(KTXFI2EBNF) Physics II. Lecture

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November 3, 2025

Exams, Tests, etc.

- I had to announce the exams on short notice; therefore, you can take them on December 16, 2025, January 5, 19, and February 2, 2026, from 14:00 to 16:00.
- The first exam is on a Tuesday, while the rest are on Mondays. You can also retake midterm tests and obtain your signature on December 16, 2025.
- You must take or retake the midterm exams before December 7, 2025. Therefore, I propose December 1, 2025, for the midterm exam and December 8, 2025, for the midterm retake.
- I will give you your 2nd and 3rd homework assignments before December 1, 2025.
- I currently have no idea when I will give you your 4th and 5th homework assignments. . .
- We will have lectures and practice sessions on November 3, 10, and 24, 2025.

Where are we? I

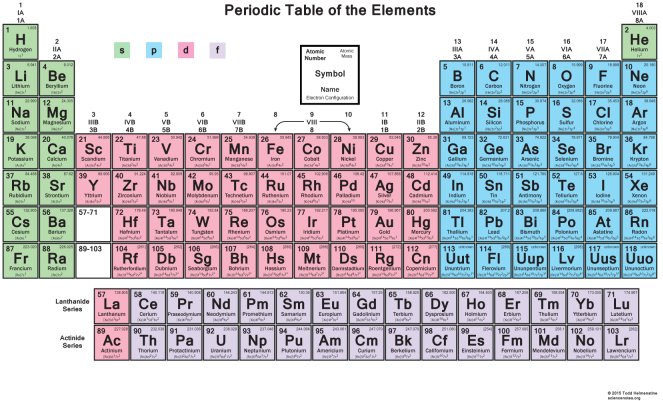
- ~~Motion of charged particles in electromagnetic fields.~~
- ~~Elements of quantum mechanics. Heisenberg's uncertainty principle. The stationary Schrödinger equation and its applications.~~
- ~~Limits of the classical conceptual framework. Thermal radiation. Photoelectric effect. Compton effect. The dual nature of electromagnetic radiation. The dual nature of particles.~~
- ~~Moving reference frames. Inertial forces in accelerating reference frames. Elements of special relativity. Dirac-equation, antimatter.~~
- ~~The classical theory of atomic structure (Rutherford, Franck-Hertz experiment, Bohr model, quantum numbers, Pauli exclusion principle).~~
- ~~Physics of condensed matter. Metallic bonding. Electrical conduction in metals based on the free electron model and the wave model. Hall effect. Band theory of solids.~~

Where are we? II

- **Semiconductors. Elements of Fermi-Dirac statistics.** Thermoelectric phenomena. Magnetic properties.
- Ferroelectricity. Piezoelectricity and electrostriction. Liquid crystals. Superconductivity.
- Luminescence. Lasers. Basic knowledge of nuclear physics. Basic knowledge of particle physics.

Physical background of photovoltaic devices I

Silicon electron configuration: $1s^2 2s^2 2p^6 3s^2 3p^2$.



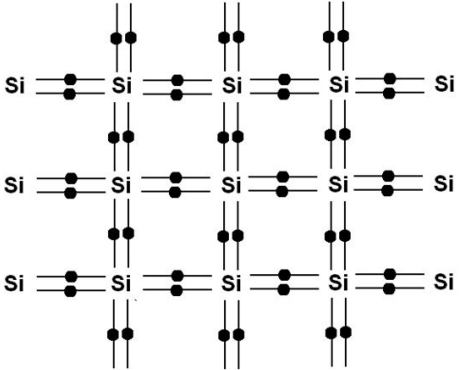
Physical background of photovoltaic devices II

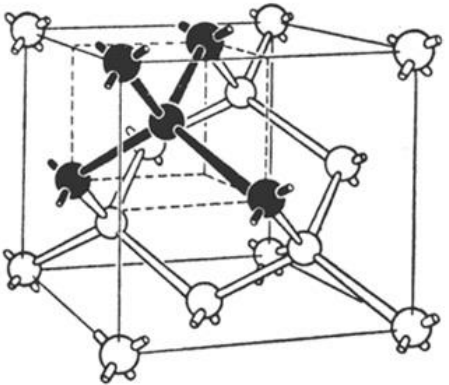
Photovoltaic devices — physical operating principles.

