Name:______________________________
Student number:______________________

DEPARTMENT OF PHYSICS AND PHYSICAL OCEANOGRAPHY

MEMORIAL UNIVERSITY OF NEWFOUNDLAND

Final Exam **Physics 3000** **December 16, 2009**

Fall 2009 **120 minutes**

INSTRUCTIONS:

1. Answer all six (6) questions. The marks for each question are indicated. The total number of marks on the paper is 100. Budget time accordingly.
2. Write answers in the spaces provided. If additional space is needed, use the backs of sheets but indicate clearly where your answer is continued.
3. Where appropriate, units must be included for answers to be considered complete.
4. A list of useful formulae, a table of constants, and tables of semiconductor properties are attached at the end of the paper (last three pages). For your convenience, three particularly useful parameters are listed below.

Particularly useful parameters:

Relative permittivity (dielectric constant) for silicon: $\epsilon_{\text{Si}} = 11.7$

Permittivity of free space: $\epsilon_0 = 8.85 \times 10^{-14}$ F/cm

Intrinsic carrier concentration for silicon at 300 K: $n_{i,\text{Si}} = 1.5 \times 10^{10}$ cm^{-3}

Thermal voltage $\left(V_t = \frac{kT}{e}\right)$ at 300 K: $V_t(300\text{ K}) = 0.0259$ V

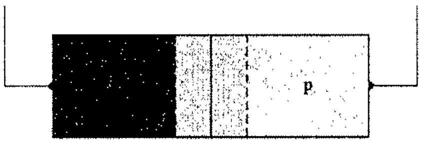
Electron charge: $e = 1.6 \times 10^{-19}$ C

Planck's constant: $h = 6.625 \times 10^{-34}$ J-s $= 4.135\times10^{-15}$ eV-s

1. [16 marks]

(a) The diagram at the right represents a photodiode.

(i) (3 marks) Should this junction be forward-biased, reverse-biased, or unbiased if it is to function as a photodetector?



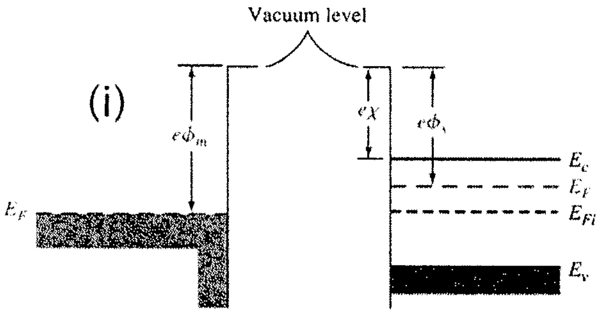
(ii) (3 marks) For what reason might a designer choose a photodiode over a photoconductor for a photon detection application?

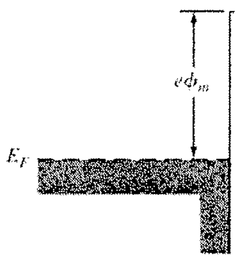
(b) (4 marks) The visible spectrum spans wavelengths from ~0.45 μm (violet) to ~0.7 μm (red) with yellow near the middle. The bandgap for GaP is 2.26 eV which corresponds to a photon wavelength of 0.547 μm. Do you expect the absorption coefficient for GaP to be larger for violet photons or for red photons. Briefly justify your answer.

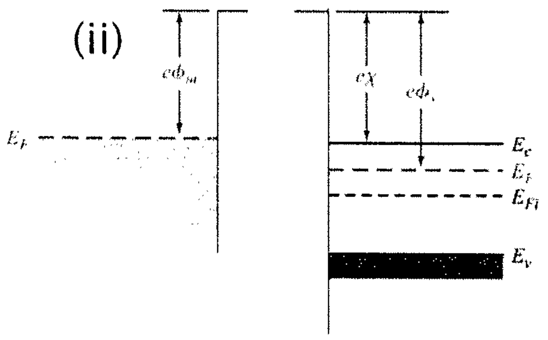
(c) (6 marks) The absorption coefficient for GaAs at $\lambda = 0.75\ \mu\text{m}$ is $\alpha = 0.7 \times 10^4\ \text{cm}^{-1}$. The electron-hole pair generation rate at a given depth in the semiconductor is found to be $g' = 1.33 \times 10^{21}\text{cm}^{-3}\text{s}^{-1}$. What is the photon intensity at this point in the semiconductor in units of W/cm^2 ?

