Semiconductors

Conductivity of materials

Conductivity is proportional to the concentration n of free electrons

A good conductor: $n \approx 10^{28}$ electrons / m^3

An insulator: $n \approx 10^{7}$ electrons / m^3

semiconductors are materials which have a conductivity between conductors and nonconductors or insulators

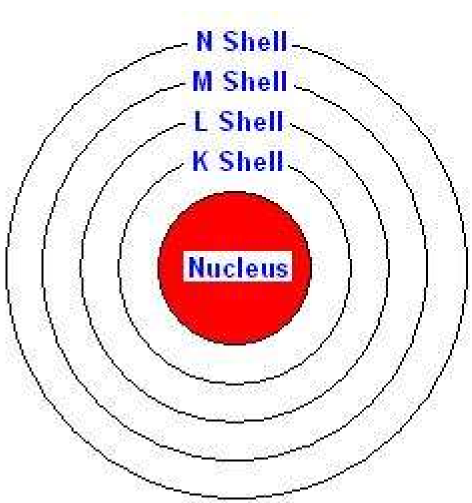
Semiconductors are made from pure elements, typically silicon or geranium, or compounds such as gallium arsenide.

Conductivity is caused by movement of free electrons

Electrons are moving around the nucleus in different shells

Shells are divided in subshells

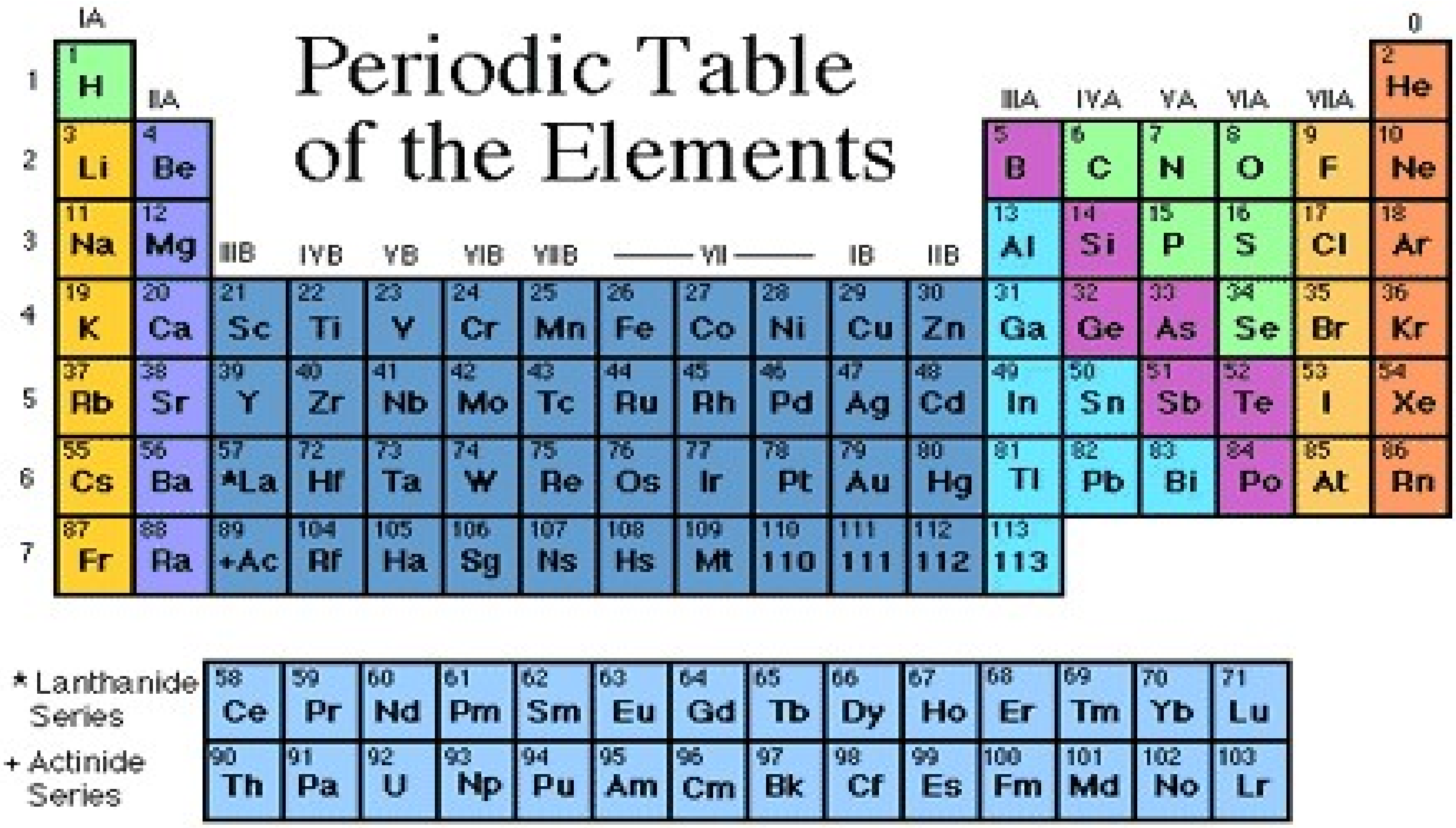
The maximum no of electrons that in be present in a shell or subshell is fixed



Electron shell and subshells

shell	K	L		M			N			
n	1	2		3			4			
l	0	0	1	0	1	2	0	1	2	3
subshell	s	s	p	s	p	d	s	p	d	f
No of Electrons	2	2	6	2	6	10	2	6	10	14
	2	8		18			32			

Who are semiconductors?



Availability of free electrons is dependent on the element

Electronic configuration in Group IV A

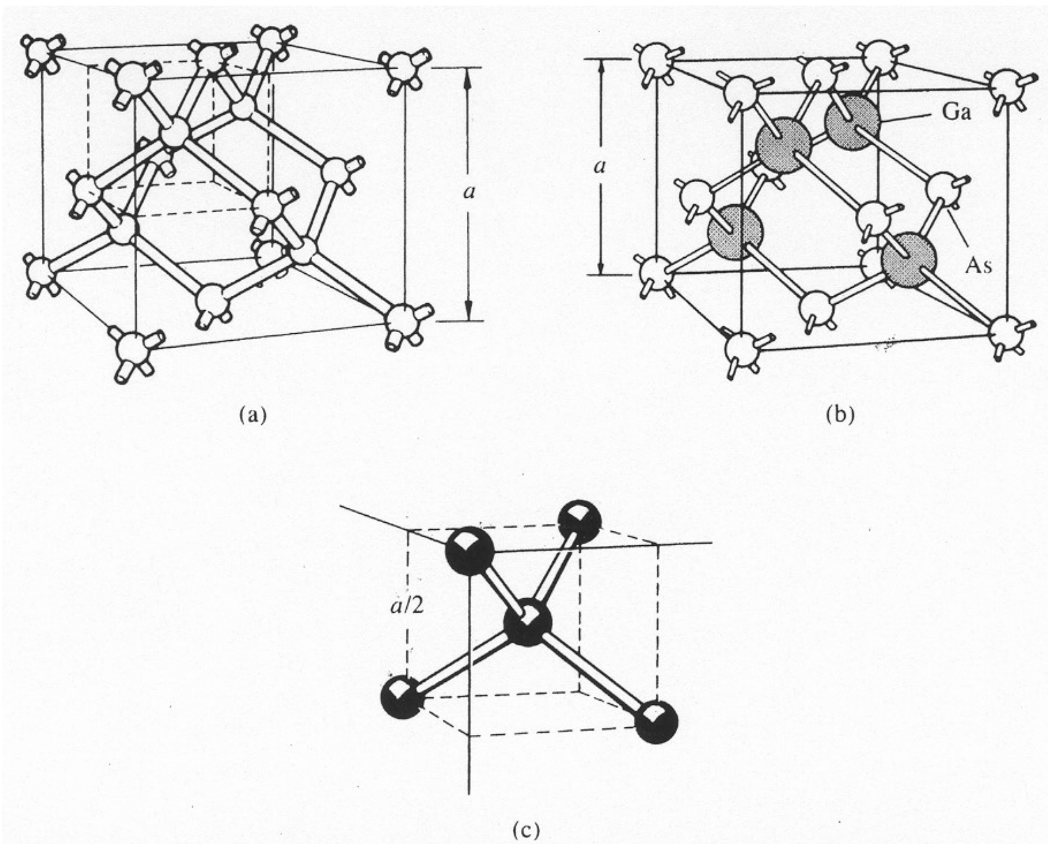
Element	Atomic number	Configuration
C	6	$1s^2\ 2s^2\ 2p^2$
Si	14	$1s^2\ 2s^2\ 2p^6 3s^2\ 3p^2$
Ge	32	$1s^2\ 2s^2\ 2p^6 3s^2\ 3p^6 3d^{10} 4s^2\ 4\ p^2$
Sn	50	$1s^2\ 2s^2\ 2p^6 3s^2\ 3p^6 3d^{10} 4s^2\ 4\ p^6 4d^{10} 5s^2\ 5p^2$

C, Si, Ge, Sn are in same Group IV A in periodic table

Each has completely filled subshells except for outermost p subshell having only two of six possible electrons

C in crystalline form: an insulator
Si, Ge: semiconductors
Sn: metal

Most metals and semiconductors are crystalline in structure



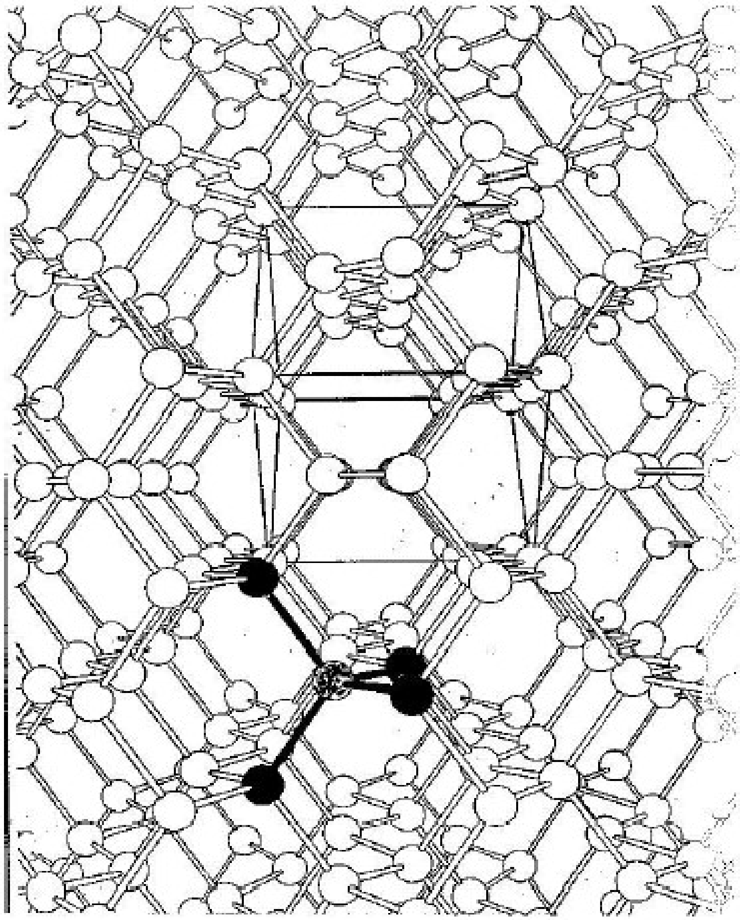
Diamond Lattice

- Tetrahedral structure
- 4 nearest neighbors

A crystal consists of a space array of atoms built up by regular repetition in three dimensions of some fundamental structural unit

The characteristics at any point is the result of contributions from every atom

The Crystal Structure



A crystal consists of a space array of atoms built up by regular repetition in three dimensions of some fundamental structural unit

The characteristics at any point is the result of contributions from every atom

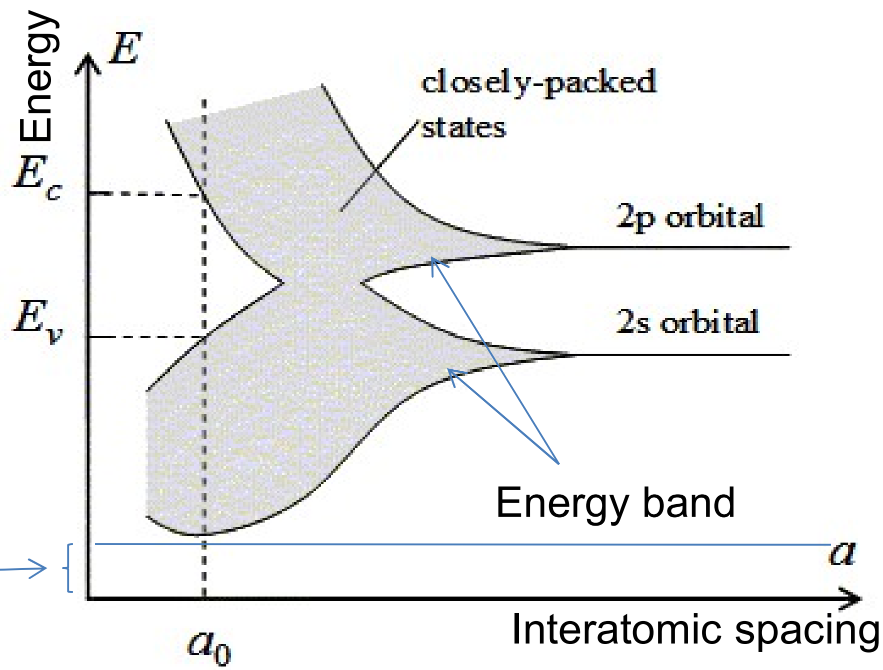
Most metals and semiconductors are crystalline in structure

