

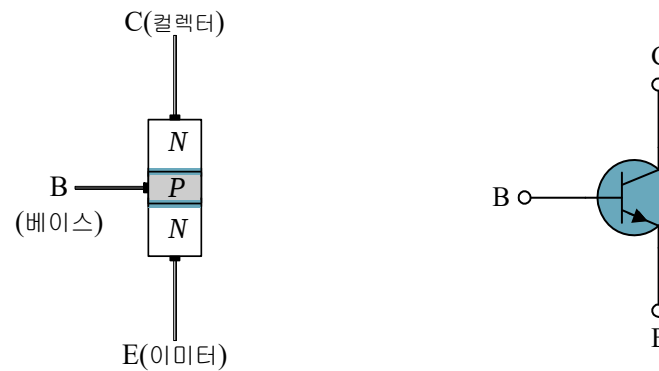


CHAPTER 5

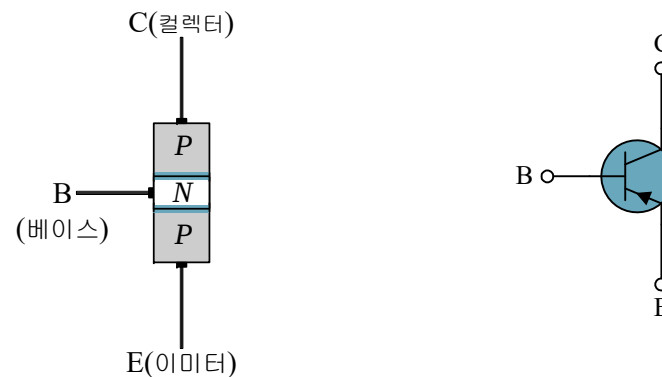
Bipolar Junction Transistors (BJTs)

Bipolar Junction Transistor (BJT)

- Bipolar Junction Transistor에 개의 반도체를 연속 접합 시킨 구조의 트랜지스터
- 각 반도체에 연결된 단자의 명칭: 이미터(emitter), 컬렉터(collector), 베이스(base)
- NPN형 트랜지스터

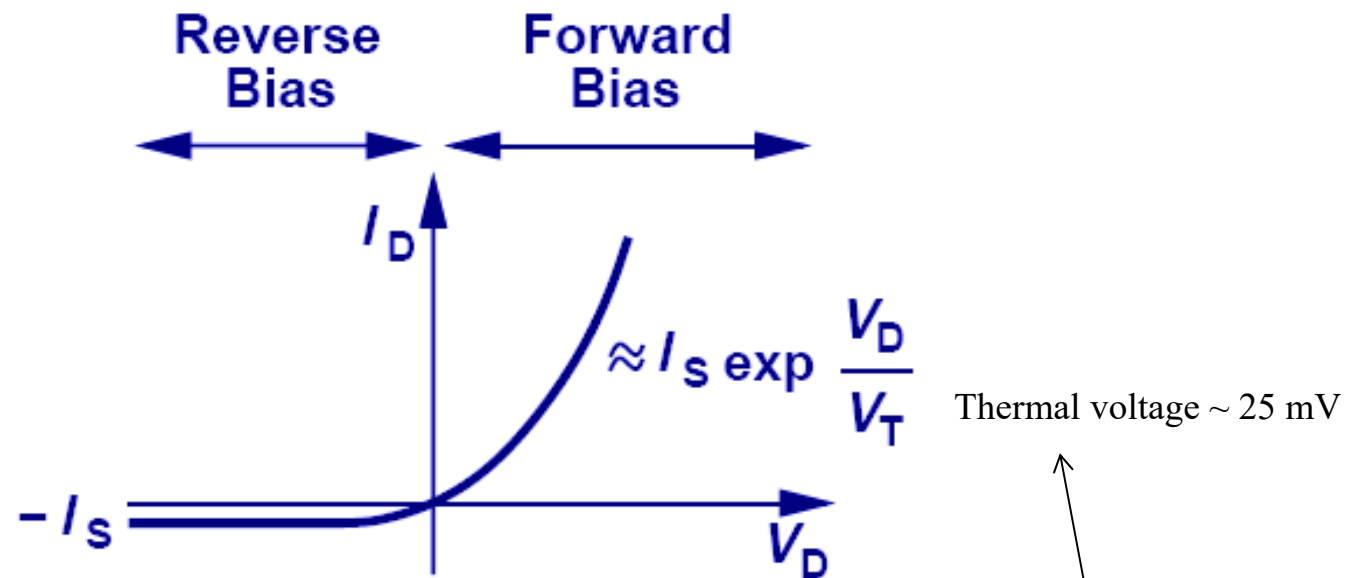


- PNP형 트랜지스터



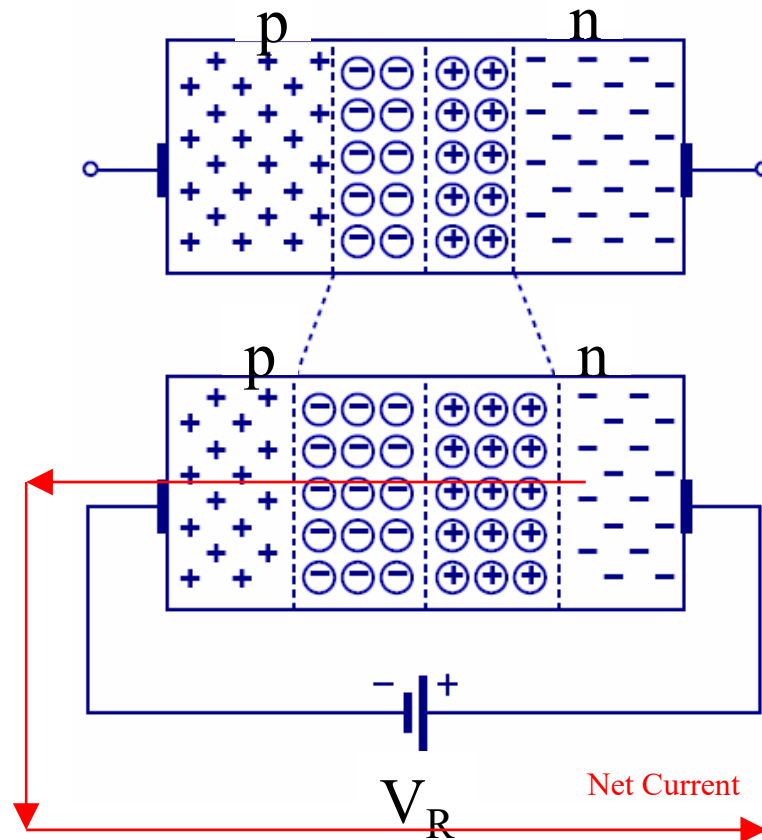
BJT의 동작 원리

- BJT의 동작 원리를 이해하기 위해서는 p-n junction diode의 동작에 대한 정확한 이해가 반드시 필요 => BJT는 두 개의 p-n junction diode가 붙어있는 형태

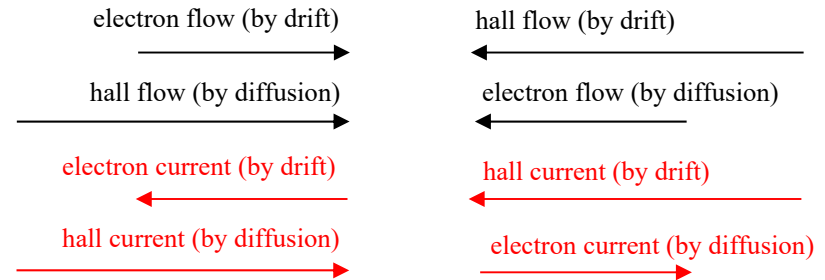


$$I_D = I_S \left(\exp \frac{V_D}{V_T} - 1 \right)$$

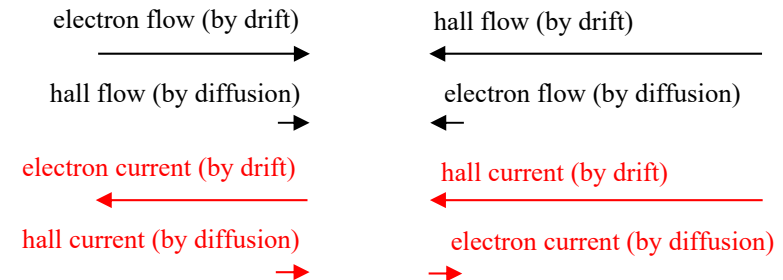
BJT의 동작 원리



바이어스가 인가되지 않은 경우 (평형 상태)



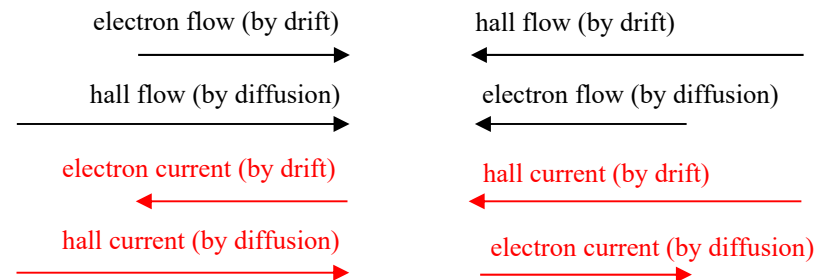
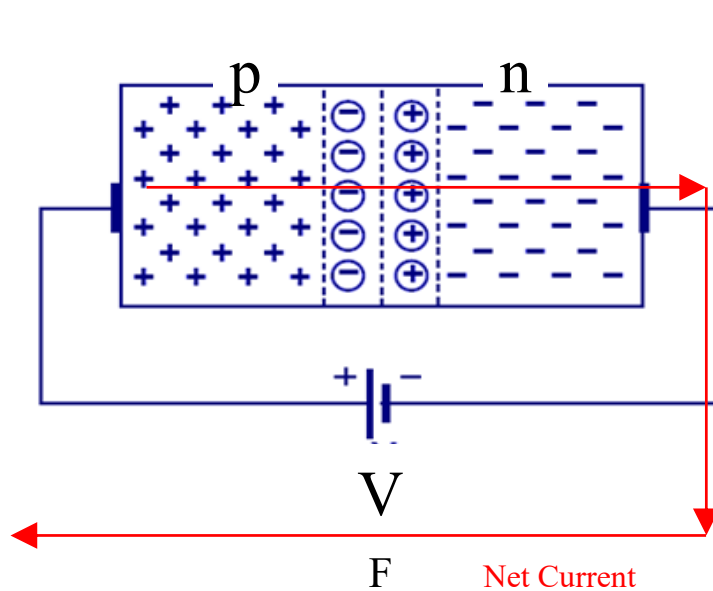
역방향 바이어스가 인가된 경우



