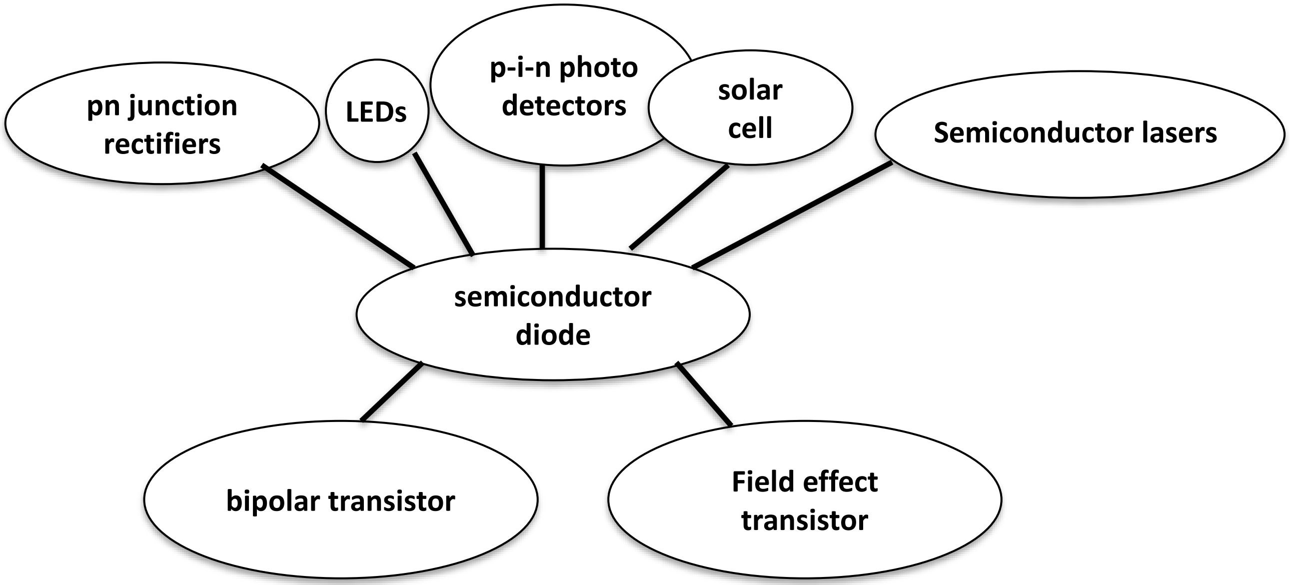
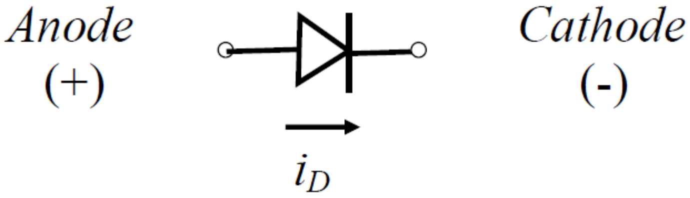
p-n junction. Operation principles of a semiconductor diode

Why we are discussing diodes? Because understanding the diode operation principles is the first step to understanding the operation principles of most of the electronic devices



