Appendix

Table A.1 Chemical symbols for the elements

Ac	Actinium	Co	Cobalt	In	Indium	Os	Osmium	Sm	Samarium
Ag	Silver	Cr	Chromium	Ir	Iridium	P	Phosphorous	Sn	Tin
Al	Aluminum	Cs	Cesium	K	Potassium	Pa	Protactinium	Sr	Strontium
Am	Americium	Cu	Copper	Kr	Krypton	Pb	Lead	Ta	Tantalum
Ar	Argon	Dy	Dysprosium	La	Lanthanum	Pd	Palladium	Tb	Terbium
As	Arsenic	Er	Erbium	Li	Lithium	Pm	Promethium	Tc	Technetium
At	Astatine	Es	Einsteinium	Lr	Lawrencium	Po	Polonium	Te	Tellurium
Au	Gold	Eu	Europium	Lu	Lutetium	Pr	Praseodymium	Th	Thorium
B	Boron	F	Fluorine	Md	Mendelevium	Pt	Platinum	Ti	Titanium
Ba	Barium	Fe	Iron	Mg	Magnesium	Pu	Plutonium	Tl	Thallium
Be	Beryllium	Fm	Fermium	Mn	Manganese	Ra	Radium	Tm	Thulium
Bi	Bismuth	Fr	Francium	Mo	Molybdenum	Rb	Rubidium	U	Uranium
Bk	Berkelium	Ga	Gallium	N	Nitrogen	Re	Rhenium	V	Vanadium
Br	Bromine	Gd	Gadolinium	Na	Sodium	Rh	Rhodium	W	Tungsten
C	Carbon	Ge	Germanium	Nb	Niobium	Rn	Radon	Xe	Xenon
Ca	Calcium	H	Hydrogen	Nd	Neodymium	Ru	Ruthenium	Y	Yttrium
Cd	Cadmium	He	Helium	Ne	Neon	S	Sulfur	Yb	Ytterbium
Ce	Cerium	Hf	Hafnium	Ni	Nickel	Sb	Antimony	Zn	Zinc
Cf	Californium	Hg	Mercury	No	Nobelium	Sc	Scandium	Zr	Zirconium
Cl	Chlorine	Ho	Holmium	Np	Neptunium	Se	Selenium		
Cm	Curium	I	Iodine	O	Oxygen	Si	Silicon		

Table A.2 SI multiples

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deka	da	10^{-18}	atto	a

Table A.3 Derivative SI units

Quantity	Name of unit	Expression in terms of basic units
Area	square meter	m^2
Volume	cubic meter	m^3
Frequency	hertz (Hz)	s^{-1}
Density (concentration)	kilogram per cubic meter	kg/m^3
Velocity	meter per second	m/s
Angular velocity	radian per second	rad/s
Acceleration	meter per second squared	m/s^2
Angular acceleration	radian per second squared	rad/s^2
Volumetric flow rate	cubic meter per second	m^3/s
Force	newton (N)	$kg\ m/s^2$
Pressure	newton per square meter (N/m^2) or pascal (Pa)	$kg/m\ s^2$
Work energy heat torque	joule (J), newton-meter (N m) or watt-second (W s)	$kg\ m^2/s^2$
Power heat flux	watt (W) Joule per second (J/s)	$kg\ m^2/s^3$
Heat flux density	watt per square meter (W/m^2)	kg/s^3
Specific heat	joule per kilogram degree (J/kg deg)	m^2/s^2 deg
Thermal conductivity	watt per meter degree (W/m deg) or (J m/s m^2 deg)	$kg\ m/s^3$ deg
Mass flow rate (mass flux)	kilogram per second	kg/s
Mass flux density	kilogram per square meter-second	$kg/m^2\ s$
Electric charge	coulomb (C)	A s
Electromotive force	volt (V) or (W/A)	$kg\ m^2/A\ s^3$
Electric resistance	ohm (Ω) or (V/A)	$kg\ m^2/A^2\ s^3$
Electric conductivity	ampere per volt-meter (A/V m)	$A^2s^3/kg\ m^3$
Electric capacitance	farad (F) or (A s/V)	$A^3\ s^4/kg\ m^2$
Magnetic flux	weber (Wb) or (V s)	$kg\ m^2/A\ s^2$
Inductance	henry (H) or (Vs/A)	$kg\ m^2/A^2\ s^2$
Magnetic permeability	henry per meter (H/m)	$kg\ m/A^2\ s^2$
Magnetic flux density	tesla (T) or weber per square meter (Wb/m^2)	$kg/A\ s^2$
Magnetic field strength	ampere per meter	A/m
Magnetomotive force	ampere	A
Luminous flux	lumen (lm)	cd sr
Luminance	candela per square meter	cd/m^2
Illumination	lux (lx) or lumen per square meter (lm/m^2)	$cd\ sr/m^2$

Tables A.4 SI conversion multiples (to make a conversion to SI, a non-SI value should be multiplied by a number given in the table)

Acceleration: (m/s^2)			
Ft/s^2	0.3048	gal	0.01
free fall (g)	9.80665	in/s^2	0.0254
Angle: radian (rad)			
degree	0.01745329	second	4.848137×10^{-6}
minute	2.908882×10^{-4}	grade	1.570796×10^{-2}
Area: (m^2)			
acre	4,046.873	hectare	1×10^4
are	100.00	mi^2 (US statute)	2.589998×10^6
ft^2	9.290304×10^{-2}	yd^2	0.8361274

