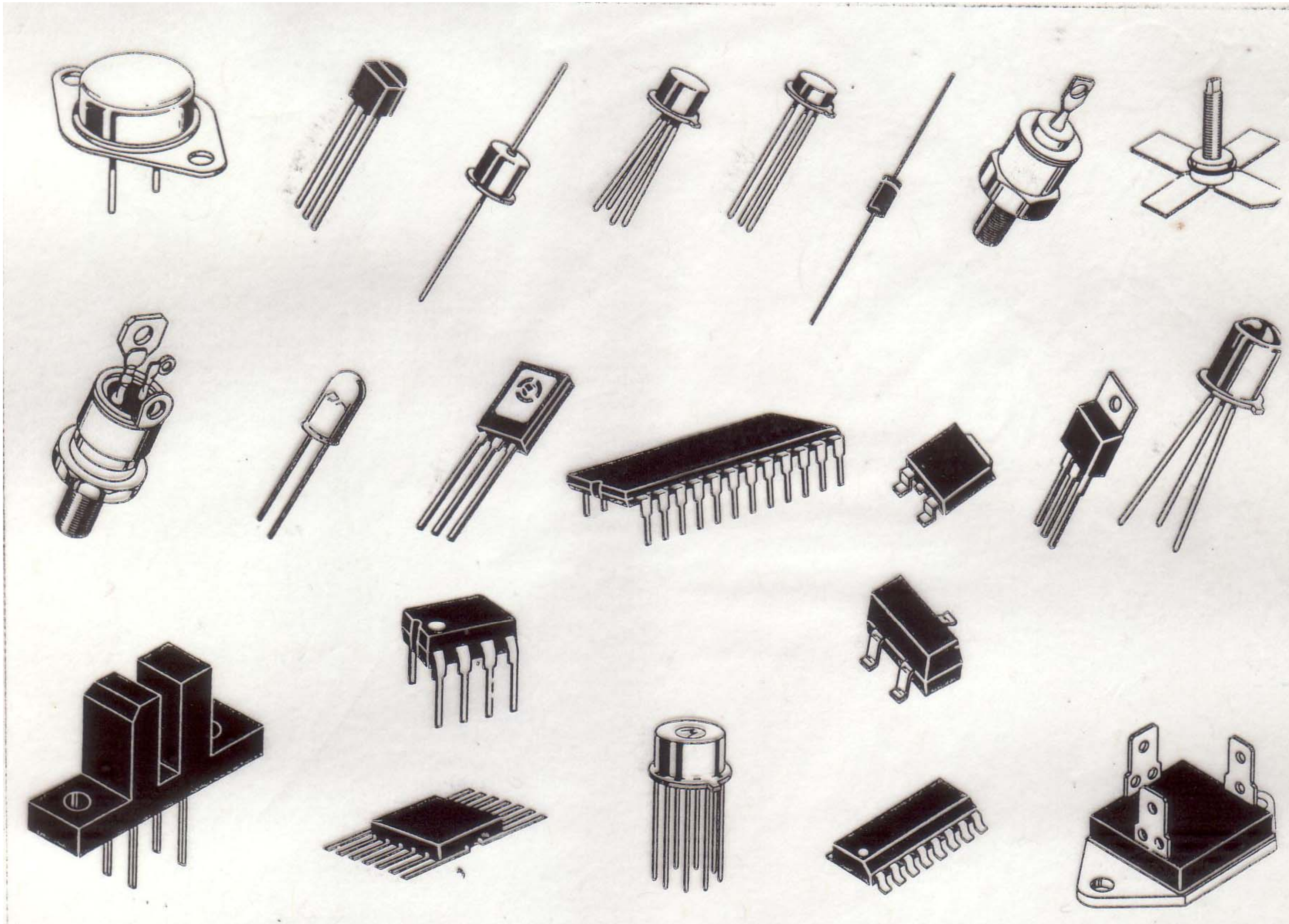
CLASS 1 & 2

REVISION ON SEMICONDUCTOR PHYSICS

Reference: Electronic Devices by Floyd

ELECTRONIC DEVICES

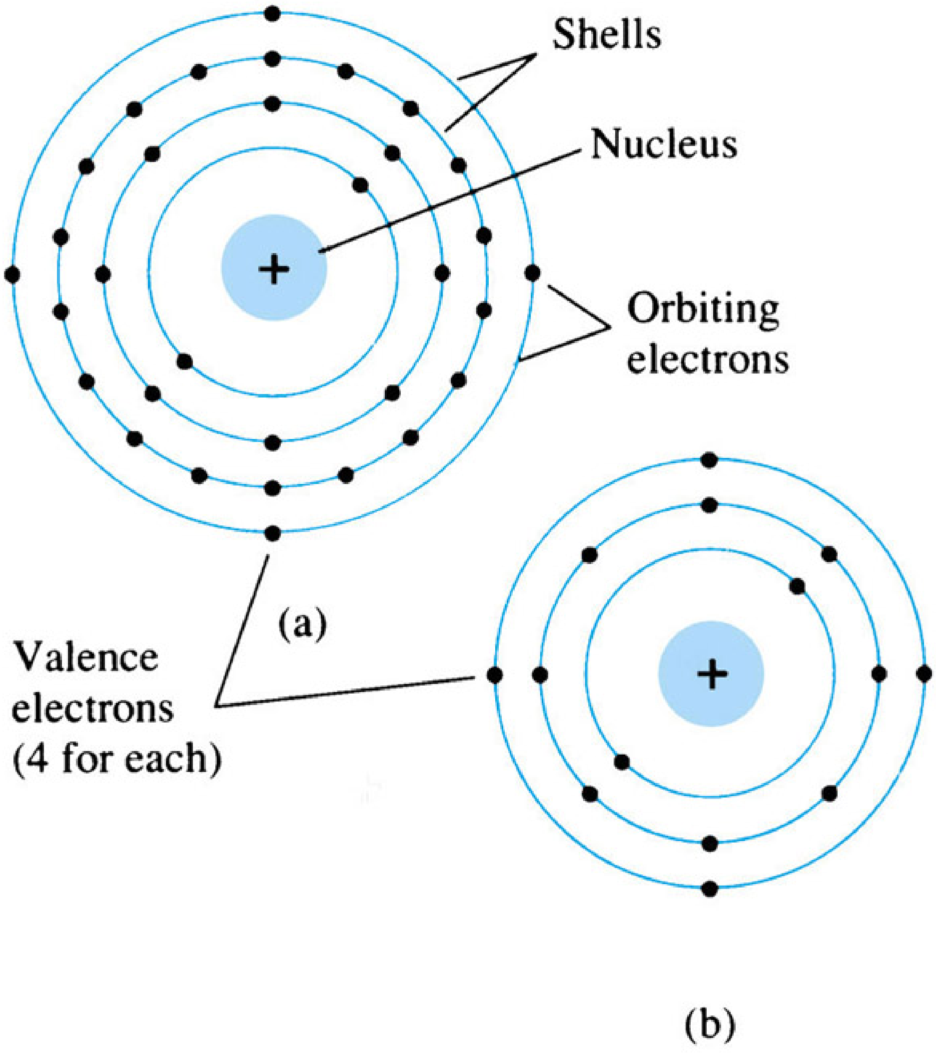
- Diodes, transistors and integrated circuits (IC) are typical devices in electronic circuits.
- All the mentioned devices are made of semiconductor materials.
- To understand how each device operates, basic knowledge on the structure of atoms and the interaction of atomic particles in the semiconductor material is necessary. The p-n junction formed by adjacent p and n semiconductors is the basis to the operation of transistors.



