# The CRYSTRAN HANDBOOK

## of Infra-Red and Ultra-Violet OPTICAL MATERIALS

CRYSTRAN
UV · VISIBLE · IR SPECIALIST OPTICS

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# A COMPREHENSIVE SOURCE ACROSS THE SPECTRUM

This handbook is published by Crystran Ltd as a service to optics professionals. It is designed to help you determine the best material for your application.

The materials that we work with are mainly crystal or innovative glasses used for their particular transmission properties. We also have a great deal of experience within the company of the crystal growth techniques used in making the raw materials.

If your requirement is for prototypes or for production quantities our technical team are happy to help.

For more information on our materials and services, please contact us:

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Trade shows, visits, and small triumphs.

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**Material Data**



## INTRODUCTION TO THE HANDBOOK

This Handbook, as well as being a catalogue of the range of materials and production capabilities available to you at Crystran Ltd, is hoped to be a useful reference source for optical, physical and chemical data.

The data in this Handbook is provided in good faith and reviews have been made to verify the sources of information where possible; however Crystran Ltd can accept no responsibility for accuracy of data. It is not always possible to verify data where there are conflicting figures in different publications, revisions are a continuing process and we have applied our best judgement where appropriate. References are stated where possible, and in most cases, transmission scans are original Crystran company data.

Formulae and notes included within the Handbook are not intended to be comprehensive. We have found them a useful reference and have been consulted on numerous occasions.

Values quoted in the Handbook are, as standard, SI units except where alternative units are in common usage – an Appendix is included containing unit conversion tables.

Crystran Ltd would like to acknowledge the help of our associate company Korth Kristalle GmbH in Germany and our associate Mr T Enju of Enju Inc. Japan for providing additional information.

## INTRODUCTION TO CRYSTRAN LTD



Crystran Ltd is a manufacturer and supplier of high quality optical components. We manufacture windows, lenses, prisms and specialist optics as both standard products and to the designs of our customers. For over 21 years we have specialised in crystal materials and exotic glasses and used them to manufacture highly precise optical components for the Infrared, Ultraviolet and Visible regions of the spectrum.

You can see a full list of the materials we work with on our website.

Crystran Ltd no longer grow crystal in-house, however we still retain the experience and understanding that is invaluable when talking to suppliers and customers alike. Crystran holds extensive stocks of crystal as ingots to offer a comprehensive range of crystals and crystal products for UV, IR and visible applications.

Crystal materials can be supplied in a number of different forms – raw boule, cut and shaped blanks, and polished optics. Our production facilities include cutting and several polishing shops for the production of components to customer specifications.

Our dedication to investment in both staff and equipment enables us to work to increasingly higher standards. Surface qualities of up to λ/20 at 633nm and parallelism of better than 2 arc seconds can be achieved (dependent on material and method required). Double sided and conventional polishing techniques, coupled with computerised interferometry and other test equipment, ensure that specifications can be met.

**Our main test equipment includes**

12” (300mm) Vertical Bespoke Interferometer
Capability λ/20

4” Intellium Horizontal Interferometer
Capability λ/20
Notes Expandable to 6”with a Jenoptik attachment.

3m Optical Bench with rail, SIOS laser and Heidenhain digital encoder
Capability ROC of lenses up to +650mm convex -900mm concave
Notes CA dependent on ø of lenses and best fit sphere

OptiLux SD Scratch Dig Evaluation System
Capability S/D 10/5 against MIL 13830
Certified against Davidson Optronics D667 comparator plates SN:2444

Trioptics PrismMaster and Opti-Angle measuring systems
Capability <2” for parallelism and angles

Baty Venture Vision measuring system
Capability 0.5µm resolution
Notes 3-axis automated non-contact

Taylor Hobson CCI 6000 Talysurf
Capability 0.1Å

PE Frontier FT-IR Spectrometer
Capability 2µm to 25µm

PE Lambda 750 Spectrometer UV/VIS/IR
Capability 195nm to 3000nm

Vacuum UV transmission test for specific testing at Lyman-α wavelength
Capability 121.6nm

Trioptics Spherocompact
Capability 2µm resolution
Notes Contact measurement of lens ROC

Davidson optical thickness gauge
Non contact method
Resolution 1um

**Polishing Specifications**

Specifying a polishing standard must be approached with caution. Costs can escalate rapidly for more exacting specifications, particularly if combinations of requirements are needed. For instance, ultra-flatness can be achieved at the expense of a good cosmetic finish and vice versa. Good flatness and parallelism in thin windows is possible with a double-sided polishing technique.

*Typical Polishing Specifications used at Crystran*
It is not possible to give examples of a typical specification as that will depend on several factors such as material, size and method of manufacture. We do have certain specifications that we always apply to windows as standard (some traded materials may have different specifications).

| | |
|---|---|
| *Diameter (up to 50mm)* | +0/-0.1mm |
| *Length of sides (up to 50mm)* | +0/-0.1mm |
| *Thickness* | +/-0.1mm |
| *Surface quality (IR grade)* | 60/40 or better |
| *Surface quality (UV grade)* | 40/20 |
| *Edge chips* | Up to 0.5mm |
| *Clear aperture* | 80% of diameter |

Our technical sales team will be happy to discuss and advise on these matters.

**Lens Tooling**

Crystran have an extensive list of tooling and NPL qualified test plates for the manufacture of lenses with close tolerances. Please contact us for more information.

**Hot Forging**

This is a quick and cost effective method for manufacture of silver chloride and silver bromide optics. The quality achieved by this technique, although inferior to conventional polishing, is more than adequate for a wide range of infra-red applications.

The technique is particularly appropriate for spectroscopic mini-cell windows where the surface has a small depression for liquid films.

In the course of our hot-forging operations we have acquired a stock of tooling which it is economical to design around. Please contact us about sizes available.

**Bubbles & Flaws (ISO/BS/MIL Specification 1/)**

These are normally associated with glasses and rarely with crystal, however present in soft crystals such as CsI, KRS5 etc.
*Example: 1/5 x 0.06 is 5 flaws less than 0.06mm.*

**Stria (ISO/BS/MIL Specification 2/)**

Stria are vitreous inclusions mainly in glass and rarely with crystal. There are 5 grades of increasing severity.
*Example: 2/01 is the lowest number of stria.*

**Flatness (ISO/BS/MIL Specification 3/)**

Flatness is specified in terms of the wavelength of light which represents the degree of power, with the addition of form error which defines the allowed irregularity of the fringe pattern.
*Example: 3/2(0.5) is 2 fringes power/0.5 fringes irregularity*

**Parallelism**

The parallelism of a window can be specified in terms of angle, usually as minutes of arc. Sometimes it is in terms of thickness variation or 'run-out'. Conventional polishing will typically produce <3-10 arc minutes. Double-sided polishing can produce <5 arc seconds. To prevent multiple reflections between faces (an etalon effect) it may be prudent to have a small wedge angle specified.

**Lens Centration (ISO/BS/MIL Specification 4/)**

Lenses involve variations on other specifications. 'Flatness' is the radius of curvature as measured against a reference standard test plate, whilst 'parallel' is more accurately specified as centration error.
*Example: 4/3 is 3 minutes centration.*

**Cosmetic Finish (ISO/BS/MIL Specification 5/)**

Visual appearance is often a subjective matter and is still commonly specified by scratch/dig. This classifies the surface in terms of the maximum length of small scratches after polishing.

Under this classification, S/D 80/50 would be regarded as quite poor and appropriate for simple spectroscopic windows and S/D 20/10 is an exacting standard suitable for low scattering laser applications. S/D 60/40 is a reasonably routine finish.

| SCRATCH | | |
|---|---|---|
| MIL-PRF-13830B * | MIL-F-48616<br>MIL-C-48497A | Width (µm) |
| 5 | A | 5 |
| 10 | B | 10 |
| 20 | C | 20 |
| 40 | D | 40 |
| 60 | E | 60 |
| 80 | F | 80 |
| 120 | G | 120 |

| DIG | | |
|---|---|---|
| MIL-PRF-13830B | MIL-F-48616<br>MIL-C-48497A | Width (mm) |
| 5 | A | 0.05 |
| 10 | B | 0.1 |
| 20 | C | 0.3 |
| 30 | D | 0.4 |
| 40 | E | 0.5 |
| 50 | F | 0.6 |
| 70 | G | 0.7 |
| 100 | H | 1 |

* This parameter is a measure of the brightness of scatter rather than the physical width of the scratch.

**Working Equivalents Applied at Crystran**

These are not absolute measures but used as a guide based upon our experience.

| S/D | < 30mm Ø optics | 30 to 40mm Ø optics |
|---|---|---|
| 80/50 | 5/3 x 0.25 ; K5 x 0.016 | 5/4 x 0.4 ; K5 x 0.016 |
| 80/40 | 5/2 x 0.25 ; K5 x 0.016 | 5/3 x 0.4 ; K5 x 0.016 |
| 60/40 | 5/2 x 0.25 ; K3 x 0.016 | 5/3 x 0.4 ; K3 x 0.016 |
| 60/30 | 5/3 x 0.16 ; K3 x 0.016 | 5/3 x 0.25 ; K3 x 0.016 |
| 40/20 | 5/2 x 0.16 ; K4 x 0.01 | 5/3 x 0.25 ; K4 x 0.01 |
| 40/10 | 5/3 x 0.063 ; K4 x 0.01 | 5/3 x 0.1 ; K4 x 0.01 |
| 20/10 | 5/3 x 0.063 ; K2 x 0.01 | 5/3 x 0.1 ; K2 x 0.01 |
| 15/5 | 5/4 x 0.025 ; K2 x 0.0063 | 5/4 x 0.04 ; K2 x 0.0063 |
| 10/5 | 5/4 x 0.025 ; K2 x 0.004 | 5/4 x 0.04 ; K2 x 0.004 |

| S/D | 40 to 50mm Ø optics | > 50mm Ø optics |
|---|---|---|
| 80/50 | 5/8 x 0.4 ; K5 x 0.016 | 5/20 x 4 x 0.4 ; K5 x 0.016 |
| 80/40 | 5/6 x 0.4 ; K5 x 0.016 | 5/20 x 3 x 0.4 ; K5 x 0.016 |
| 60/40 | 5/2 x 0.4 ; K3 x 0.016 | 5/20 x 3 x 0.4 ; K3 x 0.016 |
| 60/30 | 5/8 x 0.25 ; K3 x 0.016 | 5/20 x 4 x 0.25 ; K3 x 0.016 |
| 40/20 | 5/6 x 0.25 ; K4 x 0.01 | 5/20 x 3 x 0.25 ; K4 x 0.01 |
| 40/10 | 5/6 x 0.1 ; K4 x 0.01 | 5/20 x 3 x 0.1 ; K4 x 0.01 |
| 20/10 | 5/6 x 0.1 ; K2 x 0.01 | 5/20 x 3 x 0.1 ; K2 x 0.01 |
| 15/5 | 5/8 x 0.04 ; K2 x 0.0063 | 5/20 x 4 x 0.04 ; K2 x 0.063 |
| 10/5 | 5/8 x 0.04 ; K2 x 0.004 | 5/20 x 4 x 0.04 ; K2 x 0.004 |

Surface finish can also be specified in terms of surface roughness (Roughness Average, Ra) and can be measured by interferometric profiling

**Stresses (ISO/BS/MIL Specifications 6/)**

Stresses, known as strain birefringence, are variations in refractive index generally caused during the annealing of the glass or crystal. It is defined as the optical path difference caused by the stressed region in terms of nm path difference per cm reference path. Generally, $CaF_2$ and similar crystal is controlled better than 5nm/cm.

*Example: 6/10 defines strain birefringence of 10nm/cm.*

**Chamfers**

Chamfers are usually required both to protect the work from chipping during polishing and also in use. Protective chamfers are referred to as 'break edge' and may be removed by the polishing process. For operational reasons Crystran may choose not to apply chamfers to some, especially small windows. Some polishing operations may require slightly larger chamfers.

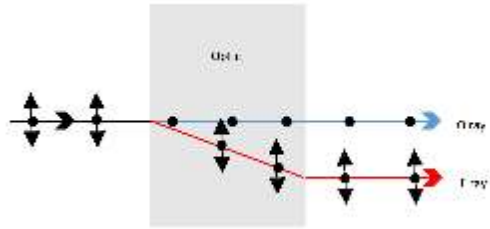
Chamfers are usually 45° (nominally) and measured down the edge of the optic unless otherwise specified. The size of chamfers is considered uncritical unless specifically requested.

**Optic Axis (Birefringence)**

Birefringence is a phenomenon that occurs in non-cubic crystals. Most materials are isotropic and the speed of light is the same in all directions as it passes through. Birefringent materials are anisotropic and the speed of light depends on the plane of polarisation and direction of propagation of the light.

When light is incident on a birefringent material, it is split into 2 rays – the ordinary (o ray) and the extraordinary (e ray). As illustrated below, the rays become polarised in perpendicular directions. These rays travel at different speeds and may travel in different directions.

There is one direction in a birefringent material where the 2 rays travel with the same speed – this is known as the optic axis. The light will behave as it would in an isotropic material. When light is incident at any angle to the optic axis, the e and o rays are split and are separated in space. The e ray will rotate around the o ray if the material is rotated.



For windows in Sapphire, Quartz, Calcite or $MgF_2$ the optic axis is usually specified as perpendicular to the surface, known as z-cut or Zero degree.

**Reflection Loss, Brewster Angle & Critical Angle**

When light is incident on a boundary between two media, some of the light is lost in reflection; this loss is calculated as a percentage of the intensity of the original beam and is dependent on the reflective indices of the material, the angle of incidence and state of polarisation of the light. The reflection loss of unpolarised light normally incident on a surface from one surface is:

$$\text{Reflection Loss} = \frac{(n - 1)^2}{(n + 1)^2}$$

For transparent materials, the second surface must be accounted for. Thus, the internal transmittance of a parallel plate is:

$$\text{Transmittance} = \frac{2n}{(n^2 + 1)}$$

Unpolarised light reflected from a plane surface boundary of two transparent media is partially polarised. At the polarising angle (Brewster's angle $\theta_b$) the reflected light is completely polarised and perpendicular to the refracted ray.

$$\text{Brewsters Angle: } \tan \theta_b = \frac{n_1}{n_2}$$

Total internal reflection occurs when the angle of incidence of a beam of light incident upon an interface is increased until the angle of refraction is 90°. This critical angle $\theta_c$ can be found in terms of the index of refraction for the two media by solving Snell's Law when $\theta_r = 90°$.

$$\text{Snell's Law: } n = n_1 \sin \theta_i = n_2 \sin \theta_r$$

$$\sin \theta_c = \frac{n_1}{n_2} \quad \sin 90°$$

This phenomenon only occurs when the light is emerging from a denser medium, i.e. when $n_1$ is greater than $n_2$.

**Reststrahlen**

For many inorganic materials used in optical applications, the refractive index remains constant and the absorption coefficient is zero or very small over the majority of its transmission range. When Reststrahlen materials are illuminated at wavelengths that excite the atomic, or crystal lattice structure, a number of resonance effects are noticed. As the Reststrahlen maximum frequency is approached, the refractive index (*n*) undergoes a rapid change, the extinction coefficient (*k*) rises rapidly and the Fresnel reflection coefficient (*R*) may become high. Therefore, at the Reststrahlen maximum frequency for a particular material, the reflectance of that material rises sharply:

$$R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2}$$

The Reststrahlen effect occurs notably in the 6µm to 300µm range. There are not many satisfactory filters in this region; hence the effect is often used for the extraction of a narrow spectral region from a spectral continuum.

In practical applications, some properties of Reststrahlen materials are significant; particularly the fact that the maximum reflectance increases as the temperature is reduced. When used as thin films (for coatings on mirrors and lenses) they exhibit interference maxima and minima on the short wavelength side of the reflectance peaks.

**Metrological Wavelengths**

| λ (nm) | Code | Spectral Line | λ (nm) | Code | Spectral Line |
|---|---|---|---|---|---|
| 10640.0 | | CO2 laser | 546.0740 | e | Green mercury |
| 2325.42 | | IR mercury | 486.1327 | F | Blue hydrogen |
| 1970.09 | | IR mercury | 479.9914 | F’ | Blue cadmium |
| 1529.582 | | IR mercury | 435.8343 | g | Blue mercury |
| 1064.0 | | Nd:YAG laser | 404.6561 | h | Violet mercury |
| 1013.98 | t | IR mercury | 365.0146 | i | UV mercury |
| 852.11 | s | IR caesium | 334.1478 | | UV mercury |
| 706.5188 | r | Red helium | 312.5663 | | UV mercury |
| 656.2725 | C | Red hydrogen | 296.7278 | | UV mercury |
| 643.8469 | C’ | Red cadmium | 280.4 | | UV mercury |
| 632.8 | | He:Ne laser | 248.3 | | UV mercury |
| 589.2938 | D | Yellow sodium | 121.567 | | Lyman α |
| 587.5618 | d | Yellow helium | | | |

## Kodak™ IRTRAN™ Numbers

IRTRAN-1 = $MgF_2$ IRTRAN-4 = ZnSe
IRTRAN-2 = ZnS IRTRAN-5 = MgO
IRTRAN-3 = $CaF_2$ IRTRAN-6 = CdTe

## UV Bands

UV-A = 400 - 320nm
UV-B = 320 - 290nm
UV-C = 290 - 100nm

## Neutral Density Filters

Transmission % = $100 / 10^{ND}$
Where ND is the optical density

**Hardness Scales**

The Knoop scale (HK) is the most commonly used, the others being; Moh, Vickers, Rockwell and Brinell.

The experimental procedure for the derivation of a value on the Knoop scale is to use a pyramidal diamond point which is pressed into the material in question with a known force. The indentation made by the point is then measured and the Knoop number calculated from this measurement. The test has been designed for use on a surface that has not been work-hardened in the lattice direction in which the hardness value is being measured. The hardness is usually stated as a Knoop figure but the units are actually kgf $mm^{-2}$

The values on the Moh scale are arrived at by measuring the relative hardness of materials by observing which materials are able to scratch other materials. The Moh scale, which is not linear, is limited by the softest material Talc (Moh=1) and the hardest material Diamond (Moh=10).

| | | | |
|---|---|---|---|
| 1 | Talc | 6 | Feldspar |
| 2 | Gypsum | 7 | Quartz |
| 3 | Calcite | 8. | Topaz |
| 4 | Fluorite | 9. | Sapphire |
| 5 | Apatite | 10. | Diamond |

**Elastic Coefficients**

Elastic coefficients, otherwise known as Elastic Stiffness Constants are the constants of proportionality between the components of stress and strain. They are therefore related to the elastic moduli.

For cubic crystals the coefficients are three: $C_{11}, C_{12}, C_{44}$
For tetragonal crystals, five: $C_{11}, C_{12}, C_{13}, C_{33}, C_{44}$
For hexagonal crystals, six: $C_{11}, C_{12}, C_{13}, C_{14}, C_{33}, C_{44}$

The three moduli relate to these coefficients as follows:

Youngs modulus $= E = (C_{11} + 2C_{12})(C_{11} - C_{12}) / (C_{11} + C_{12})$
Bulk modulus $= K = (C_{11} + 2C_{12}) / 3$
Shear modulus $= G = C_{44}$

**Some Useful Definitions**

Transmittance = $\frac{I_E}{I_o}$ $\frac{\text{Intensity of exit beam}}{\text{Intensity of Incident beam}}$

*Transmittance is usually expressed as a percentage.*

Transmissivity = Internal Transmittance per unit thickness

Absorptance = $\frac{I_o - I_E}{I_o}$ $\frac{\text{Intensity of absorbed beam}}{\text{Intensity of Incident beam}}$

*The complement of transmittance*

Absorbance = $\log_{10}\left(\frac{I_o}{I_e}\right)$

*Example: 20% transmittance is* $\log_{10}\left(\frac{100}{20}\right)$ *= 0.7 absorbance.*

Wave Number = $\frac{1}{\text{wavelength}}$ (cm) = $\frac{10000}{\text{wavelength}}$ (μm)

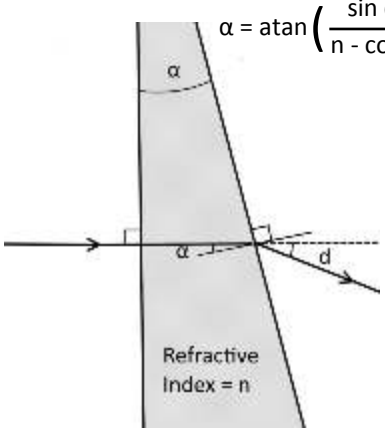
Focal length (mm) = $\frac{1000}{\text{dioptre}}$

*Example: 20 dioptre = 50mm F.L.*

**Beam Deviation through Wedge**

Angle (α) to provide a given deviation.

$\alpha = \text{atan}\left(\frac{\sin d}{n - \cos d}\right)$




**Transmission Absorption Coefficient**

$T_i = \exp(-\mu \cdot L)$

$\mu = -(\ln T) / L$

μ = Absorption Coefficient ($cm^{-1}$)
L = Path Length (cm)
$T_i$ = Internal Transmission (%/100)
$T_e = T_i$ + Reflection losses
n = Refractive Index

*Example: n = 1.5492 ; Path length 10cm*
*External Transmission = 76.8% = 0.768*
*Reflection loss is 0.0887 (page 14)*
*Ti = 0.768 + 0.0887 = 0.8567*
*μ = - (ln 0.8567) / 10 = 0.0155 $cm^{-1}$*

**S.I. Prefixes**

| | | | | | |
|---|---|---|---|---|---|
| Y | Yotta | $10^{24}$ | d | deci | $10^{-1}$ |
| Z | Zetta | $10^{21}$ | c | centi | $10^{-2}$ |
| E | Exa | $10^{18}$ | m | milli | $10^{-3}$ |
| P | Peta | $10^{15}$ | µ | micro | $10^{-6}$ |
| T | Tera | $10^{12}$ | n | nano | $10^{-9}$ |
| G | Giga | $10^{9}$ | p | pico | $10^{-12}$ |
| M | Mega | $10^{6}$ | f | femto | $10^{-15}$ |
| K | Kilo | $10^{3}$ | a | atto | $10^{-18}$ |
| h | hecto | $10^{2}$ | z | zepto | $10^{-21}$ |
| da | deka | 10 | y | yocto | $10^{-24}$ |

**Units Conversions**

| | | | | |
|---|---|---|---|---|
| 1 Å | = $10^{-4}$ µm | = $10^{-7}$ mm | = $10^{-8}$ cm | = $10^{-10}$ m |
| λ (µm) | 1.234 /ev | | | |
| 1 µm | $10^{3}$ nm | $10^{-3}$ mm | $10^{-4}$ cm | $10^{-6}$ m |
| 1 mm | 0.04” (40 thou) | | | |
| 1 microinch | 254 Å | 25.4 nm | 0.0254 µm | $10^{-6}$ inch |
| 1 thou | 0.001” | 25.4 µm | | |
| 1 inch | 25.5mm | 2.54 cm | | |
| 1 radian | 57.30° | | | |
| 1 mile | 1.609344 km | | | |
| 1° | 17.45 x $10^{-3}$ rad | | | |
| π rad | 180° | | | |
| Degrees °C = | 5 . (°F - 32) / 9 | Degrees °F = | 32 + ( 9 x °C) / 5 | |
| 1 lb | 0.4535 kg | 1 kg | 2.205 lb | |
| 1 imp gallon | 4.5454 litre | 1 litre | 0.22 imp gallon | 1.76 imp pint |
| Frequency MHz | 300 / λ metres | | | |
| Frequency GHz | 300 / λ mm | | | |
| Frequency THz | 300 / λ µm | | | |

**Pressure**

| | GPa | N $mm^{-2}$ | Kgf $cm^{-2}$ | Kgf $mm^{-2}$ | Mbar | lbf $in^{-2}$ | Dyne $cm^{-2}$ | Torr |
|---|---|---|---|---|---|---|---|---|
| Gpa | 1 | $1x10^{3}$ | $1.02x10^{4}$ | $1.02x10^{2}$ | 0.01 | $1.45x10^{5}$ | $1x10^{10}$ | $7.5x10^{6}$ |
| N $mm^{-2}$ | $1x10^{-3}$ | 1 | 10.2 | 0.102 | $1x10^{-5}$ | 145.0 | $1x10^{7}$ | $7.5x10^{3}$ |
| Kgf $cm^{-2}$ | $9.81x10^{-5}$ | $9.81x10^{-2}$ | 1 | 0.01 | $9.81x10^{-7}$ | 14.223 | $9.81x10^{5}$ | 735.6 |
| Kgf $mm^{-2}$ | $9.81x10^{-3}$ | 9.81 | 100 | 1 | $9.81x10^{-5}$ | $1.42x10^{3}$ | $9.81x10^{7}$ | $7.36x10^{4}$ |
| Mbar | 100 | $1x10^{5}$ | $1.02x10^{6}$ | $1.02x10^{4}$ | 1 | $1.45x10^{7}$ | $1x10^{12}$ | $7.5x10^{8}$ |
| lbf $in^{-2}$ | $6.89x10^{-6}$ | $6.89x10^{-3}$ | $7.03x10^{-2}$ | $7.03x10^{-4}$ | $6.89x10^{-8}$ | 1 | $6.89x10^{4}$ | 51.71 |
| Dyne $cm^{-2}$ | $1x10^{-10}$ | $1x10^{-7}$ | $1.02x10^{-6}$ | $1.02x10^{-8}$ | $1x10^{-12}$ | $1.45x10^{-5}$ | 1 | $7.5x10^{-4}$ |
| Torr | $1.33x10^{-7}$ | $1.33x10^{-4}$ | $1.36x10^{-3}$ | $1.36x10^{-5}$ | $1.33x10^{-9}$ | 0.019 | 1333.2 | 1 |

## Normal Atmospheric Pressure (1 atm)

| | |
|---|---|
| (1) pounds/sq inch | 14.7 psi |
| (2) inches of mercury | 29.9213" |
| (3) mm of mercury ( torr ) | 760 mm ( 760 torr ) |
| (4) millibar | 1013.240 mBar |
| (5) Pascals | 101.324 kPa |

*(2) and (3) are measures of a column of mercury supported by 1 atmosphere.*
*(4) and (5) are actual measures of force/area and take account of the density of mercury (13.595gm/cc at 0°C) and the acc of gravity (980.665 cm/sec²) when converting from a mercury barometer reference.*

Medium vacuum 20 to $10^{-2}$ torr — High vacuum $10^{-2}$ to $10^{-6}$ torr

Very high vacuum $10^{-6}$ to $10^{-9}$ torr — Ultra high vacuum >$10^{-9}$ torr

LEO (eg ISS orbit = $10^{-10}$ torr — Interplanetary Space = $10^{-16}$ torr

## Specific Heat

| | J $g^{-1}$ $K^{-1}$ | J $Kg^{-1}$ $K^{-1}$ | cal $g^{-1}$ $K^{-1}$ |
|---|---|---|---|
| 1 J $g^{-1}$ $K^{-1}$ = | 1 | 1000 | 0.2388 |
| 1 J $Kg^{-1}$ $K^{-1}$ = | 0.001 | 1 | 238.8 x $10^{-6}$ |
| 1 cal $g^{-1}$ $K^{-1}$ = | 4.1868 | 4186.8 | 1 |

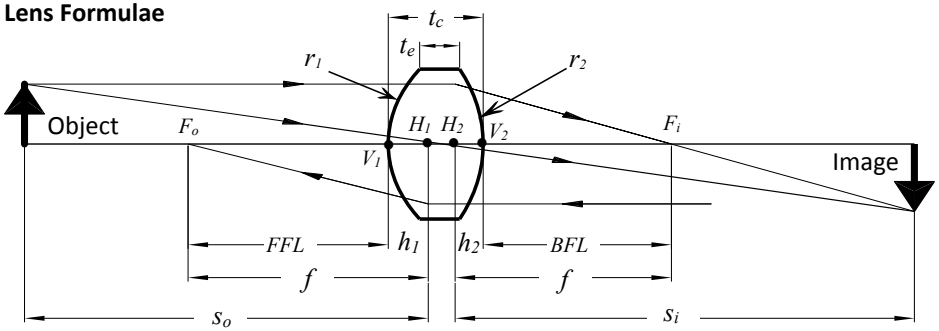
## Thermal Conductivity

| | W. $cm^{-1}$. $K^{-1}$ | W. $m^{-1}$. $K^{-1}$ | cal. $cm^{-1}$. s. $K^{-1}$ | Btu $ft^{-1}$. hr. $F^{-1}$ |
|---|---|---|---|---|
| 1 W. $cm^{-1}$. $K^{-1}$ = | 1 | 100 | 0.2388 | 694 |
| 1 W. $m^{-1}$. $K^{-1}$ = | 0.01 | 1 | 2.388 x $10^{-3}$ | 6.94 |
| 1 cal. $cm^{-1}$. s. $K^{-1}$ = | 4.1868 | 418.68 | 1 | 2903 |
| 1 Btu $ft^{-1}$. hr. $F^{-1}$ = | 1.44 x 10-3 | 0.144 | 34.5 x $10^{-4}$ | 1 |

## FORMULAE

## MATERIALS DATA

### Lens Formulae




Thin Lens Equation :

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

Lens Makers Equation :

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2} + \frac{(n-1)\,t_c}{n\,r_1\,r_2}\right)$$

For a thin lens, it reduces to :

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

For a plano-vex or plano-cave lens the equation reduces to :

$$\frac{1}{f} = \frac{(n-1)}{r}$$

Principal point distances are given :

$$h_1 = \frac{f\,(n-1)\,t_c}{n\,r_2} \qquad h_2 = \frac{f\,(n-1)\,t_c}{n\,r_1}$$

Thus :

$$BFL = f - h_2$$

Sag is the distance from the lens vertex to the lens edge

$$sag_1 = r_1 \pm \sqrt{r_1^2 - \frac{D^2}{4}} \qquad c_t = e_t + sag_1 + sag_2$$

Magnification of a lens = $\frac{s_i}{s_o} = \frac{f}{(f - s_o)}$ Conventionally taken as ≡ 0.25 P

*Sign convention of +ve and -ve radii and linear measurements must be applied consistently.*

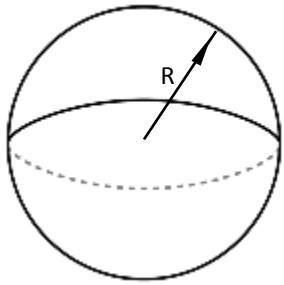
$s_o$ = Object distance
$F_1$ = Front focal point
$V_1$ = Front vertex
$H_1$ = First principal point
$r_1$ = Front radius of curvature
$f$ = Effective focal length
FFL = Front focal length
n = Lens Refractive Index in air

$s_i$ = Image distance
$F_2$ = Back focal point
$V_2$ = Back vertex
$H_2$ = Second principal point
$r_2$ = Back radius of curvature
D = Diameter of lens
BFL = Back focal length
P = Power in dioptre

**Spheres**

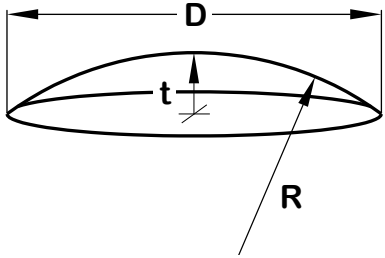
Area of surface = $4\pi R^2$

Volume = $\frac{4\pi R^3}{3}$




**Segment of a Sphere (Lens)**

The segment is a volume cut off from a sphere by a chord plane.



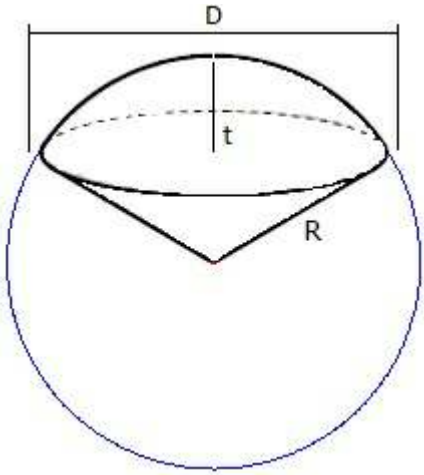

Spherical Area = $2\pi R T$

Total Area = $\frac{\pi (D^2 + 8R t)}{4}$

Volume = $\frac{\pi t (3D^2 + 4 t^2)}{24}$

**Sector of a Sphere**

The circular sector is a three dimensional portion of a sphere enclosed by the curved surface and the cone to the centre.




Total area = $\pi R ( 2t + \frac{D}{2})$

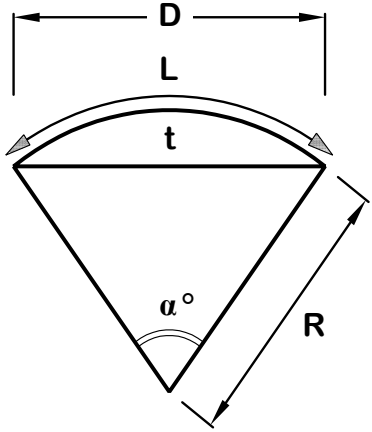
Total volume = $\frac{2}{3} \pi R^2 t$

## FORMULAE

### Segment of a Circle

The segment is a portion of a circle informally defined as a area cut off from the rest of the circle by a chord.

$$\text{Area} = \frac{(RL - RD - Dt)}{2} = \frac{(\pi R^2 \alpha°)}{360°} - \frac{(RD - Dt)}{2}$$




### Sector of a Circle

The circular sector is a wedge of a circle enclosed by the curved edge and the angle to the centre.

