Appendix I
Definitions of Commonly Used Symbols[1]

a	Chapter 1: unit cell dimension (Å); Chapter 6: metallurgical channel half-width for an FET (cm)
$\mathbf{a}, \mathbf{b}, \mathbf{c}$	basis vectors
A	area (cm^2)
$\mathcal{B}$	magnetic flux density (Wb/cm^2)
B	base transport factor for a BJT
B, E, C	base, emitter, collector of a BJT
c	speed of light (cm/s)
C	capacitance/area in MOS (F/cm^2)
$\mathrm{C}_i, \mathrm{C}_d, \mathrm{C}_{it}$	insulator, depletion, interface-state MOS capacitance/area (F/cm^2)
C_j	junction capacitance (F)
C_s	charge storage capacitance (F)
D, D_n, D_p	diffusion coefficient for dopants, electrons, holes (cm^2/s)
D, G, S	drain, gate, source of an FET
e	Napierian base
e^-	electron
$\mathscr{E}$	electric field strength (V/cm)
E	energy[2] (J, eV); battery voltage (V)
E_a, E_d	acceptor, donor energy level (J, eV)
E_c, E_v	conduction band, valence band edge (J, eV)
E_F	equilibrium Fermi level (J, eV)
E_g	band gap energy (J, eV)
E_i	intrinsic level (J, eV)
E_r, E_t	recombination, trapping energy level (J, eV)
$f(E)$	Fermi–Dirac distribution function
F_n, F_p	quasi-Fermi level for electrons, holes (J, eV)
g, g_{op}	EHP generation rate, optical generation rate (cm^{-3}-s^{-1})

[1]This list does not include some symbols that are used only in the section where they are defined. Units are given in common semiconductor usage, involving cm where appropriate; it is important to note, however, that calculations should be made in the MKS system in some formulas.

[2]In the Boltzmann factor $\exp(-\Delta E/kT)$, ΔE can be expressed in J or eV if k is expressed in J/K or eV/K, respectively.

g_m	mutual transconductance (Ω^{-1}, S)
h	Planck's constant (J-s, eV-s); Chapter 6: FET channel half-width (cm)
$\hbar$	Planck's constant divided by 2π (J-s, eV-s)
$h\nu$	photon energy (J, eV)
h, k, l	Miller indices
h^+	hole
i, I	current[3] (A)
I (subscript)	inverted mode of a BJT
i_B, i_C, i_E	base, collector, emitter current in a BJT (A)
I_{CO}, I_{EO}	magnitude of the collector, emitter saturation current with the emitter, collector open (A)
I_{CS}, I_{ES}	magnitude of the collector, emitter saturation current with the emitter, collector shorted (A)
I_D	channel current in an FET, directed from drain to source (A)
I_0	reverse saturation current in a p-n junction (A)
j	$\sqrt{-1}$
J	current density (A/cm^2)
k	Boltzmann's constant (J/K, eV/K)
k_N, k_P	transconductance of NMOSFET, PMOSFET divided by V_D (A/V^2)
$\mathbf{k}$	wave vector (cm^{-1})
k_d	distribution coefficient
K	scaling factor
K	$4\pi\epsilon_0$ (F/cm)
l, L	length (cm)
L_D	Debye length (cm)
$\bar{l}$	mean free path for carriers in random motion (cm)
m, m^*	mass, effective mass (kg)
m_n^*, m_p^*	effective mass for electrons, holes (kg)
m_l, m_t	longitudinal, transverse electron effective mass (kg)
m_{lh}, m_{hh}	light, heavy hole effective mass (kg)
m_0	rest mass of the electron (kg)
M	avalanche multiplication factor
m, n	integers; exponents
n	concentration of electrons in the conduction band (cm^{-3})
n	n-type semiconductor material
n$^+$	heavily doped n-type material
n_i	intrinsic concentration of electrons (cm^{-3})
n_n, n_p	equilibrium concentration of electrons in n-type, p-type material (cm^{-3})
n_0	equilibrium concentration of electrons (cm^{-3})
N (subscript)	normal mode of a BJT
N_a, N_d	concentration of acceptors, donors (cm^{-3})
N_a^-, N_d^+	concentration of ionized acceptors, donors (cm^{-3})
N_c, N_v	effective density of states at the edge of the conduction band, valence band (cm^{-3})
p	concentration of holes in the valence band (cm^{-3})
p	p-type semiconductor material

[3]See note at the end of this list.

p^+	heavily doped p-type material
p	momentum (kg-m/s)
p_i	intrinsic hole concentration (cm^{-3}) = n_i
p_n, p_p	equilibrium concentration of holes in n-type, p-type material (cm^{-3})
p_0	equilibrium hole concentration (cm^{-3})
q	magnitude of the electronic charge (C)
Q_+, Q_-	total positive, negative charge (C)
Q_d	depletion region charge/area (C/cm^2)
Q_f	oxide fixed charge/area (C/cm^2)
Q_i	effective MOS interface charge/area (C/cm^2)
Q_{it}	interface trap charge/area (C/cm^2)
Q_m	mobile ionic charge/area (C/cm^2)
Q_n, Q_p	charge stored in an electron, hole distribution (C)
Q_n	mobile charge/area in FET channel (C/cm^2)
Q_{ot}	oxide trapped charge/area (C/cm^2)
$R_p, \Delta R_p$	projected range, straggle (cm)
r, R	resistance (Ω)
R_H	Hall coefficient (cm^3/C)
S	subthreshold slope (mV/decade)
t	time (s)
t	sample thickness (cm)
$\bar{t}$	mean free time between scattering collisions (s)
t_{sd}	storage delay time (s)
T	temperature (K)
v, V	voltage[4] (V)
V	potential energy (J)
$\mathcal{V}$	electrostatic potential (V)
V_{CB}, V_{EB}	voltage from collector to base, emitter to base in a BJT (V)
V_D, V_G	voltage from drain to source, gate to source in an FET (V)
$\mathcal{V}_n, \mathcal{V}_p$	electrostatic potential in the neutral n, p material (V)
V_0	contact potential (V)
V_P	Chapter 6: pinch-off voltage for an FET; Chapter 11: forward breakover voltage for an SCR (V)
V_T, V_{FB}	MOS threshold voltage, flat-band voltage (V)
v, v_d	velocity, drift velocity (cm/s)
w	sample width (cm)
W	depletion region width (cm)
W_b	base width in a BJT, measured between the edges of the emitter and collector junction depletion regions (cm)
x	distance (cm), alloy composition
x_n, x_p	distance in the neutral n region, p region of a junction, measured from the edge of the transition region (cm)
x_{n0}, x_{p0}	penetration of the transition region into the n region, p region, measured from the metallurgical junction (cm)
Z	atomic number; dimension in z-direction (cm)
α	emitter-to-collector current transfer ratio in a BJT

[4]See note at the end of this list.

