

Appendix

A. Material Parameters

In the table below, an * is used to indicate that the material's Z Factor is not known. A method of determining Z Factor empirically follows the materials table.

Formula	Density	Z-Ratio	Material Name
Ag	10.500	0.529	Silver
AgBr	6.470	1.180	Silver Bromide
AgCl	5.560	1.320	Silver Chloride
Al	2.700	1.080	Aluminum
Al ₂ O ₃	3.970	0.336	Aluminum Oxide
Al ₄ C ₃	2.360	*1.000	Aluminum Carbide
AlF ₃	3.070	*1.000	Aluminum Fluoride
AlN	3.260	*1.000	Aluminum Nitride
AlSb	4.360	0.743	Aluminum Antimonide
As	5.730	0.966	Arsenic
As ₂ Se ₃	4.750	*1.000	Arsenic Selenide
Au	19.300	0.381	Gold
B	2.370	0.389	Boron
B ₂ O ₃	1.820	*1.000	Boron Oxide
B ₄ C	2.370	*1.000	Boron Carbide
BN	1.860	*1.000	Boron Nitride
Ba	3.500	2.100	Barium
BaF ₂	4.886	0.793	Barium Fluoride
BaN ₂ O ₆	3.244	1.261	Barium Nitrate
BaO	5.720	*1.000	Barium Oxide
BaTiO ₃	5.999	0.464	Barium Titanate (Tetr)
BaTiO ₃	6.035	0.412	Barium Titanate (Cubic)
Be	1.850	0.543	Beryllium
BeF ₂	1.990	*1.000	Beryllium Fluoride
BeO	3.010	*1.000	Beryllium Oxide
Bi	9.800	0.790	Bismuth
Bi ₂ O ₃	8.900	*1.000	Bismuth Oxide
Bi ₂ S ₃	7.390	*1.000	Bismuth Trisulphide
Bi ₂ Se ₃	6.820	*1.000	Bismuth Selenide
Bi ₂ Te ₃	7.700	*1.000	Bismuth Telluride
BiF ₃	5.320	*1.000	Bismuth Fluoride
C	2.250	3.260	Carbon (Graphite)
C	3.520	0.220	Carbon (Diamond)
C ₈ H ₈	1.100	*1.000	Parlyene (Union Carbide)

Formula	Density	Z-Ratio	Material Name
Ca	1.550	2.620	Calcium
CaF ₂	3.180	0.775	Calcium Fluoride
CaO	3.350	*1.000	Calcium Oxide
CaO-SiO ₂	2.900	*1.000	Calcium Silicate (3)
CaSO ₄	2.962	0.955	Calcium Sulfate
CaTiO ₃	4.100	*10~	Calcium Titanate
CaWO ₄	6.060	*1.000	Calcium Tungstate
Cd	8.640	0.682	Cadmium
CdF ₂	6.640	*1.000	Cadmium Fluoride
CdO	8.150	*1.000	Cadmium Oxide
CdS	4.830	1.020	Cadmium Sulfide
CdSe	5.810	*1.000	Cadmium Selenide,
CdTe	6.200	0.980	Cadmium Telluride
Ce	6.780	*1.000	Cerium
CeF ₃	6.160	*1.000	Cerium (III) Fluoride
CeO ₂	7.130	*1.000	Cerium (IV) Dioxide
Co	8.900	0.343	Cobalt
CoO	6.440	0.412	Cobalt Oxide
Cr	7.200	0.305	Chromium
Cr ₂ O ₃	5.210	*1.000	Chromium (III) Oxide
Cr ₃ C ₂	6.680	*1.000	Chromium Carbide
CrB	6.170	*1.000	Chromium Boride
Cs	1.870	*1.000	Cesium
Cs ₂ SO ₄	4.243	1.212	Cesium Sulfate
CsBr	4.456	1.410	Cesium Bromide
CsCl	3.988	1.399	Cesium Chloride
CsI	4.516	1.542	Cesium Iodide
Cu	8.930	0.437	Copper
Cu ₂ O	6.000	*1.000	Copper Oxide
Cu ₂ S	5.600	0.690	Copper (I) Sulfide (Alpha)
Cu ₂ S	5.800	0.670	Copper (I) Sulfide (Beta)
CuS	4.600	0.820	Copper (II) Sulfide
Dy	8.550	0.600	Dysprosium
Dy ₂ O ₃	7.810	*1.000	Dysprosium Oxide
Er	9.050	0.740	Erbium
Er ₂ O ₃	8.640	*1.000	Erbium Oxide
Eu	5.260	*1.000	Europium
EuF ₂	6.500	*1.000	Europium Fluoride

