QUICK REFERENCE MANUAL FOR SILICON INTEGRATED CIRCUIT TECHNOLOGY

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PREFACE

It has been our observation that workers in the semiconductor industry make extensive use of handy curves and graphs in their work. These design aids often represent data accumulated over several years of experience by an individual or a small group of associates. Often it takes the form of a set of curves or a clever nomograph. Unfortunately, despite the usefulness of such information, it usually has very limited circulation throughout the design community. This manual is a collection of such reference data, gleaned by the authors in their various roles in the design, development, processing, manufacture, and characterization of silicon devices and integrated circuits.

Topics include: properties of silicon, mathematical expressions, measurements, chemical recipes, diffusion, ion implantation, process data, conductivity of diffused layers, properties of p-n and metal-semiconductor junctions, surfaces, MOS, and reliability. A comprehensive table of the physical constants is also provided. Again, the manual emphasizes graphs, charts, nomographs, simple expressions, etc. designed to provide quick answers to questions. The intent is not to educate, explanations are at best terse, rather, the manual is intended to augment the designers basic knowledge with "quick" reference data.

The editors are indebted to the authors for providing their design tools and supplying their energies to this task. Special thanks are given to F. Cohen and D. D. Williams whose thorough work and infinite patience helped shape this large data base into a useful manual and R. T. Cronan for his skillful rendering of the information contained in the figures used throughout this manual. Finally we thank our management, R. L. Batdorf and J. Godfrey for their continuing support of this project.

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1. PHYSICAL CONSTANTS

TABLE 1-1

RECOMMENDED CONSISTENT VALUES OF THE FUNDAMENTAL CONSTANTS[1]

QUANTITY	SYMBOL	VALUE*	UNCERTAINTY (ppm)
Atomic mass unit	$u = (10^{-3}\ \text{kg mol}^{-1})/N_A$	$1.6605655(86) \times 10^{-27}$ kg	5.1
Avogadro's constant	N_A	$6.022045(31) \times 10^{23}\ \text{mol}^{-1}$	5.1
Bohr magneton	$\mu_B = e\hbar/2m_e$	$9.274078(36) \times 10^{-24}\ \text{J T}^{-1}$	3.9
Bohr radius	$a_0 = \alpha/4\pi R_\infty$	$0.52917706(44) \times 10^{-10}$ m	0.82
Boltzmann constant	$k = R/N_A$	$1.380662(44) \times 10^{-23}\ \text{J K}^{-1}$	32
Classical electron radius	$r_e = \mu_0 e^2/4\pi m_e$ $= \alpha \lambda\!\!\!^{-}_C$	$2.8179380(70) \times 10^{-15}$ m	2.5
Diamagnetic shielding factor, spherical H_2O sample	$1 + \sigma(H_2O)$	1.000025637(67)	0.067
Electron Compton wavelength	$\lambda_C = \alpha^2/2R_\infty$ $\lambda\!\!\!^{-}_C = \lambda_C/2\pi = \alpha a_0$	$2.4263089(40) \times 10^{-12}$ m $3.8615905(64) \times 10^{-13}$ m	1.6 1.6
Electron g-factor	$g_e/2 = \mu_e/\mu_B$	1.0011596567(35)	0.0035
Electron magnetic moment	μ_e	$9.284832(36) \times 10^{-24}\ \text{J T}^{-1}$	3.9
Electron rest mass	m_e	$0.9109534(47) \times 10^{-30}$ kg $5.4858026(21) \times 10^{-4}$ u	5.1 0.38
Elementary charge	e	$1.6021892(46) \times 10^{-19}$ C	2.9
Faraday constant	$F = N_A e$	$9.648456(27) \times 10^4\ \text{C mol}^{-1}$	2.8
Fine structure constant, $\mu_0 ce^2/2h$	α α^{-1}	0.0072973506(60) 137.03604(11)	0.82 0.82
Gas constant	R	$82.0568(26)\ \text{cm}^3\ \text{atm mol}^{-1}\ \text{K}^{-1}$ $1.98719(6)\ \text{cal mol}^{-1}\ \text{K}^{-1}$	31 31
Gravitational constant	G	$6.6720(41) \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2}$	615
Josephson frequency-voltage ratio	2e/h	$483.5939(13)\ \text{THz V}^{-1}$	2.6
Magnetic flux quantum	$\phi_0 = h/2e$ h/e	$2.0678506(54) \times 10^{-15}$ Wb $4.135701(11) \times 10^{-15}\ \text{J Hz}^{-1}\ \text{C}^{-1}$	2.6 2.6
Molar gas constant	R	$8.31441(26)\ \text{J mol}^{-1}\ \text{K}^{-1}$	31

* The digits in parentheses following a numerical value represent the standard deviation of that value in terms of the final listed digits. For definitions of the symbols shown in this column, see page 1-5.