(*continued*)

Tables A.4 (continued)

Bending moment or torque: (N m)			
dyne cm	1×10^{-7}	lbf in	0.1129848
kgf m	9.806650	lbf ft	1.355818
ozf in	7.061552×10^{-3}		
Electricity and Magnetism[a]			
ampere hour	3,600 coulomb (C)	EMU of inductance	8.987×10^{11} henry (H)
EMU of capacitance	10^{9} farad (F)	EMU of resistance	8.987×10^{11} (Ω)
EMU of current	10 ampere (A)	faraday	9.65×10^{19} coulomb (C)
EMU of elec. potential	10^{-8} volt (V)	gamma	10^{-9} tesla (T)
EMU of inductance	10^{-9} henry (H)	gauss	10^{-4} tesla (T)
EMU of resistance	10^{-9} ohm (Ω)	gilbert	0.7957 ampere (A)
ESU of capacitance	1.112×10^{-12} farad (F)	maxwell	10^{-8} weber (Wb)
ESU of current	3.336×10^{-10} ampere (A)	mho	1.0 siemens (S)
EMU of elec. potential	299.79 volt (V)	ohm centimeter	0.01 ohm meter (Ω m)
Energy (work): joule (J)			
British thermal unit (Btu)	1,055	kilocalorie	4,187
calorie	4.18	kW h	3.6×10^{6}
calorie (kilogram)	4,184	ton (nuclear equiv. TNT)	4.184×10^{9}
electronvolt	1.60219×10^{-19}	therm	1.055×10^{8}
erg	10^{-7}	W h	3,600
ft lbf	1.355818	W s	1.0
ft-poundal	0.04214		
Force: newton (N)			
dyne	10^{-5}	ounce-force	0.278
kilogram-force	9.806	pound-force (lbf)	4.448
kilopond (kp)	9.806	poundal	0.1382
kip (1,000 lbf)	4,448	ton-force (2,000 lbf)	8,896
Heat			
Btu ft/(h ft2 °F) (thermal conductivity)	1.7307 W/(m K)	cal/cm^2	4.18×10^{4} J/m^2
Btu/lb	2,324 J/kg	cal/(cm^2 min)	697.3 W/m^2
Btu/(lb °F) = cal/(g °C) (heat capacity)	4,186 J/(kg K)	cal/s	4.184 W
Btu/ft^3	3.725×10^{4} J/m^3	°F h ft^2/Btu (thermal resistance)	0.176 K m^2/W
cal/(cm s °C)	418.4 W/(m K)	ft^2/h (thermal diffusivity)	2.58×10^{-5} m^2/s
Length: meter (m)			
angstrom	10^{-10}	microinch	2.54×10^{-8}
astronomical unit	1.495979×10^{11}	micrometer (micron)	10^{-6}
chain	20.11	mil	2.54×10^{-5}
fermi (femtometer)	10^{-15}	mile (nautical)	1,852.000
foot	0.3048	mile (international)	1,609.344

(*continued*)

Tables A.4 (continued)

inch	0.0254	pica (printer's)	4.217×10^{-3}
light year	9.46055×10^{15}	yard	0.9144
Light			
cd/in^2	1,550 cd/m^2	lambert	3.183×10^3 cd/m^2
footcandle	10.76 lx (lux)	lm/ft^2	10.76 lm/m^2
footlambert	3.426 cd/m^2		
Mass: kilogram (kg)			
carat (metric)	2×10^{-4}	ounce (troy or apothecary)	3.110348×10^{-2}
grain	6.479891×10^{-5}	pennyweight	1.555×10^{-3}
gram	0.001	pound (lb avoirdupois)	0.4535924
hundredweight (long)	50.802	pound (troy or apothecary)	0.3732
hundredweight (short)	45.359	slug	14.5939
kgf s^2/m	9.806650	ton (long, 2,240 lb)	907.184
ounce (avoirdupois)	2.834952×10^{-2}	ton (metric)	1,000
Mass: per unit time (includes Flow)			
perm (0°C)	5.721×10^{-11} kg/(Pa s m^2)	lb/(hp h) SPC – specific fuel consumption	1.689659×10^{-7} kg/J
lb/h	1.2599×10^{-4} kg/s	ton (short)/h	0.25199 kg/s
lb/s	0.4535924 kg/s		
Mass per unit volume (includes Density and Capacity): (kg/m^3)			
oz (avoirdupois)/gal (UK liquid)	6.236	oz (avoirdupois)/gal (US liquid)	7.489
oz (avoirdupois)/in^3	1,729.99	slug/ft^3	515.3788
lb/gal (US liquid)	11.9826 kg/m^3	ton (long)/yd^3	1,328.939
Power: watt (W)			
Btu (International)/s	1,055.056	horsepower (electric)	746
cal/s	4.184	horsepower (metric)	735.499
erg/s	10^{-7}	horsepower (UK)	745.7
horsepower (550 ft lbf/s)	745.6999	ton of refrigeration (12,000 Btu/h)	3,517
Pressure or Stress: pascal (Pa)			
atmosphere, standard	1.01325×10^5	dyne/cm^2	0.1
atmosphere, technical	9.80665×10^4	foot of water (39.2°F)	2,988.98
bar	10^5	poundal/ft^2	1.488164
centimeter of mercury (0°C)	1,333.22	psi (lbf/in^2)	6,894.757
centimeter of water (4°C)	98.0638	torr (mmHg, 0°C)	133.322
Radiation units			
curie	3.7×10^{10} becquerel (Bq)	rem	0.01 sievert (Sv)
rad	0.01 gray (Gy)	roentgen	2.58×10^{-4} C/kg
Temperature			
°Celsius	TK = t°C + 273.15 K	°Fahrenheit	T°C = (t°F − 32)/1.8°C
°Fahrenheit	TK = (t°F + 459.67)/1.8 K	°Rankine	TK = T°R/1.8

