Crystal Structure

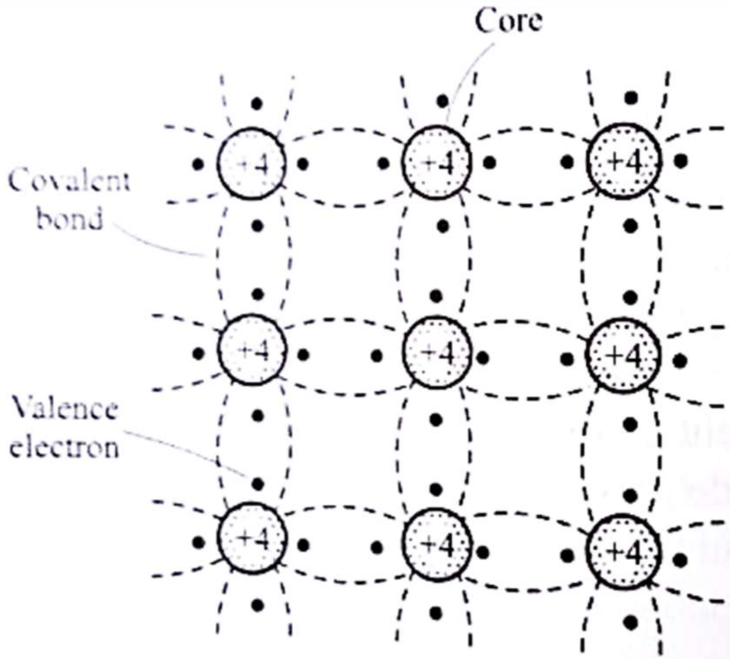
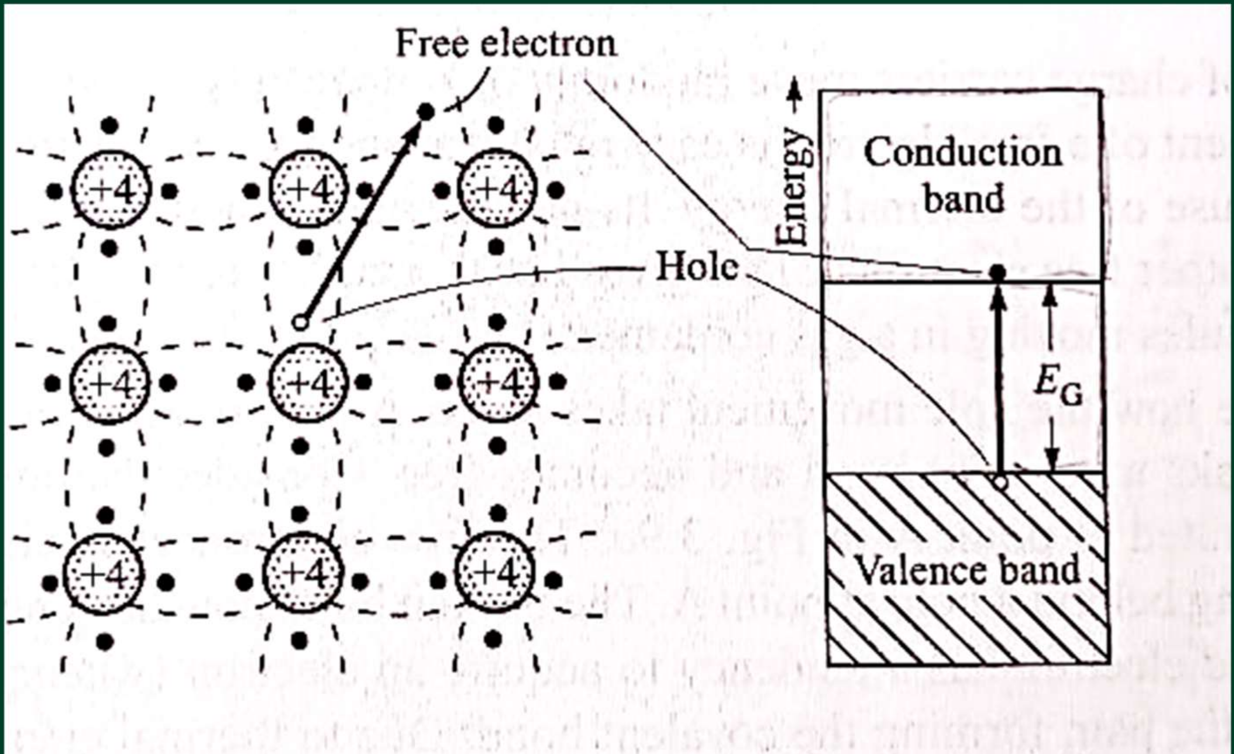


