ECE2: Physics for Electrical Engineers

Midterm Spring 2018

May 2nd 2017, 2 to 3:55 pm, Humanities Building A65

Instructors: Prof. Chee Wei Wong, Jin Ho Kang and Jiahui Huang
Closed book, but with 1-sheet (2-sides of 8.5" × 11" paper) of notes.
Please use calculator.

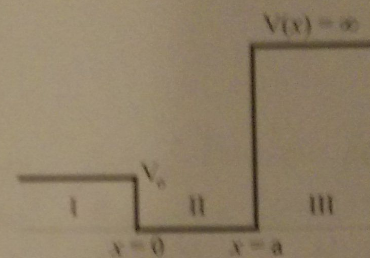
Question 1. (30 points) Chapter 1 and 2: The Crystal Structure of Solids & Introduction to Quantum Mechanics

Consider the one-dimensional potential function shown on the right. Assume the total energy E of an electron is less than V_o.

1.A. (10 points). Write the wave solutions for each region.

1.B. (14 points). Write the set of equations that result from applying the boundary conditions.

1.C. (6 points). Explain whether the energy levels of the electron would be quantized.

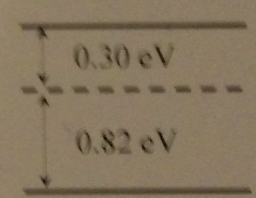


Question 2. (25 points) Chapter 3: Introduction to the Quantum Theory of Solids

Consider a semiconductor with the energy levels shown on the right.
Let $T = 300$ K.

2.A. (13 points). Calculate the probability that an energy state at $E = E_1$ is occupied by an electron.

2.B. (12 points). Calculate the probability that an energy state at $E = E_2$ is empty.



Question 3. (35 points) Chapter 4: The Semiconductor in Equilibrium

3.A. (15 points). Consider an *n*-doped extrinsic semiconductor. Plot the Fermi-Dirac distribution function $f_F(E)$ and the density of states $g(E)$ on the same plot, as taught in class. Draw the intrinsic Fermi level, E_{Fi}. Draw where the Fermi level E_F would be compared to E_{Fi}. Repeat the same plots for a *p*-doped extrinsic semiconductor; where does the Fermi level E_F sit compared to E_{Fi}?

3.B. (20 points) In a silicon chip at $T = 300$ K, it is found that $N_a = 7 \times 10^{15}$ cm^{-3} and $p_o = 2 \times 10^4$ cm^{-3}.

3.B.1. (8 points) Is the material *n*-type or *p*-type?

3.B.2. (12 points) What are the majority and minority carrier concentrations?

Question 4. (10 points) Chapter 5: Carrier Transport Phenomena

Describe the difference between carrier drift and carrier diffusion, and how do we express the drift current density (J_{drf}) in terms of mobility μ?

Helpful constants:
Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/K
Planck's constant $h = 6.625 \times 10^{-34}$ J-s
Electronic charge $e = 1.60 \times 10^{-19}$ C
Electron mass $m = 9.11 \times 10^{-31}$ kg

100

$\psi_1(x) = A_1 e^{-k_1 x} + B_1 e^{k_1 x}$, $k_1 = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}}$ ✓

$\psi_2(x) = A_2 e^{jk_2 x} + B_2 e^{-jk_2 x}$, $k_2 = \sqrt{\frac{2mE}{\hbar^2}}$ ✓

III $\psi_3(x) = 0$ ✓

b) $A_2 e^{jk_2 a} + B_2 e^{-jk_2 a} = 0$

$A_2 + B_2 = A_1 + B_1$

$jk_2 A_2 e^{jk_2 a} - jk_2 B_2 e^{-jk_2 a} = 0$

$jk_2 A_2 - jk_2 B_2 = -k_1 A_1 + k_1 B_1$ ✓

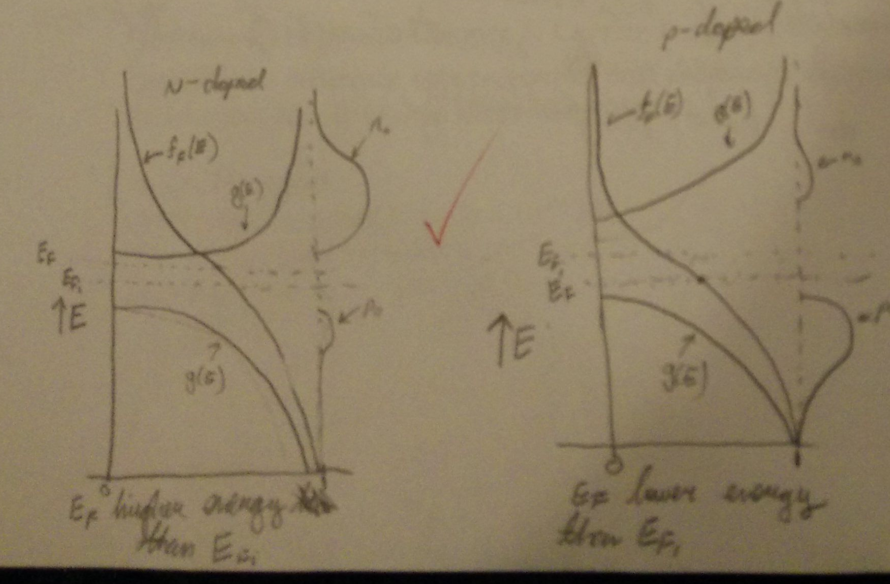
$\int_{-\infty}^{0} |A_1 e^{-k_1 x} + B_1 e^{k_1 x}|^2 dx + \int_{0}^{a} |A_2 e^{jk_2 x} + B_2 e^{-jk_2 x}|^2 dx = 1$

c) At $x = a$, $\psi(x)$ must be 0. Because we do not control the phase of the wave function, only particular values of k_2 and k_1 will satisfy the this boundary condition. So the energy levels of the electron must be <u>quantized</u> within region 2. we must have a standing wave in region 2 ✓

2) a) $f_F(E_1) = f_F(E_F + 0.3\text{eV}) = \frac{1}{1 + \exp\left(\frac{0.3}{0.0259}\right)} = \boxed{9.32 \times 10^{-6}}$ ✓

b) $\left[1 - f_F(E_F - 0.82\text{eV})\right] = 1 - \frac{1}{1 + \exp\left(\frac{-0.82}{0.0259}\right)} \approx \boxed{0}$ ✓

3) a)



✓ ✓

3) continued

b) 1) **n-type**

2) minority carrier concentration: $p_0 = 2 \times 10^{4}\ cm^{-3}$

majority carrier concentration: n_0

$$p_0 = \frac{N_a}{2} + \sqrt{\left(\frac{N_a}{2}\right)^2 + n_i^2}$$

$$n_i^2 = 1.837 \times 10^{32}\ cm^{-3}$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{4}} = 1.13 \times 10^{16}\ cm^{-3}$$

4) Carrier drift is an average movement of carriers due to an applied electric field. Carrier drift gives rise to a drift current density. Carrier diffusion is an average movement of carriers due to a non-zero carrier concentration gradient. Similarly, carrier diffusion can also give rise to a diffusion current density. Diffusion current moves in the direction to equalize the concentration gradient.

The drift current of some set of particles with charges q is given as $J_{drf} = q \mu n E$, where n is the concentration of charges and E is the electric field.

The drift current due to electrons and holes is

$$J_{drf} = e(\mu_n n + \mu_p p)E$$

where e is the electronic charge and μ_n and μ_p are the mobility of electrons and holes respectively and n and p are the concentrations of electrons and holes, respectively.