African Centre for Advanced Studies

National Advanced School of Engineering, UYI

ELECTRIC AND ELECTRONIC CIRCUITS

PHY 225

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Overview

Objectives: Communicate to the student the basic concepts of design and analysis of analog electrical and electronic circuits

Expected results: Design and analysis of electrical and electronic circuits (Electrical Engineering)

Methodology: Lecture and tutorials

Mandatory documentation: Lecture's mark

Optional documentation: internet links; textbooks:

tests: intermediate 40 percent; final exam 60 percent:

Homeworks: there will be homeworks: groups and or individuals ones

Syllabus

DIODES and APPLICATIONS: Introduction to semiconductors; PN junction; PN junction diodes; Half-wave rectifier; Full-wave rectifier; Zener diode; voltage stabilization by a Zener diode

Transistors: Introduction; Bipolar junction transistor; Transistor effect; Characteristics of transistors; Field effect transistors; Junction field effect transistors;

Amplifier Transistors: Biopolar Transistor Amplifiers; Field Effect Biopolar Transistors

Operational Amplifiers: Description; Characteristics and parameters of OA; Linear Approximation of OA circuits; Nonlinear approximation of OA circuits

Diodes and transistors in commutation: Diodes in Switching; Biopolar Transistors in Switching; Field Effect Transistors in Switching;

Introduction

Electronic conduction: passage of free electrons through a material.

(a) Copper Cu

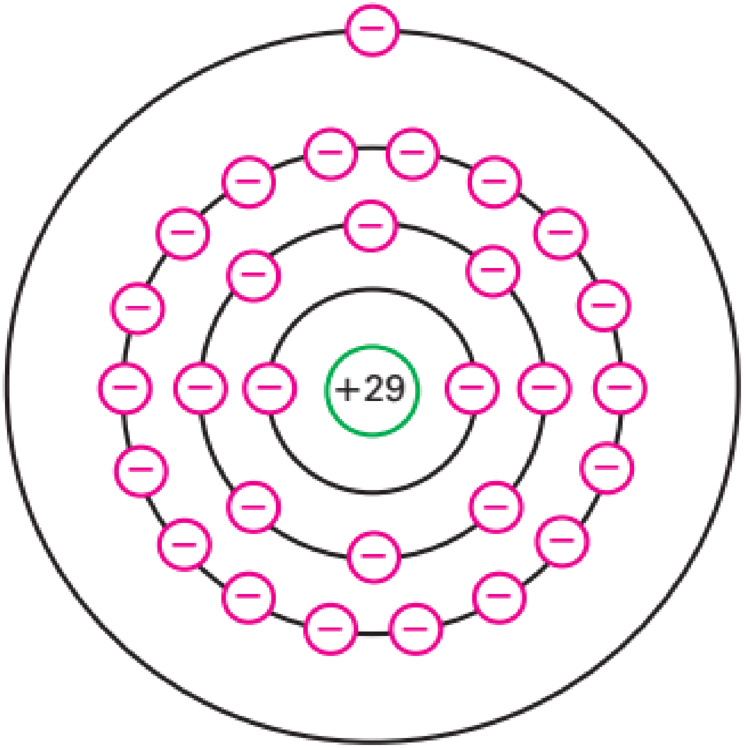
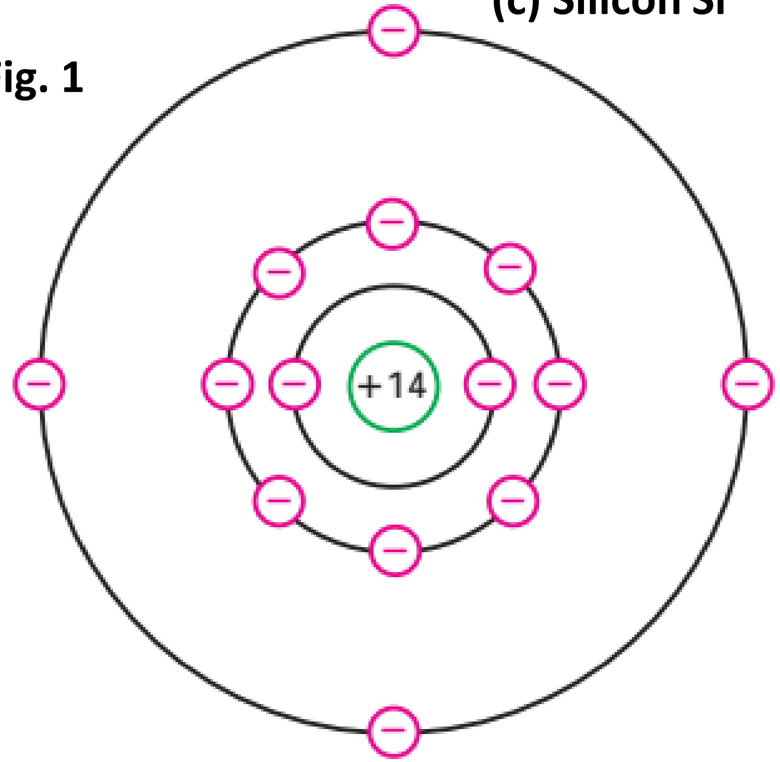


Fig. 1

(c) Silicon Si



Electrical conductors: Some materials which electricity pass through them easily.

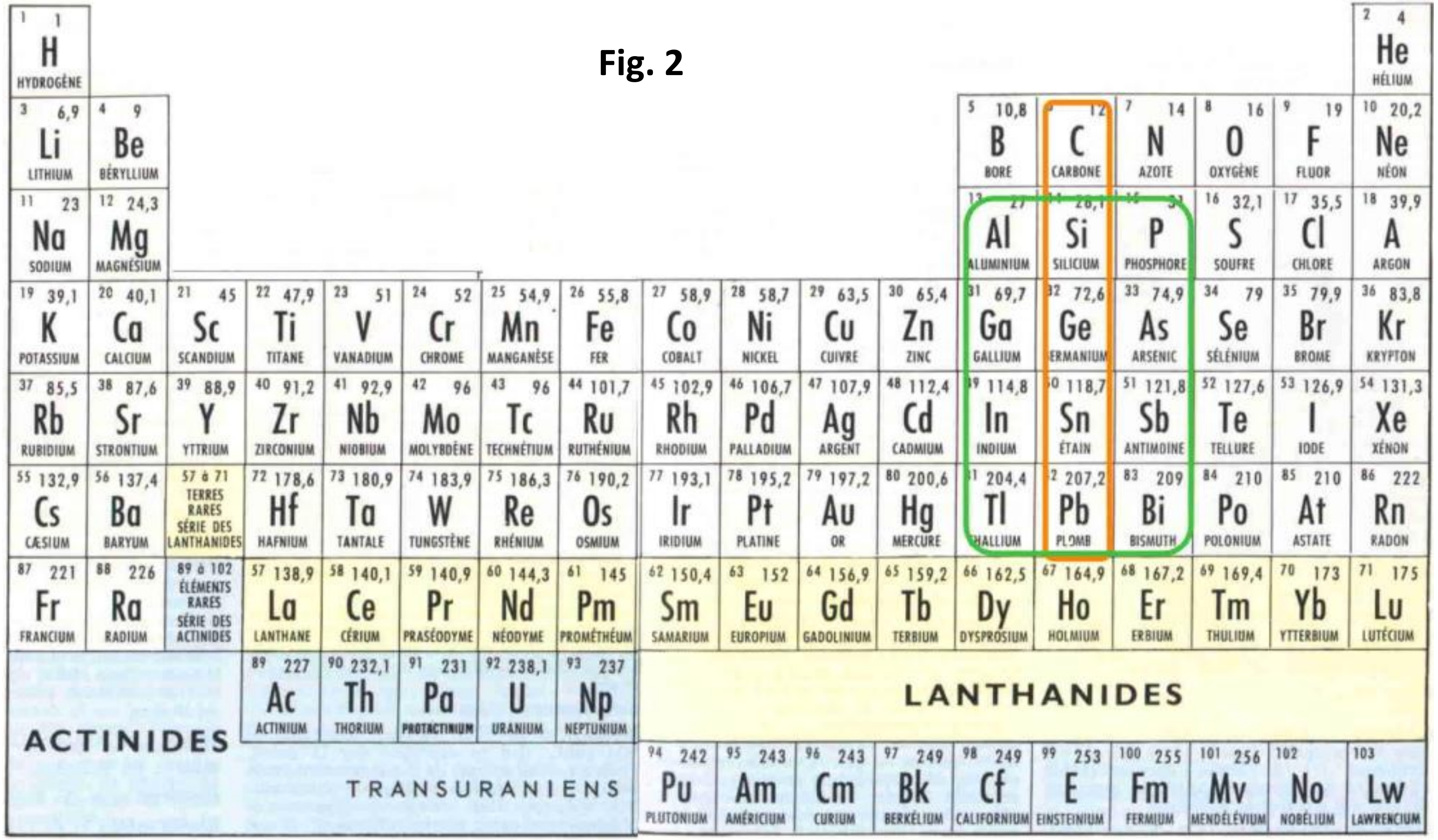
Electrical insulator: a material whose internal electric charges do not flow freely.

Electrical semiconductors: Some materials which electricity pass through them easily.

Introduction to semiconductors

Best conductors (silver, copper, and gold) : 1 valence electron $\sigma \approx 10^{8}\ \mathrm{S/m}$

Fig. 2



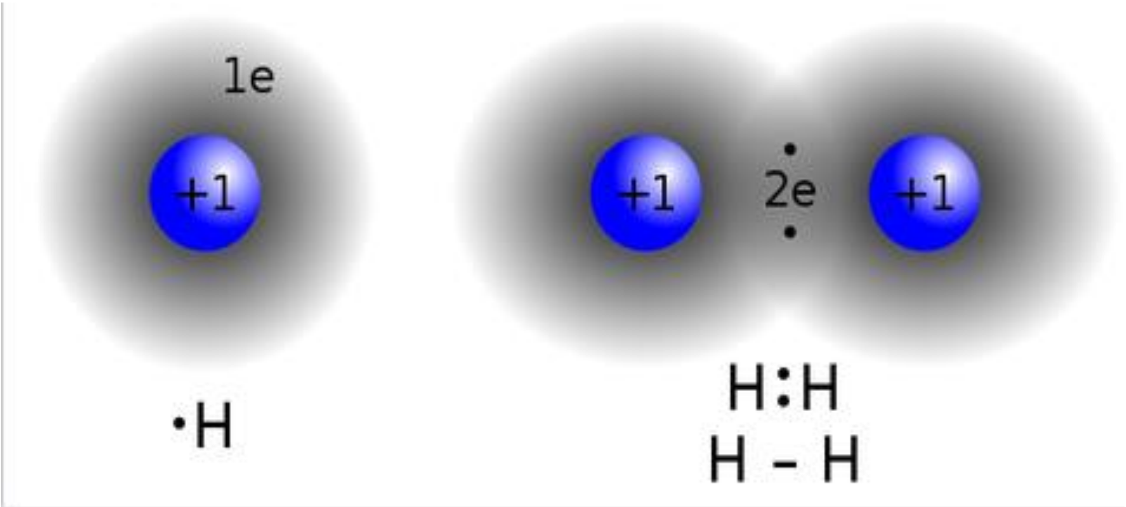
Best insulators : 8 valence electrons $\sigma < 10^{-6}\ \mathrm{S/m}$

Best semiconductors : 4 valence electrons $\sigma \approx 0{,}1 \text{ à } 10^{-4}\ \mathrm{S/m}$

Introduction to semiconductors

Crystal or crystalline solid: solid material whose constituents (such as atoms, molecules, or ions) are arranged in a highly ordered microscopic structure, forming a crystal lattice that extends in all directions.

