ENGINEERING TRIPOS PART IIA

Tuesday 8 May 2007 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) (i) Describe an experiment providing evidence for the wave nature of electrons. [10%]

(ii) Explain what is meant by *quantum mechanical tunnelling* and how this effect forms the basis for the operation of the scanning tunnelling microscope. [30%]

(iii) Calculate the wavelength of an electron, whose initial velocity is equal to 0, when accelerated through a potential of 100 V. [10%]

(b) Light of frequency f in the range $10^{14} - 10^{15}$ Hz is incident on the surface of a metal A. The extracted electrons are collected by applying a voltage V to the collecting electrode B. The voltage V can take positive or negative values with respect to the metal A. The apparatus is sketched in Fig. 1. The glass chamber is evacuated and the walls are completely reflecting for the electrons. For light of frequency less than 5×10^{14} Hz, no current is measured by the ammeter G, irrespective of the voltage applied. For higher frequencies, a current is measured for values of the voltage V greater than V_{min} which depends on the light frequency.

(i) Explain why no current is measured for light of frequency less than 5×10^{14} Hz. [10%]

(ii) Plot the kinetic energy of the emitted electrons as a function of the light frequency in the relevant range, and calculate the maximum and minimum value of the kinetic energy. [20%]

(iii) Derive the relationship between V_{min} and the light frequency. [20%]

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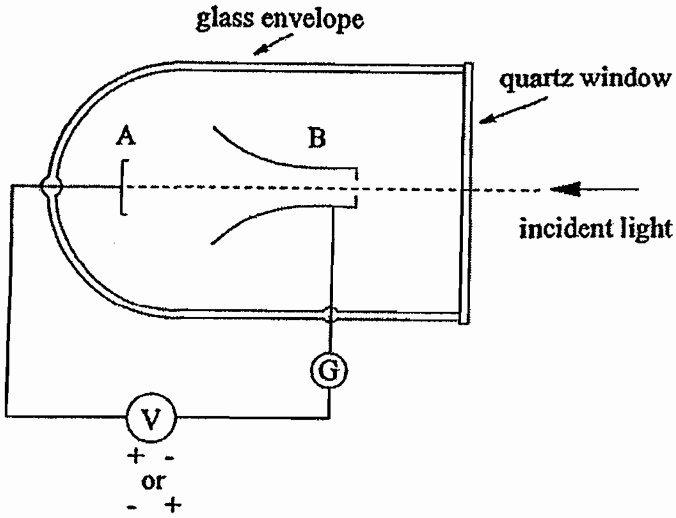

Fig. 1

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2 (a) The wavefunction of an electron in the 1s state of a hydrogen atom is given by

$$\psi(r) = A\exp(-ar),$$

where A is a normalization constant, r is the distance from the centre of the nucleus and $a = 1.8939\times10^{10}\ \mathrm{m}^{-1}$. The differential probability of finding the electron at a distance r from the nucleus is given by

$$dP = P(r)dr.$$

(i) Find the value of r for which $P(r)$ is a maximum. [25%]

(ii) Find the value of the normalization constant A. [25%]

(b) In an ionized hydrogen molecule H_2^+, a single electron is subject to the field of two protons at positions $\mathbf{r}_1$ and $\mathbf{r}_2$. The two lowest energy levels for the electrons are E_1 and E_2, where $E_1 < E_2$, and the corresponding wavefunctions are ψ_1 and ψ_2.

(i) By using a symmetry argument, derive the expressions for ψ_1 and ψ_2. [25%]

(ii) Sketch the electronic charge, corresponding to ψ_1 and ψ_2 as a function of x, the straight line through the centres of the two protons, for $-\infty < x < +\infty$. With reference to your graph, explain the meaning of *bonding* and *anti-bonding states*. [25%]

3 (a) Explain how a p$^+$np bipolar junction transistor (BJT) operates, with reference to the currents that flow in the device. Your answer should include a band diagram of the BJT under an applied bias and a diagram showing the current flow. [35%]

(b) The current flow across a p$^+$n junction is given by

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

where V is the voltage applied to the p$^+$-side of the junction with respect to the n-side, D_e and D_h are the diffusion coefficients of electrons and holes, respectively, and L_e and L_h are the diffusion lengths of electrons and holes, respectively. Both sides of the junction are made from the same semiconductor, which has an intrinsic carrier concentration n_i. N_A and N_D are the acceptor and donor doping densities on the p$^+$-side and n-side of the junction, respectively. Starting from this expression, show that the emitter injection efficiency 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%]

(c) Calculate the base-to-collector current amplification factor β for this BJT, if the mobility of electrons and holes in the semiconductor is $0.135\ \mathrm{m^2\,V^{-1}\,s^{-1}}$ and $0.048\ \mathrm{m^2\,V^{-1}\,s^{-1}}$, respectively. The ratio W_b/L_e for the device is 0.05 and the base transport factor B is 0.999. [15%]

(d) Explain how the design of this BJT could be changed to increase β. [20%]

NOTE: For a BJT,

$$\alpha = B\gamma = \frac{I_C}{I_E};\ \beta = \frac{I_C}{I_B}.$$

4 (a) What is meant by the term *pinch-off voltage* in reference to a JFET? [5%]

(b) Starting from the Gauss Law of Electrostatics, show that the pinch-off voltage V_p for the n-channel JFET shown in Fig. 2 is given by

$$V_p = \frac{-h^2 e N_D}{8\varepsilon_0 \varepsilon_r},$$

where ε_r is the relative permittivity of the n-type semiconductor. You may assume that the doping density in the n-type channel N_D is much lower than that in the p-type gate N_A and that the built-in potential is negligible. [50%]

(c) The drain-source current I_{DS} in the JFET is given by

$$I_{DS} = \frac{dhN_D e\mu_e V_p}{L}\left\{\frac{V_{DS}}{V_p} - \frac{2}{3}\left(\frac{V_{GS}}{V_p}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{GS}-V_{DS}}{V_p}\right)^{3/2}\right\}$$

where d is the depth of the channel (into the page in Fig. 1) and μ_e is the electron mobility in the n-type semiconductor.

(i) For what relationship between V_{DS} and V_{GS} is this equation valid? [5%]

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

(iii) Hence, explain how a JEFT should be designed to maximise g_m. [15%]

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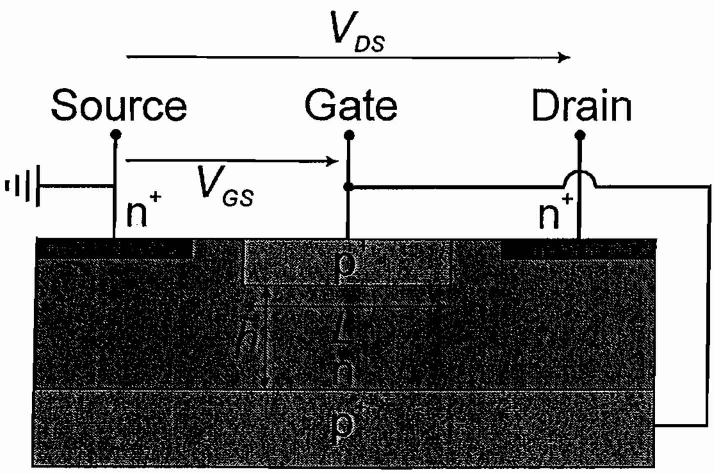

Fig. 2

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