							VIIIA
		IIIA	IVA	VA	VIA	VIIA	2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
IB	IIB	13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

Physical background of photovoltaic devices III

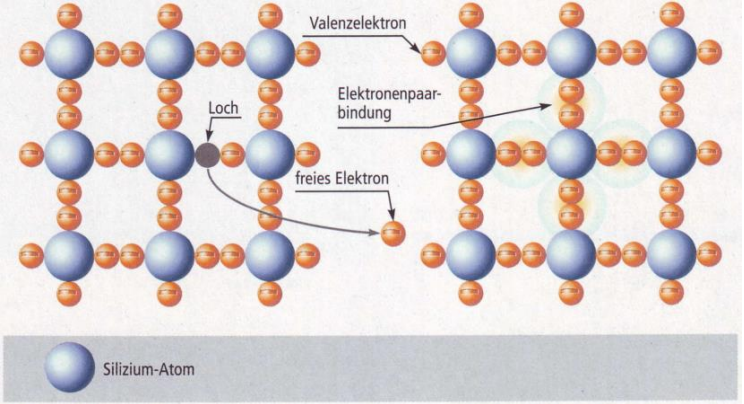
Covalent Bond in the Silicon Crystal Lattice





Charge carriers in semiconductors I

- Electrons — mobile negative charge carriers in the conduction band.

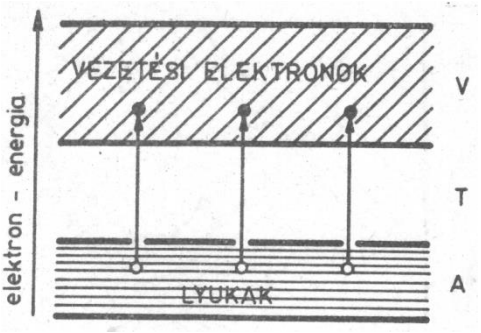


Charge carriers in semiconductors II

- Intrinsic (pure) semiconductor: silicon
  - Hole (positive charge carrier).
  - Valence electron and covalent bond formed by electron pairs.
  - Free electron (when a bond is broken by excitation).
  - Silicon atom lattice.
  - Initial state (Silicon, Si): four valence electrons in covalent bonds; tetrahedral crystal structure.
  - Thermal excitation: covalent bonds may break, producing free electrons and enabling electrical current.
  - Holes: the vacant site left in the covalent bond when an electron is excited — a positive charge carrier.

Charge carriers in semiconductors III

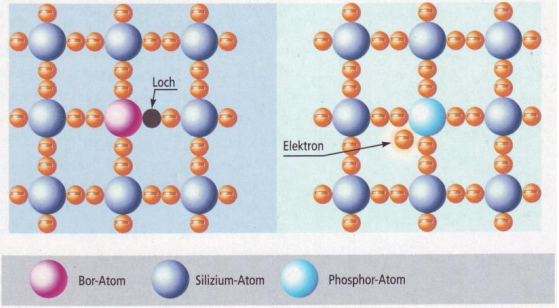
- Band-to-band excitation and forbidden gap



- Electrons can be excited from the valence band (A) into the conduction band (V) by sufficient energy input.
- Electrons can never occupy states within the forbidden gap (T).

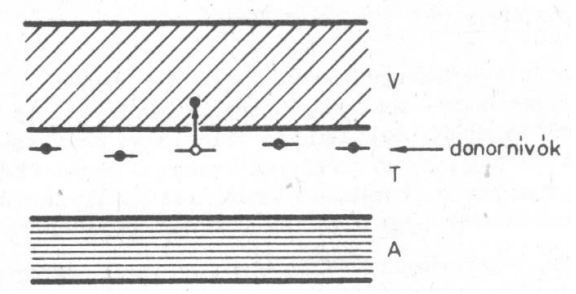
Charge carriers in semiconductors IV

- Extrinsic (doped) semiconductors
  - p-type doping: acceptor levels near the valence band introduce holes (positive carriers).
  - n-type doping: donor levels near the conduction band introduce extra electrons (negative carriers).



