Physics 2. Electrical Engineering

Week 11 Semiconductors. PN Junction

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Objectives

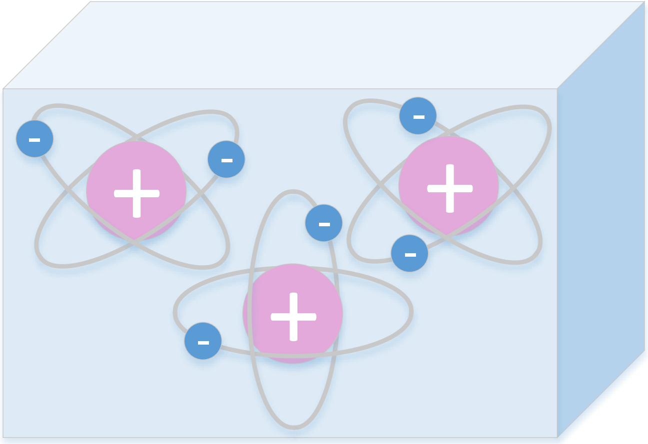
The main objectives of today's lecture are:

- Learn what are semiconductors
- Study the PN junction
- Learn the fundamentals of semiconductor diodes

Conductivity: Review

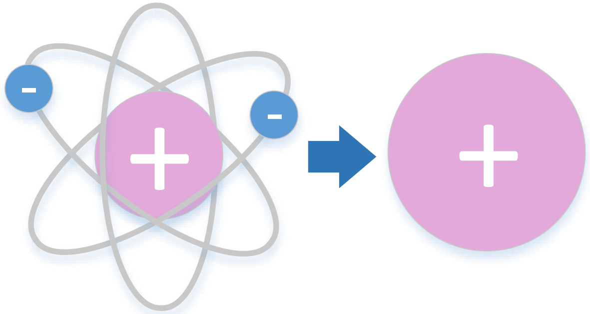
Electric Charge (1)

Assume you have a bulk of some material that contains many atoms (6×10^{23} per mole).

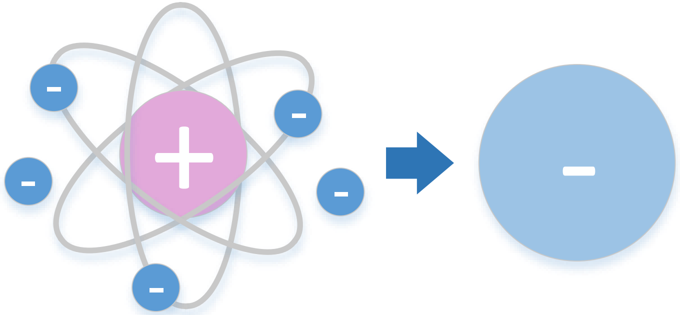


Atoms that have either a deficit or a surplus of electrons are called ions.

- If there is an excess of positive ions in a bulk of material, its net charge Q will be positive, and vice versa.
- Electric charge is measured in coulomb [C].