(*continued*)

Tables A.4 (continued)

Velocity (includes Speed): (m/s)			
ft/s	0.3048	mi/h (International)	0.44704
in/s	2.54×10^{-2}	rpm (r/min)	0.1047 rad/s
knot (International)	0.51444		
Viscosity: (Pa s)			
centipose (dynamic viscosity)	10^{-3}	lbf s/in^2	6,894.757
centistokes (kinematic viscosity)	10^{-6}	rhe	10 1/(Pa s)
poise	0.1	slug/(ft s)	47.88026
poundal s/ft^2	1.488164	stokes	10^{-4} m^2/s
lb/(ft s)	1.488164		
Volume (includes Capacity): (m^3)			
acre-foot	1,233.489	gill (U.S.)	1.182941×10^{-4}
barrel (oil, 42 gal)	0.1589873	in^3	1.638706×10^{-5}
bushel (U.S.)	3.5239×10^{-2}	liter	10^{-3}
cup	2.36588×10^{-4}	ounce (U.S. fluid)	2.957353×10^{-5}
ounce (U.S. fluid)	2.95735×10^{-5}	pint (U.S. dry)	5.506105×10^{-4}
ft^3	2.83168×10^{-2}	pint (U.S. liquid)	4.731765×10^{-4}
gallon (Canadian, U.K. liquid)	4.54609×10^{-3}	tablespoon	1.478×10^{-5}
gallon (U.S. liquid)	3.7854×10^{-3}	ton (register)	2.831658
gallon (U.S. dry)	4.40488×10^{-3}	yd^3	0.76455

[a]ESU means electrostatic cgs unit; EMU means electromagnetic cgs unit

Table A.5 Dielectric constants of some materials at room temperature (25°C)

Material	κ	Frequency (Hz)	Material	κ	Frequency (Hz)
Air	1.00054	0	Paraffin	2.0–2.5	10^6
Alumina ceramic	8–10	10^4	Plexiglas	3.12	10^3
Acrylics	2.5–2.9	10^4	Polyether sulfone	3.5	10^4
ABS/Polysulfone	3.1	10^4	Polyesters	3.22–4.3	10^3
Asphalt	2.68	10^6	Polyethylene	2.26	10^3–10^8
Beeswax	2.9	10^6	Polypropylenes	2–3.2	10^4
Benzene	2.28	0	Polyvinyl chloride	4.55	10^3
Carbon tetrachloride	2.23	0	Porcelain	6.5	0
Cellulose nitrate	8.4	10^3	Pyrex glass (7070)	4.0	10^6
Ceramic (titanium dioxide)	14–110	10^6	Pyrex glass (7760)	4.5	0
Cordierite	4–6.23	10^4	Rubber (neoprene)	6.6	10^3
Compound for thick film capacitors	300–5,000	0	Rubber (silicone)	3.2	10^3
Diamond	5.5	10^8	Rutile ⊥ optic axis	86	10^8
Epoxy resins	2.8–5.2	10^4	Rutile ‖ optic axis	170	10^8
Ferrous oxide	14.2	10^8	Silicone resins	3.4–4.3	10^4
Flesh (skin, blood, muscles)	97	40×10^6	Tallium chloride	46.9	10^8
Flesh (fat, bones)	15	40×10^6	Teflon	2.04	10^3–10^8
Lead nitrate	37.7	6×10^7	Transformer oil	4.5	0
Methanol	32.63	0	Vacuum	1	–
Nylon	3.5–5.4	10^3	Water	78.5	0
Paper	3.5	0			

Table A.6 Properties of magnetic materials (adapted from Sprague, CN-207 Hall effect IC applications, 1986)

Material	MEP (G Oe) 10^6	Residual induction (G) 10^3	Coercive force (Oe) 10^3	Temperature coefficient %/°C	Cost
R.E.-Cobalt	16	8.1	7.9	−0.05	Highest
Alnico 1,2,3,4	1.3–1.7	5.5–7.5	0.42–0.72	−0.02 to −0.03	Medium
Alnico 5,6,7	4.0–7.5	10.5–13.5	0.64–0.78	−0.02 to −0.03	Medium/high
Alnico 8	5.0–6.0	7–9.2	1.5–1.9	−0.01 to 0.01	Medium/high
Alnico 9	10	10.5	1.6	−0.02	high
Ceramic 1	1.0	2.2	1.8	−0.2	low
Ceramic 2,3,4,6	1.8–2.6	2.9–3.3	2.3–2.8	−0.2	low/medium
Ceramic 5,7,8	2.8–3.5	3.5–3.8	2.5–3.3	−0.2	Medium
Cunife	1.4	5.5	0.53	–	Medium
Fe-Cr	5.25	13.5	0.6	–	Medium/high
Plastic	0.2–1.2	1.4	0.45–1.4	−0.2	Lowest
Rubber	0.35–1.1	1.3–2.3	1–1.8	−0.2	Lowest

