Chapter 1: Diode and Semi-conductor

1.1.Introduction

In semiconductor physics, a **PN junction** refers to a region of a crystal where the doping changes abruptly, from P-type to N-type. When the P-doped region comes into contact with the N-doped region, electrons and holes spontaneously diffuse across the junction. This diffusion leads to the formation of a **depletion region**, where the concentration of free charge carriers is almost zero. The width of the depletion region depends on the voltage applied across the junction: the narrower this region is, the lower the junction resistance becomes.

This chapter is devoted to the study of semiconductors, the PN junction, and other fundamental concepts related to this topic.

1.2. Reminder on the Structure of Matter

Matter is composed of atoms, which consist of a central nucleus and electrons that move around it.

The nucleus is made up of **protons**, which are positively charged particles with a mass of **1.67×10^{-27} kg** and an electric charge of **$+1.6 \times 10^{-19}$ C**, and **neutrons**, which are electrically neutral and have a mass close to that of protons.

Electrons are much lighter particles, with a mass of **9.1×10^{-31} kg** and a negative elementary electric charge of **-1.6×10^{-19} C**. They occupy the space surrounding the nucleus and are responsible for the electrical properties of matter.

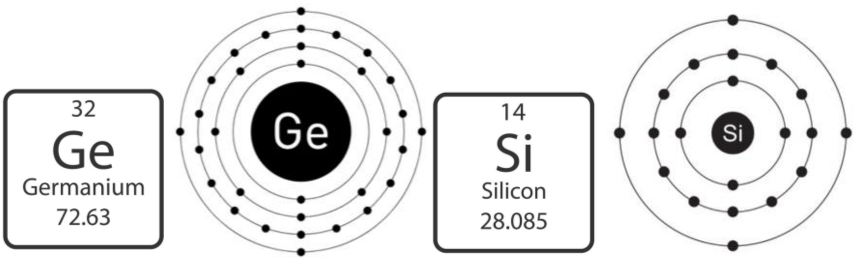


Figure 1.1: Silicon and Germanium atoms.

1.3. Energy Bands

In a solid, atomic electrons occupy energy bands separated by forbidden gaps. Only the **two outer bands** determine the electrical properties.

- **Conduction Band (CB):** the highest energy band; electrons in this band are free to move and contribute to electrical conduction. It may be empty.
- **Valence Band (VB):** located below the conduction band; it contains bound electrons and is never empty.

- **Band Gap (Forbidden Band):** the energy region between the valence band and the conduction band where no electron states exist.

Electrons can exist in three energy states:

- **V state:** bound electrons in the valence band.
- **C state:** free electrons in the conduction band.
- **S state:** electrons that have left the solid (zero energy level).

1.4. Classification of Materials

Solid materials are classified into **conductors, insulators, and semiconductors** according to their electrical properties.

- **Conductors:** very low resistivity; the valence band and conduction band overlap, allowing free movement of electrons and high conductivity (e.g., copper, silver, aluminum).
- **Insulators:** very high resistivity (> 10^6 Ω·m); a wide band gap (~7 eV) separates the valence and conduction bands, preventing current flow under normal conditions (e.g., glass, wood, plastic).
- **Semiconductors:** intermediate resistivity (10^{-4} to 10^2 Ω·m); a small band gap (~1 eV). At 0 K they behave as insulators, but their conductivity increases with temperature (e.g., silicon, germanium).

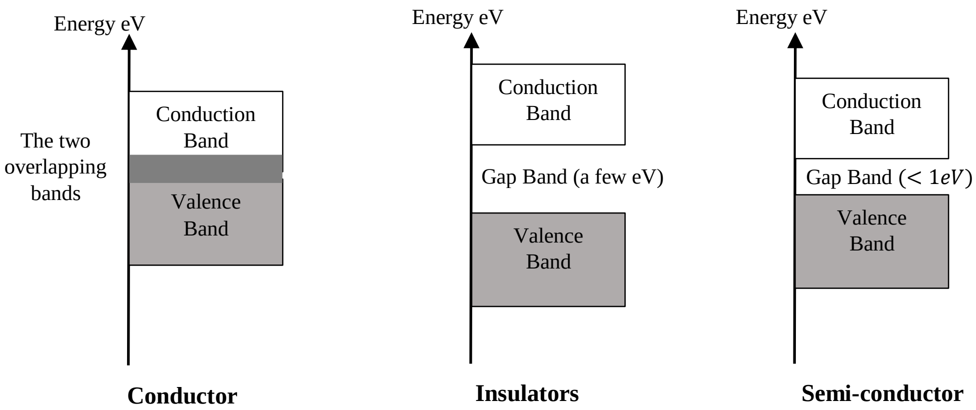


Figure 1.2: Position of the energy bands for a conductor, an insulator, and a semiconductor.

1.5. Intrinsic Semiconductors

Pure semiconductors, called intrinsic, are neither good conductors nor good insulators. Common elemental semiconductors include Silicon (Si), Germanium (Ge), and Carbon (C), while compounds like Gallium Arsenide (GaAs) are also used.

