THE UNIVERSITY OF BRITISH COLUMBIA
Department of Electrical and Computer Engineering
EECE 352 – Electrical Engineering Materials

Closed Book. Equation Sheet Provided at Back. Answer all problems.
Time: 150 minutes.
This examination consists of 12 pages. Please check that you have a complete copy. You may use both sides of each sheet if needed. There are five extra marks.

[redacted] [redacted]
Surname First name

[redacted]
Student Number

#	MAX	GRADE
1	5	
2	10	
3	6	
4	5	
5	6	
6	12	
7	8	
8	10	
9	17	
10	11	
11	7	
12	8	
TOTAL	105	

READ THIS

IMPORTANT NOTE: The announcement "stop writing" will be made at the end of the examination. Anyone writing after this announcement will receive a score of 0. No exceptions, no excuses.

All writings must be on this booklet. The blank sides on the reverse of each page may also be used.
Each candidate should be prepared to produce, upon request, his/her Library/AMS card.
Read and observe the following rules:

No candidate shall be permitted to enter the examination room after the expiration of one-half hour, or to leave during the first half-hour of the examination.

Candidates are not permitted to ask questions of the invigilators, except in cases of supposed errors or ambiguities in examination-questions.

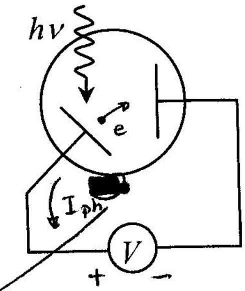
***Caution** - Candidates guilty of any of the following, or similar, dishonest practices shall be immediately dismissed from the examination and shall be liable to disciplinary action:*

Making use of any books, papers or memoranda, audio or visual cassette players or other memory aid devices other than as authorized by the examiners.
Speaking or communicating with other candidates.
Purposely exposing written papers to the view of other candidates.

The plea of accident or forgetfulness shall not be received.

Name:

1. (5) In a photoelectric experiment, we use a light source with wavelength of $\lambda = 260$ nm and a metal electrode with work function of 4.5 eV.



(a) (3) Find the maximum kinetic energy and the maximum speed of the emitted electrons.

$E_{ph} = h\nu \rightarrow E_{ph} = h\frac{c}{\lambda} = 4.78$ eV

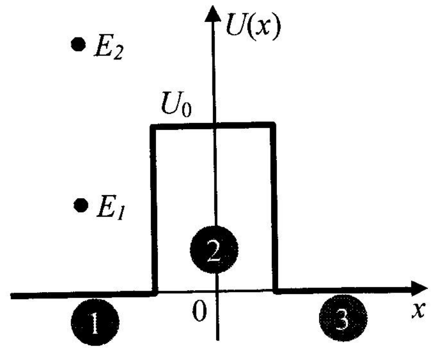
$K.E. = E_{ph} - \Phi_M = 4.78 - 4.5 = \boxed{0.28 \text{ eV}} = \boxed{4.48\times10^{-20} \text{ J}}$

$K.E. = \frac{m}{2}v_e^2 \rightarrow v_e = \sqrt{\frac{2\cdot K.E.}{m}} = \boxed{3.14\times10^5 \text{ m/s}}$

(b) (2) Show the direction of the photocurrent and find the minimum voltage required to stop the photocurrent.

$V = \frac{K.E.}{q} = \boxed{0.28 \text{ V}}$

2. (10) For the given potential energy $U(x)$,



(a) (2) Write the time-independent one-dimensional (1-D) Schrödinger's equation in region 1 and 2 for a particle with energy E.

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\vec{r}) + U(\vec{r})\psi(\vec{r}) = E\psi(\vec{r})$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x) + U_0\,\psi(x) = E\,\psi(x) \quad 2$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x) = E\,\psi(x) \quad 1$$

(b) (4) Using Schrödinger's equation, write the general solution for the wave function $\psi_i(x)$ in regions i =1, 2, and 3 for a particle with energy $E_1 = U_0/2$. What is the wavenumber k_i in each region.