α	optical absorption coefficient (cm^{-1})
α_r	recombination coefficient (cm^3/s)
β	base-to-collector current amplification factor in a BJT
γ	emitter injection efficiency; in a p-n-p, the fraction of i_E due to the hole current i_{Ep}
δ, Δ	incremental change
$\delta n, \delta p$	excess electron, hole concentration (cm^{-3})
$\Delta n_p, \Delta p_n$	excess electron, hole concentration at the edge of the transition region on the p side, n side (cm^{-3})
$\Delta p_C, \Delta p_E$	excess hole concentration in the base of a BJT, evaluated at the edge of the transition region of the collector, emitter junction (cm^{-3})
$\epsilon, \epsilon_r, \epsilon_0$	permittivity, relative dielectric constant, permittivity of free space (F/cm); $\epsilon = \epsilon_r\epsilon_0$
λ	wavelength of light (μm, Å)
μ	mobility (cm^2/V-s)
ν	frequency of light (s^{-1})
ρ	resistivity (Ω-cm); charge density (C/cm^3)
σ	conductivity $(\Omega\text{-cm})^{-1}$
τ_d	dielectric relaxation time (s); in a BJT, delay time (s)
τ_n, τ_p	recombination lifetime for electrons, holes (s)
τ_t	transit time (s)
ϕ	flux density $(cm^2\text{-s})^{-1}$; potential (V), dose (cm^{-2})
ϕ_F	$(E_i - E_F)/q$ (V)
ϕ_s	surface potential (V)
Φ	work function potential (V)
Φ_B	metal–semiconductor barrier height (V)
Φ_{ms}	metal–semiconductor work function potential difference (V)
ψ, Ψ	time-independent, time-dependent wave function
ω	angular frequency (s^{-1})
$\langle\ \rangle$	average of the enclosed quantity

Note: For d-c voltage and current, capital symbols with capital subscripts are used; lowercase symbols with lowercase subscripts represent a-c quantities; lowercase symbols with capital subscripts represent total (a-c + d-c) quantities. For voltage symbols with double subscripts, V is positive when the potential at the point referred to by the first subscript is higher than that of the second point. For example, V_{GD} is the potential difference $V_G - V_D$.

Appendix II

Physical Constants and Conversion Factors[1]

Quantity	Value
Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

Conversions	Prefixes:		
1 Å (angstrom) $= 10^{-8}$ cm	milli-,	m-	$= 10^{-3}$
1 μm (micron) $= 10^{-4}$ cm	micro-,	μ-	$= 10^{-6}$
1 nm = 10Å $= 10^{-7}$ cm	nano-,	n-	$= 10^{-9}$
2.54 cm = 1 in.	pico-,	p-	$= 10^{-12}$
1 eV $= 1.6 \times 10^{-19}$ J	kilo-,	k-	$= 10^{-3}$
	mega-,	M-	$= 10^{6}$
	giga-,	G-	$= 10^{9}$

A wavelength λ of 1 μm corresponds to a photon energy of 1.24 eV.

[1]Since cm is used as the unit of length for many semiconductor quantities, caution must be exercised to avoid unit errors in calculations. When using quantities involving length in formulas which contain quantities measured in MKS units, it is usually best to use all MKS quantities. Conversion to standard semiconductor usage involving cm can be accomplished as a last step. Similar caution is recommended in using J and eV as energy units.

Appendix III

Properties of Semiconductor Materials

		E_g (ev)	μ_n (cm²/V-s)	μ_p (cm²/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm³)	Melting point (°C)
Si	(i/D)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
Ge	(i/D)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
SiC (α)	(i/W)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
AlP	(i/Z)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
AlAs	(i/Z)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
AlSb	(i/Z)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
GaP	(i/Z)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
GaAs	(d/Z)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
GaN	(d/Z, W)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
GaSb	(d/Z)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
InP	(d/Z)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
InAs	(d/Z)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
InSb	(d/Z)	0.18	10^5	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
ZnS	(d/Z, W)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
ZnSe	(d/Z)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
ZnTe	(d/Z)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
CdS	(d/W, Z)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
CdSe	(d/W)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
CdTe	(d/Z)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
PbS	(i/H)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
PbSe	(i/H)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
PbTe	(i/H)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

All values at 300 K.

*Vaporizes

The first column lists the semiconductor, the second indicates band structure type and crystal structure. Definitions of symbols: *i* is indirect; *d* is direct; *D* is diamond; *Z* is zincblende; *W* is wurtzite; *H* is halite (NaCl). Values of mobility are for material of high purity.

Crystals in the wurtzite structure are not described completely by the single lattice constant given here, since the unit cell is not cubic. Several II–VI compounds can be grown in either the zincblende or wurtzite structures.

Many values quoted here are approximate or uncertain, particularly for the II–VI and IV–VI compounds. The gaps indicate that the values are unknown.

For electrons, the first set of band curvature effective masses is the longitudinal mass, the second set the transverse. For holes, the first set is for light holes, the second for heavy holes.