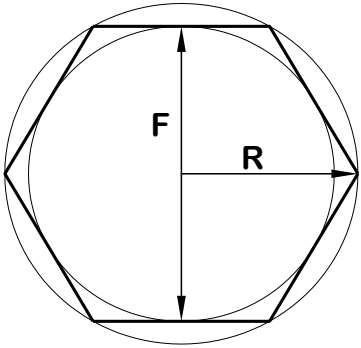
$$\text{Area} = \frac{(\pi R^2 \alpha°)}{360°} = \frac{(R\ L)}{2}$$

### Hexagon

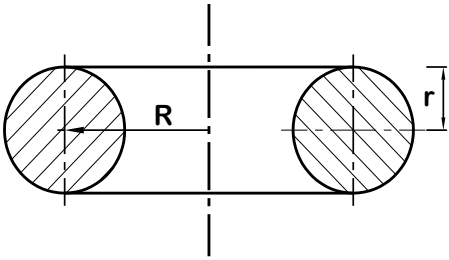
$$\text{Area} = 3 R^2 \cos 30° = 2.6 R^2$$
$$= F^2 \cos 30° = 0.866 F^2$$

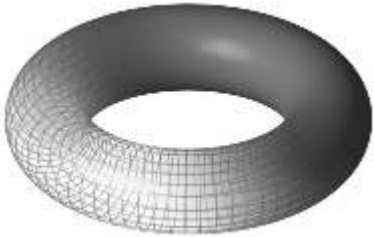
$$\text{Area External Circle} = \pi R^2 = 1.05 F^2$$

$$\text{Area Internal Circle} = \pi \frac{F^2}{4} = 2.35 R^2$$




### Torus



Area of Surface = $4\pi^2 . R. r$

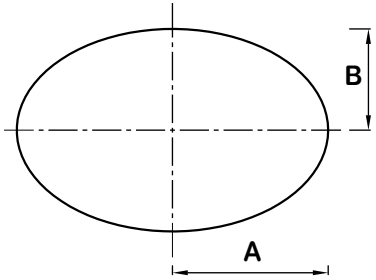
Volume = $2\pi^2 . R. r^2$

## FORMULAE

## MATERIALS DATA

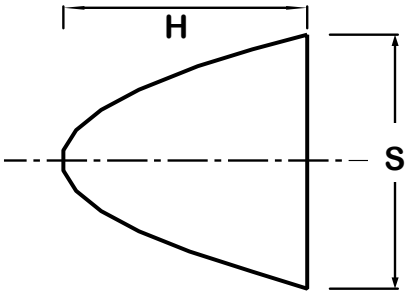
**Ellipse**

Area $= \pi\ A\ B$




**Parabola**

$$\text{Area} = \frac{S\ H}{3}$$




**Frustum of a Pyramid**

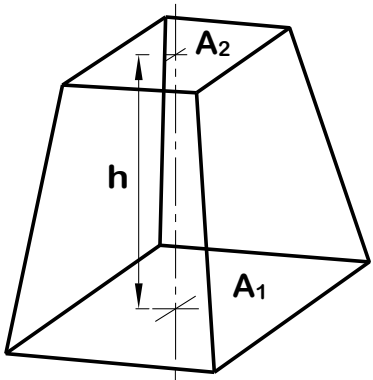
$$\text{Volume} = \frac{A_1 + A_2 + h\sqrt{(A_1\ A_2)}}{3}$$

$A_1$ = area of base $A_2$ = area of top

H = height

For a pyramid $A_2 = 0$

For a prism $A_1 = A_2$




**Frustum of a Cone**

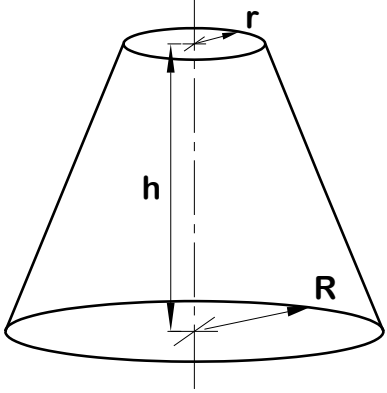
$$\text{Volume} = \frac{\pi\ h\ (R^2 + r^2 + R\ r)}{3}$$

R = radius of base r = radius of top

H = height

For a cone r = 0

For a cylinder R = r



Calculation of thickness of optical windows used in vacuum or pressure application

| DEFINITIONS | | | |
|---|---|---|---|
| $S_{max}$ | = Maximum Stress | R | = L/W |
| SF | = Safety Factor | T | = Thickness |
| $F_a$ | = Apparent Elastic Limit | P | = Load per Unit Area |
| K | = Empirical Constant | L, W | = Length and Width |
| D | = Unsupported Diameter for an unsupported window | | |

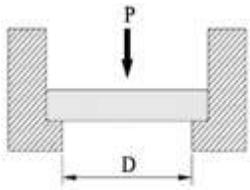
The maximum stress $S_{max}$ on a uniformly loaded window is given by:

$S_{max} = (K \cdot D^2 \cdot P) / (4 \cdot T^2)$ *and also* $S_{max} = F_a / SF$ *(See Safety Factor Box)*

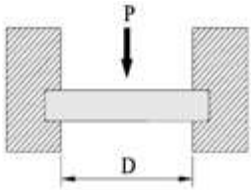
And then solving for thickness, T

$T = D \cdot \sqrt{(SF \cdot K / 4)} \cdot \sqrt{(P / F_a)}$ *(CIRCULAR WINDOWS)*

$T = L \cdot \sqrt{(SF\ K / 2)} \cdot \sqrt{(P / (F_a (1 + R^2)))}$ *(RECTANGULAR WINDOWS)*




**Unclamped, $S_{max}$ at centre**




**Clamped, $S_{max}$ at edge**

**CLAMPED**

Circular Window (Safety Factor of 4 & $K_c = 0.75$) $T = 0.866\ D\ \sqrt{(P / F_a)}$

Rectangular Window (Safety Factor of 4 & $K_c = 0.75$) $T = 1.23\ L\ \sqrt{(P / (F_a (1 + R^2)))}$

**UNCLAMPED**

Circular Window (Safety Factor of 4 & $K_u = 1.125$) $T = 1.06\ D\ \sqrt{(P / F_a)}$

Rectangular Window (Safety Factor of 4 & $K_u = 1.125$) $T = 1.50\ L\ \sqrt{(P / (F_a (1 + R^2)))}$

**CONSTANT K**

The value of **K** depends on the method of support, upon the force introduced in clamping and upon the brittle / ductile character of the window material involved.

Empirically, a **K** value of 0.75 is found suitable for most optical crystals when the perimeter is clamped, and a value 50% greater when unclamped.

$$K_c = 0.75 \qquad K_u = 1.125$$

**SAFETY FACTOR**

To avoid plastic deformation, the maximum stress ($S_{max}$) should be less than the Apparent Elastic Limit ($F_a$) by an appropriate Safety Factor (SF)

$$S_{max} = F_a / SF$$

A modest safety factor of 4 (i.e., maximum stress equals one quarter of the elastic limit) seems to suffice for many laboratory applications where the operating conditions are reasonably under control. Severe conditions such as thermal shock require special consideration and may even result in a decision to use a *reduced* thickness. The published Apparent Elastic Limit of some materials may not be completely reliable. Crystals vary and cleavage may occur according to grain boundaries or the particular cut of the ingot. Ultimately, the final design thickness must be a carefully considered decision and may need to be empirically tested. Crystran Ltd can accept no responsibility for the adoption of these calculations and recommendations.

**NOTES:**

- A carefully designed window may still break before any significant loading if the mounting introduces any localised stress.
- Mismatch of expansion coefficients generally dictates the use of resilient material between window and mounting.
- Thermal outgassing used in UHV systems should be undertaken with caution with crystal windows as thermal shock may initial cleavage in some crystals
- The constant for clamped mounting allows for no flexure at the wall. The use of soft gaskets may allow flexure so the formula for the "unclamped" condition should be used.

The standard aspheric formula is:

$$Z = \frac{cr^2}{1+\sqrt{1-(1+K)c^2r^2}} + A_4r^4 + A_6r^6 + A_8r^8 + A_{10}r^{10} \ldots$$

Where:

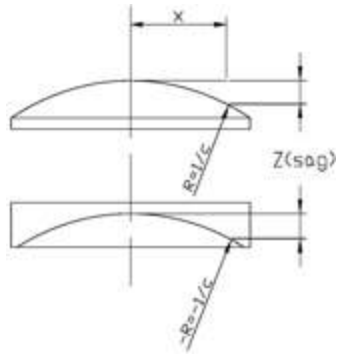
Z = Depth or "Sag" of the curve

r = Distance from the centre

C = Curvature ( = 1 / Radius)

K = Conic Constant

$A_x$ = Higher order terms




Be aware that for some reason many designers show c as the Radius (R) and forget to show the reciprocal. This of course renders the equation obviously unworkable in most cases but it can catch you out. The Radius (R) does not represent the closest spherical surface, but the spherical surface from which the aspheric terms cause the curve to diverge from it, either shallower or deeper than the spherical curve. The closest or "best fit" spherical surface is the Radius which matches the aspheric sag at the largest useful diameter.

Taking care to obey the sign conventions, the sag figure must be added to the lens centre thickness to derive the actual lens thickness at any point. Do not simply present sag data to the machinist, they are likely to generate to that figure and produce a lens with zero edge thickness.

Most optical designers use only the even-order terms from $A_2$ to $A_{20}$, but should they be required the odd-order terms are available, for the profile only, from $A_1$ to $A_{19}$

The conic constant K has traditionally been used to design the first aspheres; simple parabolas and hyperbolas. It is now largely redundant in the above equation as the $A_x$ terms can define any surface. A spherical surface is defined by the above equation when K=0 and all $A_x$ terms are zero.

## GUIDES - Cleaning Optics

Crystal optics are delicate and should be treated carefully if they are to be cleaned. Described is a method, but the technique comes with practice. Handle optics by the edge using lint-free nylon gloves or plastic protective gloves when cleaning with solvent, checking that the solvent does not attack the glove. Handle optics as little as possible. Cleaning may create fine scratches which you cannot see easily but which may contribute to scattering, particularly in the UV. If the optic is mounted, try never to let solvent creep into the mounting ring. Use an air jet only for removal of dust.

**Very Delicate Materials: CsI, KRS5, Germanium, Zinc Selenide, Zinc Sulphide.**

Soft materials are inclined to take marks (sleeks) or show up marks easily. Wash in a solvent such as methanol or propanol for light marking. Use an environment friendly solvent such as NuSol Rapide (a replacement for trichloroethylene which is available in the UK) or otherwise acetone, for greasy or waxy contaminants. Soak the optic and wipe whilst wet with cotton wool (absorbent cotton in the USA) dipped in the solvent and let the optic dry by evaporation or assist it with airflow as it is wiped.

**Delicate Materials: Fluorides, Silicon.**

These should be treated as above where practical, but it is often preferable to clean them carefully with a damp tissue. We use Kimtech Science 100 professional wipes. Do not rub the optic, but wipe gently and allow the thinnest film of solvent to dry by evaporation.

**Harder Materials: Glasses, Sapphire.**

We treat these materials in the same manner as delicate materials.

**Coated Materials:** Coatings should be treated as delicate even though they can be more rugged than the crystal base material. DLC on germanium is an example of a very tough coating.

**Aqueous Cleaning: Calcium Fluoride, Magnesium Fluoride, Lithium Fluoride**

We have become aware that very small absorptions (< 1%) can occur due to closely bonded organic surface contamination. Notably, this is found at 3.4μm and probably due to waxes used in the polishing process. Aqueous cleaning using demineralized water with a surfactant detergent such as Alconox can be effective. Use a bath of the fresh warm solution in place of, or additionally to, the solvent methods. Soak the optic for 10 minutes and wipe while wet with cotton wool dipped in the solvent. Rinse in clean warm demineralized water dry by evaporation or assist it with airflow.

## GUIDES - Materials

Crystran publish a number of guides with practical details relating to the grades and uses of the materials that we supply. Because these guides are reviewed on a regular basis as old grades and trade designations disappear or new ones become available, we reference the guides here with a link to our website repository where the latest versions will be available.

Please go to our website at www.crystran.co.uk/documents

Guide to Calcium Fluoride Grades

Guide to Silica Glass

Guide to Quartz Crystal

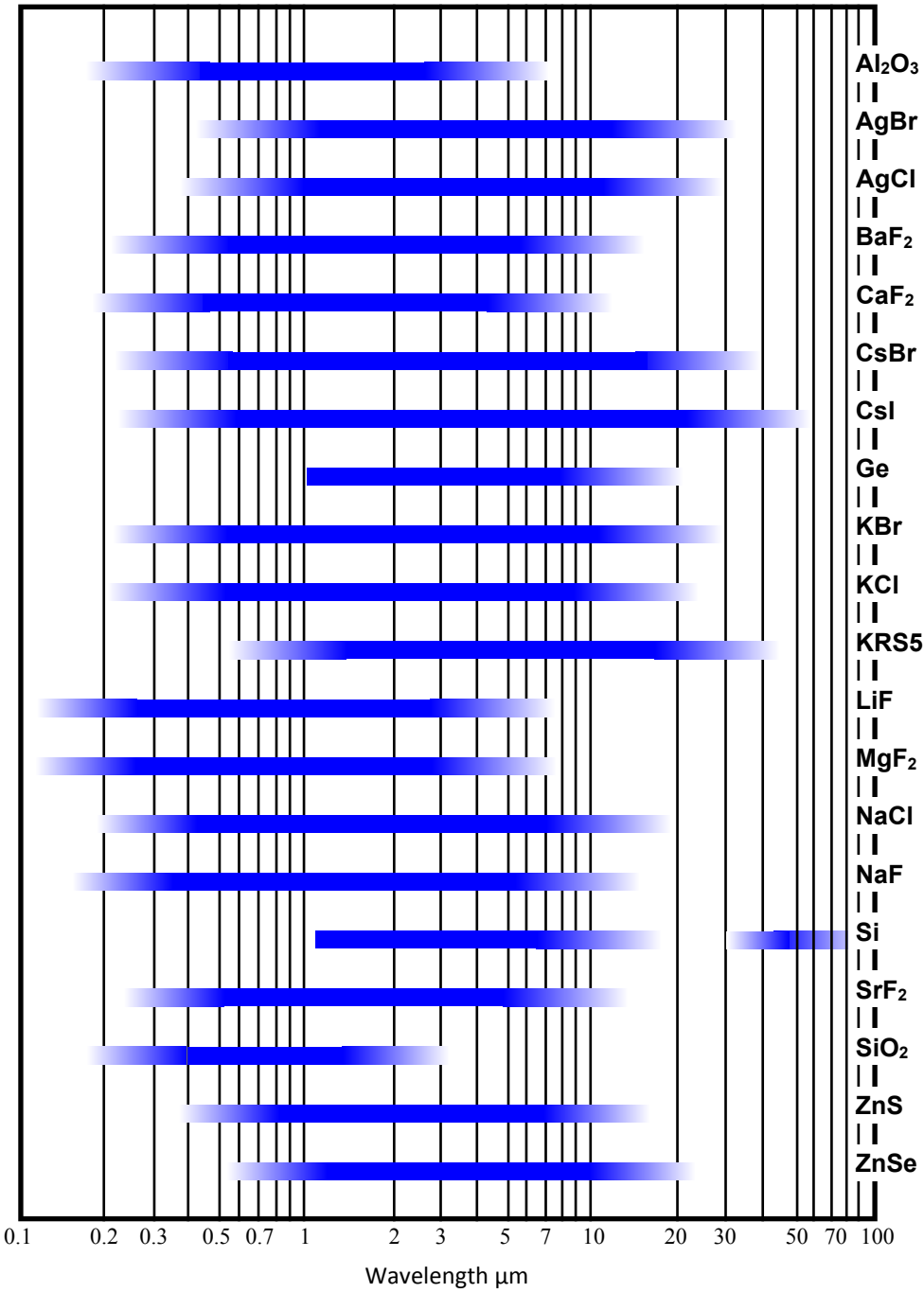
Guide to Sapphire

Guide to Lanthanum Fluoride

Guide to Crystal Quality

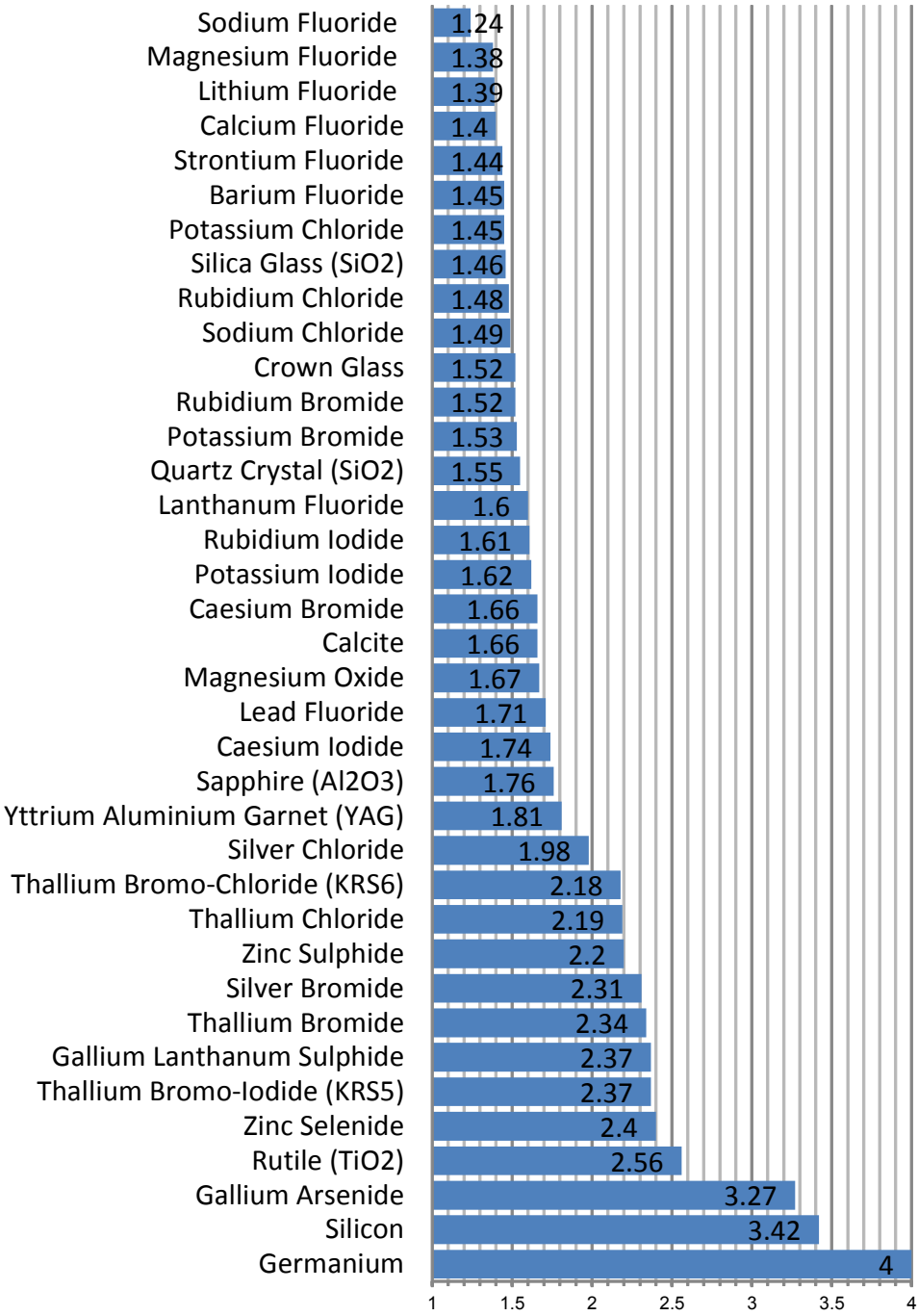
Guide to Raman Material

All MSDS


$Al_2O_3$
AgBr
AgCl
$BaF_2$
$CaF_2$
CsBr
CsI
Ge
KBr
KCl
KRS5
LiF
$MgF_2$
NaCl
NaF
Si
$SrF_2$
$SiO_2$
ZnS
ZnSe
0.1
0.2
0.3
0.5
0.7
1
2
3
5
7
10
20
30
50
70
100
Wavelength µm

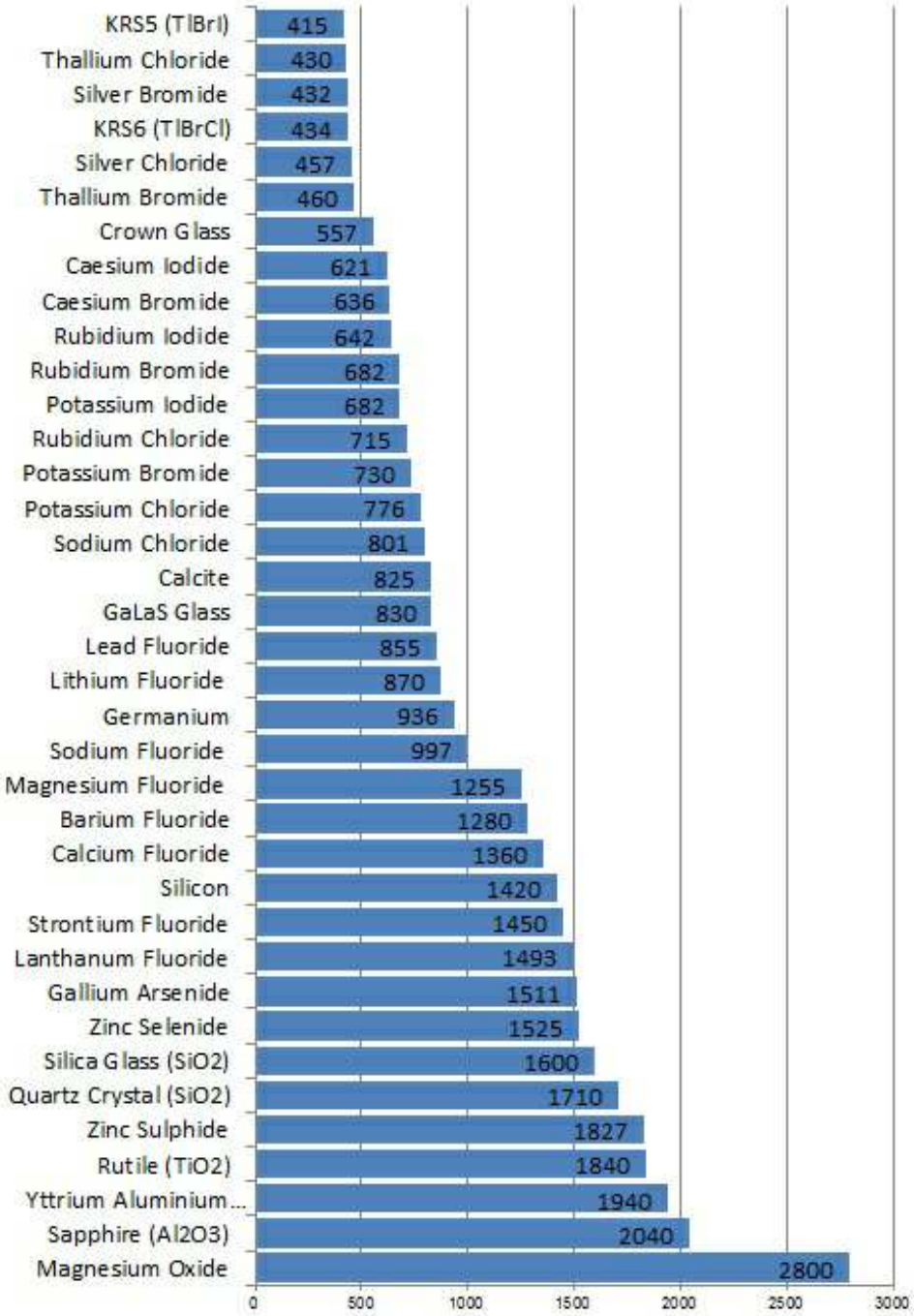
**COMPARISON OF DATA - Refractive Index**

**MATERIALS DATA**



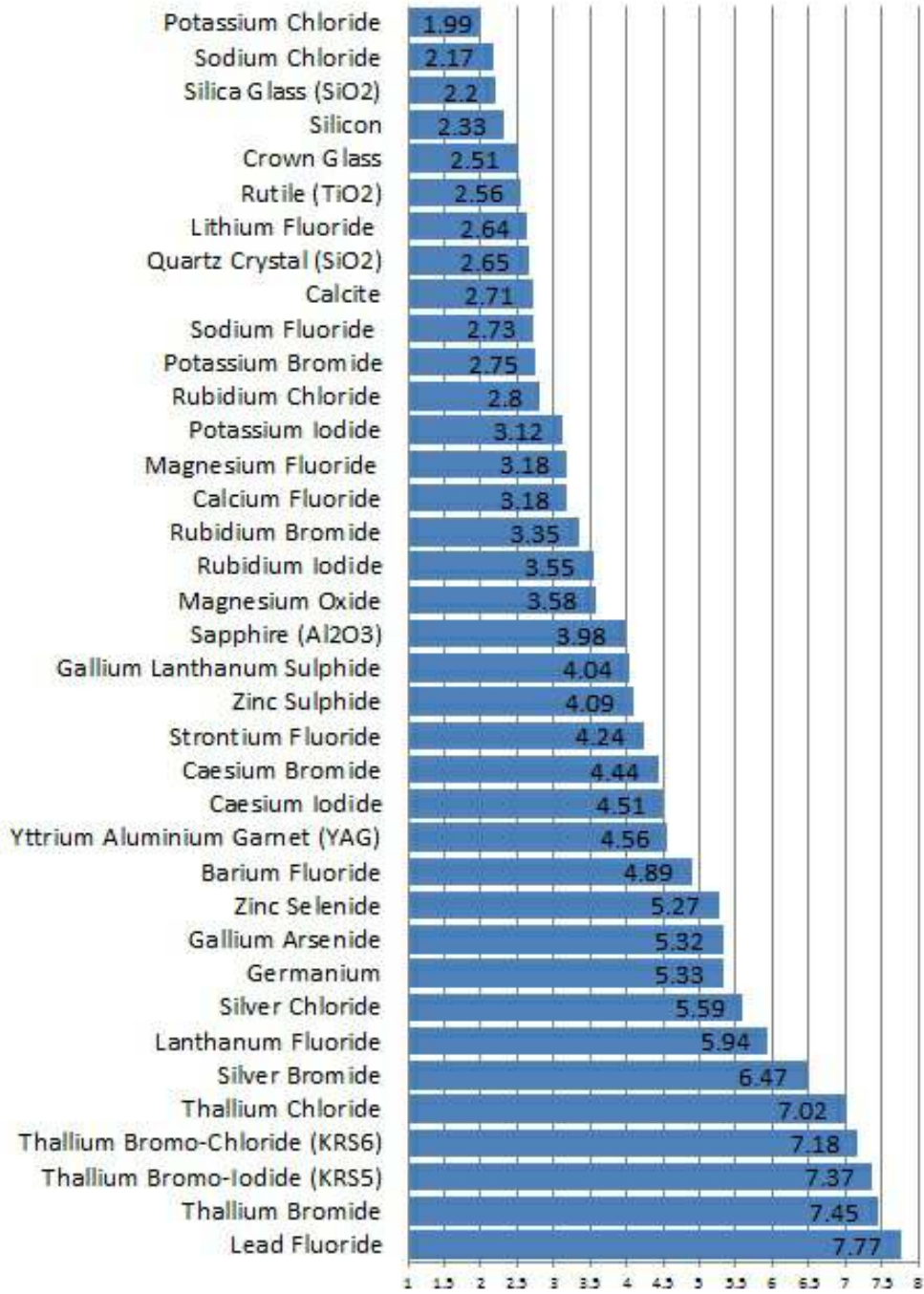
**COMPARISON OF DATA - Melting Point °C**

**MATERIALS DATA**

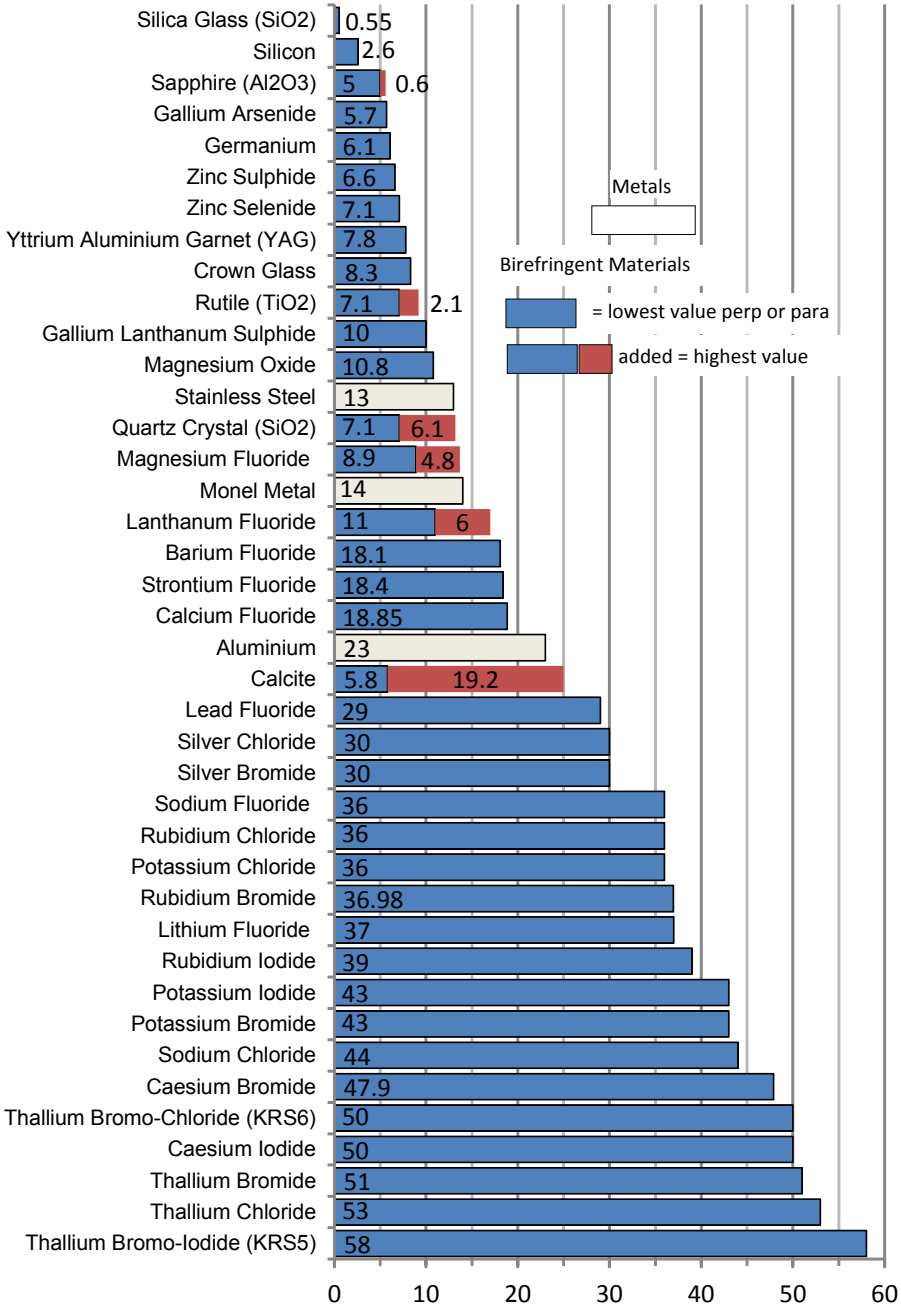


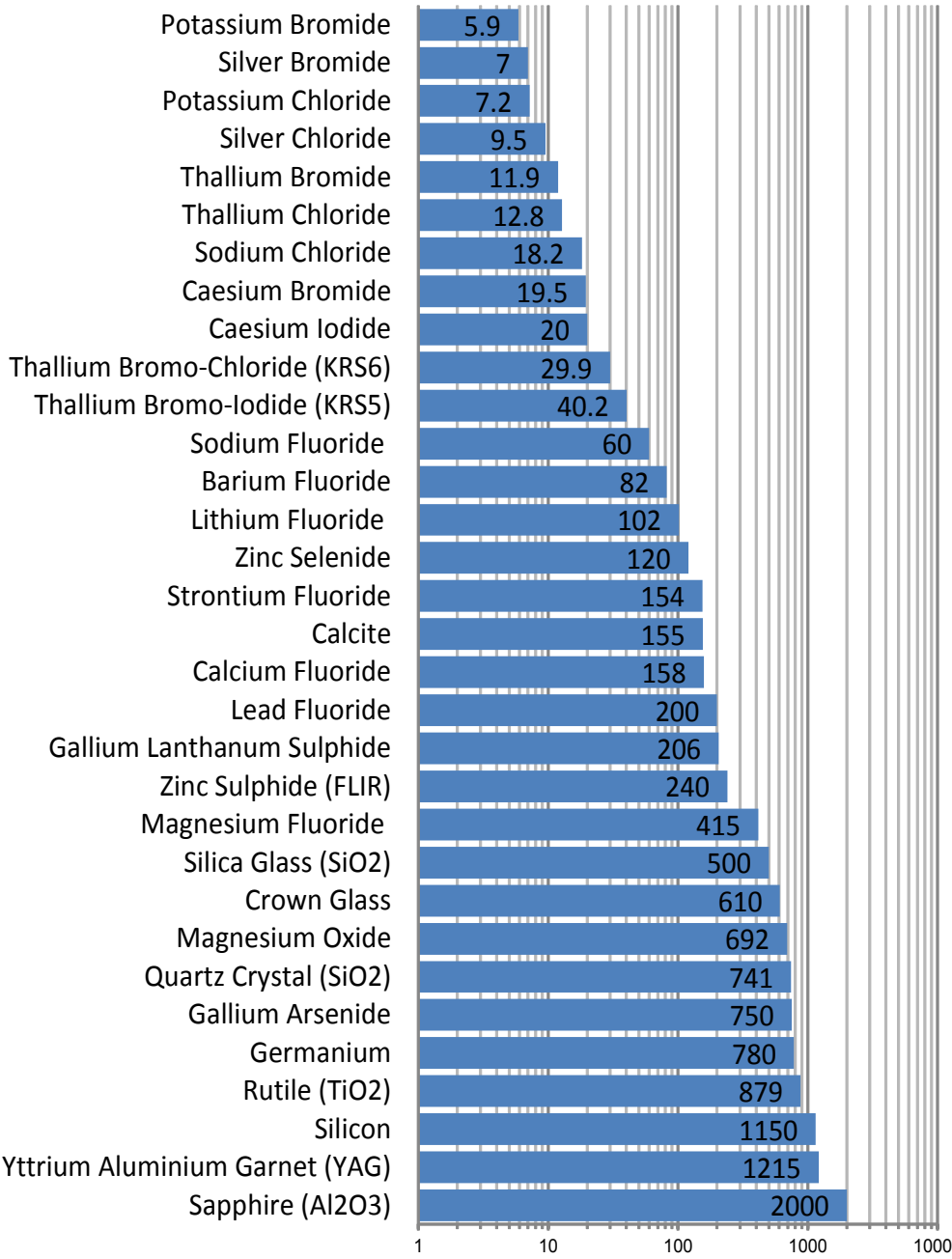
**COMPARISON OF DATA - Density g/cc**

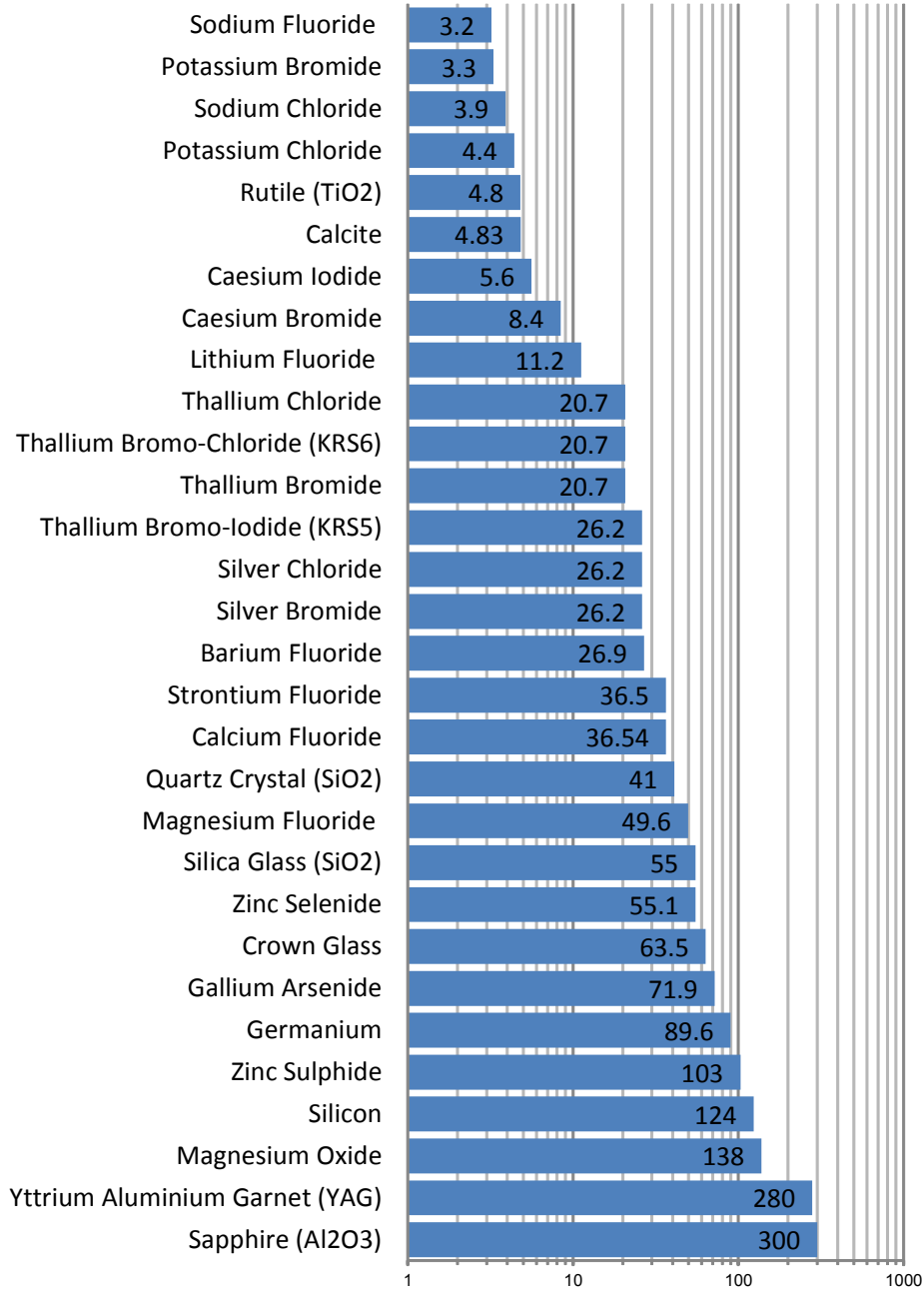
**MATERIALS DATA**



## COMPARISON OF DATA - Expansion Coefficient x $10^{-6}$ MATERIALS DATA




Potassium Bromide 5.9
Silver Bromide 7
Potassium Chloride 7.2
Silver Chloride 9.5
Thallium Bromide 11.9
Thallium Chloride 12.8
Sodium Chloride 18.2
Caesium Bromide 19.5
Caesium Iodide 20
Thallium Bromo-Chloride (KRS6) 29.9
Thallium Bromo-Iodide (KRS5) 40.2
Sodium Fluoride 60
Barium Fluoride 82
Lithium Fluoride 102
Zinc Selenide 120
Strontium Fluoride 154
Calcite 155
Calcium Fluoride 158
Lead Fluoride 200
Gallium Lanthanum Sulphide 206
Zinc Sulphide (FLIR) 240
Magnesium Fluoride 415
Silica Glass (SiO2) 500
Crown Glass 610
Magnesium Oxide 692
Quartz Crystal (SiO2) 741
Gallium Arsenide 750
Germanium 780
Rutile (TiO2) 879
Silicon 1150
Yttrium Aluminium Garnet (YAG) 1215
Sapphire (Al2O3) 2000
1
10
100
1000
10000


Sodium Fluoride 3.2
Potassium Bromide 3.3
Sodium Chloride 3.9
Potassium Chloride 4.4
Rutile (TiO2) 4.8
Calcite 4.83
Caesium Iodide 5.6
Caesium Bromide 8.4
Lithium Fluoride 11.2
Thallium Chloride 20.7
Thallium Bromo-Chloride (KRS6) 20.7
Thallium Bromide 20.7
Thallium Bromo-Iodide (KRS5) 26.2
Silver Chloride 26.2
Silver Bromide 26.2
Barium Fluoride 26.9
Strontium Fluoride 36.5
Calcium Fluoride 36.54
Quartz Crystal (SiO2) 41
Magnesium Fluoride 49.6
Silica Glass (SiO2) 55
Zinc Selenide 55.1
Crown Glass 63.5
Gallium Arsenide 71.9
Germanium 89.6
Zinc Sulphide 103
Silicon 124
Magnesium Oxide 138
Yttrium Aluminium Garnet (YAG) 280
Sapphire (Al2O3) 300
1
10
100
1000

## Barium Fluoride ($BaF_2$)

Barium Fluoride is grown by vacuum Stockbarger technique. Unlike CaF2, BaF2 is not found in the native state and all material must be synthesised chemically making BaF2 relatively expensive to produce. Barium Fluoride cleaves easily and is highly susceptible to thermal shock. It polishes well and can be etched (5). The highest purity VUV material can be qualified as fast scintillator grade.