Table A.7 Resistivities (ρ) $10^{-8}\Omega{\cdot}m$ ((at room temperature) and temperature coefficients of resistivity (TCR) 10^{-3}/°K of some materials at room temperature)

Material	ρ	TCR (α)	Material	ρ	TCR (α)
Alumina[a]	$>10^{20}$		Palladium	10.54	3.7
Aluminum (99.99%)	2.65	3.9	Platinum	10.42	3.7
Beryllium	4.0	0.025	Platinum + 10% Rhodium	18.2	
Bismuth	10^6		Polycrystalline glass[a]	6.3×10^{14}	
Brass (70Cu, 30Zn)	7.2	2.0	Rare earth metals	28–300	
Carbon	3,500	–0.5	Silicon (very sensitive to purity)	$(3.4 \text{ to } 15)\times10^6$	
Chromium plating	14–66		Silicon bronze (96Cu, 3Si, 1Zn)	21.0	
Constantan (60Cu, 40Ni)	52.5	0.01	Silicon nitride	10^{19}	
Copper	1.678	3.9	Silver	1.6	6.1
Evanohm (75Ni, 20Cr, 2.5Al, 2.5Cu)	134		Sodium	4.75	
Germanium (polycrystalline)	46×10^6		Stainless steel (cast)	70–122	
Gold	2.24	3.4	Tantalum	12.45	3.8
Iridium	5.3		Tantalum carbide	20	
Iron (99.99%)	9.71	6.5	Tin	11.0	4.7
Lead	22	3.36	Titanium	42	
Manganese	185		Titanium and its alloys	48–199	
Manganin	44	0.01	Titanium carbides	105	
Manganin (84Cu, 12Mn, 4Ni)	48		Tungsten	5.6	4.5
Mercury	96	0.89	Zinc	5.9	4.2
Mullite[a]	10^{21}		Zircon[a]	$>10^{20}$	
Nichrome	100	0.4	Zirconium and its alloys	40–74	
Nickel	6.8	6.9			

[a]Volume resistivity

Table A.8 Properties of piezoelectric materials at 20°C

	PVDF	$BaTiO_3$	PZT	Quartz	TGS
Density ($\times 10^3$ kg/m^3)	1.78	5.7	7.5	2.65	1.69
Dielectric constant, ε_r	12	1,700	1,200	4.5	45
Elastic modulus (10^{10} N/m)	0.3	11	8.3	7.7	3
Piezoelectric constant (pC/N)	$d_{31} = 20$ $d_{32} = 2$ $d_{33} = -30$	78	110	2.3	25
Pyroelectric constant (10^{-4} C/m^{2}K)	4	20	27	–	30
Electromechanical coupling constant (%)	11	21	30	10	–
Acoustic impedance (10^6 kg/m^{2}s)	2.3	25	25	14.3	–

Table A.9 Physical properties of pyroelectric materials (from Meixner H, Mader G, and Kleinschmidt P (1986) Infrared sensors based on the pyroelectric polymer polyvinylidene fluoride (PVDF). Siemens Forsch-u Entwicl Ber Bd 15(3):105–114)

Material	Curie temperature (°C)	Thermal conductivity (W/(mK))	Relative permitivity (ε_r)	Pyroelectric charge coef. (C/(m^{2}K))	Pyroelectric voltage coef. (V/(mK))	Coupling (k_p^2 (%))
Single crystals						
TGS	49	0.4	30	3.5×10^{-4}	1.3×10^6	7.5
$LiTa0_3$	618	4.2	45	2.0×10^{-4}	0.5×10^6	1.0
Ceramics						
$BaTiO_3$	120	3.0	1,000	4.0×10^{-4}	0.05×10^6	0.2
PZT	340	1.2	1,600	4.2×10^{-4}	0.03×10^6	0.14
Polymers						
PVDF	205	0.13	12	0.4×10^{-4}	0.40×10^6	0.2
Polycrystalline layers						
$PbTiO_3$	470	2 (monocrystal)	200	2.3×10^{-4}	0.13×10^6	0.39

Note: The above figures may vary depending on manufacturing technologies

Table A.10 Characteristics of thermocouple types

Junction materials	Sensitivity μV/°C (@ 25°C)	Temperature range (°C)	Applications	Designation
Copper/Constantan	40.9	−270 to +600	Oxidation, reducing, inert, vacuum. Preferred below 0°C. Moisture resistant	T
Iron/Constantan	51.7	−270 to +1,000	Reducing and inert atmosphere. Avoid oxidation and moisture	J
Chromel/Alumel	40.6	−270 to 1,300	Oxidation and inert atmospheres	K
Chromel/Constantan	60.9	−200 to 1,000		E

(*continued*)

Table A.10 (continued)