The energy levels of inner shell electrons are not affected appreciably by the presence of neighboring atoms

The levels of the outer shell electrons are changed considerably, since they are shared by more than one atom in the crystal

Energy Band Theory of Crystals

Imagine that the spacing between atoms may vary



Inner shell atomic energy levels unaffected by crystal formation

If atoms are far away, interaction between them is negligible, energy levels coincide with those of isolated atom

If interatomic spacing decreases,

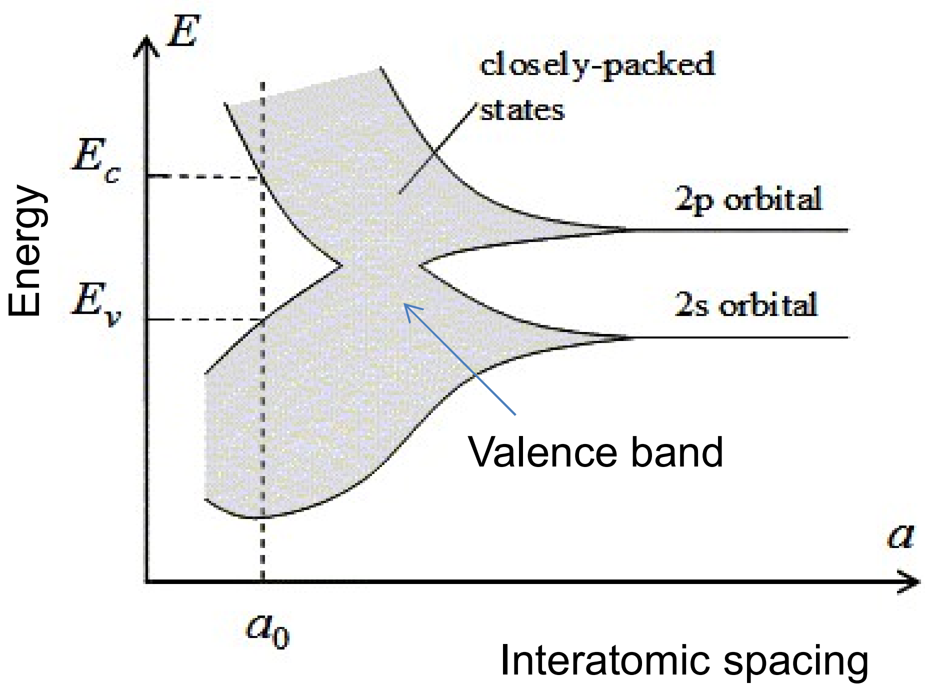
(i) An atom will exert an electric force on its neighbors.

(ii) The crystal becomes an electronic system (follow Pauli exclusion principle)

(iii) s and p states spread out in energy

As no of atoms per cm^3 is very large ($\sim 10^{23}$), the total spread between minimum and maximum energy may be several electron volts (energy band)

Energy Band Theory of Crystals



For small enough distance

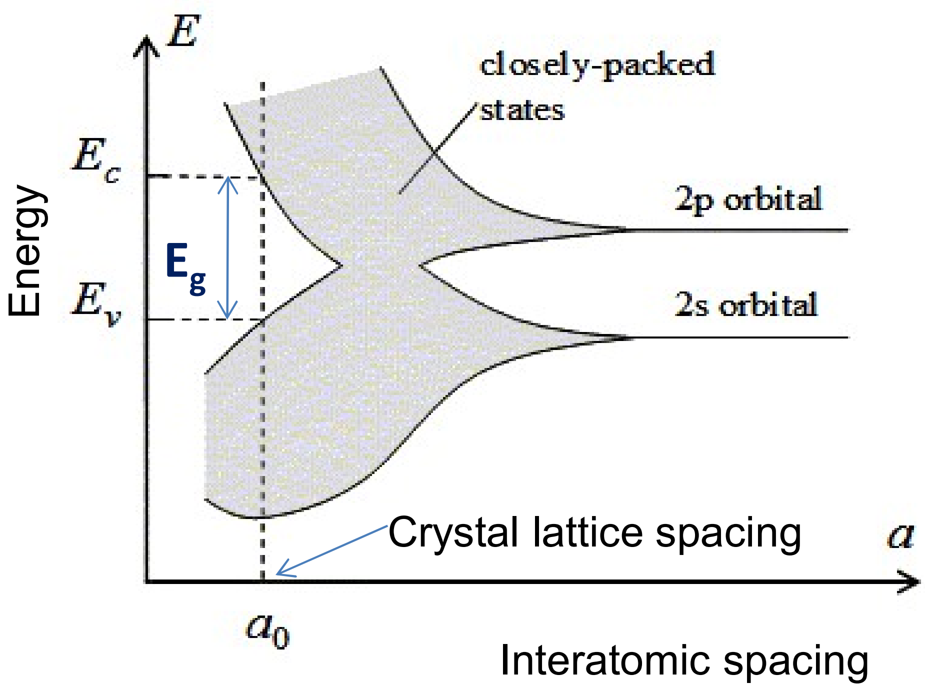
(i) the bands overlap

(ii) each atom gives up 4 electrons;

These electrons can no longer be in s or p subshell, they belong to the crystal as a whole

The band these electrons occupy is called as valence band

Energy Band Theory of Crystals



If interatomic spacing decreases further, say below the distance at which the bands overlap, the interaction between atoms become very large

The energy band structure becomes dependent upon

(i) orientation of the atoms relative to another in space (crystal structure)

(ii) atomic number

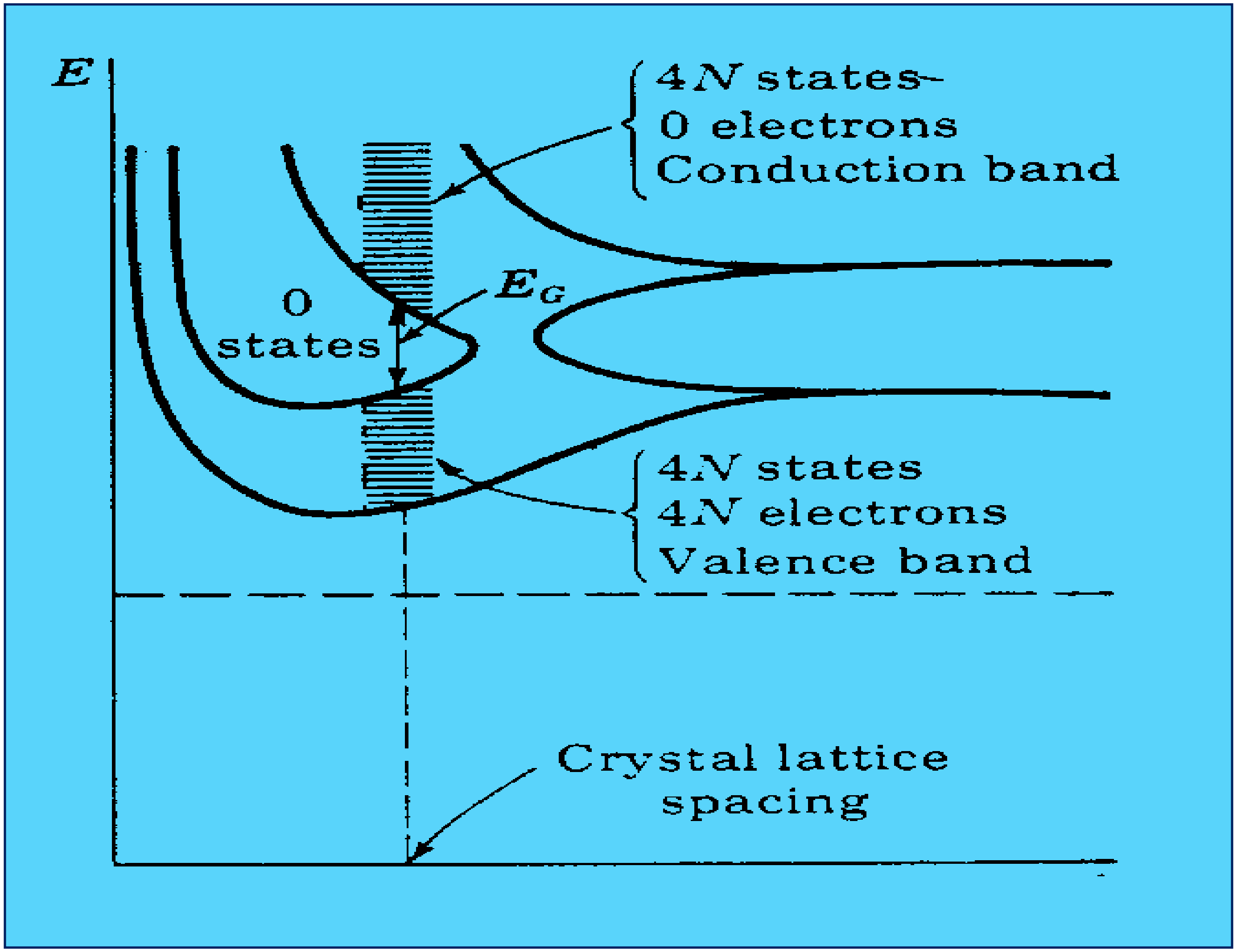
Behavior follows Schrodinger's equation

At the crystal lattice spacing a_0, valence band is filled with 4 electrons separated by a forbidden band (no allowed energy state) of extent E_g from an empty band

The upper vacant band is called conduction band

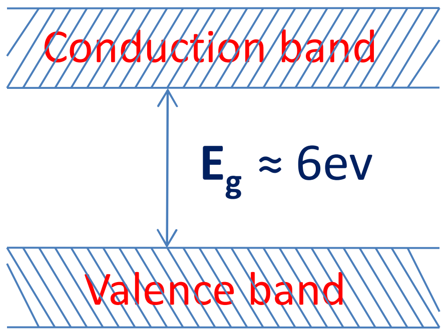
Energy Bands in Semiconductors

- **Let there be N atoms in the crystal**



- The space between the bands is the energy gap, or forbidden band

Energy Band Structure

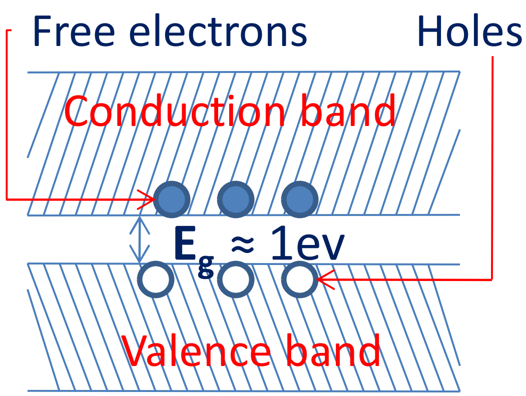


Insulator

The large forbidden band

For diamond (carbon) crystal, $E_g \approx 6ev$

The energy that can be supplied to an electron is too small to carry it to conduction band from the filled into valance band



Semiconductor

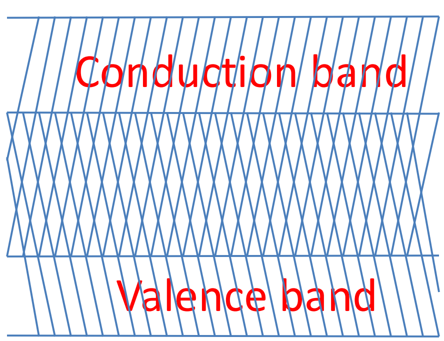
The small forbidden band. Behaves like insulator at low temperature

$E_g = 0.72$ (1.21) ev for Ge (Si) at room temperature

Energies of this magnitude cannot be supplied by an electric field

If the temperature increases, some elctrons from valence band jump into the empty conduction band to become free electrons

The absence of an electron in valence band creats a hole



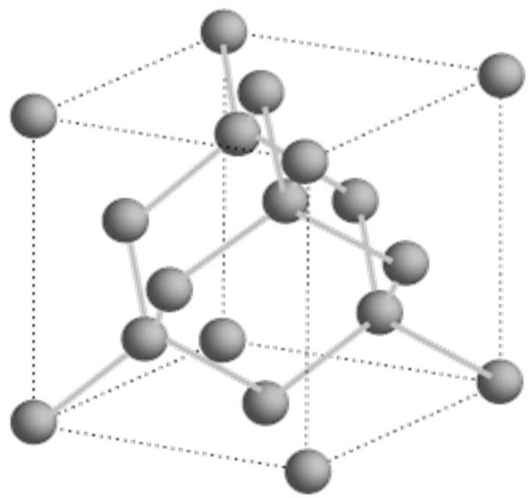
Metal

No forbidden band.