TABLE 1-1 (Contd)

RECOMMENDED CONSISTENT VALUES OF THE FUNDAMENTAL CONSTANTS

QUANTITY	SYMBOL	VALUE*	UNCERTAINTY (ppm)
Molar standard volume, ideal gas (T_0 = 273.15 K, p_0 = 1 atm)	$V_m = RT_0/p_0$	0.02241383(70) $m^3\ mol^{-1}$	31
Muon g-factor	$g_\mu/2$	1.00116616(31)	0.31
Muon magnetic moment	μ_μ	4.490474(18) × 10^{-26} J T^{-1}	3.9
Muon rest mass	m_μ	1.883566(11) × 10^{-28} kg 0.11342920(26) u	5.6 2.3
Neutron Compton wavelength	$\lambda_{C,n} = h/m_n c$ $\lambda\!\!\!^{-}_{C,n} = \lambda_{C,n}/2\pi$	1.3195909(22) × 10^{-15} m 2.1001941(35) × 10^{-16} m	1.7 1.7
Neutron rest mass	m_n	1.6749543(86) × 10^{-27} kg 1.008665012(37) u	5.1 0.037
Nuclear magneton	$\mu_N = e\hbar/2m_p$	5.050824(20) × 10^{-27} J T^{-1}	3.9
Permeability of vacuum	μ_0	4π × 10^{-7} H m^{-1} = 12.5663706144 × 10^{-7} H m^{-1}	
Permittivity of vacuum	$\epsilon_0 = (\mu_0 C^2)^{-1}$	8.85418782(7) × 10^{-12} F m^{-1}	0.008
Planck's constant	h $\hbar = h/2\pi$	6.626176(36) × 10^{-34} J Hz^{-1} 1.0545887(57) × 10^{-34} J s	5.4 5.4
Proton Compton wavelength	$\lambda_{C,p} = h/m_p c$ $\lambda\!\!\!^{-}_{C,p} = \lambda_{C,p}/2\pi$	1.3214099(22) × 10^{-15} m 2.1030892(36) × 10^{-16} m	1.7 1.7
Proton gyromagnetic ratio	γ_p	2.6751987(75) × 10^8 s^{-1} T^{-1}	2.8
Proton gyromagnetic ratio (uncorrected)	γ'_p $\gamma'_p/2\pi$	2.6751301(75) × 10^8 s^{-1} T^{-1} 42.57602(12) MHz T^{-1}	2.8 2.8
Proton magnetic moment	μ_p	1.4106171(55) × 10^{-26} J T^{-1}	3.9
Proton magnetic moment in Bohr magnetons	μ_p/μ_B	1.521032209(16) × 10^{-3}	0.011
Proton moment in nuclear magnetons	μ_p/μ_N	2.7928456(11)	0.38

* The digits in parentheses following a numerical value represent the standard deviation of that value in terms of the final listed digits. For definitions of the symbols shown in this column, see page 1-5.

TABLE 1-1 (Contd)