$i=1 \rightarrow \quad \frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x) = \frac{U_0}{2}\psi(x) \rightarrow \psi_1(x) = A_1 e^{jk_1x} + B_1 e^{-jk_1x}, \quad k_1 = \sqrt{\frac{mU_0}{\hbar^2}}$

$i=2 \rightarrow \quad \psi_2(x) = A_2 e^{k_2x} + B_2 e^{-k_2x}, \quad k_2 = \sqrt{\frac{m}{\hbar^2}\frac{2U_0 - U_0}{2}} = \sqrt{\frac{mU_0}{\hbar^2}}$

$i=3 \rightarrow \quad \psi_3(x) = A_3 e^{jk_3x} + B_3 e^{-jk_3x}, \quad k_3 = k_1 = \sqrt{\frac{mU_0}{\hbar^2}}$

Name:

(c) (2) Find the wavenumber k_i in regions 1, 2, and 3 for a particle with energy $E_2 = 3U_0/2$. What is the difference between the wavefunction of this particle in region 2 and that of the particle in part (b)?

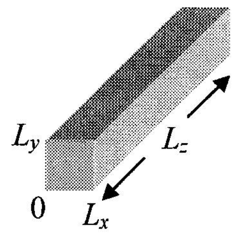
$E_2 = \frac{3U_0}{2} \longrightarrow$ $k_1 = \sqrt{\frac{3mU_0}{\hbar^2}}$, $k_2 = \sqrt{\frac{mU_0}{\hbar^2}}$, $k_3 = \sqrt{\frac{3mU_0}{\hbar^2}}$

This particle has a travelling wave solution in region 2 but the particle in part (b) has an exponentially decaying solution

(d) (2) Find the momentum of the particle with energy $E_2 = 3U_0/2$ in each region.

$$p = \hbar k = \begin{cases} \sqrt{3mU_0} & \text{region } 1,3 \\ \sqrt{mU_0} & \text{〃 } 2 \end{cases}$$

3. (6) A nanowire with a square cross section can be modeled by a 3-D potential well ($U(x,y,z) = 0$ inside the box). The quantized energy levels for an electron inside this nanowire are $E_{n_x,n_y,n_z} = \frac{h^2}{8\pi^2 m_0}\left(k_x^2 + k_y^2 + k_z^2\right)$, where $k_x = \frac{n_x \pi}{L_x}$, $k_y = \frac{n_y \pi}{L_y}$, and $k_z = \frac{n_z \pi}{L_z}$.



(a) (4) For a nanowire with dimensions $L_x = L_y = 0.7$ nm and $L_z = 70$ nm, what is the wavelengths of the photon emitted when the electron makes the transition $\psi_{1,2,10} \rightarrow \psi_{1,1,10}$. Is this photon visible?

$\Psi_{1,2,10} \longrightarrow \Psi_{1,1,10} \Rightarrow E_{ph} = E_{1,2,10} - E_{1,1,10}$

$$\Delta E = \frac{h^2}{8\pi^2 m_0}\left(\frac{\pi^2}{(0.7n)^2}\left((2)^2 - (1)^2\right)\right) = \frac{3h^2}{8m_0(0.7n)^2} = 2.31 \text{ eV}$$

$\lambda = (\Delta E)^{-1} \times hc = \boxed{538 \text{ nm}}$ Yes visible

(b) (2) How many states are in the range 1.54 eV $< E <$ 3.08 eV. (Hint: $\frac{h^2}{8m_0 L_x^2}(2) = 1.54$ eV and $\frac{h^2}{8m_0 L_x^2}(2+2) = 3.08$ eV).

$$2 = \left(\frac{n_z^2}{L_z^2} \times L_x^2\right) \longrightarrow 2 = \frac{n_z^2}{10^4} \longrightarrow n_z = 100\sqrt{2} = 141.4 \longrightarrow$$

