GLASGOW COLLEGE UESTC

Exam paper

Electronic Devices (UESTC3002)

Date: 14th Dec 2023

Time: 19:00-21:00

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.

DATA/FORMULAE SHEET IS PROVIDED AT THE END OF PAPER

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Q1: Semiconductor Fundamentals **[25]**

(a) Define Atomic packing factor (APF). [2]

(b) What is the electronic configuration of the Germanium atom [atomic number (Z) = 32]? [2]

(c) Why only small amounts of impurities (e.g., one impurity atom for every million host atoms) are added into a pure Si crystal during the doping process? [2]

(d) Why do holes have lower mobility than electrons? [2]

(e) What is the photoelectric effect? Elaborate your answer using a diagram. [2]

(f) State two differences between Intrinsic and Extrinsic semiconductors. [2]

(g) Calculate the hole drift velocity when an electric field of 10^3 V/cm is applied to the semiconductor. Given the hole mobility is 470 cm^2/Vs? [2]

(h) Write an expression for total carrier current in a semiconductor for a general case. [2]

(i) What wavelengths of light can be absorbed by a Si photodetector given the energy bandgap E_g of Si is 1.1 eV? Can such a photodetector be used in fibre-optic communications at 1.31 μm and 1.55 μm light wavelengths? [4]

(j) Define Fermi energy or level. What is the Fermi–Dirac distribution function? Sketch the Fermi-Dirac distribution function and explain it. [5]

Q2: PN Junction **[25]**

(a) Draw and accurately label the energy band diagram of PN Junction under Equilibrium. Highlight the electric field, contact potential, separation of the energy bands and drift and diffusion current directions. [5]

(b) A PN junction diode has a concentration of 10^{16} acceptor atoms cm^{-3} on the p-side and a concentration of 10^{17} donor atoms cm^{-3} on the n-side. Calculate the built-in potentials for the Silicon (Si) and Gallium arsenide (GaAs) based junction. The intrinsic concentrations of Si and GaAs are 1.0×10^{10} cm^{-3} and 2.1×10^{6} cm^{-3}, respectively. Show all steps of calculations. [4]

(c) An abrupt Si PN junction has acceptor concentration of 10^{18} cm^{-3} on one side and donor concentration of 5×10^{15} cm^{-3} on the other. The intrinsic carrier concentration is 1.5×10^{10} cm^{-3}.

(i) Calculate the Fermi level positions at 300 K in the p and n regions. [2]

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(ii) Draw an equilibrium band diagram for the junction and determine the contact potential from the diagram. [3]

(d) Consider a P^+N junction, with a heavily doped p-side relative to the n-side.

(i) What is the depletion width for a PN junction of Si diode that has been doped with 10^{18} acceptor atoms cm^{-3} on the p-side and 10^{16} donor atoms cm^{-3} on the n-side? Relative dielectric constant of Si is 11.9. Show all steps of calculations. [4]

(ii) Indicate where the majority of depletion region is located, n-side or p-side and explain why? [2]

(e) What is Avalanche Breakdown and Zener Breakdown? Elaborate your answer using diagrams. [5]

Q3 Field Effect Transistor (FET) and Bipolar Junction Transistor (BJT) [25]

(a) What is the distinction between a current controlled versus voltage controlled three terminal transistors with respect to input impedance? Which is preferable in terms of power consumption? [2]

(b) Consider the n-channel JFET common source amplifier shown in Figure Q3. The JFET has an I_{DSS} of 10 mA and a pinch-off voltage V_P of 5 V. If the gate dc bias voltage supply, $V_{GG} = -1.5$ V, the circuit supply voltage, V_{DD} = 18 V, and the drain load resistor, R_D = 2000 Ω. Calculate the small signal voltage amplification assuming the measurement circuit at the 'Output signal' node is a very high impedance? [6]

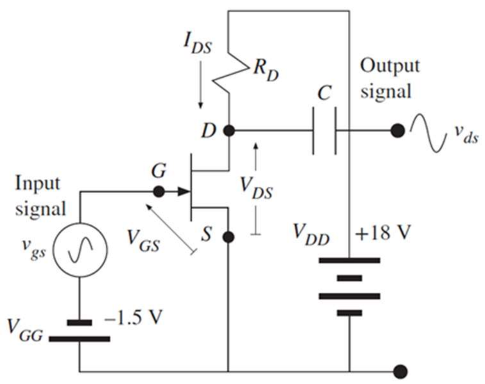

Figure Q3

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(c) Explain what is meant by the Pinch-off condition for JFET. Illustrate your answer by drawing a diagram for the pinched-off channel and label the important features. [4]

A bipolar junction transistor (BJT) is a type of transistor that uses both electrons and holes as charge carriers. This three-terminal device can commonly function as an electronic switch or a signal amplifier.