ATOM

- Smallest particle of an element.
- Each element has its on atomic structure.
- Each atom of an element has its own number of electrons and protons that differentiates it from the atom of another element. Ex: hydrogen (H) atom has 1 proton and 1 electron. Helium (He) atom has 2 protons, 2 electrons and 2 neutrons.

FIGURE 1-6 Atomic structure: (a) germanium (b) silicon. Electrons moving around the nucleus in orbits. Nucleus contains protons and neutrons.



ATOMIC NUMBER AND WEIGHT

Elements are arranged in a periodic table in accordance to:

- the element’s atomic number. Atomic number is the number of electrons in the element’s atom under neutral condition.
- the element’s atomic weight. Atomic weight is the number of protons and neutrons in the atom’s nucleus.

Ex: H - Atomic no. is 1. Atomic weight is 1.

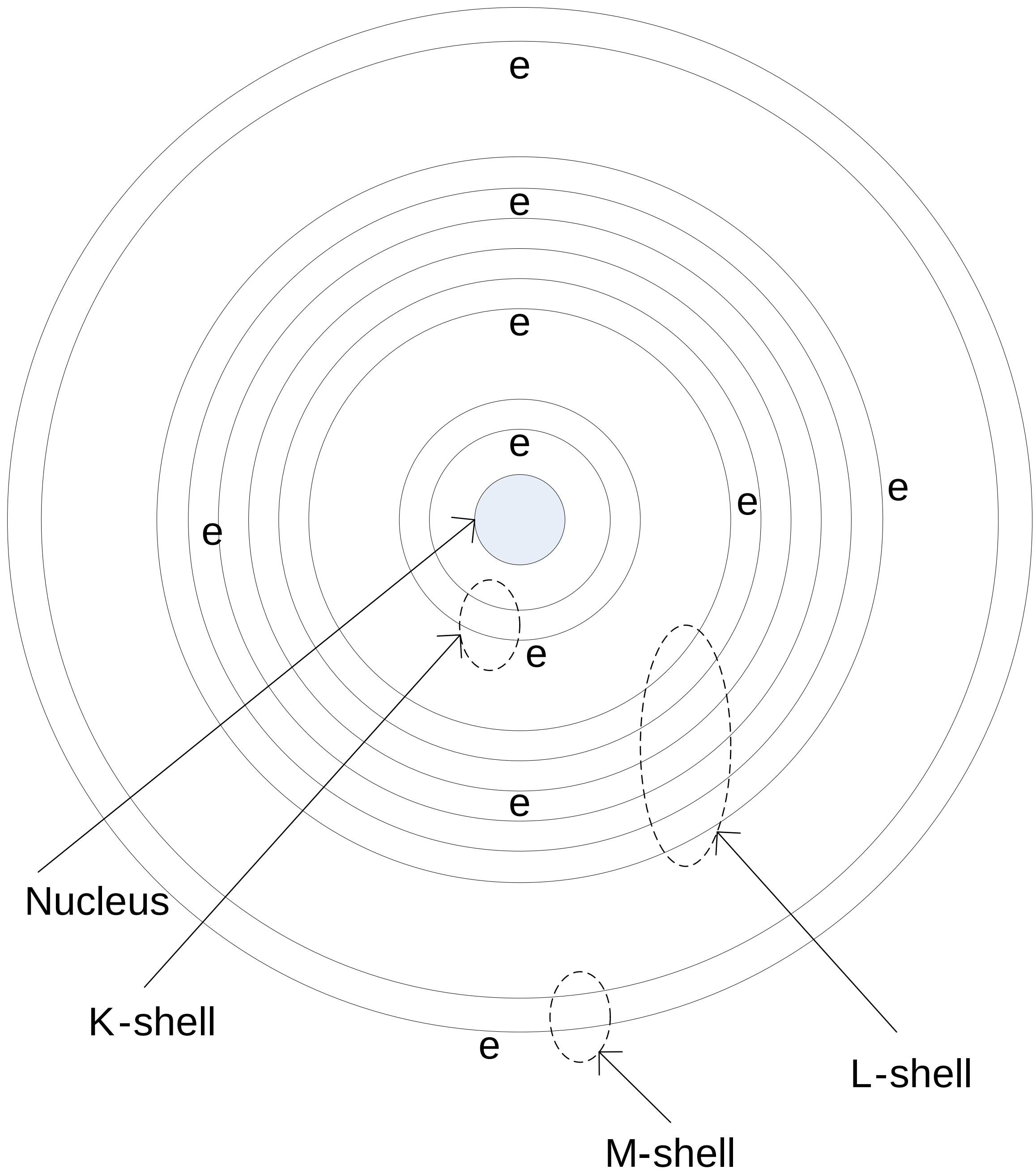
He - Atomic no. is 2. Atomic weight is 4.

Under normal/neutral condition, an element has equal number of electrons and protons. Hence, the positive charges will neutralize the negative charges, resulting in a net charge of 0.

ELECTRON ORBITS AND ENERGY LEVELS

- An atom consists of a nucleus surrounded by 1 or more electrons moving in orbits. An atom has a specific number of orbits. Orbits represent energy level.
- In atomic and semiconductor theory, the energy unit is electron volt, eV.
- eV = total energy gained or lost when an electron moves following or against 1 V of potential.
- 1 eV = 1.6×10^{-19} Joule

- Only discrete electron energy is allowed. An electron does not have an energy between 1 eV and 2 eV, but has a definite value such as 1.5 eV.
- A group of energy levels or orbits are combined to form an electron shell. The difference between energy levels in a shell is smaller than the energy difference between shells. The number of electrons existing in a shell determines the chemical properties of the atom.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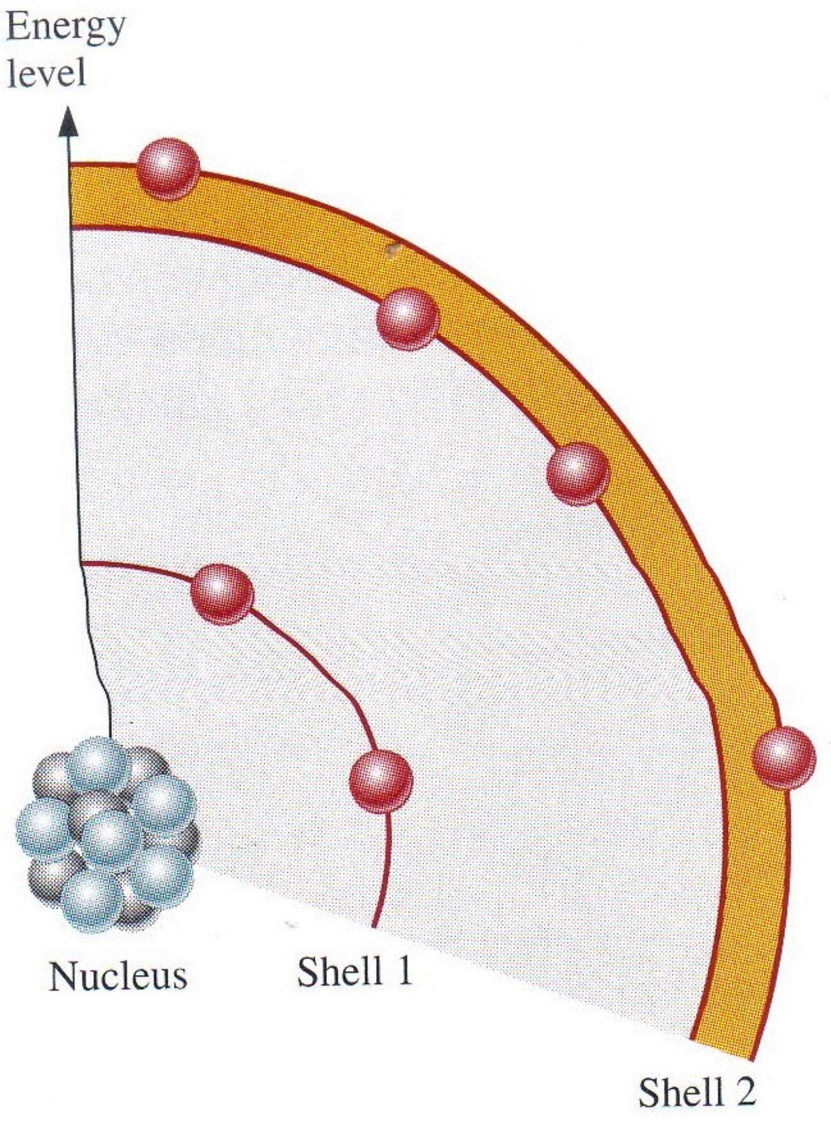
Nucleus
K-shell
L-shell
M-shell

