Benha University
Benha Faculty of Engineering
Date: 12 / 1 /2022
Semester: January 2022
Examiners: Physics Staff
Total marks: 90

Department: Basic Eng. Sciences
Program: Bachelor (Corrective)
Time: 3 hours
Subject: Modern Physics
Code: B1133
No. of Pages: 2

Answers of Final written exam:

Question ① 《20 points》

a) [5 points] Calculate the temperature of a blackbody if the spectral distribution peaks at **(i)** gamma rays, $\lambda = 1.50 \times 10^{-14}$ m; **(ii)** x rays, 1.50 nm; **(iii)** red light, 640 nm; **(iv)** broadcast television waves, $\lambda = 1.00$ m; and **(v)** AM radio waves, $\lambda = 204$ m.

$$\text{(a) } T = \frac{2.898\times10^{-3}\ \text{m}\cdot\text{K}}{1.50\times10^{-14}\ \text{m}} = 1.932\times10^{11}\ \text{K}$$

$$\text{(b) } T = \frac{2.898\times10^{-3}\ \text{m}\cdot\text{K}}{1.50\times10^{-9}\ \text{m}} = 1.932\times10^{6}\ \text{K}$$

$$\text{(c) } T = \frac{2.898\times10^{-3}\ \text{m}\cdot\text{K}}{640\times10^{-9}\,\text{m}} = 4528\ \text{K}$$

$$\text{(d) } T = \frac{2.898\times10^{-3}\ \text{m}\cdot\text{K}}{1\ \text{m}} = 2.898\times10^{-3}\ \text{K}$$

$$\text{(e) } T = \frac{2.898\times10^{-3}\ \text{m}\cdot\text{K}}{204\ \text{m}} = 1.42\times10^{-5}\ \text{K}$$

b) [5 points] An experimenter finds that no photoelectrons are emitted from tungsten unless the wavelength of light is less than 270 nm. Her experiment will require photoelectrons of maximum kinetic energy 2.0 eV. What frequency of light should be used to illuminate the tungsten?

$$\phi = \frac{hc}{\lambda_t} = \frac{1240\ \text{eV}\cdot\text{nm}}{270\ \text{nm}} = 4.59\ \text{eV}\,; \quad K = 2.0\ \text{eV} = hf - \phi$$

