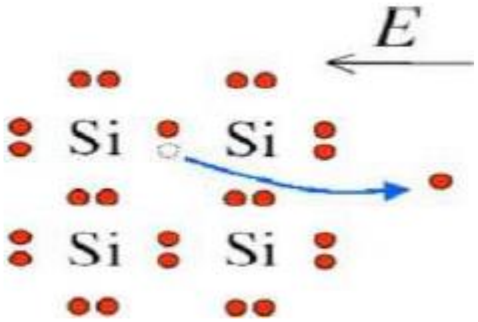
In this part, an introduction to semiconductors and the PN junction is presented without going into depth. We are interested in the basis of manufacture and operation of a junction diode while characterizing its response to different polarization methods.

1. Semiconductor Physics Basics

1.1 Intrinsic Electrical Conduction

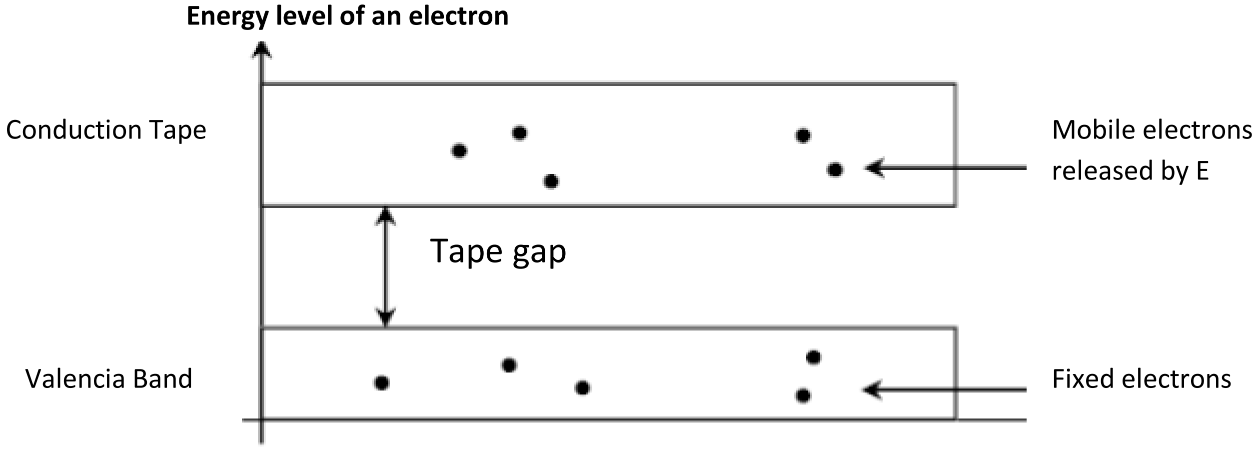
In a material with a crystalline structure, atoms are linked together by so-called covalent bonds. If this bond between electrons is weak, an external energy input (an electric field) may be sufficient to mobilize these electrons: these electrons are said to be "free", free to move in the crystal structure: this is the phenomenon of intrinsic electrical conduction.



When leaving its initial position, an electron that has become free leaves behind a "hole". The atom is initially neutral, so a hole is positively charged. A hole can of course be filled by another free electron from a neighboring atom. In this case, the hole moves in the opposite direction to the electron's movement. Electrical conduction can be interpreted as a displacement of holes as well as a displacement of electrons.

Free electrons are called negative charge carriers. The holes are the positive charge carriers.

We model the ability of electrons to mobilize to participate in a conduction phenomenon by Energy bands:

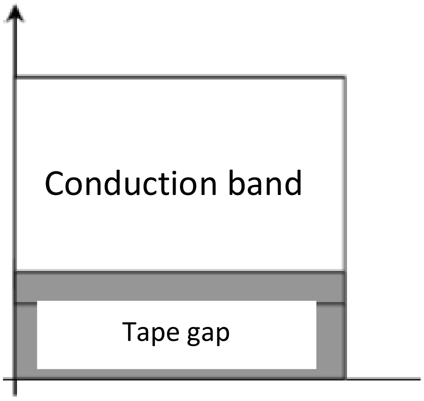


- Valence band (BV): the electron in this band participates in a covalent bond within the crystal.

