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NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2016-2017

EE2003 – SEMICONDUCTOR FUNDAMENTALS

April / May 2017 Time Allowed: 2½ hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 11 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 is provided in Appendix A from page 7 to page 9, a Table of Physical Constants is provided in Appendix B on page 10, and a Table of Material Properties is provided in Appendix C on page 11.

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1. (a) When an appropriate amount of silicon (Si) and germanium (Ge) atoms are mixed uniformly, $Si_{1-x}Ge_x$ ($0 \le x \le 1$) alloy is formed. The lattice constants of Si and Ge are $a_{Si} = 5.43$ Å and $a_{Ge} = 5.65$ Å at 300 K respectively, while that of $Si_{1-x}Ge_x$ can be approximated as $(1-x)\times a_{Si} + x\times a_{Ge}$. The unit cell of $Si_{1-x}Ge_x$ has diamond crystal structure (lattice constant $a_x = a_y = a_z = a$) as shown in Figure 1 on page 2. Consider an alloy of $Si_{1-x}Ge_x$ with $x = 0.20$ at 300 K:

   (i) What is the effective lattice constant of this alloy?

   (ii) Calculate the volume density (in atom/cm^3) of the alloy.

   (iii) External stresses are applied on the crystal such that $a_x = a_y = 0.98a$ and $a_z = 1.04a$. Recalculate the value in part (ii).

(8 Marks)

Note: Question No. 1 continues on page 2.

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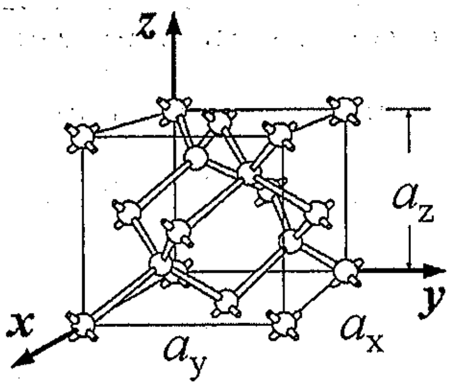

Figure 1

(b) Three commonly known semiconductor materials are provided: GaAs, Si and Ge. The properties of these materials at 300 K are listed in the Appendix C on page 11.

(i) Select one material that can be used to make light emitting device and estimate its emission wavelength. Briefly explain your choice of the material with a suitable *E-k* diagram.

(ii) In one particular application, it is desirable to detect light with a wavelength of 905 nm. Identify all possible materials that can be used from the list.

(8 Marks)

(c) A germanium sample is doped with 1×10^{13} cm^{-3} of acceptor atoms. The intrinsic carrier concentration of germanium is 2.4×10^{13} cm^{-3} at 300 K.

(i) By applying the charge neutrality principle, calculate the electron and hole concentrations in this sample.

(ii) What is the position of the Fermi level E_f with respect to the intrinsic Fermi energy level E_i?

(iii) If the sample is then counter-doped with 2×10^{13} cm^{-3} of donor atoms, recalculate the values in part (i) and part (ii).

(9 Marks)

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2. (a) A semiconductor bar with the cross sectional area of 10^{-4} cm^2 and length of 100 μm is uniformly doped with donors to a concentration of $N_d = 10^{16}$ cm^{-3}. The electron and hole mobilities for this sample are μ_n = 1,000 cm^2/Vs and μ_p = 480 cm^2/Vs, respectively. Assume that the mobilities are constant and temperature T = 300 K.

(i) When a voltage of 1.0 V is applied across this sample, what is the current flowing through this sample?

(ii) The sample is then doped with additional donors non-uniformly. The concentration of the additional donors varies as $\Delta N_d(x) = 10^{16}(x/L)$ cm^{-3}, where x ($0 \le x \le L$ = 100 μm) is the distance along the semiconductor. If a constant current of 0.02 A is maintained across this sample, estimate the electric field at x = 50 μm.

(9 Marks)

(b) A semiconductor, doped to a concentration of 5.2×10^{16} cm^{-3} of acceptor impurity, has been exposed to a light source for a long time. Electron-hole pairs (EHPs) are generated uniformly everywhere inside the semiconductor at a rate of 2.4×10^{20} cm^{-3}s^{-1}. The carrier lifetime is 0.5 μs.

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

(ii) What EHP generation rate, if exceeded, will violate the low-level injection approximation?

(iii) The light source is switched off at a time defined as t = 0 s. What fraction of the excess carriers would remain at t = 1.1 μs?