- The electron shells in an atom are labeled as K, L, M, N, ……., Z. The K shell is closest to the nucleus.
- An atom is more complex if it has more electron orbits. Ex: A silicon (Si) atom is more complex than a lithium (Li) atom as it has 3 shells and 14 electrons as compared to 2 shells and 3 electrons property of the Li atom.

- Electron in an orbit far from the nucleus is less influenced by the electrostatic force of the proton in the nucleus as compared to the electron in an orbit nearer to the nucleus.
- The further the orbit from the nucleus, the higher the energy level possessed by the electron in this orbit. Hence, this electron can easily escape from its orbit.
- Electron in an orbit closer to the nucleus (ex: electrons in the K shell) has less energy and is bonded more to the nucleus by the electrostatic force. It is very difficult for this electron to escape from its orbit.

Ref: Fig 1.3 Floyd. Shell 1 is the K-shell, Shell 2 is the L-shell.



SILICON AND GERMANIUM ATOMS

- 2 semiconductor materials used to fabricate most diodes and transistors are germanium (Ge) and silicon (Si).
- Similarity - each Ge and Si has 4 electrons in its outermost shell.
- Difference – Si has 14 protons but Ge has 32.
- Si is more popular as the devices that are made of Si have better performance at higher temperature.

VALENCE ELECTRON

- The chemical properties of an atom are determined by the performance of the electrons in the outermost shell. These electrons have the highest energy and are involved in chemical reactions and bonding. Electrons in the outermost shell are called valence electrons.
- Atom with 1 electron in its outermost shell, such as the H atom, is said to be of valency 1. In general, an atom with n number of valence electrons is known as valency n atom. Ex: Li and Si are valency 1 and 4 atoms, respectively.

- Valence electrons of Ge are in the 4th shell. Valence electrons of Si are in the 3rd shell. Hence, Ge valence electrons are of higher energy and require smaller amount of additional energy to escape from the atom. This property makes Ge more unstable at high temperatures.

ATOM EXCITATION

The energy of an electron that moves in an orbit is constituted of the

- kinetic energy due to the movement
- potential energy due to the electrostatic attraction by the nucleus

When an external energy is given to the electron, both energies will be increased.

- When the electron receives the additional energy, it moves to a higher energy level in the orbit and consequently, further away from the nucleus. The electron is said to be excited.
- The electron that loses energy will fall to a lower energy level into an orbit which is nearer to the nucleus.

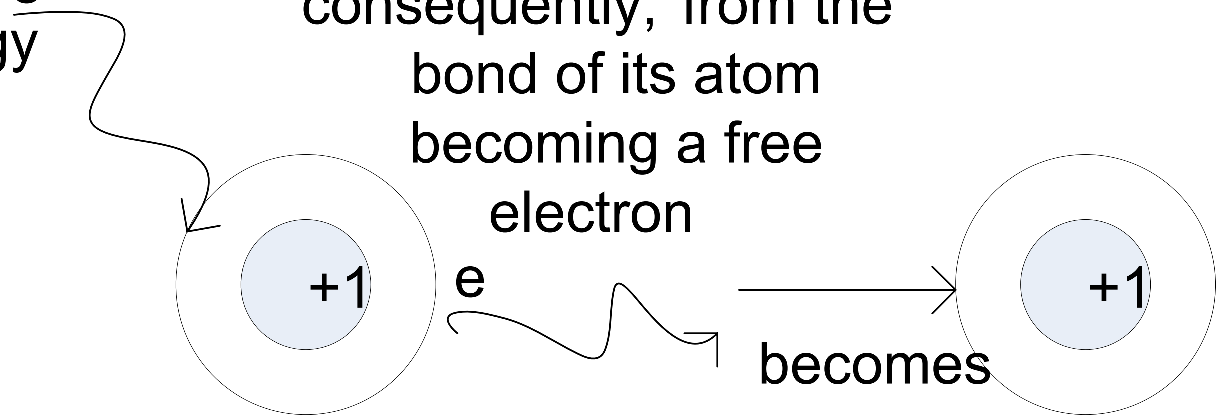
- Additional energy can be obtained from the heat and light.
- If the valence electrons receive sufficient energy, they can escape from the outermost shell and consequently, from the atoms influence.
- The loss of 1 valence electron will change the formerly neutral atom into a positively charged atom (protons > electrons).

- The process of losing (or gaining) a valence electron is known as ionization and the resulted positively (or negatively) charged atom is called +ve (or –ve) ion.
- Ex: Chemical symbol for hidrogen is H. When it loses a valence electron, it becomes a +ve ion and written as H^+.
- The escaped valence electron is known as a free electron.

IONIZATION

Heat / light energy

Electron will escape from its shell and consequently, from the bond of its atom becoming a free electron



H atom

No. of proton = 1
No. of electron = 0
The atom is a + ve charge, H^+

Neutral charge

+ ve ion

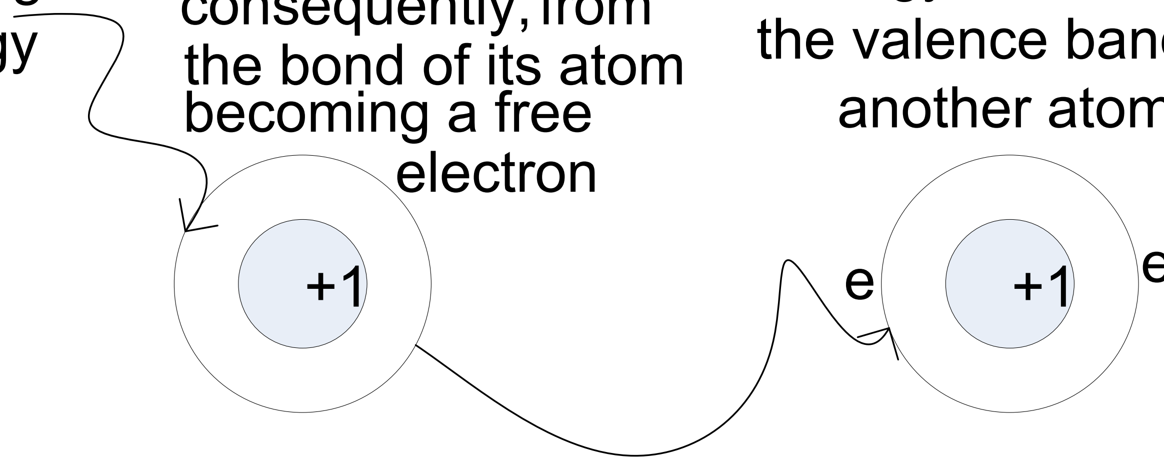
- When a free electron falls into the outermost shell of a neutral H atom, the atom becomes negatively charged (electrons > protons) and is called a –ve ion, symbolized as H^-.

