NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2017-2018

EE2003 – SEMICONDUCTOR FUNDAMENTALS

November / December 2017 Time Allowed: 2½ hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 10 pages.
2. Answer ALL questions.
3. All questions carry equal marks.
4. This is a closed book examination.
5. Unless specifically stated, all symbols have their usual meanings.
6. A List of Formulae and Table of Physical Constants are provided in Appendices A and B on pages 6 - 8 and 9, respectively. A Table of Material Properties is provided in Appendix C on page 10.

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1. (a) A bcc lattice structure has a lattice constant of 1 Å. Assume that each atom is a hard sphere in this structure with the surface of each atom in contact with the surface of its nearest neighbor. Calculate: $\mathring{A} = 10^{-8}$ cm

   (i) The separating distance between the nearest atoms (in unit of Å).

   (ii) The volume of each atom (in unit of Å).

   (iii) The percentage of total unit cell volume that is occupied by the atoms.

(6 Marks)

Note: Question No. 1 continues on page 2.

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$4\times10^{-20}\cdot k^2\cdot e$

$k = 10^{-10}x$

$\frac{1}{m^*} = \frac{1}{\hbar^2}\cdot 8$ $8k\cdot$

(b) (i) A semiconductor has an electron band structure $E(k) = (4k^2 + 5)$ eV, where k is in the unit of Å^{-1}. (1 Å = 10^{-10} m). Calculate the effective mass of the electrons in the unit of kg.

Why is the effective mass different from the actual electron mass of 9.1×10^{-31} kg?

$(4\times10^{-20}\cdot k^2+5)\times e\cdot V$

$4\times e\cdot\times10^{-20}\times2$

(5 Marks)

(ii) Consider an n-type semiconductor rectangular bar. If the length of the bar is four times that of its original length (L), and the doping concentration (n) is decreased by half of its original doping, how will they affect the conductivity (σ) and current density (J_n) through the bar? Assume that the applied voltage remains the same.

$\ln\left(\frac{4N_c}{N_v}\right) = \frac{E_c+E_v-2E_F}{K_B T}$

$\cancel{2E_F}\ 2E_F = -K_B\cdot T\ln\left(\frac{4N_c}{N_v}\right)$

0.66eV

$-E_F+E_v+E_c - E_F$

Hint: $\sigma = \dfrac{nq^2 L}{m_n^*}$

(6 Marks)

$\times P_0$

(c) In a germanium sample at T = 250 K, it is found that $p_o = 4n_o$ and $N_d = 0$. Given that $N_c = 1.04\times10^{19}$ cm^{-3}, $N_v = 6.0\times10^{18}$ cm^{-3} and the energy bandgap of germanium is 0.66 eV, determine:

$P_o = \frac{N_a + \sqrt{N_a^2+4n_i^2}}{2}$

(i) The intrinsic carrier concentration (n_i).

$\frac{n_o}{n_i}$

(ii) The acceptor concentration (N_a).

$4 = \frac{N_v}{N_c}\cdot e^{\frac{E_c+E_v-2E_F}{K_B T}}$

$2P_o = N_a + \sqrt{N_a^2+4n_i^2}$

(8 Marks)

2. (a) In an n-type semiconductor bar, there is an increase in the electron concentration from left to right and an electric field is pointing to the left.

(i) With a suitable sketch, indicate the directions of the electron drift and diffusion current flow, respectively, and explain why.

(ii) If we double the electron concentration everywhere, what will happen to the diffusion current and the drift current? Explain your answers with appropriate equations.

Note: Question No. 2 continues on page 3.

$(2P_o-a)^2 = a+4n_i^2$

E

$\frac{1+4P_o+\sqrt{(1+4P_o)^2-16P_o^2+16n_i^2}}{2}$

$4P_o^2 + a^2 - 4aP_o = a+4n_i^2$

$\cancel{a^2 - (a+4P_o)}$

$a^2+(-1-4P_o)a+4P_o^2-4n_i^2=0$

$V+b = aV - 0.55a$

$\frac{V_{bi}+b}{V_{bi}-0.55} = \left(\frac{2.5}{0.4}\right)^2$ $\cancel{0.55 = (a-1)V}$ $\cancel{V = \frac{b.55}{a-1}}$ $\frac{b+0.55a}{a-1} = V$

$\cancel{V_{bi}}$ $V+b = aV - 0.55a$

(iii) If we add a constant concentration of electrons everywhere, what will happen to the drift and diffusion currents? Explain your answers with appropriate equations.