Appendix IV
Derivation of the Density of States in the Conduction Band

In this derivation we shall consider the conduction band electrons to be essentially free. Constraints of the particular lattice can be included in the effective mass of the electron at the end of the derivation. For a free electron, the three-dimensional Schrödinger wave equation becomes

$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi \qquad \text{(IV–1)}$$

where ψ is the wave function of the electron and E is its energy. The form of the solution to Eq. (IV–1) is

$$\psi = (\text{const.})e^{j\mathbf{k}\cdot\mathbf{r}} \qquad \text{(IV–2)}$$

We must describe the electron in terms of a set of boundary conditions within the lattice. A common approach is to use periodic boundary conditions, in which we quantize the electron energies in a cube of material of side L. This can be accomplished by requiring that

$$\psi(x + L, y, z) = \psi(x, y, z) \qquad \text{(IV–3)}$$

and similarly for the y- and z-directions. Thus our wave function can be written as

$$\psi_n = A \exp\left[j\frac{2\pi}{L}(\mathbf{n}_x x + \mathbf{n}_y y + \mathbf{n}_z z)\right] \qquad \text{(IV–4)}$$

where the $2\pi\mathbf{n}/L$ factor in each direction guarantees the condition described by Eq. (IV–3), and A is a normalizing factor. Substituting ψ_n into the Schrödinger equation (IV–1), we obtain

$$-\frac{\hbar^2}{2m}A\nabla^2 \exp\left[j\frac{2\pi}{L}(\mathbf{n}_x x + \mathbf{n}_y y + \mathbf{n}_z z)\right] = EA \exp\left[j\frac{2\pi}{L}(\mathbf{n}_x x + \mathbf{n}_y y + \mathbf{n}_z z)\right] \quad \text{(IV–5)}$$

Let us determine the number of allowed states per unit volume as a function of energy [the density of states, $N(E)$] in various cases such as 1, 2, or 3- dimensions. We first count states in **k**-space, then we can use the bandstructure, $E(\mathbf{k})$, to convert to $N(E)$.

For the the 3-D case in Eq. (IV–5), the components of the **k**-vector are $\mathbf{k}_x = 2\pi\,\mathbf{n}_x/L$, $\mathbf{k}_y = 2\pi\,\mathbf{n}_y/L$, and $\mathbf{k}_z = 2\pi\,\mathbf{n}_z/L$. Since there is one **k**-state for every distinct choice of integer quantum numbers, $(\mathbf{n}_x, \mathbf{n}_y, \mathbf{n}_z)$, the volume per **k**-state is $(2\pi)^3/L^3 = (2\pi)^3/V$, where $V = L^3$ is the three-dimensional volume. Hence, the number of states for 3-D in a **k**-space of $\Delta\mathbf{k}$, taking into account the factor of 2 spin degeneracy, is

$$\left\{\frac{L^3}{(2\pi)^3}\Delta\mathbf{k}\right\} \times (2)\, spin \qquad \text{(IV–6a)}$$

The number of states per unit volume for 3-D is

$$\frac{2}{(2\pi)^3}(\Delta\mathbf{k}) \qquad \text{(IV–6b)}$$

In general, for p-dimensions we can generalize this expression as

$$\text{Number of states per unit volume} = \frac{2}{(2\pi)^p}(\Delta\mathbf{k}) \qquad \text{(IV–7a)}$$

We can then transform from **k**-space to E-space using the $E(\mathbf{k})$ bandstructure relationship by setting

$$N(E)\,\Delta E = \frac{2}{(2\pi)^p}(\Delta\mathbf{k}) \qquad \text{(IV–7b)}$$

As described in Sec. 3.2.2, the simplest bandstructure is parabolic:

$$E(\mathbf{k}) = \frac{\hbar^2 k^2}{2m^*} \qquad \text{(IV–8a)}$$

This is often a good approximation, particularly near the bottom of the conduction band or top of the valence band. Using this, we get the relation between **k** and E as follows:

$$k = \sqrt{\frac{2m^* E}{\hbar^2}} \qquad \text{(IV–8b)}$$

$$dk = \left\{\sqrt{\frac{m^*}{2}}\,\frac{1}{\hbar}\right\}\frac{1}{\sqrt{E}}\,dE \qquad \text{(IV–8c)}$$

For $p = 3$ we have the 3-D case, which is typical of bulk semiconductors. The volume in **k**-space between two constant-k spherical surfaces at k and $k + dk$ is (Figure IV–1a):

$$\Delta\mathbf{k} = 4\pi k^2 dk \qquad \text{(IV–9a)}$$

neglecting terms with dk multiplied by itself.

The density-of-states then becomes:

$$N(E)dE = \frac{2}{(2\pi)^3}\,4\pi k^2 dk = \frac{\sqrt{2}}{\pi^2}\left(\frac{m^*}{\hbar^2}\right)^{3/2} E^{1/2} dE \qquad \text{(IV–9b)}$$

We see that if we plot $N(E)$ versus E, we get a parabolic density-of-states function in 3-D for a parabolic bandstructure relationship (Figure IV–2a).

For $p = 2$, we get a so-called 2-D electron gas (2-DEG) or hole gas. This can arise, for example, in a quantum well (Section 3.2.5) or in the inversion layer of a MOSFET.

In this case, the "volume" in **k**-space is the annular region between two circles, k and $k+dk$, as shown in Figure (IV–1b), where

$$\Delta \mathbf{k} = (2\pi k)dk \tag{IV–10a}$$

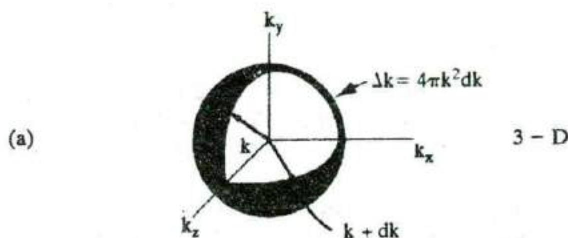
again neglecting dk^2.

