NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2020-2021

EE2003 – SEMICONDUCTOR FUNDAMENTALS

April / May 2021

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) The doping concentration in a n-type silicon is 3.43×10^{14} cm^{-3}. At $T = 300$ K, the bandgap of silicon is 1.12 eV and the intrinsic carrier concentration is 1.5×10^{10} cm^{-3}, determine:

   (i) The probability that an energy state at the conduction band edge is occupied by an electron.

   (ii) The probability that an energy state at the valance band edge is empty.

   (8 Marks)

   (b) Silicon atoms at a concentration of 7×10^{15} cm^{-3} are added to a gallium arsenide crystal. Assume that the silicon atoms act as fully ionized dopant atoms and that 5% of the concentration added replace gallium atoms and 95% replace arsenic atoms. At $T = 300$ K, the intrinsic carrier concentration of gallium arsenide is 1.8×10^{6} cm^{-3}.

Note: Question No. 1 continues on page 2.

(i) Determine the donor and acceptor concentrations.
(ii) Calculate the electron and hole concentrations.
(iii) Determine the position of the Fermi level with respect to E_{Fi}.

(9 Marks)

(c) A silicon semiconductor resistor is in the shape of a rectangular bar with a cross-sectional area of 8.5×10^{-4} cm^2, a length of 0.075 cm, and is doped with a concentration of 2×10^{16} cm^{-3} boron atoms. A bias of 2 V is applied across the length of the resistor. At $T = 300$ K, assuming that the hole mobility is 400 cm^2/V.s,

(i) Calculate the current in the resistor.
(ii) Determine the average drift velocity of the holes.

(8 Marks)

2. (a) In a silicon sample, the electron and hole concentrations are given by the following expressions:

$$n(x) = 10^{15} \exp\left(-\frac{x}{L_n}\right) \quad \text{for } x \geq 0$$

$$p(x) = 5 \times 10^{15} \exp\left(\frac{x}{L_p}\right) \quad \text{for } x \leq 0$$

The diffusion lengths for electrons and holes are $L_n = 2\times10^{-3}$ cm and $L_p = 5\times10^{-4}$ cm, respectively. The electron and hole diffusion coefficients are $D_n = 25$ cm^2/s and $D_p = 10$ cm^2/s, respectively. The total current density is defined as the sum of the electron and hole diffusion current densities at $x = 0$. Calculate the total current density.

(8 Marks)

(b) At 300 K, a light source generates electron-hole pairs (EHPs) uniformly across an n-type silicon sample at a rate of 5.3×10^{20} cm^{-3}s^{-1}. The dopant concentration of the silicon sample is 2×10^{17} cm^{-3}.

(i) Determine the steady-state excess carrier concentration if the carrier lifetime is 2.2 μs?
(ii) Does the excess carrier concentration correspond to low-level injection? Justify your answer.

Note: Question No. 2 continues on page 3.

(iii) What percentage of the excess carrier concentration would remain at a time interval twice as long as the carrier lifetime after switching off the light?
(iv) If the light source is switched off for a very long time, estimate the carrier concentration in the silicon sample.

(9 Marks)

(c) A silicon NPN bipolar junction transistor has a doping concentration of 5×10^{16} cm^{-3} in the base region, a base region width $W_b = 0.5$ µm, and a cross-section of 5×10^{-3} mm^2. The electrons in the base region have a mobility μ_n = 1350 cm^2/V.s. Assume that the transistor is operating in the forward active mode at T = 300 K and a collector current of 100 mA is measured, calculate the base-emitter bias voltage of the transistor.

(8 Marks)

3. (a) The spatial distribution of carrier concentration in an abrupt silicon p-n junction diode during operation at 300 K is shown in Figure 1. Assume the following: $\varepsilon_r = 11.8$, $n_i = 1\times10^{10}$ cm^{-3}, and the cross-sectional area of the diode is 10^{-3} cm^2.

(i) Calculate the built-in voltage V_o at thermal equilibrium.
(ii) State whether the diode is forward or reverse biased. Justify your answer.
(iii) Compute the value of the applied biasing voltage.
(iv) Briefly explain how the current is generated during the biasing as stated in part (ii).

