ENGINEERING TRIPOS PART IIB

Thursday 6 May 2010 2.30 to 4

Module 4B5

NANOTECHNOLOGY

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *number of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering data book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the invigilator

1 (a) Define Nanotechnology. Why has there been such a high level of interest in the field? [15%]

(b) The physical properties of nanostructures are different to those of the bulk. Explain this statement with the aid of two examples. [35%]

(c) Discuss how Nanotechnology has already become part of our everyday lives. [30%]

(d) What was the breakthrough that gave rise to the field of Nanotechnology? Why did it have such an impact? [20%]

2 Electrons at an energy E are incident from the left on the one-dimensional potential step of height V (where $E > V$), as shown below in Fig. 1.

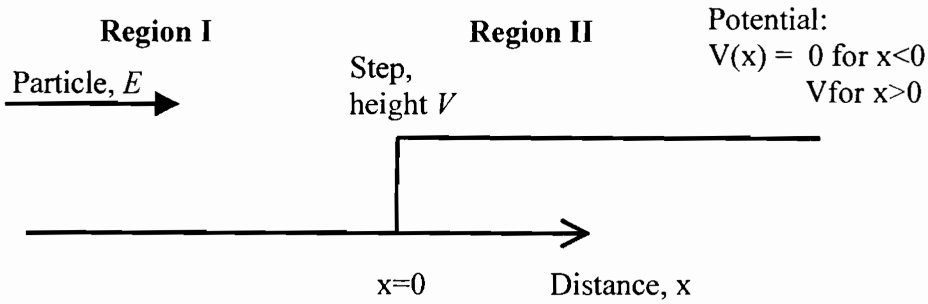

Fig. 1

(a) Derive an expression for the probability flux in quantum mechanics, and hence, or otherwise, derive an expression for the transmission probability, T for this potential step, clearly stating any assumptions/approximations made. Explain how to interpret T for the case of a single electron incident on the step. If we were to assume the electron is represented by a wave-packet, how would that change things? [60%]

(b) For the case of a beam of electrons where $E = 1$ eV and $V = 0.5$ eV, calculate T. Sketch the wave-functions and the probability densities in regions I & II. [20%]

(c) Now consider the case where E = 0.5 eV, V =1 eV and the electron is represented as a wave-packet. Describe the evolution of the electron and its wave-packet before, during and after encountering the step. [20%]

3 (a) Describe the impact of the Pauli exclusion principle on the electron energy levels of atoms that are brought into close proximity of each other. [20%]

(b) State the main assumptions used in the free electron model, and how we have to modify these for the case of the nearly-free electron model. For an atomic potential of the form $V(x) = V_0 + V_1 e^{iG_1 x} + V_{-1} e^{iG_{-1} x}$ where $G_n = 2\pi n/a$ are the reciprocal lattice vectors, show that

$$\left(\frac{\hbar^2 k^2}{2m} + E - V_0\right)\left(\frac{\hbar^2 (k + G_{-1})^2}{2m} + E - V_0\right) = V_1 V_{-1} = |V_1|^2$$

where E is the electron energy. [50%]

(c) Sketch the dispersion relationship (E *vs* k) for a nearly-free electron, in the reduced-zone scheme, clearly labelling the salient features. Derive the energy for electrons at the valence- and conduction-band edges, and sketch their wave-functions. Do these electrons contribute to electrical conduction? [30%]

4 (a) In conventional optical microscopy, what is the minimum feature size that can be resolved? What is the Rayleigh criterion? Briefly describe how this limit to resolution can be overcome. [20%]

(b) Describe the basic principle of operation of Scanning-Probe Microscopes. [20%]

(c) Sketch the configuration of an atomic force microscope (AFM), and describe the three most commonly used modes in which it can operate. [30%]

(d) We would like to obtain a high-resolution (~ 1 nm) map of the electric potential across a working electronic device, which is made of metal. Discuss how to use an AFM for this purpose, and the measurement principle.

[30%]

5 (a) Consider a potential step from 2 eV down to 1 eV, which is produced in a semiconductor heterostructure. For the ideal case at zero Kelvin, and where there are no defects present in the semiconductor materials, sketch the kinetic energy versus position of an electron at 3 eV that is incident from the left hand side. After the electron has passed the first interface what term can we use to describe it? [20%]

(b) Assuming now that band-bending can occur in the heterostructure, show how a 2-dimensional electron gas (2DEG) arises. Discuss the differences between 3-D and 2-D in quantum systems. [40%]

(c) What property of the 2-dimensional electron gas (2DEG) makes it so desirable from a device standpoint? How would you actually incorporate a 2DEG in a device to improve its operation? [30%]

(d) Briefly comment on the practical applications of semiconductor heterostructures in everyday devices

[10%]

END OF PAPER

4B5 2010 short answers

2. (a) $j = |\psi|^2 \frac{\hbar k}{m}$ is the probability flux

(b) T = 0.97