1.6. Extrinsic Semiconductors

These are intrinsic semiconductors with added impurities (doping), which alter their electrical properties. Extrinsic semiconductors have unequal electron and hole densities, higher conductivity, and conductivity depends on impurity concentration and temperature. They are classified as N-type or P-type.

1.6.1. Semiconductor Doping:

Conductivity is increased by adding impurities (doping) to introduce free charges. If extra electrons are added, the semiconductor is N-type; if positive charges (holes) are added, it is P-type. Common dopants come from groups III and V of the periodic table.

III	IV	V
B (Boron)	C (Carbon)	N (Nitrogen)
Al (Aluminium)	Si (Silicon)	P (Phosphorus)
Ga (Gallium)	Ge (Germanium)	As (Arsenic)
In (Indium)	–	Sb (Antimony)

For common semiconductors (Si, Ge), dopants are either pentavalent (with five valence electrons, e.g., As, Sb, P), resulting in N-type material, or trivalent (with three valence electrons, e.g., B, Ga, In), resulting in P-type material. Doping makes the semiconductor extrinsic.

In an N-type semiconductor: the majority carriers are electrons, moving through a lattice of fixed positive ions.

In a P-type semiconductor: the majority carriers are holes, moving through a lattice of fixed negative ions.

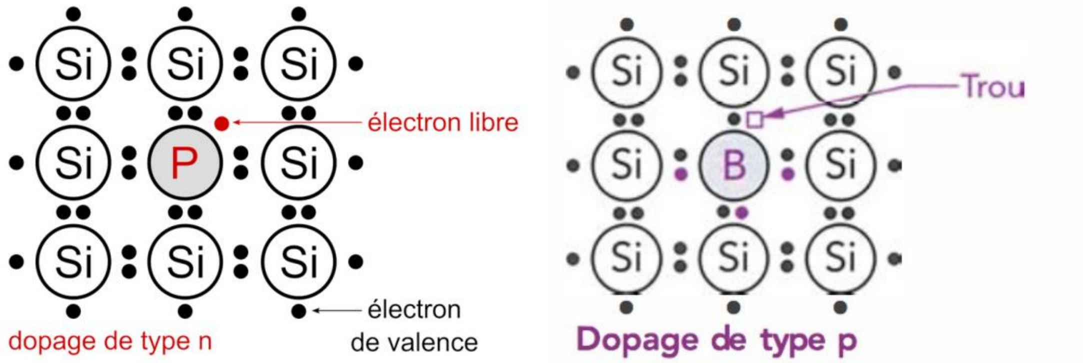


Figure 1.3: N-type and P-type Doping.

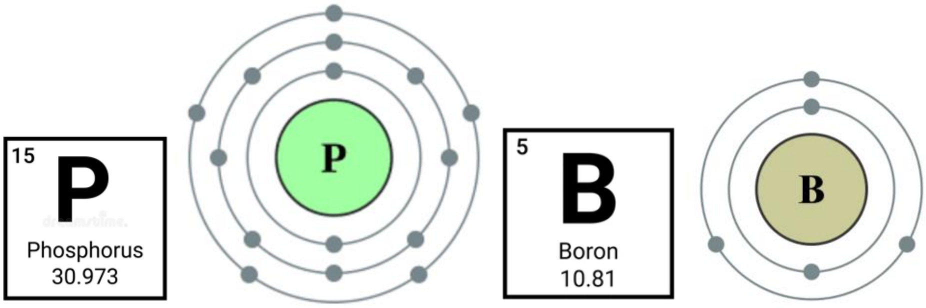


Figure 1.4: Phosphorus and Boron atoms.

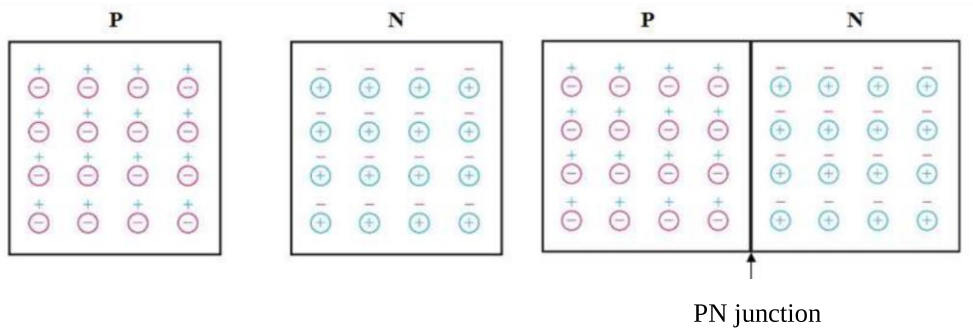
Example 1.1:

When pure silicon is doped with a trivalent element (an element with three valence electrons), it results in P-type doping.

When pure silicon is doped with a pentavalent element (an element with five valence electrons), it results in N-type doping.

1.7. PN Junction

A PN junction is formed by joining P-type and N-type regions within the same semiconductor crystal. The boundary between these regions is called the metallurgical junction. PN junctions are fundamental to modern electronics, as they are the basis of devices such as diodes, transistors, integrated circuits, photovoltaic cells, and light-emitting diodes.



