# Semiconductor Materials and Properties

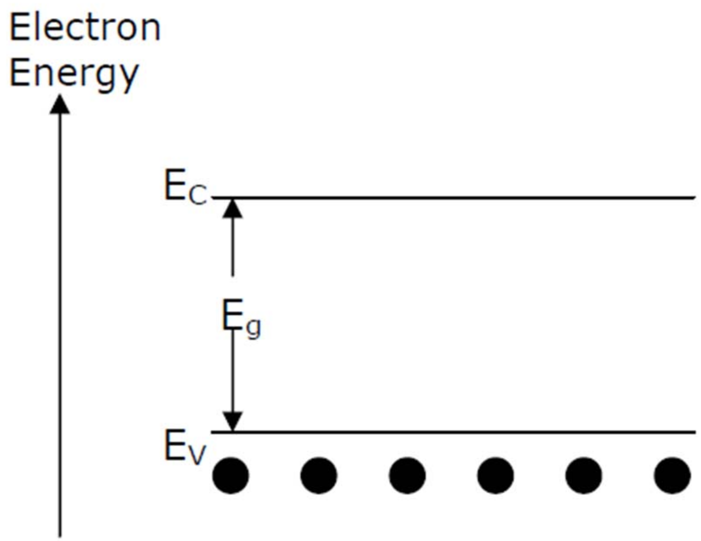
## Drift and Diffusion Currents:

- Negatively charged electrons & positively charged holes creation
- Movement of these charged “particles” generates current & they are referred to as carriers
- Two basic processes causing electrons or holes to move:
  - Drift (by electric fields)
  - Diffusion (by variation in concentration)

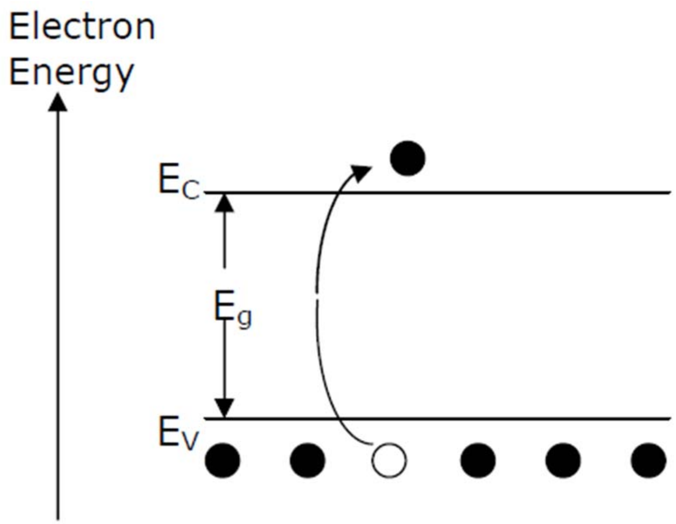
- Concentration gradients can be created by a nonhomogeneous doping distribution, or by the injection of a quantity of electrons or holes into a region

## Drift Current:

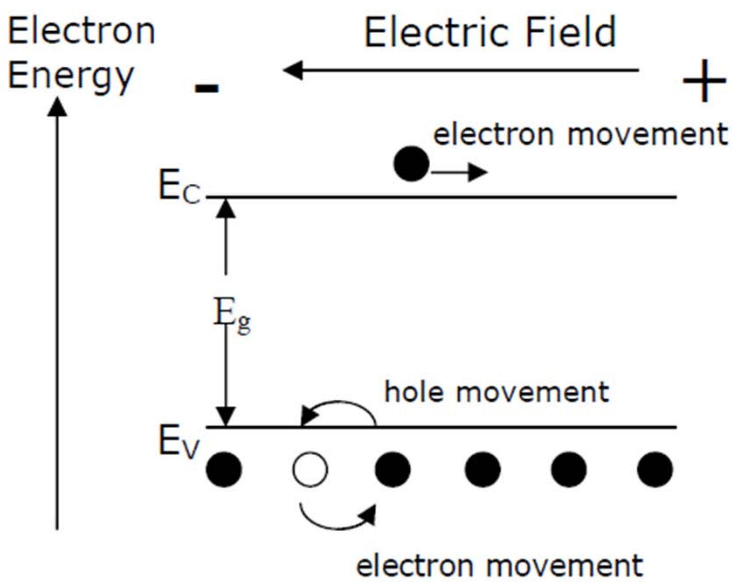
## Intrinsic semiconductors at 0 K:



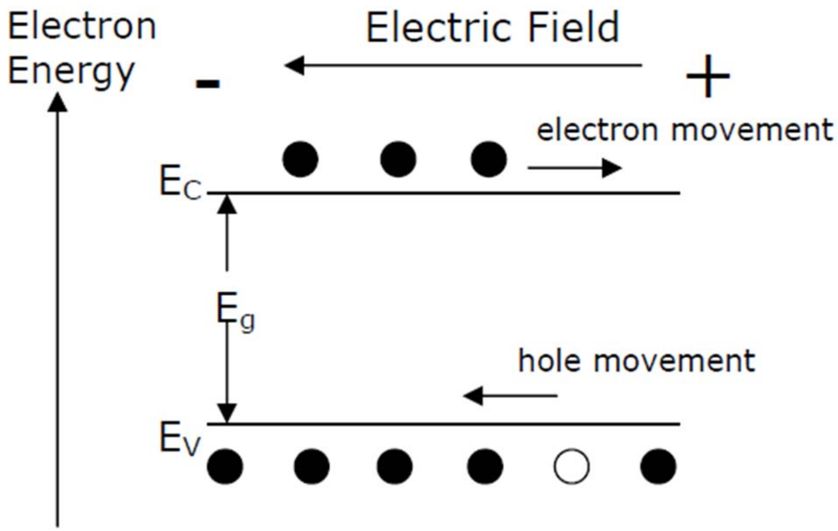
# Intrinsic semiconductors at room temperature:



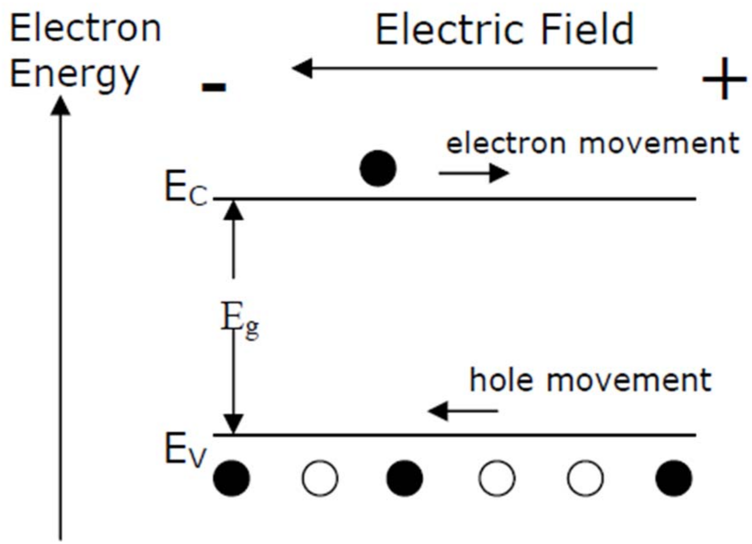

# Intrinsic semiconductors at room temperature under an electric field:



n-type semiconductors at room temperature under an electric field:




p-type semiconductors at room temperature under an electric field:



Assuming there in no difference in concentration:

Without an externally applied potential –
The result is electron motion that is totally random, yielding a zero net movement and therefore a zero net current.

- The field produces a force that acts on free electrons and holes, which then experience a net drift velocity and net movement.

An electric field *E* applied in one direction produces force on electrons / holes in the opposite / same direction. For n-type semiconductor, The drift velocity can be written as

$$v_{dn} = -\mu_n E$$

Opposite direction  cm$^2$/V-s  V/cm

$\mu_n$ is a constant (for a material) called the electron mobility

The mobility can be thought of as a parameter indicating how well an electron can move in a semiconductor.