Valence band merges into empty band

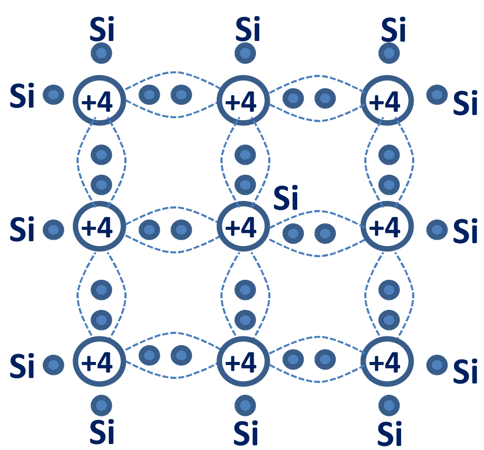
Under influence of an electric field the elctrons acquire additional energy and move into higher energy states to constitute a current

Electrons and holes in semiconductor



Crystal structure of semiconductor consists of a space array of atoms built up by regular repetition in three dimensions of a unit cell having the form of an tetrahedron

For ease of understanding, let the crystal structure of semiconductor is symbolically illustrated in two dimensions



The inert core of Si atom carries a positive charge of + 4

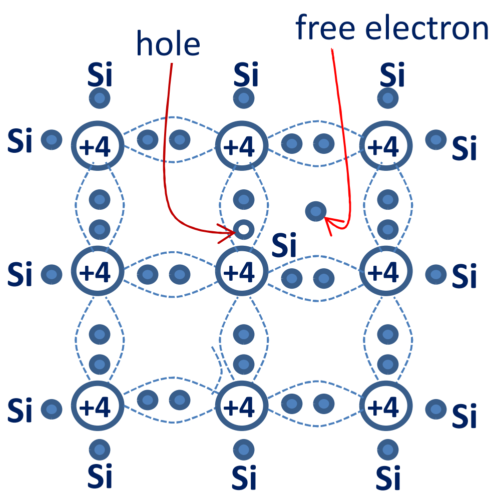
Each of the valence electron of a Si atom is shared by one of its nearest neighbours

This electron pair forms covalent bond

Valence becomes tightly bound to nucleus

At low temperature (say 0^0 K), the crystal becomes an insulator

Electrons and holes in semiconductor



At room temperature, some of the covalent bonds will be broken

Some electrons may be dislodged to become free to wander in random fashion throughout the crystal

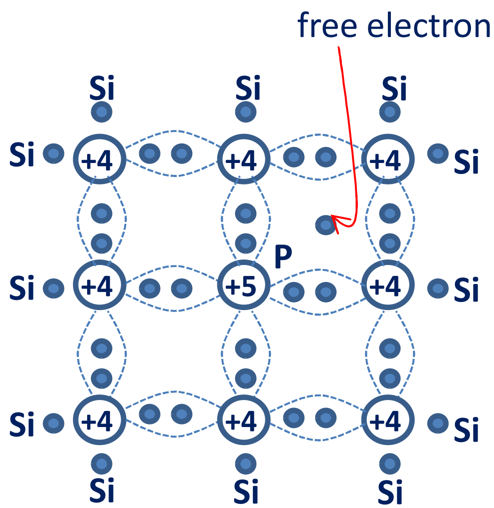
Absence of electron in covalent bond is called a hole

When a hole exists, a valence electron in neighboring atom may leave its covalent bond to fill this hole – thus the hole moves

This hole in new position may now be filled by an electron from another covalent bond, causing further movement of hole

Conduction of electricity is possible without involving free electrons

Donor impurity in semiconductor



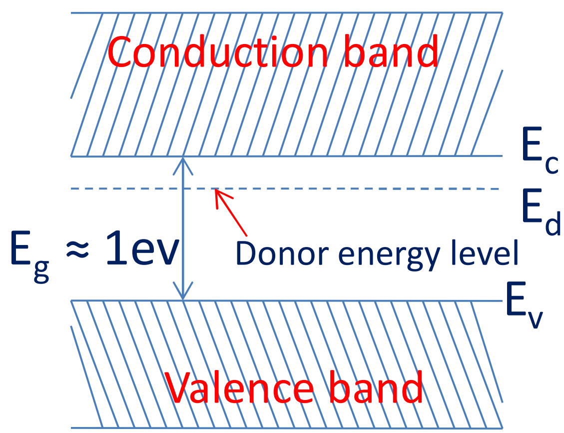
A small amount of impurity with 5 valence electrons is added

Four of five valence electrons occupy covalent bonds, the fifth is unbound and becomes free

The type of impurity is donor, as it donates electrons

It is called n-type semiconductor

Suitable pentavalent impurites: P, Sb, As



n-type Semiconductor

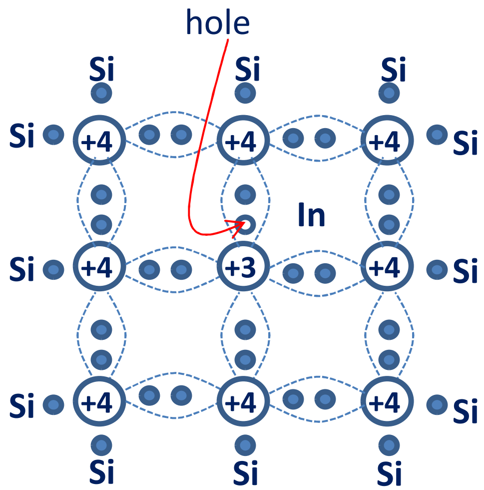
Allowable energy levels are introduced a very small distance [(0.01 {0.05} ev for Ge {Si}),] below conduction band

This new allowable level is discrete, as added impurity atoms are far apart in crystal structure, their interaction is small

Energy required to detach this fifth electron from atom to raise it in conduction band is only 0.01 {0.05} ev for Ge {Si},

The presence of large no of electrons increases rate of recombination of holes and electrons, thus decreases the no of holes below that is available in intrinsic semiconductor

Acceptor impurity in semiconductor



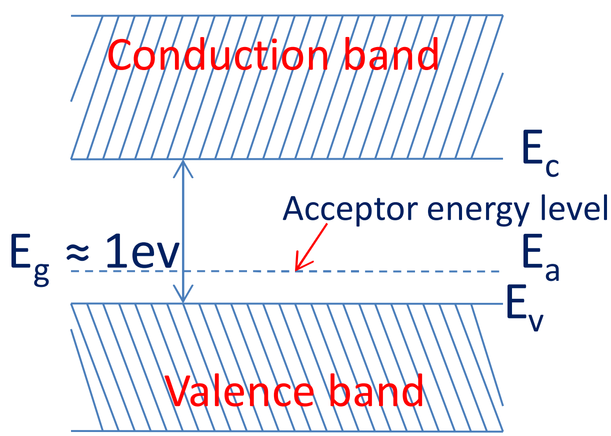
A small amount of impurity with 3 valence electrons is added

Three valence electrons fill three covalent bonds, a vacancy exists in 4^{th} bond, creating a hole that can accept electron

The type of impurity is acceptor, as it accepts electrons

It is called p-type semiconductor

Suitable trivalent impurites: B, Ga, In



p-type Semiconductor

Allowable energy levels are introduced which is just above valence band

This new allowable level is discrete, as added impurity atoms are far apart in crystal structure, their interaction is small

Very small amount of energy is required for an electron to leave valence band and occupy acceptor energy level

The presence of large no of holes increases rate of recombination of holes and electrons, thus decreases the no of electrons below that is available in intrinsic semiconductor

Result of doping in semiconductor

Increases conductivity

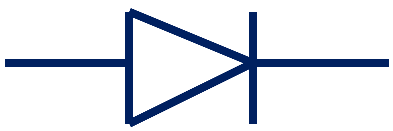
Produces conductors in which electric carriers are either predominantly holes or predominantly electrons

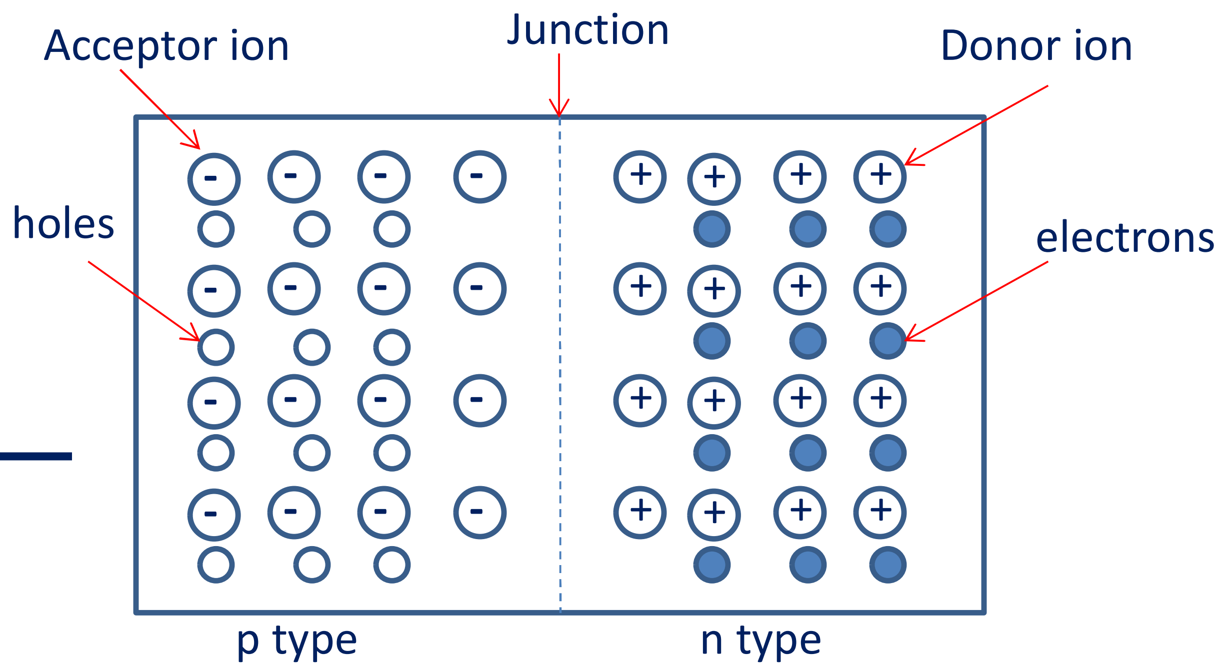
In n-type semiconductor, majority carrier is electrons and minority carrier is holes

In p-type semiconductor, majority carrier is holes and minority carrier is electrons

By combining n-type and p-type semiconductors materials that conduct only under certain conditions can be created

Semiconductor Diode





Donor and acceptor impurities are introduced in two sides of a single crystal of semiconductor

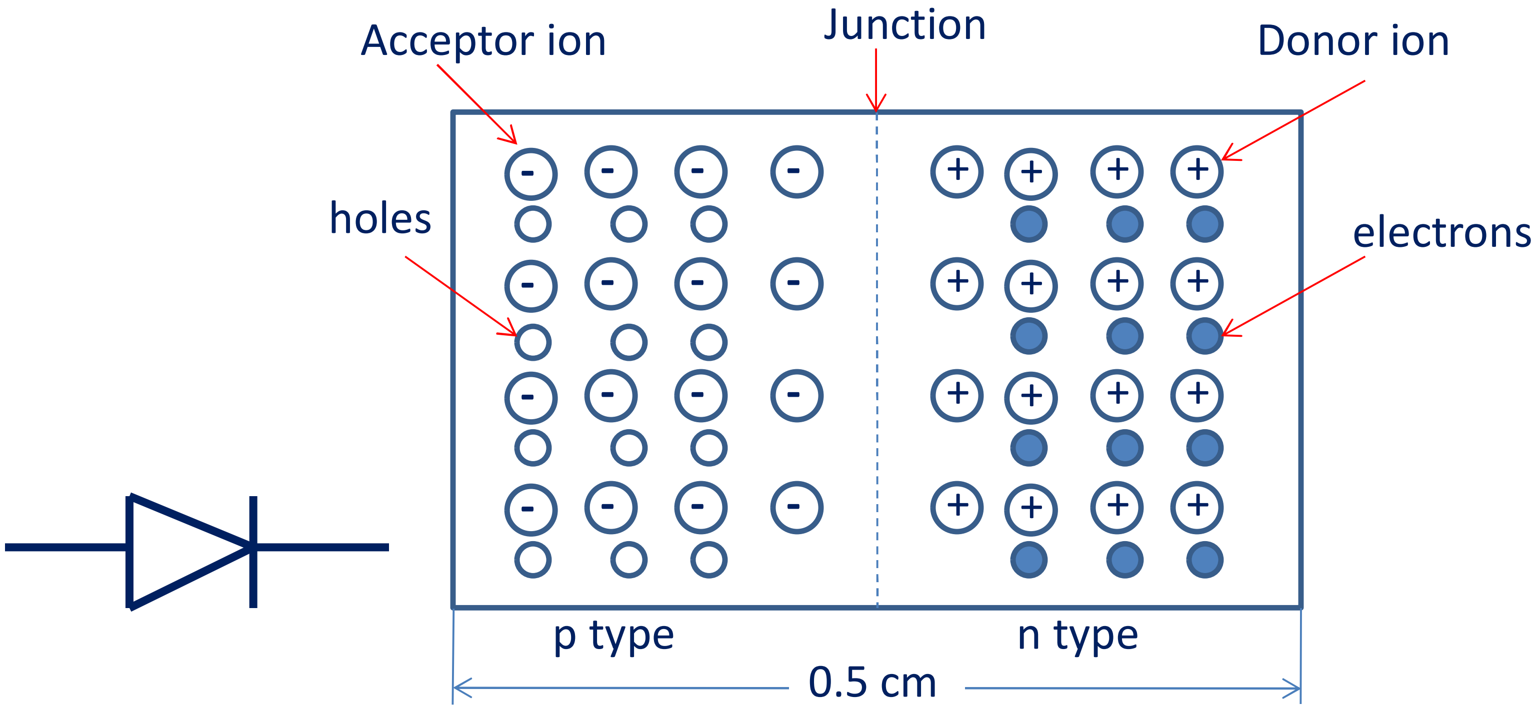
By donating an electron a donor impurity atom becomes a positive ion

