ENGINEERING TRIPOS PART IIB

Mon 23rd April 2007 9 to 10:30

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

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1 (a) Define the term "Nanotechnology". With reference to the relevant length-scales, discuss why the physical properties of objects differ from their bulk values once the object's dimensions are on the nanometre (nm) scale. [30%]

(b) Briefly discuss, with appropriate examples, the relevance of quantum mechanics to nanotechnology. [20%]

(c) In quantum mechanics, what is the physical significance of the wave-function, ψ of a system? [10%]

(d) Fig. 1, parts (i)-(iv), illustrates a time sequence of the interaction of an electron beam with a double-barrier structure, where the beam energy, E is indicated. The beam is incident from the left. Discuss how the wave-function describing the electrons evolves during this sequence. If the units along the x-axis are Angstroms, what is the approximate energy of the electron beam, assuming the electron mass is constant throughout the structure and equal to the free electron mass? [40%]

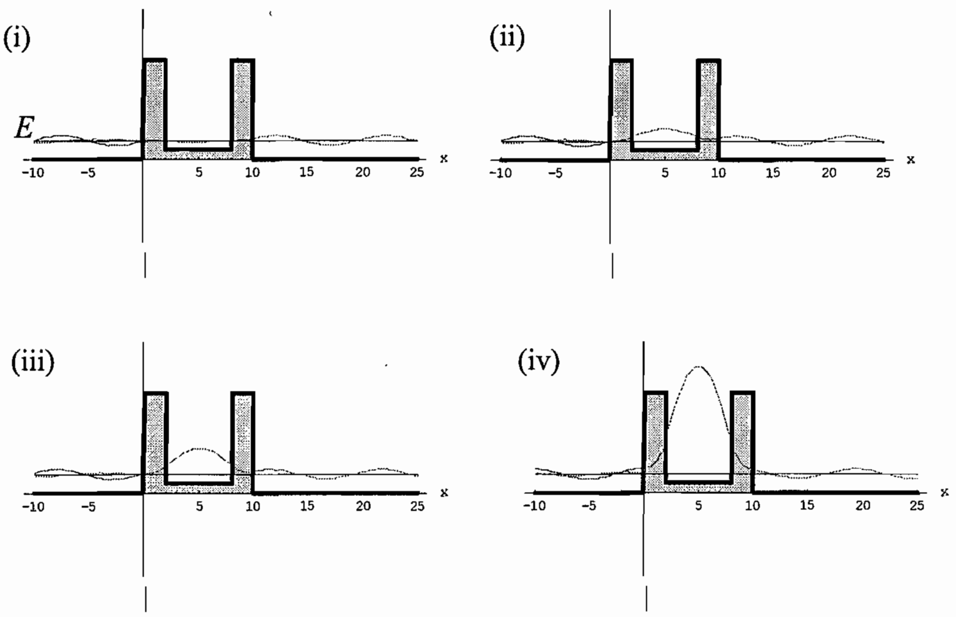

Fig. 1

2 (a) The band-gap of GaAs is 1.43 eV, and of $Ga_{1-x}Al_xAs$ is (1.424 + 1.247x) eV. For the case of 40% substitution of Al atoms for Ga atoms, sketch the potential as seen by an electron in a 15 nm wide quantum well formed using these materials, indicating which material is used, and where. [20%]

(b) Assuming that the electron effective mass in both materials is 0.067 times the free-electron mass, estimate the energy of the ground state in the well. Which assumptions were used in arriving at this estimate, and at which point would they start to break down? [50%]

(c) Sketch the wave-function and the probability density for an electron in the ground state of this quantum well. Determine the value of the characteristic decay length of the electron outside the well, using the above estimate for the electron energy. [30%]

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3 (a) Describe, in detail, what happens to the electrical resistivity of a metallic wire as its dimensions decrease from 100 nm down to a single atom, with reference to surface specularity, mean grain size and electronic mean free path. [45%]

(b) Describe the principle of operation of the single-electron transistor (SET), with sketches of the principal components and the current-voltage characteristics. Estimate the capacitance and hence the electrostatic charging energy of a SET capacitor which consists of a metal sphere of diameter 2 nm on a SiO_2 substrate which has a relative permittivity of 3.7. Determine whether this will exhibit SET-like characteristics at room temperature. [45%]

(c) Briefly discuss the applications of SETs. [10%]

4 (a) Write down the Schrödinger equation for a quantum simple harmonic oscillator (QSHO) of stiffness k. By assuming a power-series solution to this equation, derive an expression for the energy levels of the oscillator. [50%]

(b) For the case of a molecule where $k = 10^2$ N.m^{-1} and the mass of the molecule is 10^{-26} kg, determine the ground state vibration energy of this molecule in eV. [30%]

(c) Under which circumstances do the quantum and classical descriptions of the simple harmonic oscillator converge? [20%]

5 (a) There are a wide range of techniques now available which may be used to obtain high-resolution images of nanostructures. Briefly discuss the reasons why one might choose to use a scanning-probe technique as opposed to optical or electron microscopy. [20%]

(b) Describe the principle of operation of the scanning tunneling microscope (STM), with particular reference to the shape of the electrostatic potential as seen by an electron, the type of information one may obtain using an STM, and any considerations which should be taken into account when designing an STM. [30%]

(c) What is the dependence of tunnel current on electrode separation? Consider the case of tunneling between two gold electrodes with a work-function of 4.5 eV, separated by 0.8 nm. By how much will the tunnel current change if the tip-sample separation decreases to 0.6 nm? What is the value of the characteristic decay length of the tunnel current? [40%]

(d) Comment on the origin of surface states of a semiconductor, and how they may be probed using STM. [10%]

END OF PAPER

Solutions to paper 4B5 – Nanotechnology. 2007

Short answers:

2(a) well is 0.499 eV deep.
 (b) Ground state energy = 0.025 eV.
 (c) 1.085 nm

3 (b) 0.82×10^{-18} F. 0.097 eV charging energy.

4(b) 0.033 eV.

5(c) factor of 78. Decay length = 0.45 Angstroms.