Diode in electronic circuits

Symbolic representation of a Diode *in circuits*



An ideal diode conducts the current only in one direction

“Arrow” shows direction of the current in circuit

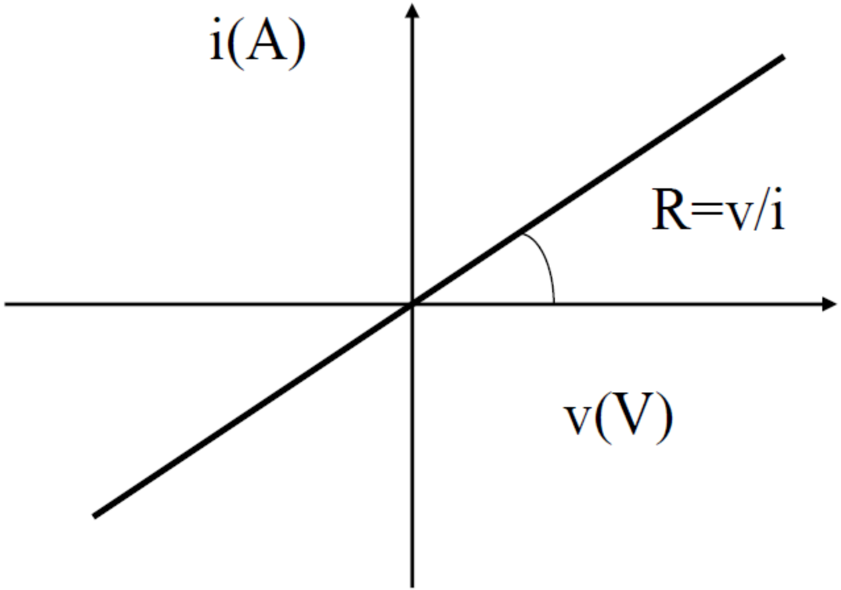
Positive polarity of the voltage at an anode and negative one at a cathode correspond to a forward bias condition