Using Eq. IV–7a, this leads to a density of states (per unit area)

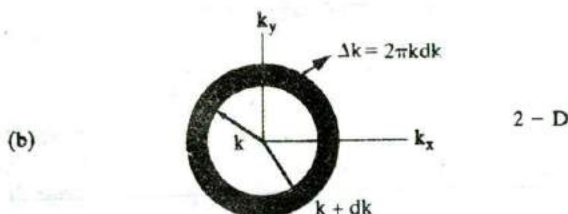
$$N(E)dE = \frac{2}{(2\pi)^2}(2\pi k)dk = \frac{m^*}{\pi\hbar^2}dE \tag{IV–10b}$$

We see that for 2-D, the density of states is a constant in energy, unlike the parabolic density of states for 3-D (Figure IV–2b). Actually, for the 2-DEG

(a)



(b)



(c)

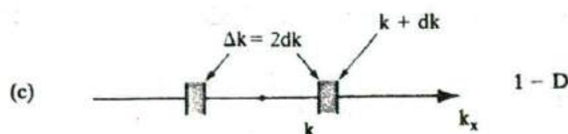


Figure IV–1a-c Volume in **k**-space: (a) 3-D systems; (b) 2-D systems; (c) 1-D systems.

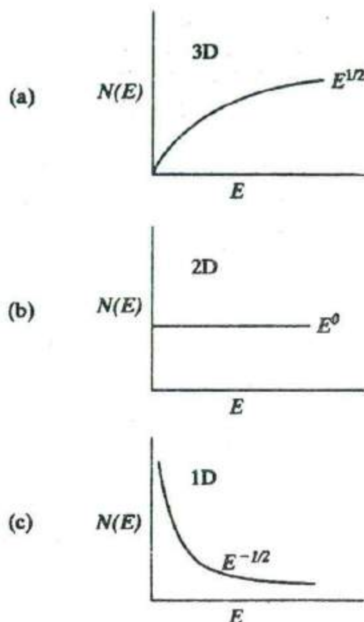


Figure IV–2 Density of states: (a) in 3-D or bulk; (b) in 2-D electron or hole gases; (c) in 1-D quantum "wires".

in a quantum well or inversion layer (see Chapter 6) we must add the various constant 2-D densities-of-states for the different "particle-in-a-box" levels that were discussed in Sections 2.4.3 and 3.2.5, leading to a so-called "staircase" density of states.

For $p = 1$, we get 1-D quantum "wires." These more esoteric structures can be grown, for example, by MBE or MOCVD. In this case, the "volume" in **k**-space in the region between **k** and $k+dk$ in 1-D is (Figure IV–1c):

$$\Delta \mathbf{k} = 2(dk) \tag{IV–11a}$$

Using Eq. IV–7a, this leads to a density of states

$$N(E)dE = \frac{2}{(2\pi)^1}(2dk) = \frac{\sqrt{2m^*}}{\pi\hbar\sqrt{E}}dE \tag{IV–11b}$$

By examining the density of states in 3, 2 and 1-D (Eqs. IV–9b, IV–10b and IV–11b, respectively) we notice a very interesting trend. Every time we go to a lower dimensionality system, the dependence of density of states on energy changes by $1/\sqrt{E}$. In fact, one finds that for 0-D quantum "dots" the density of states is indeed proportional to $1/E$. In the 1 and 0-D cases, we see that the density of states has singularities in energy, which has very important implications for semiconductor devices. Unfortunately, those discussions are beyond the scope of this book.

To include the probability of occupation of any energy level E, we use the Fermi–Dirac distribution function:

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad \text{(IV–12)}$$

The concentration of electrons in the range dE is given by the product of the density of allowed states in that range and the probability of occupation. Thus the density of occupied electron states N_e in dE is

$$N_e dE = N(E)f(E)dE \quad \text{(IV–13)}$$

For the 3-D case we may calculate the concentration of electrons in the conduction band at a given temperature by integrating Eq. (IV–13) across the band:

$$n = \int_0^\infty N(E)f(E)dE = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{E_F/kT}\int_0^\infty E^{1/2}e^{-E/kT}dE \quad \text{(IV–14)}$$

In this integration we have referred the energies in the conduction band to the band edge (E_c taken as $E = 0$). Furthermore, we have taken the function $f(E)$ to be

$$f(E) = e^{(E_F-E)/kT} \quad \text{(IV–15)}$$

for energies such that $(E - E_F) \gg kT$.

The integral in Eq. (IV–14) is of the standard form:

$$\int_0^\infty x^{1/2}e^{-ax}dx = \frac{\sqrt{\pi}}{2a\sqrt{a}} \quad \text{(IV–16)}$$

Thus Eq. (IV–14) gives

$$n = 2\left(\frac{2\pi mkT}{h^2}\right)^{3/2} e^{E_F/kT} \quad \text{(IV–17)}$$

If we refer to the bottom of the conduction band as E_c instead of $E = 0$, the expression for the electron concentration is

$$n = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} e^{(E_F-E_c)/kT} \quad \text{(IV–18)}$$

which corresponds to Eq. (3–15). We have included constraints of the lattice through the effective mass of the electron in the crystal, m_n^*.

Appendix V
Derivation of Fermi–Dirac Statistics

In this section, we will give a simplified derivation of Fermi–Dirac statistics. We will not go through all the details, but will instead point out the physical assumptions involved. The distribution function is determined by calculating the number of distinct ways (W_k) we can put n_k indistinguishable electrons in g_k states at an energy level E_k, subject to the Pauli exclusion principle.

The assumptions are:

1. Each allowed state has a maximum of one electron (Pauli principle).
2. The probability of occupancy of each allowed (degenerate) quantum state is the same.
3. All electrons are indistinguishable.

The number of distinct ways we can put the electrons in a particular level is

$$W_k = \frac{(g_k)(g_k - 1)(g_k - \overline{n_k - 1})}{n_k!} = \frac{g_k!}{(g_k - n_k)!n_k!} \qquad \text{(V–1)}$$

For N levels in a band, the number of distinct ways we can put in the various electrons gives us the so-called "multiplicity function,"

$$W_b = \prod_k W_k = \prod_k \frac{g_k!}{(g_k - n_k)!n_k!} \qquad \text{(V–2)}$$

If we ask, "What is the most probable distribution of the n_k electrons in the various E_k levels (degeneracy of g_k in level E_k)?", the statistical mechanical answer is:

> In thermal equilibrium, the distribution which is most disordered (i.e., has the maximum entropy, or which can occur in the largest number of ways) is the most probable.

We therefore have to maximize W_b with respect to n_k.