$b+0.55a = (a-1)V$

(9 Marks)

(b) The junction capacitance values C_J measured for a *pn*-junction diode are 2.5 pf and 0.4 pf at the forward bias of 0.55 V and reverse bias of 6 V, respectively.

(i) At thermal equilibrium (i.e. zero bias), what will the electric potential V_o across the junction be?

(ii) State whether the charge storage capacitance values C_S measured at the same biasing voltages will be higher or lower to the corresponding values of C_J in each case. Briefly explain for each case.

(8 Marks)

(c) Consider a $P^{++}N^{+}P$ bipolar junction transistor uniformly doped in each region. Sketch the energy band diagram for the case when the transistor is:

(i) In thermal equilibrium condition.

(ii) Biased in forward active mode.

Mark clearly the conduction band, the valence band and the Fermi level in the diagram, and briefly explain your drawing.

(8 Marks)

3. (a) An abrupt Si *p-n* junction is formed at 300 K with the dopant concentration $N_a = 1\times10^{16}$ cm^{-3} on the *p*-side. Assume the built-in potential across the junction $V_o = 0.757$ V, the dielectric constant $\varepsilon_r = 11.7$ and the intrinsic carrier concentration $n_i = 1\times10^{10}$ cm^{-3}.

(i) Determine the donor concentration N_d at the *n*-side.

(ii) Calculate the depletion width x_{po} on the *p*-side of the junction in μm.

$V_{bi} = \frac{KT}{q}\cdot \ln\left(\frac{N_a N_d}{n_i^2}\right)$

(8 Marks)

$e^{\frac{Vq}{KT}} = \frac{N_a \cdot N_d}{n_i^2}$

Note: Question No. 3 continues on page 4.

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(b) Two abrupt silicon p^+-n junction diodes D1 and D2 at 300 K have dopant concentrations $N_{D1} = 1\times10^{15}\text{cm}^{-3}$ and $N_{D2} = 1\times10^{16}\text{cm}^{-3}$, respectively. Assume that the hole carrier mobility μ_p and the minority carrier life time τ_p are independent of the dopant concentration.

(i) Starting from the expression for I_0, show that:

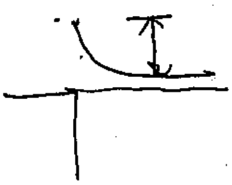
$$\frac{I_{01}}{I_{02}} = \frac{N_{D2}}{N_{D1}} \qquad \frac{N_{D2}}{N_{D1}}$$

where I_{01} and I_{02} are the reverse saturation currents for diodes D1 and D2, respectively. Note that the minority carrier density n_{p0} is very small when the p-side is highly doped.

(ii) The reverse saturation current I_{02} determined for D2 is 1 μA. Calculate the reverse saturation current I_{01} for D1, and briefly explain the difference in the two values.

(8 Marks)

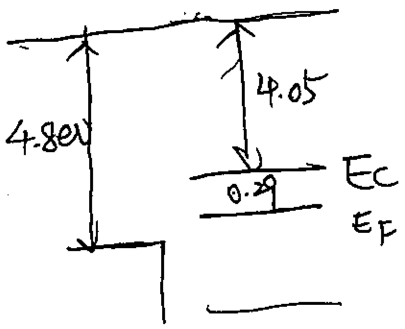
(c) A layer of gold metal is deposited on Si to form an ideal metal-semiconductor contact at 300 K. The Fermi level in Si is located 0.29 eV below the conduction band edge E_c. The bandgap and the electron affinity of Si are 1.1 eV and 4.05 eV, respectively. The work function of gold is 4.8 eV and the intrinsic carrier concentration n_i of Si at 300 K is 1.5×10^{10} cm^{-3}.



(i) Determine the semiconductor work function $q\Phi_S$ and the values of energy barriers for the carriers at the metal and semiconductor sides.

(ii) State and justify whether the contact designed is ohmic or Schottky.