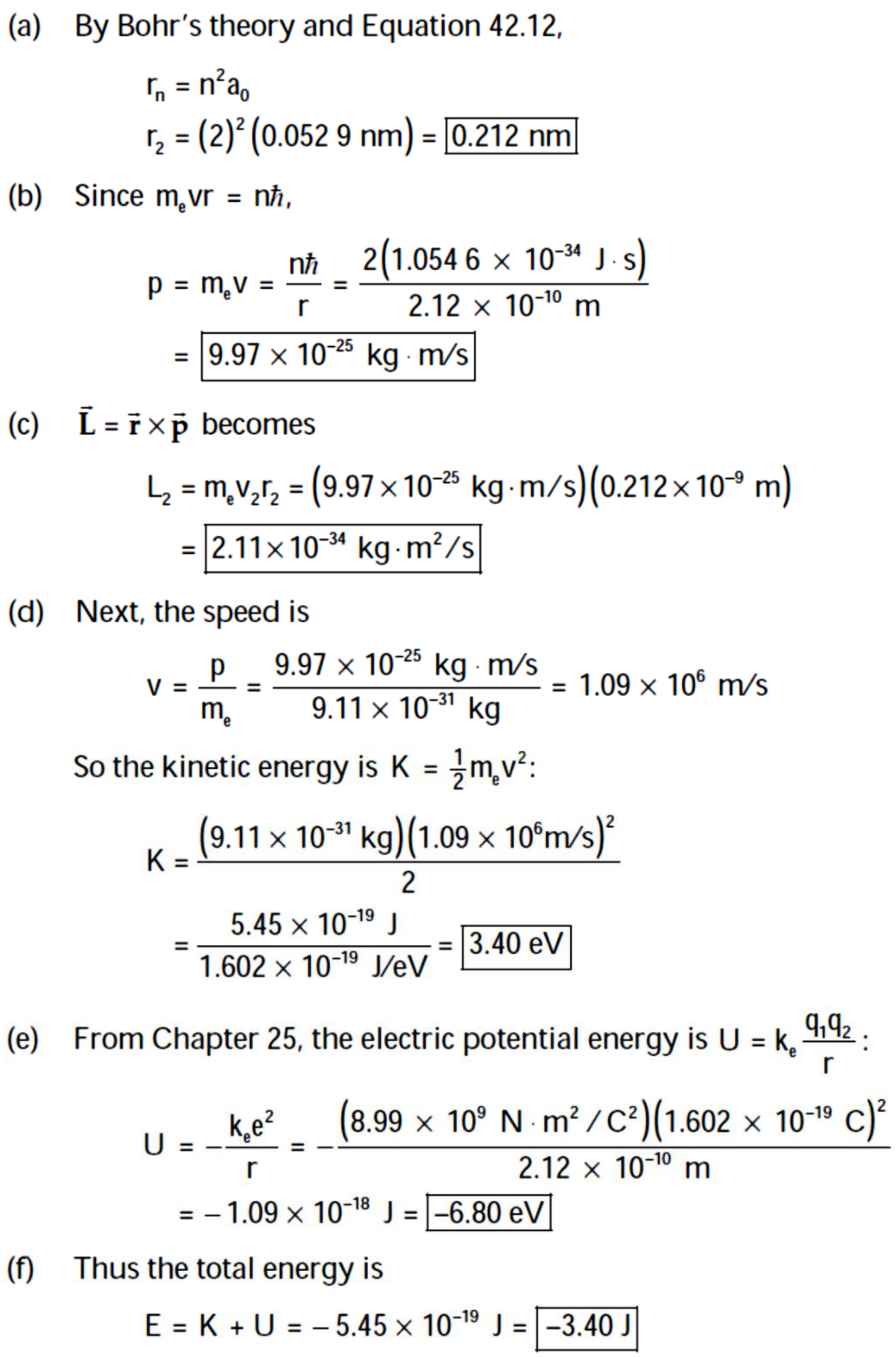
$$f = \frac{K+\phi}{h} = \frac{2.0\ \text{eV} + 4.59\text{eV}}{4.136\times10^{-15}\ \text{eV}\cdot\text{s}} = 1.59\times10^{15}\ \text{Hz}$$

c) [5 points] A photon having 40 keV scatters from a free electron at rest. What is the maximum energy that the electron can obtain?

The maximum change in the photon's energy is obtained in backscattering ($\theta = 180^\circ$), so $1-\cos\theta = 2$ and $\Delta\lambda = \dfrac{2h}{mc} = 4.853\times10^{-12}$ m. The photon's original wavelength was $\lambda = \dfrac{hc}{E} = \dfrac{1240\ \text{eV}\cdot\text{nm}}{40000\ \text{eV}} = 0.0310\ \text{nm} = 3.10\times10^{-11}$ m and the new wavelength is $\lambda' = \lambda + \Delta\lambda = 3.585\times10^{-11}$ m. The electron's recoil energy equals the change in the photon's energy, or

$$K = \frac{hc}{\lambda} - \frac{hc}{\lambda'} = \frac{1240\ \text{eV}\cdot\text{nm}}{3.10\times10^{-2}\ \text{nm}} - \frac{1240\ \text{eV}\cdot\text{nm}}{3.585\times10^{-2}\ \text{nm}} = 5411\ \text{eV} = 5.41\ \text{keV}$$

d) [5 points] A hydrogen atom is in its first excited state (n = 2). Calculate **(i)** the radius of the orbit, **(ii)** the linear momentum of the electron, **(iii)** the angular momentum of the electron, **(iv)** the kinetic energy of the electron, **(v)** the potential energy of the system, and **(vi)** the total energy of the system.



