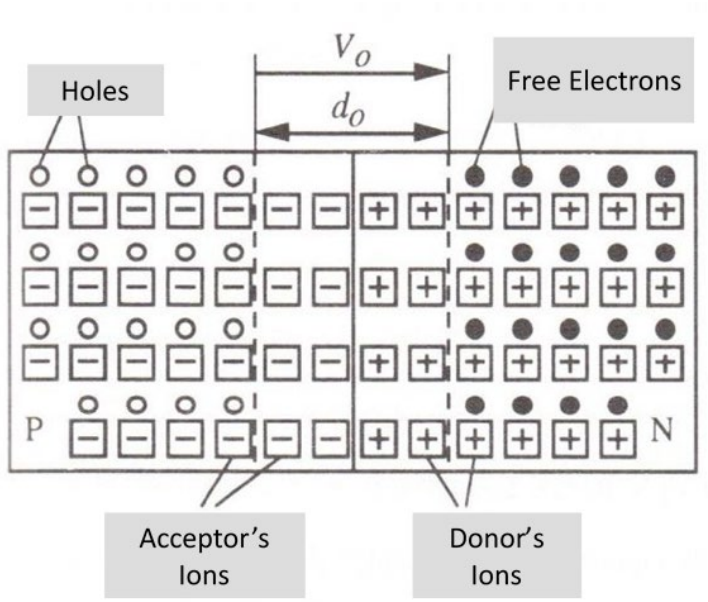
PN Junction and diodes

I. PN junction

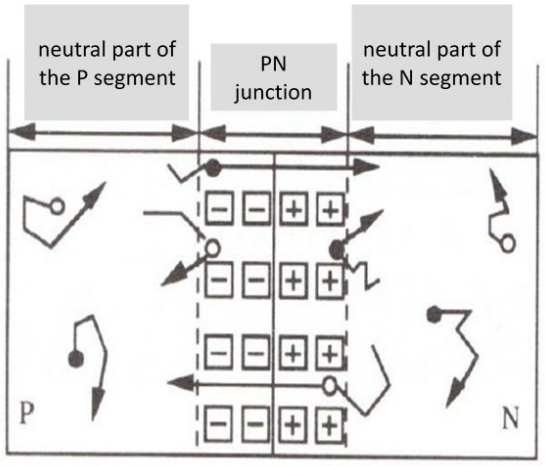


Let's set a silicon crystal composed of a segment of type P and a segment of type N. At the very moment of the creation of the junction between the two segments a diffusion process is triggered: the excess holes in the P segment begin to penetrate the N segment and the excess free electrons in the N segment begin to penetrate the P segment. The diffusion is due to the differences in the concentration of the free electrons and the holes in each of the segments.
Arriving in the N segment, the holes recombine with the electrons, and conversely, arriving in the P segment, the electrons recombine with the holes.

Consequence: the layers of donor atoms closest to the metallurgical limit between the two segments are deprived of free electrons and transform into an immobile positive charge composed of donor ions and silicon atoms (neutral). And, conversely, the layers of recipient atoms closest to the limit are devoid of holes and transform into an immobile negative charge, composed of acceptor ions and silicon atoms (neutral). This zone with + and – stationary loads is called **the PN junction**.

Between these two charges equal in absolute value and opposite, an electric field is created whose intensity is proportional to their quantity. The direction of this field is such that it opposes the scattering of the holes and electrons by which it was created. As the electric field intensifies, the diffusion decreases.

At the same time, in both crystal segments, the process of thermogeneration of electron/hole pairs by silicon atoms exists.



During their chaotic movement, some holes of segment P enter the zone of motionless loads (junction PN), but are pushed back by the electric field and return to the zone P. Conversely, some free electrons of segment P can enter the junction and are, on the other hand, accelerated by the electric field until entering the neutral part of segment N.

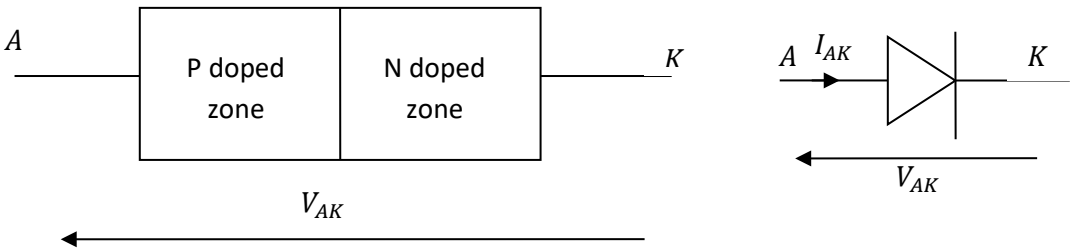
Similarly, the N-zone electrons that enter the PN junction are pushed back to the N-segment and the holes are accelerated until they enter the neutral part of the P-segment.

