Module III

PN Junction Diode:

How PN Junction is formed

- **. Starting Material - Wafer Preparation**
  - The process begins with a thin, flat wafer of pure semiconductor material, usually silicon, which serves as the substrate.
  - The wafer is created through a process called **Czochralski crystal growth**, in which a single silicon crystal is grown and then sliced into wafers.
  - The wafers are polished and cleaned to remove any impurities or surface irregularities.

How PN Junction is formed

2. Doping to Create P-type and N-type Regions
   - Photolithography:
     - A photosensitive material (photoresist) is applied to the wafer, and a specific pattern is transferred to the wafer by exposing it to light through a mask.
     - This pattern determines where doping will occur.
   - Etching:
     - After photolithography, the exposed photoresist is chemically etched away to reveal areas where doping is required.

- Doping Process:
  - There are two main doping methods:
  - Diffusion Doping:
    - The wafer is exposed to a high-temperature environment containing a gas with the desired dopant (e.g., boron for P-type, phosphorus for N-type).
    - At high temperatures, the dopant atoms diffuse into the exposed silicon areas.
  - Ion Implantation:
    - A high-energy beam of ions (dopant atoms) is directed at the wafer. The ions penetrate the silicon in the exposed regions, embedding themselves at controlled depths and concentrations.

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How PN Junction is formed

- **3. Formation of the PN Junction**
  - By selectively doping the wafer with P-type and N-type materials in adjacent regions, a **PN junction** is formed where the two regions meet.
  - The doping concentrations and junction depth are controlled to set the electrical properties of the PN junction.
  - This step creates the depletion region around the junction, crucial for the diode's rectifying properties.

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Junction Theory

- The most important characteristic of a PN junction is its ability to conduct current in one direction only.
- In the other (reverse) direction, it offers very high resistance.
  - PN Junction with no External Voltage
  - PN Junction with Forward Bias
  - PN Junction with Reverse Bias

PN Junction with no External Voltage

- The P region has holes and negatively charged ions.
- The N region has free electrons and positively charged impurity ions.
- Holes and electrons are mobile charges, but the ions are immobile.
- The sample as a whole is electrically neutral and so are the P region and N region considered separately.
- Therefore in the P region, the charge of moving holes equal the total charges on its free electrons and immobile ions.
- Similarly in the N region, the negative charge of its majority carriers is compensated by the charge of its minority carriers and immobile ions.