We assume here that the total number of electrons in the band is fixed.

$$\sum_k n_k = n = \text{constant} \Rightarrow \sum_k dn_k = 0 \qquad \text{(V–3)}$$

We also assume that the total energy in the band is constant.

$$E_{tot} = \sum_k E_k n_k = \text{constant, implying } \sum_k E_k dn_k = 0 \qquad \text{(V–4)}$$

To maximize or minimize some function $f(x_i)$ of q variables $x_i (i = 1, \ldots, q)$ subject to the constraints that $g(x_i)$ and $h(x_i)$ are constant, we use the method of Lagrange undetermined multipliers.

We have

$$df = 0 \quad \text{(for extremal value of } f) \qquad \text{(V–5)}$$

$$dg = 0, dh = 0 \quad \text{(because } g \text{ and } h \text{ are constant)} \qquad \text{(V–6)}$$

Introducing two Lagrange undetermined multipliers α and β, we get

$$\sum_i \frac{\partial}{\partial x_i}[f(x_i) + \alpha g(x_i) + \beta h(x_i)]dx_i = 0$$

$$\frac{\partial}{\partial x_i}[f(x_i) + \alpha g(x_i) + \beta h(x_i)] = 0 \qquad \text{(V–7)}$$

for $i = 1, \ldots q$

$$g(x_i) = \text{const.} \quad h(x_i) = \text{const.} \qquad \text{(V–8)}$$

We thus get $(q + 2)$ equations in $(q + 2)$ unknowns of (x_i, α, β)

We apply this technique to our problem at hand. Instead of maximizing W_b, we maximize $\ln W_b$ instead because it makes the mathematics simpler. Since the log function increases monotonically with the argument, maximizing one is the same as maximizing the other.

$$\ln W_b = \sum_k [\ln(g_k)! - \ln(g_k - n_k)! - \ln(n_k)!] \qquad \text{(V–9)}$$

To simplify these terms, we use Stirling's approximation for factorials of large numbers. $\ln x! = x \ln x - x$ for large x.

$$\ln W_b = \sum_k [g_k \ln(g_k) - g_k - (g_k - n_k)\ln(g_k - n_k) + (g_k - n_k) - n_k \ln(n_k) + n_k]$$

$$= \sum_k [g_k \ln(g_k) - (g_k - n_k)\ln(g_k - n_k) - n_k \ln(n_k)] \qquad \text{(V–10)}$$

Now $dg_k = 0$ because these are system constraints. We then get

$$d(\ln W_b) = \sum_k \frac{\partial[\ln W_b]}{\partial n_k} dn_k = \sum_k \ln\left(\frac{g_k}{n_k} - 1\right) dn_k = 0 \qquad \text{(V–11)}$$

Also, from the two constraints we get

$$\sum_k dn_k = 0 \text{ and } \sum_k E_k dn_k = 0 \qquad \text{(V–12)}$$

Then,

$$\sum_k \left[\ln\left(\frac{g_k}{n_k} - 1\right) - \alpha - \beta E_k \right] dn_k = 0 \tag{V–13}$$

$$\ln\left(\frac{g_k}{n_k} - 1\right) - \alpha - \beta E_k = 0 \tag{V–14}$$

From this,

$$\frac{n_k}{g_k} = f(E_k) = \frac{1}{1 + e^{\alpha + \beta E_k}} \tag{V–15}$$

From basic thermodynamics, it can be shown that

$$\alpha = -\frac{E_F}{kT}, \quad \beta = \frac{1}{kT} \tag{V–16}$$

to get the Fermi–Dirac distribution function,

$$f(E_k) = \frac{1}{\exp\left[\dfrac{E_k - E_F}{kT}\right] + 1} \tag{V–17}$$

For the limit of high energies,

$$E \gg E_F, \quad f(E) \simeq \exp\frac{E_F - E}{kT}. \tag{V–18}$$

This is the classical Maxwell–Boltzmann limit of the Fermi–Dirac distribution function. Once we have the probabilities of electron occupancy, the probability of hole occupancy becomes

$$1 - f(E) = \frac{1}{\exp\dfrac{E_F - E}{kT} + 1} \tag{V–19}$$

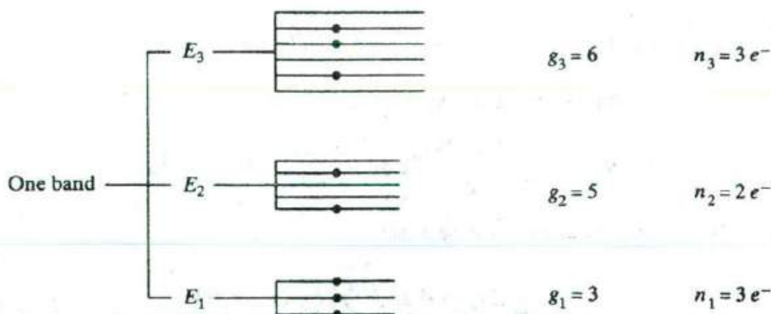
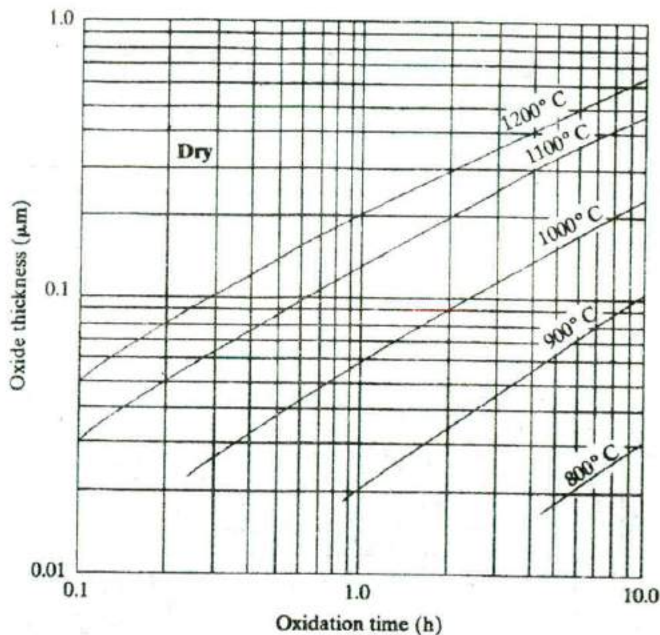