The electron drift produces a drift current density given by

$$J_n = -env_{dn} = -en(-\mu_n E) = +en\mu_n E$$

A/cm² C cm⁻³ cm/s

*n* is the electron concentration, *e* is the magnitude of the electronic charge

Conventional drift current is in the opposite direction from the flow of negative charge. So, drift current in an n-type semiconductor is in the same direction as the applied electric field.

In a p-type semiconductor, an electric field *E* applied in one direction produces a force on the holes in the same direction, because of the positive charge on the holes. The drift velocity is:

$$v_{dp} = +\mu_p E$$

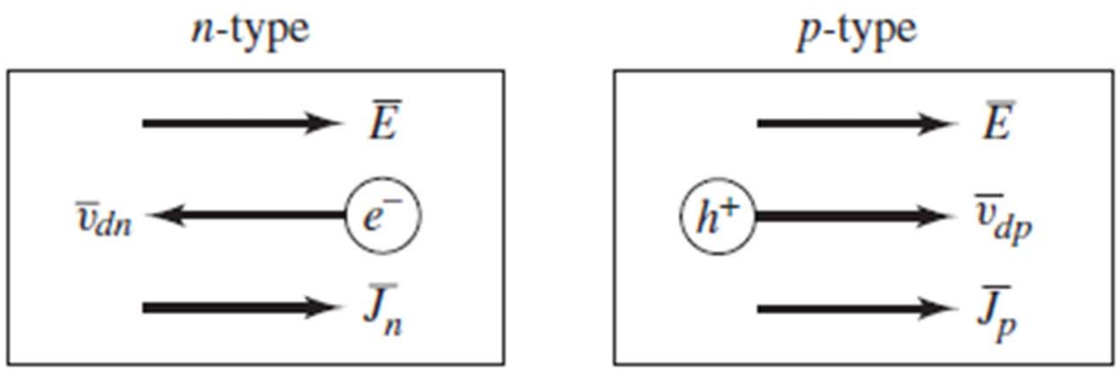
$\mu_p$ is a constant (for a material) called the hole mobility with same unit as electron mobility

The hole drift produces a drift current density

$$J_p = +epv_{dp} = +ep(+\mu_p E) = +ep\mu_p E$$

*p* is the hole concentration

$\mu_n$ = 1350 cm2/V-s and $\mu_p$ = 480 $cm^2$/V-s for silicon




Conventional drift current is in the same direction from the flow of positive charge. So, drift current in an p-type semiconductor is in the same direction as the applied electric field.

Since a semiconductor contains both electrons and holes, the total drift current density is

$$J = en\mu_n E + ep\mu_p E = \sigma E = \frac{1}{\rho} E$$

$$\sigma = en\mu_n + ep\mu_p$$

where σ is the conductivity of the semiconductor in (Ω-cm)−1 and where ρ = 1/σ is the resistivity of the semiconductor in (Ω-cm).

- The conductivity is related to the concentration of electrons and holes.
- Conductivity can be changed from strongly n-type, $n >> p$, by donor impurity doping to strongly p-type, $p >> n$, by acceptor impurity doping.

Being able to control the conductivity of a semiconductor by selective doping is what enables us to fabricate the variety of electronic devices

- Carrier drift velocities are linear functions of the applied electric field. This is true for relatively small electric fields. Carrier drift velocities will reach a maximum value of approximately $10^7$ cm/s. Any further increase in electric field will not produce an increase in drift velocity.

- The mobility values are actually functions of donor and/or acceptor impurity concentrations. As the impurity concentration increases, the mobility values will decrease.