Minus at the anode and plus at the cathode correspond to reverse biasing

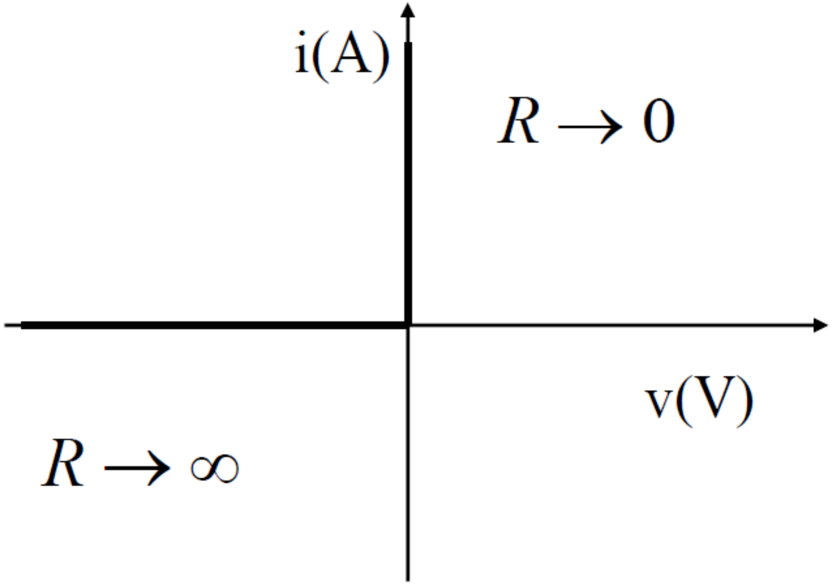
Diode as a non-linear resistor

Current-Voltage (I-V) Characteristics

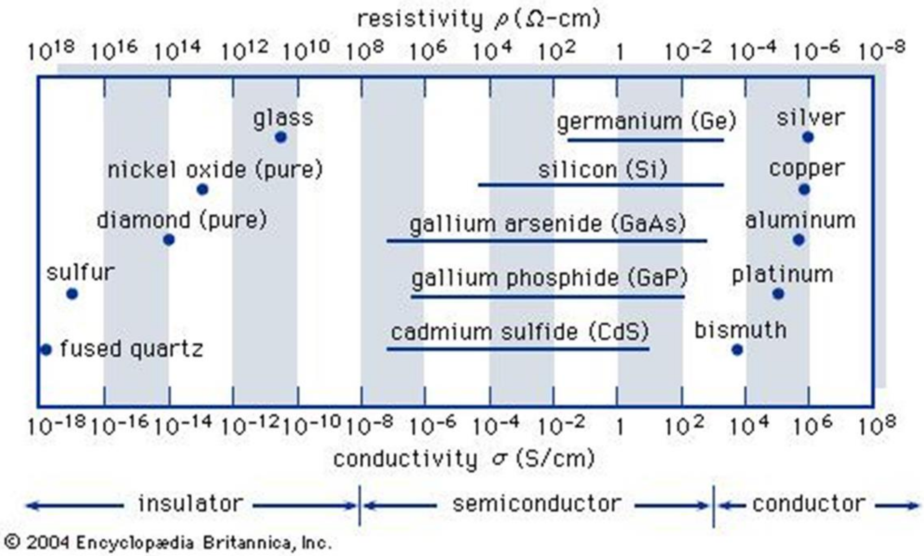
I-V of a LINEAR RESISTOR



I-V of an IDEALIZED DIODE



Why semiconductors?



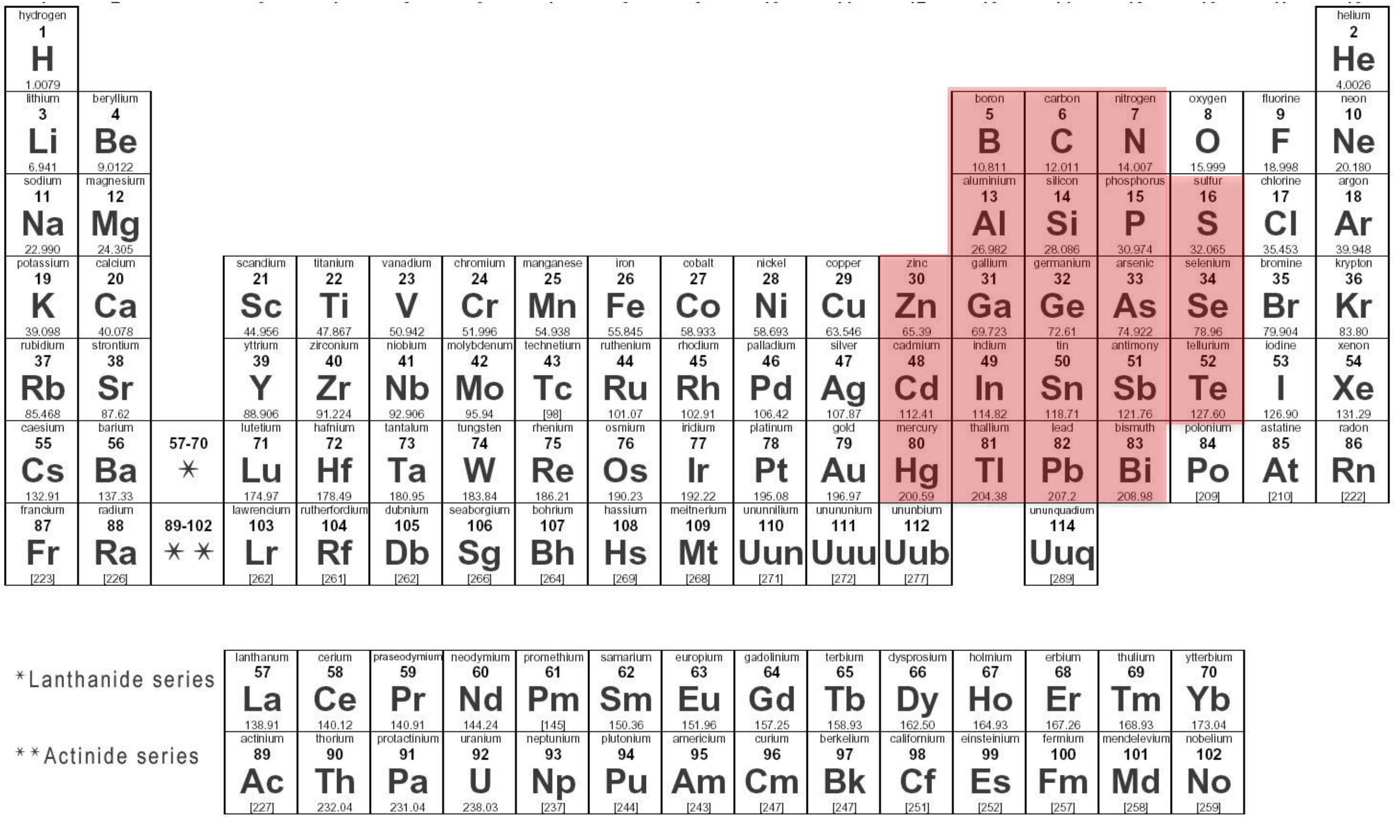
1. Semiconductors can be manufactured with conductivity varying within a wide range.