Fig. 3.7 *Simplified representation of the crystalline structure of a semiconductor at absolute zero*

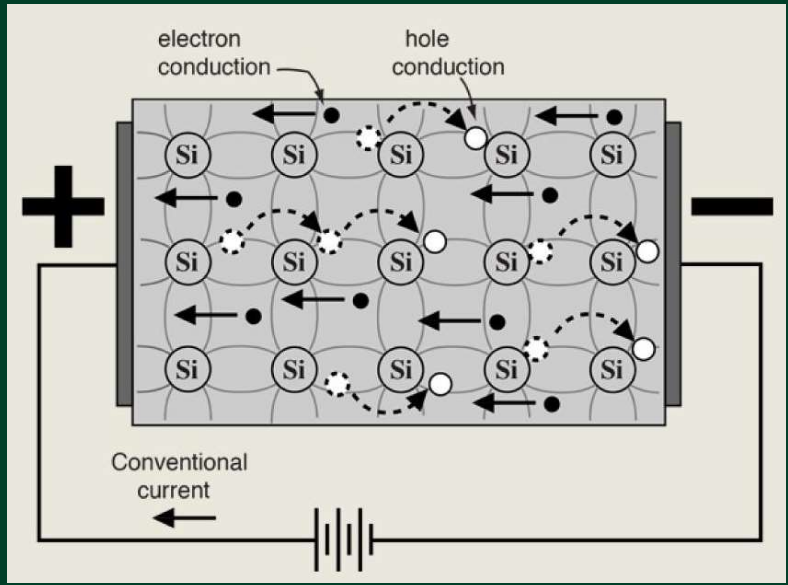
Generation of electron-hole pair in an intrinsic semiconductor



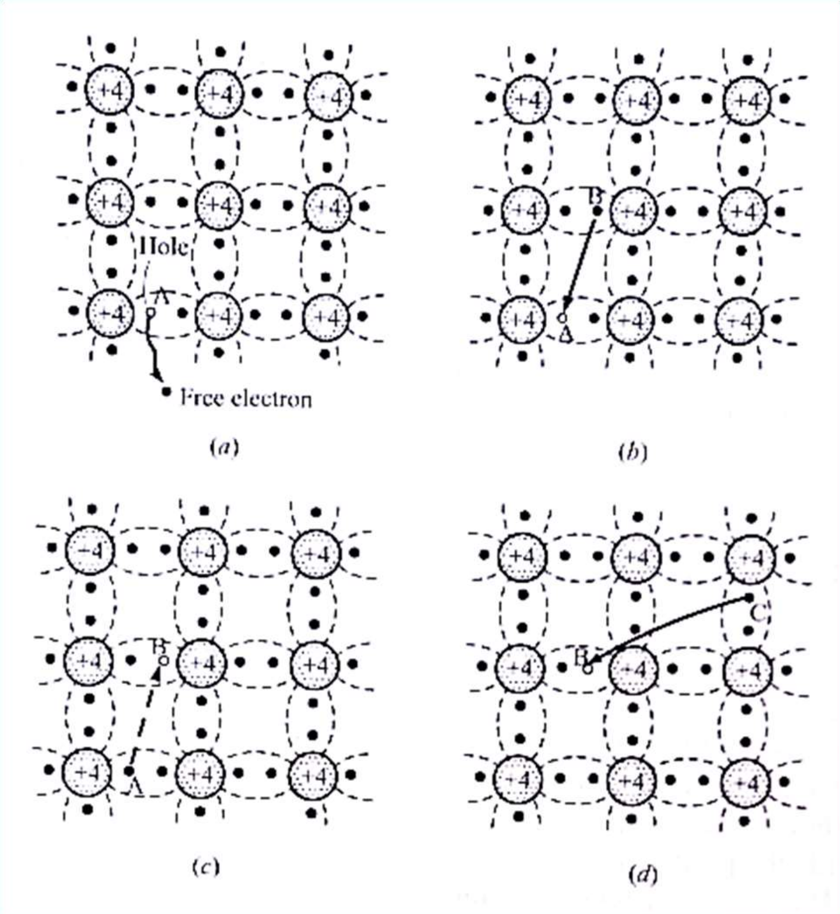
(a) Crystal structure (b) Energy-band diagram

Generation of electron-hole pair in an intrinsic semiconductor

- *A hole is the absence of an electron in the valence band, behaving as a positively charged particle.*
- Holes are not physical particles but represent a lack of electrons, giving rise to apparent positive charge movement.
- Holes play a crucial role in semiconductor conductivity, allowing current flow in devices like diodes and transistors.