(iii) Assume that the same metal/Si contact is made at a higher temperature (>300 K). State and comment whether the energy barrier at the Si-side will increase, decrease or remain the same. Comment whether the contact type will be the same as determined in part (ii).



(9 Marks)

$4.8 - 4.05 - 0.55$

0.2

4. (a) What is a photodiode? What is the function of a photodiode? Briefly explain its operation principle.

(6 Marks)

(b) Sketch the current-voltage characteristics of a photodiode for different optical powers. Label clearly the photodiode voltage and photocurrent axes.

(4 Marks)

(c) Assuming that a photodiode is made of silicon semiconductor material, calculate its cut-off wavelength. Can the photodiode be used in the fibre-optic communication systems to detect optical signals with the wavelength of 1.55 μm?

(5 Marks)

$r = 0.2 \times 10^{-1}$ cm

(d) A silicon photodiode has an active area of diameter $\varnothing$ = 0.4 mm. When a yellow light beam (λ = 580 nm) with an intensity of 0.2 mW/cm^2 is incident on this photodiode, a photocurrent of 60 nA is generated. Determine the responsivity and quantum efficiency of the photodiode at 580 nm.

(6 Marks)

(e) Both light emitting diodes (LEDs) and laser diodes (LDs) are light emitting devices made of direct bandgap semiconductors. While the light emitted by the LD normally has narrow spectral profile, the light emitted by an LED has broad spectral bandwidth. Based on the light generation processes in the devices, explain why they have such spectral differences.

(4 Marks)

$$R = \eta \cdot \frac{e\lambda}{hc}$$

$$\eta = \frac{Rhc}{e\lambda}$$

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APPENDIX A

List of Selected Formulae

$$\xi = \frac{1}{q}\frac{dE}{dx}, \quad E_{ph} = h\nu = \frac{hc}{\lambda}, \quad \frac{1}{m^*} = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}, \quad E_n = -\frac{q^4}{2(4\pi\,\hbar)^2}\left(\frac{m_n^*}{\varepsilon_r^2\varepsilon_0^2}\right)\frac{1}{n^2},$$

$$f(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{k_BT}\right]}, \quad g_c(E) = \frac{4\pi\left(2m_n^*\right)^{3/2}}{h^3}\sqrt{E-E_c}, \quad g_v(E) = \frac{4\pi\left(2m_p^*\right)^{3/2}}{h^3}\sqrt{E_v-E},$$

$$n_0 = N_c \exp\left[-\frac{E_c-E_F}{k_BT}\right], \quad N_c = 2\left(\frac{2\pi\, m_n^*\, k_BT}{h^2}\right)^{3/2},$$

$$p_0 = N_v \exp\left[-\frac{E_F-E_v}{k_BT}\right], \quad N_v = 2\left(\frac{2\pi\, m_p^*\, k_BT}{h^2}\right)^{3/2},$$

$$p_0 + N_d = n_0 + N_a, \quad E_{thermal\,(3-D)} = \frac{3}{2}k_BT, \quad v_{dp} = \mu_p\,\xi, \quad \mu_p = \frac{q\,\tau_{cp}}{m_p^*},$$

$$v_{dn} = -\mu_n\,\xi, \quad \mu_n = \frac{q\,\tau_{cn}}{m_n^*}, \quad J_{p\,drift} = q\,p\,\mu_p\,\xi, \quad J_{n\,drift} = q\,n\,\mu_n\,\xi,$$

$$J_{drift} = J_{n\,drift} + J_{p\,drift} = \sigma\,\xi, \quad \sigma = q\,\mu_n\,n + q\,\mu_p\,p, \quad \rho = \frac{1}{\sigma}, \quad J = \frac{I}{A}, \quad \xi = \frac{V}{l},$$

$$R_R = \rho\frac{l}{A}, \quad l = v_{th}\,\tau_{cn}, \quad v_{th}\,l = D_n, \quad J_{n\,diff} = q\,D_n\frac{dn}{dx}, \quad J_{p\,diff} = -q\,D_p\frac{dp}{dx},$$

$$J_n = J_{n\,drift} + J_{n\,diff}, \quad J_p = J_{p\,drift} + J_{p\,diff}, \quad J_{total} = J_n + J_p,$$