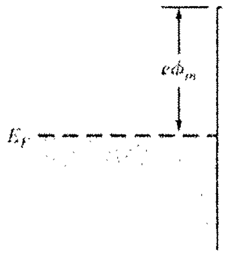
2. [16 marks]

Before contact **After contact**









(a) (8 marks) Diagrams (i) and (ii) above show metal and semiconductor energy bands, **before** contact, for two cases: (i) where the metal work function is greater than the semiconductor work function and (ii) where the metal work function is less than the semiconductor work function. To the right of each diagram, fill in and label, as carefully as possible, the corresponding energy band diagrams for the semiconductor **after** contact.

(b) (3 marks) Which of the two cases sketched above corresponds to ohmic contact? Briefly justify (explain) your choice.

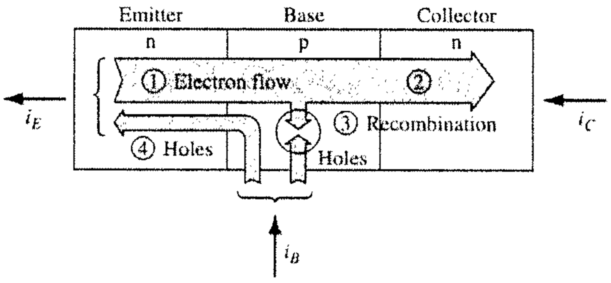
(c) (3 marks) How are ohmic contacts used in semiconductor devices?

(d) (2 marks) What kind of junction is represented by the diagram that does not represent ohmic contact?

3. [15 marks]

(a) (6 marks) List two causes of carrier scattering in semiconductors and describe how each affects carrier mobility.

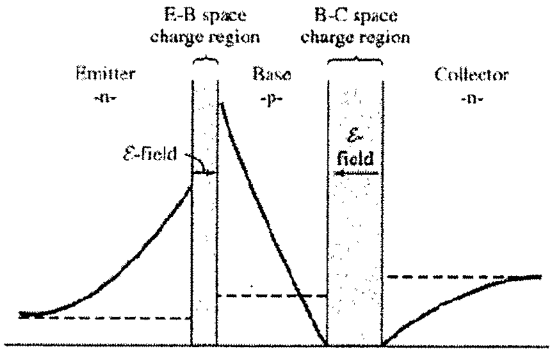
(b) The diagram shows charge flow in an npn bipolar transistor biased in the forward-active mode.



(i) (2 marks) In the forward-active mode illustrated, is the base-emitter junction forward-biased, reverse-biased, or unbiased?

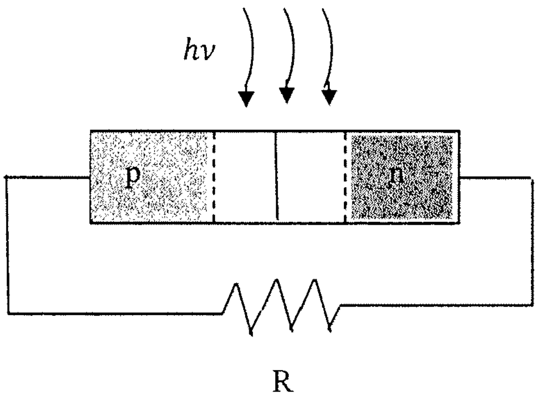
(ii) (2 marks) In the forward-active mode illustrated, is the base-collector junction forward-biased, reverse-biased, or unbiased?

(iii) (2 marks) The diagram to the right illustrates carrier concentrations in the forward-active npn transistor. Does the **solid line in the base region** represent electrons or holes and are they minority or majority carriers?



(iv) (3 marks) **Briefly** explain why the carrier concentration represented by the **solid line in the base region** decreases from the emitter to the collector side of the base.

4. [18 marks] The diagram shows a pn junction solar cell connected to a resistive load.



(a) (4 marks) Indicate the direction of the electric field in the space charge region and describe the source of this electric field.

(b) (4 marks) Indicate the direction of the photocurrent, I_L, on the diagram and **briefly** justify your answer.

