African Centre for Advanced Studies

National Advanced School of Engineering, UYI

ELECTRIC AND ELECTRONIC CIRCUITS

PHY 225

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Transistors

Overview

Introduction

Bipolar junction transistors, transistor effect, characteristics; polarization, operating point, temperature stabilization

Field effect transistor

Junction field effect transistor

Insulated gate field effect transistor

Transistors I: BJTs

Introduction

December 23 afternoon at Bell Telephone Laboratories, 1947, Walter H. Brattain and John Bardeen and William Schockley demonstrated the amplifying action of the first transistor

In 1951, William B. Schockley invented the first junction transistor, a semiconductor device that can amplify (enlarge) electronic signals such as radio and television signals

Transistors I: BJTs

Introduction

Fig. 1 First transistor

1956, physics Nobel prize received by Brattain, Bardeen Schockley for ‘their research on semiconductors and the discovery of the transistor effect’

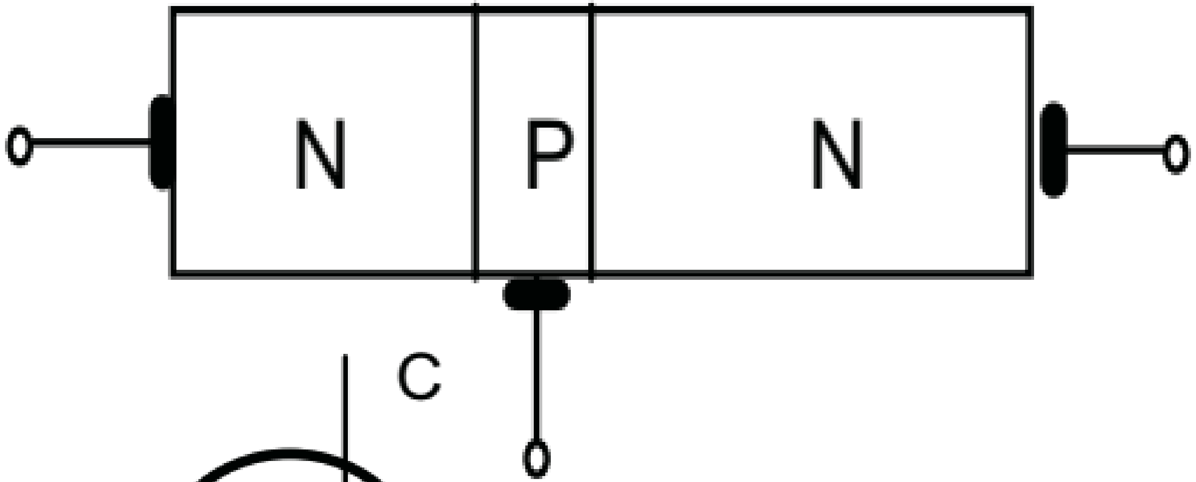
Applications of transistors

- Current regulation
- Swiching signals
- Amplification of an input signal
- in Ics are found everywhere

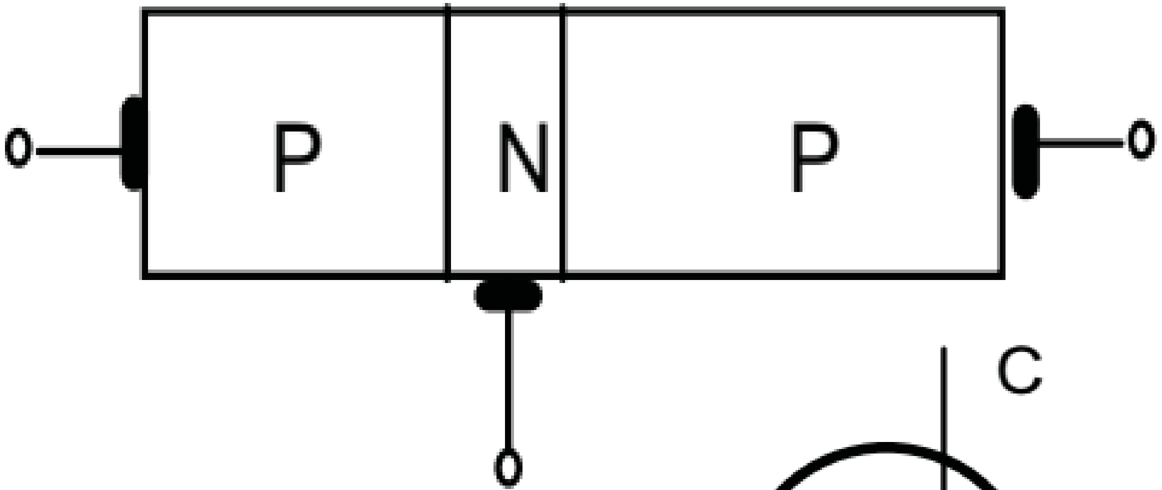
Transistor: BJTs

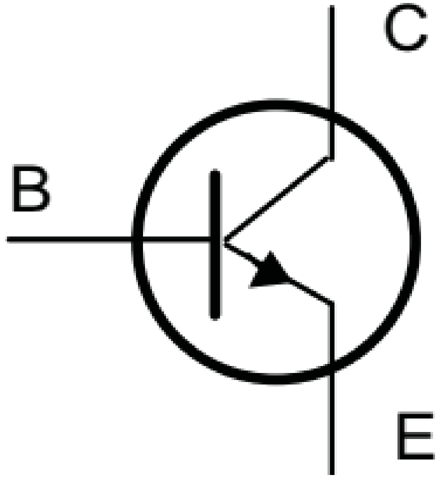
A BJT: semiconductor doped to obtain a series of two opposite junctions. 2 types exist: NPN and PNP