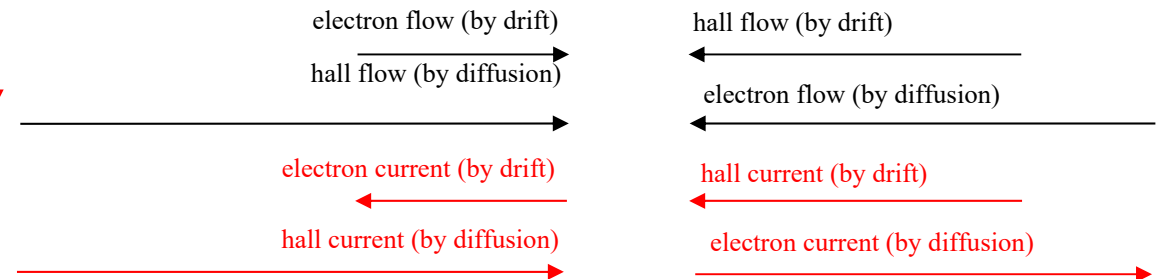
- The drift currents are limited by the number of minority carriers
- Small net currents flow by the drift of minority carriers

BJT의 동작 원리

바이어스가 인가되지 않은 경우 (평형 상태)



순방향 바이어스가 인가된 경우



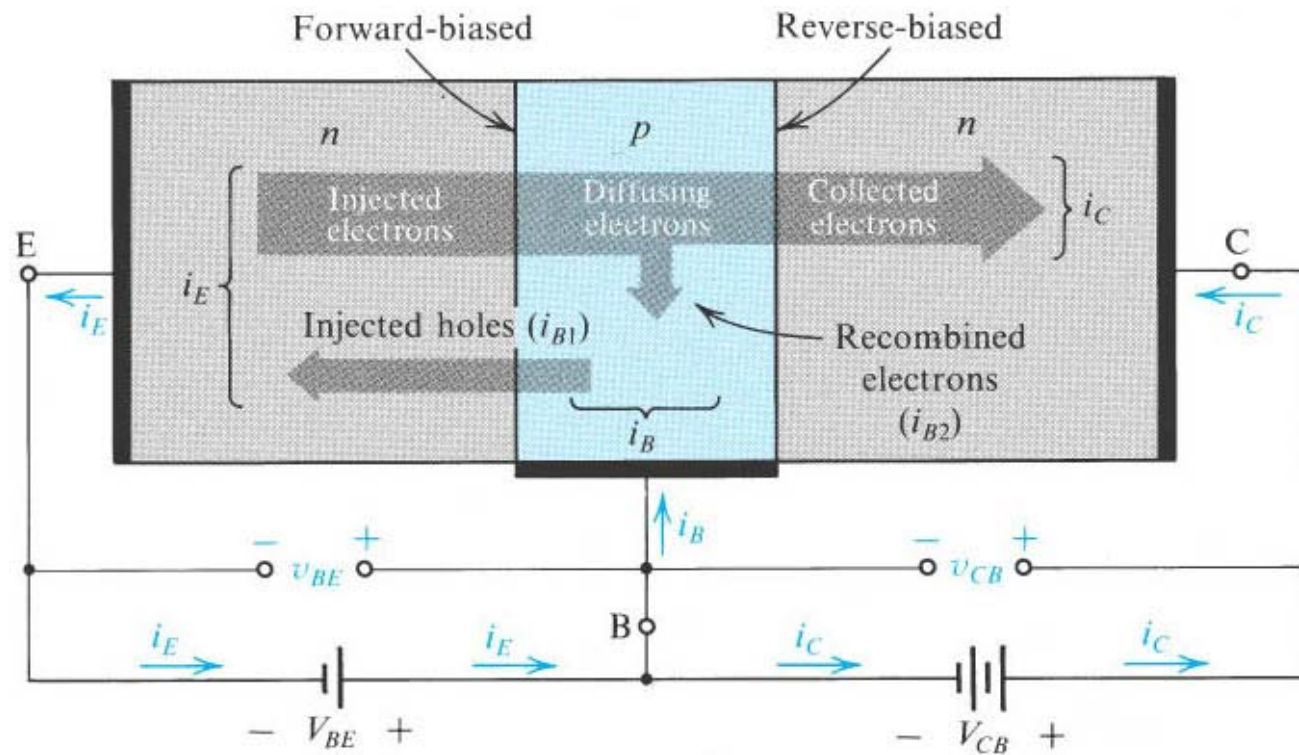
➤ Large net currents flow by the diffusion of majority carriers

인가 전압에 따른 BJT의 동작 모드

TABLE 5.1 BJT Modes of Operation

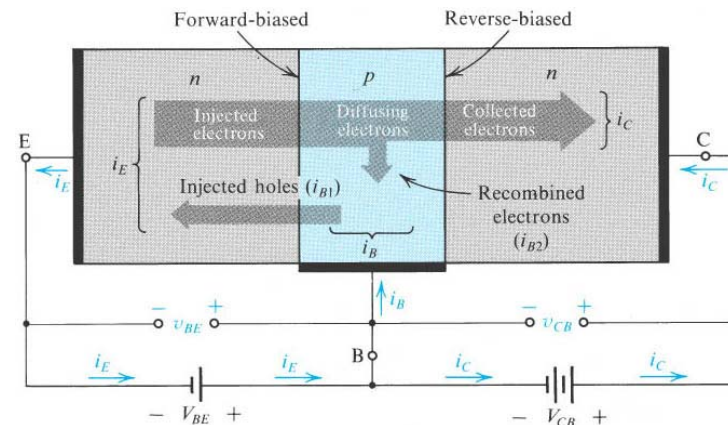
Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Reverse active	Reverse	Forward
Saturation	Forward	Forward

Bipolar Junction Transistor 전류와 이득



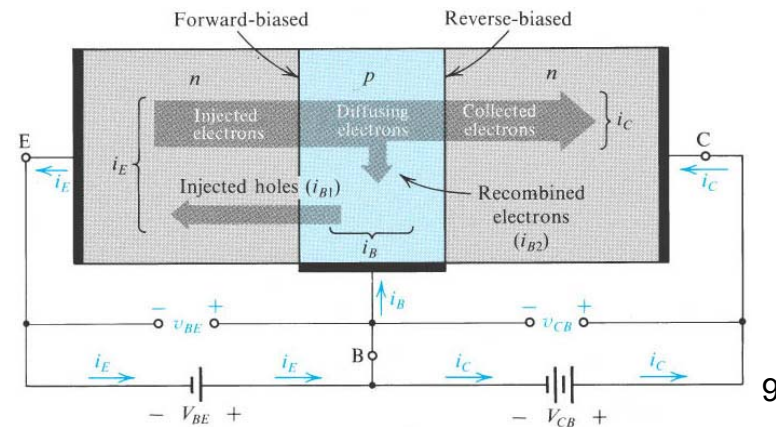
이미터 효율 (Γ_E)

- 순방향 바이어스된 E-B 접합의 n형 에미터는 p형 베이스로 전자를 방출하며 I_{nE} 전류를 형성한다. 이 전류는 역방향 바이어스가 인가된 B-C 접합에 전자를 공급한다.
- E-B 접합의 다른 전류는 베이스에서 이미터로 들어오는 정공에 의한 전류 (I_{pE})이다.
- 총 전류 중 유용한 전류 (I_{nE})의 비율이 에미터 효율이다. ($\Gamma_E = I_{nE}/I_E = I_{nE}/(I_{nE}+I_{pE})$)
- I_{nE} 를 최대화하고 I_{pE} 를 최소화하기 위해서는 n-type 반도체(npn BJT의 에미터)의 도핑 농도를 높이고, p-type 반도체(npn BJT의 컬렉터)의 도핑 농도를 낮추어야 한다.



전달 요소 (α_F)

- 에미터에서 방출된 대부분의 전자는 컬렉터로 이동함.
- 에미터에서 방출된 일부 전자가 베이스 영역에서 정공과 재결합되어 소멸되고, 베이스 전류를 통해 베이스에서 손실된 정공을 보충 (베이스 전류)
- 에미터에서 방출된 전자 중, 성공적으로 컬렉터로 이동한 전자의 비율을 전달 요소 (α_F)라고 하며 I_{nC}/I_{nE} 로 정의함.
- 전달 요소를 최대화하기 위해서는 베이스에서 재결합은 최소가 되어야 하고, 이것은 베이스 영역을 가능한 한 얇게 제작함으로써 가능함.