The directions of displacement of electrons and thermogeneration holes under the influence of the electric field of the junction PN are opposite to those of electrons and diffusion holes. Their quantity does not depend on the field intensity, but on the temperature and the transverse surface of the junction. As the diffusion decreases as the intensity of the field increases, a balance will be created: the amount of stationary loads and the field stop increasing. A dynamic balance is established in the junction. This balance is characterized by an E0 intensity of the field, a width d0 of the junction and a potential difference V0 between the 2 stationary and opposite loads in the junction, also called contact potential.

Ex : $V_0 = 0{,}5\ to\ 0{,}7V$ for Silicium
$V_0 = 0{,}2\ to\ 0{,}3V$ for Germanium

II. PN junction diode

If the previous silicon crystal is equipped with two electrodes, it becomes a PN junction diode. The electrodes are called anode (A) and cathode (K). The symbol of a diode is given below:



When the V_{AK} voltage applied between the anode and cathode is positive, the diode is polarized in Direct mode (Forward).

When the V_{AK} voltage applied between the anode and cathode is negative, the diode is polarized in reverse mode.

The behavior of the forward and reverse polarized diode is described by a single formula:

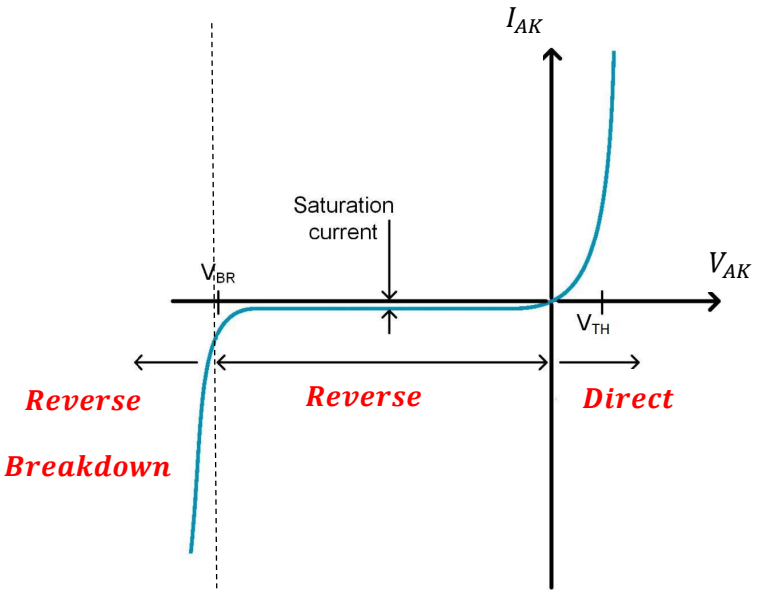
$$I_{AK} = I_s(e^{\frac{V_{AK}}{mV_T}} - 1)$$

with:

- V_T *= thermal potential= 26 mV,*
- m *= empirical coefficient= 1 to 2*
- I_S *= inverse current (or saturation current or thermal current)* This is the current passing through the diode when it is polarized inversely. Because its origin is thermal, I_S is highly dependent on temperature.
  The empirical expression $I_s = I_{S0}.e^{a(T-T0)}$ is often used where
  - I_S = saturation current at temperature *T*
  - I_{S_0} *= saturation current at* T_0
  - a *= empirical coefficient (*$a \approx 0{,}1$ *for silicon diodes,*
    $a \approx 0{,}07$ *for germanium diodes)*

To calculate I_s, it is enough to know I_{S0} and T_0. These values are normally given in data books.

Diode characteristics.



The formula giving I_D *is represented above graphically. It's the characteristic of the diode:*

- ✓ *In direct polarization (*$V_{AK} > 0$*), the characteristic is exponential and takes an almost linear look for* V_{AK} *values close to* V_0*. For practical calculations, the approximate value of* V_0 *is obtained by extending the linear part of the direct characteristic to the intersection with abscissa.*
- ✓ *In reverse polarization (*$V_{BR} < V_{AK} < 0$*), the characteristic quickly becomes horizontal. Since the inverse current* I_S *is much smaller than the direct current, its scale on the*

characteristic must be much larger than that of the direct current, otherwise it could not be distinguished from the abscissa.

