NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2017-2018

EE2003 – SEMICONDUCTOR FUNDAMENTALS

April/May 2018 Time Allowed: 2.5 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 10 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 Selected Formulae is provided in Appendix A from page 6 to page 8, and a Table of Physical Constants is provided in Appendix B on page 9 and a Table of Material Properties is provided in Appendix C on page 10.

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1. (a) Silicon has a diamond crystal structure as shown in Figure 1. At 300 K, the lattice constant of Si a_{Si} = 5.43 Å. It is possible to prepare Silicon with any of the three surfaces, i.e. (100), (110) or (111).

   (i) Sketch the Silicon atom placement on these three surfaces.

   (ii) In one particular application, a surface with the lowest surface density is desired. Which surface would you recommend? Support your recommendation with numerical data.

   (iii) Name another semiconductor that also has a diamond crystal structure.

(9 Marks)

Note: Question No. 1 continues on page 2

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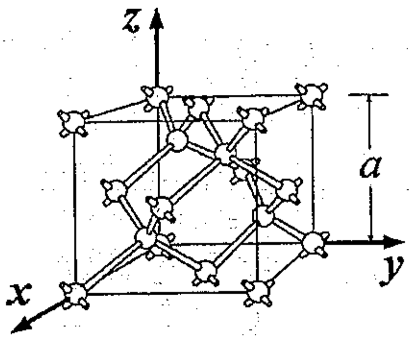

Figure 1

(b) GaAs, Si and Ge are three commonly known semiconductor materials. The properties of these materials at room temperature are listed in Appendix C.

(i) When the temperature fluctuates, which semiconductor demonstrates the largest change in the electron concentration in the conduction band? Explain your answer.

(ii) It is desirable to detect light in the wavelength range of 1,300 to 1,600 nm. Identify all possible material(s) that can be used from the list above.

(8 Marks)

(c) At 300 K, one silicon sample is pre-doped such that the Fermi level E_f is 0.28 eV above the intrinsic Fermi energy level E_i. Use intrinsic carrier concentration $n_i = 1.5 \times 10^{10}$ cm^{-3} and assume that E_i lies at the mid-gap.

(i) Calculate the majority and minority carrier concentrations.

(ii) A controlled amount of impurity is now mixed with this sample such that the Fermi level is re-positioned at 0.28 eV below the intrinsic Fermi energy level E_i. What is the required impurity concentration? Recalculate the values in part (i).

(iii) Propose one suitable impurity that can be used in part (ii).

(8 Marks)

2. (a) A Silicon resistor is designed with cross-sectional area = 10^{-4} cm^2 and length = 100 μm. It is uniformly doped with donor atoms to a concentration of $N_d = 2 \times 10^{16}$ cm^{-3} at 300 K. Assume that the electron diffusion coefficient $D_n = 25.9$ cm^2/s.

Note: Question No. 2 continues on page 3

(i) Estimate the electrical conductivity of the Silicon resistor.

(ii) In order to maintain a total current flow of 50 mA, what is the required voltage drop across the resistor?

(iii) The donor concentration is then varied as $N_d(x) = 10^{16}(2 - x/L)$ cm^{-3}, where x $(0 \le x \le L = 100$ μm) is the distance along the semiconductor. If the current is held constant at 50 mA across the resistor, what is the electric field at $x = 100$ μm?

(9 Marks)

(b) A rectangular piece of n-Si sample, doped uniformly to a concentration of 1×10^{15} cm^{-3}, has a length, breadth and height of 10 mm, 5 mm and 1 mm, respectively. A voltage of 1 V is applied across its length. At time $t = 0$ s, light is directed at the sample, generating electron-hole pairs uniformly throughout the sample at a rate of 2×10^{20} cm^{-3}s^{-1}. The electron and hole lifetimes are 2 μs and 0.4 μs, respectively. Assume the temperature to be 300 K.

(i) Calculate the current that flowed in the sample at $t < 0$ s.

(ii) Calculate the steady-state current flowing in the sample under illumination.

(iii) What would be the current flowing in the sample after the light is switched off for a long time? Briefly explain.

(8 Marks)

(c) For a uniformly doped $\boldsymbol{n^{++}p^{+}n}$ bipolar transistor in the forward-active mode of operation, the emitter region has the largest doping and the collector region has the smallest doping.