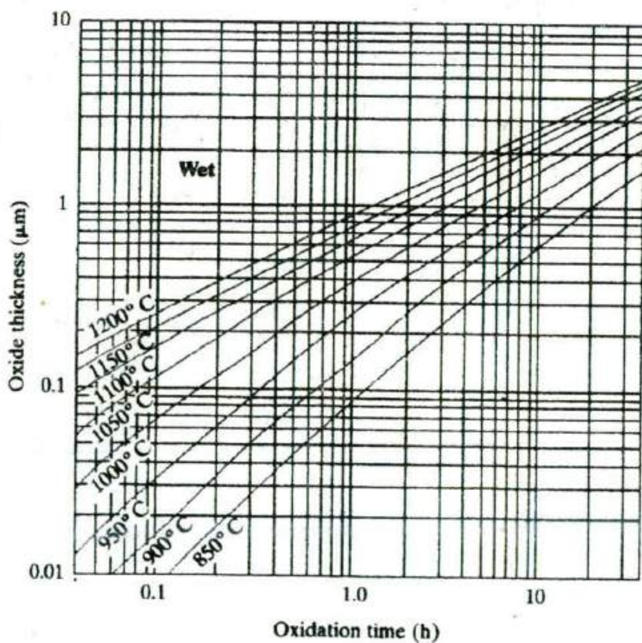
Figure V–1 Example showing three energy levels in a band, having different degeneracies, g, and electron occupancies, n, as shown.

Appendix VI

Dry and Wet Thermal Oxide Thickness Grown on Si (100) as a Function of Time and Temperature[1]

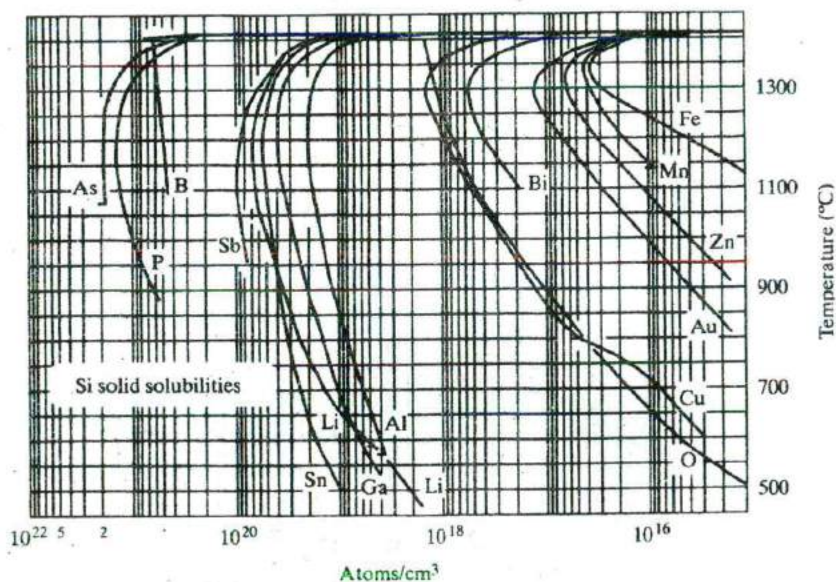
[1]From B. Deal. "The Oxidation of Silicon in Dry Oxygen, Wet Oxygen and Steam." *J. Electrochem. Soc.* 110 (1963): 527.


Dry
1200° C
1100° C
1000° C
900° C
800° C
Oxide thickness (μm)
1.0
0.1
0.01
0.1
1.0
10.0
Oxidation time (h)


Wet
1200° C
1150° C
1100° C
1050° C
1000° C
950° C
900° C
850° C
Oxide thickness (μm)
10
1
0.1
0.01
0.1
1.0
10
Oxidation time (h)

Appendix VII

Solid Solubilities of Impurities in Si[1]

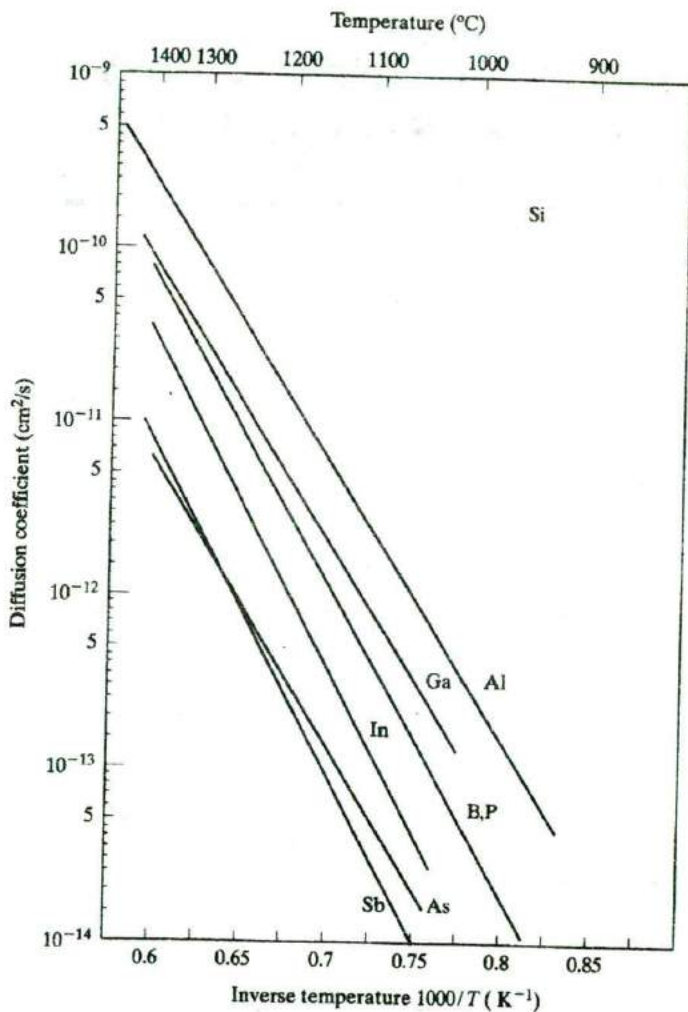


[1]From **F. A. Trumbore.** "Solid Solubilities of Impurity Elements in Si and Ge," *Bell System Technical Journal* 39, no. 1, pp. 205–233 (January 1960) copyright 1960, The American Telephone and Telegraph Co., reprinted by permission. Alterations have been made to include later data.