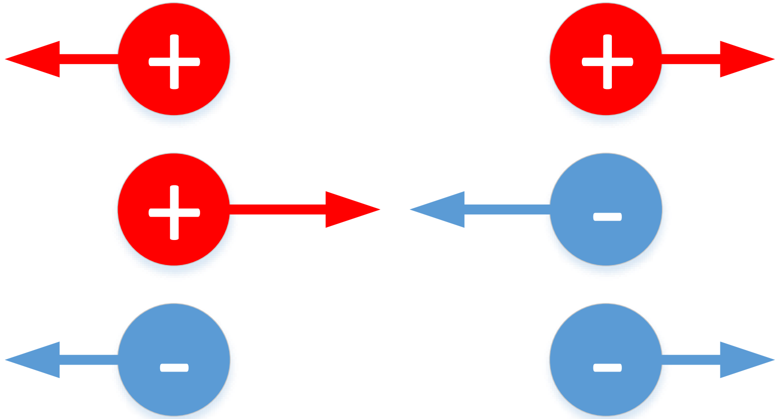
Positive ion



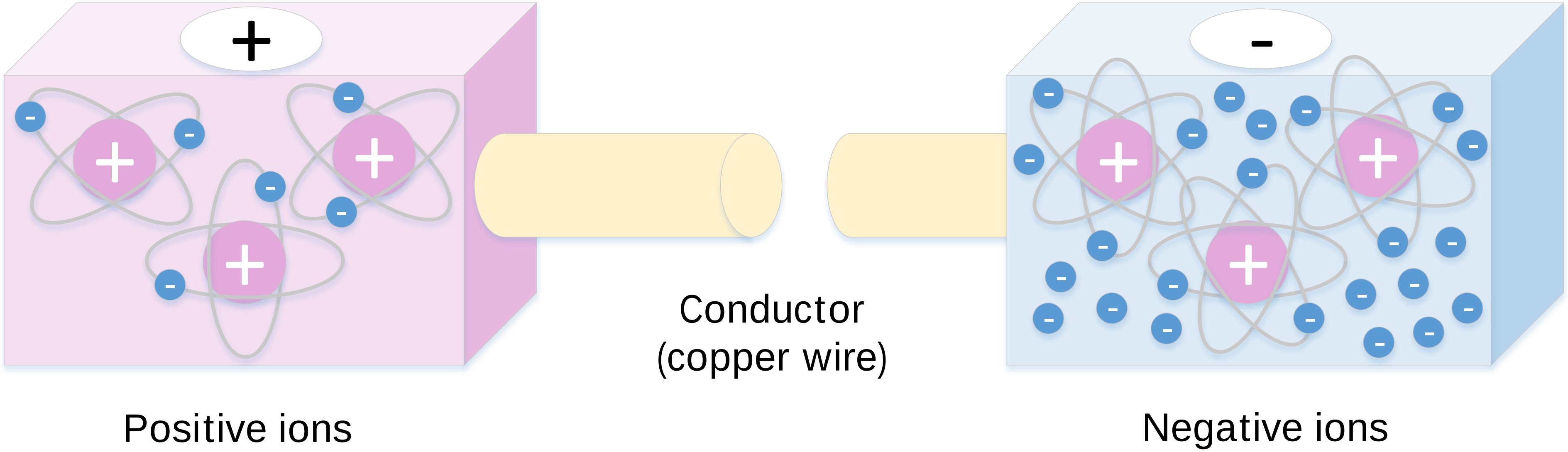
Negative ion

Electric Charge (2)

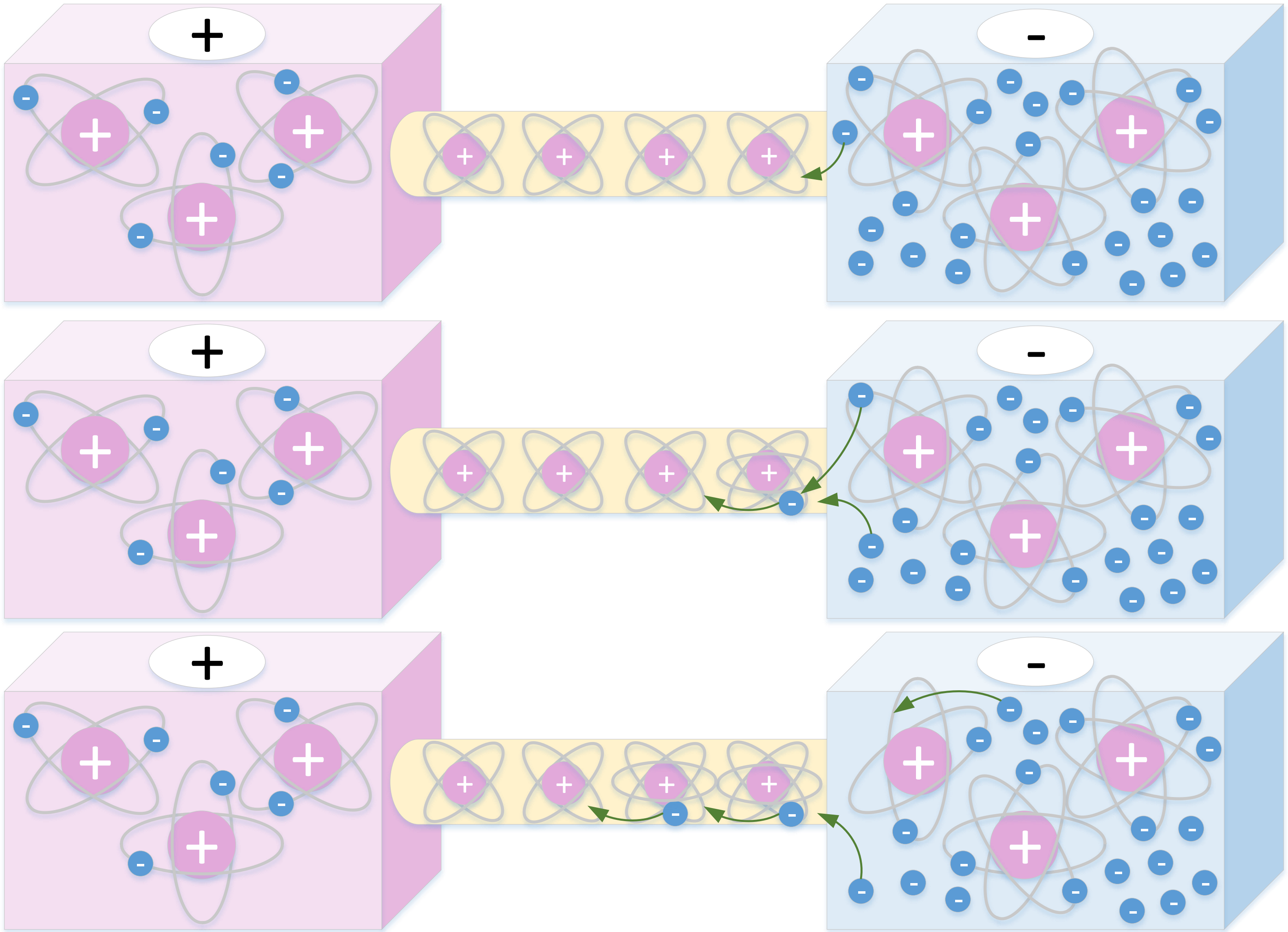
Particles of the same (like) charge repel each other, while particles of opposite (unlike) charge attract each other.