(i) Sketch the circuit diagram of this bipolar junction transistor under this mode of operation.

(ii) Draw the energy band diagram across the emitter region, the base region, and the collector region. Mark the conduction band, the valence band and the Fermi levels.

(iii) Plot its minority carrier distribution across the emitter region, the base region, and the collector region. Indicate the minority carrier distributions under the thermal equilibrium condition in these three regions.

(8 Marks)

3. (a) A Si *p-n* junction has twice as large space charge width in the *p*-region than in the *n*-region. The built-in voltage is 0.75 V at 300 K. The critical electric field is 3.5×10^5 Vcm^{-1}.

(i) Determine the doping concentration of the *p*-region and *n*-region that would satisfy the above specifications.

(ii) Calculate the space charge width in the *p*-region and *n*-region that correspond to a peak electric field equal to the critical electric field. Hence, determine the avalanche breakdown voltage of the *p-n* junction.

(iii) The *p-n* junction is forward biased at a voltage of 0.72 V. Does this bias condition violate the low-level injection assumption?

(13 Marks)

(b) An *n*-type Si, of a uniform doping concentration of 5×10^{15} cm^{-3}, is used to form a contact with a metal. Assume the temperature to be 300 K.

(i) Calculate the work function of the *n*-type Si.

(ii) Two metals, A and B, of work function 4.82 eV and 3.91 eV, respectively, are available for forming the contact. Which metal would you choose to form a Schottky contact? Briefly explain.

(iii) A voltage of +1.5 V is applied to the *n*-type Si side while a voltage of −1.5 V is applied to the metal side of the contact formed in part (b). Sketch the energy band diagram of the contact for this bias condition. Would a large current flow across the contact in this case? Briefly explain.

(12 Marks)

4. (a) An $n^{++}p^{+}n$ silicon bipolar transistor has the following base region parameters. The electron diffusion coefficient $D_n = 20$ cm^2/s, the cross-sectional area $A_{BE} = 400$ cm^2, and the thermal-equilibrium electron concentration in the base $n_{B0} = 2 \times 10^4$ cm^{-3}.

(i) When it is biased at $v_{BE} = 0.25$ V, the collector current $|i_c| = 2$ mA. What is the required width of the base region x_B?

(ii) Using the results of part (i), what is the value of v_{BE} such that $|i_c| = 5$ mA?

Note: Question No. 4 continues on page 5

(iii) Using the collector current of part (ii), for a common-emitter current gain $\beta = 99$, determine the common-base current gain α, and the emitter and base currents.

(12 Marks)

(b) For a typical semiconductor laser diode,

(i) Draw the physical schematic structure, including the electrode contacts.

(ii) Sketch the energy band diagrams of this laser diode under the equilibrium and the forward bias conditions.

(iii) What are the different characteristics between a light-emitting diode and a laser diode?

(8 Marks)

(c) Using a figure illustration, explain how a *p-n* junction solar cell works. Draw a diagram showing the current-voltage characteristics of this solar cell with and without light illumination.

(5 Marks)

APPENDIX A

List of Selected Formulae

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

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

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

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

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

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

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

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

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

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

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

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

List of Selected Formulae (cont'd)

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

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

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

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

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

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

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

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

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

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

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

List of Selected Formulae (cont'd)

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

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

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

$$I(x) = I_0\exp(-\alpha x), G = R_1R_2\exp(2(k-\gamma)L),\quad k_{th} = \gamma+\frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$$

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

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

$$i_C = \frac{-eD_nA_{BE}}{x_B}\times n_{B0}\exp\left(\frac{v_{BE}}{kT/e}\right);\quad \frac{i_C}{i_E}\equiv\alpha,\quad \frac{i_C}{i_B}\equiv\beta,\quad \frac{1}{\alpha} = \frac{1}{\beta}+1,$$

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

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

1. c) i) $E_f - E_i = 0.28\ eV$ | $T = 300K$, $k_BT = 0.0259$

$n_i = 1.5\times10^{10}\ cm^{-3}$

Since E_f lies above E_i, it is N type.