$$D_n = \frac{k_B\,T}{q}\mu_n, \quad D_p = \frac{k_B\,T}{q}\mu_p$$

$$n_0 = n_i \exp\left[\frac{E_F-E_i}{k_BT}\right]$$

$$p_0 = n_i \exp\left[\frac{E_i-E_F}{k_BT}\right] \qquad n_0p_0 = n_i^2$$

$$n_i = n_0 \cdot \exp\left(\frac{E_i - E_F}{k_BT}\right)$$

List of Selected Formulae (cont'd)

$$R = \alpha_r np\,,\quad G_{th} = \alpha_r n_i^2\,,\ \tau_n = \frac{1}{\alpha_r p_0}\,,\quad \tau_p = \frac{1}{\alpha_r n_0}$$

$$\frac{dn}{dt} = \frac{d\Delta n}{dt} = G_L + G_{th} - R = G_L - \frac{\Delta n}{\tau_n}\,,\quad \Delta n_{ss} = G_L \tau_n\,,\quad \Delta n(t) = \Delta n(t=0)\exp\left(-\frac{t}{\tau_n}\right)$$

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + G_L - \frac{\Delta n}{\tau_n}\,,\quad \Delta n(x) = \Delta n(x=0)\exp\left(-\frac{x}{L_n}\right),\quad L_n = \sqrt{D_n \tau_n}$$

$$\frac{dp}{dt} = \frac{d\Delta p}{dt} = G_L + G_{th} - R = G_L - \frac{\Delta p}{\tau_p}\,,\quad \Delta p_{ss} = G_L \tau_p\,,\quad \Delta p(t) = \Delta p(t=0)\exp\left(-\frac{t}{\tau_p}\right)$$

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + G_L - \frac{\Delta p}{\tau_p}\,,\quad \Delta p(x) = \Delta p(x=0)\exp\left(-\frac{x}{L_p}\right),\quad L_p = \sqrt{D_p \tau_p}$$

$$n = n_0 + \Delta n = n_i \exp\left(\frac{E_{Fqn} - E_i}{kT}\right),\quad p = p_0 + \Delta p = n_i \exp\left(\frac{E_i - E_{Fqp}}{kT}\right)$$

$$\frac{d^2V(x)}{dx^2} = -\frac{d\xi(x)}{dx} = -\frac{\rho_c}{\varepsilon_r \varepsilon_0} = -\frac{q}{\varepsilon_r \varepsilon_0}(p - n + N_d - N_a)$$

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{p_{p0}}{p_{n0}}\right) = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right),\quad \frac{p_{p0}}{p_{n0}} = \frac{n_{n0}}{n_{p0}} = \exp\left(\frac{qV_{bi}}{kT}\right)$$

$$N_d x_n = N_a x_p\,,\quad \xi_{max} = -\frac{qN_d x_n}{\varepsilon_r \varepsilon_0} = -\frac{qN_a x_p}{\varepsilon_r \varepsilon_0}\,,\quad W = \left[\frac{2\varepsilon_r \varepsilon_0 (V_{bi} - V_a)}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

$\frac{Na+Nd}{NaNa}$

$$\frac{p_{p0}}{p_n(x_n)} = \frac{n_{n0}}{n_p(-x_p)} = \exp\left[\frac{q}{kT}(V_{bi} - V_a)\right],\quad \frac{p_n(x_n)}{p_{n0}} = \frac{n_p(-x_p)}{n_{p0}} = \exp\left(\frac{qV_a}{kT}\right)$$

$$\Delta n_p(x) = \Delta n_p(-x_p)\exp\left(-\frac{x}{L_n}\right) = n_{p0}\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]\exp\left(-\frac{x}{L_n}\right)$$

$$\Delta p_n(x) = \Delta p_n(x_n)\exp\left(-\frac{x}{L_p}\right) = p_{n0}\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]\exp\left(-\frac{x}{L_p}\right)$$

$$I = I_0\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right],\quad I_0 = qA\left(\frac{D_p}{L_p}p_{n0} + \frac{D_n}{L_n}n_{p0}\right),\quad C_j = \left|\frac{dQ_j}{dV_a}\right| = \frac{\varepsilon_r \varepsilon_0}{W}$$