A PN Junction when just formed

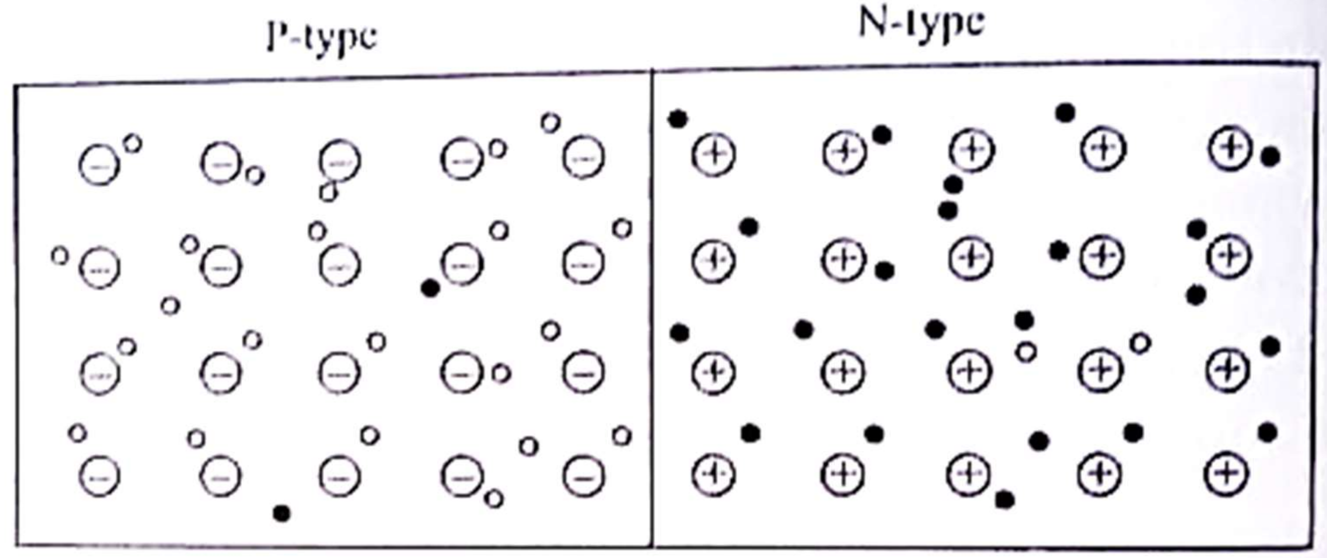

Fig. 4.1 *A PN-Junciton when just formed*

A PN Junction when just formed

- **Formation of Depletion Region:**
  - When a p-type and n-type semiconductor are joined, electrons from the n-region diffuse into the p-region and recombine with holes. Similarly, holes from the p-region diffuse into the n-region.
  - This creates a region devoid of free carriers (depletion region) near the junction.
  - Fixed ions are left behind in the depletion region: negatively charged ions in the p-region and positively charged ions in the n-region.
- **Built-in Electric Field:**
  - The recombination of carriers leaves behind a built-in electric field across the junction.
  - This electric field opposes further diffusion of carriers.
- **Equilibrium:**
  - A dynamic equilibrium is established, where the diffusion of carriers is balanced by the drift caused by the electric field.
  - The net current across the junction is zero.

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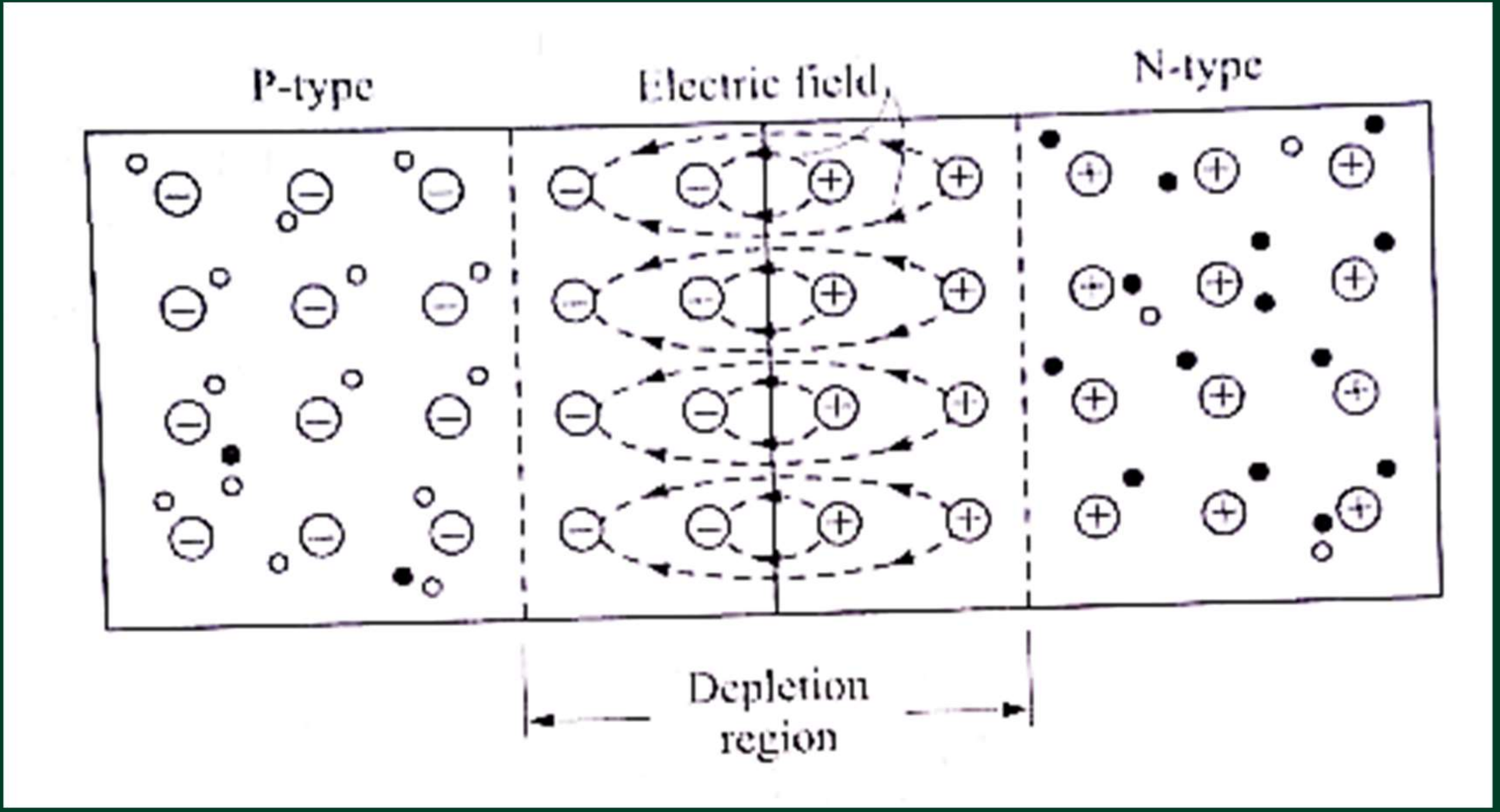
Space charge region or depletion region is formed on the vicinity of the junction



