GLASGOW COLLEGE UESTC

Main Exam Paper

Electronic Devices (UESTC 3002)

Date: Dec. 9th, 2022
Time: 19:00-21:00PM

Attempt all PARTS. Total 100 marks

Use one answer sheet for each of the questions in this exam.
Show all work on the answer sheet.
For Multiple Choice Questions, use the dedicated answer sheet provided.

Make sure that your University of Glasgow and UESTC Student Identification Numbers are on all answer sheets.

An electronic calculator may be used provided that it does not allow text storage or display, or graphical display.

All graphs should be clearly labelled and sufficiently large so that all elements are easy to read.

The numbers in square brackets in the right-hand margin indicate the marks allotted to the part of the question against which the mark is shown. These marks are for guidance only.

FORMULAE SHEET IS PROVIDED AT THE END OF PAPER
Fundamental Constants and Useful Material Properties

$$q = 1.6 \times 10^{-19}\ C$$
$$T = 300\ K$$
$$J = 1.38 \times 10^{-23} JK^{-1}$$
$$\epsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$$
$$h = 6.62\ \times\ 10^{-34}\ m^2kg/s$$

$$Band\ Gap\ Si,\ E(Si) = 1.1\ eV$$
$$m_0 = 9.1 \times 10^{-31}\ kg$$

Question 1 - Fundamental Semiconductor Concepts **[25 marks]**

Answer the following questions:

(a) Define:

i. Long-range order [1]

ii. Bravais Lattice [1]

iii. Face-centered cubic structure [1]

iv. Electron affinity [1]

v. Valence electrons [1]

(b) During Si doping only small amounts of impurity (e.g., one impurity atom for every million host atoms) is being added, why? [1]

(c) Draw and label the band diagrams with the appropriate $\mathbf{E_c}$, $\mathbf{E_v}$, $\mathbf{E_g}$, and Fermi levels for

i. Si [2]

ii. n-Si [2]

iii. p-Si [2]

(d) A piece of silicon is doped with $3 \times 10^{15}\text{cm}^{-3}$ of donors and $7 \times 10^{15}\text{cm}^{-3}$ of acceptors. With the mobility of 410 cm^2/V.s at 300 K, what is the hole diffusion constant?

[2]

(e) What is the resistance, R, of a piece of silicon material (resistivity 0.084 Ω.cm) with a length of 1 μm and cross-sectional area of 0.1 μm^2 ? [1]

(f) The intrinsic concentration of a Si sample at room temperature is approximately 1.5 x 10^{10} cm^{-3}. This sample is then doped with 10^{17} As atoms/cm^3.

i. What is the equilibrium hole concentration (p_0) at 300 K? [1]

ii. Calculate the E_F. [1]

iii. Where is E_F relative to E_i, draw the resulting band diagram. [2]

(g) The circuit diagram of the Haynes–Shockley experiment with an n-type Ge sample is shown in Figure 1. The length of the sample is 1 cm, and the probes (1) and (2) are separated by 0.95 cm. The battery voltage E_0 is 2 V. A pulse arrives at point (2) 0.25 ms after injection at (1); the width of the pulse Δt is 117 ms. Calculate

i. Hole mobility [2]

ii. Diffusion coefficient [2]

iii. Check the results against the Einstein relation [2]