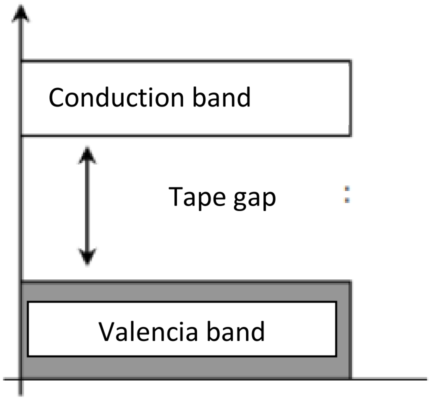
- Conduction band (BC): an electron that has acquired enough energy may be in this band; it is then mobile and can participate in a conduction phenomenon.

- Band gap: quantum mechanics has shown that electrons cannot take on any energy levels, but that these are quantized; Between the valence band and the conduction band there may therefore be a band gap. To make an electron mobile, it is therefore necessary to provide sufficient energy to cross this gap.

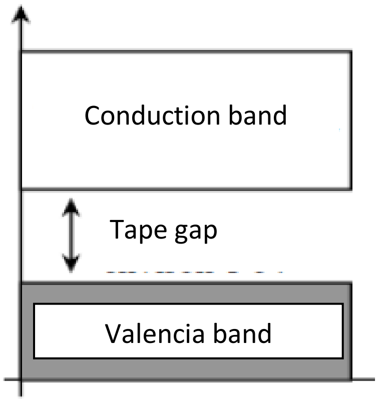
Depending on the arrangement of these bands, and especially the width of the band gap, the materials can be insulating, conductive or semiconductor :



Conductive material



Insulating material



Semiconductor

- A conductor: the conduction band is partially filled. The solid therefore contains mobile electrons that are likely to participate in conduction phenomena without providing energy.

- An insulator: the conduction band is empty and the gap is large (e.g. around 10 eV). The solid then contains no electrons capable of participating in conduction.

- A semiconductor: the conduction band is empty but the gap is smaller (around 1 to 2 eV). The solid is therefore insulating at zero temperature (T = 0K), but a rise in temperature allows electrons to pass from the valence band to the conduction band. Conductivity increases with temperature.

1.2 Intrinsic Semiconductors

When a semiconductor is pure, it is said to be intrinsic. There are as many free electrons as there are holes: let n and p be the respective numbers of negative carriers (electrons) in the conduction band and positive carriers (holes) in the valence band per unit volume (concentrations); We show that :

$$n = p = n_i$$

$$n.p = n_i^2 = AT^3 e^{\frac{-\Delta E_i}{KT}}$$

with: A: material-dependent constant,

T : absolute temperature in kelvins,

ΔE i : width of the bandgap in eV,

k = 1.38 × 10^{-23} JK^{-1} : constante of Boltzmann.

These n and p concentrations are called intrinsic carrier concentrations. For silicon, which is the most widely used semiconductor, we have : ΔEi = 1.2 eV, ni = 1.5x1010 $cm-3$ *à T* =300*K*.

- At room temperature, kT is of the order of 0.025 eV. The electron density is then very low, and the intrinsic conductivity is low for most semiconductors.
- The main semiconductor families are :