2. Semiconductors possess mobile charges with two opposite signs: (-) and (+).

3. External electric field can penetrate the semiconductor and thus suppress or reinforce the internal atomic electric field.

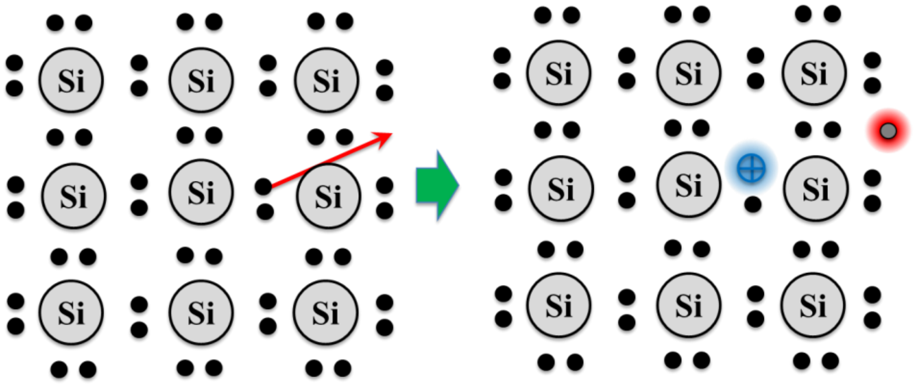
The principal nature of p-n junction performance is based on the above semiconductor properties. These properties do not characterize either insulators or metals. Insulators do not possess enough free charges to conduct current. On the other hand, the concentration of free carriers in metals is too high to allow external electric field to penetrate creating the screening effect.

Below is the periodic table of elements. Our elements of interest are highlighted. Chemical compositions of these elements and some elements are semiconductors: Si, Ge, GaAs, PbTe etc.



Charge transport in semiconductors: electrons and holes

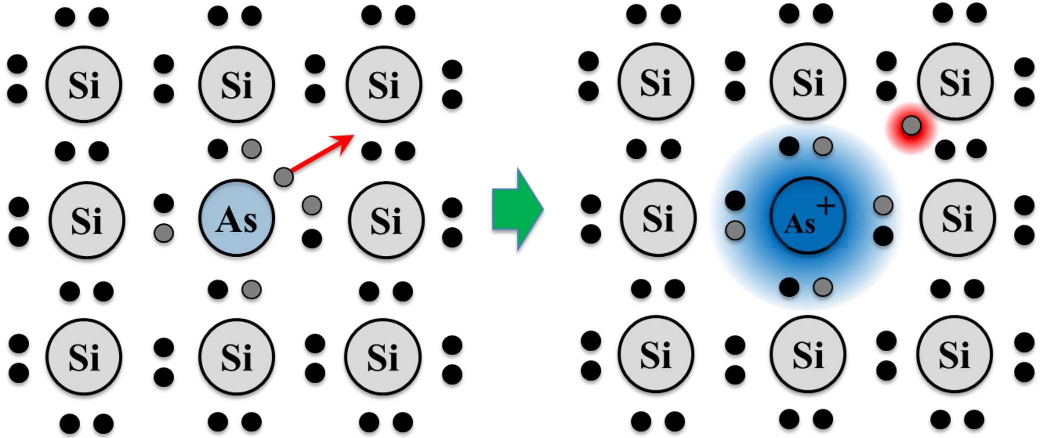
Below at the right side is a simplified scheme of a Si crystal. Each Si atom has 4 ”hands” – outer electrons which form chemical bonds. In Figure below these electrons are shown as the black dots. One pair of dots is the “handshake” between Si atoms. So each atom can connect with 4 others and form a crystal – solid material where atoms are in almost perfect order. Electrons are bound to atoms and cannot move. However, if we spend some energy (illuminate or heat the crystal) , and rip the electron out of the bond, the electron will be able to move in the crystal and transfer the electric current. If there are many of such electrons, the material becomes conductive.



