ENGINEERING TRIPOS PART IIA

Tuesday 4 May 2010 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

Final Version

1 (a) The time-independent Schrödinger equation in one dimension is given by

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

Identify each of the terms in this equation and explain its overall physical significance. [20%]

(b) A particle exists in a one-dimensional, infinitely deep potential well where

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

(i) Show that the quantum mechanical wavefunction of the particle is given by

$$\psi = \left(\frac{2}{L}\right)^{1/2} \sin\left(\frac{n\pi x}{L}\right) ,$$

where n is a quantum number which takes integer values greater than 0. [40%]

(ii) Hence, derive an expression for the lowest possible energy that the particle can possess (i.e. when it is in the *ground state*). [20%]

(iii) Sketch the probability of finding the particle as a function of position for $0 \le x \le L$ for each of the two lowest energy states that the particle can exist in. Explain how this would be different if the particle was behaving classically. [20%]

2 Fig. 1 shows a schematic diagram of an experiment that would demonstrate the *Hall Effect* in a sample of silicon where a classical current, I, is flowing in the positive x-direction. The intrinsic carrier concentration of silicon is $10^{16}\ \mathrm{m}^{-3}$ and the mobility of holes and electrons is $0.048\ \mathrm{m}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$ and $0.14\ \mathrm{m}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$ respectively.

(a) Explain how the Hall Effect can be used to determine both the sign and density of the majority carriers in the semiconductor. [15%]

(b) Assuming that the current flows uniformly through the cross-section of the sample in the y-z plane, show that the measured voltage, V_H, identified in Fig.1 is given by

$$V_H = \frac{IB}{qt},$$

where B is the magnetic flux density and q is the charge density of majority carriers in the semiconductor. [35%]

(c) The semiconductor sample is silicon that has been doped with a number density of $10^{22}\ \mathrm{m}^{-3}$ of boron atoms. It has dimensions of w = 1 mm, t = 1 μm and l = 1 mm. What V_H is measured when I = 100 nA and B = 0.1 T? State any assumptions made. [20%]

(d) Calculate the total conductivity of the silicon sample and the ratio of the conductivity due to electrons with respect to holes. How would you expect your answers to change if the number density of boron atoms was increased to $10^{24}\ \mathrm{m}^{-3}$? [30%]

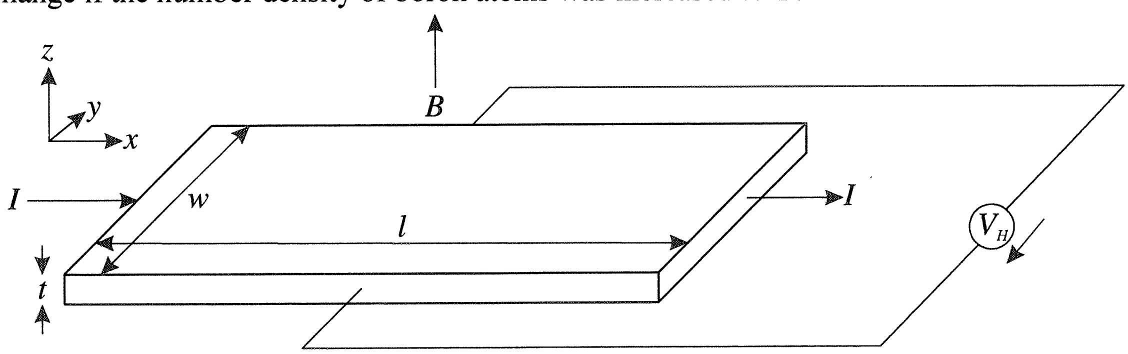

Fig. 1

3 (a) A Schottky barrier diode is fabricated from n-type silicon with a donor density of 8×10^{22} m^{-3} and a metal with a work function of 4.8 eV. The silicon has an electron affinity of 4.05 eV and an effective density of states in the conduction band of 2.8×10^{25} m^{-3}. Calculate the built-in potential, V_0, at room temperature (298 K) stating all assumptions made. Indicate eV_0 in an equilibrium band diagram of the diode. [30%]