- ✓ *The diode operation in reverse breakdown polarization ($V_{AK} < V_{BR}$) will be treated in the last chapter (Zener diode)*

III. Static models of the PN junction diode

A model is a simplified representation of a complex thing. Models are used to facilitate the analysis of phenomena and systems.

The diode, for example, is a nonlinear element because the formula $I_{AK} = f(V_{AK})$ is nonlinear. The analysis of an electrical circuit with diodes is difficult because the system of equations describing the circuit is non-linear.

To facilitate this analysis, the diodes are replaced by linear models.

Linear models of electrical components and circuits are composed exclusively of linear elements: ideal voltage and current generators, short circuits, open circuits, resistors, capacities, inductance…

This simplification is done at the expense of precision. According to the complexity of the circuit and the accuracy of the analyzes, we use models ± complex.

There are also different models depending on the goal pursued and the regime considered.

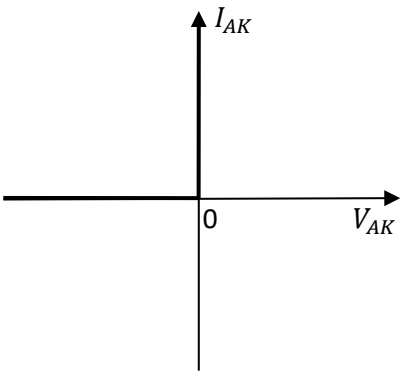
Models of electrical components and circuits can be represented graphically, analytically, or as an equivalent diagram.

1. Ideal model

Analytical form:

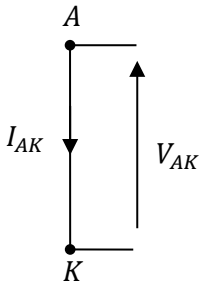
- ✓ In direct mode, the diode is considered as short circuit (wire): $V_{AK} = 0$ pour $I_{AK} \geq 0$.
- ✓ In inverse mode, the diode is considered as an open circuit $I_{AK} = 0$ pour $V_{AK} \leq 0$.

Graphical mode:

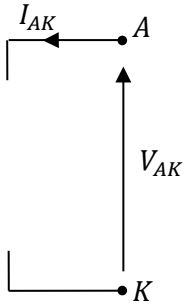


Equivalent diagram

Diode in direct mode



Diode en inverse



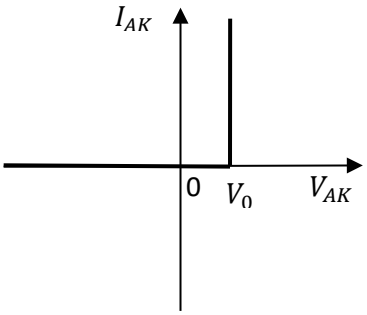
This model is the simplest, but the least accurate. It is used for quick estimations, or complex circuit analysis.

2. The threshold model or practical model

Analytical form

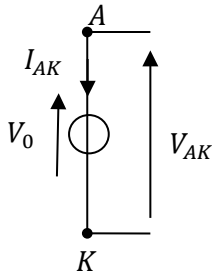
- ✓ $V_{AK} = V_0$ for $I_{AK} \geq 0$
- ✓ $I_{AK} = 0$ for $V_{AK} \leq V_0$ with V_0 = threshold voltage

Graphical form

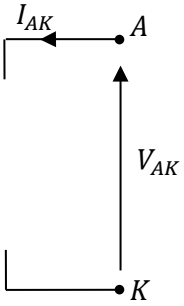


Equivalent diagram

Diode in direct mode



Diode in inverse mode

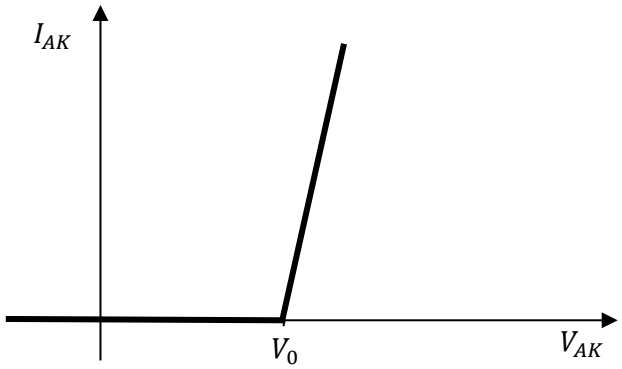


3. Linear model or real model

Analytical form

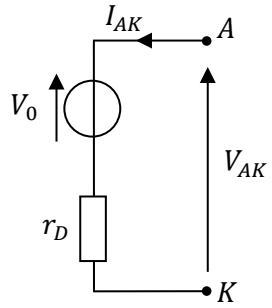
- ✓ $V_{AK} = V_0 + r_d I_{AK}$ for $I_{AK} \geq 0$ with r_D = dynamic resistance. It is determined by the average slope of the used part of the diode characteristic.
- ✓ $I_{AK} = 0$ for $V_{AK} \leq V_0$

