جلسه ۱۰

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CHAPTER 2

Carrier Transport Phenomena

- ✓Carrier transport
- ✓Carrier recombination and generation
- ✓Continuity equation
- ✓The drift-diffusion model

2.7- Carrier transport

2.7.1. Carrier drift

2.7.2. Mobility and Conductivity

2.7.3. Velocity saturation

2.7.4. Carrier diffusion

- Any motion of free carriers in a semiconductor leads to a current.

- This motion can be caused by an electric field due to an externally applied voltage, since the carriers are charged particles. We will refer to this transport mechanism as carrier drift.

- In addition, carriers also move from regions where the carrier density is high to regions where the carrier density is low.
- We will refer to this transport mechanism as carrier diffusion.

(referring to animation)

- The total current in a semiconductor equals the sum of the drift and the diffusion current.

- As one applies an electric field to a semiconductor, the electrostatic force causes the carriers to first accelerate and then reach a constant average velocity, v, due to collisions with impurities and lattice vibrations.
- The ratio of the velocity to the applied field is called the mobility.
- The velocity saturates at high electric fields reaching the saturation velocity.
- Additional scattering occurs when carriers flow at the surface of a semiconductor, resulting in a lower mobility due to surface or interface scattering mechanisms.

- Diffusion of carriers is obtained by creating a carrier density gradient. Such gradient can be obtained either by varying the doping density or applying a thermal gradient in a semiconductor.

- Both carrier transport mechanisms are related since the same particles and scattering mechanisms are involved. This leads to a relationship between the mobility and the diffusion constant called the Einstein relation.

2.7.1. Carrier drift

- The motion of a carrier drifting in a semiconductor due to an applied electric field, , is illustrated in Figure 2.7.1. The field causes the carrier to move on average with a velocity, v.

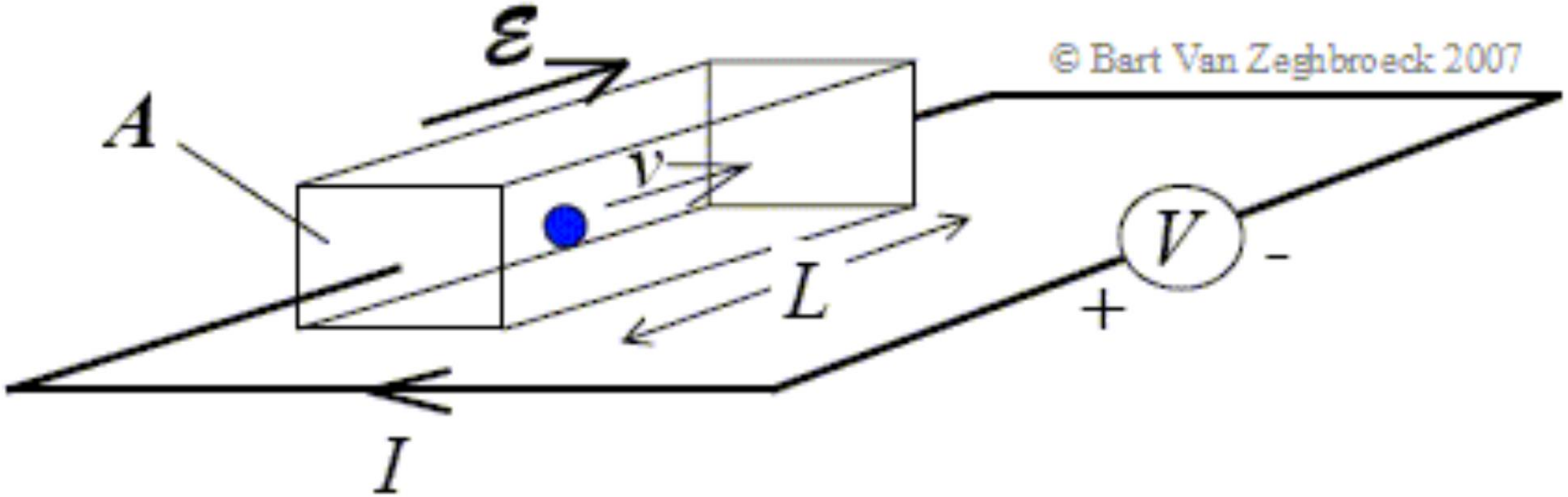

Figure 2.7.1 : Drift of a carrier due to an applied electric field.

Assuming that all the carriers in the semiconductor move with the same average velocity, the current can be expressed as the total charge in the semiconductor divided by the time needed to travel from one electrode to the other, or:

$$I = \frac{Q}{t_r} = \frac{Q}{L/v} \qquad (2.7.1)$$

where t_r is the transit time of a particle, traveling with velocity, v, over the distance L. The current density, J, can then be rewritten as a function of the charge density, r :

$$\vec{J} = \frac{\vec{I}}{A} = \frac{Q}{AL}\vec{v} = \rho\vec{v} \qquad (2.7.2)$$

If the carriers are negatively charged electrons, the current density equals:

$$\vec{J} = -qn\vec{v} \qquad (2.7.2a)$$

while for positively charged holes it is:

$$\vec{J} = qp\vec{v} \qquad (2.7.2b)$$

Where n and p are the electron and hole density in the semiconductor.

- It should be noted that carriers do not follow a straight path along the electric field lines.

- Instead they bounce(جست و خیز کردن) around in the semiconductor and constantly change direction and velocity due to scattering.

- This behavior occurs even when no electric field is applied and is due to the thermal energy of the carriers.