No. states $= \boxed{141}$

Name:

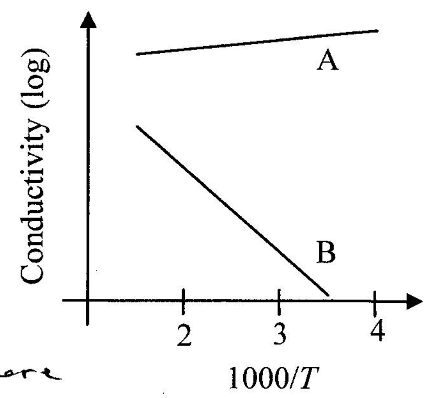
4. (5) A Zinc Oxide (ZnO) film has a bandgap of 3.4 eV. What is the type of this material metal, semiconductor, or dielectric? Is this film opaque or transparent to visible light? Explain.

dielectric [redacted] since $E_g > 3\,eV$ [redacted]

$E_{max\ visible} = 3.1\ eV \rightarrow$ This energy is not enough to excite carriers from valence to conduktion band edge.

So it is transparent. [redacted]

5. (6) Given the temperature dependence of conductivity for materials A and B, what is the best guess for the type of these two materials (metal or semiconductor)? Briefly explain the difference in temperature dependence of conductivity in metals and semiconductors using equations that generally describe the temperature dependence.



A: metal [redacted] B: semiconducter

In metals, the ~~...~~ scattering becomes more as temperature increases

This reduces conductivity $\sigma \propto 1/\tau_p$ [redacted]

In semicanducters, there are more carriers available for conduction as temperature increases $\sigma \propto e^{-E_g/kT}$

[redacted]

6. (12) A semiconductor has an intrinsic carrier density of $n_i = 2\times10^{10}$ cm^{-3} and conduction and valence band densities of $N_C = N_V = 10^{19}$ cm^{-3} at room temperature.

(a) (2) What is the band gap of this semiconductor at room temperature?

$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} \rightarrow$

$E_g/2kT = \ln \frac{\sqrt{N_c N_v}}{n_i} \rightarrow E_g = 2kT \ln \frac{\sqrt{N_c N_v}}{n_i} = \boxed{1.04\ eV}$ [redacted]

Name:

(b) (4) This semiconductor is doped by donor atoms with a density of $N_A = 10^{16}$ cm^{-3} followed by acceptor atoms with a density of $N_D = 8\times10^{15}$ cm^{-3}. If the ionization efficiency of both dopants is 100%, find the densities and types of the majority and minority carriers.

$p_o = N_A - N_D = 10^{16} - 8\times10^{15} = 2\times10^{15}$ cm^{-3} majority

$n_o = \frac{n_i^2}{p_o} = 2\times10^{5}$ cm^{-3} minority

(c) (3) Given the electron and hole mobilites of $\mu_n = 5\mu_p = 1000$ cm^2/Vs, find the resistivity (Ω-cm) of the intrinsic and doped semiconductors at room temperature.

$\rho_o = \frac{1}{q\mu_n n + q\mu_p p} = \frac{1}{q(1000\times2\times10^5 + 200\times2\times10^{15})} = 15.62$ Ω-cm

$\rho_i = \frac{1}{q(\mu_n+\mu_p)n_i} = 2.6\times10^5$ Ω-cm

(d) (3) If we want to increase the resistivity to $\rho = 100$ Ω-cm of the doped semiconductor while keeping the semiconductor type, find the type and density of the required additional doping.

$\rho = 100$ Ω-cm $\rightarrow \rho \cong \frac{1}{q(\mu_p p)} \rightarrow p = \frac{1}{q\rho\mu_p} = 3.125\times10^{14}$ cm^{-3}

So we should dope n-type with $N_D = 2\times10^{15} - 3.125\times10^{14}$

$\boxed{= 1.687\times10^{15}}$

7. (8) We use a semiconductor ($n_i = 10^{10}$ cm^{-3} at room temperature) to build two samples with different acceptor doping densities of $N_{A1} = 10^{16}$ and $N_{A2} = 10^{14}$ cm^{-3}.

