UNIVERSITY OF SWAZILAND

MAIN EXAMINATION, SECOND SEMESTER

MAY 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 five questions in this paper. Answer any FOUR 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 (9) PAGES INCLUDING THIS PAGE

QUESTION ONE *(25 marks)*

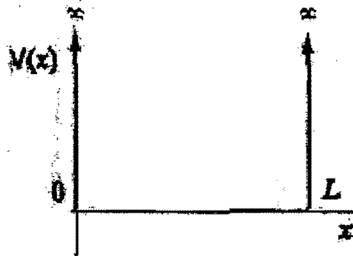
Schrödinger wave equation is used to denote the wave particle duality in quantum mechanics. The time independent Schrödinger wave equation can be derived as:

$$E\Psi = -\frac{\hbar^2}{2m}\frac{d^2\Psi}{dx^2} + V\Psi$$

And the time dependent Schrödinger wave equation can be denoted as:

$$i\hbar\frac{d\Psi}{dx} = -\frac{\hbar^2}{2m}\frac{d^2\Psi}{dx^2} + V\Psi$$

Consider a particle trapped in an infinite potential well such as denoted by the function below:

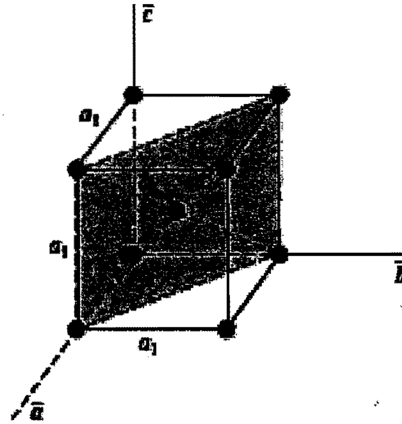


$$V(x) = 0, \ 0 < x < L$$
$$V(x) = \infty, \ x = 0, L$$

Solve the Schrodinger wave equation to find the wave function for a particle trapped in an infinite potential well.

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

(a) Consider the body centered cubic lattice structure and the plane (110) shown in the figure below.



Assume the atoms can be represented as hard spheres with the closest atoms touching each other and also assume that the lattice constant is $a_1 = 5\text{Å}$, determine

(i) The number of atoms in the lattice plane (110) shown. (3)

(ii) The surface density (atoms per unit area) in the lattice plane shown. (4)

(b) According to classical physics, the average energy of an electron in an electron gas at thermal equilibrium is $\frac{7kT}{2}$. Determine, for T=300 K,

(i) The average electron energy (in eV), (2)

(iii) The average electron momentum, and (3)

(iv) The de Broglie wavelength. (4)

(c) The Fermi energy level for a particular material at T = 300 K is 6.25 eV. The electrons in this material follow the Fermi-Dirac distribution function.

(i) Find the probability of an energy level at 6.50 eV being occupied by an electron (3)

(ii) Repeat this if the temperature is increased to T = 950 K. (Assume that E_F is a constant.) (2)

(iii) Calculate the temperature at which there is a 10 percent probability that a state 0.50 eV below the Fermi level will be empty of an electron. (4)

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) A silicon semiconductor material at T=300K is doped with Arsenic atoms to a concentration of $2 \times 10^{15}\text{cm}^{-3}$ and with Boron atoms to a concentration of $1.2 \times 10^{15}\text{cm}^{-3}$.

(i) Is the material p type or n type? Elaborate (3)

(ii) Determine n_0 and p_0. (5)

(iii) Additional Boron atoms are to be added such that the hole concentration is $4 \times 10^{15}\text{cm}^{-3}$. What concentration of Boron atoms are to be added and what is the new value of n_0? (6)

(b) For a particular semiconductor, $E_g = 1.35\ eV$, $m_p^* = 10m_n^*$, T=300K and $n_i = 1.5 \times 10^{10}\text{cm}^{-3}$.

(i) Determine the position of the intrinsic Fermi Energy level with respect to the centre of the band gap. (4)

(ii) Impurity atoms are added such that the Fermi level is 0.45 eV below the centre of the bandgap. Are acceptor or donor atoms added? What is the concentration of impurity atoms is added? (4)

(c) The doping concentrations in a uniformly doped silicon pn junction are $N_a = 4 \times 10^{16}\text{cm}^{-3}$ and $N_d = 2 \times 10^{15}\text{cm}^{-3}$. The measured built-in potential barrier is $V_{bi} = 0.55V$. Determine the temperature at which this result occurs. (3)

QUESTION FIVE (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

$$J \propto \exp\left(\frac{-E_g}{kT}\right)\exp\left(\frac{eV_a}{kT}\right) \qquad J_s = en_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_n}{T_{n0}}}+\frac{1}{N_d}\sqrt{\frac{D_p}{T_{p0}}}\right) \qquad n_0 = n_i\exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right) = V_t\ln\left(\frac{N_aN_d}{n_i^2}\right) \qquad E_{max} = -\left\{\frac{2e(V_{bi}+V_R)}{\epsilon_s}\left(\frac{N_aN_d}{N_a+N_d}\right)\right\}^{1/2} \qquad p_0 = n_i\exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]$$

$$E_{Fi} - E_{midgap} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$A^* = \frac{4\pi e m_n^* k^2}{h^3} \qquad W = \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a+N_d}{N_aN_d}\right]\right\}^{1/2} \qquad C' = \left\{\frac{e\epsilon_s N_aN_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2}$$

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

$$x_n = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{1/2} \qquad \phi_{Bn} = (\phi_m - \chi)$$

$$C' = \left\{\frac{ea\epsilon_s^2}{12(V_{bi}+V_R)}\right\}^{1/3}$$

$$I_D = \frac{W\mu_n C_{ox}}{L}(V_{GS}-V_T)V_{DS} \qquad V_{p0} = \frac{ea^2N_d}{2\epsilon_s}$$

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