공통 베이스 및 공통 에미터 전류 이득 α, β

- 공통 베이스 전류 이득 $\alpha = I_C/I_E$
- 공통 에미터 전류 이득 $\beta = I_C/I_B$
- $\alpha = \Gamma_E(\text{에미터 효율}) \alpha_T(\text{전달요소})$
- $\beta = \alpha/(1 - \alpha), \alpha = \beta/(1 + \beta)$
- Generally, $\alpha > 0.99 (<1), \beta > 100$

Summary of Currents

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

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

$$I_S = \frac{A_E q D_n n_i^2}{N_E W_B}$$

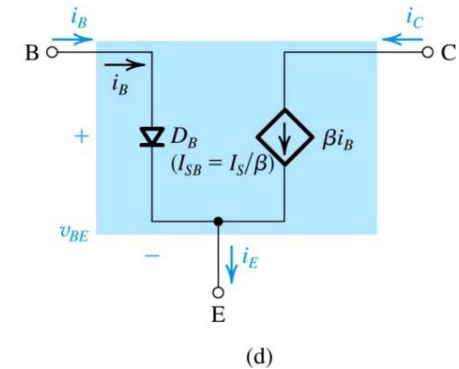
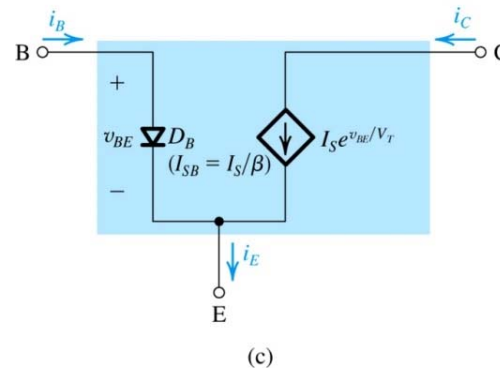
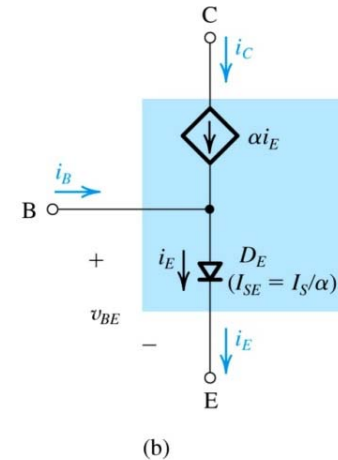
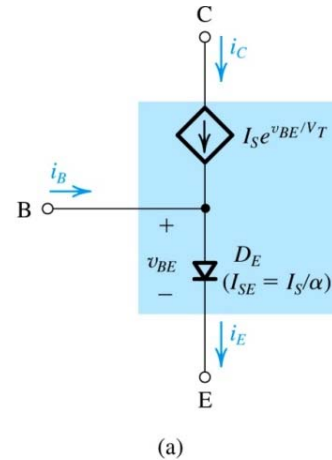
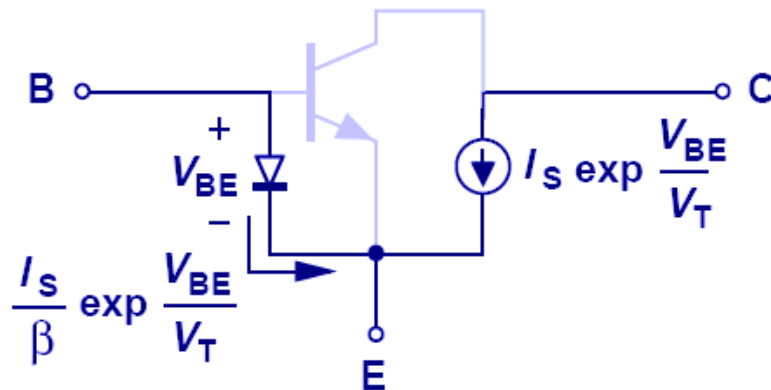
$$I_C = I_S \exp \frac{V_{BE}}{V_T}$$

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

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

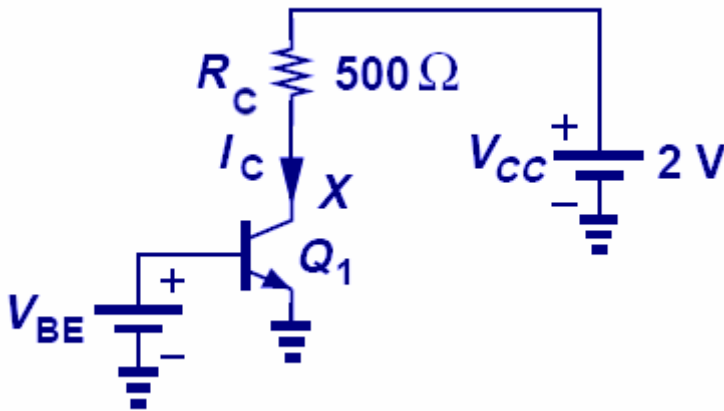
$$\frac{\beta}{\beta + 1} = \alpha$$

Bipolar Transistor Large Signal Model



- A diode is placed between base and emitter and a voltage controlled current source is placed between the collector and emitter.

Example: Maximum R_L



$$I_{S,Q1} = 5 \times 10^{-17} \text{ A}, V_{BE} = 800 \text{ mV}, \beta = 100$$

(a) 트랜지스터의 단자 전압과 전류를 구하고, 소자가 *active* 영역에 있는지 증명하라

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) = 1.153 \text{ mA}$$

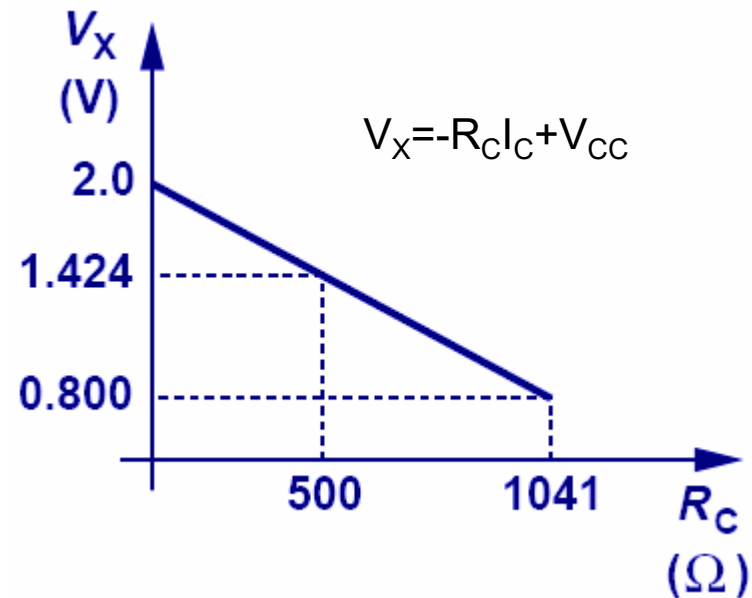
$$I_B = \frac{1}{\beta} I_S \exp\left(\frac{V_{BE}}{V_T}\right) = 11.53 \mu\text{A}$$

$$I_E = \frac{\beta+1}{\beta} I_S \exp\left(\frac{V_{BE}}{V_T}\right) = 1.165 \text{ mA}$$

$$V_{CC} = R_C I_C + V_X, V_X = 1.424 \text{ V}, \text{ active region}$$

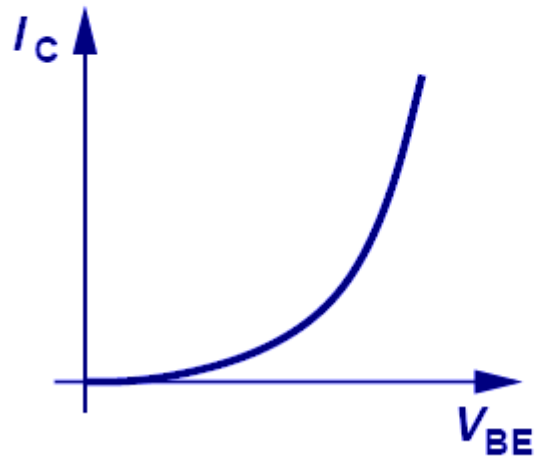
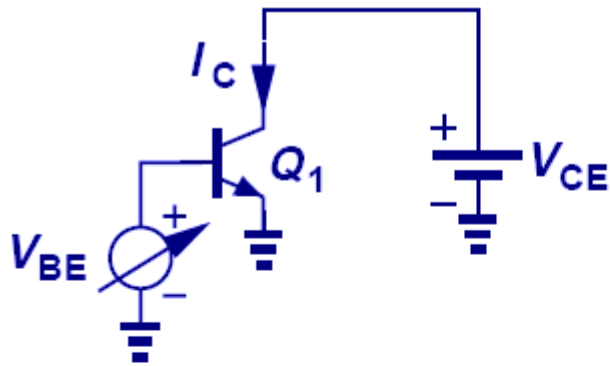
(b) *active* 영역에서 동작할 수 있는 최대 R_C 를 구하라

$$R_C = \frac{V_{CC} - V_X}{I_C}, V_X = 800 \text{ mV에 대하여}, R_C = 1041 \Omega$$

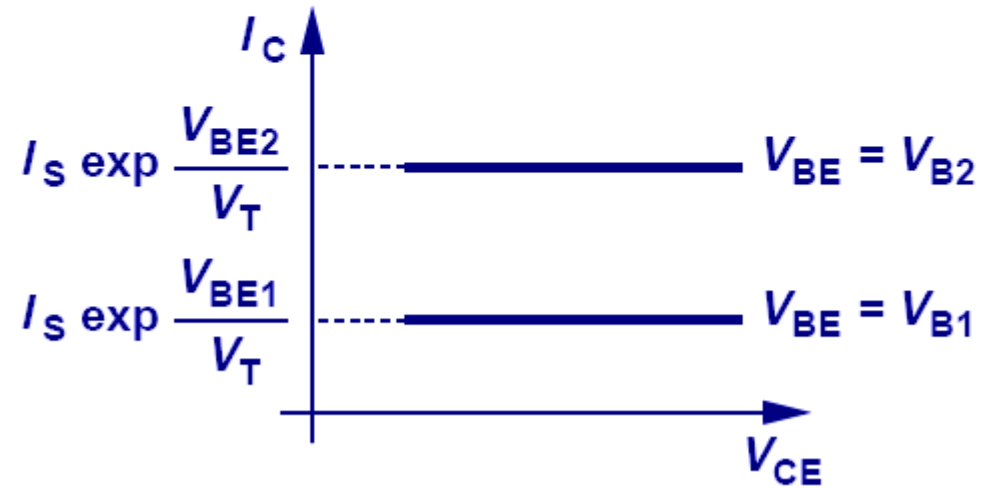
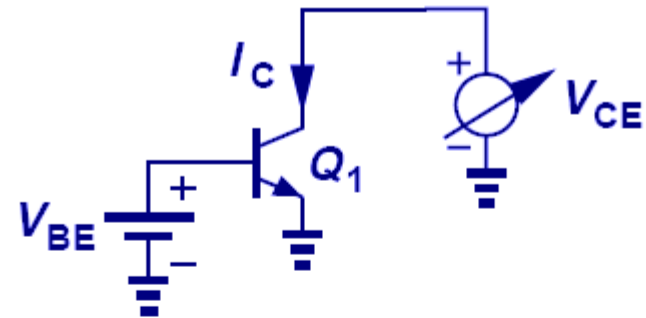


- As R_C increases, V_X drops and eventually forward biases the collector-base junction. This will force the transistor out of forward active region.
- Therefore, there exists a maximum tolerable collector resistance.