(a) (b)

Figure 1.5: (a) Two types of semiconductors, (b) PN junction

Non-polarized PN junction

In an unbiased PN junction at thermal equilibrium, majority carriers (holes from the P region and electrons from the N region) diffuse across the junction and recombine. This creates a depletion region containing fixed ions and no free carriers. The resulting electric field opposes further diffusion and establishes a built-in potential barrier (about 0.7 V for silicon and 0.3 V for germanium).

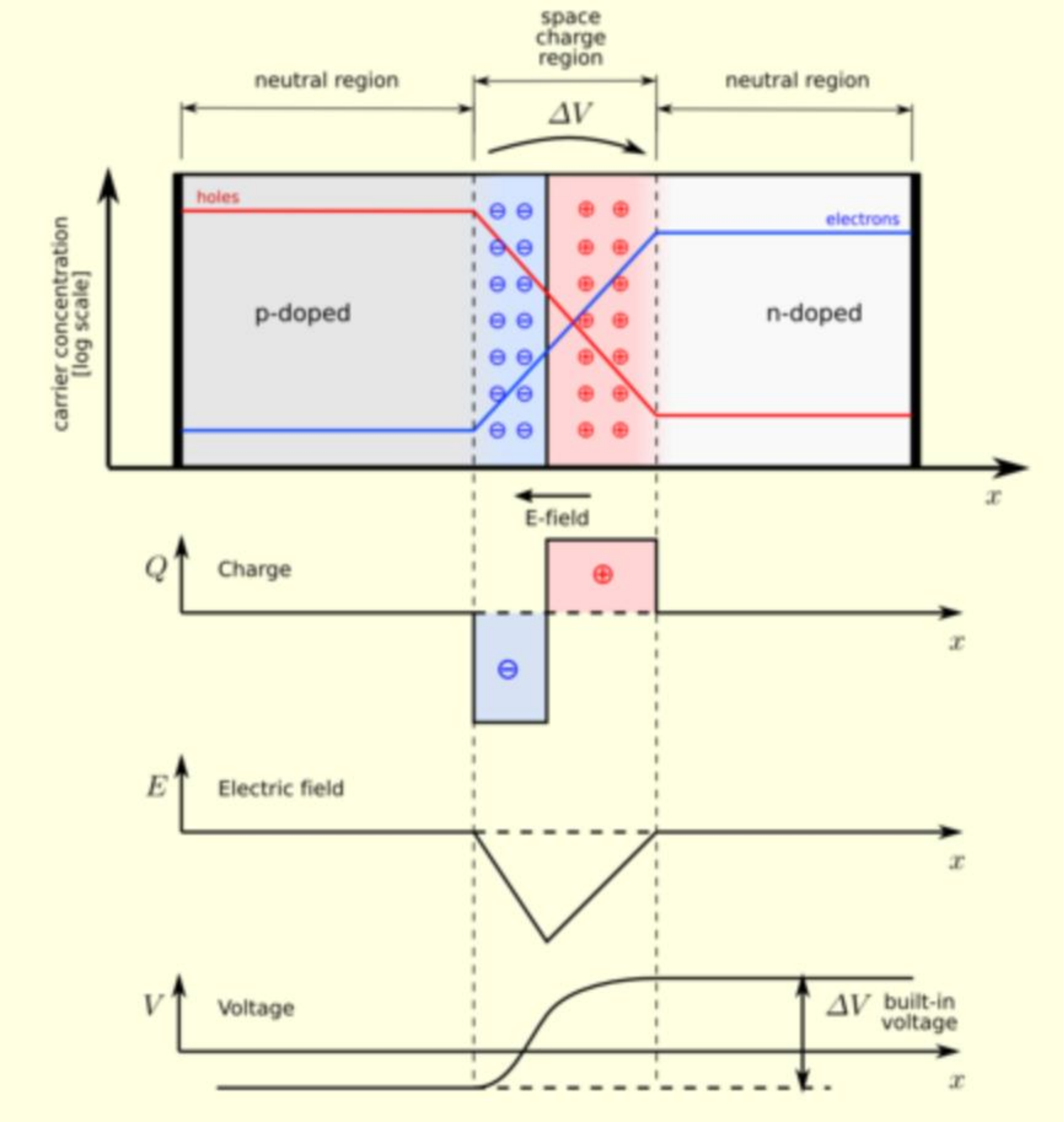


Figure 1.6: Depletion tension

Polarized PN junction:

To polarize a PN junction, an external voltage source is applied.

Forward polarized PN junction:

A DC voltage source V is applied across the PN junction, with the negative terminal connected to the N side and the positive terminal connected to the P side. This configuration corresponds to forward bias (Figure 1.8).

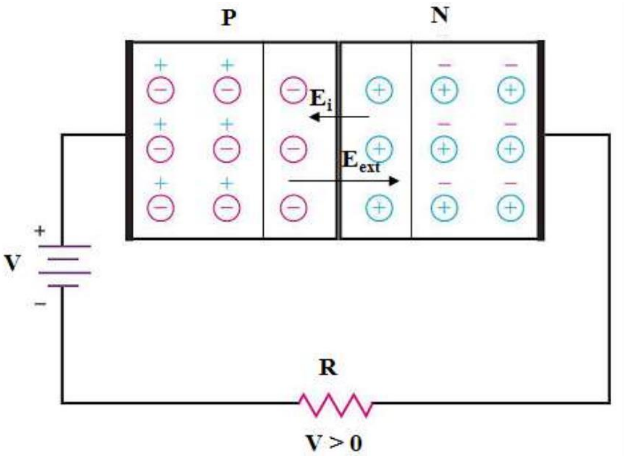


Figure 1.8: Forward polarized PN junction.