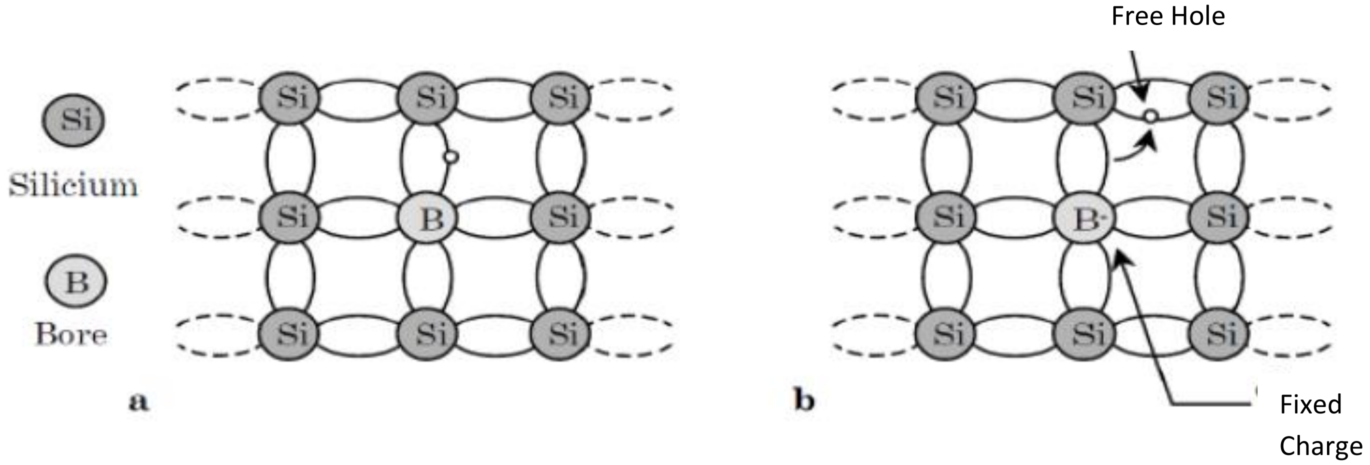
Primary Valence IV Compounds	Binary compounds		Ternary compounds	
	Group III-V	Group II-VI	Group III-V	Group II-VI
Si Ge	GaAs AlAs GaP	ZnSe CdTe	GaxAl1-xAs	CdxMn1-xTe

1.3 Doped or extrinsic semiconductors

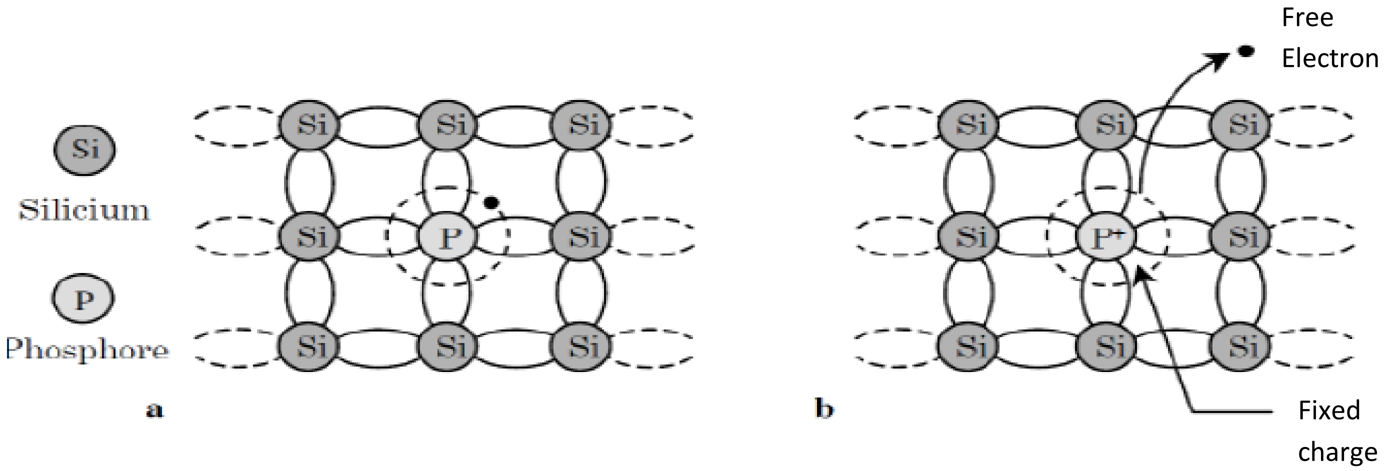
If we replace certain atoms in a pure crystal with atoms of another simple body, we say that we are doping the crystal with impurities.

Example: silicon (Si) is a tetravalent material (column IV), doping can be carried out with atoms:

- trivalent (boron (B), aluminium (Al) or Gallium (Ga) of column III). In this case, a supply of holes will be created. The semiconductor is said to be P-doped and the impurities introduced are electron acceptors.



- pentavalent (phosphorus (P), arsenic (As) or antimony (Sb) of column V). An additional electron supply is then created. The semiconductor is N-doped and the impurities are said to be electron donors.