PN Junction showing Forward Bias

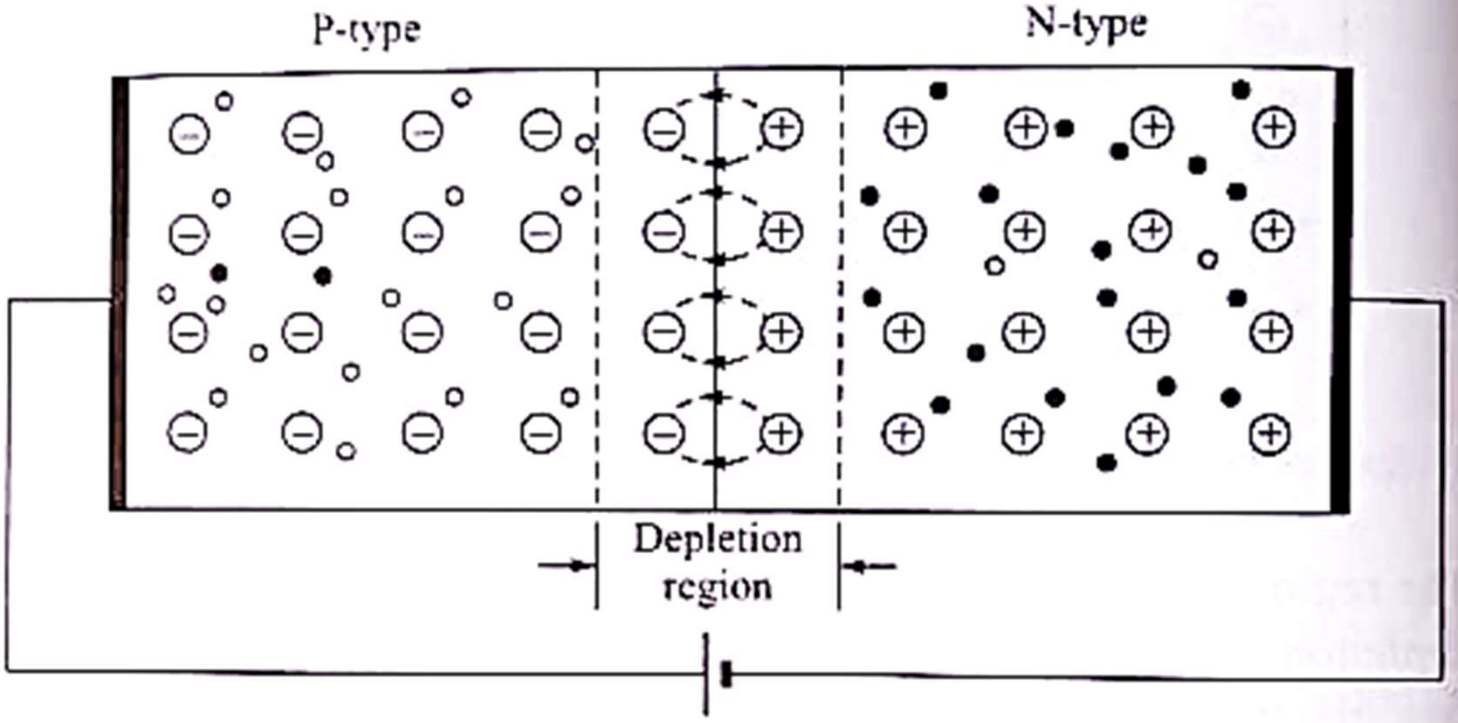


Fig. 4.3 *PN-junction showing forward bias*

PN Junction showing Forward Bias

- External Voltage Applied:
  - The p-side is connected to the positive terminal, and the n-side to the negative terminal of a voltage source.
- Reduction of Depletion Region:
  - The external voltage reduces the built-in electric field by supplying energy that allows carriers to overcome the potential barrier.
  - This narrows the depletion region.
- Carrier Movement:
  - Electrons from the n-side move toward the junction and recombine with holes in the p-side.
  - Holes from the p-side move toward the junction and recombine with electrons in the n-side.
- Current Flow:
  - A significant current flows through the junction due to the movement of majority carriers.