RECOMMENDED CONSISTENT VALUES OF THE FUNDAMENTAL CONSTANTS

QUANTITY	SYMBOL	VALUE*	UNCERTAINTY (ppm)
Proton moment in nuclear magnetons (uncorrected)	μ'_p/μ_N	2.7927740(11)	0.38
Proton rest mass	m_p	$1.6726485(86) \times 10^{-27}$ kg 1.007276471(11) u	5.1 0.011
Quantum of circulation	$h/2m_e$ h/m_e	$3.6369455(60) \times 10^{-4}$ J Hz^{-1} kg^{-1} $7.273891(12) \times 10^{-4}$ J Hz^{-1} kg^{-1}	1.6 1.6
Radiation constant, first	$C_1 = 2\pi hc^2$	$3.741832(20) \times 10^{-16}$ W m^2	5.4
Radiation constant, second	$C_2 = hc/k$	0.01438786(45) m K	31
Ratio, electron to proton magnetic moments	μ_e/μ_p	658.2106880(66)	0.010
Ratio, muon mass to electron mass	m_μ/m_e	206.76865(47)	2.3
Ratio, muon moment to proton moment	μ_μ/μ_p	3.1833402(72)	2.3
Ratio, proton mass to electron mass	m_p/m_e	1836.15152(70)	0.38
Rydberg constant	R_∞	$1.097373177(83) \times 10^7$ m^{-1}	0.075
Second radiation constant	$C_2 = hc/k$	0.01438786(45) m K	31
Specific electron charge	e/m_e	$1.7588047(49) \times 10^{11}$ C kg^{-1}	2.8
Speed of light in vacuum	c	299792458(1.2) m s^{-1}	0.004
Stefan-Boltzmann constant	$\sigma = (\pi^2/60)\, k^4/\hbar^3 c^2$	$5.67032(71) \times 10^{-8}$ W m^{-2} K^{-4}	125

*The digits in parentheses following a numerical value represent the standard deviation of that value in terms of the final listed digits. For definitions of the symbols shown in this column, see below.

SYMBOL	UNIT	SYMBOL	UNIT	SYMBOL	UNIT
C	coulomb	K	kelvin	s	second
F	farad	kg	kilogram	T	tesla=webers/meter^2
H	henry	m	meter	V	volt
Hz	hertz	mol	mole (gram molecular wt)	W	watt
J	joule	N	newton	Wb	weber

TABLE 1-2

MISCELLANEOUS CONSTANTS

QUANTITY	VALUE
kT/q (300K)	0.0259 volt
(298K)	0.0257 volt
(293K)	0.0252 volt
(273K)	0.0235 volt
1 eV	$1.6021892(46) \times 10^{-19}$ J
1 eV/molecule	23.06 Kcal/mole
Voltage-wavelength product	12398.520(32) eV•Å
Thermochemical calorie	4.184 J

TABLE 1-3

LENGTH CONVERSION FACTORS

UNIT	QUANTITY IN EQUIVALENT UNITS					
	inch	mil	cm	mm	μm	Å
inch	1	10^3	2.54	25.4	2.54×10^4	2.54×10^8
mil	10^{-3}	1	2.54×10^{-3}	2.54×10^{-2}	25.4	2.54×10^5
cm	0.3937	3.937×10^2	1	10	10^4	10^8
mm	3.937×10^{-2}	39.37	0.1	1	10^3	10^7
μm	3.937×10^{-5}	3.937×10^{-2}	10^{-4}	10^{-3}	1	10^4
Å	3.937×10^{-9}	3.937×10^{-6}	10^{-8}	10^{-7}	10^{-4}	1

TABLE 1-4

PHYSICAL CONSTANTS OF Ge AND Si AT 300K[2] [3]

QUANTITY	Ge	Si
Atomic Weight	72.60	28.09
Atoms, Total (cm^{-3})	4.418×10^{22}	4.995×10^{22}
Boiling Point (°C)	2700	2600
Burger's Vector, b (Å)	—	3.74
Coefficient of Thermal Expansion	—	See Figure 2-35
Compliance ($cm^2 \cdot dyne^{-1}$) <111>		5.32×10^{-13} [4]
Crystal Structure	Diamond 8 atoms/unit cell	Diamond 8 atoms/unit cell
Density (ρ) (g/cm^3)	5.32	2.33
Density of Surface Atoms (cm^{-2})		
(100)	6.24×10^{14}	6.78×10^{14}
(110)	8.83×10^{14}	9.59×10^{14}
(111)	7.21×10^{14}	7.83×10^{14}
Dielectric Constant	16.0	11.8
Effective Density of States (see Section 2.01)		
Conduction Band, N_C (cm^{-3})	1.04×10^{19}	3.22×10^{19}
Valence Band, N_V (cm^{-3})	6.0×10^{18}	1.83×10^{19}
Elastic Constant ($dyne \cdot cm^{-2}$) [5]		
C_{11}	1.29×10^{12}	1.66×10^{12}
C_{12}	0.483×10^{12}	0.639×10^{12}
C_{44}	0.671×10^{12}	0.795×10^{12}
Electron Affinity (eV) (111)	—	4.85 (111) [6]
Electron-Effective Mass (at 4K) [7]		
Longitudinal: (m_l/m_o)	1.58	0.98
Transverse: (m_t/m_o)	0.082	0.19
*Density of States: (m^*/m_o)	0.55	1.08
Energy Gap (eV)	0.67	1.12

*See Figure 2-2.