(9 Marks)

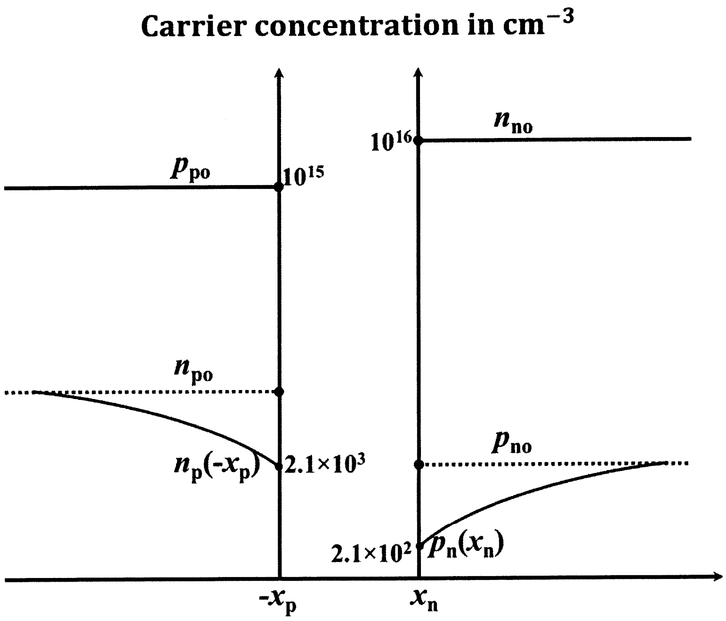


Figure 1

Note: Question No. 3 continues on page 4.

(b) Explain briefly which capacitance (junction capacitance or charge storage capacitance) dominates during reverse biased conditions of a p-n junction diode.

(2 Marks)

(c) Consider an ideal metal-semiconductor contact fabricated using silicon at 300 K. The Fermi level in Si is located 0.2 eV below the conduction band edge E_c. The bandgap energy and electron affinity of Si are 1.1 eV and 4.05 eV, respectively. The work function of the metal used is 4.8 eV and the intrinsic carrier concentration n_i of Si at 300 K is 1.0×10^{10} cm^{-3}.

(i) Determine the values of semiconductor work function and the barrier heights at the metal-side and silicon-side, in eV.
(ii) State and justify whether the contact fabricated is ohmic or Schottky.
(iii) Compute the value of dopant concentration in Si.
(iv) Assume that the operating temperature of the metal-semiconductor contact is increased to 350 K and the intrinsic carrier concentration n_i is 2×10^{12} cm^{-3} in Si at 350 K. Calculate and verify if the contact made is still the same as stated in part (ii), assuming that the bandgap energy of Si is independent of temperature.

(14 Marks)

4. (a) A Germanium photodiode has a responsivity of 0.5 A/W at λ = 800 nm and an active area of 0.1 mm^2. A laser beam at the above wavelength is incident on the photodiode. Assume that the laser beam has an intensity of 10 mW/cm^2, calculate the photocurrent generated in the circuit? What is the quantum efficiency of the photodiode?

(5 Marks)

(b) Both light emitting diodes (LEDs) and laser diodes (LDs) are light emitting devices made based on a semiconductor PN-junction structure. However, one type of the devices emits coherent light while the other type emits incoherent light.

(i) State which type of the devices emits coherent light and which type emits incoherent light?
(ii) Based on the operation principle of the devices, briefly explain why light emitted by them have such different properties.
(iii) To fabricate the devices, what kind of semiconductor materials should be used? Explain why?
(iv) In order to have coherent light emission from the devices, the population inversion is a necessary condition. Briefly explain how one could achieve the population inversion in the devices.

(12 Marks)

Note: Question No. 4 continues on page 5.

(c) A semiconductor rod with a length L and a cross-sectional area S is illuminated by a constant intensity light beam. As a result, uniform electron-hole pairs are generated in the rod with a generation rate G. If a voltage of V is added to the two ends of the rod, show that the photocurrent generated by the light illumination is determined by $I_{ph} = qGS(\mu_n\tau_n + \mu_p\tau_p)\frac{V}{L}$, where μ_n and μ_p are the electron and hole mobilities, respectively, and τ_n and τ_p are the excess electron and hole lifetimes, respectively, in the rod.

