NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2018-2019

EE2003 – SEMICONDUCTOR FUNDAMENTALS

April / May 2019 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 Selected Formulae, Table of Physical Constants and Table of Material Properties are provided in Appendices A, B and C, respectively, on pages 6-8, 9 and 10.

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1. (a) A hypothetical compound semiconductor, made up of two different atoms A and B, has a diamond crystal structure of lattice constant a. The diameter of atom B is 0.75 times that of atom A. The atoms are closely packed such that the surface of one atom (assumed to be spherical in shape) is in contact with its nearest neighbours.

   (i) If r is the radius of atom A, express r in terms of the lattice constant a.

   (ii) Determine the percentage of the unit cell volume occupied by the atoms.

   (iii) Sketch the placement of atoms on the (110) plane. If the surface density of atoms on this plane is 5.4×10^{14} atoms/cm^2, calculate a.

   (12 Marks)

Note: Question No. 1 continues on page 2.

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(b) Figure 1 shows the thermal equilibrium energy band diagram of a uniformly doped semiconductor at 350 K. The intrinsic carrier concentration is 3.3×10^{14} cm^{-3} at this temperature.

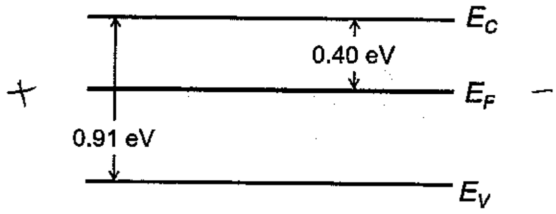

Figure 1

(i) Determine the doping type and density.

(ii) Additional doping is added and as a result, the Fermi level is shifted to 0.35 eV above the valence band edge E_V. What is the doping type and density required to achieve that?

(iii) A voltage of 0.5 V is applied across the semiconductor, with the positive terminal of the voltage source connected to the left end. Sketch and label the energy band diagram under this condition.

(13 Marks)

2. (a) A p-type semiconductor bar of length L = 30 μm has non-uniform doping concentration N_A that varies with distance x according to

$$N_A(x) = N_{A0} exp\left(-\frac{x}{d}\right) \text{ cm}^{-3},$$

where $0 \leq x \leq L$, $N_{A0} = 2.6 \times 10^{16}$ cm^{-3} and d = 12 μm. $N_A(x)$ is everywhere much greater than the intrinsic carrier concentration. The mobility of the majority carriers is 750 cm^{2}V^{-1}s^{-1} at 300 K.

(i) At thermal equilibrium, what would be the drift current density and electric field strength at the middle of the bar?

(ii) A voltage source connected across the bar results in a total current density of +15 A/cm^2. Determine an expression for the applied electric field.

(9 Marks)

Note: Question No. 2 continues on page 3.

(b) A semi-infinitely long p-type semiconductor sample, doped uniformly to a concentration of 2×10^{16} cm^{-3}, is injected with excess minority carriers at one end ($x = 0$) at 300 K. The steady-state diffusion current density J_n at $x = 0$ is -50 mA·cm^{-2}. The minority carriers have a lifetime of 2 µs and a mobility of 950 cm^{2}V^{-1}s^{-1}. The intrinsic carrier concentration is 1.5×10^{12} cm^{-3}.

(i) Determine the excess minority carrier concentration at $x = 0$.

(ii) Is low-level injection condition valid?

(iii) At what distance into the semiconductor would the diffusion current density become half of its value at $x = 0$?

(8 Marks)

(c) A silicon ***n-p-n*** bipolar junction transistor has impurity concentrations of 3×10^{18}, 5×10^{16} and 5×10^{15} cm^{-3} in the emitter, base and collector, respectively. The base width of the transistor is W_b=1.0 µm and the device cross-section area is 10^{-3} mm^2. Assume that the lifetime of minority carriers in all 3 sections is 0.1 µs, the mobility of the electrons and holes are μ_n = 1250 cm^2/V-s, and μ_p = 350 cm^2/V-s, respectively, and the device is operating under the forward active mode at T = 300 K. If the base-emitter junction is biased at 0.5 V, determine:

(i) the minority carrier charge in the base region.