$$n_0 = n_i\, e^{\frac{E_f - E_i}{k_BT}}$$

$$= 1.5\times10^{10} \times e^{\frac{0.28}{0.0259}}$$

$$= 7.433\times10^{14}\ cm^{-3}$$

$$p_0 = \frac{n_i^2}{n_0} = 3.027\times10^{5}\ cm^{-3}$$

ii) Since E_f lies below E_i, it is P type., $E_i - E_f = 0.28\ eV$

$$p_0 = n_i\, e^{\frac{E_i - E_f}{k_BT}} = 7.433\times10^{14}\ cm^{-3}$$

$$n_0 = 3.027\times10^{5}\ cm^{-3}$$

Amount of doping (counterdoping) needed = N_a

$$N_a = 2p_0 = 2\times7.433\times10^{14} = 1.4866\times10^{15}\ cm^{-3}$$

iii) Boron (group 3)

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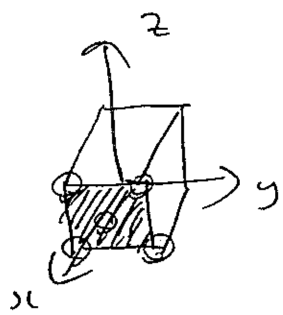
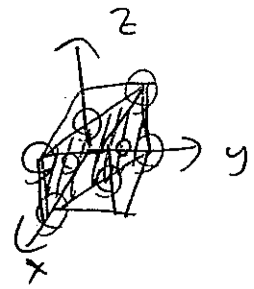
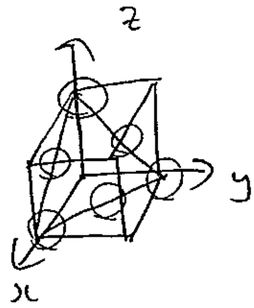
1. a) (100) (110) (111)

i)







ii) (100) has lowest SD:

$$(100) \rightarrow SD = \frac{2}{(5.43\times10^{-8})^2} = 6.783\times10^{14}\ cm^{-3}$$

$$(110) \rightarrow SD = \frac{4}{\sqrt{2}(5.43\times10^{-8})^2} = 9.593\times10^{14}\ cm^{-3}$$

$$(111) \rightarrow SD = \frac{2}{\sqrt{3}/2\,(5.43\times10^{-8})^2} = 7.832\times10^{14}\ cm^{-3}$$

iii) Ge, germanium

1. b) i) Since $E_{g\,Ge} < E_{g\,Si} < E_{g\,GaAs}$

Ge has smallest E_g, e's easier to jump to conduction band from valance band

ii) $E_{ph} = hf = \frac{hc}{\lambda}$ $E_{ph\,Si} = 1.12eV$, $c = 3\times10^8\ ms^{-1}$

$E_{ph\,GaAs} = 1.42eV$ $\approx 3\times10^{10}\ cms^{-1}$

$\lambda = \frac{\cancel{E_{ph}}\,hc}{E_{ph}}$ $E_{ph\,Ge} = 0.66eV$ $h = 6.626\times10^{-34}\ Js$

Try it out yourself!! Jia you :)

2. a) CS $A = 10^{-4}\ cm^2$, $L = 100\ \mu m = 100 \times 10^{-4}\ cm$

$N_d = 2 \times 10^{16}\ cm^{-3}$ | $T = 300K$, $D_n = 25.9\ cm^2/s$

$$\mu_n = \frac{25.9}{0.0259} = 1000\ cm^2/Vs$$

(Einstein's relationship)

i) $\sigma = q \mu_n n$

$= 1.6 \times 10^{-19} \times 1000 \times 2 \times 10^{16} = 3.2\ (\Omega cm)^{-1}$

ii) $I = 50\ mA$, $V = ?$

$$J_{ndrift} = \sigma \mathcal{E}$$

$$\frac{I}{A} = \sigma \times \frac{V}{l}$$

$$V = \frac{I \times L}{\sigma A} = \frac{50 \times 10^{-3} \times 100 \times 10^{-4}}{3.2 \times 10^{-4}}$$

$$= 1.5625\ V/cm$$

iii) $N_d(x) = 10^{16}\left(2 - \frac{x}{L}\right)\ cm^{-3}$ $(0 \le x \le L = 100\mu m)$