(a) (3) Assuming a 80% ionization efficiency, what are the conductivity of these two samples if $\mu_n = 5\mu_p = 1000$ cm^2/Vs.

$\sigma_1 = q\mu_n n + q\mu_p p = 0.32$ Ω^{-1}-cm^{-1}

$\sigma_2 = 3.2\times10^{-3}$ Ω^{-1}-cm^{-1}

(b) (5) If under light illumination a steady-state excess electron-hole-pairs (EHP) density of 10^{14} cm^{-3} is generated what is the new conductivity of the two samples? Which sample is better for building a photodetector?

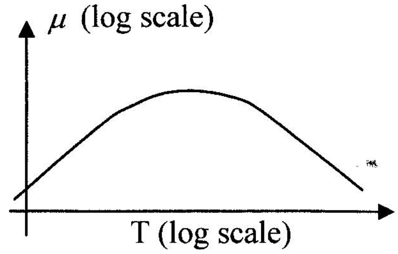
1) $n = n_0 + \hat{n} =$
$p = p_0 + \hat{p} =$ [redacted]

$\boxed{\sigma_1 = 0.339 \ \Omega^{-1}\text{-cm}^{-1}}$ [redacted]

2) [redacted] $\boxed{\sigma_2 = 0.0224 \ \Omega^{-1}\text{-cm}^{-1}}$ [redacted]

Sample 2 is more sensitive to light, better for photo detector. [redacted]

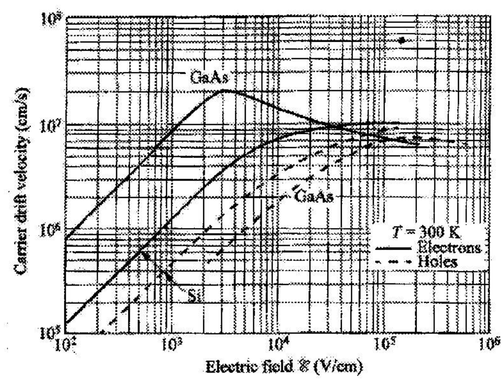
8. (10) (a) (5) Given the temperature-dependence of mobility for a doped semiconductor as shown in the figure, explain the mechanisms responsible for reduction in mobility at low and high temperatures.



At low T, impurity scattering is responsible [redacted]

At high T lattice scattering is responsible. [redacted]

(b) (5) Write the relationship between carrier drift velocity and electric field and explain why the electron velocity saturates at high electric field in Si (as shown in the figure).



$v_d = \mu \mathcal{E}$ [redacted]

The velocity saturates as at high fields the ~~sat~~ scattering limits the maximum speed of the electrons. [redacted]

9. (17) A silicon wafer (Si: $n_i = 1.3 \times 10^{10}$ cm^{-3} and $\varepsilon_r = 11.8$) is used to make a PN junction over a square area with the side $a = 1$ mm. Boron is used as a p-type dopant with density of 10^{17} cm^{-3}, and Phosphorus as a n-type dopant with density of 10^{16} cm^{-3}.