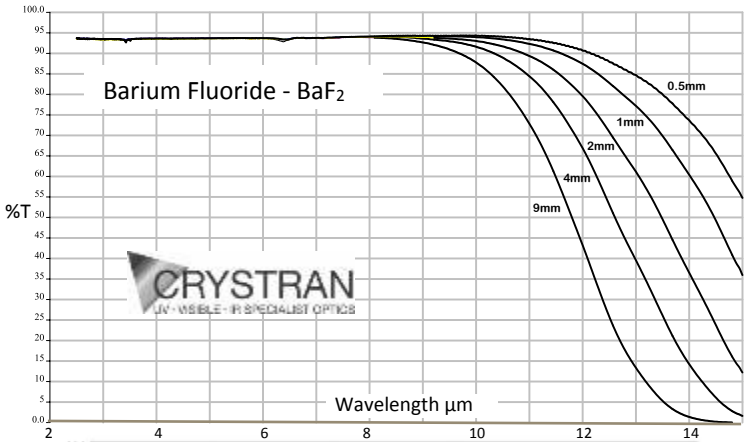
**APPLICATIONS:** Barium Fluoride is used in spectroscopic components. It is often suitable for applications in the passive IR band (8 to 14µm) and is often used as a view-port window for thermography. For an equivalent thickness the transmission extends approximately 1µm further into the IR than CaF2. The highest quality $BaF_2$ also has application as the fastest known scintillator material and is used in High Energy Physics Experiments.

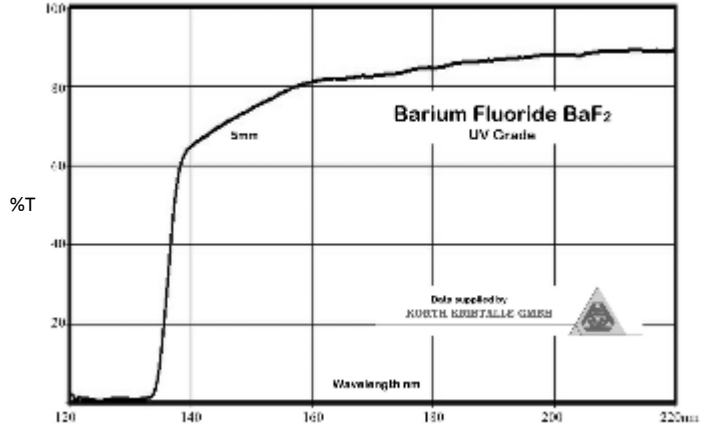
| | |
|---|---|
| Transmission Range | 0.15 to 12µm |
| Refractive Index | 1.45 at 5µm (1) |
| Reflection Loss | 6.5% at 5µm (2 surfaces) |
| Absorption Coefficient | $3.2 \times 10^{-4}$ $cm^{-1}$ @ 6µm |
| Reststrahlen Peak | 47 µm |
| dn/dT | $-15.2 \times 10^{-6}$/°C (2) |
| dn/dµ = 0 | 1.95µm |
| Density | 4.89 g/cc |
| Melting Point | 1386°C |
| Thermal Conductivity | 11.72 W $m^{-1}$ $K^{-1}$ @ 286 K |
| Thermal Expansion | $18.1 \times 10^{-6}$ $K^{-1}$ @ 273 K |
| Hardness | Knoop 82 with 500g indenter (4) |
| Specific Heat Capacity | 410 J $Kg^{-1}$ $K^{-1}$ (3) |
| Dielectric Constant | 7.33 at 1 MHz |
| Youngs Modulus (E) | 53.07 GPa (3) |
| Shear Modulus (G) | 25.4 GPa (3) |
| Bulk Modulus (K) | 56.4 GPa |
| Elastic Coefficients | $C_{11}$ = 89.2 $C_{12}$ = 40.0 $C_{44}$ = 25.4 (2) |
| Apparent Elastic Limit | 26.9 MPa (300psi) (4) |
| Poisson Ratio | 0.343 |
| Solubility | 0.17g/100g water at 23°C |
| Molecular Weight | 175.36 |
| Class/Structure | Cubic $Fm\bar{3}m$ (#225) Fluorite structure<br>Cleaves on (111) |

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) I.H.Malitson; J.Opt.Soc.Am. Vol52, p1377, 1962
(3) D.Girlich; Elastic Constants of BaF2; Phys.Rev. Vol135, p1826, 1964
(4) S.Ballard et al; J.Opt.Soc.Am. Vol42, p684, 1952
(5) US patent. Chemical polish. 4,040,896 1977
(6) M.Laval et al; Nu. Insts.Meth, V206 p169, 1983

## Barium Fluoride ($BaF_2$)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.1408 | 1.815 | 0.1452 | 1.7820 | 0.1477 | 1.7670 |
| 0.1500 | 1.6780 | 0.2000 | 1.557 | 0.2652 | 1.5122 |
| 0.2803 | 1.5066 | 0.2893 | 1.5039 | 0.2967 | 1.5019 |
| 0.3021 | 1.5004 | 0.3130 | 1.4978 | 0.3254 | 1.4952 |
| 0.3403 | 1.4925 | 0.3466 | 1.4915 | 0.3610 | 1.4894 |
| 0.3663 | 1.4887 | 0.4046 | 1.4844 | 0.5461 | 1.4759 |
| 0.5893 | 1.4744 | 0.6438 | 1.4730 | 0.6563 | 1.4727 |
| 0.7065 | 1.4718 | 0.8521 | 1.4699 | 0.8944 | 1.4694 |
| 1.0140 | 1.4685 | 1.1287 | 1.4678 | 1.3673 | 1.4667 |
| 1.5295 | 1.4661 | 1.6810 | 1.4656 | 1.7012 | 1.4655 |
| 1.9701 | 1.4647 | 2.3254 | 1.4636 | 2.6738 | 1.4623 |
| 3.2434 | 1.4602 | 3.4220 | 1.4594 | 5.1380 | 1.4501 |
| 5.5490 | 1.44732 | 6.2380 | 1.4422 | 6.6331 | 1.4390 |
| 7.0442 | 1.4353 | 7.2680 | 1.4331 | 9.7240 | 1.4051 |
| 10.346 | 1.3936 | | | | |



## Cadmium Telluride (CdTe)

***CAUTION: Cadmium salts are considered TOXIC and should be handled with care.***

CdTe is rarely used because of its toxicity. The finished optics are not particularly hazardous but should be handled with care. However, difficulties with processing cadmium compounds means that very few optical companies will cut and polish the material. Crystran Ltd does not supply CdTe. This data is provided for reference only. A form of CdTe was originally utilised as the obsolete Kodak designation of IRTRAN-6

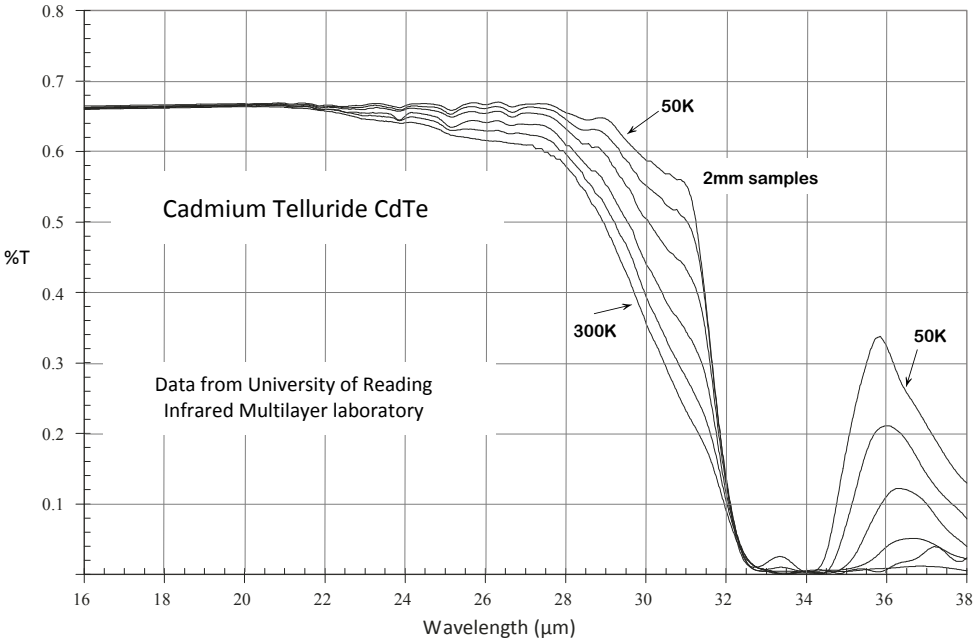
**APPLICATIONS:** Cadmium Telluride can be used for spectroscopy and where deep IR transmission is required. It is relatively workable and offers transmission to >20µm. CdTe has some application for solar cells.

| | |
|---|---|
| Transmission Range | 0.85 to 28µm (1)(3) |
| Refractive Index | 2.653 @ 10µm (1) |
| Reflection Loss | 32% @ 10µm |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | $50 \times 10^{-6}\ K^{-1}$ |
| dn/dµ = 0 | n/a |
| Density | $6.2\ g\ cm^{-3}$ (2) |
| Melting Point | 1092°C (4) |
| Thermal Conductivity | $6.2\ W\ m^{-1}\ K^{-1}$ at 293 K |
| Thermal Expansion | $5.9 \times 10^{-6}\ K^{-1}$ at 293 K |
| Hardness | Knoop 54 (3) |
| Specific Heat Capacity | $210\ J\ Kg^{-1}\ K^{-1}$ at 293 K |
| Dielectric Constant | 11 @ 1MHz |
| Youngs Modulus (E) | 36.52 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 25 GPa |
| Elastic Coefficients | $C_{11}$=53.51; $C_{12}$=36.81; $C_{44}$=19.94 |
| Apparent Elastic Limit | 5.9 MPa (3) |
| Poisson Ratio | 0.41 |
| Solubility | Insoluble in water |
| Molecular Weight | 240.02 |
| Class/Structure | Cubic ZnS (110) cleavage |

(1) Handbook Optical Constants, ed. Palik, V1, ISBN 0-12-544420-6
(2) Capper; Properties of Narrow Gap Cadmium-Based Compounds, IET, ISBN 978-0-85296-880-2
(3) Hawkins, Sherwood, Djotni; Mid IR Filters for astronomical and remote sensing instrumentation, invited paper SPIE Conference, Glasgow (2008)
(4) David R Lide; CRC Handbook of Chemistry and Physics, 78th ed (1997)

## Cadmium Telluride (CdTe)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.8 | 2.876 | 1.0 | 2.840 | 2.0 | 2.713 |
| 2.5 | 2.702 | 3.0 | 2.695 | 3.5 | 2.691 |
| 4.0 | 2.6807 | 5.0 | 2.684 | 6.0 | 2.681 |
| 7.0 | 2.679 | 8.0 | 2.677 | 10.0 | 2.653 |
| 12.5 | 2.646 | 15.5 | 2.6407 | 20.0 | 2.614 |
| 22.2 | 2.601 | 24.8 | 2.5801 | 26.32 | 2.570 |
| 27.03 | 2.564 | | | | |



## Caesium Bromide (CsBr)

CsBr is grown by sealed ampoule Stockbarger technique. It is a soft pliable material.

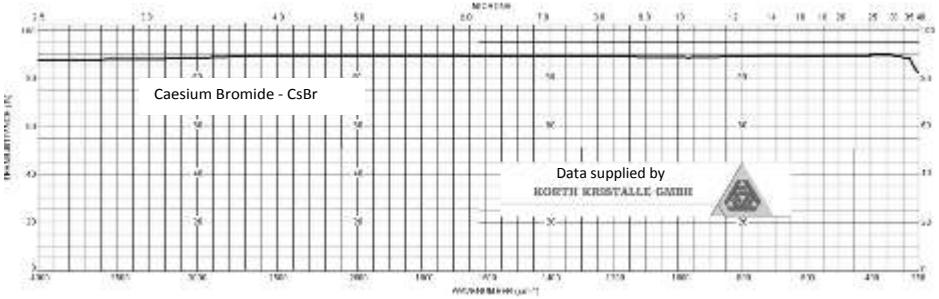
**APPLICATIONS:** Caesium Bromide has limited application in the deep IR. It is slightly more amenable to optical working than CsI and is sometimes used as a beamsplitter component in wide-band spectrophotometers

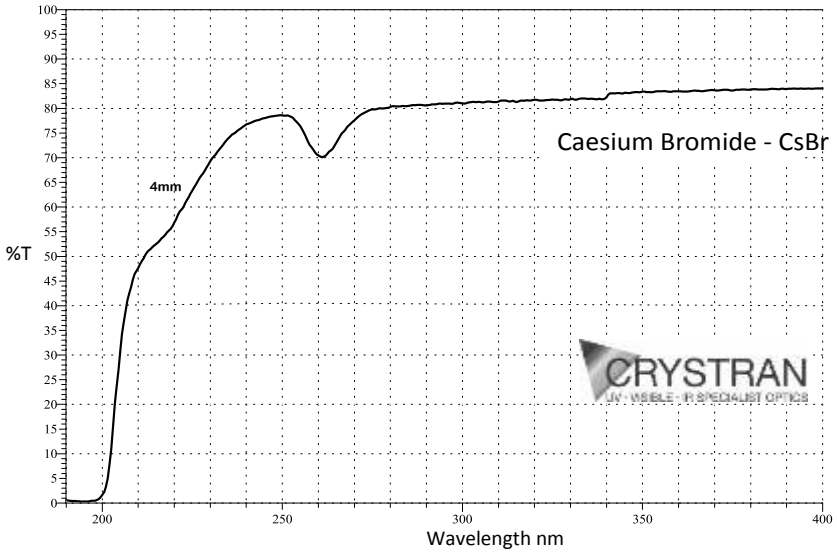
| | |
|---|---|
| Transmission Range | 0.25 to 40µm (1) |
| Refractive Index | 1.6612 at 11µm (1) |
| Reflection Loss | 11.6% at 11µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 121.2µm (2) |
| dn/dT | $-84 \times 10^{-6}$/°C at 0.6µm (5) |
| dn/dµ = 0 | 5.3µm |
| Density | 4.44 g/cc |
| Melting Point | 636 °C |
| Thermal Conductivity | 0.94 W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | $47.9 \times 10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 19.5 with 200g indenter |
| Specific Heat Capacity | 263.8 J $Kg^{-1}$ $K^{-1}$ (3) |
| Dielectric Constant | 6.51 at 2 MHz |
| Youngs Modulus (E) | 15.85 GPa (4) |
| Shear Modulus (G) | 7.5 GPa |
| Bulk Modulus (K) | 13.01 GPa |
| Elastic Coefficients | $C_{11}$=30.97; $C_{12}$=4.03; $C_{44}$=7.5 |
| Apparent Elastic Limit | 8.4 MPa (1220 psi) (4) |
| Poisson Ratio | 0.279 |
| Solubility | 124.3g/100g water at 273K |
| Molecular Weight | 212.83 |
| Class/Structure | Cubic CsCl, Pm3m, no cleavage planes |

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Mitsuishi et al., J Opt Soc. Am. V52, p14, 1962
(3) Kelly, Bureau of Mines Bulletin, No371, p51, 1934
(4) S.Ballard et al; J.Opt.Soc.Am. Vol42, p684, 1952
(5) H.H.Li; J.Phys. Chem. Ref. Data. Vol 5, No 2. 1976

## Caesium Bromide (CsBr)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.5 | 1.70896 | 1.0 | 1.67793 | 2.0 | 1.67061 |
| 3.0 | 1.66901 | 4.0 | 1.66813 | 5.0 | 1.66737 |
| 6.0 | 1.66659 | 7.0 | 1.66573 | 8.0 | 1.6477 |
| 9.0 | 1.6637 | 10.0 | 1.66251 | 11.0 | 1.6612 |
| 12.0 | 1.65976 | 13.0 | 1.6582 | 14.0 | 1.6561 |
| 15.0 | 1.65468 | 16.0 | 1.65272 | 17.0 | 1.65062 |
| 180 | 1.64838 | 19.0 | 1.646 | 20.0 | 1.64348 |
| 21.0 | 1.6408 | 22.0 | 1.63798 | 23.0 | 1.635 |
| 25.0 | 1.62856 | 26.0 | 1.62509 | 27.0 | 1.62146 |
| 28.0 | 1.61764 | 29.0 | 1.61365 | 30.0 | 1.60947 |
| 31.0 | 1.6051 | 32.0 | 1.60053 | 33.0 | 1.59576 |
| 34.0 | 1.59078 | 35.0 | 1.58558 | 36.0 | 1.58016 |



## Caesium Iodide (CsI)

Caesium Iodide is grown by sealed ampoule Stockbarger techniques with ingots of approximately 70mm diameter. CsI is very soft and pliable.

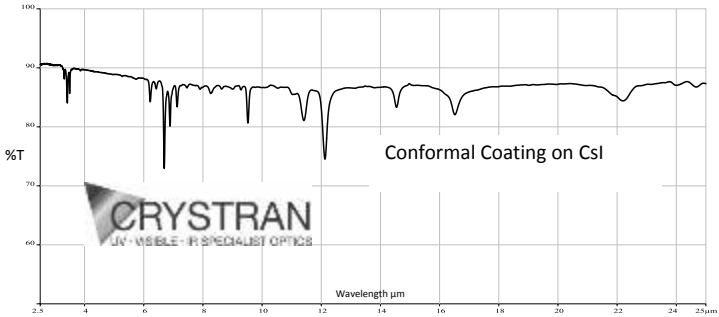
**APPLICATIONS:** Caesium Iodide is the material with the deepest known IR transmission, and is sometimes used for components in the widest range spectrophotometers. An extremely soft material, Caesium Iodide is extremely difficult to polish, and so performance is compromised for range. Doped with Thallium, CsI(Tl) is a useful scintillator which emits at a wavelength that is a good match for Silicon photodiodes. Arrays of Caesium Iodide(Tl) are used in security imaging systems.

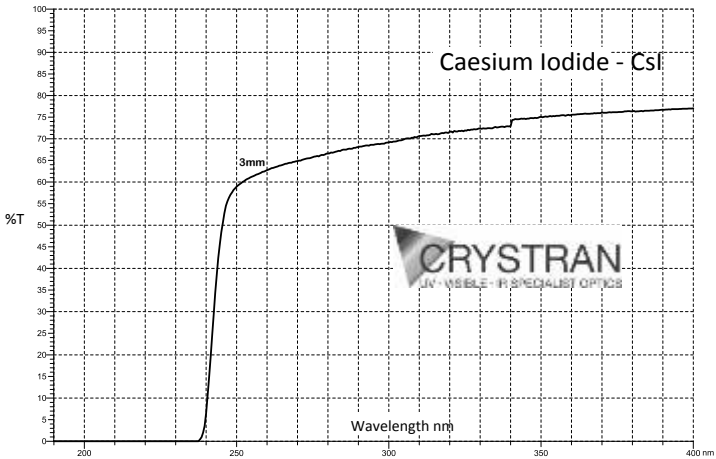
| | |
|---|---|
| Transmission Range | 0.25 to 55µm (1) |
| Refractive Index | 1.73916 at 10µm (1)(2) |
| Reflection Loss | 13.6% at 10µm |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 145.8µm |
| dn/dT | $-99.3 \times 10^{-6}$ /°C (2) |
| dn/dµ = 0 | 6µm |
| Density | 4.51 g/cc |
| Melting Point | 621 °C |
| Thermal Conductivity | 1.1 W $m^{-1}$ $K^{-1}$ at 298 K (3) |
| Thermal Expansion | $48.3 \times 10^{-6}$ $K^{-1}$ at 293 K (3) |
| Hardness | Knoop 20 with 200g indenter |
| Specific Heat Capacity | 201 J $Kg^{-1}$ $K^{-1}$ (4) |
| Dielectric Constant | 5.65 at 1 MHz |
| Youngs Modulus (E) | 5.3 GPa |
| Shear Modulus (G) | 6.24 GPa |
| Bulk Modulus (K) | 12.67 GPa |
| Elastic Coefficients | $C_{11}$=24.6 $C_{12}$=6.7 $C_{44}$=6.24 |
| Apparent Elastic Limit | 5.6 MPa (810psi) |
| Poisson Ratio | 0.214 |
| Solubility | 44 g/100 g water at 0 °C |
| Molecular Weight | 259.83 |
| Class/Structure | Cubic CsCl, Pm3m, no cleavage, deforms |

(1) Handbook Optical Constants, ed Palik, V2, ISBN 0-12-544422-2
(2) Rodney, J.Opt.Soc.Am. V45, p987, 1955
(3) Combes et al, J.Opt.Soc.Am. V41, p215, 1951
(4) Kelly, Bureau of Mines Bulletin, No371, p51, 1934

## Caesium Iodide (CsI)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.5 | 1.8064 | 1.0 | 1.7572 | 2.0 | 1.7466 |
| 3.0 | 1.7440 | 4.0 | 1.7431 | 5.0 | 1.7424 |
| 6.0 | 1.7418 | 7.0 | 1.7412 | 8.0 | 1.7406 |
| 9.0 | 1.7399 | 10.0 | 1.7392 | 11.0 | 1.7384 |
| 12.0 | 1.7375 | 13.0 | 1.7365 | 14.0 | 1.7355 |
| 15.0 | 1.7344 | 16.0 | 1.7332 | 17.0 | 1.7319 |
| 18.0 | 1.7306 | 19.0 | 1.7291 | 20.0 | 1.7276 |
| 21.0 | 1.7260 | 22.0 | 1.7244 | 23.0 | 1.7226 |
| 24.0 | 1.7207 | 25.0 | 1.7188 | 26.0 | 1.7168 |
| 27.0 | 1.7147 | 28.0 | 1.7125 | 29.0 | 1.7101 |
| 30.0 | 1.7077 | 31.0 | 1.7052 | 32.0 | 1.7027 |
| 33.0 | 1.7000 | 34.0 | 1.6972 | 35.0 | 1.6943 |
| 36.0 | 1.6913 | 37.0 | 1.6882 | 38.0 | 1.6849 |
| 39.0 | 1.6816 | 40.0 | 1.6781 | 41.0 | 1.6746 |
| 42.0 | 1.6709 | 43.0 | 1.6671 | 44.0 | 1.6631 |
| 45.0 | 1.6591 | 46.0 | 1.6549 | 47.0 | 1.6505 |
| 48.0 | 1.6460 | 49.0 | 1.6414 | 50.0 | 1.6366 |



## Calcite ($CaCO_3$)

Calcite is mined naturally, not manufactured synthetically. Crystran Ltd has a stock of small calcite "rhombs" of good clear optical quality. Calcite cuts and polishes well.

**APPLICATIONS:** Calcite, or Iceland Spar, is a strongly birefringent material and is used for polarisers and retardation plates.

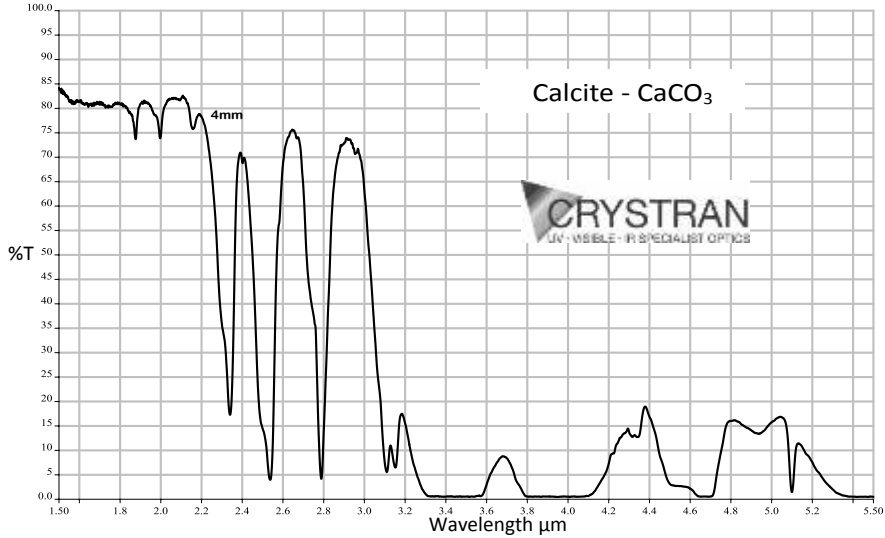
| | |
|---|---|
| Transmission Range | 0.3 to 2.3µm |
| Refractive Index | No 1.6654 at 0.51µm |
| Reflection Loss | 11.7% at 0.51µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | 3 (para) 13 (perp) x $10^{-6}$ $K^{-1}$ at 0.5µm |
| dn/dµ = 0 | n/a |
| Density | 2.71 g/cc |
| Melting Point | 825°C (Decomposes) |
| Thermal Conductivity | 5.526 (para) 4.646 (perp) W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | 25 (para) 5.8 (perp) x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 155 Moh 3 |
| Specific Heat Capacity | 852 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 8 (para) 8.5 (perp) at 10kHz at 293K |
| Youngs Modulus (E) | 72.35 (perp) 88.19 (para) GPa |
| Shear Modulus (G) | 35 GPa |
| Bulk Modulus (K) | 129.53 GPa |
| Elastic Coefficients | $C_{11}$=137; $C_{12}$=45; $C_{13}$=45; $C_{14}$=21; $C_{33}$=79 |
| Apparent Elastic Limit | 4.83 MPa (700 psi) |
| Poisson Ratio | n/a |
| Solubility | 0.0014g/100g water at 25°C |
| Molecular Weight | 100.09 |
| Class/Structure | Trigonal (hex), R3c, (1014) cleavage (1) |

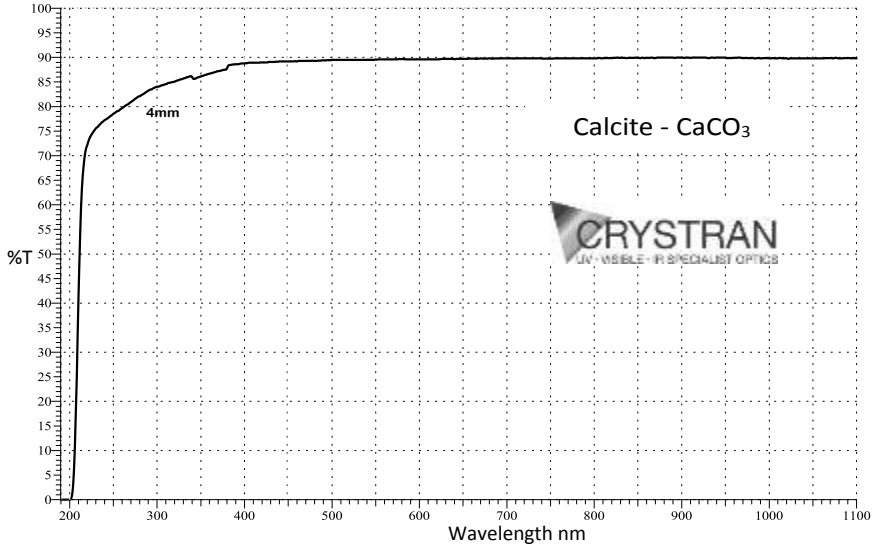
CLEAVAGE PLANE : *There can be confusion in the definition of the cleavage plane in calcite. Conventionally this has always been referred to as {1011} but recent papers on AFM studies use {1014}. Calcite cleaves between the bonds of the $CO_3$ groups (in the $CO_3$ layer). The $CO_3$ group are offset relative to each other and inclined to the c-axis giving 3 cleavage directions defining a rhomb. Following the {1011} nomenclature the unit cell requires ¼ the length of the c axis as measured from XRD (on a dimension 4 times longer). The correct Miller indices are {1014} but the conventional {1011} is often used in order not to confuse and for easier comparison.*

(1) Private Communication. J.A.Elliott. Material Science, University of Cambridge. 2011

## Calcite ($CaCO_3$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.20 | 1.9028 | 1.5765 | 0.30 | 1.7196 | 1.5137 |
| 0.41 | 1.6801 | 1.4954 | 0.51 | 1.6653 | 1.4896 |
| 0.64 | 1.6550 | 1.4849 | 0.71 | 1.6521 | 1.4835 |
| 0.80 | 1.6487 | 1.4822 | 0.91 | 1.6458 | 1.4810 |
| 1.04 | 1.6428 | 1.4799 | 1.50 | 1.6346 | 1.4774 |
| 1.91 | 1.627 | 1.4757 | 2.10 | 1.622 | 1.4749 |



## Calcium Fluoride ($CaF_2$)



Calcium fluoride is grown by vacuum Stockbarger technique in diameters of up to about 250mm. Material for IR use is grown using naturally mined fluorite, in large quantities at a relatively low cost. For UV applications chemically prepared raw material is generally used. For Excimer applications, we use only the highest grade of specially selected material and crystal.

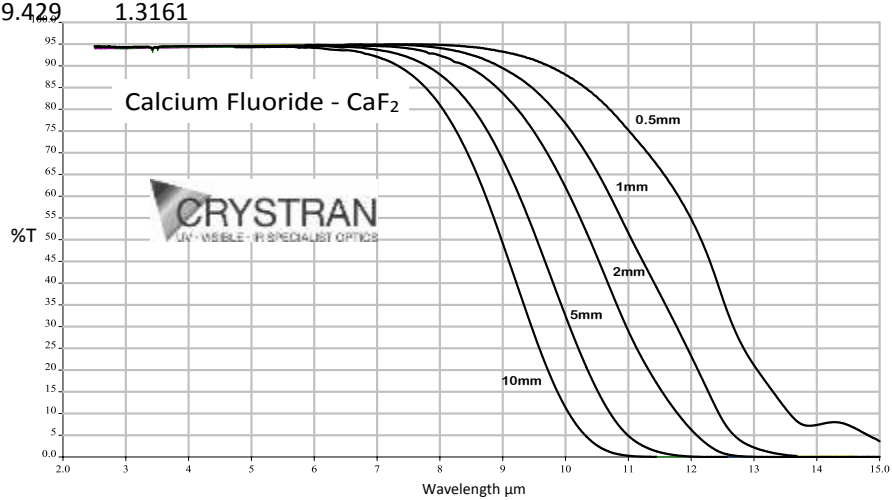
**APPLICATIONS:** Calcium Fluoride has widespread IR application as spectroscopic windows, prisms and lenses. Especially pure grades of Calcium Fluoride find useful application in the UV and as UV Excimer laser windows. Specially selected material is used for Raman work as it has no interfering fluorescence peaks. Use the links on page 30 for more data on Raman Grade and Crystal Quality.