(a) By Bohr's theory and Equation 42.12,

$$r_n = n^2 a_0$$

$$r_2 = (2)^2(0.052\,9\text{ nm}) = \boxed{0.212\text{ nm}}$$

(b) Since $m_e vr = n\hbar$,

$$p = m_e v = \frac{n\hbar}{r} = \frac{2(1.054\,6\times10^{-34}\text{ J}\cdot\text{s})}{2.12\times10^{-10}\text{ m}}$$

$$= \boxed{9.97\times10^{-25}\text{ kg}\cdot\text{m/s}}$$

(c) $\vec{\mathbf{L}} = \vec{\mathbf{r}}\times\vec{\mathbf{p}}$ becomes

$$L_2 = m_e v_2 r_2 = (9.97\times10^{-25}\text{ kg}\cdot\text{m/s})(0.212\times10^{-9}\text{ m})$$

$$= \boxed{2.11\times10^{-34}\text{ kg}\cdot\text{m}^2/\text{s}}$$

(d) Next, the speed is

$$v = \frac{p}{m_e} = \frac{9.97\times10^{-25}\text{ kg}\cdot\text{m/s}}{9.11\times10^{-31}\text{ kg}} = 1.09\times10^6\text{ m/s}$$

So the kinetic energy is $K = \frac{1}{2}m_e v^2$:

$$K = \frac{(9.11\times10^{-31}\text{ kg})(1.09\times10^6\text{m/s})^2}{2}$$

$$= \frac{5.45\times10^{-19}\text{ J}}{1.602\times10^{-19}\text{ J/eV}} = \boxed{3.40\text{ eV}}$$

(e) From Chapter 25, the electric potential energy is $U = k_e\frac{q_1q_2}{r}$:

$$U = -\frac{k_e e^2}{r} = -\frac{(8.99\times10^9\text{ N}\cdot\text{m}^2/\text{C}^2)(1.602\times10^{-19}\text{ C})^2}{2.12\times10^{-10}\text{ m}}$$

$$= -1.09\times10^{-18}\text{ J} = \boxed{-6.80\text{ eV}}$$

(f) Thus the total energy is

$$E = K + U = -5.45\times10^{-19}\text{ J} = \boxed{-3.40\text{ J}}$$

Question ② 《20 points》

a) [5 points] A ruby laser emits 694.3-nm light. Assume light of this wavelength is due to a transition of an electron in a box from its n = 2 state to its n = 1 state. Find the length of the box.

$$\Delta E = \frac{hc}{\lambda} = \left(\frac{h^2}{8m_e L^2}\right)\left[2^2 - 1^2\right] = \frac{3h^2}{8m_e L^2}$$

Solving for the length of the box then gives

$$L = \sqrt{\frac{3h\lambda}{8m_e c}}$$

$$= \sqrt{\frac{3\left(6.626\times10^{-34}\ \text{J}\cdot\text{s}\right)\left(694.3\times10^{-9}\ \text{m}\right)}{8\left(9.11\times10^{-31}\ \text{kg}\right)\left(3.00\times10^{8}\ \text{m/s}\right)}}$$

$$= 7.95\times10^{-10}\ \text{m} = \boxed{0.795\ \text{nm}}$$

b) [5 points] An electron with kinetic energy E = 5.00 eV is incident on a barrier of width L = 0.200 nm and height U = 10.0 eV. What is the probability that the electron **(i)** tunnels through the barrier? **(ii)** Is reflected?

