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

Examinations: June 2026
Physical Electronics I (ENEL2PAH1)

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

Examiners: Internal: Prof Leigh Jarvis
External: Dr Seare Rezenom

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 – Matter Waves

(a) Discuss the logic behind de Broglie in suggesting the hypothesis of the matter wave.

(4)

(b) An electron is accelerated from rest through a potential difference of 200 V between two parallel plates producing a uniform electric field. Hint: The electron gains kinetic energy from the electric field: $eV=1/2mv^2$

(i) Determine the momentum of the electron after acceleration.

(4)

(ii) Hence calculate its de Broglie wavelength in nm.

(4)

Question 2 – Origin of "Band Theory"

How is Schrödinger's time-independent equation connected to semiconductors and the origin of the energy band gap

(6)

Question 3 – Fermi Influence

Using a suitable energy band diagram, explain how the position of the Fermi level influences the conductivity in extrinsic semiconductors.

(7)

Section B – *Semiconductor Equilibrium*

23 Marks

Question 4 – The Power of Doping

(a) E_F moves up or down when a semiconductor is doped, but the product term "$n_o p_o$" does not change with doping, prove that this.

(7)

(b) Using the value of the silicon bandgap energy, Eg(Si), calculate:

(i) The intrinsic carrier concentration, n_i, for silicon. [Note: the answer is different from the data sheet.]

(4)

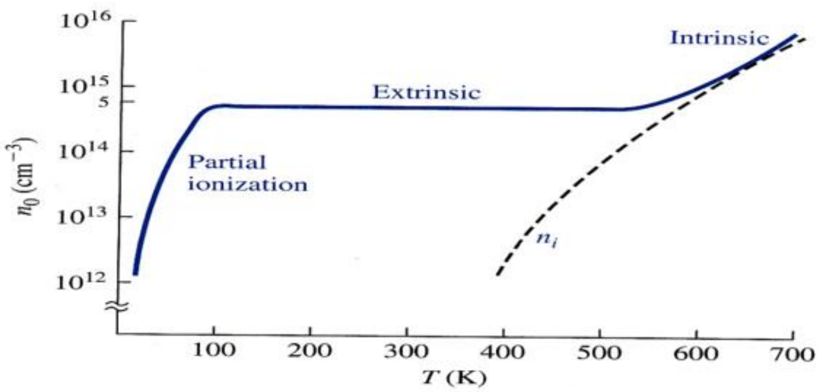
(ii) The electron concentration and hole concentration for intrinsic silicon.

(4)

(iii) If the silicon is doped with a donor concentration of 3×10^{12} cm^{-3}, determine the new electron and hole carrier concentrations.

(4)

Question 5 – Extrinsic Semiconductor



Explain the constant electron concentration of 5 x 10^{14} cm^{-3}, shown above.

(4)

Section C – *Semiconductor Devices* 52 Marks

Question 6 – Charge Desert

(a) Under zero bias conditions, explain the dynamics and the formation of the space charge region?

(10)

(b) Starting from the definition for the built-in potential,

$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|,$$

derive the following built-in voltage expression:

$$V_{bi} = V_t ln\left(\frac{N_a N_d}{n_i^2}\right).$$

(8)

(c) Consider a uniformly doped semiconductor (n_i = 1.0 x 10^{10} cm^{-3}) pn junction with doping concentration N_a=5 x 10^{17} cm^{-3}. Calculate the donor concentration, N_d such that the pn- junction will conduct in the forward bias mode with an applied voltage = 0.75 V at T = 300 K.

(4)

Question 7 – Semiconductors for Superconductors!

In superconductivity experiments, it is often necessary to measure cryogenic temperatures accurately, for example near liquid nitrogen temperature (77 K). A silicon pn junction diode can be used as a temperature sensor, by use of the following forward biased relationship:

$$J \propto exp(-Eg/kT)\, exp(eVa/kT)$$

A silicon diode is initially biased at V_{a1} = 0.60 V at T_1 = 300 K. Assume E_g = 1.12 eV.

