PN junction

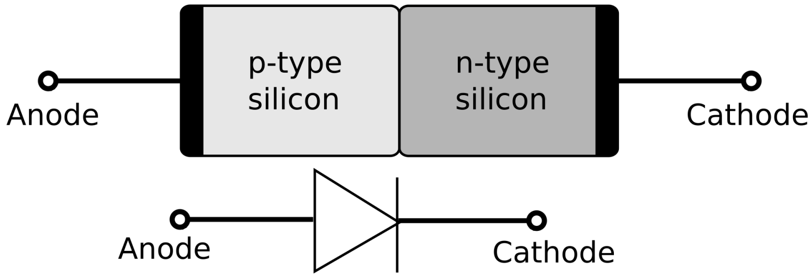
1. P-N junction: structure
2. P-N junction in equilibrium
3. Polarized P-N junction
4. Characteristic curve I-V
5. LEDs
6. Circuits with diodes

Recommended readings

- https://www.electronics-tutorials.ws/diode/diode_2.html

1. p-n junction: structure

A p-n junction consists of a union a n-type and p-type semiconductors (a single semiconductor crystal with two doped regions).



Basic properties:

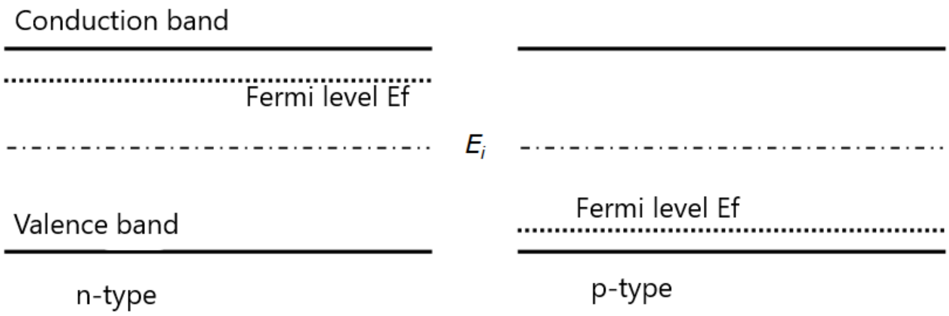
- Depending on the voltage applied, the junction between the two doped regions can become depleted of mobile charge carriers (called **depletion region**), leaving ionized impurities left, hence becoming non-conductive.
- As a result of having a depletion region, a p–n junction diode allows electric charges to flow in one direction, but not in the opposite direction; electrons can easily flow through the junction from n to p but not from p to n, while the reverse holds for holes. A **diode** is a circuit element defined by **allowing a flow of electricity in one direction but not the the opposite**. **Forward bias** is defined in the direction of easy current flow, while **reverse bias** is in the direction of little or no current flow.

It's crucial to understand how a p-n junction works, because it is the essential building block used in practically all kind of electronic devices: diodes, transistors, solar cells, LEDs, rectifiers...

2. p-n junction in equilibrium

2.1 Reaching the steady state

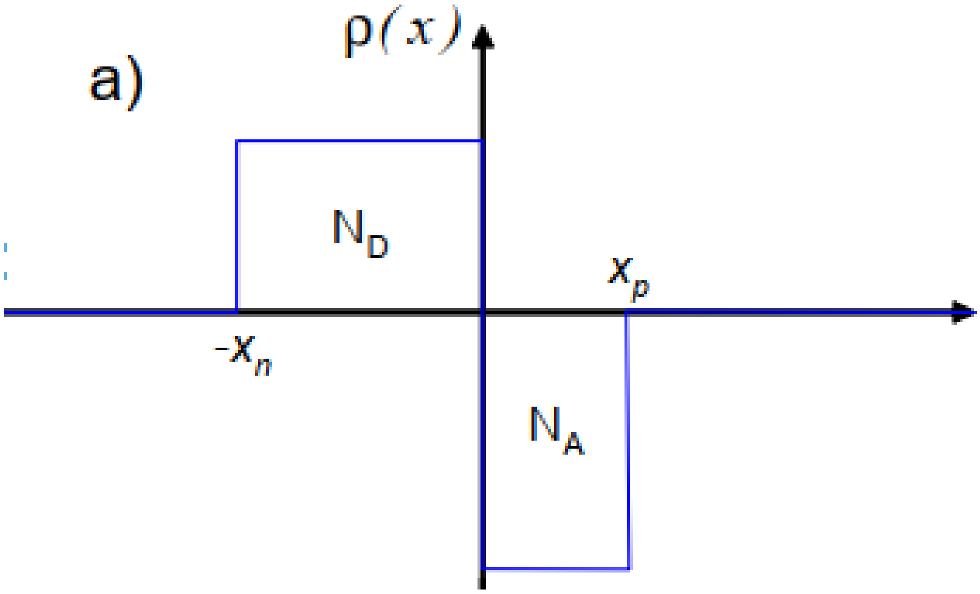
I. Before the junction, we have two separate band diagrams, with two different Fermi levels.