## Diffusion Current:

## Diffusion Current Density

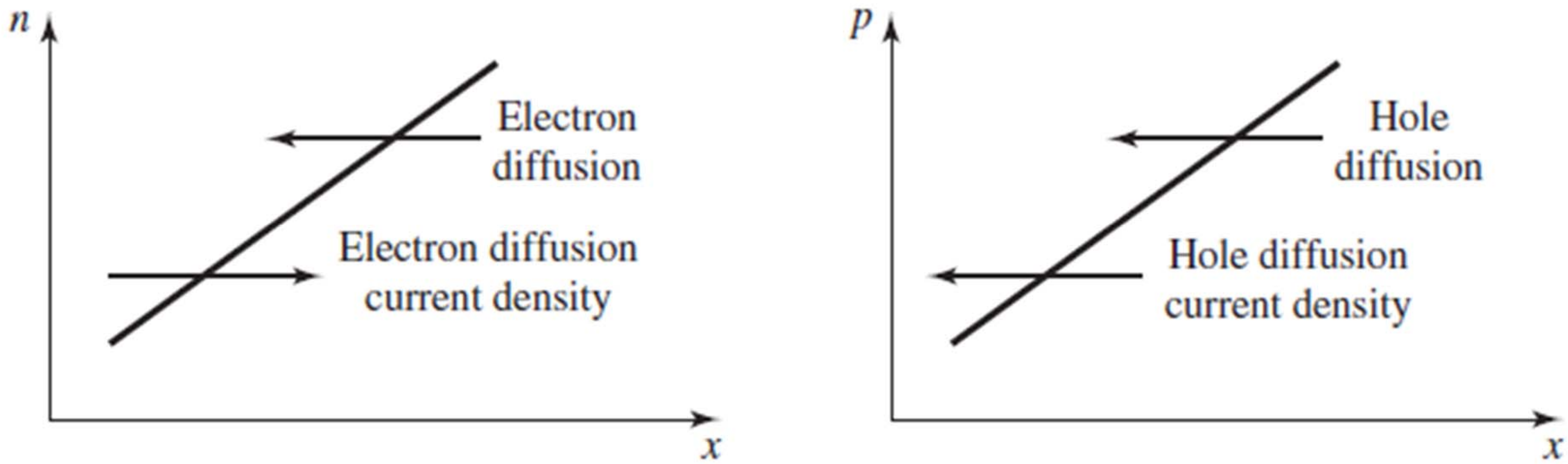
- Electrons and holes in a semiconductor are in continuous motion at room temperature in random directions.

- Assume low and high concentration region has equal extent. Approximately, half of the particles in the high (low)-concentration region are moving away from that region toward the lower (higher)-concentration region.

- But concentration is higher in high concentration region! So half of the particles in high concentration region is more than half of the particles in low concentration.

- So, the net result is a flow of particles away from the high-concentration region and toward the lower-concentration region

The Diffusion Process!




The diffusion current density due
to the diffusion of electrons:

$$J_n = eD_n \frac{dn}{dx}$$

dn/dx is the gradient of the electron concentration,
and $D_n$ is the electron diffusion coefficient.

$$\frac{dn}{dx} \equiv E \qquad -\frac{dn}{dx} \equiv v_{dn}$$

Electron diffusion direction

The diffusion current density due to the diffusion of holes:

$$J_p = -eD_p \frac{dp}{dx}$$

dp/dx is the gradient of the hole concentration, and $D_p$ is the hole diffusion coefficient.

$$-\frac{dp}{dx} \equiv v_{dp}$$

The mobility values in the drift current equations and the diffusion coefficient values in the diffusion current equations are not independent quantities. They are related by the Einstein relation:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e} \cong 0.026 \text{ V}$$

@ Room Temperature

The total current density is the sum of the drift and diffusion components. In most cases, only one component dominates the current at any one time in a given region of a semiconductor.

# Excess Carriers

Semiconductors not in thermal equilibrium: when a voltage is applied this happens

For example, valence electrons may acquire sufficient energy to break the covalent bond and become free electrons if they interact with high-energy photons incident on the semiconductor.

This generates additional electrons and holes are called excess electrons and excess holes.

Increase in electron / hole concentration:

$$n = n_o + \delta n \qquad\qquad p = p_o + \delta p$$

But this does not happen indefinitely as free electrons recombines with a hole, in a process called electron–hole recombination. A steady state value of the excess is usually reached.

The mean time over which an excess electron and hole exist before recombination is called the excess carrier lifetime.

# pn Junction

## GOAL:

- Properties of a pn junction including the ideal current-voltage characteristics of the pn junction diode.

