ECE 111

Carrier motion in Semiconductors Drift and diffusion currents

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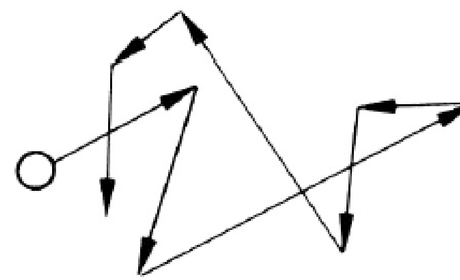
Random Thermal Motion of Carriers

- At a finite temperature, both types of carriers, electrons and holes in a semiconductor are constantly in motion. As they move, they undergo collisions (or scattering) now and then with:
    1) ionized impurities
    2) lattice vibrations.

$$\mathscr{E}=0:\ v_d=0$$



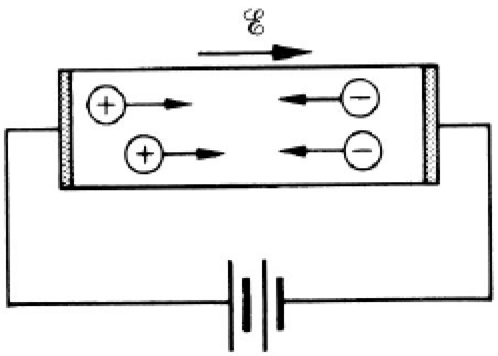
As a result of collisions, the carrier velocity changes. Some collisions (e.g. due to ionized impurities) change only the direction of the carrier without changing its magnitude. Some other collisions (e.g. lattice vibrations) may change both magnitude and velocity. These collisions are called randomizing collisions.

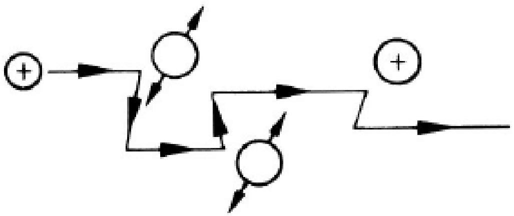
- At any given time, the velocities of the carriers are distributed **completely randomly** in all directions. The magnitudes of velocities are distributed according to Fermi-Dirac statistics or in a simpler approximation according to Maxwell - Boltzmann statistics. This motion of carriers is known as the random thermal motion.

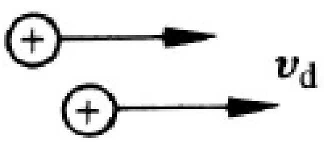
- Since the thermal motion is randomly distributed in all directions, **there is no net current in thermal equilibrium**. The net velocity averaged over all the electrons (or holes) is zero.

Drift motion in an applied electric field

When an electric field is applied, the carriers are accelerated by the force due to the electric field (Newton's law).
Of course, the carrier can not continue to accelerate indefinitely. Sooner or later, it will undergo a collision.
Since the collisions are randomizing, the carrier will restart with a completely random velocity, to be accelerated by the electric field all over again.
As a result of the repeated acceleration and randomizing collisions, the average motion of the carrier over a period of time appears to be the same as if it were moving with a constant velocity in the direction (or in the opposite direction) of the field. This net motion due to the electric field is called the 'drift' motion.







Remember - The drift motion is superimposed over the random thermal motion.

Average drift velocity

The drift motion as we learnt in the previous slide is the combined effect of acceleration due to electric field and retarding collisions. Assume the average time between collisions is **τ** and the electric field is **E**.

We will derive a simple expression for the net drift velocity for a hole.

- The force on the hole due to an electric field = **$q\,E$**
- Acceleration due to this force = **$q\,E\,/m^*$**
- Net velocity gained during the time t between collisions = **$q\,\tau\,E\,/m^*$**

Not all the holes will have the same average time between collisions. Some will undergo collision more frequently than the others since they are moving with different velocities. If **$<\tau>$** is the collision time averaged (mean) over all the holes, then the average drift velocity is given by