An acceptor impurity atom becomes a negative ion after accepting an electron

Holes diffuse to the right and electrons to the left across the junction

As holes and electrons combine across the junction, they disappear near the junction

Semiconductor Diode



An electric field appears across the junction

Equilibrium is established, when field is large enough to restrain the process of diffusion

For further movement of holes and electrons, they have to cross a potential barrier (i.e. we have to apply an external field)

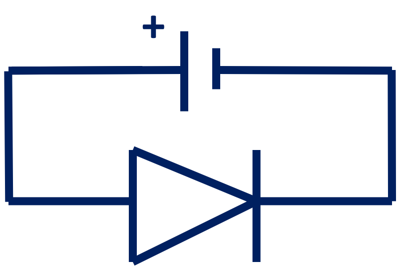
Unneutralized ions in the neighborhood of the junction are uncovered charges

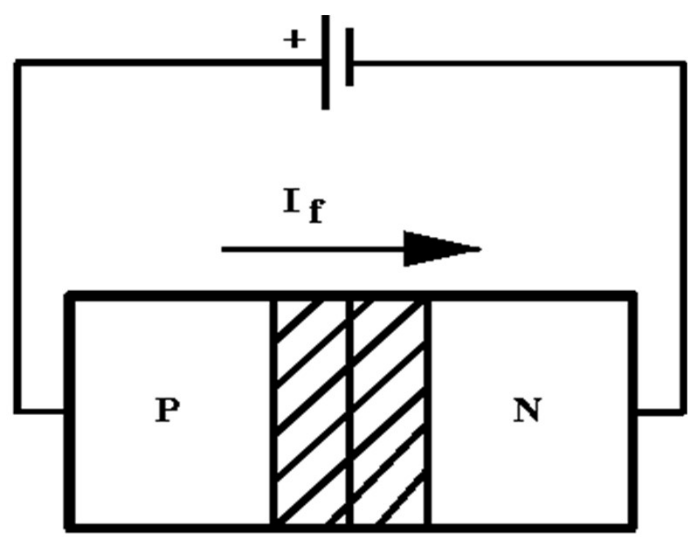
The region across is called space charge region or depletion region

Thickness of depletion region is very small (10^{-4} cm)

P-N Junction – Forward Bias

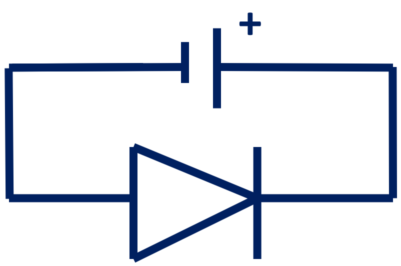
- positive voltage placed on p-type material
- holes in p-type move away from positive terminal, electrons in n-type move further from negative terminal
- depletion region becomes smaller - resistance of device decreases
- voltage increased until critical voltage is reached, depletion region disappears, current can flow freely

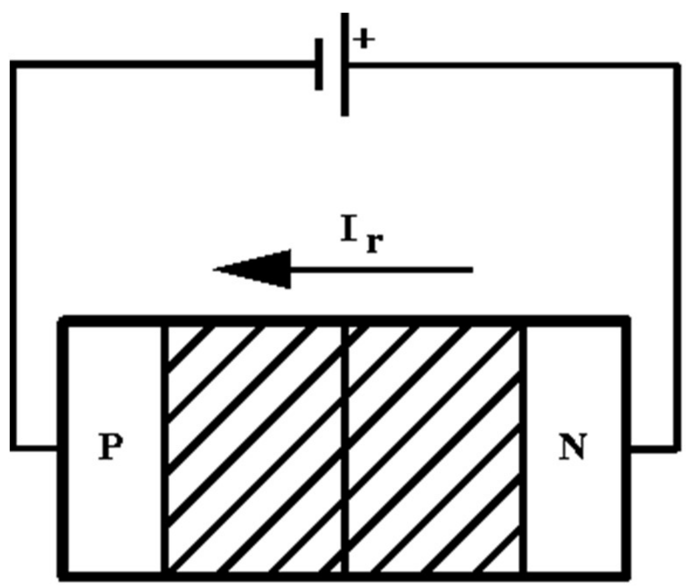




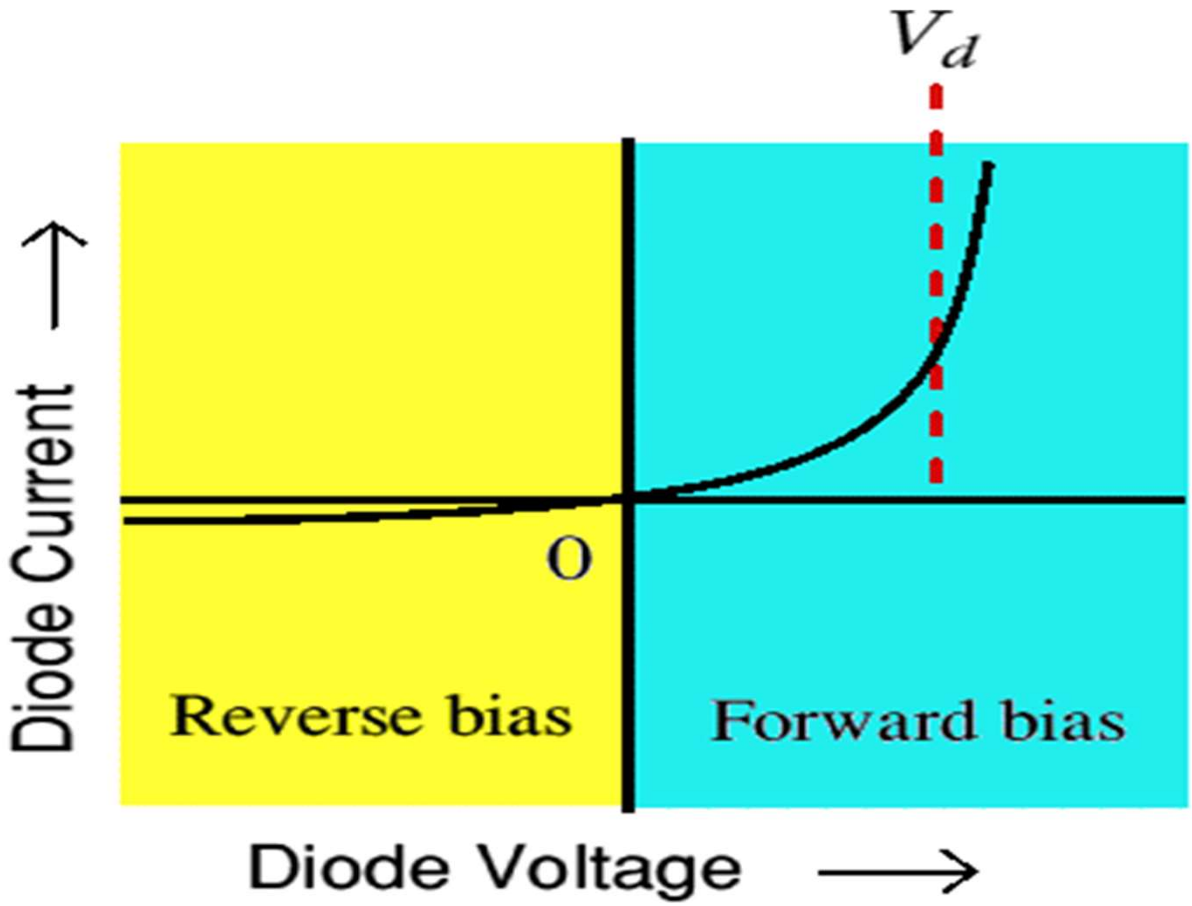
P-N Junction – Reverse Bias

- positive voltage placed on n-type material
- electrons in n-type move closer to positive terminal, holes in p-type move closer to negative terminal
- width of depletion region increases
- allowed current is essentially zero (small “drift” current)

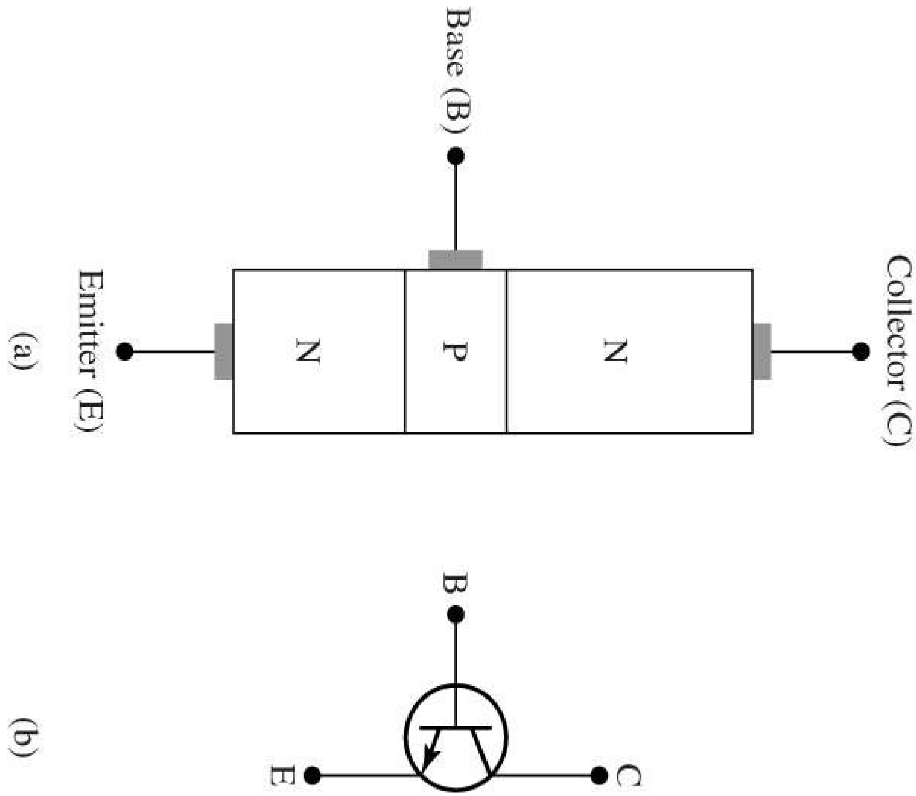




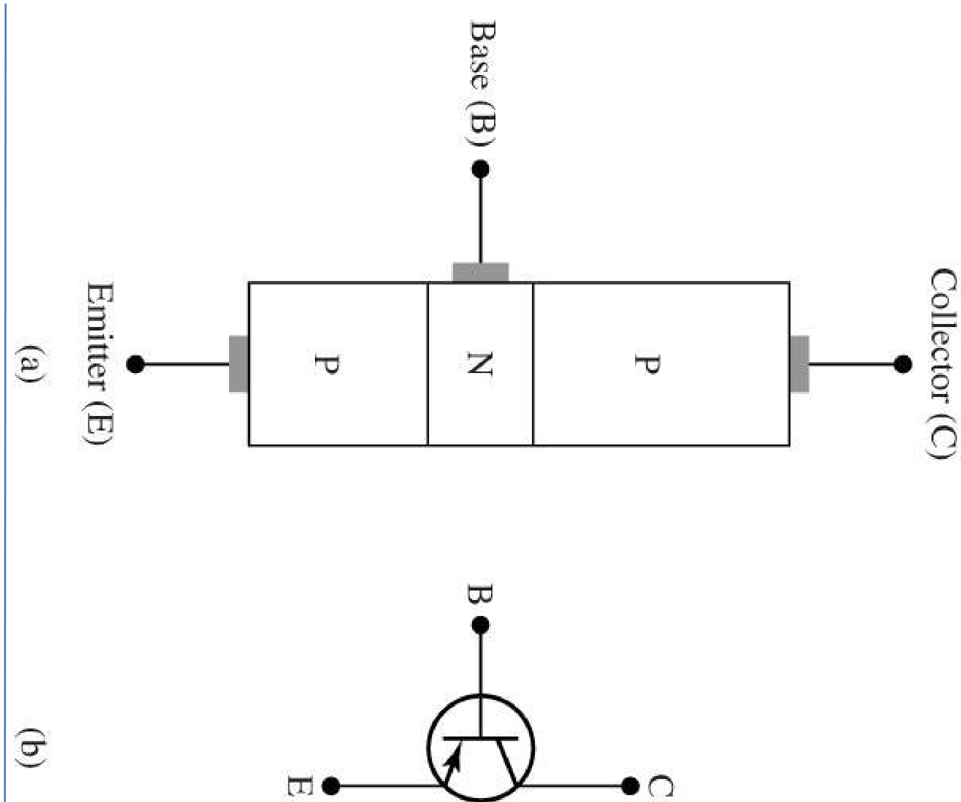
IV Characteristics of Diode



Semiconductor Transistor

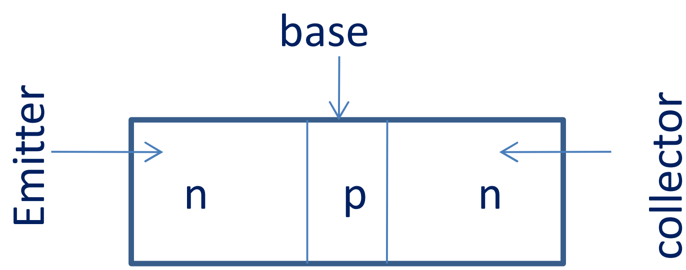


n-type semiconductor is sandwiched between two layers of p-type

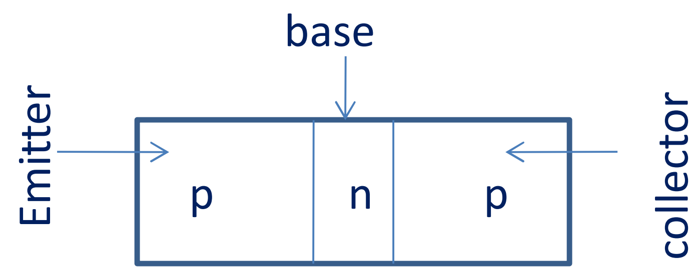


p-type semiconductor is sandwiched between two layers of n-type

Bipolar Junction Transistor (BJT)



