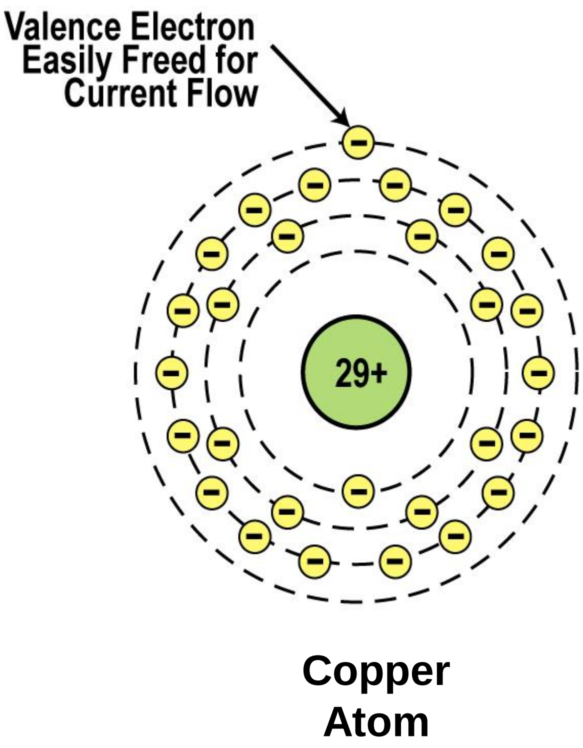
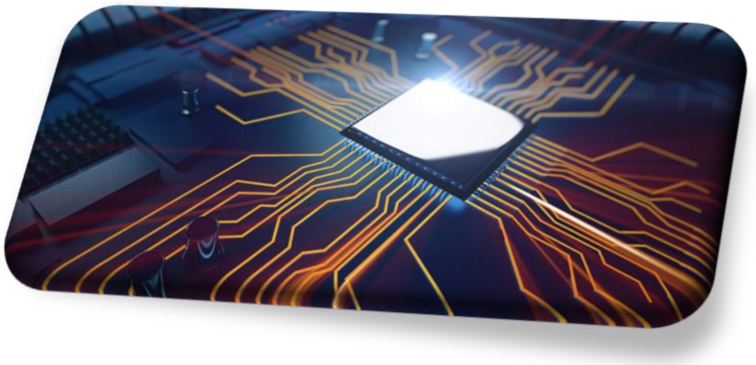
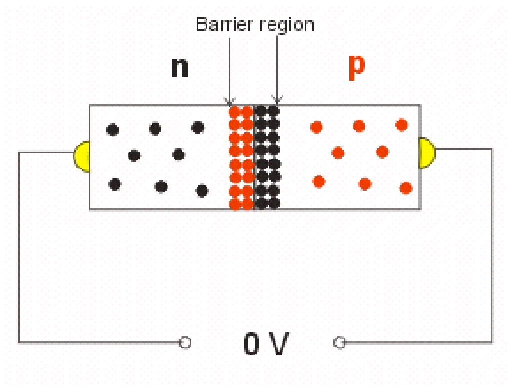
Introduction to Semiconductor Materials



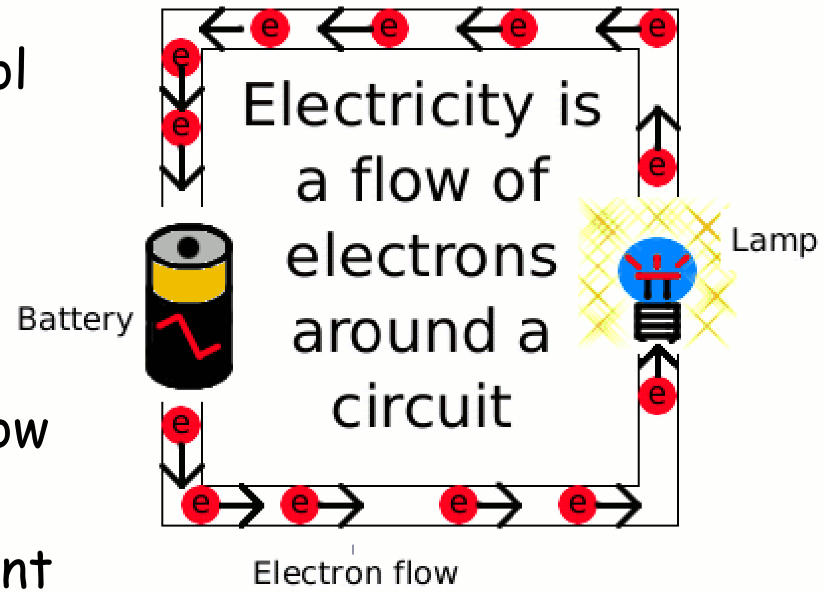




Diode with no bias

Electronic Materials

The goal is to generate and control the flow of an electrical current.