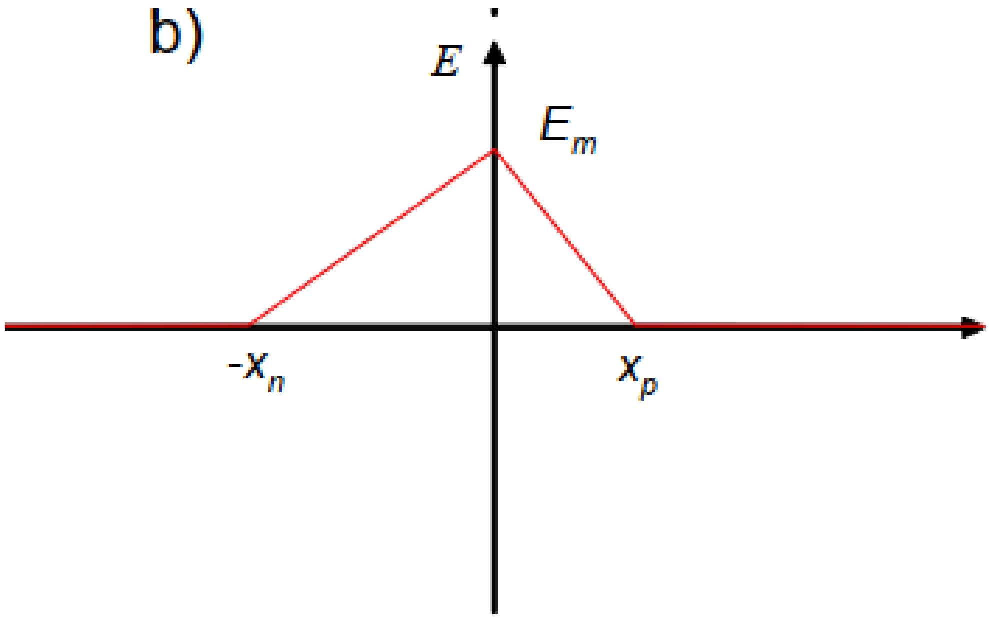
II. After the junction, there exists a strong **gradient of concentration** of impurities, which originates a current flux of carriers

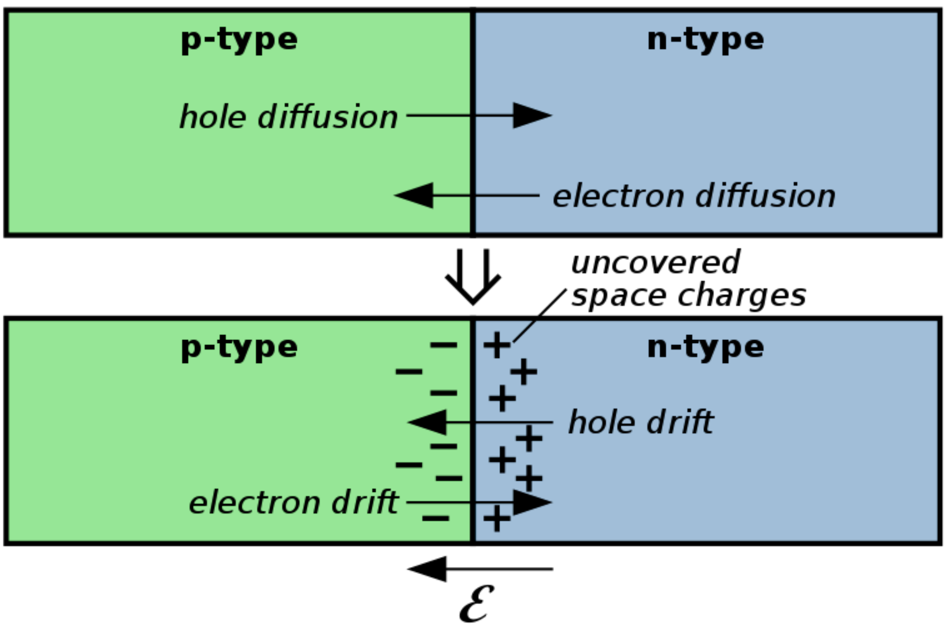
- electrons e^- from n to p
- holes h^+ from p to n