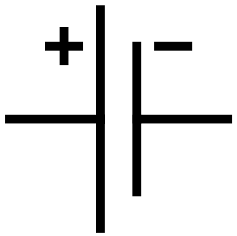
Assume you have 2 pieces of some material with positive and negative net charges, and you connect them with a conductive wire.



Electric Charge (3)



There is a difference in charge levels (electric potential)!



Semiconductors

Electrical Resistivity

The electric resistivity and its inverse, electrical conductivity, is a fundamental property of a material that quantifies how strongly it resists or conducts electric current.

Various materials have different resistivity and conductivity (shown here for 20 °C).

Material	Resistivity, ρ	Conductivity
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Gold	2.44×10^{-8}	4.11×10^{7}
Calcium	3.36×10^{-8}	2.98×10^{7}
Carbon (graphite)	3.10×10^{-3}	3.3×10^{2}
Sea water	2.00×10^{-1}	5
Diamond	10^{12}	10^{-12}
Rubber	10^{13}	10^{-13}
PET	10^{21}	10^{-21}
Teflon	10^{24}	10^{-24}

Semiconductors (1)

Semiconductors are materials whose electrical properties fall somewhere between those of conducting and of insulating materials.

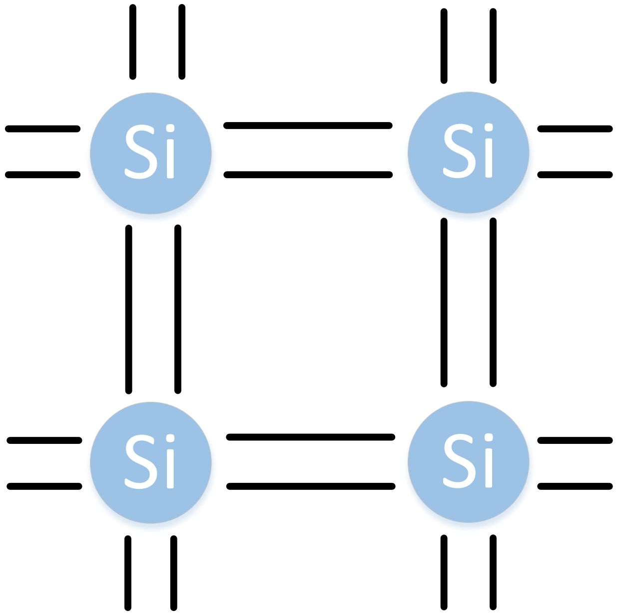
For example, consider the conductivity of these materials shown on the right.

Material	Conductivity
Silver	6.30×10^{7}
Copper	5.96×10^{7}
Gold	4.11×10^{7}
Calcium	2.98×10^{7}
Germanium	2.17
Silicon	4.35×10^{-4}
Diamond	10^{-12}
Rubber	10^{-13}
PET	10^{-21}
Teflon	10^{-24}

Semiconductors (2)

A conducting material is characterized by large number of conduction band electrons, which have very weak bond with the basic structure of the material and can easily flow with current.

- Thus, an electric field easily imparts energy to the outer electrons in a conductor and enables the flow of electric current.
- In a semiconductor, on the other hand, one needs to consider the lattice structure of the material, which in this case is characterized by covalent bonding.
- Let us look at the lattice arrangement for Silicon (Si).



