EE-110 – Basic Electronics

Bipolar Junction Transistor (BJT)

- Introduction

Subtopics

3.0 Bipolar Junction Transistors (6 Hours)

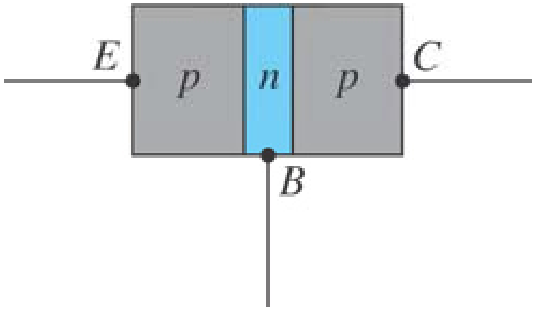
- 3.1 Transistor construction and operation
- 3.2 Transistor configuration
- 3.3 Transistor datasheet and terminal identification

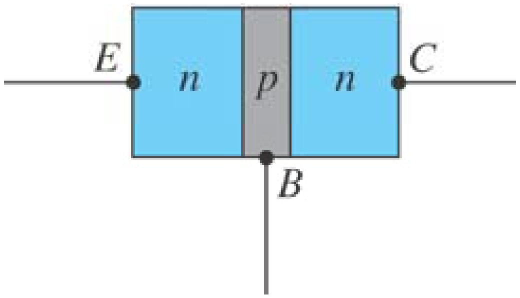
Introduction

- Bipolar means there are two polarities involve in this transistor when operating
- The polarities are the carries involve in the operation of the transistor: holes and electrons
- If only one carrier is employed (holes or electrons), it is said to be unipolar (ex: Diode)

Introduction

- BJT is a three-layer semiconductor
- Two types of BJT
  - pnp:
  - npn:





  - E = emitter, B = base, C = collector

Transistor Construction

- Layer width:
  - outer layer >> inner layer
- Doping:
  - emitter layer is highly doped (more conductivity)
  - collector layer is lightly doped (less conductivity)
  - base layer is more lightly doped (lesser conductivity)
  - doping: E > C > B

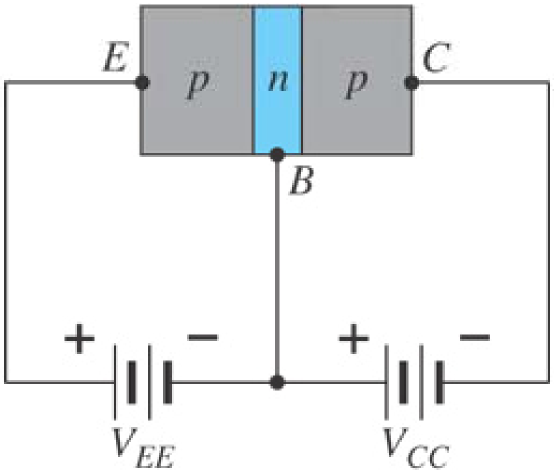
Transistor Operation

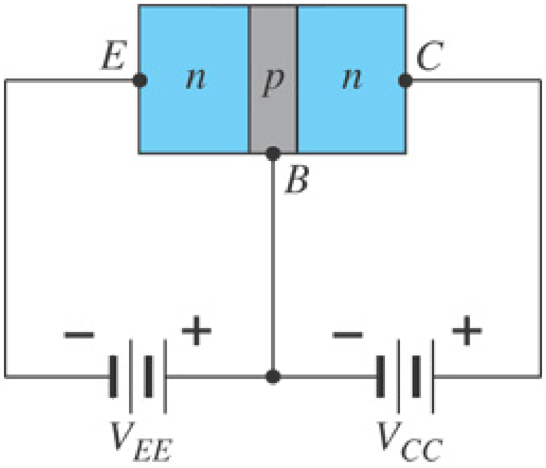
- The operation of pnp and npn are the same except for the current flow
  - For pnp:
    - Current flow from E to B and C
  - For npn:
    - Current flow from B and C to E
- As for that, both type will have the current equation:

$$I_E = I_B + I_C$$

Transistor Operation

- Proper biasing for pnp and npn transistor:
  - pnp
  - npn

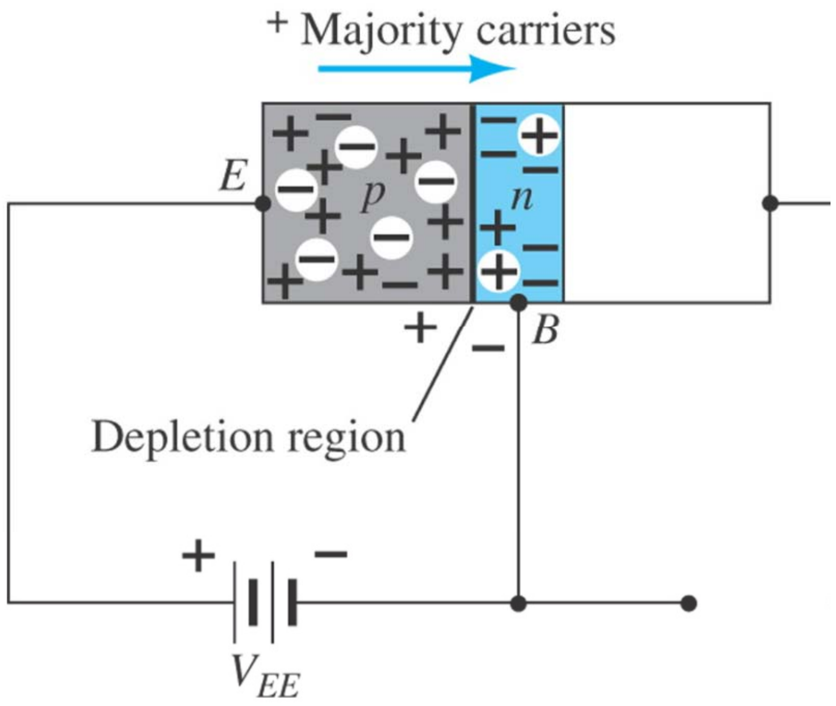




  - This proper biasing is for transistor operation in active region (will be discussed in DC biasing)

Transistor Operation

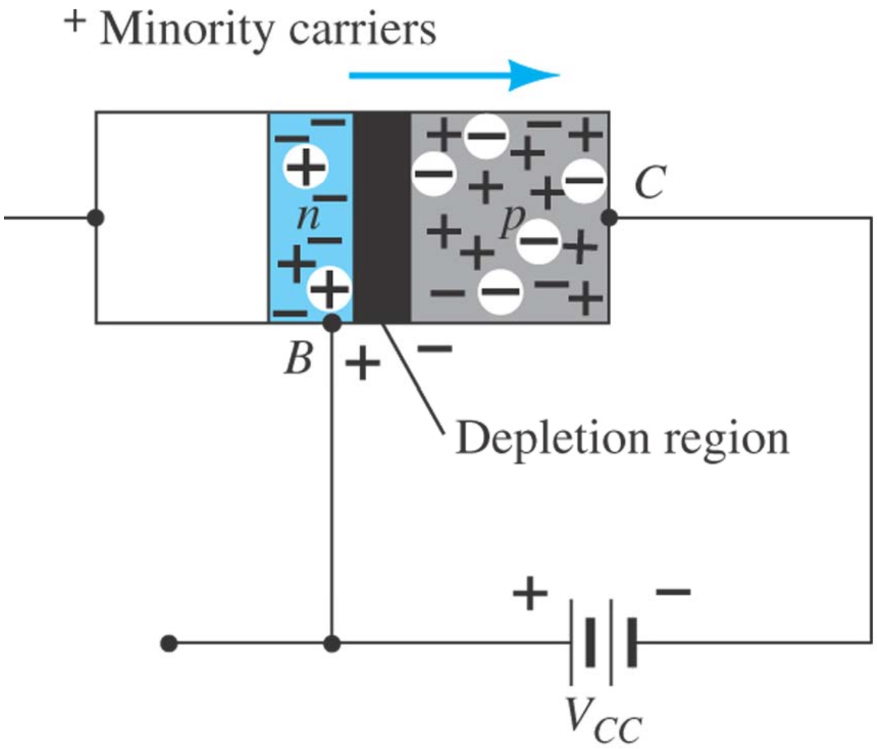
- Examine the pnp transistor for its forward biased junction at terminal E to B:



- It is very similar to a forward-biased diode
- Majority carrier (holes) flows from E to B
- Minority carrier (electrons) flows from B to E
- Resulting in small depletion region
- This means that the current flows heavily from E to B

Transistor Operation

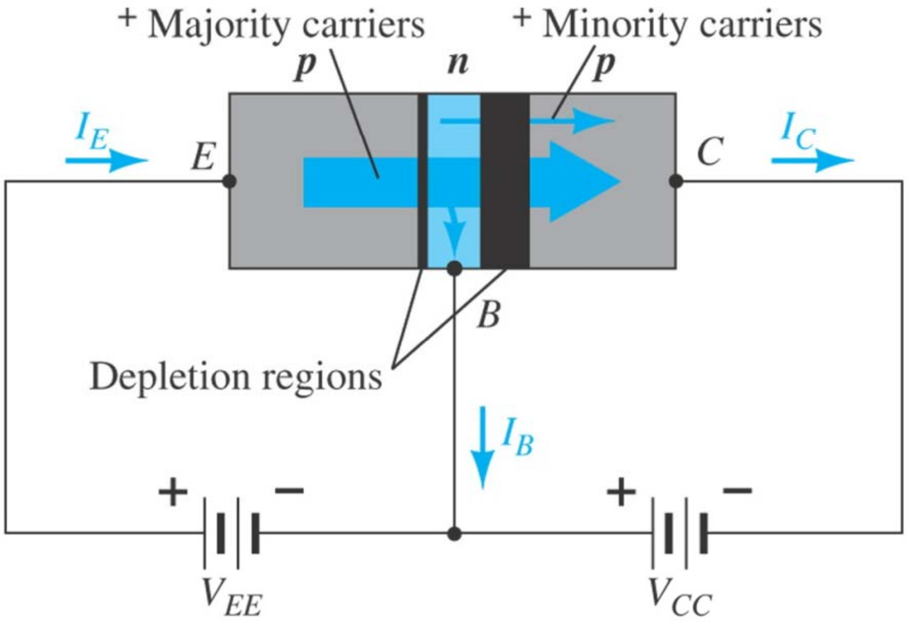
- Next, examine its reverse biased junction at terminal B to C:



- It is very similar to a reverse-biased diode
- Only minority carrier (holes) flows from B to C
- There are no majority carrier flows
- Resulting in big depletion region
- This means that the current flows lightly from E to B

Transistor Operation

- Combine both operation discussed:



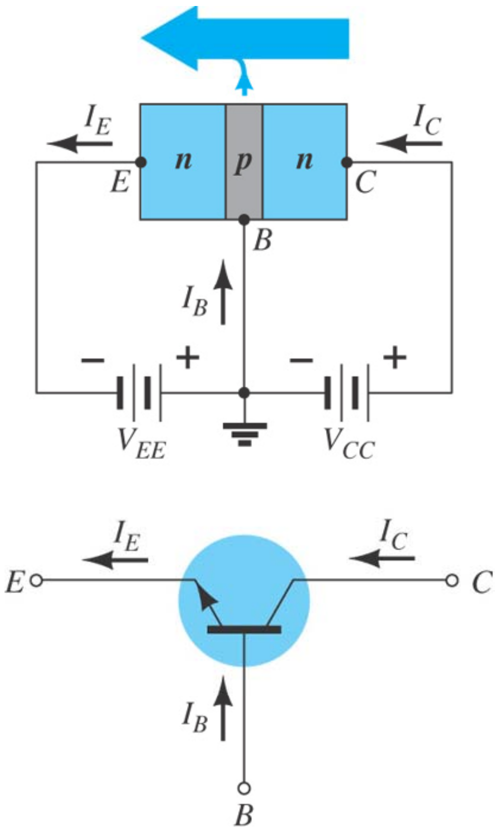
- Despite of big depletion region at B-C, but the majority carriers along with minority carriers will flow through region C, resulting in $I_E \approx I_C$ (usually in milliamperes)
- Very few minority carrier will flow to terminal B due to the minority carrier, resulting in I_B in only a few microamperes
- For npn transistor, all the discussion above are reversed, by mean the current flows

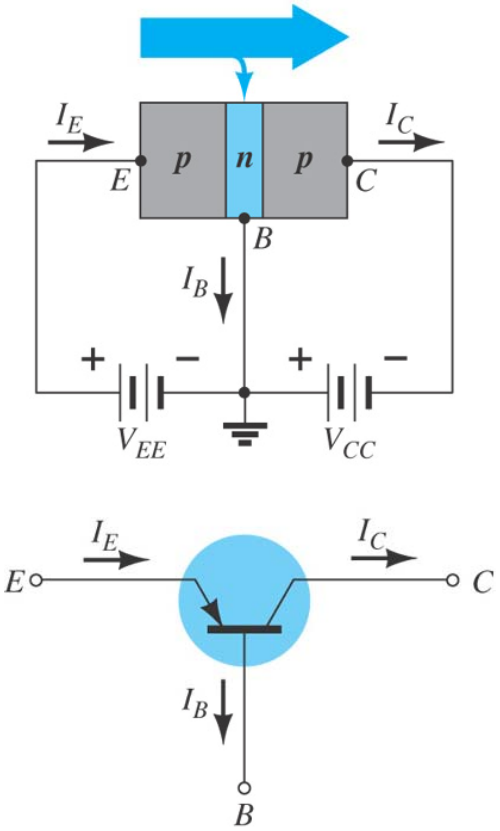
Transistor Configuration

- There are three commonly used configuration in BJT
  - Common-base (CB) configuration
  - Common-emitter (CE) configuration
  - Common-collector (CC) configuration
- Further on, these configuration will be discussed on npn transistor first, the pnp transistor is the exact reverse (in means of current flows) of the npn transistor

CB Configuration

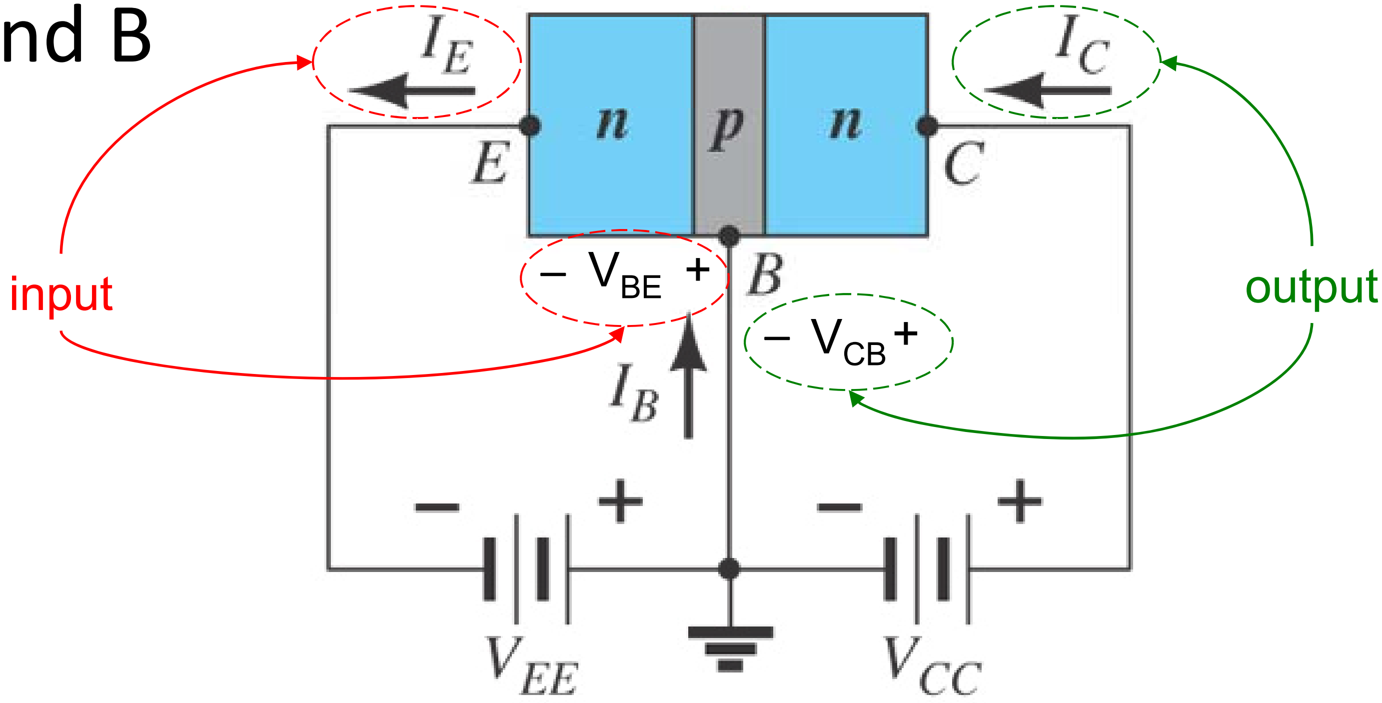
- By applying the proper biasing and grounding the base terminal:



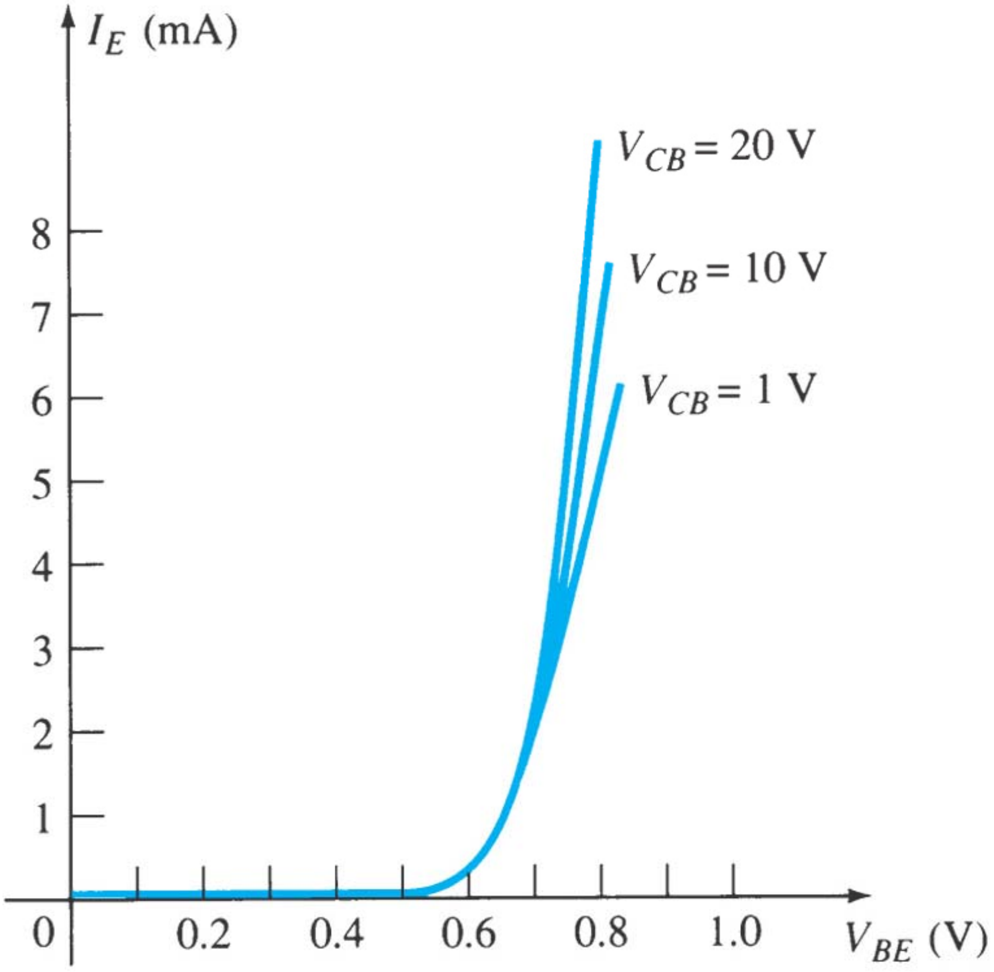


CB Configuration

- In CB configuration, the input terminal is between terminal E and B (due to ground at B)
- The output terminal is fixed between terminal C and B



