University of KwaZulu-Natal
School of Engineering
Electrical, Electronic & Computer Engineering

Examinations: June 2014

Physical Electronics I (ENEL2PAH1)

Duration: 2 hours **Total Marks: 100**

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General Instructions:

1. Full marks equal 100 marks.
2. Answer ALL questions.
3. Your answers should be neat and concise.
4. The use of any calculator is permitted.

Section A - *Quantum Mechanics and Statistical Mechanics* 25 Marks

Question 1

(a) (i) What did the Davisson-Germer experiment prove? (2)

(ii) With a well labeled sketch, explain the DG experimental. (9)

(b) Explain how a Scanning Electron Microscope uses 'wave-particle duality' to image objects. (3)

(c) Discuss the importance of the Fermi Energy level, especially its relevance to our understanding of electron flow in a pn-junction diode (one or two drawings may help). (6)

(d) The Fermi level of a newly discovered semiconductor is 6.25 eV. Assuming a Fermi-Dirac distribution, calculate the temperature at which there is a 3 % probability that a state 0.35 eV below the Fermi energy level will <u>not</u> contain an electron. (5)

[25]

Section B – *Semiconductor Equilibrium* 25 Marks

Question 2

(a) Derive an expression for the intrinsic concentration 'parameter', n_i, that is dependent on the energy gap, E_g. (5)

(b) Determine the thermal equilibrium electron and hole concentration for an n-type silicon semiconductor ($N_d = 10^{16}$ cm^{-3}) at $T = 300$ K. (5)

Question 3

Explain briefly what the Hall effect is and how an engineer could use the effect in an alarm system.
(6)

Question 4

A silicon crystal having a cross -sectional area of 0.001 cm2 and a length of 10-3 cm is connected at its ends to a 10-volt battery. At T = 300 K, we want a current of 100 mA in the silicon. Calculate the required:

(i) resistance R,
(2)

(ii) the required conductivity
(2)

(iii) the density of the donor atoms to be added to this conductivity
(2)

(iv) the density of the acceptor atoms to be added to form a compensated p-type material with the conductivity given from part (ii) if the initial concentration of donor atoms is Nd = 1015 cm-3.
(3)
[25]

Section C - *Devices* 50 Marks

Question 5 – *pn-Junctions*

(a) Discuss the formation of a pn-junction 'space charge region'.
(6)

(b) Draw the energy band diagram of a pn-junction diode under reverses bias.
(8)

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

(i) Calculate V_{bi} at T = 300 K
(3)

(ii) Determine the temperature at which V_{bi} decreases by 1 percent.
(5)

(d) Sketch the equivalent circuit of the small-signal model of a pn-junction and explain the physical origin of each component.
(8)
[30]

Question 6 – *Bipolar Transistors*

(a) Define the transistor action.
(3)

(b) Draw the energy band diagrams of an NPN bipolar transistor under (i) zero bias and (ii) 'forward active' mode and (iii) what is the nature of each biased junction when in forward active mode.

(10)

(c) With a bipolar transistor in 'forward active' mode, derive and <u>explain</u> the following expression,

$$i_C = -(eD_nA_{BE})/(x_B)[n_{B0}\exp(V_{BE}/V_t)].$$

(7)

[20]

END!

Data Sheet

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 Temperature (°C)	1415	1238	937
Dielectric constant	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, χ, (volts)	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 (density of states)			
Electrons (m_n^*/m_0)	1.08	0.067	0.55
Holes (m_p^*/m_0)	0.56	0.48	0.37

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	1.60×10^{-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	$\varepsilon_0 = 8.85 \times 10^{-14}$ 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 $\hbar = h/2\pi = 1.054 \times 10^{-34}$ 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)	$V_t = kT/e = 0.0259$ volt $kT = 0.0259$ eV

A FEW useful equations

(this is not considered a complete set)

$$J_{drift} = e\mu n\mathrm{E} \qquad g_d = \frac{I_{DQ}}{V_t} \qquad \sigma = \frac{L}{RA} \qquad \mu_p = \frac{d}{E_0 t_0}$$

$$\sigma = e(\mu_n n + \mu_p p) \qquad V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) \qquad W = \left[\frac{2\varepsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right]^{1/2}$$

$$E_{\max} = -\frac{eN_z x}{\varepsilon_s} \qquad C_d = \frac{I_{DQ}\tau_{po}}{2V_t} \qquad V_{BE} = V_t \ln\left(\frac{n_p(0)}{n_{p0}}\right)$$

$$I_f \approx I_s exp\left({eV}/{kT}\right) \qquad n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \qquad n_i^2 = N_c N_V \exp\left[\frac{-E_g}{kT}\right]$$

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \qquad f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \approx \exp\left[\frac{-(E - E_F)}{kT}\right]$$

$$J_{diff} = eD_n \frac{dn}{dx} \qquad n_0 p_0 = n_i^2 \qquad g_T = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\int_{E_C}^{E_C+kT}\sqrt{E - E_C}\,.dE$$

$$x_n = \left[\frac{2\varepsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right]^{1/2} \qquad C' = \left[\frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right]^{1/2}$$

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2} \qquad \frac{E_g - eV_{a2}}{kT_2} = \frac{E_g - eV_{a1}}{kT_1}$$

$$V_H = \frac{I_x B_z}{epd} \qquad \mu = \frac{I_x L}{enV_x Wd} \qquad D_p = \frac{(\mu_p E_0)^2(\Delta t)^2}{16t_0}$$

$$D_n\frac{\partial^2(\delta n)}{\partial x^2} + \mu_n E\frac{\partial(\delta n)}{\partial x} + g' - \frac{\delta n}{\tau_{no}} = \frac{\partial(\delta n)}{\partial t} \qquad L_n = \sqrt{(D_n\tau_{n0})}$$

$$V_H = E_H W \qquad n = -\frac{I_x B_z}{edV_H} \qquad C_T = \frac{\epsilon A}{W}$$

$$E_{Fi} - E_F = kT\ln\left(\frac{p_0}{n_i}\right) \qquad \rho = \frac{1}{e\mu_x N_x} \qquad J_n = eD_n d\frac{(\delta n)}{dx}$$