Characteristics of Bipolar Transistor



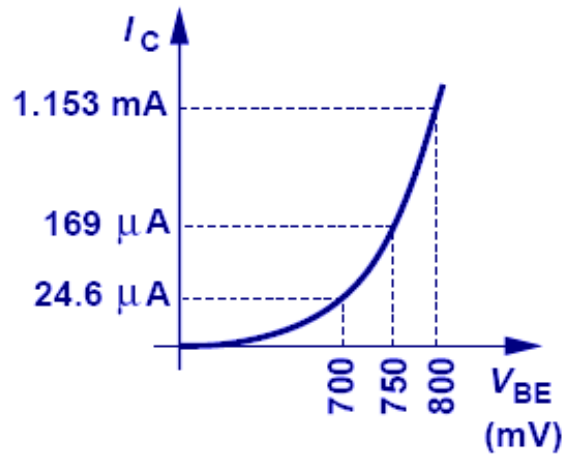
(a)



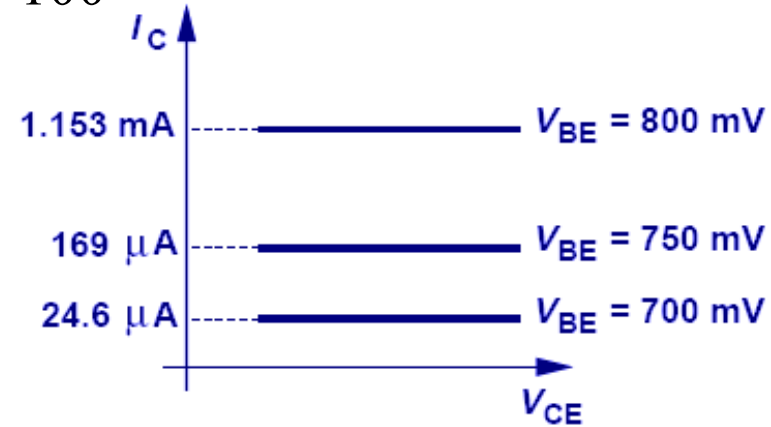
(b)

Example: IV Characteristics

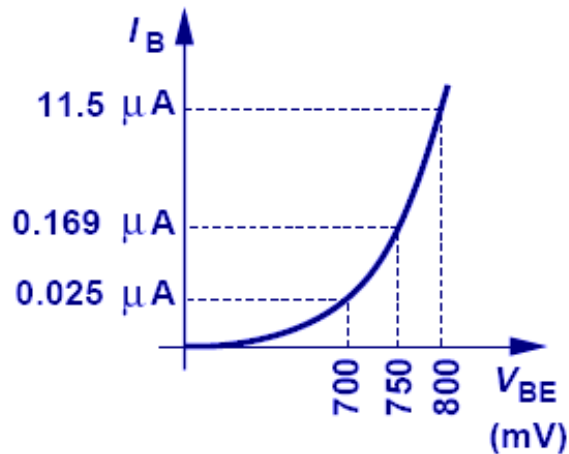
$$I_{S,Q1} = 5 \times 10^{-17} \text{ A}, V_{BE} = 800 \text{ mV}, \beta = 100$$



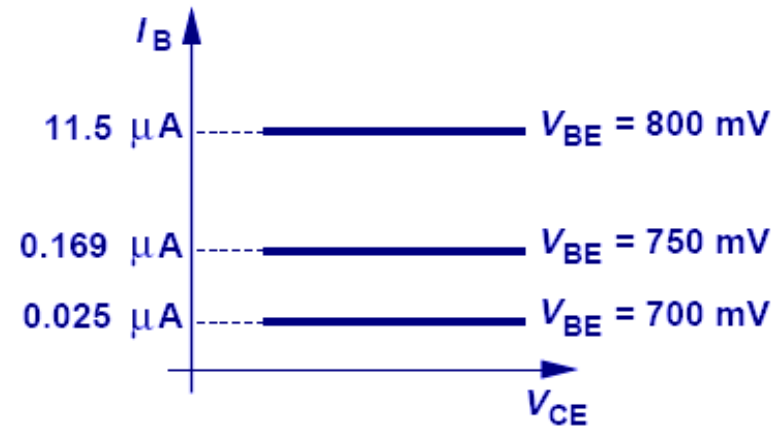
(a)



(b)

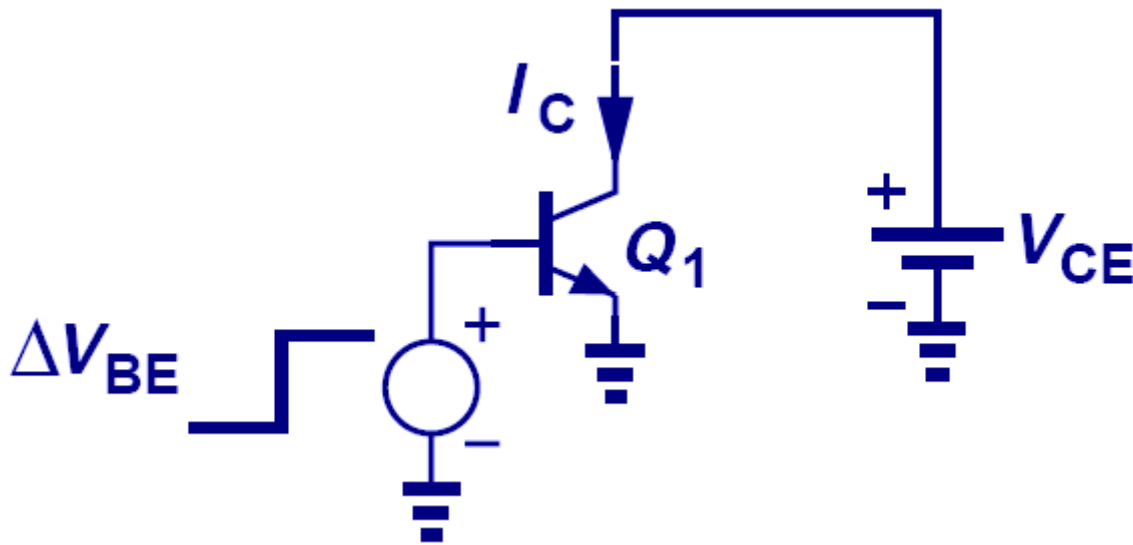


(c)



(d)