IONIZATION – Both H atoms are originally of neutral charge as the no. of protons equals the no. of electrons.

Heat / light energy

Electron will escape from its shell and consequently, from the bond of its atom becoming a free electron

Free electron loses energy and enters the valence band of another atom



Originally neutral charge will become a +ve ion as the atom loses 1 electron

+ve ion, H^+

No. of proton = 1

No. of electron = 2

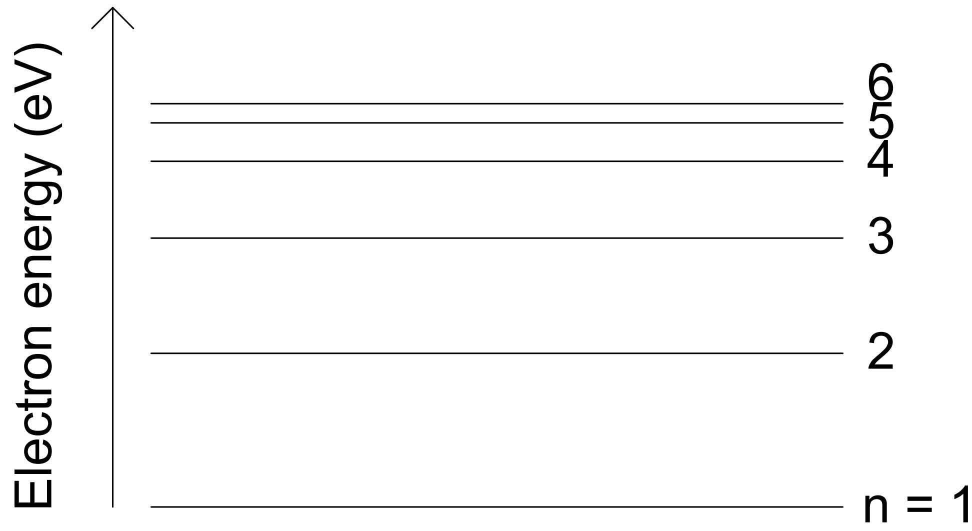
The atom is a –ve charge, H^-

–ve ion, H^-

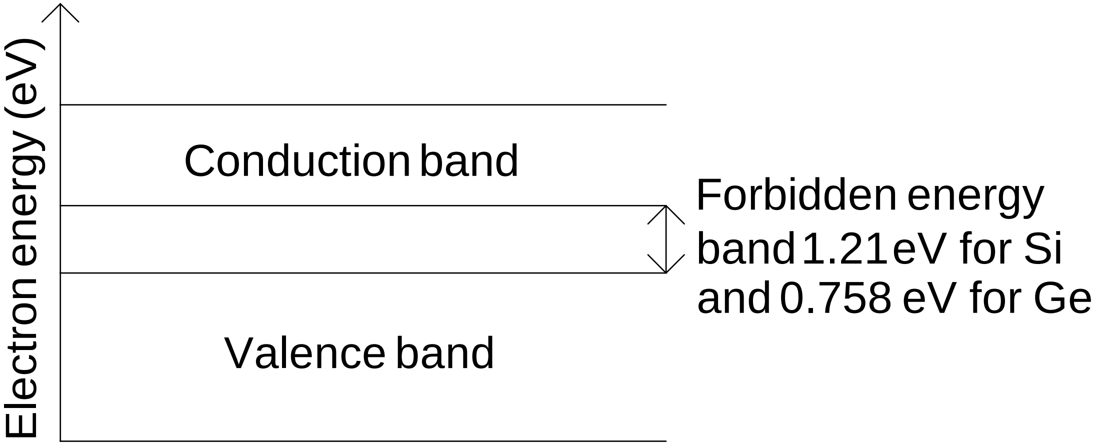
ELECTRON ENERGY IN THE SOLID'S ENERGY BAND

For an atom, the difference in the electron's energy level can be shown by a diagram.

The energy levels are written as n=1,2, …. As the energy increases, the electron orbit goes further away from the nucleus. Observe that the energy levels become closer at the higher n.



The diagram shows the 2 outermost (highest) energy band for an atom in a semiconductor crystal. There are many more bands before the valence band, however, the 2 bands shown are important in determining the electrical properties of the material.



- The highest energy band is the conduction band. The forbidden energy band separates the two bands. No electron should exists in the forbidden band.
- The valence band contains all energy levels possessed by the valence electrons. Valence electrons are bonded to the atom and do not move as freely as the electrons in the conduction band.

- Electrons entering the conduction band are electrons from the valence band that had obtained sufficient energy to enter the conduction band.
- The electrons in the conduction band have sufficient energy to move freely and be influenced by external energy.
- Electrons in this band are not bonded to the atom.
- Electrons do not always stay in the conduction band. They can lose energy and drop back into the valence band.

- The electrons existing at the top energy level of the valence band in a Si require 1.21 eV (at 0°K) to overcome the forbidden band and enter the lower energy levels of the conduction band.
- The energy across the forbidden band determines whether the solid is a conductor, insulator or a semiconductor.

INSULATOR, SEMICONDUCTOR AND METAL

- Insulator – a very weak electrical conductor
- Metal – a very good electrical conductor
- Semiconductor – its conductance is between the conductance of the insulator and metal

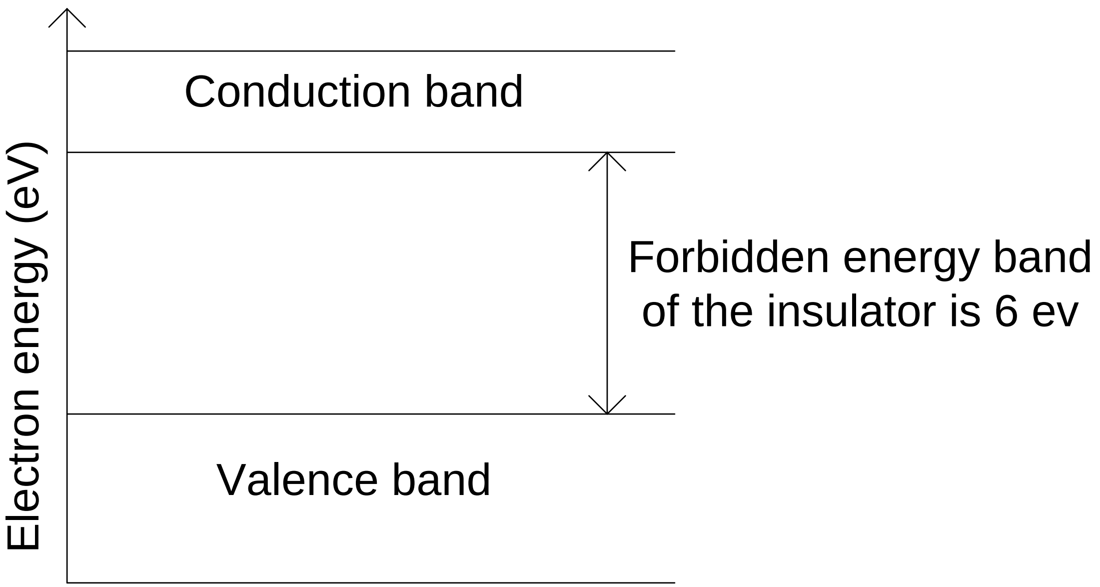
INSULATOR

A large forbidden band separates the filled valence band from the almost empty conductance band.

