

List of Selected Formulae

$$\xi = \frac{1}{q} \frac{dE}{dx}, \quad E_{ph} = h\nu = \frac{hc}{\lambda}, \quad \frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2 E}{dk^2}, \quad E_n = -\frac{q^4}{2(4\pi \hbar)^2} \left(\frac{m_n^*}{\epsilon_r^2 \epsilon_0^2} \right) \frac{1}{n^2},$$

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

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

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

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

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

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

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

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

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

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

$$n_0 p_0 = n_i^2$$

List of Selected Formulae (cont'd)

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

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

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

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

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

$$\frac{d^2 V(x)}{dx^2} = -\frac{d\xi(x)}{dx} = -\frac{\rho_c}{\epsilon_r \epsilon_0} = -\frac{q}{\epsilon_r \epsilon_0} (p - n + N_d - N_a)$$

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

$$N_d x_n = N_a x_p, \quad \xi_{max} = -\frac{qN_d x_n}{\epsilon_r \epsilon_0} = -\frac{qN_a x_p}{\epsilon_r \epsilon_0}, \quad W = \left[\frac{2\epsilon_r \epsilon_0 (V_{bi} - V_a)}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2}$$

$$\frac{p_{p0}}{p_n(x_n)} = \frac{n_{n0}}{n_p(-x_p)} = \exp\left[\frac{q}{kT}(V_{bi} - V_a)\right], \quad \frac{p_n(x_n)}{p_{n0}} = \frac{n_p(-x_p)}{n_{p0}} = \exp\left(\frac{qV_a}{kT}\right) \quad V_{br} \approx \frac{\epsilon_r \epsilon_0 (N_A + N_D)}{2qN_A N_D} E_c^2$$

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

Hole diffusion length; cm

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

$$L_p = (D_p \tau_p)^{1/2}$$

$$I = I_0 \left[\exp\left(\frac{qV_a}{kT}\right) - 1 \right], \quad I_0 = qA \left(\frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0} \right), \quad C_j = \left| \frac{dQ_j}{dV_a} \right| = \frac{\epsilon_r \epsilon_0 A}{W}$$

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

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

List of Selected Formulae (cont'd)

$$I(x) = I_0 \exp(-\alpha x), \quad G = R_1 R_2 \exp(2(k - \gamma)L), \quad k_{th} = \gamma + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$$

$$\frac{n\lambda}{2} = L, \quad f = \frac{nc}{2L}, \quad \Delta f = \frac{\Delta nc}{2L}, \quad \frac{hc}{\lambda} = E_{ph}$$

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

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

$$V_B + I \times R_L + V = 0$$

APPENDIX B

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	Jmol ⁻¹ K ⁻¹
Electron-volt	1 eV	1.6×10^{-19}	J
Thermal voltage ($T = 300$ K)	$k_B T/q$	0.0259	V

APPENDIX C

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 (\AA)	5.43	5.65	5.65
Melting point ($^{\circ}\text{C}$)	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 ($\text{cm}^2/\text{V-s}$) Electron, μ_n Hole, μ_p	1350 480	8500 400	3900 1900