Version CD/4

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 3 May 2017 9:30 to 11

Module 4B5

NANOTECHNOLOGY

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

All questions carry the same number of marks.

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

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper.

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

1 (a) There are some situations in quantum mechanics where it is appropriate to describe electrons as plane waves, and others where we should use wave-packets. Discuss the circumstances under which each of these approaches should be applied, with particular consideration to the differences between the properties of plane waves and wave-packets. [20%]

(b) Describe the differences in properties between the wave-packets used to represent electromagnetic waves and matter. [20%]

(c) Consider a simple transistor with a gate length of 32 nm and where the current flow through it is driven by a potential difference of 1.5V. Calculate the wavelength of the electrons assuming they have an effective mass of 0.2 times the free electron mass. Discuss whether you expect quantum effects to be observable at room temperature in this transistor, and how they might be manifested. As the transistor is reduced in size in all dimensions, discuss how the electrical properties should evolve. [60%]

2 (a) The band-gap of GaAs is 1.45 eV, and that of $Ga_{1-x}Al_xAs$ is (1.424 + 1.247x) eV. For the case of 70% substitution of Al atoms for Ga atoms, sketch the electrostatic potential as seen by an electron in a 25 nm wide quantum well formed using these materials, indicating which material is used and where. Assume that the change in band-gap is shared equally between the conduction and valence bands. [20%]

(b) Assuming that the electron and hole effective masses are 0.067 and 0.45 times the free electron mass, respectively, estimate the energy of the ground state of electrons and holes in the well, and the transition energy between the two, clearly stating any assumptions made. [50%]

(c) Assuming that there are two bound states for both electrons and holes in the well, sketch the expected optical absorption spectrum, and briefly describe the origin of any peaks present. [30%]

3 (a) The atoms in a material are held together by bonds that, for small displacements can be thought of as springs with stiffness 500 N/m. By considering this as a quantum harmonic oscillator and solving the relevant Schrödinger equation, calculate the lowest vibrational energy level (the ground state), assuming an atomic mass of $1.99\text{x}10^{-26}$ kg. Clearly indicate the steps taken and briefly discuss any assumptions made. [80%]

(b) Sketch the form of the probability density of the wavefunction associated with the ground state and comment on the discrepancy between it and the classically expected behaviour. [20%]

4 (a) Consider a semiconductor heterostructure designed to have a potential step down as seen by electrons as they travel across the junction and fabricated using two materials which have a difference in conduction band energy of 0.25 eV. Sketch the potential as a function of position across the interface before and after considering band-bending, clearly indicating any salient features. [30%]

(b) Consider the flow of electrons across this junction and discuss, with the aid of a qualitative sketch what the current-voltage characteristics should be like, for the cases of no band-bending and band-bending. [30%]

(c) What property of a 2-Dimensional Electron Gas (2DEG) is desirable from a device standpoint? Discuss how you would design a device with a 2DEG. [40%]

5 (a) State the Rayleigh criterion, and then using it, calculate the minimum separation between two point objects that can be resolved using light of wavelength 500 nm. [20%]

(b) Describe the principle of operation of the Scanning Tunneling Microscope (STM), taking into account the sensitivity, mechanical design, resolution and the nature of the tunnelling current. As part of your answer, include a sketch showing the basic design of an STM. [60%]

(c) Sketch the electrical potential as seen by an electron as it flows from an STM tip into a metal sample via a tunnel gap of 1 nm. [20%]

END OF PAPER

Short answers

1(c) 2.23 nm

2(b) 8.9 meV, 1.33 meV

3(a) 0.988 eV