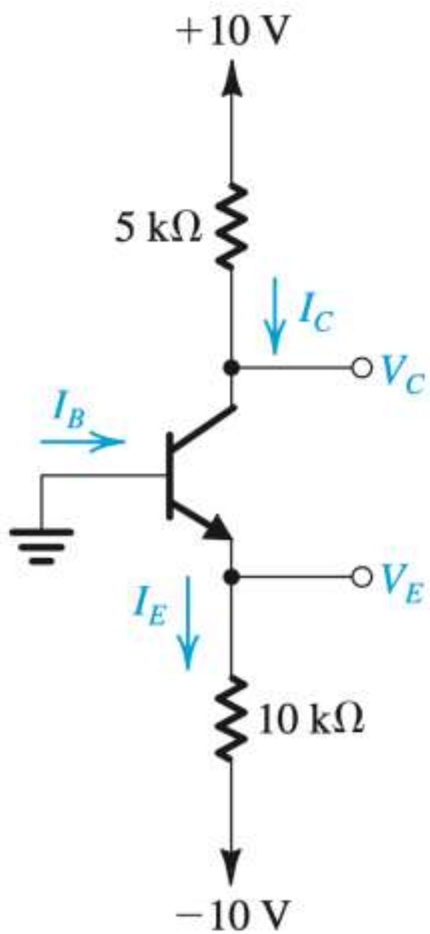


Figure E6.13

Ans. 0.93 mA; 18.2 μA; 0.91 mA; +5.45 V

6.14 In the circuit shown in Fig. E6.14, measurement indicates V_B to be +1.0 V and V_E to be +1.7 V. What are α and β for this transistor? What voltage V_C do you expect at the collector?

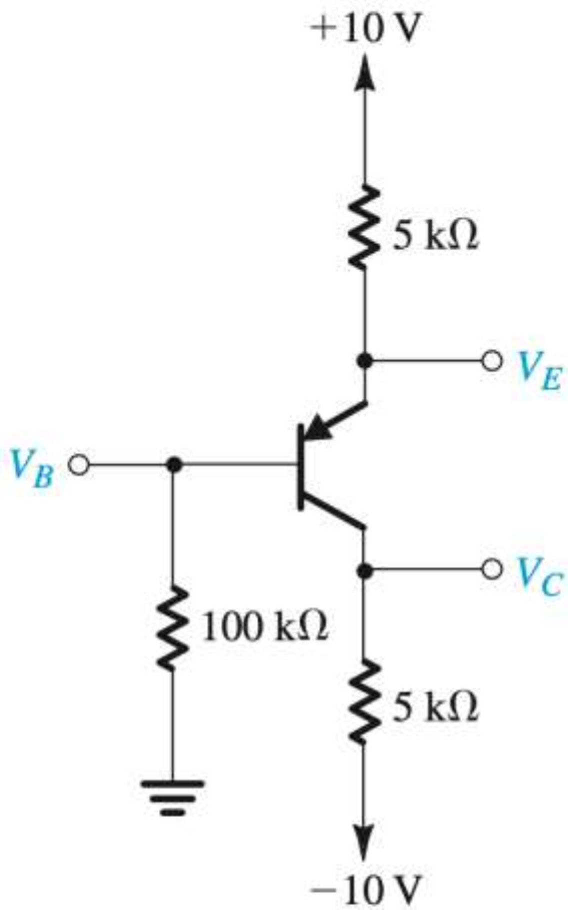


Figure E6.14

Ans. 0.994; 165; –1.75 V

6.17 Find the output resistance of a BJT for which $V_A = 100$ V at $I_C = 0.1$, 1, and 10 mA.

Ans. 1 MΩ; 100 kΩ; 10 kΩ

6.21 For the circuit in Fig. 6.22, let V_{BB} be set to the value obtained in Example 6.3, part (a), namely, $V_{BB} = 1.7$ V. Verify that the transistor is indeed operating in the active mode. Now, while keeping V_{BB} constant, find the value to which R_C should be increased in order to obtain (a) operation at the edge of saturation and (b) operation deep in saturation with $\beta_{forced} = 10$.

Ans. (a) 1.94 kΩ; (b) 9.8 kΩ

For simplicity, assume that V_{BE} remains constant at 0.7 V. The transistor β is specified to be 50.

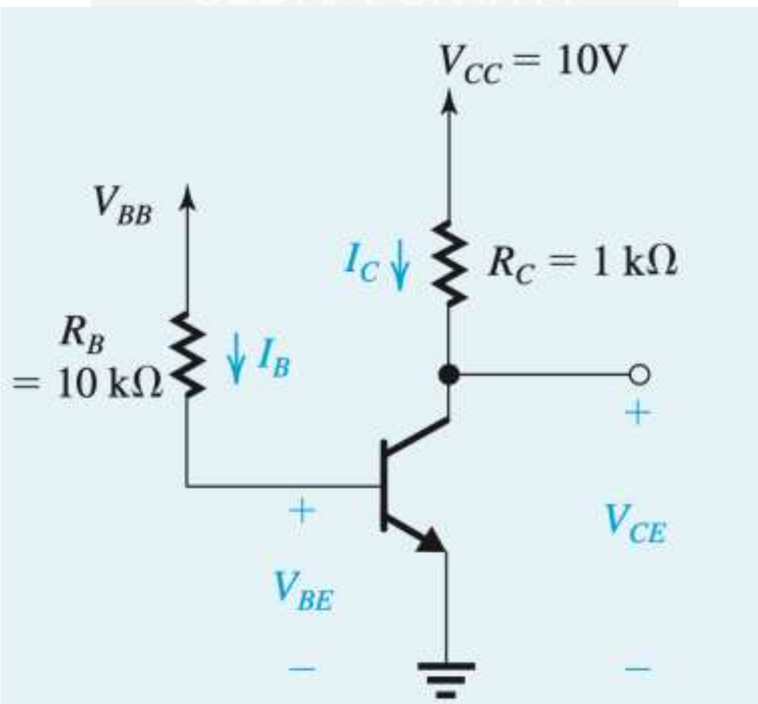


Figure 6.22 Circuit for Example 6.3.