$I = 50mA$. $\mathcal{E}\big|_{x=100\mu m} = ?$

$$J_{ndrift} + J_{ndiff} = \frac{I}{A}$$

$$q n \mu_n \mathcal{E} + q D_n \frac{dn}{dx} = \frac{I}{A}$$

$$1.6 \times 10^{-19} \times 10^{16}\left(2 - \frac{x}{L}\right) \times 1000\, \mathcal{E} + 1.6 \times 10^{-19} \times 25.9 \times \left(-\frac{10^{16}}{L}\right) = \frac{50 \times 10^{-3}}{10^{-4}}$$

$$1.6\left(2 - \frac{x}{L}\right)\mathcal{E} + \left(-\frac{0.04144}{L}\right) = 500$$

$$1.6\left(2 - \frac{x}{L}\right)\mathcal{E} = 504.144$$

$$\mathcal{E}\big|_{x=100\mu m} = 315.09\ V/cm$$

2. b) Si : $N_d = 10^{15}\,cm^{-3}$, $L = 10mm$, $W = 5mm$, $H = 1mm$

$V = 1V$, $G_L = 2\times10^{20}\,cm^{-3}s^{-1}$, $\tau_s = 2\mu s$, $\tau_p = 0.4\mu s$.

$T = 300K$. , $\mu_n = 1350\,cm^2/Vs$, $\mu_p = 480\,cm^2/Vs$

i) $J_{ndrift} = q\,n\,\mu_n\,\mathcal{E} = \frac{I}{A}$

$$I = q\mu_n \times n \cdot \mathcal{E} \times A$$

$$= 1.6\times10^{-19} \times 1350 \times 10^{15} \times \frac{1}{10\times10^{-1}} \times \frac{5\times1\times}{10^{-2}}$$

$$= 10.8\,mA \quad (t<0s)$$

$t<0$, there will be no excess minority carrier generated. Only majority carrier will contribute to current flow.

ii) $$\Delta p_{ss} = G_L \tau_p = 2\times10^{20} \times 0.4\times10^{-6} = 8\times10^{13}\,cm^{-3}$$

$$\sigma = q\mu_n(n_0 + \Delta n_{ss}) + q\mu_p(p_0 + \Delta p_{ss})$$

Since Ntype; $n_0 \gg p_0$. Δp_{ss} is the contributor to have excess current

$$\sigma = q\mu_n(n_0\cancel{+}) + q\mu_p(\Delta p_{ss})$$

$$= (1.6\times10^{-19} \times 1350 \times 10^{15}) + (1.6\times10^{-19} \times 480 \times 8\times10^{13})$$

$$= 0.222144\,(\Omega cm)^{-1}$$

$$\sigma\mathcal{E} = \frac{I}{A}$$

$$I = A \times \mathcal{E} \times \sigma$$

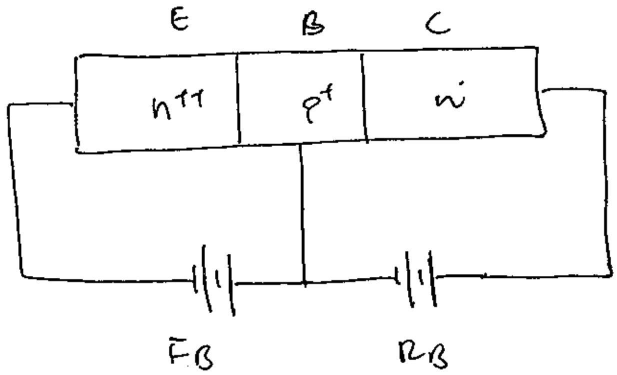
$$= 10^{-2} \times 5\times1 \times \frac{1}{10\times10^{-1}} \times 0.222144$$

$$= 11.107\,mA$$

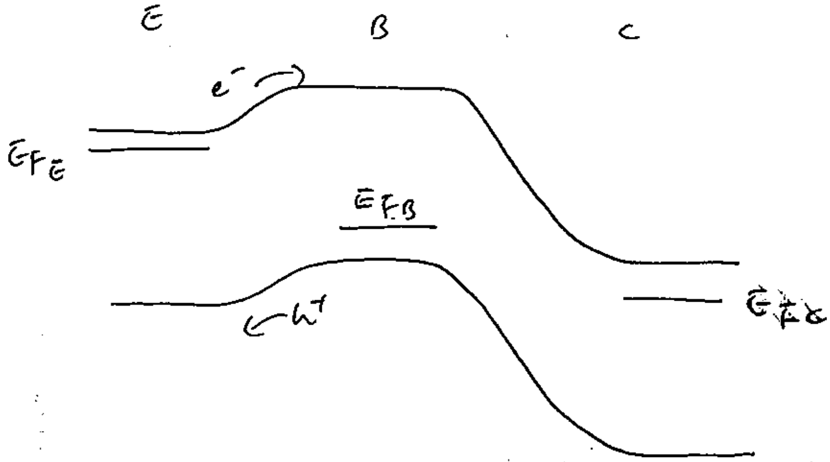
iii) Minority carrier Δp will be completedly recombined.