(d) To function as a good p-n-p transistor, we would prefer that almost all the holes injected by the emitter into the base be collected. Explain how this requirement can be met, and why satisfying this requirement contributes to efficient transistor operation. [4]

(e) Consider an NPN bipolar transistor with an emitter current (i_E) of 100 mA. If this transistor's collector's current (i_c) is 95 mA, calculate the magnitude of the base current (i_B). (Hint: the DC gain factor β relating the collector current to the base current amplification factor needs to be calculated). [5]

(f) Based on the biasing polarities (forward or reverse bias) of both the base-collector and base-emitter junctions, draw a diagram showing the four different regions of operation of a N-P-N transistor and label each specific operation mode. [4]

Q4 Optoelectronic Devices [25]

(a) Optoelectronic devices are electronic devices that can both emit and detect light, making them crucial components in various applications. Consider a photodetector which has the following parameters:

The cross-sectional area of the junction (A): 4 cm^2
The diffusion length for holes (L_p): 2 μm
The diffusion length for electrons (L_n): 2 μm
The width of the depletion region (W) = 0.5 μm
The absolute temperature (T): 300 K

(i) Find the optically generated current (I_{op}) if assuming the generation rate of electron-hole pairs (g_{op}) is 10^{20} EHP/cm^3-s. [3]

(ii) There is an open circuit across this device. Compute the relevant open circuit voltage, while the thermally generated current would be 20 nA [3]

(iii) Calculate the responsivity (R) of the photodetector given the incident light power of 10 mW. [2]

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(b) A light-emitting diode (LED) is essentially a pn junction diode typically made from a direct bandgap semiconductor.

(i) Define two concepts of “injection electroluminescence”, and “spontaneous photon emission” in the context of semiconductors. [4]

(ii) In the context of LEDs, the equation $n_1.\sin(\theta_c) = n_2$ plays a critical role. This equation relates to the phenomenon of total internal reflection and is essential for understanding and optimizing LED performance. What do n_1 and n_2 represent, and how does the θ_c relate to the LED's performance? [3]

(iii) You are studying semiconductor materials and their optical properties. Consider a semiconductor with an energy bandgap of 2 eV. Calculate the wavelength (λ) of the light that can be emitted by this semiconductor when electrons make transitions from the conduction band to the valence band. [2]

(c) A solar cell, or photovoltaic cell, is an electronic device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical phenomenon. Consider two hypothetical solar cells, Cell X and Cell Y, with its own set of characteristics as below:

Cell X:
Open-circuit voltage = 35 volts
Short-circuit current = 8 ampers

Cell Y:
Open-circuit voltage = 38 volts
Short-circuit current = 9 ampers

While assuming the same current for both cells to achieve their maximum power output, according voltage at which achieve their maximum power output is 30 volts for cell X and 32 volts for cell Y.

(i) Compare both cells in terms of efficiency (i.e., converting a portion of available sunlight into electricity under optimal conditions). [4]

(ii) Which cell can generate more electricity under optimal conditions and why? [2]

(iii) There are several types of solar cells, each with its own materials and operating principles. List any two types of solar cells. [2]

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Physical Constants

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

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FORMULAE SHEET

SEMICONDUCTOR PHYSICS

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

Kinetic: $E = \frac{1}{2}m^*\mathsf{v}^2 = \frac{1}{2}\frac{\mathsf{p}^2}{m^*} = \frac{\hbar^2}{2m^*}\mathbf{k}^2$ (3–4) Effective mass: $m^* = \frac{\hbar^2}{d^2E/d\mathbf{k}^2}$ (3–3)

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

Fermi-Dirac e^- distribution: $f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \cong e^{(E_F - E)/kT}$ for $E \gg E_F$ (3–10)