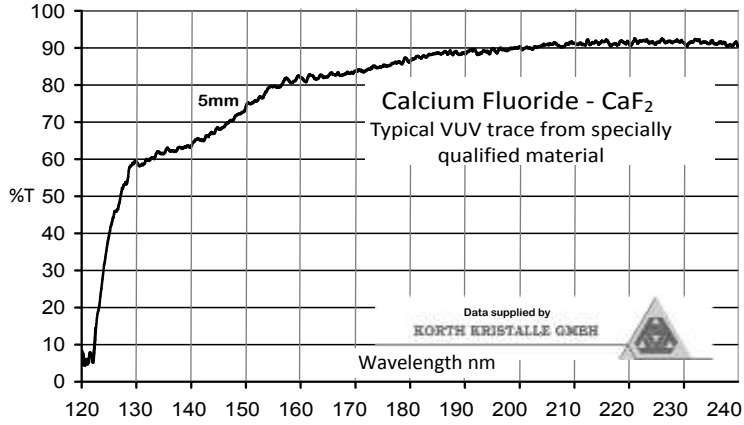
| | |
|---|---|
| Transmission Range | 0.13 to 10µm |
| Refractive Index | 1.39908 at 5µm (1) (2) |
| Reflection Loss | 5.4% at 5µm |
| Absorption Coefficient | $7.8 \times 10^{-4}$ $cm^{-1}$ @ 2.7µm |
| Reststrahlen Peak | 35µm |
| dn/dT | $-10.6 \times 10^{-6}$ $K^{-1}$ (3) |
| $dn/d\mu = 0$ | 1.7µm |
| Density | 3.18 g/cc |
| Melting Point | 1360°C |
| Thermal Conductivity | 9.71 W $m^{-1}$ $K^{-1}$ (4) |
| Thermal Expansion | $18.85 \times 10^{-6}$ $K^{-1}$ (5)(6) |
| Hardness | Knoop 158.3 (100) with 500g indenter |
| Specific Heat Capacity | 854 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 6.76 at 1MHz (7) |
| Youngs Modulus (E) | 75.8 GPa (7) |
| Shear Modulus (G) | 33.77 GPa (7) |
| Bulk Modulus (K) | 82.71 GPa (7) |
| Elastic Coefficients | $C_{11} = 164$ $C_{12} = 53$ $C_{44} = 33.7$ (7) |
| Apparent Elastic Limit | 36.54 MPa |
| Poisson Ratio | 0.26 |
| Solubility | 0.0017g/100g water at 20°C |
| Molecular Weight | 78.08 |
| Class/Structure | Cubic $Fm\bar{3}m$ (#225) Fluorite structure<br>Cleaves on (111) |

(1) Handbook Optical Constants, ed Palik, V2, ISBN 0-12-544422-2
(2) Dressler et al., Cryst.Res.Technol. V27, p413, 1992
(3) I.H.Malitson; J.Opt.Soc.Am. Vol52, p1377, 1962
(4) Ballard et al; Rev. Sci. Instr., V21, p905, 1950
(5) Batchelder & Simmons, J.Chem. Phys. V41, p2324 N8 1964
(6) Schumann & Neumann, Crys. Res. Tech V19, 1984
(7) Dickinson, IR laser windows, AFCRL-TR-0318, Air Force, Cambridge 1975

## Calcium Fluoride ($CaF_2$)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.149 | 1.5800 | 0.161 | 1.5490 | 0.195 | 1.5000 |
| 0.200 | 1.4950 | 0.222 | 1.4800 | 0.248 | 1.4680 |
| 0.266 | 1.4621 | 0.280 | 1.4584 | 0.300 | 1.454 |
| 0.337 | 1.4481 | 0.400 | 1.4419 | 0.486 | 1.4370 |
| 0.588 | 1.4339 | 0.656 | 1.4325 | 0.687 | 1.4320 |
| 0.728 | 1.4314 | 0.884 | 1.4298 | 1.014 | 1.4288 |
| 1.100 | 1.4283 | 1.250 | 1.4275 | 1.650 | 1.4256 |
| 1.900 | 1.4244 | 2.058 | 1.4236 | 2.450 | 1.4214 |
| 2.700 | 1.4199 | 2.800 | 1.4192 | 3.050 | 1.4175 |
| 3.400 | 1.4149 | 4.000 | 1.4096 | 4.400 | 1.4057 |
| 4.800 | 1.4014 | 5.000 | 1.3991 | 5.304 | 1.3952 |
| 5.893 | 1.3871 | 6.483 | 1.3782 | 7.072 | 1.3681 |
| 7.661 | 1.357 | 8.251 | 1.3444 | 8.840 | 1.3308 |
| 9.429 | 1.3161 | | | | |



## Diamond ( C ) - Cubic Carbon



Diamond is available as single crystal (Type IIa) natural or synthetic or as CVD film. Single crystal is available economically up to about 4mm diameter. CVD diamond of 75mm diameter is available. The IR transmission has a range of absorptions in the mid-IR between 2.5 and 7µm due to inherent lattice resonance. The UV transmission may be limited to 350nm in poorer quality samples. Single crystal diamond is selected into four forms: Ia ~98% of natural yield (>100ppm Nitrogen - yellow)
Ib ~0.1% of natural yield (~100ppm Nitrogen)
IIa ~2% of natural yield (1ppm Nitrogen)
IIb - Synthetic only (100ppm boron for electronic applications)

Only Type IIa is used for optical applications. CVD diamond transmission and characteristics are very similar to Type IIa.

**APPLICATIONS:** Diamond is used for transmission windows and domes.

| | |
|---|---|
| Transmission Range | 300nm to 2.5µm and 7µm to >100µm (1) |
| Refractive Index | 2.4175 @ 0.589µm (1) |
| Reflection Loss | 30% @ 0.589µm |
| Absorption Coefficient | ~0.09 $cm^{-1}$ @ 10.6µm |
| Reststrahlen Peak | n/a |
| dn/dT | 30 x $10^{-6}$ $K^{-1}$ @ 300K (3) |
| dn/dµ = 0 | n/a |
| Density | 3.51 |
| Melting Point | 3497°C (Oxidises in air at 700°C - see note) |
| Thermal Conductivity | 2600 W $m^{-1}$ $K^{-1}$ @ 273K (2) |
| Thermal Expansion | 1 x $10^{-6}$ $K^{-1}$ at 293K |
| Hardness | Knoop 5700 to 10400 |
| Specific Heat Capacity | 502 J $Kg^{-1}$ $K^{-1}$ @ 300K (4) |
| Dielectric Constant | 5.68 @ 1.68Mhz at 300K (2) |
| Youngs Modulus (E) | 1050 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 442 GPa |
| Elastic Coefficients | $C_{11}$=1076; $C_{12}$=125; $C_{44}$=577 |
| Apparent Elastic Limit | 276 MPa |
| Poisson Ratio | 0.16 to 0.29 |
| Solubility | Insoluble in water |
| Molecular Weight | 12.01 |
| Class/Structure | Cubic Diamond, Fd3m |

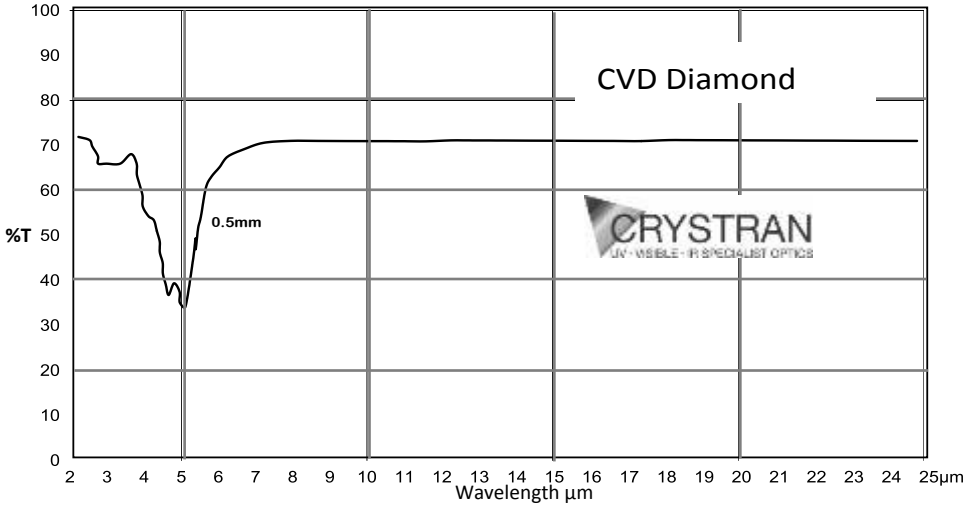
*Note:Being a form of carbon, diamond oxidises in air over 700°C. In the absence of oxygen such as in a flow of argon gas, diamond can be heated to 1700°C. The surface blackens but can be recovered by polishing.*

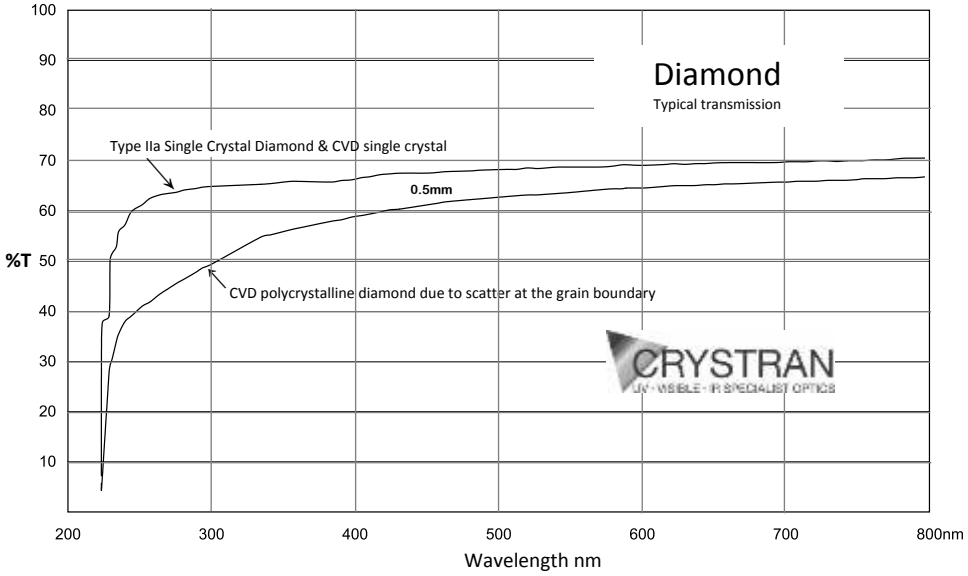
(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Properties of Polycrystalline Diamond, Sussmann et. al. Diamond & Rel. Mat. 3(1994) 303-312
(3) Fontenella et. al. App. Optics **16**, 2949 (1977)
(4) Slack & Bartram J.Appl. Phys. **46**, 89 (1975)

## Diamond ( C ) - Cubic Carbon



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.232 | 2.6917 | 0.298 | 2.5429 | .405 | 2.4626 |
| 0.589 | 2.4175 | 0.656 | 2.4104 | 1.00 | 2.3905 |
| 2.0 | 2.3813 | 3.0 | 2.3795 | 4.0 | 2.3787 |
| 5.0 | 2.3783 | 6.0 | 2.3779 | 10.0 | 2.3765 |
| 20 | 2.3741 | | | | |



## Gallium Arsenide (GaAs)

Gallium Arsenide is produced by Czochralski or horizontal Bridgeman crystal growth techniques. As it is arsenic bearing, precautions in handling and working should be observed.

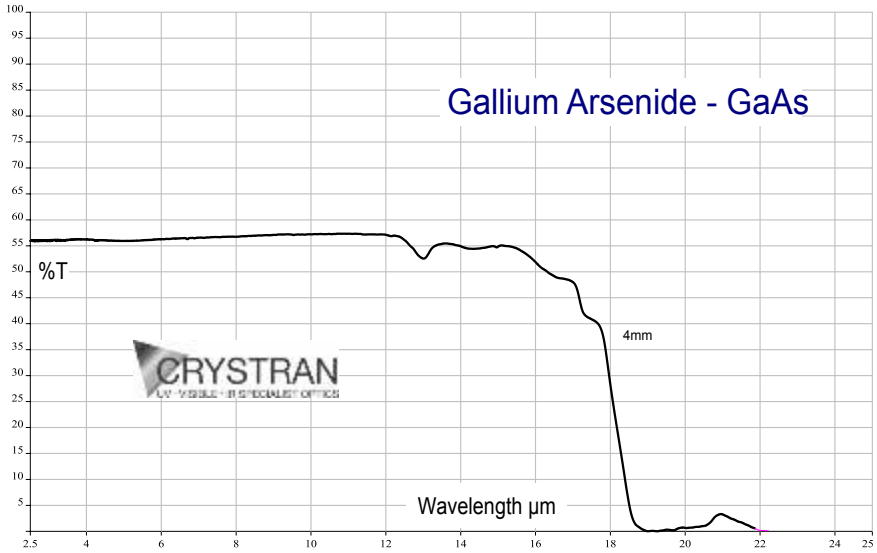
**APPLICATIONS:** Gallium Arsenide has specialist applications in far IR optics and lens systems.

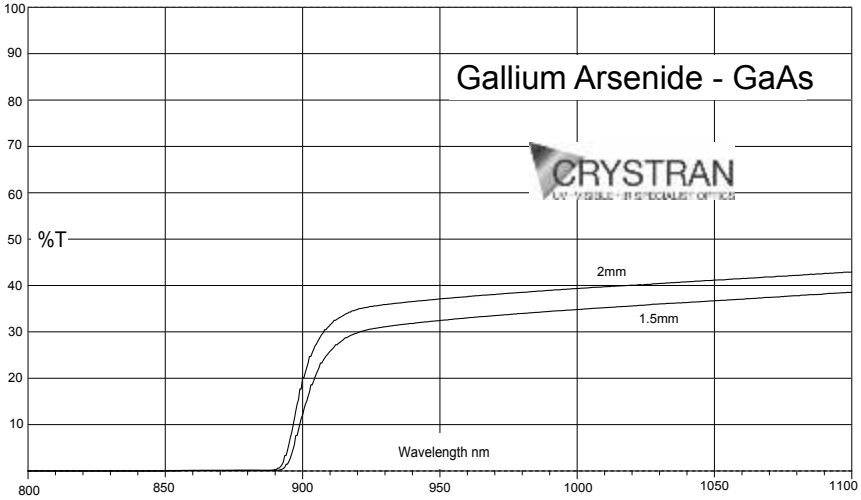
| | |
|---|---|
| Transmission Range | 0.9 to 16µm (1) |
| Refractive Index | 3.2727 @ 10.33µm (1) |
| Reflection Loss | 44% @ 10.33 µm |
| Absorption Coefficient | 0.01 $cm^{-1}$ |
| Reststrahlen Peak | n/a |
| dn/dT | 147 x $10^{-6}$ $K^{-1}$ @ 10µm (4) |
| dn/dµ = 0 | 6.3µm |
| Density | 5.315 g/cc |
| Melting Point | 1511°C |
| Thermal Conductivity | 48 W $m^{-1}$ $K^{-1}$ @ 273K (2) |
| Thermal Expansion | 5.7 x $10^{-6}$ /°C at 300K (3) |
| Hardness | Knoop 750 |
| Specific Heat Capacity | 360 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 12.91 at low frequencies |
| Youngs Modulus (E) | 84.8 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 75.5 GPa |
| Elastic Coefficients | n/a |
| Apparent Elastic Limit | 71.9 MPa |
| Poisson Ratio | 0.31 |
| Solubility | Insoluble in water |
| Molecular Weight | 144.64 |
| Class/Structure | Cubic ZnS, F43m, (100) cleavage |

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Deutch, J.Electron. Mater. V4 p679
(3) Sze, Physics of Semiconductor Devices, Wiley 1981
(4) M.Cardona, Proc. Int. Conf. Semicond. Phys., Prague 1960 p.388.

## Gallium Arsenide (GaAs)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 1.033 | 3.492 | 1.550 | 3.3737 | 2.066 | 3.338 |
| 2.480 | 3.324 | 3.100 | 3.3125 | 4.133 | 3.3027 |
| 4.959 | 3.2978 | 6.199 | 3.2921 | 7.293 | 3.2874 |
| 8.266 | 3.2831 | 9.537 | 3.2769 | 10.33 | 3.2727 |
| 11.27 | 3.2671 | 12.40 | 3.2597 | 13.78 | 3.2493 |
| 15.50 | 3.2336 | 17.71 | 3.2081 | 19.07 | 3.1866 |



## Gallium Lanthanum Sulphide (GLS)



Gallium Lanthanum Sulphide (GLS) glass is produced by proprietary processes under conditions of the highest purity. Particular effort is made in removing transition metal impurities to a level of better than 1 ppm total metallic impurities with $SH^-$ and $OH^-$ less than 1 ppm. GLS is routinely processed from ingots of 500 grams. Other glass compositions are available including rare earth doped (Ce, Pr, Nd, Tb, Dy, Ho, Er, Tm, Yb), halide (F, Cl), and Ag doped samples.

**APPLICATIONS:** Gallium Lanthanum Sulphide is a chalcogenide glass, an alternative to toxic arsenic-based glasses. Developed at Southampton University, GLS has found use in a wide range of optoelectronic applications and is available as polished optical components, thin and thick films and in optical fibre form.

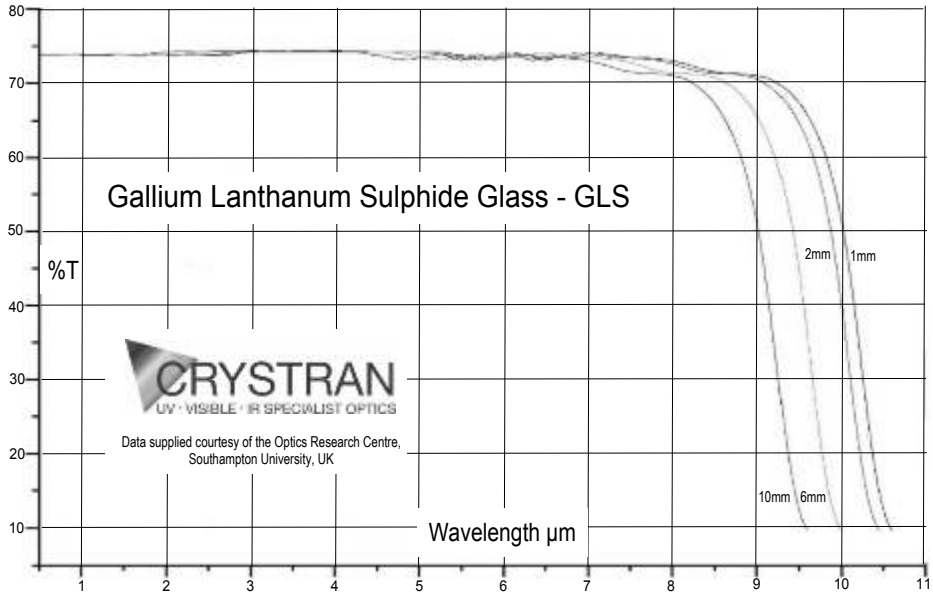
| | |
|---|---|
| Transmission Range | 0.5 to 10µm |
| Refractive Index | 2.398 at 1.014µm |
| Reflection Loss | 29% at 1.014µm |
| Absorption Coefficient | <0.005 $cm^{-1}$ |
| Reststrahlen Peak | n/a |
| dn/dT | +75 x $10^{-6}$ /°C |
| dn/dµ = 0 | 4µm |
| Density | 4.04 g/cc |
| Melting Point | 830°C |
| Thermal Conductivity | 0.43 W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | 10 x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 206 with 200g indenter |
| Specific Heat Capacity | 0.54 J $g^{-1}$ $K^{-1}$ |
| Dielectric Constant | 8.1 at 1KHz |
| Youngs Modulus (E) | 59 GPa |
| Shear Modulus (G) | 23 GPa |
| Bulk Modulus (K) | 24.5 GPa |
| Elastic Coefficients | n/a |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | 0.24 |
| Solubility | Negligible in water |
| Molecular Weight | 276.9 |
| Class/Structure | Amorphous glass |

*Damage Threshold >200MW $cm^{-2}$ at 1550nm*
*Acousto-optic Figure of Merit: M2 = 6 x $10^{-15}$*
*Verdet Constant = 0.205 min/Oe/cm*

Petrovich, Hewak et al Journal of Non-Crystalline Solids 326&327 (2003) 93–97

## Gallium Lanthanum Sulphide (GLS)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.5461 | 2.522 | 0.5790 | 2.500 | 0.6439 | 2.467 |
| 0.6678 | 2.458 | 0.7065 | 2.466 | 1.0140 | 2.398 |
| 1.3673 | 2.379 | 1.7101 | 2.371 | | |



## Germanium (Ge)

Germanium is grown using the Czochralski technique by a small number of manufacturers in Belgium, USA, China and Russia. The refractive index of Germanium changes rapidly with temperature and the material becomes opaque at all wavelengths a little above 350°K as the band gap floods with thermal electrons.

**APPLICATIONS:** Germanium is a high index material that is used to manufacture Attenuated Total Reflection (ATR) prisms for spectroscopy. Its refractive index is such that Germanium makes an effective natural 50% beamsplitter without the need for coatings. Germanium is also used extensively as a substrate for production of optical filters. Germanium covers the whole of the 8-14µm thermal band and is used in lens systems for thermal imaging. Germanium can be AR coated with Diamond producing an extremely tough front optic.

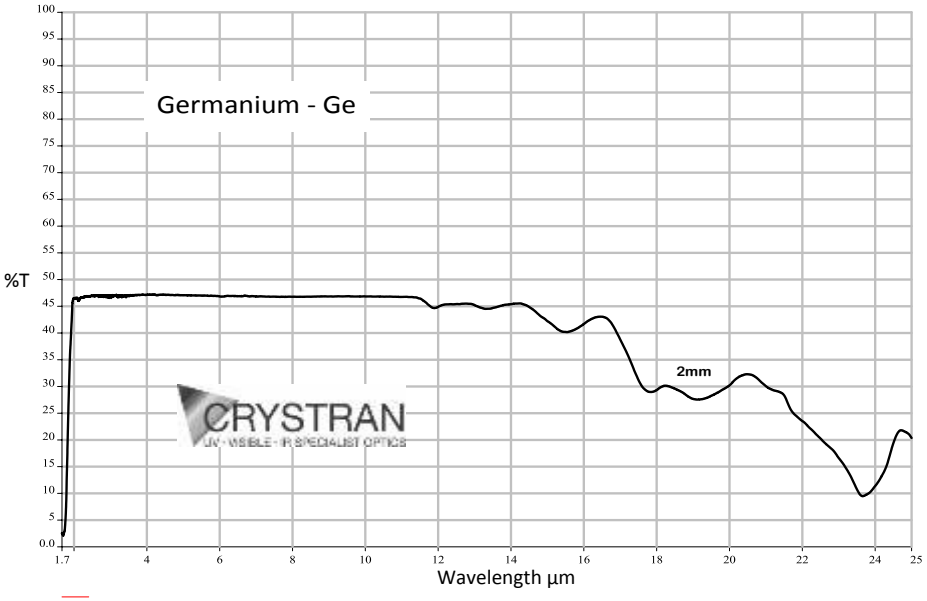
| | |
|---|---|
| Transmission Range | 1.8 to 23µm (1) |
| Refractive Index | 4.0026 at 11µm (1)(2) |
| Reflection Loss | 53% at 11µm (Two surfaces) |
| Absorption Coefficient | <0.027 $cm^{-1}$ @ 10.6µm |
| Reststrahlen Peak | n/a |
| dn/dT | 396 x $10^{-6}$ $K^{-1}$ (2)(6) |
| dn/dµ = 0 | Almost constant |
| Density | 5.33 g/cc |
| Melting Point | 936 °C (3) |
| Thermal Conductivity | 58.61 W $m^{-1}$ $K^{-1}$ at 293K (6) |
| Thermal Expansion | 6.1 x $10^{-6}$ $K^{-1}$ at 298K (3)(4)(6) |
| Hardness | Knoop 780 |
| Specific Heat Capacity | 310 J $Kg^{-1}$ $K^{-1}$ (3) |
| Dielectric Constant | 16.6 at 9.37 GHz at 300K |
| Youngs Modulus (E) | 102.7 GPa (4) (5) |
| Shear Modulus (G) | 67 GPa (4) (5) |
| Bulk Modulus (K) | 77.2 GPa (4) |
| Elastic Coefficients | $C_{11}$=129; $C_{12}$=48.3; $C_{44}$=67.1 (5) |
| Apparent Elastic Limit | 89.6 MPa (13000 psi) |
| Poisson Ratio | 0.28 (4) (5) |
| Solubility | Insoluble in water |
| Molecular Weight | 72.59 |
| Class/Structure | FCC Cubic, Fm3m (#225) Diamond structure |

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Li, Refractive Index of Germanium etc, J.Phys Chem, V9, p561, 1980
(3) Pearson & Brattain, Proc. Inst. Radio Eng. V43, p1794, 1955
(4) Fine, J.App.Phys, V24, p338, 1953
(5) Wortman & Evans, V36, (1), P153 (1965)
(6) Hawkins, Sherwood, Djotni: Mid IR Filters for astronomical and remote sensing instrumentation. Invited Paper SPIE Conference Glasgow 2008

## Germanium (Ge)



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 2.058 | 4.102 | 2.153 | 4.0919 | 2.313 | 4.0786 |
| 2.437 | 4.0708 | 2.577 | 4.0609 | 2.714 | 4.0562 |
| 2.998 | 4.0452 | 3.303 | 4.0369 | 4.258 | 4.0216 |
| 4.866 | 4.017 | 6.238 | 4.0094 | 8.660 | 4.0043 |
| 9.720 | 4.0034 | 11.04 | 4.0026 | 12.00 | 4.0023 |
| 13.02 | 4.0021 | | | | |



## KRS5 Thallium Bromo-Iodide (TlBr-TlI)



***CAUTION: Thallium salts are considered TOXIC and should be handled with care.***

KRS5 crystallises by the sealed-ampoule Stockbarger technique. Starting materials of the highest purity are selected to ensure that there are no anionic absorption bands between 2µm and 16µm and all crystals are checked for quality by using a pathlength of 120mm.

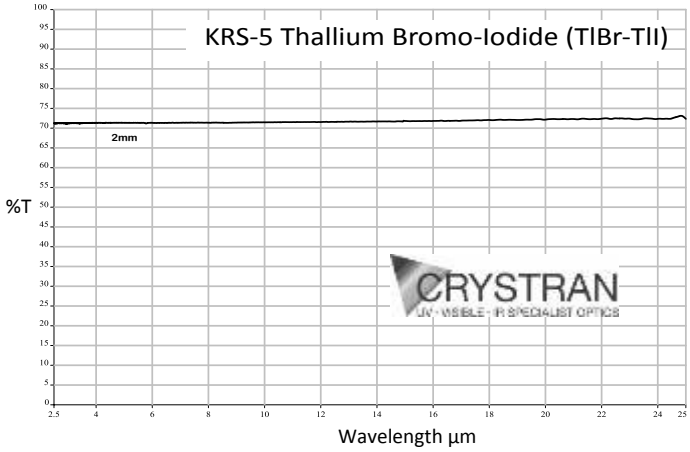
**APPLICATIONS:** KRS5 is a deep IR material with a high refractive index, KRS5 is used extensively in spectroscopy for ATR prisms, windows and lenses. In conjunction with Germanium, KRS5 can also be used in thermally compensated IR imaging systems.

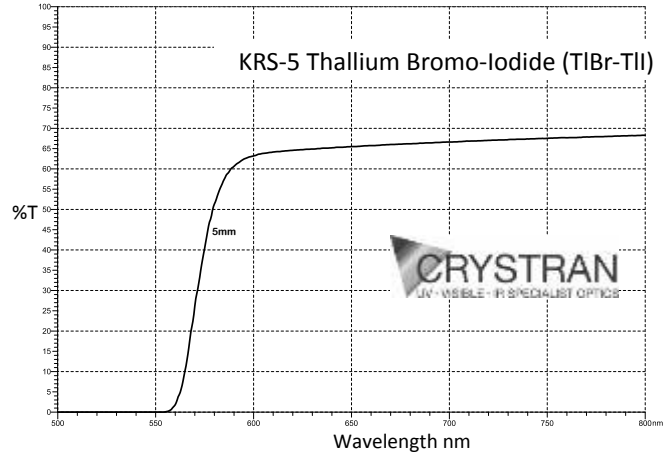
| | |
|---|---|
| Transmission Range | 0.6 to 40µm |
| Refractive Index | 2.371 at 10µm (1) (3) |
| Reflection Loss | 28.4% at 10µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | $-235 \times 10^{-6}\ K^{-1}$ |
| dn/dµ = 0 | 7µm |
| Density | 7.371 g/cc (3) |
| Melting Point | 414.5°C (3) |
| Thermal Conductivity | $0.544\ W\ m^{-1}\ K^{-1}$ at 293K |
| Thermal Expansion | $58 \times 10^{-6}\ K^{-1}$ (2) |
| Hardness | Knoop 40.2 (2) |
| Specific Heat Capacity | $200\ J\ Kg^{-1}\ K^{-1}$ at 273K |
| Dielectric Constant | 32.5 |
| Youngs Modulus (E) | 15.85 GPa (2) |
| Shear Modulus (G) | 5.79 GPa (2) |
| Bulk Modulus (K) | 19.78 GPa (2) |
| Elastic Coefficients | $C_{11}$=331; $C_{12}$=13.2; $C_{44}$=5.79 |
| Apparent Elastic Limit | 26.2 MPa (2) |
| Poisson Ratio | 0.369 |
| Solubility | 0.05g/100g water at 293K |
| Molecular Weight | 42 mole% TlBr; 58 mole% TlI |
| Class/Structure | Cubic, CsCl structure, Pm3m, No cleavage (3) |

(1) Rodney and Malitson J.Opt Soc.Am. V46, p 956, 1953
(2) Combes, Ballard, McCarthy: J.Opt Soc.Am. V41, p 215, 1951
(3) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## KRS5 Thallium Bromo-Iodide (TlBr-TlI)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.54 | 2.68059 | 1.00 | 2.44620 | 1.50 | 2.40774 |
| 2.00 | 2.39498 | 3.00 | 2.38574 | 4.00 | 2.38204 |
| 5.00 | 2.37979 | 6.00 | 2.37797 | 7.0 | 2.37627 |
| 8.0 | 2.37452 | 9.0 | 2.37267 | 10.0 | 2.37069 |
| 11.0 | 2.36854 | 12.0 | 2.36622 | 13.0 | 2.36371 |
| 14.0 | 2.36101 | 15.0 | 2.35812 | 16.0 | 2.35502 |
| 17.0 | 2.35173 | 18.0 | 2.34822 | 19.0 | 2.34451 |
| 20.0 | 2.34058 | 21.0 | 2.33643 | 22.0 | 2.33206 |
| 23.0 | 2.32746 | 24.0 | 2.32264 | 25.0 | 2.31758 |
| 26.0 | 2.31229 | 27.0 | 2.30676 | 28.0 | 2.30098 |
| 29.0 | 2.29495 | 30.0 | 2.28867 | 31.0 | 2.28212 |
| 32.0 | 2.27531 | 33.0 | 2.26823 | 34.0 | 2.26087 |
| 35.0 | 2.25322 | 36.0 | 2.24528 | 37.0 | 2.23705 |
| 38.0 | 2.22850 | 39.0 | 2.21965 | 40.0 | 2.21047 |



## KRS6 Thallium Bromo-Chloride (TlBr-TlCl)



***CAUTION: Thallium salts are considered TOXIC and should be handled with care.***

KRS6 crystals are grown by the sealed-ampoule Stockbarger technique. Starting materials of the highest purity are selected to ensure that there are no anionic absorption bands between 2 and 16µms and all crystals are checked for quality by using a pathlength of 120mm. Thallium salts are toxic, and KRS6 has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required.

**APPLICATIONS:** KRS6 has only a few applications. Occasionally, it is required for research.

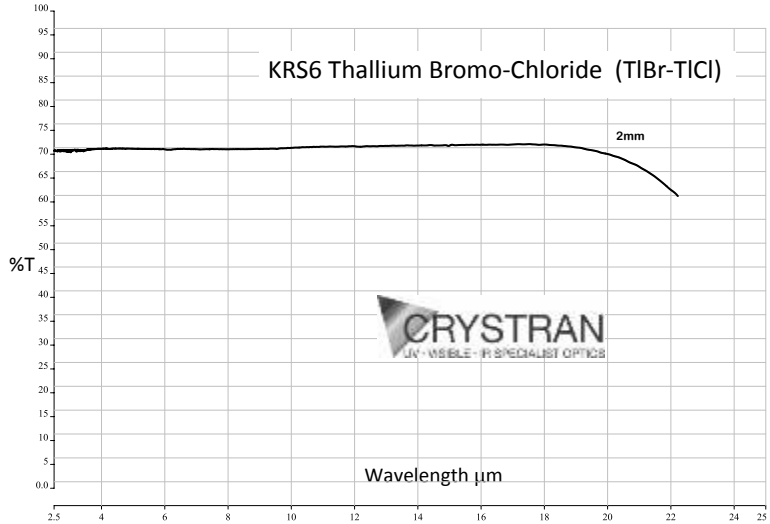
| | |
|---|---|
| Transmission Range | 0.4 to 25µm |
| Refractive Index | 2.1723 at 11µm (1) |
| Reflection Loss | 24.0% at 11µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 91.5µm |
| dn/dT | n/a |
| dn/dµ = 0 | 5µm |
| Density | 7.18 g/cc (3) |
| Melting Point | 423°C (3) |
| Thermal Conductivity | 0.7 W $m^{-1}$ $K^{-1}$ at 329°K |
| Thermal Expansion | 50 x $10^{-6}$ $K^{-1}$ (2) |
| Hardness | Knoop 29.9 with 500g indenter (2) |
| Specific Heat Capacity | 188 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 32 at 1 MHz |
| Youngs Modulus (E) | 20.68 GPa (2) |
| Shear Modulus (G) | 8.48 GPa (2) |
| Bulk Modulus (K) | 22.81 GPa (2) |
| Elastic Coefficients | $C_{11}$=38.5; $C_{12}$=14.9; $C_{44}$=7.37 |
| Apparent Elastic Limit | 20.7 MPa (3000 psi) |
| Poisson Ratio | 0.219 |
| Solubility | 0.3g/100g water at 20°C |
| Molecular Weight | 40 mole% TlBr; 60 mole% TlCl |
| Class/Structure | Cubic, CsCl structure, Pm3m, no cleavage planes |

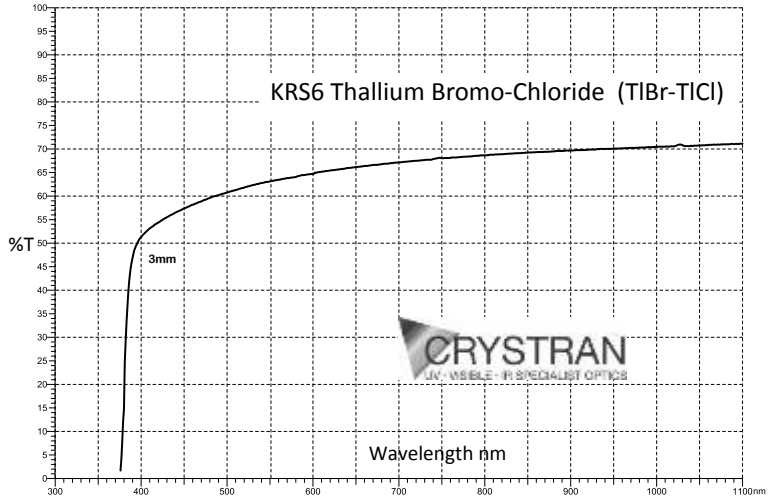
(1) Hettner and Leisegang; Optik, V3, p305, 1948
(2) Combes, Ballard, McCarthy: J.Opt Soc.Am. V41, p 215, 1951
(3) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## KRS6 Thallium Bromo-Chloride (TlBr-TlCl)



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.6 | 2.3294 | 0.7 | 2.2982 | 0.8 | 2.2660 |
| 0.9 | 2.251 | 1.0 | 2.2404 | 1.5 | 2.2148 |
| 2.0 | 2.2059 | 3.0 | 2.199 | 4.0 | 2.1956 |
| 5.0 | 2.1928 | 6.0 | 2.190 | 7.0 | 2.187 |
| 8.0 | 2.1839 | 9.0 | 2.1805 | 10.0 | 2.1767 |
| 11.0 | 2.1723 | 12.0 | 2.1674 | 13.0 | 2.162 |
| 14.0 | 2.1563 | 15.0 | 2.1504 | 16.0 | 2.1442 |
| 17.0 | 2.1377 | 18.0 | 2.1309 | 19.0 | 2.1236 |
| 20.0 | 2.1154 | 21.0 | 2.1067 | 22.0 | 2.0976 |
| 23.0 | 2.0869 | 24.0 | 2.0752 | | |



## Lanthanum Fluoride ($LaF_3$)



Lanthanum Fluoride is grown as small ingots of about 10mm diameter as it is difficult to anneal. Doped with Europium, it is a pale yellow colour.