2 c) $n^{++} p^{+} n^{+}$

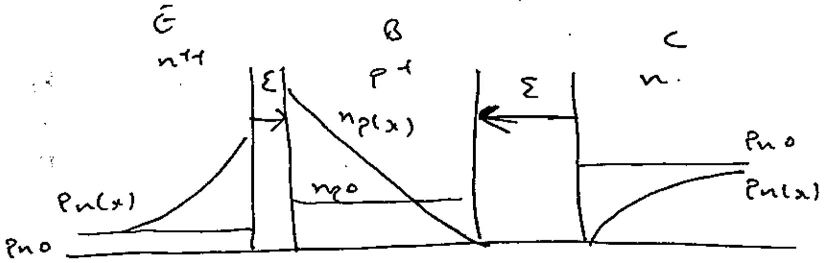
i)



ii)



iii)



3. a)

i)

$x_{p0} = 2x_{n0}$

$N_d x_{n0} = N_a x_{p0}$

$N_d \cancel{x_{n0}} = N_a 2\cancel{x_{n0}}$

$N_d = 2N_a$ — ①

$V_{bi} = \frac{k_BT}{q} \ln\left(\frac{N_aN_d}{n_i^2}\right)$

$N_aN_d = e^{\left(\frac{V_{bi}}{kT/q}\right)} \times n_i^2$

$= e^{\frac{0.75}{0.0259}} \times (1.5\times10^{10})^2$

$= 8.4777 \times 10^{32}\ cm^{-3}$ — ②

① & ②;

$N_a(2N_a) = 8.4777\times10^{32}$

$N_a = 2.0588\times10^{16}\ cm^{-3}$

$N_d = 4.1177\times10^{16}\ cm^{-3}$

ii)

$V_{bi} = \frac{1}{2} \times E_{max} \times w_0$

$w_0 = \frac{V_{bi}\times2}{E_{max}} = \frac{0.75\times2}{3.5\times10^5} = 4.2857\times10^{-6}\ cm$

$x_{p0} = \frac{N_d}{N_d+N_a} \times w_0 = 2.8572\times10^{-6}\ cm$

$x_{n0} = \frac{N_a}{N_a+N_d} \times w_0 = 1.4285\times10^{-6}\ cm$

$(V_{bi} - V_{br}) = \frac{1}{2} E_c \times w_0$

sub w_0.

you will have this following eq:

$+V_{bi} - V_{br} = \frac{\varepsilon_r\varepsilon_0(N_a+N_d)}{2qN_aN_d} \times E_c^2$

$$-V_{br} = \frac{11.7 \times 8.85\times10^{-14}\left[(2.0588\times10^{16}) + (4.1177\times10^{16})\right] \times (3.5\times10^{5})^2}{2\times1.6\times10^{-19}\times(2.0588\times10^{16})\times(4.1177\times10^{16})} - 0.75$$

$$= 28.129\ V$$

iii) Since avalanche breakdown occurs, LLI, low level injection might not be valid.

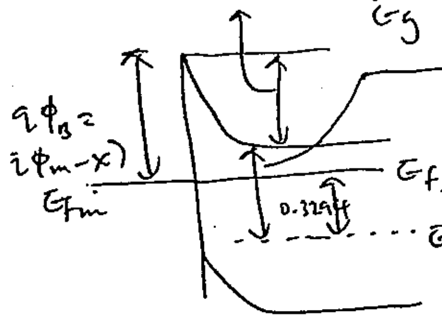
3.b) i) $Si: n_o = n_i e^{\frac{E_f - E_i}{k_B T}}$

$$E_f - E_i = \ln\left(\frac{n_o}{n_i}\right) \times k_B T = \ln\left(\frac{5\times10^{15}}{1.5\times10^{10}}\right) \times 0.0259$$