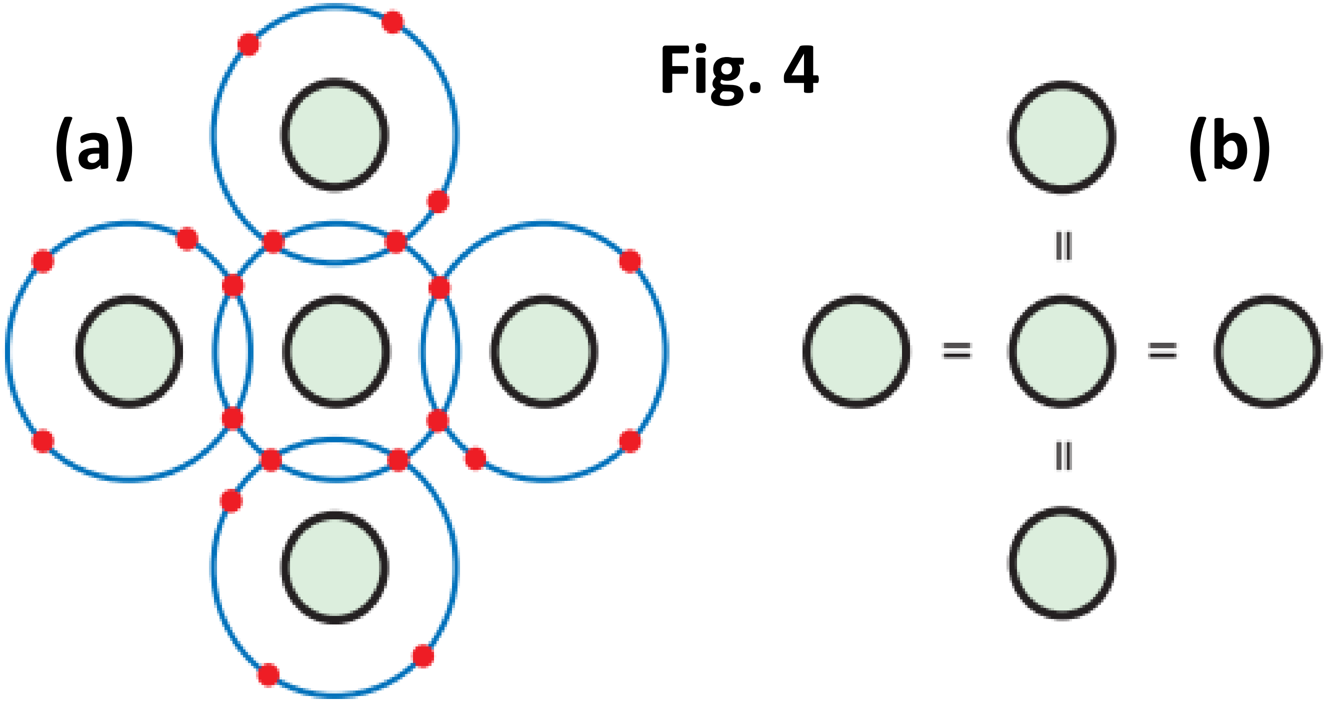
Covalent Bond: chemical bond that involves the sharing of electron pairs between atoms



A covalent bond forming H_2 (right) where two hydrogen atoms share the two electrons

Fig. 3

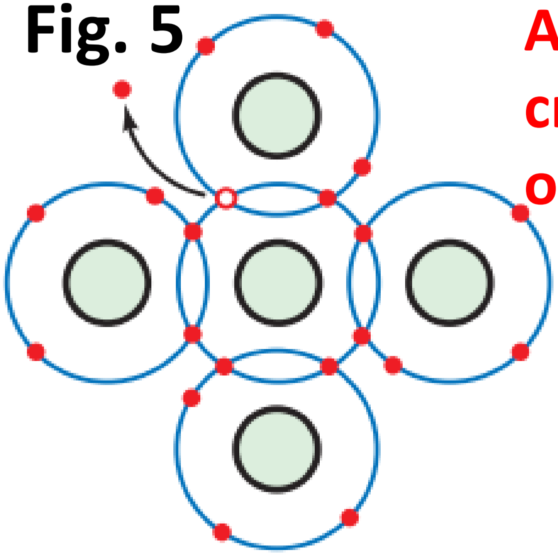
Fig. 4



1 Si atom in crystal has 4 neighbors, 1 neighbor shares 1 electron with the central atom, 5 atoms have 8 atoms on each outer shell

Introduction to semiconductors

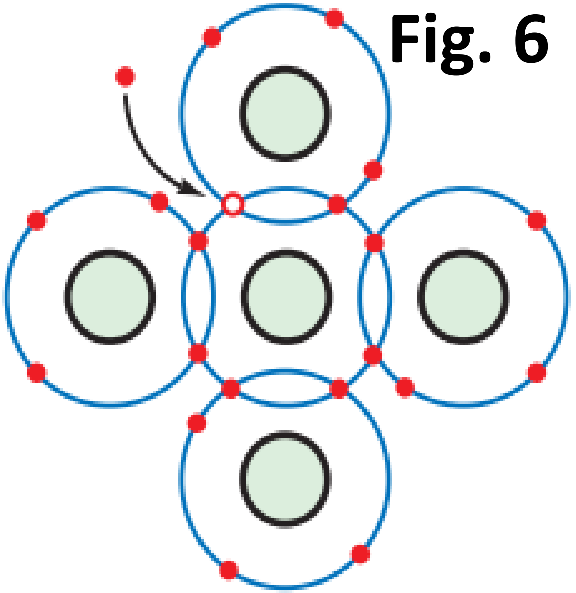
Fig. 5



Ambient Temperature > 0, heat energy induces vibrations of Si atoms in the crystal, some electrons of outer shells may be dislodged, move to higher orbit, thus are free to move along the crystal, *few electrons are produced*

HOLE: The departure of the electron creates a vacancy in the valence orbit called a hole that behaves like a positive ion (departure of electron = positive ion) and attract any electron in its attract and capture any electron in the immediate vicinity.

Fig. 6



Free electrons move randomly throughout the crystal. Occasionally, a free electron will approach a hole, feels its attraction, and fall into it

Recombination: merging of a free electron and a hole

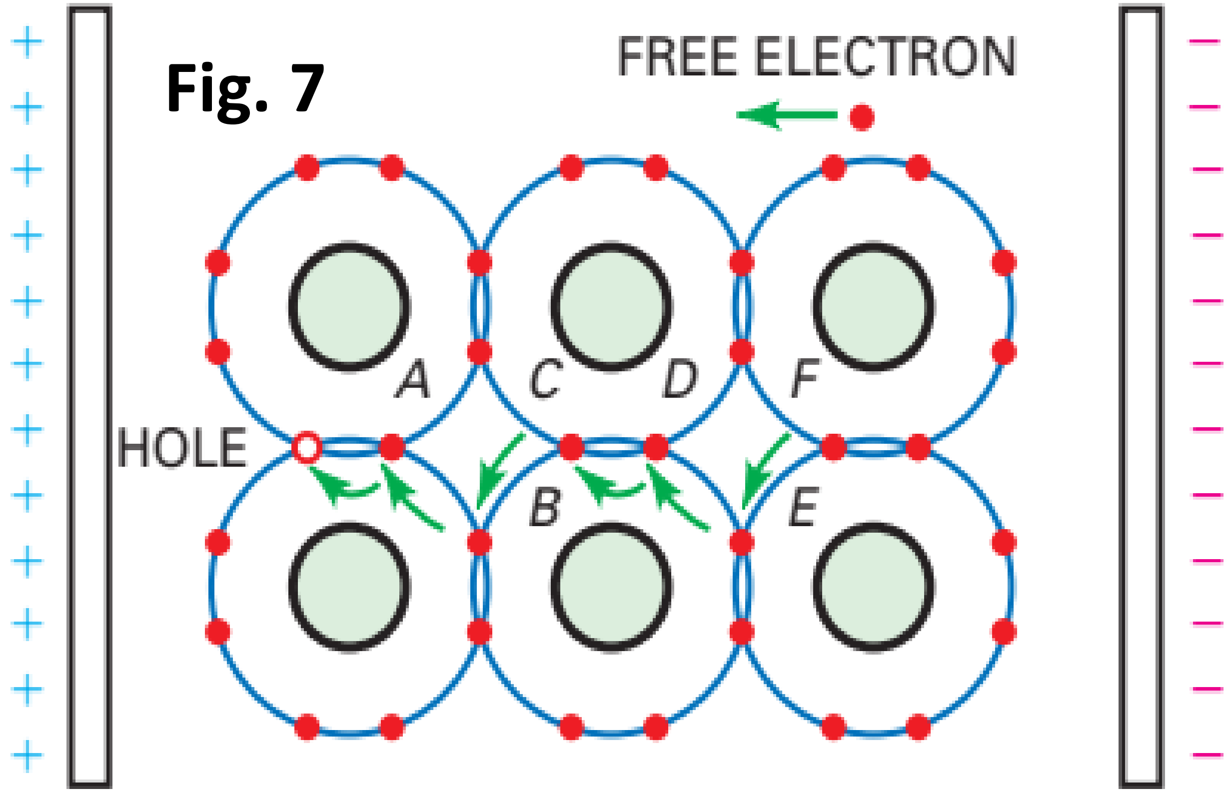
lifetime: amount of time between the creation and disappearance of a free electron, from nanoseconds to microseconds

Introduction to semiconductors

Intrinsic semiconductors: Pure semiconductors, have less than one impurity per 10^{15} atoms; characteristics close to insulators

A free electron in a large orbit at right end of crystal, due to negatively charged plate, is repelled to the left, can move from one large orbit to the next until it reaches the positive one

Fig. 7



The free electron at A is attracted and captured by the hole on the left, a hole is created where the just moved electron was, at the end, electrons move following the arrows, the hole can move the opposite way, along path A-B-C-D-E-F, acting the same as a positive charge.

Introduction to semiconductors

Two opposite flows in an intrinsic semiconductor

Thermal agitation creates same number of free electrons and holes

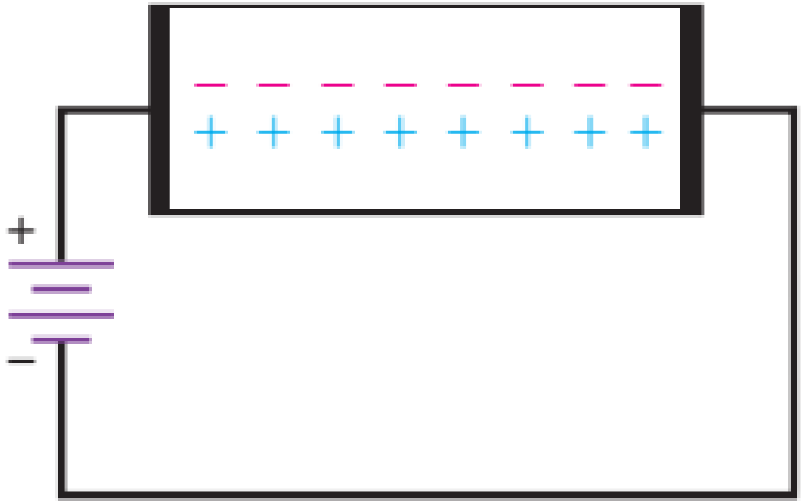


Fig. 8

The applied voltage forces free electrons to flow left but holes to flow right; free electrons arriving at left end of the crystal enter the external wire and flow to the positive battery terminal

Free electrons at the negative battery terminal flow to right end of the crystal, enter the crystal and recombine with holes that arrive at the right end of crystal.

