جلسه ۱۲

http://ecee.colorado.edu/~bart/book/book/title.htm

CHAPTER 2

Carrier Transport Phenomena

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

2.7.4.1 Diffusion current

2.7.4.2 Total current

2.8. Carrier recombination and generation

- Carrier diffusion is due to the thermal energy, kT, which causes the carriers to move at random even when no field is applied.

- This random motion does not yield a net flow of carriers nor does it yield a net current in material with a uniform carrier density since any carrier which leaves a specific location is on average replace by another one.

- However if a carrier gradient is present, the diffusion process will even out the carrier density variations:

- carriers diffuse from regions where the density is high to regions where the density is low.
- The diffusion process is not unlike the motion of sand on a vibrating table; hills as well as valleys are smoothed out over time.
- In this section we will first derive the expression for the current due to diffusion and then combine it with the drift current to obtain the total drift-diffusion current.

2.7.4.1 Diffusion current

- The derivation is based on the basic notion(ایده) that carriers at non-zero temperature (Kelvin) have an additional thermal energy, which equals kT/2 per degree of freedom.
- It is the thermal energy, which drives(هدایت کردن) the diffusion process. At T = 0 K there is no diffusion.
- To further simplify the derivation, we will derive the diffusion current for a one-dimensional semiconductor in which carriers can only move along one direction.

- We now introduce the average values of the variables of interest, namely the thermal velocity, v_{th}, the collision time, t_c, and the mean free path, l.
- The thermal velocity is the average velocity of the carriers going in the positive or negative direction.
- The collision time is the time interval between two collisions of charge carriers with an atom or with another carrier.
- The mean free path is the average length a carrier will travel between collisions.

- These three averages are related by:

$$v_{th} = \frac{l}{\tau_c} \qquad (2.7.20)$$

- Variable carrier density, n(x) is shown in Figure 2.7.8:

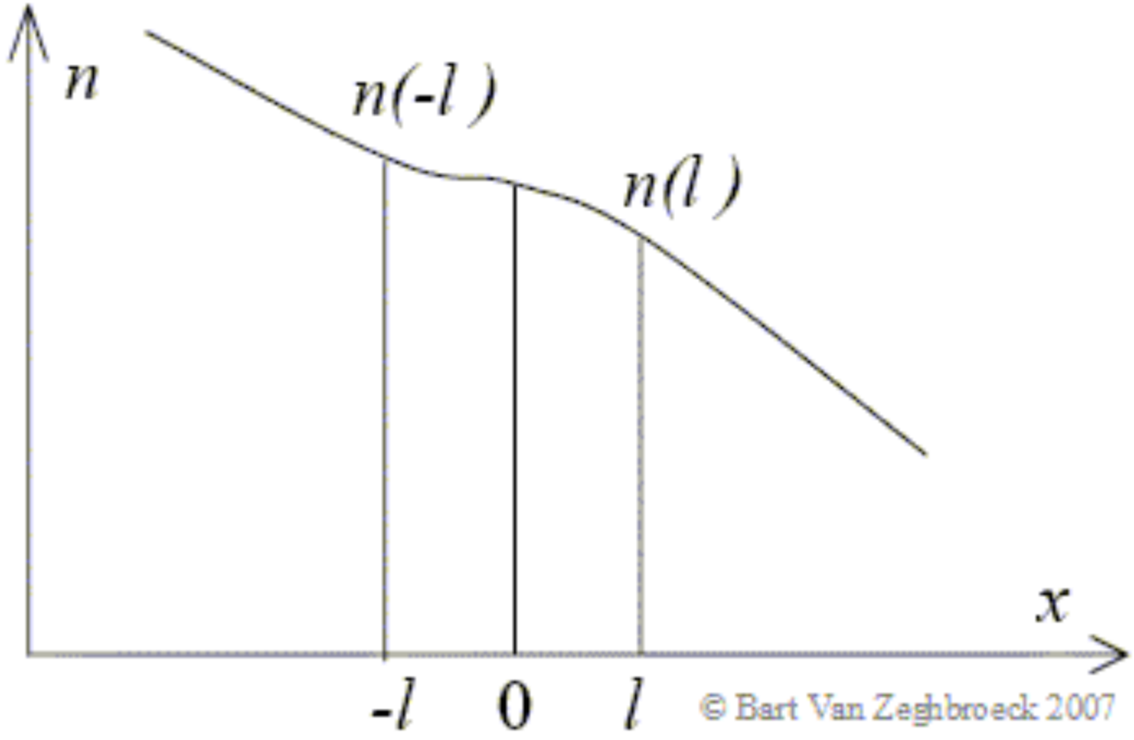

Figure 2.7.8: Carrier density profile used to derive the diffusion current expression