Movement of a hole through semiconductor crystal



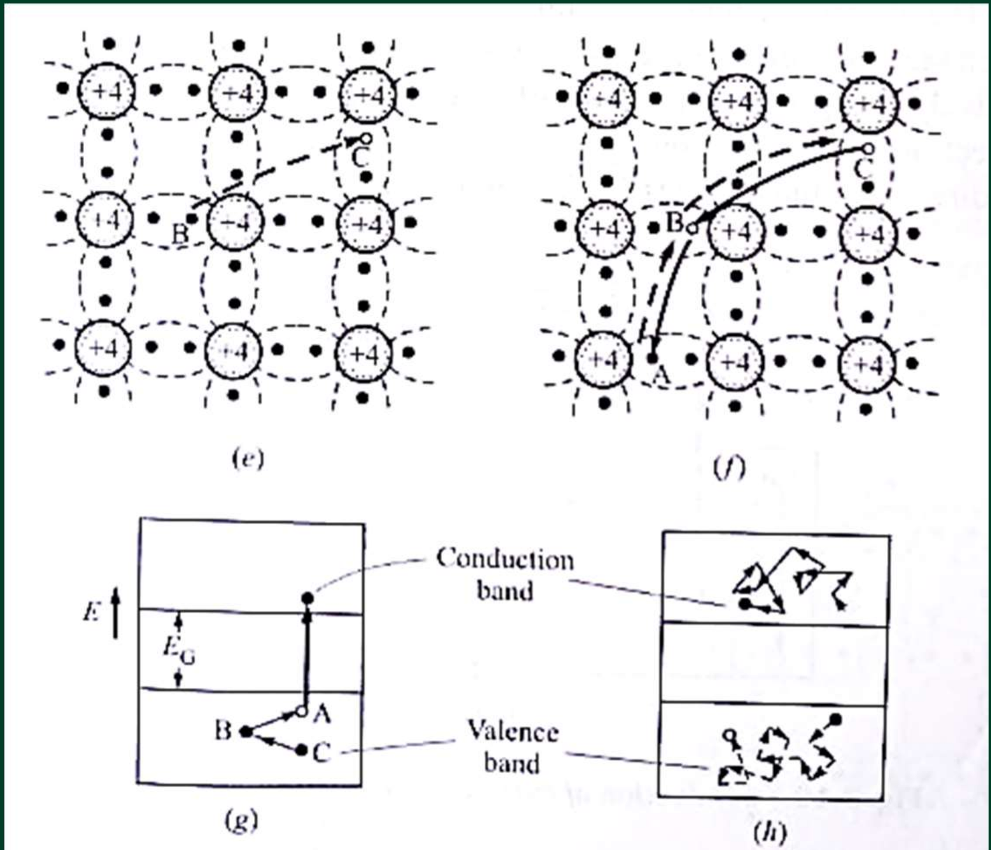


Fig. 3.9 *Movement of a hole through a semiconductor crystal*

Movement of a hole through semiconductor crystal

- *Electron-Hole Pair Creation*: Electrons gain energy (e.g., thermal, light) and jump from the valence to the conduction band.
- Holes "move" as electrons from neighboring atoms fill the empty spot, creating a new hole.
- *Analogy*: Similar to moving an empty seat down a row as people shift over.
- This phenomenon enables holes to act as mobile positive charges.

Movement of a hole through semiconductor crystal

- **1. Random Motion of Electrons in the Conduction Band**
  - **Thermal Energy**:
    - At room temperature, electrons in the conduction band possess enough thermal energy to move randomly.
    - This movement is influenced by collisions with the crystal lattice and other particles within the material.
  - **No Net Current Without Electric Field**:
    - In the absence of an electric field, the random motion of electrons results in no net current, as electrons move equally in all directions.
  - **Kinetic Energy Distribution**:
    - The electrons in the conduction band have a range of kinetic energies, influenced by the distribution of thermal energy across them, typically following a Maxwell-Boltzmann distribution.

Movement of a hole through semiconductor crystal

- **2. Random Motion of Holes in the Valence Band**
  - **Nature of Holes**:
    - Holes represent the absence of electrons in the valence band, so they "move" as neighboring electrons shift to fill these vacancies.
  - **Random Thermal Motion of Holes**:
    - Similar to electrons, holes experience random movement due to thermal energy. This motion is the result of neighboring electrons filling the empty states (holes) in different directions.
  - **Impact on Current**:
    - Without an electric field, the random movement of holes also leads to no net current, as these movements cancel each other out.