(8 Marks)

(c) For a uniformly doped $p^{++}n^{+}p$ bipolar junction 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 in the forward-active mode of operation

(ii) Sketch the energy band diagram across the emitter region, the base region, and the collector region.

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

(8 Marks)

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3. (a) Figure 2 shows the energy band diagram of a uniformly doped *p*- and *n*-type germanium before contact. The *p*-type region is doped such that the Fermi level E_F is equal to the valence band edge E_V.

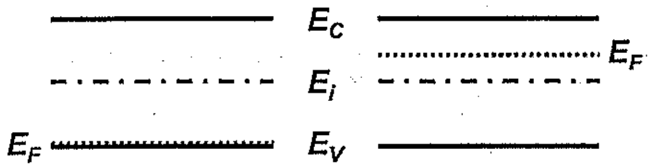

Figure 2

(i) What should be the maximum difference between E_F and E_i, respective Fermi level and intrinsic Fermi level of the *n*-type region, if the built-in voltage of the diode formed using the two regions is not to exceed 0.45 V? Hence, determine the maximum doping density of the *n*-region.

(ii) For the doping density determined in part (i), sketch to reasonable accuracy a *labelled* energy band diagram of the diode at thermal equilibrium.

(7 Marks)

(b) Table 1 shows the properties of a Si *p*-*n* junction diode. The diode is forward biased at 0.72 V.

Table 1

	p-region	*n*-region
Doping density (cm^{-3})	7.5×10^{16}	7.5×10^{16}
Hole mobility ($cm^2V^{-1}s^{-1}$)	450	400
Electron mobility ($cm^2V^{-1}s^{-1}$)	1300	1450
Hole lifetime (s)	3.0×10^{-7}	2.2×10^{-6}
Electron lifetime (s)	1.2×10^{-6}	5.8×10^{-7}

(i) Determine the minimum doping density of the *p*-region such that the low-level injection approximation would not be violated at the bias condition.

Note: Question No. 3 continues on page 5.

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(ii) Calculate the ratio of the hole diffusion current at the n-side depletion edge to the electron diffusion current at the p-side depletion edge.

(iii) Calculate the storage capacitance per unit area.

(10 Marks)

(c) Figure 3 shows the energy band diagram of a metal-semiconductor contact at thermal equilibrium. The intrinsic carrier concentration is 7.0×10^{9} cm^{-3}.

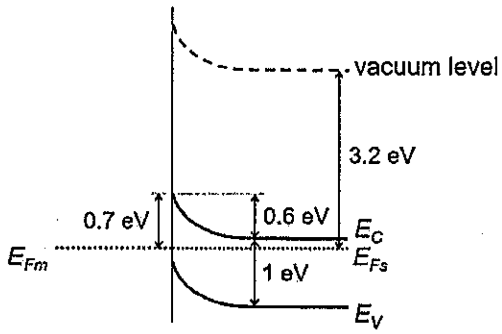

Figure 3

(i) Is the contact Schottky or Ohmic? Briefly justify your answer.

(ii) Calculate the doping density of the semiconductor.

(iii) A voltage of −1.5 V is applied to the metal and a voltage of +0.5 V is applied to the semiconductor. Sketch the *labelled* energy band diagram of the contact for this bias condition.

(8 Marks)

4. (a) A photodetector consists of an absorbing thin layer of a type of semiconductor with a thickness of 500 nm. The photodetector is subject to incident surface-normal light from air with a total power of 1 mW. Assume that the incident light wavelength is 1.5 μm, the absorption coefficient of this semiconductor is 2×10^{4} cm^{-1}, and its refractive index is 3.2 at the light frequency.

(i) Determine the power absorbed within the absorbing layer of the semiconductor, i.e. from the surface to the depth of 500 nm in the semiconductor layer.

Note: Question No. 4 continues on page 6.

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(ii) Assume that 80% of photons absorbed in part (i) are converted to electrons. Calculate the responsivity of this photodetector.

(iii) What is the measured current if the incident light intensity is 50 mW for this photodetector?

(12 Marks)

(b) Consider a typical semiconductor light emitting diode.

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

(ii) Sketch the energy band diagrams of this light emitting diode under the equilibrium and the forward bias conditions, respectively.

(iii) Plot the light output versus the pumping current characteristics of a light emitting diode and a diode laser.

(7 Marks)

(c) Describe how Liquid Crystal Displays (LCDs) work. Use figures to explain.