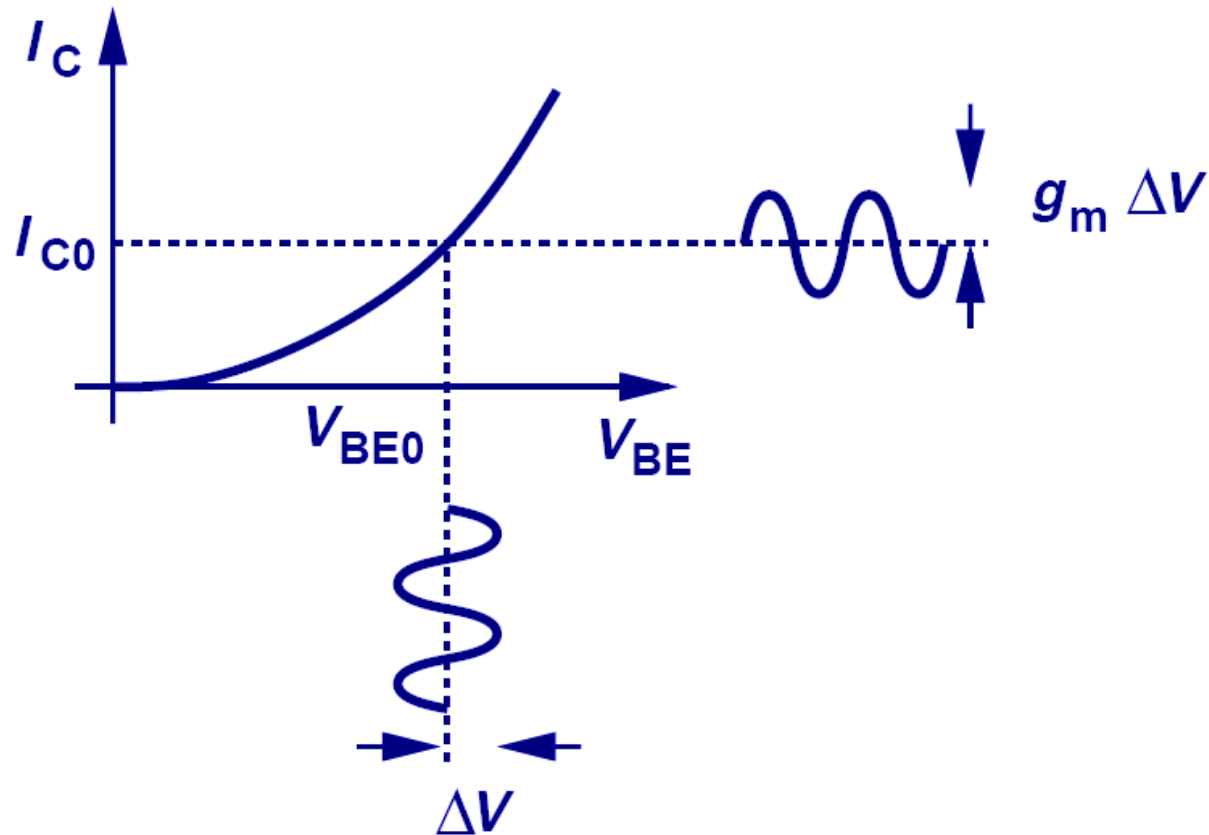
Transconductance



$$g_m = \frac{d}{dV_{BE}} \left(I_S \exp \frac{V_{BE}}{V_T} \right)$$
$$g_m = \frac{1}{V_T} I_S \exp \frac{V_{BE}}{V_T}$$
$$g_m = \frac{I_C}{V_T}$$

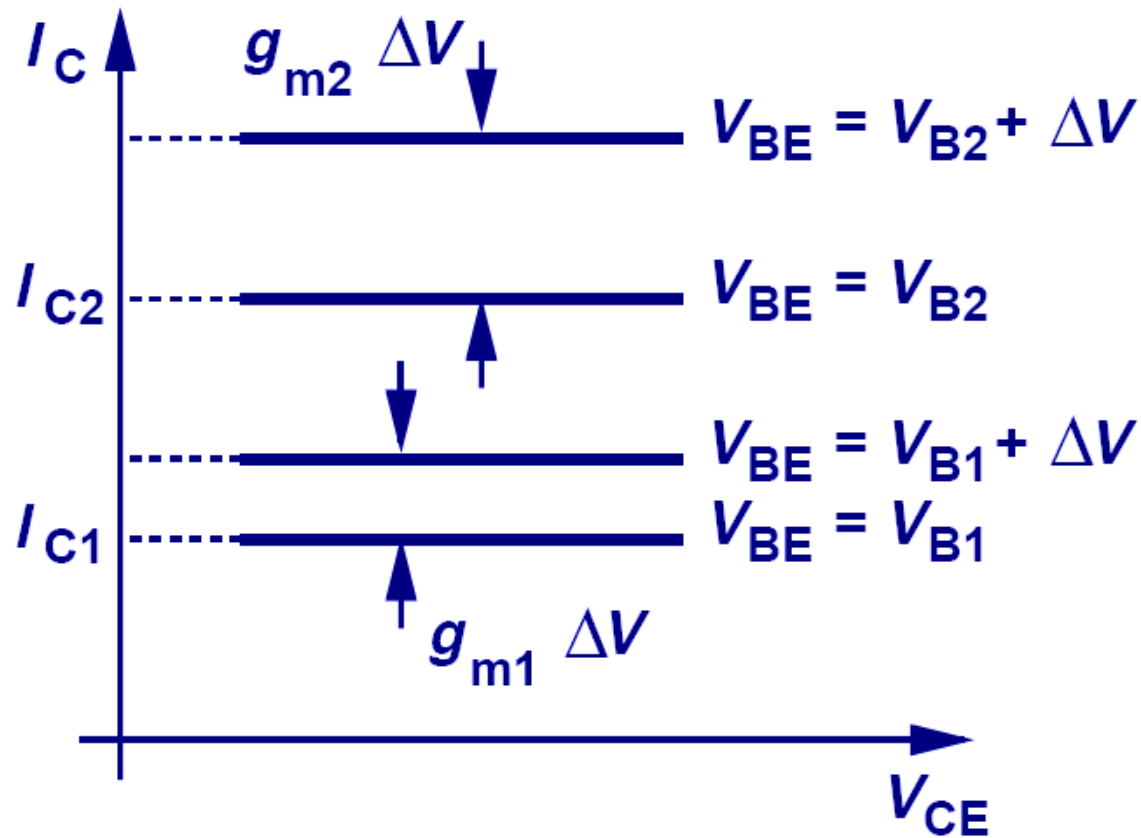
- Transconductance, g_m shows a measure of how well the transistor converts voltage to current.
- It will later be shown that g_m is one of the most important parameters in circuit design.

Visualization of Transconductance



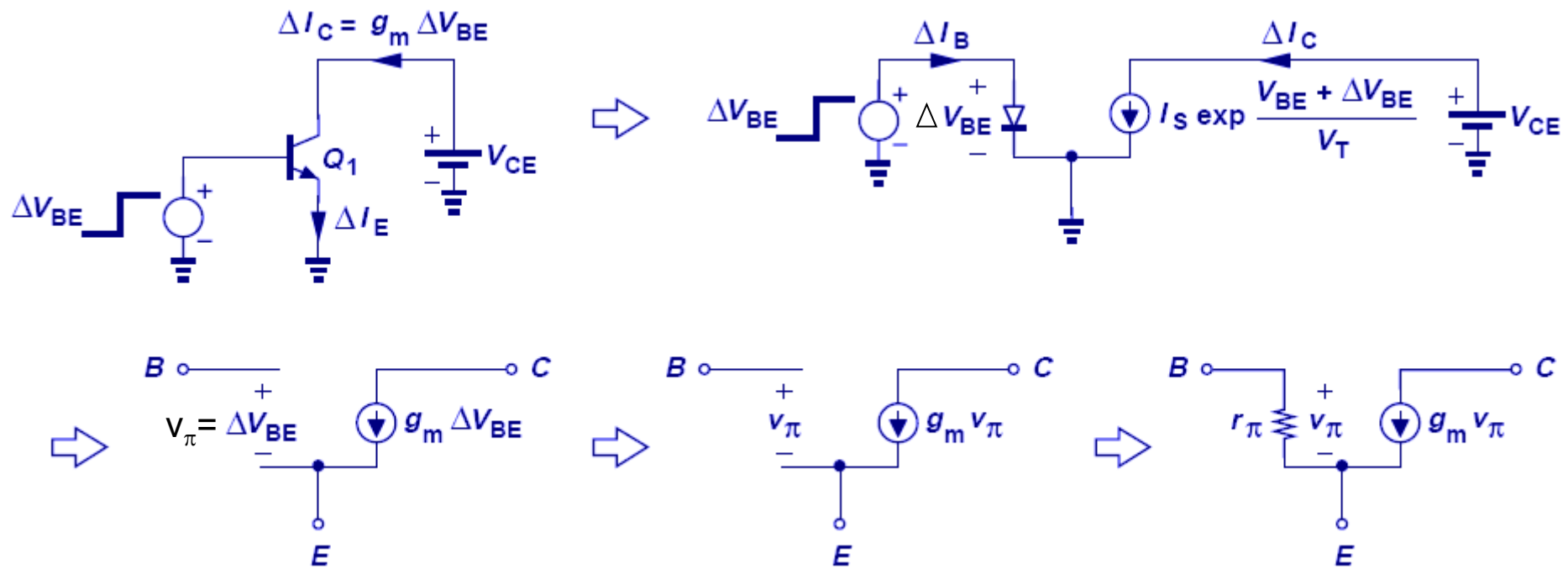
- g_m can be visualized as the slope of I_C versus V_{BE} .
- A large I_C has a large slope and therefore a large g_m .

Transconductance and I_c



- The figure above shows that for a given V_{BE} swing, the current excursion around I_{C2} is larger than it would be around I_{C1} . This is because g_m is larger I_{C2} .

Small-Signal Model of BJT



$$\Delta I_B = \frac{\Delta I_C}{\beta} = \frac{g_m}{\beta} \Delta V_{BE}, r_\pi = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{\beta}{g_m}$$

Small-Signal Model (hybrid π model)

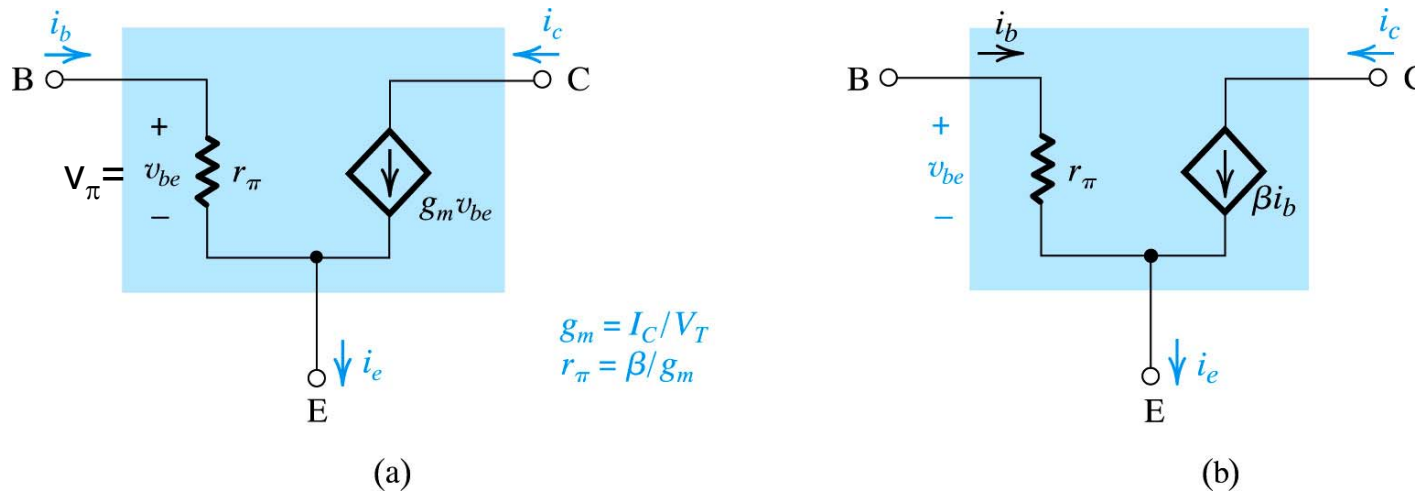


Figure 6.40 Two slightly different versions of the hybrid- π model for the small-signal operation of the BJT. The equivalent circuit in (a) represents the BJT as a voltage-controlled current source (a transconductance amplifier), and that in (b) represents the BJT as a current-controlled current source (a current amplifier).