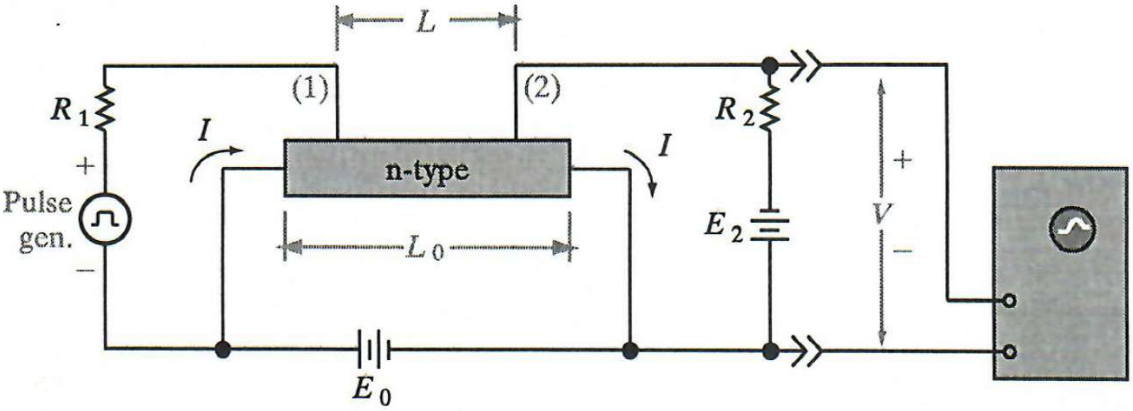

Figure 1. The circuit schematic of the Haynes–Shockley experiment setup

Question 2 - PN junction **[25 marks]**

(a) A p^+n junction has acceptor density of $N_a = 10^{20} cm^3$ and donor density of $N_d = 10^{17} cm^{-3}$. Find

(i) The built-in potential [2]

(ii) Depletion-layer width [2]

(iii) The widths of the depletion layers on the two sides of the junction [3]

(b) Consider a Si p-n junction operating as a rectifier at room temperature (300 K).

(i) Explain the function of this junction as a rectifier in terms of I_F and electrical conductivity σ [2]

(ii) Explain the effects of increasing the operating temperature to 350 K, on the effectiveness of the device as a rectifier. [2]

(iii) What happens to the rectifying property of the junction, if the operating temperature increases to 550 K? Explain why. [2]

(c) A p-n junction has $N_a = 10^{19}$ cm^{-3} and $N_d = 10^{16}$ cm^{-3}. Calculate

(i) At V = 0, what are the minority carrier densities at the edges of depletion region? [2]

Assume V = 0.6 V for (ii)–(iv).

(ii) What are the minority carrier densities at the edges of depletion region? [2]

(iii) What are the excess minority carrier densities? [2]

(iv) Under the reverse bias of 1.8 V, what are the minority carrier concentrations at the edges of depletion region? [2]

(d) Consider a bar of an n-type semiconductor in which the dopant density decreases toward the right (as shown in Figure 2). Assume the semiconductor is at equilibrium, and therefore the Fermi level E_F is constant. Derive a relationship between the diffusion constant, D_n, and mobility. [4]

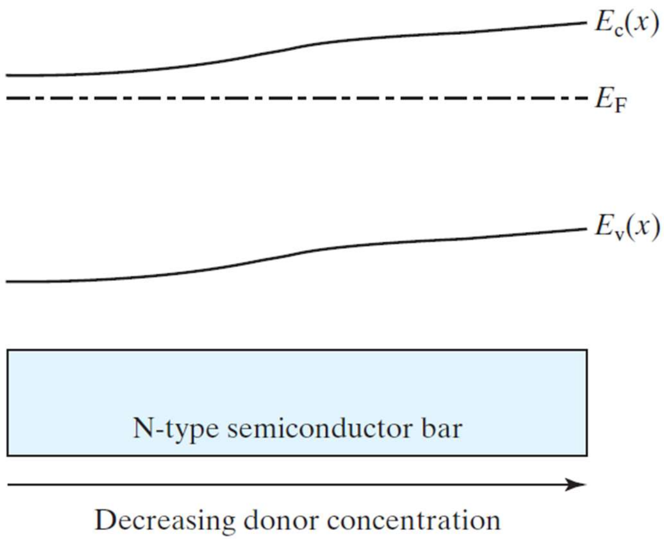

Figure. 2 Dopant density of n-type semiconductor bar

Question 3 – BJTs [25 marks]

a) What is the significance of the arrow-head in the symbol of BJTs and why there is no arrow-head for collector? [4]

b) List down the consequences if the BJT is not biased properly. [4]

c) Which of the transistor currents is always the largest? [1]
Which is always the smallest? [1]
Which two currents are relatively close in magnitude? [1]

d) Why is the width of the base region of a transistor is kept very small compared to other regions? [2]

e) In a common base connection, α = 0.95. The voltage drops across the 2 kΩ resistance which is connected in the collector is 2V. Find the base current from the Figure 3. [8]