NPN BJT



PNP BJT

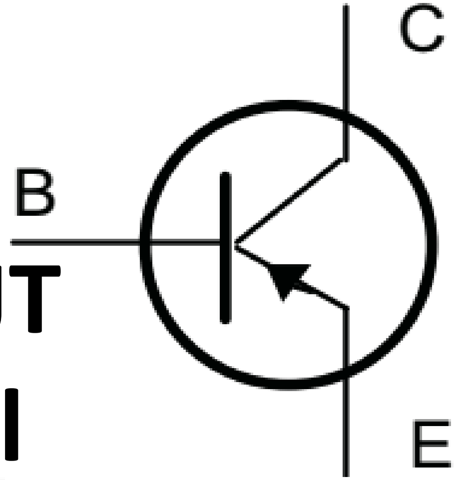




NPN BJT symbol

Fig. 2

PNP BJT symbol



Transistors: focused NPN BJTs

Unbias transistor

collector

intermediate doping

base

lightly doped

emmiter

heavily doped

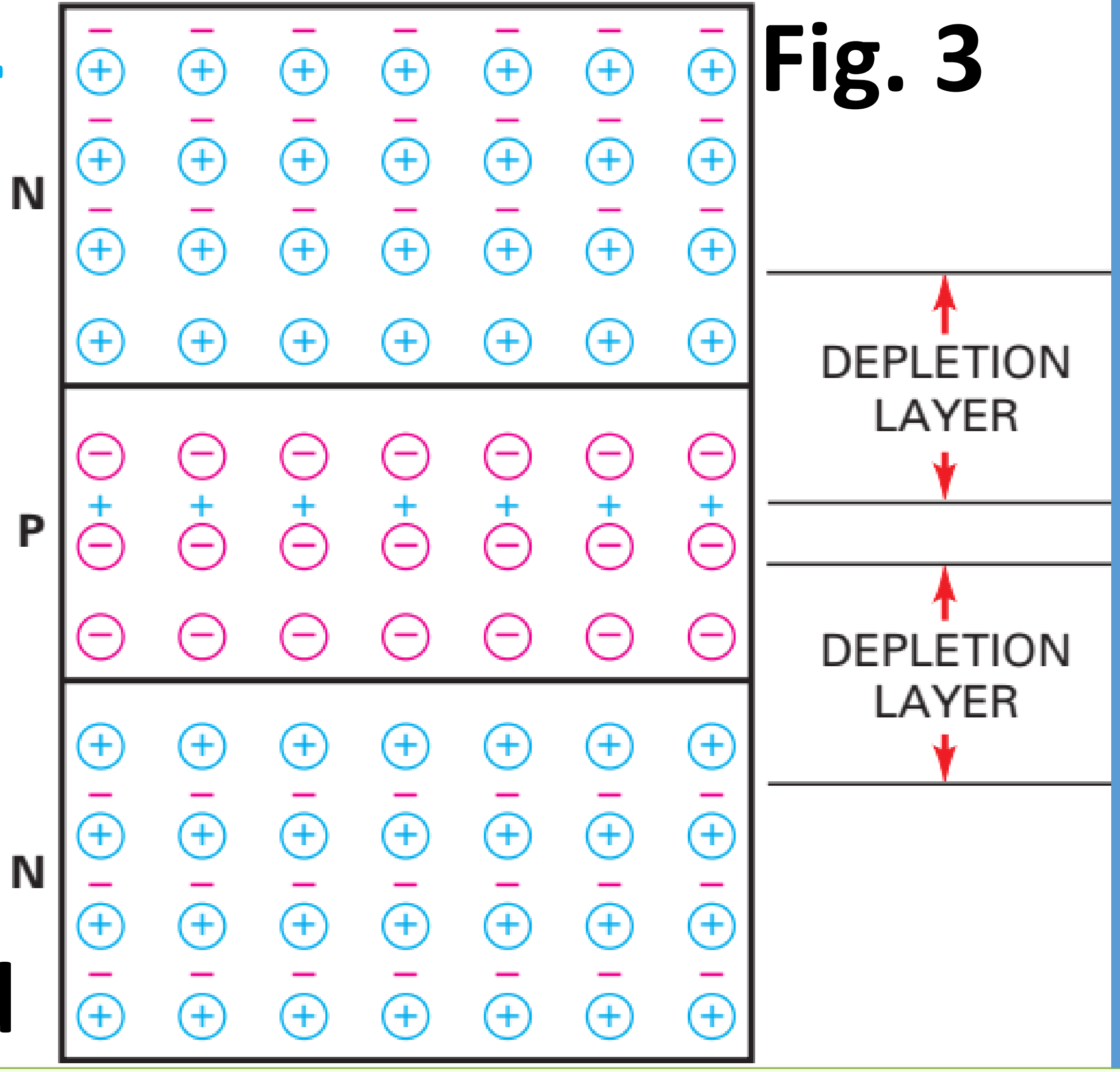


Fig. 3

base much thinner than collector and emmiter regions

$$V_0 = 0.7\,V$$

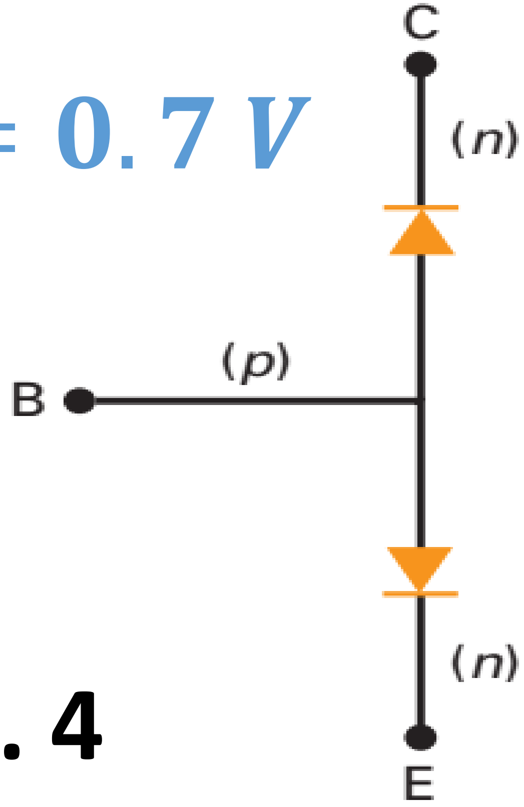
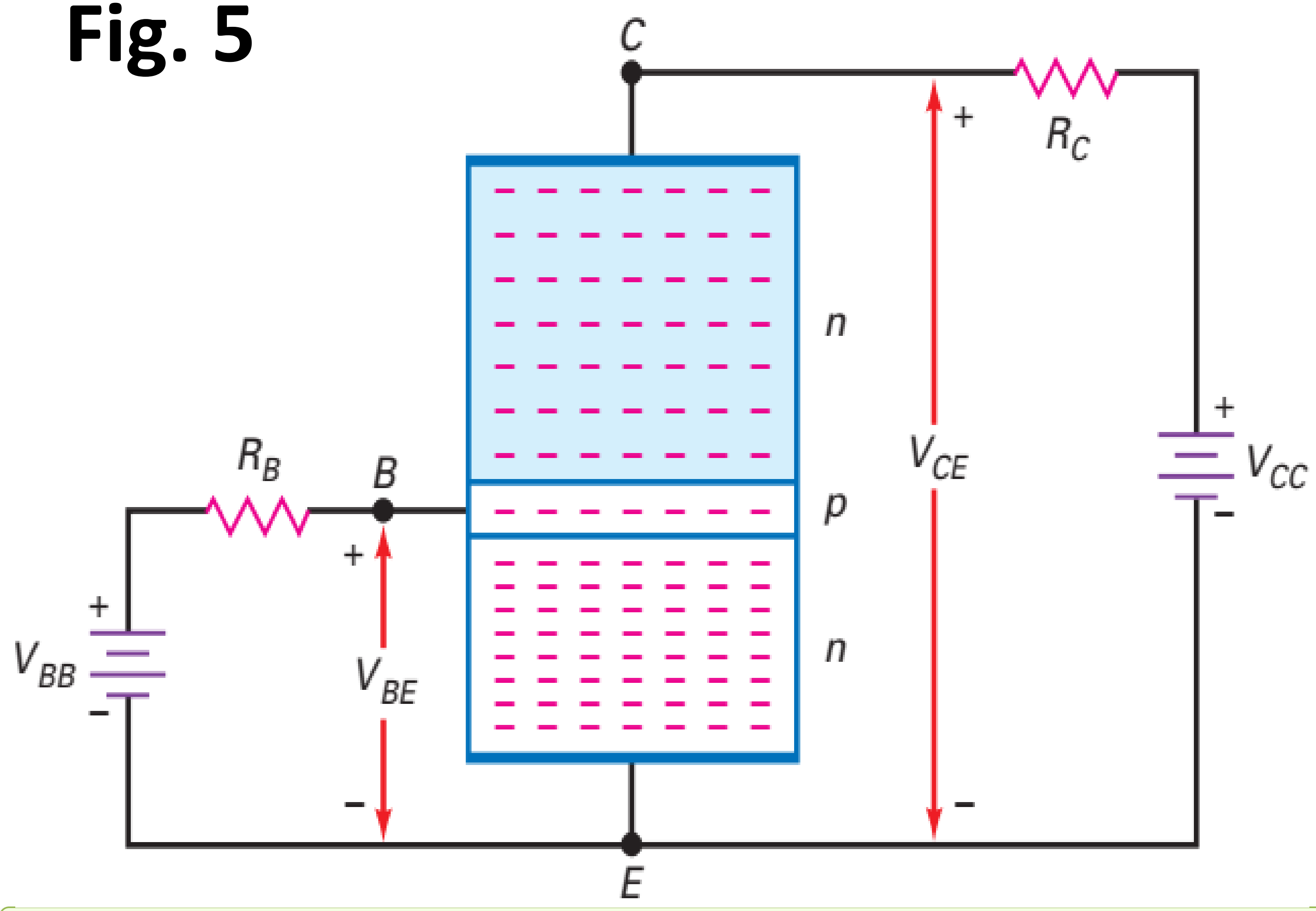


Fig. 4

Transistors: focused NPN BJTs

bias transistor

Fig. 5



$\mathbf{V}_{BB}$: forward biases emmiter diode

$\mathbf{V}_{CC}$: reverse biases collector diode

Transistors: focused NPN BJTs

bias transistor

Emmiter role: injects its free e^- into the base

Base role: pass emmiter-injected e^- on to the collector

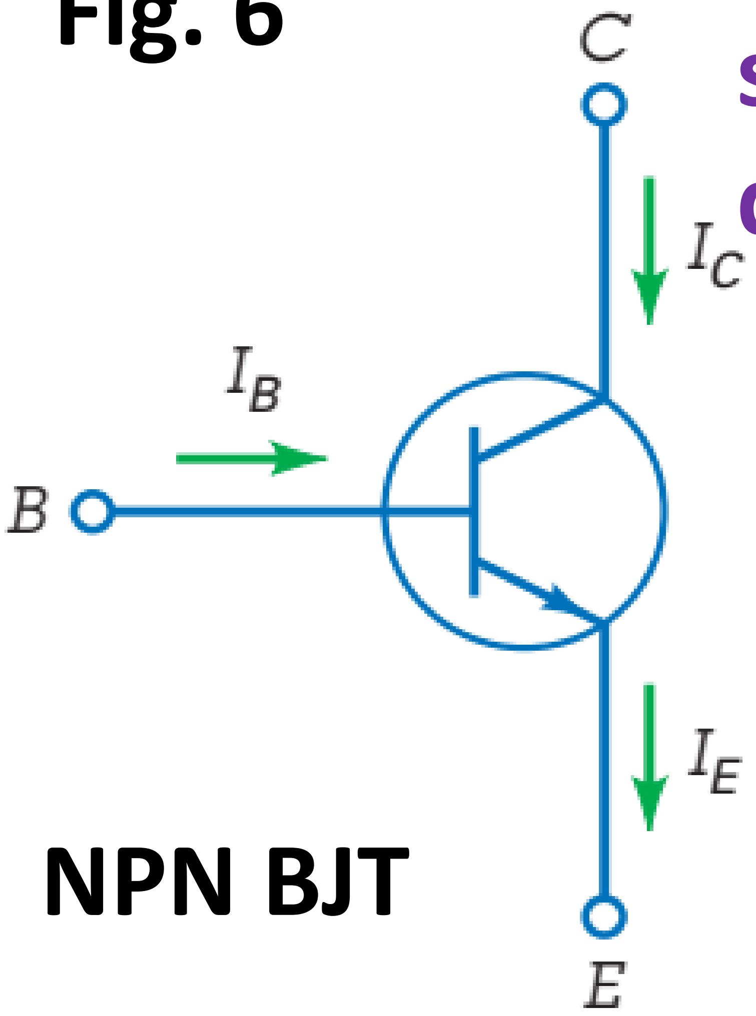
Collector role: collects most of all free e^- from the base

Free e^- from emmiter diffuse to the base, few recombine with holes, most cross the base as the latter width is small, free e^- in collector feel the attraction of $\mathbf{V}_{CC}$, flow through the collector and enter the circuit

Transistors: focused NPN BJTs

BJT currents

Fig. 6



NPN BJT

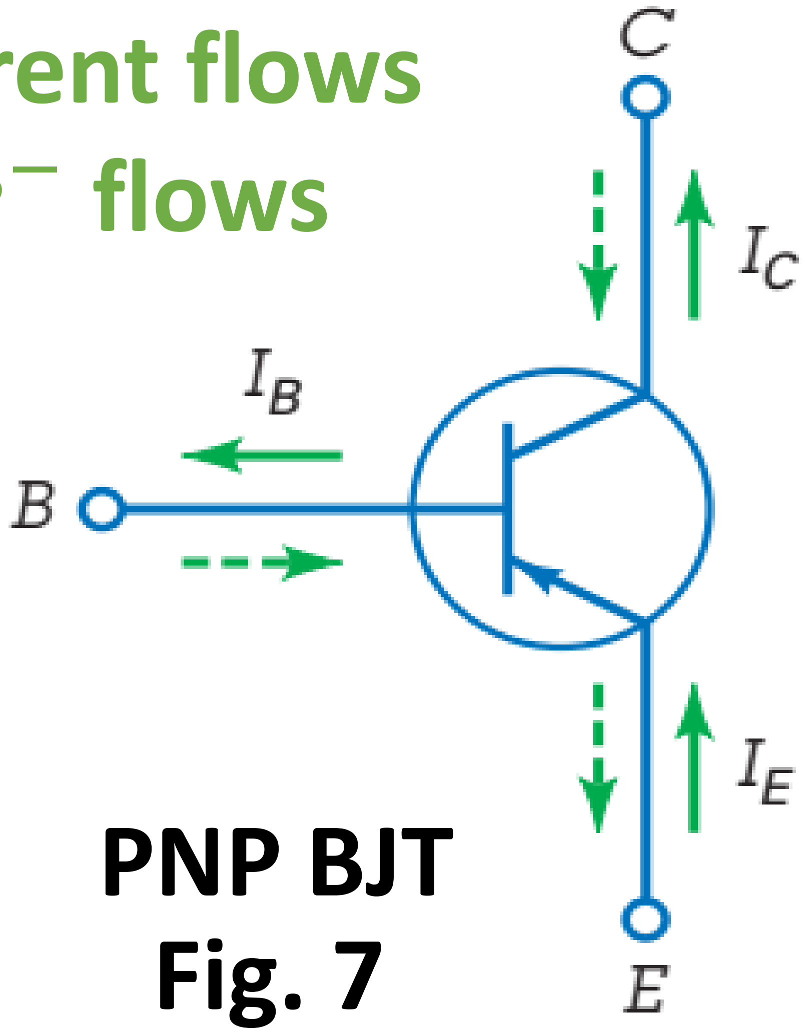
solid line arrows: current flows

dashed line arrows: e^- flows

I_C: collector current

I_B: base current

I_E: emmiter current



PNP BJT

Fig. 7

Transistors: focused NPN BJTs

BJT currents

Kirchoff law: $$I_E = I_C + I_B$$ Eq.(1)

α: proportion of free e^- injected from emmiter that arrive to the collector, typically $0.95 \leq \alpha \leq 0.99$

$$I_C = \alpha I_E$$ Eq.(2)

$$I_C = \frac{\alpha}{1-\alpha} I_B$$ Eq.(3)

BJT currents

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{Eq.(4)}$$

β is very large as α tends to 1

Transistor effect

$$I_C = \beta I_B \quad \text{Eq.(5)}$$

Eq.(5) means that from a small base current, one obtains an amplfied collector current, a phenomenon known as **the transistor effect**

BJT currents

Examples:

1) A transistor has a collector current of 10 mA and a base current of 40 µA. What is the current gain of the transistor?

2) A transistor has a current gain of 175. If the base current is 0.1 mA, what is thecollector current?