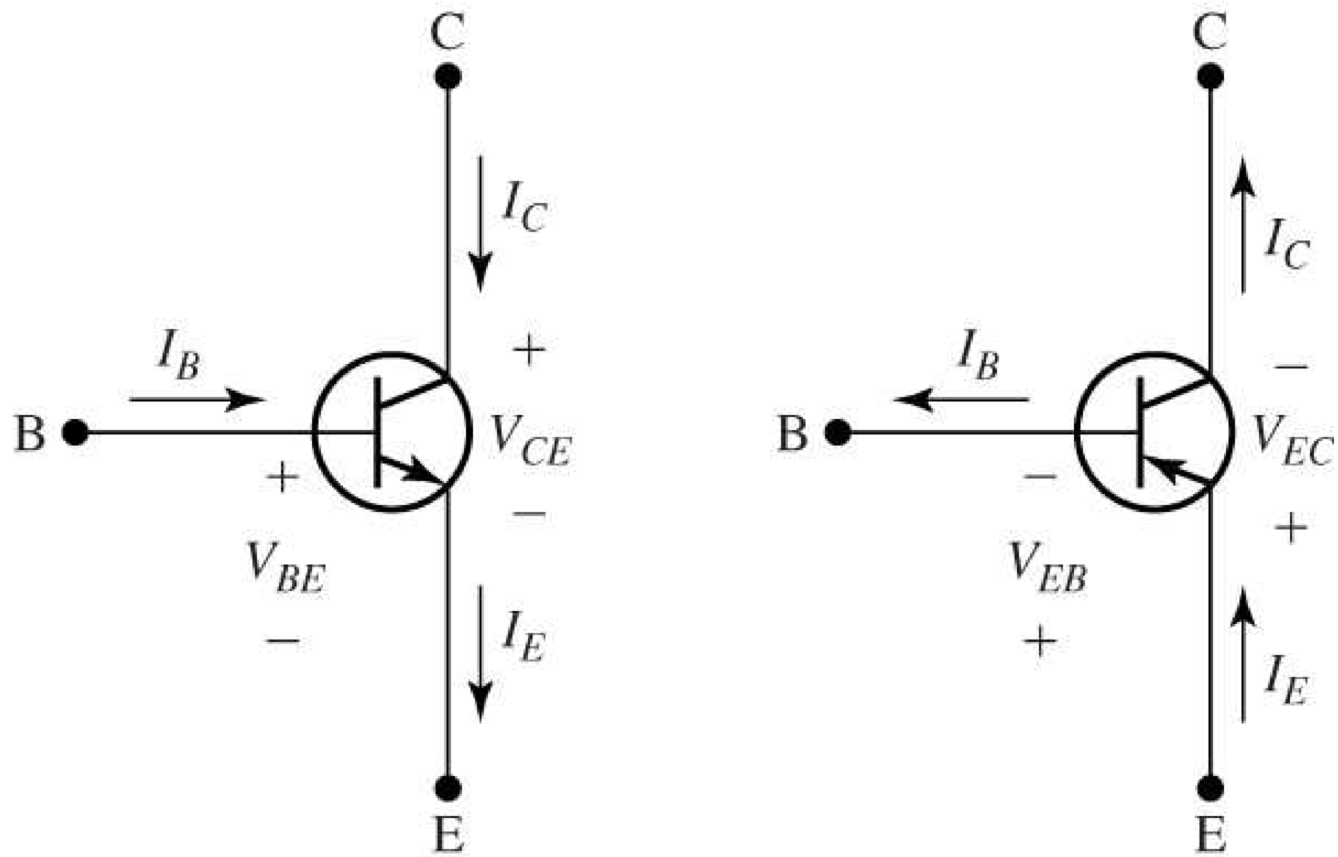
Flow of electrons



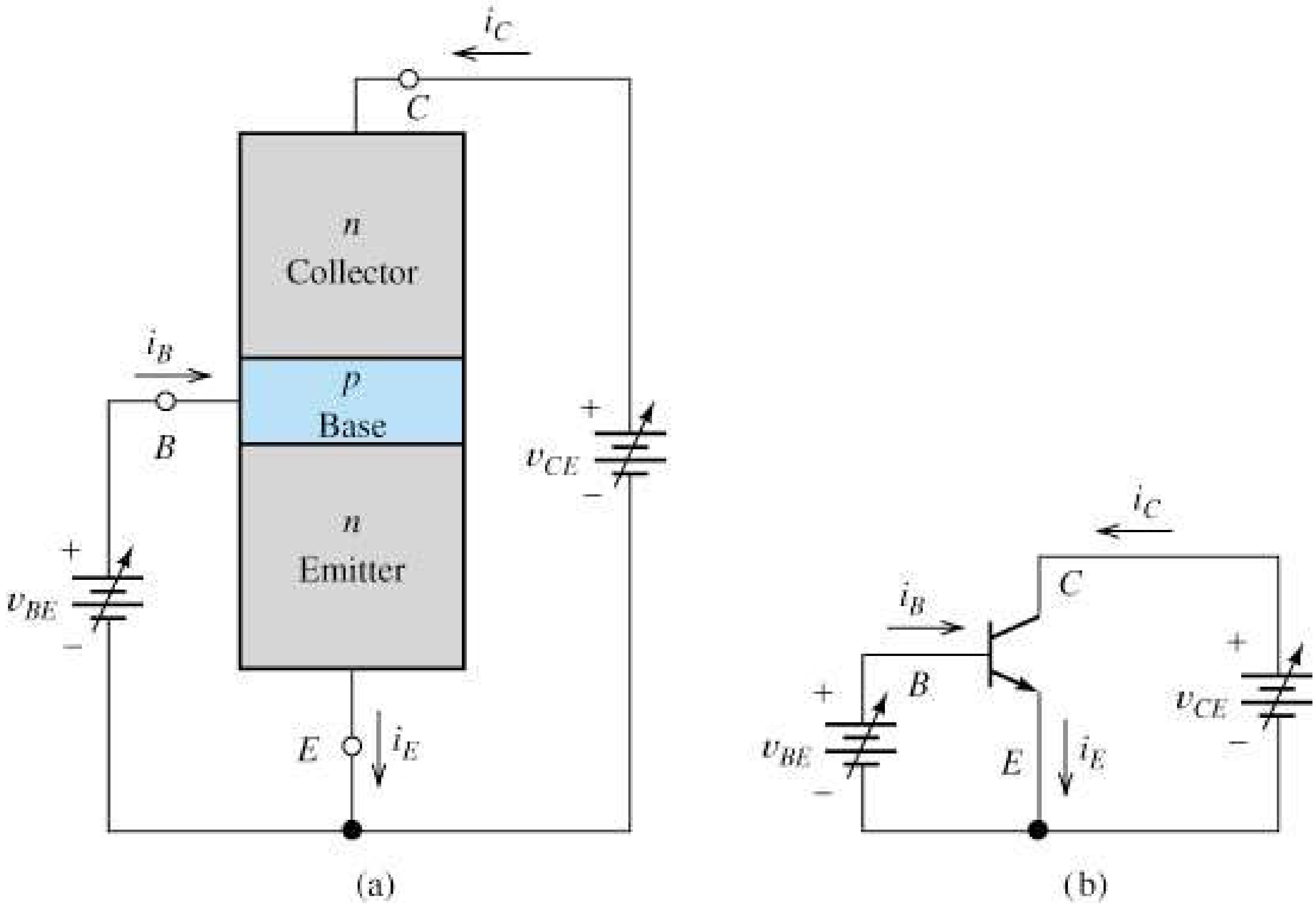
Flow of holes

Currents flow mainly due to majority carriers

Reference positive directions for both NPN and PNP transistors.

