UNIVERSITY OF SWAZILAND

SUPPLEMENTARY EXAMINATION, SECOND SEMESTER

JULY 2017

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

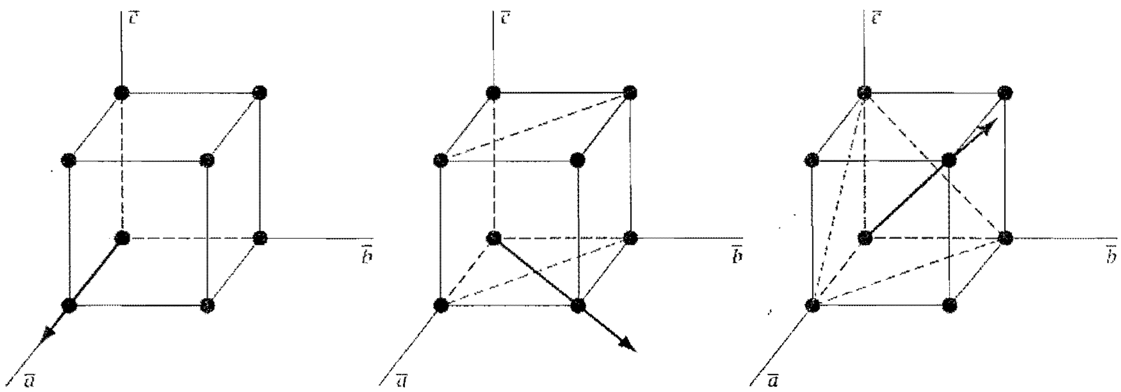
<u>QUESTION ONE *(25 marks)*</u>

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

b) For each of the diagrams below, determine

i. The plane shown (shaded) (3)

ii. The direction indicated by the arrow. (3)



A. B. C.

c) Consider the plane (100) in a face centered cubic lattice. Determine

i. The number of atoms in the plane (2)

ii. The surface density of the atoms if the lattice constant is 5 Å. NB: the surface density is the number of atoms per plane / surface area of the plane. (3)

d) The probability that a state at $E_c + kT$ is occupied by an electron is equal to the probability that a state at $E_v - kT$ is empty. Determine the position of the Fermi energy level as a function of E_c and E_v. (5)

e) The de Broglie wavelength of an electron is 85 Å. Determine the electron energy (eV), momentum, and velocity. (3)

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

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

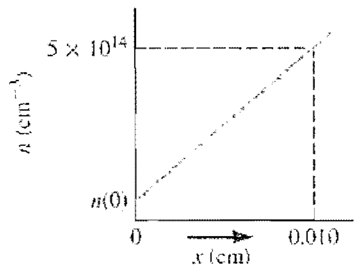
a) If the density of states function in the conduction band of a particular semiconductor is a constant equal to $g_c(E) = K$ where K is a constant, derive the expression for the thermal-equilibrium concentration of electrons in the conduction band, assuming Fermi–Dirac statistics and assuming the Boltzmann approximation is valid. (5)

b) Silicon at T=300K is doped with acceptor atoms at a concentration of $7\times10^{15} cm^{-3}$

i. Determine $E_F - E_V$. (3)

ii. Calculate the concentration of acceptor atoms that must be added to move the position of the Fermi level 1kT closer to the valence-band edge (5)

c) Consider a sample of silicon at T=300K. Assume that the electron concentration varies linearly with distance as shown in the figure below. The diffusion current density is found to be $J_n = 0.19\ \mathrm{A}/cm^2$. If the electron diffusion coefficient is $\mathrm{D_n} = 25\mathrm{cm^2/s}$, determine the electron concentration at $\mathrm{x} = 0$. (6)



d) The electron concentration at T=300K is given by

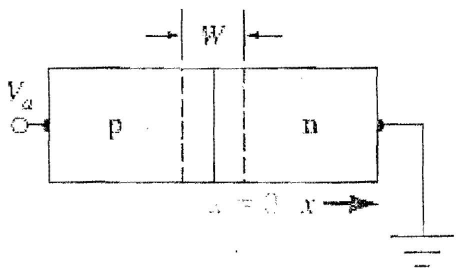
$$n(x) = 10^{16} exp\left(\frac{-x}{18}\right) cm^{-3}$$

where x is measured in Nm and is limited to $0 \leq x \leq 25$. The electron diffusion coefficient is $\mathrm{D_n} = 25\mathrm{cm^2/s}$ and the electron mobility is $\mu_n = 960\mathrm{cm^2/Vs}$. The total current density through the semiconductor is constant and equal to $\mathrm{J_n} = 40A/cm^2$. The electron current density has both drift and diffusion current density components. Determine the electric field as a function of x which must exist in the semiconductor. (6)

QUESTION THREE *(25 marks)*

(a) In Silicon, the hole concentration is given by $p(x) = 10^{15}exp(-x/L_p)$ for $x \geq 0$ and the electron concentration is given by $n(x) = 5\times10^{14}exp(x/L_n)$ for $x \leq 0$. The values of L_p and L_n are 5×10^{-4}cm and 10^{-3}cm respectively. The hole and electron diffusion coefficient are $10cm^2/s$ and $25cm^{2/s}$ respectively. The total current density is defined as the sum of the hole diffusion current density at $x = 0$ and the electron diffusion current density at $x = 0$. Calculate the total current density. (4)

(b) Consider the ideal long silicon pn junction shown in the figure below at T=300K. The n-region is doped with 10^{16}donor atoms per cm^3 and the p-region is doped with 5×10^{16} acceptor atoms per cm^3. The minority carrier lifetimes are $\tau_{n0} = 0.05\mu s$ and $\tau_{p0} = 0.01\mu s$. The minority carrier diffusion coefficients are $D_n = 23cm^2/s$ and $D_p = 8cm^2/s$. The forward-bias voltage is $V_a = 0.610V$.



Calculate

(i) the excess hole concentration as a function of x for $x \geq 0$ (5)

(ii) the hole diffusion current density at $x = 3\times10^{-4}$cm (3)

(c) Consider a uniformly doped silicon pn junction with doping concentrations $N_a = 5\times10^{17}$cm^{-3} and $N_d = 10^{17}$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)

(d) A Schottky diode is formed by depositing Au on n-type GaAs doped at $N_d = 5\times10^{16}$cm^{-3}, T=300K. Determine the forward-bias voltage required to obtain $J_n = 5$A/cm^2. Assume $\emptyset_{Bn} = 0.867V$. (3)

QUESTION FOUR (*25 marks*)

(a) A silicon pn junction in thermal equilibrium at T=300K is doped such that $E_F - E_{Fi} = 0.365\ eV$ in the n region and $E_{Fi} - E_F = 0.33\ eV$ in the p region.

(i) Sketch the energy band diagram for the pn junction. (3)

(ii) Find the impurity concentration in each region. (4)

(iii) Determine V_{bi}. (3)

(b) Consider a uniformly doped silicon pn junction at T=300K. At zero bias, 20% of the total space charge region is in the p region. The built in potential barrier is $V_{bi} = 0.71V$. Determine

(i) N_a (5)

(ii) N_d (2)

(iii) X_n (3)

(iv) X_p (2)

(v) $|E_{max}|$ (3)

USEFUL INFORMATION AND EQUATIONS

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx}$$

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

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

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

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

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

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

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

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

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

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

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

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