Movement of a hole through semiconductor crystal

- **3. Effect of Electric Field on Random Motion**
  - **Directionality Introduced by Electric Field**:
    - When an electric field is applied across the semiconductor, the random motion of electrons and holes is modified to include a drift component.
    - Electrons experience a net movement (or drift) in the direction opposite to the electric field, while holes move in the same direction as the field.
    - This drift component superimposes on the random motion, resulting in a net current flow in the direction of the field.

Conduction of current in an Intrinsic Semiconductor

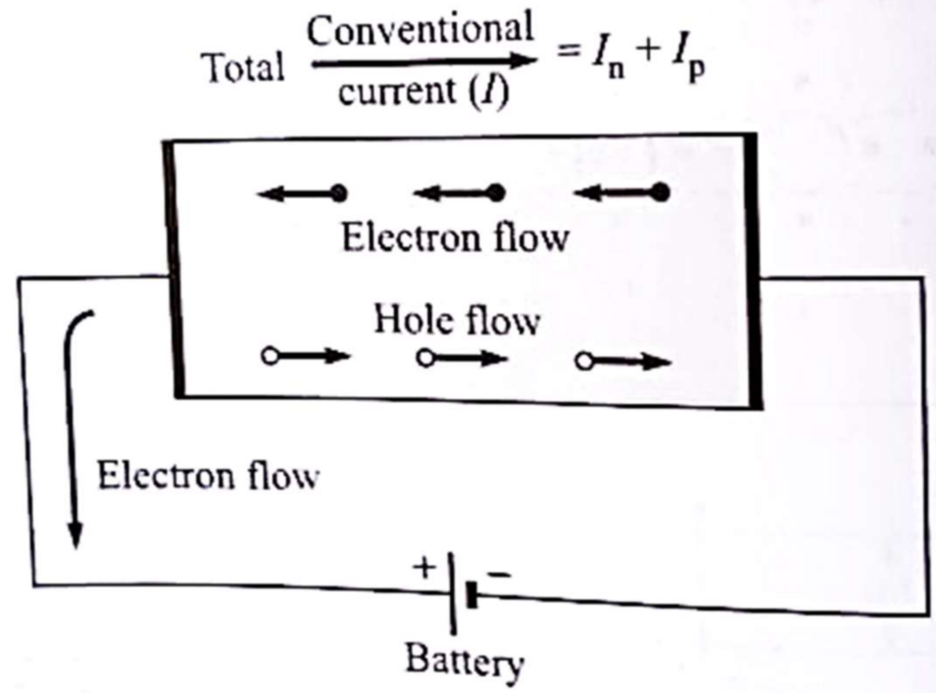


Fig. 3.10 *Conduction of current in an intrinsic semiconductor*

Conduction of current in an Intrinsic Semiconductor

- Random motion does not contribute to any electric current.
- The free electrons drift towards the positive terminal of the battery and the holes towards the negative terminal.
- The electric current flows through the semiconductor in the same direction as in which the holes are moving (the holes have positive charge).
- Since electrons are negatively charged, the direction of electric current (conventional) is opposite the direction of their motion.
- Although, the two types of charge carriers move in opposite directions, the two currents are in the same direction. They add together ($I_n + I_p$)

Conduction of current in an Intrinsic Semiconductor

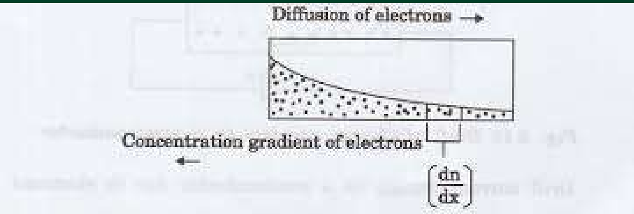


Fig. 3.14 Uneven distribution of electrons in a semiconductor

- When the flow of carriers is dud to an applied voltage, the resultant current is called as drift current.
- Another current also exists in a semiconductor called as diffusion current.
- It is result of a gradient of carrier concentration (i.e. the difference of carrier concentration from one region to another.
- A gradient of carrier concentration arises near the boundary of a PN Junction
- The diffusion current is also due to the motion of both holes and electrons.

Conduction of current in an Intrinsic Semiconductor

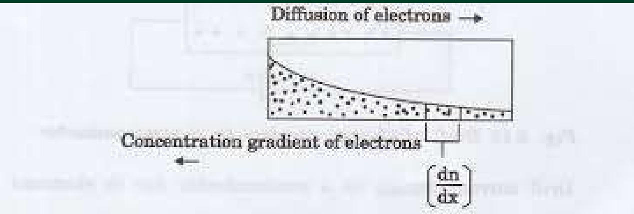


Fig. 3.14 Uneven distribution of electrons in a semiconductor

- Drift Current:
  - Caused by the movement of electrons and holes under an electric field, contributing to a net current.
- Diffusion Current:
  - Arises due to the concentration gradient of carriers, where electrons and holes move from regions of high concentration to low concentration, leading to current even without an applied electric field.

