NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2019-2020

EE2003 – SEMICONDUCTOR FUNDAMENTALS

November / December 2019 Time Allowed: 2½ hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 9 pages.
2. Answer all 4 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 5 - 8. A Table of Material Properties is provided in Appendix C on page 9.

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1. (a) (i) The Miller indices of a plane in a cubic crystal are given as (241). Sketch this plane in a *xyz* coordinate space.

   (ii) 55% of the unit cell of a body centered cubic crystal is occupied by atoms. The lattice constant is 5.7 Å. Calculate the atomic diameter if all the atoms are identical and each is a perfect sphere.

   (iii) Figure 1 on page 2 shows the unit cell of the wurtzite crystal of a compound semiconductor, where A and B are two different atoms. The top and bottom surfaces are rhombuses with dimensions and internal angles as shown. Calculate the volume density of atom B.

(13 Marks)

Note: Question No. 1 continues on page 2.

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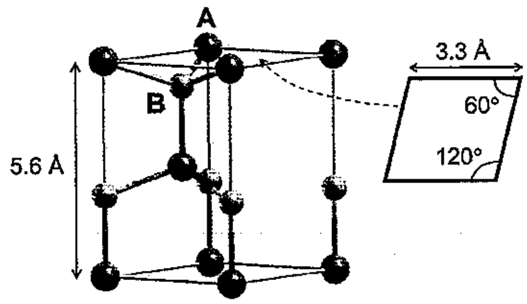

Figure 1

(b) Figure 2 shows the energy band diagram of a semiconductor at 300 K. The intrinsic carrier concentration is 1.2×10^{9} cm^{-3}.

(i) What is the type of doping? Is the doping uniform or non-uniform? Briefly explain your answers.

(ii) Acceptor impurity atoms of density 6.7×10^{15} cm^{-3} are added uniformly throughout the sample. Sketch the resultant energy band diagram, indicating the position of the Fermi level in the bandgap.

(12 Marks)

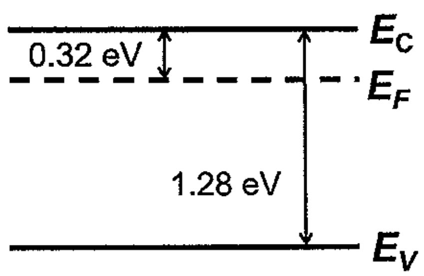

Figure 2

2. (a) A voltage is applied across a uniformly doped n-type silicon sample and the current is measured as a function of temperature. The measurement result is shown in Figure 3 on page 3. Provide a possible explanation for the observation.

(8 Marks)

Note: Question No. 2 continues on page 3.

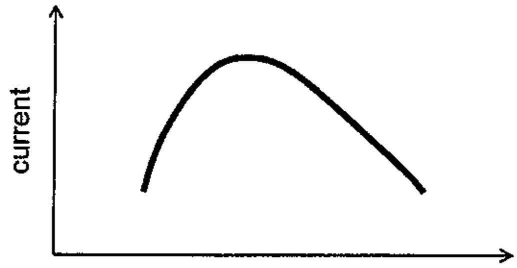

Figure 3

(b) A uniformly doped p-type germanium sample has a cross-sectional area of 1×10^{-4} cm^2. A voltage applied across the length of the sample yields a uniform electric field of 50 V/cm and a current of 3.8 mA at 300 K. The sample is then illuminated by a light source resulting in the uniform generation of electron-hole pairs inside the sample. The current measured after the light has been turned on for a long time is 4.2 mA.

(i) Is the low-level injection approximation valid?

(ii) Calculate the rate of electron-hole pair generation per unit volume if the minority carrier lifetime is 10 μs.

(9 Marks)

(c) (i) A semiconductor material has an energy bandgap E_g = 1.55 eV. If the semiconductor is used to make a photodetector, what is the longest wavelength of light that can be detected by the detector?