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List of Selected Formulae (cont'd)

$$C_s = \left|\frac{dQ_n}{dV_a}\right| = \frac{q}{kT}|Q_n| = \frac{q}{kT} I\tau_n \text{ (n}^+\text{p diode)}, \quad C_s = \frac{dQ_p}{dV_a} = \frac{q}{kT} Q_p = \frac{q}{kT} I\tau_p \text{ (p}^+\text{n diode)}$$

$$Q_n = -qAL_n\Delta n_p, \quad Q_p = qAL_p\Delta p_n$$

$$I(x) = I_0 \exp(-\alpha x), \quad G = R_1 R_2 \exp(2(k-\gamma)L), \quad k_{th} = \gamma + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

$$\frac{n\lambda}{2} = L, \quad f = \frac{nc}{2L}, \quad \Delta f = \frac{\Delta nc}{2L}, \quad I = I_S\left[\exp\left(\frac{qV}{\beta kT}\right) - 1\right], \quad \frac{hc}{\lambda} = E_{ph},$$

$$\text{Reflectivity, } r = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2, \quad I_t = (1-r)I_o, \quad I = I_S\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$$

$$I = RP, \quad R = \eta\frac{e}{E_{ph}}, \quad \eta = \frac{N_e}{N_p}$$

Table of Physical Constants

	Symbol	Value	Unit
Planck's constant	h	6.626×10^{-34}	J-s
Speed of light	c	3.0×10^{8}	m/s
Electronic charge	e (or q)	1.6×10^{-19}	C
Boltzmann's constant	k_B (or k)	1.38×10^{-23}	J/K
Free electron rest mass	m_0	9.1×10^{-31}	kg
Proton rest mass	m_p	1.67×10^{-27}	kg
Avogadro's number	N_A	6.02×10^{23}	mol^{-1}
Permeability of free space	μ_0	$4\pi \times 10^{-7}$	H/m
Permittivity of free space	ε_0	8.85×10^{-12} ~~8.85×10-10~~	F/m
Rydberg constant	R_d	1.097×10^{7}	m^{-1}
Bohr radius	a_0	5.292×10^{-11}	m
Gas constant	R	8.31	$\mathrm{Jmol}^{-1}\mathrm{K}^{-1}$
Electron-volt	1 eV	1.6×10^{-19}	J
Thermal voltage ($T = 300$ K)	k_BT/q	0.0259	V

8.85×10^{-14} F/cm

APPENDIX C

Properties of Silicon, Gallium Arsenide, and Germanium ($T = 300$ K)

Property	**Si**	**GaAs**	**Ge**
Atomic density (cm^{-3})	5.00×10^{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	5.43	5.65	5.65
Melting point (°C)	1415	1238	937
Dielectric constant	Si: 11.7 SiO_2: 3.8	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity (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 ($cm^2/V\text{-}s$) Electron, μ_n Hole, μ_p	 1350 480	 8500 400	 3900 1900

END OF PAPER

EE2003 Examination Solution (for reference only)
November 2017

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1.(a)

(i) $Å = 10^{-8}$ cm

In BCC lattices:

$\sqrt{3}a = 4r$, where r is the radius of each atom.

$\Rightarrow r = \frac{\sqrt{3}}{4} Å$

(ii)

$V = \frac{4}{3}\pi r^3 = 0.34 Å^3$

(iii)

No. of atoms $= 1 + 8 \times \frac{1}{8} = 2$

$2V/a^3 = 68\%$

1.(b)

(i) Since the calculated mass is in S.I. unit, we need to convert the unit into SI unit.

$E(k) = (4 \times 10^{-20} \cdot k^2 + 5) \times e \cdot V$, where k is in the unit of m.

$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2E}{dk^2}$$

$$\Rightarrow \frac{1}{m^*} = \frac{1}{\hbar^2} \cdot (8 \times 10^{-20} \times e)$$

$$\Rightarrow m^* = 8.677 \times 10^{-31} (kg)$$

In a real crystal, both external and internal forces will act on the electrons. We adopt the notion "effective mass" to take into account the actual ~~fa~~ mass and internal forces of electrons. The effective mass is thus different from actual mass.