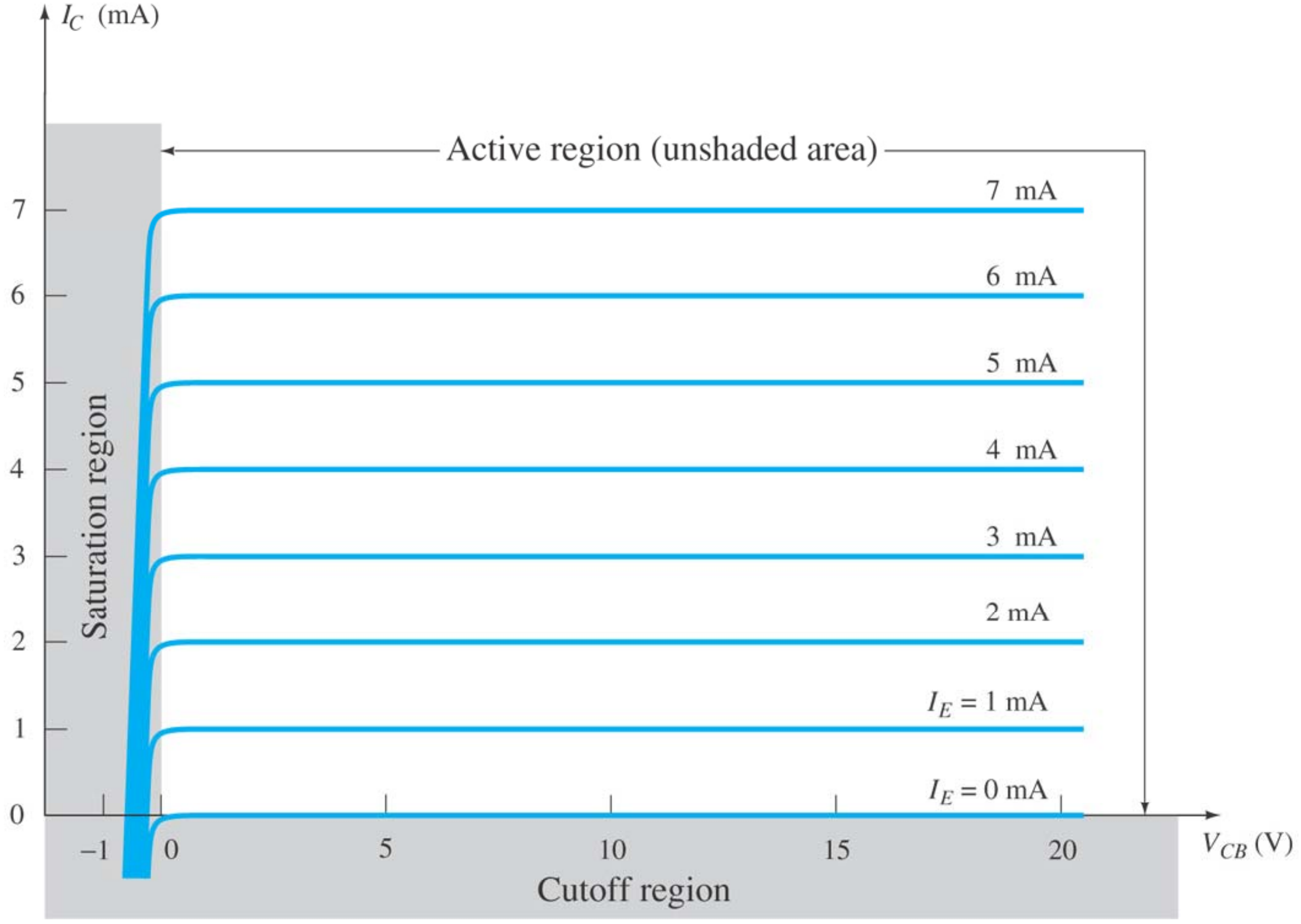
CB Configuration



- By examining the input, plotting the V_{BE} and I_E, the output V_{CB} is fixed at $V_{BE} \approx 0.7$ V
- Despite the increasing of output voltage, the input voltage remains the same
- Recall back for semiconductor diode in forward-biased, the voltage is 0.7
- BJT used the same material as in diode

CB Configuration

- Examine the output at terminal C and B:



CB Configuration

- There are 3 region of operation:
  - Active region
  - Cutoff region
  - Saturation region
- In active region, there’s a relation between IE and IC (this is only approximation):

$$I_E \cong I_C$$

CB Configuration

- In cutoff region, output (collector) current is zero (open-circuit equivalent):

$$I_C = 0\ \mathrm{A}$$

- In saturation region, output (collector-base) voltage is zero (short-circuit equivalent):

$$V_{CB} = 0\ \mathrm{V}$$

Alpha (α)

- By assuming IE = IC, it is assumed that IB = 0, even though IB is in microamperes (this is only approximation)
- For the exact value (IB ≠ 0), the emitter and collector current will be:

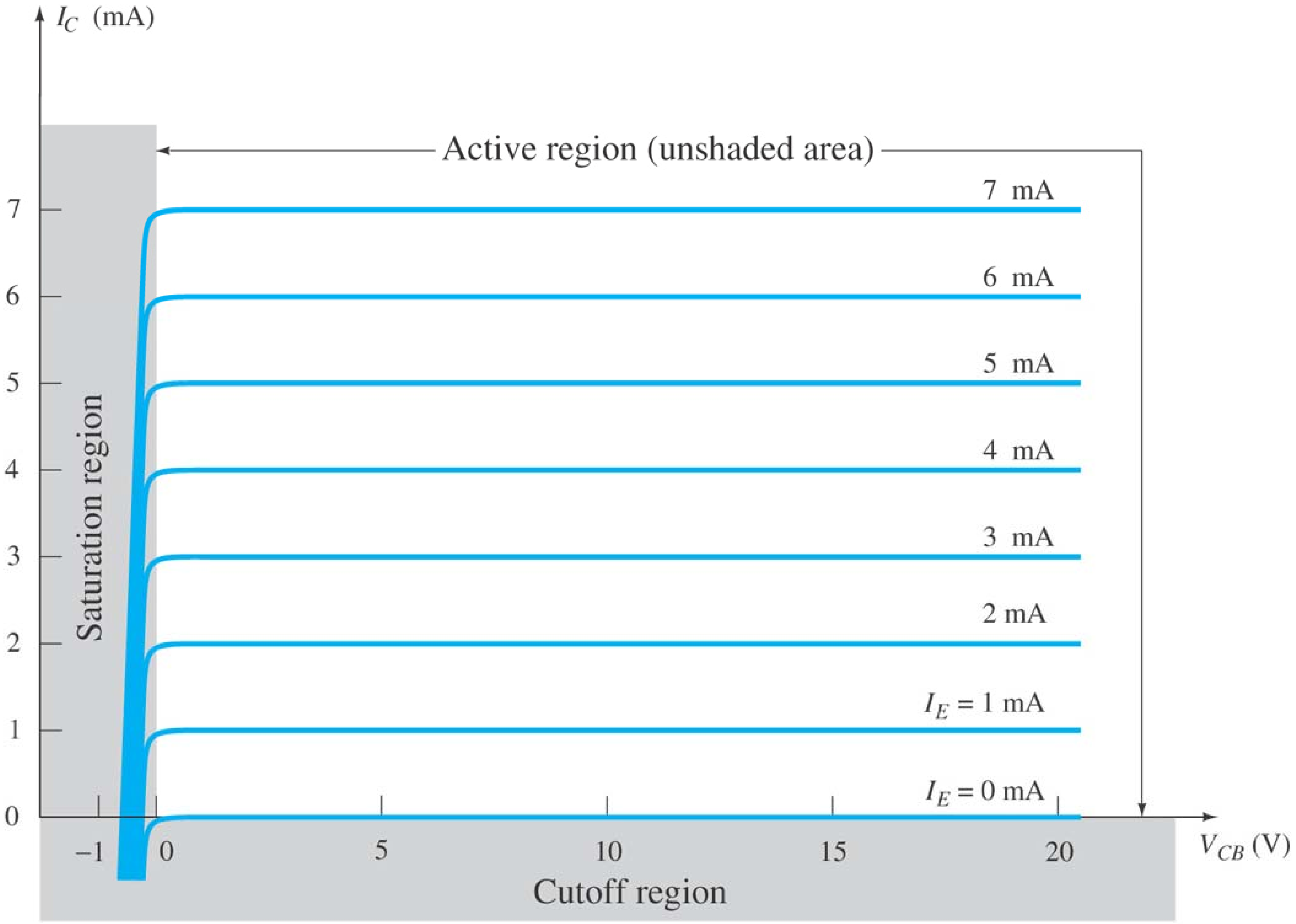
$$I_C = \alpha I_E$$

- The value of α is below 1 but near 1 (range 0.90 to 0.998)

Problem 3.13

- Question:
  - By using the characteristic given,
    - a) Determine the collector current if IE = 4.5 mA and VCB = 4 V
    - b) Determine the collector current if IE = 4.5 mA and VCB = 16 V
    - c) How have the change in VCB affected the resulting level of IC
    - d) On an approximate basis, how are IE and IC related?

Problem 3.13



I_C (mA)
Active region (unshaded area)
7 mA
6 mA
5 mA
4 mA
3 mA
2 mA
$I_E = 1$ mA
$I_E = 0$ mA
Saturation region
Cutoff region
7
6
5
4
3
2
1
0
−1
0
5
10
15
20
V_{CB} (V)

Problem 3.13

- Solution:

a) For IE = 4.5 mA and VCB = 4 V, IC = 4.5 mA

b) For IE = 4.5 mA and VCB = 16 V, IC = 4.5 mA

c) Negligible (not change – not depend on voltage)

d) IE = IC

Problem 3.15

- Question:
  a) Given α = 0.998, determine IC if IE = 4 mA
  b) Determine α if IE = 2.8 mA and IB = 20 μA

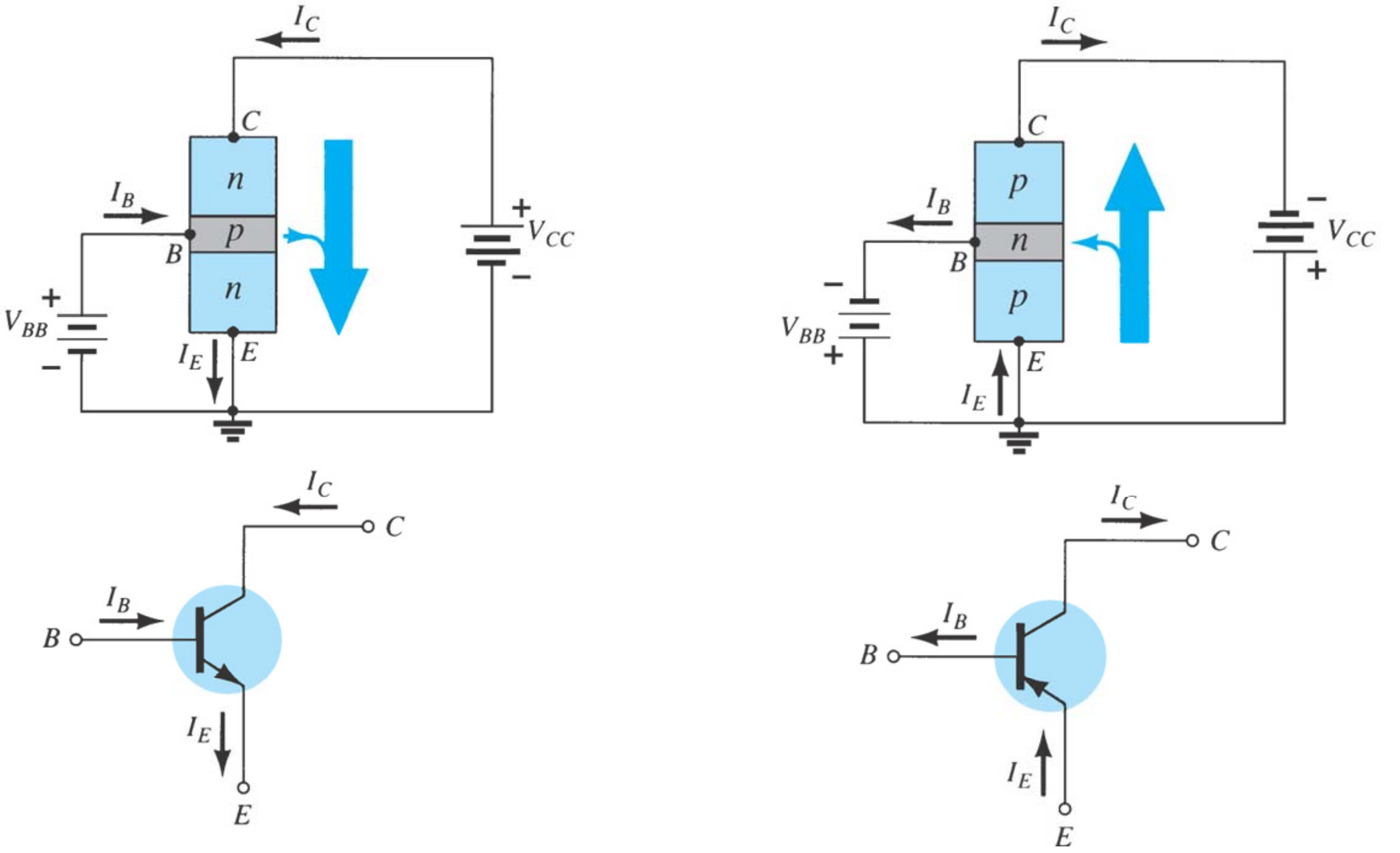
Problem 3.15

- Solution:
  a) $$I_C = \alpha I_E = (0.998)(4m) = 3.993\,\text{mA}$$
  b) $$I_E = I_C + I_B$$
  $$\therefore I_C = I_E - I_B = 2.8m - 20\mu = 2.78\,\text{mA}$$

  $$I_C = \alpha I_E$$
  $$\therefore \alpha = \frac{I_C}{I_E} = \frac{2.78m}{2.8m} = 0.9929$$