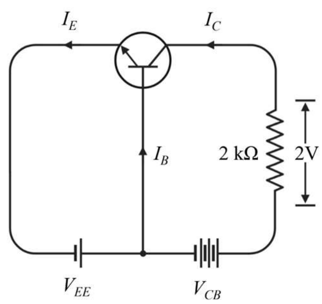

Figure 3

(d) Which of the BJT currents is always the largest? [1]
Which is always the smallest? [1]

Which two currents are relatively close in magnitude? [1]

(e) What are 'emitter injection efficiency' and 'base transport factor' and how do they influence the transistor operation? [1]

Question 4 – Field Effect Transistors [25 marks]

a) Why FET is called as "voltage operated device"? [2]

b) Compare the characteristics of BJT and MOSFET. [10]

(c) List the major applications of a JFET? [6]

(d) Which parameter of a transistor varies with temperature? [3]

(e) Is it possible to interchange the source and drain terminals in a FET circuit? Is it possible to do the same with the emitter and collector terminals of a BJT circuit? [4]

EQUATION SHEET

Electron momentum: $\mathsf{p} = m^*\mathsf{v} = \hbar\mathbf{k} = \dfrac{h}{\lambda}$ Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \dfrac{1}{2}m^*\mathsf{v}^2 = \dfrac{1}{2}\dfrac{\mathsf{p}^2}{m^*} = \dfrac{\hbar^2}{2m^*}\mathbf{k}^2$ Effective mass: $m^* = \dfrac{\hbar^2}{d^2E/d\mathbf{k}^2}$

Total electron energy $= P.E. + K.E. = E_c + E(\mathbf{k})$

Fermi-Dirac e^- distribution: $f(E) = \dfrac{1}{e^{(E-E_F)/kT} + 1} \cong e^{(E_F - E)/kT}$ for $E \gg E_F$

Equilibrium: $n_0 = \displaystyle\int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c - E_F)/kT}$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \qquad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

$$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F - E_v)/kT}$$

$$n_i = N_c e^{-(E_c - E_i)/kT}, \quad p_i = N_v e^{-(E_i - E_v)/kT}$$

$$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$$

Equilibrium: $n_0 = n_i e^{(E_F - E_i)/kT}$, $p_0 = n_i e^{(E_i - E_F)/kT}$ $\qquad n_0 p_0 = n_i^2$

Steady state: $n = N_c e^{-(E_c - F_n)/kT} = n_i e^{(F_n - E_i)/kT}$, $p = N_v e^{-(F_p - E_v)/kT} = n_i e^{(E_i - F_p)/kT}$ $\qquad np = n_i^2 e^{(F_n - F_p)/kT}$

$$\mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

Poisson: $\dfrac{d\mathscr{E}(x)}{dx} = -\dfrac{d^2\mathscr{V}(x)}{dx^2} = \dfrac{\rho(x)}{\epsilon} = \dfrac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$

$\mu \equiv \dfrac{q\bar{t}}{m^*}$ (3–40a) Drift: $\mathsf{v}_d \cong \dfrac{\mu\mathscr{E}}{1 + \mu\mathscr{E}/\mathsf{v}_s}\begin{cases} = \mu\mathscr{E} & \text{(low fields, ohmic)} \\ = \mathsf{v}_s & \text{(high fields, saturated vel.)}\end{cases}$