Graphical form

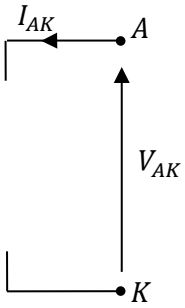


Equivalent scheme

Diode in direct mode



Diode in inverse mode



The 3 static models of the diode are linear. Among them, the linearized model is the most accurate, but the most complex. It represents a very good linear approximation of the characteristic of a real diode.

IV. The Zener diode

1. Breakdown phenomenon: Inverse characteristic ($V_{AK} < 0$):

In reverse bias, when the applied voltage exceeds a value specified by the manufacturer, the current decreases very quickly. (This current is already negative). If not limited by external elements, there is a quick destruction of the diode.

Two phenomena are at the root of this result:

- ✓ Avalanche phenomenon: When the electric field at the junction becomes too intense, the accelerated electrons can ionize atoms, which releases other electrons that are in turn accelerated, and will ionize other atoms...

  The phenomenon becomes uncontrollable, like the creation of an avalanche, and the current becomes significant.
- ✓ Zener effect[1] (tunnel effect): Electrons are torn out of atoms directly by the electric field in the transition zone and create a current that quickly becomes intense when the voltage drops below V_Z (=Zener voltage).

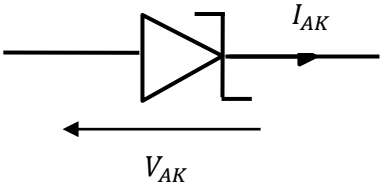
If we build the diode so that the Zener effect prevails over the avalanche phenomenon (by arranging for the width of the PN junction to be small), we obtain a Zener diode.

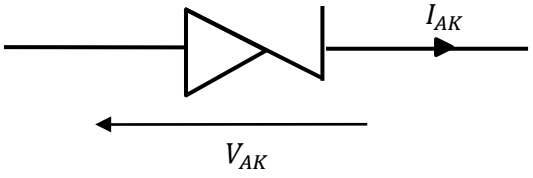
2. Zener diode

a. Definition:

A Zener diode is a type of diode that permits current to flow in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage. It supports, with no damage, a reverse current relatively strong. In other words, the breakdown for this diode is non-destructive and reversible. This property is obtained by proper and careful doping of the semiconductor.

Representations of the Zener diode: 2 symbols are used to represent the Zener diode





[1] The diode was named after **Clarence Melvin Zener**, who discovered the Zener effect.

b. Feature:

In direct mode, a Zener diode behaves like a normal diode.

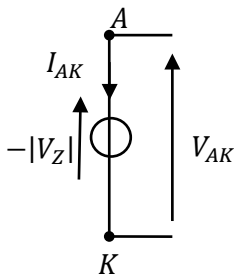
In reverse mode, we make sure that, by construction, the Zener effect occurs at a well determined voltage, denoted V_Z, and called Zener voltage, and that it is not destructive. The reverse characteristic then looks like a voltage generator with low internal resistance, provided it does not exceed the current I_{Z_m} corresponding to the maximum admissible power dissipated in the diode.

c. Equivalent models:

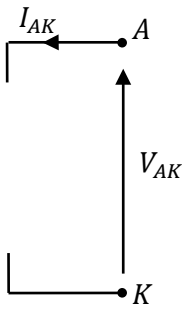
Note: in direct mode, the Zener diode behaves like an ordinary diode therefore it can be substituted by one of the static models above.

i. Threshold model:

Reverse breakdown

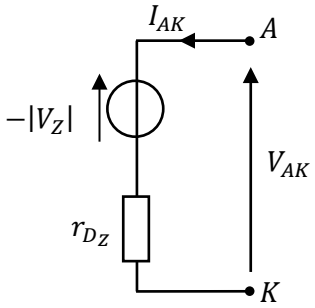


Reverse mode



ii. Linear model:

Reverse breakdown



Reverse mode