Transistors: focused NPN BJTs

BJT characteristics

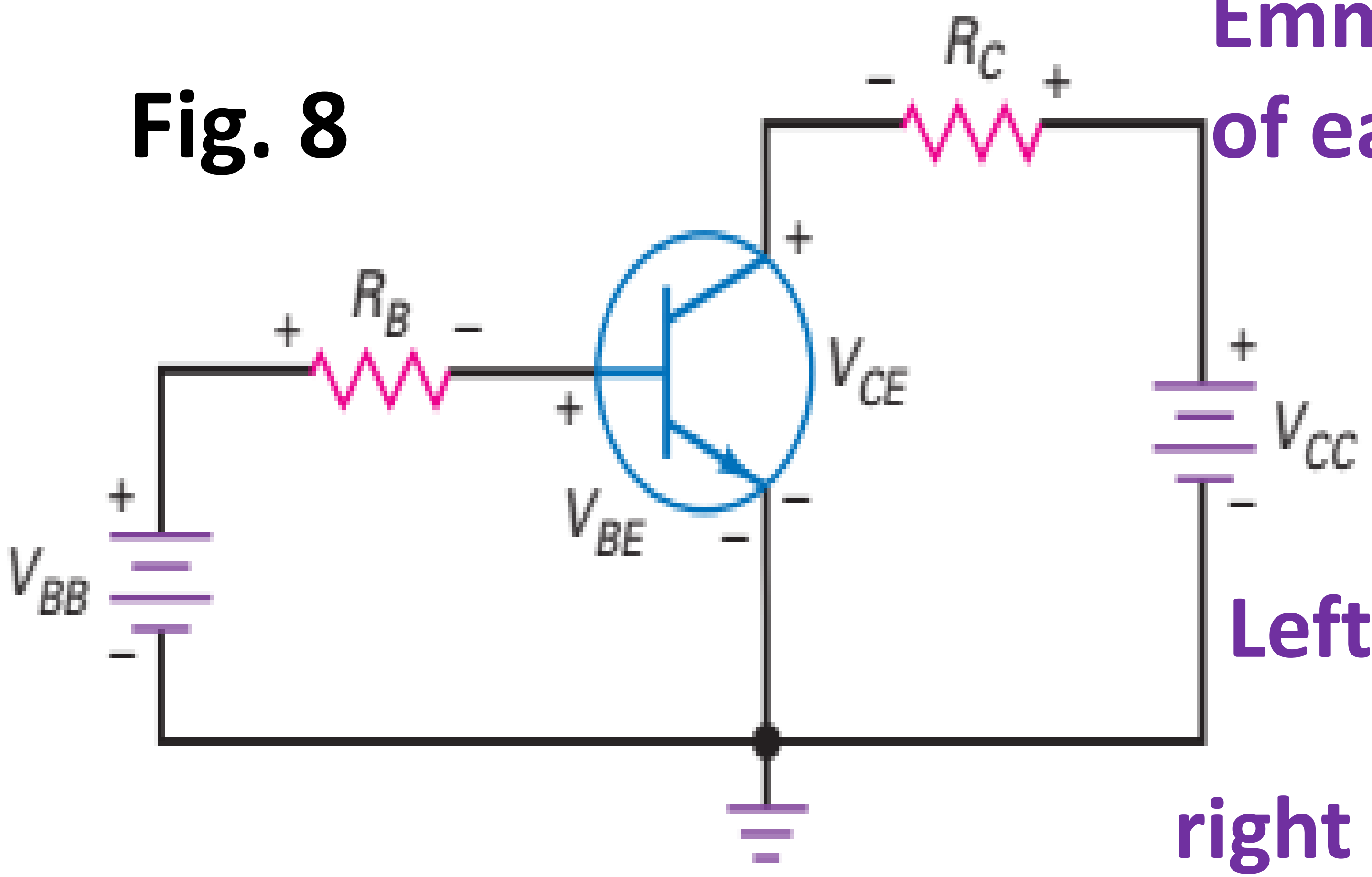
3 ways to connect a transistor: (a) CE (common emitter), (b) CC (common collector), or (c) CB (common base)

Common here is understood as connection to the common or ground of each source voltage

We focus on CE connection that is widely used with

BJT characteristics

Fig. 8



Emmiter connected to ground of each source voltage

Left loop referred to as input

right loop referred to as output

BJT characteristics

Notations

Double subscripts: same subscripts mean source voltage: V_{BB} base voltage source, V_{CC} collector voltage source; different subscript mean voltage between 2 points: V_{BE} voltage between base and emmiter

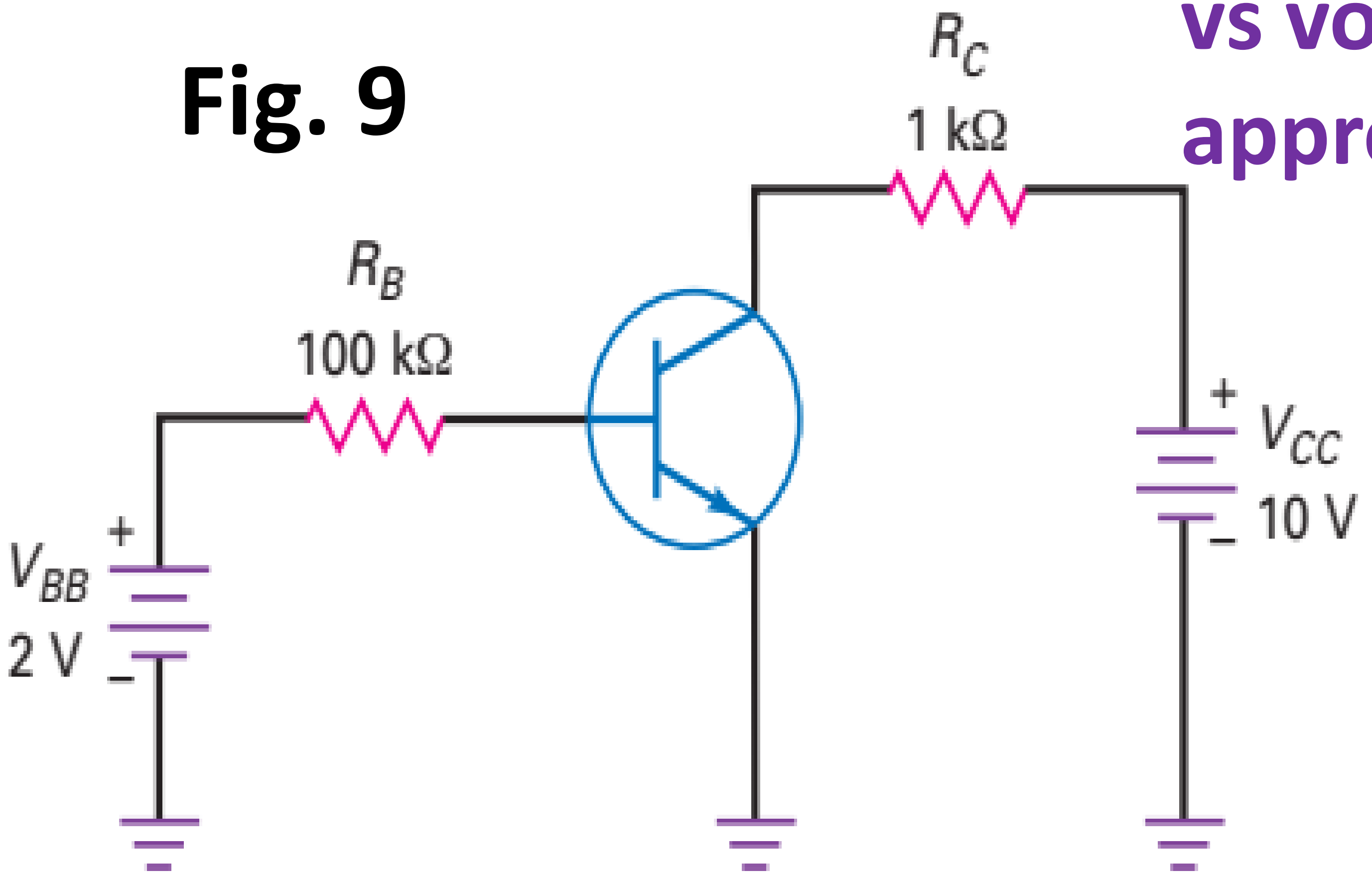
single subscripts mean node voltage or voltage between the subscripted point and the ground: $V_C = V_C - V_E = V_{CE}$

BJT characteristics

Base characteristics

Emmiter diode, same current vs voltage curve, choose approximation

Fig. 9



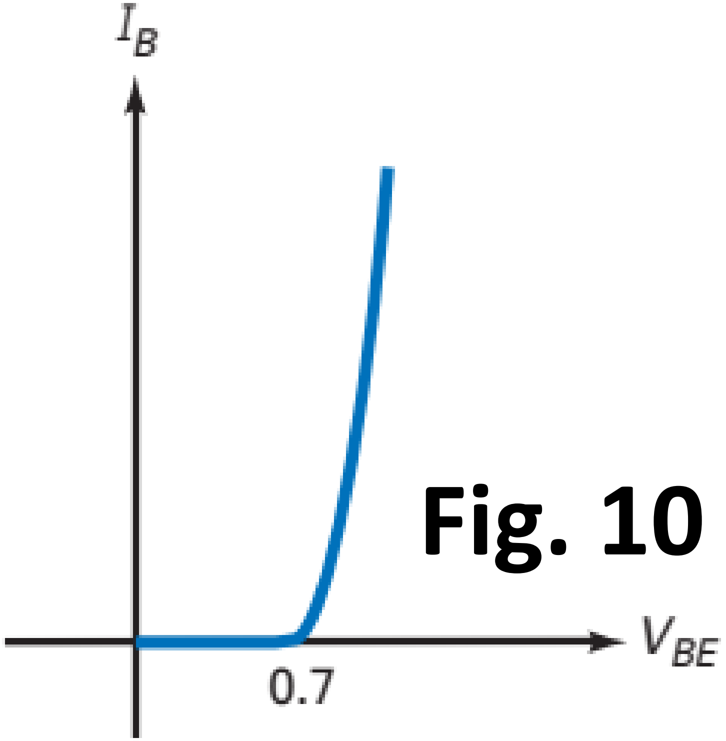


Fig. 10

BJT characteristics

Base characteristics

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \qquad \text{Eq.(6)}$$

example

Use the second approximation to calculate the base current in Fig. 9. What is the voltage across the base resistor? The collector current if β =200?