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PN Junction showing Forward Bias

- **Forward Bias Connection**:
  - The **positive terminal** of the battery is connected to the **P-side**.
  - The **negative terminal** of the battery is connected to the **N-side**.
  - This configuration reduces the potential barrier at the PN junction, allowing current to flow.

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PN Junction showing Forward Bias

- **Behavior in Forward Bias**:
  - **Holes (P-side)**:
    - The positive terminal of the battery repels the holes, pushing them towards the junction.
  - **Electrons (N-side)**:
    - The negative terminal repels electrons, causing them to drift toward the junction.
  - The movement of majority carriers (holes and electrons) reduces the width of the **depletion region**.
  - The **barrier potential** decreases, enabling charge carriers to diffuse across the junction.
  - When majority carriers (holes and electrons) meet at the junction, they **recombine**, producing a continuous flow of current.

PN Junction showing Forward Bias

- External Current Flow:
  - For every recombination at the junction:
  - An electron from the battery enters the N-side, replenishing free electrons.
  - A hole is created in the P-side, replenished by electrons from the battery.
  - The circuit maintains a continuous flow of charge.
- Effect of Increased Voltage:
  - Raising the battery voltage further reduces the barrier potential.
  - This increases the diffusion of majority carriers, leading to a higher current through the diode.

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PN Junction showing Reverse Bias