Since the atoms are electrically neutral, after the electron leaves the atom it leaves a positively charged empty space, kind of a positively charged bubble – “the hole”. Another electron from the neighbor atom can fill in the empty space – it looks as the positively charged “hole” jumped the the next atoms. The holes, as well as the electrons can transfer the current.

n-type semiconductor: electrical current is a flow of the negatively charged electrons

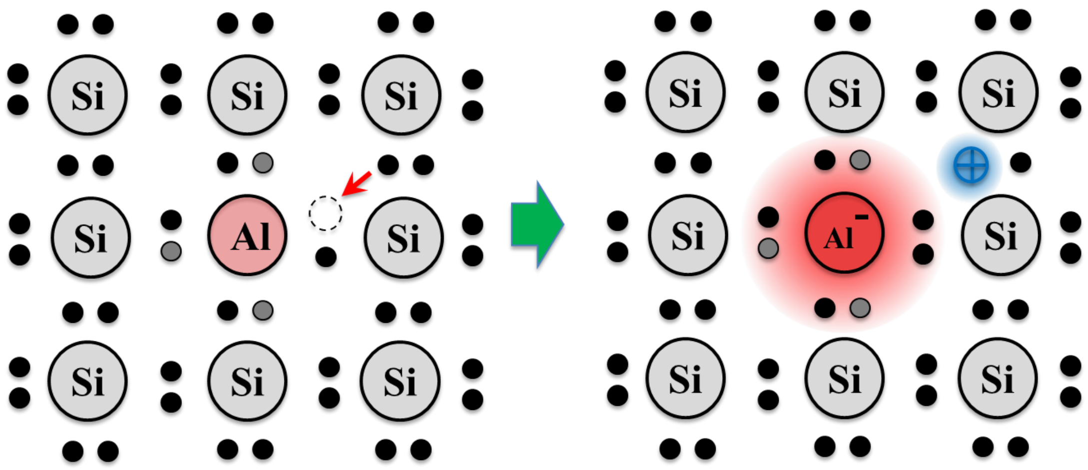
Normally, heating up or illuminating a pure semiconductor crystal we create equal amount of electrons and holes, so the current is transferred by both positive and negative charge carriers. But we can make a crystal which will contain mostly electrons or holes. Let us replace part of the Si atoms by As (arsenic) ones. Each As atom has 5 “hands” – 5 valence electrons. 4 of these will be occupied in the chemical bonds – connected to the neighbor Si atoms. The fifth one has no bond to fill in and is almost free. It takes just a little energy to rip these electron out of the As atom and send it to “free sail”. At room temperature most of the extra electrons are free. Introduction of As into Si or Ge crystal makes this crystal conductive and the current is transferred by negatively charged electrons. Such material is called “n-type semiconductor” and As or any other atom providing electrons is called “donor impurity” or simply “donor”