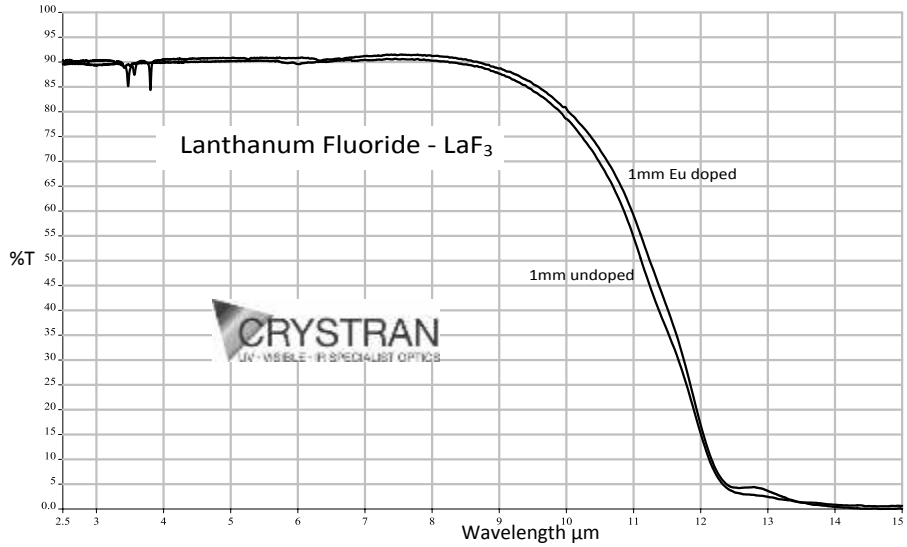
**APPLICATIONS:** Lanthanum Fluoride is not often used as an optical material. Lanthanum Fluoride is usually doped with Europium at a nominal level of 0.3% mole. In this form, the usual application is as the active element in an ion-selective electrode for the detection and measurement of Fluoride ions in solution. Use the QR link on page 30 for application notes on ion-selective electrodes.

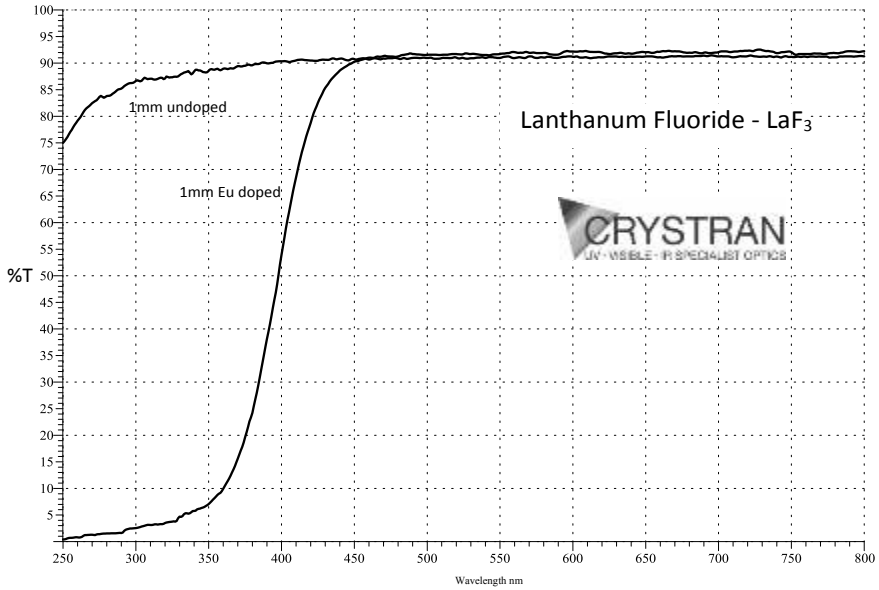
| | |
|---|---|
| Transmission Range | 0.2 to 11µm |
| Refractive Index | No 1.506 at 0.55µm |
| Reflection Loss | 10.3% at 0.55µm |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | n/a |
| $dn/d\mu = 0$ | n/a |
| Density | 5.94 g/cc |
| Melting Point | 1493 °C (1) |
| Thermal Conductivity | 5.1 W $m^{-1}$ $K^{-1}$ at 300K |
| Thermal Expansion | $11.0x10^{-6}$ (para) $15.8x10^{-6}$ /K(perp) at 298K (2) |
| Hardness | Moh 4.5 |
| Specific Heat Capacity | 506 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 14 (3) |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | n/a |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | Insoluble in water |
| Molecular Weight | 195.9 |
| Class/Structure | Trigonal (hex), $P6_3/mcm$ (2), no cleavage |

1) Jones and Shand, J.Crys.Growth. **2** (1968) p361
(2) Sher, Solomon, Lee, and Meuller. Phys.Rev. **144**, p593 (1966)
(3) Electronic Processes in Ionic Crystals (OU Press, NY, 1940) p.41.

## Lanthanum Fluoride ($LaF_3$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.254 | 1.656 | 1.649 | 0.405 | 1.618 | 1.612 |
| 0.436 | 1.617 | 1.609 | 0.547 | 1.606 | 1.602 |



## Lead Fluoride ($PbF_2$)



***CAUTION: Lead salts are considered TOXIC and should be handled with care.***

Lead fluoride has been grown by vacuum Stockbarger, but is not known to be in regular production. Crystran hold a very small stock of crystal ingot.

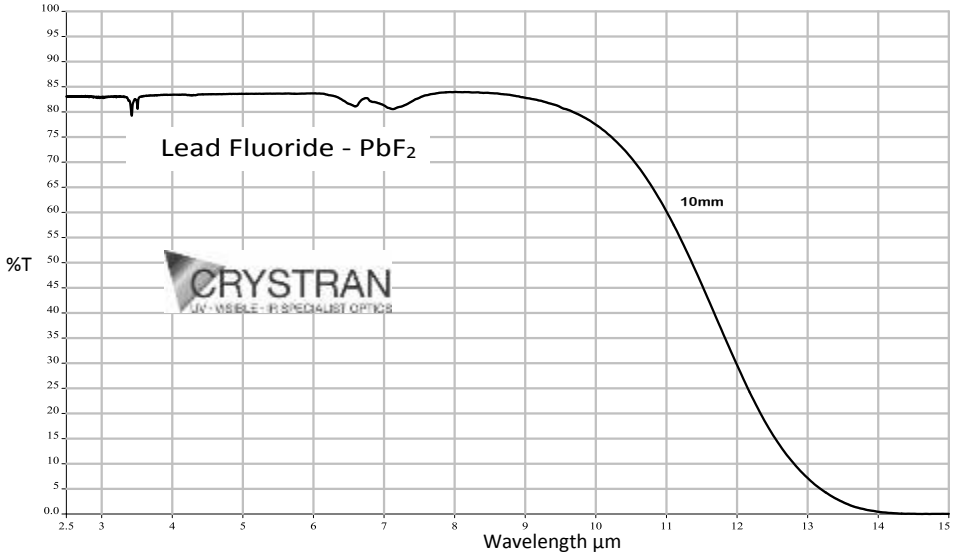
**APPLICATIONS:** Lead Fluoride has little optical application. Lead Fluoride has been used as a scintillator material as it has excellent stopping power for gamma rays.

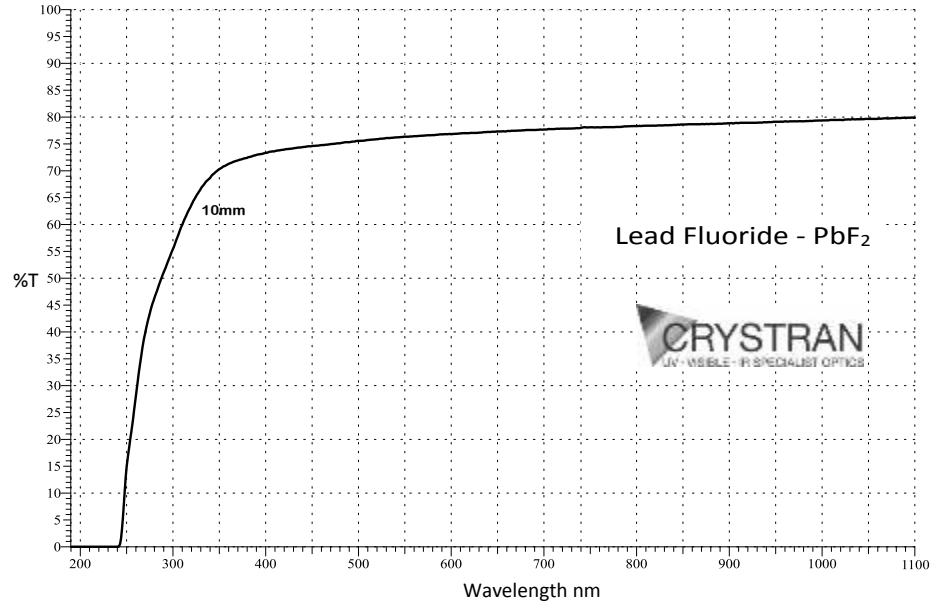
| | |
|---|---|
| Transmission Range | 250nm to 11µm |
| Refractive Index | 1.7808 @ 5µm |
| Reflection Loss | 12.8% @ 5µm (2 surfaces) |
| Absorption Coefficient | 0.018 $cm^{-1}$ @ 4µm |
| Reststrahlen Peak | n/a |
| dn/dT | n/a |
| dn/dµ = 0 | 3.3µm |
| Density | 7.77 g $cm^{-3}$ (1) |
| Melting Point | 855°C |
| Thermal Conductivity | n/a |
| Thermal Expansion | 29 x $10^{-6}$ $K^{-1}$ @ 283K |
| Hardness | Knoop 200 |
| Specific Heat Capacity | 301 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 13 @ 1MHz |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | $C_{11}$=91, $C_{12}$=46, $C_{44}$=23 |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | 0.064 g/100g water at 20°C |
| Molecular Weight | 245.21 |
| Class/Structure | Cubic, CaF2, Fm3m, (111) cleavage |

(1) Crystran Data

## Lead Fluoride ($PbF_2$)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.3 | 1.93665 | 0.4 | 1.81804 | 0.5 | 1.78220 |
| 0.6 | 1.76489 | 0.7 | 1.75502 | 0.8 | 1.74879 |
| 0.9 | 1.74455 | 1.0 | 1.74150 | 3.0 | 1.72363 |
| 5.0 | 1.70805 | 7.0 | 1.68544 | 9.0 | 1.65504 |



## Lithium Fluoride (LiF)



Lithium Fluoride is grown by vacuum Stockbarger technique in ingots approximately 100mm diameter. Lithium Fluoride cleaves easily and must be worked with extreme care. Polishing, particularly steep radii, often causes surface "rip-out".

**APPLICATIONS:** Lithium fluoride is the material with the most extreme UV transmission of all and is used for special UV optics. Lithium fluoride transmits well into the VUV region at the hydrogen Lyman-alpha line (121nm) and beyond. Lithium fluoride is also used for X-ray monochromator plates where its lattice spacing makes it the most useful analysis crystal.

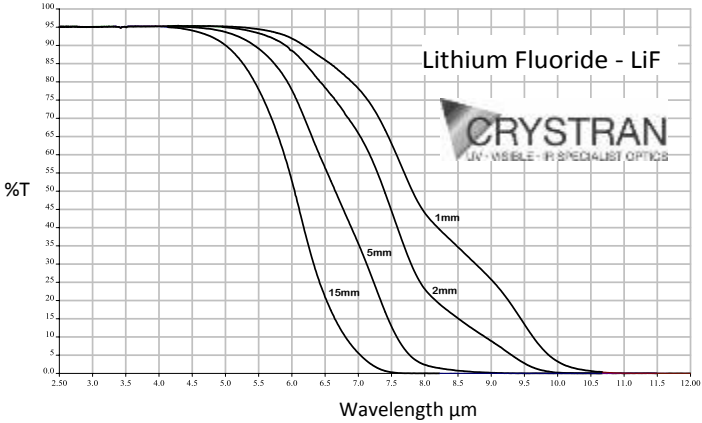
| | |
|---|---|
| Transmission Range | 0.12 to 6µm |
| Refractive Index | 1.392 at 0.6µm (1) |
| Reflection Loss | 5.2% at 0.6µm (2 Surfaces) |
| Absorption Coefficient | $5.9 \times 10^{-3}$ $cm^{-1}$at 4.3µm @ 300K (5) |
| Reststrahlen Peak | 25µm |
| dn/dT | $-16 \times 10^{-6}$ at 1.15µm |
| dn/dµ = 0 | 1.3µm |
| Density | 2.639 g/cc |
| Melting Point | 848 °C (6) |
| Thermal Conductivity | 11.3 W $m^{-1}$ $K^{-1}$ at 314 K (2) |
| Thermal Expansion | $37 \times 10^{-6}$ $K^{-1}$ at 283 K (2) |
| Hardness | Knoop 102 with 600g indenter (2) |
| Specific Heat Capacity | 1562 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 0.1 |
| Youngs Modulus (E) | 64.97 GPa (2) |
| Shear Modulus (G) | 55.14 GPa (2) |
| Bulk Modulus (K) | 62.03 GPa (2) |
| Elastic Coefficients | $C_{11}$=112; $C_{12}$=46; $C_{44}$=63.5 (3) |
| Apparent Elastic Limit | 11.2 MPa (1620 psi) (4) |
| Poisson Ratio | 0.326 (calculated) |
| Solubility | 0.27g / 100g water at 20 °C |
| Molecular Weight | 25.94 |
| Class/Structure | Cubic FCC, Fm3m (#221), NaCl Structure<br>(100) cleavage |

(1) Laporte et. al. J.Opt. Soc. Am. V73, No 8, p1062
(2) Combes et. al. J.Opt. Soc. Am. V41, p215. 1951
(3) Huntingdon, Phys Review. V72, p321, 1947
(4) Ballard et. al. J.Opt. Soc. Am. V42, p684. 1952
(5) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980
(6) T.B.Douglas & J.L.Dever, J. Am. Chem.Soc, 1954,76 (19), p4826

## Lithium Fluoride (LiF)

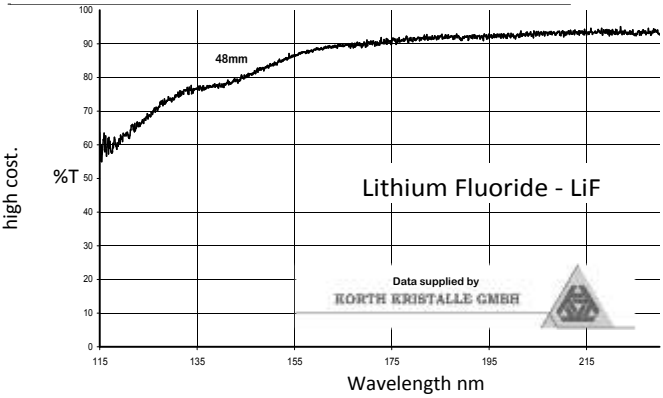


| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.106 | 1.9130 | 0.108 | 1.8330 | 0.110 | 1.7770 |
| 0.121 | 1.6240 | 0.130 | 1.5690 | 0.140 | 1.5300 |
| 0.150 | 1.5030 | 0.160 | 1.4840 | 0.170 | 1.4690 |
| 0.180 | 1.4850 | 0.190 | 1.4455 | 0.200 | 1.4391 |
| 0.220 | 1.4291 | 0.250 | 1.4189 | 0.260 | 1.4164 |
| 0.270 | 1.4141 | 0.280 | 1.4121 | 0.290 | 1.4103 |
| 0.300 | 1.4087 | 0.310 | 1.4073 | 0.320 | 1.4060 |
| 0.330 | 1.4048 | 0.340 | 1.4037 | 0.350 | 1.4028 |
| 0.360 | 1.4019 | 0.400 | 1.3989 | 0.500 | 1.3943 |
| 0.600 | 1.3918 | 0.700 | 1.3902 | 0.800 | 1.3890 |
| 0.900 | 1.3880 | 1.000 | 1.3871 | 1.500 | 1.3832 |
| 2.000 | 1.3788 | 2.500 | 1.37327 | 3.000 | 1.3666 |
| 3.500 | 1.3587 | 4.000 | 1.3494 | 4.500 | 1.3388 |
| 5.000 | 1.3266 | 5.100 | 1.3240 | 5.200 | 1.3213 |
| 5.300 | 1.3186 | 5.400 | 1.3158 | 5.500 | 1.3129 |
| 5.600 | 1.3099 | 5.700 | 1.3069 | 5.800 | 1.3038 |
| 5.900 | 1.3007 | 6.000 | 1.2975 | | |




Routine transmission at 121nm is usually a minimum of 40% through a 2mm sample.

This curve represents the maximum transmission that we can achieve under ideal conditions of material and polish at high cost.



## Magnesium Fluoride ($MgF_2$)



Magnesium Fluoride is grown by vacuum Stockbarger technique in ingots of various diameters. Magnesium Fluoride is a tough material and polishes well. Therefore, it can be worked to the highest standards. MgF2 is slightly birefringent and usually supplied with the optic axis cut perpendicular to the window faces.

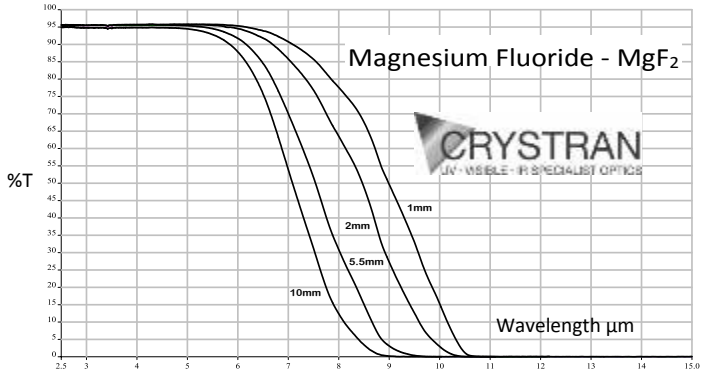
**APPLICATIONS:** Magnesium Fluoride transmits well into the VUV region to the hydrogen Lyman-alpha line (121nm) and beyond. Magnesium Fluoride is used mostly for UV optics and is excellent for Excimer laser applications.

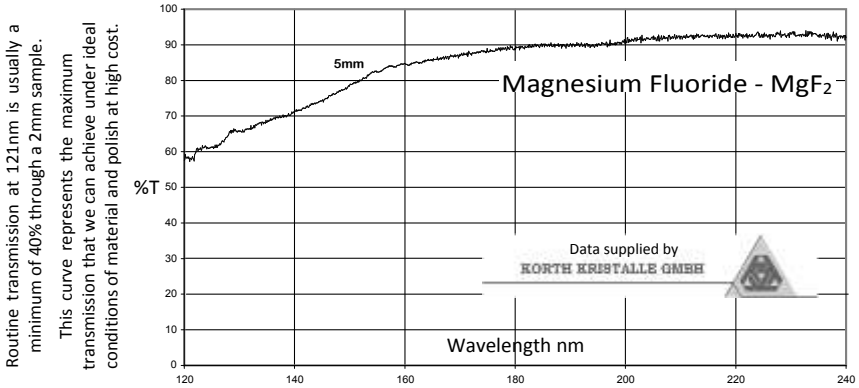
| | |
|---|---|
| Transmission Range | 0.12 to 7µm(1) |
| Refractive Index | No 1.413 at 0.22µm (4) |
| Reflection Loss | 5.7% at 0.22µm (2 surfaces) |
| Absorption Coefficient | $5.5 \times 10^{-3}$ $cm^{-1}$ at 2.8µm (5) |
| Reststrahlen Peak | 20µm (1) |
| dn/dT | 2.3 (para) 1.7 (perp) at 0.4µm (1) |
| dn/dµ = 0 | 1.4µms |
| Density | 3.1766g/cc at 25°C |
| Melting Point | 1255°C |
| Thermal Conductivity | 21 (para) 33.6 (perp) W $m^{-1}$ $K^{-1}$ at 300K (3) |
| Thermal Expansion | 13.7 (para) 8.9 (perp) x $10^{-6}$ /K (1) |
| Hardness | Knoop 415 |
| Specific Heat Capacity | 1003 J Kg $m^{-1}$ $K^{-1}$ |
| Dielectric Constant | 4.87 (para) 5.45 (perp) at 1MHz (1) |
| Youngs Modulus (E) | 138 GPa (2) |
| Shear Modulus (G) | 54.66GPa (2) |
| Bulk Modulus (K) | 101.32 GPa (2) |
| Elastic Coefficients | $C_{11}$=140 $C_{12}$=89 $C_{44}$=57 $C_{13}$=63 $C_{66}$=96 (2) |
| Apparent Elastic Limit | 49.6 MPa (7200 psi) |
| Poisson Ratio | 0.276 (2) |
| Solubility | 0.0002g/100g water |
| Molecular Weight | 62.32 |
| Class/Structure | Tetragonal P42/mnm (#136) Rutile Structure. Can cleave on c-axis but not easily. |

(1) Duncanson et.al. Proc.Phys.Soc. V72, p1001, 1958
(2) Kandil et.al. J.App.Phys. V52, p749, 1981
(3) Kashnow & MCarthy, J.Phys.Chem. V30, p813, 1969
(4) Laporte et. al. J.Opt. Soc. Am. V73, No 8, p1062
(5) Corning Inc published data

## Magnesium Fluoride ($MgF_2$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.1137 | 1.7805 | | 0.1149 | 1.7420 | |
| 0.1179 | 1.6800 | | 0.1198 | 1.6510 | |
| 0.121 | 1.628 | 1.632 | 0.130 | 1.566 | 1.568 |
| 0.140 | 1.5095 | 1.523 | 0.150 | 1.480 | 1.494 |
| 0.160 | 1.461 | 1.475 | 0.170 | 1.448 | 1.462 |
| 0.180 | 1.439 | 1.453 | 0.190 | 1.431 | 1.444 |
| 0.200 | 1.423 | 1.437 | 0.220 | 1.413 | 1.426 |
| 0.248 | 1.403 | 1.416 | 0.257 | 1.401 | 1.414 |
| 0.266 | 1.399 | 1.412 | 0.280 | 1.396 | 1.409 |
| 0.300 | 1.393 | 1.405 | 0.330 | 1.389 | 1.402 |
| 0.337 | 1.389 | 1.401 | 0.350 | 1.387 | 1.400 |
| 0.355 | 1.386 | 1.399 | 0.400 | 1.384 | 1.396 |
| 0.546 | 1.379 | 1.390 | 0.700 | 1.376 | 1.388 |
| 1.087 | 1.373 | 1.385 | 1.512 | 1.370 | 1.382 |
| 2.000 | 1.368 | 1.379 | 2.5 | 1.364 | 1.375 |
| 3.030 | 1.360 | 1.370 | 3.571 | 1.354 | 1.364 |
| 4.000 | 1.349 | 1.359 | 4.546 | 1.341 | 1.350 |
| 5.000 | 1.334 | 1.343 | 5.556 | 1.324 | 1.332 |
| 6.060 | 1.314 | 1.321 | | | |



## Magnesium Oxide (MgO)

Magnesium Oxide is grown in relatively small sizes, mainly in Japan and China.

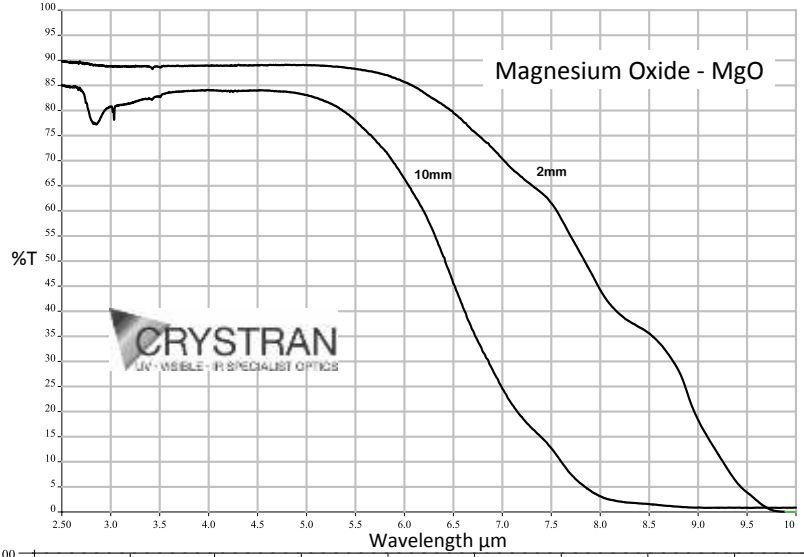
**APPLICATIONS:** Magnesium Oxide can be used for high temperature windows and substrates. HTSC substrates.

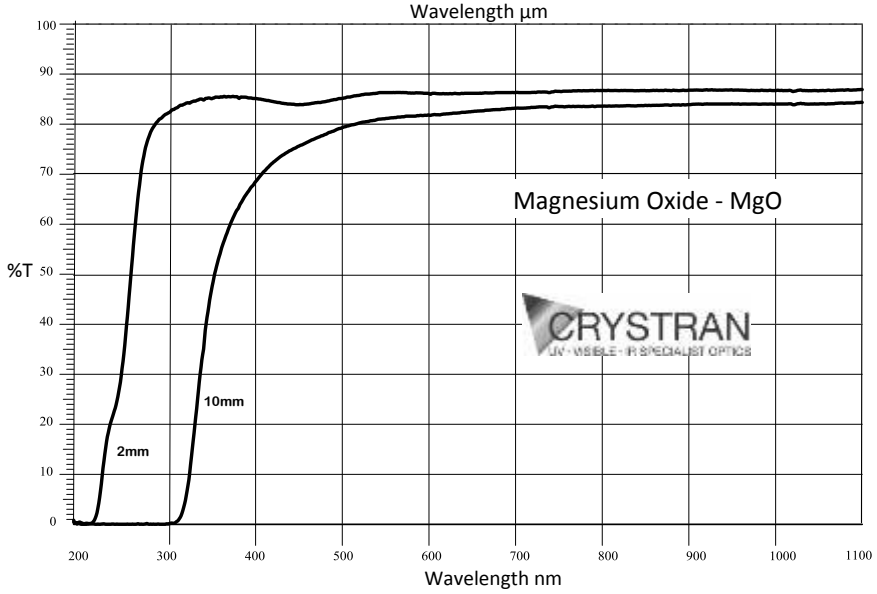
| | |
|---|---|
| Transmission Range | 0.3 to 6µm |
| Refractive Index | 1.7085 at 2µm (1) |
| Reflection Loss | 12.8% at 2µm (2 surfaces) |
| Absorption Coefficient | 0.05 $cm^{-1}$ at 5.5µm |
| Reststrahlen Peak | n/a |
| dn/dT | +19 x $10^{-6}$ $K^{-1}$ |
| dn/dµ = 0 | n/a |
| Density | 3.58 g/cc |
| Melting Point | 2800 °C |
| Thermal Conductivity | 42 W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | 10.8 x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 692 with 600g indenter |
| Specific Heat Capacity | 877 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 9.65 at 1 MHz |
| Youngs Modulus (E) | 249 GPa |
| Shear Modulus (G) | 155 GPa |
| Bulk Modulus (K) | 155 GPa |
| Elastic Coefficients | $C_{11}$=294; $C_{12}$=93; $C_{44}$=155 |
| Apparent Elastic Limit | 138 MPa (20,000 psi) |
| Poisson Ratio | 0.18 |
| Solubility | 0.00062g / 100g water |
| Molecular Weight | 40.32 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) Handbook of Optical constants of Solids II ISBN 0-12-544422-2

## Magnesium Oxide (MgO)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.171 | 2.319 | 0.180 | 2.138 | 0.191 | 2.039 |
| 0.200 | 1.986 | 0.230 | 1.892 | 0.276 | 1.824 |
| 0.310 | 1.795 | 0.382 | 1.7668 | 0.436 | 1.75471 |
| 0.50 | 1.754 | 0.644 | 1.734 | 1.00 | 1.7229 |
| 2.00 | 1.7085 | 3.00 | 1.6915 | 4.00 | 1.6679 |
| 5.00 | 1.6373 | 6.02 | 1.5957 | 7.04 | 1.543 |
| 8.07 | 1.475 | 9.09 | 1.389 | 10.64 | 1.209 |



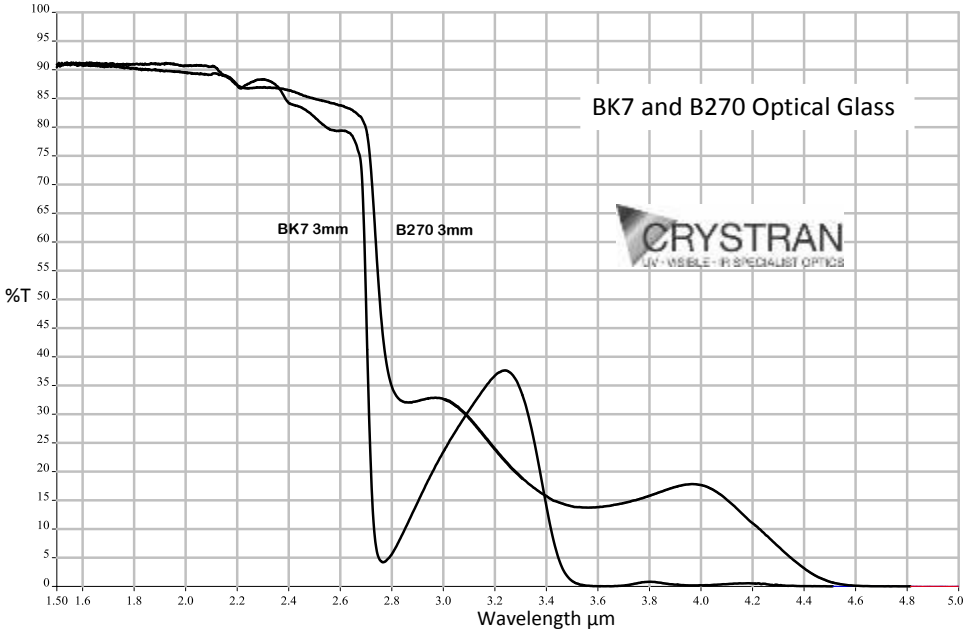



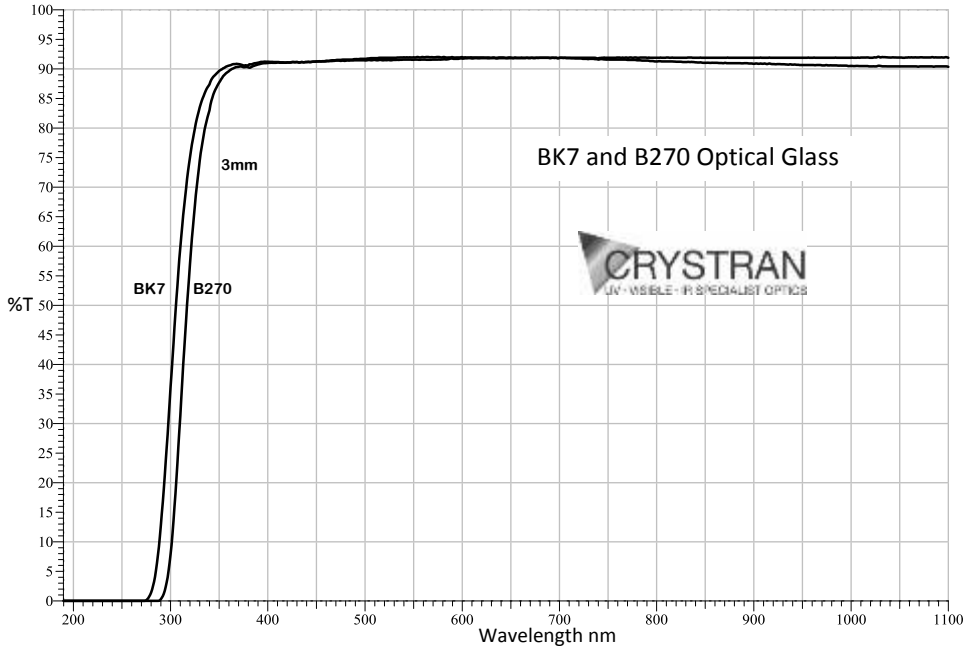
## Optical Glass (N-BK7 types)



**APPLICATIONS:** N-BK7 is a Schott™ designation for the most common Borosilicate Crown glass used for a wide variety of visible applications. The basic data here is given for N-BK7. We recommend that full optical design data on N-BK7 and other glasses be found by referring to the relevant glass manufacturer.

| | |
|---|---|
| Transmission Range | 350nm to 2.5µm |
| Refractive Index | 1.51680 @ 587.5618nm (Yellow Helium Line) |
| Reflection Loss | 8.1% at 587.5618nm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | n/a |
| $dn/d\mu = 0$ | n/a |
| Density | 2.51 g/cc |
| Melting Point | 557°C (Transformation Temperature) |
| Thermal Conductivity | 1.114 W $m^{-1}$ $K^{-1}$ |
| Thermal Expansion | 7.1 x $10^{-6}$ $K^{-1}$ |
| Hardness | Knoop 610 |
| Specific Heat Capacity | 858 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | n/a |
| Youngs Modulus (E) | 82 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 34 GPa |
| Elastic Coefficients | n/a |
| Apparent Elastic Limit | 63.5MPa (9206psi) |
| Poisson Ratio | 0.206 |
| Solubility | Insoluble in water |
| Molecular Weight | n/a |
| Class/Structure | Amorphous glass |


BK7 and B270 Optical Glass
CRYSTRAN
UV · VISIBLE · IR SPECIALIST OPTICS
BK7 3mm
B270 3mm
%T
Wavelength µm


BK7 and B270 Optical Glass
CRYSTRAN
UV · VISIBLE · IR SPECIALIST OPTICS
3mm
BK7
B270
%T
Wavelength nm

## Potassium Bromide (KBr)



Potassium Bromide is produced in large ingots by the Kyropoulos growth method. Potassium Bromide cleaves easily. With care Potassium Bromide can be polished to a high standard under humidity controlled conditions. Polymer coating can be applied.

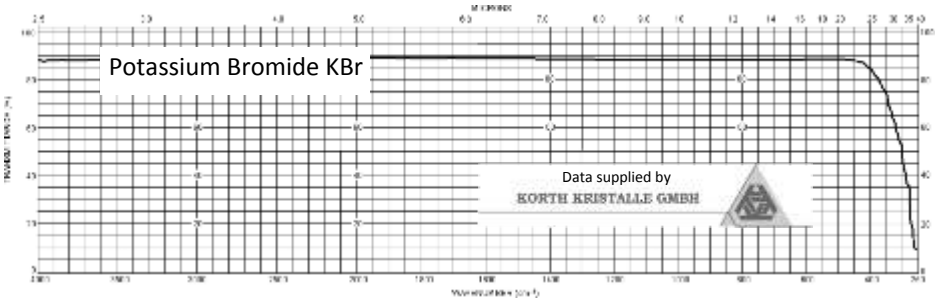
**APPLICATIONS:** Potassium Bromide is one of the most useful materials for general purpose spectroscopic windows and applications where sensitivity to moisture is unimportant. Potassium Bromide is the most commonly used beamsplitter material for IR spectrophotometers. It can be supplied with a conformal polymer coating to give some protection against atmospheric humidity.

