

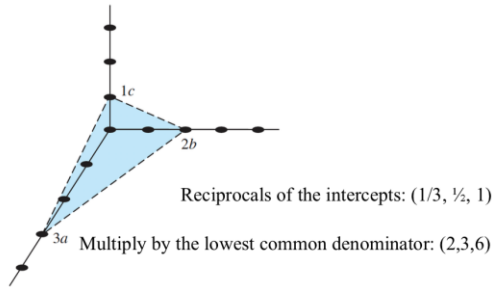
Resistivity:

Conductors	Semiconductors	Insulators
$< 10^{-3} \Omega \cdot \text{cm}$	$10^{-3} - 10^9 \Omega \cdot \text{cm}$	$> 10^9 \Omega \cdot \text{cm}$
Metals (Au, Al, Cu, Hg...)	Si, Ge, GaAs, InP...	SiO ₂ , HfO ₂ ...
Solids, liquids (Hg)	Solids	Solids, liquids gases

Unit cell: any small volume of crystal to reproduce the entire crystal.

Primitive cell: smallest unit cell

Crytalline Plane and Miller Index



$$\frac{\partial^2 y}{\partial x^2} = k^2 y \quad \text{General solution: } y = Ae^{bx}$$

Plug into the equation: $b^2 Ae^{bx} = k^2 Ae^{bx}$

$$\Rightarrow b = \pm k$$

$$\Rightarrow y = A_1 e^{kx} + A_2 e^{-kx}$$

$$\frac{\partial^2 y}{\partial x^2} = -k^2 y \quad \text{General solution: } y = Ae^{bx}$$

Plug into the equation: $b^2 Ae^{bx} = -k^2 Ae^{bx}$

$$\Rightarrow b = \pm ki$$

$$\Rightarrow y = A_1 e^{ikx} + A_2 e^{-ikx}$$

$$K = \frac{2\pi}{\lambda}, E = mc^2 = h\nu = \frac{hc}{\lambda}, p = \frac{h}{\lambda} = m\nu$$

$$\frac{\partial^2 \psi(x)}{\partial x^2} + \frac{2m}{\hbar^2} (E - V(x)) \psi(x) = 0$$

$$E = \frac{k^2 \hbar^2}{2m} = \frac{n^2 \pi^2 \hbar^2}{2ma^2}$$

$$k = \frac{n\pi}{a} \quad n = 0, \pm 1, \pm 2, \dots$$

$$p = \hbar k = m\nu$$

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \xrightarrow{m\nu = \hbar k} \frac{\hbar m\nu}{m} = \hbar\nu$$

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

$$v = \frac{1}{\hbar} \frac{dE}{dk}$$

$$J = qNv_d = q \sum_i^N v_i$$

Conduction Band:

$$E = E(k) = E_c + \frac{\hbar^2}{2m_n^*} (k - k_1)^2$$

Valence Band:

$$E = E(k) = E_c - \frac{\hbar^2}{2m_p^*} (k - k_2)^2$$

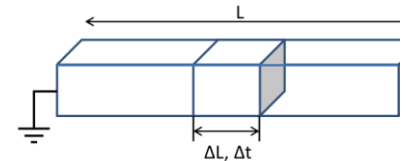
$$E - E_c = C_1(k)^2$$

$$\frac{1}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{2C_1}{\hbar^2}$$

$$\frac{1}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{2C_1}{\hbar^2} = \frac{1}{m^*}$$

n type semiconductor

$$I = \frac{\Delta Q}{\Delta t} = \frac{nqA_c \Delta L}{\Delta t} = nqA_c v$$



$$v = \mu E = \mu V / L$$

$$I = \frac{\Delta Q}{\Delta t} = \frac{nqA_c \Delta L}{\Delta t} = nqA_c \mu V / L \quad \Rightarrow \quad \sigma = \frac{I}{V} = \frac{n_D q A_c \mu}{L}$$