TABLE 1-4 (Contd)

PHYSICAL CONSTANTS OF Ge AND Si AT 300K

QUANTITY	Ge	Si
Ground-State Degeneracy Factor g_D	—	2
g_A	—	4
Hole-Effective Mass (at 4K)		[8]
Heavy: (m_1/m_0)	0.28	0.537
Light: (m_2/m_0)	0.044	0.153
*Density of States: m^*/m_0	0.29	0.591
Intrinsic Carrier Concentration †		
n_i (cm^{-3})	2.4×10^{13}	1.38×10^{10}
$n_i^2 (cm^{-6})$	5.76×10^{26}	1.90×10^{20}
Intrinsic Debye Length $L = \left[\frac{kT\epsilon}{2q^2 n_i}\right]^{1/2}$ (μm)	0.69	28.7
$n_i L (cm)^{-2}$	1.65×10^9	4.0×10^7
Intrinsic Resistivity (ohm•cm)	47	2.3×10^5
Lattice Constant (Å)	5.66	5.43
Lattice Contraction Coefficient, $\beta (cm^3)$ [9]		
For Phosphorus in Lattice	—	7.2×10^{-25}
For Boron in Lattice	—	2.3×10^{-24}
Melting Point (°C)	937	1415
Poisson's Ratio, γ	—	0.27
Refractive Index	4.0	3.4
Scattering Limited Velocity $(cm \cdot s^{-1})$		See Figure 2-34
Electron	6.2×10^6	$\sim 1.0 \times 10^7$
Hole	5.7×10^6	$\sim 8.4 \times 10^6$
Shear Modulus, μ (dyne/cm^2)	—	7.55×10^{11}
Specific Heat, C_p [J/ (g • °C)]	0.31	0.7
Thermal Conductivity, K_{th} [w/(cm•°C)]	0.6	1.5[10] See Figure 2-43
Thermal Diffusivity $D_{th} = \frac{K_{th}}{\rho C_p} \left(\frac{cm^2}{sec}\right)$	0.36	0.9
[7] D_{th} (@ 400K)		0.52
(@ 600K)		0.29
(@ 800K)		0.19
(@ 1000K)		0.14
(@ 1200K)		0.12

*See Figure 2-3. †See Figure 2-4

TABLE 1-5

PHYSICAL CONSTANTS OF SiO_2, Si_3N_4, Si-O_x-N_y, AND SIPOS AT 300K

	SiO_2[2]	Si_3N_4	Si-O_x-N_y	SIPOS[11]
STRUCTURE	AMORPHOUS	AMORPHOUS	AMORPHOUS	AMORPHOUS
DC Resistivity ($\Omega \cdot cm$):				
@ 25°C	$10^{14} - 10^{16}$	$\sim 10^{14}$	—	$10^6 - 10^{14}$
@ 500°C	—	$\sim 2 \times 10^{13}$	—	
Density ($g \cdot cm^{-3}$)	2.27	3.1	—	2.2 — 2.33
Dielectric Constant	3.8 — 3.9	7.5	4.77 — 6.12	5.0 — 9.0
Dielectric Strength ($V \cdot cm^{-1}$)	$\sim 5 \times 10^6$	$\sim 1 \times 10^7$	$\sim 5 \times 10^6$	—
Energy Gap (eV)	~8	~5.0	—	—
Etch Rate in Buffered HF* (Å/min)	1000	5 — 10	33 — 400	~0
Infrared Absorption Band (μm)	9.3	11.5 — 12.0	9.3 and 12.0	9.0 — 12.0
Linear Expansion Coefficient ($°C^{-1}$)	5.0×10^{-7}	—	—	
Melting Point (°C)	~1700	—	—	
Molecular Weight	60.08			
Molecules/cm^3	2.3×10^{22}			
Refractive Index	1.46	2.05	1.60 — 1.88	2.0--3.6†
Specific Heat [$J/(g \cdot °C)$]	1.0			
Stress in the Film on Silicon (dyne/cm^2)	$2 - 4 \times 10^9$[12][13] compression	$9 - 10 \times 10^9$[14]		$1 - 6 \times 10^9$ both compression & tension
Thermal Conductivity [$W/(cm \cdot °C)$]	0.014	—	—	
Thermal Diffusivity (cm^2/s)	0.006			