(a) Other than being forward biased, what other operating condition must a pn junction diode satisfy in order to be used as a temperature sensor for superconductivity experiments?

(2)

(b) Based on your answer in (a) derive the relationship between V_{a1}, V_{a2}, T_1, and T_2.

(8)

(c) Calculate the forward-bias voltage V_{a2} at liquid nitrogen temperature.

(4)

(d) What is the average voltage sensitivity in mV/K between the two temperatures?

(4)

Question 8 – *Bipolar Transistors*

(a) Define the transistor action.

(3)

(b) Draw the energy band diagrams of an NPN bipolar transistor under zero bias

(3)

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

$$i_C = \frac{-eD_n A_{BE}}{x_B} . n_{B0} exp\left(\frac{V_{BE}}{V_t}\right).$$

(6)

END!
Data Sheet

Silicon, gallium arsenide, and germanium properties (T = 300 K)			
Property	**Si**	**GaAs**	**Ge**
Atoms (cm^{-3})	5.0 x 10^{22}	4.42x10^{22}	4.42x10^{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 (^oC)	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 x 10^{19}	4.7x10^{17}	1.04x10^{19}
Effective density of states in valence band, N_v, (cm^{-3})	1.04 x 10^{19}	7.0x10^{18}	6.0x10^{18}
Intrinsic carrier concentration (cm^{-3})	1.5 x 10^{10}	1.8x10^{6}	2.4x10^{13}
Mobility (cm^2/V-s) Electron, μ_n Hole, μ_p	 1350 480	 8500 400	 3900 1900
Effective mass (density of states) Electrons (m_n^*/m_0) Holes (m_p^*/m_0)	 1.08 0.56	 0.067 0.48	 0.55 0.37

Physical Constants	
Avogadro's number	N_A = 6.02 x 10^{23} atoms per gram molecular weight
Boltzmann's constant	k = 1.38 x 10^{-23} J/K = 8.62 x 10^{-5} eV/K
Electronic charge	1.60 x 10^{-19} C
Free electron rest mass	m_0 = 9.11 x 10^{-31} kg
Permeability of free space	μ_0 = 4π x 10^{-7} H/m
Permittivity of free space	ε_0 = 8.85 x 10^{-14} F/cm = 8.85 x 10^{-12} F/m
Planck's constant	h = 6.625 x 10^{-34} J-s = 4.135 x 10^{-15} eV.s $\hbar$=h/2π=1.054 x 10^{-34} J-s
Proton rest mass	M = 1.67 x 10^{-27} kg
Speed of light in vacuum	c = 2.998 x 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)

$J_{drift} = e\mu nE$ $\quad g_d = \frac{I_{DQ}}{V_t}$ $\quad \sigma = \frac{L}{RA}$ $\mu_p = \frac{d}{E_0 t_0}$

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

$E\frac{eN_z x}{\varepsilon_s}{}_{max}$ $\quad C_d = \frac{I_{DQ}\tau_{po}}{2V_t}$ $\quad V_{BE} = V_t\, ln\left(\frac{n_p(0)}{n_{po}}\right)$

$I_f \approx I_s exp\left({}^{eV}/_{kT}\right)$ $\quad n_0 = N_c\, exp\left[\frac{-(E_c - E_F)}{kT}\right]$ $\quad E = \frac{hc}{\lambda}$

$n_i^2 = N_c N_V\, exp\left[\frac{-E_g}{kT}\right]$

$V = \frac{E}{e}$ $\quad \lambda = \frac{h}{p}$ $\quad p = \sqrt{(2meV)}$

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

$J_{diff} = eD_n \frac{dn}{dx}$ $\quad n_0 p_0 = n_i^2$

$g_T = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\int_{E_C}^{E_C + kT}\sqrt{E - E_C}\,.dE$ $\quad n_0 = n_i = N_c \exp\left(\frac{-(E_c - E_{Fn})}{kT}\right)$

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

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

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

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

$V_H = E_H W$ $\quad n = -\frac{I_x Bz}{edV_H}$ $\quad R = \frac{L}{\sigma A}$ $\quad C_T = \frac{\varepsilon A}{W}$

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