ENGINEERING TRIPOS PART IIA

Tuesday 10 May 2005 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.

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

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Version 6

1 (a) Discuss the experimental evidence supporting wave-particle duality. [30%]

(b) The solution to Shroedinger's equation for a hydrogen atom can be written as

$$\Psi(r,\theta,\phi) = R(r)Y(\theta,\phi) \ . \qquad (1)$$

Explain the meaning of r, θ, ϕ and of $R(r)$ and $Y(\theta, \phi)$. [10%]

(c) Assuming $Y(\theta, \phi) = 1$ (spherically symmetric case), $R(r)$ is a solution of equation (2):

$$\frac{d^2R}{dr^2} + \frac{2}{r}\frac{dR}{dr} + \frac{2m}{\hbar^2}\left(E + \frac{e^2}{4\pi\varepsilon_0 r}\right)R = 0 \ , \qquad (2)$$

where E is the electron energy, m is the electron mass, e is the electron charge and ε_0 is the permittivity of free space. By inspection, the solution of equation 2 is :

$$R(r) = C\exp(-ar) \ ,$$

where C and a are constants. Find the expressions for E and a. [30%]

(d) Calculate the constant C in terms of a. [30%]

2 (a) Sketch the band structure of metals, insulators and semiconductors and explain how such structure influences the electrical conduction in these materials. [15%]

(b) Explain why sodium, with electronic configuration $1s^2\ 2s^2\ 2p^6\ 3s^1$, is a good conductor. Explain why magnesium with electronic configuration, $1s^2\ 2s^2\ 2p^6\ 3s^2$, is also a good conductor. [15%]

(c) Explain how the conductivity of silicon can be changed by doping the crystal with donor and acceptor impurities. Explain how one can dope GaAs with donor and acceptor impurities. [20%]

(d) Calculate the Fermi Energy for an intrinsic silicon crystal at room temperature. [20%]

(e) Calculate the Fermi Energy in silicon at room temperature when the crystal is doped with a density of boron atoms $N_A = 1\times10^{22}\ \text{m}^{-3}$ and $N_A >> N_D$. Assume all acceptors are ionized. [15%]

(f) Calculate the built-in potential of a silicon p-n junction, at room temperature, where the concentration of acceptors in the p-side and donors in the n-side are $N_A = 1\times10^{22}\ \text{m}^{-3}$ and $N_D = 1\times10^{21}\ \text{m}^{-3}$ respectively. [15%]

Note: For silicon at room temperature:
Effective density of states in the Conduction Band, $N_C = 2.8\times10^{25}\ \text{m}^{-3}$.
Effective density of states in the Valence Band, $N_V = 1.04\times10^{25}\ \text{m}^{-3}$.
Energy gap, $E_g = 1.12$ eV.

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3 (a) Fig. 1 is a schematic diagram of the structure of a High Electron Mobility Transistor (HEMT). Explain why the HEMT has a faster switching speed and higher source drain current in the on state than an equivalent metal semiconductor field effect transistor (MESFET) employing GaAs. Use a band diagram of the cross section x—x shown in Fig. 1 to illustrate your answer. [30%]

(b) The GaAlAs used in an HEMT has a band gap of 1.80 eV, an electron affinity of 3.75 eV and an effective density of states in the conduction band of 8.0×10^{23} 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 4.0×10^{23} m^{-3}. Both materials have been doped with a density of 3.3×10^{20} m^{-3} donor atoms, and the device is operated at a temperature of 298 K.

(i) Calculate the work function of both the GaAlAs and the GaAs, stating any assumptions made. [20%]

(ii) Estimate the concentration of free electrons in the conduction band of the GaAs at the interface with the GaAlAs. Assume that any band bending is shared equally between the two materials at their junction, but state any other assumptions that you make. [20%]

(iii) The width w of the depletion region in the GaAlAs is given by

$$w^2 = \frac{2\varepsilon_0\varepsilon_r V_0}{eN_D}$$

where V_0 is the built in potential difference across that side of the junction, ε_0 is the permittivity of free space, which is 8.854×10^{-12} F m^{-1}, ε_r is the relative permittivity of the material, which is 12.2, and N_D is the doping density. Estimate the thickness of the accumulated electron layer in the GaAs at the interface with the GaAlAs, assuming that the electron concentration is uniform throughout the accumulated layer. [30%]