(ii) A photodiode at λ = 800 nm has a quantum efficiency η = 80%. If the photodiode is used to detect a light beam with a power of 10 mW at the wavelength λ = 800 nm, what would be the photocurrent generated in the circuit?

(8 Marks)

3. (a) Consider a gallium arsenide n$^+$p junction diode with a cross-sectional area of 2×10^{-4} cm^2 and a built-in voltage of 1.1 V at 300 K. Junction capacitance measurement at 0 V bias yields a value of 3 pF. The minority carrier lifetime is the same for both n and p regions and is equal to 0.1 μs.

(i) Calculate the doping concentration of the p-region.

(ii) Calculate the current flow under a forward bias of 0.92 V.

(iii) It is noticed that light is emitted from this forward-biased diode. Briefly explain why this is so.

(13 Marks)

Note: Question No. 3 continues on page 4.

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(b) A metal electrode of work function 3.8 eV is deposited on a non-degenerately doped n-type silicon substrate. The substrate doping density is $5\times10^{15}\ \text{cm}^{-3}$.

(i) Without performing any calculation, state the type of contact formed. Briefly explain your answer.

(ii) Sketch the energy band diagram of the contact under thermal equilibrium and for the case when a +2 V is applied on the metal with respect to the substrate.

(iii) What is the energy barrier seen by the electrons in the metal side of the contact?

(iv) Suggest a way by which the contact resistance may be decreased.

(12 Marks)

4. (a) A silicon crystal sample has a cross-sectional area of 1 cm² and a thickness of 0.1 mm. The crystal sample is illuminated uniformly by a light beam of wavelength $\lambda = 800$ nm. The absorption coefficient of silicon at 800 nm is $5\times10^{4}\ \text{cm}^{-1}$ and the intensity of the light beam incident on the sample is 1 mW/cm². Assuming that 90% of the photons absorbed by the silicon sample are converted into electron-hole pairs, determine the number of electron-hole pairs that are generated per second in the sample.

(7 Marks)

(b) For a uniformly doped $\mathbf{n^{++}p^{+}n}$ bipolar junction transistor in the forward active region, sketch its minority carrier distribution across the emitter region, the base region, and the collector region. Indicate the electric field directions in the emitter-base and the base-collector space charge regions.

(6 Marks)

(c) The base region of the transistor in part (b) has a width W_B = 0.5 µm, a cross-sectional area of $5\times10^{-5}\ \text{cm}^2$ and a doping concentration of $5\times10^{16}\ \text{cm}^{-3}$. The base-emitter junction is biased at 0.6 V. Assuming that the electrons in the base region has a diffusion coefficient $D_n = 18\ \text{cm}^2/\text{s}$, calculate the collector current.

(8 Marks)

(d) If the transistor in part (c) has a base current of I = 1.5 µA, determine its β, α, and the emitter current.

(4 Marks)

List of Selected Formulae

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

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

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

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

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

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

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

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

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

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

$$n_0 = n_i \exp\left(\frac{E_F-E_i}{k_BT}\right), \quad p_0 = n_i \exp\left(\frac{E_i-E_F}{k_BT}\right)$$

$$n_0 p_0 = n_i^2$$

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List of Selected Formulae (cont'd)

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

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

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

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

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

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

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

$$N_dx_n=N_ax_p,\ \ \xi_{max}=-\frac{qN_dx_n}{\varepsilon_r\varepsilon_0}=-\frac{qN_ax_p}{\varepsilon_r\varepsilon_0},\ \ W=\left[\frac{2\varepsilon_r\varepsilon_0(V_{bi}-V_a)}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2}$$

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

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

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

$$I=I_0\left[\exp\left(\frac{qV_a}{kT}\right)-1\right],\ \ I_0=qA\left(\frac{D_p}{L_p}p_{n0}+\frac{D_n}{L_n}n_{p0}\right),\ \ C_j=\left|\frac{dQ_j}{dV_a}\right|=\frac{\varepsilon_r\varepsilon_0A}{W}$$