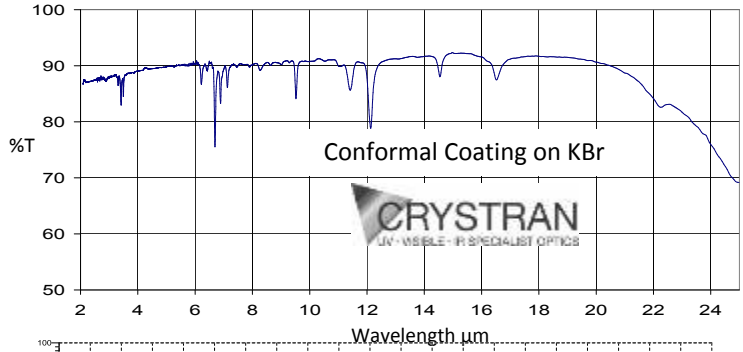
| | |
|---|---|
| Transmission Range | 0.23 to 25µm |
| Refractive Index | 1.527 at 10µm (1) |
| Reflection Loss | 8.3% at 10µm |
| Absorption Coefficient | $3 \times 10^{-6}$ @ 1064nm : $14 \times 10^{-6}$ $cm^{-1}$ @ 10.6 (7) |
| Reststrahlen Peak | 77.6µm |
| dn/dT | $-40.83 \times 10^{-6}$ $K^{-1}$ (1) |
| $dn/d\mu = 0$ | 4.2µm |
| Density | 2.753 g/cc (2) |
| Melting Point | 730°C |
| Thermal Conductivity | 4.816 W $m^{-1}$ $K^{-1}$ @ 319K (3) |
| Thermal Expansion | $43 \times 10^{-6}$ $K^{-1}$ @300K (4) |
| Hardness | Knoop 7 in <100> with 200g indenter (4) |
| Specific Heat Capacity | 435 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 4.9 @ 1MHz (6) |
| Youngs Modulus (E) | 26.8 GPa (4) |
| Shear Modulus (G) | 5.08 GPa (4) |
| Bulk Modulus (K) | 15.03 GPa (4) |
| Elastic Coefficients | $C_{11}$=34.5 $C_{12}$=5.4 $C_{44}$=5.08 (5) |
| Rupture Modulus | 3.3 MPa (475psi) (4) |
| Poisson Ratio | 0.203 |
| Solubility | 53.48g/100g water at 273K |
| Molecular Weight | 119.01 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

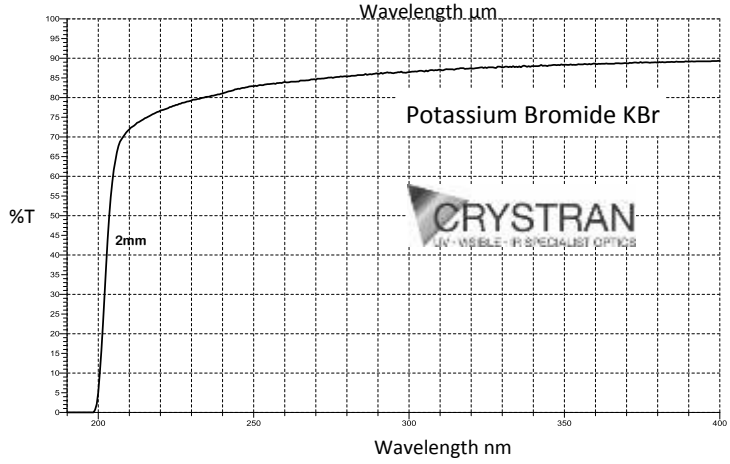
(1) Stephens et. al.; J.Opt. Soc. Am. V43, p111, 1953
(2) Kohler; Z. Physik. Volk 78, p375. 1932
(3) Ballard, McCarthy & Davis; Rev. Sci. Insts, V21, p905, 1970
(4) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.
(5) Huntingdon; Phys.Rev. V72, p321, 1947
(6) Hipple; Dielectric Materials & Applications. Wiley
(7) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

## Potassium Bromide (KBr)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.405 | 1.5898 | 0.436 | 1.5815 | 0.486 | 1.5718 |
| 0.508 | 1.5684 | 0.546 | 1.5639 | 0.587 | 1.5600 |
| 0.643 | 1.5559 | 0.707 | 1.5524 | 1.014 | 1.5441 |
| 2.440 | 1.5373 | 3.419 | 1.5361 | 4.258 | 1.5352 |
| 6.238 | 1.5329 | 8.662 | 1.5290 | 9.724 | 1.5270 |
| 11.04 | 1.5240 | 14.29 | 1.5150 | 17.40 | 1.5039 |
| 19.91 | 1.4929 | 23.86 | 1.4714 | 25.14 | 1.4632 |
| 28.00 | 1.4423 | 30.00 | 1.4253 | | |



## Potassium Chloride (KCl)



Potassium Chloride is produced in large ingots by the Kyropoulos growth method. Potassium Chloride cleaves easily. With care Potassium Chloride can be polished to a high standard under humidity controlled conditions.

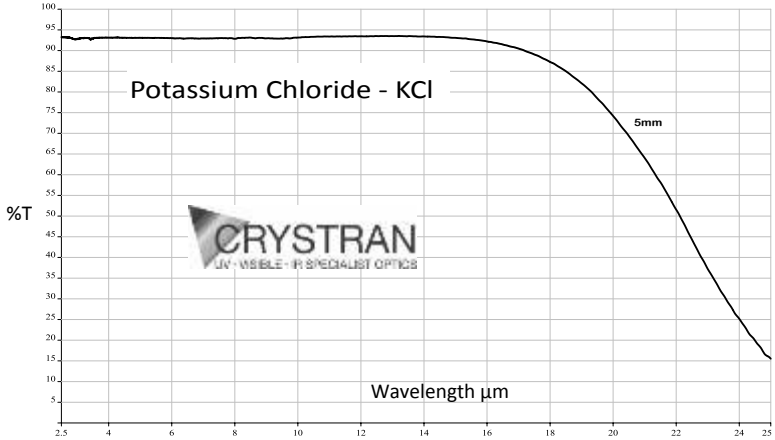
**APPLICATIONS:** Potassium Chloride is mainly used for CO2 laser protection windows as an inexpensive disposable material with a low refractive index.

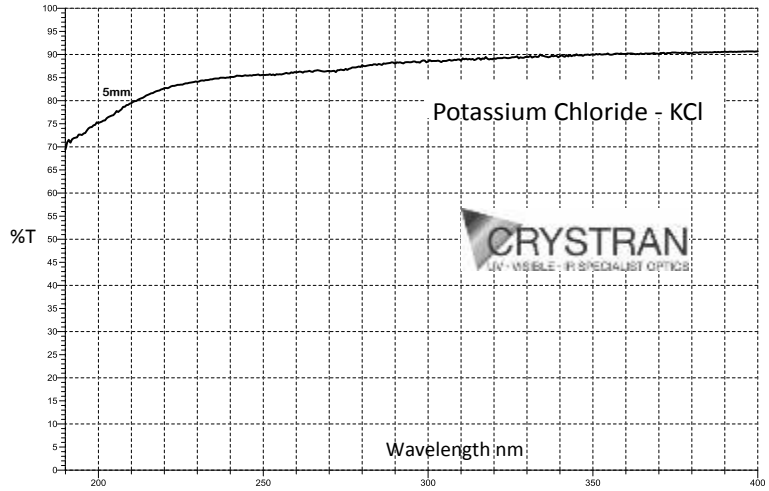
| | |
|---|---|
| Transmission Range | 0.21 to 20µm |
| Refractive Index | 1.45644 at 10µm (2) |
| Reflection Loss | 6.7% at 10µm |
| Absorption Coefficient | $6.5 \times 10^{-3}$ $cm^{-3}$ at 10.6µm @ 300K (6) |
| Reststrahlen Peak | 63.1µm |
| dn/dT | $-33.2 \times 10^{-6}$ $K^{-1}$ (1) |
| dn/dµ = 0 | n/a |
| Density | 1.99 g/cc |
| Melting Point | 776°C |
| Thermal Conductivity | 6.53 W $m^{-1}$ $K^{-1}$ at 322K (3) |
| Thermal Expansion | $36 \times 10^{-6}$ $K^{-1}$ at 300k |
| Hardness | Knoop 7.2 <110>, 9.3 <100> with 200g (4) |
| Specific Heat Capacity | 690 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 4.64 at 1MHz at 300K |
| Youngs Modulus (E) | 29.67 GPa (4) |
| Shear Modulus (G) | 6.24 GPa (4) |
| Bulk Modulus (K) | 17.36 GPa (4) |
| Elastic Coefficients | $C_{11}$=39.8; $C_{12}$=6.2; $C_{44}$=6.25 (5) |
| Rupture Modulus | 4.4 MPa (635 psi) (4) |
| Poisson Ratio | 0.216 |
| Solubility | 34.7g/100g water |
| Molecular Weight | 74.55 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) Mentzel; Z. Physik. V 88, p178. 1934
(2) H.H.Li; RI of Alkali Halides. J. Phys and Chem Reference Data V5(2), p421, 1976
(3) Ballard, McCarthy & Davis; Rev. Sci. Insts, V21, p905, 1970
(4) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.
(5) Galt; Phys.Rev. V36, p1460, 1948
(6) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

## Potassium Chloride (KCl)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.185 | 1.8271 | 0.200 | 1.7187 | 0.251 | 1.5897 |
| 0.308 | 1.54136 | 0.410 | 1.50907 | 0.509 | 1.4962 |
| 0.671 | 1.48669 | 0.883 | 1.48142 | 0.982 | 1.4800 |
| 1.179 | 1.47831 | 2.357 | 1.47475 | 2.947 | 1.47383 |
| 3.536 | 1.47305 | 4.715 | 1.47112 | 5.000 | 1.47048 |
| 6.000 | 1.46842 | 7.000 | 1.466 | 8.000 | 1.4629 |
| 9.000 | 1.46002 | 10.00 | 1.45644 | 11.00 | 1.45244 |
| 12.00 | 1.44801 | 13.00 | 1.44313 | 14.00 | 1.43779 |
| 15.00 | 1.43197 | 16.00 | 1.42563 | 17.00 | 1.41877 |
| 18.00 | 1.41134 | 19.00 | 1.40333 | 20.00 | 1.39469 |
| 21.00 | 1.38538 | 22.00 | 1.37537 | 23.00 | 1.36461 |
| 24.00 | 1.35303 | 25.00 | 1.34059 | 26.00 | 1.32721 |
| 27.00 | 1.31281 | 28.00 | 1.29731 | | |



## Potassium Iodide (KI)



Potassium Iodide is produced in large ingots by the Kyropoulos growth method. Potassium Iodide cleaves easily. Potassium Iodide is only useful in controlled laboratory conditions as it is very soft and very water soluble.

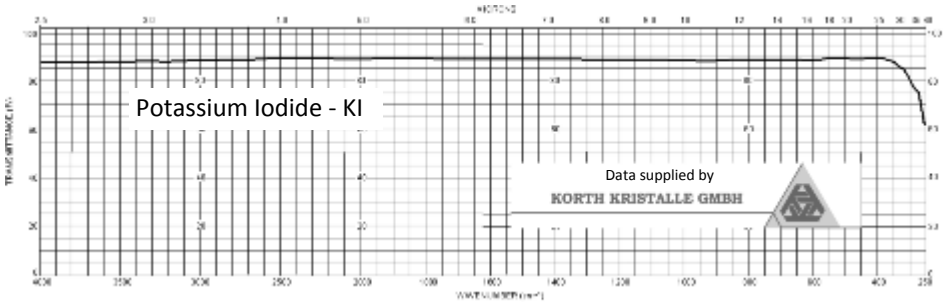
**APPLICATIONS:** Potassium Iodide has few specific applications but has some uses in the very deep Infra Red.

| | |
|---|---|
| Transmission Range | 0.38 to 35µm |
| Refractive Index | 1.6201 at 10µm (1) |
| Reflection Loss | 10.6% at 10µm (2 surfaces) |
| Absorption Coefficient | $4.5 \times 10^{-3}$ @ 20µm (2) |
| Reststrahlen Peak | 82 to 100µm |
| dn/dT | $-50 \times 10^{-6}\ K^{-1}$ |
| dn/dµ = 0 | 2.1µm |
| Density | 3.12 g/cc |
| Melting Point | 682°C |
| Thermal Conductivity | 2.1 $W\ m^{-1}\ K^{-1}$ at 298K |
| Thermal Expansion | $43 \times 10^{-6}\ K^{-1}$ at 298K |
| Hardness | Moh 5 |
| Specific Heat Capacity | 313 $J\ Kg^{-1}\ K^{-1}$ |
| Dielectric Constant | 4.94 at 2 MHz |
| Youngs Modulus (E) | 31.49 GPa |
| Shear Modulus (G) | 6.2 GPa |
| Bulk Modulus (K) | 12 GPa |
| Elastic Coefficients | $C_{11}$=27.4; $C_{12}$=4.3; $C_{44}$=3.7 |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | 127.5g/100g water at 273K |
| Molecular Weight | 166.02 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) K.Korth, Z.Physik. Vol 84, p677-685 (1933)
(2) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

## Potassium Iodide (KI)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.302 | 1.82769 | 0.405 | 1.71843 | 0.546 | 1.67310 |
| 0.768 | 1.6494 | 1.014 | 1.6396 | 2.360 | 1.6295 |
| 3.540 | 1.6275 | 4.130 | 1.6268 | 5.890 | 1.6252 |
| 7.660 | 1.6235 | 8.840 | 1.6218 | 10.02 | 1.6201 |
| 11.79 | 1.6172 | 12.97 | 1.615 | 14.14 | 1.6127 |
| 15.91 | 1.6085 | 18.10 | 1.603 | 19.00 | 1.5997 |
| 20.00 | 1.5964 | 21.00 | 1.593 | 22.00 | 1.5895 |
| 23.00 | 1.5858 | 24.00 | 1.5819 | 25.00 | 1.5775 |
| 26.00 | 1.5729 | 27.00 | 1.5681 | 28.00 | 1.5629 |
| 29.00 | 1.5571 | | | | |



## Quartz Crystal ($SiO_2$)



Quartz is mined naturally, but more commonly produced synthetically in large, long-faceted crystals. Quartz is positive birefringent. Be careful not to confuse terminology in this material, as "Fused Quartz" is often used to denote the glassy non-crystalline form better known as Silica. Normal Quartz is Alpha Quartz and normally RH rotating. LH rotating is available on special order. At temperatures >490°C, Crystal Quartz starts to revert to glassy state, a process which is complete by 530°C.

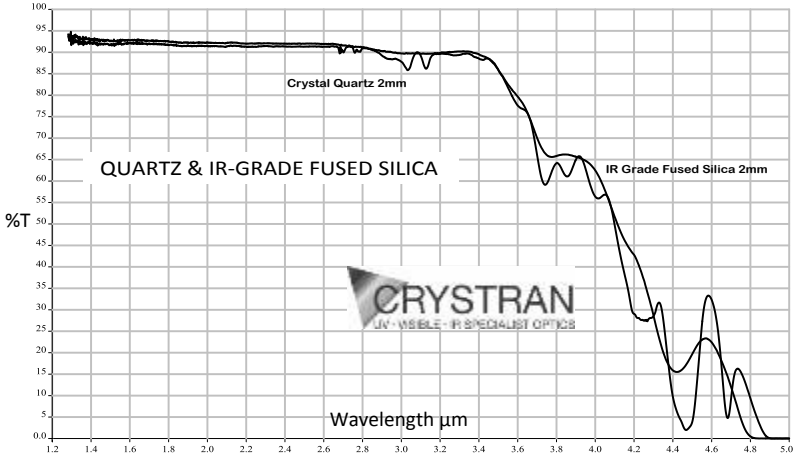
**APPLICATIONS:** Optically, Crystalline Quartz is used extensively as a wave retardation medium. The birefringent properties of Quartz are of use in quarter-wave plates and in polarisers. Quartz should not be processed or used at temperatures greater than 490°C. Use the QR link on page 30 for notes on quartz .

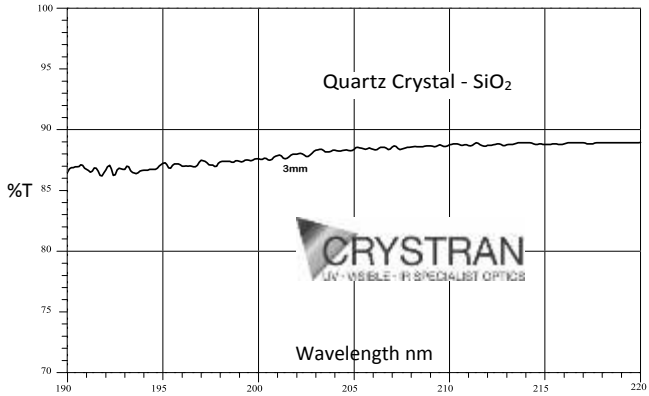
| | |
|---|---|
| Transmission Range | 0.18 to 3.5µm and 40µm to 100µm |
| Refractive Index | No 1.54421; Ne 1.55333 at 0.6µm |
| Reflection Loss | 8.8% at 0.6µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT (3) (4) | $-5.5 \times 10^{-6}$ (para) & $-6.5 \times 10^{-6}$ $K^{-1}$ (perp) @ 633nm |
| $dn/d\mu = 0$ | 1.3µm |
| Density | 2.649 g/cc |
| Melting Point | 1710 °C |
| Thermal Conductivity | 10.7 (para) 6.2 (perp) W $m^{-1}$ $K^{-1}$ at 323 K |
| Thermal Expansion | 7.1 (para) 13.2 (perp) x $10^{-6}$ K |
| Hardness | Knoop 741 with 500g indenter |
| Specific Heat Capacity | 710 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 4.34 (para) 4.27 (perp) at 30MHz |
| Youngs Modulus (E) | 97.2 (para) 76.5 (perp) GPa |
| Shear Modulus (G) | 31.14 GPa |
| Bulk Modulus (K) | 36.4 GPa |
| Elastic Coefficients (1) (2) | $C_{11}$=87 $C_{12}$=7 $C_{44}$=58 $C_{13}$=13 $C_{14}$=(-)18 $C_{33}$=106 |
| Apparent Elastic Limit | 41MPa (5950psi) |
| Poisson Ratio | n/a |
| Solubility | Insoluble in water |
| Molecular Weight | 60.06 |
| Class/Structure | Trigonal (hex) P3(2)21 (RH) and P3(1)21 (LH) |

(1)J.V.Atansoff and P.J.Hart, Phys. Rev. Vol.59, pp 85-96 1941
(2)A.W.Lawson, Phys. Rev. Vol 59, pp.838-839, 1941
(3) F.J.Micheli, Ann.Physik 4:7 (1902)
(4) Toyoda & Yabe J. Phys. D: Appl. Phys.,1 6 (1983)

## Quartz Crystal ($SiO_2$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.193 | 1.661 | 1.675 | 0.213 | 1.632 | 1.645 |
| 0.222 | 1.622 | 1.634 | 0.226 | 1.619 | 1.630 |
| 0.248 | 1.602 | 1.613 | 0.257 | 1.596 | 1.607 |
| 0.280 | 1.585 | 1.596 | 0.308 | 1.576 | 1.586 |
| 0.325 | 1.571 | 1.581 | 0.351 | 1.565 | 1.575 |
| 0.400 | 1.558 | 1.567 | 0.458 | 1.552 | 1.561 |
| 0.488 | 1.550 | 1.559 | 0.515 | 1.548 | 1.557 |
| 0.532 | 1.547 | 1.556 | 0.590 | 1.544 | 1.553 |
| 0.633 | 1.543 | 1.552 | 0.670 | 1.541 | 1.551 |
| 0.694 | 1.541 | 1.550 | 0.755 | 1.539 | 1.548 |
| 0.780 | 1.539 | 1.548 | 0.800 | 1.538 | 1.547 |
| 0.820 | 1.538 | 1.547 | 0.860 | 1.537 | 1.547 |
| 0.980 | 1.535 | 1.546 | 1.064 | 1.534 | 1.543 |
| 1.320 | 1.531 | 1.539 | 1.550 | 1.528 | 1.536 |
| 2.010 | 1.521 | 1.529 | | | |



## Rubidium Bromide (RbBr)



Rubidium Bromide is produced by the sealed-ampoule Stockbarger technique.

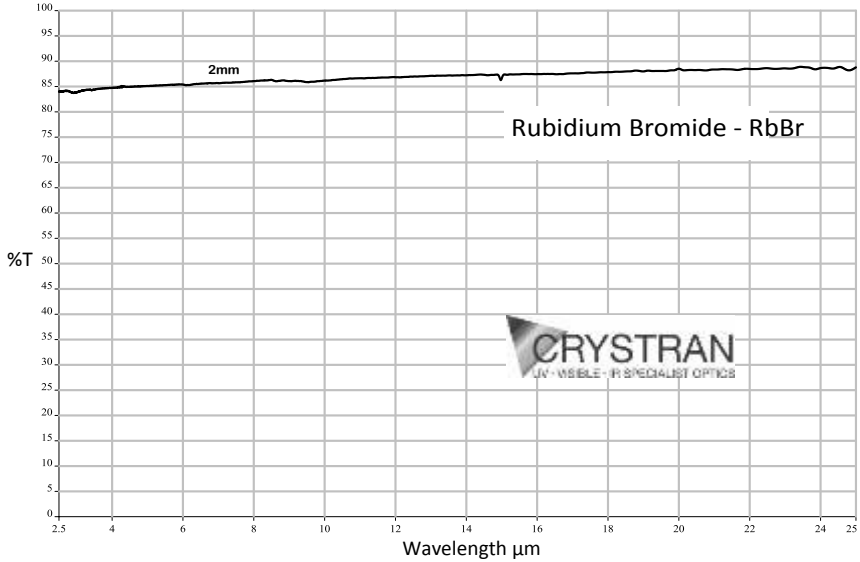
**APPLICATIONS:** Rubidium Bromide has only specialist applications.

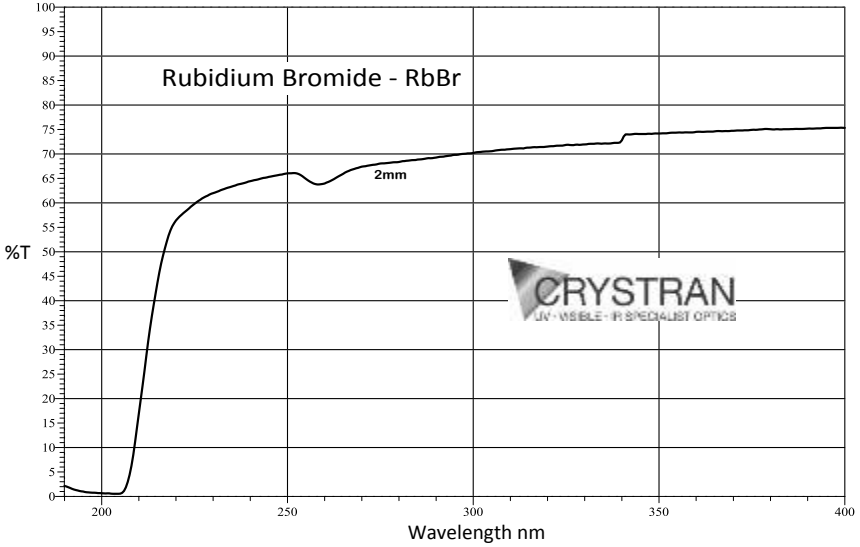
| | |
|---|---|
| Transmission Range | 0.22 to 40µm |
| Refractive Index | 1.525 at 10µm (1) |
| Reflection Loss | 8.2% at 10µm (2 surfaces) |
| Absorption Coefficient | $1.6 \times 10^{-3}$ $cm^{-1}$ at 10.6µm |
| Reststrahlen Peak | n/a |
| dn/dT | $-45 \times 10^{-6}$ $K^{-1}$ |
| dn/dµ = 0 | n/a |
| Density | 3.35 g/cc |
| Melting Point | 682°C |
| Thermal Conductivity | 12.2 W $m^{-1}$ $K^{-1}$ at 378K |
| Thermal Expansion | $36.98 \times 10^{-6}$ $K^{-1}$ at 273K |
| Hardness | n/a |
| Specific Heat Capacity | 311 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 55 |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 13.7 GPa |
| Elastic Coefficients | $C_{11}$=31.5; $C_{12}$=4.8; $C_{44}$=3.82 |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | 98g/100g water |
| Molecular Weight | 165.38 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## Rubidium Bromide (RbBr)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.240 | 1.754 | 0.350 | 1.603 | 0.400 | 1.583 |
| 0.500 | 1.563 | 0.600 | 1.552 | 0.70 | 1.546 |
| 0.80 | 1.543 | 0.90 | 1.540 | 1.00 | 1.538 |
| 2.00 | 1.533 | 5.00 | 1.530 | 10.0 | 1.525 |
| 15.0 | 1.517 | 20.0 | 1.505 | 25.0 | 1.489 |
| 30.0 | 1.469 | 35.0 | 1.444 | 40.0 | 1.412 |



## Rubidium Chloride (RbCl)

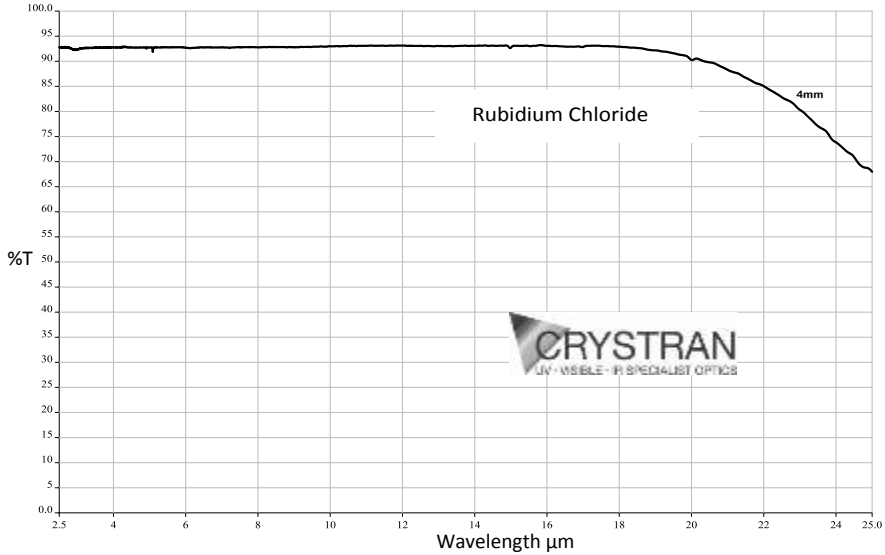
Rubidium Chloride is produced by the sealed-ampoule Stockbarger technique.

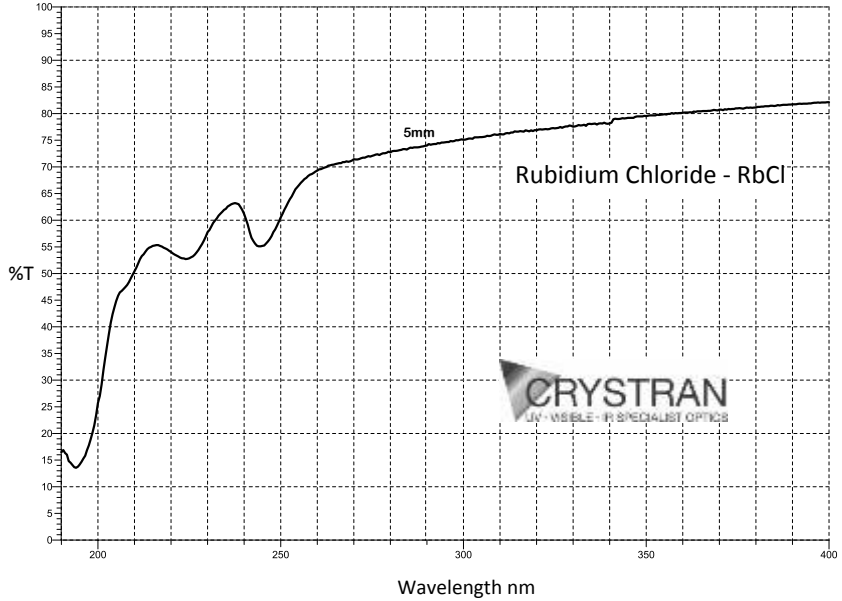
**APPLICATIONS:** Rubidium Chloride has only specialist applications.

| | |
|---|---|
| Transmission Range | 0.2 to 25µm |
| Refractive Index | 1.46 at 10.6µm |
| Reflection Loss | 6.8% at 10.6µm (2 surfaces) |
| Absorption Coefficient | $1 \times 10^{-3}$ $cm^{-1}$ at 10.6µm |
| Reststrahlen Peak | n/a |
| dn/dT | $-39 \times 10^{-6}$ $K^{-1}$ |
| $dn/d\mu = 0$ | n/a |
| Density | 2.8 g/cc |
| Melting Point | 715°C |
| Thermal Conductivity | 7.6 W $m^{-1}$ $K^{-1}$ |
| Thermal Expansion | $36 \times 10^{-6}$ $K^{-1}$ at 300K |
| Hardness | n/a |
| Specific Heat Capacity | 418 J $Kg^{-1}$ $K^{-1}$ at 283K |
| Dielectric Constant | 55 |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 16.3 GPa |
| Elastic Coefficients | $C_{11}$=36.4; $C_{12}$=6.3; $C_{44}$=4.7 |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | 77g/100g water |
| Molecular Weight | 120.92 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

## Rubidium Chloride (RbCl)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.248 | 1.60 | 0.351 | 1.53 | 0.488 | 1.50 |
| 0.590 | 1.49 | 0.633 | 1.49 | 1.060 | 1.48 |
| 1.550 | 1.48 | 2.800 | 1.48 | 10.60 | 1.46 |



## Rubidium Iodide (RbI)

Rubidium Iodide is produced by the sealed-ampoule Stockbarger technique. It is the most deliquescent of the rubidium salts.

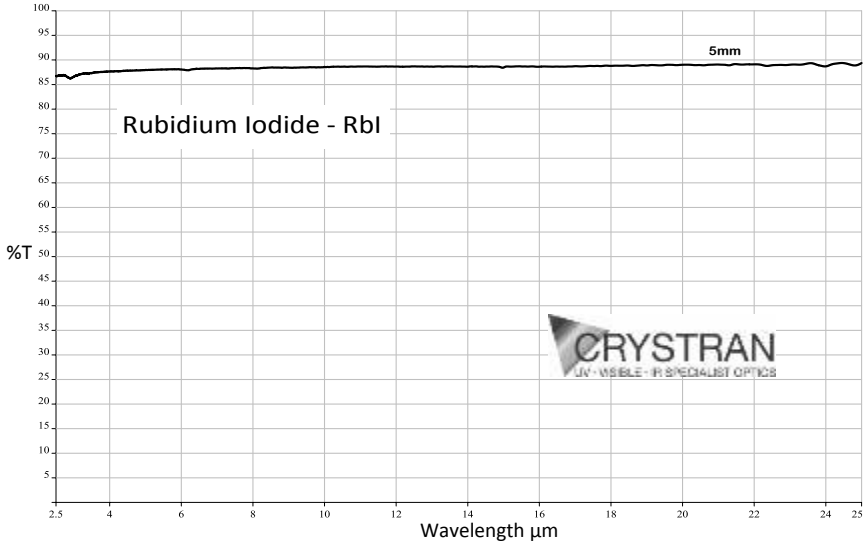
**APPLICATIONS:** Rubidium Iodide has only specialist applications.

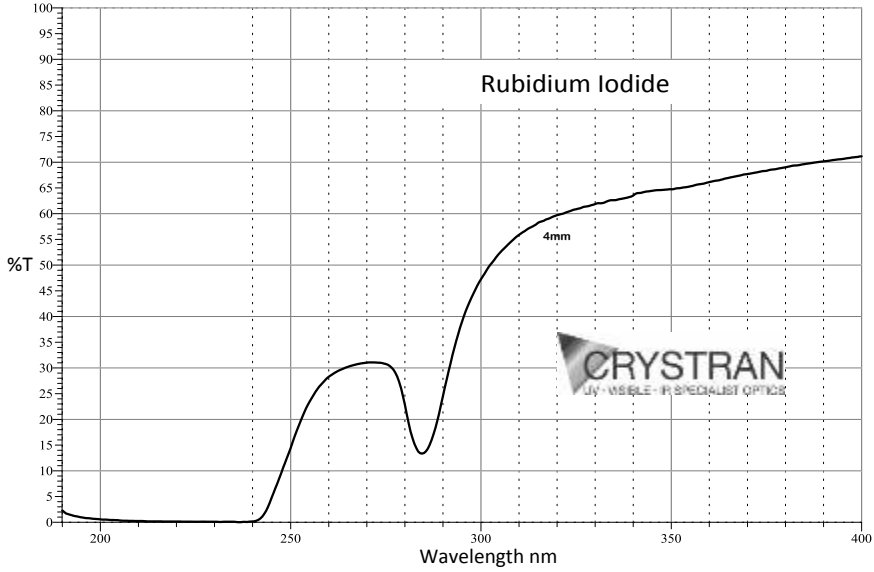
| | |
|---|---|
| Transmission Range | 0.3 to 50µm |
| Refractive Index | 1.609 at 10µm (1) |
| Reflection Loss | 10.4% at 10µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | $-56 \times 10^{-6}\ K^{-1}$ |
| $dn/d\mu = 0$ | n/a |
| Density | 3.55 g/cc |
| Melting Point | 642°C |
| Thermal Conductivity | $9.9\ W\ m^{-1}\ K^{-1}$ |
| Thermal Expansion | $39 \times 10^{-6}\ K^{-1}$ at 283K |
| Hardness | n/a |
| Specific Heat Capacity | $242\ J\ Kg^{-1}\ K^{-1}$ at 283K |
| Dielectric Constant | n/a |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 11 GPa |
| Elastic Coefficients | $C_{11}$=27.6; $C_{12}$=3.7; $C_{44}$=2.79 |
| Apparent Elastic Limit | n/a |
| Poisson Ratio | n/a |
| Solubility | 152g/100g water |
| Molecular Weight | 212.37 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## Rubidium Iodide (RbI)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.25 | 2.059 | 0.35 | 1.736 | 0.50 | 1.663 |
| 0.80 | 1.631 | 1.00 | 1.624 | 2.00 | 1.615 |
| 5.00 | 1.612 | 10.0 | 1.609 | 20.0 | 1.596 |
| 30.0 | 1.573 | 40.0 | 1.537 | 45.0 | 1.514 |
| 50.0 | 1.486 | 55.0 | 1.452 | 60.0 | 1.411 |



## Rutile ($TiO_2$)



Rutile is grown by the Czochralski method typically up to 25mm diameter and up to 80mm long.

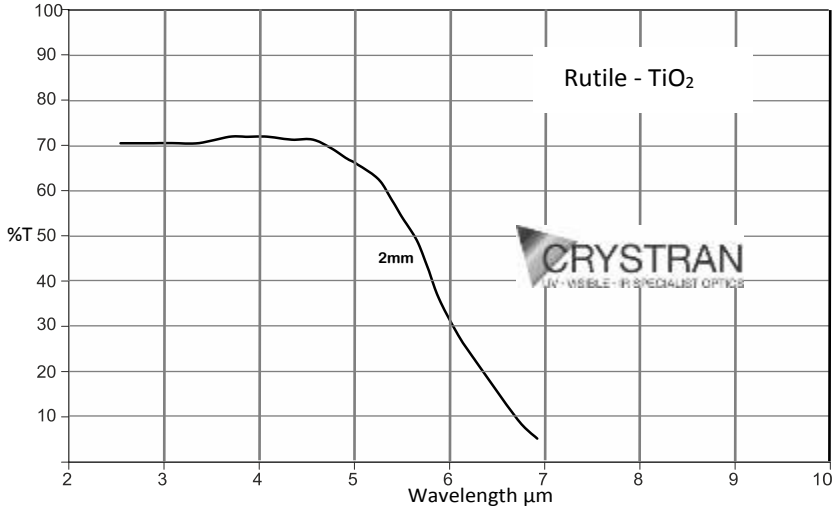
**APPLICATIONS:** Rutile is a high index material used mainly for optical coupling prisms and also as substrates for epitaxial growth.