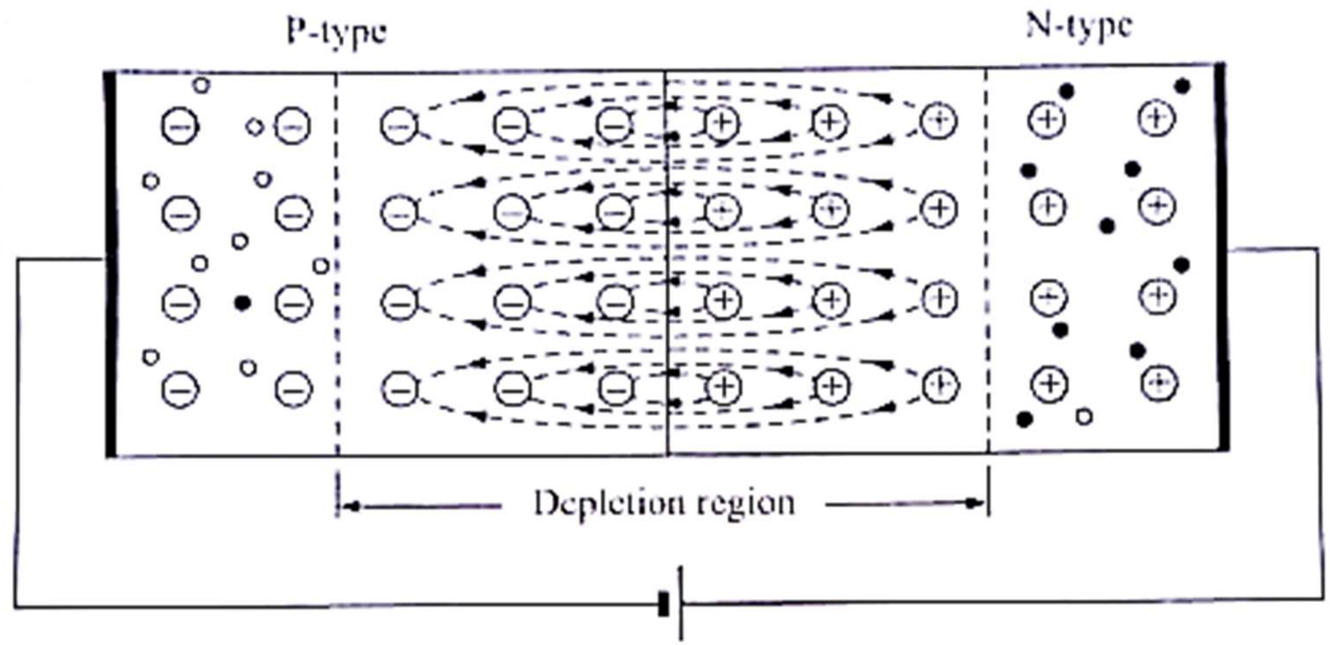

Fig. 4.4 *PN-junction showing reverse bias*

PN Junction showing Reverse Bias

- The holes in the P-region are attracted towards the negative terminal of the battery.
- The electrons in the N-region are attracted to the positive terminal of the battery.
- The majority carriers are drawn away from the junction. This action widens the depletion region and increases the barrier potential

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PN Junction showing Reverse Bias

- The increased barrier potential makes it more difficult for the majority carriers to diffuse across the junction.
- However, this barrier potential is helpful to the minority carriers in crossing the junction.
- In fact, as soon as a minority carrier is generated, it is swept (or drifted) across the junction because of the barrier potential.
- The rate of generation of minority carriers depends upon temperature.
- If the temperature is fixed, the rate of generation of minority carriers remains constant.
- Therefore, the current due to the flow of minority carriers remains the same whether the battery voltage is low or high. For this reason, this current is called **reverse saturation current.**
- This current is very small as the number of minority carriers is small.
- It is of the order of nanoamperes in silicon diodes and microamperes in germanium diodes.

PN Junction showing Reverse Bias

- There is another point to note.
- The reverse-biased PN-junction diode has a region of high resistivity (space charge or depletion region) sandwiched between two regions (P and N regions away from the junction) of relatively low resistivity.
- The P and N regions act as the plates of a capacitor and the space-charge region acts as the dielectric.
- Thus, the PN-junction in reverse bias has an effective capacitance called **transition or depletion capacitance.**

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PN Junction showing Reverse Bias

- We have seen that a PN-junction allows a very small current to flow when it is reverse biased.
- This current is due to the movement of minority carriers.
- It is almost independent of the voltage applied.
- However, if the reverse bias is made too high, the current through the PN-junction increases abruptly (see Fig. 4.5).
- The voltage at which this phenomenon occurs is called **breakdown voltage**.
- At this voltage, the crystal structure breaks down. In normal applications, this condition is avoided.
- The crystal structure will return to normal when the excess reverse bias is removed, provided that overheating has not permanently damaged the crystal.

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PN Junction showing Reverse Bias

- Depletion Region Expansion:
  - The external voltage widens the depletion region, as shown by the extended charge separation.
  - The negative terminal of the battery repels holes in the p-type region, while the positive terminal attracts electrons in the n-type region.
- Built-in Electric Field Enhancement:
  - The external voltage adds to the built-in potential, increasing the barrier for carrier movement.
- Minority Carrier Flow:
  - The current is due to the drift of minority carriers (electrons in the p-region and holes in the n-region), but this current is extremely small (reverse saturation current).
- No Majority Carrier Flow:
  - Majority carriers are prevented from crossing the junction because of the enhanced barrier.

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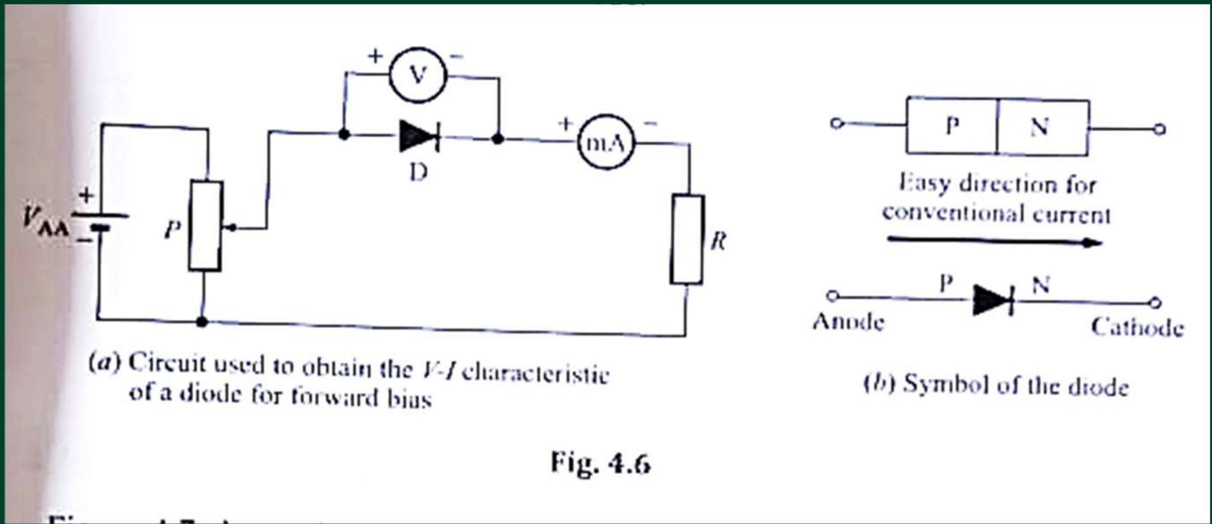
PN Junction showing Reverse Bias