III. Such diffusion current holds as long as there exists a gradient of concentrations. Each e^- that abandons the n-type region leaves behind a fixed positive ion. Similarly, each h^+ leaves behind a negative ion. As a result, a **depletion region** is created around the junction where there is a spatial separation of positive and negative charges, with **charge density** $\rho(x)$.



IV. Such charge density $\rho(x)$ leads to an **electric field** $\vec{E}$ from n to p. Such electric field will **drift** electrons e^- from p to n and holes h^+ from n to p.

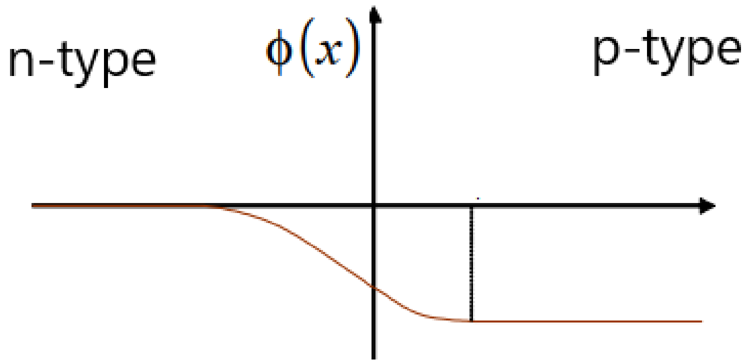




IV. At equilibrium, we reach a ***dynamical balance*** by which diffusion currents equal drift currents,

$$J_n|_{\text{dri}} = J_n|_{\text{dif}}$$
$$J_p|_{\text{dri}} = J_p|_{\text{dif}}$$

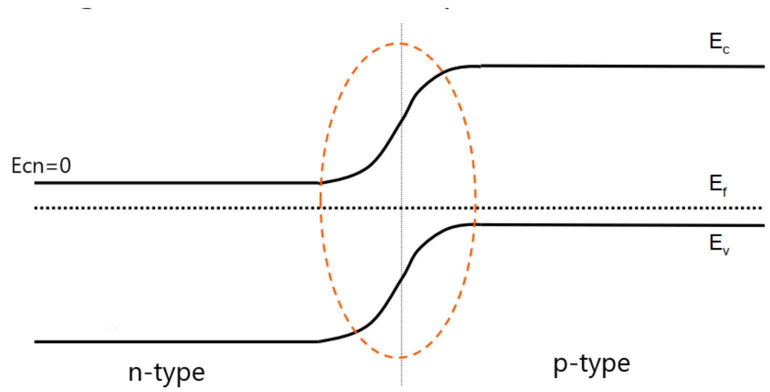
with a constant depletion region around the junction of width W. Such **inhomogeneous charge distribution** is associated with an electric field, and consequently, a potential difference across the junction, called **built-in potential** V_{bi}.



Convention: we define $V(x) = 0$ on the n side: all potential is applied to the p side, so $V_{bi} = V_p - V_n > 0$

2.2 Band diagram in equilibrium

Recall: a band diagram is a representation of the energy of electrons.