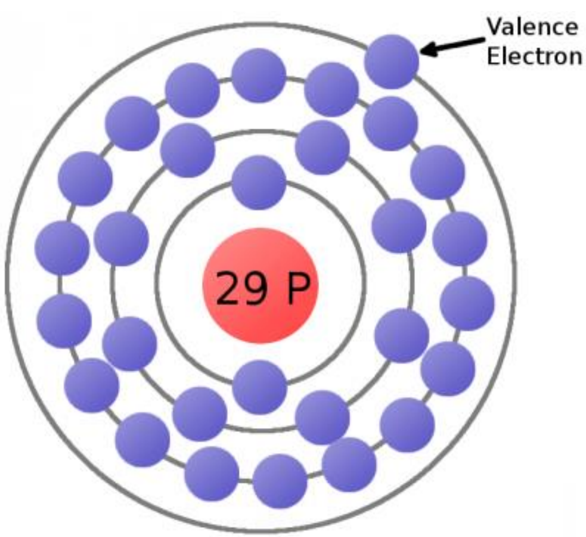


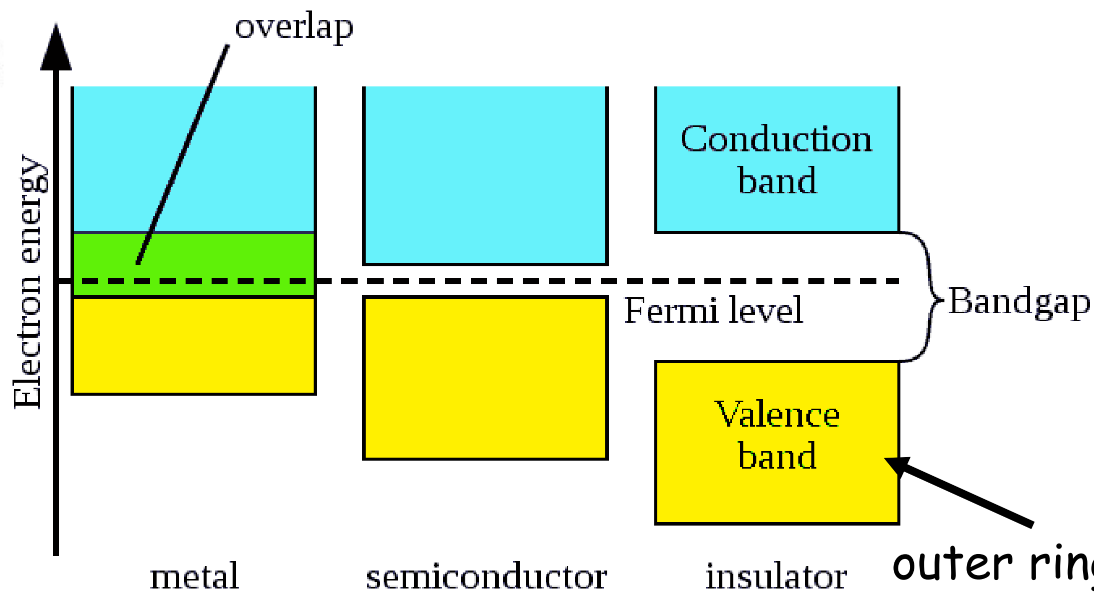
Electronic materials include:

1. <u>Conductors</u>: have low resistance which allows electrical current flow
2. <u>Insulators</u>: have high resistance which suppresses electrical current flow
3. <u>Semiconductors</u>: can allow or suppress electrical current flow

Conductors

This is a **copper atom diagram**: 29 protons in the nucleus, surrounded by bands of circling electrons. Electrons closer to the nucleus are hard to remove while the valence (outer ring) electron requires relatively little energy to be ejected from the atom.



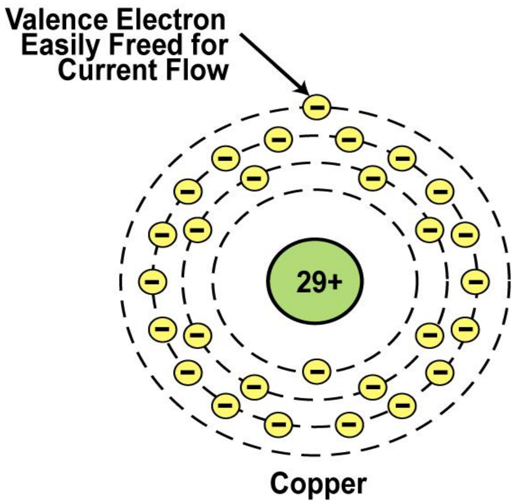


outer ring
energy level

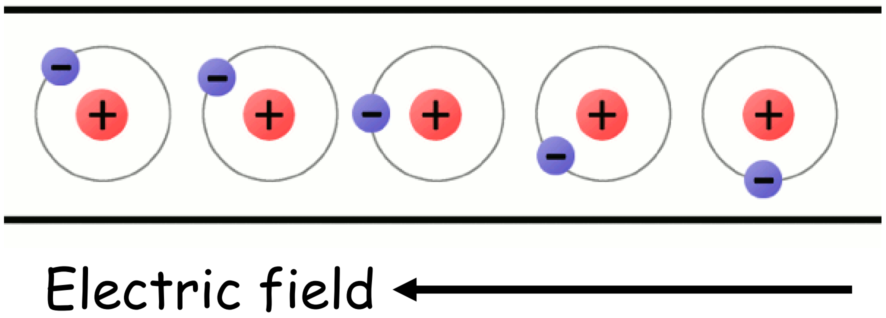
Conductors

Good conductors have low resistance. Electrons flow through them with ease.

The atomic structure of good conductors usually includes only <u>one electron in their outer shell</u>. It is called a valence electron. It is easily striped from the atom, producing current flow.



Copper Atom

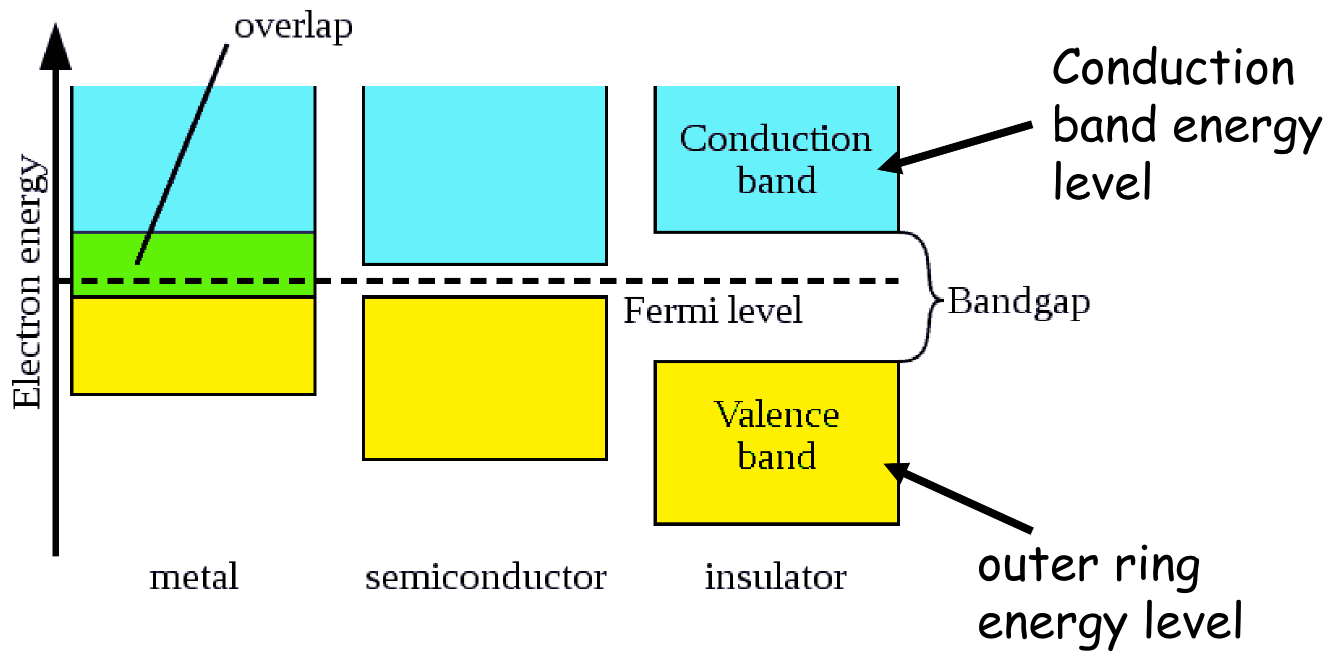


Insulators

Insulators have a high resistance so current does not flow in them. The atoms are tightly bound to one another so electrons are difficult to strip away for current flow.