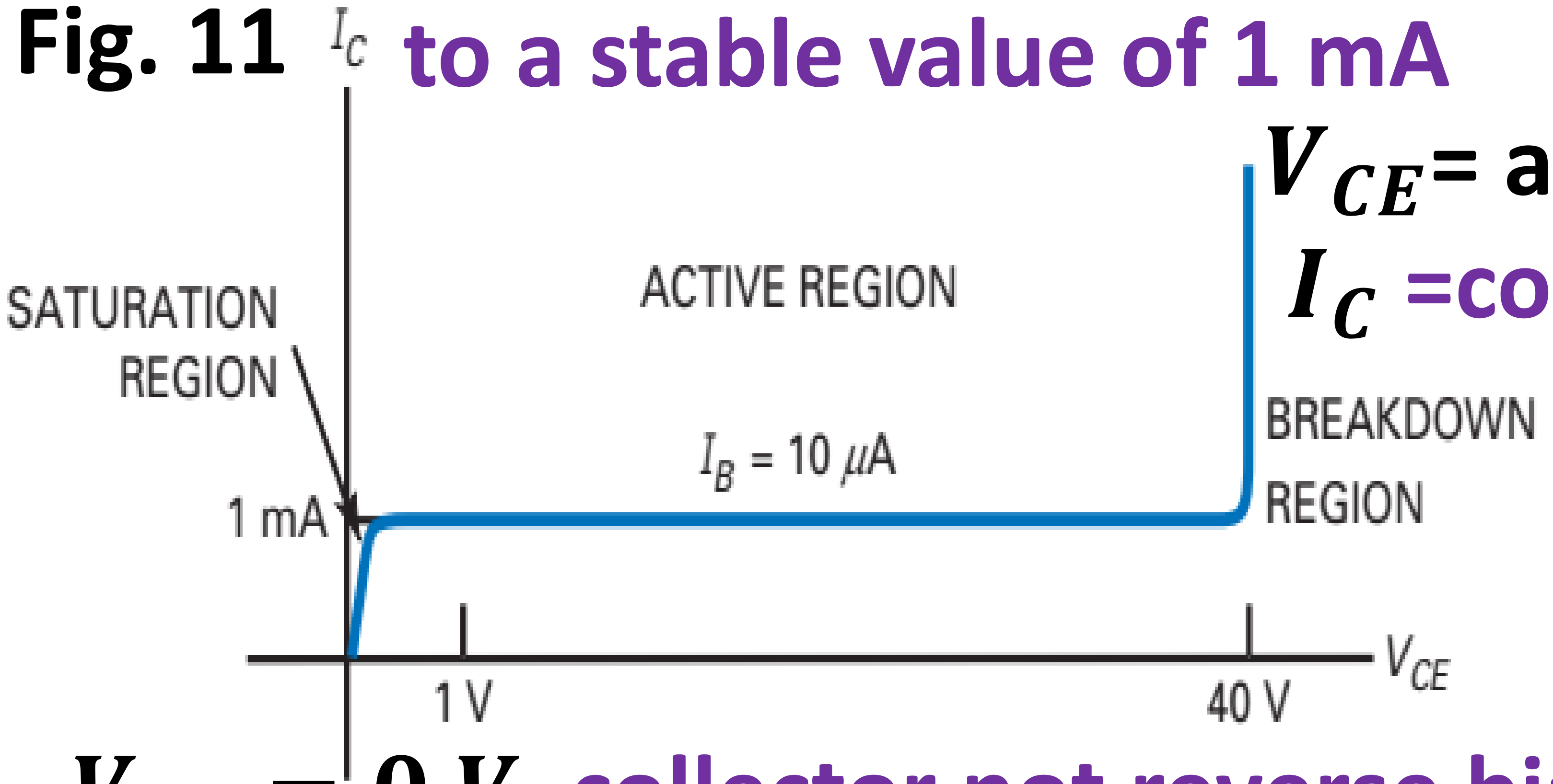
Transistors: focused NPN BJTs

BJT characteristics

collector characteristics

small increase of V_{CE}, sharp increase of I_C up to a stable value of 1 mA

Fig. 11



V_{CE}= a few tens of 1 V-40 V, I_C =constant= 1 mA

$V_{CE} = 0\ V$, collector not reverse bias, $I_C = 0\ A$

BJT characteristics

collector characteristics

$V_{CE} >$40 V, collector breaks down, transistor effect lost

Constant region in Fig. 10 means further increase of V_{CE} cannot increase I_C as it is due only to free e^- from the base

Collector voltage: $V_{CE} = V_{CC} - R_C\, I_C$ Eq.(7)

Power dissipation: $P_D = V_{CE}\, I_C$ Eq.(8)

Power dissipation heats up the transistor may damaging it

BJT characteristics

collector characteristics

Regions of operation

Active region: I_C constant, transistor in normal operation

Saturation region: early rising part of the curve, V_{CC} is insufficient to collect all free e^- from the base, $I_B > I_C$

Breakdown region: almost vertical part of curve, transistor gets damage in this region

BJT characteristics

collector characteristics

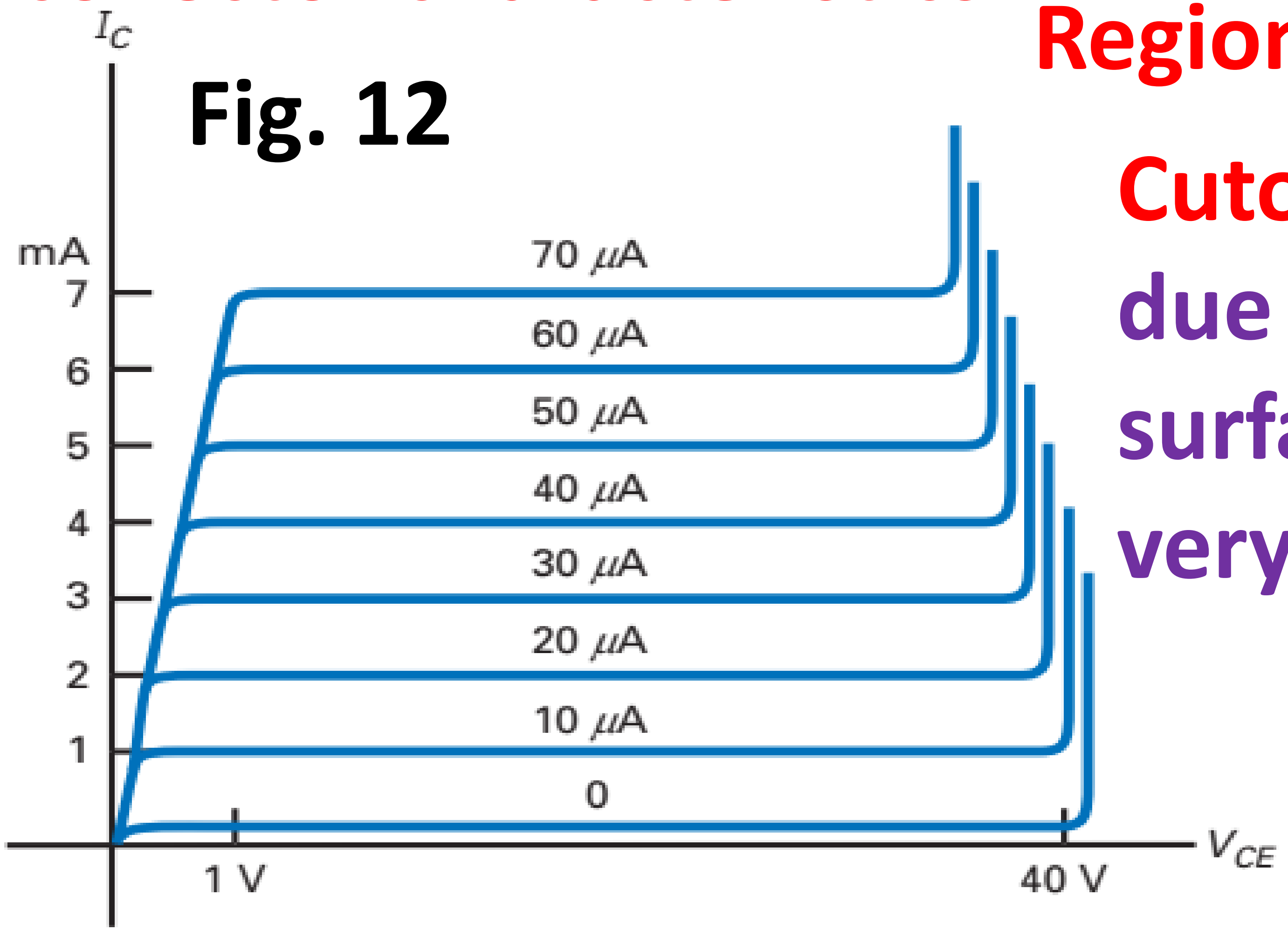


Fig. 12

Regions of operation

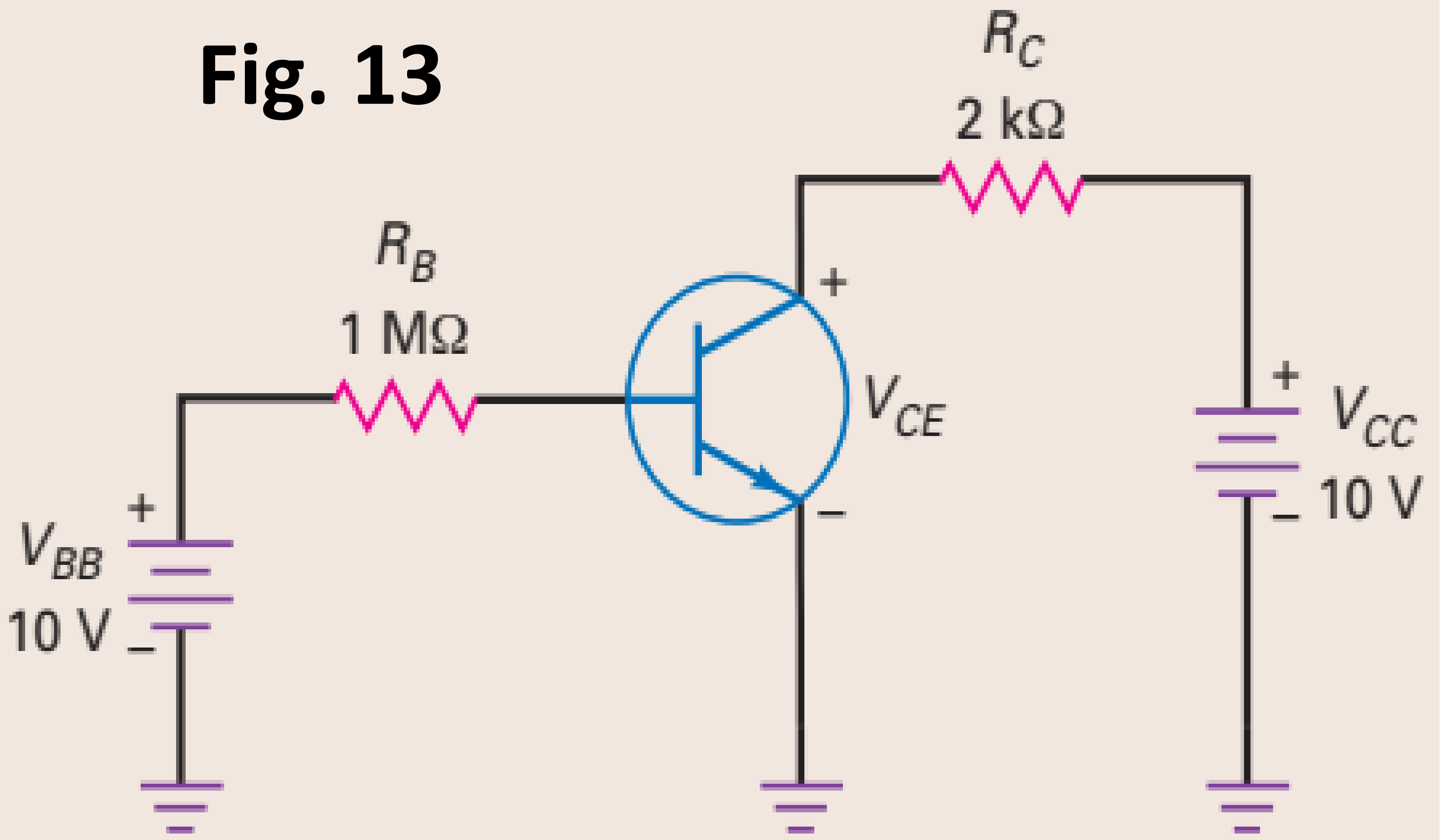
Cutoff region: $I_B = 0\ A,\ I_C \neq 0$ due to minority carriers and surface leakage current, I_C is very small orders of 50 nA

BJT characteristics

collector characteristics

Example: what are I_B, I_C, V_{CE} and P_D?