Drift current density: $\dfrac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$

$$E_F - E_i = kT\ln\frac{n_0}{n_i}$$

$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}$$

Conduction current: drift diffusion

$$J_p(x) = q\mu_p p(x)\mathscr{E}(x) - qD_p \frac{dp(x)}{dx}$$

$$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C\frac{dV}{dt}$$

Continuity: $\dfrac{\partial p(x,t)}{\partial t} = \dfrac{\partial \delta p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - \dfrac{\delta p}{\tau_p}$ $\qquad$ $\dfrac{\partial \delta n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - \dfrac{\delta n}{\tau_n}$

For steady state diffusion: $\dfrac{d^2\delta n}{dx^2} = \dfrac{\delta n}{D_n\tau_n} \equiv \dfrac{\delta n}{L_n^2}$ $\qquad$ $\dfrac{d^2\delta p}{dx^2} = \dfrac{\delta p}{L_p^2}$

Diffusion length: $L \equiv \sqrt{D\tau}$ $\qquad$ Einstein relation: $\dfrac{D}{\mu} = \dfrac{kT}{q}$

p-n JUNCTIONS

Equilibrium: $V_0 = \dfrac{kT}{q}\ln\dfrac{p_p}{p_n} = \dfrac{kT}{q}\ln\dfrac{N_a}{n_i^2/N_d} = \dfrac{kT}{q}\ln\dfrac{N_aN_d}{n_i^2}$

$\dfrac{p_p}{p_n} = \dfrac{n_n}{n_p} = e^{qV_0/kT}$ $\qquad$ $W = \left[\dfrac{2\epsilon(V_0 - V)}{q}\left(\dfrac{N_a + N_d}{N_aN_d}\right)\right]^{1/2}$

One-sided abrupt p^+-n: $x_{n0} = \dfrac{WN_a}{N_a + N_d} \simeq W$ $\qquad$ $V_0 = \dfrac{qN_dW^2}{2\epsilon}$

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$$

Ideal diode: $I = qA\left(\dfrac{D_p}{L_p}p_n + \dfrac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$

Non-ideal: $I = I_0'(e^{qV/\mathbf{n}kT} - 1)$
($\mathbf{n}$ = 1 to 2)

With light: $I_{\text{op}} = qAg_{\text{op}}(L_p + L_n + W)$

$$E_a - E_b = h\nu_{ab} = \frac{mq^4}{8h^2\varepsilon^2}\left[\frac{1}{b^2} - \frac{1}{a^2}\right]$$

$$np = n_i^2$$

$$f_{FD}(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{k_BT}\right)}$$

$$n = N_C \exp((E_F - E_C)/k_BT)$$

$$p = N_V \exp((E_V - E_F)/k_BT)$$

$$n_i = (N_c N_V)^{1/2} \exp\left(\frac{-E_g}{2k_bT}\right)$$

$$J_{n,drift} = qnv_d = qn\mu_n E$$

$$J_{p,drift} = qpv_d = qp\mu_p E$$

$$\mu_n = \frac{q\tau_n}{m_e} \quad \mu_p = \frac{q\tau_p}{m_h}$$

$$\mu_L = AT^{-3/2} \quad \mu_I = \frac{BT^{+3/2}}{N_i}$$

$$J_{n,diff} = qD_n\frac{dn}{dx} \quad J_{p,diff} = -qD_p\frac{dp}{dx}$$

$$\psi_0 = \frac{E_F^n - E_F^p}{q} = \frac{k_BT}{q}\ln\left(\frac{N_DN_A}{n_i^2}\right)$$

$$w = x_p + x_n = \left(\frac{2\varepsilon_0\varepsilon_S(\psi_0+V)(N_D+N_A)}{qN_AN_D}\right)^{1/2}$$

