جلسه ۸

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

2.6.4. Doped semiconductors

- Doped semiconductors are semiconductors, which contain impurities, foreign atoms incorporated into the crystal structure of the semiconductor.

- Either these impurities can be unintentional(ناخواسته), due to lack of control during the growth of the semiconductor, or they can be added on purpose to provide free carriers in the semiconductor.

- The generation of free carriers requires not only that impurities are present, but also that the impurities give off electrons to the conduction band in which case they are called donors. If they give off holes to the valence band, they are called acceptors (since they actually accept an electron from the filled valence band).

- The ionization of shallow donors and acceptors are illustrated by Figure 2.6.5. Indicated are the donor and acceptor energies, E_d and E_a. The donor energy level is filled prior(قبل) to ionization. Ionization causes the donor to be emptied, yielding an electron in the conduction band and a positively charged donor ion.

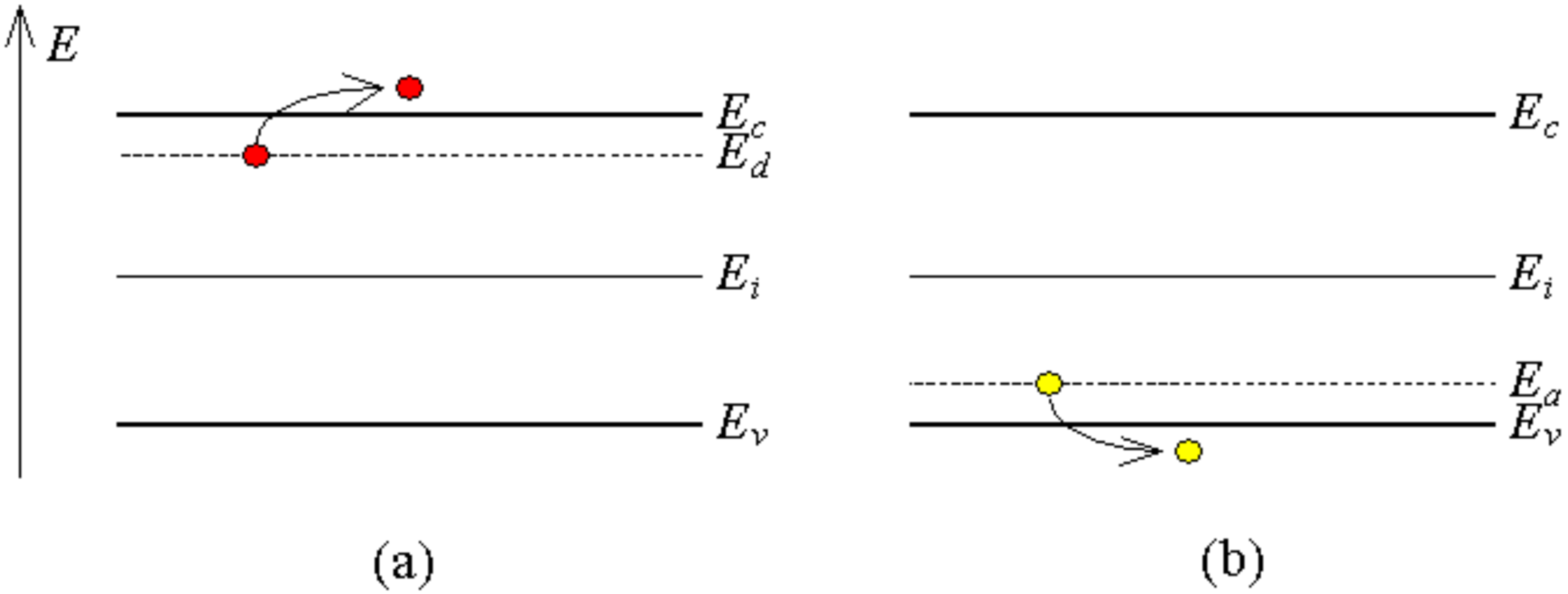

Figure 2.6.5: Ionization of a) a shallow donor and b) a shallow acceptor

- The acceptor energy is empty prior to ionization.

- Ionization of the acceptor corresponds to the empty acceptor level being filled by an electron from the filled valence band.

- This is equivalent to a hole given off by the acceptor atom to the valence band.

- A semiconductor doped with impurities, which are ionized (meaning that the impurity atoms either have donated or accepted an electron), will therefore contain free carriers.

- Shallow impurities are impurities, which require little energy - typically around the thermal energy, kT, or less - to ionize.

- Deep impurities require energies much larger than the thermal energy to ionize so that only a fraction of the impurities present in the semiconductor contribute to free carriers.

- Deep impurities, which are more than five times the thermal energy away from either band edge, are very unlikely to ionize.