Junction materials	Sensitivity μV/°C (@ 25°C)	Temperature range (°C)	Applications	Designation
Pt (10%)/Rh-Pt	6.0	0–1,550	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	S
Pt (13%)/Rh-Pt	6.0	0–1,600	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	R
Slver-Paladium	10.0	200–600		
Constantan-Tungsten	42.1	0–800		
Silicon-Aluminum	446	−40 to 150	Used in thermopiles and micromachined sensors	

Table A.11 Thermoelectric coefficients and volume resistivities of selected elements (adapted from Schieferdecker J et al (1995) Infrared thermopile sensors with high sensitivity and very low temperature coefficient. Sens Actuators A 46–47:422–427)

Element	α (μV K^{-1})	ρ (μΩ m)
p-Si	100–1,000	10–500
p-Poly-Si	100–500	10–1,000
Antimony (Sb)	32	18.5
Iron (Fe)	13.4	0.086
Gold (Au)	0.1	0.023
Copper (Cu)	0	0.0172
Silver (Ag)	−0.2	0.016
Aluminum (Al)	−3.2	0.028
Platinum (Pt)	−5.9	0.0981
Cobalt (Co)	−20.1	0.0557
Nickel (Ni)	−20.4	0.0614
Bismuth (Bi)	−72.8	1.1
n-Si	−100 to −1,000	10–500
n-Poly-Si	−100 to −500	10–1,000

Table A.11a Thermocouples for very low and very high temperatures

Materials	Useful range °C	Approx sensitivity μV/°C
Iron-Constantan	down to −272	−32
Copper-Constantan	down to −273	−22.9
Cromel-Alumel	down to –272	−23.8
Tantalum-Tungsten	up to 3,000	6.1
Tangsten-Tangsten(50)Molybdenum	up to 2,900	2.8
Tangsten-Tangsten(20)Rhenium	up to 2,900	12.7

Table A.12 Densities (kg/m^3) of some materials at 1atm pressure and 0°C

Best laboratory vacuum	10^{-17}	Silica	1,938–2,657
Hydrogen	0.0899	Graphite recrystallized	1,938
Helium	0.1785	Borosilicate glass (TEMPAX®)[a]	2,200
Methane	0.7168	Asbestos fibers	2,400–3,300
Carbon monoxide	1.250	Silicon	2,333
Air	1.2928	Polycrystalline glass	2,518–2,600
Oxygen	1.4290	Aluminum	2,700
Carbon dioxide	1.9768	Mullite	2,989–3,293
Plastic foams	10–600	Silicon nitride	3,183
Benzene	680–740	Alumina ceramic	3,322–3,875
Alcohol	789.5	Zinc alloys	5,200–7,170
Turpentine	860	Vanadium	6,117
Mineral oil	900–930	Chromium	7,169
Natural rubber	913	Tin and its alloys	7,252–8,000
Polyethylene, low density	913	Stainless steel	8,138
Ice	920	Bronzes	8,885
Polyethylene, high density	950	Copper	8,941
Carbon and graphite fibers	996–2,000	Cobalt and its alloys	9,217
Water	1,000	Nickel and its alloys	9,245
Nylon 6	1,100	Bismuth	9,799
Hydrochloric acid (20%)	1,100	Silver	10,491
Acrylics	1,163–1,190	Lead and its alloys	11,349
Epoxies	1,135–2,187	Palladium	12,013
Coal tar	1,200	Mercury	13,596
Phenolic	1,246–2,989	Molybdenum	13,729
Glycerin	1,260	Tantalum and its alloys	16,968
PVC	1,350	Gold	19,320
Saran fibers	1,700	Tungsten and its alloys	19,653
Sulfuric acid (20%)	1,700	Platinum	21,452
Polyester	1,800	Iridium	22,504
Beryllium and its alloys	1,855–2,076	Osmium	22,697

[a]TEMPAX® is a registered trademark of Schott Glasswerke, Mainz, Germany

Table A.13 Mechanical properties of some solid materials

Material	Modulus of elasticity (GPa)	Poisson's ratio (ν)	density (kg/m^3)
Aluminum	71	0.334	2,700
Beryllium copper	124	0.285	8,220
Brass	106	0.324	8,530
Copper	119	0.326	8,900
Glass	46.2	0.245	2,590
Lead	36.5	0.425	11,380
Molybdenum	331	0.307	10,200
Phosphor bronze	11	0.349	8,180
Steel (Carbon)	207	0.292	7,800
Steel (Stainless)	190	0.305	7,750

Table A.14 Mechanical properties of some crystalline materials (from Petersen KE (1982) Silicon as a mechanical material. Proc IEEE 70(5):420–457)

Material	Yield strength (10^{10} dyne/cm^2)	Knoop hardness (kg/mm^2)	Young's modulus (10^{12} dyne/cm^2)	Density (g/cm^3)	Thermal conductivity (W/cm°C)	Thermal expansion (10^{-6}/°C)
Diamond[a]	53	7,000	10.35	3.5	20.0	1.0
SiC[a]	21	2,480	7.0	3.2	3.5	3.3
TiC[a]	20	2,470	4.97	4.9	3.3	6.4
Al_2O_3[a]	15.4	2,100	5.3	4.0	0.5	5.4
Si_3N_4[a]	14	3,486	3.85	3.1	0.19	0.8
Iron[a]	12.6	400	1.96	7.8	0.803	12.0
SiO_2 (fibers)	8.4	820	0.73	2.5	0.014	0.55
Si[a]	7.0	850	1.9	2.3	1.57	2.33
Steel (max. strength)	4.2	1,500	2.1	7.9	0.97	12.0
W	4.0	485	4.1	19.3	1.78	4.5
Stainless Steel	2.1	660	2.0	7.9	0.329	17.3
Mo	2.1	275	3.43	10.3	1.38	5.0
Al	0.17	130	0.70	2.7	2.36	25.0