Appendix VIII
Diffusivities of Dopants in Si and SiO_2[1]

[1]Silicon diffusivity data from **C. S. Fuller and J. A. Ditzenberger.** "Diffusion of Donor and Acceptor Elements in Silicon." *J. Appl. Physics*, 27 (1956), 544.

SiO_2 diffusivity data from **M. Ghezzo and D. M. Brown.** "Diffusivity Summary of B, Ga, P, As and Sb in SiO_2," *J. Electrochem. Soc.* 120 (1973), 146.



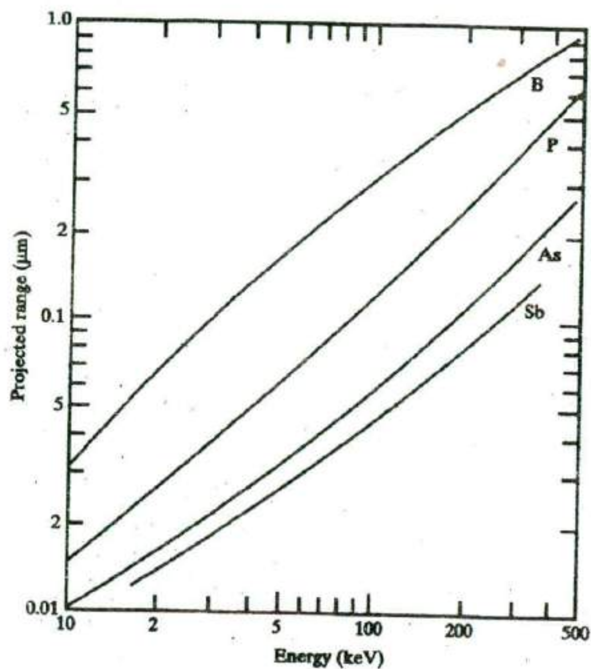
Diffusivity of various impurities in SiO_2		
Element	D_o(cm²/sec)	E_A(eV)
Boron	3×10^{-4}	3.53
Phosphorus	0.19	4.03
Arsenic	250	4.90
Antimony	1.31×10^{16}	8.75

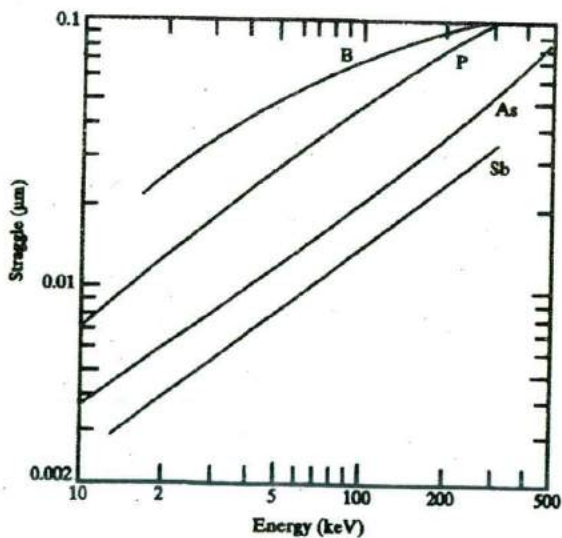
Appendix IX

Projected Range and Straggle as Function of Implant Energy in Si[1]

[1] From **J. F. Gibbons, W. S. Johnson and S. W. Mylroie.** *Projected Range Statistics: Semiconductors and Related Materials*. Stroudsburg: Dowden, Hutchison and Ross, 1975.

The projected ranges in SiO_2 are very close to those in Si.


1.0
5
2
0.1
5
2
0.01
B
P
As
Sb
Projected range (µm)
10
2
5
100
200
500
Energy (keV)


0.1
0.01
0.002
B
P
As
Sb
Straggle (µm)
10
2
5
100
200
500
Energy (keV)

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Boldfaced numbers refer to illustrations.

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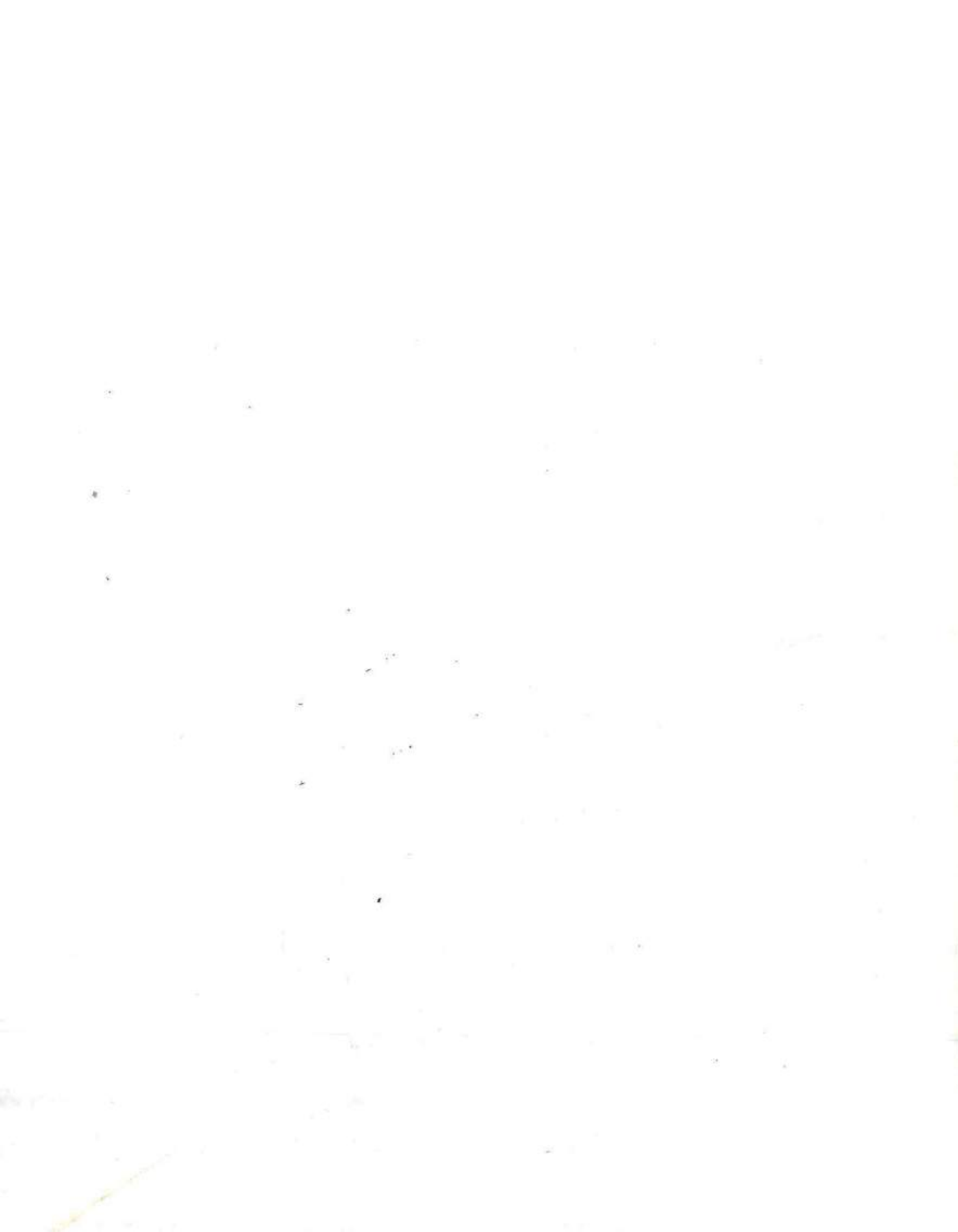

