EGT2
ENGINEERING TRIPOS PART IIA

Monday 8 May 2017   2 to 3.30

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.*

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 one-dimensional solid of total length L consists of a line of atoms which are all of the same element. The centre-to-centre distance between any two neighbouring atoms is a where $a << L$. The resulting E-k diagram for electrons in this solid covering the first two Brillouin Zones is shown in Fig. 1. The group velocity and effective mass of an electron in any state is given by the equations

$$v = \frac{1}{\hbar}\frac{\partial E}{\partial k} \text{ and } m^* = \frac{\hbar^2}{\partial^2 E / \partial k^2}$$

The total number of electrons in the solid is equal to the total number of electron states in the First Brillouin Zone.

(a) (i) Why there are forbidden electron states when $k = n\pi/a$, where n is an integer? [10%]

(ii) Explain why there are energy gaps in the E-k diagram and why they occur around the forbidden states. [15%]

(b) Draw graphs covering the first two Brillouin Zones showing how the following properties of the electrons in this solid depend on k:

(i) The velocity v. [10%]

(ii) The effective mass m^*. [15%]

(c) A state in the valence band of the solid is unoccupied due to the excitation of an electron into the conduction band. The group velocity of the electron in that state before excitation is v_e and its effective mass is m_e^*.

(i) Explain how the concept of holes can be used to consider the occupation of the valence band states. [15%]

(ii) Derive an expression showing how the group velocity of the hole that is associated with the unoccupied electron state v_h is related to v_e. [15%]

(iii) Derive an expression showing how the effective mass of the hole that is associated with the unoccupied electron state m_h^* is related to m_e^*. [5%]

(iv) Is the effective mass of electrons at the bottom of the conduction band greater or less than the effective mass of holes at the top of the valence band? Justify your answer. [15%]

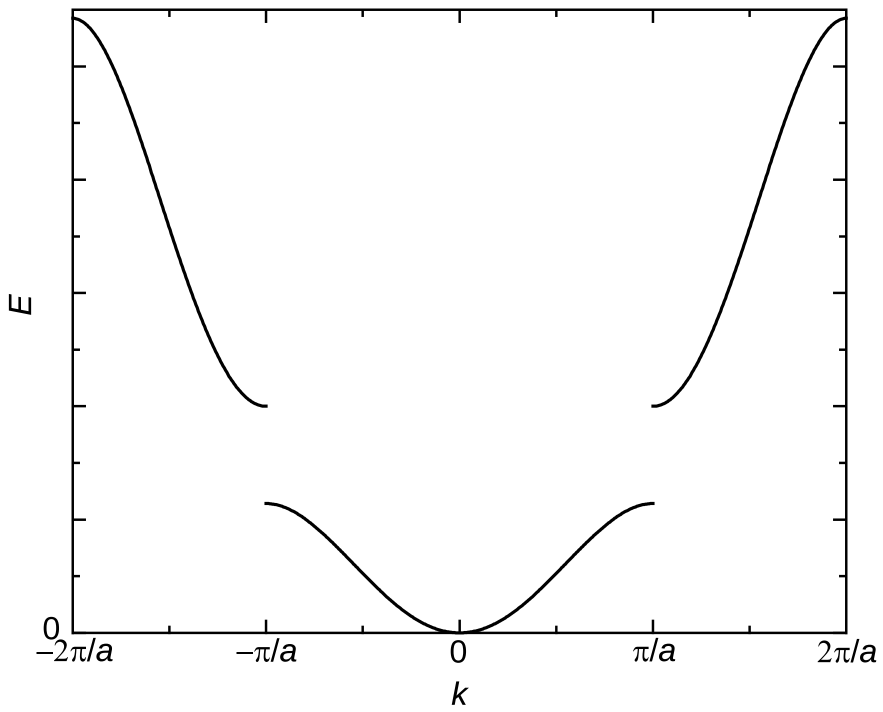

Fig. 1

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2 (a) What is the experimental evidence for each of the following postulates of quantum mechanics?

(i) The *Einstein postulate* that $E = h\nu$. [10%]

(ii) The *de Broglie postulate* that $\lambda = h/p$. [10%]

(b) The wavefunction of a free particle moving in a one-dimensional space is

$$\psi(x,t) = A\exp[\mathrm{j}(kx - \omega t)]$$

where $\mathrm{j} = \sqrt{-1}$ and other symbols have their usual meaning. Show, by substitution of this wavefunction, that the one-dimensional Schrödinger Equation is consistent with the conservation of energy. The one-dimensional Schrödinger Equation is

$$\frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\{\psi(x,t)\} + V(x,t)\{\psi(x,t)\} = j\hbar\frac{\partial}{\partial t}\{\psi(x,t)\}$$ [25%]

(c) A particle exists in an infinitely-deep, one dimensional potential well of width L which is time-independent. The potential well is given by

$$V(x) = \begin{cases} 0 & \text{for } 0 \le x \le L \\ \infty & \text{for } x < 0 \text{ and } x > L \end{cases}$$

(i) Show that the time-independent wavefunction of the particle is

$$\Psi(x) = \left(\frac{2}{L}\right)^{1/2} \sin\left(\frac{n\pi x}{L}\right)$$ [30%]