The energy given to the electron by the provided field is too small to be able to move the electrons from the valence band to the conductance band.

Since the electrons are unable to obtain sufficient energy, conductance is impossible.

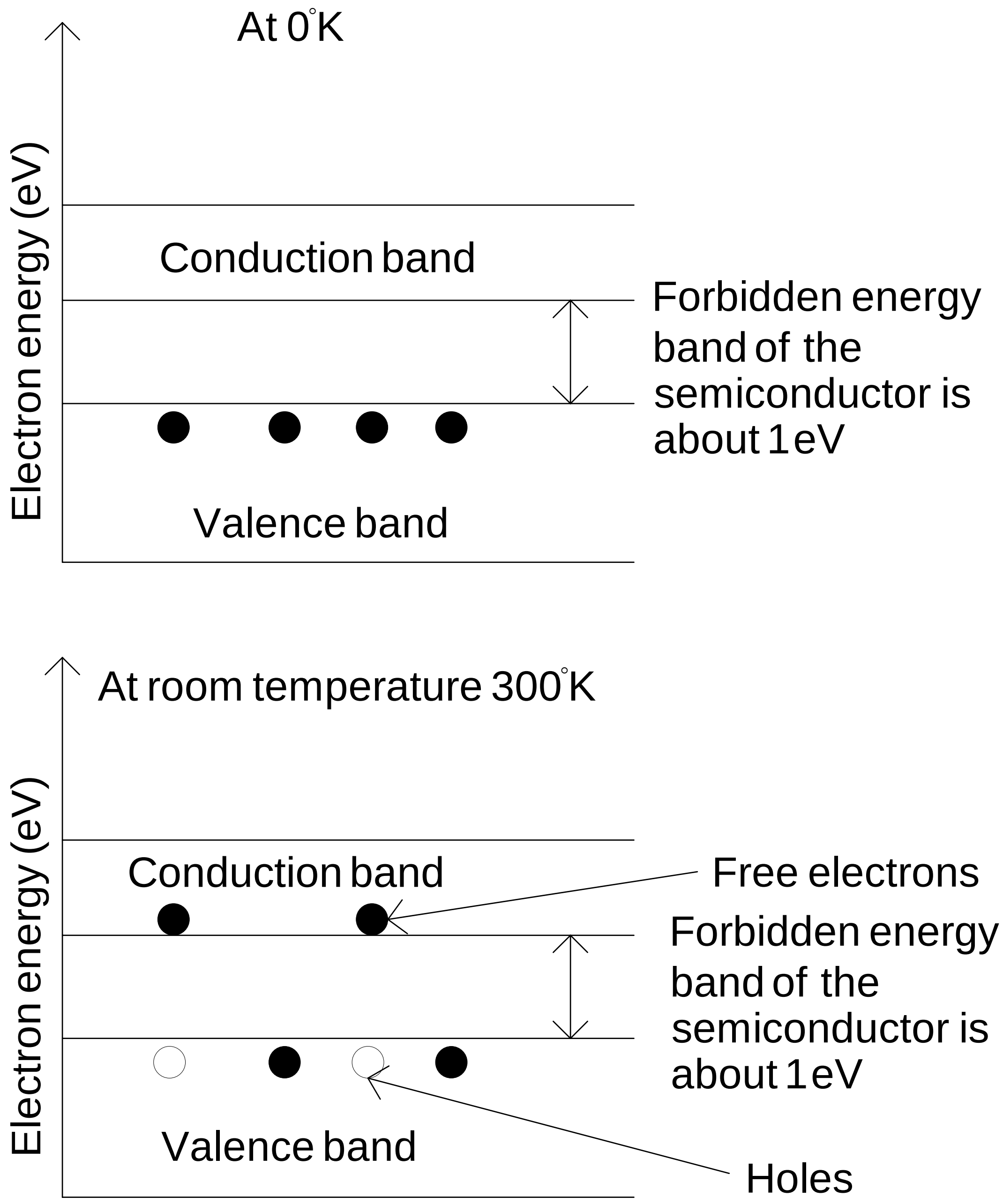
Ex. of an insulator is the diamond.



SEMICONDUCTOR

- The most important semiconductors are Ge and Si. The forbidden band (or energy gap, E_G) of the Ge is 0.785 eV and for the Si, E_G = 1.21 eV at 0°K. An energy with this magnitude is unobtainable from the provided field. The valence band will still be filled, whereas the conduction band will be quite empty. At low temperatures, semiconductors are insulators. However, conductivity will increase with temperature. This type of semiconductors are called intrinsic semiconductors.

- When the temperature is increased, some of the valence electrons will have thermal energy > E_G. These electrons will be able to go to the conduction band. These electrons will then become free electrons and are able to move even though the provided field is small. The once insulator will now behave like a conductor, and is known as a semiconductor.

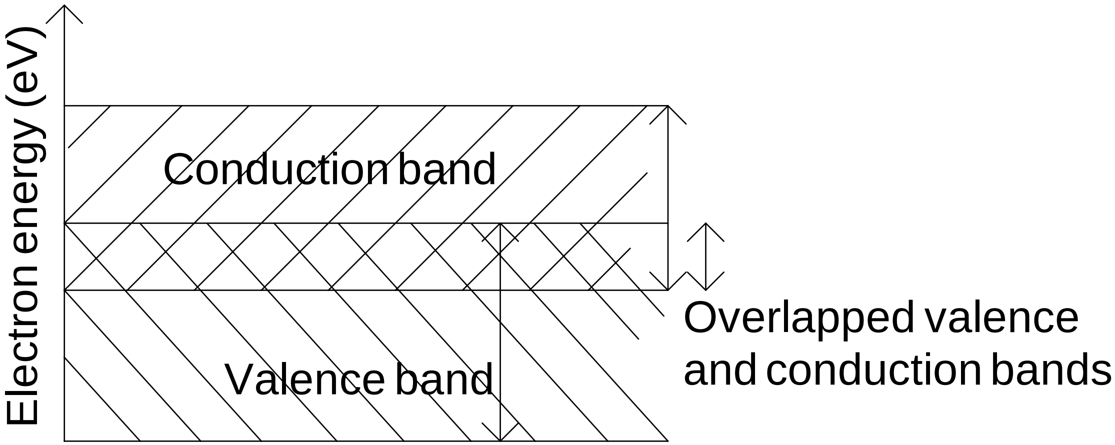

At 0°K
Electron energy (eV)
Conduction band
Forbidden energy band of the semiconductor is about 1 eV
Valence band
At room temperature 300°K
Electron energy (eV)
Conduction band
Free electrons
Forbidden energy band of the semiconductor is about 1 eV
Valence band
Holes

- The free electrons in the conduction band had left an equal number of empty spaces in the valence band. These empty spaces are called holes.
- Holes in the semiconductor represent empty energy levels in the valence band.
- Holes can also be electrical carriers such as free electrons.