Insulators have **8 valence electrons**.

Good insulators include: Glass, ceramic, plastics, & wood.

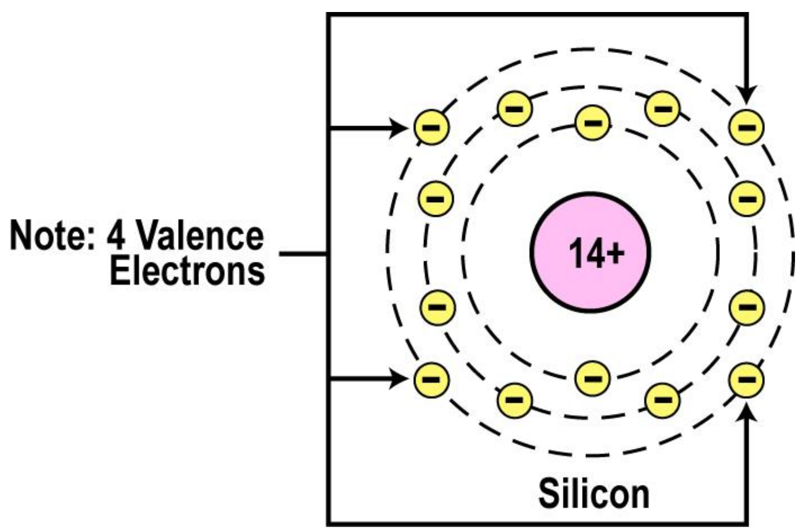


Semiconductors

Semiconductors are materials that essentially can be conditioned to act as good conductors, or good insulators, or any thing in between.

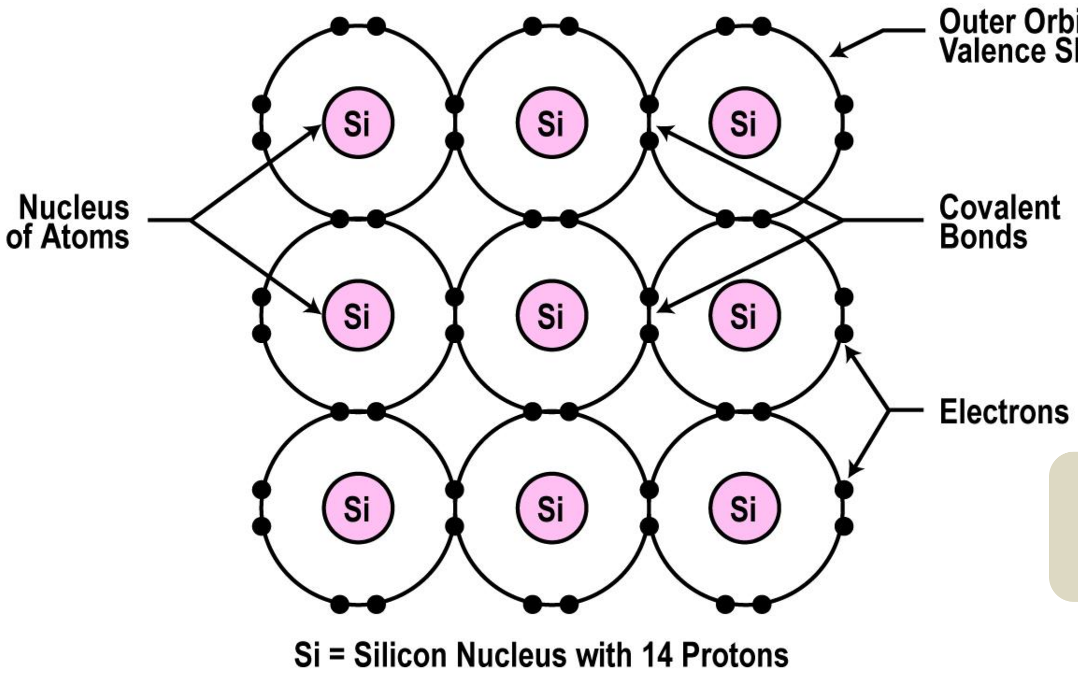
The main characteristic of a semiconductor element is that it has _4 valence electrons_ in its outer or valence orbit.

Common semiconductors elements such as **carbon**, **silicon**, and **germanium**. Silicon is the best and most widely used semiconductor.



Crystal Lattice Structure

- Semiconductor atoms form a physical structure called a crystal lattice.
- The atoms link together with one another sharing their outer electrons.
- These links are called <u>covalent bonds</u>.

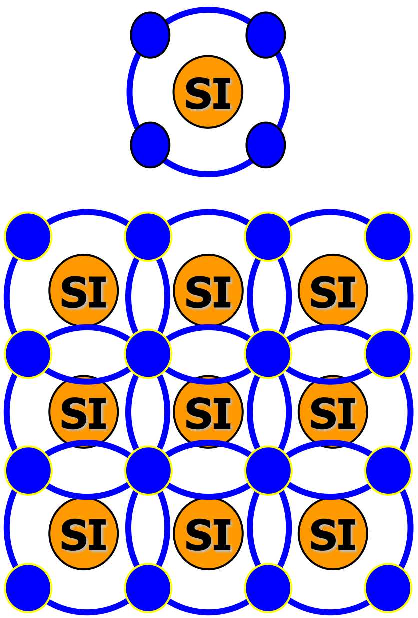


2D Crystal Lattice Structure

Semiconductor material in this form is an insulator.