The concentration of doping impurities always remains very low in any case: on the order of 1 atom of impurity for 107 silicon atoms. If the semiconductor is N-doped, there are many more free electrons than holes. Electrons are said to be the majority charge carriers.
In the case of P doping, it is the holes that are the main carriers. In both cases we have: $n \neq p$.
On the other hand, we always have: $n.p = n_i^2$

- Pour un semi-conducteur dopé **N**, soit N_D la concentration en impureté donneuses d'électrons.
On a alors : $n \approx N_D$ *et* $p = 0$ à T = 300 K,

- For a P-doped semiconductor, i.e. N_A is the concentration of electron accepting impurities. We then have :

$P \approx NA$ et $n = 0$ à T = 300 K,
The conduction in these materials is said to be extrinsic.

2. Junction diode

2.1. PN junction

En dopant respectivement **N** et **P** deux parties d'un même cristal semi-conducteur, on forme un dipôle appelé « **diode à jonction** ». La jonction est la surface de contact située entre les deux parties du cristal dopées différemment.

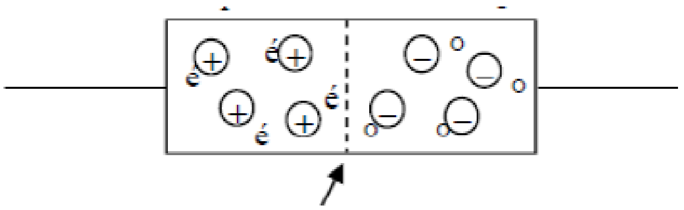
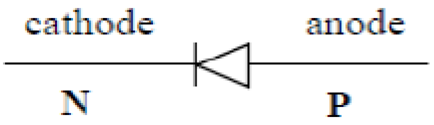
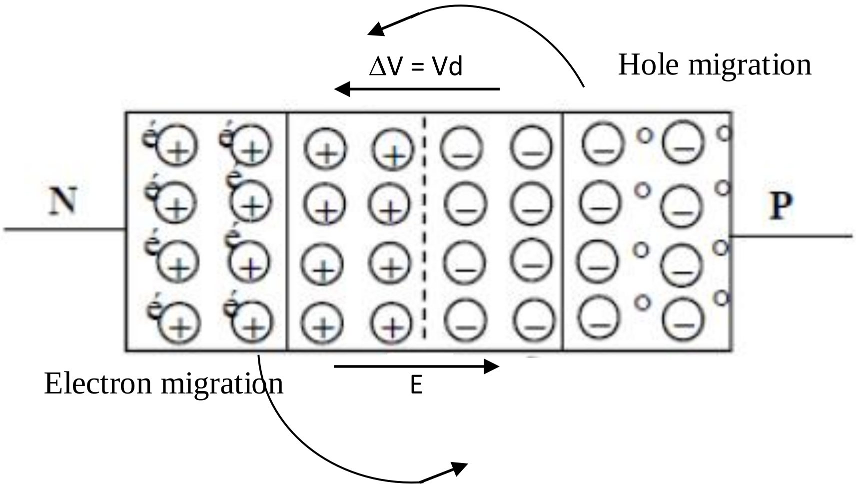


Diagram of a PN junction diode



Symbol

Although initially each of the two zones is electrically neutral, the contact of the two parts induces a phenomenon of migration of majority carriers on either side of the junction: some holes in the P zone move towards the N zone, while some electrons in the N zone migrate towards the P zone.



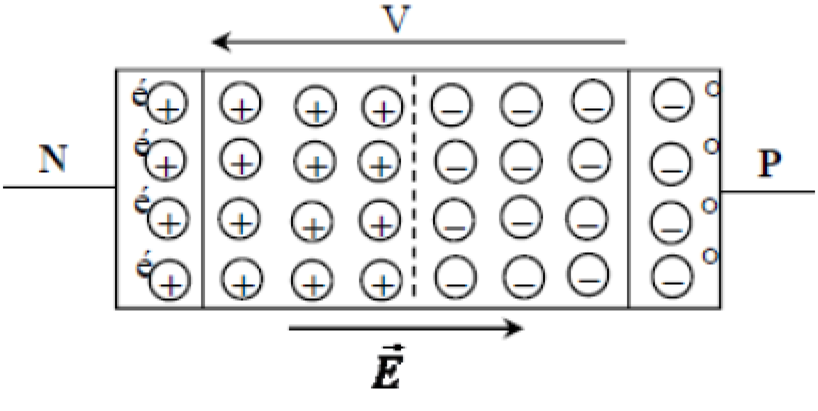
An equilibrium is established around the junction, creating an internal electric field $\vec{E}$. The area around the junction corresponding to this electric field is called the depletion zone.