The decay constant for the wave function inside the barrier is:

$$k = \frac{\sqrt{2m(U-E)}}{\hbar}$$

$$= \frac{\sqrt{2\left(9.11\times10^{-31}\ \text{kg}\right)\left(10.0\ \text{eV} - 5.00\ \text{eV}\right)\left(1.60\times10^{-19}\ \text{J/eV}\right)}}{6.626\times10^{-34}\ \text{J}\cdot\text{s}/2\pi}$$

$$= 1.14\times10^{10}\ \text{m}^{-1}$$

$$T_o = 16\,\frac{E}{U}\left(1-\frac{E}{U}\right) = 16\,\frac{5}{10}\left(1-\frac{5}{10}\right)$$

$$= 4$$

(a) The probability of transmission is

$$T = T_o\, e^{-2kL} = 4 . e^{-2\left(1.14\times10^{10}\ \text{m}^{-1}\right)\left(2.00\times10^{-10}\ \text{m}\right)} = \boxed{0.0418}$$

(b) $R = 1 - T = \boxed{0.958}$, a 96% chance of reflection.

c) [5 points] (i) Write out the electronic configuration of the ground state for zinc (Z = 30). **(ii)** Write out the values for the possible set of quantum numbers n, ℓ, m_ℓ, and m_s for the electrons in zinc.

(i) $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2$

(ii)

Zinc															
n	1	2				3									4
ℓ	0	0	1			0	1			2					0
m_ℓ	0	0	−1	0	+1	0	−1	0	+1	−2	−1	0	+1	+2	0
m_s	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓

d) [5 points] Determine the surface density of atoms for silicon with lattice constant of 5.43 Å on the **(i)** (100) plane, **(ii)** (110) plane, and **(iii)** (111) plane.

(a) (100) plane: - similar to a fcc:

$$\text{Surface density} = \frac{2}{\left(5.43\times10^{-8}\right)^2}$$

$$= 6.78\times10^{14}\ \text{cm}^{-2}$$

(b) (110) plane:

$$\text{Surface density} = \frac{4}{\sqrt{2}\left(5.43\times10^{-8}\right)^2}$$

$$= 9.59\times10^{14}\ \text{cm}^{-2}$$

(c) (111) plane:
Surface density

$$= \frac{2}{\left(\sqrt{3}/2\right)\left(5.43\times10^{-8}\right)^2}$$

$$= 7.83\times10^{14}\ \text{cm}^{-2}$$

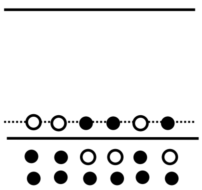
Question ③ ❰21 points❱

Choose the correct answer justifing your choice (answers without justification are ignored):

1. [3 points] At 0 K, ... have the same electrical conductivity.
(a) semiconductors and metals (b) dielectrics and metals
(c) metals and insulators **(d) semiconductors and dielectrics**
(e) none of the above choices

2. [3 points] If the Fermi function at certain energy is 0.3, the probability of finding a hole at this energy is … ……
(a) 1 (b) 0 (c) 0.5 (d) 0.3 **(e) 0.7**

3. [3 points] The Energy band diagram beside is likely to depict the situation inside a semiconductor which is ....
(a) *n*-type at $T < 100$ K (b) *p*-type at $T \approx 300$ K
(c) *n*-type at $T > 400$ K **(d) *p*-type at $T < 100$ K**
(e) *n*-type at $T \approx 300$ K



4. [3 points] Applying an electric field in the positive *x*-direction causes an electron drift current that is …
(a) in the negative *y*-direction (b) in the negative *x*-direction
(c) inversely proportional to the value of the field **(d) in the positive *x*-direction**
(e) directly proportional to the resistivity of the material

5. [3 points] The built-in potential of a *pn*-junction at equilibrium is
(a) is higher at the *p*-side **(b) is directly proportional to doping densities**
(c) does not depend on temperature (d) is inversly proportional to doping densities
(e) is always zero

6. [3 points] Consider a *pn*-junction at equilibrium. If this junction is forward biased,
(a) the width of the depletion layer is reduced (b) the current is reduced
(c) the potential barrier remains the same (d) the current will reverse direction
(e) none of the above choices

7. [3 points] Consider a *pn*-junction at equilibrium. If this junction is reverse biased, the current ....
(a) will be mainly drift current (b) will be mainly diffusion current
(c) will increase (d) will pass in the external circuit from from *n*-side to *p*-side
(e) none of the above choices

Question ④ 《18 points》

1. **[4 points]** Two semiconductor materials have exactly the same properties except that material A has a bandgap of 1 eV and material B has a bandgap energy of 2 eV, both at temperature 199 K. Find the ratio of intrinsic concentration of material A to that of material B.