- Of interest are the carrier densities which are one mean free path away from $x = 0$, since the carriers, which will arrive at $x = 0$ originate either at $x = -l$ or $x = l$. The flux at $x = 0$ due to carriers that originate at $x = -l$ and move from left to right equals:

$$\Phi_{n,left \to right} = \frac{1}{2} v_{th} n(x = -l) \qquad (2.7.21)$$

- where the factor 1/2 is due to the fact that only half of the carriers move to the left while the other half moves to the right. The flux at $x = 0$ due to carriers that originate at $x = +l$ and move from right to left, equals:

$$\Phi_{n,right \to left} = \frac{1}{2} v_{th} n(x = l) \qquad (2.7.22)$$

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$$\Phi_{n,right \rightarrow left} = \frac{1}{2} v_{th} n(x = l) \qquad (2.7.22)$$

- The total flux of carriers moving from left to right at x = 0 therefore equals:

$$\Phi_n = \Phi_{n,left \to right} - \Phi_{n,right \to left} = \frac{1}{2} v_{th} [n(x = -l) - n(x = l)] \tag{2.7.23}$$

- Where the flux due to carriers moving from right to left is subtracted from the flux due to carriers moving from left to right.

- Given that the mean free path is small we can write the difference in densities divided by the distance between x = -l and x = l as the derivative of the carrier density:

$$\Phi_n = -l v_{th} \frac{n(x = l) - n(x = -l)}{2l} = -l v_{th} \frac{dn}{dx} \tag{2.7.24}$$

- The electron diffusion current equals this flux times the charge of an electron, or:

$$J_n = -q\Phi_n = q l v_{th} \frac{dn}{dx} \quad (2.7.25)$$

- We now replace the product of the thermal velocity, v_{th}, and the mean free path, l, by a single parameter, namely the diffusion constant, D_n, so that:

$$J_n = q D_n \frac{dn}{dx} \quad (2.7.26)$$

- Repeating the same derivation for holes yields:

$$J_p = -q D_p \frac{dp}{dx} \quad (2.7.27)$$

2.7.4.2. Total current

The total electron current is obtained by adding the current due to diffusion to the drift current, resulting in:

$$J_n = qn\mu_n\mathcal{E} + qD_n\frac{dn}{dx} \qquad (2.7.33)$$

and similarly for holes:

$$J_p = qp\mu_p\mathcal{E} - qD_p\frac{dp}{dx} \qquad (2.7.34)$$

The total current is the sum of the electron and hole current densities multiplied with the area, *A*, perpendicular to the direction of the carrier flow:

$$I_{total} = A(J_n + J_p) \qquad (2.7.35)$$

2.8. Carrier recombination and generation

- Recombination of electrons and holes is a process by which both carriers annihilate each other:
- electrons occupy - through one or multiple steps - the empty state associated with a hole. Both carriers eventually disappear in the process.
- The energy difference between the initial and final state of the electron is released in the process. This leads to one possible classification of the recombination processes.
- In the case of radiative recombination, this energy is emitted in the form of a photon.

- In the case of non-radiative recombination, it is passed on to one or more phonons.
- In the case of Auger recombination it is given off in the form of kinetic energy to another electron.
- These different processes are further illustrated with Figure 2.8.1.