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

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

List of Selected Formulae (cont'd)

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

$\frac{n\lambda}{2} = L$, $\quad f = \frac{nc}{2L}$, $\quad \Delta f = \frac{\Delta nc}{2L}$, $\quad \frac{hc}{\lambda} = E_{ph}$

Reflectivity, $r = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$, $\quad I_t = (1-r)I_0$, $\quad I = RP$, $\quad R = \eta \frac{e}{E_{ph}}$, $\quad \eta = \frac{N_e}{N_p}$

$i_C = \frac{-eD_n A_{BE}}{x_B} \times n_{B0} \exp\left(\frac{ev_{BE}}{kT}\right)$, $\quad \frac{i_C}{i_E} \equiv \alpha$, $\quad \frac{i_C}{i_B} \equiv \beta$, $\quad \frac{1}{\alpha} = \frac{1}{\beta} + 1$,

$V_B + I \times R_L + V = 0$

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APPENDIX B

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}	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	Jmol^{-1}K^{-1}
Electron-volt	1 eV	1.6×10^{-19}	J
Thermal voltage ($T = 300$ K)	k_BT/q	0.0259	V

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 (Å)	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-s) Electron, μ_n Hole, μ_p	 1350 480	 8500 400	 3900 1900

END OF PAPER

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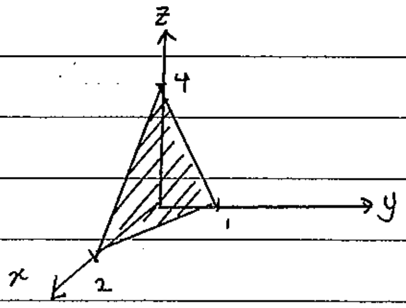
1-a) i. Miller Indices (2 4 1)

$\times 4$ ($\frac{1}{2}$ $\frac{1}{4}$ $\frac{1}{1}$

2 4 4



* make sure that the planes do not pass through the origin

ii. no. of atoms in BCC $= \frac{1}{8} \times 8 + 1 = 2$ atoms

lattice constant, $a = 5.7Å = 5.7 \times 10^{-10} m = 5.7 \times 10^{-8} cm$

percentage of total unit cell volume occupied by BCC:

$$0.55 = \frac{\text{volume of atoms}}{\text{volume of BCC}}$$

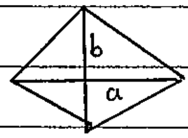
$$0.55 = \frac{2 \times \frac{4}{3}\pi r^3}{a^3}$$

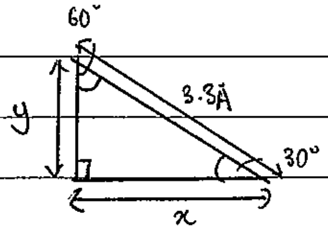
$$r^3 = \frac{3(0.55 a^3)}{8\pi} = \frac{3(0.55)(5.7 \times 10^{-8})^3}{8\pi}$$

$$r = 2.3 \times 10^{-8} cm$$

$\therefore$ diameter $= 2r = 4.60 \times 10^{-8}$ cm

iii. area of a rhombus $= \frac{1}{2}ab$





$x = 3.3Å \cos 30° = 2.86 \times 10^{-8} cm$

$a = 2x = 5.72 \times 10^{-8} cm$

$y = 3.3Å \cos 60° = 1.65 \times 10^{-8} cm$

$b = 2y = 3.3 \times 10^{-8} cm$

area $A = \frac{1}{2}ab = 9.44 \times 10^{-16} cm^2$

volume of crystal $V = A \times 5.6Å = 5.29 \times 10^{-23} cm^3$

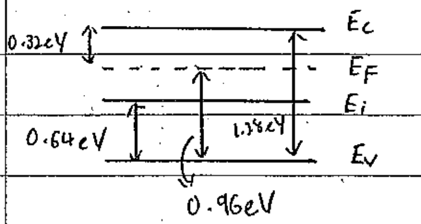
1\. a) iii. no. of B atoms in wurtzite crystal $= 1 + 4\left(\frac{1}{4}\right) = 2$ atoms