Formula	Density	Z-Ratio	Material Name
Fe	7.860	0.349	Iron
Fe ₂ O ₃	5.240	*1.000	Iron Oxide
FeO	5.700	*1.000	Iron Oxide
FeS	4.840	*1.000	Iron Sulphide
Ga	5.930	0.593	Gallium
Ga ₂ O ₃	5.880	*1.000	Gallium Oxide (B)
GaAs	5.310	1.590	Gallium Arsenide
GaN	6.100	*1.000	Gallium Nitride
GaP	4.100	*1.000	Gallium Phosphide
GaSb	5.600	*1.000	Gallium Antimonide
Gd	7.890	0.670	Gadolinium
Gd ₂ O ₃	7.410	*1.000	Gadolinium Oxide
Ge	5.350	0.516	Germanium
Ge ₃ N ₂	5.200	*1.000	Germanium Nitride
GeO ₂	6.240	*1.000	Germanium Oxide
GeTe	6.200	*1.000	Germanium Telluride
Hf	13.090	0.360	Hafnium
HfB ₂	10.500	*1.000	Hafnium Boride,
HfC	12.200	*1.000	Hafnium Carbide
HfN	13.800	*1.000	Hafnium Nitride
HfO ₂	9.680	*1.000	Hafnium Oxide
HfSi ₂	7.200	*1.000	Hafnium Silicide
Hg	13.460	0.740	Mercury
Ho	8.800	0.580	Holmium
Ho ₂ O ₃	8.410	*1.000	Holmium Oxide
In	7.300	0.841	Indium
In ₂ O ₃	7.180	*1.000	Indium Sesquioxide
In ₂ Se ₃	5.700	*1.000	Indium Selenide
In ₂ Te ₃	5.800	*1.000	Indium Telluride
InAs	5.700	*1.000	Indium Arsenide
InP	4.800	*1.000	Indium Phosphide
InSb	5.760	0.769	Indium Antimonide
Ir	22.400	0.129	Iridium
K	0.860	10.189	Potassium
KBr	2.750	1.893	Potassium Bromide
KCl	1.980	2.050	Potassium Chloride
KF	2.480	*1.000	Potassium Fluoride
KI	3.128	2.077	Potassium Iodide

Formula	Density	Z-Ratio	Material Name
La	6.170	0.920	Lanthanum
La ₂ O ₃	6.510	*1.000	Lanthanum Oxide
LaB ₆	2.610	*1.000	Lanthanum Boride
LaF ₃	5.940	*1.000	Lanthanum Fluoride
Li	0.530	5.900	Lithium
LiBr	3.470	1.230	Lithium Bromide
LiF	2.638	0.778	Lithium Fluoride
LiNbO ₃	4.700	0.463	Lithium Niobate
Lu	9.840	*1.000	Lutetium
Mg	1.740	1.610	Magnesium
MgAl ₂ O ₄	3.600	*1.000	Magnesium Aluminate
MgAl ₂ O ₆	8.000	*1.000	Spinel
MgF ₂	3.180	0.637	Magnesium Fluoride
MgO	3.580	0.411	Magnesium Oxide
Mn	7.200	0.377	Manganese
MnO	5.390	0.467	Manganese Oxide
MnS	3.990	0.940	Manganese (II) Sulfide
Mo	10.200	0.257	Molybdenum
Mo ₂ C	9.180	*1.000	Molybdenum Carbide
MoB ₂	7.120	*1.000	Molybdenum Boride
MoO ₃	4.700	*1.000	Molybdenum Trioxide
MoS ₂	4.800	*1.000	Molybdenum Disulfide
Na	0.970	4.800	Sodium
Na ₃ AlF ₆	2.900	*1.000	Cryolite
Na ₅ Al ₃ F ₁₄	2.900	*1.000	Chiolite
NaBr	3.200	*1.000	Sodium Bromide
NaCl	2.170	1.570	Sodium Chloride
NaClO ₃	2.164	1.565	Sodium Chlorate
NaF	2.558	0.949	Sodium Fluoride
NaNO ₃	2.270	1.194	Sodium Nitrate
Nb	8.578	0.492	Niobium (Columbium)
Nb ₂ O ₃	7.500	*1.000	Niobium Trioxide
Nb ₂ O ₅	4.470	*1.000	Niobium (V) Oxide
NbB ₂	6.970	*1.000	Niobium Boride
NbC	7.820	*1.000	Niobium Carbide
NbN	8.400	*1.000	Niobium Nitride
Nd	7.000	*1.000	Neodymium
Nd ₂ O ₃	7.240	*1.000	Neodymium Oxide
NdF ₃	6.506	*1.000	Neodymium Fluoride