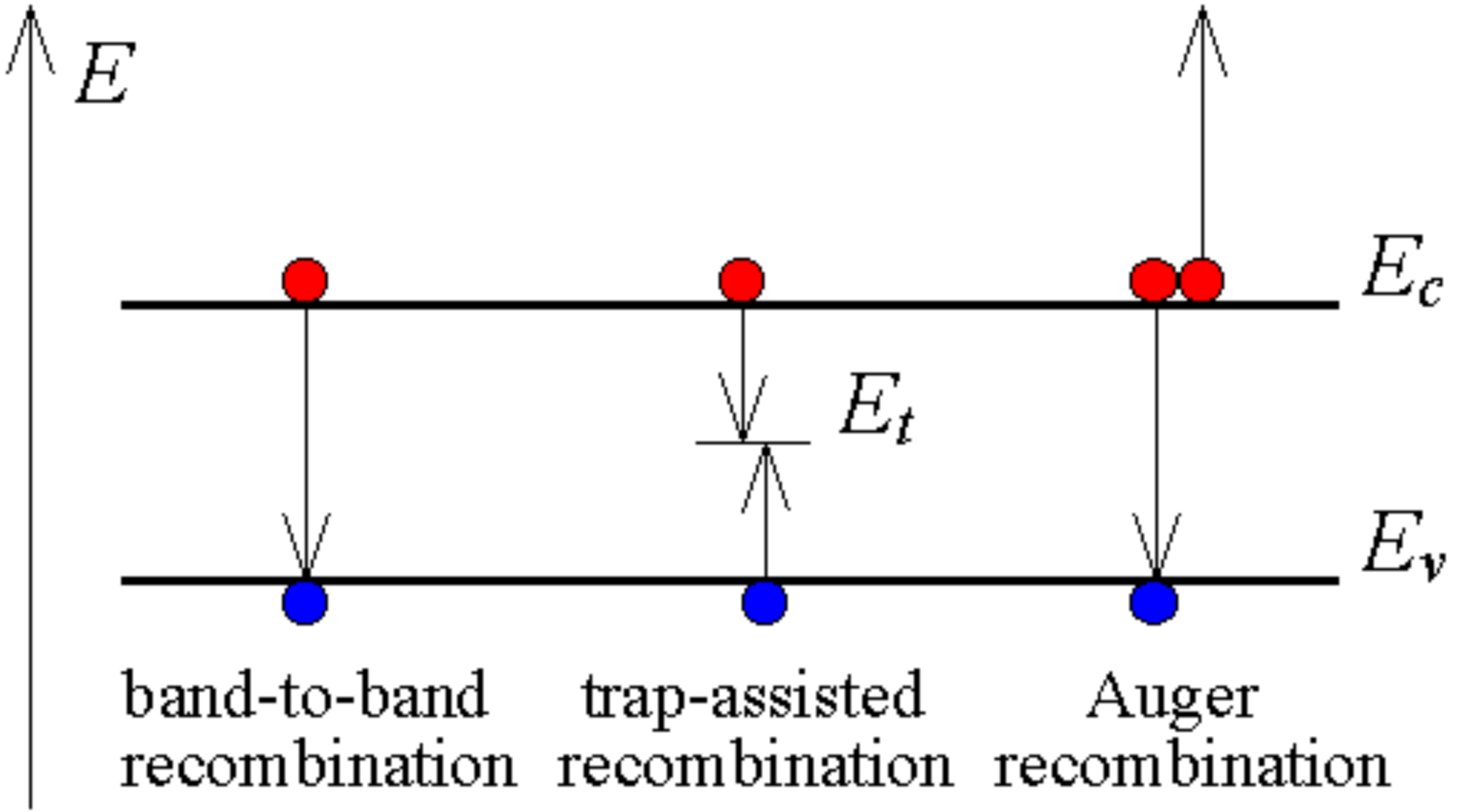

Figure 2.8.1 : Carrier recombination mechanisms in semiconductors

Animatiion:https://www.pveducation.org/pvcdrom/pn-junctions/types-of-recombination

- Band-to-band recombination occurs when an electron moves from its conduction band state into the empty valence band state associated with the hole. This band-to-band transition is typically also a radiative transition in direct bandgap semiconductors.

- Trap-assisted recombination(بازترکیب به کمک تله) occurs when an electron falls into a "trap", an energy level within the bandgap caused by the presence of a foreign atom or a structural defect.

- Once the trap is filled it cannot accept another electron.

- The electron occupying the trap, in a second step, moves into an empty valence band state, thereby completing the recombination process.

- One can envision(تجسم) this process as a two-step transition of an electron from the conduction band to the valence band or as the annihilation of the electron and hole, which meet each other in the trap.

- We will refer to this process as Shockley-Read-Hall (SRH) recombination.

- Auger recombination is a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole.

- The involvement(وجود) of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination.
- Each of these recombination mechanisms can be reversed leading to carrier generation rather than recombination.
- A single expression will be used to describe recombination as well as generation for each of the above mechanisms.

- In addition, there are generation mechanisms, which do not have an associated recombination mechanism, such as generation of carriers by light absorption or by a high-energy electron/particle beam. These processes are referred(یاد می شوند) to as ionization processes.

- The generation mechanisms are illustrated with Figure 2.8.2.