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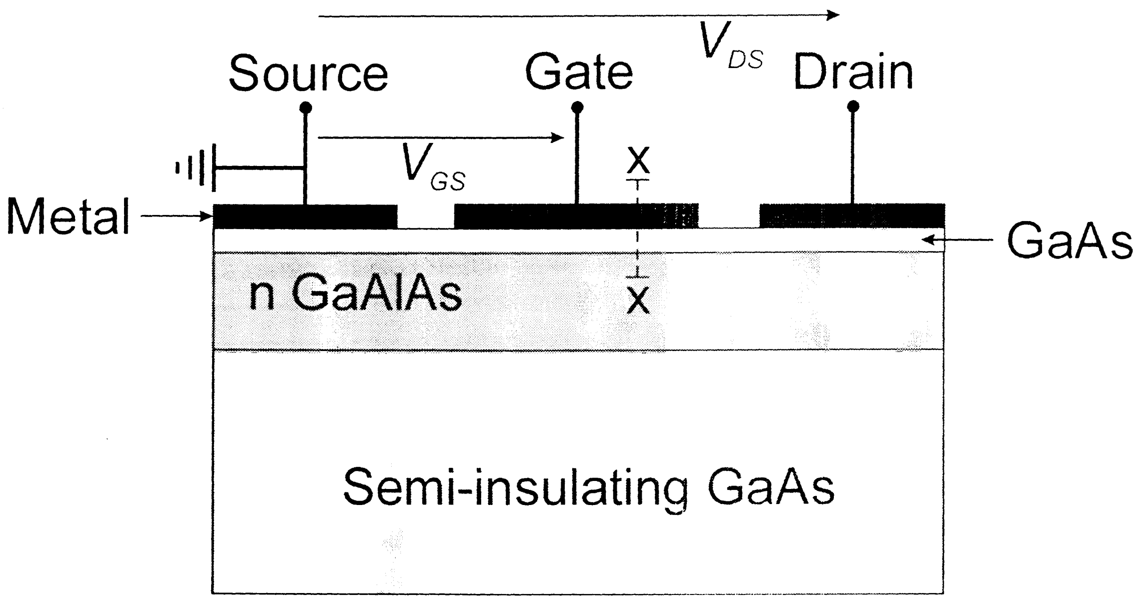

Fig. 1

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4 (a) The threshold voltage V_T for strong inversion of a 'normally off' metal oxide semiconductor field effect transistor (MOSFET) employing a n-type semiconductor channel material is given by

$$V_T = \frac{\phi_m - \phi_{sc}}{e} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} - 2V_f \ . \qquad (1)$$

Identify all of the terms in equation 1, and in each case briefly explain their physical origin and why they influence the threshold voltage of the device. [30%]

(b) The voltage applied to the gate of the MOSFET with respect to the source V_{GS}, and the flat band voltage V_{FB}, are related to the surface potential in the semiconductor V_s according to

$$V_{GS} - V_{FB} = \frac{-(Q_d + Q_f)}{C_i} - V_s \ ,$$

where Q_f is the free carrier charge density per unit area in the inverted region.

(i) Show that if a voltage V_{DS} is applied to the drain with respect to the source when the device is in strong inversion, then

$$Q_f = -C_i\left[V_{GS} - V_T - V(x)\right] \ ,$$

where $V(x)$ is the voltage induced in the channel by V_{DS}. [25%]

(ii) Using this result, derive the expression for the drain source current I_{DS} below saturation,

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

where μ_{hFE} is the field effect mobility of holes, W is the channel width and L is the channel length between the source and drain. [35%]

(iii) The switching speed of a MOSFET may be increased by reducing L. What other geometrical changes must be made to the device to achieve this? [10%]

END OF PAPER

PART IIA 2005

3B5 Semiconductor engineering

Principal Assessor: **Prof. P Migliorato**

Module 3B5 Semiconductor Engineering – 2005 Numerical Answers

2 (d) $E_F = 0.547$ eV
(e) $E_F = 0.178$ eV
(f) $V_{bi} = 0.675$ V

3 (b) (i) $\phi_{GaAs} = 4.25$ eV, $\phi_{GaAlAs} = 3.95$ eV
(ii) $n = 1.24\times10^{23}$ m^{-3}
(iii) $t = 2.08$ nm