* Buffered HF: 34.6% (wt.) NH_4F, 6.8% (wt.) HF, 58.6% H_2O.

† At 589 nm

TABLE 1-6

SIN FILM PROPERTIES FOR 50 kHz AND 13.56 MHz FROM A RADIAL FLOW PLASMA REACTOR[15]

	50 kHz	13.56 MHz
Deposition rate (Å/min)	130*	100
Film uniformity (%)	± 5	± 10
Refractive index	1.93	1.96 2.02
Refractive index uniformity (%)	0.1	1.5
Pinholes density (n/cm^2)	0.5	1.0
Etch Rate (BHF 10-1) (nm/min)	15	30
Stress (10^9 dynes/cm^2)	compressive 3	tensile 2
H content (at %)	18	24
Si/N ratio	.82	.93 — 1.0
Breakdown voltage (x 10^6 V/cm)	6	9

This figure was originally presented at the Spring 1983 Meeting of the Electrochemical Society, Inc., held in San Francisco, California.

TABLE 1-7

FREE ENERGY OF FORMATION OF METAL OXIDES AT 500K[16]

OXIDE	$-F^\circ$ (Kcal/mole)*	$-F^\circ$ [(Kcal/g • atom O)]
Al_2O_3	362.1	120.7
Cr_2O_3	240.2	80.1
MoO_2	114.5	57.2
Na_2O	83.0	83.0
NiO	46.1	46.1
SiO_2	187.9	94.0
Ta_2O_5	434.9	87.0
TiO	112.2	112.2
ZrO_2	238.4	119.2

*F°: free energy at the standard state

TABLE 1-8

PHYSICAL CONSTANTS OF SELECTED METALS[17]

METAL	ATOMIC NO.	ATOMIC WEIGHT	DENSITY P (20°C) (g/cm^3)	MELTING POINT (°C)	SPECIFIC HEAT Cp at 20°C [cal/(g•°C)]	COEF OF LINEAR THERMAL EXPANSION NEAR 20°C (10^{-6}/°C)	THERMAL CONDUCTIVITY (10°C) [cal/(cm•°C•s)]	RESISTIVITY (20°C) ($\mu\Omega$•cm)
Ag	47	107.88	10.49	960.8	0.0559 (0°C)	19.68 (0–100°C)	1.0 (0°C)	1.59
Al	13	26.98	2.699	660	0.215	23.6 (20–100°C)	0.53	2.6548
Au	79	197.0	19.32	1063	0.0312 (18°C)	14.2	0.71 (0°C)	2.35
Be	4	9.013	1.848	1277	0.45	11.6 (25–100°C)	0.35	4
Cr	24	52.01	7.19	1875	0.11	6.2	0.16	12.9 (0°C)
Cu	29	63.54	8.96	1083	0.092	16.5	0.941	1.673
Fe	26	55.85	7.87	1536.5	0.11	11.76 (25°C)	0.18 (0°C)	9.71
Ga	31	69.72	5.907	29.78	0.079	18 (0–30°C)	0.07–0.09 Melting	17.4($\vec{a}$); 8.1($\vec{b}$); 54.3($\vec{c}$)
In	49	114.82	7.31	156.2	0.057	33	0.057	8.37
Mo	42	95.95	10.22	2610	0.066	4.9 (20–100°C)	0.34	5.2 (0°C)
Ni	28	58.71	8.902 (25°C)	1453	0.105	13.3 (0–100°C)	0.22 (25°C)	6.84
Pb	82	207.21	11.36 (rolled)	327.4	0.0309 (0°C)	29.3 (17–100°C)	0.083 (0°C)	20.648
Pd	46	106.7	12.02	1552	0.0584 (0°C)	11.76	0.168 (18°C)	10.8
Pt	78	195.09	21.45	1769	0.0314 (0°C)	8.9	0.165	10.6
Rh	45	102.91	12.44	1966	0.059 (0°C)	8.3	0.21 (17°C)	4.51
Sn	50	118.70	7.2984 (β)	231.9	0.054	23(Poly, 0–100°C)	0.150 (0°C)	11 White Sn (0°C)
Ta	73	180.95	16.6	2996 ± 50	0.034 (25°C)	6.5	0.13	12.45 (25°C)
Ti	22	47.90	4.507	1668	0.124	8.41	0.037 (50°C)	42
W	74	183.86	19.3	3410	0.033	4.6	0.397 (0°C)	5.65 (27°C)
Zn	30	65.38	7.133 (25°C)	419.5	0.0915	39.7 (20–250°C)	0.27 (25°C)	5.916
Kovar[18]	—	—	8.36	1450	0.105 (0°C)	4.6–5.2	0.0395 (30°C)	49 (25°C)
					0.155 (300°C)	(30–400°C)	0.0485 (300°C)	62.7 (100°C)
							0.0585 (500°C)	