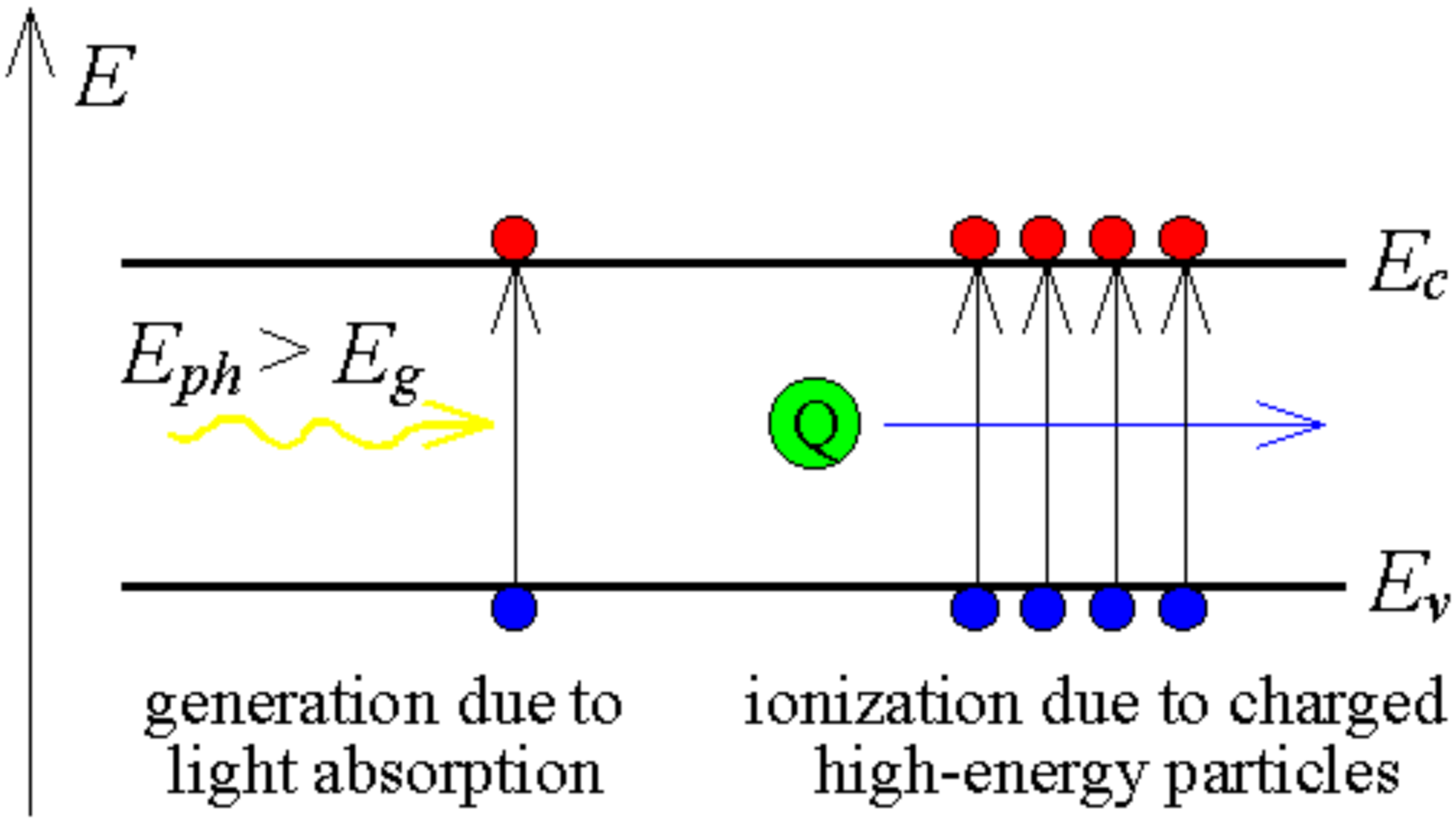

Figure 2.8.2 : Carrier generation due to light absorption and ionization due to high-energy particle beams

Animation:https://www.pveducation.org/pvcdrom/pn-junctions/absorption-of-light

- Carrier generation due to light absorption occurs if the photon energy is large enough to raise an electron from the valence band into an empty conduction band state, thereby generating one electron-hole pair.

- The photon energy needs to be larger than the bandgap energy to satisfy this condition.

- The photon is absorbed in this process and the excess energy, E_{ph} - E_g, is added to the electron and the hole in the form of kinetic energy.

- Carrier generation or ionization due to a high-energy beam consisting of *charged* particles is similar except that the available energy can be much larger than the bandgap energy so that multiple electron-hole pairs can be formed.
- The high-energy particle gradually loses its energy and eventually stops.
- This generation mechanism is used in semiconductor-based nuclear particle counters. As the number of ionized electron-hole pairs varies with the energy of the particle, one can also use such detector to measure the particle energy.