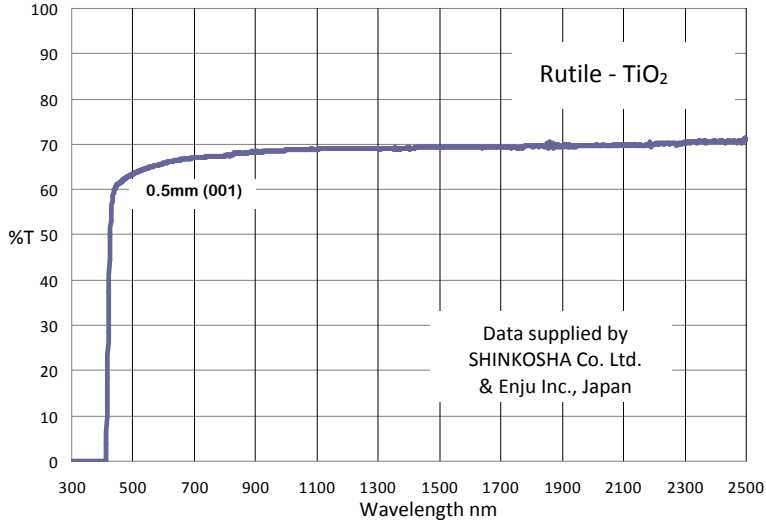
| | |
|---|---|
| Transmission Range | 0.43 to 5.0µm |
| Refractive Index | No 2.555 at 0.69µm (1)(2) |
| Reflection Loss | 30% at 2µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | n/a |
| dn/dµ = 0 | 2.81µm |
| Density | 4.252 g/cc |
| Melting Point | 1840°C |
| Thermal Conductivity | 12.5 (para) 8.7 (perp) W $m^{-1}$ $K^{-1}$ |
| Thermal Expansion | 9.2 (para) 7.1 (perp) x $10^{-6}$ /°C |
| Hardness | Knoop 879 with 500g indenter |
| Specific Heat Capacity | 711 J $kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 160 at 1 MHz |
| Youngs Modulus (E) | n/a |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | $C_{11}$=269;$C_{12}$=177;$C_{13}$=146;$C_{33}$=480;$C_{44}$=124 |
| Apparent Elastic Limit | 4.8 MPa (700 psi) |
| Poisson Ratio | 0.28 |
| Solubility | Insoluble in water |
| Molecular Weight | 79.9 |
| Class/Structure | Tetragonal, P42/mnm, (#136) Rutile Structure. |

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544423-6
(2) Shenoy; 1EE Poceedings-J, Vol. 139, No. 2, Apr 1992

## Rutile ($TiO_2$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.436 | 2.853 | 3.216 | 0.492 | 2.725 | 3.051 |
| 0.496 | 2.718 | 3.042 | 0.546 | 2.652 | 2.958 |
| 0.577 | 2.623 | 2.921 | 0.579 | 2.621 | 2.919 |
| 0.589 | 2.616 | 2.903 | 0.691 | 2.555 | 2.836 |
| 0.708 | 2.548 | 2.826 | 1.01 | 2.484 | 2.747 |
| 1.530 | 2.454 | 2.710 | 2.42 | 2.40 | 2.59 |
| 3.38 | 2.41 | 2.58 | 3.79 | 2.39 | 2.57 |
| 4.28 | 2.34 | 2.51 | 4.89 | 2.32 | 2.49 |
| 5.73 | 2.24 | 2.43 | | | |



## Sapphire ($Al_2O_3$)

Sapphire is grown by a variety of methods. Verneuil and Czochralski methods are usual for standard grade Sapphire material. Higher quality Sapphire, particularly for electronic substrates is manufactured by Kyropulos growth and this can be very pure with excellent UV transmission. Large thin sheets of Sapphire can be made by ribbon growth. Sapphire is slightly birefringent, general purpose IR windows are usually cut in a random way from crystal but for specific applications where the birefringence is an issue, an orientation is selected. Usually this is with the optic axis at 90 degrees to the surface plane and is known as "zero degree" material. Synthetic optical sapphire has no colouration.

**APPLICATIONS:** Sapphire is used for its extreme toughness and strength. Sapphire is a very useful optical window material for use in the UV, visible, and near infra-red. Use the QR ink on page 30 for our guide to sapphire.

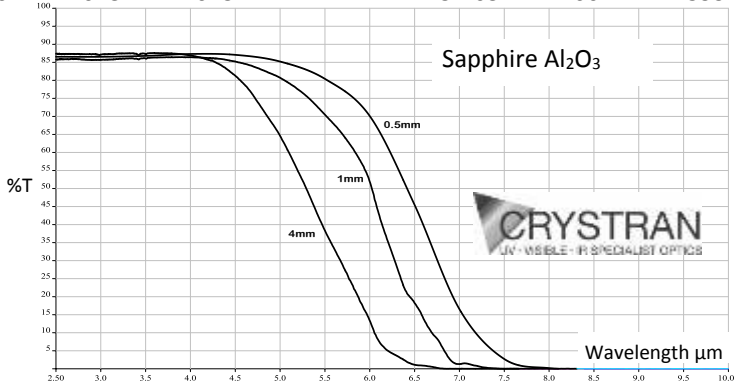
| | |
|---|---|
| Transmission Range | 0.17 to 5.5µm |
| Refractive Index | No 1.75449; Ne 1.74663 at 1.06µm (1) |
| Reflection Loss | 14% at 1.06µm |
| Absorption Coefficient | $0.3 \times 10^{-3}$ $cm^{-1}$ at 2.4µm (2) |
| Reststrahlen Peak | 13.5µm |
| dn/dT | $13.1 \times 10^{-6}$ at 0.546µm (3) |
| dn/dµ = 0 | 1.5µm |
| Density | 3.97 g/cc |
| Melting Point | 2040°C |
| Thermal Conductivity | 27.21 W $m^{-1}$ $K^{-1}$ at 300K |
| Thermal Expansion | 5.6 (para) & 5.0 (perp) x $10^{-6}$ $K^{-1}$ * |
| Hardness | Knoop 1800 (para) 2200 (perp) |
| Specific Heat Capacity | 763 J $Kg^{-1}$ $K^{-1}$ at 293K (4) |
| Dielectric Constant | 11.5 (para) 9.4 (perp) at 1MHz |
| Youngs Modulus (E) | 335 GPa |
| Shear Modulus (G) | 148.1 GPa |
| Bulk Modulus (K) | 240 GPa |
| Elastic Coefficients | $C_{11}$=496 $C_{12}$=164 $C_{13}$=115 $C_{33}$=498 $C_{44}$=148 |
| Apparent Elastic Limit | 300 MPa (45,000 psi) |
| Poisson Ratio | 0.25 |
| Solubility | $98 \times 10^{-6}$ g/100g water |
| Molecular Weight | 101.96 |
| Class/Structure | Trigonal (hex), R3c |

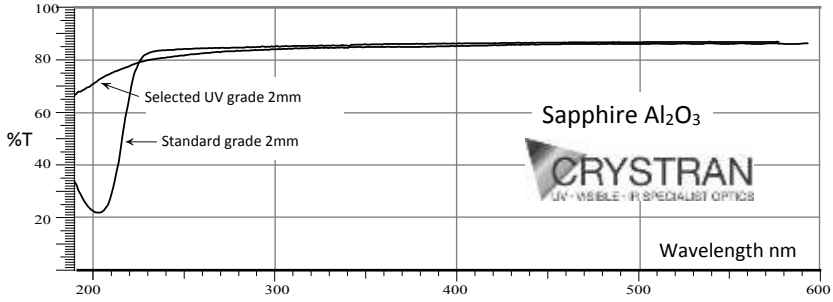
** Note that manufacturers appear to disagree at times on figures for thermal expansion.*

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Harrington et al, Appl.Opt. V15, 1953-1959 (1976)
(3) Malitson, J.Opt.Soc.Am., V52, 1377- 1379 (1962)
(4) Ditmars, et. al., J. Res. Nat. Bur. Stand., 87, (2), 159-163 (1982).

## Sapphire ($Al_2O_3$)

| µm | No | Ne | µm | No | Ne |
|---|---|---|---|---|---|
| 0.193 | 1.9288 | 1.9174 | 0.213 | 1.8890 | 1.8784 |
| 0.222 | 1.8754 | 1.8650 | 0.226 | 1.8702 | 1.8599 |
| 0.244 | 1.8506 | 1.8407 | 0.248 | 1.8470 | 1.8372 |
| 0.257 | 1.8393 | 1.8297 | 0.266 | 1.8330 | 1.8236 |
| 0.280 | 1.8244 | 1.8151 | 0.308 | 1.8110 | 1.8020 |
| 0.325 | 1.8047 | 1.7958 | 0.337 | 1.8001 | 1.7921 |
| 0.351 | 1.7969 | 1.7882 | 0.355 | 1.7960 | 1.7883 |
| 0.442 | 1.7804 | 1.7721 | 0.458 | 1.7784 | 1.7702 |
| 0.488 | 1.7753 | 1.7671 | 0.515 | 1.7730 | 1.7649 |
| 0.532 | 1.7717 | 1.7636 | 0.590 | 1.7680 | 1.7600 |
| 0.633 | 1.7659 | 1.7579 | 0.670 | 1.7643 | 1.7563 |
| 0.694 | 1.7634 | 1.7554 | 0.755 | 1.7614 | 1.7535 |
| 0.780 | 1.7607 | 1.7527 | 0.800 | 1.7601 | 1.7522 |
| 0.820 | 1.7596 | 1.7517 | 0.980 | 1.7561 | 1.7482 |
| 1.064 | 1.7545 | 1.7466 | 1.320 | 1.7501 | 1.7423 |
| 1.550 | 1.7462 | 1.7384 | 2.010 | 1.7375 | 1.7297 |
| 2.249 | 1.7323 | 1.7243 | 2.703 | 1.719 | 1.711 |
| 2.941 | 1.712 | 1.711 | 3.333 | 1.701 | 1.693 |
| 3.704 | 1.687 | 1.679 | 4.000 | 1.674 | 1.666 |
| 4.348 | 1.658 | 1.65 | 4.762 | 1.636 | 1.628 |
| 5.000 | 1.623 | 1.615 | 5.263 | 1.607 | 1.599 |



## Silica Glass ($SiO_2$)

Fused Silica is the glassy form of Quartz and is thus isotropic. Fused Silica is tough and hard and has a very low expansion. Normal varieties of Fused Silica contain water which gives strong absorption in the Infra-red. Water-free varieties of Fused Silica are available.

**APPLICATIONS:** Fused Silica is a hard, high temperature pure glass. Fused Silica is used for UV and visible components. Infra-red grades of Fused Silica are available for NIR use. Use the QR link on page 30 for our guide to silica glass.

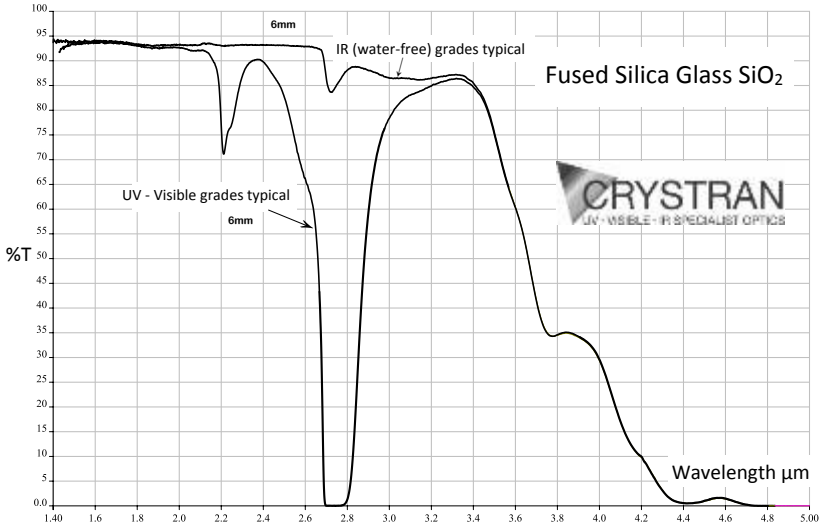
| | |
|---|---|
| Transmission Range | 0.18 to 2.2µm (3µm for IR grades) |
| Refractive Index | 1.47012 at 4µm (1) |
| Reflection Loss | 7.0% at 0.4µm (2 surfaces) |
| Absorption Coefficient | $10 \times 10^{-6}$ $cm^{-1}$ at 1µm |
| Reststrahlen Peak | n/a |
| dn/dT | $+12.9 \times 10^{-6}$ $K^{-1}$ (2) |
| dn/dµ = 0 | 1.3µm |
| Density | 2.203 g/cc |
| Melting Point | 1600 °C (softening) * |
| Thermal Conductivity | 1.38 W $m^{-1}$ $K^{-1}$ |
| Thermal Expansion | $0.55 \times 10^{-6}$ $K^{-1}$ at 300K |
| Hardness | Knoop 500 with 200g indenter |
| Specific Heat Capacity | 703 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 3.78 at 25GHz |
| Youngs Modulus (E) | 73.1 GPa |
| Shear Modulus (G) | 31.2 GPa |
| Bulk Modulus (K) | 36.7 GPa |
| Elastic Coefficients | n/a |
| Apparent Elastic Limit | 55 MPa (7980 psi) |
| Poisson Ratio | 0.17 |
| Solubility | Insoluble in Water |
| Molecular Weight | 28.09 |
| Class/Structure | Amorphous glass |

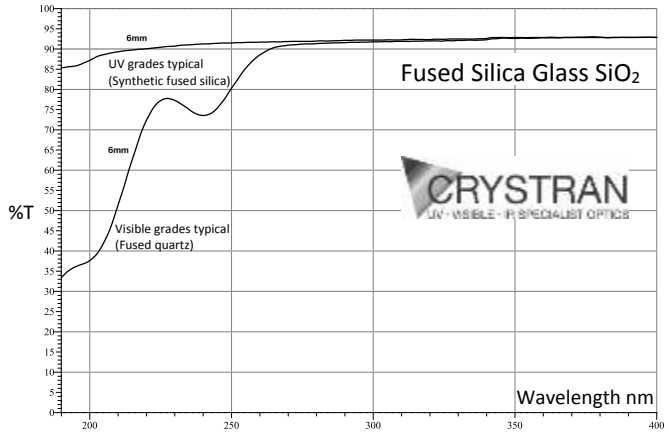
** The normal maximum working temperature is 1050°C*

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Toyoda & Yabe J. Phys. D: Appl. Phys.,1 6 (1983)

## Silica Glass ($SiO_2$)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.20 | 1.55051 | 0.25 | 1.50745 | 0.30 | 1.48779 |
| 0.36 | 1.47529 | 0.40 | 1.47012 | 0.45 | 1.46557 |
| 0.50 | 1.46233 | 0.55 | 1.46008 | 0.60 | 1.45804 |
| 0.65 | 1.45653 | 0.70 | 1.45529 | 0.75 | 1.45424 |
| 0.8 | 1.45332 | 0.85 | 1.4525 | 0.90 | 1.45175 |
| 1.0 | 1.45042 | 1.1 | 1.4492 | 1.2 | 1.44805 |
| 1.3 | 1.44692 | 1.5 | 1.44462 | 1.6 | 1.44342 |
| 1.7 | 1.44217 | 1.8 | 1.44087 | 1.9 | 1.43951 |
| 2.0 | 1.43809 | 2.2 | 1.43501 | 2.4 | 1.43163 |
| 2.6 | 1.42789 | 2.8 | 1.42377 | 3.0 | 1.41925 |
| 3.2 | 1.41427 | 3.37 | 1.41099 | | |



## Silicon (Si)



Silicon is grown by Czochralski pulling techniques (CZ) and contains some oxygen which causes an absorption band at 9µm. To avoid this, Silicon can be prepared by a Float-Zone (FZ) process. Optical Silicon is generally lightly doped ( 5 to 40 ohm cm) for best transmission above 10µm. Silicon has a further pass band 30 to 100µm which is effective only in very high resistivity uncompensated material. Doping is usually Boron (p-type) and Phosphorus (n-type).

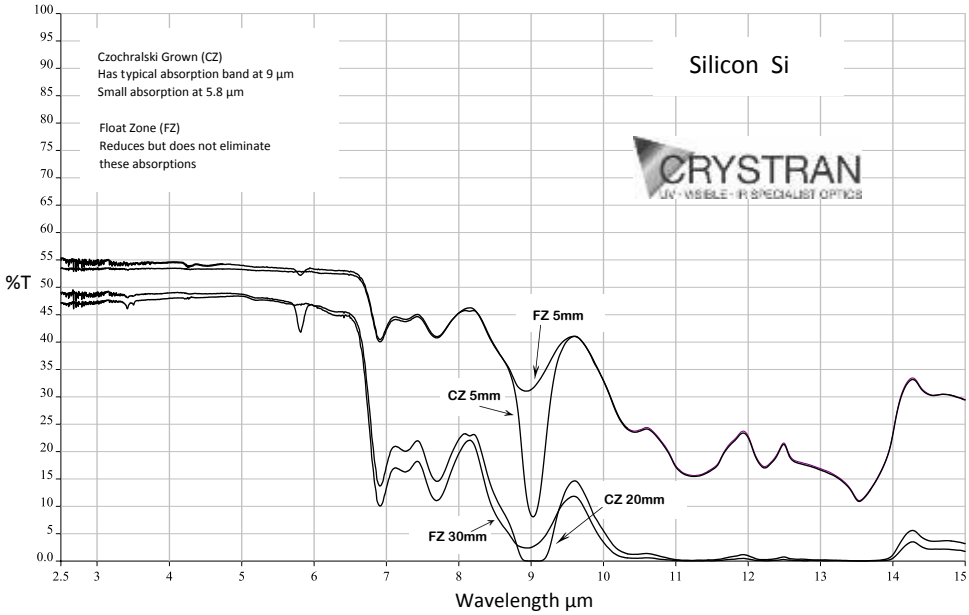
**APPLICATIONS:** Silicon is used as an optical window primarily in the 3 to 5 micron band and as a substrate for production of optical filters. Large blocks of Silicon with polished faces are also employed as neutron targets in Physics experiments

| | |
|---|---|
| Transmission Range | 1.2 to 15µm and 30 to >100µm (1) |
| Refractive Index | 3.4223 @ 5µm (1) (2) |
| Reflection Loss | 46.2% at 5µm (2 surfaces) |
| Absorption Coefficient | 0.01 $cm^{-1}$ at 3µm |
| Reststrahlen Peak | n/a |
| dn/dT | 160 x $10^{-6}$ /°C (3) |
| dn/dµ = 0 | 10.4µm |
| Density | 2.33 g/cc |
| Melting Point | 1420 °C |
| Thermal Conductivity | 163.3 W $m^{-1}$ $K^{-1}$ at 273 K |
| Thermal Expansion | 2.6 x $10^{-6}$ $K^{-1}$ at 20°C |
| Hardness | Knoop 1150 |
| Specific Heat Capacity | 703 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 13 at 10 GHz |
| Youngs Modulus (E) | 131 GPa (4) |
| Shear Modulus (G) | 79.9 GPa (4) |
| Bulk Modulus (K) | 102 GPa |
| Elastic Coefficients | $C_{11}$=167; $C_{12}$=65; $C_{44}$=80 (4) |
| Apparent Elastic Limit | 124.1MPa (18000 psi) |
| Poisson Ratio | 0.266 (4) |
| Solubility | Insoluble in Water |
| Molecular Weight | 28.09 |
| Class/Structure | Cubic diamond, Fd3m |

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Li, Refractive Index of Germanium etc, J.Phys Chem, V9, p561, 1980
(3) Icenogle et al, Appl. Opt. V15, 2348 (1976)
(4) Wortman & Evans, V36, (1), P153 (1965)

## Silicon (Si)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 1.357 | 3.4975 | 1.367 | 3.4962 | 1.395 | 3.4929 |
| 1.5295 | 3.4795 | 1.660 | 3.4696 | 1.709 | 3.4664 |
| 1.813 | 3.4608 | 1.970 | 3.4537 | 2.153 | 3.4476 |
| 2.325 | 3.4430 | 2.714 | 3.4358 | 3.000 | 3.4320 |
| 3.303 | 3.430 | 3.500 | 3.4284 | 4.000 | 3.4257 |
| 4.258 | 3.4245 | 4.500 | 3.4236 | 5.000 | 3.4223 |
| 5.500 | 3.4213 | 6.000 | 3.4202 | 6.500 | 3.4195 |
| 7.000 | 3.4189 | 7.500 | 3.4186 | 8.000 | 3.4184 |
| 8.500 | 3.4182 | 10.00 | 3.4179 | 10.50 | 3.4178 |
| 11.04 | 3.4176 | | | | |



## Silver Bromide (AgBr)



Silver Bromide is grown in small ingots by sealed ampoule Stockbarger techniques. Silver Bromide is malleable and deep yellow, it darkens in sunlight, but less readily than Silver Chloride.

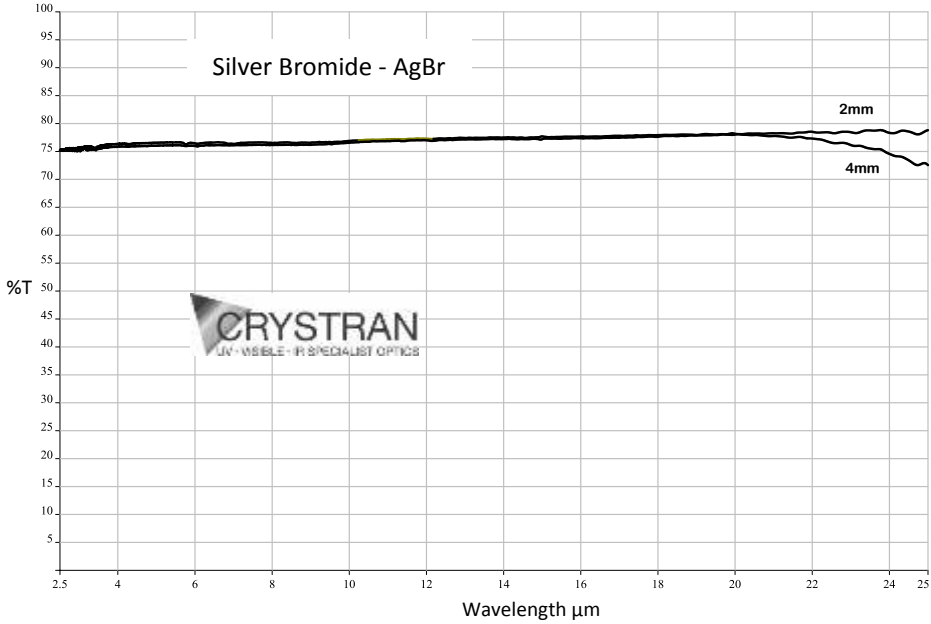
**APPLICATIONS:** Silver Bromide is useful material for very deep Infra Red applications where sensitivity to moisture is a problem. Silver Bromide crystal growth was developed relatively recently by the standards of many IR materials. The parameters of Silver Bromide have not been researched as thoroughly as those of Silver Chloride. This soft crystal deforms under heat and pressure and can be forged in polished dies to create Infra Red windows and lenses.

| | |
|---|---|
| Transmission Range | 0.45 to 35µm (1) |
| Refractive Index | 2.167 at 10µm (1) (2) |
| Reflection Loss | 23.9% at 10µm (2 surfaces) |
| Absorption Coefficient | Not known |
| Reststrahlen Peak | 112.7µm |
| dn/dT | Not known |
| dn/dµ = 0 | Not known |
| Density | 6.473 g/cc |
| Melting Point | 432 °C |
| Thermal Conductivity | 1.21 W $m^{-1}$ $K^{-1}$ at 273 K |
| Thermal Expansion | 30 x $10^{-6}$ $K^{-1}$ at 273 K |
| Hardness | Knoop 7 |
| Specific Heat Capacity | 292 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 13.1 at 1MHz (2) |
| Youngs Modulus (E) | 31.97 GPa |
| Shear Modulus (G) | Not Known |
| Bulk Modulus (K) | 44.03 GPa |
| Elastic Coefficients | $C_{11}$=56.3 $C_{12}$=32.3 $C_{44}$=7.25 |
| Apparent Elastic Limit | 26.2 MPa |
| Poisson Ratio | Not Known |
| Solubility | 12 x $10^{-6}$g/100g water at 20°C |
| Molecular Weight | 187.78 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, No cleavage, cold flows |

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) White; Optical Properties of Silver Bromide. J.Opt. Soc. Am. V62, N2, (1973)

## Silver Bromide (AgBr)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.391 | 2.416 | 0.477 | 2.33 | 0.496 | 2.313 |
| 0.55 | 2.27 | 0.6 | 2.25 | 0.65 | 2.24 |
| 0.781 | 2.205 | 9.926 | 2.167 | 12.66 | 2.162 |



## Silver Chloride (AgCl)

Silver Chloride is grown into small ingots by the sealed-ampoule Stockbarger techniques. Silver chloride is malleable and milky-white it darkens in sunlight, but mild darkening does not affect the IR performance.

**APPLICATIONS:** Silver Chloride is a useful material for deep IR applications where sensitivity to moisture is a problem. This soft crystal deforms under heat and pressure and can be forged in polished dies to create IR windows and lenses. A major use for Silver Chloride is in the manufacture of small disposable cell windows for spectroscopy, known as mini-cells. These windows have a depression of controlled thickness pressed into the surface. The inherent cost of Silver Chloride material is offset against ease of manufacture.

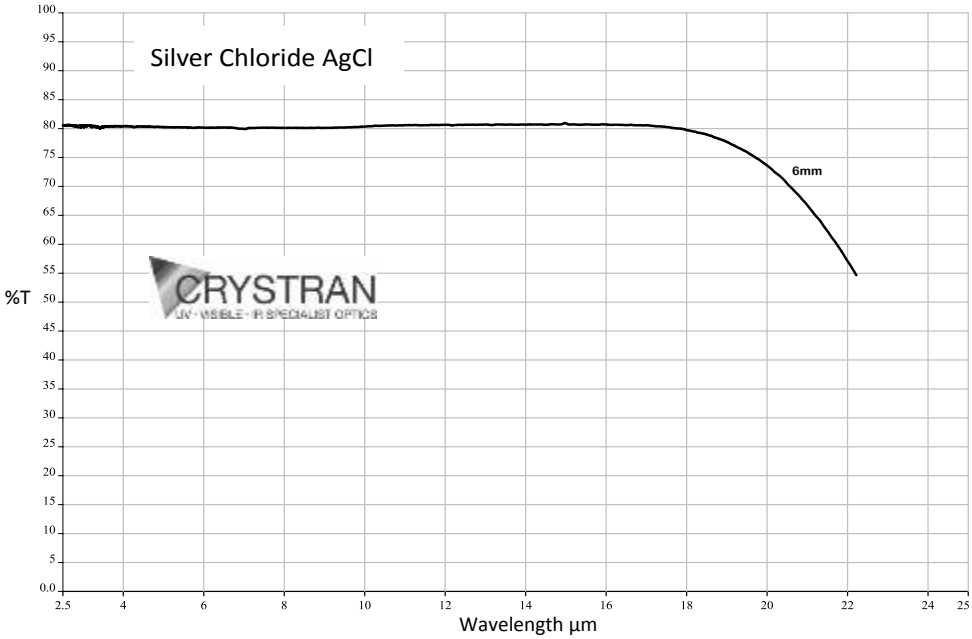
| | |
|---|---|
| Transmission Range | 0.4 to 25µm (1) |
| Refractive Index | 1.98 at 10µm (1) |
| Reflection Loss | 19.5% at 10µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 81.5µm |
| dn/dT | $-61 \times 10^{-6}\ K^{-1}$ |
| dn/dµ = 0 | 4.5µm |
| Density | 5.59 g/cc |
| Melting Point | 457 °C |
| Thermal Conductivity | 1.15 W $m^{-1}\ K^{-1}$ at 278 K |
| Thermal Expansion | $31 \times 10^{-6}\ K^{-1}$ at 302 K |
| Hardness | Knoop 9.5 with 200g indenter |
| Specific Heat Capacity | 355 J $Kg^{-1}\ K^{-1}$ |
| Dielectric Constant | 12.3 at 1MHz |
| Youngs Modulus (E) | 19.98 GPa |
| Shear Modulus (G) | 7.099 GPa |
| Bulk Modulus (K) | 44.04 GPa |
| Elastic Coefficients | $C_{11}$=60.1 $C_{12}$ =36.2 $C_{44}$=6.25 |
| Apparent Elastic Limit | 26.2MPa (3800 psi) |
| Poisson Ratio | 0.4 |
| Solubility | $52 \times 10^{-6}$ g/100g water at 50°C |
| Molecular Weight | 143.34 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, No cleavage, cold flows |

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## Silver Chloride (AgCl)



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.500 | 2.09658 | 1.000 | 2.02239 | 1.500 | 2.01047 |
| 2.000 | 2.00615 | 2.500 | 2.00386 | 3.000 | 2.0023 |
| 3.500 | 2.00102 | 4.000 | 1.99983 | 4.500 | 1.99866 |
| 5.000 | 1.99745 | 5.500 | 1.99618 | 6.000 | 1.99483 |
| 6.500 | 1.99339 | 7.000 | 1.99185 | 7.500 | 1.99021 |
| 8.000 | 1.98847 | 8.500 | 1.98661 | 9.000 | 1.98464 |
| 9.500 | 1.98255 | 10.00 | 1.98034 | 10.50 | 1.97801 |
| 11.00 | 1.97556 | 11.50 | 1.97297 | 12.00 | 1.97026 |
| 12.50 | 1.96742 | 13.00 | 1.96444 | 13.50 | 1.96133 |
| 14.00 | 1.95807 | 14.50 | 1.95467 | 15.00 | 1.95113 |
| 15.50 | 1.94743 | 16.00 | 1.94358 | 16.50 | 1.93958 |
| 17.00 | 1.93542 | 17.50 | 1.93109 | 18.00 | 1.9266 |
| 18.50 | 1.92194 | 19.00 | 1.91710 | 19.50 | 1.91208 |
| 20.00 | 1.90688 | 20.50 | 1.90149 | | |



## Sodium Chloride (NaCl)

Sodium Chloride is produced in large ingots by the Kyropoulos growth method. Sodium Chloride cleaves easily. With care Sodium Chloride can be polished to a high standard under humidity controlled conditions

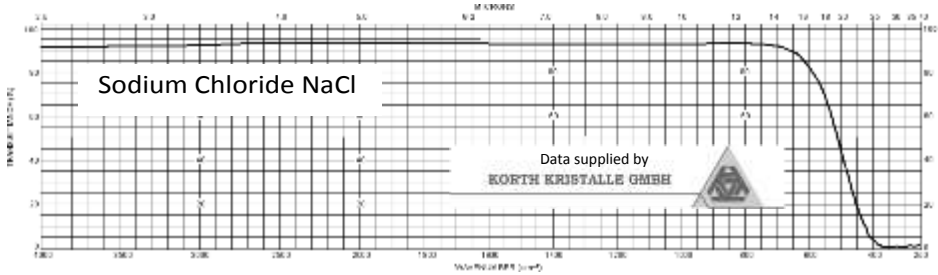
**APPLICATIONS:** Sodium Chloride, common rock salt, is one of the most useful materials for general purpose spectroscopic windows and applications where sensitivity to moisture is unimportant.

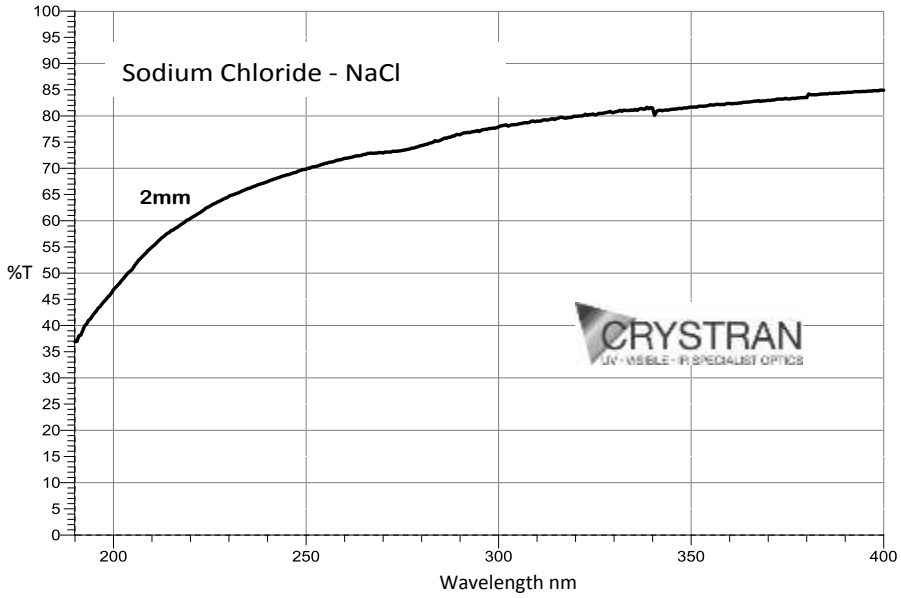
| | |
|---|---|
| Transmission Range | 0.2 to 15µm |
| Refractive Index | 1.49065 at 10.6µm |
| Reflection Loss | 7.5% at 10.6µm (2 surfaces) |
| Absorption Coefficient | $7 \times 10^{-6}$ $cm^{-1}$ at 1.06µm (1) |
| Reststrahlen Peak | 50.1µm |
| dn/dT | $-40.83 \times 10^{-6}$ $K^{-1}$ |
| dn/dµ = 0 | n/a |
| Density | 2.17 g/cc |
| Melting Point | 801 °C |
| Thermal Conductivity | 1.15 W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | $44 \times 10^{-6}$ $K^{-1}$ |
| Hardness | Knoop 18.2 in <100> with 200g indenter |
| Specific Heat Capacity | 854 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 5.9 at 1MHz |
| Youngs Modulus (E) | 39.98 GPa |
| Shear Modulus (G) | 12.61 GPa |
| Bulk Modulus (K) | 24.42 GPa |
| Elastic Coefficients | $C_{11}$=48.5; $C_{12}$=12.3; $C_{44}$=12.61 |
| Rupture Modulus | 3.9 MPa (560 psi) (2) |
| Poisson Ratio | 0.252 |
| Solubility | 35.7g/100g water at 273K |
| Molecular Weight | 58.45 |
| Class/Structure | Cubic FCC, NaCl, Fm3m (#221), (100) cleavage |

(1) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980
(2) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.

## Sodium Chloride (NaCl)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.589 | 1.54427 | 0.640 | 1.54141 | 0.760 | 1.53682 |
| 0.884 | 1.53395 | 0.972 | 1.53253 | 1.054 | 1.53153 |
| 1.555 | 1.53815 | 2.074 | 1.52736 | 9.000 | 1.501 |
| 9.500 | 1.4998 | 10.60 | 1.49065 | 11.40 | 1.48476 |
| 12.50 | 1.47568 | 13.50 | 1.4666 | 14.60 | 1.45572 |
| 16.00 | 1.4399 | 17.80 | 1.41649 | 19.80 | 1.38559 |
| 20.57 | 1.3735 | 22.30 | 1.3403 | | |



## Sodium Fluoride (NaF)

Sodium Fluoride is produced by vacuum Stockbarger techniques. The Sodium Fluoride is very difficult to anneal and cleaves readily limiting the useful size of pieces to about 80mm. Sodium Fluoride polishes well but must be kept in dry air to maintain the quality of the surfaces and retain the deep UV transmission needed for Cerenkov radiation from this material.