Formula	Density	Z-Ratio	Material Name
Ni	8910	0.331	Nickel
NiCr	8.500	*1.000	Nichrome
NiCrFe	8.500	*10~	Inconel
NiFe	8.700	*1.000	Permalloy
NiFeMo	8.900	*10~	Supermalloy
NiO	7.450	*1.000	Nickel Oxide
P ₃ N ₅	2.510	*1.000	Phosphorus Nitride
Pb	11.300	1.130	Lead
PbCl ₂	5.850	*1.000	Lead Chloride
PbF ₂	8.240	0.661	Lead Fluoride
PbO	9.530	*1.000	Lead Oxide
PbS	7.500	0.566	Lead Sulfide
PbSe	8.100	*1.000	Lead Selenide
PbSnO ₃	8.100	*1.000	Lead Stannate
PbTe	8.160	0.651	Lead Telluride
Pd	12.038	0.357	Palladium
PdO	8.310	*1.000	Palladium Oxide
Po	9.400	*1.000	Polonium
Pr	6.780	*1.000	Praseodymium
Pr ₂ O ₃	6.880	*1.000	Praseodymium Oxide
Pt	21.400	0.245	Platinum
PtO ₂	10.200	*1.000	Platinum Oxide
Ra	5.000	*1.000	Radium
Rb	1.530	2.540	Rubidium
RbI	3.550	*1.000	Rubidium Iodide
Re	21.040	0.150	Rhenium
Rh	12.410	0.210	Rhodium
Ru	12.362	0.182	Ruthenium
S8	2.070	2.290	Sulphur
Sb	6.620	0.768	Antimony
Sb ₂ O ₃	5.200	*1.000	Antimony Trioxide
Sb ₂ S ₃	4.640	*1.000	Antimony Trisulfide
Sc	3.000	0.910	Scandium
Sc ₂ O ₃	3.860	*1.000	Scandium Oxide
Se	4.810	0.864	Selenium
Si	2.320	0.712	Silicon
Si ₃ N ₄	3.440	*1000	Silicon Nitride
SiC	3.220	*1.000	Silicon Carbide
SiO	2.130	0.870	Silicon (II) Oxide
SiO ₂	2.648	1.000	Silicon Dioxide