Small-Signal Model (T model)

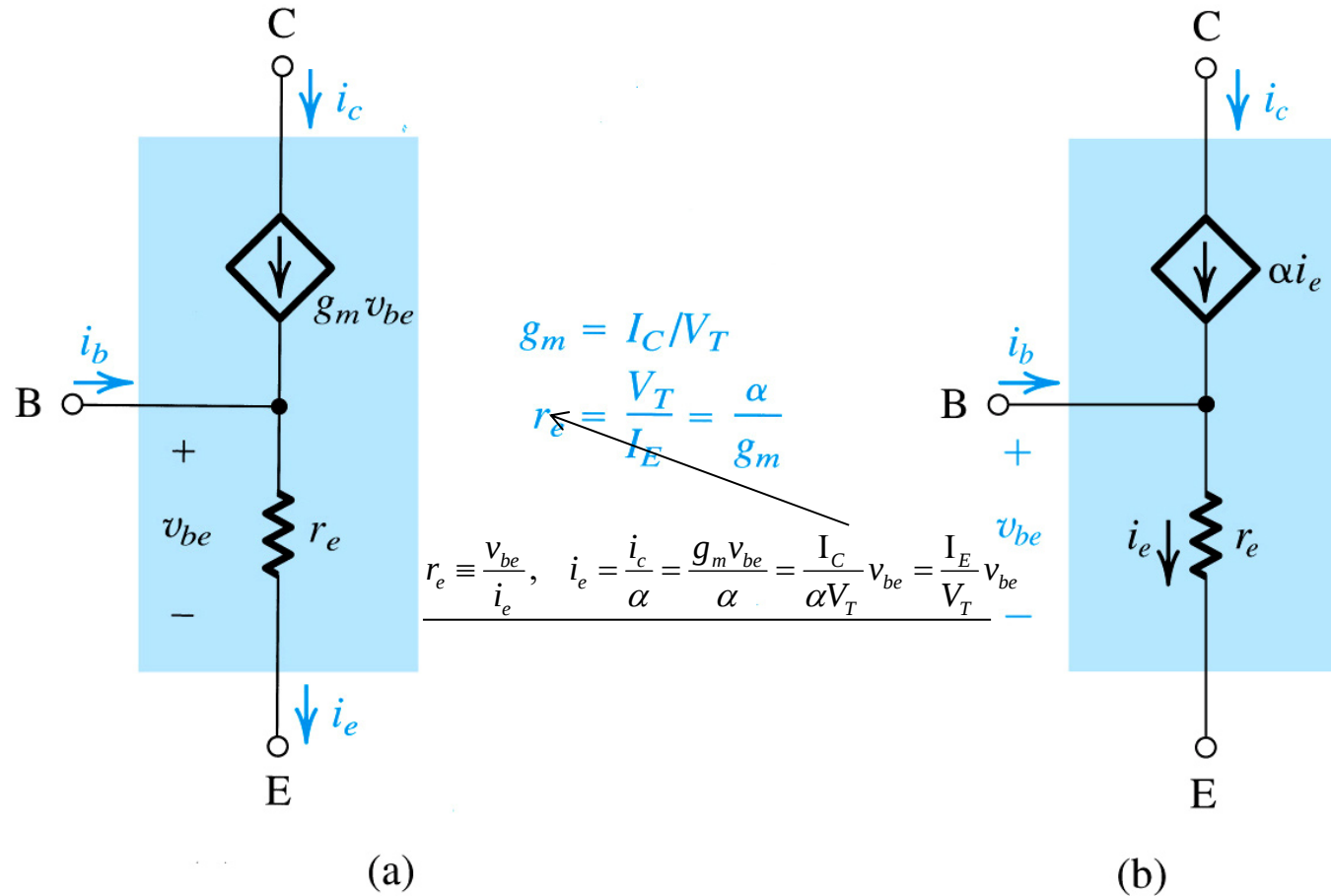
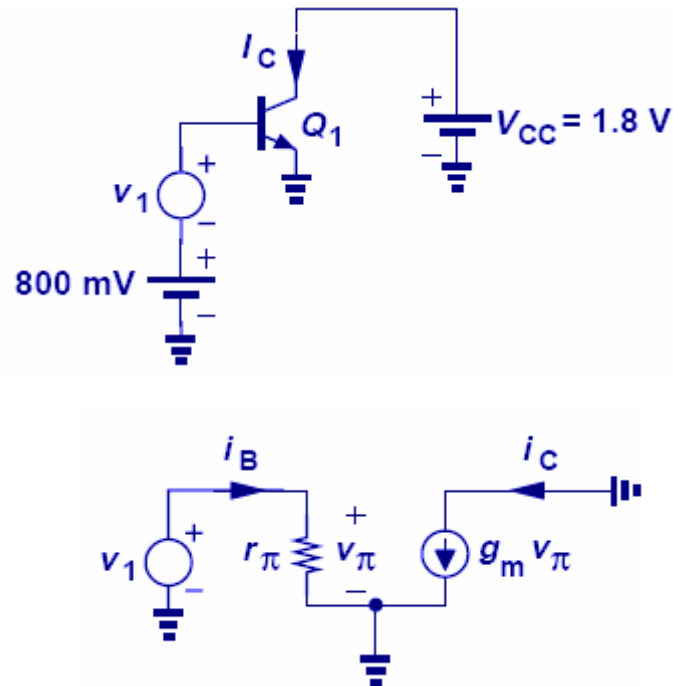


Figure 6.41 Two slightly different versions of what is known as the *T model* of the BJT. The circuit in **(a)** is a voltage-controlled current source representation and that in **(b)** is a current-controlled current source representation. These models explicitly show the emitter resistance r_e rather than the base resistance r_π featured in the hybrid- π model.

Small Signal Example I



$$I_S = 3 \times 10^{-16} \text{ A}, \beta = 100, Q_1: \text{active region}$$

(a) $v_1 = 0$ 일 때 Q_1 의 소신호 매개변수를 구하여라

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) = 6.92 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{1}{3.75 \Omega}$$

$$r_\pi = \frac{\beta}{g_m} = 375 \Omega$$

(b) 회로가 1mV 신호를 발생시킨다면, 컬렉터와 베이스 전류의 변화량은 얼마인가?

$$\Delta I_C = g_m v_1 = \frac{1 \text{ mV}}{3.75 \Omega} = 0.267 \text{ mA}$$

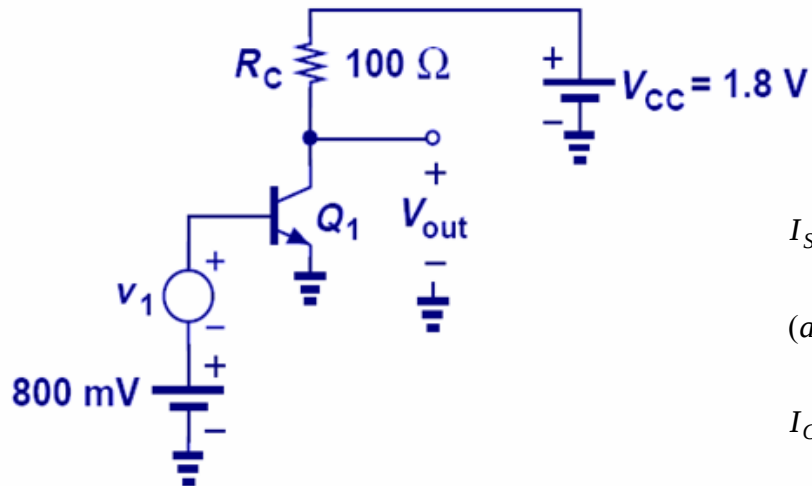
$$\Delta I_B = \frac{v_1}{r_\pi} = \frac{1 \text{ mV}}{375 \Omega} = 2.67 \text{ uA} = \Delta I_C / \beta$$

$$g_m = \frac{I_C}{V_T} = \frac{1}{3.75 \Omega}$$

$$r_\pi = \frac{\beta}{g_m} = 375 \Omega$$

➤ Here, small signal parameters are calculated from DC operating point and are used to calculate the change in collector current due to a change in V_{BE} .