Doping

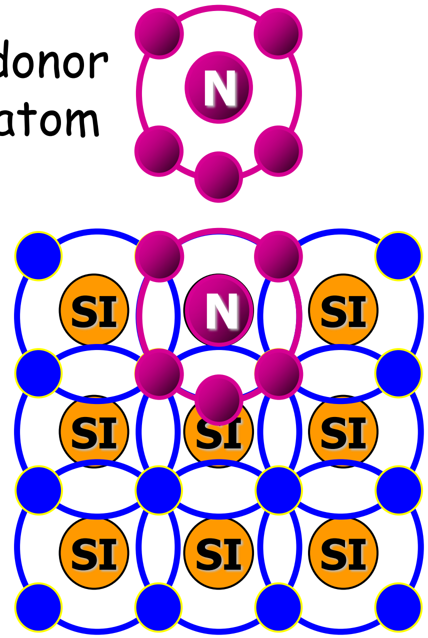
To make the semiconductor **conduct electricity**, other atoms called impurities must be added.



Covalent Bonding

Undoped Material
Shares its 4 electrons w/other atoms and forms a pure crystal.

donor atom

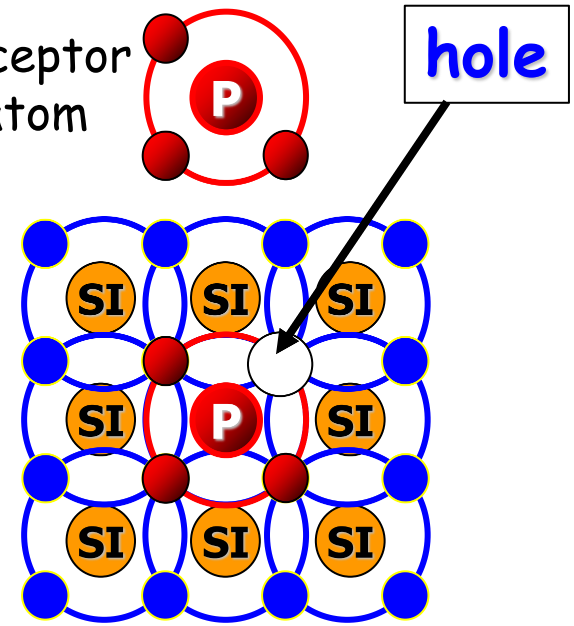


N type Material

Impurities that have an excess of electrons are added.

\- charged

acceptor atom



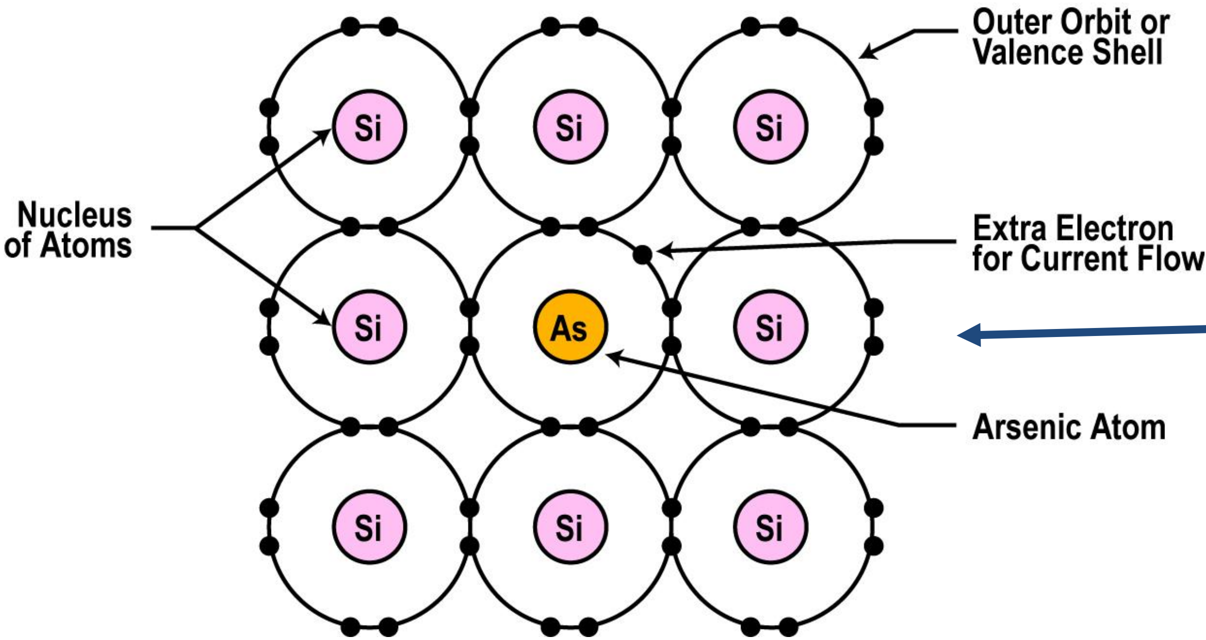
P type Material.

Impurities that have missing electron are added.

\+ charged.

Semiconductors can be Conductors

- An impurity, or element like arsenic, has 5 valence electrons.
- Adding arsenic (doping) will allow four of the arsenic valence electrons to bond with the neighboring silicon atoms.
- The one electron left over for each arsenic atom becomes available to conduct current flow.



n-type material

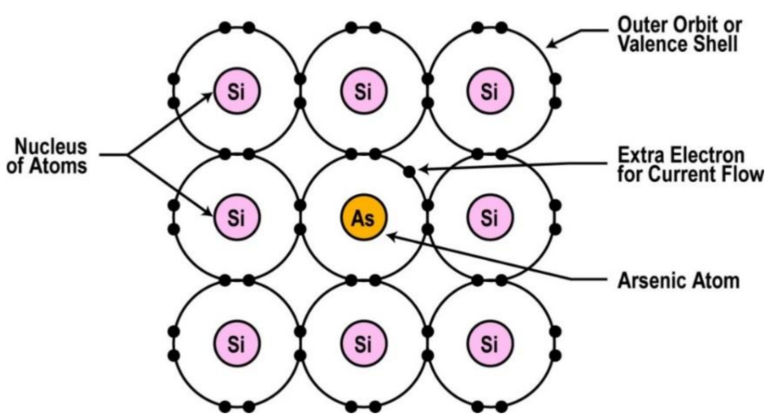
n-type material

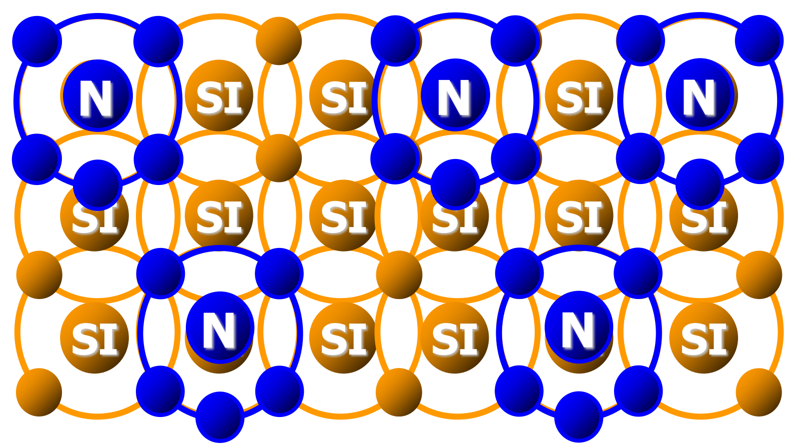
If you use lots of arsenic atoms for doping, there will be lots of extra electrons so the resistance of the material will be low and current will flow freely.