Semiconductors (3)

For semiconductors,

- at sufficiently high temperatures, thermal energy causes the atoms in the lattice to vibrate
- when sufficient kinetic energy is present, some of the valence electrons break their bonds with the lattice structure and become available as conduction electrons.

These free electrons enable current flow in the semiconductor.

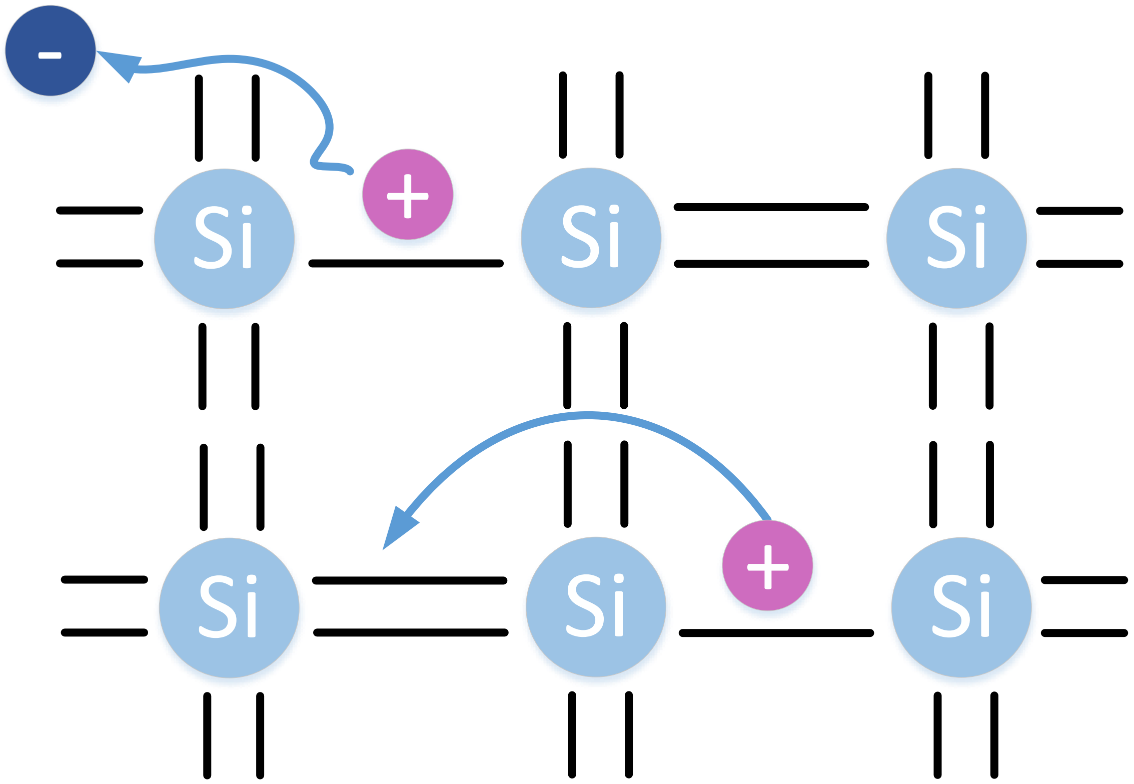
Note that in a conductor, valence electrons have a very loose bond with the nucleus and are therefore available for conduction to a much greater extent than valence electrons in a semiconductor.

Semiconductors (4)

Whenever a free electron leaves the lattice structure, it creates a corresponding positive charge within the lattice.

The vacancy caused by the departure of a free electron is called a hole.

- When the hole is present, we have, in effect, a positive charge
- If a valence band electron “jumps” to fill a neighboring hole, it correspondingly creates a new hole at a different location (positive charge moves to the right)



Semiconductors (5)

Thus,

- we have two electric current carrier types: free electrons and holes.

Mobility (the ease with which charge carriers move across the lattice) is much greater for electrons than the one for holes, since

- free electron has already broken the covalent bond, whereas
- for a hole to travel through the structure, an electron must overcome the covalent bond each time the hole jumps to a new position.

Semiconductors (6)

Therefore, holes and free electrons travel in opposite directions when the semiconductor is subjected to an external electric field.

Occasionally, a free electron traveling in the immediate neighborhood of a hole will “join” it.

- This phenomenon, called recombination, reduces the number of charge carriers in a semiconductor.

Whenever this phenomenon takes place, two charges are lost.

Semiconductors (7)

However, the net balance is such that a number of free electrons always exist at a given temperature. The number of free electrons available for a given material is called the intrinsic concentration n_i.