(ii) the collector current I_c. (8 Marks)

3. (a) Figure 2 shows the electric field profile of an abrupt uniformly doped Ge p-n junction diode under thermal equilibrium at 300 K. The electron and hole lifetimes are 2 µs and 0.5 µs, respectively and are the same in both the p and n regions. The cross-sectional area is 2.5×10^{-4} cm^2 and the critical electric field is 1.1×10^5 V·cm^{-1}.

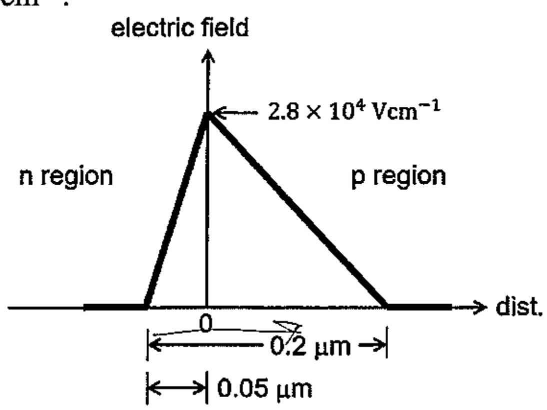

Figure 2

Note: Question No. 3 continues on page 4.

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(i) Determine the built-in voltage and the doping concentrations of the p and n regions.

(ii) A reverse-bias voltage of 50 V is applied across the diode. Calculate the maximum electric field under this condition. Is it safe to operate the diode at this voltage? Briefly justify your answer.

(iii) Assuming that the diode is ideal, calculate the hole drift current at the edge of the space-charge region on the p-side at a forward-bias voltage of 0.19 V.

(14 Marks)

(b) The following table lists the work function of three metals, A, B and C.

Metal	Work Function (eV)
A	2.21
B	4.10
C	4.75

(i) What metal(s) is(are) suitable for forming a Schottky contact on an n-type Si doped uniformly to a concentration of 5×10^{16} cm^{-3} at 300 K? Justify your answer.

(ii) For one of the suitable metal(s) identified in part (b)(i), sketch a labelled energy band diagram of the contact at thermal equilibrium, indicating clearly the barriers on the metal and semiconductor sides.

(iii) For the metal chosen in part (b)(ii), what is the junction capacitance per unit area of the contact at a reverse-bias voltage of 5 V?

(11 Marks)

4. (a) Figure 3 shows the energy band diagrams of two semiconductors in the ***E-k*** space. Which one (left or right) is a direct bandgap semiconductor and which one is an indirect bandgap semiconductor? Briefly explain why it is unlikely to obtain direct electron-hole recombination in an indirect bandgap semiconductor?

(5 Marks)

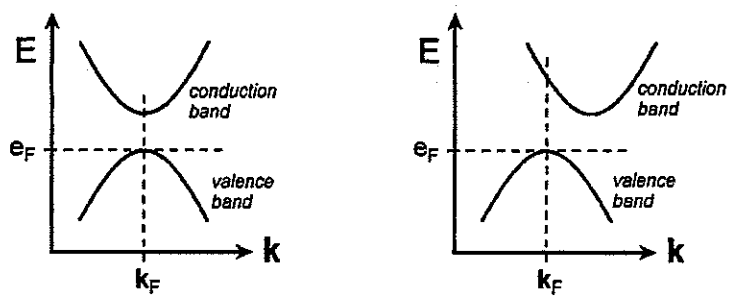

Figure 3

Note: Question No. 4 continues on page 5.

(b) A photodetector whose active area is 5×10^{-2} cm^2 is irradiated by yellow light (λ = 600 nm) with an intensity of 2 mW/cm^2. Assuming that the quantum efficiency of the detector $\eta = 85\%$, calculate:

(i) The number of electron-hole pairs (EHPs) generated per second.

(ii) The photocurrent generated in the detector.

(iii) The responsivity of the photodetector.

(9 Marks)

(c) Consider a GaAs light emitting diode (LED). The bandgap E_g of GaAs at 300 K is 1.42 eV, which decreases with temperature as $\frac{dE_g}{dT} = -4.5 \times 10^{-4}\ \text{eV} \cdot \text{K}^{-1}$. What would be the change in the emission wavelength if the temperature of the GaAs LED is increased by 10 °C?