$$= 0.3294\ eV$$

$qV_o = q(\phi_m - \phi_s)$

$E_g = 1.12\ eV$, $\frac{E_g}{2} = 0.56\ eV$



$$q\phi_s = q\chi + (0.56 - 0.3294)$$

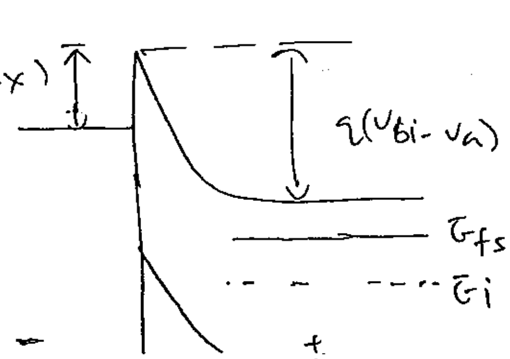
$$= 4.01 + 0.2306$$

$$= 4.2406\ eV$$

ii) To form schottky contact; $q\phi_m > q\phi_s$ ntype:

Therefore; choose A : $q\phi_m = 4.82\ eV > q\phi_s$

iii)



→ The semiconductor will pull down making bigger barrier of $(V_{bi} - V_a)q$ for e^- & h^+ to flow through harder

→ lesser current will flow through

4. a) i) $|i_C| = \frac{-e D_n A_{BE}}{x_B} \times n_{B0} \, e^{\frac{V_{BE}}{kT/e}}$

$$x_B = \frac{-1.6\times10^{-19} \times 20 \times 400}{2\times10^{-3}} \times 2\times10^{4} \times e^{\frac{0.25}{0.0259}}$$

$$= 1.992\times10^{-4} \text{ cm}$$

ii) $\ln\left(\frac{i_C \times x_B}{e D_n A_{BE} \cdot \times n_{B0}}\right) = \frac{V_{BE}}{kT/e}$

$$V_{BE} = \frac{kT}{e} \times \ln\left(\frac{i_C \times x_B}{e D_n \times A_{BE} \times n_{B0}}\right)$$

$$= 0.0259 \times \ln\left(\frac{5\times10^{-3} \times 1.992\times10^{-4}}{1.6\times10^{-19} \times 20 \times 400 \times 2\times10^{4}}\right)$$

$$= 0.27737 \text{ V}$$

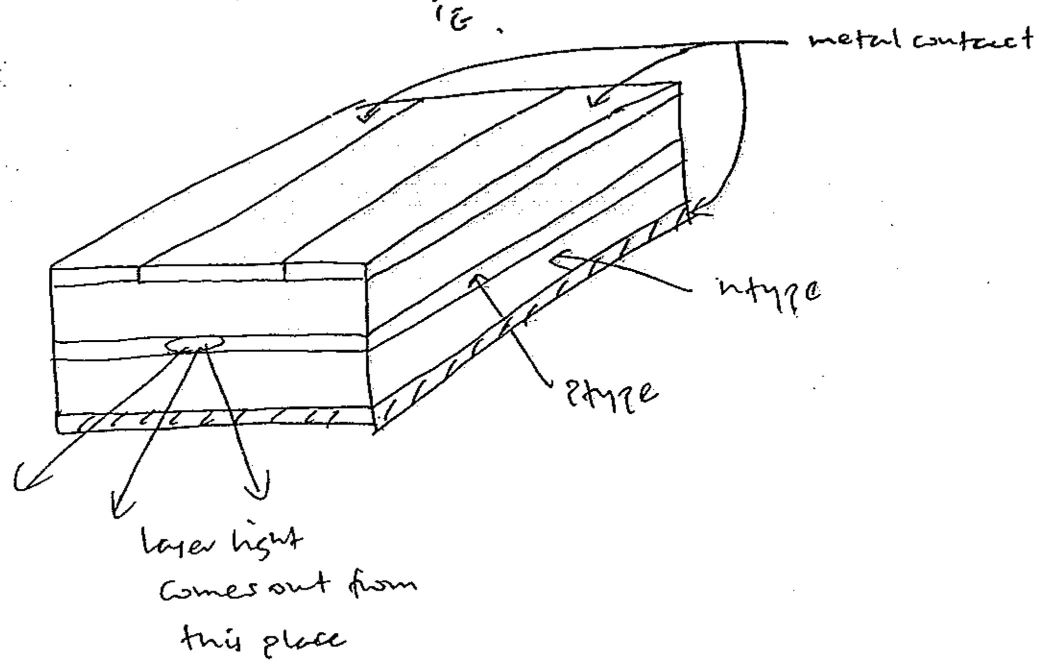
iii) $i_C = 5\text{ mA}$; $\beta = 99$

$$\beta = \frac{i_C}{i_B} \Rightarrow i_B = \frac{i_C}{\beta} = 5.0505\times10^{-5} \text{ A}$$