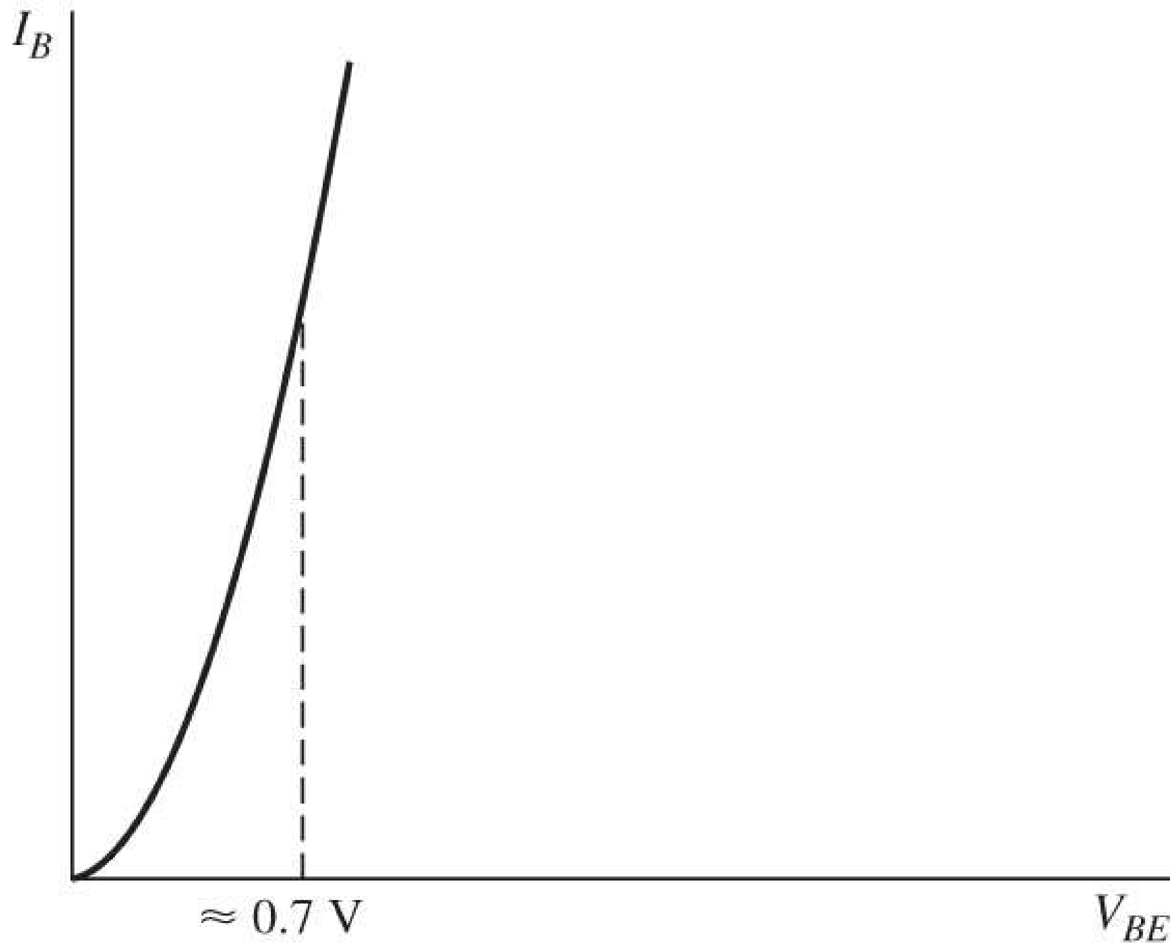


(a) NPN (b) PNP

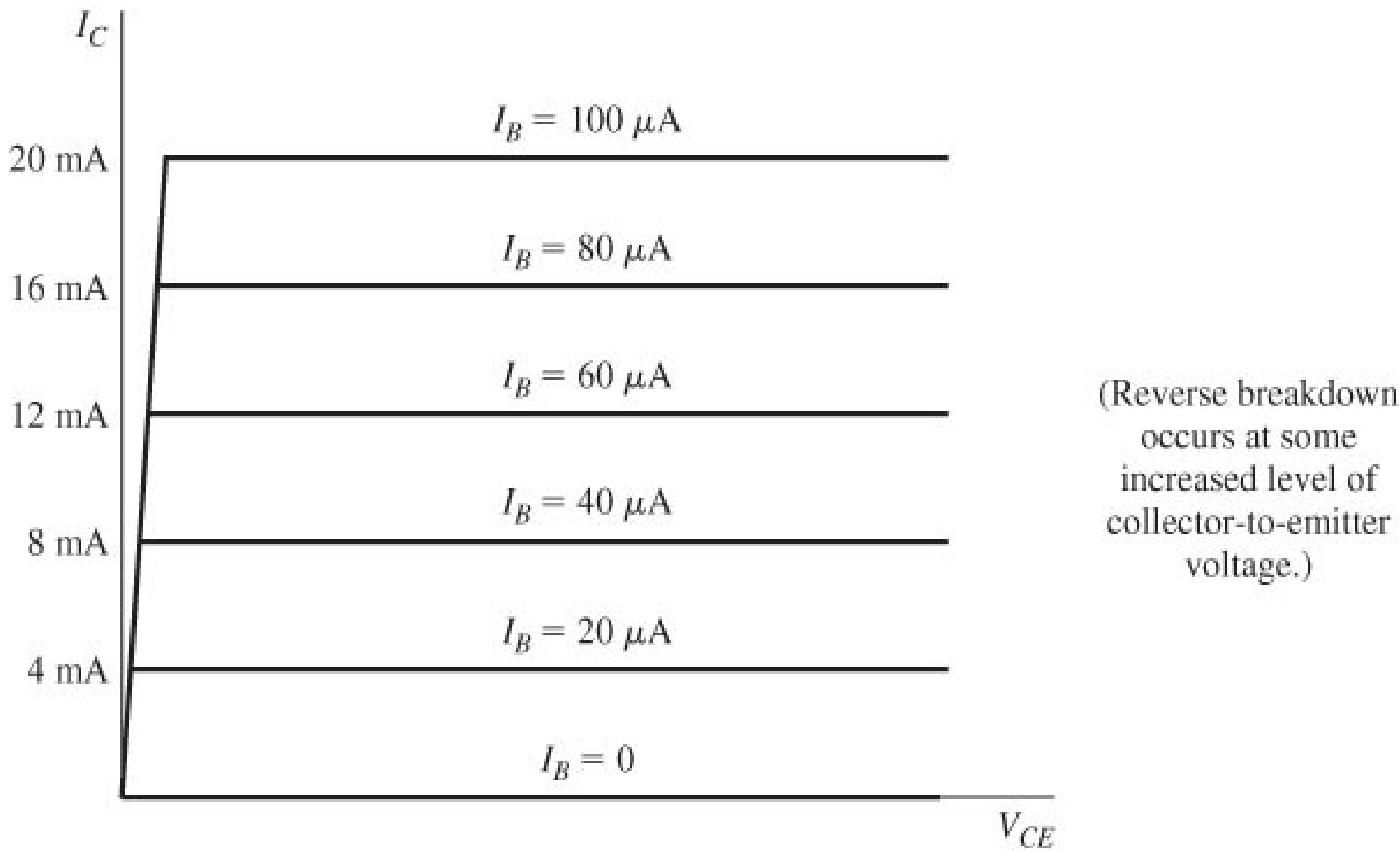


An *npn* transistor with variable biasing sources (common-emitter configuration).

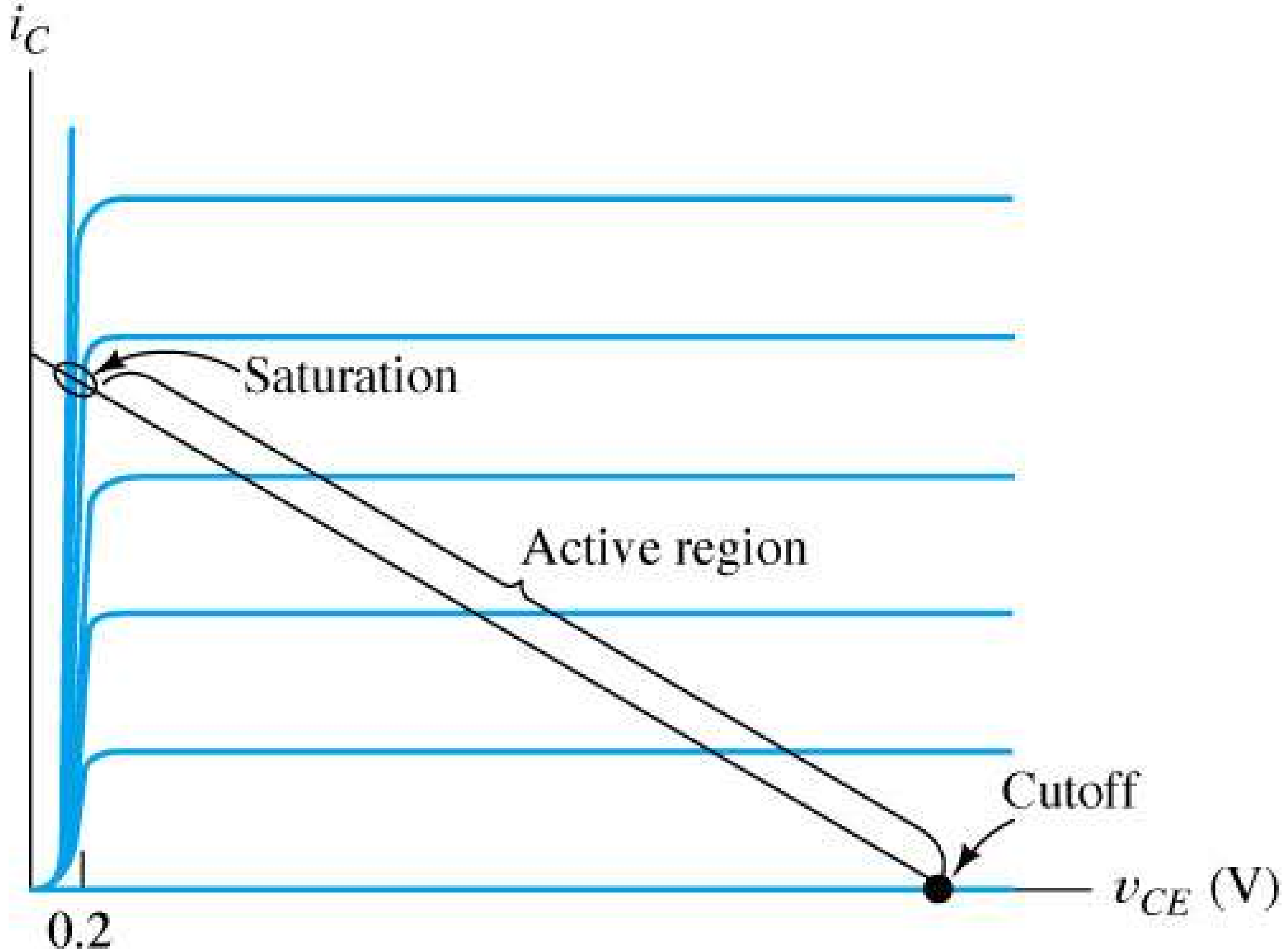
Base characteristic with collector-to-emitter voltage constant.



Collector characteristics of an ideal representative BJT.



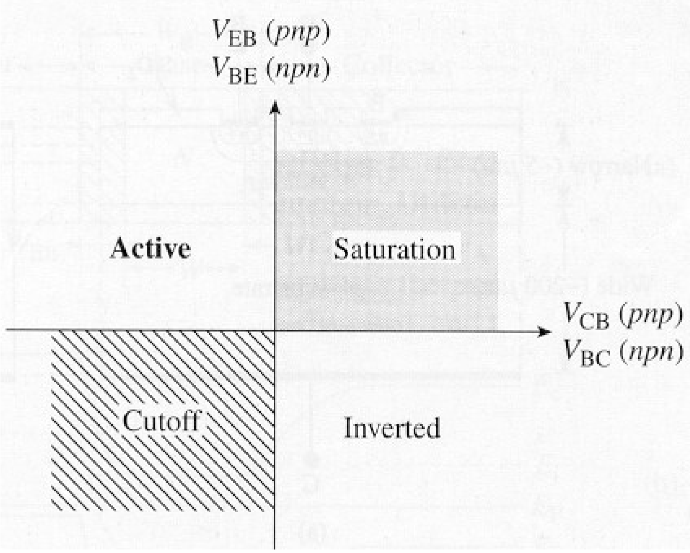
Three regions of operation for a BJT.

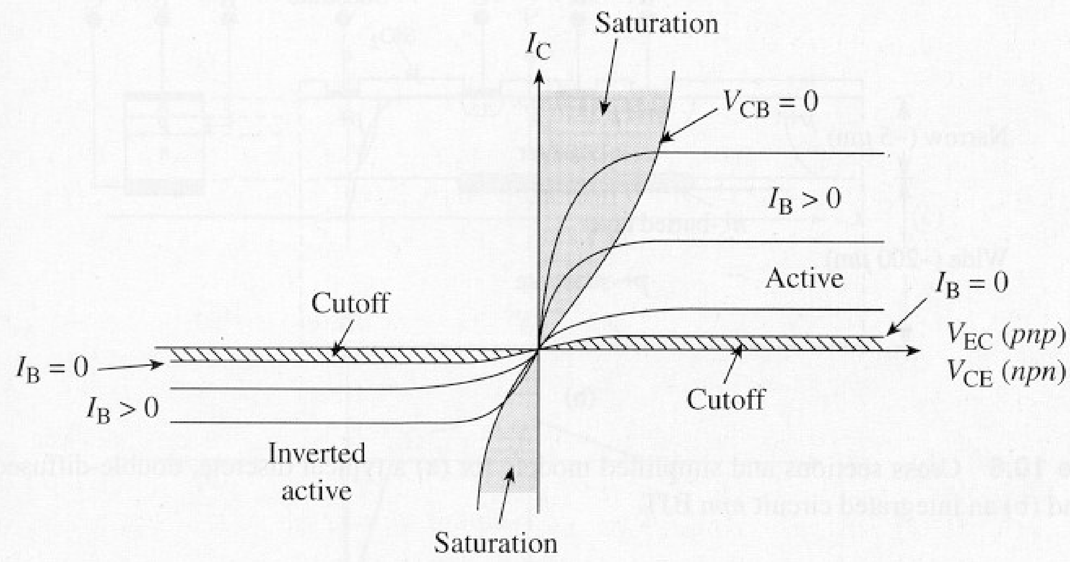


Amplification occurs in the active region. In saturation, $v_{CE} < 0.2$ V.

Modes of Operation

Common-emitter output characteristics (I_C vs. V_{CE})

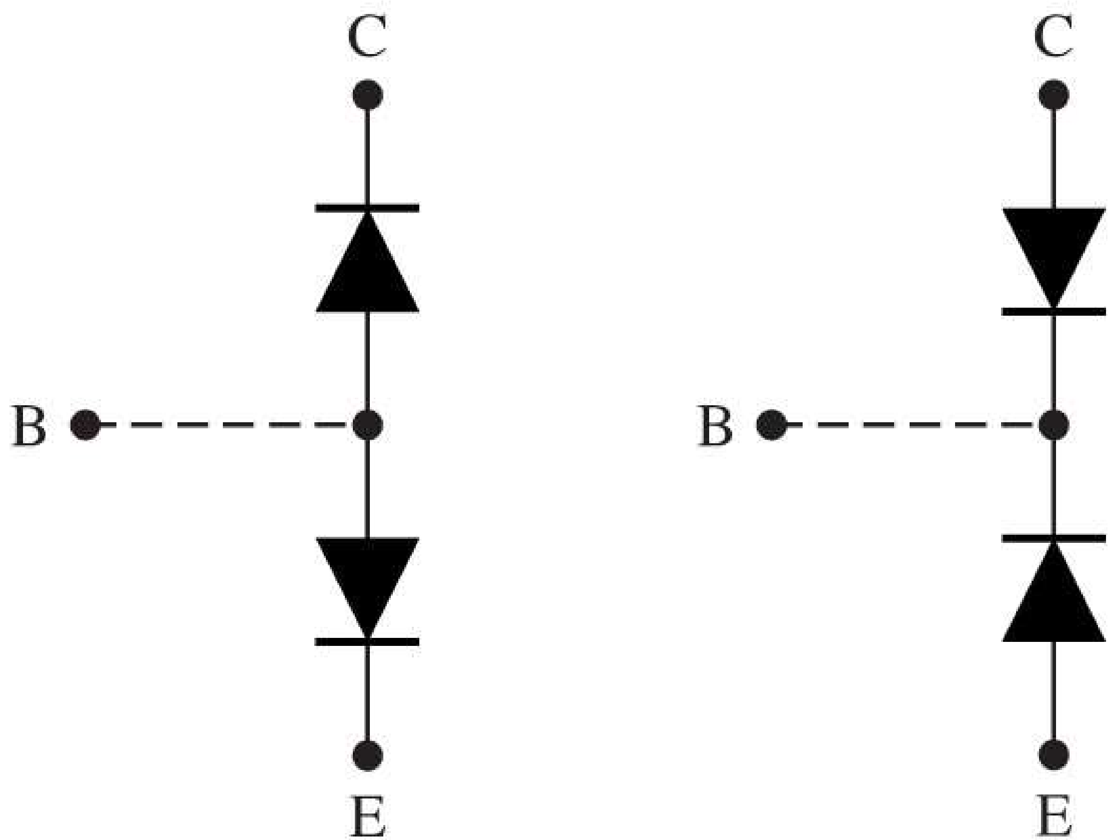




Mode	Emitter Junction	Collector Junction
CUTOFF	reverse bias	reverse bias
Forward ACTIVE	forward bias	reverse bias*
Reverse ACTIVE	reverse bias*	forward bias
SATURATION	forward bias	forward bias