Reverse polarization PN junction

By reversing the DC voltage source V (P →N), the configuration shown in Figure 1.9 is obtained. The P side is now connected to the negative terminal and the N side to the positive terminal. This type of connection corresponds to reverse polarization.

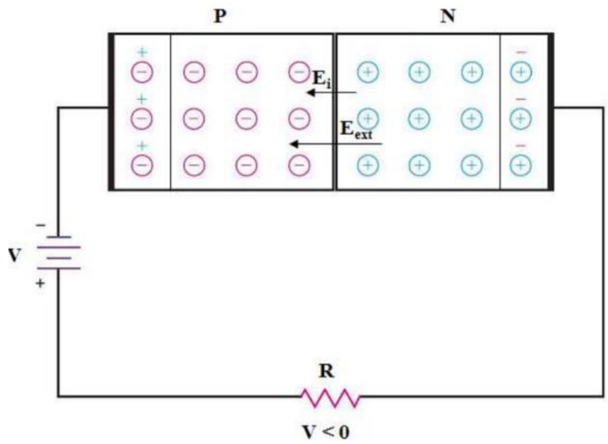


Figure 1.9: Reverse polarization PN junction

PN junction Diode

A PN junction diode is a passive, nonlinear semiconductor device with two electrodes: the anode (P side) and the cathode (N side). It allows electric current to flow in only one direction, behaving like a controlled switch. The diode is formed by joining P-type and N-type semiconductor regions, hence the name PN junction diode.

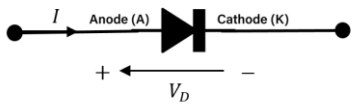


Figure 1.10: Diode symbols

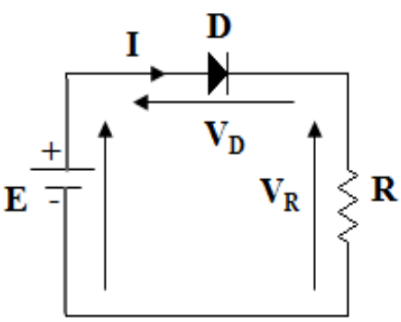
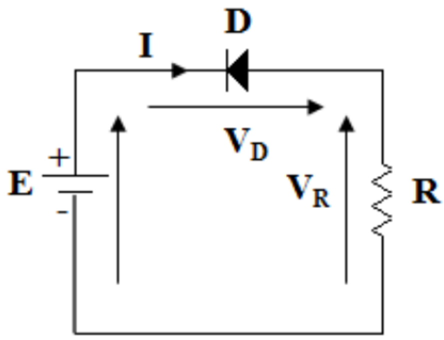
Diode polarization

A diode is a switching device with two operating modes:

• Diode in the ON state (conducting).

• Diode in the OFF state (blocked).

Thus, the diode can switch between the conducting and blocked states. Table illustrates the difference between a forward polarization diode and a reverse polarization diode.

Forward Polarization	**Reverse Polarization**
 Diode in the ON state (conducting).	 Diode in the OFF state (blocked).
Calculation of the current I: The diode D is forward biased ($V_D > 0$) The current I flows from the anode to the cathode. According to Kirchhoff's voltage law (loop law): $E - V_D - V_R = 0 \Rightarrow V_R = E - V_D$ $I \times R = E - V_D \Rightarrow I = \frac{E - V_D}{R}$	Calculation of the current I: The diode D is reverse biased ($V_D < 0$). The current I does not flow. $I = 0\,A$

Current–voltage characteristic of a diode:

The behavior of a diode can be determined from its current–voltage ($I-V$) characteristic.

$$I_D = I_S \left[\exp\left(\frac{qV_D}{\eta K_B T} \right) - 1 \right]$$

I_D is the current through the diode.

I_S is the diode's reverse current (also called leakage current).

q is the electron charge, $q = 1.6 \times 10^{-19}\, C$.

V_D is the voltage across the diode.

k_B is Boltzmann's constant, $k_B = 1.38 \times 10^{-23}\, J/K = 8.62 \times 10^{-5}\, eV/K$.

T is the absolute temperature in kelvin (K).

η is the diode ideality factor, ranging from 1 to 2 (ideal diode).

The resulting curve is not a straight line; the diode is a nonlinear element. This means the current through the diode is not proportional to the applied voltage and does not follow Ohm's law alone.