- If impurity atoms are injected into the crystal, the impurity level will increase the conductivity. This type of semiconductor is known as extrinsic semiconductor.

METAL (CONDUCTOR)

A solid that has a partially filled band structure is called a metal. When an electrical field is provided across the metal, electrons will obtain additional energy and will move to a higher level. As free electrons produces current, this material is called conductor and the partially filled region is the conduction band. An example of a metal's band structure is shown in the diagram. It is observed that the valence and conduction bands are overlapped.



- The metal's structure condition enables the conducting electrons to be always available. Even without external energy, the valence electrons will always have sufficient energy to enter the conduction band.
- As a comparison, free electron density (n) for:

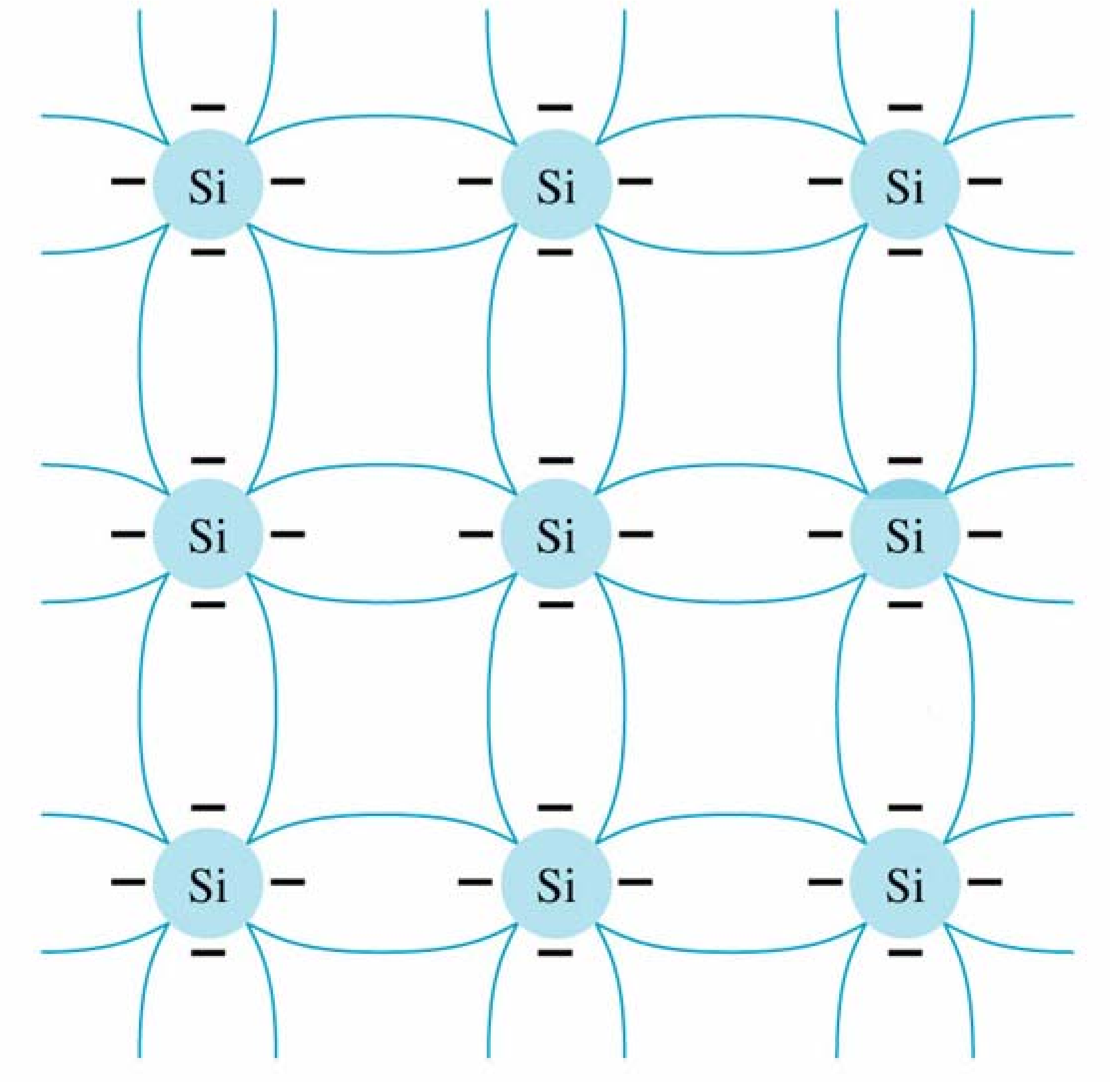
1. a conductor is $n = 10^{28}$ electrons/m^3
2. an insulator is $n = 10^{7}$ electrons/m^3

Semiconductor has n between the two values stated above.

INTRINSIC AND EXTRINSIC SEMICONDUCTORS

Intrinsic semiconductor

Semiconductors made from pure Ge or Si materials are called intrinsic semiconductors. An intrinsic Si crystal is shown in the diagram.



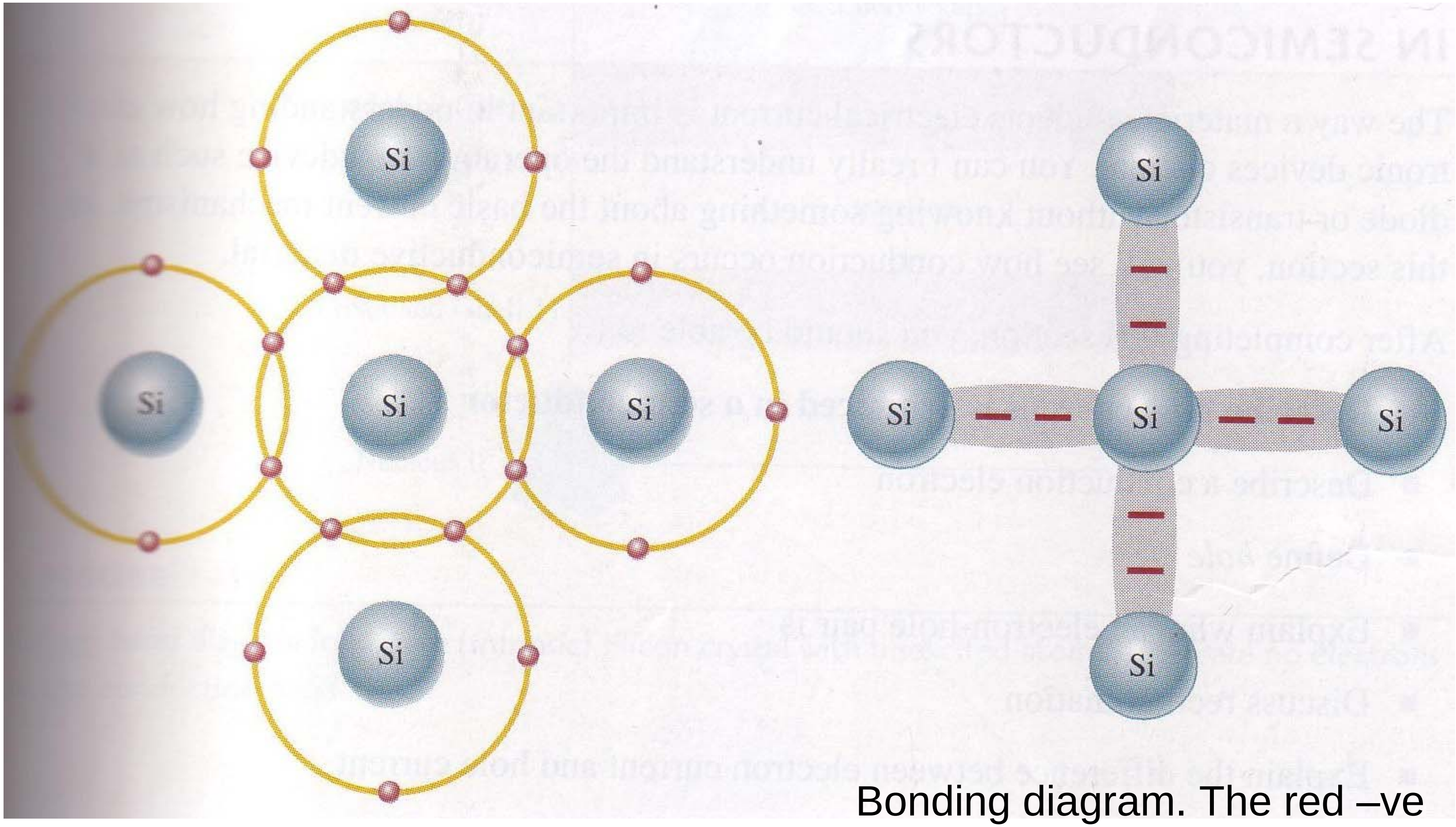
- There are no impurity atoms in the crystal. All the valence electrons are bonded to their own atom and the other atoms by what is called as covalent bond. At 0°K, intrinsic semiconductor behaves like an insulator as it does not have free electrons to flow current.