Charge carriers in semiconductors V

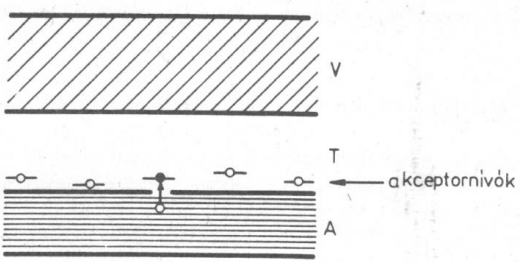
- n-type doping and donor levels



- In n-type doping, donor levels form close to the conduction band edge. Electrons introduced by the dopant occupy these donor levels.
- These donor electrons are more easily thermally excited into the conduction band where they act as free charge carriers and contribute to electrical conduction.

Charge carriers in semiconductors VI

- p-type doping and acceptor levels



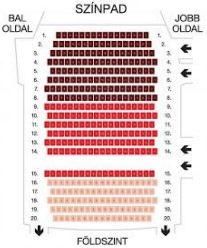
- In p-type doping, acceptor levels form near the top of the valence band. The holes introduced by the dopant occupy those acceptor levels.
- These holes can recombine with electrons in the valence band or facilitate excitation of valence electrons into the acceptor level more easily than into the conduction band, due to the smaller energetic separation (smaller local gap).

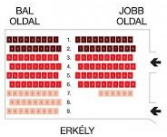
Elements of Fermi–Dirac statistics I

- Basics of Fermi–Dirac statistics
  - For systems with a large number of particles, statistical descriptions are required to characterize their physical properties (similar to classical statistics for gases).
  - Electrons behave analogously to gas particles in such statistical descriptions.
  - Enrico Fermi developed the model for fermions in 1920 (Rome).
  - Applies to fermions (half-integer spin particles), including electrons.
- Assumptions of Fermi–Dirac statistics
  - Particles are indistinguishable.
  - Energy levels are quantized (Bohr postulates apply).
  - Pauli exclusion principle: no more than one fermion (per spin state) can occupy the same quantum state.
  - Heisenberg uncertainty relations limit phase-space cell size: $\Delta p \cdot \Delta x$ defines a phase-space cell volume.

Elements of Fermi–Dirac statistics II

- Fermi distribution function



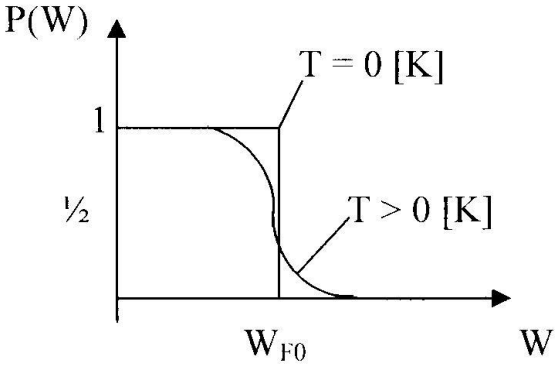


$$P(W) = \frac{1}{\exp\left(\frac{W-W_F}{kT}\right)+1}$$

- W_F: Fermi energy (to be defined).
- k: Boltzmann constant. W: energy level. T: absolute temperature (K).

Elements of Fermi–Dirac statistics III

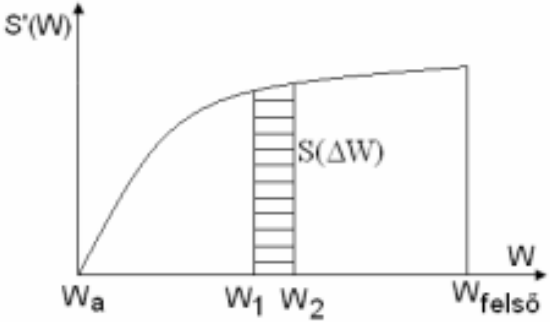
- Interpretation of the Fermi function



- The Fermi function gives the probability that an energy level W is occupied by an electron.
- At $T = 0\,\mathrm{K}$, $f(W) = 1$ for $W < W_F$, and $f(W) = 0$ for $W > W_F$.
- At $T > 0\,\mathrm{K}$, $f(W_F) = \frac{1}{2}$.