[a]Single crystal

Table A.15 Speed of sound waves

Medium	Speed (m/s)
Air (dry at 20°C)	331
Steam (134°C)	494
Hydrogen (20°C)	1,330
Water (fresh)	1,486
Water (sea)	1,519
Lead	1,190
Copper	3,810
Aluminum	6,320
Pyrex® glass	5,170
Steel	5,200
Beryllium	12,900

Gases at 1 atm pressure, solids in long thin rods

Table A.16 Coefficient (α) of linear thermal expansion of some materials (per $°C \times 10^{-6}$)

Material	α	Material	α
Alnico I (Permanent magnet)	12.6	Nylon	90
Alumina (polycrystalline)	8.0	Phosphor-bronze	9.3
Aluminum	25.0	Platinum	9.0
Brass	20.0	Plexiglas (Lucite)	72
Cadmium	30.0	Polycarbonate (ABS)	70
Chromium	6.0	Polyethylene (high density)	216
Comol (Permanent magnet)	9.3	Silicon	2.6
Copper	16.6	Silver	19.0

(*continued*)

Table A.16 (continued)

Material	α	Material	α
Fused quartz	0.27	Solder 50–50	23.6
Glass (Pyrex®)	3.2	Steel (SAE 1020)	12.0
Glass (regular)	9.0	Steel (stainless: type 304)	17.2
Gold	14.2	Teflon	99
Indium	18.0	Tin	13.0
Invar	0.7	Titanium	6.5
Iron	12.0	Tungsten	4.5
Lead	29.0	Zinc	35.0
Nickel	11.8		

Table A.17 Specific heat and thermal conductivity of some materials (at 25°C)

Material	Specific heat $\left(\frac{J}{kg\,°C}\right)$	Thermal conductivity $\left(\frac{W}{m\,°C}\right)$	Density $\left(\frac{kg}{m^3}\right)$
Air (1 atm)	995.8	0.024	1.2
Alumina	795	6	4,000
Aluminum	481	88–160	2,700
Bakelite	1,598	0.23	1,300
Brass	381	26–234	8,500
Chromium	460	91	
Constantan	397	22	8,800
Copper	385	401	8,900
Diamond		99–232	
Fiberglass	795	0.002–0.4	60
Germanium		60	
Glass (Pyrex)	780	0.1	2,200
Glass (regular)		1.9–3.4	
Gold	130	296	19,300
Graphite		112–160	
Iron	452	79	7,800
Lead	130	35	11,400
Manganin	410	21	8,500
Mercury	138	8.4	13,500
Nickel and its alloys	443	6–50	8,900
Nylon	1,700	0.24	1,100
Platinum	134	73	21,400
Polyester	1,172	0.57–0.73	1,300
Polyurethane foam		0.024	40
Silicon	668	83.7	2,333
Silicone oil	1,674	0.1	900
Silver	238	419	10,500
Stainless steel	460	14–36	8,020
Styrofoam	1,300	0.003–0.03	50
Teflon TFE	998	0.4	2,100
Tin	226	64	7,300
Tungsten	139	96.6	19,000
Water	4,184	0.6	1,000
Zinc	389	115–125	7,100

Table A.18 Typical emissivities of different materials (from 0 to 100°C)

Material	Emissivity	Material	Emissivity
Blackbody (ideal)	*1.00*	Green leaves	0.88
Cavity Radiator	*0.99–1.00*	Ice	0.96
Aluminum (anodized)	0.70	Iron or Steel (rusted)	0.70
Aluminum (oxidized)	0.11	Nickel (oxidized)	0.40
Aluminum (polished)	0.05	Nickel (unoxidized)	0.04
Aluminum (rough surface)	0.06–0.07	Nichrome (80Ni-20Cr) (oxidized)	0.97
Asbestos	0.96	Nichrome (80Ni-20Cr) (polished)	0.87
Brass (dull tarnished)	0.61	Oil	0.80
Brass (polished)	0.05	Silicon	0.64
Brick	0.90	Silicone Rubber	0.94
Bronze (polished)	0.10	Silver (polished)	0.02
Carbon filled latex paint	0.96	Skin (human)	0.93–0.96
Carbon Lamp Black	0.96	Snow	0.85
Chromium (polished)	0.10	Soil	0.90
Copper (oxidized)	0.6–0.7	Stainless Steel (buffed)	0.20
Copper (polished)	0.02	Steel (flat rough surface)	0.95–0.98
Cotton cloth	0.80	Steel (ground)	0.56
Epoxy Resin	0.95	Tin plate	0.10
Glass	0.95	Water	0.96
Gold	0.02	White Paper	0.92
Gold-black	0.98–0.99	Wood	0.93
Graphite	0.7–0.8	Zinc (polished)	0.04