(6 Marks)

* The solution is only for your references

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1 a i. $a_{Si} = 5.43\text{Å}$

$a_{Ge} = 5.65\text{Å}$

$x = 0.20$

$a = (1-x) \times a_{Si} + x \times a_{Ge}$

$= (1-0.20) \times 5.43\text{Å} + 0.20 \times 5.65\text{Å}$

$= 5.474\text{Å}$

ii. Volume density $= \frac{8}{a^3}$ (Number of atoms in an unit cell of diamond = 8)

$= \frac{8}{(5.474 \times 10^{-8})^3}$

$= 4.877 \times 10^{22}$ atom/cm^3

iii. New volume $= a_x \cdot a_y \cdot a_z$

$= 0.98a \times 0.98a \times 1.04a$

$= 0.998816a^3$ cm^3

New volume density $= \frac{8}{0.998816a^3}$

$= 4.883 \times 10^{22}$ atom/cm^3

* The solution is only for your references

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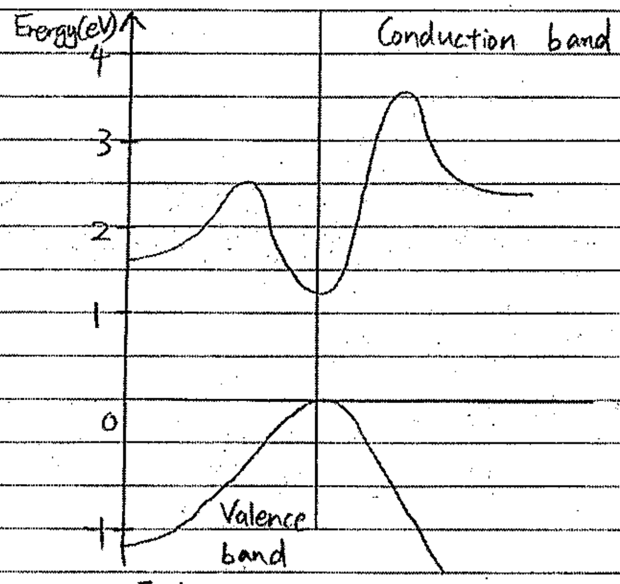
bi. GaAs

GaAs is a direct bandgap semiconductor. The transitions do not require changes in the crystal momentum. Therefore, the transitions are very efficient. For the transitions from the conduction band to the valence band, the energy is given off as photon or light.



E-k diagram of GaAs

ii. $E = \frac{hc}{\lambda} \approx \frac{1240}{\lambda}$, λ in nm

For GaAs, $\lambda_1 = \frac{1240}{1.42} = 873.24\text{ nm}$

For Si, $\lambda_2 = \frac{1240}{1.12} = 1107.14\text{ nm}$

For Ge, $\lambda_3 = \frac{1240}{0.66} = 1878.79\text{ nm}$

$\because$ λ_2 and λ_3 are greater than 905nm

$\therefore$ Si and Ge can be used

*The solution is only for your references

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i. $p_o = \dfrac{(N_a - N_d) + \sqrt{(N_a - N_d)^2 + 4n_i^2}}{2}$ $(N_a = 1\times10^{13}\,cm^{-3},\ n_i = 2.4\times10^{13}\,cm^{-3})$

$= \dfrac{1\times10^{13} + \sqrt{(1\times10^{13})^2 + 4(2.4\times10^{13})^2}}{2}$

$= 2.9515\times10^{13}\,cm^{-3}$

$n_o = \dfrac{n_i^2}{p_o}$

$= \dfrac{(2.4\times10^{13})^2}{2.9515\times10^{13}}$

$= 1.9515\times10^{13}\,cm^{-3}$

ii. $p_o = n_i \exp\left[\dfrac{E_i - E_F}{k_B T}\right]$

$\dfrac{2.9515\times10^{13}}{2.4\times10^{13}} = \exp\left[\dfrac{E_i - E_F}{0.025875}\right]$

$E_i - E_F = 5.3524\times10^{-3}\,eV$

iii. $n_o' = \dfrac{(N_d - N_a) + \sqrt{(N_d - N_a)^2 + 4n_i^2}}{2}$

$= \dfrac{1\times10^{13} + \sqrt{(1\times10^{13})^2 + 4(2.4\times10^{13})^2}}{2}$

$= 2.9515\times10^{13}\,cm^{-3}$

$p_o' = \dfrac{n_i^2}{n_o'}$

$= 1.9515\times10^{13}\,cm^{-3}$

$n_o' = n_i \exp\left[\dfrac{E_F - E_i}{k_B T}\right]$

$\dfrac{2.9515\times10^{13}}{2.4\times10^{13}} = \exp\left[\dfrac{E_F - E_i}{0.025875}\right]$