No hole flows outside the semiconductor

Free electrons and holes are often called carriers because they carry a charge from one place to another

Introduction to semiconductors

DOPING A SEMICONDUCTOR

Extrinsic semiconductors: adding impurities to a pure semiconductor to the order of 1 impurity per 10^5 - 10^8 atoms results to a drastic dropping of its resistivity hence increasing it electrical conductivity; the semiconductor is a called a doped semiconductor or an extrinsic semiconductor

Increase the number of free electrons

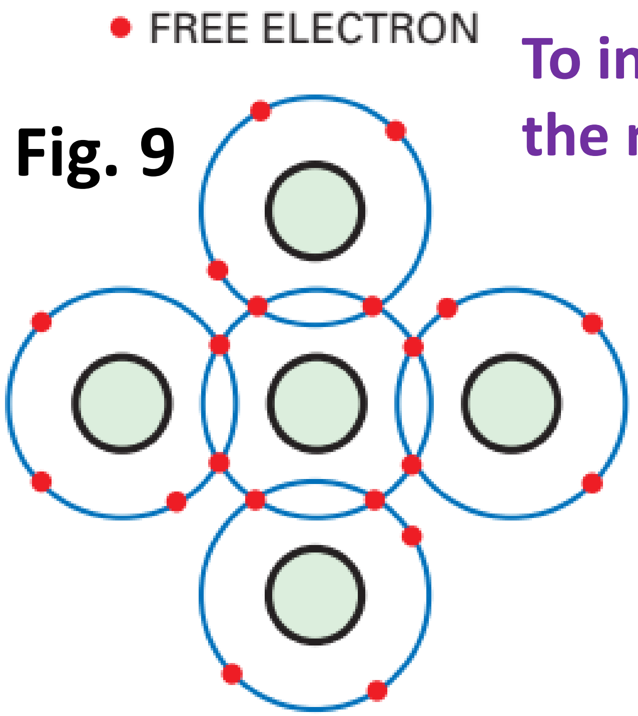


Fig. 9

To increase the number of free electrons, pentavalent atoms are added to the molten pure semiconductor, thus the pure semiconductor is first melted

Fig. 8 case of Si pure semiconductor, each pentavalent atom brings 1 free electron as the four other enter four covalent bonds with 4 neighboring Si atoms, each pentavalent atom is called **a donor atom**

Heavily doped semiconductors have lower resistance, thus higher electrical conductivity

Introduction to semiconductors

Increase the number of holes

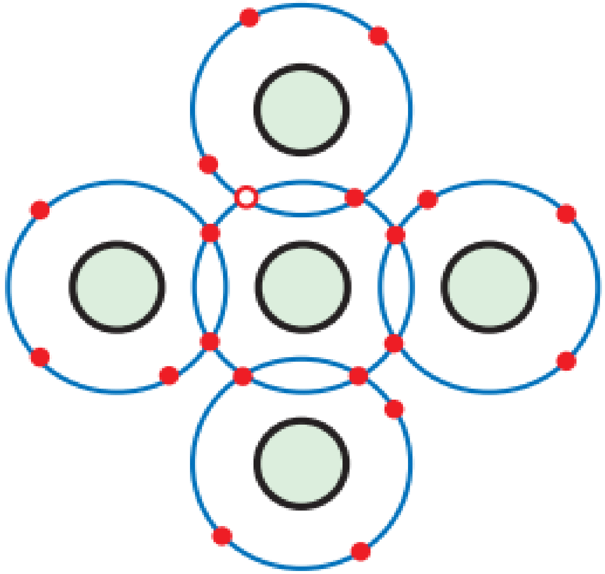


Fig. 10

Adding a trivalent impurity in a pure semiconductor, one whose atoms have only three valence electrons, a semiconductor with an excess holes is created

Fig. 10 case of a pure Si semiconductor doped with a trivalent atom, the trivalent atom at the center shares its 3 valence electrons with its 4 Si atoms neighbors, a hole appears since there are only 7 electrons on the valence orbit of the trivalent atom

The inserted trivalent atom is called an acceptor atom since each hole can accepts or captures a free electron

Introduction to semiconductors

Types of extrinsic simiconductors

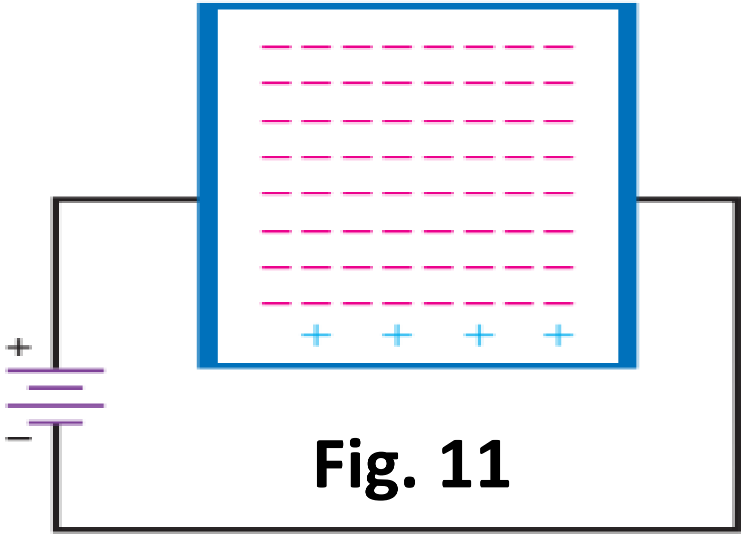


Fig. 11

N-type semiconductor: a semiconductor that has been doped with a pentavalent impurity; it has an excess of free electrons, free electrons outnumber the holes see Fig. 11

Free electrons: majority carriers

Holes: minority carriers

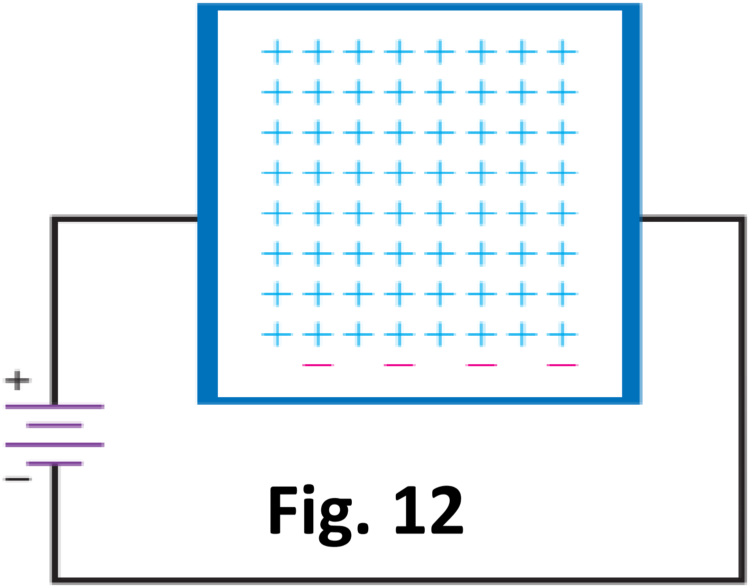


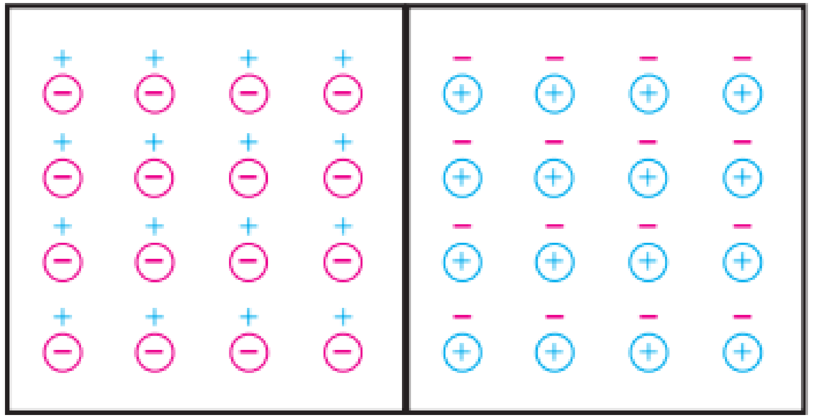
Fig. 12

P-type semiconductor: a semiconductor that has been doped with a trivalent impurity; it has an excess of holes, holes outnumber free electrons see Fig. 12

Holes: majority carriers

Electrons: minority carriers

Introduction to semiconductors



PN- junction: border between P-type and N-type semiconductors

Fig 12 left side: red circled - are trivalent atoms, blue + are holes right side: blue circled + are pentavalent atoms, red – free electrons, this PN crystal is also called a junction diode is

Fig. 13

Diffusion: free electrons in the N- side of Fig, 13 diffuse due to repulsions among them; some cross the junction, a free electron that enter the P region becomes a minority carriers, has a short lifetime as it soon recombines with a hole, hence becomes a valence electron and the hole 'disappears'

Ions pairs creation: each free electron that diffuses across the junction induces a pentavalent positively charge in N-side, it creates a negative ion in P-side as it is captured by a hole from a trivalent atom, both ions created in each side of the junction are fixe object since they cannot move like free electrons due to covalent bonding

Introduction to semiconductors

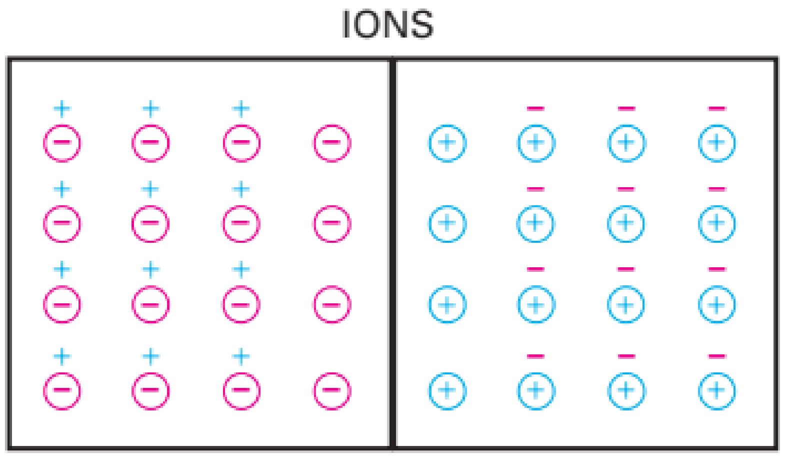


Fig. 14

Fig. 14 circled + are positive ions, circled – negative ions, Creation of ions near the junction

Dipole: a pair of positive and negation ions near the junction, the creation of a dipole means a reduction charge carriers (e-)