Table A.19 Refractive indices (n) of some materials

Material	n	wavelength (μm)	note
Vacuum	1		
Air	1.00029		
Acrylic	1.5	0.41	
AMTIR-1	2.6	1	Amorphous glass[a]
($Ge_{33}As_{12}Se_{55}$)	2.5	10	
AMTIR-3 ($Ge_{28}Sb_{12}Se_{60}$)	2.6	10	Amorphous glass[a]
As_2S_3	2.4	8.0	Amorphous glass[a]
CdTe	2.67	10.6	
Crown glass	1.52		
Diamond	2.42	0.54	Excellent thermal conductivity
Fused silica (SiO_2)	1.46	3.5	
Borosilicate glass	1.47	0.7	TEMPAX®[b]. Transparent: 0.3–2.7μm
GaAs	3.13	10.6	Laser windows
Germanium	4.00	12.0	
Heaviest flint glass	1.89		
Heavy flint glass	1.65		
Irtran 2 (ZnS)	2.25	4.3	Windows in IR sensors
KBr	1.46	25.1	Hygroscopic
KCl	1.36	23.0	Hygroscopic
KRS-5	2.21	40.0	Toxic
KRS-6	2.1	24	Toxic
NaCl	1.89	0.185	Hygroscopic, corrosive
Polyethylene	1.54	8.0	Low cost IR windows/lenses

(*continued*)

Table A.19 (continued)

Material	n	wavelength (μm)	note
Polystyrene	1.55		
Pyrex 7740	1.47	0.589	Good thermal and optical properties
Quartz	1.54		
Sapphire (Al_2O_3)	1.59	5.58	Chemically resistant
Silicon	3.42	5.0	Windows in IR sensors
Silver Bromide (AgBr)	2.0	10.6	Corrosive
Silver Chloride (AgCl)	1.9	20.5	Corrosive
Water [20°C]	1.33		
ZnSe	2.4	10.6	IR windows, brittle

[a]Available from Amorphous Materials, Inc. Garland, TX 75042
[b]TEMPAX® is a registered trademark of Schott Glasswerke, Mainz, Germany

Table A.20 Characteristics of C-Zn and Alkaline cells (from Powers RA (1995) Batteries for low power electronics. Proc IEEE83(4):687–693)

Battery	Wh/L	Wh/kg	Drain rate	Shelf life
Carbon-Zinc	150	85	Low-medium	2 years
Alkaline	250	105	Medium-high	5 years

Table A.21 Lithium-manganese dioxide primary cells (from Powers RA (1995) Batteries for low power electronics. Proc IEEE 83(4):687–693)

Construction	Voltage	Capacity (mAh)	Rated d.c. current (mA)	Pulse current (mA)	Energy density (W h/L)
Coin	3	30–1,000	0.5–7	5–20	500
Cyl. Wound	3	160–1,300	20–1,200	80–5,000	500
Cyl. Bobbin	3	650–500	4–10	60–200	620
Cyl. "D" cell	3	10,000	2,500		575
Prismatic	3	1,150	18		490
Flat	3/6	150–1,400	20–125		290

Table A.22 Typical characteristics of "AA"-size secondary cells

System	Volts	Capacity (mAh)	Rate (C)[a]	W h/L	W h/kg	Cycles	Loss/Mo (%)
NiCad	1.2	1,000	10	150	60	1,000	15
Ni-MH	1.2	1,200	2	175	65	500	20
Pb Acid	2	400	1	80	40	200	2
Li Ion (CoO_2)	3.6	500	1	225	90	1,200	8
Li/MnO_2	3	800	0.5	280	130	200	1

[a]Discharge rate unit, C, (in mA) is equal numerically to the nominal capacity (in mA h).

Table A.23 Miniature secondary cells and batteries

Manufacturer	Part	Type	Size	Capacity (mAh)	Voltage	Price $ (appx)
Avex Corp. Bensalem, PA 800-345-1295		RAM	AA	1.4	1.5	1
GN National Electric Inc. Pomona, CA 909-598-1919	GN-360	NiCd	15.5×19 mm	60	3.6	1.10
GP Batteries USA, San Diego, CA 619–674–5620	Green-Charge	NiMH	2/3AA, AA, 2/3 AF, 4/5AF	600–2,500	1.2	2–7
Gould, Eastlake, OH 216–953–5084	3C120M	$LiMnO^2$	3×4×0.12 cm	120	3	2.71
House of Batteries Inc., Huntington Beach, CA 800–432–3385	Green Cell	NiMH	AA, 4/5A, 7/5A	1,200–2,500	1–2	3.50–12
Maxell Corp., Fairlawn, NJ 201–794–5938	MHR-AAA	NiMH	AAA	410	1.2	4
Moli Energy Ltd., Maple Ridge, BC, Canada, 604–465–7911	MOLICEL	Li-ion	18(dia)×65 mm	1,200	3.0–4.1	25
Plainview Batteries, Inc., Plainview, NY 516–249–2873	PH600	NiMH	48×17×7.7 mm	600	1.2	4
Power Coversion, Inc., Elmwood Park, NJ 201–796–4800	MO4/11	$LiMnO^2$	1/2AA	1,000	3.3	5–8
Power Sonic Corp., Redwood City, CA, 415–364–5001	PS-850AA	NiCd	AA	850	1.2	1.75
Rayovac Corp., Madison, WI 608–275–4690	Renewal	RAM	AA; AAA	1,200; 600	1.5	from 0.50
Renata U.S., Richardson, TX 214–234–8091	CR1025	Li	10 mm	25	3.0	0.50
Sanyo Energy (U.S.A.), San Diego, CA, 691–661–7992	Twicell	NiMH	10.4×44.5 ×67 mm	450	1.2	3.85
Saft America, Inc., San Diego, CA, 619–661–7992	VHAA	NiMH	AA	1,100	1.2	2.95
Tadiran Electronics, Port Washington, NY, 516–621–4980		Li	1/AA-DD packs	370 mAh to 30 Ah	3–36	1+