$\therefore$ volume density $= \dfrac{2}{5.29 \times 10^{-23}} = 3.78 \times 10^{22}$ atoms / volume ※

b) i. E_F is closer to E_C ⇒ n-type doping

E_F is a horizontal line ⇒ uniform doping

ii. First, find the n_0 and p_0 before impurity atoms are added



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

$$= (1.2 \times 10^{9}) \exp\left[\frac{(0.96 - 0.64) \times 1.6 \times 10^{-19}}{1.38 \times 10^{-23} \times 300}\right]$$

$$= 2.82 \times 10^{14}\ cm^{-3}$$

$$p_0 = \frac{n_i^2}{n_0} = 5106.38\ cm^{-3}$$

$N_A = 6.7 \times 10^{15}\ cm^{-3}$ is added,

$$N_A^* = N_A - n_0 = 6.7 \times 10^{15} - 2.82 \times 10^{14} = 6.418 \times 10^{15}\ cm^{-3}$$

$$p_0 = \frac{n_i^2}{p_0} + N_A^*$$

$$p_0^2 - N_A^* p_0 - n_i^2 = 0$$

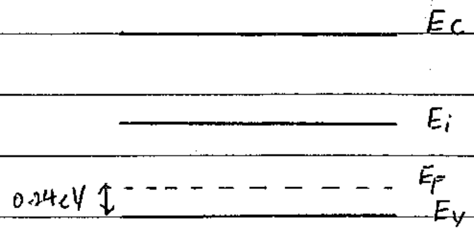
$$p_0 = \frac{N_A^* + \sqrt{N_A^2 + 4n_i^2}}{2} \qquad N_A^* \gg n_i$$

$$p_0 \approx N_A^* = 6.418 \times 10^{15}\ cm^{-3}$$

$$p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

$$E_i - E_F = kT \ln\left(\frac{p_0}{n_i}\right) = (1.38 \times 10^{-23})(300) \ln\left(\frac{6.418 \times 10^{15}}{1.2 \times 10^{9}}\right) = 0.4eV$$

$$E_F = E_i - 0.4 = 0.64 - 0.4 = 0.24eV \text{ ※}$$



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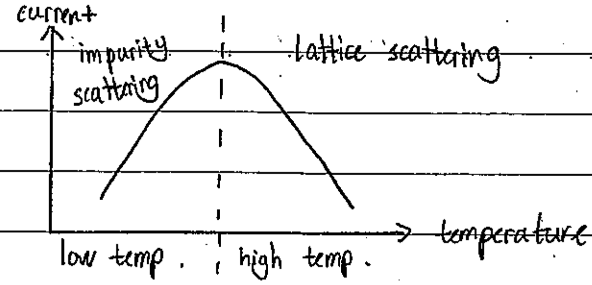
2. a)



current, $I = JA = q n \mu_n \mathcal{E} \cdot A \Rightarrow I \propto \mu_n$ current is directly proportional to electron mobility (n-type semiconductor)

At low temperature region, when temperature increases, current increases, this is because electron mobility, μ_n will increase. (dominated by impurity scattering)

$\Rightarrow$ In this region, when temperature increases, random thermal velocity of carriers increases. It reduces the time the carriers spend in the vicinity of ionized impurity center. The less time spent in the vicinity of a coulomb force, the smaller the scattering effect and thus increasing the electron mobility.

At high temperature region, when temperature increases, current decreases, this is because electron mobility, μ_n will decrease. (dominated by lattice scattering)

$\Rightarrow$ Lattice vibrations are expected to increase with increasing temperature, which implies that the number of scatterings per unit time increases. The average time between collision decreases and hence electron mobility decreases.