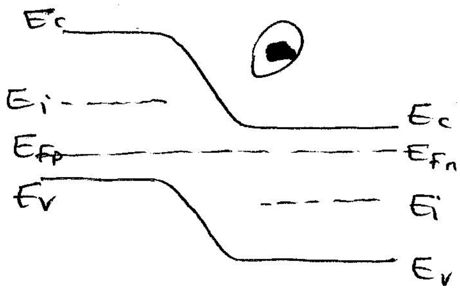
(a) (4) Find the Fermi energies E_{Fn} and E_{Fp} in the n-type and p-type regions far from the junction with respect to the intrinsic Fermi energy E_i.

$$E_{Fn} - E_i = kT \ln \frac{N_D}{n_i} \approx 0.35 \text{ eV}$$

$$E_{Fp} - E_i = kT \ln \frac{n_i}{N_A} = -0.41 \text{ eV}$$

(b) (4) Draw the band diagram for the PN junction, and find the built-in voltage V_0.

$$V_0 = 0.35 + 0.41 = 0.76 \text{ V}$$



(c) (3) Find the depletion width W and the maximum electric field $\mathscr{E}_0$ in the depletion region.

$$W = \sqrt{V_0 \frac{2\varepsilon}{q} \frac{N_A + N_D}{N_A N_D}} = \boxed{330 \text{ nm}}$$

$$\mathscr{E}_0 = -\frac{2V_0}{W} \approx \boxed{-4.6 \frac{\text{MV}}{\text{m}}}$$

(d) (3) Given $\mu_n = \mu_p = 1000$ cm^2/Vs and $\tau_n = \tau_p = 1$ µs, find the diode reverse saturation current I_0 and the current at $V = 10kT/q$.

$$D_n = \frac{kT}{q}\mu = 25.9$$

$$L_n = L_p = \sqrt{D_n \tau_n} \approx 5 \times 10^{-3} \text{ cm}$$

$$I_0 = qA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right) = 1.5 \times 10^{-13} \text{ A}$$

$$I = I_0\left(e^{qV/kT} - 1\right) = 3.39 \times 10^{-9} \text{ A}$$

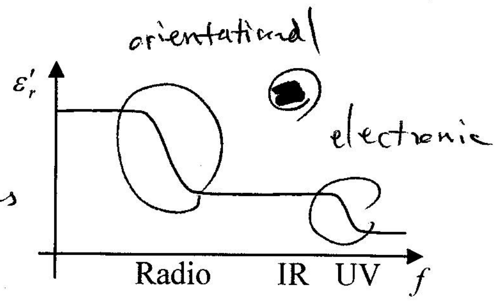
(e) (3) What are the two mechanisms of breakdown in PN junction? Which one happens in lightly doped junctions?

Zener

avalanche $\longrightarrow$ happens in lightly doped

10. (11) A liquid dielectric with molecule density $N = 2\times10^{22}$ cm^{-3} has only orientational and electronic polarization mechanisms (orientational polarizability $\alpha_d = 10^{-35}$ F/cm^2 and electronic polarizability $\alpha_e = 2\times10^{-36}$ F/cm^2).

(a) (4) Explain these two polarization mechanisms and their speed in responding to electric field oscillations. Indicate which polarization mechanism is responsible for each step in ε_r' curve.



Orientation : the dipoles align themselves with external field
low speed

electronic : the electron cloud around nuclei displaces with external field

$\mathcal{E}$

P

(b) (3) Using Clausius-Mossotti equation, find the optical refractive index of this material.

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N}{3\epsilon_0}(\alpha_e) = 0.15 \rightarrow \epsilon_r = \frac{1+2(0.15)}{1-0.15}$$

$$\epsilon_r = 1.529 \rightarrow n = \sqrt{\epsilon_r} = 1.23$$

(c) (3) What is the dielectric constant of this material at low frequencies?

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N}{3\epsilon_0}(\alpha_e + \alpha_d) = 0.904$$

$$\boxed{\epsilon_r = 19.83}$$

(d) (1) If an electromagnetic wave with a frequency much higher than UV frequencies is going through this material, what is the change in speed and intensity of this wave?

No change

11. (7) A material has a complex dielectric constant of $\varepsilon = \varepsilon_0 + 9\varepsilon_0/(1 + j9\omega)$.