$E_F - E_i = 5.3524\times10^{-3}\,eV$

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2a. $A = 10^{-4}\,cm^2$, $N_d = 10^{16}\,cm^{-3}$, $\mu_n = 1000\,cm^2/Vs$, $\mu_p = 480\,cm^2/Vs$, $T = 300K$, $l = 100\,\mu m$

i. $V = 1V$

$J_{ndrift} = qn\mu_n \xi$

$= 1.6\times10^{-19} \times 10^{16} \times 1000 \times 100$

$= 160\,A/cm^2$

$\xi = \frac{V}{l}$

$= \frac{1\,V}{100\times10^{-4}\,cm}$

$= 100\,V/cm$

$J_{ndiff} = qD_n \frac{dn}{dx}$

$= 1.6\times10^{-19} \times 25.875 \times 1\times10^{18}$

$= 4.14\,A/cm^2$

$D_n = \frac{k_B T}{q}\mu_n$

$= \frac{1.38\times10^{-23}\times300}{1.6\times10^{-19}}\times1000$

$= 25.875$

$J_n = 160 + 4.14 = 164.14\,A/cm^2$

$\frac{dn}{dx} = \frac{10^{16}}{100\times10^{-4}}$

$= 1\times10^{18}$

$I = 10^{-4} \times 164.14 = 0.0164\,A$

ii. $x = 50\,\mu m = 50\times10^{-4}\,cm$

$n = N_d = 10^{16}\left(\frac{x}{L}\right)$

$= 10^{16}\left(\frac{50\mu}{100\mu}\right)$

$= 5\times10^{15}\,cm^{-3}$

$J_{ndrift} = qn\mu_n \xi$

$= 1.6\times10^{-19} \times 5\times10^{15} \times 1000\,\xi$

$= 0.8\,\xi$

$\frac{dn}{dx} = \frac{d}{dx}\left(10^{16}\cdot\frac{x}{L}\right)$

$= 10^{16}\cdot\frac{1}{L}$

$= 1\times10^{18}$

$J_{ndiff} = qD_n \frac{dn}{dx}$

$= 1.6\times10^{-19} \times 25.875 \times 1\times10^{18}$

$= 4.14\,A/cm^2$

$0.02 = 10^{-4} \times (0.8\,\xi + 4.14)$

$200 = 0.8\,\xi + 4.14$

$\xi = 244.825\,V/cm$

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bi. $N_A = 5.2 \times 10^{16} cm^{-3}$

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

$= 2.4 \times 10^{20} \times 0.5\mu$

$= 1.2 \times 10^{14} cm^{-3}$

$\because \Delta n_{ss} < 10\%$ of N_A

$\therefore$ Low level injection approximation is valid

ii. $10\% \times N_A = 5.2 \times 10^{15} cm^{-3}$

The low level injection approximation will be violated if EHP generation rate exceeded $5.2 \times 10^{15} cm^{-3}$