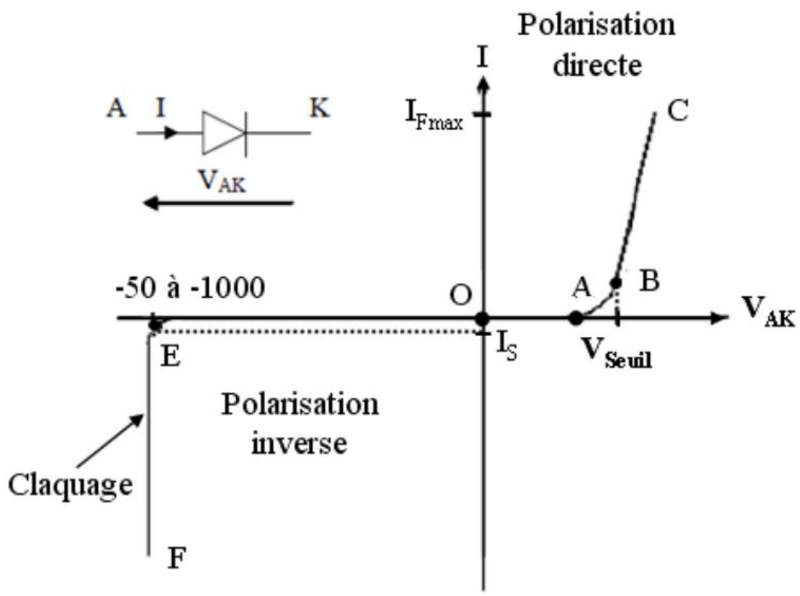


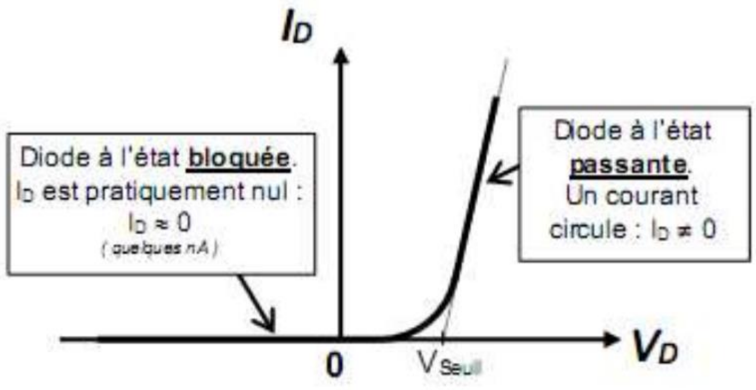
Figure 1.11: Current–voltage characteristic of a junction diode.

- **Forward polarization:** The threshold voltage is the minimum voltage needed for the diode to conduct. $V_{threshold} = 0.7\, V$ for Si, $0.3\, V$ for Ge.
- **Above threshold:** Current mainly depends on the circuit resistance; the diode voltage typically ranges from 0.6 V to 0.8 V.
- **Reverse current:** Very small (nanoampere range) until the breakdown voltage is reached, which varies from 10 V to 1000 V depending on the diode type.
- **Diode operation summary:**
  - Forward polarization : V≈0.7 V,I≠0; diode is conducting.
  - Reverse polarization: I≈0, V arbitrary; diode is blocked.

Diode characteristics:

The characteristic of a diode represents the variation of the current I_D flowing through the diode as a function of the applied voltage V_D.

Real Diode:



D is flow current $V_D > 0$

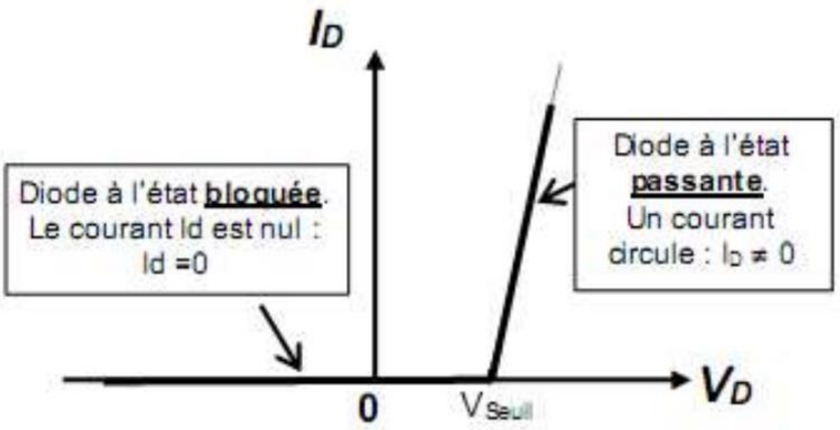
$$I_D = I_S\, e^{\frac{qV_D}{K_B T}}$$

D is block current $V_D < 0$

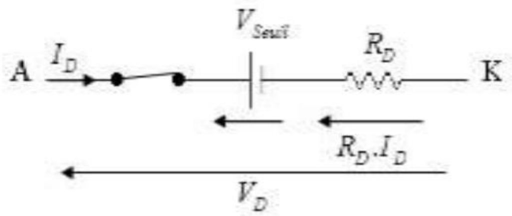
$$I_D = -I_S$$

To determine the operating point of an electrical circuit.

Semi real diode (with threshold voltage and dynamic resistance):



D is flow current $I_D > 0$



$$V_D = V_{Seuil} + R_D \, I_D$$

Dynamic resistance

$$R_D = \frac{\Delta V_D}{\Delta I_D}$$

$V_{threshold} = 0.7\ V$ for a silicon diode.