(a) (3) What are ε_r' and ε_r''?

$$\epsilon = \epsilon_0\left(1 + \frac{9}{1+9j\omega}\right)$$

$$\epsilon = \epsilon_0(\epsilon_r' - j\epsilon_r'') = \epsilon_0\left(1 + \frac{9(1-9j\omega)}{1+81\omega^2}\right)$$

$$\epsilon_r' = 1 + \frac{9}{1+81\omega^2}, \quad \epsilon_r'' = + \frac{81\omega}{1+81\omega^2}$$

(b) (2) What is the conductivity as a function of angular frequency?

$$\sigma = \epsilon_0 \omega \epsilon_r'' = \frac{-81\omega^2\epsilon_0}{1+81\omega^2}$$

(c) (2) Find the angular frequency for which ε_r'' has a maximum?

$$\epsilon_r'' = -\frac{81\omega}{1+81\omega^2}$$

$$\frac{d\epsilon_r''}{d\omega} = \frac{+81(1+81\omega^2) \mp (+81\omega)(+2\times 81\omega)}{(1+81\omega^2)^2} = 0$$

$$81 + 81^2\omega^2 \mp 2\,81^2\omega^2 = 0$$

$$\cancel{81 - 81\omega^2 = 0}$$

$$\cancel{81\omega^2 = 0 \to \boxed{\omega = \sqrt{81} = 9 \ \frac{rad}{s}}}$$

$$1 - 81\omega^2 = 0 \to \omega = \sqrt{\frac{1}{81}} = 1/9 \ \frac{rad}{s}$$

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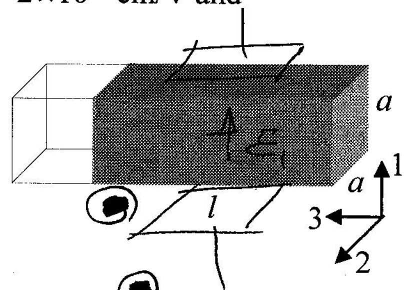
12. (8) A micro-positioning system uses a piezoelectric actuator beam with a square cross-section (cross section a^2 and length l) that produces a maximum travel of 5 µm. The piezoelectric material is PZT with piezoelectric coefficients $d_{31} = 2\times10^{-8}$ cm/V and $d_{33} = 4\times10^{-8}$ cm/V and a dielectric strength of 1.2×10^{6} V/cm.

(a) (5) For a maximum power supply voltage of 120 V, find the minimum dimensions of the beam (a and l). Sketch how the electric field is applied.



$$S_3 = d_{31}\mathcal{E}_1 + d_{33}\mathcal{E}_3$$

$$\frac{\Delta\ell_3}{\ell_3} = d_{31}\frac{V}{\ell_1} + d_{33}\frac{V}{\ell_3} \longrightarrow \Delta\ell_3 = d_{31}V\frac{\ell_3}{\ell_1} + d_{33}V$$

$d_{33}V = 4.8\times10^{-6}$ cm $\quad d_{31}V = 2.4\times10^{-6}$ cm

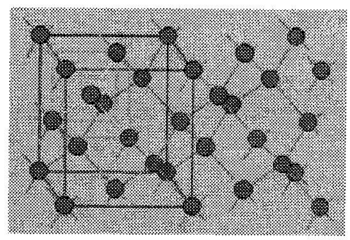
We should apply V_a in direction 1.

$$\Delta\ell_3 = 5\times10^{-4} \text{ cm} \longrightarrow \frac{\ell_3}{\ell_1} = \frac{\Delta\ell_3}{d_{31}V} = 208.3$$

$$a = \ell_{1\,min} = \frac{V}{\mathcal{E}_{max}} = 10^{-4} \text{ cm} = 1\ \mu m$$

$$\ell = 208.3\,a = 0.0208 \text{ cm} = 208\ \mu m$$

(b) (3) Diamond, Silicon and Germanium have the crystal structure shown in the figure. Are these materials piezoelectric? Explain.



No, since they have no dipoles and they have centre of symmetry.