Answer:

$$KT(199) = 0.02585\times199/200 = 0.0171\ \text{eV}$$
$$E_{gA} = 1,\ E_{gB} = 2,$$
$$\text{ratio} = \exp(-(E_{gA} - E_{gB})/(2\times KT)) = 4.6\times10^{12}$$

2. **[6 points]** For silicon at $T = 300$ K, determine the equilibrium concentration of

(i) electrons if it is doped with acceptors of concentration 5×10^{16} cm^{-3}

(ii) holes if it is doped with equal acceptor and donor concentration of 2×10^{16} cm^{-3}

(iii) holes if it is doped with donor concentration of 1×10^{15} cm^{-3}

Answer:

(i) $$n = \frac{n_i^2}{N_A - N_D} = \frac{(1\times10^{10})^2}{5\times10^{16}} = 2\times10^3\ \text{cm}^{-3}$$

(ii) $$p = n_i = 1\times10^{10}\ \text{cm}^{-3}$$

(iii) $$p = \frac{n_i^2}{N_D - N_A} = \frac{(1\times10^{10})^2}{1\times10^{15}} = 1\times10^5\ \text{cm}^{-3}$$

3. **[8 points]** Determine the drift current passing through a sample of silicon when we apply 0.1 V bias on its terminals. The following information is given: The sample is doped with donors of concentration 1×10^{14} cm^{-3} and acceptors of concentration 1×10^{16} cm^{-3}, the temperature is 300 K, the length of the sample is 64 nm, the cross-sectional area of the sample is 4×10^4 nm^2.

Answer:

$$p \approx N_A = 1\times10^{16}\ \text{cm}^{-3}$$

$$n = \frac{n_i^2}{N_A - N_D} = \frac{(1\times10^{10})^2}{1\times10^{16}} = 1\times10^4\ \text{cm}^{-3}$$
$$\sigma = qp\mu_p = (1.6\times10^{-19})(1\times10^{16})(800) = 1.28\ \Omega^{-1}\text{cm}^{-1}$$
$$R = \frac{L}{\sigma A} = \frac{(64\times10^{-7})}{(4\times10^4\times10^{-14})(1.28)} = 12.5\ k\Omega$$

$$I = V/R = 0.1/12.5 = 8\ \text{mA}$$

Question ⑤ 《12 points》

(a) **[12 points]** A silicon pn junction at $T = 300$ K has doping concentrations of $N_D = 4\times10^{16}$ cm^{-3} and $N_A = 7\times10^{16}$ cm^{-3}. The cross-sectional area of the junction is 10^{-4} cm^2. The revrese satuaration current is 10^{-10} A. Calculate the following quantities:

(i) the potential difference across the junction at equilibrium.

(ii) the width of the depletion layer at equilibrium,

(iii) the current when a forward voltage of 0.6 V is applied,

(iv) the current when a reverse voltage of 10 V is applied,

Answer:

(i) $$V_{bi} = KT\times\ln(N_AN_D/n_i^2) = 0.8005\ \text{V}$$

(ii) $$W = \left[\frac{2\varepsilon}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_{bi}\right]^{\frac{1}{2}} = 201.6\ nm$$

(iii) $$I = 1\times10^{-10}\times(\exp(q\times0.6/KT) - 1) = 1.2\ \text{A}$$

(iv) $$I = I_s = 1\times10^{-10}\text{A}$$

End of the exam **Examiners:** Prof Tarek M. Abdolkader, Dr Ibrahim Maged *Best wishes*

