UNIVERSITY OF SWAZILAND

MAIN EXAMINATION, SECOND SEMESTER

MAY 2016

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)*

(a) Determine the number of atoms per unit cell in a Diamond Lattice. (3)

(b) Assume that each atom is a hard sphere with the surface of each atom in contact with the surface of its nearest neighbor. Determine the percentage of total unit cell volume that is occupied in a Diamond lattice. (5)

(c) Given that the lattice constant of Germanium is 5.65Å, determine the volume density of Germanium atoms in a germanium semiconductor. (3)

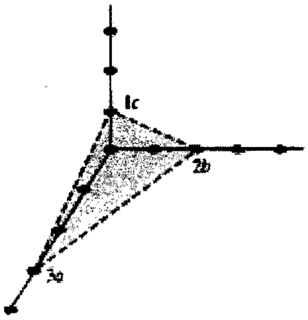
(d) According to classical physics, the average energy of an electron in an electron gas at thermal equilibrium is $\frac{3kT}{2}$. Determine, for $T = 300$ K,

- (i) the average electron energy in eV (2)
- (ii) average electron momentum (3)
- (iii) the de Broglie wavelength. (4)

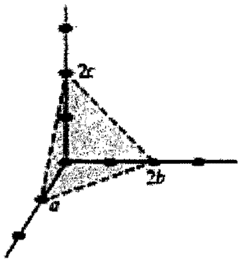
(e) An electron and a photon have the same energy. At what value of energy (in eV) will the wavelength of the photon be 10 times that of the electron? (5)

QUESTION TWO *(25 marks)*

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



(i)



(ii)

(b) The lattice constant of a simple cubic lattice is a_0, sketch the following plane directions.

- (i) [110] (2)
- (ii) [212] (2)

(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. (4)
- (ii) Repeat this if the temperature is increased to T = 950 K, assume that E_F is constant) (3)
- (iii) Calculate the temperature at which there is a 1 percent probability that a state 0.3 eV below the Fermi level will be empty of an electron. (4)

(d) 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. (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)

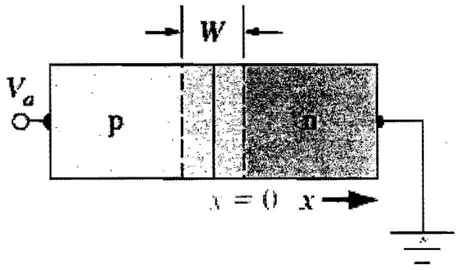
(b) A Schottky diode is formed by depositing Au on n-type GaAs doped at $N_d = 5 \times 10^{16}\text{cm}^{-3}$, T = 300K. Determine the forward-bias voltage required to obtain $J_n = 5\text{A/cm}^2$. Assume $\emptyset_{Bn} = 0.867V$. (6)

(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) 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 $x = 3 \times 10^{-4}$cm (5)

(b) Consider two ideal pn junctions at T=300K, having exactly the same electrical and physical parameters except for the bandgap energy of the semiconductor materials. The first pn junction has a bandgap energy of 0.525 eV and a forward-bias current of 10 mA with $V_a = 0.255V$. For the second pn junction, "design" the bandgap energy so that a forward-bias voltage of $V_a = 0.32V$ will produce a current of $10\mu A$. (6)

(c) An n$^+$p silicon diode at T=300K has the following parameters: $N_d = 10^{18}cm^{-3}$, $N_a = 10^{16}$cm3, $D_n = 25cm^2/s$, $D_p = 10cm^2/s$. $\tau_{n0} = \tau_{p0} = 1\mu s$, and $A = 10^{-4}cm^2$

Determine the diode current for

(i) a forward-bias voltage of 0.5 V (3)

(ii) a reverse-bias voltage of 0.5 V. (2)

(d) Calculate the applied reverse-bias voltage at which the ideal reverse current in a pn junction diode at T = 300 K reaches 90 percent of its reverse saturation current value. (4)

QUESTION FIVE (25 *marks*)

(a) The electron concentration in silicon at T= 300K is $n_0 = 5 \times 10^4 cm^{-3}$.
  (i) Determine p_0. (3)
  (ii) Is this n- or p-type material? (1)
  (iii)Determine the position of the Fermi level with respect to the intrinsic Fermi level. (3)

(b) For a particular semiconductor, $E_g = 1.50$ eV, $m_p^* = 10m_n^*$, T=300 K, and $n_i = 1 \times 10^5 cm^{-3}$.
  (i) Determine the position of the intrinsic Fermi energy level with respect to the center of the bandgap. (4)
  (ii) Impurity atoms are added so that the Fermi energy level is 0.45 eV below the center of the bandgap. Are acceptor or donor atoms added? What is the concentration of impurity atoms added? (5)

(c) Carrier transportation takes place by two methods, carrier drift and carrier diffusion, what is the difference between the two methods? (2)

(d) A silicon crystal having a cross-sectional area of $0.001 cm^2$ and a length of 10^{-3}cm is connected at its ends to a 10-V battery. At T=300 K, we want a current of 100 mA in the silicon. Calculate
  (i) the required resistance R, (2)
  (ii) the required conductivity (2)
  (iii) the density of donor atoms to be added to achieve this conductivity. (3)

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 $\left(\frac{m_{dn}^*}{m_0}\right)$	1.08	0.067	0.55
Holes $\left(\frac{m_{dp}^*}{m_0}\right)$	0.56	0.48	0.37
Conductivity effective mass			
Electrons $\left(\frac{m_{cn}^*}{m_0}\right)$	0.26	0.067	0.12
Holes $\left(\frac{m_{cp}^*}{m_0}\right)$	0.37	0.34	0.21