260

UNIVERSITY OF SWAZILAND

SUPPLEMENTARY EXAMINATION, SECOND SEMESTER

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FACULTY OF SCIENCE AND ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

TITLE OF PAPER: SOLID STATE ELECTRONICS

COURSE CODE: EE429

TIME ALLOWED: THREE HOURS

INSTRUCTIONS:

1. There are FOUR questions in this paper. Answer all questions. Each question carries 25 marks.
2. If you think not enough data has been given in any question you may assume any reasonable values.
3. A list of useful Equations and constants is attached

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THIS PAPER CONTAINS NINE (8) PAGES INCLUDING THIS PAGE

QUESTION ONE ***(25 marks)***

(a) Determine the number of atoms per unit cell in a face centered cubic Lattice. (3)

(b) The volume density of atoms for a face centered cubic lattice is $4 \times 10^{22} \text{cm}^{-3}$. Assume that the atoms are hard spheres with each atom touching its nearest neighbor. Determine the lattice constant and the radius of the atom. (5)

(c) Given that the lattice constant of GaAs is 5.65, determine the number of Ga atoms and As atoms per cm^3. (3)

(d) According to classical physics, the average energy of an electron in an electron gas at thermal equilibrium is $\frac{5kT}{2}$. Determine, for $T = 300$ K,

(i) the average electron energy in eV (2)

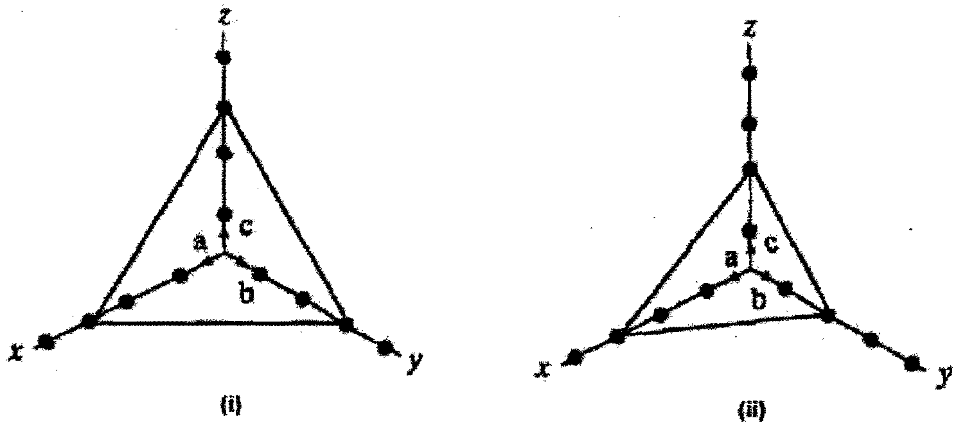
(ii) average electron momentum (3)

(iii) the de Broglie wavelength. (4)

(e) An electron and a photon have the same energy. At what value of energy (in eV) will the wavelength of the photon be 100 times that of the electron? (5)

QUESTION TWO ***(25 marks)***

(a) Describe the lattice planes shown in the figure below: (6)



(b) The Fermi energy level for a particular material at T = 300 K is 4.25 eV. The electrons in this material follow the Fermi-Dirac distribution function.

(i) Find the probability of an energy level at 4.50 eV being occupied by an electron. (4)

(ii) What is the percentage change in Fermi energy level corresponding to a 100% increase in temperature, assume E_F is constant? (5)

(iii) Assume that the Fermi energy level is 0.28 eV above the valence band energy. Determine the probability of a state being empty of an electron at E_V. What does the value obtained mean? (5)

(c) Show that the probability of an energy state being occupied ΔE above the Fermi energy is the same as the probability of a state being empty ΔE below the Femi level. (5)

QUESTION THREE *(25 marks)*

(a) Consider a uniformly doped silicon pn junction with doping concentrations $N_a = 5 \times 10^{17}\text{cm}^{-3}$ and $N_d = 10^{17}\text{cm}^{-3}$.

(i) Calculate V_{bi} at T = 300 K. (2)

The junction has a cross-sectional area of 10^{-4}cm^2 and has an applied reverse-bias voltage of V_R = 5 V. Calculate

(ii) the depletion region width W. (4)

(iii) E_{max} (2)

(iv) the total junction capacitance. (2)

(b) A Schottky diode is formed by depositing Au on n-type GaAs doped at $N_d = 5 \times 10^{16}\text{cm}^{-3}$, T = 300K. Determine the forward-bias voltage required to obtain $J_n = 5\text{A/cm}^2$. Assume $\emptyset_{Bn} = 0.867V$. (6)

(c) Consider an n-channel MOSFET with W = 15μm, L = 2μm, and $C_{ox} = 6.9 \times 10^{-8} F/cm^2$. When the transistor is biased in the saturation region, the drain current is $I_{D(sat)}$ =35μA at V_{GS}=1.5 V and $I_{D(sat)}$=75μA at V_{GS} =2.5 V. Determine the electron mobility and the threshold voltage. Assume V_{GS}=0.10V (5)

(d) Consider a p-channel GaAs pn JFET at T 300 K. The parameters are $N_d = 10^{18} cm^{-3}$ and $a = 0.65$μm. Determine the channel doping concentration such that the internal pinch-off voltage is V_{PO}=2.75 V. (4)

QUESTION FOUR ***(25 marks)***

(a) The experimentally measured junction capacitance of a one-sided silicon n+p junction biased at $V_R = 3$ V and at T = 300 K is C= 0.105 pF. The built-in potential barrier is found to be $V_{bi} = 0.765$ V. The cross-sectional area is $A = 10^{-5}$ cm^2. Find the doping concentrations. (5)

(b) Consider a silicon pn junction at T=300 K with a p-type doping concentration of $N_a = 2 \times 10^{17} cm^{-3}$.