The presence of this electric field also translates into the presence of a potential difference.

This d.d.p. d V is called the potential barrier (of the order of 0.7 V). The depletion zone behaves like an insulator and it becomes very difficult for a free electron to cross this zone.

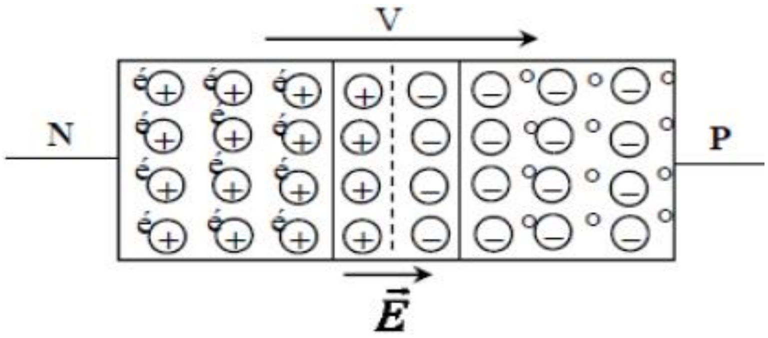
2.2. Polarization of the diode

- The application of a directed voltage V as shown in the following figure (P→ N) (reverse polarization), creates an electric field that is added to the internal electric field, thus pushing the electrons of the N zone and the holes of the P zone a away from the junction: the depletion zone widens; the junction becomes practically insulating. The diode is said to be blocked.



Enlarged depletion zone
Blocked diode

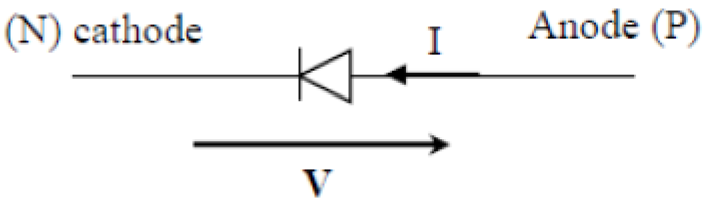
- If a voltage V oriented from N to P (N →P) (forward polarization) is applied, an external electric field is created that opposes the internal field. The potential barrier d V is thus reduced: electrons can cross the depletion zone (from N to P) which thus becomes conductive; The diode is said to be passing.



Through-pass diode

- The flow of electrons through the junction takes place from the N zone to the P zone (from the cathode to the anode), this is the direct polarization of the diode.

• Let V be the voltage across the diode and I the current flowing through it. As the current flows from the anode to the cathode (opposite direction of the electrons), voltage and current will be represented as shown in the following figure:



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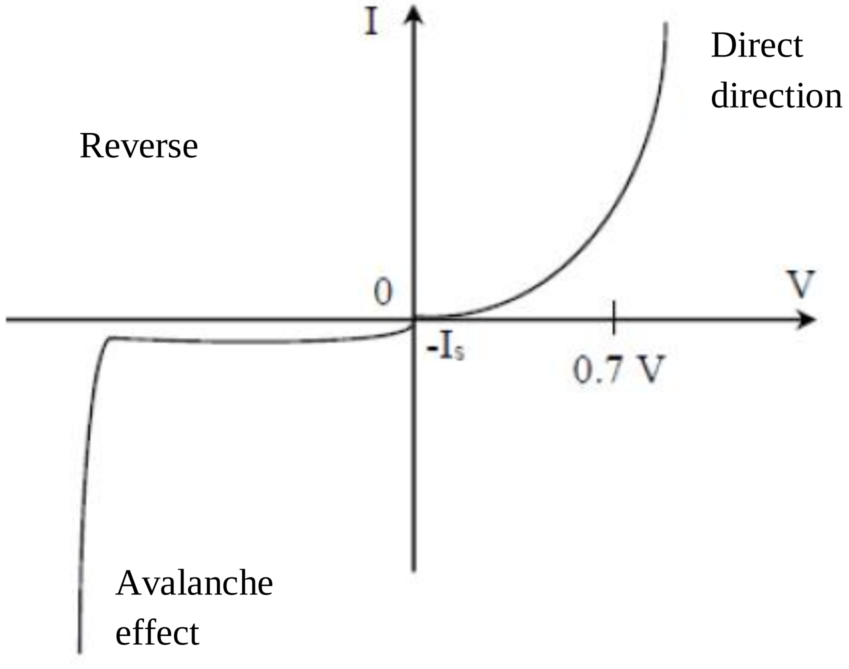


$$I = I_S e^{\frac{eV}{KT}} = I_S e^{\frac{V}{Vo}}$$

Is = 10^{-12}A.