For example, at room temperature, silicon has

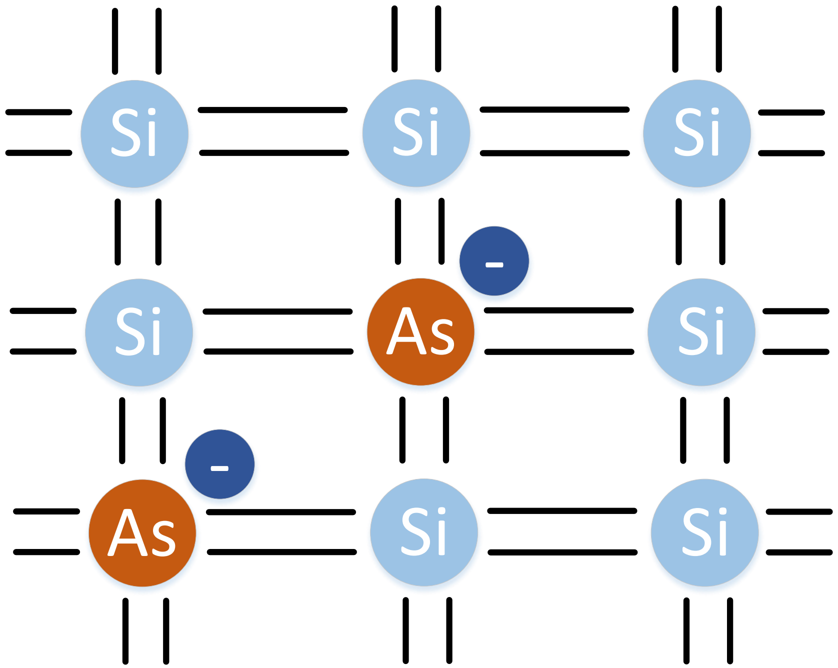
$$n_i = 1.5 \times 10^{16} \quad \text{electrons/m}^3$$

- Note that there must be an equivalent number of holes present as well
- The intrinsic concentration of holes is typically denoted by p_i

Semiconductors (8)

To control the number of charge carriers in a semiconductor, the process of doping is usually employed, which consists of adding impurities to the semiconductor.

- If the dopant is an element of group 15 (e.g., arsenic), it “donates” an additional free electron to the lattice structure, and therefore is called a donor
- If the dopant is an element of group 13 (e.g., indium), it accepts a free electron and therefore is called an acceptor.



Semiconductors (7)

Semiconductors doped with donor elements conduct current predominantly by means of free electrons and are therefore called n-type semiconductors:

$$n >> n_i$$
$$p << p_i$$

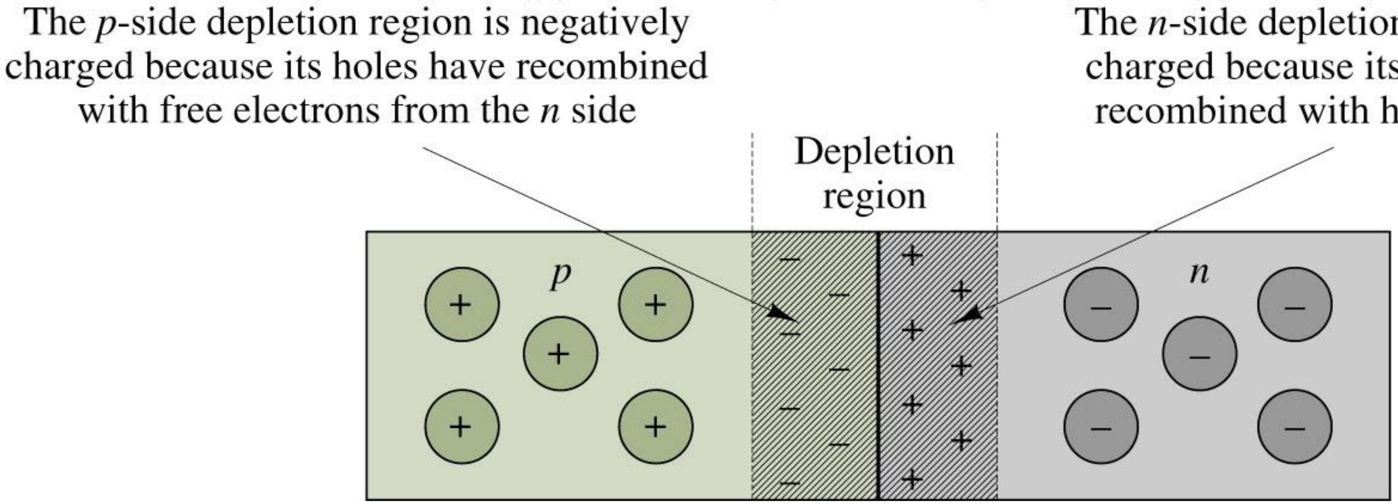
- When acceptor element is used as the dopant, the resulting semiconductor is said to be a p-type semiconductor.