Equilibrium: $n_0 = \int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c - E_F)/kT}$ (3–15)

$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ (3–16a) $N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (3–20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F - E_v)/kT}$ (3–19)

$n_i = N_c e^{-(E_c - E_i)/kT}$, $p_i = N_v e^{-(E_i - E_v)/kT}$ (3–21)

$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$ (3–23), (3–26)

Equilibrium: $\begin{aligned} n_0 &= n_i e^{(E_F - E_i)/kT} \\ p_0 &= n_i e^{(E_i - E_F)/kT} \end{aligned}$ (3–25) $n_0 p_0 = n_i^2$ (3–24)

Steady state: $\begin{aligned} n &= N_c e^{-(E_c - F_n)/kT} = n_i e^{(F_n - E_i)/kT} \\ p &= N_v e^{-(F_p - E_v)/kT} = n_i e^{(E_i - F_p)/kT} \end{aligned}$ (4–15) $np = n_i^2 e^{(F_n - F_p)/kT}$ (5–38)

$\mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} = \frac{1}{q}\frac{dE_i}{dx}$ (4–26)

Poisson: $\frac{d\mathscr{E}(x)}{dx} = -\frac{d^2\mathscr{V}(x)}{dx^2} = \frac{\rho(x)}{\epsilon} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$ (5–14)

$\mu \equiv \frac{q\bar{t}}{m^*}$ (3–40a) Drift: $\mathsf{v}_d \cong \frac{\mu\mathscr{E}}{1 + \mu\mathscr{E}/\mathsf{v}_s}\begin{cases} = \mu\mathscr{E} & \text{(low fields, ohmic)} \\ = \mathsf{v}_s & \text{(high fields, saturated vel.)} \end{cases}$ (Fig. 6–9)

Drift current density: $\frac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$ (3–43)

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Conduction current:

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

drift diffusion (4–23)

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

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

Continuity: $\dfrac{\partial p(x,t)}{\partial t} = \dfrac{\partial \delta p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - \dfrac{\delta p}{\tau_p} \qquad \dfrac{\partial \delta n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - \dfrac{\delta n}{\tau_n}$ (4–31)

For steady state diffusion: $\dfrac{d^2\delta n}{dx^2} = \dfrac{\delta n}{D_n\tau_n} \equiv \dfrac{\delta n}{L_n^2} \qquad \dfrac{d^2\delta p}{dx^2} = \dfrac{\delta p}{L_p^2}$ (4–34)

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\dfrac{D}{\mu} = \dfrac{kT}{q}$ (4–29)

p-n JUNCTIONS

Equilibrium: $V_0 = \dfrac{kT}{q}\ln\dfrac{p_p}{p_n} = \dfrac{kT}{q}\ln\dfrac{N_a}{n_i^2/N_d} = \dfrac{kT}{q}\ln\dfrac{N_aN_d}{n_i^2}$ (5–8)

$\dfrac{p_p}{p_n} = \dfrac{n_n}{n_p} = e^{qV_0/kT}$ (5–10) $\qquad W = \left[\dfrac{2\epsilon(V_0 - V)}{q}\left(\dfrac{N_a + N_d}{N_aN_d}\right)\right]^{1/2}$ (5–57)

One-sided abrupt p^+-n: $x_{n0} = \dfrac{WN_a}{N_a + N_d} \simeq W$ (5–23b) $\qquad V_0 = \dfrac{qN_dW^2}{2\epsilon}$

$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$ (5–29)

$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$ (5–31b)

Ideal diode: $I = qA\left(\dfrac{D_p}{L_p}p_n + \dfrac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$ (5–36)

Non-ideal: $I = I_0'(e^{qV/\mathbf{n}kT} - 1)$ $(\mathbf{n} = 1 \text{ to } 2)$ (5–74)

With light: $I_{op} = qAg_{op}(L_p + L_n + W)$ (8–1) $\qquad V_{oc} = \dfrac{kT}{q}\ln[I_{op}/I_{th} + 1]$

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Capacitance: $C = \left|\frac{dQ}{dV}\right|$ (5–55)

Junction depletion: $C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$ (5–62)

Stored charge exp. hole dist.: $Q_p = qA\int_0^\infty \delta p(x_n)dx_n = qA\Delta p_n \int_0^\infty e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$ (5–39)