Small Signal Example II



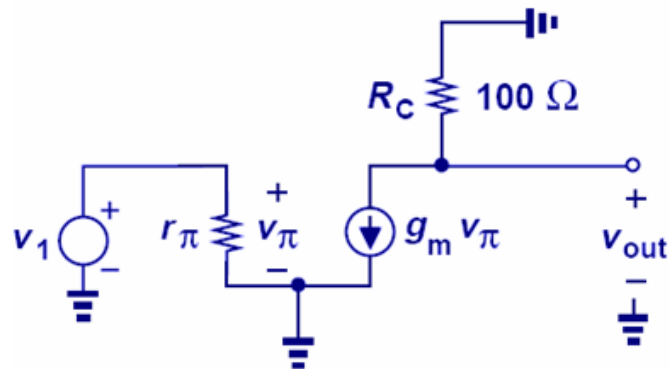
$$I_S = 3 \times 10^{-16} \text{ A}, \beta = 100, Q_1: \text{active region}$$

(a) 트랜지스터가 능동(active)영역에서 동작한다는 것을 증명하여라.

$$I_C = 6.92 \text{ mA}, I_C R_C = 692 \text{ mV}, V_{OUT} = V_{CC} - R_C I_C = 1.108 \text{ V (active region)}$$

(b) 회로가 1mV의 신호를 발생시킬 때 출력 신호를 구하여라.

$$\Delta V_{OUT} = 100 \Omega \times 0.267 \text{ mA} = 26.7 \text{ mV}$$

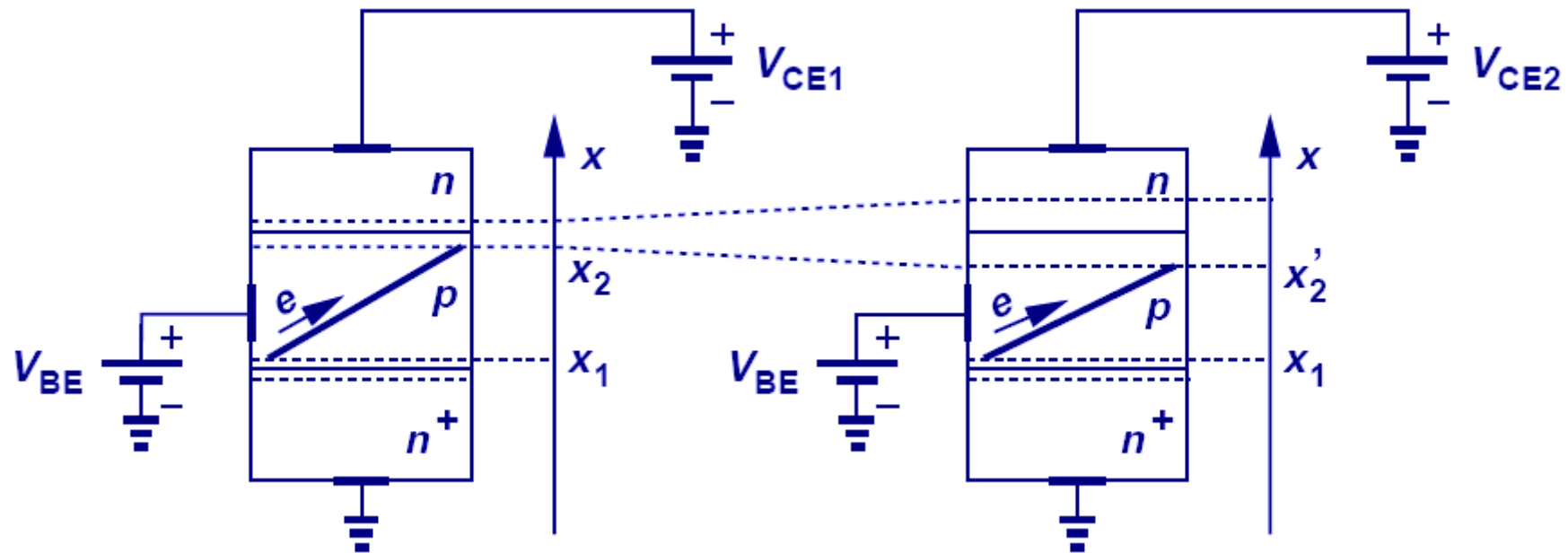


➤ In this example, a resistor is placed between the power supply and collector, therefore, providing an output voltage.

AC Ground

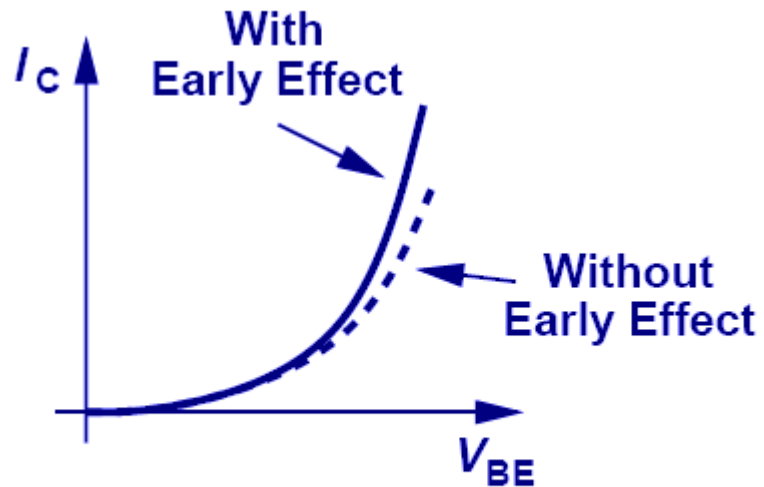
- **Since the power supply voltage does not vary with time, it is regarded as a ground in small-signal analysis.**

Early Effect

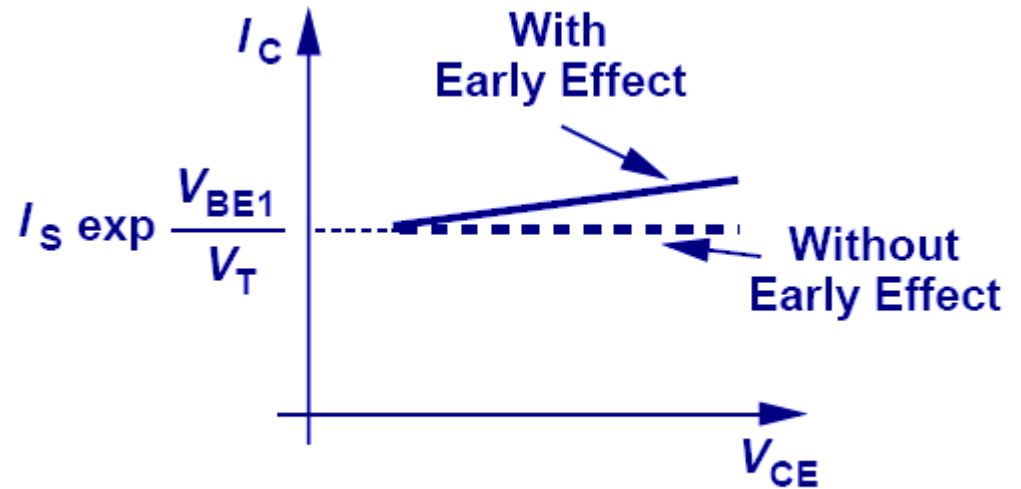


- The claim that collector current does not depend on V_{CE} is not accurate.
- As V_{CE} increases, the depletion region between base and collector increases. Therefore, the effective base width decreases, which leads to an increase in the collector current.

Early Effect Illustration



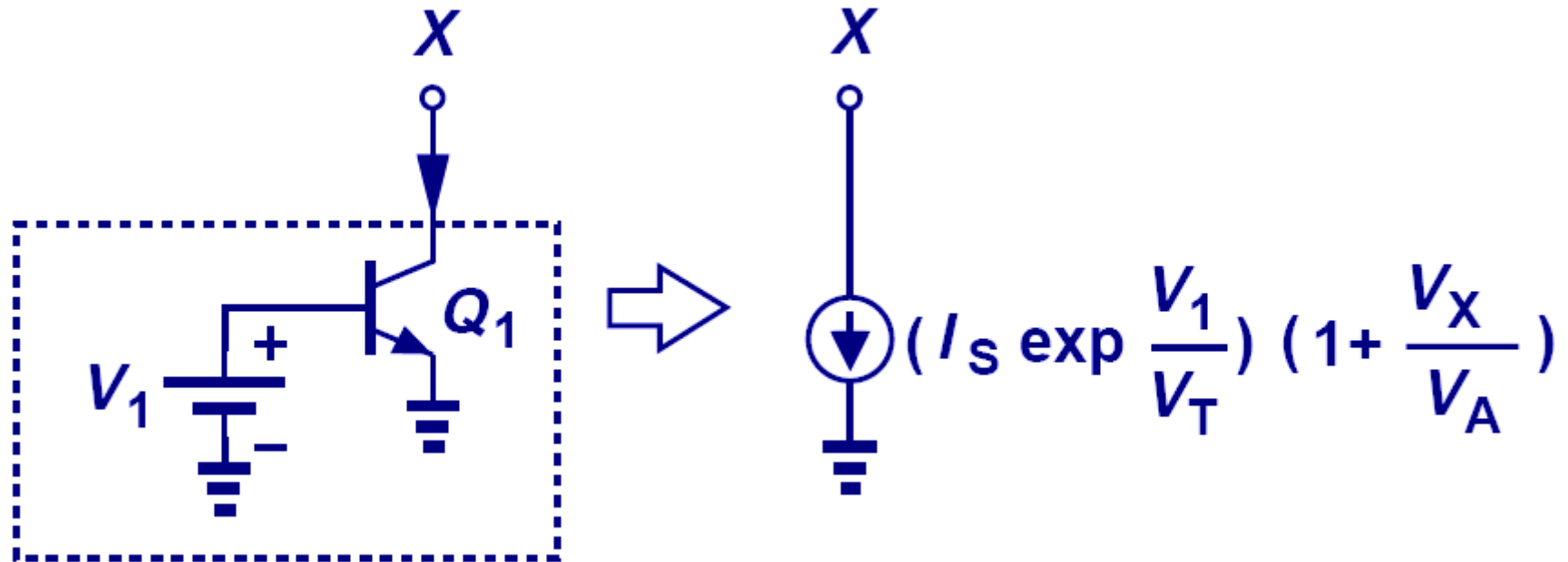
(a)