(i) Determine the n-type doping concentration such that the maximum electric field is $E_{max} = 2 \times 10^5$ V/cm at a reverse-biased voltage of V_R =25 V. (3)

(ii) What is the junction capacitance given that $A = 3 \times 10^{-3} cm^2$? (3)

(iii) What is the difference between Avalanche breakdown and Zener breakdown in pn junctions? (4)

(c) An n$^+$p silicon diode at T=300K has the following parameters: $N_d = 10^{18}$cm^{-3}, $N_a = 10^{16}$ cm^{-3}, $D_n = 25 cm^2/s$, $D_p = 10 cm^2/s$. $\tau_{n0} = \tau_{p0} = 1\mu s$, and $A = 10^{-4}$cm^2
Determine the diode current for a forward-bias voltage of 0.8 V (5)

(d) Consider an n-type gallium arsenide semiconductor at T = 300 K doped at $N_d = 5 \times 10^{16} cm^{-3}$.

(i) Determine $E_{Fn} - E_F$ if the excess-carrier concentration is $0.01 N_d$ (3)

(ii) Determine $E_{Fi} - E_{Fp}$ (2)

USEFUL INFORMATION AND EQUATIONS

$$J_p(x_n) = -eD_p \frac{d(\delta p_n(x))}{dx}\bigg|_{x=x_n} \qquad J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$J_n(-x_p) = eD_n \frac{d(\delta n_p(x))}{dx}\bigg|_{x=-x_p} \qquad J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad p_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]$$

$$\delta n_p(x) = n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right) \qquad E_{Fi} - E_{\text{midgap}} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$\sigma \approx e\mu_n n = e\mu_n (N_d - N_a)$$

$$\delta p_n(x) = p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right) \qquad \sigma \approx e\mu_p p = e\mu_p (N_a - N_d)$$

$$L_p^2 = D_p \tau_{p0} \qquad L_n^2 = D_n \tau_{n0} \qquad J \propto \exp\left(\frac{-E_g}{kT}\right)\exp\left(\frac{eV_a}{kT}\right) \qquad J_s = en_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}}\right)$$

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \qquad \mathrm{E}_{\max} = -\left\{\frac{2e(V_{bi} + V_R)}{\epsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right\}^{1/2} \qquad A^* \equiv \frac{4\pi e m_n^* k^2}{h^3}$$

$$W = \left\{\frac{2\epsilon_s (V_{bi} + V_R)}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2} \qquad C' = \left\{\frac{e\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right\}^{1/2} \qquad J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$x_p = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2} \qquad \phi_{Bn} = (\phi_m - \chi) \qquad J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

$$I_D = \frac{W\mu_n C_{ox}}{L}(V_{GS} - V_T)V_{DS}$$

$$V_{p0} = \frac{ea^2 N_d}{2\epsilon_s}$$

Typical mobility values at $T = 300$ K and low doping concentrations

	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

Work functions of some elements

Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}

Electron affinity of some semiconductors

Element	Electron affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

PHYSICAL CONSTANTS

Physical constants

Avogadro's number	$N_A = 6.02 \times 10^{+23}$ atoms per gram molecular weight
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$e = 1.60 \times 10^{-19}$ C
Free electron rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}$ H/m
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm $= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.625 \times 10^{-34}$ J-s $= 4.135 \times 10^{-15}$ eV-s $\frac{h}{2\pi} = \hbar = 1.054 \times 10^{-34}$ J-s
Proton rest mass	$M = 1.67 \times 10^{-27}$ kg
Speed of light in vacuum	$c = 2.998 \times 10^{10}$ cm/s
Thermal voltage ($T = 300$ K)	$V_t = \frac{kT}{e} = 0.0259$ V $kT = 0.0259$ eV

Silicon, gallium arsenide, and germanium properties (T = 300 K)

Property	Si	GaAs	Ge
Atoms (cm^{-3})	5.0×10^{22}	4.42×10^{22}	4.42×10^{22}
Atomic weight	28.09	144.63	72.60
Crystal structure	Diamond	Zincblende	Diamond
Density (g/cm^3)	2.33	5.32	5.33
Lattice constant (Å)	5.43	5.65	5.65
Melting point (°C)	1415	1238	937
Dielectric constant	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, χ (V)	4.01	4.07	4.13
Effective density of states in conduction band, N_c (cm^{-3})	2.8×10^{19}	4.7×10^{17}	1.04×10^{19}
Effective density of states in valence band, N_v (cm^{-3})	1.04×10^{19}	7.0×10^{18}	6.0×10^{18}
Intrinsic carrier concentration (cm^{-3})	1.5×10^{10}	1.8×10^{6}	2.4×10^{13}
Mobility (cm^2/V-s)			
Electron, μ_n	1350	8500	3900
Hole, μ_p	480	400	1900
Effective mass $\left(\frac{m^*}{m_0}\right)$			
Electrons	$m_l^* = 0.98$	0.067	1.64
	$m_t^* = 0.19$		0.082
Holes	$m_{lh}^* = 0.16$	0.082	0.044
	$m_{hh}^* = 0.49$	0.45	0.28
Density of states effective mass			
Electrons $\left(\frac{m_{dn}^*}{m_o}\right)$	1.08	0.067	0.55
Holes $\left(\frac{m_{dp}^*}{m_o}\right)$	0.56	0.48	0.37
Conductivity effective mass			
Electrons $\left(\frac{m_{cn}^*}{m_o}\right)$	0.26	0.067	0.12
Holes $\left(\frac{m_{cp}^*}{m_o}\right)$	0.37	0.34	0.21