(7 Marks)

(d) A *p-n* junction photodiode can be operated under photovoltaic condition similar to a solar cell. State three major differences between a photodiode and a solar cell.

(4 Marks)

List of Selected Formulae

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

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

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

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

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

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

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

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

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

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

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

$$n_0 p_0 = n_i^2$$

List of Selected Formulae (cont'd)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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	$\text{Jmol}^{-1}\text{K}^{-1}$
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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EE2003 PYP Solution

2018/2019 S2

Date No.

1a. i) Distance between atom A & B $= \sqrt{\left(\frac{a}{4}\right)^2 + \left(\frac{a}{4}\right)^2 + \left(\frac{a}{4}\right)^2} = \frac{a}{4}\sqrt{3}$

$r_B = 0.75 r_A$.

$\frac{a}{4}\sqrt{3} = r_A + r_B$

$= 1.75 r_A$

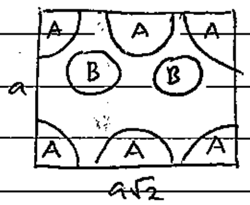
$r = r_A = 0.247a$

ii) % volume occupied $= \dfrac{4\left(\frac{4}{3}\pi r_A^3\right) + 4\left(\frac{4}{3}\pi r_B^3\right)}{a^3}$

$= 4\left(\frac{4}{3}\pi\right)(0.247)^3 + 4\left(\frac{4}{3}\pi\right)(0.247)^3(0.75)^3$

$= 0.3609$

$= 36.09\ \%$

iii) 

(110) plane

Surface density $= \dfrac{\text{no. of atoms}}{\text{area}}$

$5.4\times10^{14} = \dfrac{4}{a^2\sqrt{2}}$

$a = 7.237\ \text{Å}$

1b. $T = 350\ K$

$n_i = 3.3\times10^{14}\ /cm^3$

i) E_F is closer to E_c : n-type.

$N_D \approx n_o = n_i \exp\left(\dfrac{E_F - E_i}{k_B T}\right) = 3.3\times10^{14} \exp\left(\dfrac{\left(\frac{0.91}{2} - 0.4\right)\times1.6\times10^{-19}}{(1.38\times10^{-23})(350)}\right)$

$N_D = 2.04\times10^{15}\ /cm^3$

ii) E_F is closer to E_v : p-type.

$p_o = n_i \exp\left(\dfrac{E_i - E_F}{k_B T}\right) = 3.3\times10^{14} \exp\left(\dfrac{\left(\frac{0.91}{2} - 0.35\right)\times1.6\times10^{-19}}{(1.38\times10^{-23})(350)}\right)$

$p_o = 1.07\times10^{16}\ /cm^3$

$p_o + N_d = n_o + N_a$

$N_A \approx p_o + N_D = 1.27\times10^{16}\ /cm^3$

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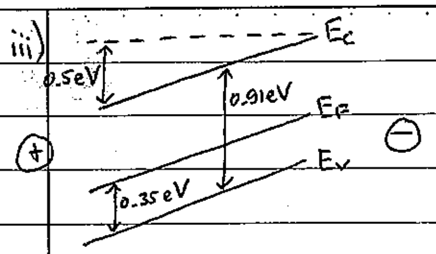
iii)



2a. $L = 30\ \mu m$ $d = 12\ \mu m$

$N_A(x) = N_{A0} \exp\left(-\frac{x}{d}\right)\ cm^{-3}$ $\mu_p = 750\ cm^2/V\cdot s$

$T = 300\ K$

$N_{A0} = 2.6\times10^{16}/cm^3$

i) At thermal equilibrium, $J_p = J_{pdrift} + J_{pdiff} = 0$.

