PCS224 - Solid State Physics - Useful Formulas

$\vec{F} = q\vec{E}$

$\vec{F} = q(\vec{v} \times \vec{B})$

$|\vec{F}| = |q||\vec{v}||\vec{B}|\sin\theta$

$|\vec{E}|_{\text{plate}} = \frac{Q}{2A\epsilon_0} = \frac{\sigma}{2\epsilon_0}$

$K = mv^2/2$

$\Delta K + \Delta U = 0$

$\Delta U = q\Delta V$

$\Delta V = -\vec{E} \cdot \Delta\vec{x}$ or $-\vec{E} \cdot \Delta\vec{y}$

$|\Delta V| = |\vec{E}||\Delta x|$ or $|\vec{E}||\Delta y|$

$\Delta V = IR$

$P = I\Delta V = I^2 R = \frac{\Delta V^2}{R}$

$f\lambda = c$

$E = hf = hc/\lambda$

$hf = K_{\max} + \phi$

$K_{\max} = eV_{\text{stop}}$

$I = \frac{\Delta Q}{\Delta t}$

$I = nqAv_d$

$J = I/A$

$\vec{J} = \sigma\vec{E}$

$\vec{v}_{\text{dp}} = \mu_p\vec{E}$

$\vec{v}_{\text{dn}} = -\mu_n\vec{E}$

$\sigma = \frac{1}{\rho} = e\left[n\mu_n + p\mu_p\right]$

$R = \rho L/A = L/(\sigma A)$

$\Delta V_H = \frac{IB}{nqt_B}$ or $\Delta V_H = \frac{IB}{nqd}$

$E_n = \frac{-13.6\text{eV}}{n^2}$

$N_C = \frac{2.5\times10^{19}}{\text{cm}^3}\left(\frac{m_n^*}{m_e}\right)^{3/2}\left(\frac{T}{300\text{ K}}\right)^{3/2}$

$N_C(T) = N_C(300\text{ K}) \cdot \left(\frac{T}{300\text{ K}}\right)^{3/2}$

$N_V = \frac{2.5\times10^{19}}{\text{cm}^3}\left(\frac{m_p^*}{m_e}\right)^{3/2}\left(\frac{T}{300\text{ K}}\right)^{3/2}$

$N_V(T) = N_V(300\text{ K}) \cdot \left(\frac{T}{300\text{ K}}\right)^{3/2}$

$n_0 = N_C e^{\frac{-(E_C-E_F)}{k_BT}} = n_i e^{\frac{E_F-E_{Fi}}{k_BT}}$

$p_0 = N_V e^{\frac{-(E_F-E_V)}{k_BT}} = n_i e^{\frac{E_{Fi}-E_F}{k_BT}}$

$n_0 p_0 = n_i^2$

$n_i^2 = N_C N_V e^{\frac{-E_g}{k_BT}}$

$N_d - N_a = n_0 - p_0$

$E_C - E_F = k_BT\ln\left(\frac{N_C}{n_0}\right)$

$E_F - E_V = k_BT\ln\left(\frac{N_V}{p_0}\right)$

$E_F = E_{Fi} + \frac{k_BT}{2}\ln\left(\frac{n_0}{p_0}\right)$

$E_{Fi} = E_{\text{mid - gap}} + \frac{3k_BT}{4}\ln\left(\frac{m_p^*}{m_n^*}\right)$

$f_F(E) = \frac{1}{1+e^{\frac{E-E_F}{k_BT}}}$

$f_H(E) = 1 - f_F(E) = \frac{1}{1+e^{\frac{E_F-E}{k_BT}}}$

$V_{\text{bi}} = \frac{k_BT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right)$

$|\vec{E}|_{\max} = \frac{eN_dx_n}{\epsilon_s} = \frac{eN_Ax_p}{\epsilon_s} = \frac{2(V_{\text{bi}}+V_R)}{W}$

where $\epsilon_s = \kappa\epsilon_0$

$$x_n N_d = x_p N_A$$

$$x_n = \sqrt{\frac{2\epsilon_s(V_{\text{bi}}+V_R)}{e}\left(\frac{N_A}{N_d}\right)\left(\frac{1}{N_A+N_d}\right)}$$

$$x_p = \sqrt{\frac{2\epsilon_s(V_{\text{bi}}+V_R)}{e}\left(\frac{N_d}{N_A}\right)\left(\frac{1}{N_A+N_d}\right)}$$

$$W = \left[\frac{2\epsilon_s(V_{\text{bi}}+V_R)}{e}\left(\frac{N_A+N_d}{N_A N_d}\right)\right]^{1/2}$$