Conduction of current in an Intrinsic Semiconductor

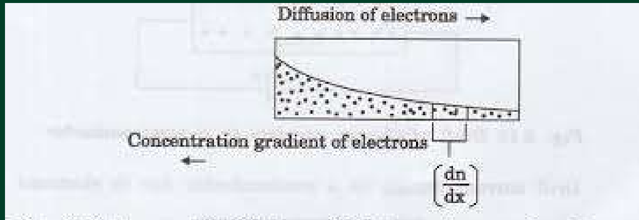


Fig. 3.14 Uneven distribution of electrons in a semiconductor

- **5. Importance of Random Motion in Semiconductors**
  - **Thermal Equilibrium**:
    - Random motion helps maintain thermal equilibrium in semiconductors, essential for the consistent operation of semiconductor devices.
  - **Conduction Characteristics**:
    - The interplay between random and drift motion determines the overall conductivity of the material.
    - The random thermal motion is a baseline effect, while applied fields or gradients introduce directionality and influence semiconductor behavior in devices.

287 Effect of Temperature on Conductivity of Intrinsic Semiconductors

- A semiconductor at absolute zero, behaves as a perfect insulator.
- At room temperature, because of thermal energy, some electron hole pairs are generated.
- E.g. Germanium at room temperature (300K) the intrinsic carrier concentration (i.e. concentration of free electrons or holes) is 2.5×10^{19} per m^3.
- The semiconductor has a small conductivity.
- Now, if we raise the temperature further, more electron holes pairs are generated.
- The higher the temperature, the higher is the concentration of charge carriers.
- Therefore, the conductivity of an intrinsic semiconductor increases with temperature.
- Semiconductors have negative temperature coefficient of resistance.

Extrinsic Semiconductor

- The process of deliberately adding impurities to a semiconductor material is called doping.
- Doping is done after the semiconductor material has been refined to a high degree of purity.
- A doped semiconductor is called as extrinsic semiconductor.
  - N - Type Semiconductors and
  - P - Type Semiconductors

289 N- Type Semiconductor

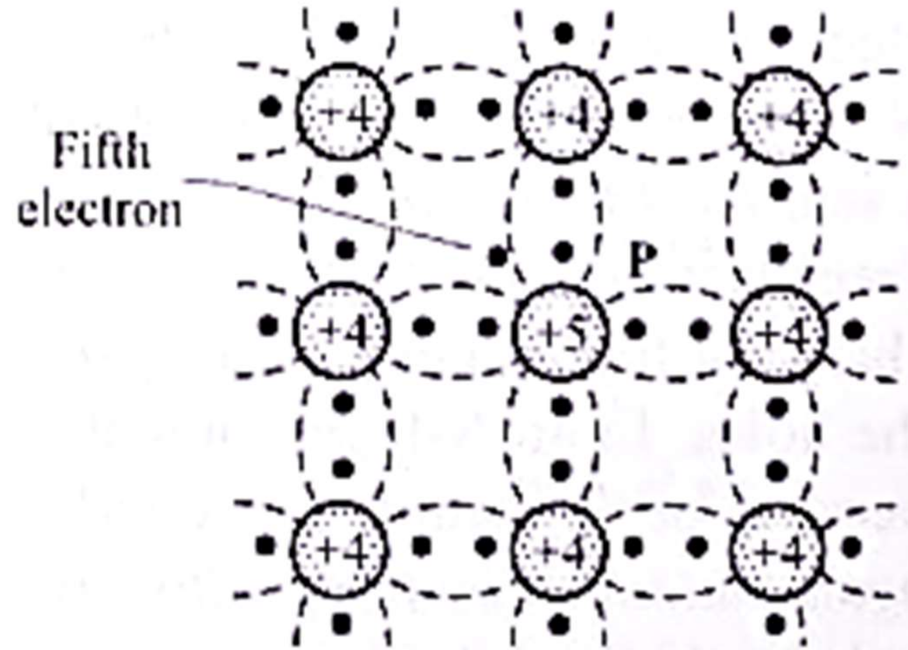


Fig. 3.11 *N-type semiconductor*

290 N- Type Semiconductor

- 1. **Free Electrons in an n-Type Semiconductor**
  - **Definition**:
    - Free electrons in an n-type semiconductor are the extra electrons provided by donor atoms (impurities) that are not bound to the atomic structure and can move freely within the conduction band.
  - Source:
    - N-type semiconductors are created by doping a pure semiconductor (like silicon) with a pentavalent element (such as phosphorus or arsenic). These elements have five valence electrons, one more than silicon.
  - Conductivity Role:
    - The extra electron from each donor atom is loosely bound and requires very little energy to move into the conduction band.
    - Once in the conduction band, these electrons are free to move under the influence of an electric field, thus carrying current.
  - Majority Carrier:
    - In n-type semiconductors, free electrons are the majority charge carriers, meaning they are primarily responsible for electrical conductivity.