$J_{pdrift} = -J_{pdiff} = qD_p \frac{dp}{dx}$

$D_p = \frac{k_B T}{q}\mu_p = 0.0259\ (750) = 19.425$

$\frac{dp}{dx} = \frac{dN_A(x)}{dx} = -\frac{N_{A0}}{d}\exp\left(-\frac{x}{d}\right)$

$J_{pdrift}\ (x = 15\ \mu m) = qD_p \frac{dN_A(x=15\mu m)}{dx}$

$= (1.6\times10^{-19})(19.425)\left(\frac{-2.6\times10^{16}}{12\times10^{-4}}\exp\left(\frac{-15\times10^{-4}}{12\times10^{-4}}\right)\right)$

$= \boxed{-19.293\ A/cm^2}$

$\mathcal{E}(x) = \frac{J_{pdrift}(x)}{qN_A(x)\mu_p} = \frac{-19.293}{(1.6\times10^{-19})(2.6\times10^{16})\left(\exp\left(\frac{-15\times10^{-4}}{12\times10^{-4}}\right)\right)(750)}$

$= \boxed{-21.583\ V/cm}$

ii) $J_p = J_{pdrift} + J_{pdiff} = 15\ A/cm^2$

As derived in part (i), $J_{pdiff} = -\frac{qD_pN_{A0}}{d}\exp\left(-\frac{x}{d}\right)$

$\mathcal{E}(x) = \frac{J_{pdrift}}{qN_a\mu_p} = \frac{15 + \frac{qD_pN_{A0}}{d}\exp\left(\frac{-x}{d}\right)}{q\mu_p\left(N_{A0}\exp\left(\frac{-x}{d}\right)\right)}$

$$\xi(x) = \frac{15}{q\mu_p N_{A0}\exp\left(\frac{-x}{d}\right)} + \frac{k_BT}{q}\frac{1}{d}$$

$$= \frac{15}{(1.6\times10^{-19})(750)(2.6\times10^{16})}\exp\left(\frac{x}{d}\right) + \frac{0.0259}{12\times10^{-4}}$$

$$\boxed{\xi(x) = 4.808\exp\left(\frac{x}{d}\right) + 21.583 \text{ V/cm}; \; d = 12\,\mu m}$$

b. $N_A = 2\times10^{16}\ /cm^3$ $\quad \tau_n = 2\mu s$ $\quad n_i = 1.5\times10^{12}\ /cm^3$

$J_{ndiff}(x=0) = -50\ mA/cm^2$ $\quad \mu_n = 950\ cm^2/V\cdot s$ $\quad T = 300K$

i) $L_n = \sqrt{D_n\tau_n} = \sqrt{\frac{k_BT}{q}\mu_n\tau_n} = \sqrt{(0.0259)(950)(2\times10^{-6})} = 7.015\times10^{-3}$

$$\Delta n(x) = \Delta n(x=0)\exp\left(-\frac{x}{L_n}\right)$$

$$\frac{d\,\Delta n(x)}{dx} = \frac{-\Delta n(x=0)}{L_n}\exp\left(-\frac{x}{L_n}\right)$$

$$J_{ndiff}(x) = qD_n\frac{d\Delta n(x)}{dx}$$

$$D_n = \frac{k_BT}{q}\mu_n = (0.0259)(950) = 24.605$$

At $x=0$, $J_{ndiff} = -50\times10^{-3}$

$$\frac{d\Delta n(x)}{dx} = \frac{-\Delta n(x=0)}{7.015\times10^{-3}}\exp\left(\frac{-0}{L_n}\right)$$

$$\Delta n(x=0) = \frac{-J_{ndiff}(x=0)}{qD_n}\cdot(7.015\times10^{-3})$$

$$= \frac{(50\times10^{-3})(7.015\times10^{-3})}{(1.6\times10^{-19})(24.605)}$$

$$= \boxed{1.270\times10^{15}\ /cm^3}$$

ii) $\Delta n(x=0) = 1.27\times10^{19} > 0.1\,N_A = 2\times10^{15}$

Hence, low-level injection condition is not valid.

iii) $J_{ndiff}(x') = 0.5\,J_{ndiff}(x=0) = -25\ mA/cm^2$

$$\frac{-\Delta n(x=0)}{L_n}\exp\left(\frac{-x'}{L_n}\right)qD_n = -25\times10^{-3}$$

$$x' = -L_n\ln\left(\frac{25\times10^{-3}L_n}{qD_n\,\Delta n(x=0)}\right) = -(7.015\times10^{-3})\ln\left(\frac{25\times10^{-3}(7.015\times10^{-3})}{(1.6\times10^{-19})(24.605)(1.27\times10^{15})}\right)$$