If you use only a few arsenic atoms, there will be fewer free electrons so the resistance will be high and less current will flow.

By controlling the doping amount, virtually any resistance can be achieved.

- <u>Majority Charge Carriers</u> are **Electrons.**





p-type material

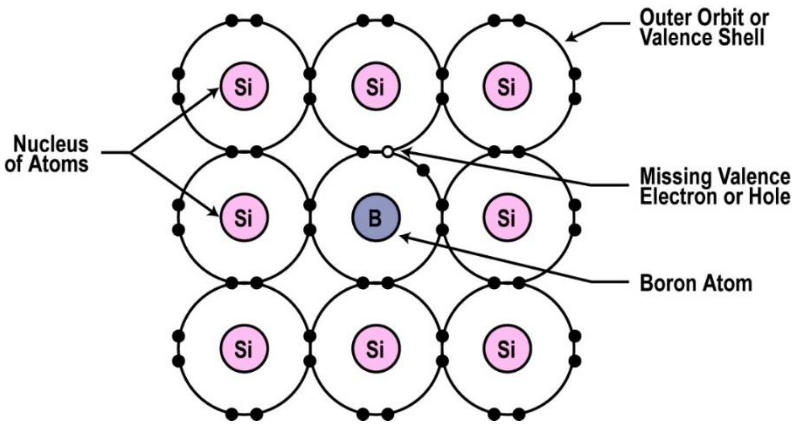
• You can also dope a semiconductor material with an atom such as boron that has only 3 valence electrons.

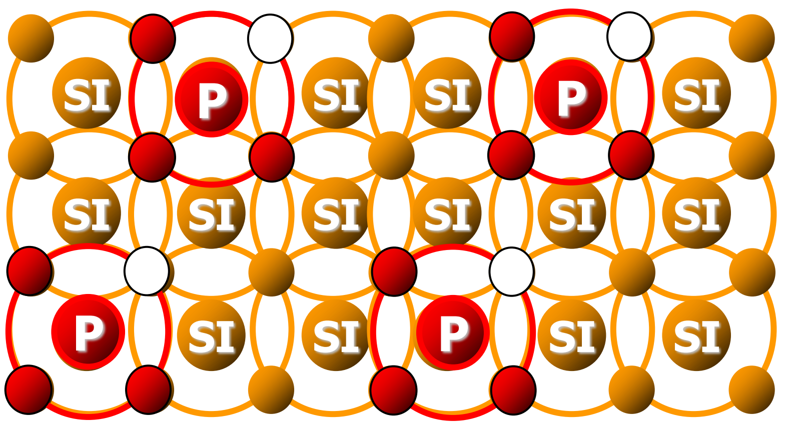
• The 3 electrons in the outer orbit do form covalent bonds with its neighboring semiconductor atoms as before. But one electron is missing from the bond. This place, where a fourth electron should be is referred to as a hole.

• The hole is assumed as a positive charge so it can attract electrons from some other source.

• Holes become a type of current carrier like the electron to support current flow.