As is a or *donor impurity* for Si

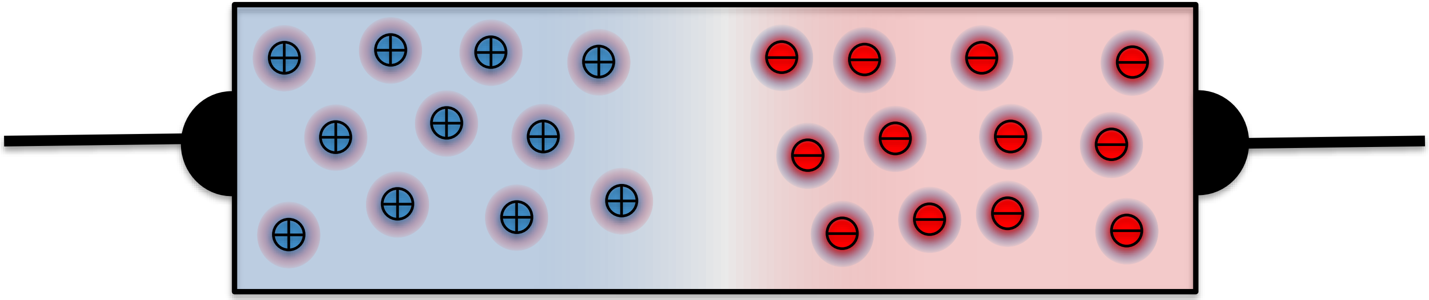
p-type material: electrical current is a flow of the positively charged vacancies – “holes”

Now, let us replace part of the Si atoms by Al (aluminum) ones. Each Al atom has just 3 valence electrons. All 3 valence electrons of Al will be occupied in the chemical bonds but one place will be empty. An electron from the neighbor atom can fjump into the empty space and form a free, positively charged hole. Again, introduction of Al into Si or Ge crystal makes this crystal conductive and the current is transferred by positively charged holes. Such material is called “p-type semiconductor” and Al or any other atom having 3 or less valence electrons is called “acceptor impurity” or simply “acceptor”



Al is an *acceptor impurity* for Si

The p-n junction is a semiconductor crystal, consisting of two parts: p-type and n-type . The p-n junction is the main element of a diode.