291 N- Type Semiconductor

- 2. **Holes in an n-Type Semiconductor**
  - Definition:
    - A hole is a vacancy in the valence band where an electron is absent, behaving like a positively charged particle.
  - Minority Carrier:
    - In n-type semiconductors, holes are present in much smaller numbers than free electrons, as they arise mainly due to thermal excitation (some electrons in the valence band gain enough energy to jump to the conduction band, leaving behind holes).
    - As the number of electrons is very large, the chances of their recombination with holes also increases.
    - Therefore, the net concentration of holes is very less compared to the intrinsic value.
    - N-type has electrons (negatively charged) as majority carriers, and holes as minority carriers.
  - Conductivity Role:
    - Although they contribute to conductivity, holes play a much smaller role in n-type materials because their concentration is low compared to the concentration of free electrons.

292 N- Type Semiconductor

- **3. Positively Charged Ions (Fixed Donor Ions)**
  - **Definition**:
    - In an n-type semiconductor, when a donor atom releases its extra electron to the conduction band, it becomes a positively charged ion (since it lost a negatively charged electron).
  - **Fixed in Lattice**:
    - These positive ions are fixed in the crystal lattice and cannot move freely; they do not contribute directly to electrical conductivity.
  - **Role in Charge Neutrality**:
    - These positively charged donor ions balance the negative charge of free electrons, helping maintain overall charge neutrality in the semiconductor material.

293 N- Type Semiconductor

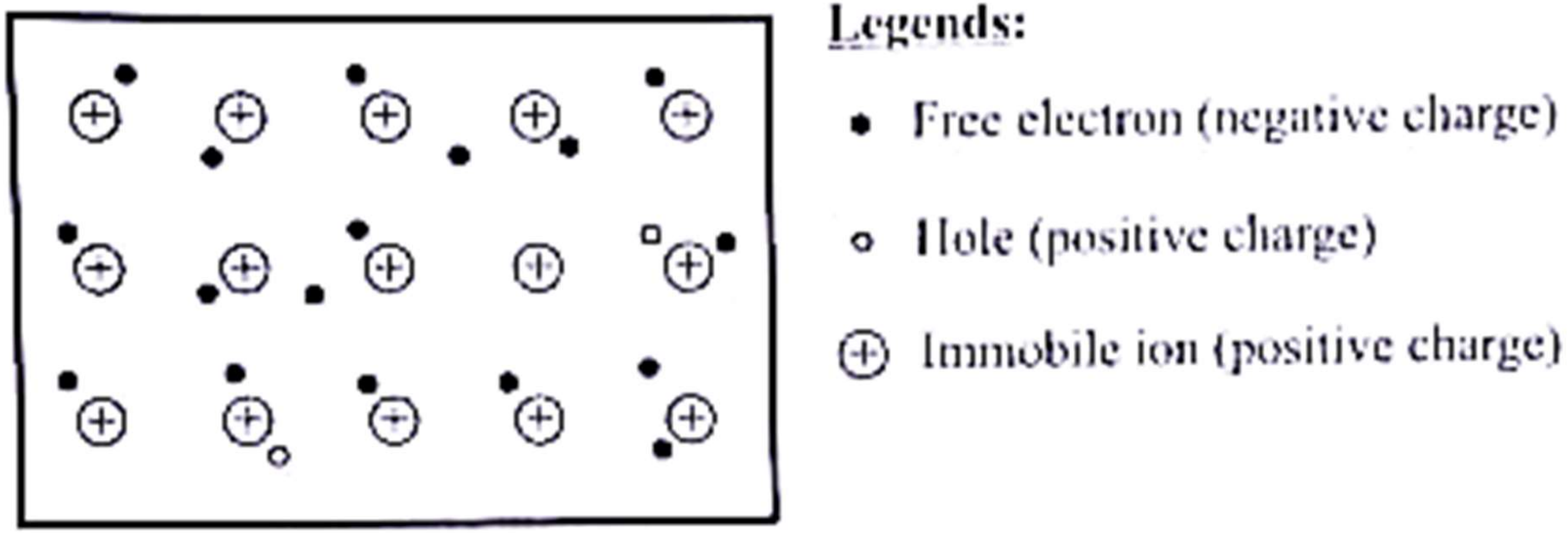


Fig. 3.12 *Representation of an N-type semiconductor*

294 N- Type Semiconductor

- **Summary of Charge Carriers and Behavior**
  - **Majority Carriers**: Free electrons are the primary carriers of electric current in an n-type semiconductor.
  - **Minority Carriers**: Holes are present but in a much smaller concentration, playing a minor role in conductivity.
  - **Fixed Ions**: Positively charged donor ions are fixed in place within the crystal lattice, serving to balance the free electrons and maintain overall charge neutrality.
  - The combined action of free electrons and fixed ions ensures that n-type semiconductors conduct electricity effectively under an electric field, with electrons providing the primary conduction path.