$$C = \frac{Q}{\Delta V} = \frac{dQ}{dV} = \frac{\epsilon_s A}{d} = \frac{\epsilon_s A}{W}$$

$$C' = C/A$$

$$C'_{\text{ox}} = \epsilon_{\text{ox}}/t_{\text{ox}}$$

$$Q_s = \tau_t I_D$$

$$Q' = Q/A$$

$$I_D = I_S\left[e^{eV/k_BT} - 1\right],\ I_S \propto \exp\left(\frac{-E_g}{k_BT}\right)$$

$$I_{\text{tot}} = I_L - I_D$$

$$V_{\text{OC}} = \frac{k_BT}{e}\ln\left[1+\frac{I_L}{I_S}\right]$$

$$e\phi_{Fp} = E_F - E_{\text{Fi, bulk}} \approx -k_BT\ln\left[\frac{N_A}{n_i}\right]$$

$$e\phi_{Fn} = E_F - E_{\text{Fi,bulk}} \approx k_BT\ln\left[\frac{N_d}{n_i}\right]$$

$$e\phi_s = E_{Fi,\text{ bulk}} - E_{\text{Fi, surface}}$$

$$\phi_{sT} = 2\left|\phi_{Fp}\right| = 2\phi_{Fn}$$

$$\left|Q_{\text{SD}}\right| = eN_A x_d A \text{ or } eN_d x_d A$$

$$x_d = \sqrt{\frac{2\epsilon_s|\phi_s|}{eN_a}} \text{ or } \sqrt{\frac{2\epsilon_s|\phi_s|}{eN_d}}$$

$$e\phi_{\text{ms}} = E_{F,\text{ semi}} - E_{\text{F,metal}}$$

$$V_{\text{FB}} = \phi_{ms} - \frac{Q_{SS}}{C_{\text{ox}}} = \phi_{ms} - \frac{Q'_{SS}t_{\text{ox}}}{\epsilon_{\text{ox}}}$$

$$V_G = \phi_{ms} + V_{\text{ox}} + \phi_s$$

$$V_{TN} = \phi_{ms} + \frac{t_{\text{ox}}\left(\left|Q'_{\text{SD,max}}\right| - Q'_{SS}\right)}{\epsilon_{\text{ox}}} + 2\left|\phi_{Fp}\right|$$

$$V_{TP} = \phi_{ms} - \frac{t_{\text{ox}}\left(\left|Q'_{\text{SD, max}}\right| + Q'_{SS}\right)}{\epsilon_{\text{ox}}} - 2\phi_{Fn}$$

$$K_n = \frac{\mu_n W\epsilon_{\text{ox}}}{2Lt_{\text{ox}}} \quad K_p = \frac{\mu_p W\epsilon_{\text{ox}}}{2Lt_{\text{ox}}}$$

$$I_D = K_n\left[2\left(V_{GS} - V_{TN}\right)V_{DS} - V_{DS}^2\right]$$

$$I_D = K_p\left[2\left(V_{SG} + V_{TP}\right)V_{SD} - V_{SD}^2\right]$$

$$V_{\text{DS,sat}} = V_{\text{GS}} - V_{\text{TN}}$$

$$V_{\text{SD,sat}} = V_{\text{SG}} + V_{\text{TP}}$$

$$I_{\text{D, sat}} = K_n\left(V_{\text{GS}} - V_{\text{TN}}\right)^2$$

OR

$$I_{\text{D, sat}} = K_p\left(V_{\text{SG}} + V_{\text{TP}}\right)^2$$

$$\left|Q'_{\text{acc}}\right| = C'_{\text{ox}}\left|V_{\text{GS}} - V_{\text{FB}}\right| \text{ or } Q'_{\text{acc}} = -C'_{\text{ox}}(V_{\text{GS}} - V_{\text{FB}})$$

$$\left|Q'_{\text{inv}}\right| = C'_{\text{ox}}\left(V_{\text{GS}} - V_{TN}\right) \text{ or } C'_{\text{ox}}\left(V_{\text{SG}} + V_{\text{TP}}\right)$$

OR

$$Q'_{\text{inv}} = -C'_{\text{ox}}\left(V_{\text{GS}} - V_T\right)$$

$$x_{DB} = \sqrt{\frac{\epsilon_s k_B T}{e^2 N_a}}$$

$$\epsilon_{ox} = 3.9$$

$$C'(\text{depl}) = \frac{\epsilon_{\text{ox}}}{t_{\text{ox}} + \frac{\epsilon_{\text{ox}}}{\epsilon_s}x_d}$$

If necessary, Figure 4.20 (Hall Effect) and Figure 6.21 (Metal-Semiconductor work functions) will be provided along with relevant equations.