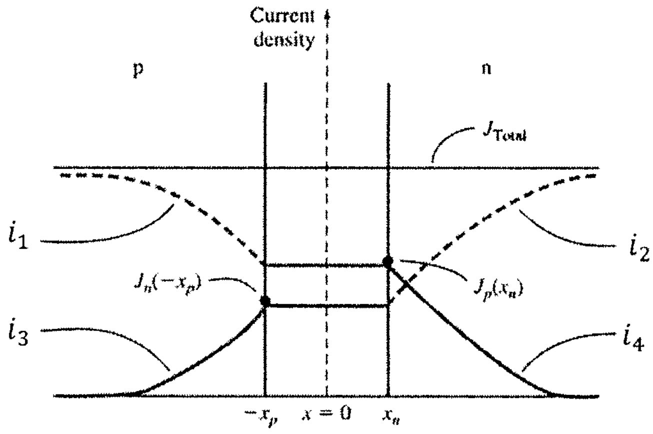
(c) (4 marks) Indicate the direction of the forward-bias current, I_F, on the diagram and **briefly** explain what causes the forward-bias current.

(d) (6 marks) For a silicon pn junction solar cell illuminated so that the photocurrent is $I_L = 0.42$ A, it is found that the maximum power is produced for a diode voltage $V_m = 0.52$ V. The reverse saturation current is $I_S = 3.6 \times 10^{-11}$ A.

(i) What is the total current, I_m, through the diode when the voltage is V_m?

(ii)What is the value of the maximum power, P_m, produced?

5. [15 marks]



The curves labeled i_1, i_2, i_3, and i_4 on the diagram to the right represent ideal contributions to the current through a forward-biased pn junction.

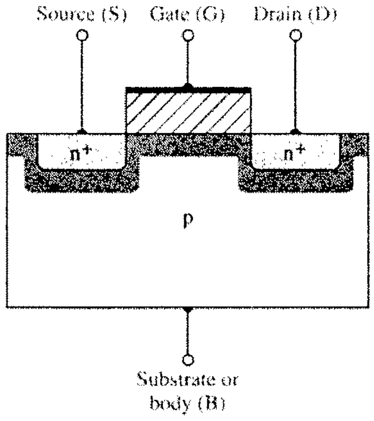
(a) (3 marks) Which of these current components is the minority carrier electron current?

(b) (3 marks) Why does the current identified in part (a) depend on position in the way shown in the diagram?

(c) (4 marks) Assume that the diagram represents a silicon pn junction at 300 K with $N_a = 5.0 \times 10^{16}$ cm^{-3} and $N_d = 1.0 \times 10^{16}$ cm^{-3}. What is the value of the thermal equilibrium minority-carrier electron concentration in the p region?

(d) (5 marks) Consider a one-sided pn junction in for which $x_n \gg x_p$ where x_n and x_p are the widths of the space charge region on the n-type and p-type sides of the junction respectively. Is this junction more heavily doped on the n-type side or the p-type side? Briefly justify your answer, perhaps using a sketch of the space charge density for this junction.

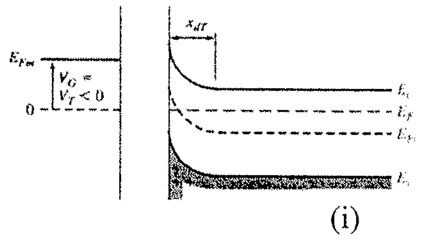
6. [20 marks] The diagram schematically represents a particular type of MOSFET with no bias voltages applied.



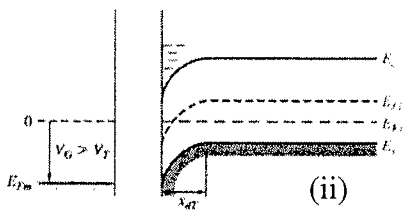
(a) (2 marks) Is this an n-channel or a p-channel device and is it an enhancement mode device or a depletion mode device?

(b) (4 marks) Assuming that the substrate is grounded, what potentials, relative to the substrate, would one need to apply to the Source, Gate, and Drain terminals in order to obtain a positive drain current, I_D?

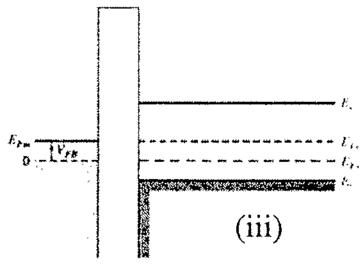
(c) (4 marks) Which of the three energy band diagrams below best represents the MOS capacitor region of **this** MOSFET when it is biased in the conducting state? Briefly justify your answer.