295 P- Type Semiconductor

- **1. Holes in a p-Type Semiconductor**
  - **Definition**:
    - Holes are the primary charge carriers in a p-type semiconductor.
    - A hole is essentially a vacancy in the valence band where an electron is missing, which behaves like a positively charged particle.
  - **Source**:
    - P-type semiconductors are created by doping a pure semiconductor (like silicon) with a trivalent element (such as boron or gallium).
    - These elements have only three valence electrons, one fewer than silicon, so they create a deficiency of electrons (holes) when bonded into the silicon lattice.
  - **Conductivity Role**:
    - Holes act as the majority charge carriers in a p-type semiconductor.
    - When an electric field is applied, nearby electrons in the valence band move to fill these holes, causing the holes to appear to "move" in the direction of the field.
    - This "movement" of holes constitutes electric current.
  - **Majority Carrier**:
    - In p-type semiconductors, holes are the majority carriers, meaning they are the main contributors to electrical conductivity.

296 P- Type Semiconductor

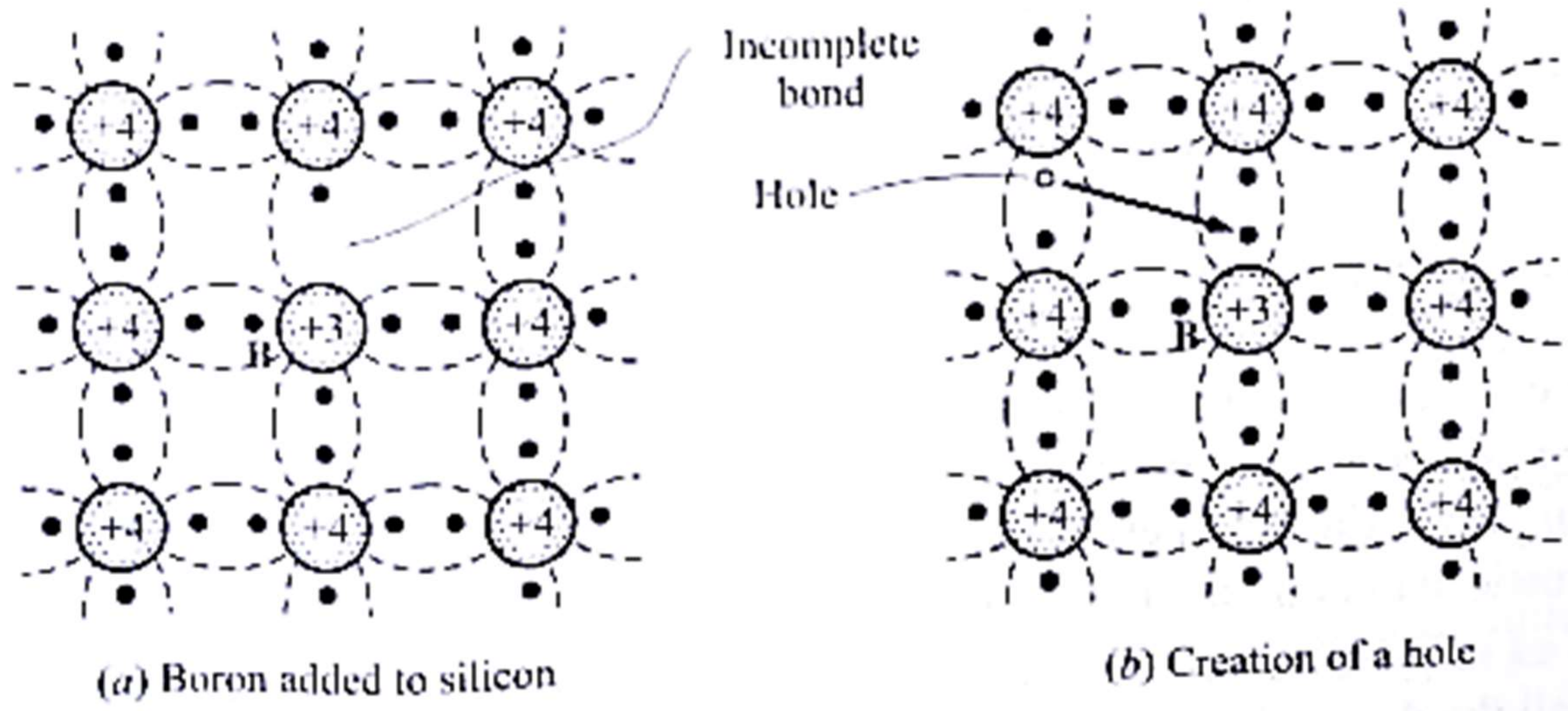


Fig. 3.13 P-type semiconductor

297 P- Type Semiconductor

- **2. Free Electrons in a p-Type Semiconductor**
  - **Definition**:
    - Free electrons are negatively charged particles that can move within the material.
  - **Minority Carrier**:
    - In p-type semiconductors, free electrons are present in much smaller numbers than holes.
    - They are created primarily by thermal excitation, where electrons gain enough energy to jump from the valence band to the conduction band, leaving behind a hole.
  - **Conductivity Role**:
    - Although they contribute to conductivity, free electrons play a much smaller role in p-type materials because they are the minority carriers.

298 P- Type Semiconductor

- **3. Negatively Charged Ions (Fixed Acceptor Ions)**
  - **Definition**:
    - In a p-type semiconductor, when an acceptor atom (like boron) "captures" an electron from the silicon lattice to complete its bond, it becomes a negatively charged ion (since it has gained an extra electron).
  - **Fixed in Lattice**:
    - These negatively charged acceptor ions are fixed in place within the crystal lattice and do not move freely, so they do not contribute to electric current.
  - **Role in Charge Neutrality**:
    - The negatively charged acceptor ions balance the positive charge of the holes, maintaining overall charge neutrality in the semiconductor.

299 P- Type Semiconductor

- **Summary of Charge Carriers and Behavior**
  - **Majority Carriers**:
    - Holes are the primary carriers of electric current in a p-type semiconductor.
  - **Minority Carriers**:
    - Free electrons are present but in a much smaller concentration, playing a minor role in conductivity.