TABLE 1-9

EUTECTIC COMPOSITION AND EUTECTIC TEMPERATURE OF BINARY ALLOYS OF Ge AND Si

ELEMENT	Ge				Si			
	ATOM % OF Ge	WT % OF Ge	TEMP ° C	REF-PG	ATOM % OF Si	WT % OF Si	TEMP ° C	REF-PG
Ag	25.9	19.0	651	19 – 23	10.6	3.0	840	20 – 10
Al	30.3	53.0	424	21 – 38	12.3	12.7	577	21 – 55
As	19.0	18.0	723	19 – 166	59.5	35.5	1073	19 – 180
	—	—	—	—	10.0	4.0	786	19 – 180
Au	27.0	12.6	356	19 – 206	18.6	3.2	370	21 – 103
Bi	<0.1	<0.1	271	21 – 183	1×10^{-8}*	—	271	21 – 198
Ca	—	—	—	—	69.0	61.0	980	19 – 408
Cd	<0.1	<0.1	319	21 – 282	—	—	—	—
Ce	—	—	—	—	81.5	47.0	1240	19 – 461
Co	25.0	29.0	1110	19 – 476	23.0	12.5	1195	19 – 503
	73.0	77	810	19 – 476	77.5	62.0	1259	19 – 503
Cu	36.0	41.0	640	19 – 585	30.2	16.1	802	19 – 631
Fe	34.0	40.8	1130	20 – 327	34.0	20.5	1200	19 – 713
	~64.5	~70.3	845	20 – 327	67.0	50.5	1212	19 – 713
	75.5	80.0	859	20 – 327	73.5	58.0	1208	19 – 713
Ga	5×10^{-3}	—	29.8	21 – 446	1.2	0.5	19	21 – 457
In	0.05	—	157	21 – 478	2×10^{-8}	—	156	21 – 553
Mg	61.0	82.3	680	19 – 765	54.5	58.0	950	19 – 917
	1.15	3.4	635	19 – 765	1.16	1.34	638	19 – 917
Mn	52.5	59.4	697	19 – 767	~68.0	~50.0	1142	20 – 507
	—	—	—	—	21.0	12.0	1040	20 – 507
Ni	62.0	67.0	775	19 – 769	46.0	29.0	964	19 – 1040
Pb	0.02	—	207	21 – 485	5×10^{-8}	—	207	21 – 722
Pt	—	—	—	—	39.0	8.4	983	20 – 624
	—	—	—	—	23.0	4.2	830	20 – 624
Sb	17.0	11.0	590	19 – 773	0.3	7×10^{-4}	629.4	21 – 801
Sn	0.3	0.002	231	21 – 490	1×10^{-5}	—	231.9	21 – 818
Te	49.9	34.4	723	21 – 491	—	—	—	—
	15.0	9.0	375	19 – 776	—	—	—	—
Ti	13.4	19.0	1360	21 – 492	13.7	8.5	1330	19 – 1198
	—	—	—	—	86.0	78.0	1330	19 – 1198
Zn	4.5	5.0	398	21 – 496	—	—	—	—

*Calculated