(8 Marks)

List of Selected Formulae

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

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

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

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

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

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

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

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

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

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

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

$$n_0 p_0 = n_i^2$$

List of Selected Formulae (cont'd)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$$

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

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

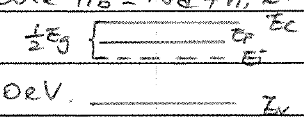
END OF PAPER

EE2003 Semiconductor Fundamentals

Subject: AY/2020/2021 Sem2. No: Date:

1 (a)(i) Using formula $n_o = n_i e^{\frac{E_F - E_i}{kT}}$. Given dopant concentration N_d is much greater than intrinsic carrier concentration n_i, take $n_o = N_d + n_i \approx N_d$

Rearranging, $E_F - E_i = kT \ln \frac{N_d}{n_i} = 0.26\,eV$.



From energy level diagram, $E_C - E_F = \frac{1}{2}E_g - (E_F - E_i) = 0.30\,eV$.

Therefore, from Fermi-Dirac distribution, probability of an energy state, E being occupied by an electron is : $f(E) = \left(1 + e^{\frac{E - E_F}{kT}}\right)^{-1}$

At conduction band edge, $E = E_c$, $f(E = E_c) = \left(1 + e^{\frac{0.30eV}{0.0259eV}}\right)^{-1} = 9.312 \times 10^{-6}$

(ii) From the above energy level diagram, $E_F - E_V = E_g - (E_C - E_F) = 0.82\,eV$

A state being empty is complement to a state being occupied.

Required probability of valence band edge being empty is then,

$1 - f(E = E_V) = 1 - \left(1 + e^{\frac{E_V - E_F}{kT}}\right)^{-1} = 1 - \left(1 + e^{\frac{-0.82eV}{0.0259}}\right)^{-1} \approx 0$

(b)(i) Gallium is group III elements with 3 valence electrons. Substituting it with Silicon (group IV element, 4 valence electrons), there will be an extra electron (free carrier ⇒ n-type). In this case, Si atoms act as a donor atom

⇒ $N_d = 0.05 \times 7 \times 10^{15} = 3.5 \times 10^{14}\,cm^{-3}$

Arsenic is group V element, with 5 valence electrons. Substituting it with Silicon (group IV element, 4 valence electrons), there will be less one electron (or equivalently, creation of an extra hole ⇒ p-type). In this case, Si atoms act as acceptor atoms.

⇒ $N_a = 0.95 \times 7 \times 10^{15} = 6.65 \times 10^{15}\,cm^{-3}$

(ii) Two types of dopants ⇒ compensated material. $N_a > N_d$, i.e. holes dominate, resulting in a p-type material. $p_o = N_a - N_d = 6.3 \times 10^{15}\,cm^{-3}$

In equilibrium, law of mass action holds, $n_o = \frac{n_i^2}{p_o} = 5.1429 \times 10^{-4}\,cm^{-3}$

(iii) Using formula $p_o = n_i e^{\frac{E_i - E_F}{kT}}$ & rearranging, $E_i - E_F = 0.5692\,eV$.

(Assumption : E_i is at the middle of bandgap). E_F is $0.5692\,eV$ below E_i.

(c)(i) Assumption : uniform doping, no concentration gradient ⇒ no diffusion current

Doped with boron (group III) ⇒ p-type material ⇒ hole drift dominates.

$I_{total} \approx I_{p,drift} = qA\mu_p p \mathcal{E} = qA\mu_p N_a \frac{V}{L} = 29.013\,mA$ ($N_a \gg n_i \Rightarrow p = N_a$)

(ii) Using formula for drift velocity : $v_{dp} = \mu_p \mathcal{E} = \mu_p \frac{V}{L} = 1.067 \times 10^4\,cms^{-1}$.