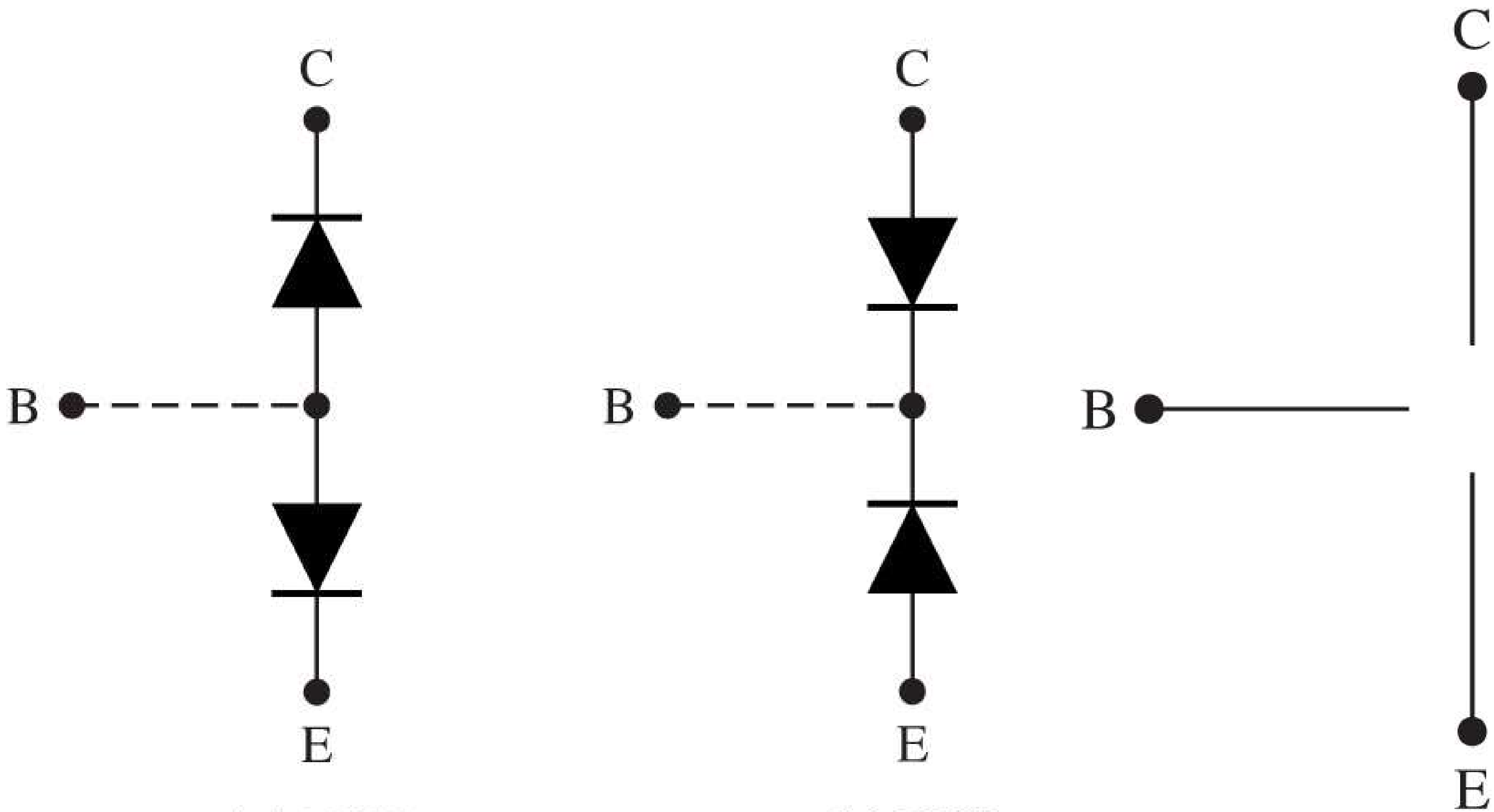
*or not strongly forward biased

Models to assist in visualizing BJT as two diodes.



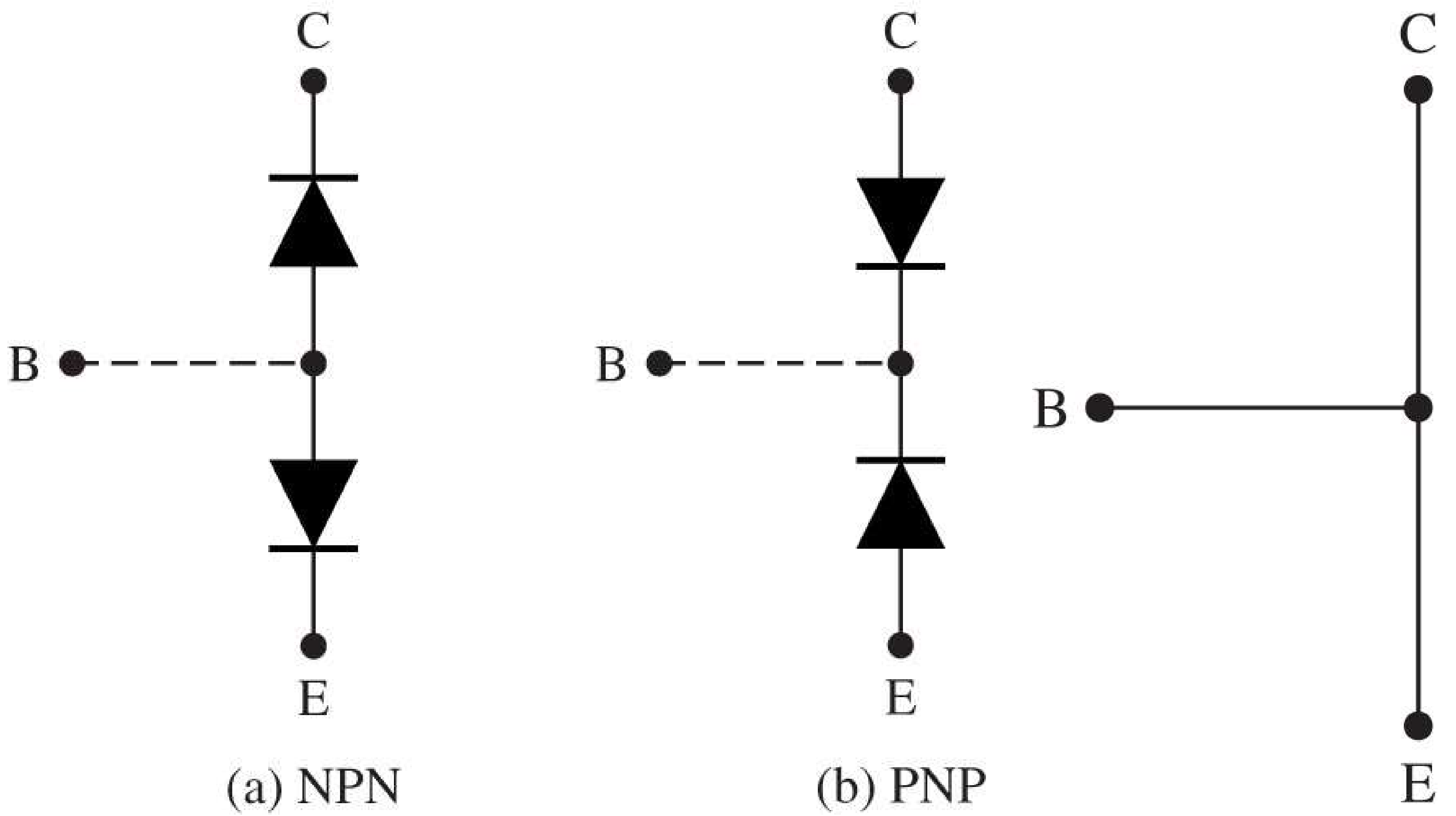
(a) NPN (b) PNP

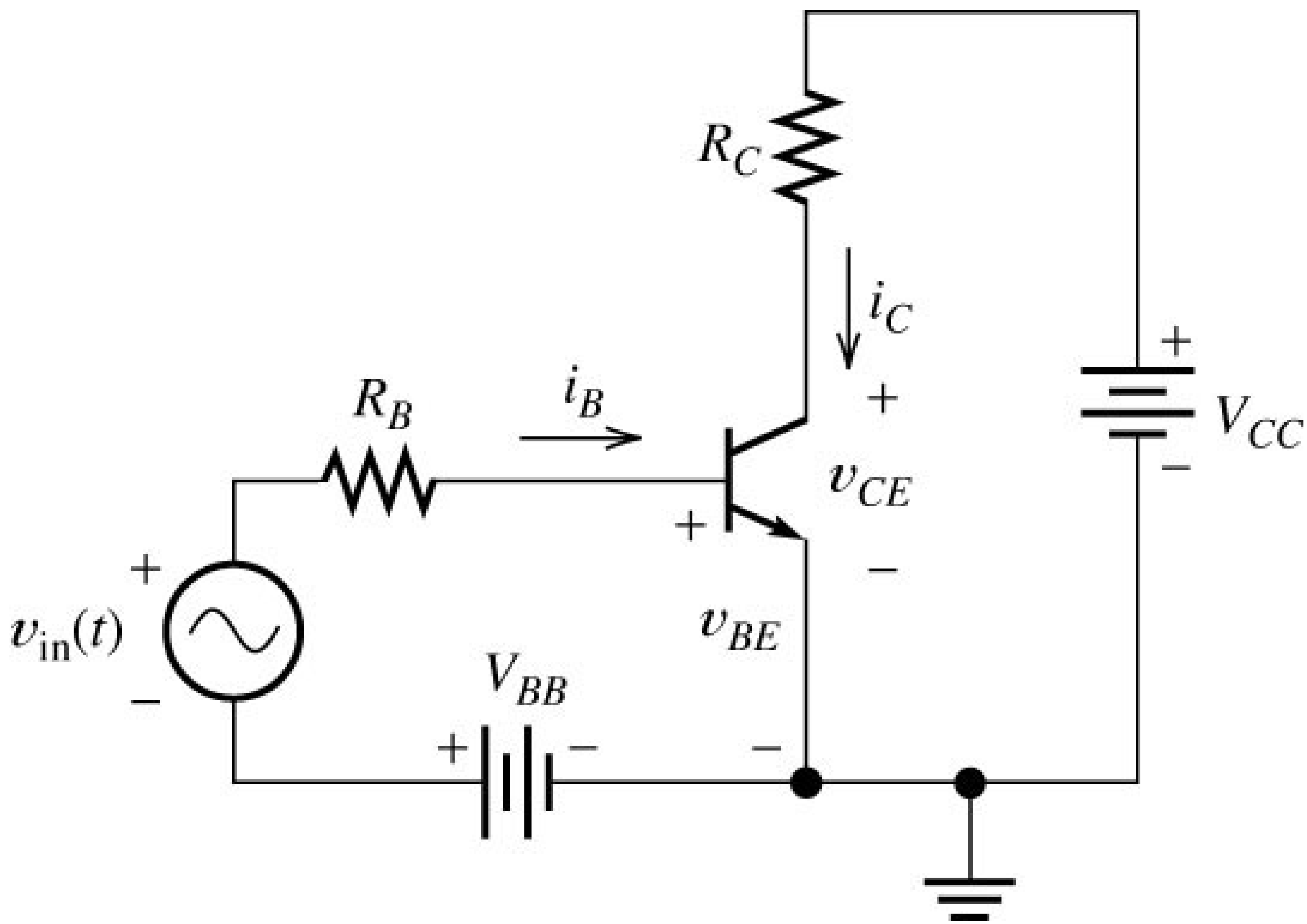
Ideal model of BJT in cutoff region.



(a) NPN (b) PNP

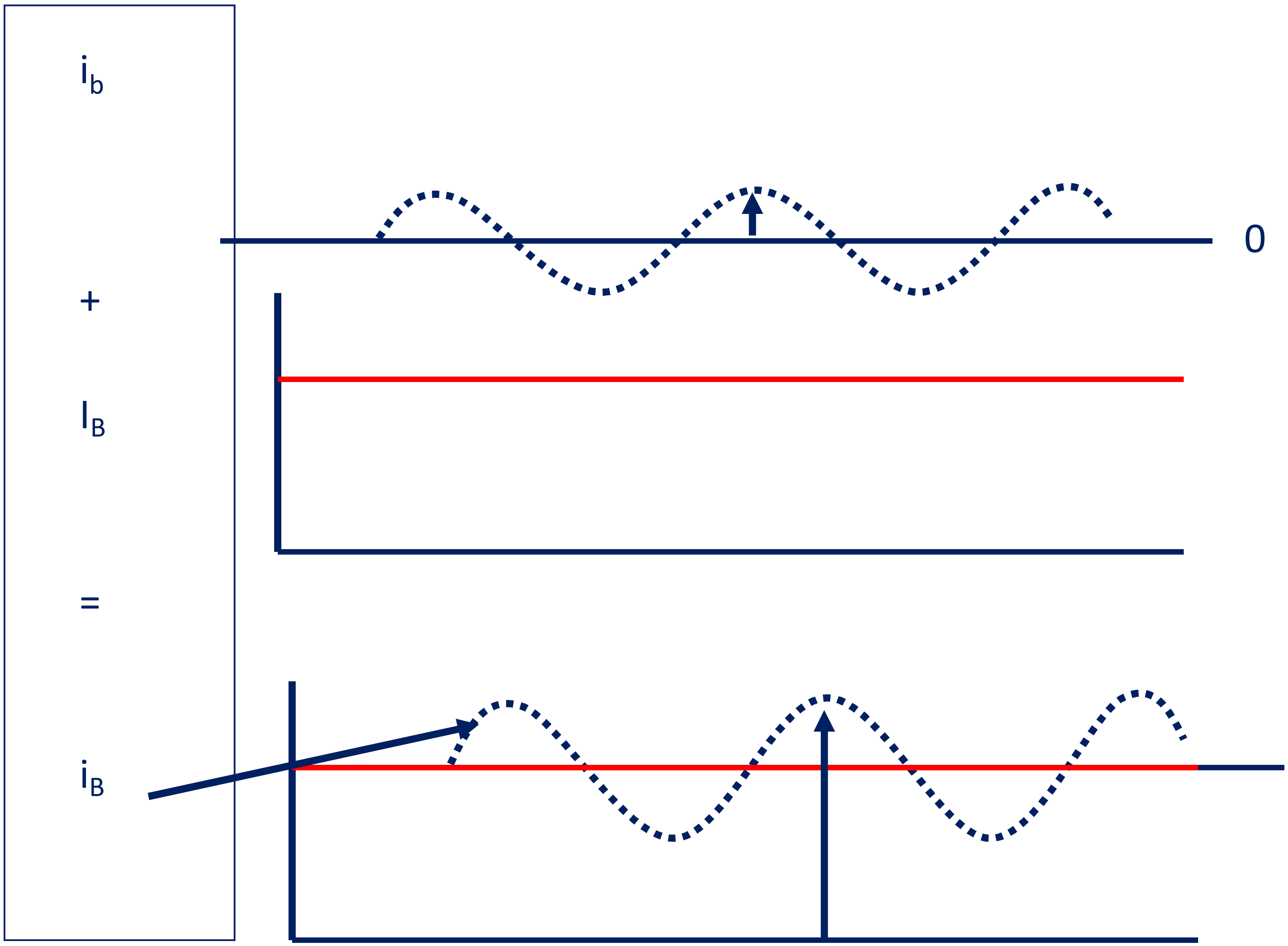
Ideal model of BJT in saturation region.