(b) Calculate the barrier to electron flow from the metal to the n-type silicon and estimate the reverse saturation current of the diode at room temperature if the metal contact is circular with a radius of 0.2 mm. The Richardson-Dushman equation for thermionic emission is given by

$$J = AT^2 \exp\left(\frac{-e\phi_b}{kT}\right),$$

where A may be taken to be 1.2×10^{6} A m^{-2} K^{-2} for this junction. [20%]

(c) The same Schottky barrier diode is used as the gate contact for a MESFET, as shown schematically in Fig. 2. Starting from the Poisson equation, show that the pinch-off voltage, V_p, is given by

$$V_p = \frac{-h^2 e N_D}{2\varepsilon_0\varepsilon_r},$$

where ε_r is the relative permittivity of the n-type silicon. State all assumptions made. [35%]

(d) Explain what work function is required for the metal source and drain contacts of this MESFET. Why in practice is it beneficial to heavily dope the silicon for these contacts? [15%]

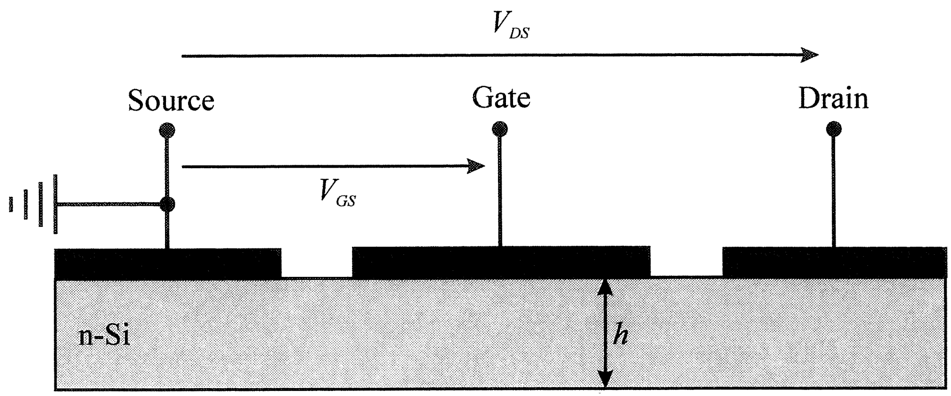

Fig. 2

4 (a) Explain what is meant by the terms *flat band condition*, *depletion* and *strong inversion* as applied to a p-channel, enhancement mode MOSFET using band diagrams where appropriate. [15%]

(b) Show that the drain-source current, I_{DS} , of the MOSFET can be expressed as

$$I_{DS} = \frac{-C_{ox}\mu_{hFE}W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right],$$

where μ_{hFE} is the field effect mobility of holes in the channel, C_{ox} is the capacitance per unit area of the gate oxide, W is the channel width and L is the channel length between the source and the drain. Use the fact that the free carrier density per unit area in the inverted region, Q_f , is given by

$$Q_f = -C_{ox}[V_{GS} - V_T - V(x)],$$

where V_{GS} is the gate-source voltage, V_T is the threshold voltage and $V(x)$ is the voltage induced in the channel by the drain-source voltage, V_{DS} . [35%]

(c) What is the maximum value of V_{DS} for which the above equation for the drain-source current in the MOSFET is valid? What has happened to the channel at this maximum V_{DS} ? [10%]

(d) Derive an expression for the small-signal mutual transconductance, g_m , in the saturated region. [25%]

(e) Explain how the analysis of g_m has to be modified for a short channel MOSFET. [15%]

END OF PAPER

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Module 3B5

SEMICONDUCTOR ENGINEERING – NUMERICAL SOLUTIONS

1 (b) (ii) $E = \frac{\hbar^2}{2m}\left(\frac{\pi}{L}\right)^2$

2 (c) 2.24 μV

(d) Total conductivity = 76.9 Ω^{-1} m^{-1} ; ratio of the electron conductivity to that of the holes is 2.9×10^{-12}.

3 (a) $V = 0.6$ V

(b) $e\phi_b = 0.75$ eV ; $I = 1.25$ nA

4 (c) I_{DS} is valid up to $V_{DS} = V_{GS} - V_T$.

(d) $$g_m = \frac{\partial I_{DS}(sat)}{\partial V_{GS}} = -\frac{C_{ox}\mu_{hFE}W}{L}(V_{GS} - V_T)$$