(i)



(ii)



(iii)

Question 6 continued

(d) (6 marks) Assume that this is a silicon based device at 300 K and that the acceptor concentration in the substrate of this MOSFET is $N_a = 5.0 \times 10^{11}$ cm^{-3}. What is the magnitude of the maximum space charge density, $|Q'_{SD}(\text{max})|$, in the depletion region?

(e) (4 marks) Assume that the threshold voltage for this MOSFET is 0.625 V and that it is biased with $V_{DS} > V_{DS}(\text{sat})$. When $V_{GS} = 2.5$ V, the drain current is found to be $I_D = 3.2$ mA. What is the drain current for $V_{GS} = 5.0$ V?

Potentially useful formulae

Photons: $E_{\text{photon}} = h\nu$; $p = h/\lambda$; $c = \nu\lambda$; Bohr Atom: $E_n = -\frac{m_0 e^4}{(4\pi\epsilon_0)^2 2\hbar^2 n^2}$; $a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_0 e^2}$

Drift curr. density: $J_n = -e\sum_{i=1}^{n} v_i$; Eff. mass: $F_{\text{ext}} = m^* a$; Free particle: $E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$

Densities of states: $g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$; $g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_v - E}$

F-D prob. function: $f_F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$; M-B approx.: $f_F(E) \approx \exp\left[-\frac{(E-E_F)}{kT}\right]$

Carrier distributions: $n(E) = g_c(E)f_F(E)$; $p(E) = g_v(E)[1 - f_F(E)]$

Effective densities of states: $N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$; $N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$

Therm. equil. carrier concentrations.: $n_0 = N_c\exp\left[-\frac{(E_c-E_F)}{kT}\right]$; $p_0 = N_v\exp\left[-\frac{(E_F-E_v)}{kT}\right]$

Intrins. carr. concentration & Fermi level: $n_i^2 = N_c N_v\exp\left[\frac{-E_g}{kT}\right]$; $E_{Fi} - E_{\text{midgap}} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)$

Extrinsic semiconductor relationships: $n_0 = n_i\exp\left[\frac{E_F-E_{Fi}}{kT}\right]$; $p_0 = n_i\exp\left[\frac{-(E_F-E_{Fi})}{kT}\right]$

Fundamental semiconductor equation: $n_0 p_0 = n_i^2$

Donor electron relationships: $n_d = N_d - N_d^+ = \frac{N_d}{1+\frac{1}{2}\exp\left(\frac{E_d-E_F}{kT}\right)}$; $\frac{n_d}{n_d+n_0} = \frac{1}{1+\frac{N_c}{2N_d}\exp\left[\frac{-(E_c-E_d)}{kT}\right]}$

Acceptor hole relationships: $p_a = N_a - N_a^- = \frac{N_a}{1+\frac{1}{g}\exp\left(\frac{E_F-E_a}{kT}\right)}$; $\frac{p_a}{p_a+p_0} = \frac{1}{1+\frac{N_v}{gN_a}\exp\left[\frac{-(E_a-E_v)}{kT}\right]}$

Compensated semiconductors, complete ionization:

$$n_0 = \frac{(N_d-N_a)}{2} + \sqrt{\left(\frac{N_d-N_a}{2}\right)^2 + n_i^2} \qquad p_0 = \frac{(N_a-N_d)}{2} + \sqrt{\left(\frac{N_a-N_d}{2}\right)^2 + n_i^2}$$

Fermi energy level relationships:

$$E_c - E_F = kT\ln\left(\frac{N_c}{n_0}\right) \ ; \ E_F - E_v = kT\ln\left(\frac{N_v}{p_0}\right) \ ; \ E_F - E_{Fi} = kT\ln\left(\frac{n_0}{n_i}\right) = -kT\ln\left(\frac{p_0}{n_i}\right)$$

Conduct. & resist.: $e(\mu_n n + \mu_p p) = \sigma = \frac{1}{\rho}$ Mobility: $\mu_p = \frac{v_{dp}}{\varepsilon} = \frac{e\tau_{cp}}{m_p^*}$; $\mu_n = \frac{v_{dn}}{\varepsilon} = \frac{e\tau_{cn}}{m_n^*}$

Drift curr. dens.: $J_{drf} = e(\mu_n n + \mu_p p)\varepsilon_x$ Diffusion curr. dens.: $J_{dif} = eD_n\frac{dn}{dx} - eD_p\frac{dp}{dx}$