- Thermodynamics teaches us that electrons in a non-degenerate and non-relativistic electron gas have a thermal energy of kT/2 per particle per degree of freedom.
- A typical thermal velocity at room temperature is around 10^7 cm/s, which exceeds(بیشتر) the typical drift velocity in semiconductors.
- The carrier motion in the semiconductor in the absence and in the presence of an electric field can therefore be visualized as in Figure 2.7.2.

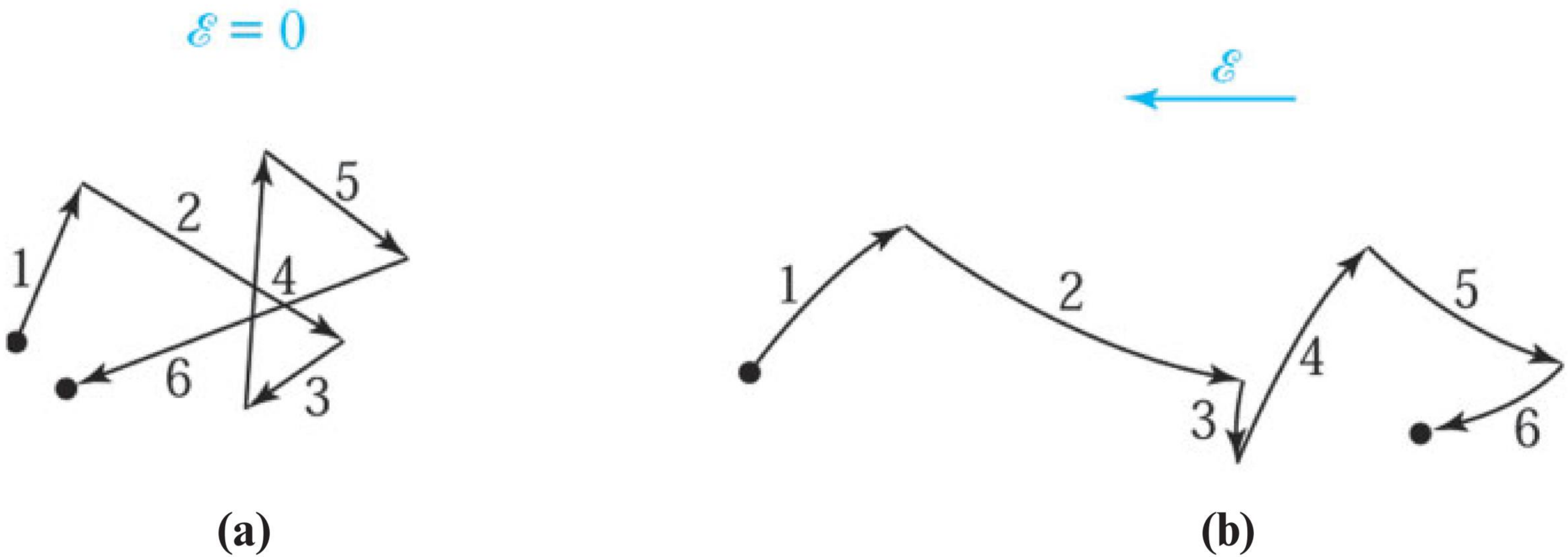

Figure 2.7.2 : Random motion of carriers in a semiconductor with and without an applied electric field.

- In the absence of an applied electric field, the carrier exhibits random motion and the carriers move quickly through the semiconductor and frequently change direction.

- When an electric field is applied, the random motion still occurs but in addition, there is on average a net motion along the direction of the field.

- Due to their different electronic charge, holes move on average in the direction of the applied field, while electrons move in the opposite direction.

- We now analyze the carrier motion considering only the average velocity of the carriers.

- Applying Newton's law, we state that the acceleration of the carriers is proportional to the applied force:

$$\vec{F} = m\vec{a} = m\frac{d < \vec{v} >}{dt} \qquad (2.7.3)$$

- The force consists of the difference between the electrostatic force and the scattering force due to the loss of momentum at the time of scattering.

- This scattering force equals the momentum divided by the average time between scattering events or collisions, t_c, so that:

$$\vec{F} = q\vec{\mathcal{E}} - \frac{m < \vec{v} >}{\tau_c} \tag{2.7.4}$$

where a particle with charge q was assumed.

- Combining both relations yields an expression for the average particle velocity:

$$q\vec{\mathcal{E}} = m\frac{d < \vec{v} >}{dt} + \frac{m < \vec{v} >}{\tau_c} \tag{2.7.5}$$

- We now consider only the steady state situation in which the particle has already accelerated and has reached a constant average velocity.

- Under such conditions, the velocity is proportional to the applied electric field and we define the mobility as the velocity to field ratio:

$$\mu = \frac{|\vec{v}|}{|\vec{\mathcal{E}}|} = \frac{q\tau_c}{m} \qquad (2.7.6)$$

- The mobility of a particle in a semiconductor is therefore expected to be large if its mass is small and the time between scattering events is large.

- The drift current, described by (2.7.2), can then be rewritten as a function of the mobility, yielding:

$$\vec{J}_n = q n \mu_n \vec{\mathcal{E}} \tag{2.7.7}$$

For electrons and

$$\vec{J}_p = q p \mu_p \vec{\mathcal{E}} \tag{2.7.8}$$

For holes

- Throughout this derivation, we simply considered the mass, *m*, of the particle. However in order to incorporate the effect of the periodic potential of the atoms in the semiconductor we must use the effective mass, m^*, rather than the free particle mass, m_0, so that:

$$\mu = \frac{q\tau_c}{m^*} \tag{2.7.9}$$

Example 2.8	Electrons in undoped gallium arsenide have a mobility of 8,800 cm^2/V-s. Calculate the average time between collisions. Calculate the distance traveled between two collisions (also called the mean free path). Use an average velocity of 10^7 cm/s.