(ii) Calculate the ground state energy of the particle if the width of the well $L = 5\,\text{nm}$. [25%]

3 (a) Sketch equilibrium band diagrams for each of the following junction and device structures:

(i) A junction between a metal with a work function of 4.2 eV and another metal with a work function of 5 eV. [10%]

(ii) A junction between p^+-doped AlGaAs and n-doped GaAs. The GaAs has a bandgap of 1.4 eV and an electron affinity of 4.07 eV. The AlGaAs has a bandgap of 1.9 eV and an electron affinity of 3.6 eV. State what assumptions you make about the position of the Fermi energy level in each material. [15%]

(iii) A junction is formed by depositing a metal with a work function of 4.2 eV onto Ge with a band gap of 0.67 eV and which is doped with a density of 10^{21} m^{-3} of boron atoms. Assume Ge has an electron affinity of 4.0 eV, and effective densities of states in the conduction band and valence bands of $N_C = 1\times10^{25}$ m^{-3} and $N_V = 6\times10^{24}$ m^{-3} respectively. Assume no interface traps and room temperature (300 K) conditions. State all other assumptions. [20%]

(b) A hypothetical semiconductor has an intrinsic carrier concentration of 1×10^{16} m^{-3} at room temperature (300K) and its effective densities of states in the conduction and valence band N_C and N_V both are equal to 10^{25} m^{-3}. The semiconductor is now doped with donor impurities at a concentration of $N_D = 10^{24}$ m^{-3}.

(i) Calculate the band gap of the semiconductor. [15%]

(ii) Calculate the equilibrium electron and hole concentrations at room temperature. [10%]

(iii) The semiconductor is illuminated with a short laser pulse, where the photon energy is higher than the band gap of the semiconductor. What are the induced changes in the electron and hole concentrations? Explain and sketch how the carrier distribution will change with time after the laser exposure. [20%]

(iv) The semiconductor is additionally doped with acceptor impurities at a concentration of $N_A = 2\times10^{24}$ m^{-3}. Calculate the new equilibrium electron and hole concentrations at room temperature. [10%]

4 Figure 2 shows the capacitance-voltage (C-V) characteristics of an ideal metal-oxide-semiconductor (MOS) capacitor with an area A. The bias is applied to the metal with respect to the semiconductor. The semiconductor is silicon (which has an intrinsic carrier concentration of 1.5×10^{16} m^{-3}) with a doping impurity concentration of 5×10^{22} m^{-3}. The dielectric has a thickness t_{ox} and a relative permittivity ε_{rox}. The temperature is 300 K.

(a) Give an expression for C_{max} and explain what happens at the so-called threshold voltage V_T. Explain what is meant by the term *strong inversion* and state if an n-type or p-type semiconductor is used here. [20%]

(b) Sketch the distribution of charge per unit area σ and electric field across the MOS capacitor for the condition where the applied voltage is V_T. Give an expression for how the electric field in the dielectric depends on the charge per unit area. [15%]

(c) Estimate the time it will take for strong inversion to occur if the scattering velocity of carriers in the semiconductor is 10^5 m s^{-1}. You should assume that the device is ideal. Based on your knowledge, you should choose a typical value for the depth over which inversion might occur. State any other assumptions made. [35%]

(d) Sketch the expected change in the C-V curve for the case where the bias voltage applied to the MOS capacitor is varied much more quickly than the time calculated in part (c). [10%]

(e) Give an expression for how V_T depends on t_{ox} if the charge per unit area in the metal at this voltage is $-\sigma_T$. Explain what other oxide characteristics can be used to control V_T. [10%]

(f) The MOS capacitor is used to fabricate an enhancement *Metal Oxide Semiconductor Field Effect Transistor* (MOSFET). Explain if the so-called subthreshold slope would increase, decrease or remain unchanged if t_{ox} is decreased. [10%]

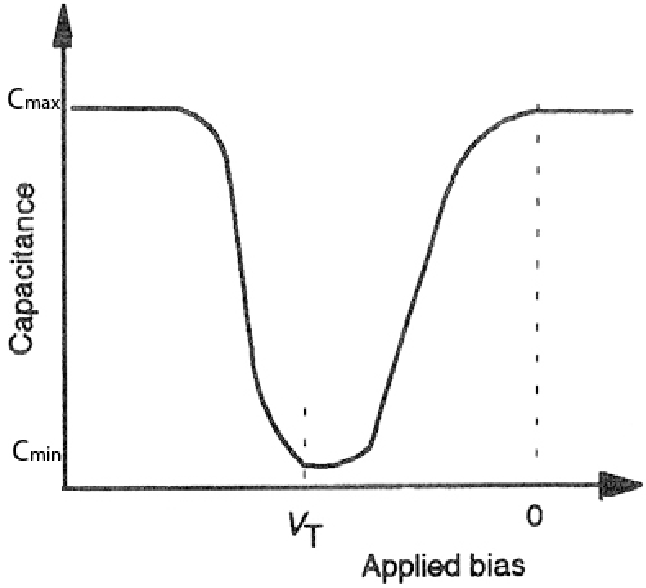

Fig. 2

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