(*continued*)

Table A.23 (continued)

Manufacturer	Part	Type	Size	Capacity (mAh)	Voltage	Price $ (appx)
Toshiba America, Deerfield, IL, 800–879–4963	LSQ8	Li-ion	8.6×3.4 ×48 mm	900	3.7	12–15
Ultralife Batteries, Inc., Newark, NJ, 315–332–7100	U3VL	Li	25.8×44.8×16.8	3,600	3.0	4.60
Varta Batteries, Inc., Elmsford, NY 914–592–2500		NiMH	AAA-F	300–8,000	1.2	0.80+

Note: *Li-ion* Lithium-ion, *LiMnO*^{2} Lithium manganese dioxide, *NiCd* Nickel-cadmium, *NiMH* Nickel-metal hydride, *RAM* Rechargeable alkaline manganese

Table A.24 Electronic ceramics (between 25 and 100°C)

	96% Alumina (Al_2O_3)	Beryllia (BeO)	Boron nitrade (BN)	Aluminum nitrade (AlN)	Silicon carbide (SiC)	Silicon (Si)
Hardness, Knopp (kg/mm^2)	2,000	1,000	280	1,200	2,800	–
Flexural Strength (10^5 N/m^2)	3.0	1.7–2.4	0.8	4.9	4.4	–
Thermal conductivity (W/(m K))	21	250	60	170–200	70	150
Thermal expansion (10^{-6}/K)	7.1	8.8	0.0	4.1	3.8	3.8
Dielectric strength (k V/mm)	8.3	19.7	37.4	14.0	15.4	–
Dielectric loss (10^{-4} tan delta at 1MHz)	3–5	4–7	4	5–10	500	–
Dielectric constant, κ (at 10 MHz)	10	7.0	4.0	8.8	40	–

Table A.25 Properties of glasses

	Soda-lime	Boro-silicate	Lead glass	Alumo-silicate	Fused silica	96% Silica
Modulus of elasticity (10^6 psi)	10.2	9.0	8.5–9.0	12.5–12.7	10.5	9.8
Softening temperature (°F)	1,285	1,510	932–1,160	1,666–1,679	2,876	2,786
Coefficient of thermal expansion (10^{-6} in/in °C)	8.5–9.4	3.2–3.4	9–12.6	4.1–4.7	0.56	0.76
Thermal conductivity (BTU—in/h ft^2 °F)	7.0	7.8	5.2	9.0	9.3	10.0
Density (lb/in^3)	0.089	0.081	0.103–0.126	0.091–0.095	0.079	0.079
Electrical resistivity (Log10Ω cm)	12.4	14	17	17	17	17
Refractive index	1.525	1.473	1.540–1.560	1.530–1.547	1.459	1.458

Table A.26 Comparison of IR Transmitting Glasses Produced by AMI

Property	AMTIR-1	AMTIR-2	AMTIR-3	AMTIR-4	AMTIR-5	AMTIR-6	C1
Composition	Ge-As-Se	As-Se	Ge-Sb-Se	As-Se	As-Se	As-S	As-Se-Te
Transmission Range μm	0.7–12	1.0–14	1.0–12	1.0–12	1.0–12	0.6–8	1.2–14
Ref Index @ 10μm	2.4981	2.7613	2.6027	2.6431	2.7398	2.3807	2.8051
DN/DT°C $\times 10^{-6}$ @ 10μm	72	5	91	−23	<1	<1(5μm)	31
Knoop Hardness	170	110	150	84	87	109	110
Therm Exp $\times 10^{-6}$/°C	12	22.4	14	27	23.7	21.6	23
Thermal Condx (cal/gm sec°C) 10^{-4}	6	5.3	5.3	5.3	5.7	8.0	5.2
Specific Heat (cal/gm °C)	0.072	0.068	0.066	0.086	0.076	0.081	0.062
Density gm/cm^3	4.4	4.66	4.67	4.49	4.51	3.2	4.69
Rupture Mod (psi)	2700	2500	2500	2358	2400	2400	2500
Young's Mod ($\times 10^6$ psi)	3.2	5.6	3.1	2.2	2.56	2.3	1.8
Shear Mod ($\times 10^6$ psi)	1.3	1.03	1.2	0.85	1.01	0.94	1.03
Poisson's Ratio	0.27	0.29	0.26	0.297	0.279	0.24	0.29
Softening Point °C	405	188	295	131	170	210	154
Glass Trans Temp (Tg °C)	368	167	278	103	143	187	133
Upper Use Temp °C	300	150	250	90	130	150	120
Dispersion Values							
3 − 5 μm	202	171	159	186	175	155	148
8 − 12 μm	109	149	110	235	172		196

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