- When the temperature is increased beyond $0^{\circ}K$, the energy in each atom of the intrinsic semiconductor increases. The valence electrons, especially the ones at the uppermost level of the valence band, will obtain enough energy to separate themselves from the atom and become free electrons. This condition will generate what is known as electron-hole pairs. Consequently, the semiconductor will be quite conducting.

COVALENT BOND

- When the Si atoms combine to form a solid, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms.

Fig. 1-8, Floyd.The centre atom shares an electron with each of the 4 surrounding atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



Bonding diagram. The red –ve signs represent the shared valence electrons

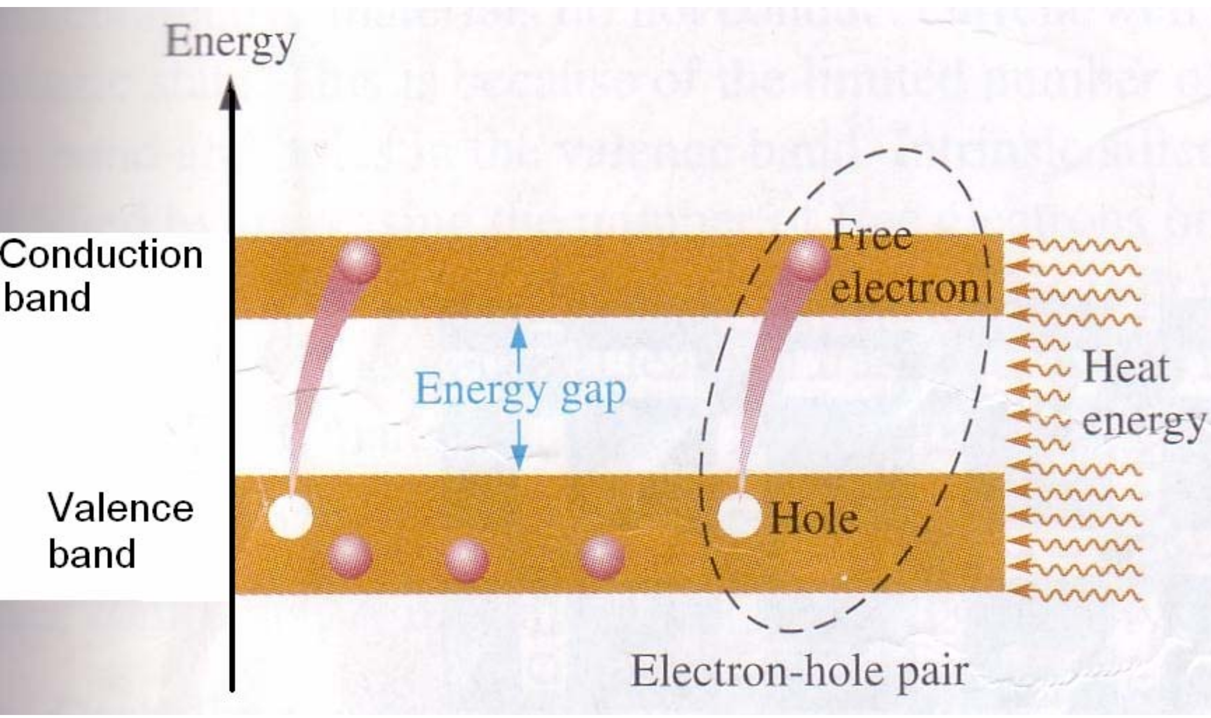
- The diagram shows how each Si atom positions itself with 4 adjacent Si atoms to form a Si crystal.
- 1 atom with its 4 valence electrons shares an electron with each of its 4 neighbours.
- This creates 8 valence electrons for 1 atom and produces a state of chemical stability.
- The sharing of valence electrons produces the valence bonds that hold the atoms together; each shared electron is attracted equally by 2 adjacent atoms which share it. This means that the valence electrons are still bonded to the nucleus. As a result, conductivity is low for pure Si.
- Covalent bonding for Ge is similar as it also has 4 valence electrons.

CONDUCTION ELECTRONS AND HOLES

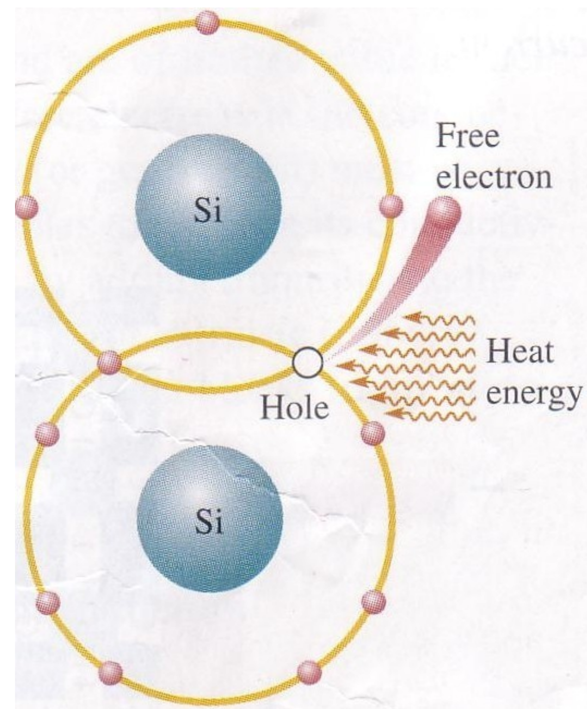
- At room temperature, the Si crystal receives thermal energy from the air. This results in some of the covalent bonds to be broken and the valence electrons will have sufficient energy to enter the conduction band. These electrons will become free electrons or conduction electrons.