- In the direct direction:

If V > 0 and V >> V_0 (e.g. for V > 0.1V), then I = $I_S e^{\frac{V}{V_0}}$

The current is growing exponentially. The diode is said to be pass-through or directly polarized. For large values of I, the voltage V varies little and is of the order of 0.6 to 0.7 V for silicon diodes (0.2 V for a germanium diode). This voltage is called threshold voltage and is denoted by V_S.

- In the opposite direction:

If V < 0 and if V >> V0 (e.g. for V > 0.1V), then I ≈ -Is

In this case, the diode is said to be inversely polarized.

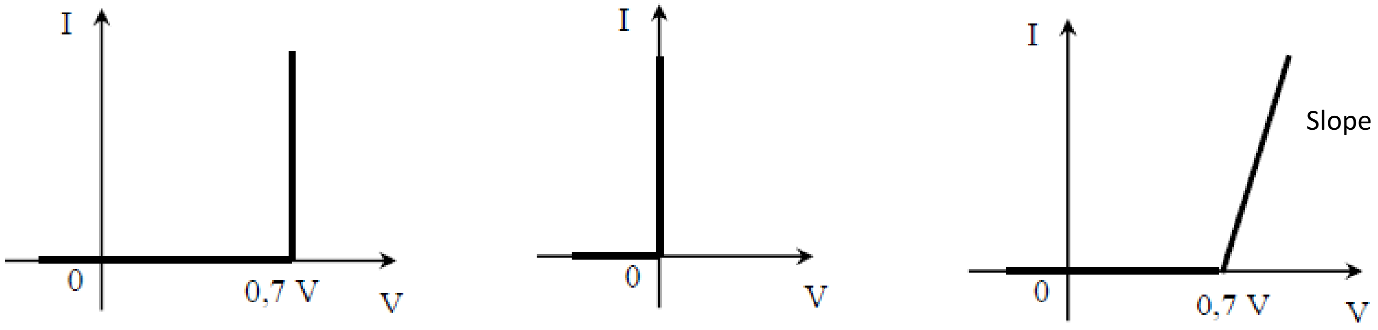
For large reverse voltages (a few tens of volts), a forced conduction effect through the junction (avalanche effect) is observed, which is generally destructive.

• In general, the following operation of the diode is accepted:

- Directly polarized diode: V = 0.7V, ∀ I; The diode is said to be passing.

- opposite-biased diode: I = 0, ∀ V; The diode is said to be blocked.

This model of a so-called perfect diode is shown in figure (a)



(a) Perfect Diode (b) Ideal diode (c) Dynamic model

• If we consider that the voltage of 0.7 V is negligible compared to the other voltages in the circuit, we then obtains the model of the so-called ideal diode, the characteristic of which is schematized in the figure (b).

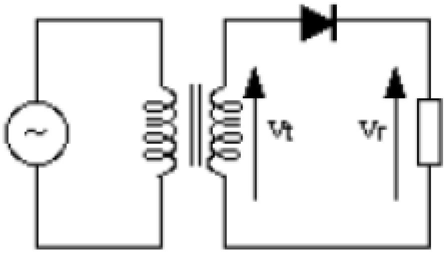
- If we want a model closer to the characteristic of the real diode, we can adopt the model known as the dynamic model shown in figure (c): this characteristic is considered to be is formed by two line segments:

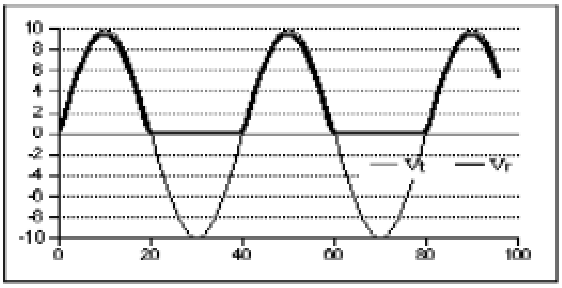
V < 0,7 volt ⇔ I= 0 (diode bloquée).
V > 0,7 volt ⇔ $I=(V-0.7)/Rd$ avec Rd résistance dynamique de la diode passante.