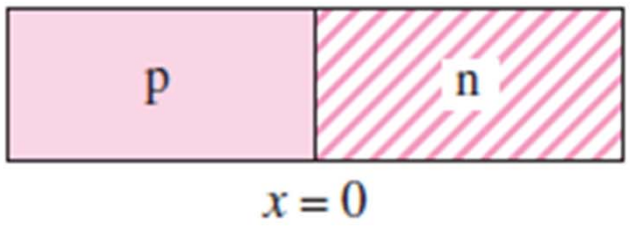
## pn junction

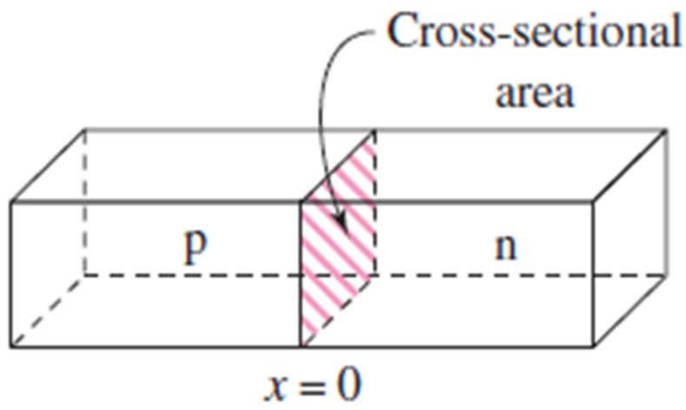
- Semiconductor electronics starts when p- and n-regions are directly adjacent to each other, forming a pn junction.

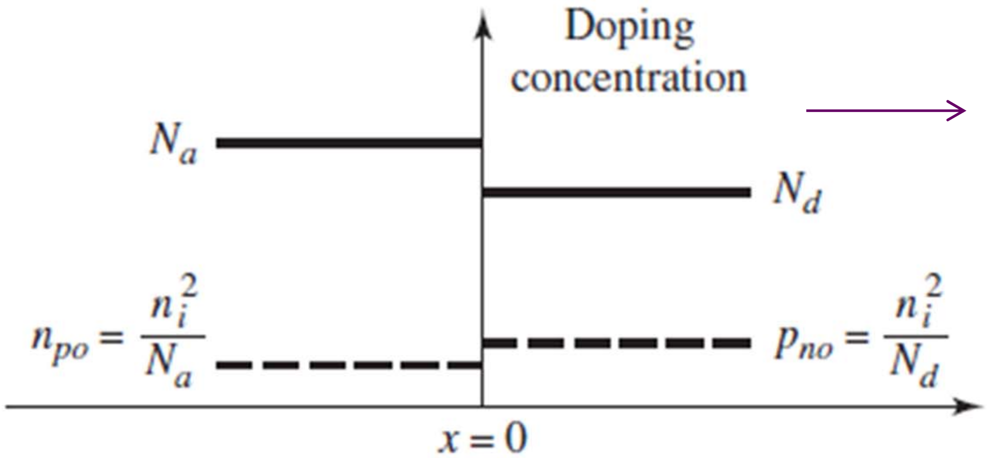
- Usually, the entire semiconductor material is a single crystal, with one region doped to be p-type and the adjacent region doped to be n-type.

# The Equilibrium pn Junction

What happens when p & n are brought together?