Elements of Fermi–Dirac statistics IV

- Density of available states $S'(W)$



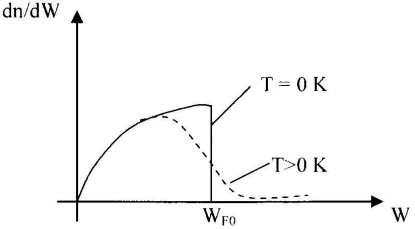
- $S'(W)$ denotes the density of available single-particle quantum states per unit volume as a function of energy W.
- Physically: the number of distinct quantum states (e.g., seats in a theater analogy) available at a given energy.

Elements of Fermi–Dirac statistics V

- Energy distribution density function

$$\frac{dn}{dW} = 4\pi\,(2m)^{3/2}/h^3 \cdot \frac{1}{\exp\left(\frac{W-W_F}{kT}\right)+1} \cdot W^{1/2}$$

This function describes how electrons populate energy levels per unit energy interval and per unit volume.



Elements of Fermi–Dirac statistics VI

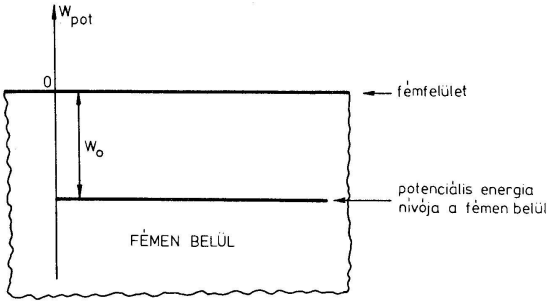
- Separation and integration of the distribution
  - The differential form: $dn = \left[4\pi(2m)^{3/2}/h^3\right] \frac{1}{e^{(W-W_F)/kT}+1} W^{1/2}\, dW$.
  - Integrating from 0 to W_F^0 at $T = 0$ K yields the electron concentration n and the zero-temperature Fermi energy W_F^0.
- Zero-temperature Fermi energy

$$S(W) = W_F^0 = \frac{3n}{8\pi}\left(\frac{h^2}{2m}\right)^{2/3}$$

- The zero-temperature Fermi energy depends only on the conduction electron concentration n and fundamental constants.

Work function and potential energy reference I

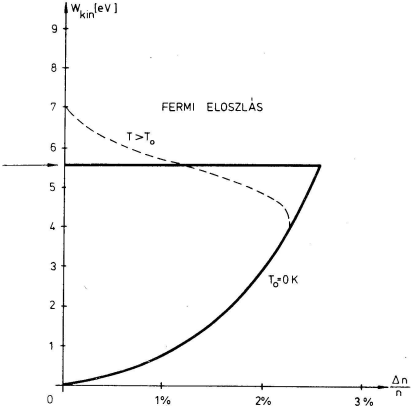
- Work function



- The potential energy of an electron bound to the atomic nucleus is negative; at infinite separation it approaches zero.
- Inside a metal the potential energy of free electrons, W_0, is negative and rises toward the surface, becoming zero outside the metal.

Work function and potential energy reference II

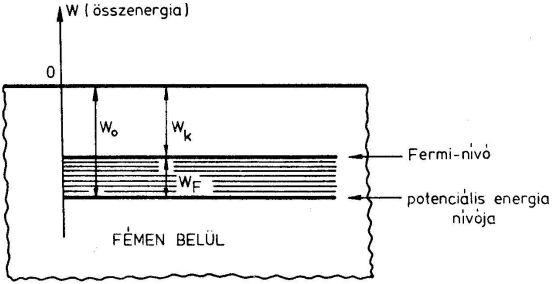
- Kinetic energy in the conduction band and Fermi level



- Electrons in the conduction band possess kinetic energy in addition to potential energy; their kinetic energy distribution depends on the electron population.
- Definition (Fermi level): the energy level corresponding to electrons with the highest occupied kinetic energy at $T = 0$ K.

Work function and potential energy reference III

- Fermi level occupancy and work function



- At $T = 0$ K all states below the Fermi level are fully occupied; states above are empty.
- Definition (work function): the energy W_k required to remove an electron at the Fermi level from the metal. It equals the absolute value of the potential energy W_0 plus the Fermi energy difference:

$$W_k = W_0 - W_F$$

The End

Thank you for your attention!