Formula	Density	Z-Ratio	Material Name
Sm	7.540	0.890	Samarium
Sm ₂ O ₃	7.430	*1.000	Samarium Oxide
Sn	7.300	0.724	Tin
SnO ₂	6.950	*1.000	Tin Oxide
SnS	5.080	*1.000	Tin Sulfide
SnSe	6.180	*1.000	Tin Selenide
SnTe	6.440	*1.000	Tin Telluride
Sr	2.600	*1.000	Strontium
SrF ₂	4.277	0.727	Strontium Fluoride
SrO	4.990	0.517	Strontium Oxide
Ta	16.600	0.262	Tantalum
Ta ₂ O ₅	8.200	0.300	Tantalum (V) Oxide
TaB ₂	11.150	*1.000	Tantalum Boride
TaC	13.900	*1.000	Tantalum Carbide
TaN	16.300	*1.000	Tantalum Nitride
Tb	8.270	0.660	Terbium
Tc	11.500	*1.000	Technetium
Te	6.250	0.900	Tellurium
TeO ₂	5.990	0.862	Tellurium Oxide
Th	11.694	0.484	Thorium
ThF ₄	6.320	*1.000	Thorium.(IV) Fluoride
ThO ₂	9.860	0.284	Thorium Dioxide
ThOF ₂	9.100	*1.000	Thorium Oxyfluoride
Ti	4.500	0.628	Titanium
Ti ₂ O ₃	4.600	*1.000	Titanium Sesquioxide
TiB ₂	4.500	*1.000	Titanium Boride
TiC	4.930	*1.000	Titanium Carbide
TiN	5.430	*1.000	Titanium Nitride
TiO	4.900	*1.000	Titanium Oxide
TiO ₂	4.260	0.400	Titanium (IV) Oxide
Tl	11.850	1.550	Thallium
TlBr	7.560	*1.000	Thallium Bromide
TlCl	7.000	*1.000	Thallium Chloride
TlI	7.090	*1.000	Thallium Iodide (B)
U	19.050	0.238	Uranium
U ₃ O ₈	8.300	*1.000	Tri Uranium Octoxide
U ₄ O ₉	10.969	0.348	Uranium Oxide
UO ₂	10.970	0.286	Uranium Dioxide
V	5.960	0.530	Vanadium
V ₂ O ₅	3.360	*1.000	Vanadium Pentoxide
VB ₂	5.100	*1.000	Vanadium Boride
VC	5.770	*1.000	Vanadium Carbide
VN	6.130	*1.000	Vanadium Nitride

Formula	Density	Z-Ratio	Material Name
VO ₂	4.340	*1.000	Vanadium Dioxide
W	19.300	0.163	Tungsten
WB ₂	10.770	*1.000	Tungsten Boride
WC	15.600	0.151	Tungsten Carbide
WO ₃	7.160	*1.000	Tungsten Trioxide
WS ₂	7.500	*1.000	Tungsten Disulphide
WSi ₂	9.400	*1.000	Tungsten Suicide
Y	4.340	0.835	Yttrium
Y ₂ O ₃	5.010	*1.000	Yttrium Oxide
Yb	6.980	1.130	Ytterbium
Yb ₂ O ₃	9.170	*1.000	Ytterbium Oxide
Zn	7.040	0.514	Zinc
Zn ₃ Sb ₂	6.300	*1.000	Zinc Antimonide
ZnF ₂	4.950	*1.000	Zinc Fluoride
ZnO	5.610	0.556	Zinc Oxide
ZnS	4.090	0.775	Zinc Sulfide
ZnSe	5.260	0.722	Zinc Selenide
ZnTe	6.340	0.770	Zinc Telluride
Zr	6.490	0.600	Zirconium
ZrB ₂	6.080	*1.000	Zirconium Boride
ZrC	6.730	0.264	Zirconium Carbide
ZrN	7.090	*1.000	Zirconium Nitride
ZrO ₂	5.600	*1.000	Zirconium Oxide

Z-Factor is used to match the acoustic properties of the material being deposited to the acoustic properties of the base quartz material of the sensor crystal.

$$\text{Z-Factor} = Z_q / Z_m$$

For example, the acoustic impedance of gold is Z=23.18, so:

$$\text{Gold Z-Factor} = 8.83 / 23.18 = .381$$

Unfortunately, Z Factor is not readily available for many materials. Z Factor can be calculated empirically using this method:

1. Deposit the material until Crystal Life is near 50%, or near the end of life, whichever is sooner.
2. Place a new substrate adjacent to the used quartz sensor.
3. Set QCM Density to the calibrated value; Tooling to 100%. Zero thickness.
4. Deposit approximately 1000 to 5000 Å of material on the substrate.
5. Use a profilometer or interferometer to measure the actual substrate film thickness.
6. Adjust the Z Factor of the instrument until the correct thickness reading is shown.

Another alternative is to change crystals frequently. For a crystal with 90% life, the error is negligible for even large errors in the programmed versus actual Z Factor.