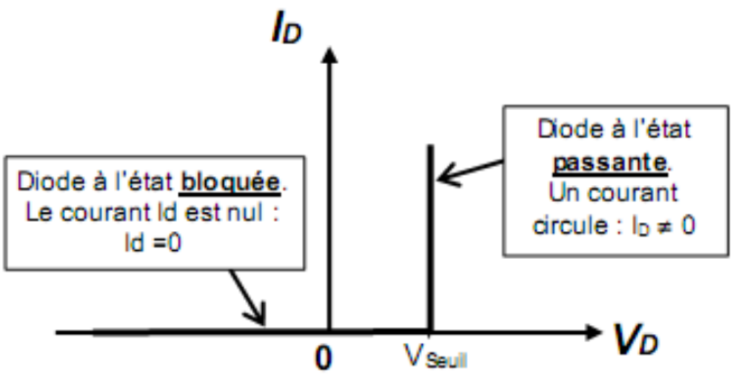
$V_{threshold} = 0.3\ V$ for a Germanium diode.

D blocked : $V_D < V_{threshold}$: $I_D = 0$

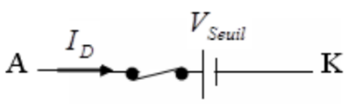
For the dynamic study of small signals.

In-depth technical analysis.

Ideal diode (with threshold):



D flow a current : $I_D > 0$



$$V_D = V_{Seuil} \cong 0{,}7\ V$$

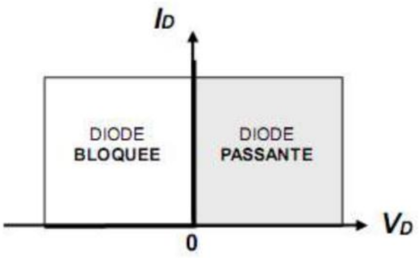
D blocked a current : $V_D < V_{threshold}$

$$I_D = 0$$

To calculate currents and voltages in a loop.

• Simple technical analysis.

Ideal diode (without threshold)



D flow current : $I_D > 0$

$V_D = 0$

D blocked current : $V_D < 0$

$I_D = 0$

The simplest model to use for troubleshooting and quick analysis.

Load line and operating point of the diode

Consider the simple diode circuit shown in Figure . The diode is powered by a DC voltage E through a resistor R.

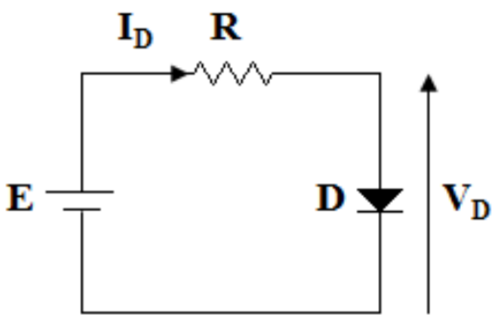


Figure : Basic circuit for defining the load line equation.

It must be plotted on the same graph:

The current–voltage characteristic of the diode:

$$I_D = I_S\left(e^{\frac{qV_D}{K_B T}} - 1\right).$$

And the load line: According to Kirchhoff's voltage law:

$$E = RI_D + V_D \Rightarrow I_D = \frac{E - V_D}{R}$$

The characteristic is plotted:

$$I_D = f(V_D) : I_D = \frac{E - V_D}{R}.$$

For $I_D = 0$: $V_D = E$

For $V_D = 0$: $I_D = \frac{E}{R}$

The point M where the load line intersects the characteristic $I = f(V)$ is called the operating point, bias point, or quiescent point (Figure).

The intersection of these two curves gives the circuit's operating point (Figure). It can be seen that for different values of R, the voltage V varies little.

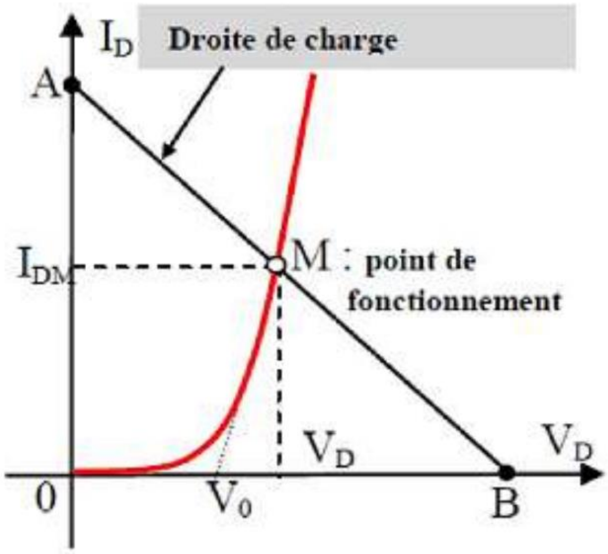
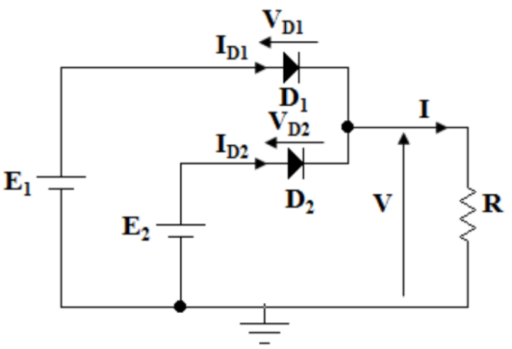
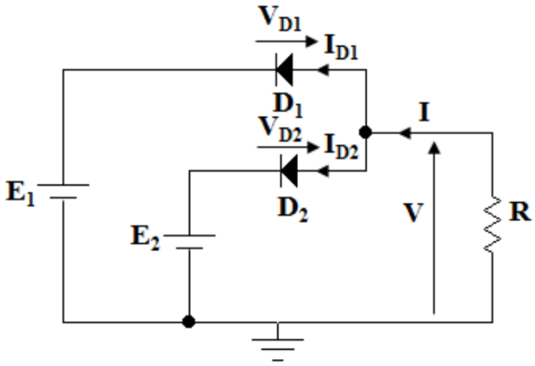