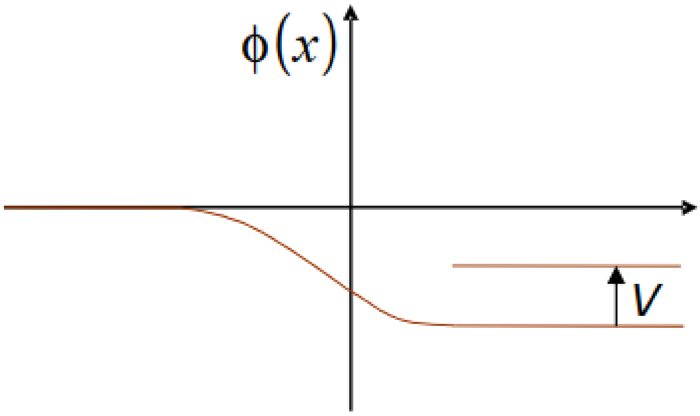
The Fermi level must be constant along the junction. There must be a difference of energy between the two regions due to the built-in potential, which makes energy of e^- in the n-type semiconductor diminish with respect to electrons in the p-type (recall potential and energy have opposite signs!).

Typically, at room temperature the voltage across the depletion layer for silicon is about 0.6 – 0.7 volts and for germanium is about 0.3 – 0.35 volts.

3. Polarized p-n junction

3.1 Band diagram

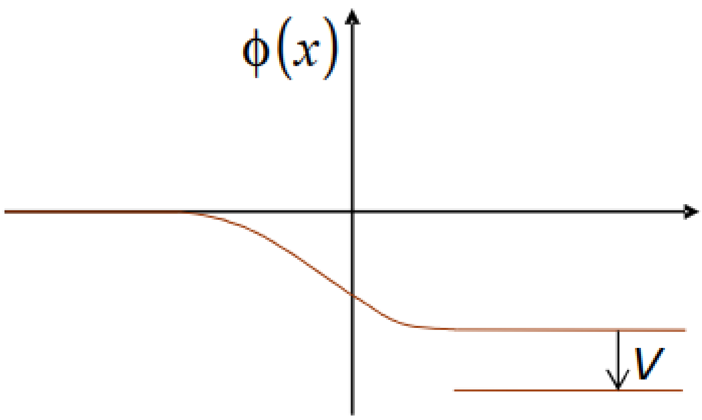
Forward bias: applying a positive voltage V (to the p-type side). Net voltage will be $= V - V_{bi}$.



We decrease the net potential in the depletion region $\implies$ net E decreases $\implies$ width W decreases.

Equilibrium was reached when the built-in electric field compensated diffusion. The external electric field opposes this field, **favoring diffusion** $\implies$ net current $I \neq 0$; current flows **from p to n**

Reverse bias: applying a negative voltage (p region). Net voltage$= V - (-V_{bi})$.



Opposite case

- W increases
- applied electric field opposes diffusion. $I = 0$

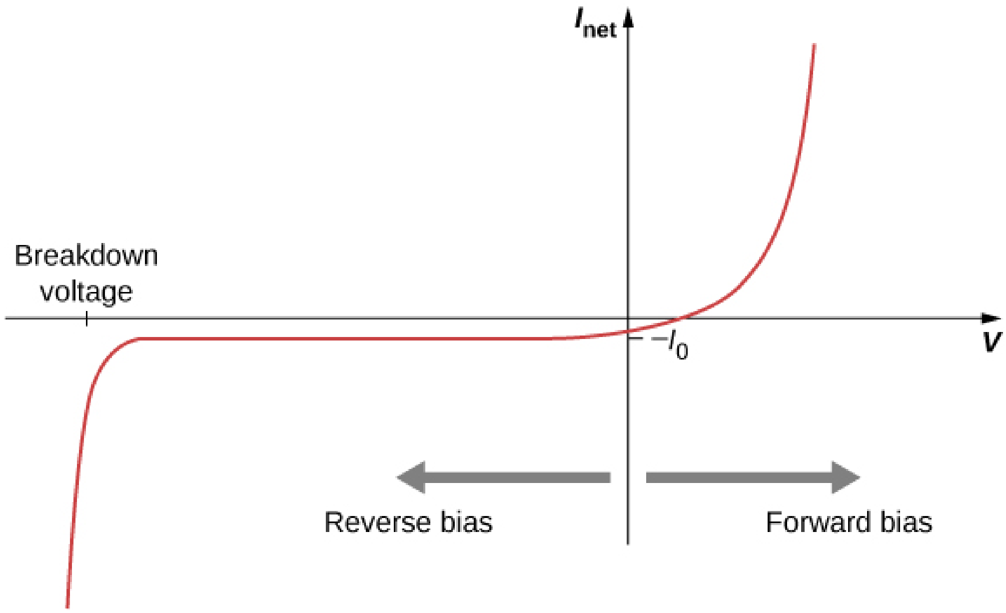
4. Characteristic curve I-V: Shockely equation

The basic mathematical model of a p-n junction was developed by Shockley in 1949 link.