Junction Depletion: $C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$ (5–62)

Stored charge
exp. hole dist.: $Q_p = qA\int_0^\infty \delta p(x_n)dx_n = qA\Delta p_n\int_0^\infty e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$ (5–39)

$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}p_n(e^{qV/kT} - 1)$ (5–40)

$G_s = \frac{dI}{dV} = \frac{qAL_p p_n}{\tau_p}\frac{d}{dV}(e^{qV/kT}) = \frac{q}{kT}I$ (5–67c)

Long p$^+$-n: $i(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}$ (5–47)

MOS-n CHANNEL

Oxide: $C_i = \frac{\epsilon_i}{d}$ Depletion: $C_d = \frac{\epsilon_s}{W}$ MOS: $C = \frac{C_i C_d}{C_i + C_d}$ (6–36)

Threshold: $V_T = \underbrace{\Phi_{ms} - \frac{Q_i}{C_i}}_{\text{Flat band}} - \frac{Q_d}{C_i} + 2\phi_F$ (6–38)

Inversion: $\phi_s\,(\text{inv.}) = 2\phi_F = 2\frac{kT}{q}\ln\frac{N_a}{n_i}$ (6–15) $W = \left[\frac{2\epsilon_s\phi_s}{qN_a}\right]^{1/2}$ (6–30)

$Q_d = -qN_a W_m = -2(\epsilon_s q N_a \phi_F)^{1/2}$ (6–32) At V_{FB}: $C_{FB} = \frac{C_i\,C_{debye}}{C_i + C_{debye}}$

Debye screening length: $L_D = \sqrt{\frac{\epsilon_s kT}{q^2 p_0}}$ (6–25) $C_{debye} = \frac{\sqrt{2}\,\epsilon_s}{L_D}$ (6–40)

Substrate bias: $\Delta V_T \simeq \frac{\sqrt{2\epsilon_s q N_a}}{C_i}(-V_B)^{1/2}$ (n channel) (6–63)

$$I_D \simeq \frac{\bar{\mu}_n Z C_i}{L}\left[(V_G - V_T)V_D - \tfrac{1}{2}V_D^2\right] \quad (6\text{–}49)$$

Saturation: $I_D(\text{sat.}) \simeq \frac{1}{2}\bar{\mu}_n C_i \frac{Z}{L}(V_G - V_T)^2 = \frac{Z}{2L}\bar{\mu}_n C_i V_D^2(\text{sat.}) \quad (6\text{–}53)$

$$g_m = \frac{\partial I_D}{\partial V_G} \; ; \; g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} \simeq \frac{Z}{L}\bar{\mu}_n C_i (V_G - V_T) \quad (6\text{–}54)$$

For short L: $I_D \simeq Z C_i (V_G - V_T) v_s \quad (6\text{–}60)$

Subthreshold slope: $S = \frac{dV_G}{d(\log I_D)} = \frac{kT}{q}\ln 10\left[1 + \frac{C_d + C_{it}}{C_i}\right] \quad (6\text{–}66)$

BJT-p-n-p

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right) \quad (7\text{–}18) \qquad \begin{aligned}\Delta p_E &= p_n(e^{qV_{EB}/kT} - 1)\\ \Delta p_C &= p_n(e^{qV_{CB}/kT} - 1)\end{aligned} \quad (7\text{–}8)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right] \quad (7\text{–}19)$$

$$B = \frac{I_C}{I_{Ep}} = \frac{\operatorname{csch} W_b/L_p}{\operatorname{ctnh} W_b/L_p} = \operatorname{sech}\frac{W_b}{L_p} \simeq 1 - \left(\frac{W_b^2}{2L_p^2}\right) \quad (7\text{–}26)$$

(Base transport factor)

$$\gamma = \frac{I_{Ep}}{I_{En} + I_{Ep}} = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n}\tanh\frac{W_b}{L_p^n}\right]^{-1} \simeq \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1} \quad (7\text{–}25)$$

(Emitter injection efficiency)

$\frac{i_C}{i_E} = B\gamma \equiv \alpha \quad (7\text{–}3)$ (Common base gain)

$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta \quad (7\text{–}6)$ (Common emitter gain)

$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t} \quad (7\text{–}7)$ (For $\gamma = 1$)