$\boxed{x' = 0.088 \text{ cm}}$

2c. $N_{d,emitter} = 3\times10^{18}/cm^3$ $W_b = 1\mu m$ $\mu_n = 1250 \ cm^2/V\cdot s$ $T = 300K$

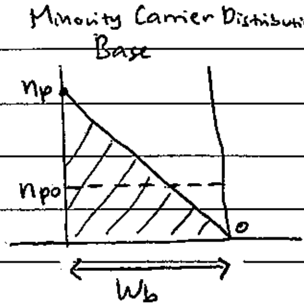
$N_{a,base} = 5\times10^{16}/cm^3$ $A = 10^{-3} \ mm^2$ $\mu_p = 350 \ cm^2/V\cdot s$

$N_{d,collector} = 5\times10^{15}/cm^3$ $\tau_p = \tau_n = 0.1\mu s$ $V_{be} = 0.5 \ V$

i) V_{bi} (between emitter and base) $= \frac{kT}{q} \ln\left(\frac{N_{a,base}\cdot N_{d,emitter}}{n_i^2}\right)$

$= 0.0259 \ln\left(\frac{5\times10^{16}\times3\times10^{18}}{(1.5\times10^{10})^2}\right)$

$= 0.884 \ V$



$n_p = n_{po}\exp\left(\frac{q}{kT}(V_{bi}-V_a)\right)$; $n_{po} = \frac{n_i^2}{N_{a,base}}$

$= \frac{(1.5\times10^{10})^2}{5\times10^{16}}\exp\left(\frac{0.884-0.5}{0.0259}\right)$

$= 1.239\times10^{10}/cm^3$

Minority carrier charge in base region $= q\cdot\frac{n_p\cdot W_b}{2}\cdot A$

$= \frac{(1.6\times10^{-19})(1.239\times10^{10})(1\times10^{-4})(10^{-7})}{2}$

$= \boxed{9.912\times10^{-21} \ C}$

ii) $I_c = \frac{-e D_n A_{BE}}{x_B} n_{Bo}\exp\left(\frac{eV_{BE}}{kT}\right)$

$= \frac{-(1.6\times10^{-19})(0.0259)(1250)(10^{-7})}{1\times10^{-4}}\frac{(1.5\times10^{10})^2}{5\times10^{16}}\exp\left(\frac{0.5}{0.0259}\right)$

$\boxed{I_c = -5.64 \ nA}$

3a. $\tau_n = 2\mu s$ $A = 2.5\times10^{-4} \ cm^2$ $T = 300K$

$\tau_p = 0.5\mu s$ $\mathcal{E}_{critical} = 1.1\times10^5 \ V/cm$

i) V_{bi} = area under $\mathcal{E}-x$ graph $= \frac{1}{2}\times2.8\times10^4\times0.2\times10^{-4} = \boxed{0.28 \ V}$

$N_d x_n = N_a x_p$

$\frac{N_d}{N_a} = \frac{0.15}{0.05} = \frac{3}{1}$

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

$$N_a(3N_a) = \exp\left(\frac{0.28}{0.0259}\right) \times (2.4\times 10^{13})^2$$

$$\boxed{\begin{aligned} N_a &= 3.085 \times 10^{15}\ /cm^3 \\ N_D &= 3N_a = 9.254\times 10^{15}\ /cm^3 \end{aligned}}$$

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

$$= \left[\frac{2\times 16\times 8.85\times 10^{-14}\,(0.28+50)}{1.6\times 10^{-19}}\left(\frac{1}{3.085\times 10^{15}}+\frac{1}{9.254\times 10^{15}}\right)\right]^{1/2}$$

$$= 6.202\ \mu m$$

$$\frac{N_d}{N_a} = \frac{x_p}{x_n} = \frac{3}{1}$$

$$x_n = \frac{1}{4}W = 1.551\ \mu m$$

$$\mathcal{E}_{max} = \frac{qN_d x_n}{\varepsilon_r\varepsilon_0} = \frac{(1.6\times 10^{-19})(9.254\times 10^{15})(1.551\times 10^{-4})}{16\times 8.85\times 10^{-14}} = \boxed{162.128\ kV/cm}$$