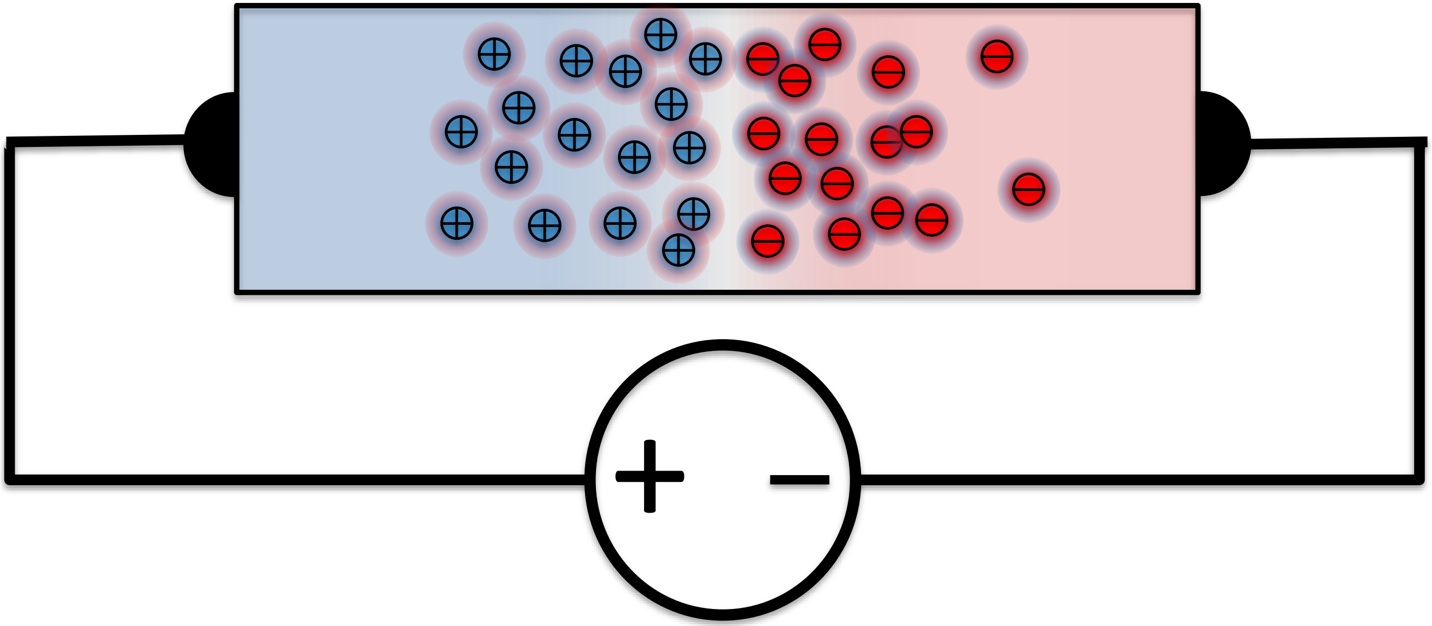


p-type part

n-type part

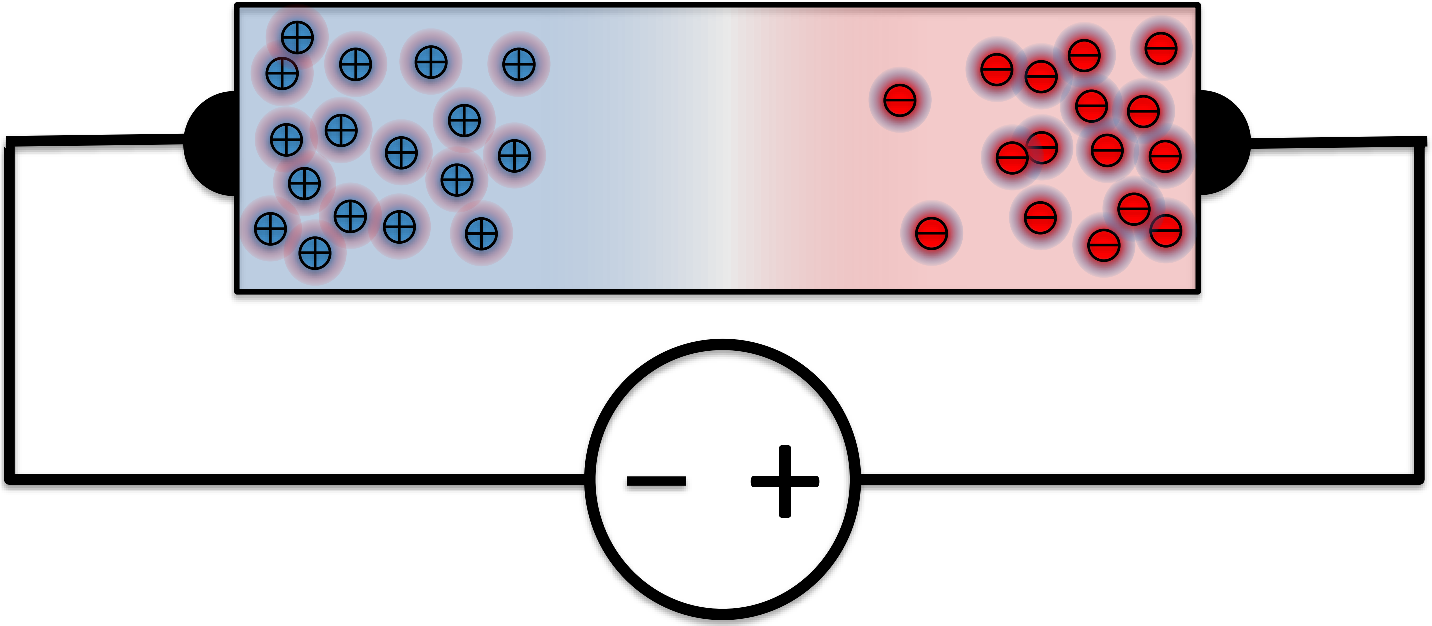
Forward bias (forward voltage): “+” to p-side, “-” to n-side. The current flows.