- Such impurities can be effective recombination centers, in which electrons and holes are captured(به دام انداختن) and annihilate(نابود کردن) each other.
- Such deep impurities are also called traps.
- Ionized donors provide free electrons in a semiconductor, which is then called n-type, while ionized acceptors provide free holes in a semiconductor, which we refer to as being a p-type semiconductor.

2.6.4.1 Dopants and impurities

❑The ionization of the impurities is dependent on the thermal energy and the position of the impurity level within the energy band gap as described by the impurity distribution functions discussed in section 2.5.3. as follows

$$f_{donor}(E_d) = \frac{1}{1 + \frac{1}{2} e^{(E_d - E_F)/kT}} \qquad (2.5.2)$$

$$f_{acceptor}(E_a) = \frac{1}{1 + 4e^{(E_a - E_F)/kT}} \qquad (2.5.3)$$

- Shallow impurities readily(به راحتی) ionize so that the free carrier density equals the impurity concentration. For shallow donors this implies that the electron density equals the donor concentration, or:

$$n_0 \cong N_d^+ = N_d \qquad (2.6.30)$$

- While for shallow acceptors the hole density equals the acceptor concentration, or:

$$p_0 \cong N_a^- = N_a \tag{2.6.31}$$

- If a semiconductor contains both shallow donors and shallow acceptors it is called *compensated*(جبران شده) since equal amounts of donor and acceptor atoms compensate each other, yielding no free carriers.

- The presence of shallow donors and shallow acceptors in a semiconductor cause the electrons given off by the donor atoms to fall into the acceptor state, which ionizes the acceptor atoms without yielding a free electron or hole.

- The resulting carrier density in compensated material is approximately equal to the difference between the donor and acceptor concentration if the donor concentration is larger, yielding *n*-type material, or:

$$n_o \cong N_d^+ - N_a^-, \quad \text{if} \quad N_d^+ - N_a^- >> n_i \qquad (2.6.32)$$

- If the acceptor concentration is larger than the donor concentration, the hole density of the resulting p-type material equals the difference between the acceptor and donor concentration, or:

$$p_o \cong N_a^- - N_d^+, \quad \text{if} \quad N_a^- - N_d^+ >> n_i \qquad (2.6.33)$$

2.6.4.2 Ionization energy model

- The energy required to remove an electron from a donor atom can be approximated using a hydrogen-like model.

- After all(گذشته از همه اینها), the donor atom consists of a positively charged ion and an electron just like the proton and electron of the hydrogen atom.

- The difference however is that the average distance, *r*, between the electron and the donor ion is much larger since the electron occupies one of the outer orbitals. This is illustrated by Figure 2.6.6.