No:

Subject:

Date:

2 (a) Using formula $J = J_{n,diff}(x=0) + J_{p,diff}(x=0) = qD_n \frac{dn}{dx}(x=0) - qD_p \frac{dp}{dx}(x=0)$,

$J = qD_n \frac{d}{dx}(N_d e^{-\frac{x}{L_n}})\Big|_{x=0} - qD_p \frac{d}{dx}(N_a e^{+\frac{x}{L_p}})$

$= -q\left[+\frac{1\times10^{15}\times D_n}{L_n}e^0 + \frac{5\times10^{15}\times D_p}{L_p}e^0\right]$

$= -18\ Acm^{-2}$

Note: For hole diffusion, if $\frac{dp}{dx} < 0$ (higher concentration on the left) $\Rightarrow$ holes diffuse to the right $\Rightarrow$ current to the right $\Rightarrow \vec{J} > 0$ (+ve direction to the right)

$\Rightarrow$ opposite sign between $\frac{dp}{dx}$ and J $\Rightarrow$ need -ve sign.

(b) (i) Steady-state, $\Delta p_{ss} = G_L \tau_p = 1.166\times10^{15} cm^{-3}$

(ii) At any time t, $\Delta p(t) = \Delta p_{ss} e^{-\frac{t}{\tau_p}} \le \Delta p_{ss}$ ($t>0$, hence $e^{-\frac{t}{\tau_p}} < 1$)

Therefore, change of minority carrier, $\Delta p(t) < 0.1 n_0 = 2\times10^{16} cm^{-3}$ for low level-injection to hold. Since $1.166\times10^{15} < 2\times10^{16}$, assumption is valid.

(iii) At $t = 2\tau_p$, $\Delta p = \Delta p_{ss} e^{-\frac{2\tau_p}{\tau_p}} = e^{-2}\Delta p_{ss} = 0.1353\,\Delta p_{ss}$

$\Rightarrow$ 13.53% of the excess carrier remains.

(iv) At $t = \infty$, $\Delta p = \Delta p_{ss} e^{-\infty} = 0$. All excess carriers generate by optical excitation has recombined. $n = n_0 = 2\times10^{17}$, $p = p_0 = \frac{n_i^2}{n_0} = 1.125\times10^3$ (all in cm^{-3})

(c) Base minority concentration, $n_{B0} = \frac{n_i^2}{p_{B0}} = 4.5\times10^3 cm^{-3}$

Collector current $|i_c| = \frac{qD_n A_{BE}}{x_B} n_{B0} e^{\frac{V_{BE}}{kT}}$ and is given as 100mA.

Rearranging, base-emitter voltage can be calculated. $V_{BE} = 0.7514V$.

Subject: No: Date:

3 (a)(i) Using formula, $V_0 = \frac{kT}{q}\ln\left(\frac{N_d N_a}{n_i^2}\right) = \frac{kT}{q}\ln\left(\frac{p_{po} n_{no}}{n_i^2}\right) = 0.656V$

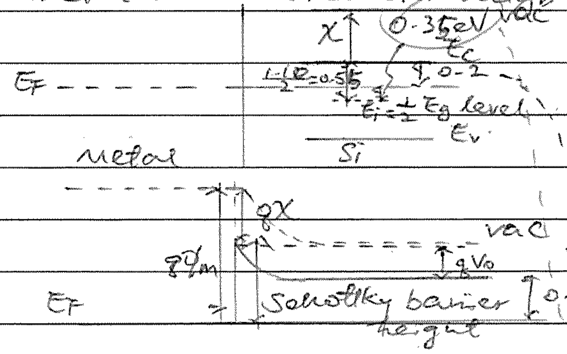
(ii) This diode is reversed-biased, as seen from the carrier concentration graph, there is carrier extraction at the edges of the depletion region, i.e. carrier concentration is lower than at equilibrium

(iii) Using formula $n_p(-x_p) = n_{po} e^{\frac{qV_a}{kT}}$, V_a is obtained as $-0.10V$.
This confirms (ii); diode is applied a reverse-bias voltage.
Note: $p_n(x_n) = p_{no} e^{\frac{qV_a}{kT}}$ gives the same answer

(iv) Small amount of minority carrier diffuse to edge of space charge region. Built-in electric field within the space charge region causes the carriers to drift from minority side to majority side (holes in ~~n-junction~~ region drifts to p-region to become majority carriers). The current flow is thus from n-region to p-region, hence the name "reverse" saturation current.
Note: "saturation" because there is very limited amount of minority carriers available to drift to the majority region.