Total current density: $J = J_{drf} + J_{dif}$ Einstein relation: $\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e}$

Graded impurity distribution: $\varepsilon_x = -\left(\frac{kT}{e}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx}$

Equil. generation & recombination rates: $G_{n0} = G_{p0} = R_{n0} = R_{p0}$; $R_{n0} = \frac{n_0}{\tau_{n0}}$; $R_{p0} = \frac{p_0}{\tau_{p0}}$

Excess carrier recombination (p-type): $\delta n(t) = \delta n(0)e^{-t/\tau_{n0}}$; $R_n' = R_p' = \frac{\delta n(t)}{\tau_{n0}}$; $\tau_{n0} = \frac{1}{\alpha_r p_0}$

Excess carrier recombination (n-type): $\delta n(t) = \delta n(0)e^{-t/\tau_{p0}}$; $R_n' = R_p' = \frac{\delta n(t)}{\tau_{p0}}$; $\tau_{p0} = \frac{1}{\alpha_r n_0}$

Hall effect: $\vec{F} = q[\vec{\varepsilon} + \vec{v_d} \times \vec{B}]$; $p = \frac{I_x B_z}{edV_H}$; $n = -\frac{I_x B_z}{edV_H}$; $\mu_p = \frac{I_x L}{epV_x Wd}$; $\mu_n = \frac{I_x L}{enV_x Wd}$

Built in potential barrier (pn junction): $V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)$

Potentially useful formulae (continued)

Poisson's equation: $\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\epsilon_s} = -\frac{d\varepsilon(x)}{dx}$

Sp. charge width: $x_n = \left[\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left(\frac{N_a}{N_d}\right)\frac{1}{N_a+N_d}\right]^{1/2}$; $x_p = \frac{N_d}{N_a}x_n$; $W = \left[\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left(\frac{N_a+N_d}{N_aN_d}\right)\right]^{1/2}$

Electric field: $\varepsilon_{\max} = -\frac{2(V_{bi}+V_R)}{W}$ Junction Capacitance: $C' = \left[\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right]^{1/2}$

Schottky barrier: $\phi_{B0} = (\phi_m - \chi)$ $V_{bi} = \phi_{B0} - \phi_n$

pn diode: $J_D = J_S\left[\exp\left(\frac{eV_D}{kT}\right) - 1\right]$

Schottky barrier diode: $J = \left[A^*T^2\exp\left(\frac{-\phi_{B0}}{kT}\right)\right]\left[\exp\left(\frac{eV_D}{kT}\right) - 1\right] = J_{ST}\left[\exp\left(\frac{eV_D}{kT}\right) - 1\right]$

MOS depletion width (p-type): $x_{dT} = \left(\frac{4\epsilon_s|\phi_{Fp}|}{eN_a}\right)^{1/2}$; $e\phi_{Fp} = E_F - E_{Fi} = -kT\ln\left(\frac{N_a}{n_i}\right)$

MOS depletion width (n-type): $x_{dT} = \left(\frac{4\epsilon_s\phi_{Fn}}{eN_d}\right)^{1/2}$; $e\phi_{Fn} = E_F - E_{Fi} = kT\ln\left(\frac{N_d}{n_i}\right)$

Metal-semiconductor work function difference (p-type): $\phi_{ms} = \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + |\phi_{Fp}|\right)\right]$

Metal-semiconductor work function difference (n-type): $\phi_{ms} = \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} - \phi_{Fn}\right)\right]$

Flat-band voltage: $V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{\text{ox}}}$ Maximum space charge density: $|Q'_{SD}(\max)| = eN_a x_{dT}$

Threshold voltage: $V_{TN} = \frac{|Q'_{SD}(\max)|}{C_{\text{ox}}} - \frac{Q'_{ss}}{C_{\text{ox}}} + \phi_{ms} + 2|\phi_{Fp}|$

MOSFET (general): $I_D = K_n[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2]$; $K_n = \frac{W}{L}\frac{\mu_n C_{\text{ox}}}{2}$; $C_{\text{ox}} = \frac{\epsilon_{\text{ox}}}{t_{\text{ox}}}$

MOSFET (saturation): $V_{DS}(\text{sat}) = V_{GS} - V_T$; $I_D(\text{sat}) = K_n(V_{GS} - V_{TN})^2$