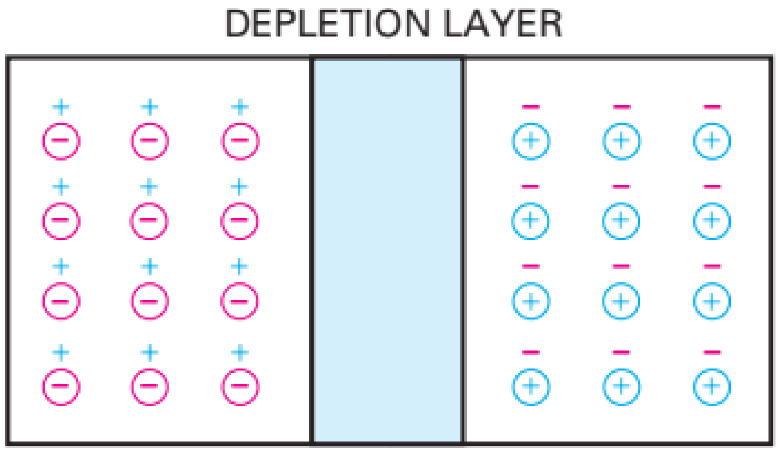


Fig. 15

Depletion layer: the number of dipoles increases, the region near the junction is emptied of charge carriers, the empty region is called depletion layer, see Fig. 15

Introduction to semiconductors

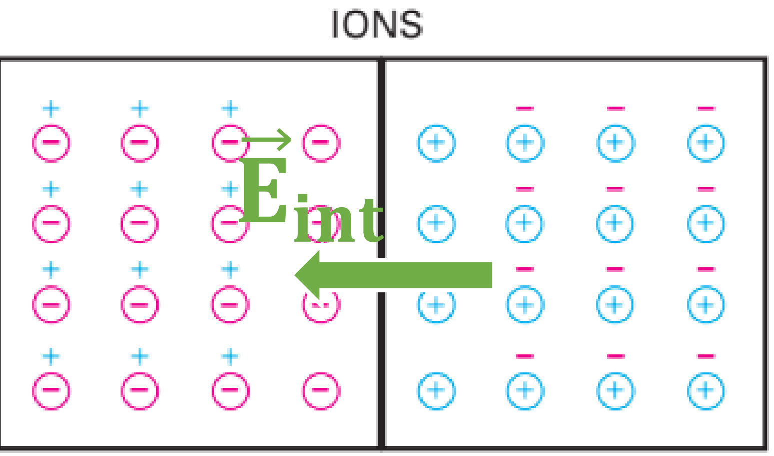


Fig. 14

Potential barrier: each dipole near the junction has an electric field the electric field near the junction is $\vec{E}_{int}$; as the number of electrons crossing the junction increase, the electric field increases too up to an equilibrium is riched; at this equilibrium, any electrons entering the depletion layer is repelled the electric field

as the number of electrons crossing the junction increases, the electric field increases too up to an equilibrium is riched; at this equilibrium, any electrons entering the depletion layer is repelled by the electric field, its electric potential, V_0, is the potential barrier

$$\vec{E}_{int} = -\overrightarrow{grad} V_0; \ V_0 \approx 0.7 \text{ V}, \text{ for a Si at } 25^0 \text{ C}$$

V_0 stops the motion of free carriers; minority carriers can cross the depletion layer; existence of a tiny electric current passing through the depletion layer due to minority carriers

Introduction to semiconductors

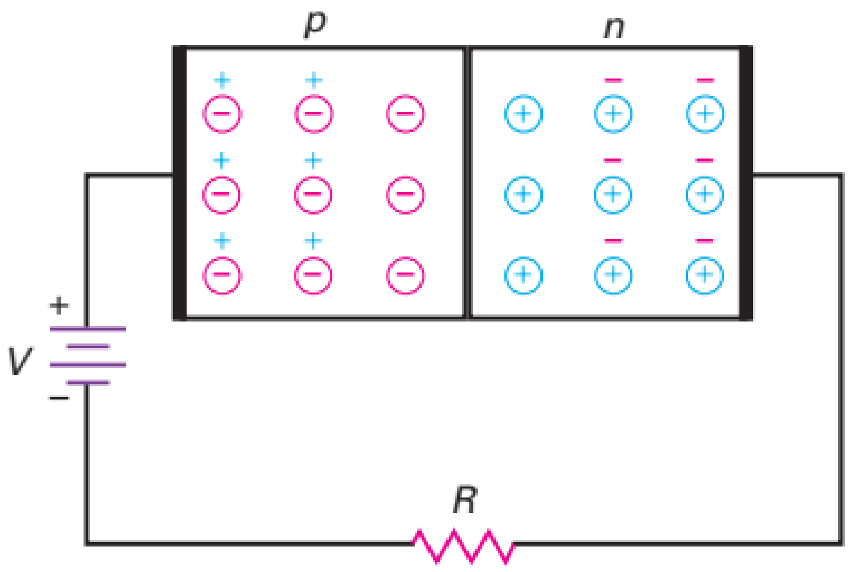


Fig. 16 forward bias diode

Forward bias diode

Positive source terminal is connected to the P-type material
Negative source terminal is connected to the N-type material

$\mathrm{V} < \mathrm{V}_0$ free electrons do not have enough energy to cross the depletion layer, they are reppelled, no current circulation

$\mathrm{V} > \mathrm{V}_0$ free electrons have enough energy to cross the depletion layer, continuous current through the diode

The width of the depletion layer reduces

$\mathrm{V} > \mathrm{V}_0 = 0.7\ \mathrm{V}$, continuous current through Si diode from P to N; this is called forward current

Introduction to semiconductors

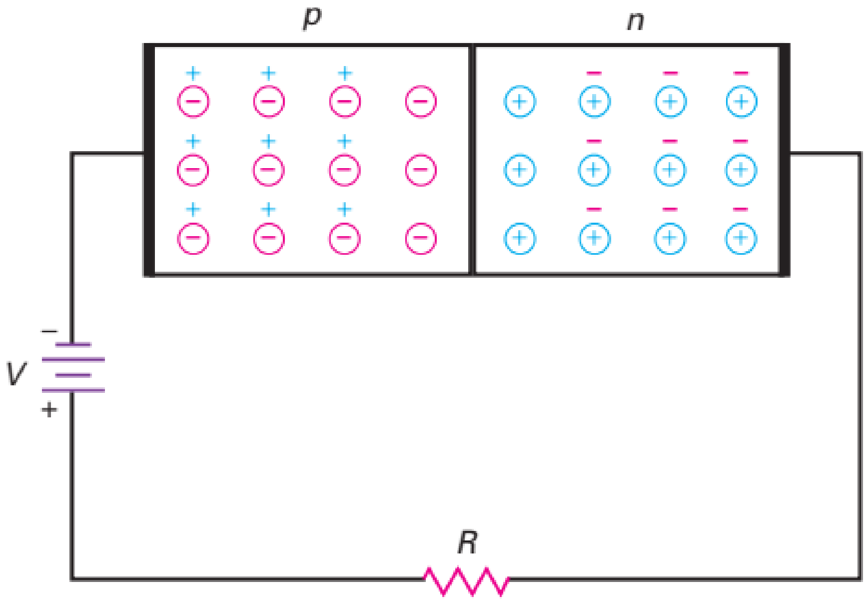


Fig. 17 reverse bias diode

Reverse bias diode

Positive source terminal is connected to the N-type material
Negative source terminal is connected to the P-type material

The depletion layer widens with encreasing applied voltage V, the depletion layer stops growing for $\mathbf{V} = \mathbf{V_0}$, electrons and holes stop moving away from the junction

There exists a current passing through the depletion layer stemming from minority carriers, this is called saturation current $\mathbf{I_S}$, $\mathbf{I_S} \approx \mathbf{0}$

Origin of $\mathbf{I_S}$: thermal energy produces free electrons and holes in the depletion layer, these minority carriers cross the depletion layer

surface-leakage current: small current flowing on the surface of the crystal due to surface impurities and imperfections of the crystal

Introduction to semiconductors

Breakdown voltage

Diodes have maximum voltage ratings, breakdown voltage is the limit voltage after which the reverse bias diode will be destroyed is the external voltage is increased

At the breakdown voltage, the diode conducts heavily as a large number of minority carriers appear in the depletion layer;

As the reverse voltage increases, the velocity of minority carriers increases too, after a collision between one minority carrier and a valence electron of an atom of the crystal, an electron might be expelled from the valence orbit to a large one and becomes a free moving carrier, now 2 moving carriers expel 2 electrons and there are 4 free carriers and so on, this the avalanche effect

Energy levels and electrical conduction

Fig. 18

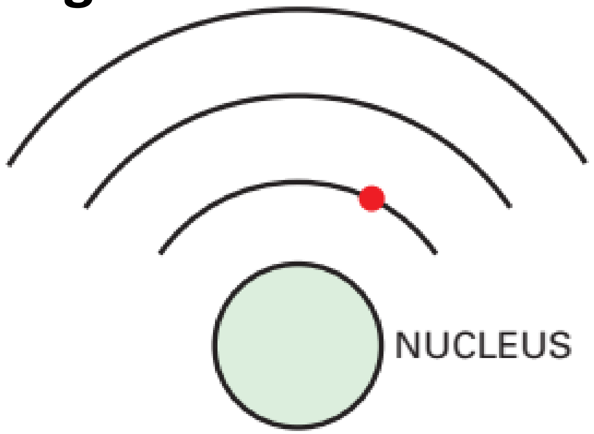
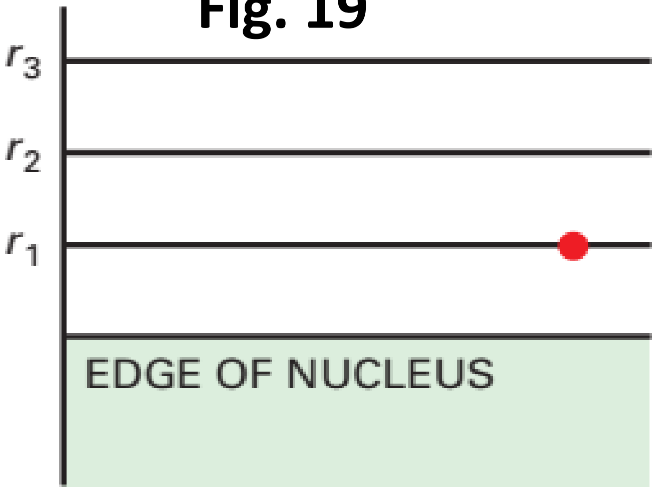


Fig. 18 In an atom, energy level of an electron is proportional to its orbit size or the radius of its orbit, electrons energy increases with increasing radiuses, the first energy level corresponds to electrons in the first orbit … only specific orbits are allowed,

Fig. 19



in order to lift an electron from its orbit (energy level) to a higher orbit (higher energy level), external energy is needed to overcome the electrostatic attraction from the nucleus, external energy that can be brought are: heat, light, voltage

Fig. 19 shows energy levels of electrons of an isolated atom; energy levels of electrons are influenced only by other charges of the atom

Introduction to semiconductors

Energy bands

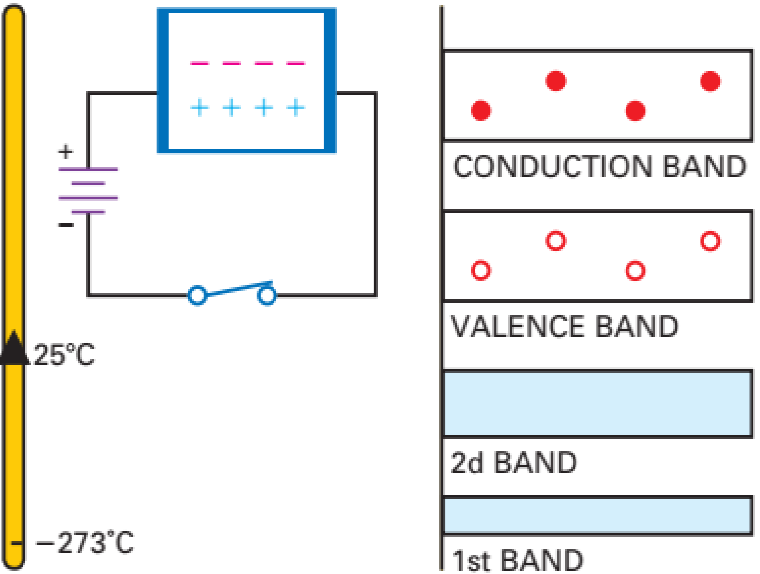


Fig. 20 energy bands of an intrinsic semiconductor

For atoms in a crystal, the energy level of each electron is influenced by the presence of the charges of that atom and also the many charges of the rest of the atoms in the crystal, each electron has a unique energy level as it is not affected in the way by other charges of the crystal