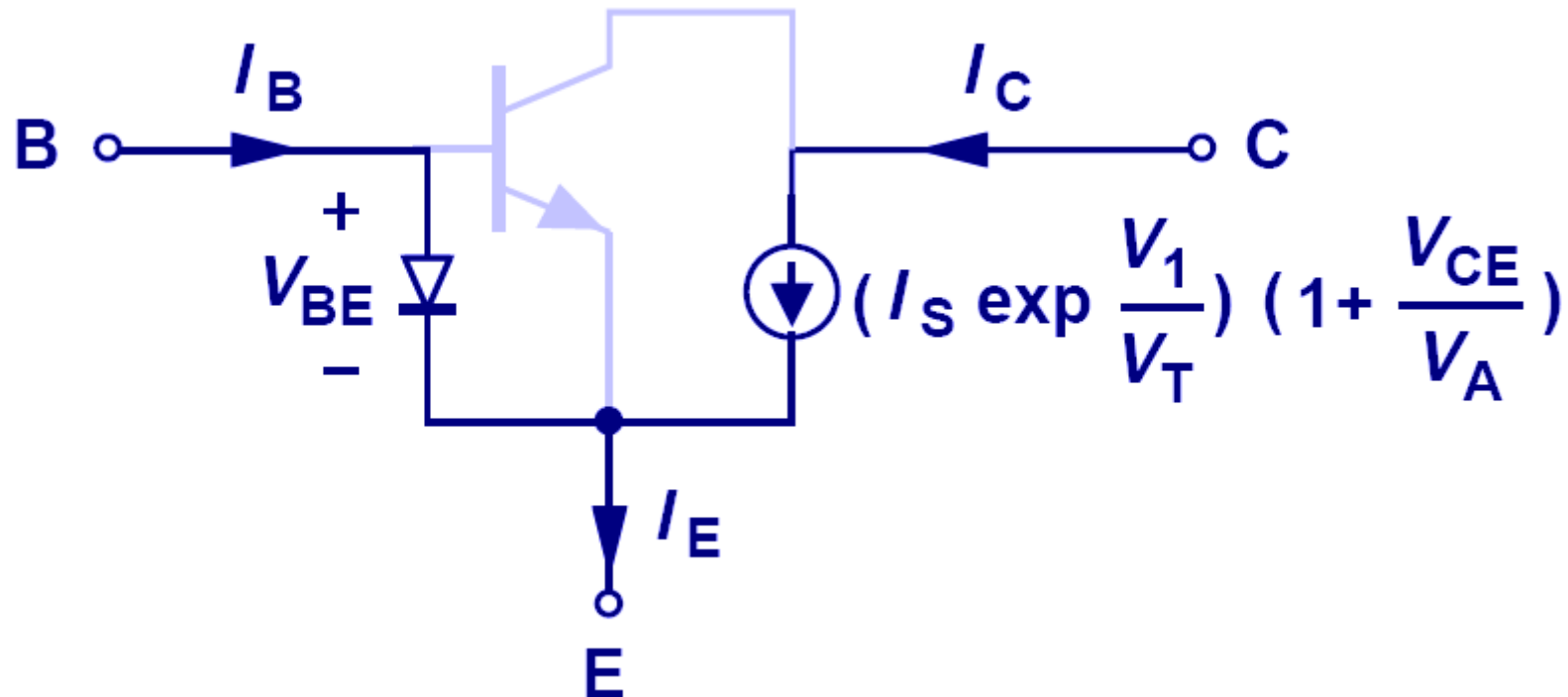
(b)

- With Early effect, collector current becomes larger than usual and a function of V_{CE} .

Early Effect Representation

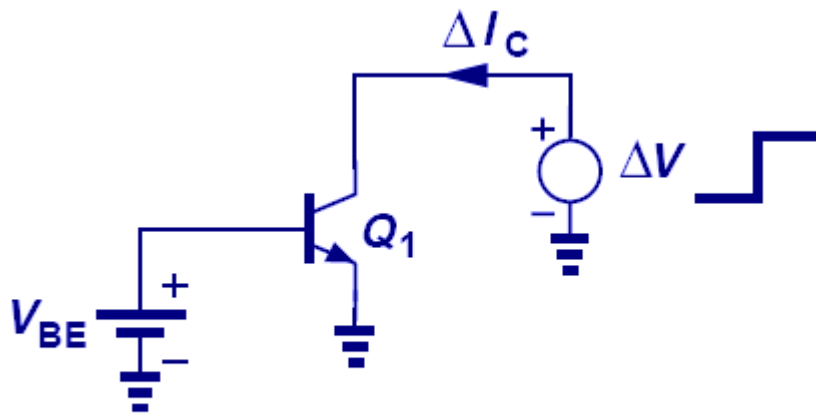


Early Effect and Large-Signal Model



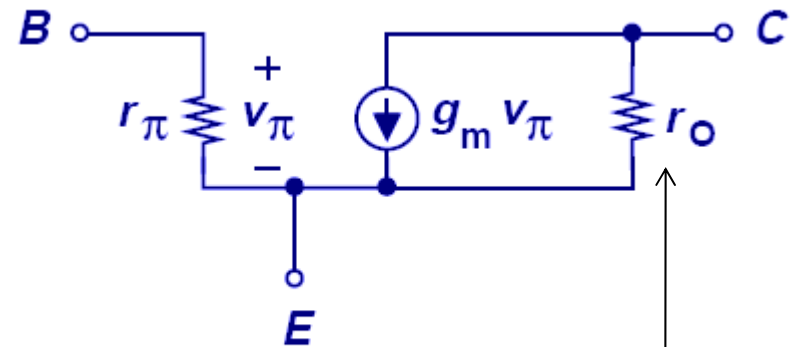
- Early effect can be accounted for in large-signal model by simply changing the collector current with a correction factor.
- In this mode, base current does not change.

Early Effect and Small-Signal Model



(a)

Early effect를 고려하지 않은 collector 전류

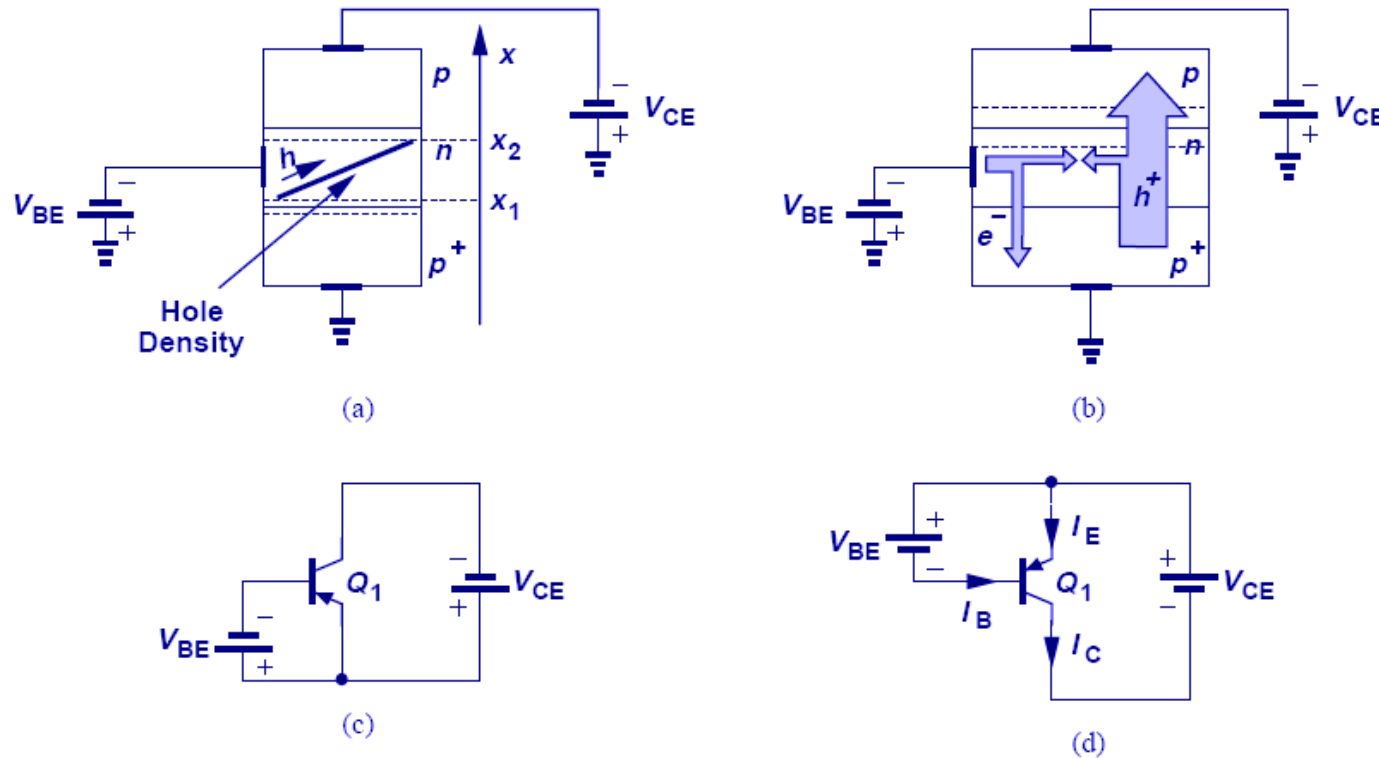


(b)

$$\frac{\delta I_C}{\delta V_{CE}} = I_S \left(\exp \frac{V_{BE}}{V_T} \right) \frac{1}{V_A} \approx \frac{I_C}{V_A}$$

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{V_A}{I_S \exp \frac{V_{BE}}{V_T}} \approx \frac{V_A}{I_C}$$

PNP Transistor



- With the polarities of emitter, collector, and base reversed, a PNP transistor is formed.
- All the principles that applied to NPN's also apply to PNP's, with the exception that emitter is at a higher potential than base and base at a higher potential than collector.

PNP Equations

Early Effect



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

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

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

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

Large Signal Model for PNP