* A complete explanation can be found in Lecture 12 slides 16 - 21

2. b) i. For low-level injection approximation to be valid : $|\Delta n| \ll P_o \Rightarrow |\Delta n| < 0.1 P_o$

p-type germanium, find P_o :

$J_p = I/A$ * uniformly doped, no diffusion current density

$q p \mu_p \mathcal{E} = \frac{I}{A}$

$P_o = \frac{I}{q \mu_p \mathcal{E} A}$ μ_p can obtain from appendix, $\mu_p = 1900\ cm^2/Vs$

$= \frac{3.8 \times 10^{-3}}{(1.6 \times 10^{-19})(1900)(50)(1 \times 10^{-4})}$ $n_o = \frac{n_i^2}{P_o} = \frac{(2.4 \times 10^{13})^2}{2.5 \times 10^{15}}$

$= 2.5 \times 10^{15}\ cm^{-3}$ $= 2.304 \times 10^{11}\ cm^{-3}$

Find Δn_p :

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

$J_{total} \cdot A = J_{n,drift} \cdot A + J_{p,drift} \cdot A$

$4.2mA = q(n + \Delta n)\mu_n \mathcal{E} \cdot A + q(p + \Delta n)\mu_p \mathcal{E} \cdot A$ * $\Delta p = \Delta n$

$\frac{4.2mA}{qA\mathcal{E}} = n\mu_n + p\mu_p + \Delta n(\mu_n + \mu_p)$ * $\mu_n = 3900\ cm^2/Vs$

$\frac{4.2 \times 10^{-3}}{(1.6 \times 10^{-19})(1 \times 10^{-4})(50)} = (2.304 \times 10^{11})(3900) + (2.5 \times 10^{15})(1900) + \Delta n(3900 + 1900)$

$\Delta n = 8.605 \times 10^{13}\ cm^{-3}$

$\therefore \frac{\Delta n}{p} = \frac{8.605 \times 10^{13}}{2.5 \times 10^{15}} = 0.03 < 0.1$

Low-level injection approximation is valid *

ii. $\Delta n_{ss} = G_L \tau_n$

$\tau_n = \frac{8.605 \times 10^{13}}{10 \times 10^{-6}} = 8.605 \times 10^{18}\ s$ *

c) i. $\frac{hc}{\lambda} > E_g$ $c = 3 \times 10^8\ m/s = 3 \times 10^{10}\ cm/s$

$\lambda_{max} < \frac{hc}{E_g} = \frac{(6.626 \times 10^{-34})(3 \times 10^{10})}{1.55 \times 1.6 \times 10^{-19}}$

$= 8.02 \times 10^{-5}\ cm$

2. c) ii. $R = \eta \frac{e}{E_{ph}}$ where $E_{ph} = \frac{hc}{\lambda}$

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

$I = RP$

$= \frac{\eta e \lambda}{hc} P$

$= \frac{(0.8)(1.6\times10^{-19})(800\times10^{-9})}{(6.626\times10^{-34})(3\times10^{-8})} \times 10\times10^{-3}$

$= 5.15\times10^{13}$ A ※

3. a) i. GaAs n^+p junction diode $\Rightarrow N_d \gg N_a$

$C_J = \frac{\varepsilon_r \varepsilon_o A}{W}$

$W = \frac{(13.1)(8.85\times10^{-14})(2\times10^{-4})}{3\times10^{-12}}$ ※ $\varepsilon_o = 8.85\times10^{-12}$ F/m $= 8.85\times10^{-14}$ F/cm

$W = 7.729\times10^{-5}$ cm

$W = \left[\frac{2\varepsilon_r\varepsilon_o V_{bi}}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2}$ Since $N_d \gg N_a$, $\frac{1}{N_d} \approx 0$

