The University Of Sheffield.

DEPARTMENT OF PHYSICS & ASTRONOMY

Spring Semester 2006-2007

PHYSICS OF SEMICONDUCTORS **2 Hours**

Answer THREE questions including at least ONE from each section.

Answers to different sections must be written in separate books, the books tied together and handed in as one.

A formula sheet and table of physical constants is attached to this paper.

All questions are marked out of ten. The breakdown on the right-hand side of the paper is meant as a guide to the marks that can be obtained from each part.

SECTION A

1 (a) Sketch a schematic energy band diagram for an abrupt p-n junction (step junction) in the absence of an externally applied voltage. Your diagram should show clearly the positions of the conduction and valence bands, the impurity energy levels, the Fermi level, the free carriers and the depletion region. [1]

(b) An abrupt p-n junction is doped with N_D donors and N_A acceptors per unit volume and is maintained under equilibrium conditions.

(i) Show that the width of the depletion region in the n-type material (x_d) is given by

$$x_d = \sqrt{\frac{2\varepsilon V_{bi} N_A}{eN_D(N_A + N_D)}} ,$$

where ε is the permittivity of the semiconductor, e is the electronic charge and V_{bi} is the built-in voltage. [3]

(ii) Show that the maximum electric field is given by

$$E = -\frac{eN_D}{\varepsilon} x_d \ .$$

[1]

(c) Explain how the above equations can be modified to predict the variation of the depletion region width when an external bias voltage is applied and sketch schematic energy band diagrams for an abrupt p-n junction under conditions of

(i) forward bias voltage;

(ii) reverse bias voltage. [2]

(d) Explain two possible physical mechanisms which may account for the reverse bias behaviour observed for a real p-n junction. [2]

(e) Two p-n junctions are found to have reverse breakdown voltages of 80 V and 4 V. Explain, with reasons, which junction has the higher doping level. [1]

2 (a) Explain the meanings of the terms *active region* and *internal quantum efficiency*, η_i, of an opto-electronic device. Also explain why η_i might have a value less than unity. [2]

(b) If G_{gen} is the rate at which carriers are generated per unit volume in the active region of a semiconductor device, show that

$$G_{gen} = \frac{\eta_i I}{eV} ,$$

where I is the current flowing into the terminals of the device, V is the volume of the device active region and e is the electronic charge. [1]

(c) Show that the radiative efficiency, η_r, of a light emitting diode can be written as

$$\eta_r = \frac{R_{sp}}{R_{sp} + R_{nr} + R_l} ,$$

where R_{sp}, R_{nr} and R_l are the spontaneous emission, non-radiative and carrier leakage rates, respectively. Explain using diagrams where appropriate, the physical origin of each of these three terms. [2]

(d) Which of the three recombination rates, R_{sp}, R_{nr} and R_l, would you expect to be different for an indirect compared to a direct band gap semiconductor? Hence explain why efficient light emitting diodes are usually fabricated from direct band gap semiconductors, giving an example of such a semiconductor. [2]

(e) A light emitting diode, emitting light at a wavelength of 650 nm, generates an optical power within the device of 5 mW when driven with a current of 10 mA. If the device has $\eta_i = 0.6$ and an active region volume 5×10^{-12} m^3, calculate:

(i) the radiative efficiency;

(ii) the spontaneous recombination rate;

(iii) the non-radiative recombination rate. [3]

You may assume that the carrier leakage rate is zero.

3 (a) Describe, using appropriate diagrams, how the variation of applied voltage between two of the terminals controls the current flow into the third terminal for the following devices:

(i) a bipolar n-p-n transistor; [2]

(ii) a junction field effect transistor. [2]

(b) By considering the current flowing into the base and collector in a bipolar transistor, show that the current gain (β) is given by

$$\beta = \frac{\alpha}{1-\alpha} \ ,$$

where α is the base transport factor. [2]

(c) Explain why the input resistances of a bipolar n-p-n transistor and a junction field effect transistor are different and state which one typically has the larger input resistance. [2]

(d) A bipolar transistor has a current gain of 100 and a field effect transistor has a gate current of 1×10^{-9} A. Calculate the ratio of the input resistances of the two devices when a collector current of 50 mA flows in the bipolar transistor. You may assume equal input voltages for the two transistors. [2]

SECTION B

4 (a) Describe crystal growth techniques which are commonly used to produce

(i) semiconductor quantum wires; [2]

(ii) semiconductor quantum dots. [2]

(b) Derive an expression for the electronic density of states as a function of energy in a quantum wire. [1.5]

(c) Calculate the density of states lying between the threshold and $2kT$ above it in a quantum wire at temperature $T = 300\text{K}$ made from a semiconductor with electron effective mass 0.12 m_e. Here m_e is the electron mass and k Boltzmann's constant. If all these electrons have mobility 1.3 $\text{m}^2\,\text{V}^{-1}\,\text{s}^{-1}$, what is the electrical resistance of the wire? [2]

(d) With the aid of a sketch, compare and contrast the density of states in a quantum wire and a quantum dot over an energy range includes the first two thresholds. [1]

(e) What are the advantages of quantum dots for making solid state lasers? [1.5]

5 (a) Describe the principles of modulation doping. Explain how this technique produces a two dimensional electron gas, and why the electron mobility may be much greater than in a conventionally doped semiconductor. Explain why it is necessary to go to a particular temperature region to see these high mobilities. [5]

(b) Derive an expression for the cyclotron frequency and explain why high mobilities are needed to observe the effects of quantum confinement under a magnetic field. What is the cyclotron frequency for an electron of effective mass 0.08 m_e in a 0.92 T magnetic field, where m_e is the electron mass? If the mobility is 900 $\text{m}^2\,\text{V}^{-1}\,\text{s}^{-1}$, how many orbits are made between scattering events? [2.5]

(c) Discuss what happens to the density of states of a two-dimensional system under a magnetic field and derive an expression for the Landau degeneracy, showing that it is independent of the effective mass. What electron density does one Landau level contain in a 0.92 T magnetic field? [2.5]

6 (a) A quantum well is formed by the sequential deposition of two lattice matched semiconductors A and B with band gaps E_A and E_B, where $E_B < E_A$.

(i) In which material is the well formed? [0.5]

(ii) Sketch the spatial variation of gap through the sample. [0.5]

(iii) If the depth of the well for holes is E_h, how deep is the electron well? [0.5]

(b) With the notation that the ***z*** direction is perpendicular to the well layer, write down an expression for the wavefunction of an electron in terms of the components of its wavevector ***k***. Derive an expression for the total energy in terms of these components in a well thickness *d*, explaining the physical significance of the two types of terms for the energy spectrum. [2.5]

(c) What is the ground state energy of an electron in an infinite well if the effective electron mass is 0.070 times the mass of the free electron? If the well is 0.350 eV deep, what is the electron ionisation energy? Is this an upper or lower limit to a more realistic calculation? Explain your answer. [1.5]

(d) By considering the behaviour of a series of samples each containing a pair of wells identical to that of part (c) above, their centres separated by a distance L, sketch the qualitative behaviour of this ionisation energy as L get smaller. What is the numerical value of the energy when $L = d$? [2]

(e) Supposing the single well of part (c) has a second energy level just below the top of the well and is used as an infra-red detector,

(i) what is the longest wavelength photon detectable; [0.5]

(ii) what is the role of the excited state; [0.5]

(iii) why should we apply an electric field and in which direction; and [0.5]

(iv) why are wells like this useful as infra-red detectors? [1]

END OF QUESTION PAPER