$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}p_n(e^{qV/kT} - 1)$ (5–40), (5–29)

$G_s = \frac{dI}{dV} = \frac{qAL_p p_n}{\tau_p}\frac{d}{dV}(e^{qV/kT}) = \frac{q}{kT}I$ (5–65)

Long p^+-n: $i(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}$ (5–47)

MOS-n CHANNEL

Oxide: $C_i = \frac{\epsilon_i}{d}$ Depletion: $C_d = \frac{\epsilon_s}{W}$ MOS: $C = \frac{C_i C_d}{C_i + C_d}$ (6–36)

Threshold: $V_T = \underbrace{\Phi_{ms} - \frac{Q_i}{C_i}}_{\text{Flat band}} - \frac{Q_d}{C_i} + 2\phi_F$ (6–38)

Inversion: $\phi_s\,(\text{inv.}) = 2\phi_F = 2\frac{kT}{q}\ln\frac{N_a}{n_i}$ (6–15) $W = \left[\frac{2\epsilon_s\phi_s}{qN_a}\right]^{1/2}$ (6–30)

$Q_d = -qN_aW_m = -2(\epsilon_s qN_a\phi_F)^{1/2}$ (6–32) At V_{FB}: $C_{FB} = \frac{C_i\,C_{\text{debye}}}{C_i + C_{\text{debye}}}$

Debye screening length: $L_D = \sqrt{\frac{\epsilon_s kT}{q^2 p_0}}$ (6–25) $C_{\text{debye}} = \frac{\epsilon_s}{L_D}$ (6–40)

Substrate bias: $\Delta V_T \simeq \frac{\sqrt{2\epsilon_s qN_a}}{C_i}(-V_B)^{1/2}$ (n channel) (6–63b)

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$$I_D = \frac{\overline{\mu}_n Z C_i}{L}\left\{(V_G - V_{FB} - 2\phi_F - \tfrac{1}{2}V_D)V_D - \frac{2}{3}\,\frac{\sqrt{2\epsilon_s q N_a}}{C_i}\left[(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}\right]\right\} \quad (6\text{–}50)$$

$$I_D \simeq \frac{\overline{\mu}_n Z C_i}{L}\left[(V_G - V_T)V_D - \tfrac{1}{2}V_D^2\right] \quad (6\text{–}49)$$

Saturation: $I_D(\text{sat.}) \simeq \frac{1}{2}\overline{\mu}_n C_i \frac{Z}{L}(V_G - V_T)^2 = \frac{Z}{2L}\overline{\mu}_n C_i V_D^2(\text{sat.})$ (6–53)

$$g_m = \frac{\partial I_D}{\partial V_G};\quad g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} \simeq \frac{Z}{L}\overline{\mu}_n C_i(V_G - V_T) \quad (6\text{–}54)$$

For short L: $I_D \simeq Z C_i (V_G - V_T) v_s$ (6–60)

Subthreshold slope: $S = \frac{dV_G}{d(\log I_D)} = \frac{kT}{q}\ln 10\left[1 + \frac{C_d + C_{it}}{C_i}\right]$ (6–66)

BJT-p-n-p

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right) \quad (7\text{–}18)$$

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1), \quad \Delta p_C = p_n(e^{qV_{CB}/kT} - 1) \quad (7\text{–}8)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right] \quad (7\text{–}19)$$

$$B = \frac{I_C}{I_{Ep}} = \frac{\operatorname{csch} W_b/L_p}{\operatorname{ctnh} W_b/L_p} = \operatorname{sech}\frac{W_b}{L_p} \simeq 1 - \left(\frac{W_b^2}{2L_p^2}\right) \quad (7\text{–}26)$$

(Base transport factor)

$$\gamma = \frac{I_{Ep}}{I_{En} + I_{Ep}} = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n}\tanh\frac{W_b}{L_p^n}\right]^{-1} \simeq \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1} \quad (7\text{–}25)$$

(Emitter injection efficiency)

$\frac{i_C}{i_E} = B\gamma \equiv \alpha$ (7–3)

(Common base gain)

$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1-\alpha} \equiv \beta$ (7–6)

(Common emitter gain)

$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t}$ (7–7)

(For $\gamma = 1$)

End of question paper