As $\mathcal{E}_{max} = 1.6\times 10^5 > \mathcal{E}_{critical} = 1.1\times 10^5$, it is not safe to operate at this voltage. The diode will experience breakdown.

iii)

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3b. i) Schottky contact : $q\phi_m > q\phi_s$

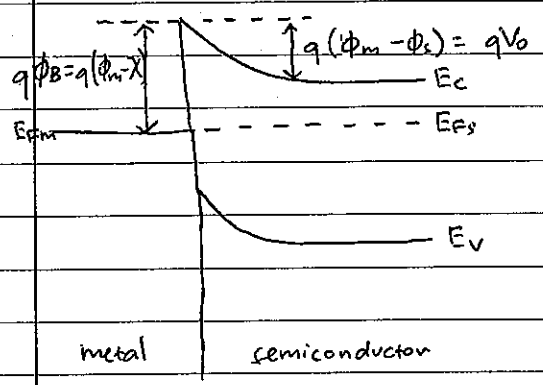
For $N_D = 5\times10^{16}$ /cm³,

$$E_c - E_F = \frac{-k_BT \ln\left(\frac{N_D}{N_c}\right)}{q} = -\frac{(1.38\times10^{-23})(300)}{1.6\times10^{-19}} \ln\left(\frac{5\times10^{16}}{2.8\times10^{19}}\right) = 0.164 \text{ eV}$$

$$q\phi_s = q\chi + E_c - E_F = 4.01 + 0.164 = 4.174 \text{ eV}$$

Metal C is suitable since $q\phi_m$ metal C is higher than 4.174 eV.

ii)



iii) $$W = \left[\frac{2\varepsilon_r\varepsilon_0(V_{bi}-V_a)}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2} ; N_a >> N_d$$

$$W = \left[\frac{2(11.7)(8.85\times10^{-14})(4.75-4.174+5)}{(1.6\times10^{-19})(5\times10^{16})}\right]^{1/2} = 0.380 \ \mu m$$

$$\frac{C_j}{A} = \frac{\varepsilon_r\varepsilon_0}{W} = \frac{11.7 \times 8.85\times10^{-14}}{0.38\times10^{-4}} = \boxed{2.725 \times 10^{-8} \text{ F/cm}^2}$$

4a. Direct bandgap semiconductor : left figure

Indirect bandgap semiconductor : right figure

In an indirect bandgap semiconductor, more energy is needed for electron-hole recombination.

4b. $A = 5\times10^{-2}$ cm² $I = 2$ mW/cm²

$\lambda = 600$ nm $\eta = 85\%$

i) $$E_{ph} = N.\frac{hc}{\lambda}$$

$$N = \frac{I.A.\lambda}{h.c} = \frac{2\times10^{-3}\times5\times10^{-2}\times600\times10^{-9}}{(6.626\times10^{-34})(3\times10^{8})} = \boxed{3.018\times10^{14} \text{ EHP/s}}$$

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ii) $I = RP = \eta \frac{e}{E_{ph}} . I . A$; $E_{ph} = \frac{1240}{\lambda(\text{in nm})}$ (in eV)

$I = 0.85 \times \frac{600}{1240} \times 2\times10^{-3} \times 5\times10^{-2} = \boxed{41.13\ \mu A}$

iii) $R = \eta \frac{e}{E_{ph}} = 0.85 \times \frac{600}{1240} = \boxed{0.411}$

4c. $\frac{dE_g}{dT} = -4.5\times10^{-4}$ eV/K

$E_{g1} = 1.42$ eV at $T_1 = 300$ K

For $T_2 = 310$ k, $E_{g2} = E_{g1} + \frac{\Delta E_g}{\Delta T} . \Delta T$

$= 1.42 - 4.5\times10^{-4}\times10$

$= 1.4155$ eV

$\lambda_1 = \frac{1240}{E_{g1}} = \frac{1240}{1.42} = 873.24$ nm

$\lambda_2 = \frac{1240}{E_{g2}} = \frac{1240}{1.4155} = 876.02$ nm

$\Delta\lambda = \lambda_2 - \lambda_1 = \boxed{2.78\ \text{nm}}$

4d. Refer to lecture notes.

All the best for your exams!

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