Fig. 13



Transistors: focused NPN BJTs

BJT characteristics

Transistor approximations

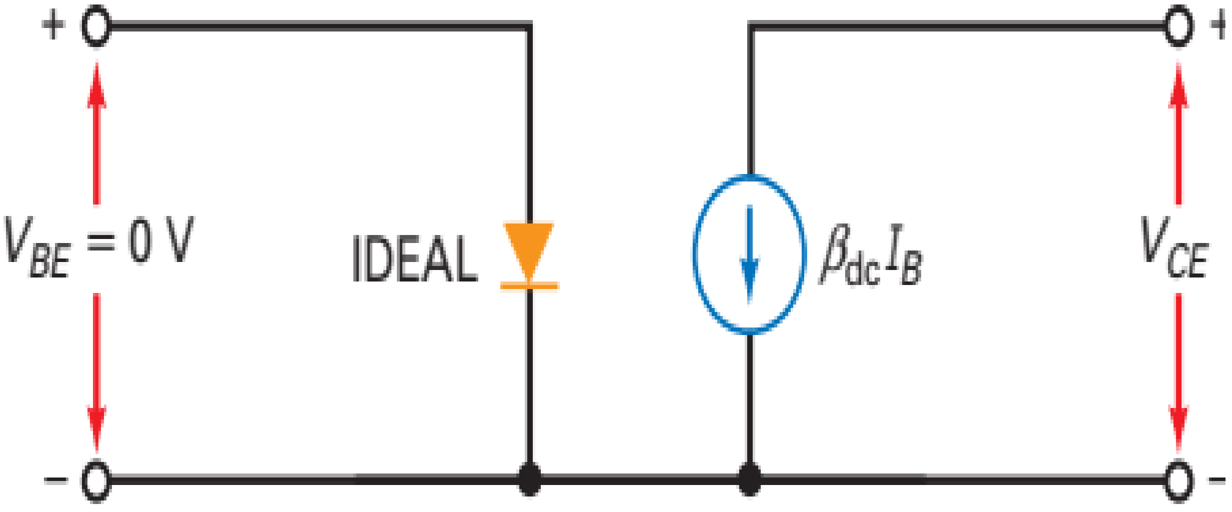


Fig. 14

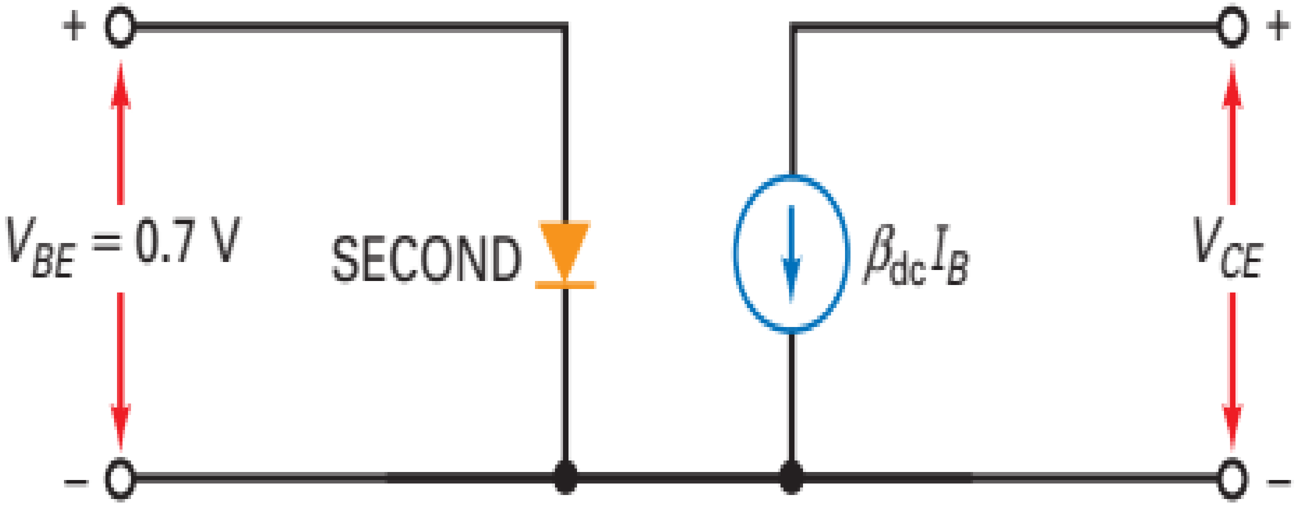


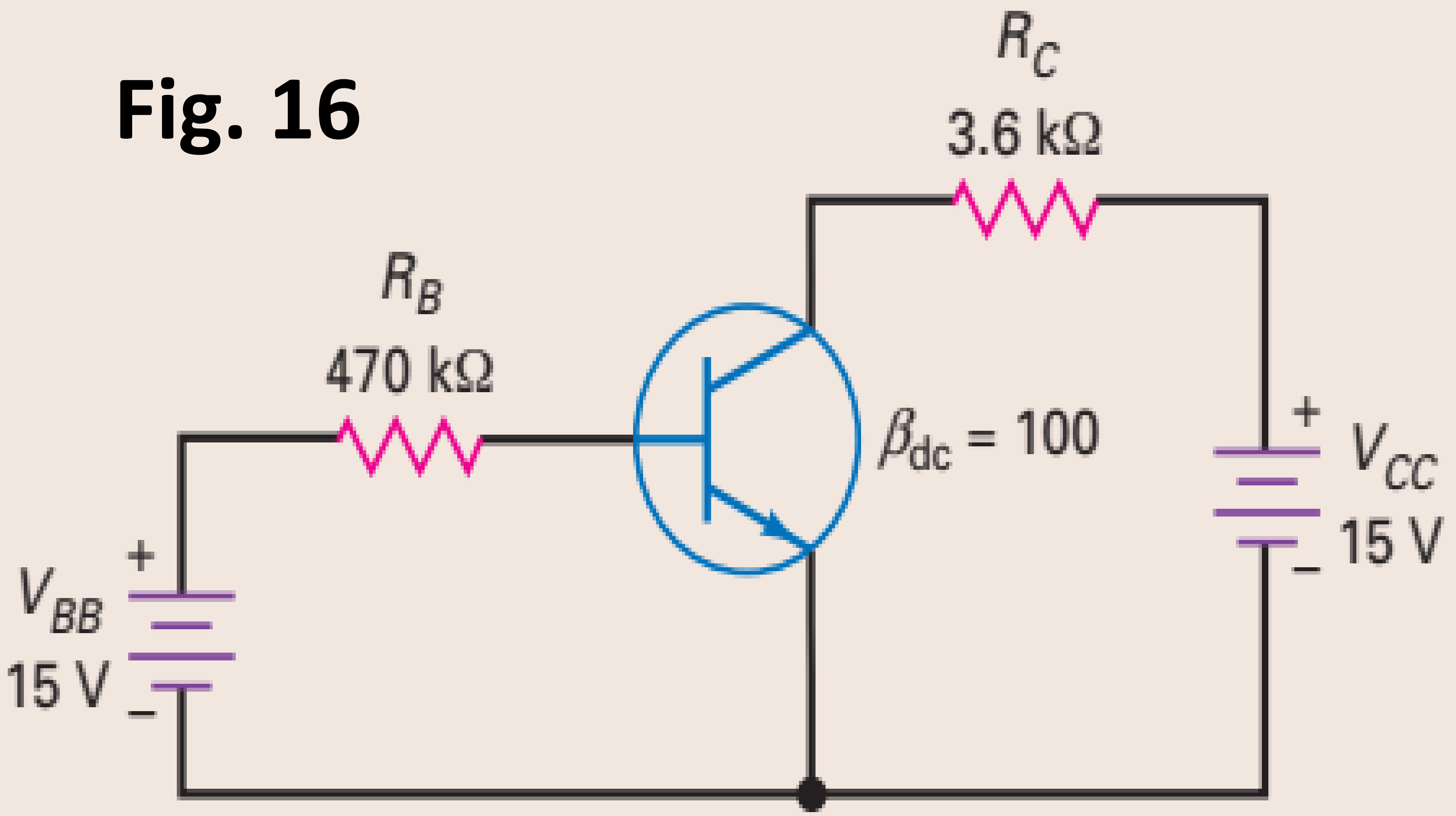
Fig. 15

BJT characteristics

Transistor approximations

Example: what is V_{CE}? Use first the ideal and second degrees approximations

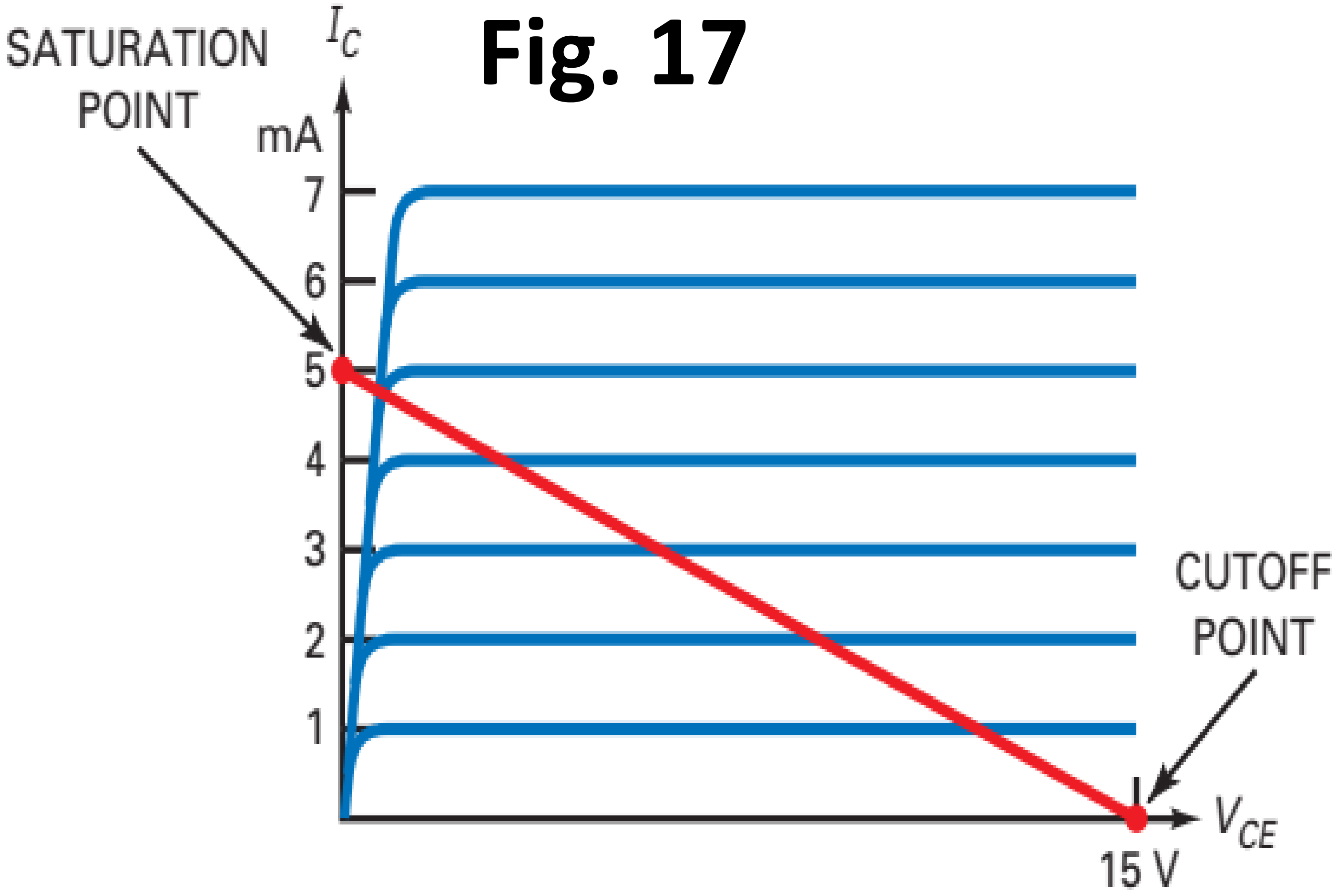
Fig. 16



BJT characteristics

Load line: base bias case, i.e., base current fixed

Fig. 17



$$I_C = \frac{V_{CC} - V_{CE}}{R_C} \quad \text{Eq.(9)}$$

Load line contains all possible operating points of the transistor

BJT characteristics

Load line: base bias case, i.e., base current fixed

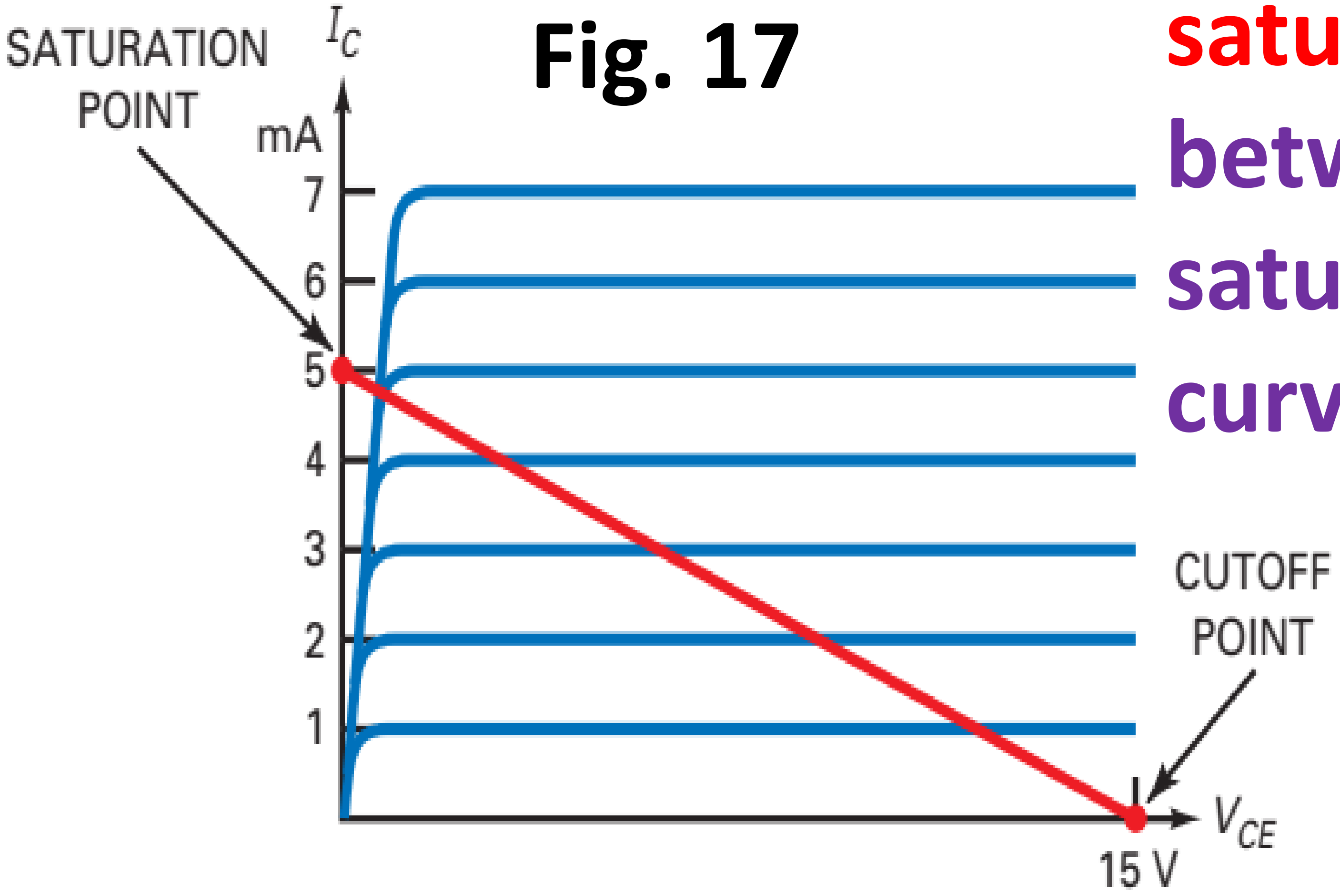


Fig. 17