For atoms in a crystal, the energy level of each electron is influenced by the presence of the charges of that atom and also the many charges of the rest of the atoms in the crystal, each electron has a unique energy level as it is not affected in the same way by other charges of the crystal, hence each energy level is occupied by many electrons with almost the same energy, one has energy bands since there are billions of atoms in the crystal

Thermal energy produces a few free electrons and holes, free electrons move to the higher energy level, the conduction band, holes move in the valence band

Introduction to semiconductors

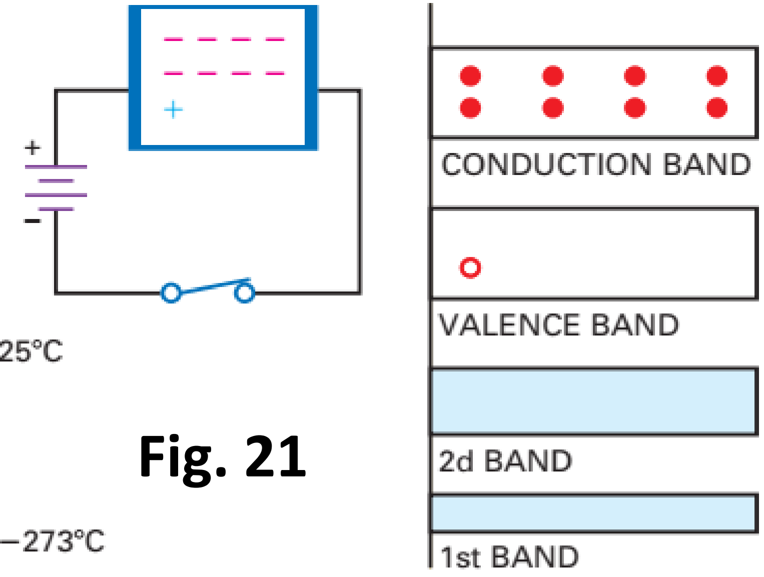


Fig. 21

Energy bands in an N-typ semiconductor

Fig. 21 There are more free electrons that occupy the conduction band, few holes in the valence band

Energy bands in a P-typ semiconductor

Fig. 22 There are more holes that occupy the conduction band, few free electrons in the valence band

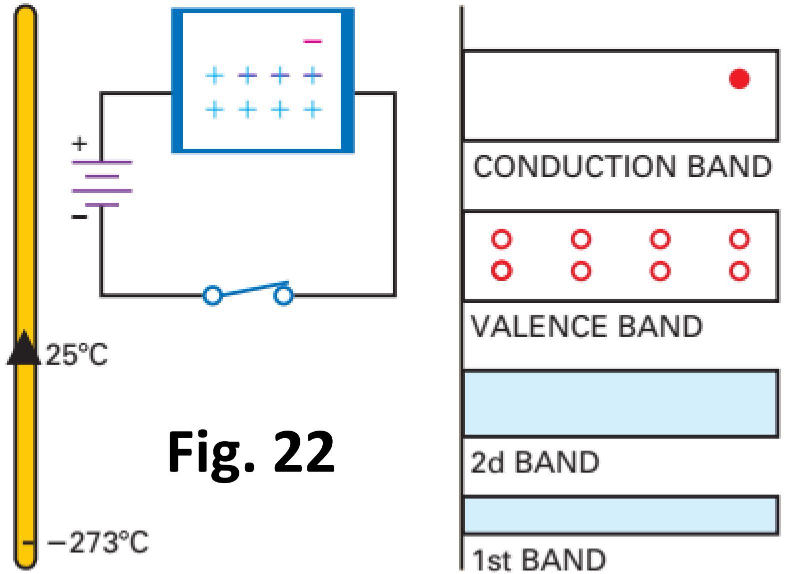


Fig. 22

Current flowing through the PN junction

Current in forward bias diode

$$I = I_S\left(e^{\frac{qV}{kT}} - 1\right) \qquad \text{Eq. (1)}$$

Current in reverse bias diode

$$I \approx 0\ A \qquad \text{Eq. (2)}$$

DIODES

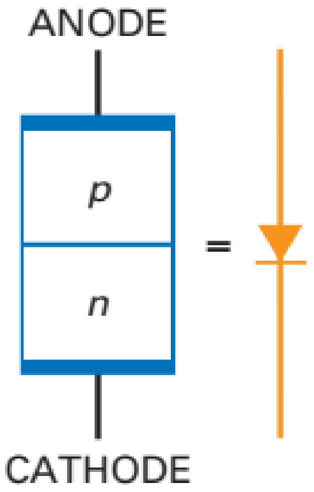


Fig. 22 Diode symbol

A diode is forward bias if the external circuit pushes the current in the direction of the diode's arrow; one might also use the Thevenin theorem to determine wether the diode is forward bias or reverse bias

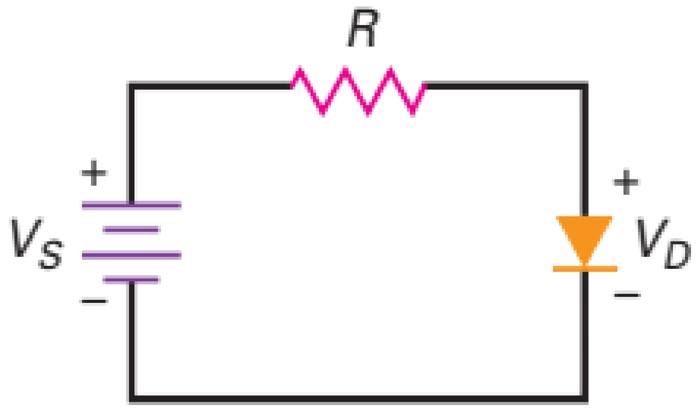


Fig. 23 diode forward bias in a circuit

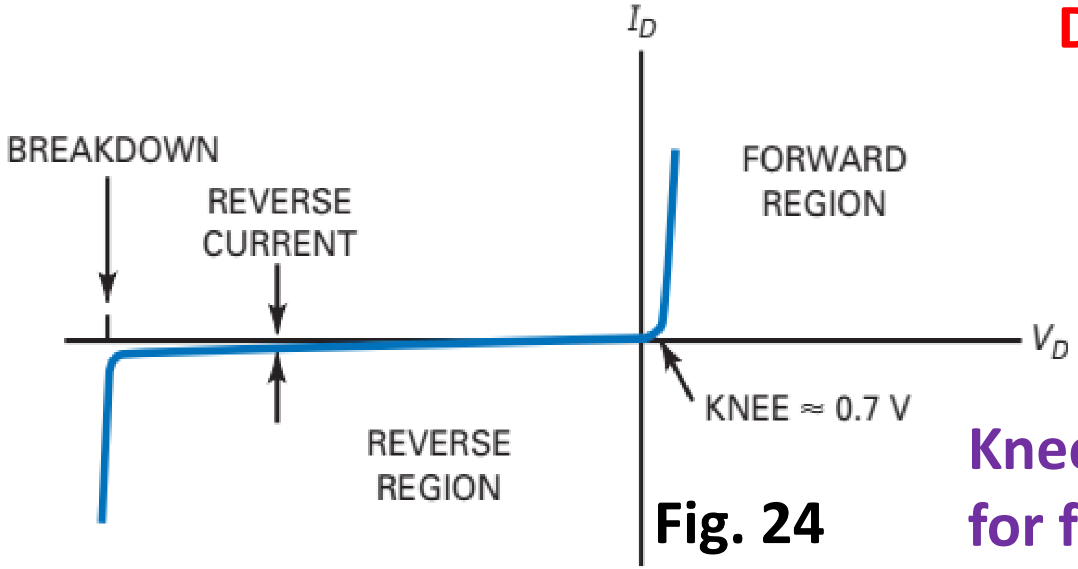


Fig. 24

Diode intensity – voltage characteristics, Fig. 24

Forward bias diode, zero current until diode's voltage becomes greater that barrier potential

reverse bias diode, zero current until diode's voltage reaches breakdown voltage, creation of large current

Knee voltage V_K voltage at which current increases fastly for forward bias diode, $V_K = V_0$

DIODES

Diode bulk resistance: sum of resistances of the P-type and N-type, $\mathrm{R_B = R_P + R_N}$

Maximum forward current: maximum current a diode can safely handle without shortening its life or degrading its characteristics

Power dissipation $P_D = V_D I_D$ **Eq. (3)**

Power rating: maximum power the diode can safely dissipate without shortening its life or degrading its properties $P_{max} = V_{max} I_{max}$ **Eq. (4)**