(b) Under reverse-biased condition, minority carrier extraction greatly reduces the concentration of minority carriers. Therefore, charge storage capacitance is negligible. Junction capacitance dominates, even though $C_j \propto 1/W$ and W is increased in reverse-biased.

(c)(i) Refer to following energy level diagrams. At equilibrium, E_F of the metal & semiconductor align.



Work function ϕ: vacuum to E_F.
Electron affinity χ: vacuum to E_c.
$\Rightarrow q\phi_s = q\chi + (E_c - E_F) = 4.25eV$.
Barrier at metal, $q\phi_B = q\phi_m - q\chi = 0.75eV$.
Barrier at Si, $qV_0 = q\phi_B - (E_c - E_F) = 0.55eV$
(Alternatively, how much the $E_{F,Si}$ need to shift to align with $E_{F,m}$: $q\phi_m - q\phi_s = 0.55eV$)

(ii) Schottky. Constant barrier at metal-side $\Rightarrow$ unidirectional

(iii) Assume $N_d >> n_i \Rightarrow n_o = N_d$, $n_o = n_i e^{\frac{E_F - E_i}{kT}} = 7.3934\times10^{15} cm^{-3}$

350K now

(iv) From $n_o = n_i e^{\frac{E_F - E_i}{kT}}$, calculate $E_F - E_i = 0.248eV$ (DON'T USE $kT = 0.0259eV$)
Therefore, $E_c - E_F = \frac{1}{2}E_g - (E_F - E_i) = 0.302eV \Rightarrow q\phi_s = q\chi + (E_c - E_F) = 4.352eV$
As $q\phi_m > q\phi_s$, for n-type silicon, contact still remains as Schottky

No:

Subject: Date:

power intensity area mW mm^2 to cm^2

4 (a) Photocurrent, $I = RP = RQA = 0.5 \times 10 \times 10^{-3} \times 0.1 \times 10^{-2} = 5\mu A$

From $R = \eta \frac{e}{E_{ph}}$, and $E_{ph} = \frac{hc}{\lambda}$, quantum efficiency $\eta = R\frac{hc}{e\lambda} = 0.7765$

(b)(i) Laser: coherent, LED: incoherent.

(ii) Laser operates by stimulated emission, in which stimulating & stimulated photons all have the same phase (coherent), wavelength & polarization. This causes laser emission to be highly directional, monochromatic & high intensity. In contrast, LED operates by spontaneous emission, in which electron hole pairs recombine randomly. Emitted photons are therefore not necessarily in phase & monochromatic.

(iii) Direct bandgap materials are used. This is because the energy local minima for both valence & conduction bands occur at the same wave number. For transition, one of the necessary conditions, momentum conservation has already been satisfied. Therefore electron hole pairs recombine directly without going through intermediate states. The energy difference is radiated as photons instead of heat.

(iv) Population inversion requires heavy doping & forward-biasing. Heavy doping creates large number of carriers in the excited state, ready ~~to~~ recombine upon injection/diffusion to opposite regions of the junction, after a forward-bias voltage is applied.

(c) Uniform optical generation $\Rightarrow$ no concentration gradient $\Rightarrow$ no diffusion.
For photocurrent due to optical excitation, only pertaining to current due to excess electron hole pairs generated. (Δn and Δp)

$$\Rightarrow I_{ph} = \underbrace{qS(\mu_n \Delta n + \mu_p \Delta p)\mathcal{E}}_{\text{drift current formula}} = q S(\mu_n \underbrace{G\tau_n + \mu_p G\tau_p}_{\text{steady-state}})\frac{V}{L} = qGS(\mu_n\tau_n + \mu_p\tau_p)\frac{V}{L}$$