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

$$E = E(k) = E_c + \frac{\hbar^2}{2m_n^*} k^2$$

$$k = \mp \frac{\sqrt{2m_n^*(E - E_c)}}{\hbar}$$

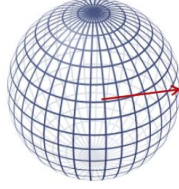


Within ΔE , we have the number of k is $\frac{d(k/\pi)}{dE} \Delta E$

$$g(E) = \frac{1}{2} \frac{d(k/\pi)}{dE}$$

$$E = E(k) = E_c + \frac{\hbar^2}{2m_n^*} k^2$$

$$k = \mp \frac{\sqrt{2m_n^*(E - E_c)}}{\hbar}$$



Within ΔE , we have the number of k is $\frac{d(4\pi(\frac{k}{\pi})^2/3)}{dE} \Delta E$

$$g(E) = \frac{1}{8} \frac{d(4\pi(\frac{k}{\pi})^2/3)}{dE}$$

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E}$$

$$n_0 = \int_{E_c}^{\infty} g_c(E) f_F(E) dE$$

$$p_0 = \int_{-\infty}^{E_v} g_v(E) [1 - f_F(E)] dE$$

$$\text{if } \exp(x - \varepsilon) > 10 \Leftrightarrow \frac{E - E_F}{kT} > 3 \Leftrightarrow E - E_F > 3kT$$

$$n_0 = \frac{2(2\pi m_n^* kT)^{3/2}}{h^3} \exp\left(\frac{E_F - E_c}{kT}\right) = N_c \exp\left(\frac{E_F - E_c}{kT}\right)$$

$$p_0 = \frac{2(2\pi m_p^* kT)^{3/2}}{h^3} \exp\left(\frac{E_v - E_F}{kT}\right) = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$n \times p = n_i^2 = N_c N_v \exp\left(\frac{E_v - E_c}{kT}\right) \Rightarrow n_i = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2kT}\right)$$

$$n = N_c \exp\left(\frac{E_F - E_c}{kT}\right) \quad p = N_v \exp\left(\frac{E_v - E_F}{kT}\right) \quad \begin{matrix} N_c \approx 10^{19} \text{ cm}^{-3} \\ N_v \approx 10^{19} \text{ cm}^{-3} \end{matrix}$$

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \quad p_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right] \quad n_i \approx 10^{10} \text{ cm}^{-3}$$

$$n = N_c \exp\left(\frac{E_{Fi} - E_c}{kT}\right) = p = N_v \exp\left(\frac{E_v - E_{Fi}}{kT}\right)$$

$$E_{Fi} = \frac{1}{2} (E_c + E_v) + \frac{1}{2} kT \ln\left(\frac{N_v}{N_c}\right)$$

$$E_{midgap} = \frac{1}{2} (E_c + E_v)$$

$$E_{Fi} = E_{midgap} + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$\begin{aligned} n_d &= N_d - N_d^+ \\ &= \frac{N_d}{1 + \frac{1}{2} \exp\left(\frac{E_d - E_F}{kT}\right)} \end{aligned}$$

$$p_a = \frac{N_a}{1 + \frac{1}{g} \exp\left(\frac{E_F - E_a}{kT}\right)} = N_a - N_a^-$$

$$n_0 + (N_a - p_a) = p_0 + (N_d - n_d)$$

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

$$n_0 = \frac{N_d^+ + \sqrt{(N_d^+)^2 + 4n_i^2}}{2} \quad (\text{but } N_d^+ \text{ unknown})$$

$$n_0 = N_c \times \frac{-1 + \sqrt{1 + \frac{8N_D}{N_c} \exp\left(\frac{E_A}{kT}\right)}}{4 \exp\left(\frac{E_A}{kT}\right)} = \begin{cases} \sqrt{\frac{N_D N_c}{2} \exp\left(-\frac{E_A}{2kT}\right)} & \text{partial ionization,} \\ N_D & \text{complete ionization} \end{cases}$$

$$n_0 = \frac{N_D + \sqrt{N_D^2 + 4n_i^2}}{2} \quad \text{Complete ionization at high T}$$