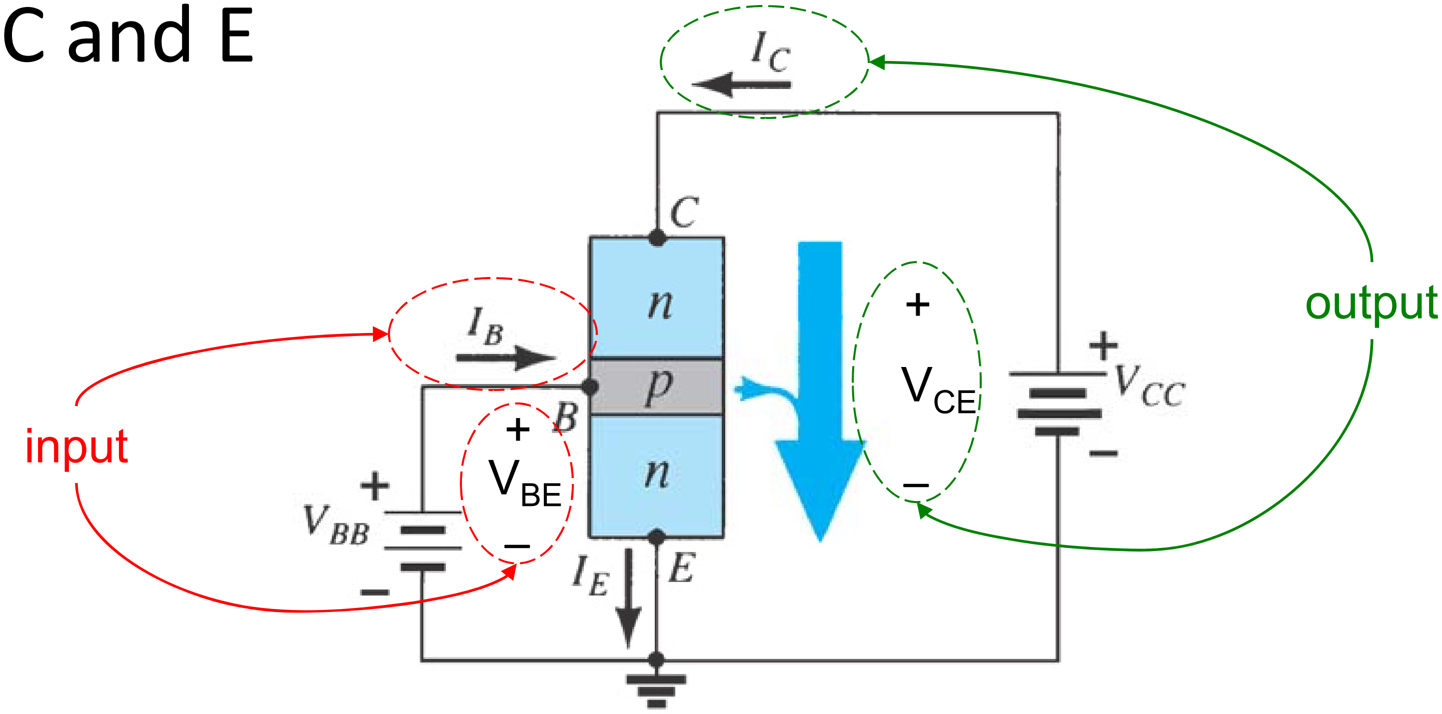
CE Configuration

- By applying the proper biasing and grounding the emitter terminal:

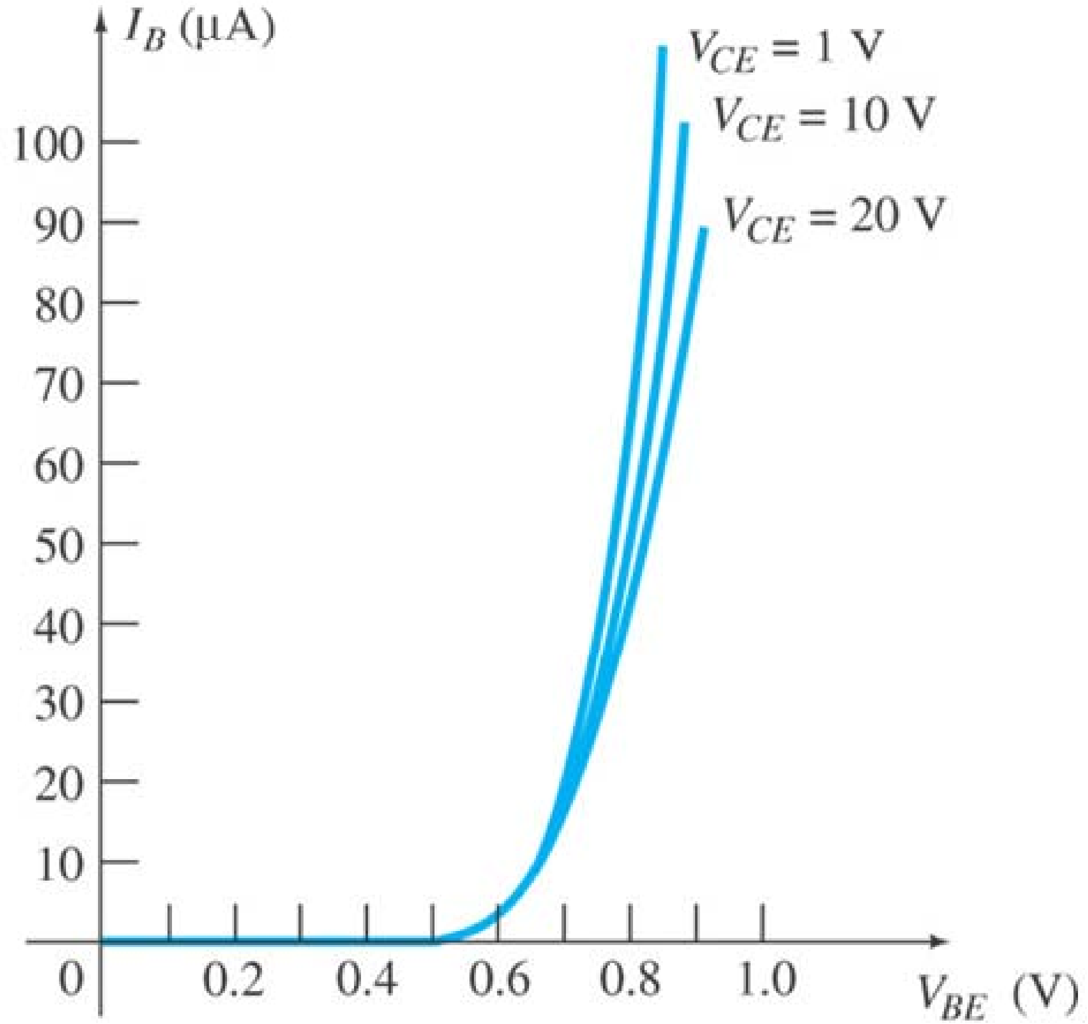


CE Configuration

- In CE configuration, the input terminal is between terminal B and E (due to ground at E)
- The output terminal is fixed between terminal C and E



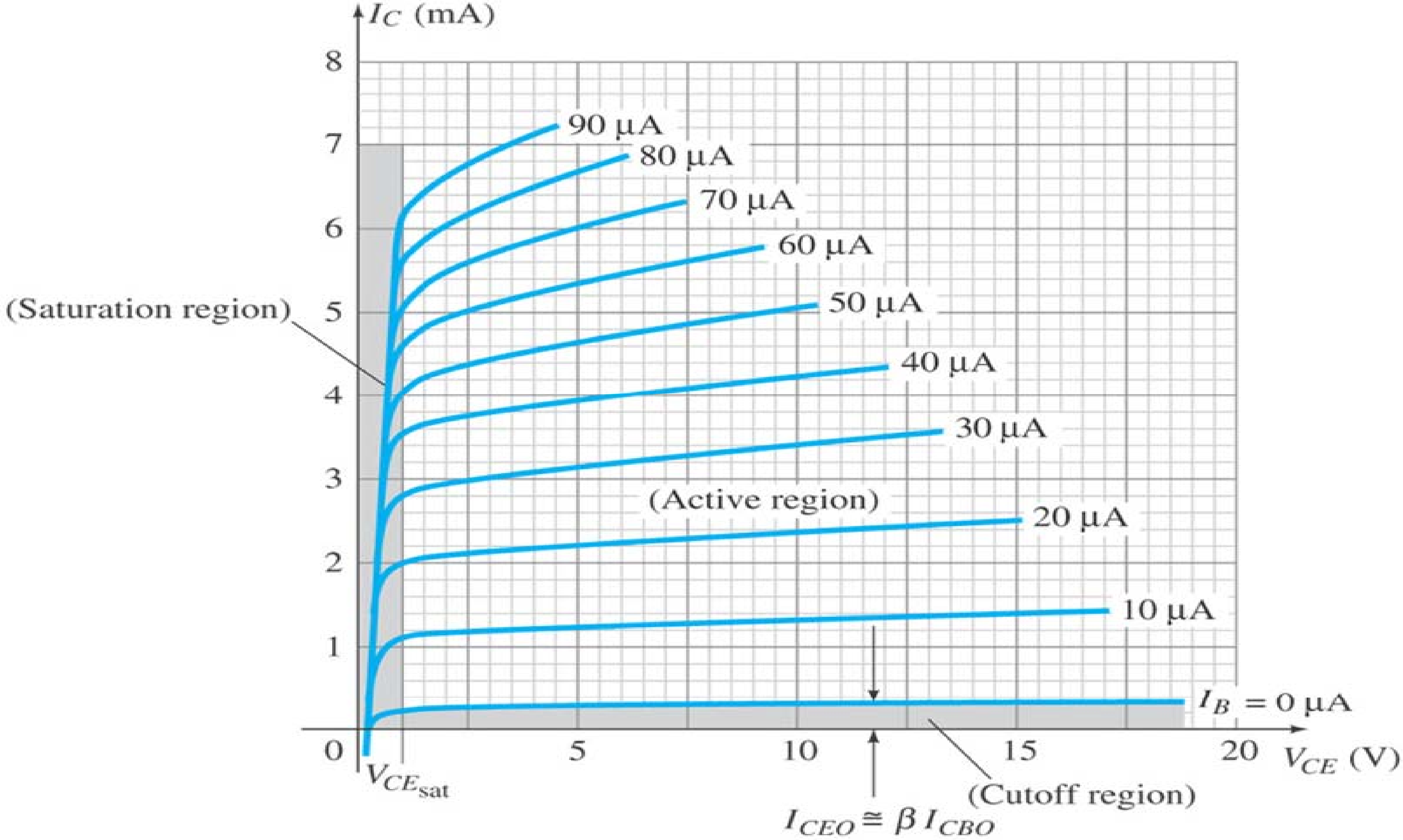
CE Configuration



- By examining the input, plotting the VBE and IB, the output VCE is fixed at VBE ≈ 0.7 V remains the same
- VBE = 0.7 V is applied to all transistor configuration including this CE configuration
- VEB = 0.7 V for pnp transistor