iii. $t = 1.1 \mu s$

$\Delta n(t) = \Delta n(t=0) \exp\left(-\frac{t}{\tau_n}\right)$

$\frac{\Delta n(t)}{\Delta n(t=0)} = \exp\left(-\frac{1.1\mu}{0.5\mu}\right)$

$= 0.1108$

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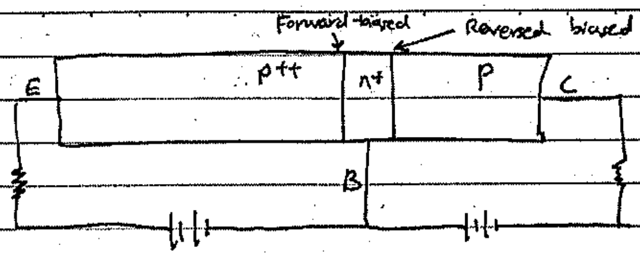
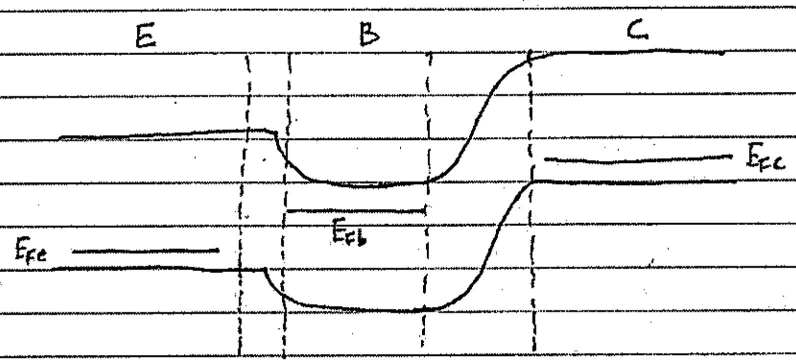
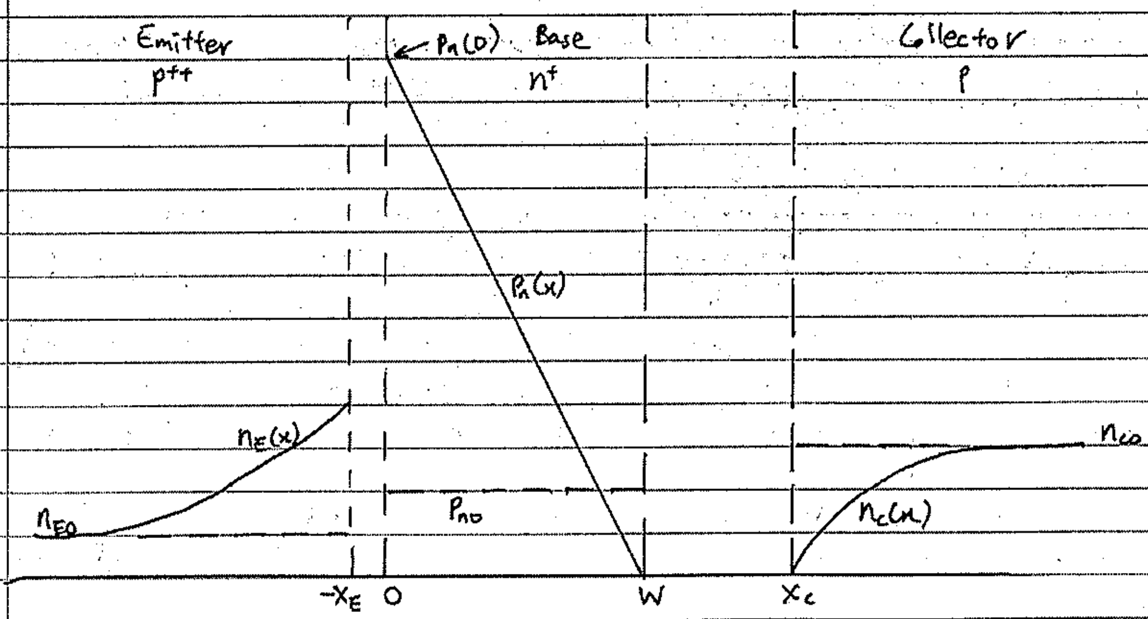
(i.



ii.



iii.



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3ai. Bandgap of Ge $= 0.66eV \Rightarrow E_c - E_v = 0.66eV$