If we apply direct voltage to the diode , which means “plus” to p-side, “:minus” to n-side, the electrons and holes are pushed toward the middle of the crystal – to the junction between p-and n- ends. The electrons and holes meet each other. When the electron mees the hole, they annihilate and the current flows. New electron enter the n-side from the wire, and exit from the p-side.

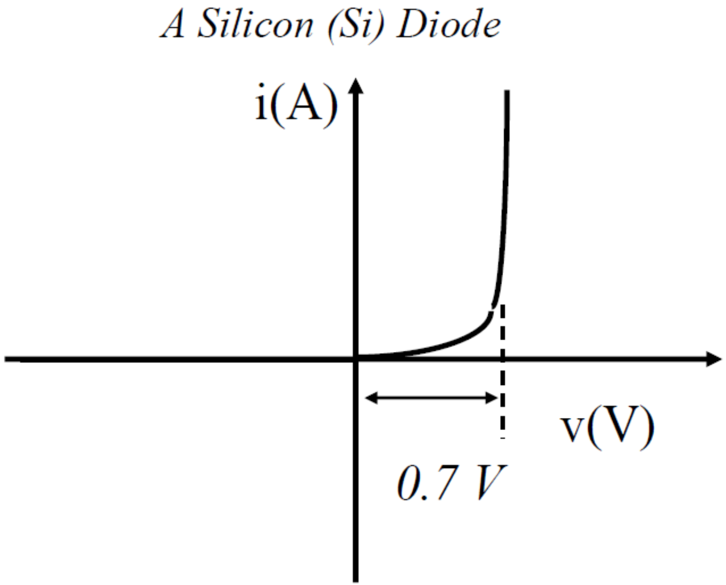


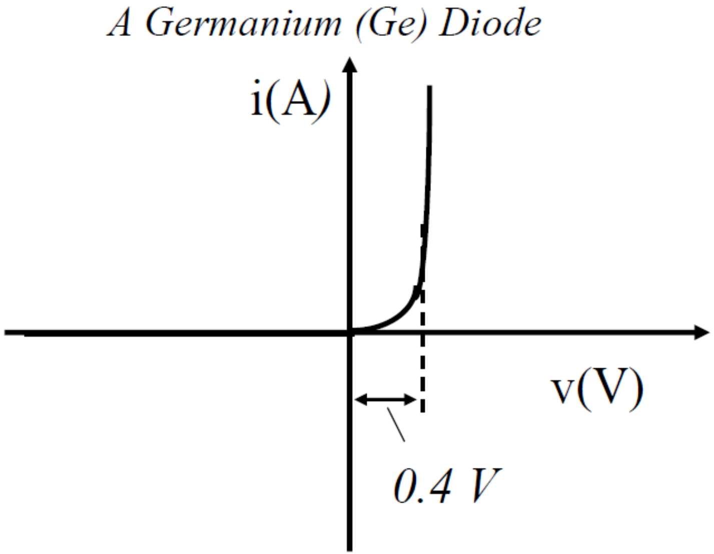
Reverse bias (reverse voltage): “+” to n-side, “-” to p-side. The current does not flow.

If we apply reverse voltage to the diode , which means “plus” to n-side, “:minus” to p-side, the electrons and holes are “sucked” out of the junction and the current doies not flow.



Current-voltage characteristic of a *real* diode





- The *typical* voltage drop across a *Si* diode at forward bias is 0.7V

In a real diode, even under the forward bias, the current starts flowing if the voltage exceeds some threshold voltage, which is called “the opening voltage”. The openonmg voltage depends on the diode material and typically is 0.7V for Si-based diodes and 0.4V for Ge-based diodes.

Question:

What happens if we introduce both donors and acceptor impurities into the same crystal and distribute them evenly over the crustal volume?