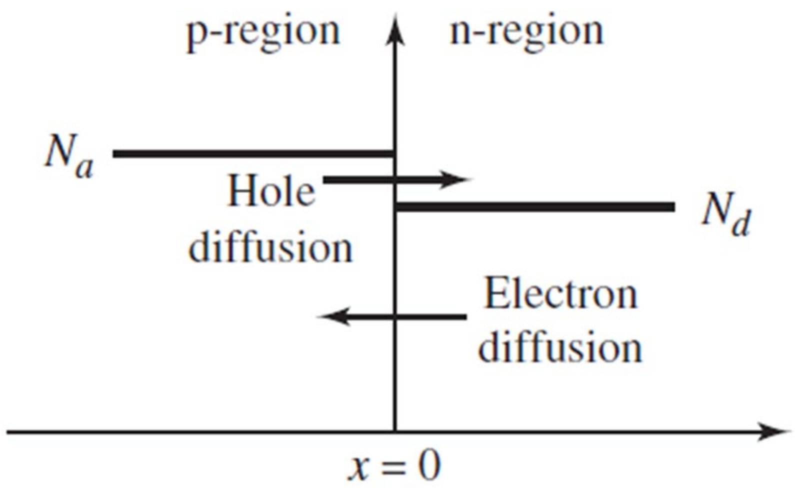




Uniform doping, thermal equilibrium

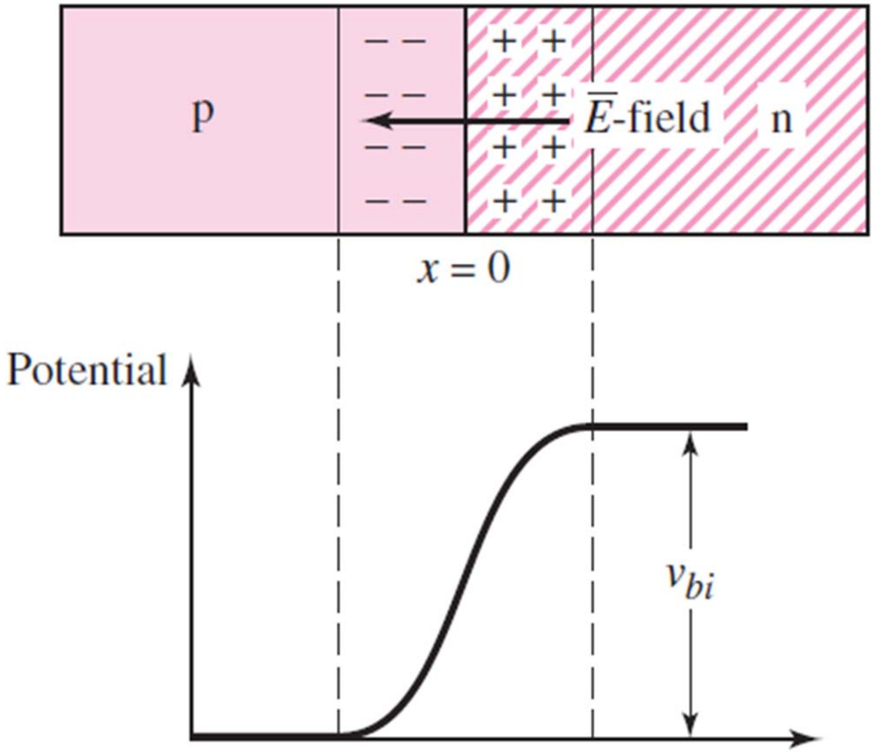
Majority & minority carrier concentration x = 0 is called the metallurgical junction

- A large density gradient in both the hole and electron concentrations occurs across this junction
- Diffusion of holes from the p-region into the n-region and diffusion of electrons from the n-region into the p-region occurs initially



- Flow of holes from p-region leaves behind negatively charged acceptor ions and flow of electrons from n-region leaves behind positively charged donor ions

This action creates a charge separation, which sets up an electric field oriented in the direction from the positive charge to the negative charge.



- The direction of the induced electric field will cause the resulting force to repel the diffusion of holes from the p-region and the diffusion of electrons from the n-region

- Equilibrium occurs when the force produced by the electric field and the "force" produced by the density gradient exactly balance.

In the equilibrium, the positively & negatively charged region comprise the space-charge/ depletion region of the pn junction, in which there are no moving electrons or holes.

The electric field in the depletion region maintains a potential difference across the region. The potential difference is called the built-in potential barrier / built-in voltage:

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$N_a$ and $N_d$ are the net acceptor and donor concentrations in the p- and n-regions.

$V_T$ is called the thermal voltage and is approximately $V_T$ = 0.026 V at room temperature, T = 300 K.

$V_{bi}$ maintains equilibrium, so no current is produced by this voltage. Hence, it is not measurable by a voltmeter.

The magnitude of $V_{bi}$ becomes important when we apply an external voltage source.

- Reverse-bias voltage.
- Forward-bias voltage.