$E_i = \frac{1}{2} \times 0.66eV = 0.33eV$

$E_F - E_i = 0.45 - 0.33$

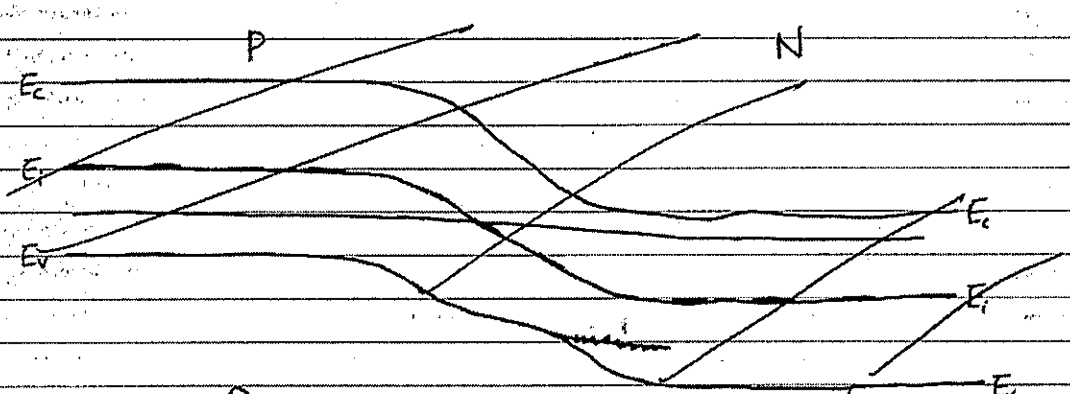
$= 0.12\,eV$

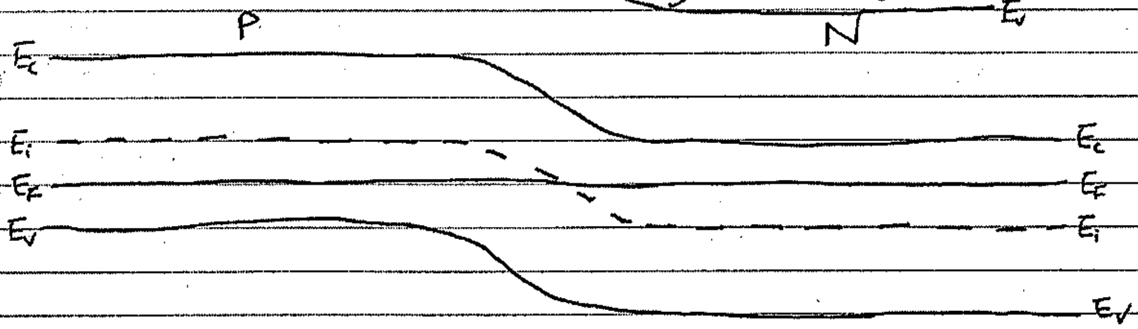
$n_o = n_i \exp\left[\frac{E_F - E_i}{k_B T}\right]$ $\qquad$ n_i of Ge $= 2.4\times10^{13}\,cm^{-3}$

$= 2.4\times10^{13} \exp\left[\frac{0.12}{0.025875}\right]$

$= 2.48\times10^{15}\,cm^{-3}$

ii.





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bi. n_i of $S_i = 1.5\times10^{10}\,cm^{-3}$

$p_{no} = \frac{(1.5\times10^{10})^2}{7.5\times10^{16}} = 3000\,cm^{-3}$

$V_{bi} = \frac{kT}{q} \ln \frac{p_{po}}{p_{no}}$

$0.72 = 0.025875 \ln \frac{p_{po}}{p_{no}}$

$\ln \frac{p_{po}}{p_{no}} = \frac{0.72}{0.025875}$

$N_a = p_{po} = 3.646\times10^{15}\,cm^{-3}$

ii. n side $I_{p\,diff} = qA \frac{D_p}{L_p} p_{no}$ $\qquad \frac{D_p}{L_p} = \sqrt{\frac{D_p}{\tau_p}}$

$= 1.6\times10^{-19} \times \sqrt{\frac{10.35}{2.2\times10^{-6}}} \times 3000 \times A$ $\qquad D_p = \frac{kT}{q}\mu_p$

$= 1.0411\times10^{-12}\times A$ $\qquad = 0.025875\times400$

p side $I_{n\,diff} = qA \frac{D_n}{L_n} n_{po}$ $\qquad = 10.35$

$= 1.6\times10^{-19} \times \sqrt{\frac{33.6375}{2.2\times10^{-6}}} \times 3000$ $\qquad \frac{D_n}{L_n} = \sqrt{\frac{D_n}{\tau_n}}$

$= 2.5413\times10^{-12}\times A$ $\qquad D_n = \frac{kT}{q}\mu_n$

Ratio $= 1.0411\times10^{-12} : 2.5413\times10^{-12}$ $\qquad = 0.025875\times1300$

$= 0.41 : 1$ $\qquad = 33.6375$

iii $C_s = \frac{q}{kT} I \tau_p = \frac{q}{kT} JA\tau_p$

$\frac{C_s}{A} = \frac{q}{kT} \times J \times \tau_p$ $\qquad J = (1.0411 + 2.5413)\times10^{-12}$

$= \frac{1}{0.025875} \times 3.5824\times10^{-12} \times 2.2\times10^{-6}$ $\qquad = 3.5824\times10^{-12}\,A/cm^2$

$= 3.046\times10^{-16}\,F$

* The solution is only for your references

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(i) Schottky contact.

A Schottky barrier is formed by contacting an n-type semiconductor with a metal having a larger work function.