saturation point: intersection between load line and saturation region of collector curves, $V_{CE} \approx 0\ V$.

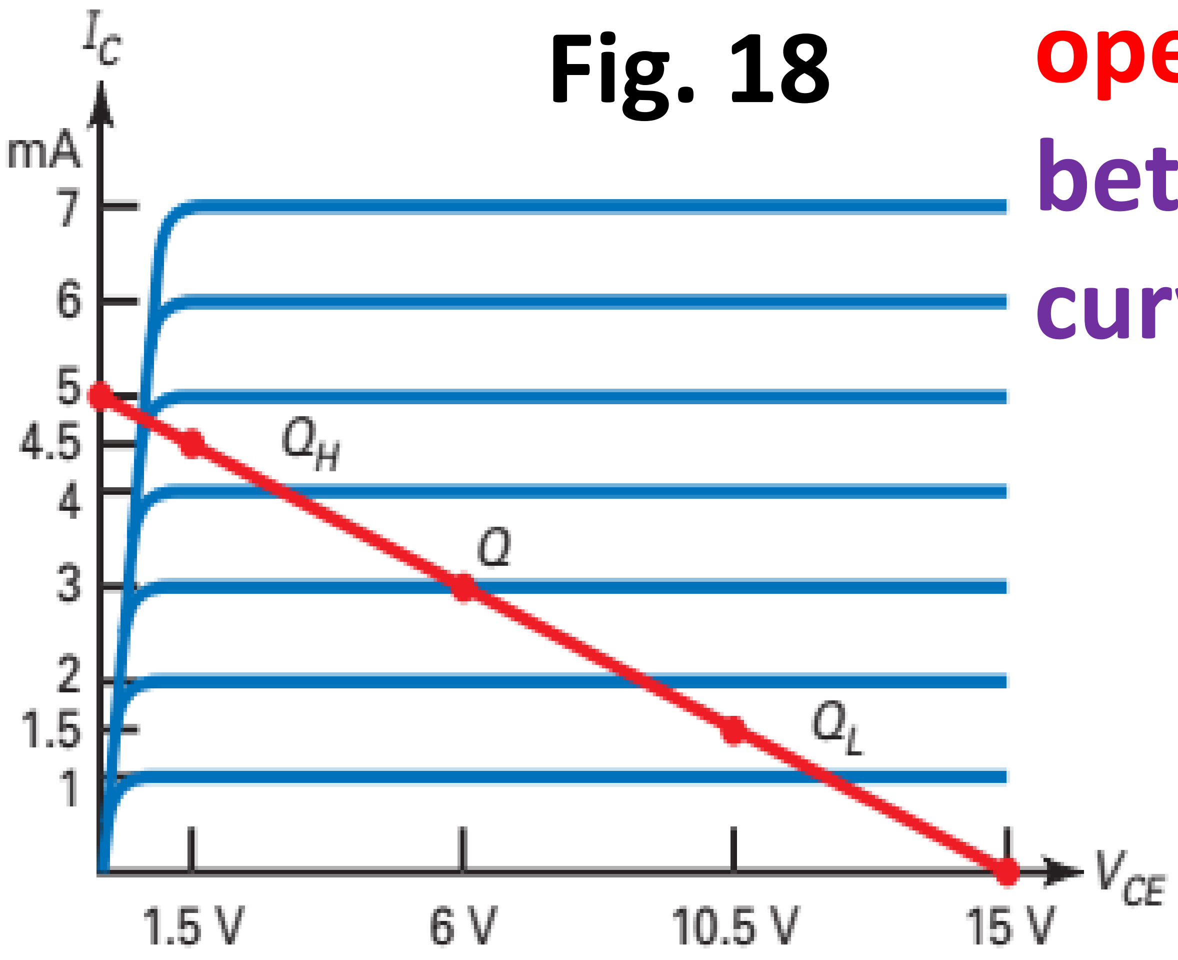
$$I_{CS} \approx \frac{V_{CC}}{R_C} \qquad \text{Eq.(10)}$$

Transistors: focused NPN BJTs

BJT characteristics

Load line: base bias case, i.e., base current fixed

Fig. 18



operating point Q: intersection between load line and $I_C\,(V_{CE})$ curve $Q(\,I_C, V_{CE})$

$$I_B = \frac{(V_{BB} - V_{BE})}{R_B}\,(V_{CE})$$

$$I_C = \beta\, I_B$$

$$V_{CE} = V_{CE} - R_C\, I_C$$

BJT characteristics

Recognize saturation

1. Assume transistor operating in active region.
2. Carry out the calculations for currents and voltages.
3. If an impossible result occurs in any calculation, the assumption is false.