1 (b)

(ii)

According to the equation $\sigma = \frac{nq^2 L}{m_n^*}$

$\sigma_{new} = 2\sigma$

$J = \sigma E$, since the applied ~~field~~ voltage remains the same, electric field will decrease by four times

$J_{new} = \frac{1}{2} J$

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1 (C)

$$\begin{cases} n_0 = N_c \cdot \exp\left(\frac{E_F - E_c}{K_B \cdot T}\right) \\ P_0 = N_v \cdot \exp\left(\frac{E_v - E_F}{K_B \cdot T}\right) \end{cases}$$

$$\therefore \frac{P_0}{n_0} = 4 = \frac{N_v}{N_c} \cdot \exp\left(\frac{E_v + E_c - 2E_F}{K_B \cdot T}\right)$$

$$\Leftrightarrow 4 = \frac{N_v}{N_c} \cdot \exp\left(\frac{0.66eV - 2E_F}{K_B T}\right)$$

$$\Rightarrow E_F = 0.309\,eV \text{ above } E_c$$

$$\therefore n_0 = 1.775 \times 10^{25} \cdot cm^{-3} = n_i \exp\left(\frac{E_F - E_i}{K_B T}\right) \Rightarrow n_i = 4.707 \times 10^{25} \cdot cm^{-3}$$

(ii)

$$P_0 = \frac{N_a^2 + \sqrt{N_a^2 + 4n_i^2}}{2}$$

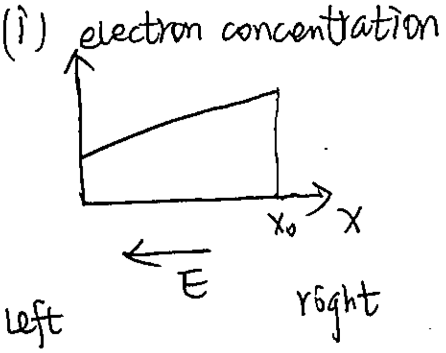
$$\Rightarrow N_a^2 = \frac{1 + 4P_0 + \sqrt{(1+4P_0)^2 - 16P_0^2 + 16n_i^2}}{2}$$

$$= 2.36 \times 10^{26} \cdot cm^{-3}$$

$$\therefore N_a = 1.53 \times 10^{13} \cdot cm^{-3}$$

2(a)

(i)



① Drift current:

Same as the external electric field, which points from right to left.

② Diffusion current:

Since electrons diffuse from right to left, the current flow is in the reverse left to right direction.

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(ii)

① Diffusion current:

$J_{ndiff} = q \cdot D_n \frac{dn}{dx}$, if electron concentration doubles, $\frac{dn}{dx}$ also doubles everywhere, thus diffusion current will double.

② $J_{drift} = q \cdot \mu_n \cdot n \cdot E$

Since n doubles, J and thus the drift current will double.

(iii)

① Diffusion current:

$J = q \cdot D_n \frac{dn}{dx}$, $\frac{dn}{dx}$ will remain the same, therefore diffusion current will not change.

② Drift current:

$J = q \cdot \mu_n \cdot n \cdot E$.

Since n increases, drift current will also increase.

2(b)

(i)

$$C_j = \frac{\varepsilon_r \varepsilon_0}{W} = \varepsilon_r \varepsilon_0 \cdot \left(\frac{q}{2\varepsilon_r \varepsilon_0 (V_{bi} - V_a)} \cdot \frac{N_a N_d}{(N_a + N_d)} \right)^{\frac{1}{2}}$$

$$\therefore C_j \propto \sqrt{\frac{1}{V_{bi} - V_a}}$$

$$\therefore \frac{2.5pf}{0.4pf} = \sqrt{\frac{V_0 + 6}{V_0 - 0.55}}$$

$$\Rightarrow V_0 = 0.722 (V)$$

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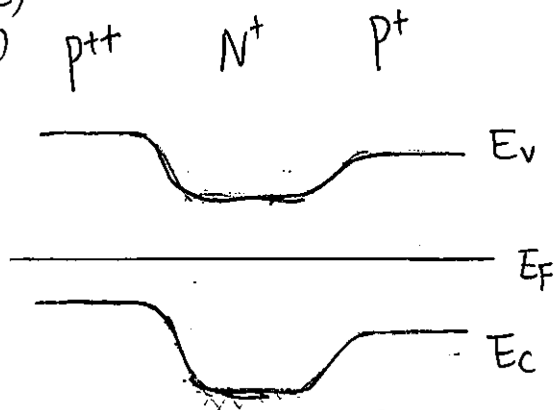
(ii)