(ii) $q(\Phi_m - \chi) = 0.7\,\text{eV}$

$q(\Phi_m - \Phi_s) = qV_0 = 0.6\,\text{eV}$

$E_c - E_{Fs} = q(\Phi_s - \chi)$

$= 0.7\,\text{eV} - 0.6\,\text{eV}$

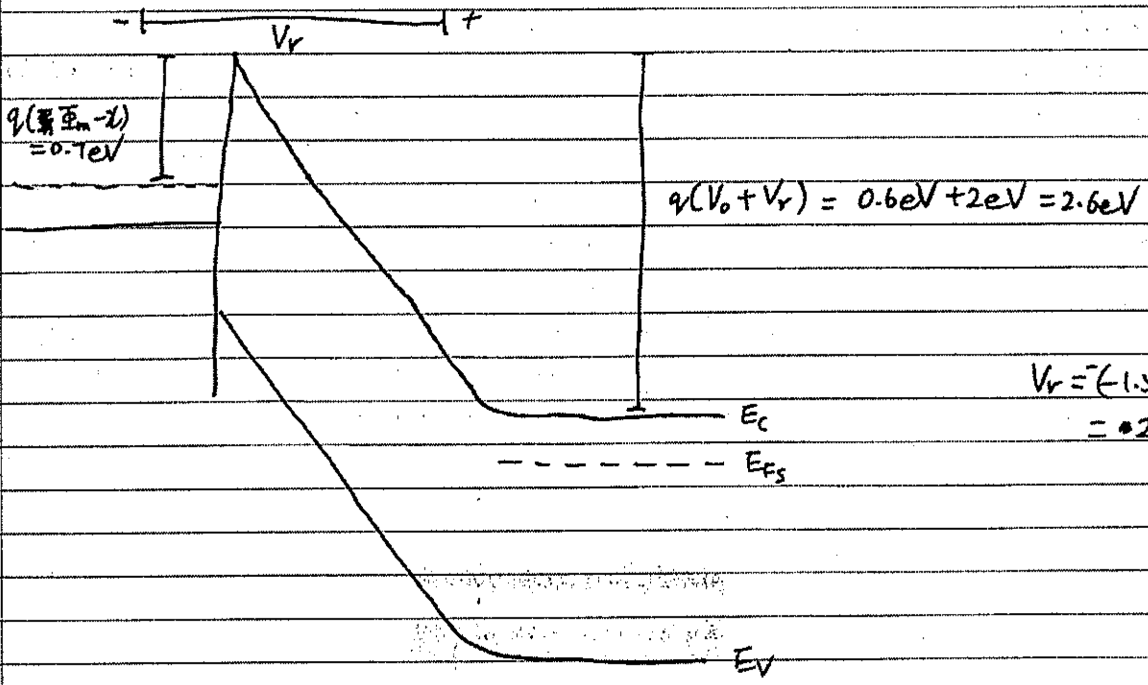
$= 0.1\,\text{eV}$

$n_0 = n_i \exp\left(\frac{0.1}{0.025875}\right)$

$= 7 \times 10^9 \exp\left(\frac{0.1}{0.025875}\right)$

$= 3.34 \times 10^{11}\,\text{cm}^{-3}$

(iii)



$V_r = -(-1.5\,\text{V} - (0.5\,\text{V}))$

$= 2\,\text{V}$

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4ai. $P = 1\,mW,\ \lambda = 1.5\,\mu m,\ x = 500\,nm = 500\times10^{-7}\,cm,\ \alpha = 2\times10^{4}\,cm^{-1},\ R = 3.2$

$r = \left(\frac{1-3.2}{1+3.2}\right)^2 = 0.274$

Transmitted power $= (1-0.274)m \times \exp(-2\times10^{4}\times500\times10^{-7})$

$= 0.267\,mW$

Absorbed power $= [(1-0.274) - 0.267]\,mW$

$= 0.459\,mW$

ii. $\eta = \frac{N_e}{N_p} = 80\%$

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

$= 0.8 \times \frac{1.6\times10^{-19} \times 1.5\times10^{-6}}{6.63\times10^{-34} \times 3\times10^{8}}$

