UNIVERSITY OF ABERDEEN: SESSION 2022/2023

Degree Examination in PX4516 Nuclear and Semiconductor Physics

3rd May 2023 9.00 – 11.00 am (2 hours)

PLEASE READ CAREFULLY

Candidates should attempt **Two** questions in section one (40 marks) and **Two** question in section two (40 marks).

Boltzmanns constant $k_B = 1.38 \times 10^{-23}\, JK^{-1}$, Avogadro's number $6.022 \times 10^{23}\, mole^{-1}$, Electron charge 1.6×10^{-19} Coulombs.
Semi Empirical Mass Formula: $B(Z,A) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_A (A-2Z)^2/A + B_p$

Section One

1. When different types of nuclei decay, several different types of radiation are observed:

a) Discuss the experimentally observed differences in the behaviour of alpha, beta and gamma radiation and what each type of radiation is. How was the existence of the neutron deduced and discovered? **[10]**

b) For Beta decay, discuss the two principle observations that led to the discovery of the Neutrino. **[4]**

c) Given that the mass of a Neutron is 939:57, the mass of a proton is 938:27 MeV and the mass of an electron is 0:51 MeV; explain why the decay of a neutron to proton is possible, but not the decay of a free proton to a neutron. Why does this become possible in some nuclei? **[2]**

d) Using the semi-empirical mass formula (given above), show that the most stable Z value for a nucleus undergoing beta- decay is given by: **[4]**

$$Z = \frac{A}{2 + \frac{a_c}{2a_A} A^{2/3}}$$

2 This question concerns the liquid drop model of the atom:

(a) What features of the atom led scientists to develop the liquid drop model of the nucleus? **[2]**

(b) By considering the semi-empirial mass formula discuss the physical meaning of B(Z,A). Express B(Z,A) in terms of the proton mass and neutron mass and the mass of the nucleus. If two nuclei of the same mass number have different B(Z,A), which will be more stable? **[3]**

(c) Explain the physical meaning and origin of each term in the mass formula **[11]**

(d) The coulomb constant a_c is smaller than the other constants. Explain why the term is nevertheless extremely important and hence why stable nuclei have more neutrons than protons. **[2]**

(e) Why is this formula not a good approximation for light nuclei? **[2]**

3 This question concerns nuclear energy derived from Fusion and Fission:

(a) Sketch a graph of binding energy against atomic number and explain energy production via fusion and fission. **[3]**

(b) Sketch (i) a gas cooled thermal reactor and (ii) a fast reactor, label your diagrams and indicate the purpose of each component. What significant advantage do breeder reactors have over thermal reactors in terms of waste? = **[10]**

(c) Explain why the long term future of a nuclear industry would have to move away from conventional thermal reactors using U235 and involve either fast breeder reactors or fusion reactors. **[2]**

(d) What is the triple proton chain for energy production in our sun – discuss if this is a suitable fusion reaction for reactors on earth. Suggest other possible fusion reactions that could be used and if and why they would be better. **[5]**

Section Two

4 Describe the following devices addressing the points of particular interest in the question, and use sketches to illustrate your answers:

a) Consider the operation of a pn junction, describing the formation of the depletion region and how it changes in forward and reverse bias. Sketch the charge distribution, electric field and potential across the device in each case. Draw a band diagram across an unbiased pn junction showing the Fermi energy. **[6]**

b) Describe the role the pn junction plays in the operation of a photo-diode and solar cell. **[4]**

c) Describe the operation of a simple MESFET transistor. **[3]**

d) Consider the operation of a Gunn diode. Explain how changes in effective mass lead to a negative differential resistivity – sketch this and so explain the formation of a Gunn domain and describe the basic operation of the diode. **[7]**

5 The number densities of electrons *n* and holes *p* in a semiconductor may be expressed in terms of energy as:

$$n = N_c \exp\left(\frac{E_F - E_C}{k_B T}\right) \qquad p = N_V \exp\left(\frac{E_V - E_F}{k_B T}\right)$$

(where N_C and N_V are the effective density of states).

a) In an intrinsic material $n = p = n_i$. Use these relationships to derive an expression for n_i in terms of the energy band gap, and show that the intrinsic Fermi energy can be written: **[7]**

$$E_{Fi} = \frac{1}{2}(E_C + E_V) + \frac{k_B T}{2} \log_e \frac{N_V}{N_C}$$

b) For extrinsic (or doped) materials, the Fermi energy depends on the ratio *n/p*. Use the expression in question 5a above to derive an expression for the Fermi energy in a material doped with N_D donors and N_A acceptors. **[6]**

c) A semiconductor at 300K with a band gap of 1.05eV with effective density of states $N_C = 10^{23}$ and $N_V = 2 \times 10^{22}$ is doped with $N_A = 5 \times 10^{20} m^{-3}$ and $N_D = 2 \times 10^{21} m^{-3}$. Calculate the intrinsic Fermi Level and the actual Fermi level. **[7]**

6 In the free electron model,

(a) How many states *N* are there up to wave vector, *k*, in volume *V* stating your assumptions and sketching the states in K space. **[4]**

(b) Now show that the *density of states, N(E)* is: **[4]**

$$N(E) = \frac{V(2m)^{3/2}}{2\pi^2\hbar^3} E^{1/2}$$

(c) Where *m* is the mass of the electron and $\hbar$ is Planck's constant. (Hint: express *N* in terms of *E)*. Sketch this function indicating on your diagram the Fermi energy and the occupancy of states, particularly at 0 Kelvin and at a finite temperature. **[4]**

(d) Write down an integral which will determine the total energy of a system of electrons in terms of the Fermi-Dirac probability of state occupancy, the energy of the state and the density of states. Justifying your approximations by sketching *f(E) at room temperature*, show that the average energy of a electron will be 3/5 of the Fermi energy. **[4]**

(e) Calculate the Fermi energy, E_f, at OK for monovalent silver (atomic weight = 107.87, density 10490 kg m^{-3}). Determine the density of states at E_F for a specimen of volume 1 cm^{-3} **[4]**

THE END