FUNDAMENTAL CONSTANTS AND UNITS

$e = 1.6 \times 10^{-19}\mathrm{C}$

$m_e = 9.1 \times 10^{-31}$ kg

$h = 6.64 \times 10^{-34}$ J $\cdot$ sec

$c = 3.0 \times 10^8 \frac{\mathrm{m}}{\mathrm{sec}}$

$hc = 1240\mathrm{eV} \cdot \mathrm{nm}$

$k_B = 1.38 \times 10^{-23}$ J/K $= 8.617 \times 10^{-5}$eV/K

$k_B T = 0.026\mathrm{eV} \left(\frac{T}{300 \text{ K}}\right)$

$k_c = 9.0 \times 10^9 \frac{\mathrm{N \cdot m^2}}{\mathrm{C^2}}$

$\epsilon_0 = 8.85 \times 10^{-12} \frac{\mathrm{F}}{\mathrm{m}} = 552000 \frac{\mathrm{e}}{\mathrm{V \cdot cm}}$

The dielectric constant of silicon dioxide $\epsilon_{ox} = 3.9\epsilon_0$

$a_0 = 0.53 \times 10^{-10}$ m

$1\mathrm{eV} = 1.6 \times 10^{-19}$ J

$1 \text{ N} = 1 \text{ kg} \frac{\mathrm{m}}{\mathrm{sec^2}}$

$1 \text{ J} = 1 \text{ N} \cdot \text{m} = 1 \text{ kg} \frac{\mathrm{m^2}}{\mathrm{sec^2}}$

$1 \text{ W} = 1 \text{ J/s}$

$1 \text{ V} = 1 \text{ J/C}$

$1 \text{ A} = 1\text{C/sec}$

$1 \text{ T} = 1 \text{ kg}/(\text{C} \cdot \text{sec}) = 1 \text{ V} \cdot \text{sec/m}^2$

$1 \text{ F} = 1\text{C/V}$

$1\text{Å} = 10^{-8}$ cm

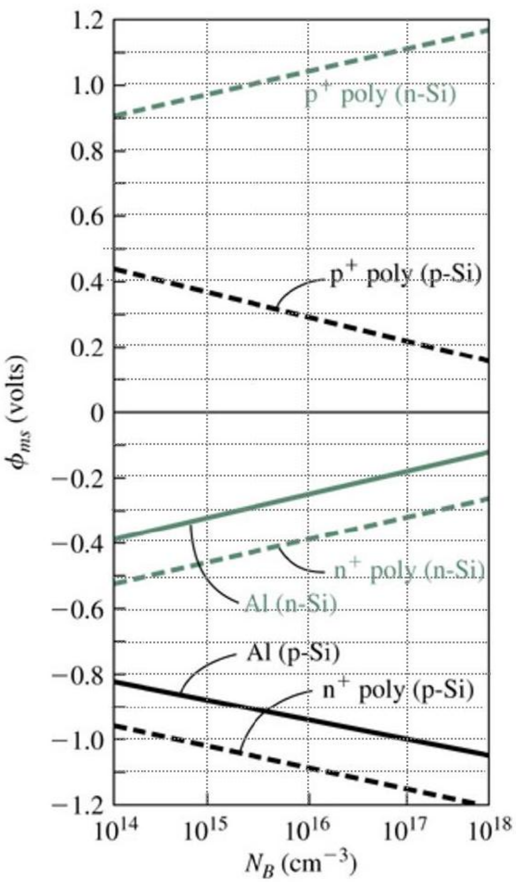

Table B.4 | Silicon, gallium arsenide, and germanium properties ($T = 300$ K)

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}
Mobility (cm^2/V-s)			
Electron, μ_n	1350	8500	3900
Hole, μ_p	480	400	1900
Effective mass $\left(\frac{m^*}{m_0}\right)$			
Electrons	$m_l^* = 0.98$	0.067	1.64
	$m_t^* = 0.19$		0.082
Holes	$m_{lh}^* = 0.16$	0.082	0.044
	$m_{hh}^* = 0.49$	0.45	0.28
Effective mass (density of states)			
Electrons $\left(\frac{m_n^*}{m_0}\right)$	1.08	0.067	0.55
Holes $\left(\frac{m_p^*}{m_0}\right)$	0.56	0.48	0.37