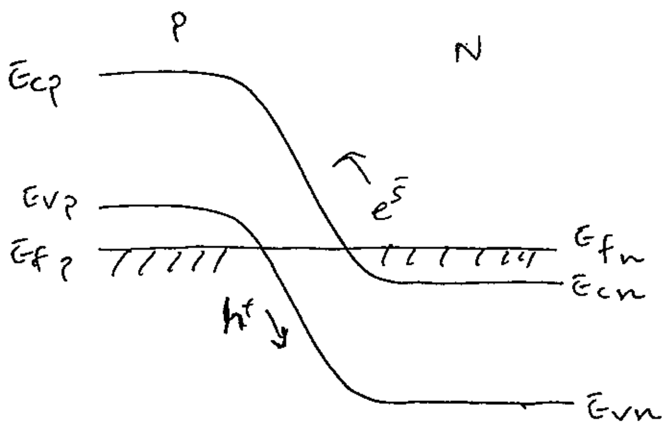
$$i_E = i_C + i_B = 5.0505\times10^{-3} \text{ A}$$

$$\therefore \alpha = \frac{i_C}{i_E} = 0.99.$$

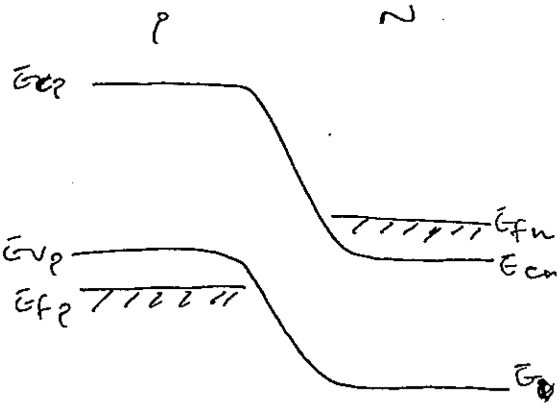
b) i)



4, b) ii)



No bias

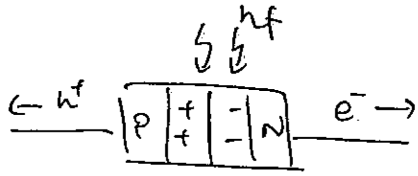


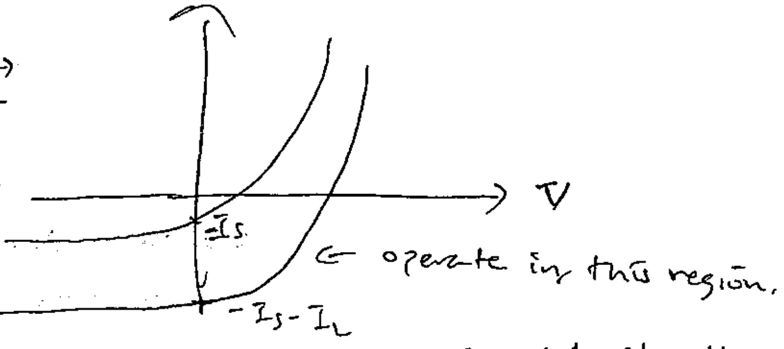
under bias (FB)

iii)

LED	LD
- non-coherent light	- coherent light
- different color	- same color (same wavelength)
- No amplification	- amplification
- Non-directional	- directional (same)
- non-polarized	- polarized

c) with illumination, excess e-h pair is generated & they are separated by internal $\mathcal{E}_{bi}$. So that, they can travel in different direction to have photovoltaic effect.





Take this soln. as pinch of salt. I do not intend to mislead or misguide you if my working(s) is/are inaccurate. My apology!!

Good luck !!

Quality counts (not quantity). Instead of doing a lot of pyp, try to understand the concepts through tutorials & 2-3 pyp either sem 1 or 2 based on your ~~notation~~ sem