Figure : Load line and operating point.

Determining the state of a diode network with common cathodes or anodes:

In power converters, we often encounter diode arrays. In this case, it is useful to know which diode is likely to conduct.

Table: Diode array

<table>
<tr><th>Diode array with common cathodes</th><th>Diode array with common anodes</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">The load current III is positive and E1>E2</td></tr>
<tr><td>

$$E_1 - E_2 = V_{D_1} - V_{D_2}$$

If D_1 conducts:

$$V_{D_1} = 0, V_{D_2} = E_2 - E_1 < 0$$

Therefore, diode D_2 is reverse polarization and blocked.

If we assume D_2 conducts:

$$V_{D_2} = 0, V_{D_1} = E_1 - E_2 > 0$$

Diode D_1 would also be conducting ($V_{D_1} = 0$)

This is impossible, since it would imply:

$$E_1 - E_2 = 0$$

Which contradicts the initial assumption.

In a common cathode diode setup, the diode with the highest anode potential becomes the only conducting diode.

</td><td>

$$E_1 - E_2 = V_{D_2} - V_{D_1}$$

If D_2 conducts:

$$V_{D_2} = 0, V_{D_1} = E_2 - E_1 < 0$$

Therefore, diode D_1 is reverse polarization and blocked.

If we assume D_1 conducts:

$$V_{D_1} = 0, V_{D_2} = E_1 - E_2 > 0$$

Diode D_2 would also be conducting ($V_{D_2} = 0$)

This is impossible, since it would imply:

$$E_1 - E_2 = 0$$

In a common anode diode setup, the diode with the lowest cathode potential becomes the only conducting diode.

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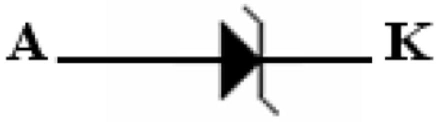
Zener Diode:

A Zener diode is a semiconductor device discovered by Clarence Zener and used in **reverse bias** to **stabilize voltage**. It maintains a constant output voltage equal to its **Zener voltage (VZ)**. It has two terminals (anode and cathode) and is widely used in **control, limiting, and clipping circuits**.

Zener diodes conduct in reverse when the applied voltage exceeds the **breakdown (avalanche) voltage**, which typically ranges from **2.4 V to over 100 V**.



Characteristic

The characteristic of the Zener diode is shown in **Figure** .

It illustrates that in **reverse bias**, the diode blocks current until the voltage reaches the **Zener (breakdown) voltage VZ**, beyond which the voltage remains nearly constant while the current increases.

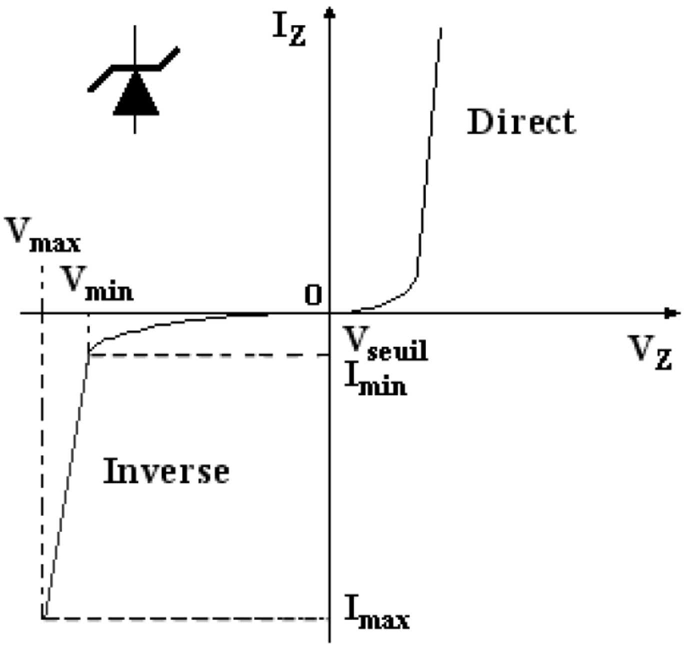


Figure : Zener Diode Characteristic

Zener Effect

The Zener effect concerns the **reverse characteristic** of the diode.