$$E_F = E_c + kT \ln\left(\frac{\sqrt{1 + \frac{8N_D}{N_c} \exp\left(\frac{E_A}{kT}\right)} - 1}{4 \exp\left(\frac{E_A}{kT}\right)}\right) = \begin{cases} \frac{E_c + E_D}{2} + \frac{kT}{2} \ln \frac{N_D}{2N_c} & T \text{ small} \\ E_c - kT \ln \frac{N_c}{N_D} & T \text{ big} \end{cases}$$

$$v_d \approx \left(\frac{q\tau_{cp}}{m_{cp}^*}\right) E \Rightarrow \frac{v_d}{E} = \frac{q\tau_{cp}}{m_{cp}^*} = \mu_p \quad (\text{for holes})$$

$$\frac{v_d}{E} = \frac{q\tau_{cn}}{m_{cn}^*} = \mu_n \quad (\text{for electrons})$$

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0 A_c \Delta L}{\Delta t} = qp_0 A_c v = qp_0 A_c \mu_p E = qp_0 A_c \mu_p \frac{V}{L} = \sigma \cdot V$$

$$J_{drf} = q(p_0 \mu_p + n_0 \mu_n) E$$

$$\frac{1}{u} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

$$v_n = \frac{v_s}{\left[1 + \left(\frac{E_{on}}{E}\right)^2\right]^{1/2}} \quad v_p = \frac{v_s}{\left[1 + \left(\frac{E_{op}}{E}\right)^2\right]^{1/2}}$$

$$J_{nx|dif} = -qF_n = qD_n \frac{dn}{dx}$$

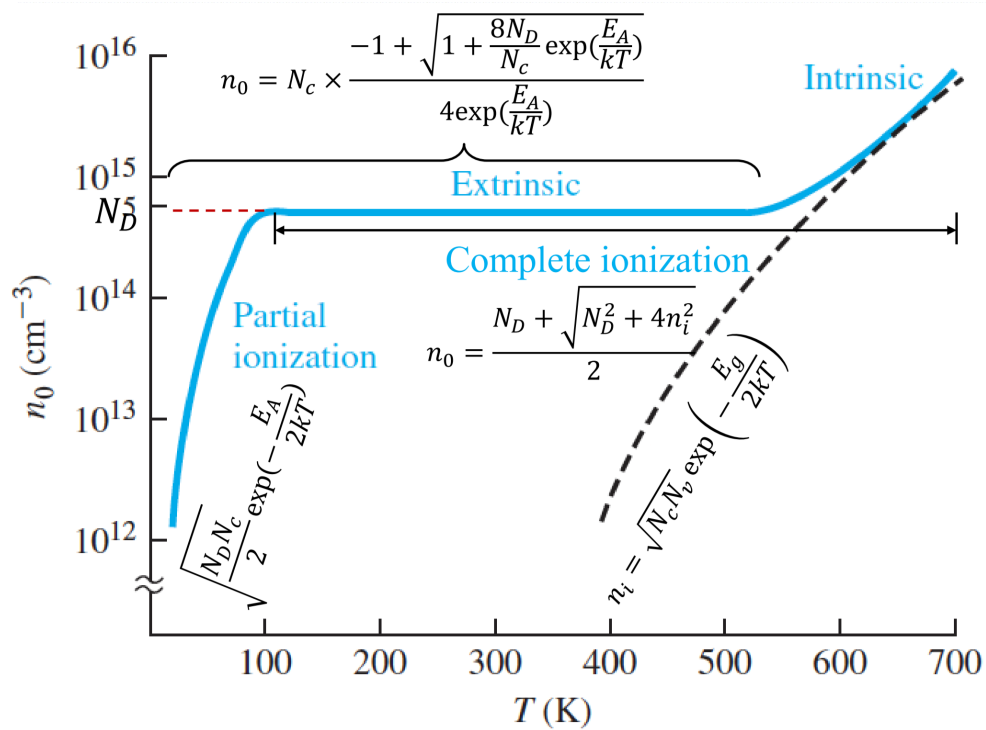
$$J_{px|dif} = qF_p = -qD_p \frac{dp}{dx}$$