$N_a = \frac{2\varepsilon_r\varepsilon_o V_{bi}}{qW^2} = \frac{2(13.1)(8.85\times10^{-14})(1.1)}{(1.6\times10^{-19})(7.729\times10^{-5})} = 2.06\times10^{11}$ cm^{-3} ※

ii. In a forward bias n^+p junction, electron injection dominates

$I = qA\left(\frac{D_n}{L_n}n_{po}\right)\exp\left(\frac{qV_a}{kT}\right)$ $D_n = \frac{kT}{q}\mu_n$

$= qA\left(\frac{D_n}{\sqrt{D_n\tau_n}}\frac{n_i^2}{N_a}\right)\exp\left(\frac{qV_a}{kT}\right)$ $= \frac{(1.38\times10^{-23})(300)}{1.6\times10^{-19}} \cdot 8500$

$= qA\left(\sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_a}\right)\exp\left(\frac{qV_a}{kT}\right)$ $= 219.9875$

$= (1.6\times10^{-19})(2\times10^{-4})\left(\sqrt{\frac{219.9875}{0.1\times10^{-6}}}\right)\left(\frac{(1.8\times10^{6})^2}{2.06\times10^{11}}\right)\exp\left(\frac{1.6\times10^{-19}\times0.92}{1.38\times10^{-23}\times300}\right)$

$= 0.065$ A ※

iii. Under forward bias, the applied voltage will oppose the built-in voltage.

$W = \left[\frac{2\varepsilon_r\varepsilon_o(V_{bi}-V_a)}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2} \Rightarrow W \propto (V_{bi}-V_a)^{1/2}$

the space charge width decreases. More electrons are now able to diffuse from n to p region. Likewise, more holes are now able to diffuse from p to n region. Carrier injection takes place across the pn junction. Hence the diode is able to conduct a large current.

※ more detailed discussion can be found on lecture note 'Effect of an Externally Applied Voltage' slides 7 – 10.

3 b) i. For Si, electron affinity $q\chi = 4.01\,eV$

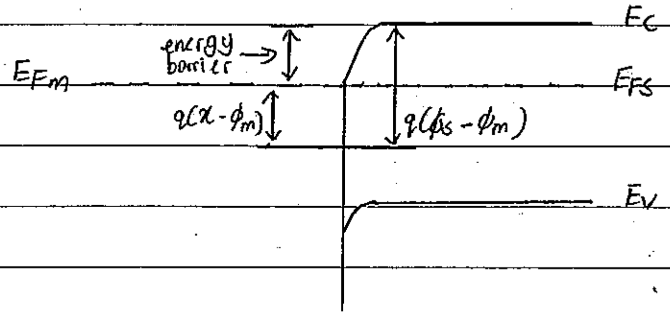
metal work function, $q\phi_m = 3.8\,eV$

semiconductor work function can be expressed as $q\phi_s = q\chi + (E_C - E_F)$

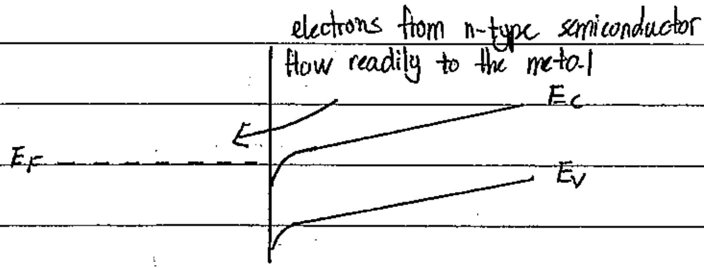
Since $q\chi > q\phi_m \Rightarrow q\phi_s > q\phi_m$