DIODES

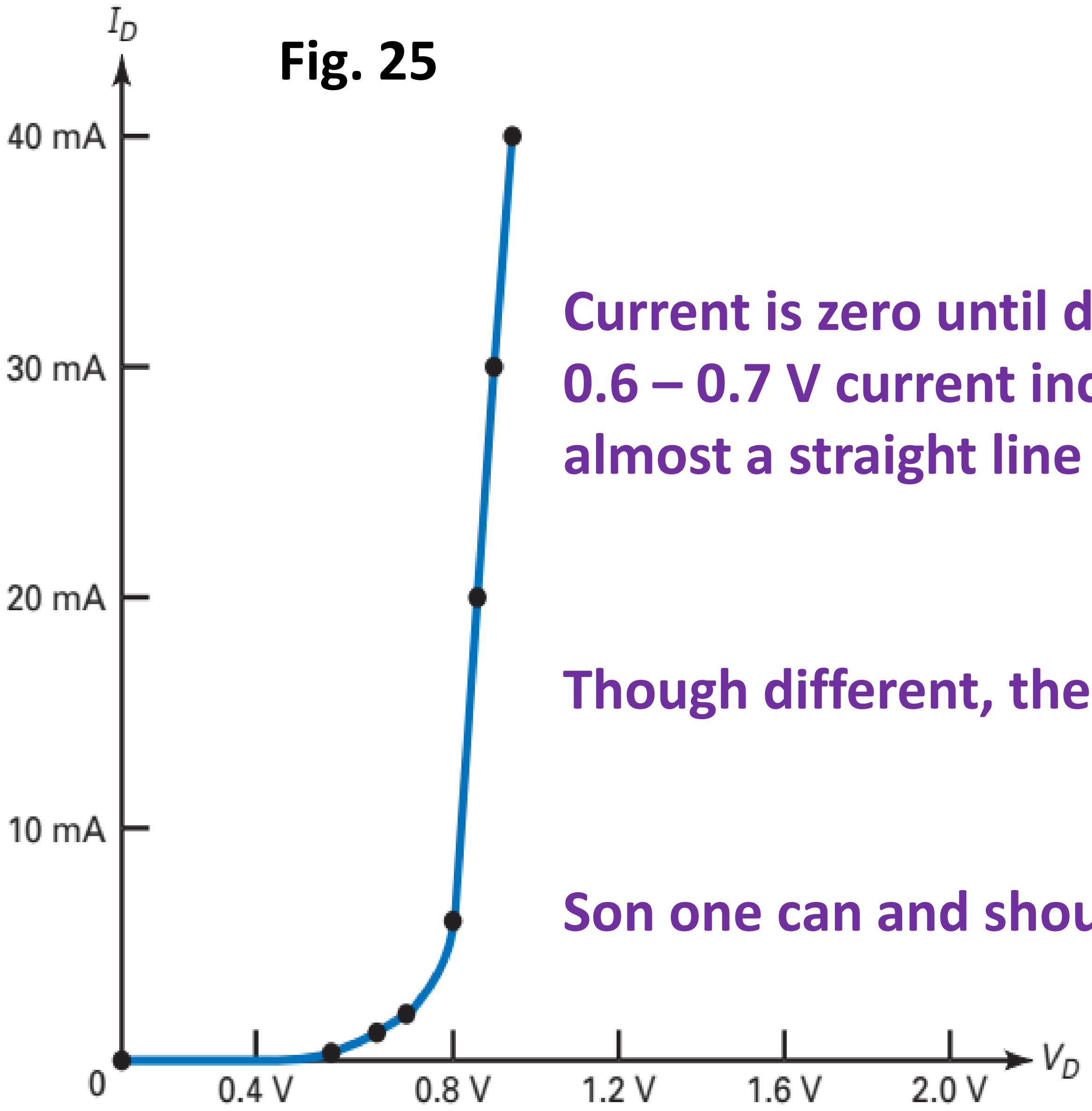


Fig. 25

Diodes approximations:

Current is zero until diode's voltage reaches the barrier potential, near 0.6 – 0.7 V current increases, after 0.8 V current increases fastly and is almost a straight line

Though different, the graph of all diodes are similar to that of Fig. 25

Son one can and should approximations for a diode

DIODES: approximations

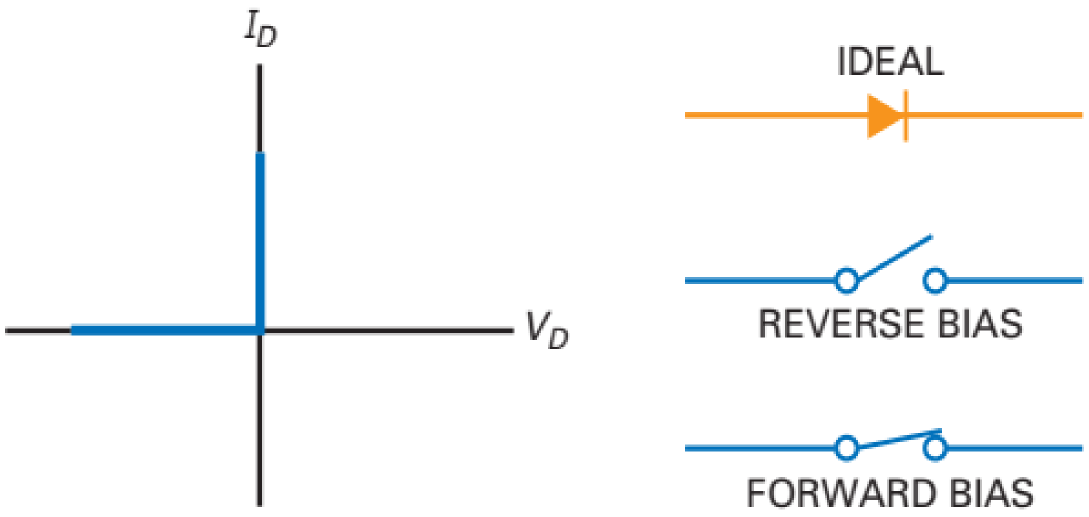


Fig. 26 ideal case, 1st approximation

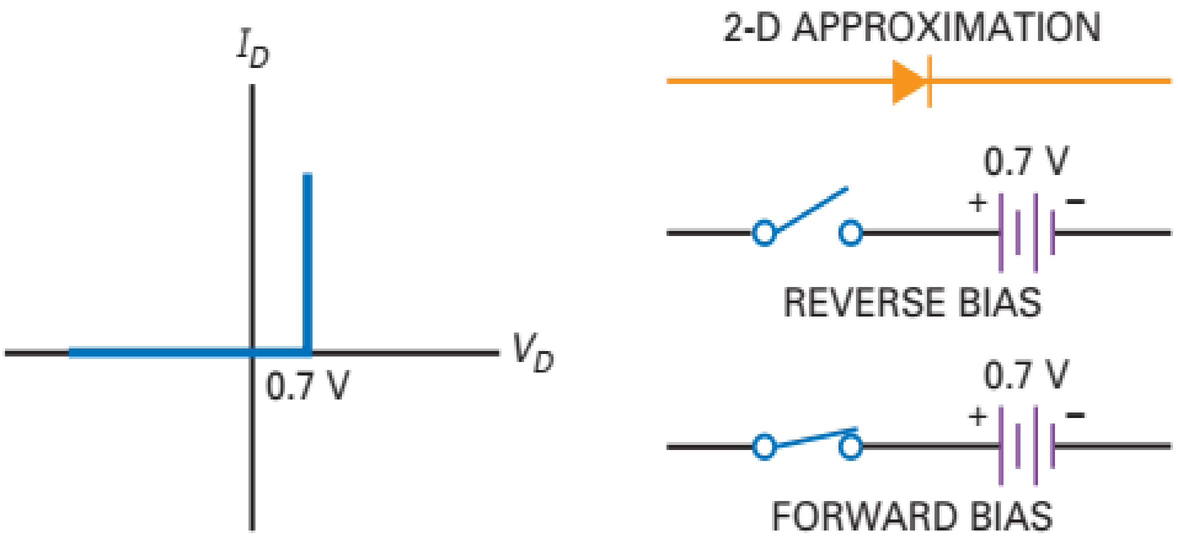


Fig. 27 2nd approximation

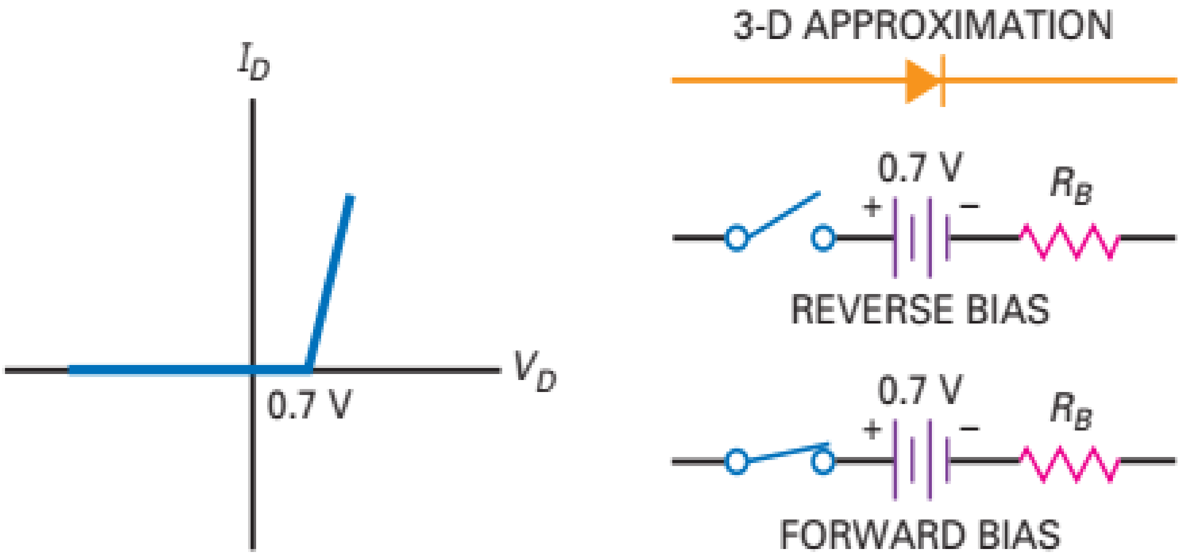


Fig. 28 3rd approximation

DIODES: approximations

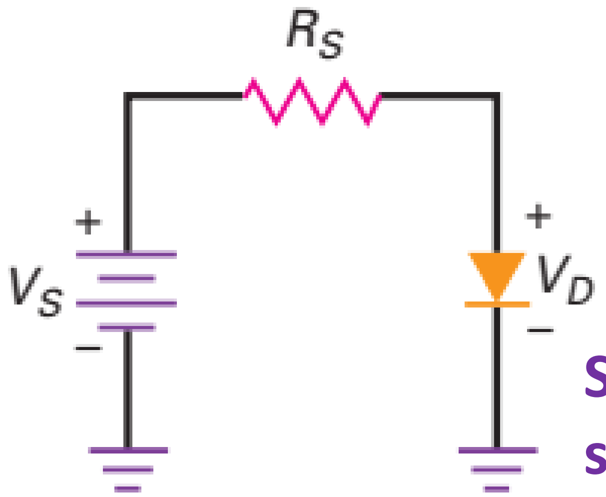


Fig. 29

Load line analysis

Current through the diode $I_D = \dfrac{V_S - V_D}{R_s}$ **Eq. (5)**

Saturation point: maximum current corresponding to source voltage V_S and load R_S, $V_D = 0$ $I_D = V_S/R_S$ **Eq. (6)**

Cutoff point: minimum diode current $I_D = 0$ $V_D = V_S$ **Eq. (7)**

Load line: geometric representation of Eq.(5)

Operating point or Q point: intersection between the load line and diode curve; it works both for the circuit and the diode