$$v_d = q <\tau> E\,/m^*$$

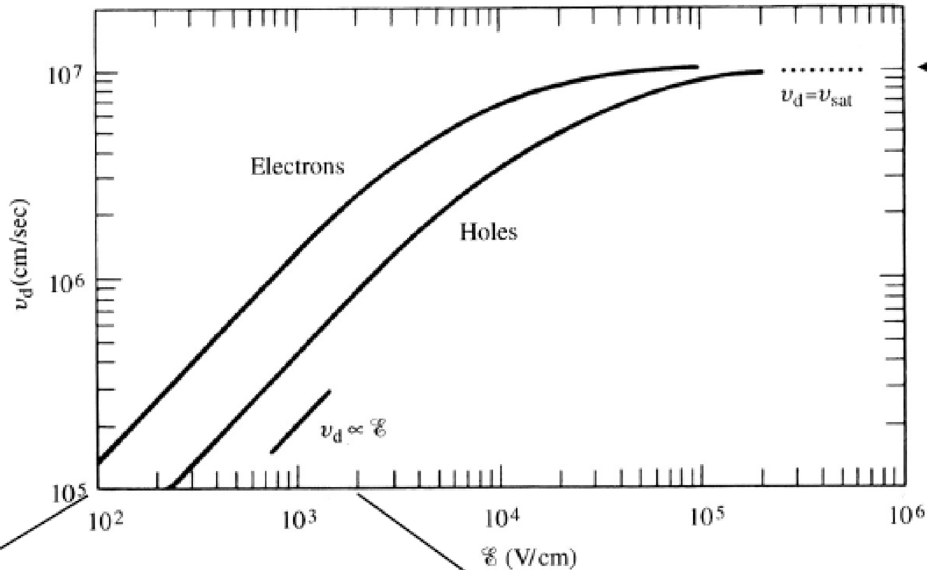
$$v_d = \mu E$$

$$\mu = q <\tau>/m^*$$

Where μ is mobility of holes

The linear relation between v_d and E is valid only at low electric fields. This relation is derived by assuming that the collision time t is independent of electric field. At high electric fields, this assumption is not true and hence v_d tends to saturate.

Drift velocity vs. electric field:



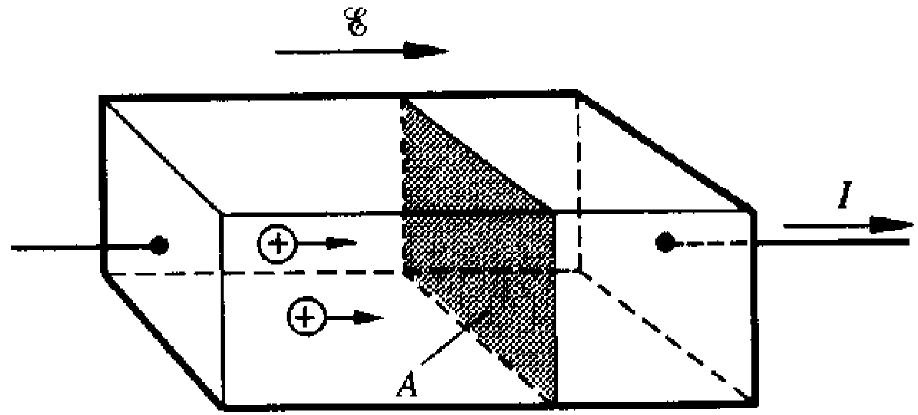
For large electric fields, the drift velocity reaches a maximum value referred to as the **saturation velocity**, v_{sat}

If the electric field is not too large, drift velocity $\mathbf{v}_d$ is proportional to electric field. The constant of proportionality is called the **mobility**:

$$\mathbf{v}_d = \mu_p \mathscr{E}$$

$$\mu_p = \text{hole mobility}$$

Drift current



The net drift motion of the *ensemble of* carriers produces an electric current.

Electric current density J_{drift} , by definition, is the **net charge** crossing per **unit area** of an arbitrary plane per **unit time.**

$$J_h = qpv_{d,h} = qp\mu_h E$$

A similar expression for the electric current due to electrons may be derived.

$$J_e = qnv_{d,e} = qn\mu_e E$$

Resistivity of a semiconductor

The current in a semiconductor is in general carried by both electrons and holes. Hence we have to add both J_n and J_p given in the earlier slide to get the total current.