$$p_n(x) = (p_n(x_n) - p_{n0})\exp\left(-\frac{(x-x_n)}{L_p}\right) + p_{n0}$$

$$n_p(x) = (n_p(-x_p) - n_{p0})\exp\left(\frac{(x+x_p)}{L_n}\right) + n_{p0}$$

$$n_p(-x_p) = n_{p0}\exp\left(\frac{V_F}{\phi_T}\right)$$

$$p_n(x_n) = p_{n0}\exp\left(\frac{V_F}{\phi_T}\right)$$

$$I = I_0\left(\exp\left(\frac{V_F}{\phi_T}\right) - 1\right)$$

I_0 : $$I_0 = qA\left(\frac{D_pp_{n0}}{L_p} + \frac{D_nn_{p0}}{L_n}\right) = qAn_i^2\left(\frac{D_p}{L_pN_A} + \frac{D_n}{L_nN_D}\right)$$

$$\frac{D_e}{\mu_e} = \frac{kT}{e} \quad \text{and} \quad \frac{D_h}{\mu_h} = \frac{kT}{e}$$

$$I = I_0\exp\left(\frac{V_F}{n\phi_T}\right)$$

$$I_o = AA^*T^2\exp(-(q\phi_B)/kT)$$

$$Q_{Bm} = -qN_ax_{dm} \quad x_{dm} = \sqrt{\frac{2\varepsilon_0\varepsilon_s 2\phi_f}{qN_a}}$$

$$V_T = -\frac{Q_{Bm}}{C_o} + 2\phi_f$$

$$Q_I = -C_o(V_G - V_T)$$

$$V_{FB} = -\frac{Q_o}{C_o} + \phi_{ms}$$

$$V_T = -\frac{Q_{Bm}}{C_o} + 2\psi_B + V_{FB}$$

$$I_D = C_o\mu_{ns}\frac{W}{L}\left[(V_G - V_T)V_D - \frac{V_D^2}{2}\right]$$

$$I_{DS} = \mu_{ns}C_o\frac{W}{2L}(V_G - V_T)^2$$

$$f_T = \frac{\mu_{ns}V_D}{2\pi L^2} \quad f_T = \frac{v_s}{2\pi L}$$

$$I_{DS} = -WQ_Iv_s = WC_ov_s(V_G - V_T)$$

$$D = D_0\exp\left(-\frac{E_A}{kT}\right)$$

$$F = -D\frac{\partial C}{\partial x}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

$$C(x,t) = C_s\operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$C(x,t) = \frac{Q}{\sqrt{\pi Dt}}\exp\left(-\frac{x^2}{4Dt}\right)$$

$$C(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p}\exp\left(-\frac{(x-R_p)^2}{2\Delta R_p}\right)$$

$$w_{ox}^2 + Aw_{ox} = B(t+\tau_i)$$

$$\tau_i = \frac{w_{ox,i}^2}{B} + \frac{w_{ox,i}}{B/A}$$

$$w_{ox} = \frac{A}{2}\left\{\left(1 + \frac{t+\tau_i}{A^2/4B}\right)^{1/2} - 1\right\}$$

$$w_{ox} = \frac{B}{A}(t+\tau_i) \quad w_{ox} = \sqrt{Bt}$$

$$\tau_t = \frac{W_B'^2}{2D_B}$$

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$$

$$I_{DS} = K(V_{GS} - V_{\text{th}})^2(1 + \lambda V_{DS})$$

$$K = \frac{Z\mu_e \varepsilon}{2L t_{\text{ox}}}$$

$$N_v = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}$$

$$N_c = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$L_n = \sqrt{D_n \tau_n}$$

$$L_p = \sqrt{D_p \tau_p}$$

$$A_V = \frac{v_{ds}}{v_{gs}} = \frac{-R_D(g_m v_{gs})}{v_{gs}} = -g_m R_D$$

$$N_d x_n = N_a x_p$$

$$x_p = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_d}{N_a(N_d + N_a)}}$$

$$x_n = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_a}{N_d(N_d + N_a)}}$$

$$W = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_a + N_d}{N_d N_a}}$$