Using some theoretical assumptions Shockley was able to derive what now is called the Shockely ideal diode equation (characteristic curve I-V),

$$I = I_0 \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right]$$

the voltage and the current do not have a linear relationship, it is a nonohmic device!

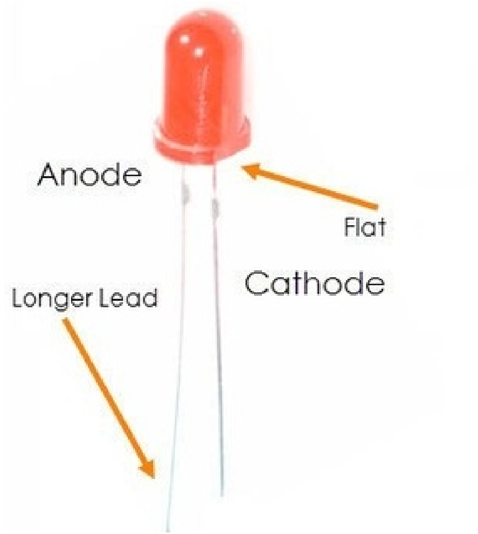


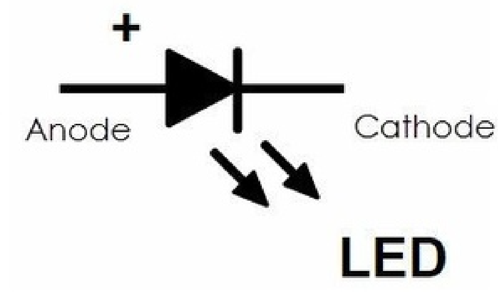
$V_{th} = \frac{k_B T}{e}$ is usually called *thermal voltage*, which is 26mV at room temperature

5. LEDs

A *light emitting diode* is a special type of diode, which emits light when is forward biased. The characteristic curve is the same as a normal diode, but the built-in potential is usually in the interval 1.7-2.7 volts.

