ENGINEERING TRIPOS PART IIA

Friday 9 May 2008 2.30 to 4

Module 3B5

SEMICONDUCTOR ENGINEERING

*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.*

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) An electron beam, accelerated through a certain potential, is directed onto a crystal, as shown in Fig.1. The angle between the beam direction and the normal to the atomic planes of the crystal is α. The separation between the crystal planes is d.

(i) By considering the phase difference between beam 1 and beam 2 of Fig. 1, deduce the Bragg diffraction law. [20%]

(ii) The angle α is fixed at 40° and the accelerating potential V is increased from 0 V to +100 V, while the electrical current associated with the diffracted beam is measured. The detected current shows the first maximum for V = 16 V. Calculate the separation d between the crystal planes. [30%]

(b) (i) Find the solution to the time-independent Schroedinger Wave Equation for a particle in the one-dimensional potential well of Fig. 2, for the case where $E << V_0$, that is when the depth of the well can be considered infinite. Deduce the formula for the energy levels of the system. State all assumptions and determine all integration constants. [30%]

(ii) Sketch the wavefunctions corresponding to the two lowest values of the energy. [20%]

NOTE: The time-independent Schroedinger Wave Equation is given by

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E - V)\psi = 0 .$$

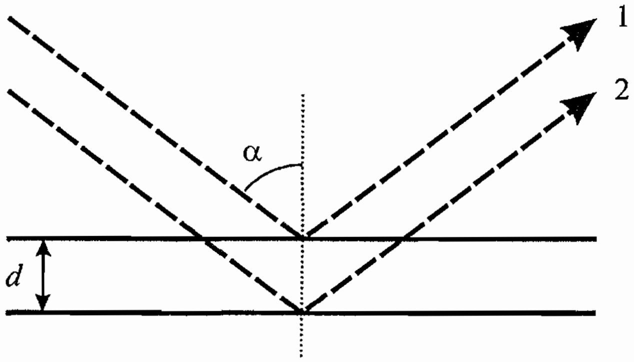

Fig. 1

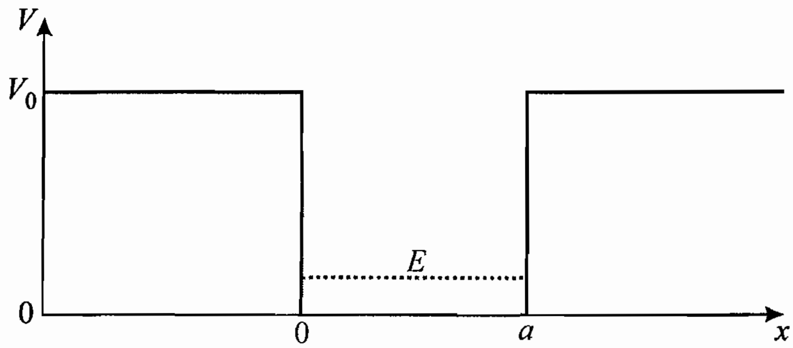

Fig. 2

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2 (a) (i) Explain how the conductivity of silicon can be changed by doping the crystal with donor and acceptor impurities. Illustrate your answer by discussing the behaviour of electrons and holes at 0 K and 300 K.

(ii) Explain how one can practically dope GaAs with donor and acceptor impurities. [40%]

(b) The density of states in the conduction band of a semiconductor is given by

$$g(E) = \frac{4\pi}{h^3}\left(2m^*\right)^{3/2}\left(E - E_C\right)^{1/2}.$$

Show that the following relationship holds for any semiconductor where $E_C - E_F >> kT$:

$$n = N_C \exp\left(\frac{E_F - E_C}{kT}\right),$$

where

$$N_C = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}.$$ [40%]

(c) Calculate $E_C - E_F$ in silicon at room temperature when the crystal is doped with a density of phosphorous atoms $N_D = 1 \times 10^{16}\ \text{cm}^{-3}$ and $N_D >> N_A$. Assume all donors are ionised. [20%]

NOTE: For silicon at room temperature, the effective density of states in the conduction band $N_C = 2.8 \times 10^{19}\ \text{cm}^{-3}$. Also,

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \quad ; \quad \int_0^\infty x^{1/2} \exp(-x) = \frac{\sqrt{\pi}}{2}.$$

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3 (a) Explain how the current between the source and drain contacts in a metal-semiconductor field effect transistor (MESFET) is modulated by the gate contact. Include a schematic diagram of a MESFET that uses n-type GaAs for the channel to illustrate your answer. Sketch how the drain-source current would vary with drain-source voltage for a number of different gate-source voltages. [35%]

(b) The n-type GaAs used in the channel of the MESFET has been doped with a donor density of $2\times10^{22}\ \mathrm{m}^{-3}$. GaAs has a band gap of 1.43 eV, an electron affinity of 4.07 eV and an effective density of states in the conduction band of $4.7\times10^{23}\ \mathrm{m}^{-3}$. Hence, show by calculation that the work function of this n-type GaAs at room temperature (298 K) is 4.15 eV, stating any assumptions that you make. [20%]

(c) Gold has a work function of 4.70 eV and aluminium has a work function of 4.10 eV. Draw band diagrams for the junctions that would be formed between the n-type GaAs described in part (b) and each of these metals. Hence, explain which metal should be used for each of the source, drain and gate contacts. [30%]

(d) Carefully explain the relative advantages and disadvantages of a MESFET that uses GaAs for the channel as opposed to one that uses Si. [15%]

4 (a) A p-n junction diode is fabricated from silicon. Starting from expressions for the free electron and hole carrier densities (n and p respectively) in a semiconductor whose band gap is E_C (where $E_V = 0$) and whose Fermi Energy is E_F, show that the contact potential V_0 is given by

$$V_0 = \frac{kT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right),$$

where N_A and N_D are the doping densities in the p- and n-type regions respectively and n_i is the intrinsic carrier concentration. State any assumptions that you make. [30%]

(b) If N_A is $5\times10^{22}\ \mathrm{m^{-3}}$ and N_D is $5\times10^{20}\ \mathrm{m^{-3}}$, show that the depletion width w across the p-n junction may be derived from the Gauss Law of Electrostatics to be

$$w = \left(\frac{2\varepsilon_0 \varepsilon_r V_0}{e N_D}\right)^{1/2},$$

where ε_r is the relative permittivity of the n-type semiconductor. [40%]

(c) Calculate the capacitance per unit area of this p-n junction diode at room temperature (298 K) if the relative permittivity of silicon is 11.8 and the intrinsic carrier concentration is $1.5\times10^{16}\ \mathrm{m^{-3}}$. [30%]

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