ENGINEERING TRIPOS   PART IIA

Tuesday 5 May 2009   9 to 10.30

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.*

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) Starting from the expression for the wave-function of a particle of momentum p, deduce the one-dimensional time-independent Schrodinger's Equation;

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

[30%]

(b) Find $\psi(x)$ for $-\infty < x < +\infty$ for the following potential energy function:

$V(x) = 0$ for $-\infty < x < 0$
$V(x) = V_0$ for $0 < x < a$, with $V_0 > E$
$V(x) = 0$ $a < x < +\infty$ [20%]

(c) Without carrying out the calculations, explain how to determine the integration constants appearing in the expressions for $\psi(x)$. Assuming that these constants are real, sketch Re $[\psi(x)]$ for $-\infty < x < +\infty$, paying attention to the relative amplitudes of the wavefunction in the various regions. [10%]

(d) Explain what is meant by tunnelling, with reference to the spatial dependence of $\psi(x)$ in the above case. [10%]

(e) Discuss the effect of increasing the barrier width a and the barrier height V_0. Describe the principle of operation of the Scanning Tunnelling Microscope. [30%]

2 (a) Discuss the *quasi-free electron approximation* for a one-dimensional solid with lattice parameter a. In particular

(i) Identify the 1st and 2nd Brillouin Zones; [15%]

(ii) Show by a symmetry argument or otherwise that the wavefunctions at the zone boundaries are standing waves; [20%]

(iii) Explain the formation of energy gaps. [5%]

(b) Starting from the expression for the electron velocity v in one dimension, where:

$$v = \frac{\hbar k}{m}$$

and considering the energy gained by a particle under the action of a force F, show that the effective mass m^* can be expressed as:

$$m^* = \hbar^2 \left(\frac{d^2 E}{dk^2} \right)^{-1} .$$

[30%]

(c) Explain the physical interpretation of a negative effective mass, in the framework of the *quasi-free electron approximation.* [30%]

3 (a) Sketch the distribution of minority carriers either side of the depletion region in a p^+n junction diode for:

(i) a positive bias applied to the p-type region with respect to the n-type region;

(ii) a negative bias applied to the p-type region with respect to the n-type region. [20%]

(b) Starting from the Continuity equation, show that the excess hole concentration $p - p_{n0}$ varies on the n-type region of a p^+n junction as

$$p - p_{n0} = p_{n0}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]\exp\left(\frac{-x}{L_h}\right)$$

with distance x from the edge of the depletion region. p_{n0} is the equilibrium concentration of holes in the bulk of the n-type semiconductor, V is the applied bias, and $L_h = (D_h \tau_h)^{\frac{1}{2}}$ is the diffusion length of the holes. The injected minority carrier concentration at $x = 0$ is given by

$$p(x = 0) = p_{n0} \exp\left(\frac{eV}{kT}\right).$$

Assume there are negligible fields outside the depletion region and state any other assumptions made. [30%]

(c) The current for the p^+n junction diode is given by

$$I = Ae\left[\left(\frac{D_e}{L_e}\right)\frac{n_i^2}{N_A} + \left(\frac{D_h}{L_h}\right)\frac{n_i^2}{N_D}\right]\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

(cont.

where A is the cross-sectional area of the junction, D_e and L_e the diffusion coefficient and diffusion length, respectively, of electrons. N_A and N_D are the acceptor and donor doping densities on the p^+-side and n-side of the junction, respectively. The device serves as an emitter-base junction in a p^+np bipolar junction transistor (BJT), which is entirely fabricated from a semiconductor with intrinsic carrier concentration n_i. Show that the emitter injection efficiency of the BJT is given by

$$\gamma = \left[1 + \left(\frac{D_e}{D_h}\right)\left(\frac{W_b}{L_e}\right)\left(\frac{N_D}{N_A}\right)\right]^{-1}$$

where W_b is the undepleted width of the base. [30%]

(d) A major drawback of the BJT of part (c) is that, in order to gain a high γ, the doping density in the base is required to be much lower than in the emitter. This introduces an undesirably high base resistance. Explain how for a heterojunction bipolar transistor (HBT) this restriction can be overcome. Give a suggestion for a suitable choice of materials. [20%]

Note: The Continuity equation for holes is

$$\frac{\partial(\Delta p)}{\partial t} = -\frac{\Delta p}{\tau_h} - \mu_h \varepsilon \frac{\partial(\Delta p)}{\partial x} + D_h \frac{\partial^2(\Delta p)}{\partial x^2}.$$

(TURN OVER

4 (a) For a p-channel enhancement metal oxide semiconductor field effect transistor (MOSFET), explain what is meant by the pinch-off condition and sketch how the drain-source current varies with drain-source voltage for a number of different gate-source voltages. [15%]

(b) An n-type MOS capacitor has been fabricated from doped silicon (intrinsic carrier concentration of 1.5×10^{16} m^{-3}) with a donor concentration of $N_D = 5\times10^{22}$ m^{-3}. The temperature is 300 K.

(i) Calculate the potential V_{si} at the silicon-silicon oxide interface at which strong inversion begins. Indicate V_{si} in an energy band diagram. [30%]

(ii) For a scattering velocity of 10^5 m/s, estimate the time it will take for strong inversion to occur. Assume a typical value for the depth over which inversion might occur. [35%]

Assume that the device is ideal, with no difference between the work functions of the metal and the semiconductor. State any other assumptions made.

(c) Draw an energy band diagram for an unbiased n-type MOS capacitor fabricated from a semiconductor which has a larger work function than the metal. Write down the expression for the voltage that needs to be applied to the metal to achieve the flat band condition. Discuss what else is likely to contribute to this voltage in practice. [20%]

Note: For a semiconductor

$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

where E_F is the Fermi energy, E_i is the Fermi energy in an intrinsic material and other symbols have their usual meaning.

END OF PAPER

3B5 2009 P. Migliorato

Answers to numerical questions.

Q. 4 b) (i) $V_{si} = 0.78$ V; (ii) $\tau_{inv} = 0.56$s