  - **Fixed Ions**:
    - Negatively charged acceptor ions are fixed in the lattice, serving to balance the positive charge of holes and maintain charge neutrality.
  - In summary, in a p-type semiconductor, the conductivity is primarily due to the movement of holes, which act as positively charged carriers. The negatively charged fixed ions ensure charge neutrality but do not participate in current conduction.

Effect of Temperature on Extrinsic Semiconductors

- In N-type semiconductor, since all the donors have already donated their free electrons at room temperature, the additional thermal energy only serves to increase the thermally generated carriers.
- As a result, the concentration of minority carriers increases.
- When a critical temperature is reached, the number of covalent bonds that are broken is very large, so that the number of holes is approximately the same as the number of electrons.
- The extrinsic semiconductor now behaves like a intrinsic semiconductor.
- The critical temperature is 85 C for germanium and 200 C for silicon.

Effect of Temperature on Extrinsic Semiconductors

- **1. Carrier Concentration**
  - In extrinsic semiconductors, charge carriers are mainly introduced by doping rather than thermal generation.
  - **Low Temperatures:**
    - At very low temperatures, dopant atoms may not have enough energy to ionize (i.e., to release free electrons or holes).
    - This means that extrinsic semiconductors can act as insulators if the temperature is too low, as very few free carriers are available.
  - **Room Temperature and Above:**
    - At moderate temperatures, most dopant atoms are ionized, contributing to a stable level of free carriers.
    - This temperature range is typically where extrinsic semiconductors operate effectively.
  - **High Temperatures:**
    - As temperature increases further, intrinsic carrier generation (due to thermal excitation) becomes significant.
    - In this regime, intrinsic carriers (electrons and holes created thermally) can outnumber the carriers introduced by doping, causing the semiconductor to behave more like an intrinsic semiconductor.

302 Effect of Temperature on Extrinsic Semiconductors

- **2. Conductivity and Resistivity**
  - **Increased Conductivity:**
    - Conductivity in semiconductors generally increases with temperature, as more carriers are generated.
    - In extrinsic semiconductors, the initial increase in temperature raises carrier mobility up to a point.
  - **Saturation and Decrease of Resistivity:**
    - With sufficient temperature increase, resistivity decreases as carrier concentration rises, but mobility might decrease due to increased lattice vibrations (phonon scattering).
  - **Onset of Intrinsic Behavior:**
    - At very high temperatures, as intrinsic carriers dominate, the material's conductivity increases sharply.