$$n << n_i$$
$$p >> p_i$$

The *pn* Junction and the Semiconductor Diode

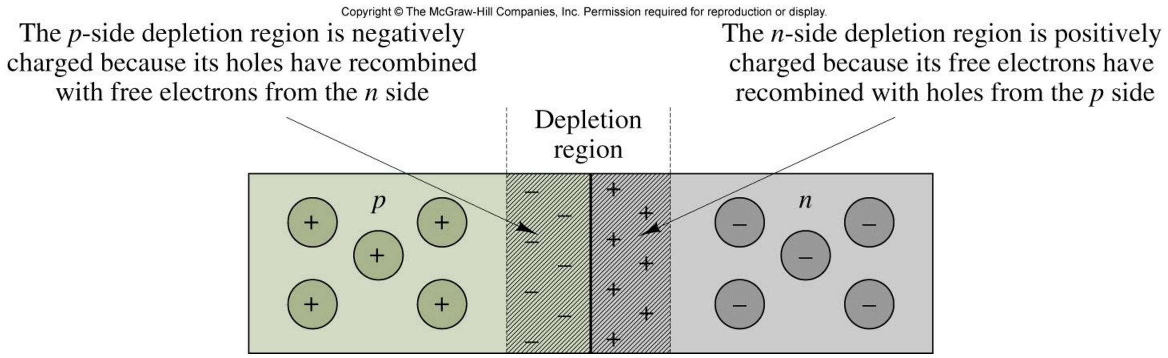
The pn Junction (1)

When a section of p-type material and a section of n-type material are brought in contact to form a pn junction, several interesting properties arise.



- Now, in the neighborhood of the junction, in a small section called the depletion region, the mobile charge carriers (holes and free electrons) come into contact with each other and recombine, thus leaving virtually no charge carriers at the junction.

The pn Junction (2)



What is left in the depletion region, in the absence of the charge carriers, is the lattice structure of the *n*-type material on the right and of the *p*-type material on the left.

However,

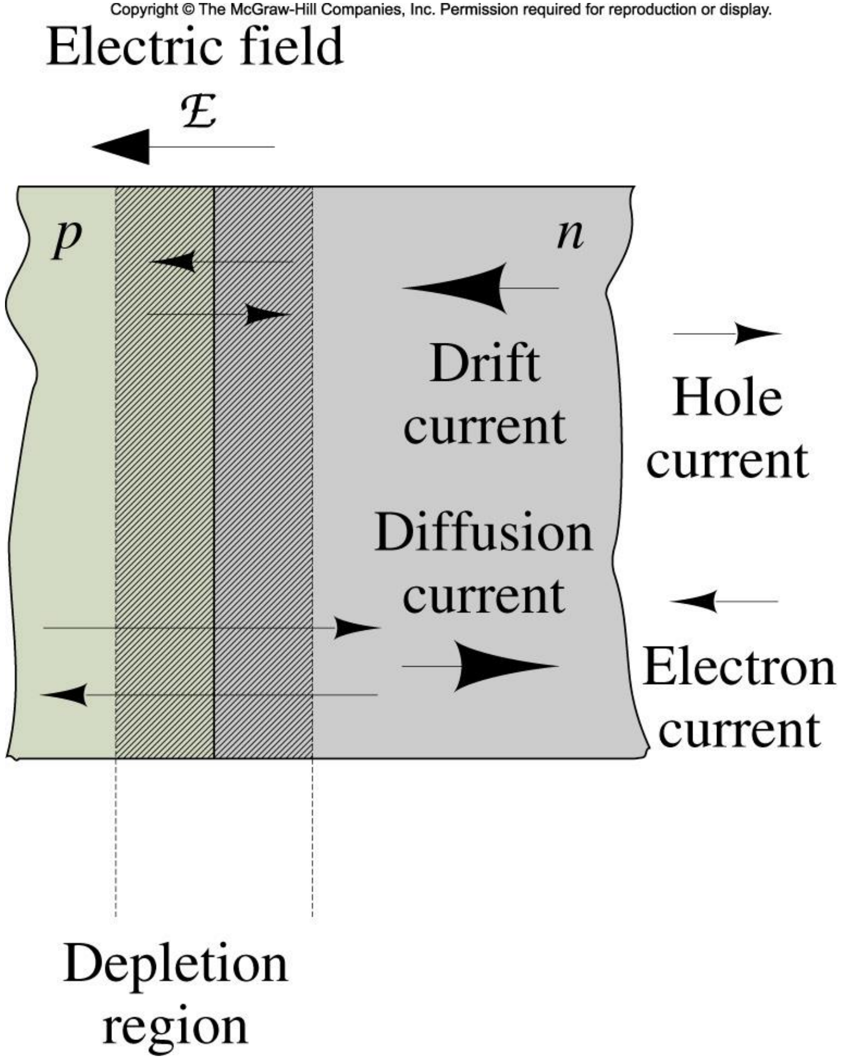
- the *n*-type material, deprived of the free electrons, which have recombined with holes in the neighborhood of the junction, is now positively charged. Similarly,
- the *p*-type material at the junction is negatively charged, because holes have been lost to recombination.
- The charge separation therefore causes a contact potential to exist at the junction.