$= 0.9653$

iii. $I = RP$

$= 0.9653 \times 50m$

$= 48.27\,mA$

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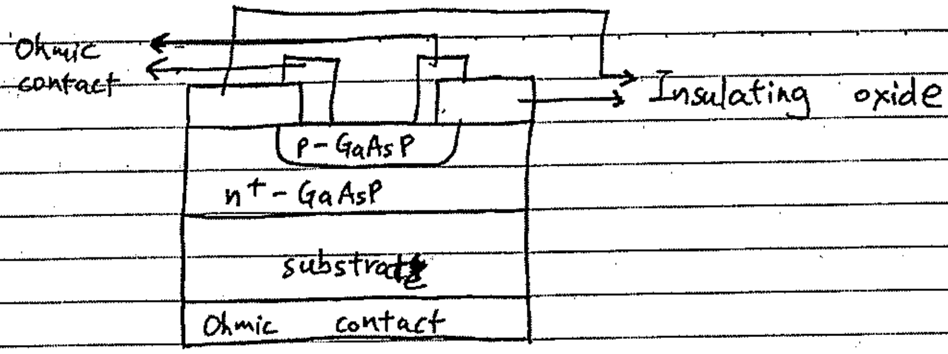
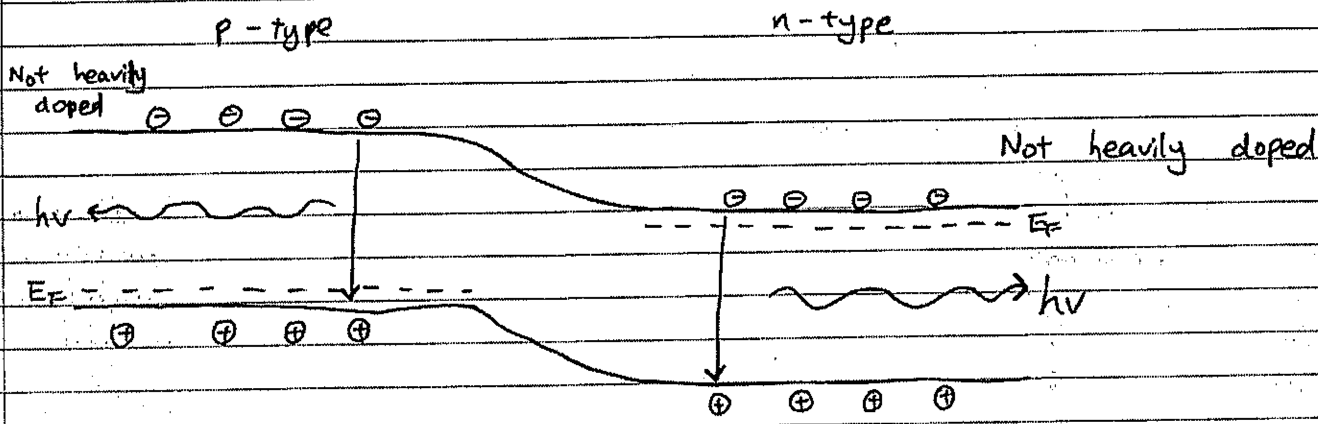
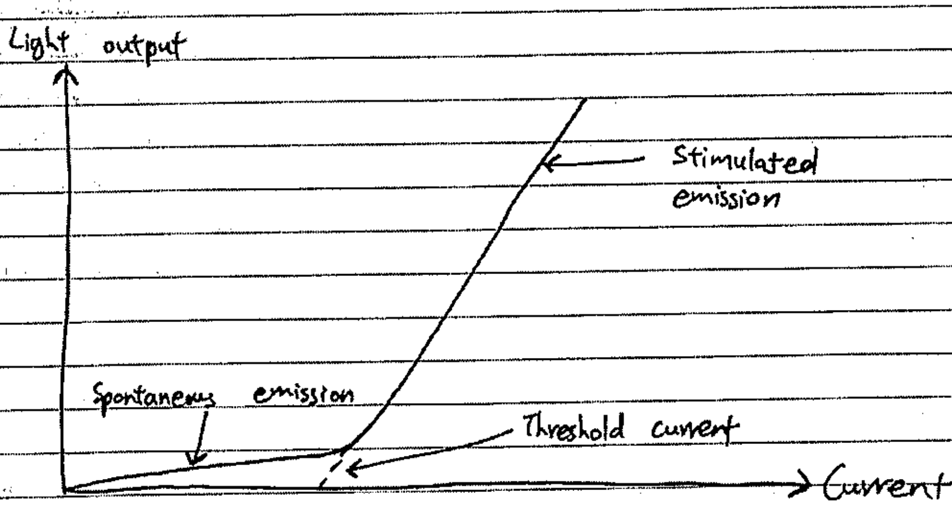
bi.



ii.



iii.



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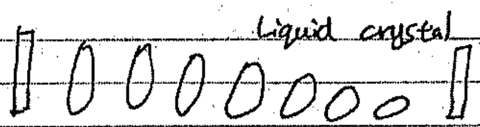
C i. Without an applied voltage

- the molecules are aligned parallel to the surface but with a 90° rotation from front surface to back surface.
- light incident on display is linearly polarized by first polarizer
- Polarization plane of the light is rotated through 90° as it passes through the material.
- light can pass through second polarizer => display is clear



ii. When voltage is applied

- the molecules rotates to resulting electric field
- the molecules have no effects on incident light
- linearly polarized light no longer rotates as it traverses the liquid crystal material
- second polarizer blocks the light
- segment appears black on a light background