Electron inversion charge density: $n_s = N_a\exp\left(\frac{\Delta\phi_s}{V_t}\right)$

Channel length mod.: $\Delta L = \sqrt{\frac{2\epsilon_S}{eN_a}}\left[\sqrt{|\phi_{FP}| + V_{DS}(\text{sat}) + \Delta V_{DS}} - \sqrt{|\phi_{FP}| + V_{DS}(\text{sat})}\right]$; $\frac{I'_D}{I_D} = \frac{L}{L-\Delta L}$

Mobility variation: $\varepsilon_{\text{eff}} = \frac{1}{\epsilon_S}\left(|Q'_{SD}(\max)| + \frac{1}{2}Q'_n\right)$; $\mu_{\text{eff}} = \mu_0\left(\frac{\varepsilon_{\text{eff}}}{\varepsilon_0}\right)^{-1/3}$

Forward-biased pn junction.:

minority carrier conc. at space charge edge: $n_p = n_{p0}\exp\left(\frac{V_a}{V_t}\right)$; $p_n = p_{n0}\exp\left(\frac{V_a}{V_t}\right)$

reverse saturation current density: $J_S = \left(\frac{e\sqrt{D_p}p_{n0}}{\sqrt{\tau_{p0}}} + \frac{e\sqrt{D_n}n_{p0}}{\sqrt{\tau_{n0}}}\right)$

common-base current gain: $\alpha = \frac{i_C}{i_E}$ common-emitter current gain: $\beta = \frac{i_C}{i_B}$

photon flux intensity: $I_\nu(x) = I_{\nu 0}e^{-\alpha x}$ electron-hole pair generation rate: $g' = \frac{\alpha I_\nu(x)}{h\nu}$

pn junct. solar cell: $I = I_L - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$; $V_{\text{oc}} = V_t\ln\left(1 + \frac{I_L}{I_S}\right)$; $\left(1 + \frac{V_m}{V_t}\right)\exp\left(\frac{V_m}{V_t}\right) = 1 + \frac{I_L}{I_S}$

photoconductor: $I_L = eG_L\tau_p(\mu_n + \mu_p)A\varepsilon$ photoconductor gain: $\Gamma_{\text{ph}} = \frac{\tau_p\varepsilon}{L}(\mu_n + \mu_p)$

pn photodiode prompt photocurrent: $J_{L1} = eG_L W$

PIN photodiode prompt photocurrent: $J_L = e\Phi_0(1 - e^{-\alpha W})$

Constants and Conversions

$$N_A = 6.02 \times 10^{23}$$

$$k = 1.38 \times 10^{-23}\ \text{J/K} = 8.62 \times 10^{-5}\ \text{eV/K}$$

$$e = 1.60 \times 10^{-19}\ \text{C}$$

$$m_0 = 9.11 \times 10^{-31}\ \text{kg}$$

$$\epsilon_0 = 8.85 \times 10^{-14}\ \text{F/cm}$$

$$h = 6.625 \times 10^{-34}\ \text{J-s} = 4.135\times10^{-15}\ \text{eV-s}$$

$$c = 2.998 \times 10^{10}\ \text{cm/s}$$

$$1\ \text{eV}=1.6\times10^{-19}\ \text{J}$$

Silicon, gallium arsenide, and germanium properties at $T = 300$ K

Property	Si	GaAs	Ge
Atoms/cm^3	5.0×10^{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	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, χ (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}
Electron mobility, μ_n (cm^2/V-s)	1350	8500	3900
Hole mobility, μ_p (cm^2/V-s)	480	400	1900
Electron effective mass (DoS) $\left(\frac{m_n^*}{m_0}\right)$	1.08	0.067	0.55
Hole effective mass (DoS) $\left(\frac{m_p^*}{m_0}\right)$	0.56	0.48	0.37

Table 3.3 | Impurity ionization energies in silicon and germanium

	Ionization Energy (eV)	
Impurity	**Si**	**Ge**
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Table 3.4 | Impurity ionization energies in gallium arsenide

Impurity	Ionization Energy (eV)
Donors	
Selenium	0.0059
Tellurium	0.0058
Silicon	0.0058
Germanium	0.0061
Acceptors	
Beryllium	0.028
Zinc	0.0307
Cadmium	0.0347
Silicon	0.0345
Germanium	0.0404