2.3. Special diodes

2.3.1. Rectifier diodes

One of the main applications of the diode is the rectification of alternating voltage to make direct voltage generators intended to supply electronic assemblies.



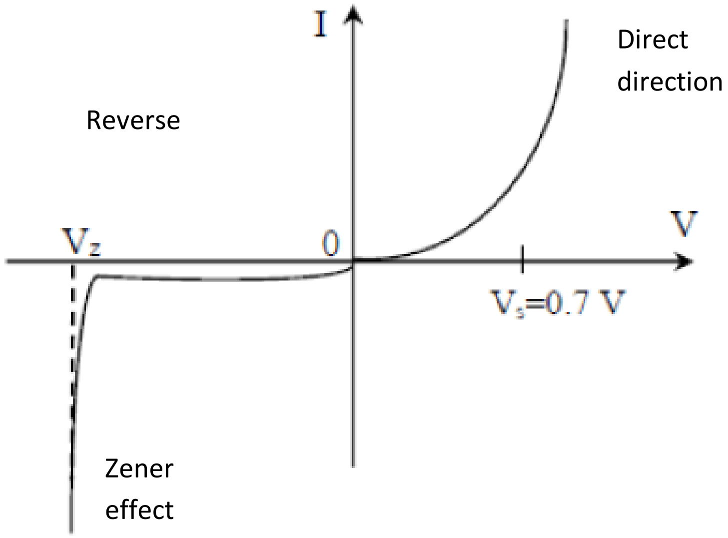


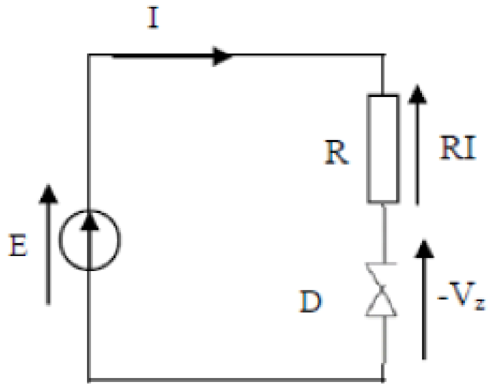
2.3.2. Zener Diodes

Symbol :

When the diode is "polarized in the opposite direction" and the voltage at its terminals is too strong, we witness the avalanche phenomenon. The reverse current flowing through the diode suddenly increases. This is called the Zener effect and such diodes are called Zener diodes.

Whatever the current that passes through it, the Zener diode has at its terminals, an almost constant voltage called the Zener voltage and denoted Vz (Vz= qq V to qq 0.1 kV). This property is widely used in voltage regulator assemblies (assembly protection).

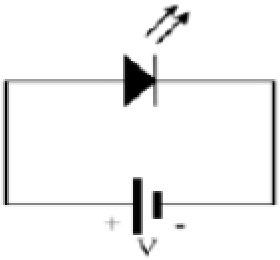


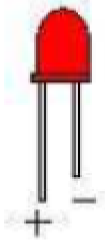


2.3.3. Schottky diodes

The Schottky diode is used in high frequency. It is made up of a metallic zone (gold, silver or platinum) and an N zone. Free electrons are the only majority carriers in the junction. This heterogeneous junction is widely used in fast logic circuits.

2.3.4. Light-emitting diodes (LEDs)

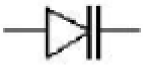




The LED (Light Emitting Diode), also known as a light-emitting diode, is a diode designed to operate in direct polarization, in order to emit invisible (infrared) or visible (red, orange, yellow, green or blue) light radiation.

These components have interesting features such as an almost unlimited lifespan (100,000 hours) and a small size. They are found everywhere: traffic lights, electronic billboards (time, temperature, etc.). Infrared diodes are used a lot in remote controls for TV sets...

2.3.5. Varicap diodes

Symbol: 

A diode has a (very low) capacitance. The capacitance of a reverse-polarized diode decreases as the reverse voltage increases. Thus we have a variable capacitor which is controlled by a voltage.