Load line analysis

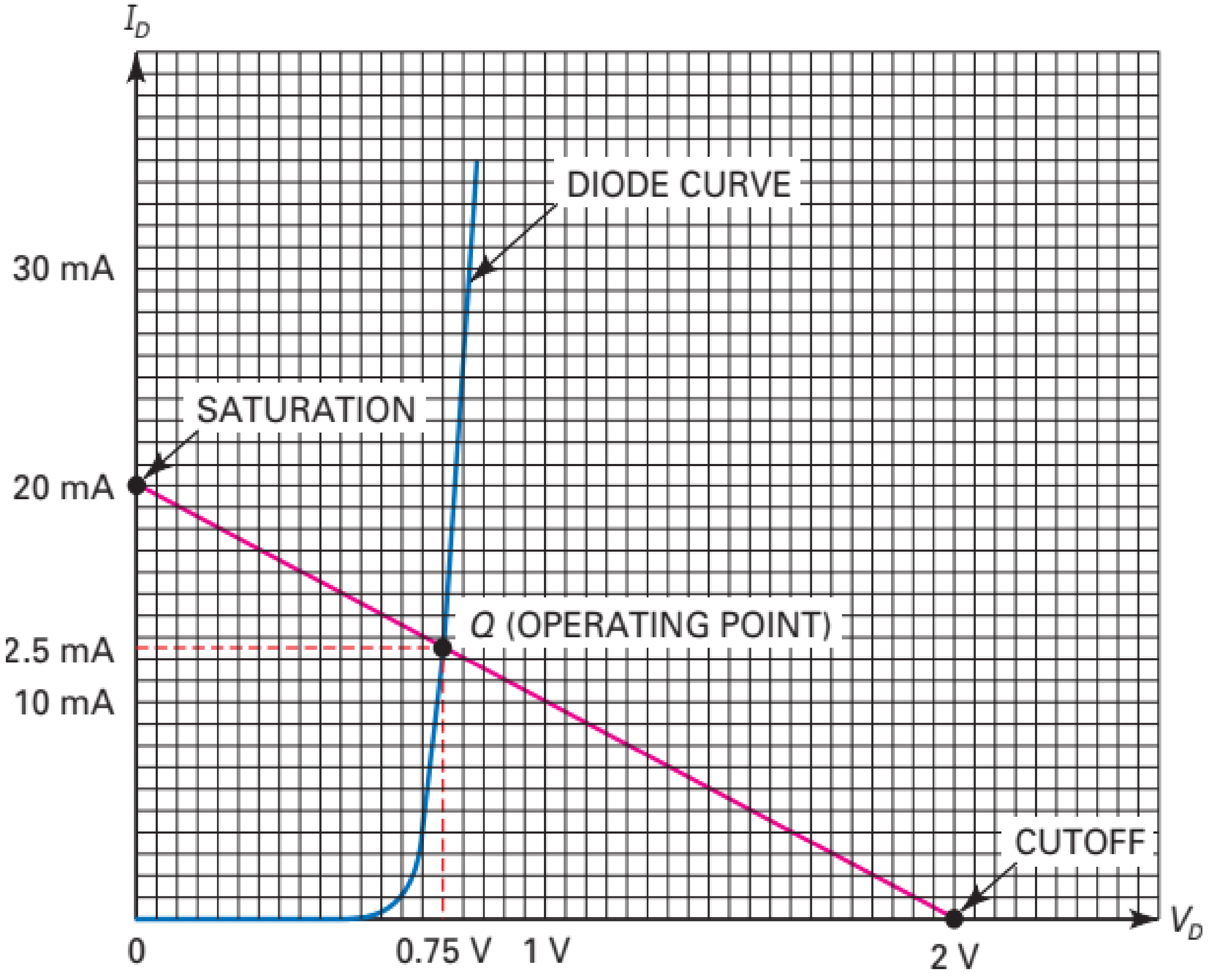


Fig. 30

Diode applications: half-wave rectifier

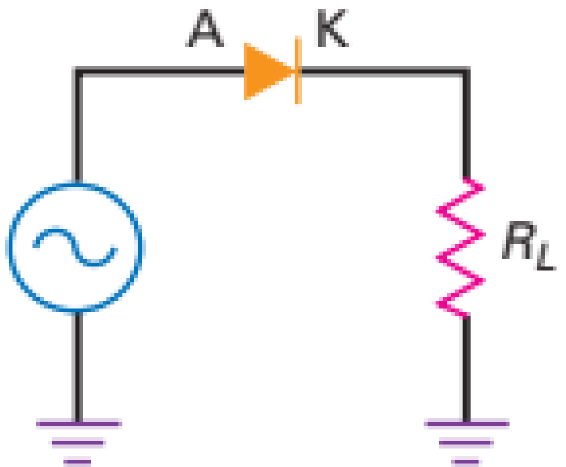


Fig. 31 half-wave rectifier circuit

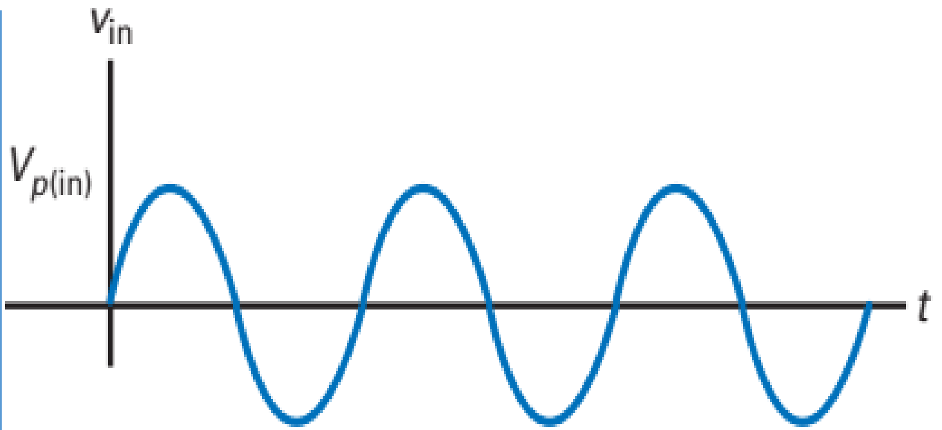
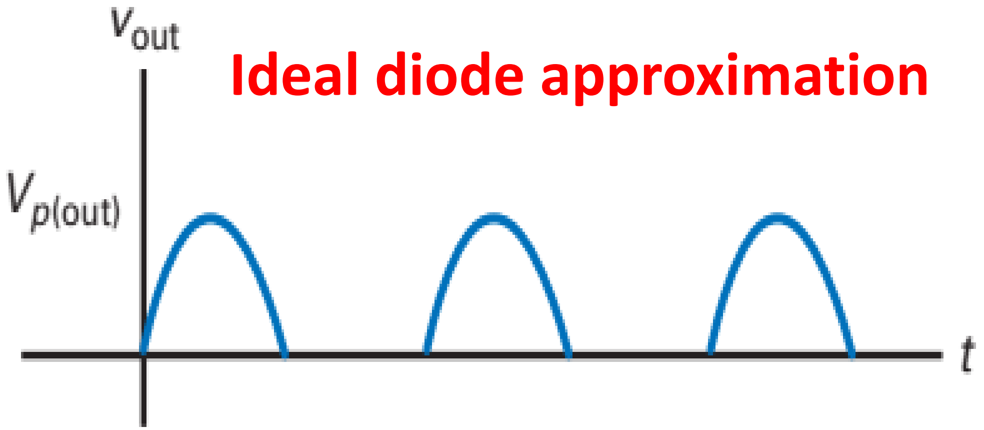


Fig. 32 sinusoidal source voltage V_{in}, $V_{\text{P(in)}}$ maximum amplitude of V_{in}



Ideal diode approximation

Fig. 33 output load voltage V_{out}, $V_{\text{P(out)}}$ maximum amplitude of V_{out}