2(c)

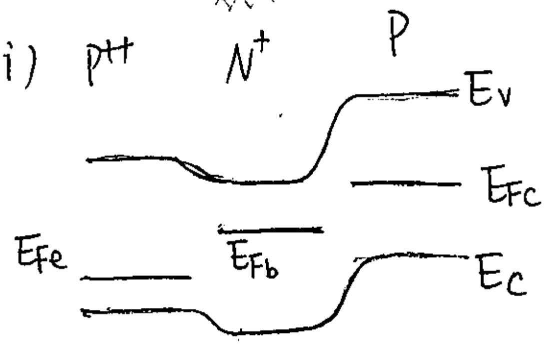
(i)



Under thermal equilibrium, Fermi level is constant across the BJT.

conduction and valence band levels vary in emitter, base and collector.

(ii)



Under forward active mode,

$E_{Fc} > E_{Fb} > E_{Fe}$

We can draw the energy band diagram based on this fact and the previous diagram.

3(a)

(i) $V_{bi} = \frac{KT}{q} \cdot \ln\left(\frac{N_a \cdot N_d}{n_i^2}\right)$

$\Leftrightarrow e^{\frac{Vq}{KT}} = \frac{N_a \cdot N_d}{n_i^2}$

$\therefore N_d = \frac{n_i^2}{N_a} \cdot e^{\frac{Vq}{KT}} = 5.285 \times 10^{16} \cdot cm^3$

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(ii) $W = \sqrt{\frac{2\varepsilon_r\varepsilon_0(V_{bi}-0)}{q} \cdot \frac{N_a+N_d}{N_a \cdot N_d}} = 3.92 \times 10^{-5} \cdot cm$

$x_{p_0} = \frac{N_d}{N_a+N_d} \cdot W = 3.297 \times 10^{-5}\ cm = 32.97\ (\mu m).$

3(b)

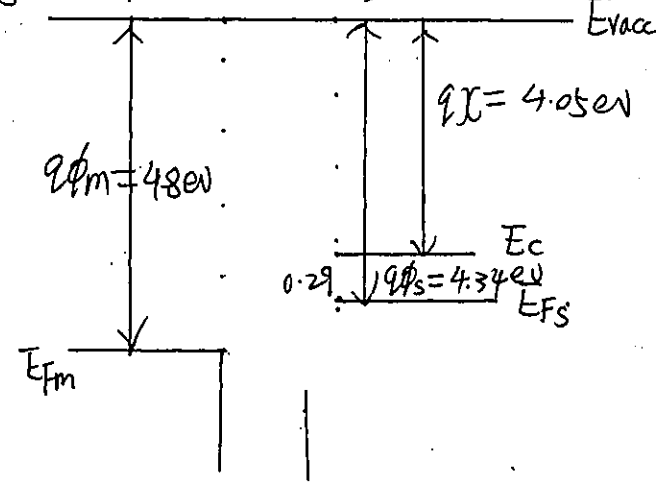
(i) $I_0 = q \cdot n_i^2 \cdot A \cdot \frac{D_n}{L_n \cdot N_D}$ (Since they are p^+n junctions)

$\Rightarrow I_0 \propto \frac{1}{N_D}$

$\therefore \frac{I_{01}}{I_{02}} = \frac{N_{D2}}{N_{D1}}$

(ii)

$I_{01} = I_{02} \cdot \frac{N_{D2}}{N_{D1}} = 10\ \mu A$



3(c)

(i)

$q\Phi_s = 0.29 + 4.05 = 4.34eV$

Electrons in the CB of Si face no potential barrier crossing to the metal.