This potential (called offset voltage) is typically on the order of a few tenths of a volt and depends on the material (about 0.6 to 0.7 V for silicon).

The pn Junction (3)

The offset voltage generates an electric field across the pn junction.

- In the *n*-type materials, some of the (thermally generated) holes drift into depletion region (to the left), while for *p*-type material, the electrons drift to the right.
- The net effect is a small reverse saturation current (I_S) which flows to the left. At room temperature, I_S is on the order of nanoamperes (10^{-9}) in silicon.
- If a hole from *p* side enters the *n* side, it is quite likely to recombine electrons on the *n* side (diffusion current I_d)

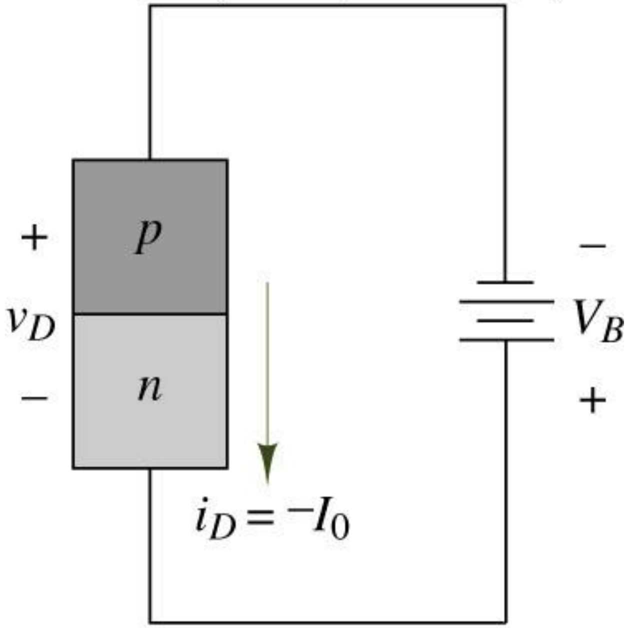


The pn Junction: Reverse Bias

The phenomena of drift and diffusion help explain how a pn junction behaves when it is connected to an external energy source.

- In case of reverse-biased direction, the contact potential is increased.
- Now, the majority carriers trying to diffuse across the junction need to overcome a greater barrier (a larger potential) and a wider depletion region.
- Thus, the diffusion current becomes negligible, and the only current that flows under reverse bias is the very small reverse saturation current:

$$i_D = -I_0 = I_S$$



(a) Reverse-biased *pn* junction

The pn Junction: Forward Bias (1)

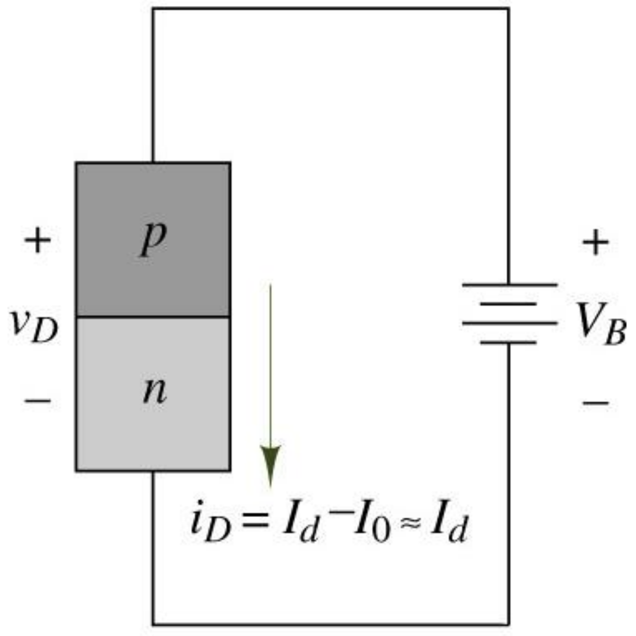
When the pn junction is forward-biased, the contact potential across the junction is lowered.