- At room temperature, the energy needed to break a covalent bond is 0.72 eV for Ge and 1.1 eV for Si.
- When 1 electron enters the conduction band, 1 empty space is left in the valence band. This empty space is called hole. Thus, an electron hole pair is created.
- The number of holes in the valence band equals the number of electrons in the conduction band.

Fig. 1-11, Floyd. Creation of electron-hole pairs in a Si crystal. Electrons in the conduction band are free electrons.



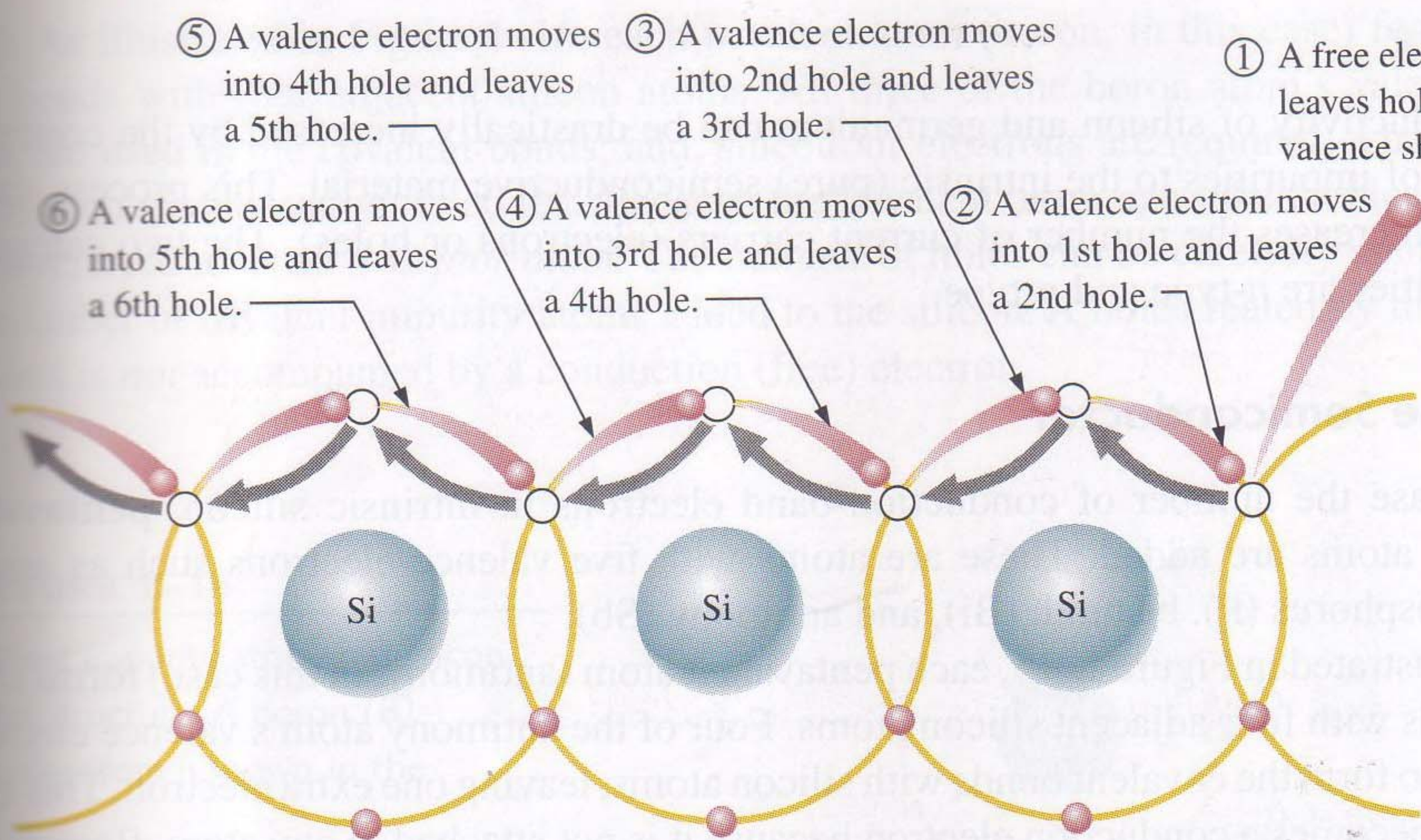
(a) Energy diagram



(b) Bonding diagram

- Holes can carry electricity just like the free electrons.The electrons in the valence band are still bonded to the atom and are unable to move randomly in the crystal structure. However, a valence electron can move to a nearby hole with very little change in energy level. Consequently, a new hole will be created at the level at which the electron comes from.

Fig. 1-14, Floyd. Hole current in intrinsic Si.



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

- The holes’ movement will always be opposite to the electrons’ movement. The movement of holes will generate what is known as hole current. In the flow of electrical current, holes represent the +ve charge that has the same magnitude as the electronic charge.

- In an intrinsic semiconductor:

  number of holes (in the valence band)

  = number of electrons (in the conduction band)

  Hole density, p = electron density, n

  = intrinsic carrier density, n_i

  $$np = n_i^2 = p_i^2 = n_i p_i$$

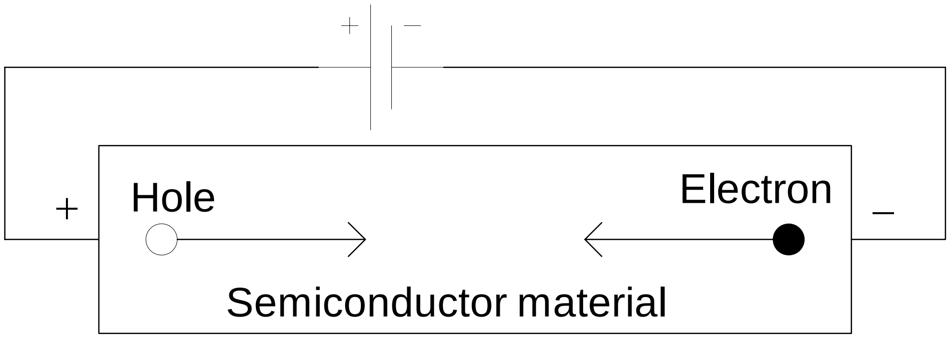
  At room temperature, the intrinsic electron and hole densities are:

  $$n_i = p_i = 2.4 \times 10^{19} \text{ for Ge}$$

  $$n_i = p_i = 1.5 \times 10^{16} \text{ for Si}$$

The flow of current in a semiconductor consists of the flow of electrons and holes.

If a voltage is connected across a semiconductor that contains free electrons and holes, the free electrons will flow towards the +ve voltage teminal and the holes will move towards the –ve voltage terminal. Hence, the current in a semiconductor is constituted of 2 parts, free electrons moving in one direction and holes moving in the opposite direction. Nett current is the total of both parts.



EXTRINSIC SEMICONDUCTOR

- If trivalen (3 valence electrons) or pentavalen (5 valence electrons) atoms are added to the intrinsic Si and Ge, extrinsic/ doped/ impure semiconductors will be formed.
- The impurity atoms are divided into 2:

1. donor impurities
2. acceptor impurities

Intrinsic semiconductor doped with the donor impurities is called extrinsic-n semiconductor.

Intrinsic semiconductor doped with the acceptor impurities is called extrinsic-p semiconductor.