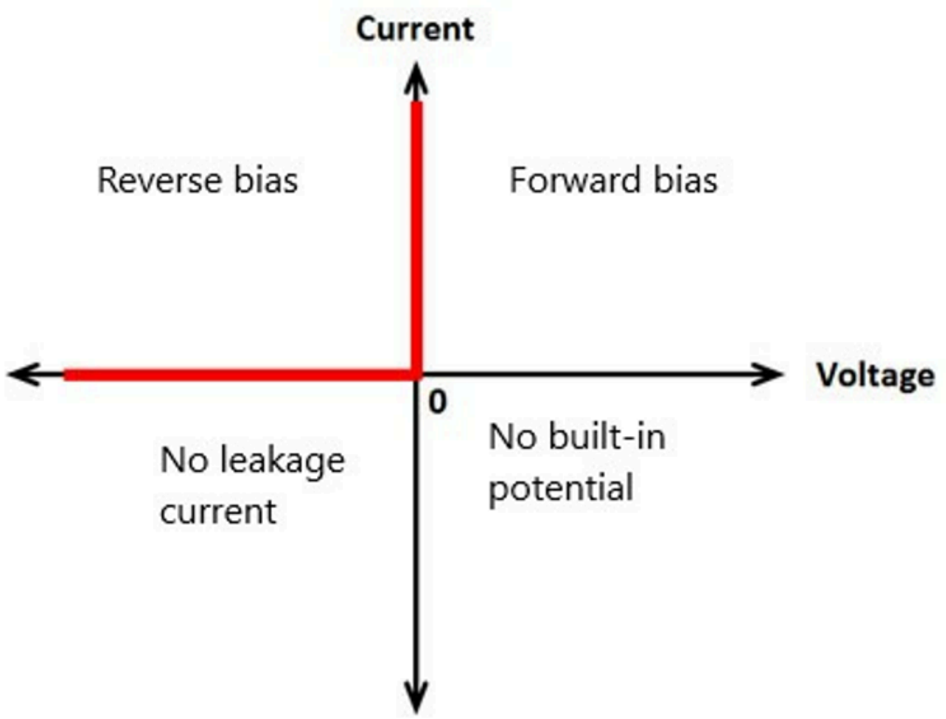
Symbol





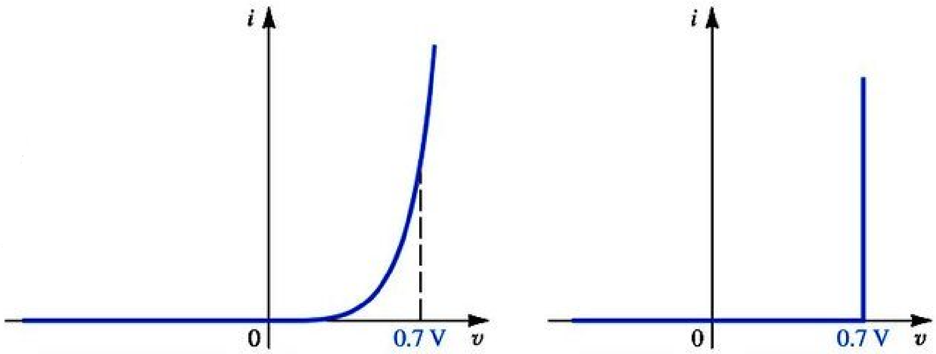
6. Circuits with diodes

6.1 Ideal diode



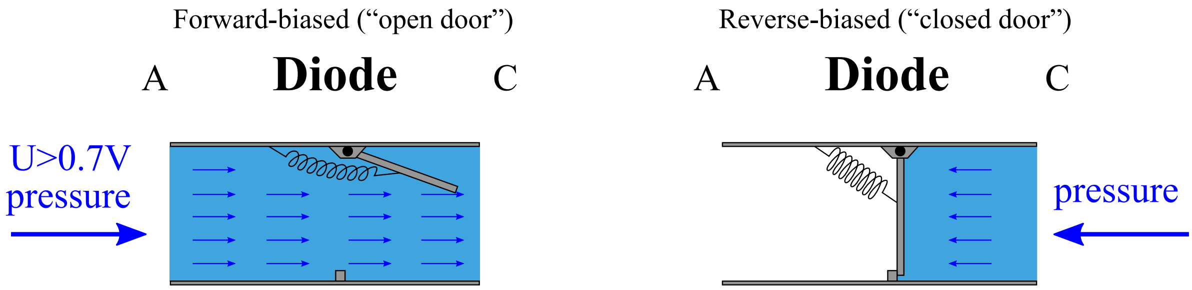
6.2 Piecewise-linear approximation

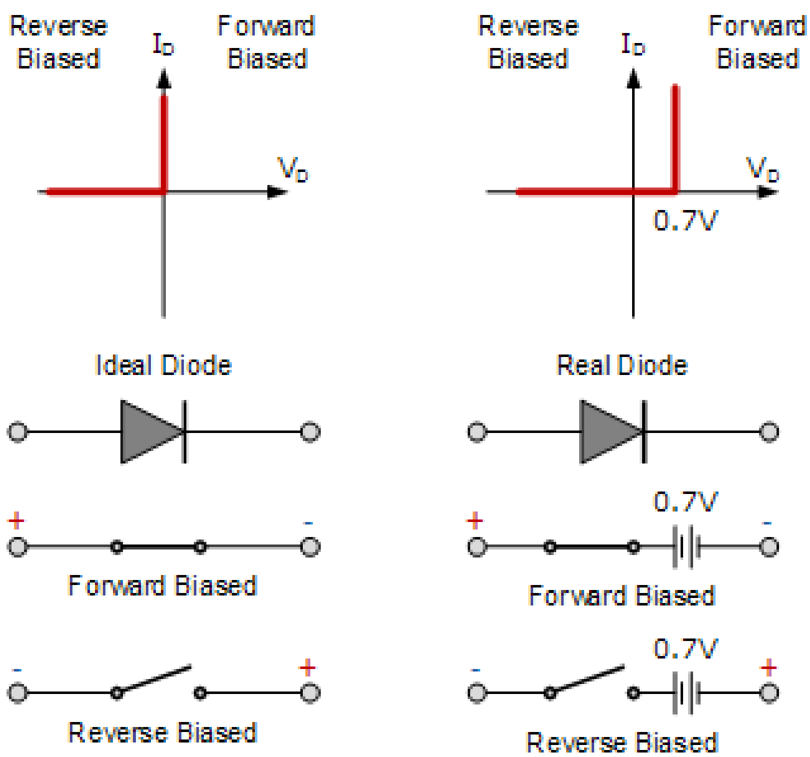
The diode equation is nonlinear, which forces us to solve nonlinear equations to solve a circuit. One can simplify the analysis by approximating the equation by a piecewise-linear function.