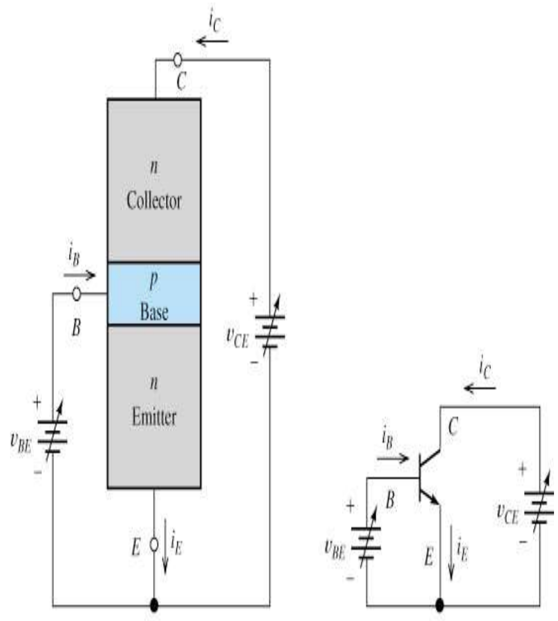




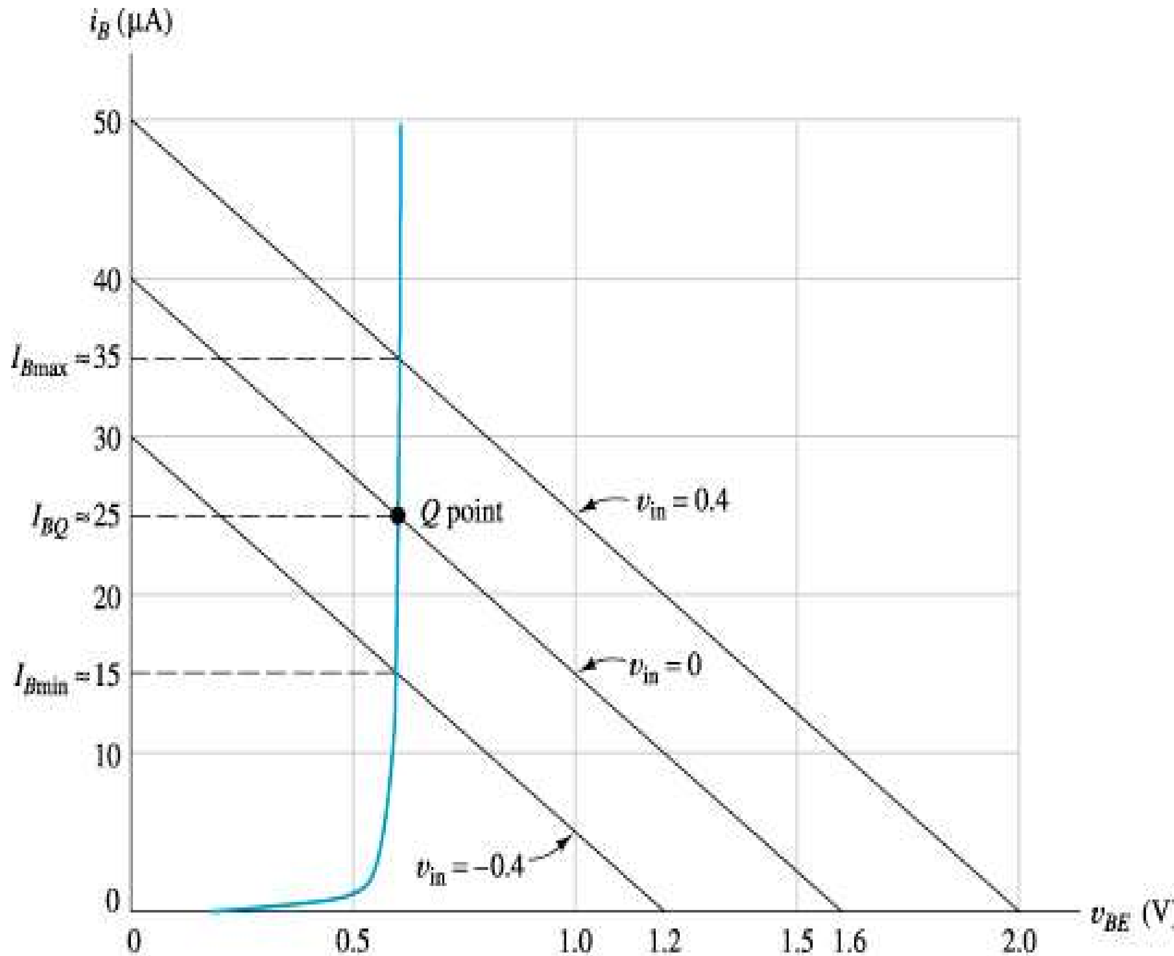
Transistor as an amplifier.

Transistor Amplifier Basics



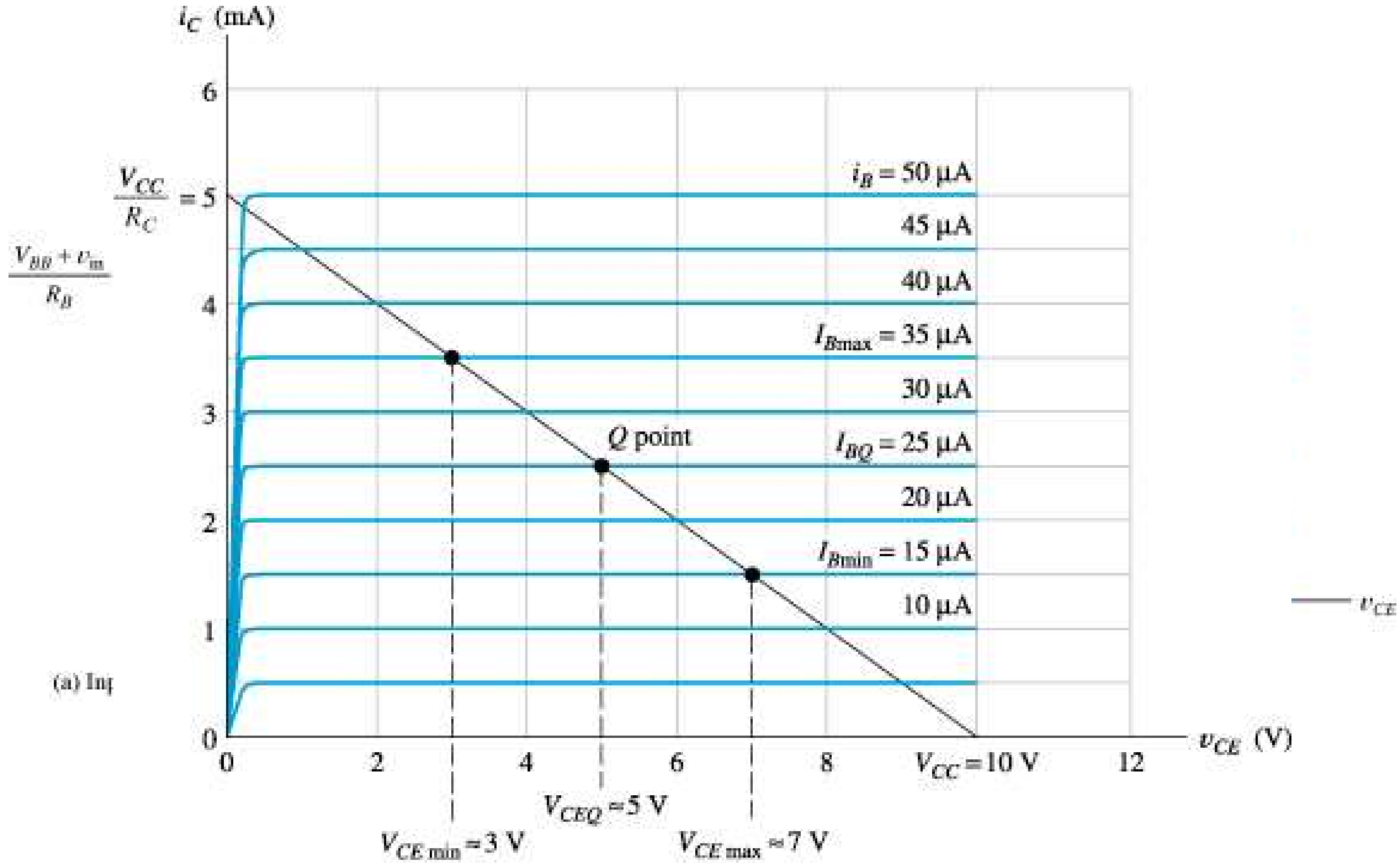


(a) (b)



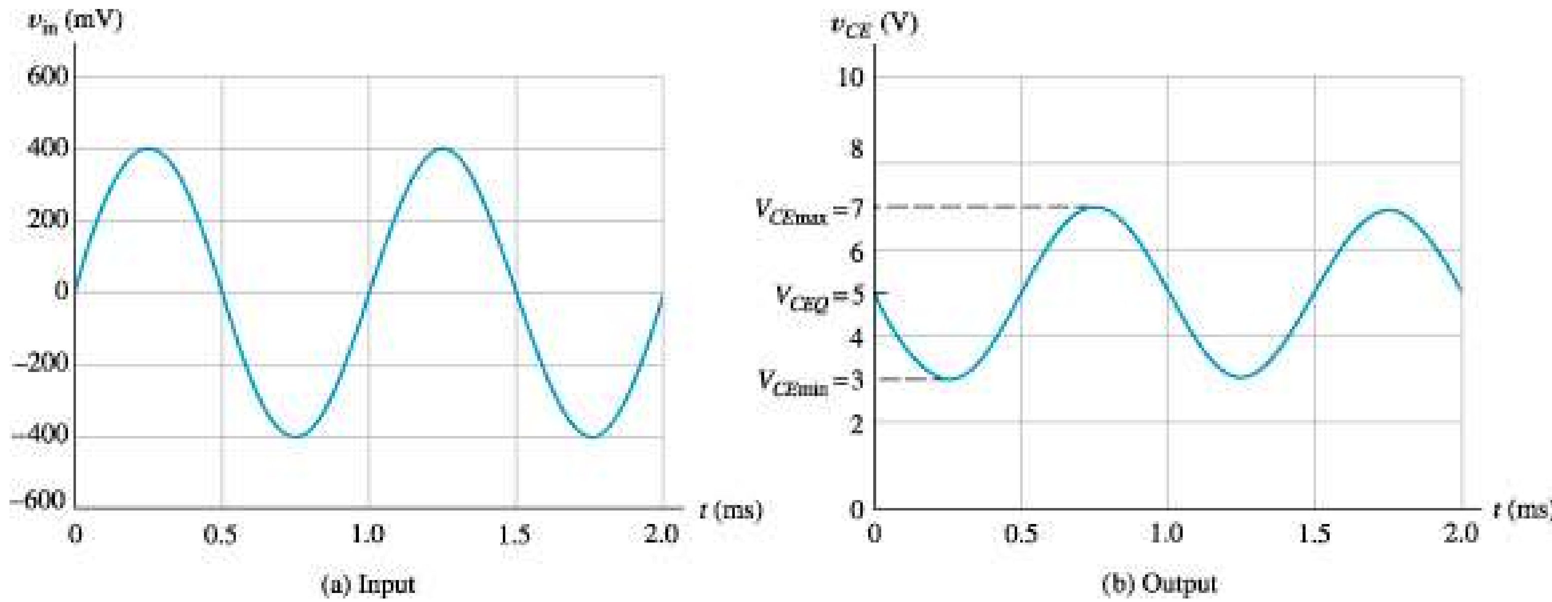
(a) Input

Load-line analysis



(b) Output

Load-line analysis of the amplifier



Voltage waveforms for the amplifier

BJT switch using an NPN transistor.