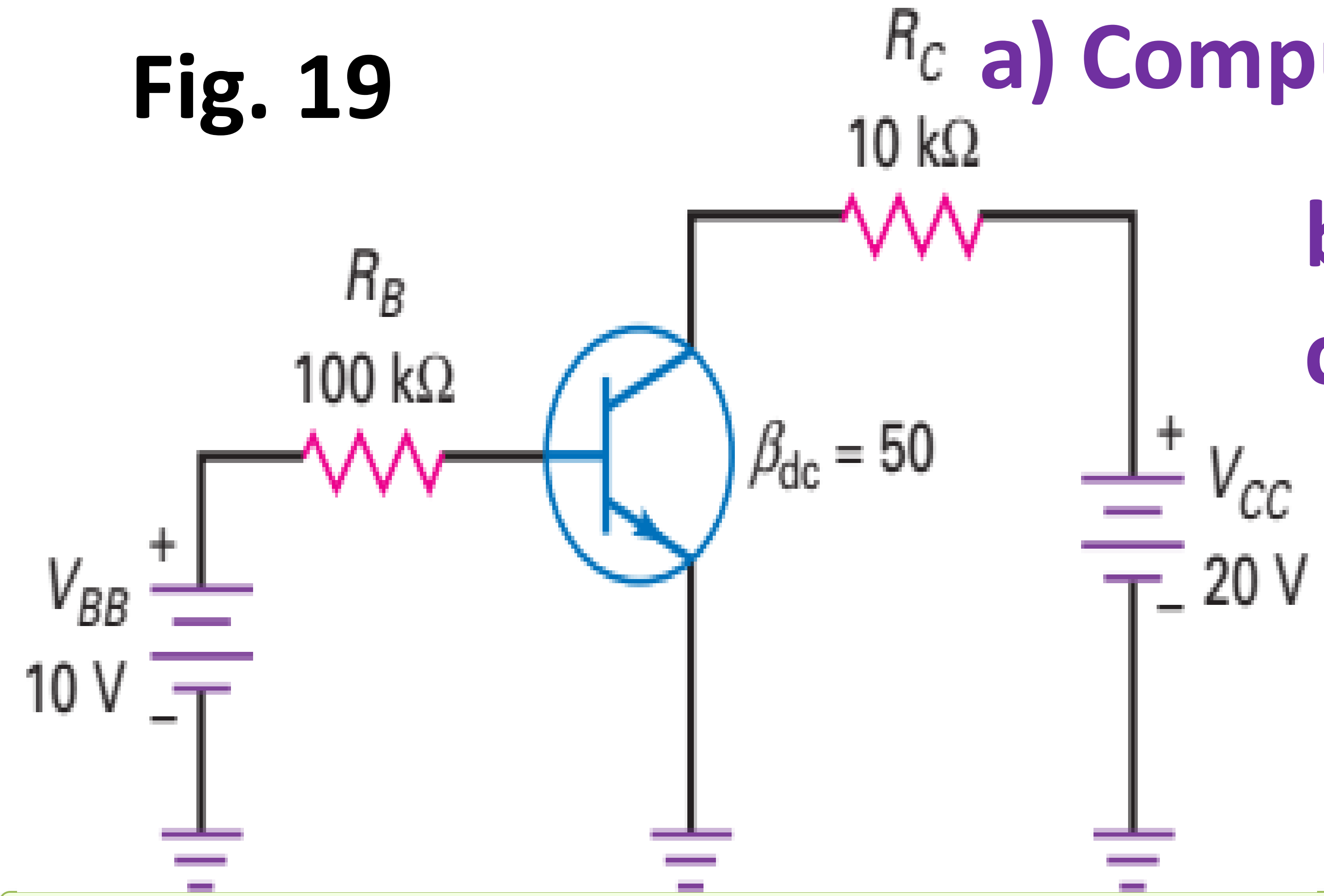
Transistors: focused NPN BJTs

BJT characteristics

Recognize saturation

example

Fig. 19

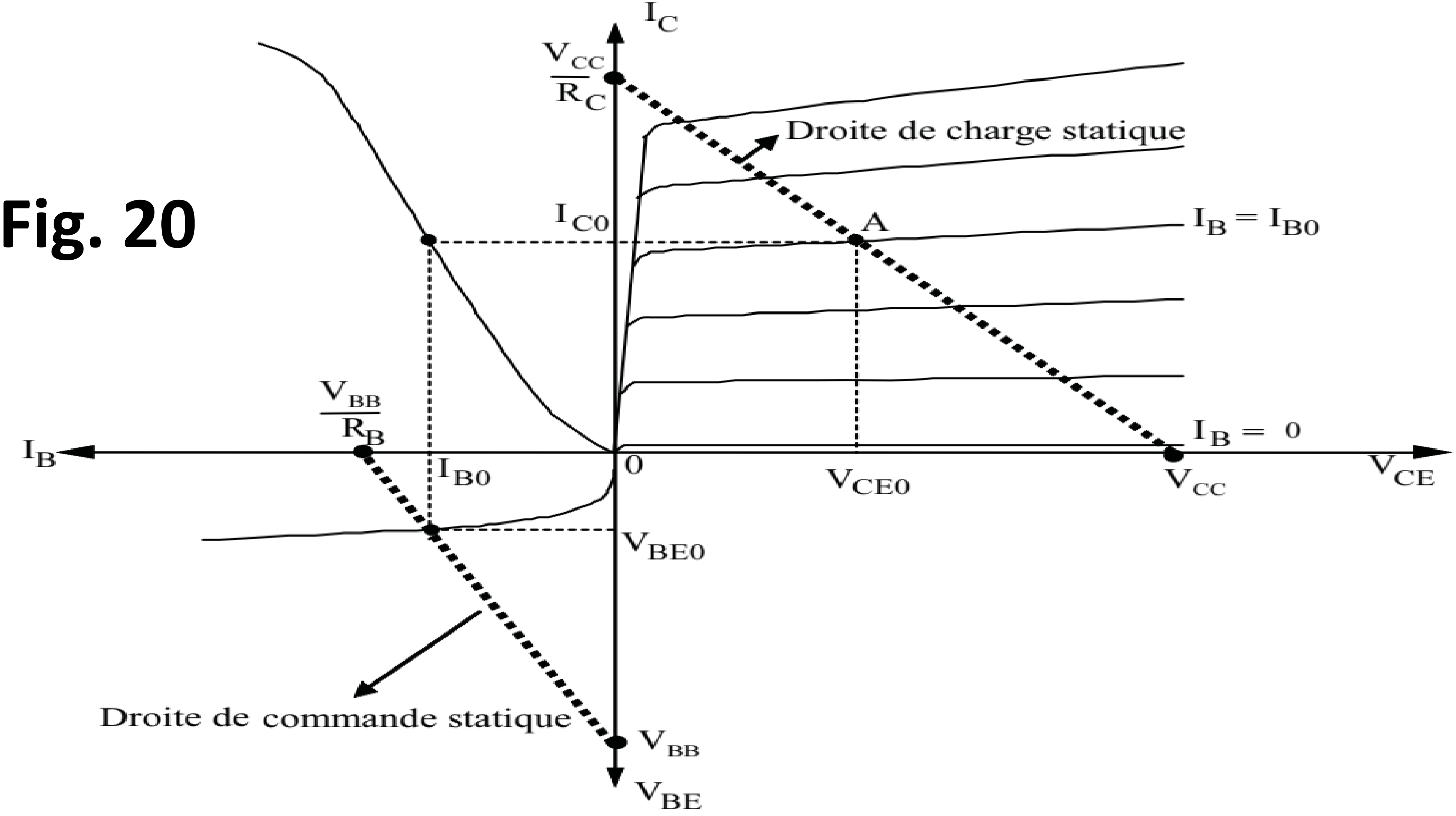


a) Compute I_B and I_C, conclude

b) Compute I_C and V_{CE}, conclude

Transistors: focused NPN BJTs

Fig. 20



Introduction

Field effect transistor (FET): unipolar device as current is due only one type of charge carriers (e^- or holes)

Advantages of FETs over BJTs

high input impedance

voltage controlled device

high degree of isolation between input and output

less noisy effect

Introduction

Types of FETs

(a) Junction FET (JFET)

(b) Metal oxide semiconductor FET (MOSFET)

Transistors: focused FETs

Junction field effect transistor (FET)

JFET: four-terminal device, terminal names: drain, gate, source, and body always connected to the source

Types of JFET

Fig. 21 N-channel JFET

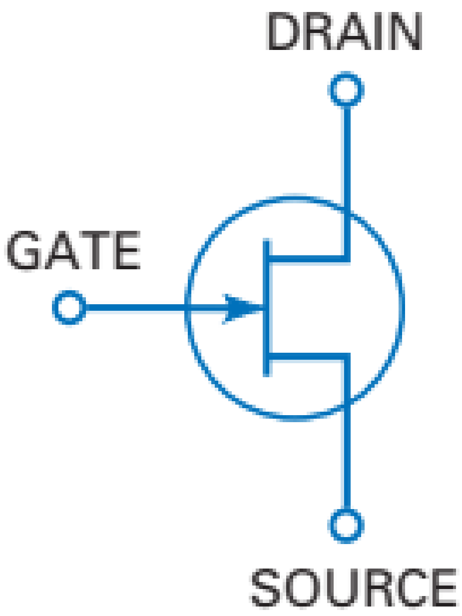
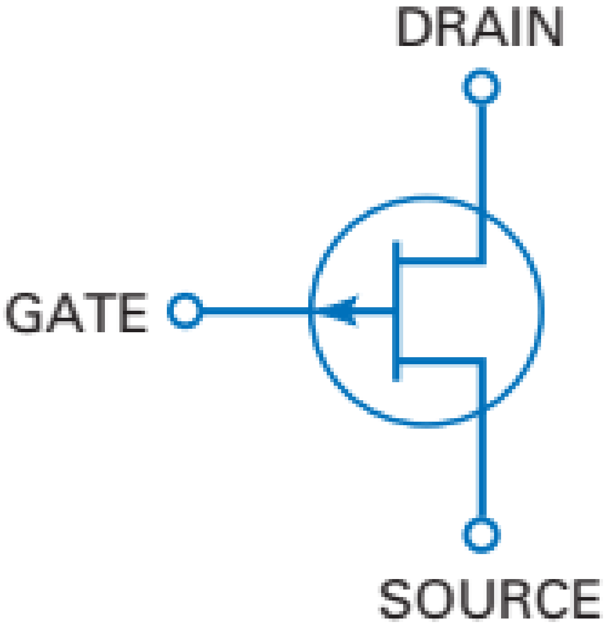


Fig. 22 P-channel JFET

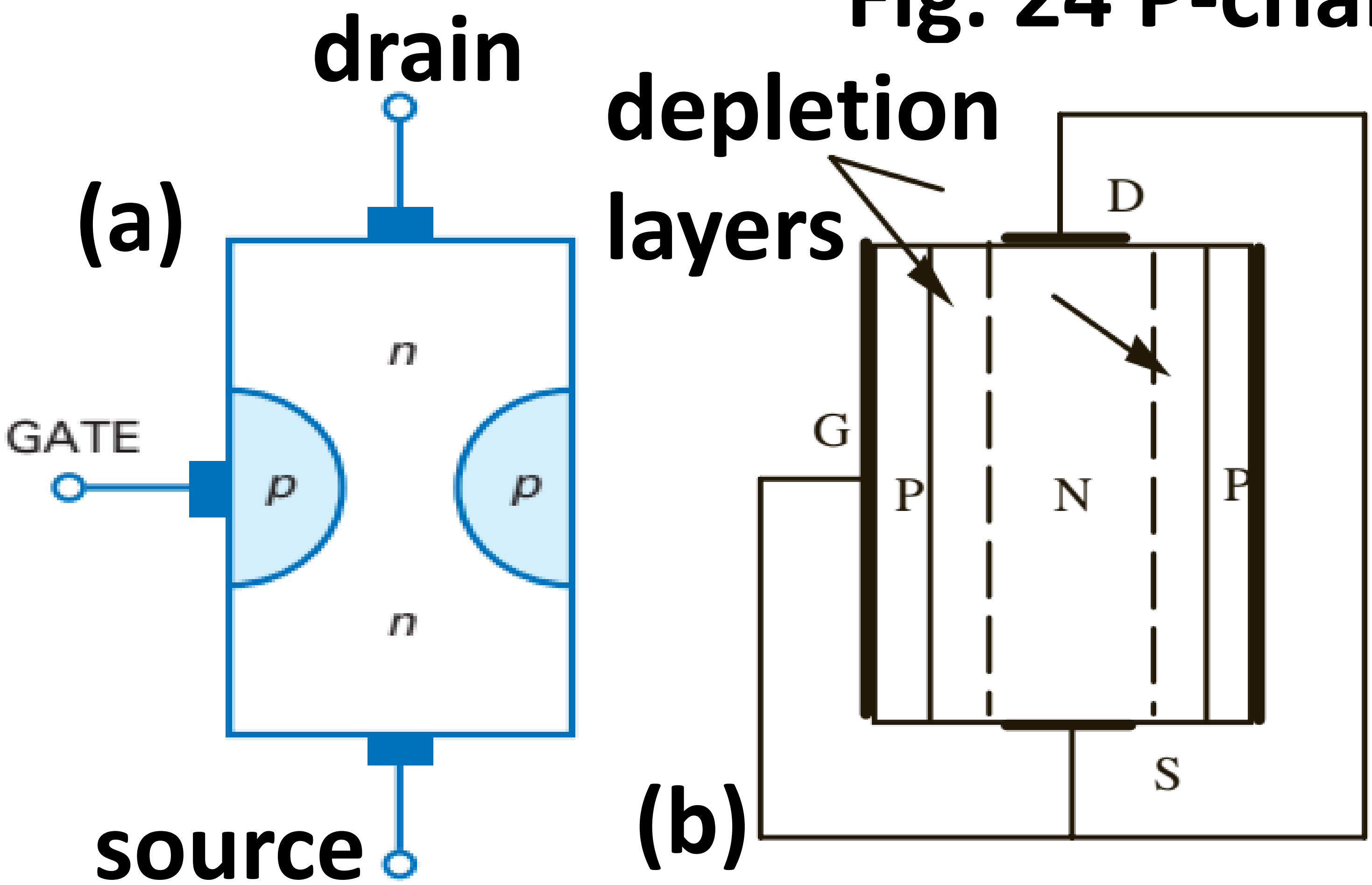


Transistors: focused FETs

Junction field effect transistor (FET)