EQUATION	CONDITION
$V = 0.7V$	$I \geq 0$
$I = 0$	$V \leq 0.7V$

See more here



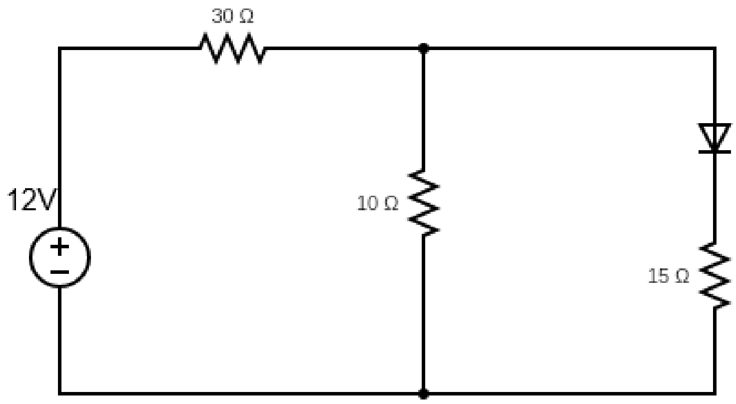


6.3 How to solve circuits with diodes?

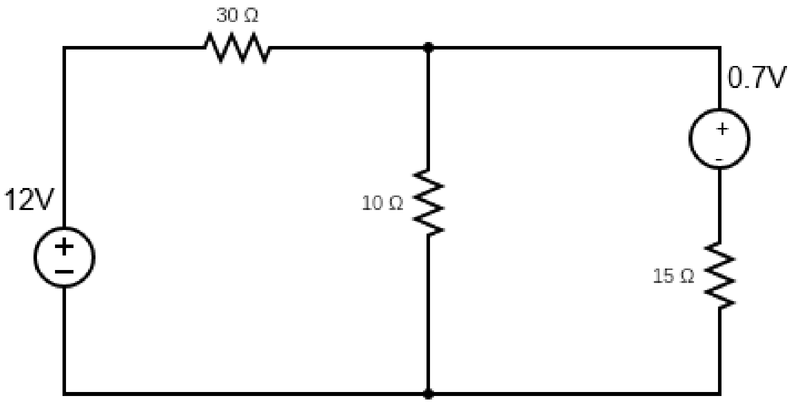
We shall assume the piecewise-linear approximation, by which we will be able to leverage the methods learned for linear circuits (like mesh analysis) when the diode is assume to be functioning in a given regime.

1. Make an hypothesis about the functioning of the diode.
2. Replace the diode by the corresponding circuit model (voltage source or open circuit).
3. Solve the circuit.
4. Check whether the result is consistent with the condition for the functioning selected.
5. In case of not being consistent, restart the process with another hypothesis.

6.4 Example



Assuming forward bias



Mesh analysis:

$$(30+10)I_1 + (-10)I_2 = 12$$
$$(-10)I_1 + (10+15)I_2 = -0.7$$

The current going through the diode is $I = 0.102A > 0$. The diode is in forward biased, so it is consistent.

In [6]:

```
import numpy as np
from numpy.linalg import solve
A=np.matrix('40,-10;-10,25')
b=np.matrix('12;-0.7')
x=solve(A,b)
print(x)
```

```
[[0.32555556]
 [0.10222222]]
```