Electrons in the metal see a barrier of $q(\phi_m - \chi) = 4.8 - 4.05 = 0.75eV$

(ii)

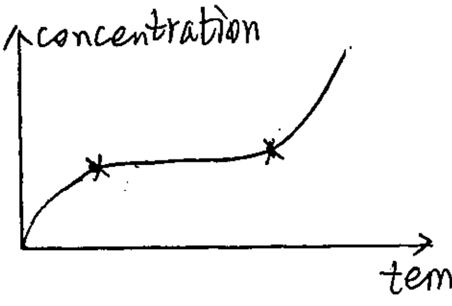
$E_c - E_f = 0.29eV < \frac{E_g}{2} \Rightarrow$ This is an n type semiconductor.

$\phi_m > \phi_s$

$\therefore$ This is a Schottky contact.

3(c)
(iii)

As the temprature further rises, carrier concentration of the semiconductor will grow exponentially after a certain point.



Si will then perform as an intrinsic semiconductor, thus the fermi level will go down gradually.

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Energy barrier at Si side ($q\phi_m - q\phi_s$) will then decrease.
E_F will no longer sink when it has reached E_{Fi}.
Under such situation, $q\phi_m - q\phi_s = 0.2eV > 0$, therefore it will remain as Schottky contact.

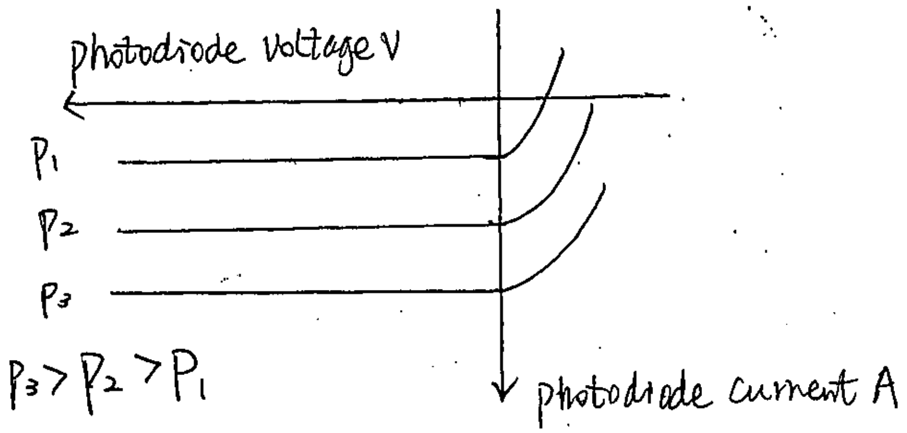
4(a)

① A photodiode is a pn junction diode operated in a reverse-biased voltage condition.

② It is used to measure incident optical power.

③ When the input optical power increases, more electron-hole pairs are generated in the pn junction, the photocurrent will thus increase. We can then calculate optical power by the photocurrent value(s).

4(b)



4(c)

$E_g = 1.12\,eV$

$$\frac{h \cdot c}{\lambda} = E_g$$

$\Rightarrow \lambda = 1.108\,\mu m$

Since $1.55\,\mu m >$ cut-off wavelength $= 1.108\,\mu m$,
this photodiode cannot be used

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4(d)

$r = 0.2 \times 10^{-1}\,cm$

$A = \pi r^2 = 1.257 \times 10^{-3}\,cm^2$

incident power $= A \cdot 0.2\,mW/cm^2 = 2.513 \times 10^{-7}\,W$

$I = RP$

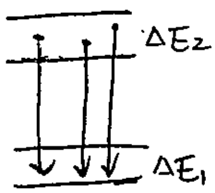
$\therefore R = I/P = 0.239\,(A/W)$

$$R = \eta \frac{e}{E_{ph}}$$

$$\Rightarrow \eta = \frac{R \cdot E_{ph}}{e} = \frac{R \cdot hc}{e\lambda} = 0.511$$

4(e)

① In LED, light is generated through spontaneous emission,
In practice, electrons are located in a vicinity of high level E_2 or low level E_1.



When spontaneous emisssion happens, electrons from ΔE_2 drop to ΔE_1, thus photons of different energys are generated. Therefore, Light generated by LED has a broad spectral bandwidth.

② In LD, light is generated through stimulated emission,
such mechanism will make sure emitted light is monochromatic.
As a result, light generated by LD has a single dominant wavelength.