- Now, the diffusion of majority carriers is aided by the external voltage source, and the diffusion current increases as a function of the applied voltage according to

$$I_d = I_0 e^{q v_D / kT}$$

where

- k = 1.381x10^{-23} J/K is Boltzmann's constant,
- q is the charge of one electron, and
- T is the temperature of the material in kelvins (K).
- I_0 is typically very small (10^{-12} to 10^{-15} A).



(b) Forward-biased *pn* junction

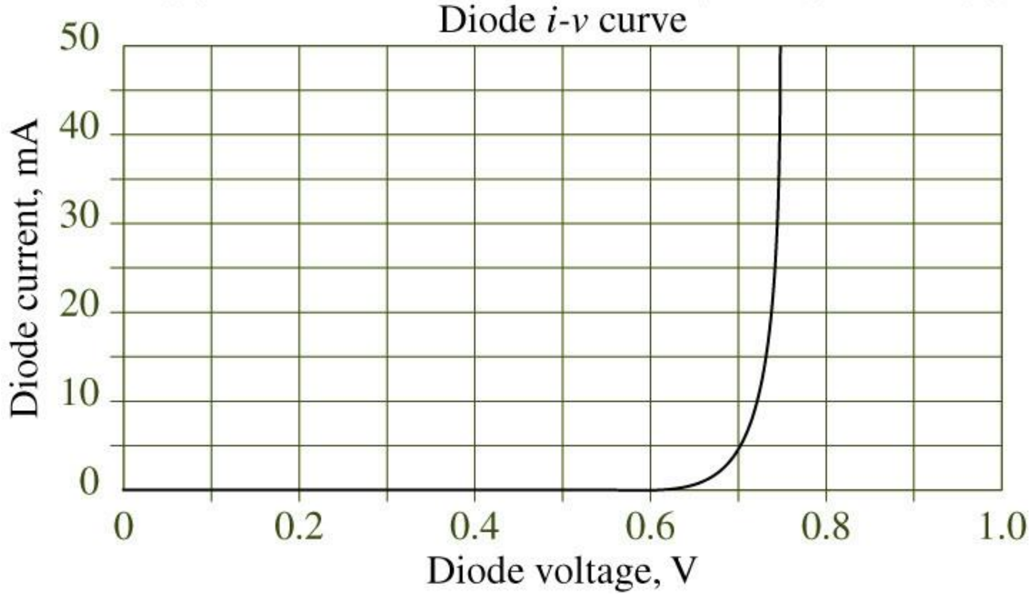
The pn Junction: Forward Bias (2)

The net pn junction current under forward bias is therefore given by

$$i_D = I_d - I_0 = I_0\left(e^{qv_D/kT} - 1\right)$$

which is known as the diode equation.

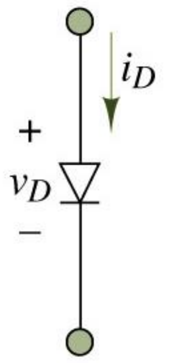
- The i-v characteristics of a pn junction is shown below.



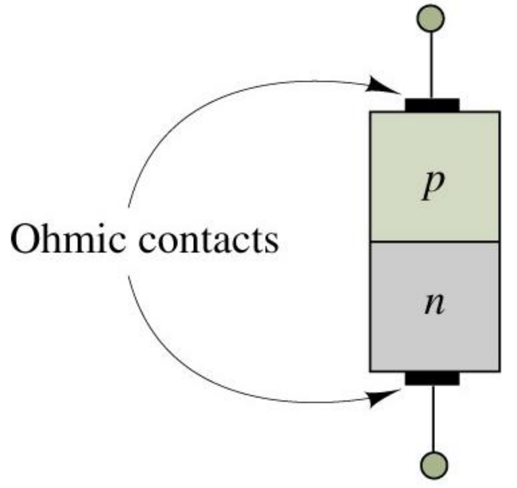
Semiconductor Diode

The ability of the pn junction to conduct current in only one direction (when the junction is forward-biased) makes it valuable in circuits applications.

- A device having a single pn junction and ohmic contacts at its terminals is called a semiconductor diode, or simply diode.



Circuit symbol



pn junction

Thank you for your attention!

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