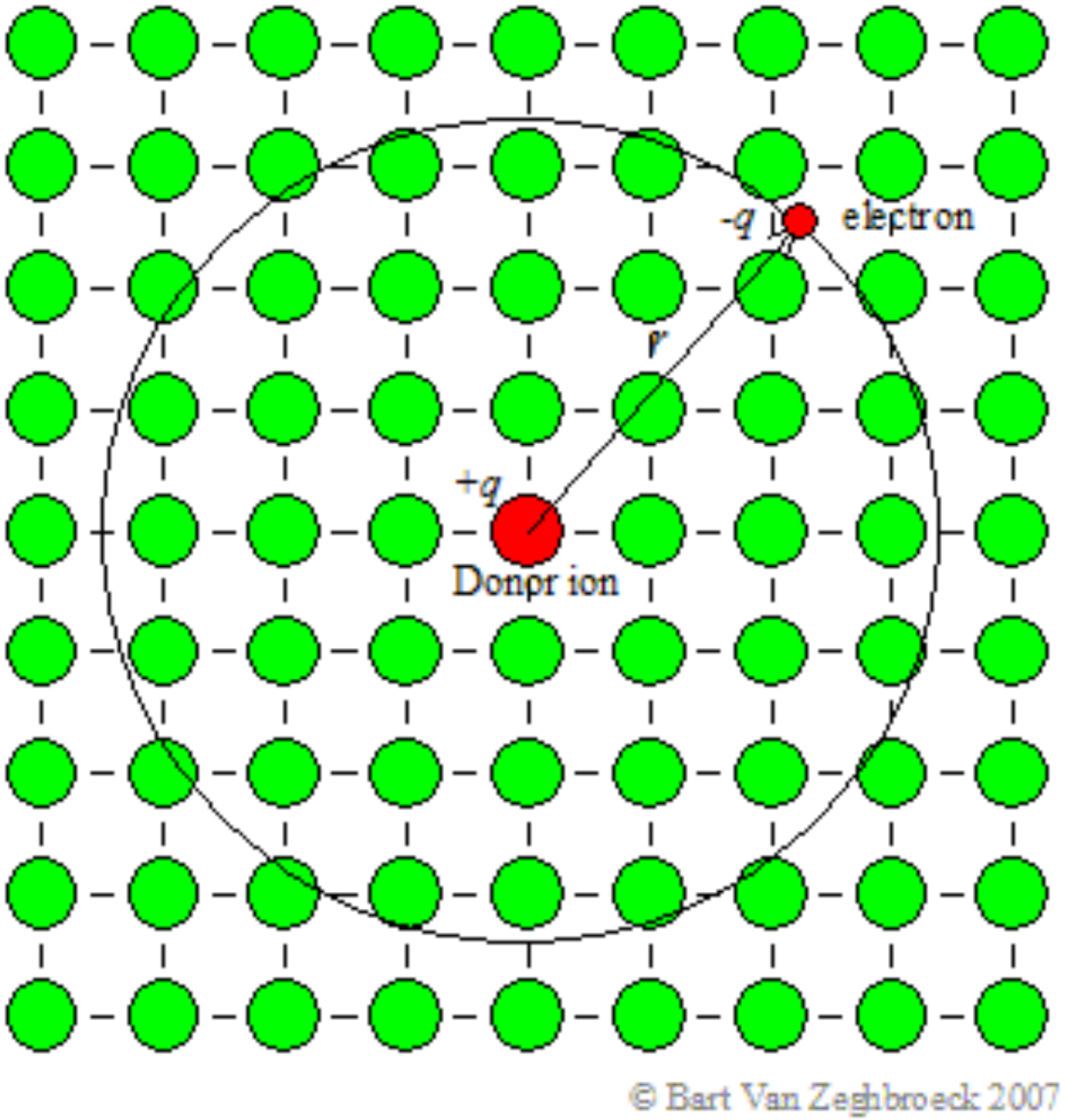

Figure 2.6.6: Trajectory of an electron bound to a donor ion within a semiconductor crystal. A 2-D square lattice is used for ease of illustration.

- For shallow donors, this distance, *r*, is much larger than the inter-atomic spacing of the semiconductor crystal.

- The ionization energy, E_d, can be estimated by modifying equation (1.2.10), which describes the electron energy in a hydrogen atom, yielding:

$$E_c - E_d = 13.6 \frac{m^*_{cond}}{m_0 \varepsilon_r^2} \text{eV} \qquad (2.6.34)$$

$$E_n = -\frac{m_0 q^4}{8 \varepsilon_0^2 h^2 n^2}, \text{ with } n = 1, 2, \ldots \qquad (1.2.10)$$

$$= -13.6 \text{eV}/n^2$$

- where m^*_{cond} is the effective mass for conductivity calculations and e_r is the relative dielectric constant of the semiconductor.

- The ionization energy is calculated as the difference between the energy of a free electron and that of an electron occupying the lowest energy level, E_1.

<table>
<tr><td>Example 2.5</td><td>Calculate the ionization energy for shallow donors and acceptors in germanium and silicon using the hydrogen-like model.</td></tr>
<tr><td>Solution</td><td>Using the effective mass for conductivity calculations (Appendix 3) one finds the ionization energy for shallow donors in germanium to be:

$$E_c - E_d = 13.6 \frac{m^*_{cond}}{m_0\, \varepsilon_r^2} \mathrm{eV} =$$

The calculated ionization energies for donors and acceptors in germanium and silicon are provided below.

<table>
<tr><th></th><th>Germanium</th><th>Silicon</th></tr>
<tr><td>donors</td><td></td><td></td></tr>
<tr><td>acceptors</td><td></td><td></td></tr>
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Note that the actual ionization energies differ from these values and depend on the actual donor atom.</td></tr>
</table>

Name	**Symbol**	**Germanium**	**Silicon**	**Gallium Arsenide**
Bandgap energy at 300 K	E_g (eV)	0.66	1.12	1.424
Breakdown Field	$\mathcal{E}_{br}$ (V/cm)	10^5	3×10^5 *	4×10^5
Density	(g/cm^3)	5.33	2.33	5.32
Effective density of states in the conduction band at 300 K	N_c (cm^{-3})	1.02×10^{19}	2.82×10^{19}	4.35×10^{17}
Effective density of states in the valence band at 300 K	N_v (cm^{-3})	5.65×10^{18}	1.83×10^{19}	7.57×10^{18}
Intrinsic concentration at 300 K	n_i (cm^{-3})	2.8×10^{13}	1.0×10^{10}	2.0×10^6
Effective mass for density of states calculations				
Electrons	m_e^* / m_0	0.55	1.08	0.067
Holes	m_h^* / m_0	0.37	0.81	0.45
Electron affinity	χ (V)	4.0	4.05	4.07
Lattice constant	a (pm)	564.613	543.095	565.33
Mobility at 300 K (undoped)				
Electrons	μ_n (cm^2/V-s)	3900	1400†	8800
Holes	μ_p (cm^2/V-s)	1900	450†	400
Relative dielectric constant	$\varepsilon_s / \varepsilon_0$	16	11.9	13.1