CE Configuration

- Examine the output at terminal C and E:



CE Configuration

- There are still 3 region of operation:
  - Active region
  - Cutoff region
  - Saturation region
- In active region, the relation between IE and IC is very different from the CB configuration
- This relation can be defined as:

$$I_C = \beta I_B$$

- where β is the ratio of IC over IB

CE Configuration

- The cutoff region remains the same with CB configuration, output (collector) current is zero (open-circuit equivalent):

$$I_C = 0\ \mathrm{A}$$

- The saturation region also remains the same with CB configuration, output (collector-emitter) voltage is zero (short-circuit equivalent):

$$V_{CE} = 0\ \mathrm{V}$$

Beta (β)

- From the equation IC = βIB, ratio of IC over IB is:

$$\beta = \frac{I_C}{I_B}$$

- β range from 50 to over 400
- For IE, substitute the equation IE = IC + IB into the β equation:

$$I_E = \beta I_B + I_B = (\beta + 1) I_B$$

Beta (β) & Alpha (α)

- Substitute all of the equation in terms of β into the α equation:

$$\alpha = \frac{I_C}{I_E} = \frac{\beta I_B}{(\beta + 1) I_B} = \frac{\beta}{\beta + 1}$$

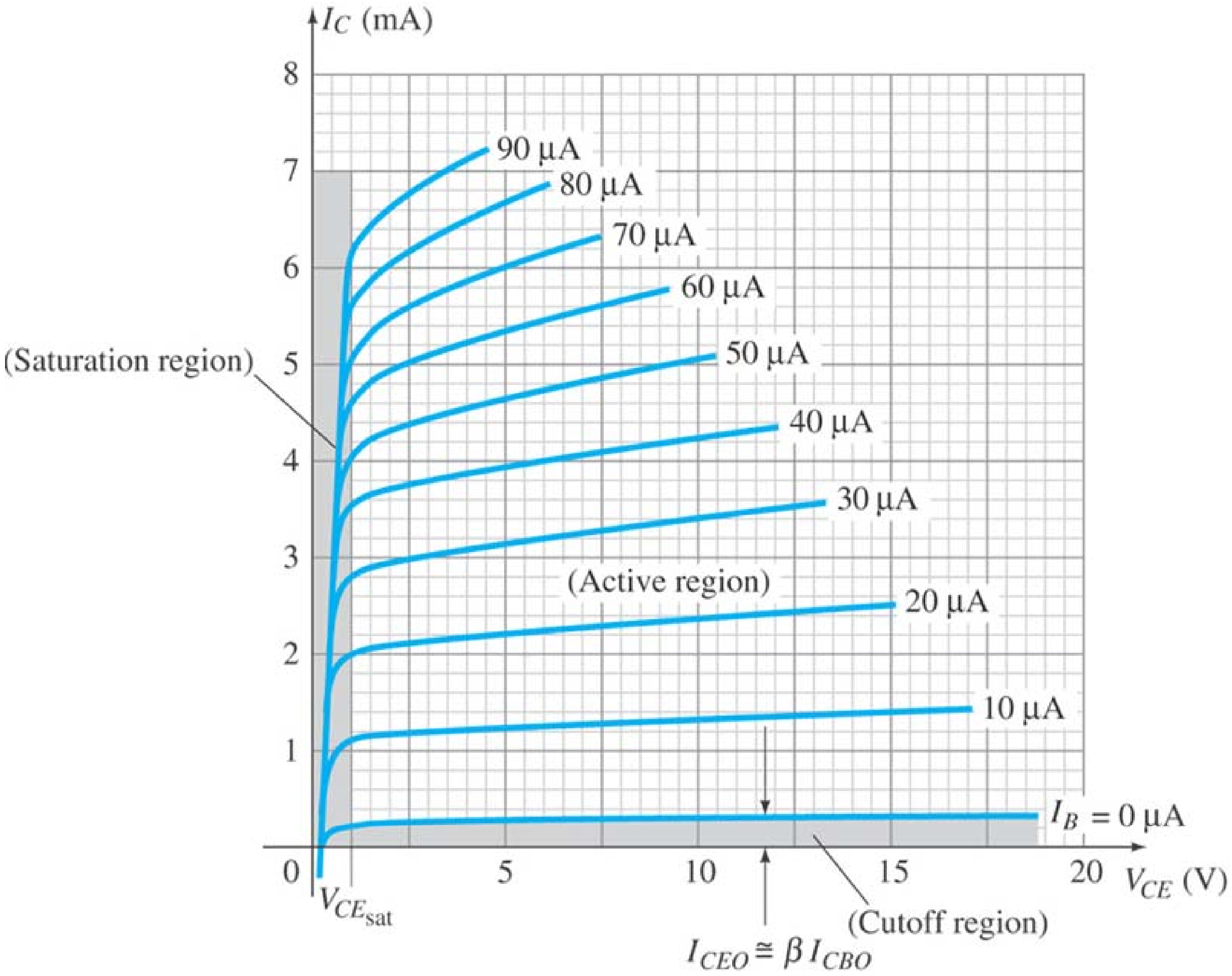
- For β in the terms of α:

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

Problem 3.21

- Question:
  a) For the CE characteristics in the figure given, find β at the operating point of V_{CE} = +8 V and I_C = 2 mA
  b) Find the value of α corresponding to this operating point

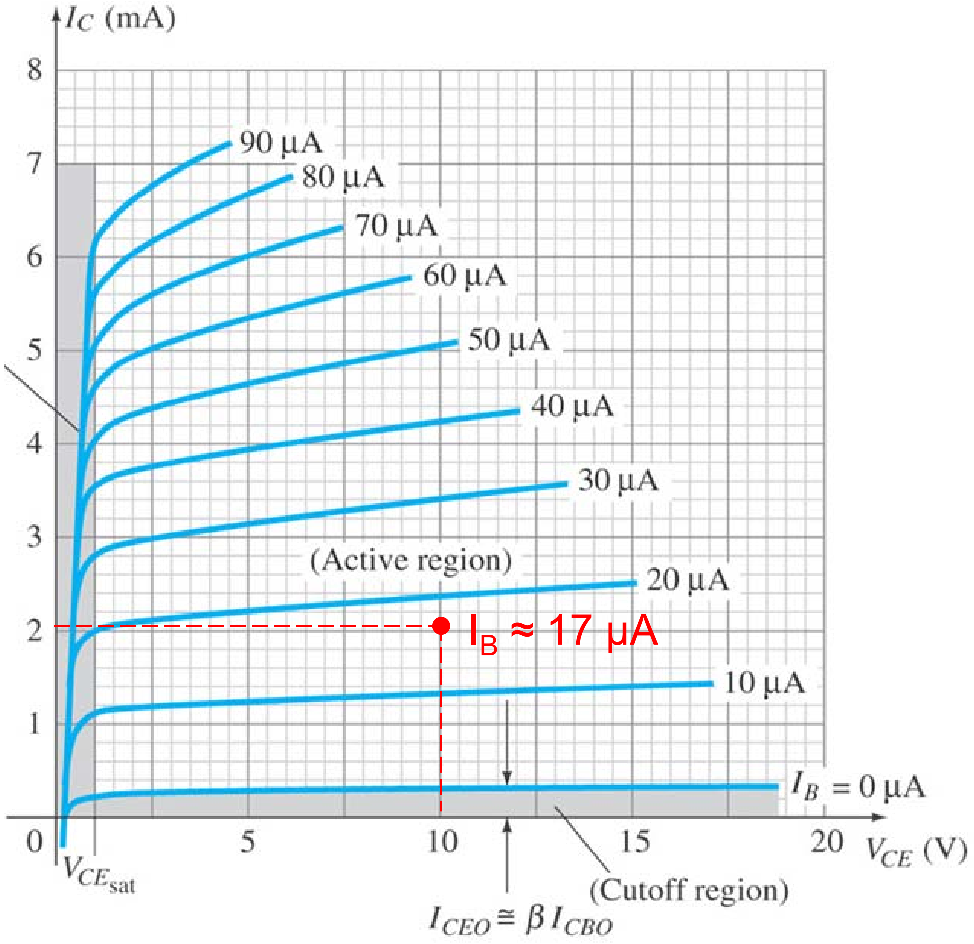
Problem 3.21


I_C (mA)
8
7
6
5
4
3
2
1
0
90 μA
80 μA
70 μA
60 μA
50 μA
40 μA
30 μA
20 μA
10 μA
$I_B = 0$ μA
(Saturation region)
(Active region)
(Cutoff region)
$V_{CE_{sat}}$
$I_{CEO} \cong \beta I_{CBO}$
5
10
15
20
V_{CE} (V)

Problem 3.21

- Solution:
  a) Plotting at the characteristic graph given the point VCE = +8 V and IC = 2 mA:

$$\beta = \frac{I_C}{I_B} = \frac{2m}{17\mu} = 117.65$$



Problem 3.21

- Solution:

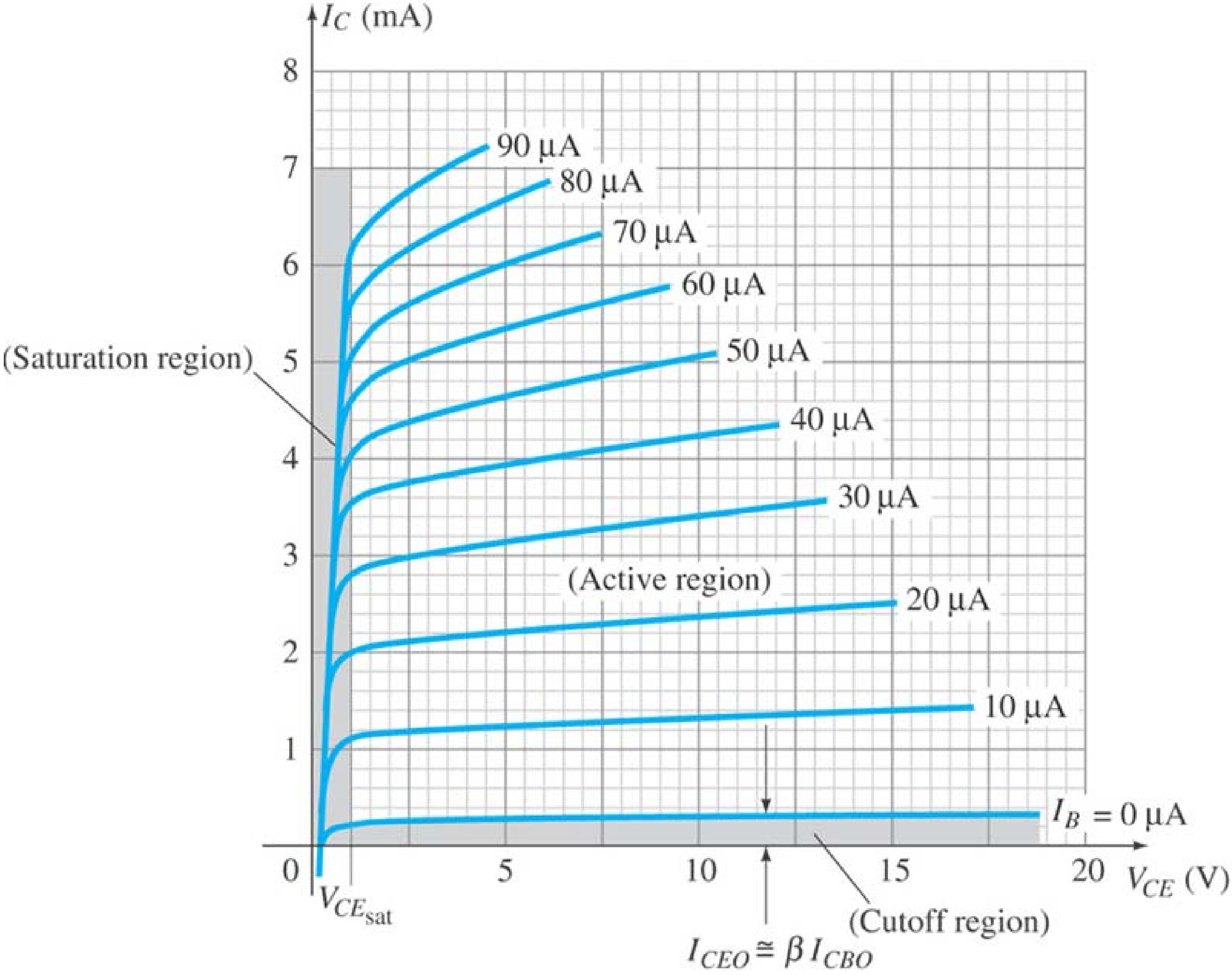
  b) α can be obtained from β value:

$$\alpha = \frac{\beta}{\beta + 1} = \frac{117.65}{117.65 + 1} = 0.9916$$

Problem 3.25

- Question:
  - Using the characteristic given, determine β at IB = 25 µA and VCE = 10 V. Then calculate α and the resulting level of IE
- Solution:
  - Find:
    - β
    - α
    - IE

Problem 3.25

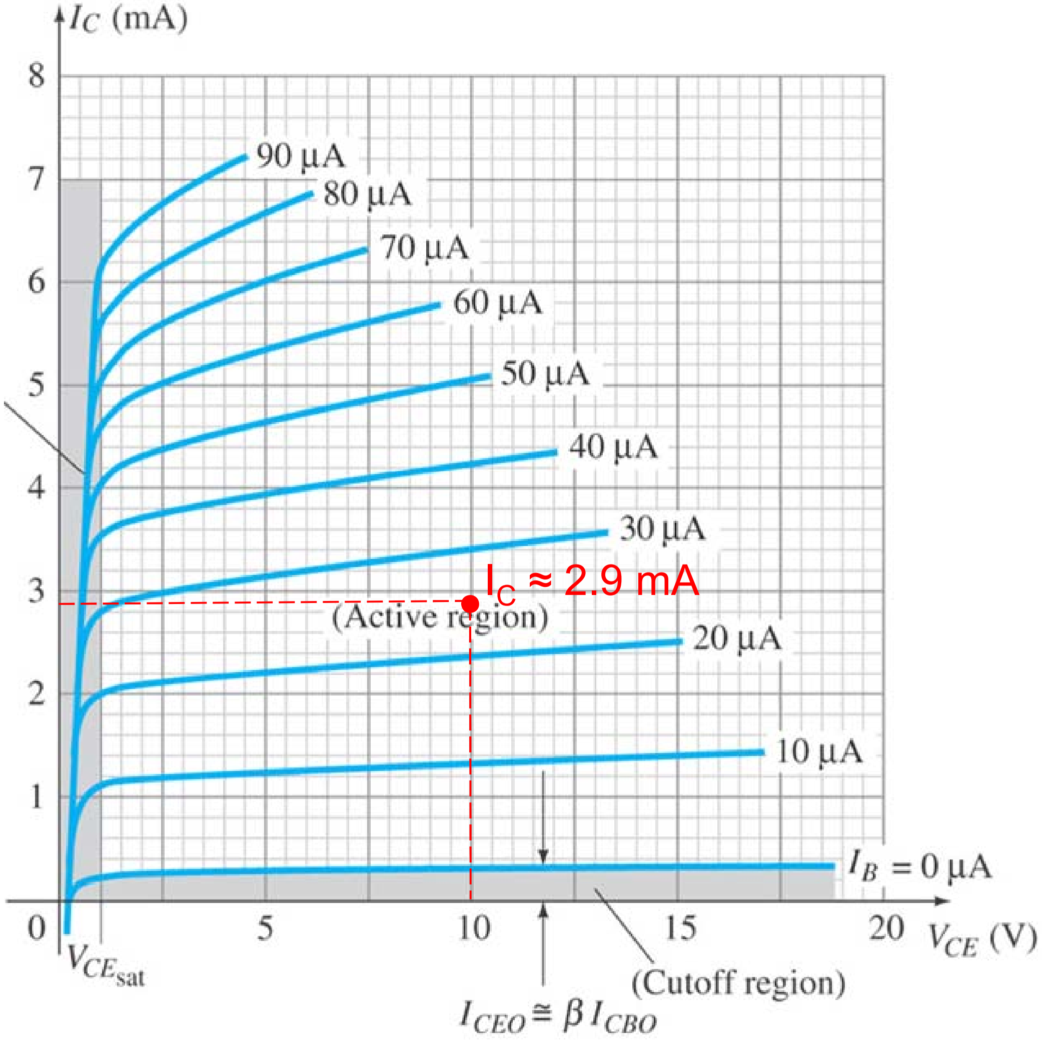


I_C (mA)
8
7
6
5
4
3
2
1
0
90 μA
80 μA
70 μA
60 μA
50 μA
40 μA
30 μA
20 μA
10 μA
$I_B = 0$ μA
(Saturation region)
(Active region)
(Cutoff region)
5
10
15
20
V_{CE} (V)
$V_{CE_{sat}}$
$I_{CEO} \cong \beta I_{CBO}$

Problem 3.25

- Plotting at the characteristic graph given the point VCE = 10 V and IB = 25 μA:

$$\beta = \frac{I_C}{I_B} = \frac{2.9m}{25\mu} = 116$$



Problem 3.25

- α can be obtained from β value:

$$\alpha = \frac{\beta}{\beta + 1} = \frac{116}{116 + 1} = 0.9915$$

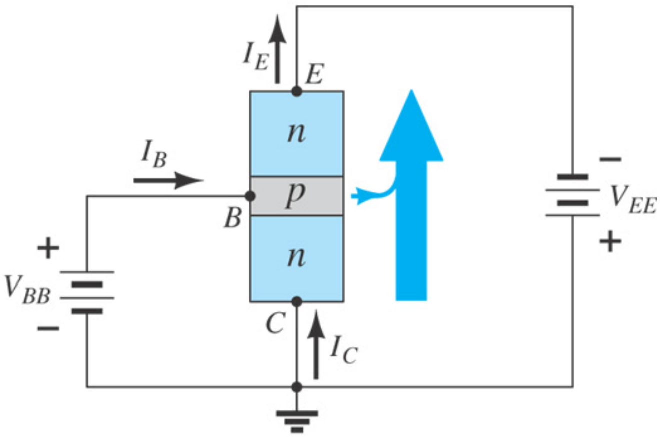
- IE can be obtained from the α equation:

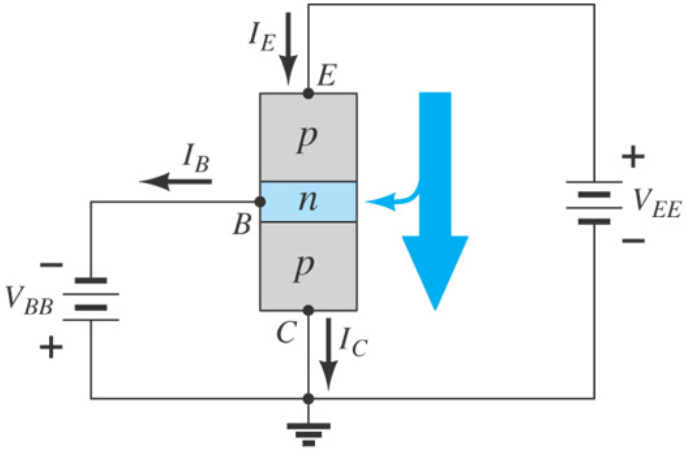
$$I_C = \alpha I_E$$

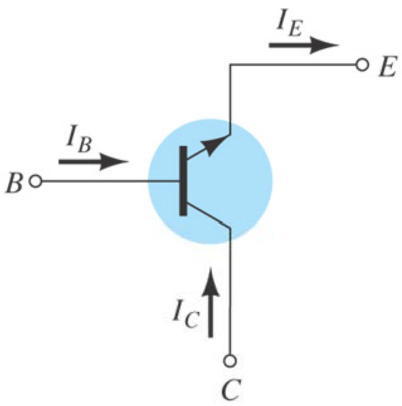
$$\therefore I_E = \frac{I_C}{\alpha} = \frac{2.9m}{0.9915} = 2.925\,\mathrm{mA}$$

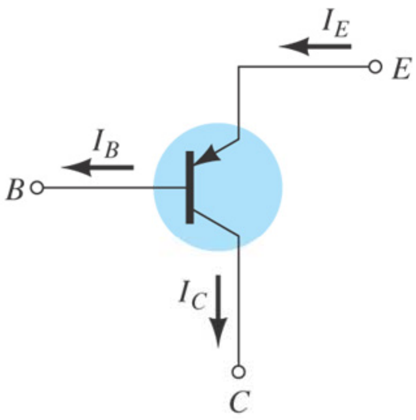
CC Configuration

- By applying the proper biasing and grounding the collector terminal:



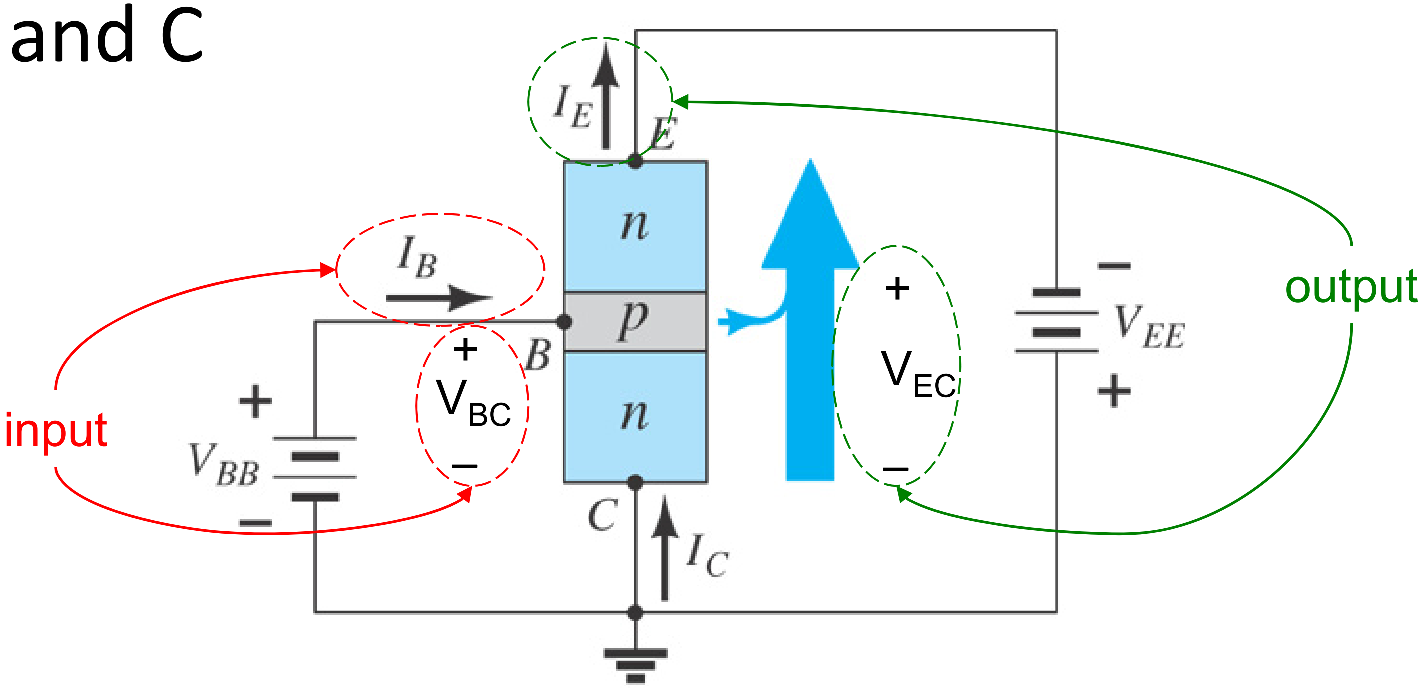






CC Configuration

- In CC configuration, the input terminal is between terminal B and C (due to ground at C)
- The output terminal is fixed between terminal E and C



CC Configuration

- By examining the input of CB and CE configuration, notice that they are the same (VBE = 0.7 V). As for that the input for CC configuration remains the same
- For CE the output voltage is VCE while the output current is IC. Meanwhile in CC, the output voltage is VEC and the output current is IE
- As for IC ≈ IE and VCE = VEC (polarity change only), it is said that the characteristic of CE and CC configuration are the same

Limits Of Operation

- For the common-emitter characteristics, the maximum dissipation level is defined by:

$$P_{C_{\max}} = V_{CE} I_C$$

- As for that, IC and VCE must be in these range to make sure their product doesn't exceed the maximum power dissipation:

cutoff region

$$I_{CEO} \le I_C \le I_{C_{\max}}$$

saturation region

$$V_{CE_{sat}} \le V_{CE} \le V_{CE_{\max}}$$

$$V_{CE} I_C \le P_{C_{\max}}$$

Limits Of Operation

- For example, if a transistor’s collector power dissipation is specified to 300 mW with ICmax = 50 mA and VCEmax = 20 V
- For ICmax value, VCE would be: $I_C = \frac{P_C}{V_{CE_{\max}}} = \frac{300m}{20} = 15\,\mathrm{mA}$
- For VCEmax value, IC would be:

$$V_{CE} = \frac{P_C}{I_{C_{\max}}} = \frac{300m}{50m} = 6\,\mathrm{V}$$

- Adding two more points to complete the curve:

$$I_C = 30\,\mathrm{mA}$$

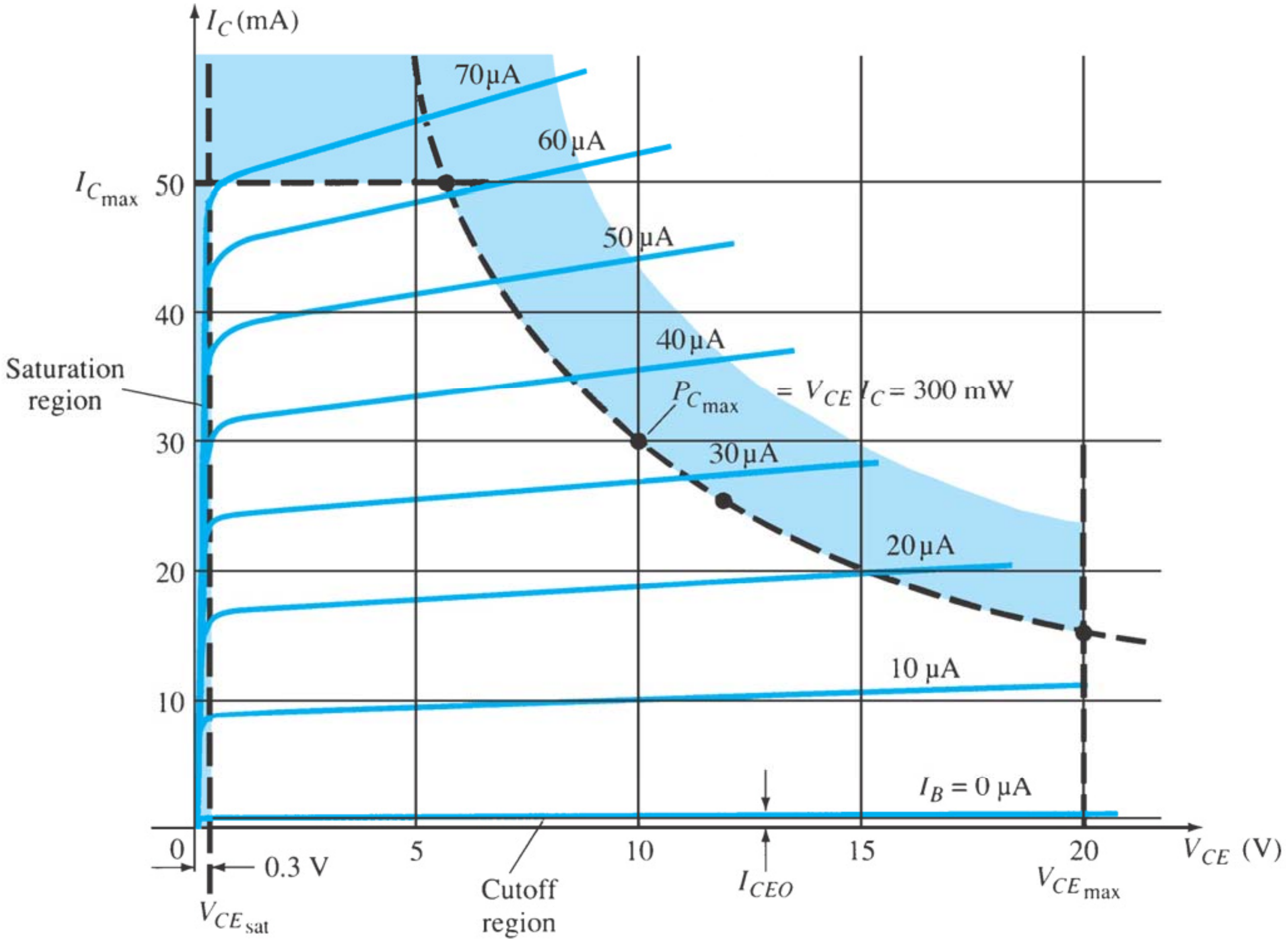
$$\therefore V_{CE} = \frac{P_C}{I_C} = \frac{300m}{30m} = 10\,\mathrm{V}$$

$$I_C = 25\,\mathrm{mA}$$

$$\therefore V_{CE} = \frac{P_C}{I_C} = \frac{300m}{25m} = 12\,\mathrm{V}$$

Limits Of Operation

- Connects all the points obtained, the curve becomes:



Limits Of Operation

- The same goes for a common-base configuration, its maximum power is defined as:

$$P_{C_{\max}} = V_{CB} I_C$$

- And the IC and VCE range is defined as:

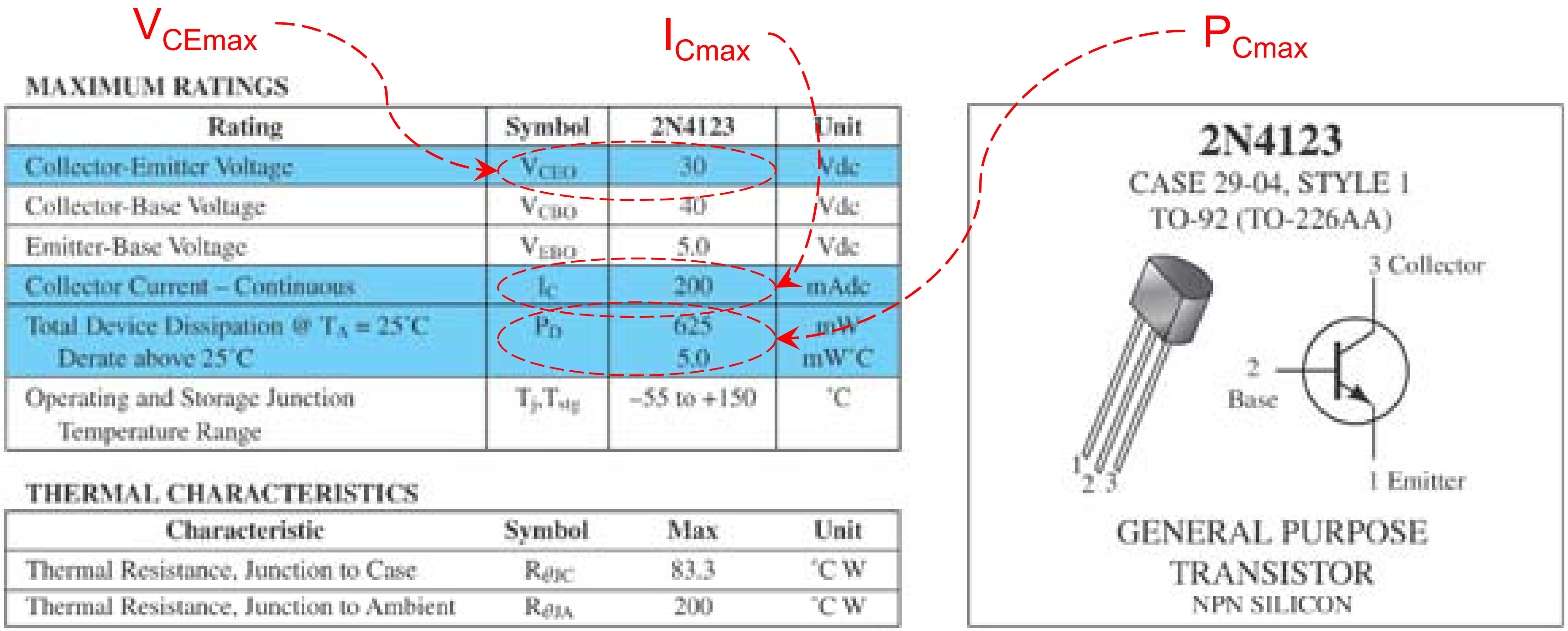
$$I_{CEO} \le I_C \le I_{C_{\max}}$$

$$V_{CB_{sat}} \le V_{CB} \le V_{CB_{\max}}$$

$$V_{CB} I_C \le P_{C_{\max}}$$

Transistor Datasheet

- Some of the important specification columns are bolded



MAXIMUM RATINGS

Rating	Symbol	2N4123	Unit
Collector-Emitter Voltage	V_{CEO}	30	Vdc
Collector-Base Voltage	V_{CBO}	40	Vdc
Emitter-Base Voltage	V_{EBO}	5.0	Vdc
Collector Current – Continuous	I_C	200	mAdc
Total Device Dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	625 5.0	mW mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−55 to +150	°C

THERMAL CHARACTERISTICS

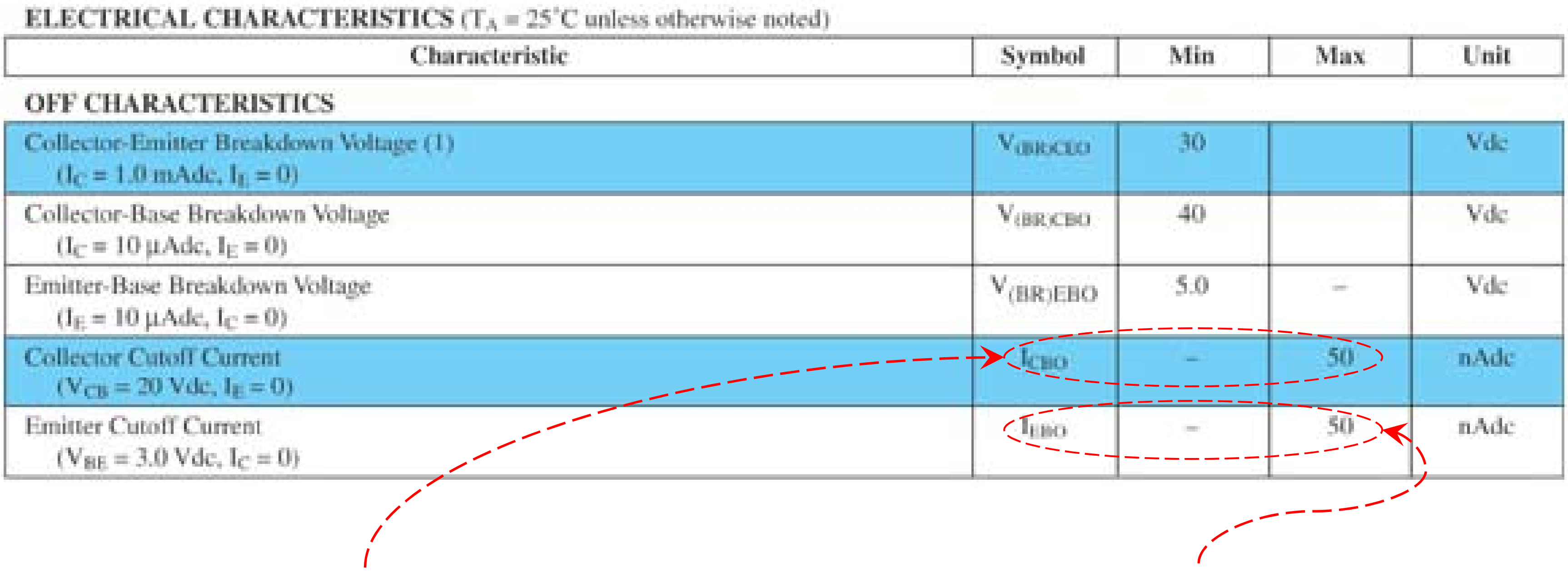
Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	°C/W
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	200	°C/W

2N4123

CASE 29-04, STYLE 1
TO-92 (TO-226AA)

GENERAL PURPOSE
TRANSISTOR
NPN SILICON

Transistor Datasheet



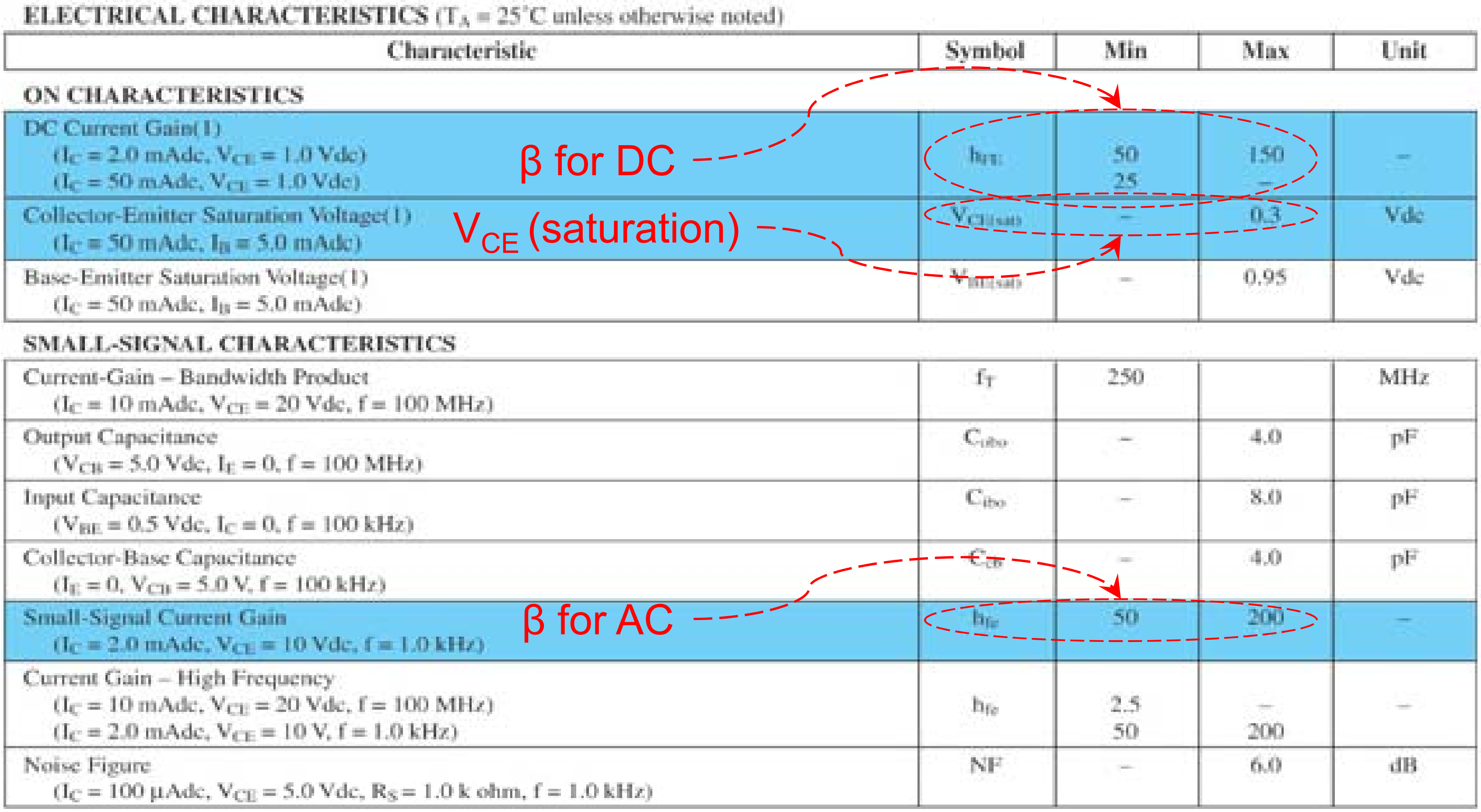
ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Emitter Breakdown Voltage (1) (I_C = 1.0 mAdc, I_B = 0)	$V_{(BR)CEO}$	30		Vdc
Collector-Base Breakdown Voltage (I_C = 10 μAdc, I_E = 0)	$V_{(BR)CBO}$	40		Vdc
Emitter-Base Breakdown Voltage (I_E = 10 μAdc, I_C = 0)	$V_{(BR)EBO}$	5.0	–	Vdc
Collector Cutoff Current (V_{CB} = 20 Vdc, I_E = 0)	I_{CBO}	–	50	nAdc
Emitter Cutoff Current (V_{BE} = 3.0 Vdc, I_C = 0)	I_{EBO}	–	50	nAdc

I_{CBO} (cutoff) for common-base

I_{CEO} (cutoff) for common-emitter

Transistor Datasheet



ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
ON CHARACTERISTICS				
DC Current Gain(1) (I_C = 2.0 mAdc, V_{CE} = 1.0 Vdc) (I_C = 50 mAdc, V_{CE} = 1.0 Vdc)	h_{FE}	50 25	150 –	–
Collector-Emitter Saturation Voltage(1) (I_C = 50 mAdc, I_B = 5.0 mAdc)	$V_{CE(sat)}$	–	0.3	Vdc
Base-Emitter Saturation Voltage(1) (I_C = 50 mAdc, I_B = 5.0 mAdc)	$V_{BE(sat)}$	–	0.95	Vdc
SMALL-SIGNAL CHARACTERISTICS				
Current-Gain – Bandwidth Product (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	f_T	250		MHz
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 100 MHz)	C_{obo}	–	4.0	pF
Input Capacitance (V_{BE} = 0.5 Vdc, I_C = 0, f = 100 kHz)	C_{ibo}	–	8.0	pF
Collector-Base Capacitance (I_E = 0, V_{CB} = 5.0 V, f = 100 kHz)	C_{cb}	–	4.0	pF
Small-Signal Current Gain (I_C = 2.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{fe}	50	200	–
Current Gain – High Frequency (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz) (I_C = 2.0 mAdc, V_{CE} = 10 V, f = 1.0 kHz)	h_{fe}	2.5 50	– 200	–
Noise Figure (I_C = 100 µAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k ohm, f = 1.0 kHz)	NF	–	6.0	dB

β for DC

V_{CE} (saturation)

β for AC