➢ Majority Carriers are **Holes.**



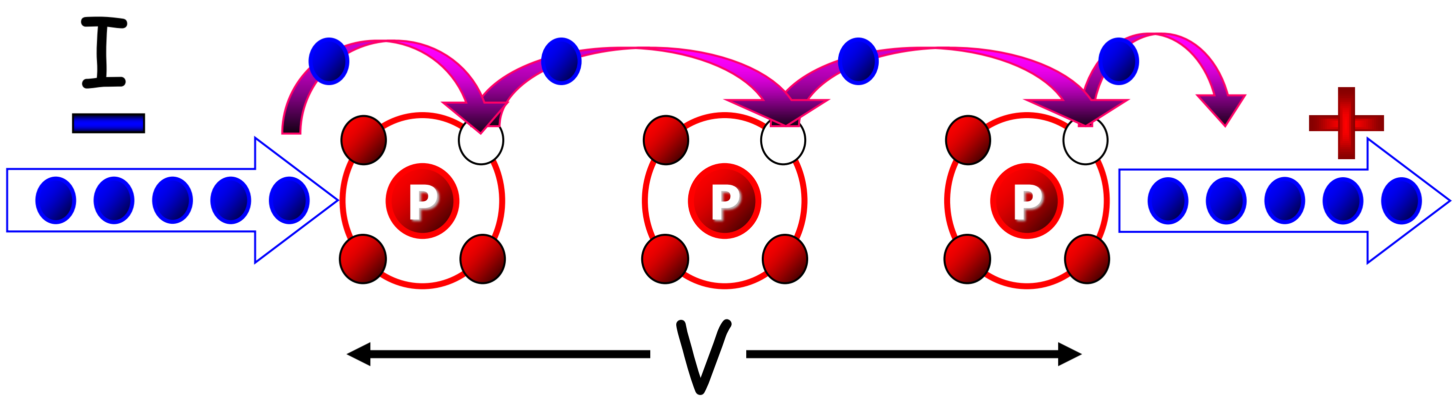


p-type material

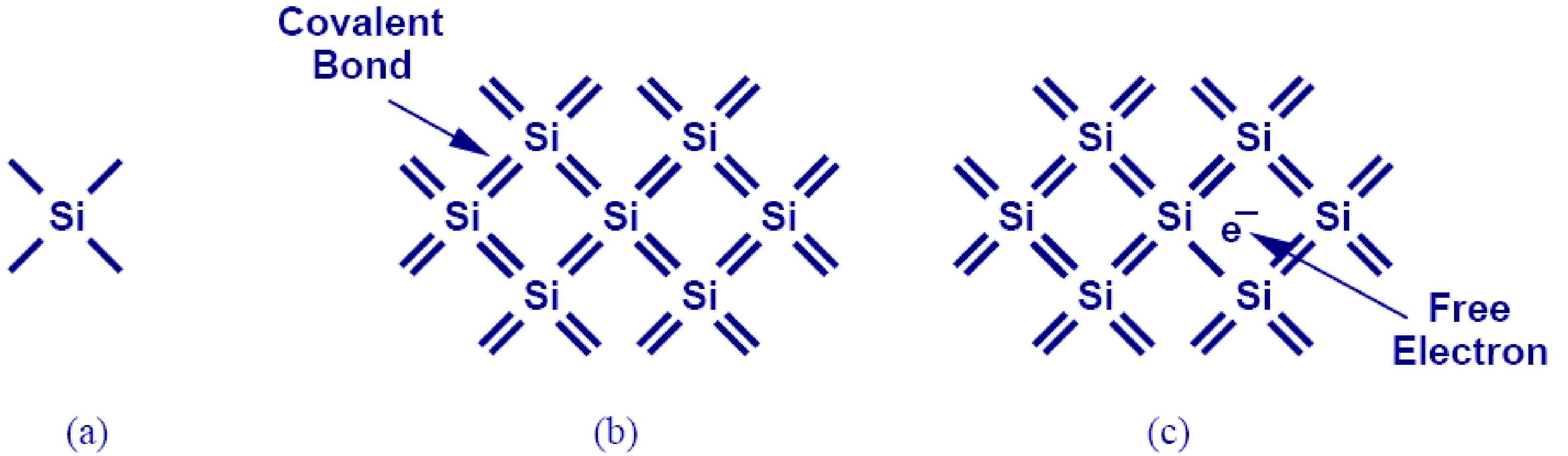
The positive terminal of the voltage source pulls the electrons from the holes and leaving the holes to attract more electrons.

Current (electrons) flows from the negative terminal to the positive terminal of the voltage source.

Inside the semiconductor, current flow is actually by the movement of the holes from positive to negative.



Silicon



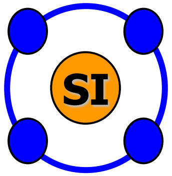
- Si has four valence electrons. Therefore, it can form covalent bonds with four of its neighbors.
- When temperature goes up, electrons in the covalent bond can become free.

Carrier Concentration

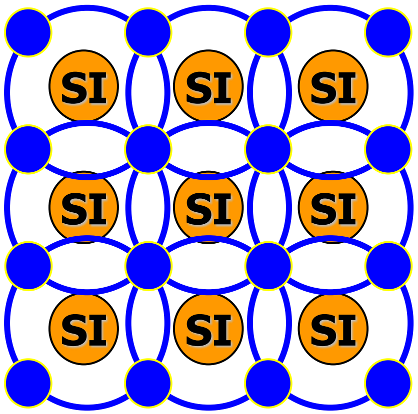
Intrinsic Semiconductors *(Pure single-crystal material)*

For an **intrinsic semiconductor**,
the concentration of electrons (n_i) in the conduction band
is equal to the concentration of holes (p_i) in the valence band.

n_i : intrinsic electron concentration
p_i : intrinsic hole concentration



$n_i = p_i$



n_i :intrinsic carrier concentration, which refers to either the intrinsic electron or hole concentration

For example: $n_i = 1.5 \times 10^{10}\ cm^{-3}$

Electron and Hole Concentrations in n and p type materials

Under thermal equilibrium conditions, the product of the conduction-electron density and the hole density is ALWAYS equal to the square of n_i

$$np = n_i^2$$

n_i : The concentration of conduction electrons or holes **in intrinsic silicon**

<u>N-type material</u>

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

Number of donor atoms

<u>P-type material</u>

$$p \approx N_A$$ Number acceptor atoms

$$n \approx \frac{n_i^2}{N_A}$$

Number of free electrons in p-type

Electron and Hole Concentrations in n and p type materials

$$np = n_i^2$$

Majority Carriers (p type metarial) : $p \approx N_A$

Minority Carriers (p type metarial) : $n \approx \frac{n_i^2}{N_A}$

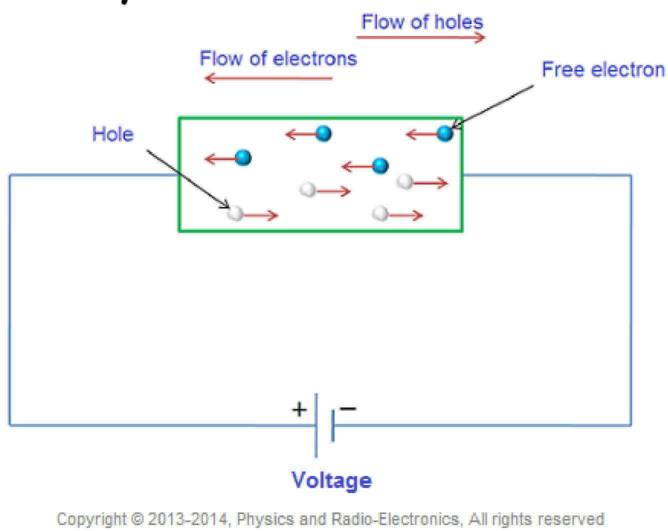
Majority Carriers (n type metarial) : $n \approx N_D$

Minority Carriers (n type metarial) : $p \approx \frac{n_i^2}{N_D}$

- The product of electron and hole densities is ALWAYS equal to the square of intrinsic electron density regardless of doping levels.

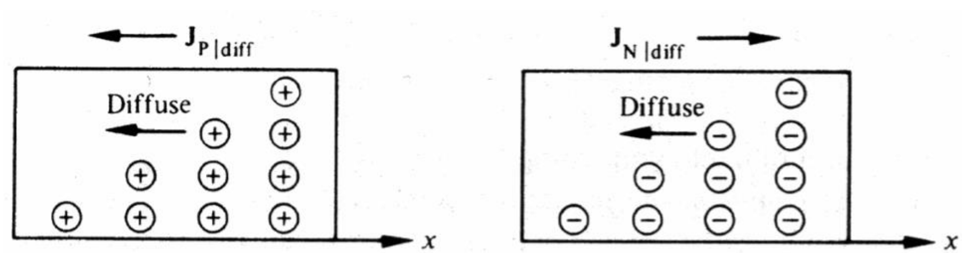
Current Flow in Semiconductors

- There are two mechanisms by which holes and electrons move through a crystal:

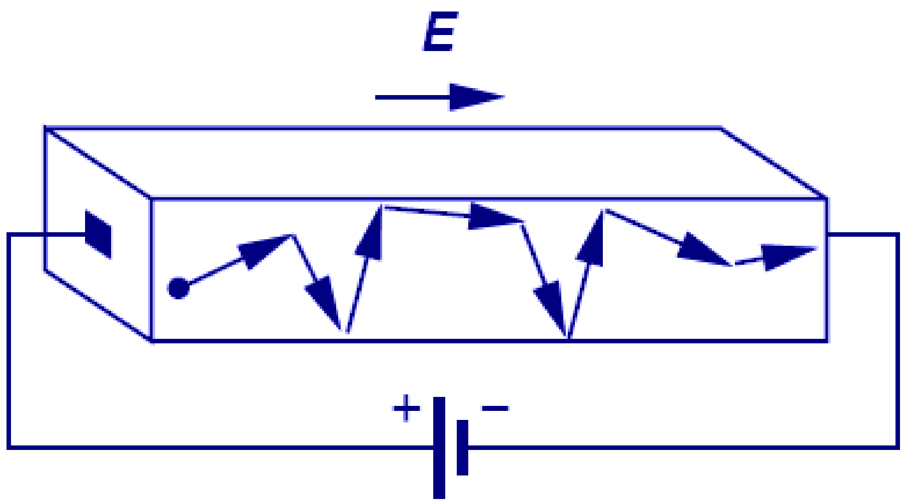


  - Drift Current

  - Diffusion Current



Drift Current



Drift current is caused by the charged particles getting pulled by an electric field.

velocity of holes

$$\vec{v}_h = \mu_p \vec{E}$$

$$\vec{v}_e = -\mu_n \vec{E}$$

Charge particles will move at a velocity that is proportional to the electric field.

velocity of free electrons

electron mobility parameter

Drift current

E (volts / cm)

μ_p (cm^2/Vs) = 480 for silicon

μ_n (cm^2/Vs) = 1350 for silicon

Electrons move with velocity 2.5 times higher than holes

$$\overbrace{v_{p-drift} = \mu_p E}^{\substack{\mu_p = \text{hole mobility} \\ E = \text{electric field}}} \qquad \overbrace{v_{n-drift} = -\mu_n E}^{\substack{\mu_n = \text{electron mobility} \\ E = \text{electric field}}}$$

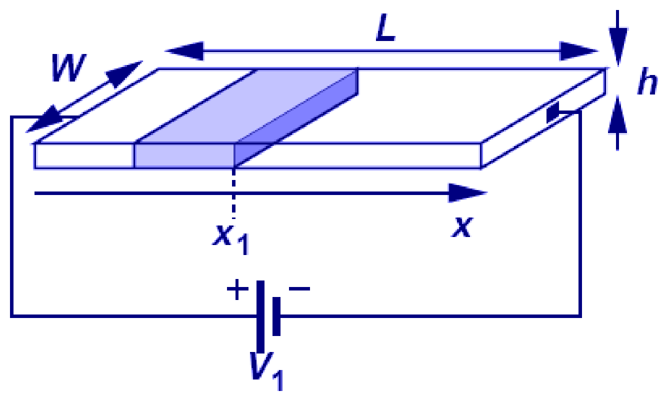
Drift velocity

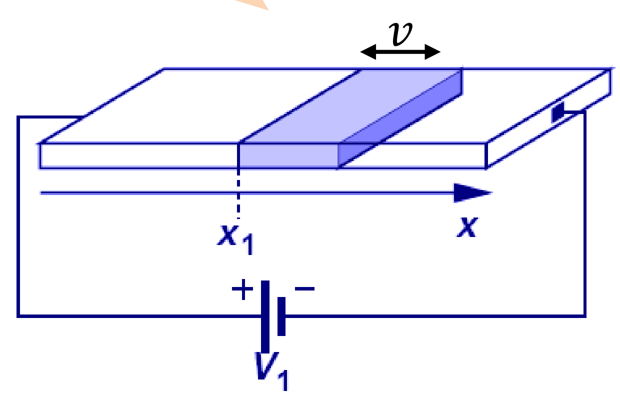
What is mobility μ?

- In solid-state physics, the **electron mobility** (hole) characterizes how quickly an **electron (hole)** can move through a metal or semiconductor, when pulled by an electric field.

Drift current

In one second ***v.W.h.n*** *number of electrons passes thru the cross-section.*





$$I = v \cdot W \cdot h \cdot n \cdot q$$

Current density: $\mathbf{J} = \dfrac{\text{total current}}{\text{total area}}$

$$J = v \cdot n \cdot q$$

n: free electron concentrations
W.h: Cross-section area
q: Charge of one electron
v: velocity of free electrons

Electric current is calculated as the **amount of charge** in ***v*** meters.

Drift current

Since velocity is equal to μE, drift characteristic is obtained by substituting velocity (v) with μE in the general current equation.

$$J_n = \mu_n E \cdot n \cdot q$$

$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$

$$= q(\mu_n n + \mu_p p)E$$

The total current density consists of both electrons and holes.

- **conductivity** (σ) – relates current density (J) and electrical field (E)
- **resistivity** (ρ) – relates current density (J) and electrical field (E)

$$\overbrace{J = \sigma E}^{\text{Ohm's Law}}$$

$$\sigma = q(p\mu_p + n\mu_n)$$

$$J = E / \rho$$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$

$$np = n_i^2$$

Majority Carriers (p type) : $p \approx N_A$

Minority Carriers (p type) : $n \approx \frac{n_i^2}{N_A}$

Majority Carriers (n type) : $n \approx N_D$

Minority Carriers (n type) : $p \approx \frac{n_i^2}{N_D}$

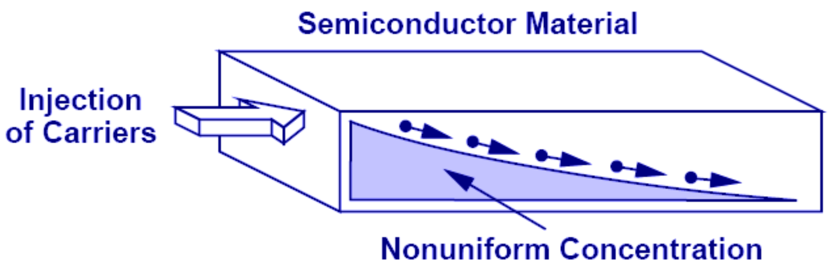
Conductivity of P type material

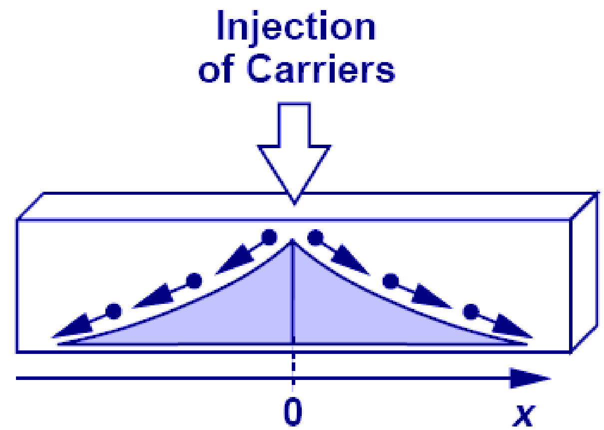
$$\sigma_p = q \cdot \left(N_A \mu_p + \frac{n_i^2}{N_A} \mu_n \right)$$