$\therefore$ Ohmic contact is formed

ii. Under thermal equilibrium,



+2V is applied on the metal



iii. Energy barrier seen by electrons in the metal :

$$E_C - E_{FS} = kT \ln\left(\frac{N_C}{N_D}\right)$$

$$= (1.38 \times 10^{-23})(300) \ln\left(\frac{2.8 \times 10^{19}}{5 \times 10^{15}}\right)$$

$$= 3.57 \times 10^{-20}\,J$$

$$= 0.223\,eV$$ ※

iv. doping the n-type semiconductor heavily with more N_d to decrease the energy barrier

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4. a) $I_{ph} = RP$

$= n \frac{e}{E_{ph}} \cdot IA$

$= (0.9)\left(\frac{e}{1.55e}\right)(1 \times 10^{-3})(1)$

$= 5.806 \times 10^{-4}\ W/cm^2$

$P_{ph} = I_{ph} \cdot A = 5.806 \times 10^{-4}\ W$

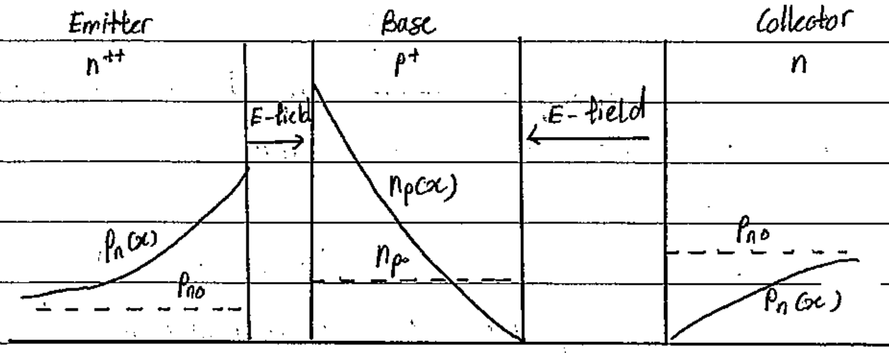
$E_{ph} = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3 \times 10^{8})}{800 \times 10^{-9}}$

$= 1.55 eV$

$P_{ph} = n E_{ph}$ where n = no. of electron-hole pairs generated per second

$n = 2.34 \times 10^{15}\ s^{-1}$ ※

b) $n^{++}p^{+}n$ BJT



c) collector current,

$i_c = \frac{eD_n A_{BE}}{x_B} \times n_{B0} \exp\left(\frac{eV_{BE}}{kT}\right)$

$= \frac{(1.6 \times 10^{-19})(18)(5 \times 10^{-5})}{0.5 \times 10^{-4}} \times 5 \times 10^{16} \times \exp\left[\frac{(1.6 \times 10^{-19})(0.6)}{(1.38 \times 10^{-23})(300)}\right]$

$= 1.69 \times 10^{9}$ A ※

d) $\beta = \frac{i_c}{i_B} = \frac{1.69 \times 10^{9}}{1.5 \times 10^{-6}} = 1.13 \times 10^{15}$

$\alpha = \frac{\beta}{\beta + 1} \approx 1$

$i_E = \frac{i_c}{\alpha} = 1.69 \times 10^{9} A$ ※

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Hi, hope you guys find this solution be useful for your revision. Although the solution may not be 100% correct, but it provides you a guide or logic how to approach the problem. Hence, if you think your way of solving the question is better, please follow your heart :)

Besides, I would like to share on some tips of scoring well in EE 2003:

1. Continuity equation never be used in any PYP

2. Q2 usually will be the hardest question, if you're not confident enough, please try to do other questions first.

3. Although examination provides all formulas you need, you must understand under which condition which formula can be used. Otherwise you will waste too much time on finding suitable formula.

4. Familiarize yourself with appendix. Most of the parameters will not be provided in question.

5. Be careful with the unit conversion.

6. Some of the sketching you must know:
   a) Energy band diagram (equilibrium, FB, RB)
   b) Schottky Contact
   c) Ohmic Contact
   d) Minority Carrier Distribution
   and others appeared in lecture notes