$$J = qn\mu_n E_x + qp\mu_p E_x + qD_n \nabla n - qD_p \nabla p$$

$$E_x = -\frac{d\phi}{dx} = \frac{1}{e} \frac{dE_i}{dx}$$

$$= \frac{1}{q} \frac{kT}{n(x)} \frac{dn(x)}{dx}$$

$$D_n = \frac{\mu_n kT}{q}$$



From textbook
Semiconductor Physics and Devices: Basic Principles 4th edition. P716-718 (Appendix B)

Table B.2 | Conversion factors

	Prefixes		
1 Å (angstrom) = 10^{-8} cm = 10^{-10} m	10^{-15}	femto-	= f
1 μm (micrometer) = 10^{-4} cm	10^{-12}	pico-	= p
1 mil = 10^{-3} in. = 25.4 μm	10^{-9}	nano-	= n
2.54 cm = 1 in.	10^{-6}	micro-	= μ
1 eV = 1.6×10^{-19} J	10^{-3}	milli-	= m
1 J = 10^7 erg	10^{+3}	kilo-	= k
	10^{+6}	mega-	= M
	10^{+9}	giga-	= G
	10^{+12}	tera	= T

Table B.3 | Physical constants

Avogadro's number	$N_A = 6.02 \times 10^{+23}$ atoms per gram molecular weight
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$e = 1.60 \times 10^{-19}$ C
Free electron rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}$ H/m
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm $= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.625 \times 10^{-34}$ J-s $= 4.135 \times 10^{-15}$ eV-s $\frac{h}{2\pi} = \hbar = 1.054 \times 10^{-34}$ J-s
Proton rest mass	$M = 1.67 \times 10^{-27}$ kg
Speed of light in vacuum	$c = 2.998 \times 10^{10}$ cm/s
Thermal voltage ($T = 300$ K)	$V_t = \frac{kT}{e} = 0.0259$ V $kT = 0.0259$ eV

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 ($^{\circ}\text{C}$)	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 ($\text{cm}^2/\text{V-s}$)			
Electron, μ_n	1350	8500	3900
Hole, μ_p	480	400	1900
Effective mass ($\frac{m^*}{m_0}$)			
Electrons	$m_l^* = 0.98$ $m_t^* = 0.19$	0.067	1.64 0.082
Holes	$m_{lh}^* = 0.16$ $m_{hh}^* = 0.49$	0.082 0.45	0.044 0.28
Density of states effective mass			
Electrons ($\frac{m_{do}^*}{m_0}$)	1.08	0.067	0.55
Holes ($\frac{m_{dp}^*}{m_0}$)	0.56	0.48	0.37
Conductivity effective mass			
Electrons ($\frac{m_{co}^*}{m_0}$)	0.26	0.067	0.12
Holes ($\frac{m_{cp}^*}{m_0}$)	0.37	0.34	0.21

Table B.5 | Other semiconductor parameters

Material	E_g (eV)	a (Å)	ϵ_r	χ	\bar{n}
Aluminum arsenide	2.16	5.66	12.0	3.5	2.97
Gallium phosphide	2.26	5.45	10	4.3	3.37
Aluminum phosphide	2.43	5.46	9.8		3.0
Indium phosphide	1.35	5.87	12.1	4.35	3.37

Table B.6 | Properties of SiO_2 and Si_3N_4 ($T = 300$ K)

Property	SiO_2	Si_3N_4
Crystal structure	[Amorphous for most integrated circuit applications]	
Atomic or molecular density (cm^{-3})	2.2×10^{22}	1.48×10^{22}
Density (g/cm^3)	2.2	3.4
Energy gap	≈ 9 eV	4.7 eV
Dielectric constant	3.9	7.5
Melting point ($^{\circ}\text{C}$)	≈ 1700	≈ 1900