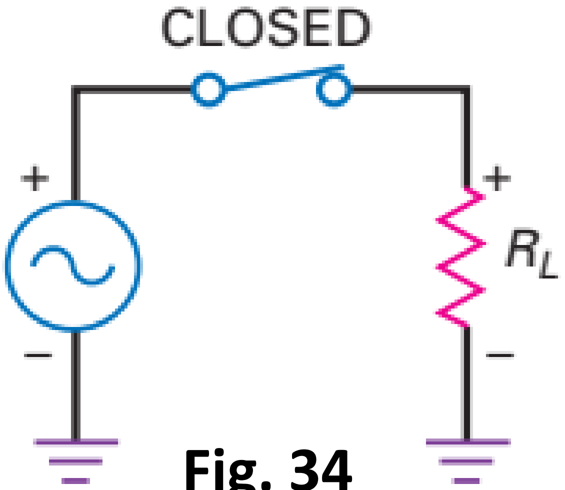


Fig. 34

positive input cycles, diode is forward bias, 1st approximation

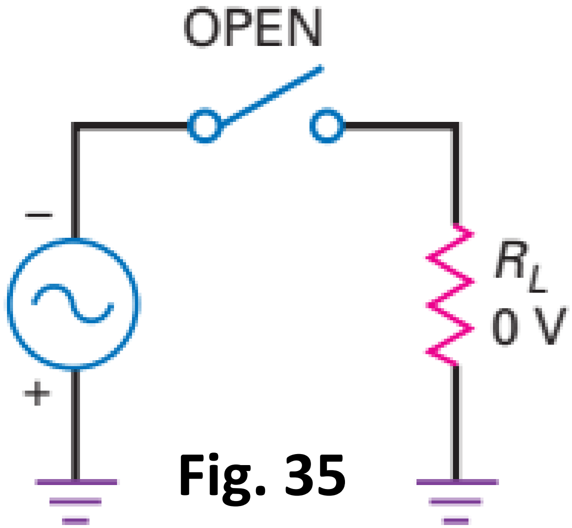


Fig. 35

negative input cycles, diode is reverse bias, 1st approximation

Diode applications: full-wave rectifier

Fig. 36 full-wave rectifier circuit

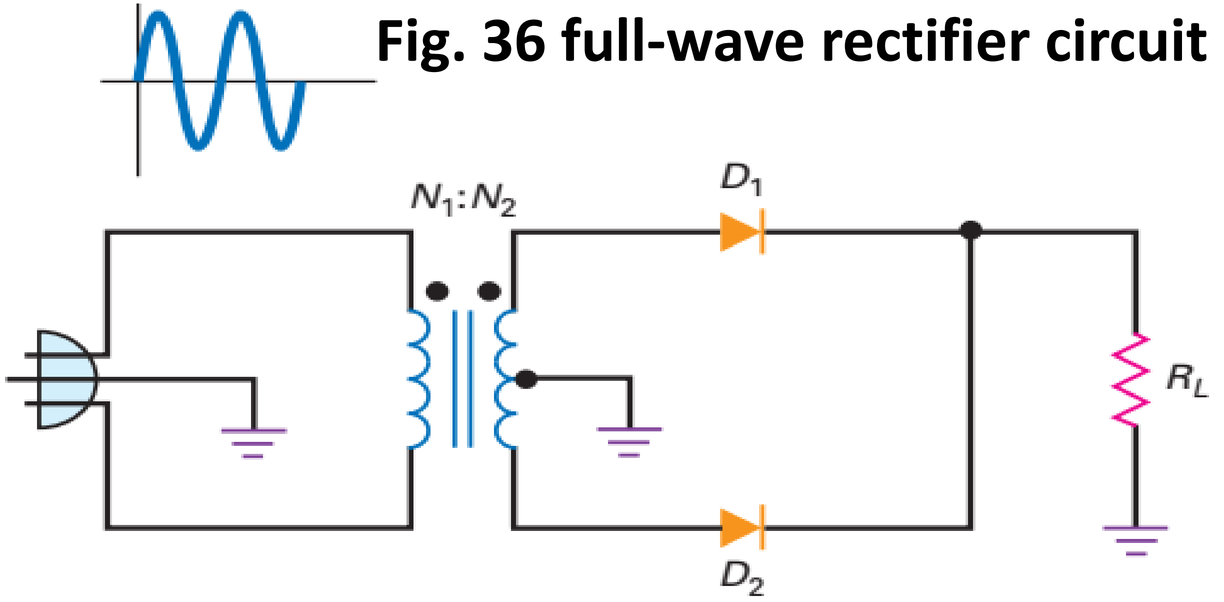


Fig. 37 source voltage positive cycles

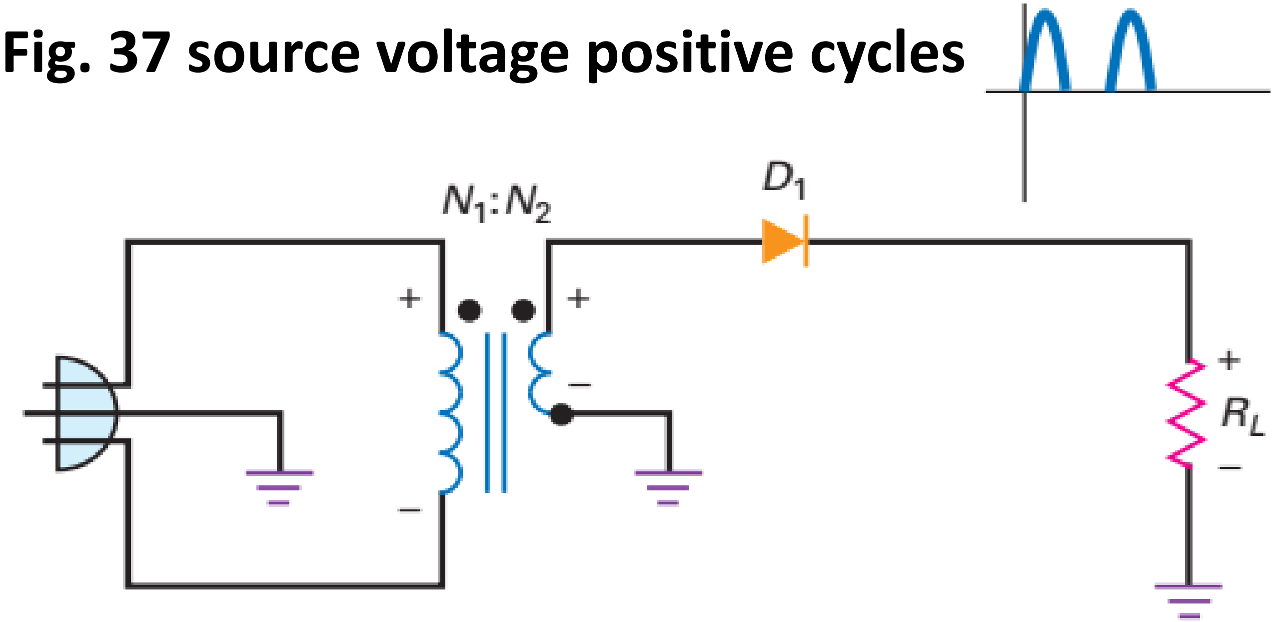
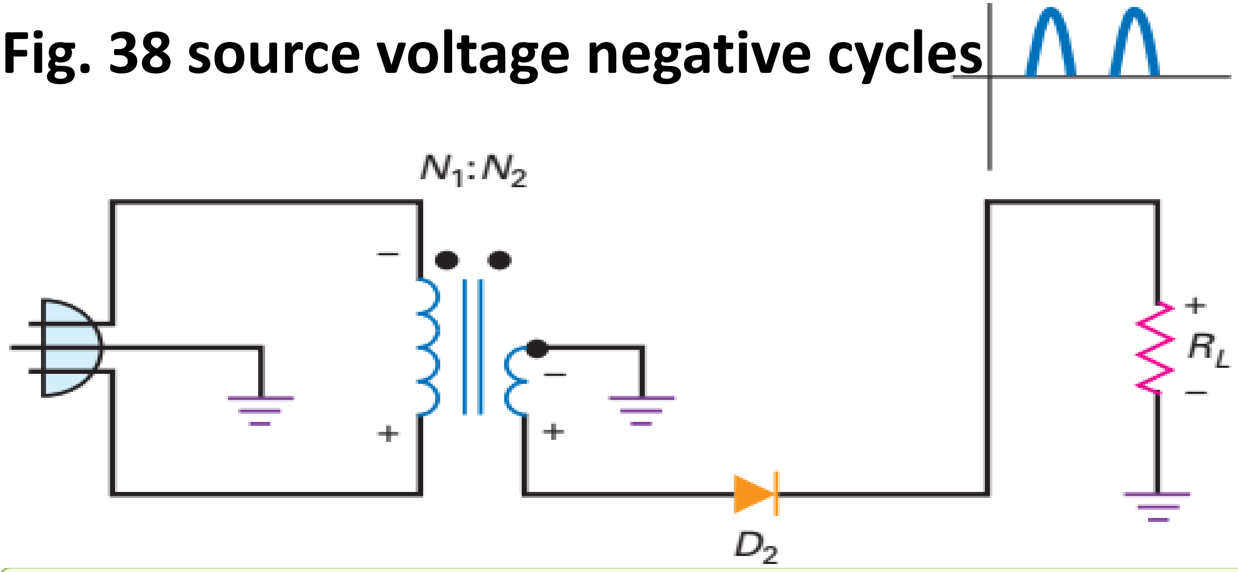


Fig. 38 source voltage negative cycles



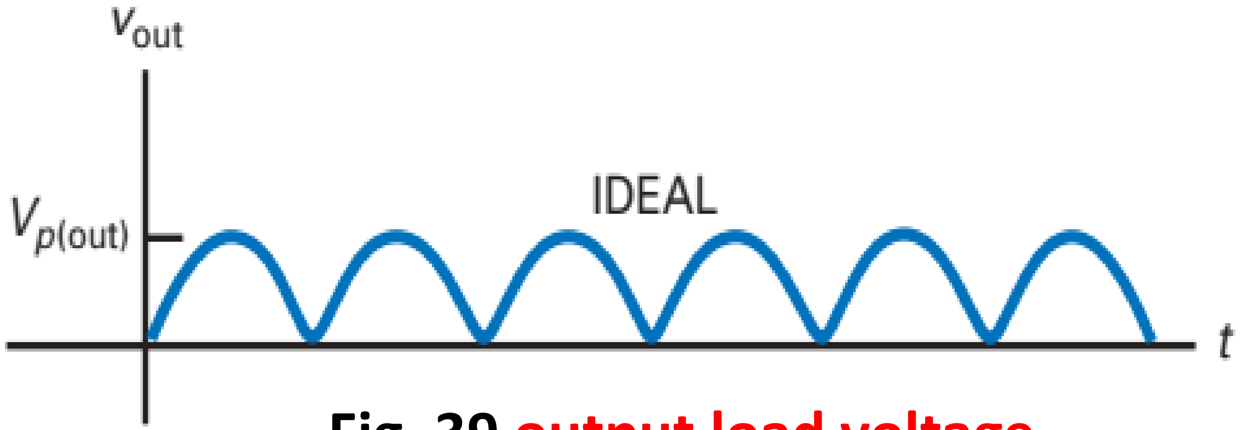


Fig. 39 output load voltage

Diode applications: zener diode

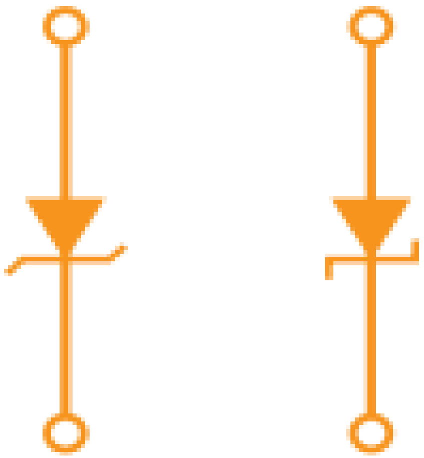
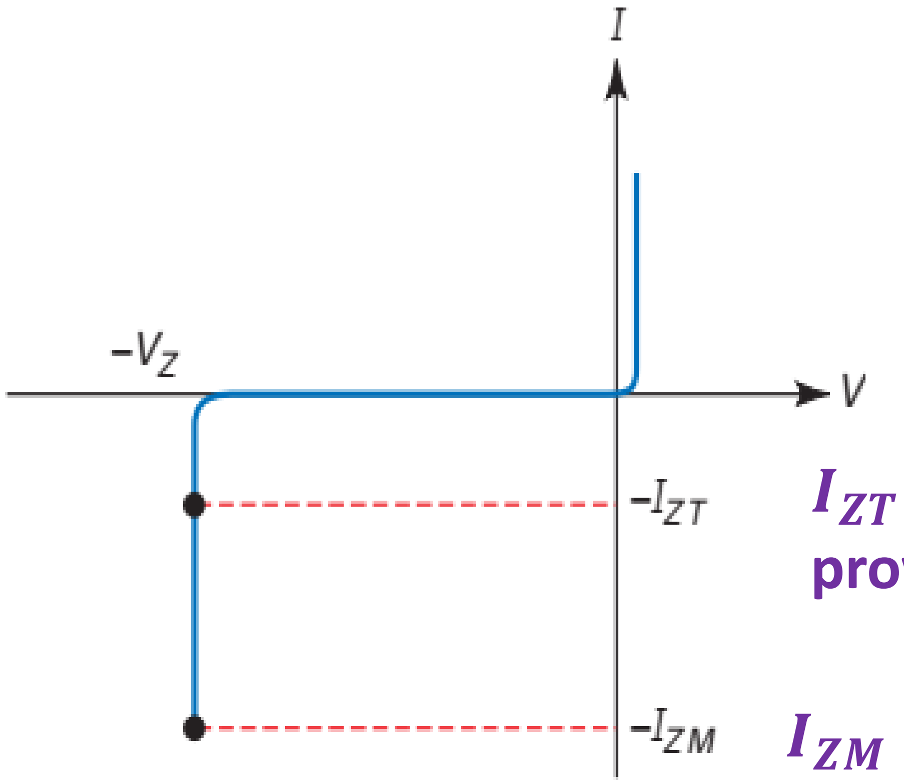


Fig. 40 Zener diode symbols



I_{ZT} test current at a special V_Z provided by the manufacturer

I_{ZM} maximum reverse current

Fig. 41 Zener diode current to voltage curve

Zener resistance: inverse of slope in the breakdown region, resistance in the breakdown region

Diode applications: zener diode

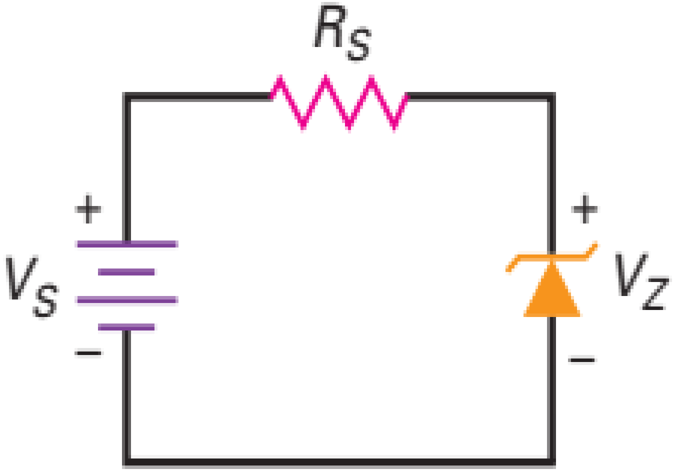


Fig. 43 Zener diode reverse bias

R_S: series resistance to limit reverse current though diode, hence avoids diode damaging current, zener diode usually used reverse bias like in Fig. 43

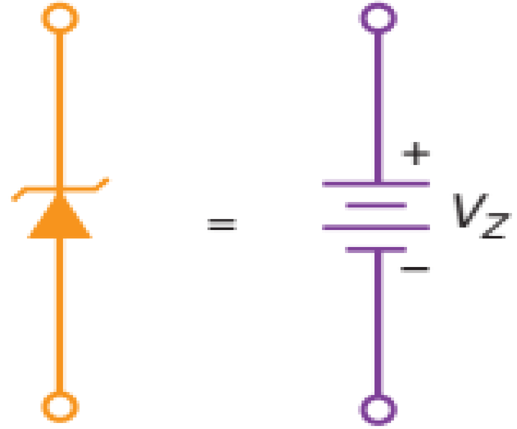


Fig. 44 ideal Zener diode

Zener effect: creation of a large number of free electrons by removing them from their valence orbit due to an intense electric field

Zener effect appears in the breakdown region of a Zener diode, the reverse current becomes very high