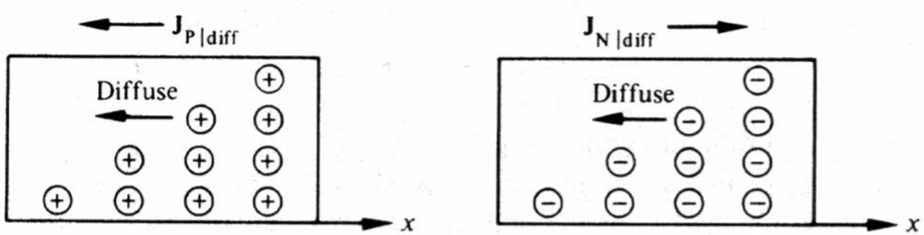
Conductivity of N type material

$$\sigma_n = q \cdot \left(\frac{n_i^2}{N_D} \mu_p + N_D \mu_n \right)$$

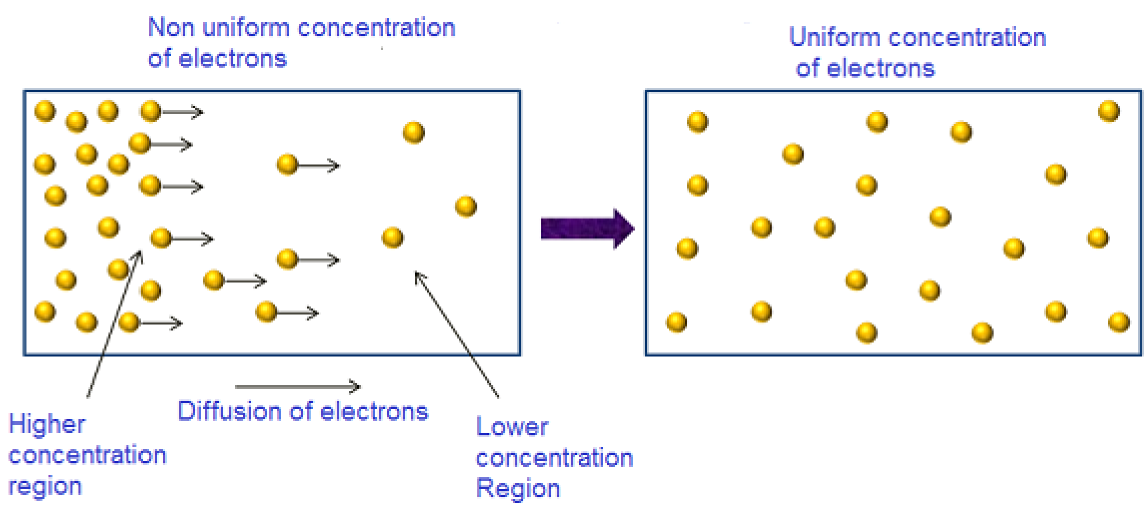
Diffusion Current







Charged particles move from a region of high concentration to a region of low concentration.



Diffusion Current

Current density: $\mathbf{J} = \dfrac{\text{total current}}{\text{total area}}$

$$I = AqD_n\frac{dn}{dx} \qquad J_p = -qD_p\frac{dp}{dx}$$

$$J_n = qD_n\frac{dn}{dx} \qquad J_{tot} = q(D_n\frac{dn}{dx} - D_p\frac{dp}{dx})$$

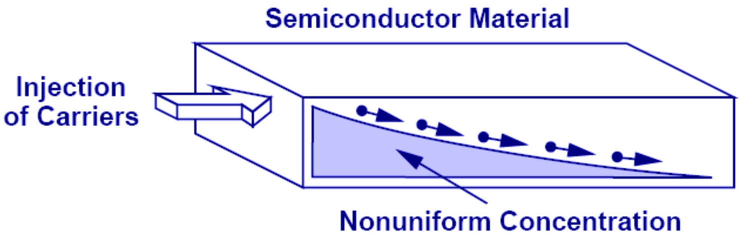
•Diffusion current is proportional to the gradient of charge (dn/dx) along the direction of current flow.

•Its total current density consists of both electrons and holes.

Notation:

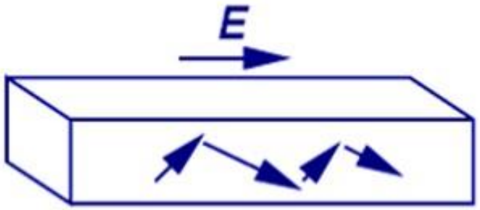
$D_p \equiv$ hole diffusion constant (cm²/s)

$D_n \equiv$ electron diffusion constant (cm²/s)



Einstein's Relation

Drift Current



$$J_n = q\,\mu_n E\, n$$

$$J_p = q\,\mu_p E\, p$$

Diffusion Current

$$J_n = q\,D_n \frac{dn}{dx}$$

$$J_n = -\,q\,D_p \frac{dp}{dx}$$

Boltzman constant

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}}$$

Temperature

Magnitude of electron charge

Einstein's relation provides a mysterious link between the drift and diffusion.

Total Current

- drift current density (J_{drift})
  - effected by – an electric field (E).
- diffusion current density (J_{diff})
  - effected by – concentration gradient in free electrons and holes.

A= cross-sectional area of silicon, q= magnitude of the electron charge,
p= concentration of holes, n= concentration of free electrons,
μ_p = hole mobility, μ_n = electron mobility, E= electric field

drift current density : $J_{drift} = J_{p-drift} + J_{n-drift} = q(p\mu_p + n\mu_n)E$

diffusion current density : $J_{diff} = J_{p-diff} + J_{n-diff} = -qD_p \dfrac{d\mathbf{p}(x)}{dx} + qD_n \dfrac{d\mathbf{n}(x)}{dx}$