$$J_T = J_n + J_p = qn\mu_e E + qp\mu_h E$$

$$J_T = (q\mu_e n + q\mu_h p)E$$

$$J_T = \sigma E$$

Where σ is semiconductor conductivity

$$\sigma = (q\mu_e n + q\mu_h p)$$

$$\rho = \frac{1}{\sigma}$$

Where ρ is semiconductor resistevity

Units of important parameters

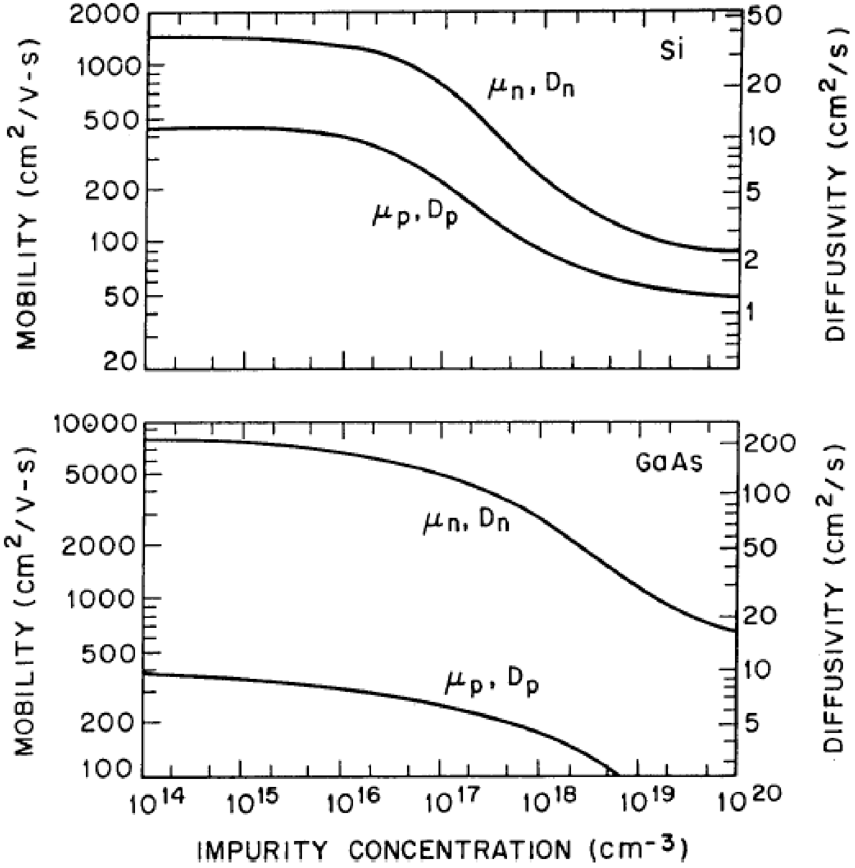
Parameter	SI units	Standard units
Current density	A/m^2	A/cm^2
Electric field	V/m	V/cm
Resistivity	Ω-m	Ω-cm
Conductivity	S (Siemens = $\Omega^{-1}m^{-1}$)	$\Omega^{-1}cm^{-1}$
Mobility	$(m/s)/(V/m)=m^2/Vs$	cm^2/Vs
carrier concentration	m^{-3}	cm^{-3}
Charge	C	C

Doping dependence and temperature dependence of mobility

As discussed earlier the two most important scattering mechanisms are due to the **lattice vibrations** and the **ionized impurities**.

In relatively purer samples (e.g. doping concentration **less than 1×10^{15} cm^{-3}**, the carrier mobility at 300 K is mainly determined by the **lattice vibrations** and hence it is independent of the doping concentration.

