GLASGOW COLLEGE UESTC

Main Exam Paper

Electronic Devices (UESTC 3002)

Date: 31st Dec. 2020
Time: 09:30am - 11:30am

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

$q = 1.6 \times 10^{-19}\ C$

$T = 300\ K$

$J = 1.38 \times 10^{-23} JK^{-1}$

$\epsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$

$h = 6.62 \times 10^{-34}\ m^2 kg/s$

$Band\ Gap\ Si,\ E(Si) = 1.1\ eV$

$m_0 = 9.1 \times 10^{-31}\ kg$

Question 1: Short Answer Questions [25 marks]

a) Silver is a material often used in Electronic Devices. It has an FCC crystal structure with a lattice parameter of = 0.4084nm. Calculate:
   i. The total number of atoms per unit cell. [2 marks]
   ii. the planar concentration of atoms (per m^2) in the 100 plane. Please show the 100 plane in your coordinate system. [4 marks]

b) Describe the difference between intrinsic and extrinsic semiconductor materials. You may explain your answer using diagrams. [4 marks]

c) Calculate the effective density of states in the conduction and valence bands of an intrinsic piece of silicon, given that its band gap is 1.1 eV, the mass of an electron is $m_e = 1.08m_0$, the mass of a hole is $m_e = 0.6m_0$, the relative permittivity of silicon is 11.9. [4 marks]

d) From your answer above, determine the intrinsic carrier concentration of silicon. [2 marks]

e) Determine the position of the Fermi level of silicon relative to the conduction band. [2 marks]

f) Using your previous answers, sketch the energy band diagram of silicon, making sure to label the various energy bands. Describe the difference between this band structure and an extrinsic material. [3 marks]

g) Determine the conductivity and resistivity of silicon for an electron mobility of 1500 cm^2 V^{-1} s^{-1} and a hole mobility of 450 cm^2 V^{-1} s^{-1}. [4 marks]

Question 2: *pn*-Junction Diode [25 Marks]

a) Draw a schematic diagram of the PN junction diode in the equilibrium state and sketch its typical energy band diagram. [2 marks]

b) As above, draw schematic diagram of the PN junction in the forward biased and reverse biased region, comparing the band diagrams and the space charge regions of each case. [4 marks]

c) Briefly describe (in words) the main differences between a forward biased and a reverse biased pn junction diode. [4 marks]

d) For a n^+p diode with $n_i = 1 \times 10^{10} cm^{-3}$, $N_a = 1 \times 10^{15} cm^{-3}$, $\mu_n = 1350\ cm^2V^{-1}s^{-1}$ on the p-side, as well as $N_d = 1 \times 10^{17} cm^{-3}$ on the n-side, $\mu_h = 375$, determine the following at equilibrium (V=0):
   i. The built-in voltage, V_{bi}. [2 marks]
   ii. width of the depletion region, assuming $\epsilon_r = 12$. [2 marks]
   iii. width of the depletion region in the p and n type materials. [2 marks]
   iv. The total charge, given that the cross-sectional area of the device, A is $0.1 \times 10^{-2} cm^2$. [2 marks]
   v. The magnitude of the electric field at x=0. [2 marks]

e) For the same diode, but at a reverse bias voltage of V=2 V, determine the following
   i. Width of the depletion region. [2 marks]
   ii. The total charge, Q. [2 marks]
   iii. The magnitude of the capacitance. [1 mark]

Question 3 – Bipolar Junction Transistors [25 Marks]

Consider an ideal $n^{+}pn$ bipolar junction transistor (BJT), with the properties listed in the table below:

Emitter Width	20 μm	Collector Width	20 μm
Emitter Doping	$5 \times 10^{24}\ m^{-3}$	Collector Doping	$2 \times 10^{22}\ m^{-3}$
Emitter Hole Lifetime, τ_E	20 ns	Base Electron Lifetime, τ_B	500 ns
Mobility of Holes μ_h in Emitter	$175 \times 10^{-4}\ m^2V^{-1}s^{-1}$	Intrinsic Carrier Concentration	$1 \times 10^{16}\ m^{-3}$
Base Width	10 μm	Cross sectional area of transistor	$0.1 \times 10^{-2} cm^2$
Base Doping	$2 \times 10^{22}\ m^{-3}$	Dielectric Constant, ϵ_r	12
Mobility of electrons, μ_n in Base.	$1000 \times 10^{-4}\ m^2V^{-1}s^{-1}$	T	300 K

a) Draw a schematic diagram of this BJT connected in the common-emitter configuration and operating in the active mode. Make sure to label and show all the appropriate connections and current directions. [2 marks]

b) Sketch the typical IV-characteristics of this BJT for a variety of V_{BE} voltages. [2 marks]

c) In the absence of any applied bias voltage, calculate:
   i. The built-in barrier voltage in the base-collector region? [2 marks]
   ii. The built-in barrier voltage in the emitter-base region? [2 marks]
   iii. The width of the depletion region in the base-collector region, W_{bc}? [2 marks]
   iv. The width of the depletion region in the n-side of the base-collector region, $W_{bc(n)}$, knowing that $W_{bc} = W_{bc(n)} + W_{bc(p)}$? [2 marks]
   v. The width of the depletion region in the emitter-base-region? [2 marks]

d) Using your calculations above, what is the effective width of the base region (i.e. the neutral base between the depletion regions)? What can you deduce from this result? [3 marks]

e) Calculate the electron diffusion coefficient in the base, D_B. [2 marks]

f) Calculate the electron diffusion length in the base. [2 marks]

g) Calculate the hole diffusion coefficient in the emitter. [2 marks]

h) Calculate the hole diffusion length in the emitter. [2 marks]

Question 4 – Field Effect Transistors [25 Marks]

An n-channel Si enhancement NMOS has a gate width (W) of 200 μm, channel length (L) of 20 μm, and oxide thickness (t_{ox}) of 100 nm. The bulk electron mobility is approximately μ_e = 1400 $cm^2V^{-1}s^{-1}$ and the threshold voltage (V_{th}) is 1.5 V (ε_r = 4 for SiO_2). Also, $V_{GS} = V_{DS} = 6\ V$ and λ = 0.01. The NMOSFET is connected as an amplifier to an input signal. The output circuit has a load (or drain) resistor of 5 kΩ.

a) Draw the circuit diagram of this amplifier circuit, making sure to annotate the location of the input circuit, the output circuit and the NMOS transistor. [4 marks]

b) Determine the K value, given that the mobility in the channel is half the mobility in the bulk. [3 marks]

c) Determine the saturation voltage, $V_{DS}(sat)$. [2 marks]

d) Using your previous results, calculate the I_{DS}. [2 marks]

e) Determine the mutual or transconductance of this transistor. [3 marks]

f) What is the small signal gain? [2 marks]

g) In this case, what is the drain voltage, V_{DD}? [2 marks]

h) Using this V_{DD} value and assuming we have 2V pk-pk input signal into this circuit, what are the AC output voltage pk-pk values, $V_{DS(max)}$ and $V_{DS(min)}$? [4 marks]

i) Describe the principle of operation of your amplifier circuit. [3 marks]

EQUATION SHEET

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

$$np = n_i^2$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$I_0 = Aq\left(\frac{D_p p_{n_0}}{L_P} + \frac{D_n n_{p_0}}{L_n}\right) = Aqn_i^2\left(\frac{D_p}{L_PN_D} + \frac{D_n}{L_nN_A}\right)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$K = \frac{Z\mu_e \varepsilon}{2Lt_{ox}}$$

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

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

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

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

$$N_d x_n = N_a x_p$$

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

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

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