- **Forward polarization:** The Zener diode behaves like a conventional junction diode.
- **Reverse polarization:** When the voltage $V \geq V_Z$, the diode becomes conductive, and the voltage across it remains **almost constant** regardless of the current I_Z, which makes the Zener diode suitable for **voltage stabilization**.

Equivalent Model of the Zener Diode:

In reverse conduction, the Zener diode can be modelled by the following circuit:

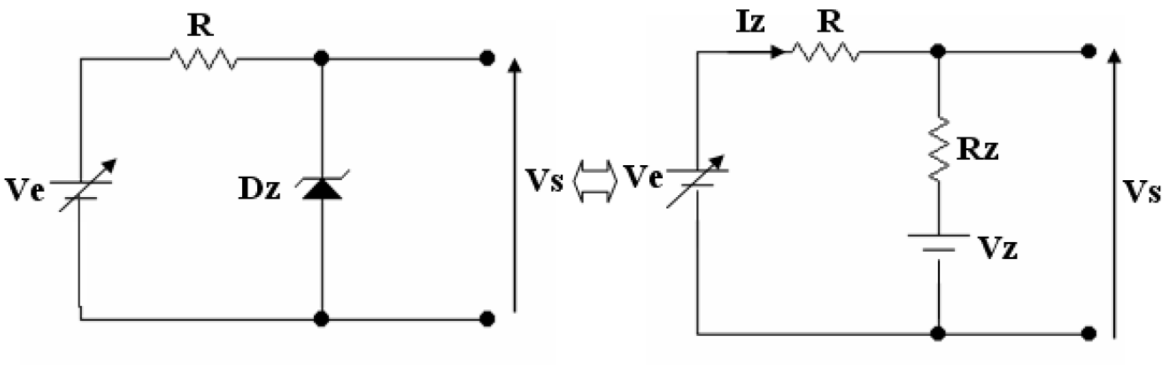


Figure 2.8: Voltage Stabilization Using a Zener Diode – Basic Circuit

$$\begin{cases} I_Z(\min) = \dfrac{V_e(\min) - V_Z}{R + R_Z} \\ I_Z(\max) = \dfrac{V_e(\max) - V_Z}{R + R_Z} \end{cases} \Rightarrow \begin{cases} V_S(\min) = V_Z + R_Z \times I_Z(\min) \\ V_S(\max) = V_Z + R_Z \times I_Z(\max) \end{cases}$$

In this circuit, the Zener diode is used to **stabilize the output voltage** against significant variations in the power supply.

Other Types of Diodes

Light Emitting Diode (LED):

The abbreviation **LED (Light Emitting Diode)** is commonly used to refer to electroluminescent diodes. A LED can be represented as shown in **Figure**.

These **LEDs** have the property of **emitting visible light** when forward-biased (anode voltage higher than cathode voltage). The emitted light can have **different colors**, such as red, green, yellow, blue, or white.

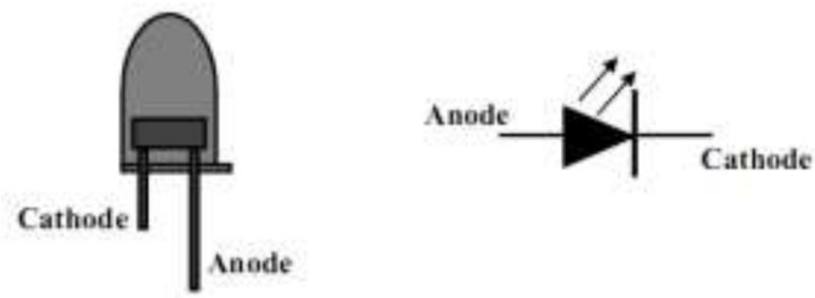


Figure: Diagram of a Light Emitting Diode (LED)

Schottky Diode

Schottky diodes are modern versions of point-contact diodes. Their **rectifying effect** comes from a **metal–semiconductor junction**. They are typically made from a **thin single-crystal of**

Silicon (Si) or Gallium Arsenide (GaAs), doped N-type, with a **metal layer (usually gold or aluminum) deposited** on top through a window in the semiconductor.

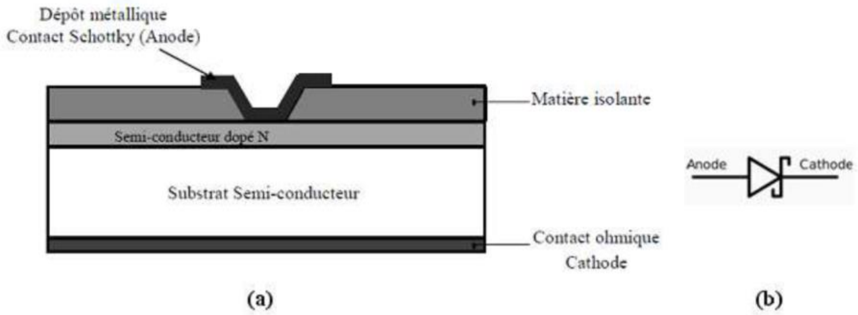


Figure : Schottky Diode Representation – (a) Construction Principle and (b) Symbol