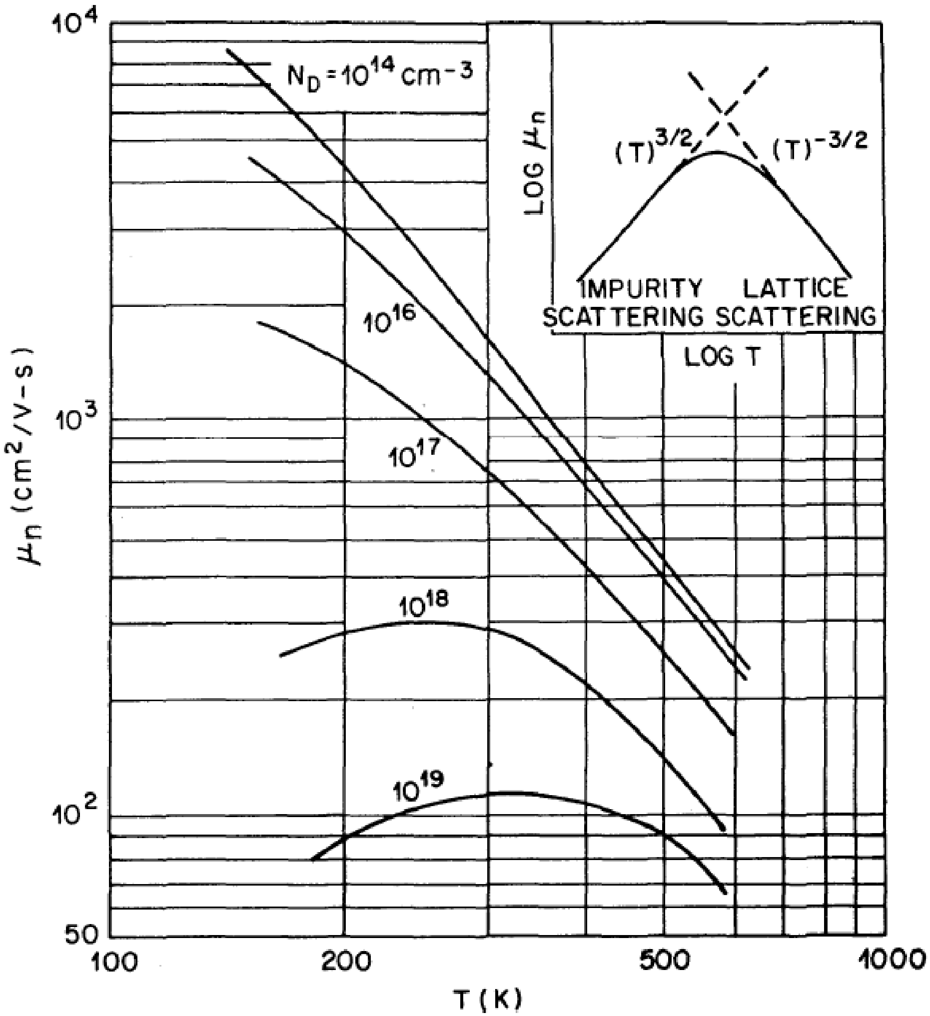
As the doping concentration increases (**above 1×10^{15} cm^{-3}**), the mobility decreases due to the **ionized impurity scattering**.



Temperature dependence of mobility

At **high** temperatures **(T>150 K)** the mobility is mainly limited by the **lattice vibrations**. μ decreases with increase of T ($\mu \propto T^{-3/2}$).

At **low** temperatures **(T<150 K)** the mobility is mainly limited by the **ionized impurities**. μ increases with increase of T ($\mu \propto T^{3/2}$).



Worked Examples

- An n-type silicon sample has a carrier concentration of 2×10^{15} cm^{-3}. Assuming the electron mobility at 300 K to be 1350 cm^2/Vs calculate the resistivity of this sample at this temperature.

  Solution:

  $\rho = 1/(qn\mu_n) = 1/(1.6\times10^{-19}\text{C}\times2\times10^{15}\ \text{cm}^{-3}\times 1350\ \text{cm}^2/\text{Vs}) = 2.31\ \Omega\text{-cm}.$

- A silicon sample is doped with 2×10^{15} cm^{-3} P atoms and 3×10^{15} cm^{-3} B atoms. Calculate the resistivity of this sample at 300 K. Assume the electron mobility to be 1350 cm^2/Vs and the hole mobility to be 450 cm^2/Vs at 300 K.

  Solution:

  $N_D = 2\times10^{15}$ cm^{-3} ; $N_A = 3\times10^{15}$ cm^{-3} ; Since $N_A > N_D$ the sample is p-type.

  Hole concentration $p = N_A - N_D = 3\times10^{15} - 2\times10^{15} = 1\times10^{15}$ cm^{-3} .

  For a p-type sample,

  $\rho = 1/(qp\mu_p) = 1/(1.6\times10^{-19}\times1\times10^{15}\times 450) = 13.9\ \Omega\text{-cm}.$

- What is the resistance of a rectangular bar of the above sample of length 1cm and cross-sectional area 1mm^2?

  Solution: $R = \rho\, l/A = 13.9\ \Omega\text{-cm}\times1\text{cm}/(0.01\ \text{cm}^2) = 1390\ \Omega.$

Worked Examples

- Calculate the resistivity of a pure intrinsic sample of Si at 300 K. The electron mobility is 1350 cm^2/Vs and the hole mobility is 450 cm^2/Vs at 300 K. Intrinsic carrier concentration in Si at 300 K is $1x10^{10}$ cm^{-3}.

$$\rho = 1/\{q(n\mu_n + p\,\mu_p)\} = 1/\{1.6x10^{-19}(1x10^{10}x1350 + 1x10^{10}x450)\} = 3.47x10^5\ \Omega\text{-cm}.$$

Good luck