Construction of JFET

Fig. 24 P-channel JFET



P-regions are internally connected to get one gate lead

Term field effet related to the presence of two depletion layers

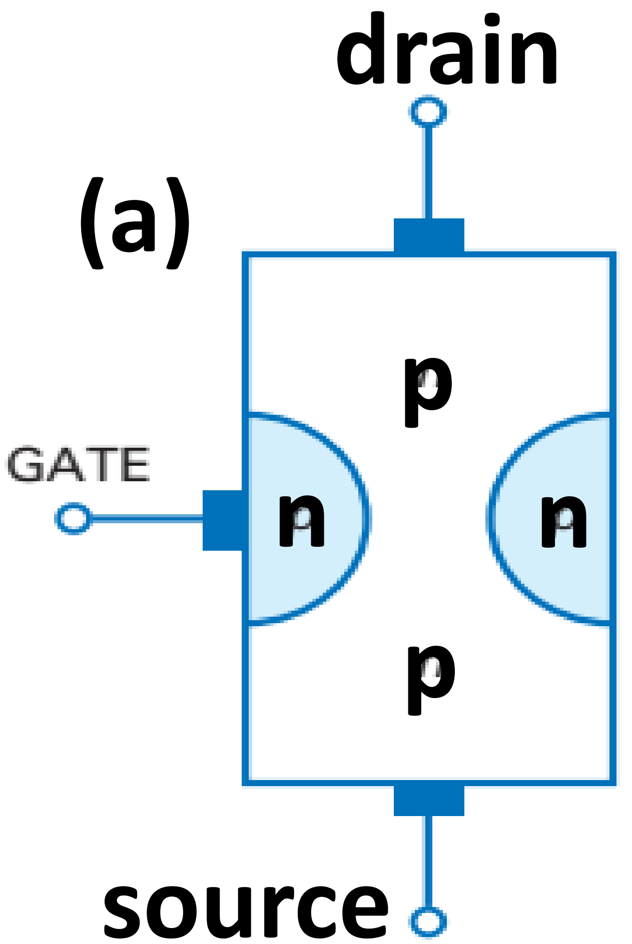
charge carriers are e^-

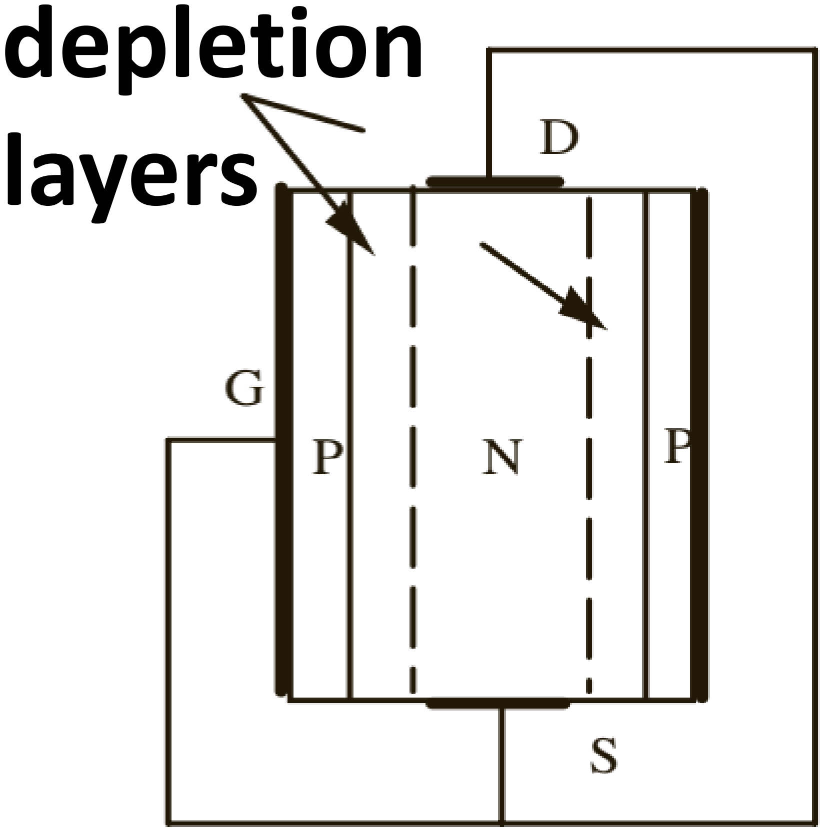
Junction field effect transistor (FET)

Construction of JFET

Fig. 25 P-channel JFET

(a)





(b)

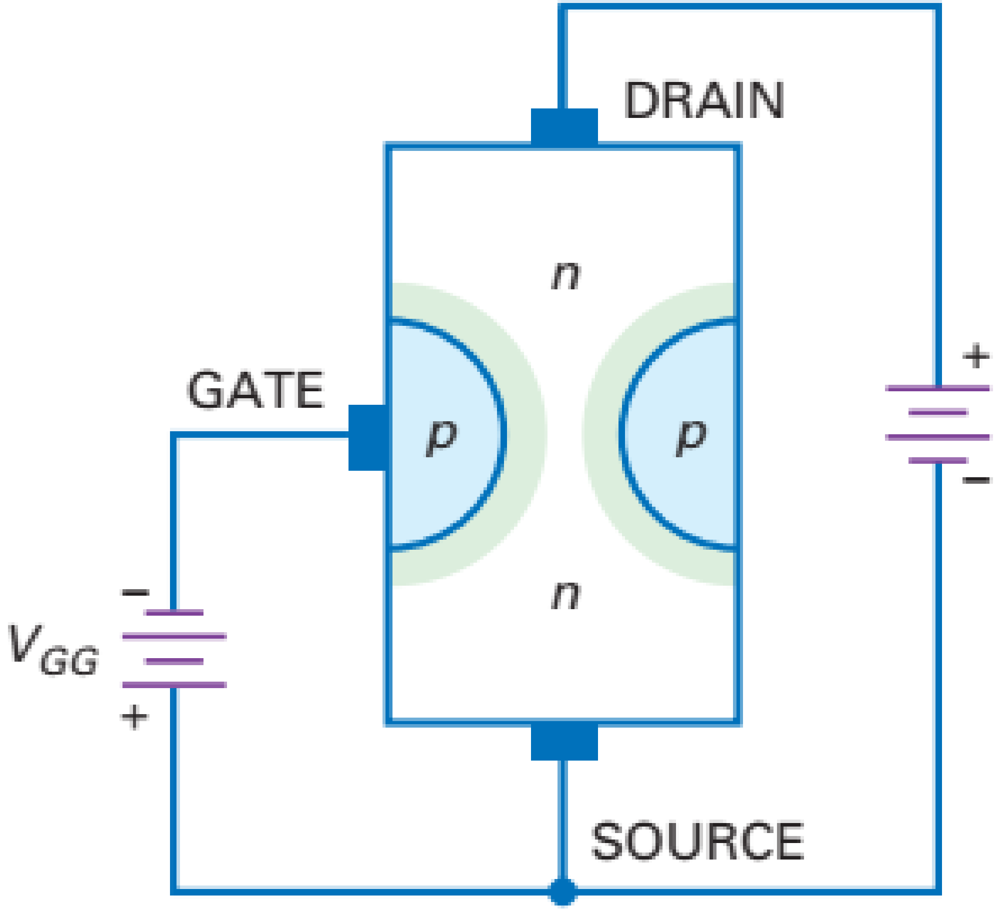
charge carriers are holes

Transistors: focused FETs

Junction field effect transistor (FET)

working of JFET

Fig. 26 Normal biasing a JFET



gate-source diode always reverse Bias, Gate current $I_G \approx 0$, input resistance almost infinite

e^- flowing from source to drain must pass through narrow channel between the depletion layers.

Junction field effect transistor (FET)

working of JFET

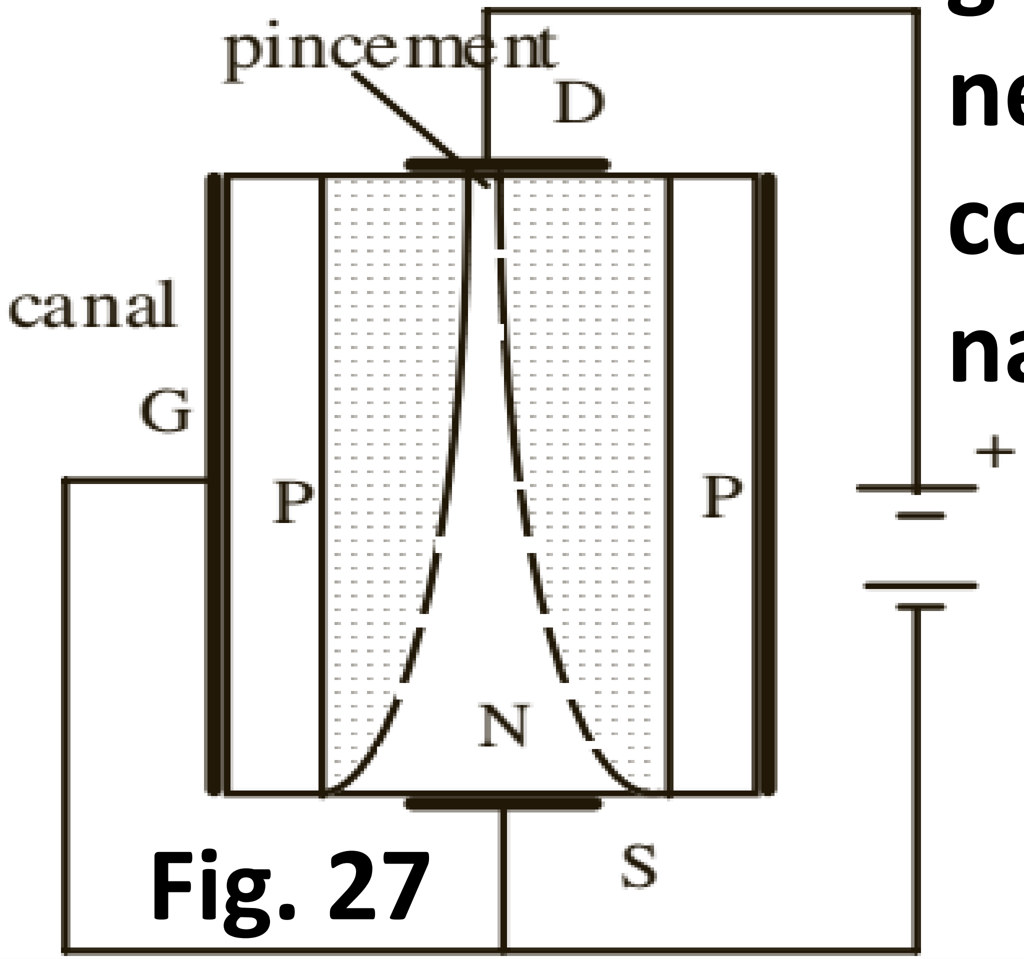


Fig. 27

gate voltage becomes more negative, depletion layers expand, conducting channel becomes narrower

V_{GS} is negative enough, depletion layers touch, drain current is cut offer

Junction field effect transistor (FET)

working of JFET

gate voltage becomes more negative, depletion layers expand, conducting channel becomes narrower

V_{GS} is negative enough, depletion layers touch, drain current is cut offer

Junction field effect transistor (FET)

working of JFET

$$U_{DS} = U_{DG} + U_{GS} = -U_{GD} + U_{GS} \quad \text{Eq.(10)}$$

$$U_{GS} = 0, \qquad U_{DS} = -U_P + 0 = -U_P (U_{DS} > 0) \quad \text{Eq.(11)}$$