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Final Written Exam

CONSTANTS: $q = 1.6 \times 10^{-19}$ C, $h = 6.626 \times 10^{-34}$ J.s, $m_e = 9.1 \times 10^{-31}$ kg, kT/q **at 300 K** $= 0.02586$ V
$k_e = 9\times10^{9}$ N.m^2/C^2, $m_p = 1.67\times 10^{-27}$ kg, $c = 3\times10^{8}$ m/s, $\sigma = 5.67\times10^{-8}$ W/m^2.K^4, $a_0 = 0.0529$ nm, $R_H = 1.1\times10^{7}$ m^{-1}
PROPERTIES OF SILICON: at T = 300 K: $E_g = 1.12$ eV, $n_i = 1 \times 10^{10}$ cm^{-3}, $\mu_n = 1500$ cm^2/(V.s), $\mu_p = 800$ cm^2/(V.s)

$$\frac{\partial(\delta p)}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G_{ext} - \frac{\delta p}{\tau_p} \qquad \frac{\partial(\delta n)}{\partial t} = +\frac{1}{q}\frac{\partial J_n}{\partial x} + G_{ext} - \frac{\delta n}{\tau_n}$$

Answer all questions:

Question ① 《20 points》

a) **[5 points** CLO: a1, a3, b3**]** Calculate the temperature of a blackbody if the spectral distribution peaks at **(i)** gamma rays, $\lambda = 1.50 \times 10^{-14}$ m; **(ii)** x rays, 1.50 nm; **(iii)** red light, 640 nm; **(iv)** broadcast television waves, $\lambda = 1.00$ m; and **(v)** AM radio waves, $\lambda = 204$ m.

b) **[5 points** CLO: a1, a3, b3**]** An experimenter finds that no photoelectrons are emitted from tungsten unless the wavelength of light is less than 270 nm. Her experiment will require photoelectrons of maximum kinetic energy 2.0 eV. What frequency of light should be used to illuminate the tungsten?

c) **[5 points** CLO: a1, a3, b3**]** A photon having 40 keV scatters from a free electron at rest. What is the maximum energy that the electron can obtain?

d) **[5 points** CLO: a1, a3, b3**]** A hydrogen atom is in its first excited state (n = 2). Calculate **(i)** the radius of the orbit, **(ii)** the linear momentum of the electron, **(iii)** the angular momentum of the electron, **(iv)** the kinetic energy of the electron, **(v)** the potential energy of the system, and **(vi)** the total energy of the system.

Question ② 《20 points》

a) **[5 points** CLO: a1, a3, b3**]** A ruby laser emits 694.3-nm light. Assume light of this wavelength is due to a transition of an electron in a box from its n = 2 state to its n = 1 state. Find the length of the box.

b) **[5 points** CLO: a1, a3, b3**]** An electron with kinetic energy E = 5.00 eV is incident on a barrier of width L = 0.200 nm and height U = 10.0 eV. What is the probability that the electron **(i)** tunnels through the barrier? **(ii)** Is reflected?

c) **[5 points** CLO: a1, a3**]** **(i)** Write out the electronic configuration of the ground state for zinc (Z = 30). **(ii)** Write out the values for the possible set of quantum numbers n, ℓ, m_ℓ, and m_s for the electrons in zinc.

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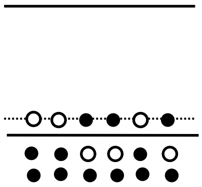
Continue with the remaining questions at the back

3. **[3 points** CLO: a1, a3**]** The Energy band diagram beside is likely to depict the situation inside a semiconductor which is ....



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(c) n-type at $T > 400$ K (d) p-type at $T < 100$ K
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Question ⑤ 《12 points》

(a) **[12 points** CLO: a1, a3, b3**]** A silicon pn junction at $T = 300$ K has doping concentrations of $N_D = 4\times10^{16}$ cm^{-3} and $N_A = 7\times10^{16}$ cm^{-3}. The cross-sectional area of the junction is 10^{-4} cm^{2}. The revrese satuaration current is 10^{-10} A. Calculate the following quantities:
(i) the potential difference across the junction at equilibrium.
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