- External Voltage Applied:
  - The p-side is connected to the negative terminal, and the n-side to the positive terminal of a voltage source.
- Expansion of Depletion Region:
  - The external voltage increases the built-in electric field, widening the depletion region.
- Carrier Movement:
  - Majority carriers are pushed away from the junction.
  - Minority carriers (thermally generated electrons in the p-side and holes in the n-side) are attracted across the junction, creating a very small reverse saturation current.
- **Current Flow:**
  - The current is minimal (reverse saturation current), as only minority carriers contribute.

Forward Bias Characteristics of Diode



(a) Circuit used to obtain the V-I characteristic of a diode for forward bias

(b) Symbol of the diode

Fig. 4.6

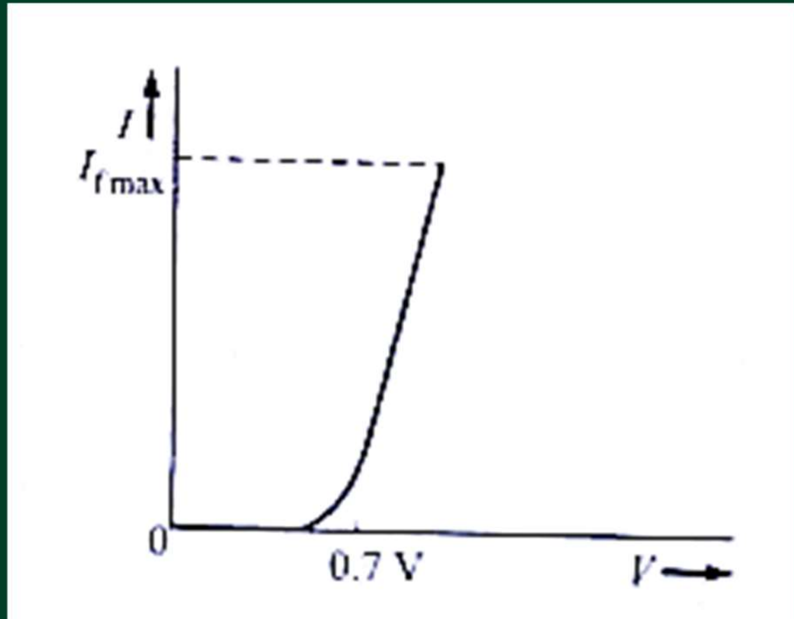
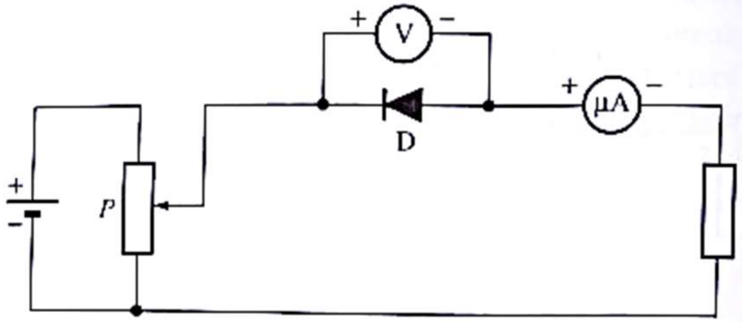


Fig. 4.7 *Forward characteristics of a silicon diode*

Reverse Bias Characteristics of a Diode



(a) Circuit to plot reverse-bias characteristics of a diode

(b) Reverse-bias characteristics

Fig. 4.8