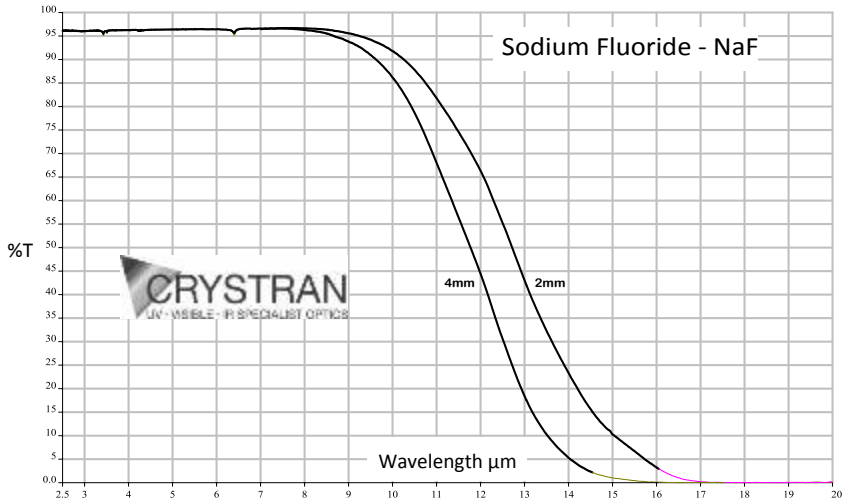
**APPLICATIONS:** Sodium Fluoride has the lowest refractive index of all common optical materials which makes it of interest as a Cerenkov radiator in Particle Physics research. Crystran Ltd. has supplied Sodium Fluoride material which has been made into large arrays at CERN. It is used in Ring Imaging Cerenkov Counters (RICH)

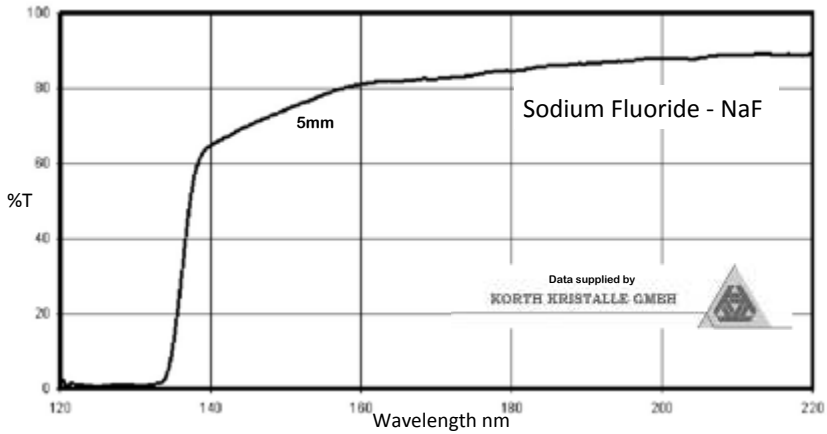
| | |
|---|---|
| Transmission Range | 0.14 to 11µm |
| Refractive Index | 1.3255 at 0.6µm |
| Reflection Loss | 3.9% at 0.6µm |
| Absorption Coefficient | $1 \times 10^{-3}$ $cm^{-1}$ at 7µm @ 300K (1) |
| Reststrahlen Peak | 35.8µm |
| dn/dT | $-13 \times 10^{-6}$ $K^{-1}$ at 293K |
| $dn/d\mu = 0$ | 1.7µm |
| Density | 2.79 g/cc @20°C |
| Melting Point | 980°C |
| Thermal Conductivity | 3.746 W $m^{-1}$ $K^{-1}$ at 273K |
| Thermal Expansion | $36 \times 10^{-6}$ /K at 300K |
| Hardness | Knoop 60 in <100> |
| Specific Heat Capacity | 1088 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 6 at 1 MHz |
| Youngs Modulus (E) | 79.01 GPa |
| Shear Modulus (G) | 12.70 GPa |
| Bulk Modulus (K) | 47.9 GPa |
| Elastic Coefficients | $C_{11}$=79.01; $C_{12}$=12.7; $C_{44}$=47.9 |
| Apparent Elastic Limit | 3.2 MPa (Estimated) |
| Poisson Ratio | 0.326 |
| Solubility | 4.22g/100g water at 18°C |
| Molecular Weight | 42.0 |
| Class/Structure | Cubic FCC, NaCl, Fm3m, (100) cleavage |

(1) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

## Sodium Fluoride (NaF)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.140 | 1.55 | 0.145 | 1.499 | 0.161 | 1.438 |
| 0.175 | 1.410 | 0.186 | 1.393 | 0.199 | 1.3805 |
| 0.203 | 1.3772 | 0.302 | 1.34232 | 0.405 | 1.33194 |
| 0.486 | 1.32818 | 0.546 | 1.3264 | 0.589 | 1.32549 |
| 0.707 | 1.32372 | 0.811 | 1.32272 | 0.912 | 1.32198 |
| 1.014 | 1.3215 | 2.000 | 1.3170 | 3.100 | 1.313 |
| 4.100 | 1.308 | 5.100 | 1.301 | 6.100 | 1.292 |
| 7.100 | 1.281 | 8.100 | 1.269 | 9.100 | 1.252 |
| 10.30 | 1.233 | 11.30 | 1.209 | 12.50 | 1.18 |
| 13.80 | 1.142 | 15.10 | 1.093 | 16.70 | 1.029 |



## Strontium Fluoride ($SrF_2$)



*S*trontium fluoride is produced by the vacuum Stockbarger growth technique.

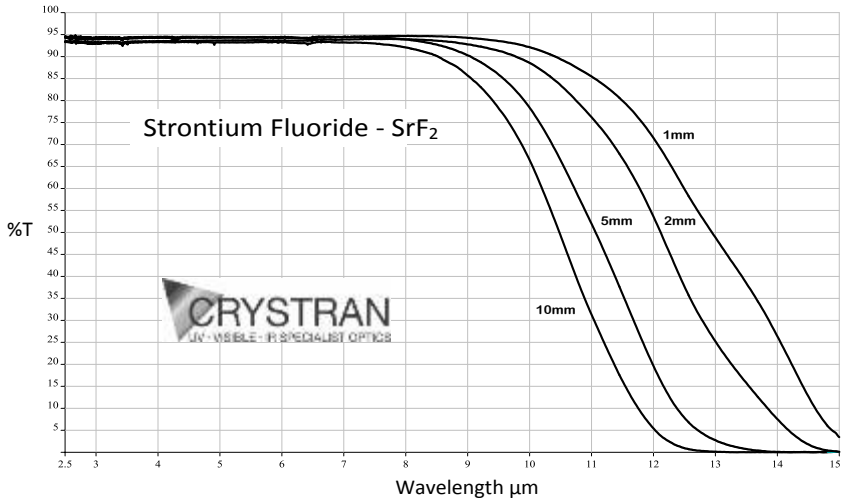
**APPLICATIONS:** Strontium Fluoride has only specialist applications. Optically, Strontium Fluoride has properties intermediate to Calcium and Barium Fluoride.

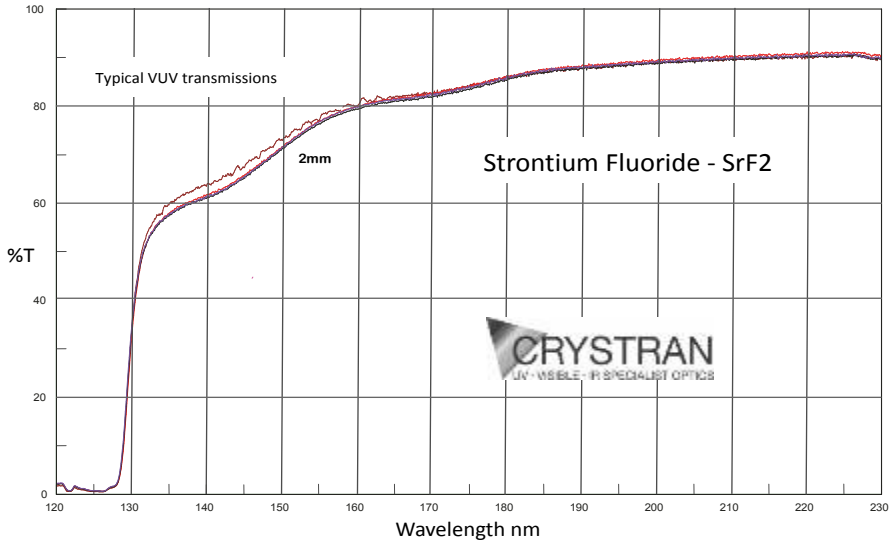
| | |
|---|---|
| Transmission Range | 0.15 to 11µm |
| Refractive Index | 1.439 at 0.55µm (1) |
| Reflection Loss | 6.3% at 0.55µm (2 surfaces) |
| Absorption Coefficient | $<1 \times 10^{-3}$ $cm^{-1}$ at 5µm |
| Reststrahlen Peak | 46µm |
| dn/dT | $-12 \times 10^{-6}$ $K^{-1}$ |
| dn/dµ = 0 | n/a |
| Density | 4.24 g/cc |
| Melting Point | 1450°C |
| Thermal Conductivity | 1.42 W $m^{-1}$ $K^{-1}$ at 298K |
| Thermal Expansion | $18.4 \times 10^{-6}$ $K^{-1}$ at 293K |
| Hardness | Knoop 154 (100) & 140 (110) |
| Specific Heat Capacity | 543 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 7.69 at 2 MHz |
| Youngs Modulus (E) | 89.91 GPa |
| Shear Modulus (G) | 34.6 GPa |
| Bulk Modulus (K) | 24.65 GPa |
| Elastic Coefficients | $C_{11}$=124; $C_{12}$=45; $C_{44}$=31.7 |
| Apparent Elastic Limit | 36.5 MPa (5300 psi) |
| Poisson Ratio | 0.25 |
| Solubility | 0.012g/100g water at 27°C |
| Molecular Weight | 125.62 |
| Class/Structure | Cubic $Fm\bar{3}m$ (#225) Fluorite structure<br>Cleaves on (111) |

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

## Strontium Fluoride ($SrF_2$)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.15 | 1.594 | 0.20 | 1.504 | 0.31 | 1.45725 |
| 0.41 | 1.44556 | 0.51 | 1.44029 | 0.61 | 1.43740 |
| 0.71 | 1.43560 | 0.81 | 1.43435 | 0.91 | 1.43343 |
| 1.01 | 1.43269 | 1.51 | 1.43003 | 2.01 | 1.42761 |
| 3.01 | 1.42159 | 4.01 | 1.41337 | 5.01 | 1.40269 |
| 6.01 | 1.38934 | 7.01 | 1.37308 | 8.01 | 1.35362 |
| 9.1 | 1.3283 | 10.1 | 1.3800 | 11.1 | 1.2686 |
| 12.35 | 1.3002 | | | | |



## Thallium Bromide (TlBr)

**CAUTION: Thallium salts are considered TOXIC and should be handled with care.**

Thallium Bromide crystals are grown by sealed-ampoule Stockbarger technique. Thallium salts are toxic, and Thallium Bromide has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required.

**APPLICATIONS:** Thallium Bromide has little practical application.

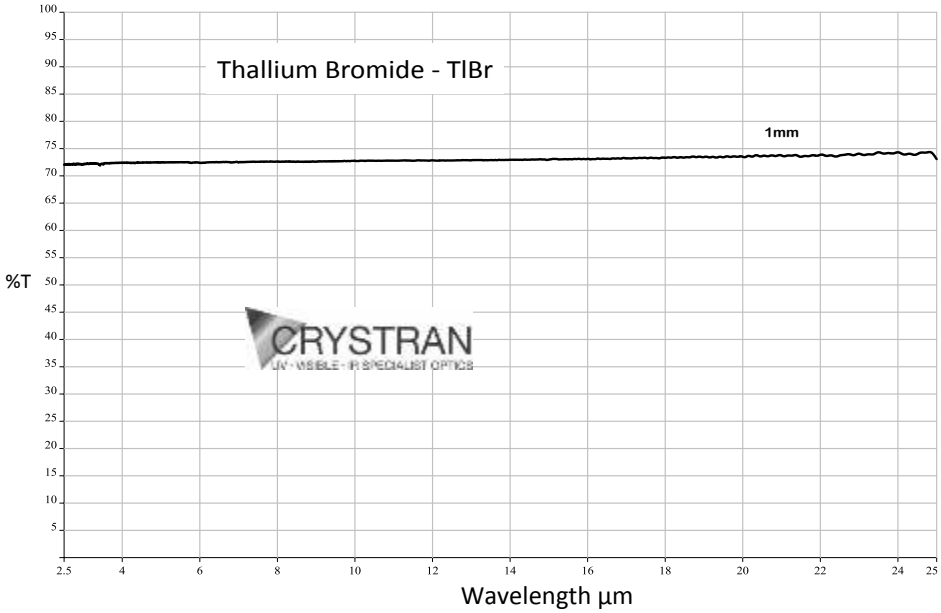
| | |
|---|---|
| Transmission Range | 0.5 to 40µm |
| Refractive Index | 2.338 at 10µm (1) |
| Reflection Loss | 27.7% at 10µm |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 172µm |
| dn/dT | n/a |
| dn/dµ = 0 | 8.5µm |
| Density | 7.453 g/cc (1) |
| Melting Point | 460.5 °C (1) |
| Thermal Conductivity | 0.586 W $m^{-1}$ $K^{-1}$ at 343K |
| Thermal Expansion | 51 x $10^{-6}$ $K^{-1}$ at 300K |
| Hardness | Knoop 11.9 with 500g indenter |
| Specific Heat Capacity | 188 J $Kg^{-1}$ $K^{-1}$ (3) |
| Dielectric Constant | 30.3 at 1 MHz |
| Youngs Modulus (E) | 29.5 GPa (2) |
| Shear Modulus (G) | 7.58 GPa (2) |
| Bulk Modulus (K) | 22.47 Gpa (2) |
| Elastic Coefficients | $C_{11}$=37.8; $C_{12}$=14.8; $C_{44}$=7.56 (2) |
| Apparent Elastic Limit | 20.7 MPa (3000 psi) |
| Poisson Ratio | 0.281 |
| Solubility | 0.05g/100g water ar 25°C |
| Molecular Weight | 248.31 |
| Class/Structure | Cubic CsCl, Pm3m, no cleavage (1) |

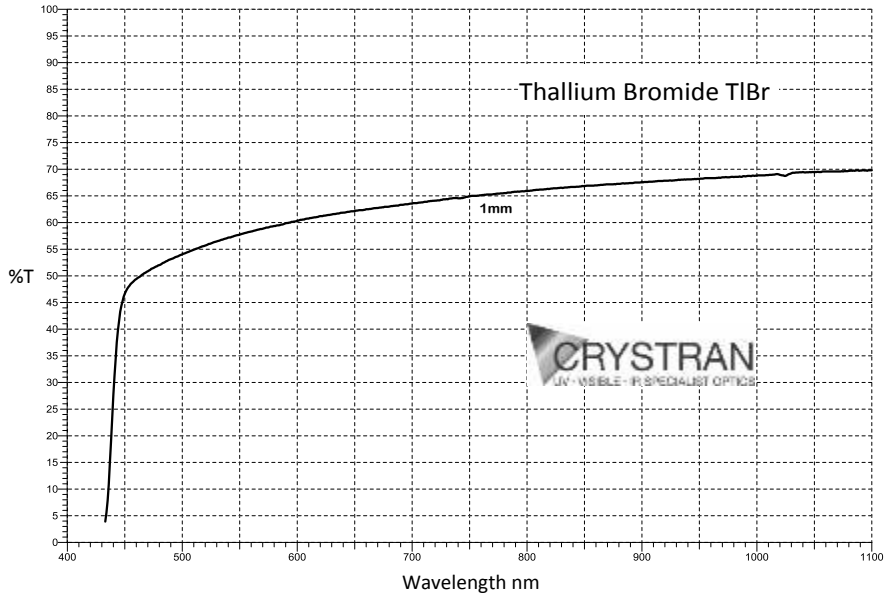
(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Arenberg, Measurements made at Naval Research Labs, USA 1948-49
(3) Kelly, Bureau of Mines Bulletin, No 371, p51. 1934

## Thallium Bromide (TlBr)



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.438 | 2.652 | 0.546 | 2.452 | 0.578 | 2.424 |
| 0.650 | 2.384 | 0.750 | 2.350 | 10.00 | 2.338 |



## Thallium Chloride (TlCl)

***CAUTION: Thallium salts are considered TOXIC and should be handled with care.***

Thallium Chloride crystals are grown by sealed-ampoule Stockbarger technique. Thallium salts are toxic, and Thallium Chloride has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required

**APPLICATIONS:** Thallium Chloride has little practical application.

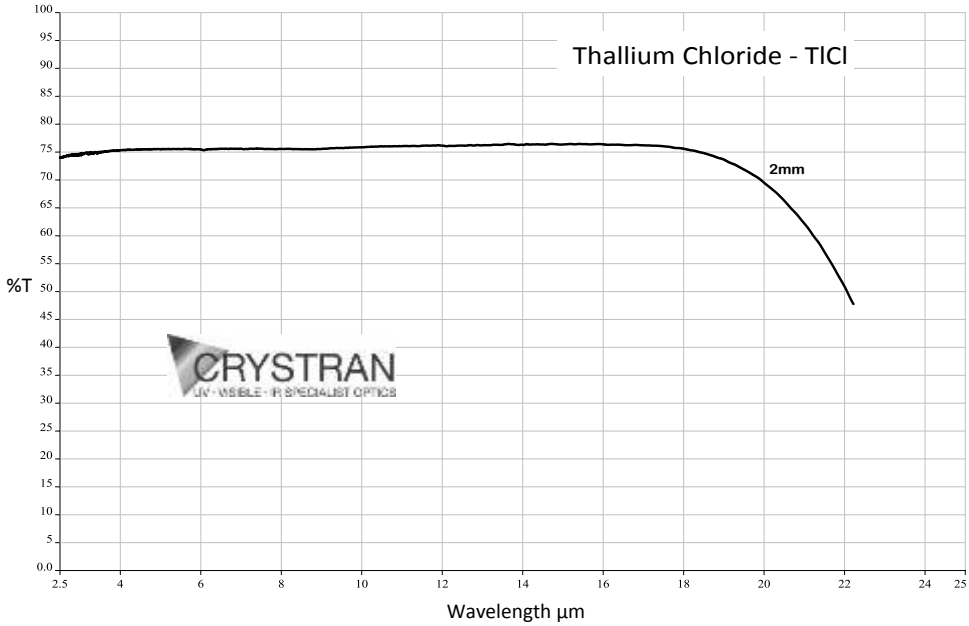
| | |
|---|---|
| Transmission Range | 0.5 to 30µm |
| Refractive Index | 2.193 at 10µm (1) |
| Reflection Loss | 24.5% at 10µm (2 surfaces) |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | 131µm |
| dn/dT | n/a |
| dn/dµ = 0 | 3.5µm |
| Density | 7.018 g/cc (1) |
| Melting Point | 430.2 °C (1) |
| Thermal Conductivity | 0.75 W $m^{-1}$ $K^{-1}$ at 311K |
| Thermal Expansion | 53 x $10^{-6}$ $K^{-1}$ at 300K |
| Hardness | Knoop 12.8 with 500g indenter |
| Specific Heat Capacity | 218 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 31.9 at 1 MHz |
| Youngs Modulus (E) | 31.71 Gpa (2) |
| Shear Modulus (G) | 7.58 GPa (2) |
| Bulk Modulus (K) | 23.57 Gpa (2) |
| Elastic Coefficients | $C_{11}$=40.1; $C_{12}$=15.3; $C_{44}$=7.6 (2) |
| Apparent Elastic Limit | 20.7 MPa (3000 psi) |
| Poisson Ratio | 0.276 |
| Solubility | 0.32g/100g water at 20°C |
| Molecular Weight | 239.85 |
| Class/Structure | Cubic CsCl, Pm3m, no cleavage planes (1) |

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Arenberg, Measurements made at Naval Research Labs, USA 1948-49

## Thallium Chloride (TlCl)



| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.436 | 2.4 | 0.546 | 2.27 | 0.578 | 2.253 |
| 0.589 | 2.247 | 0.650 | 2.223 | 0.750 | 2.198 |
| 10.00 | 2.193 | | | | |



## Yttrium Aluminium Garnet (YAG)

YAG crystal is produced by the Czochralski growth process up to approximately 100mm diameter.

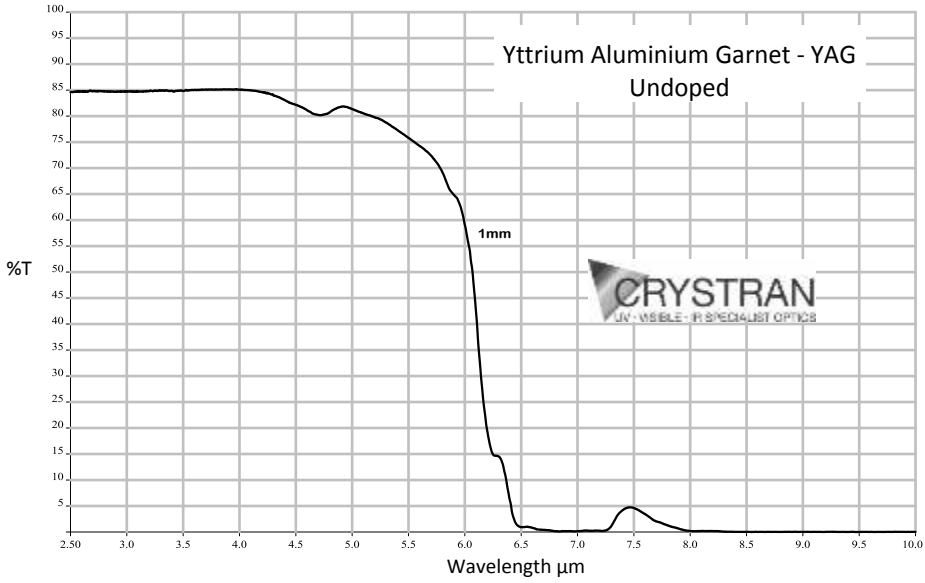
**APPLICATIONS:** YAG (Yttrium aluminium oxide $Y_3Al_5O_{12}$) is an active laser crystal when dopants such as Nd, Tm, Er, and Cr are used. Being cubic there is no double refraction and it is sometimes used for a window material substituting for sapphire.

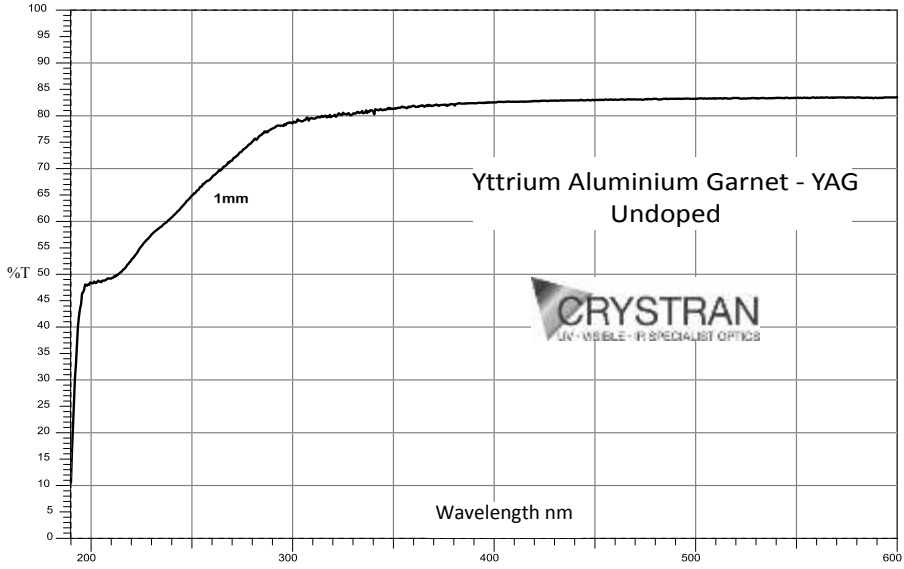
| | |
|---|---|
| Transmission Range | 0.21 to 5.5µm |
| Refractive Index | 1.81523 at 1.06µm (1) |
| Reflection Loss | 16.7% at 1.06µm |
| Absorption Coefficient | n/a |
| Reststrahlen Peak | n/a |
| dn/dT | $+9.1 \times 10^{-6}$ $K^{-1}$ at 1064nm (2) |
| dn/dµ = 0 | n/a |
| Density | 4.56 g/cc |
| Melting Point | 1940 °C |
| Thermal Conductivity | 12.9 W $m^{-1}$ $K^{-1}$ |
| Thermal Expansion | 7.8 (111), 7.7 (110), $8.2 \times 10^{-6}$ $K^{-1}$ (100) |
| Hardness | Knoop 1215 |
| Specific Heat Capacity | 590 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 11.7 |
| Youngs Modulus (E) | 300 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | $C_{11}$=333; $C_{12}$=111; $C_{44}$=115 |
| Apparent Elastic Limit | 280 MPa |
| Poisson Ratio | 0.28 |
| Solubility | Insoluble in water |
| Molecular Weight | 593.62 |
| Class/Structure | Cubic garnet, m3m |

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Wilson, Thermo-Optic Coefficients. PhD dissertation. U Southern Calif. Jan 1980

## Yttrium Aluminium Garnet (YAG)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.266 | 1.9278 | 0.354 | 1.8725 | 0.532 | 1.8368 |
| 0.800 | 1.8245 | 0.808 | 1.8217 | 0.946 | 1.8186 |
| 1.030 | 1.8173 | 1.064 | 1.8169 | 1.333 | 1.8146 |
| 1.444 | 1.8140 | 1.500 | 1.8137 | 1.640 | 1.8132 |
| 2.014 | 1.8123 | 2.097 | 1.8121 | 2.123 | 1.8121 |
| 2.940 | 1.8113 | | | | |



## Zinc Selenide (ZnSe)

Zinc Selenide is produced by synthesis from Zinc vapour and $H_2Se$ gas, forming as sheets on a graphite substrate. Zinc Selenide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Single crystal ZnSe is available, but is not common but has been reported as having lower absorption and thus more effective for $CO_2$ optics.

**APPLICATIONS:** ZnSe is used widely for IR components, windows and lenses, and for spectroscopic ATR prisms. Zinc Selenide is one of the materials of choice for $CO_2$ laser optics operating at 10.6µm.

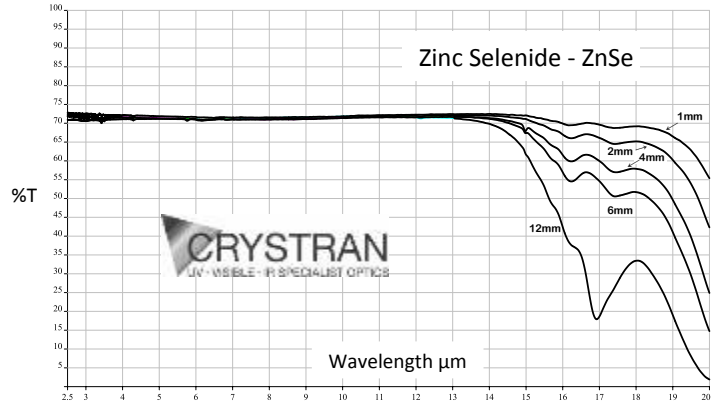
| | |
|---|---|
| Transmission Range | 0.6 to 21.0µm |
| Refractive Index | 2.4028 at 10.6µm |
| Reflection Loss | 29.1% at 10.6µm (2 surfaces) |
| Absorption Coefficient | 0.0005 $cm^{-1}$ at 10.6µm |
| Reststrahlen Peak | 45.7µm |
| dn/dT | +61 x $10^{-6}$ $K^{-1}$ at 10.6µm at 298K |
| dn/dµ = 0 | 5.5µm |
| Density | 5.27 g/cc |
| Melting Point | 1525°C *See notes below |
| Thermal Conductivity | 18 W $m^{-1}$ $K^{-1}$ at 298K |
| Thermal Expansion | 7.1 x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 120 with 50g indenter |
| Specific Heat Capacity | 339 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | n/a |
| Youngs Modulus (E) | 67.2 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | 40 GPa |
| Elastic Coefficients | Not Available |
| Apparent Elastic Limit | 55.1 MPa (8000 psi) (1) |
| Poisson Ratio | 0.28 |
| Solubility | 0.001g/100g water |
| Molecular Weight | 144.33 |
| Class/Structure | FCC Cubic, F43m (#216), Zinc Blende Structure (Polycrystalline) |

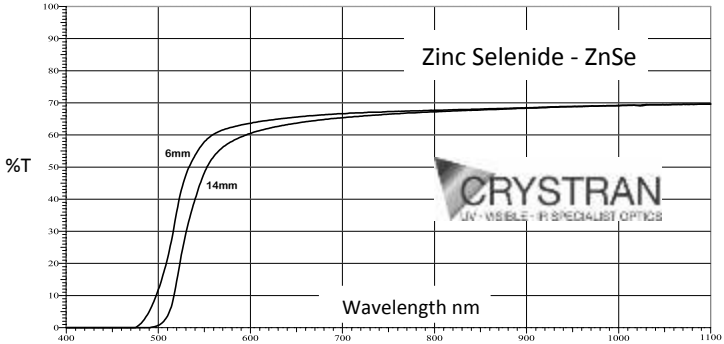
** Zinc Selenide oxidizes significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Selenide windows should not be used above 250°C in normal atmosphere*

(1) Manufacturing Methods program ZnSe blanks. US Army R&D Feb 1980

## Zinc Selenide (ZnSe)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.54 | 2.6754 | 0.58 | 2.6312 | 0.62 | 2.5994 |
| 0.66 | 2.5755 | 0.7 | 2.5568 | 0.74 | 2.5418 |
| 0.78 | 2.5295 | 0.82 | 2.5193 | 0.86 | 2.5107 |
| 0.90 | 2.5034 | 0.94 | 2.4971 | 0.98 | 2.4916 |
| 1.0 | 2.4892 | 1.4 | 2.4609 | 1.8 | 2.4496 |
| 2.2 | 2.4437 | 2.6 | 2.4401 | 3.0 | 2.4376 |
| 3.4 | 2.4356 | 3.8 | 2.4339 | 4.2 | 2.4324 |
| 4.6 | 2.4309 | 5.0 | 2.4295 | 5.4 | 2.4281 |
| 5.8 | 2.4266 | 6.2 | 2.4251 | 6.6 | 2.4235 |
| 7.0 | 2.4218 | 7.4 | 2.4201 | 7.8 | 2.4183 |
| 8.2 | 2.4163 | 8.6 | 2.4143 | 9.0 | 2.4122 |
| 9.4 | 2.4100 | 9.8 | 2.4077 | 10.2 | 2.4053 |
| 10.6 | 2.4028 | 11.0 | 2.4001 | 11.4 | 2.3974 |
| 11.8 | 2.3945 | 12.2 | 2.3915 | 12.6 | 2.3883 |
| 13.0 | 2.3850 | 13.4 | 2.3816 | 13.8 | 2.3781 |
| 14.2 | 2.3744 | 14.6 | 2.3705 | 15.0 | 2.3665 |
| 15.4 | 2.3623 | 15.8 | 2.3579 | 16.2 | 2.3534 |
| 16.6 | 2.3487 | 17.0 | 2.3438 | 17.4 | 2.3387 |
| 17.8 | 2.3333 | 18.2 | 2.3278 | | |



## Zinc Sulphide FLIR (ZnS)



Zinc Sulphide is produced by synthesis from Zinc vapour and $H_2S$ gas, forming as sheets on a graphite substrate. Zinc Sulphide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Forward Looking Infra-Red (FLIR) grade, which is pale yellow and translucent in the visible, is used as deposited without further treatment. It is stronger than multispectral grade. Single crystal ZnS is available, but is not common.

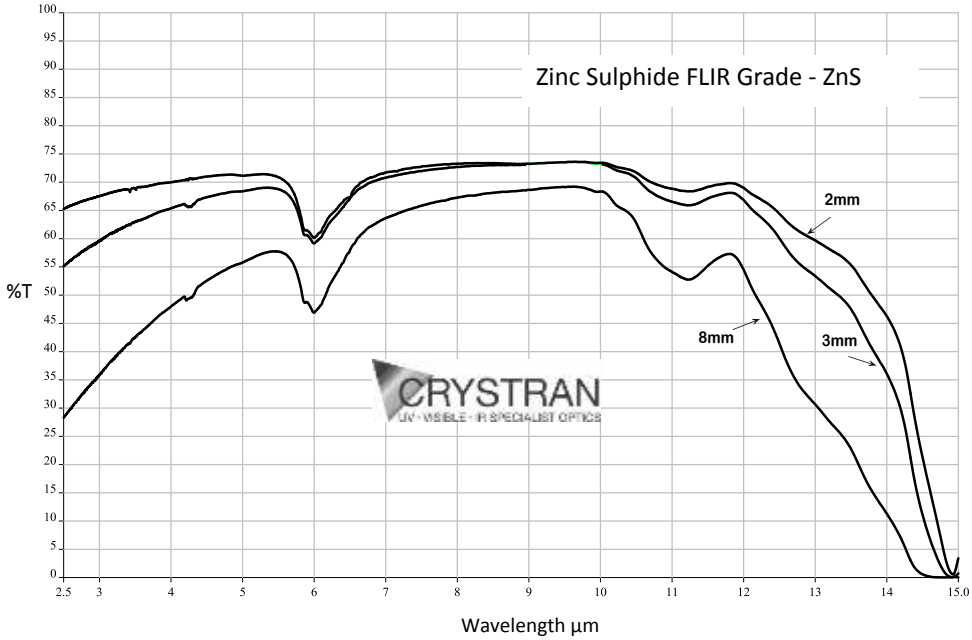
**APPLICATIONS:** ZnS FLIR is used for IR windows and lenses in the thermal band (8 to 14µm) as a tough front optic in thermal imaging systems, particularly those subjected to harsh environments.

| | |
|---|---|
| Transmission Range | 1.0 to 13µm |
| Refractive Index | 2.192 at 10.6µm |
| Reflection Loss | 24.6% at 10.6µm (2 surfaces) |
| Absorption Coefficient | 0.02 $cm^{-1}$ at 3.8µm |
| Reststrahlen Peak | 30.5µm |
| dn/dT | +43 x $10^{-6}$ $K^{-1}$ at 3.39µm |
| dn/dµ = 0 | n/a |
| Density | 4.08 g/cc |
| Melting Point | 1827°C *See notes below |
| Thermal Conductivity | 16.7 W $m^{-1}$ $K^{-1}$ at 296K |
| Thermal Expansion | 6.6 x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 160 with 50g indenter |
| Specific Heat Capacity | 469 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | n/a |
| Youngs Modulus (E) | 74.5 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | Not Available |
| Apparent Elastic Limit | 103.4 MPa (15,000 psi) |
| Poisson Ratio | 0.29 |
| Solubility | 65 x $10^{-6}$ g/100g water |
| Molecular Weight | 97.43 |
| Class/Structure | Polycrystalline cubic, ZnS, F43m |

** Zinc Sulphide oxidises significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Sulphide windows should not be used above 250°C in normal atmosphere.*

## Zinc Sulphide FLIR (ZnS)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.42 | 2.516 | 0.46 | 2.458 | 0.50 | 2.419 |
| 0.54 | 2.391 | 0.58 | 2.371 | 0.62 | 2.355 |
| 0.66 | 2.342 | 0.70 | 2.332 | 0.74 | 2.323 |
| 0.78 | 2.316 | 0.82 | 2.31 | 0.86 | 2.305 |
| 0.90 | 2.301 | 0.94 | 2.297 | 0.98 | 2.294 |
| 1.00 | 2.292 | 1.40 | 2.275 | 1.80 | 2.267 |
| 2.20 | 2.263 | 2.60 | 2.26 | 3.00 | 2.257 |
| 3.40 | 2.255 | 3.80 | 2.253 | 4.20 | 2.251 |
| 4.60 | 2.248 | 5.00 | 2.246 | 5.40 | 2.244 |
| 5.80 | 2.241 | 6.20 | 2.238 | 6.60 | 2.235 |
| 7.00 | 2.232 | 7.40 | 2.228 | 7.80 | 2.225 |
| 8.20 | 2.221 | 8.60 | 2.217 | 9.00 | 2.212 |
| 9.40 | 2.208 | 9.80 | 2.203 | 10.2 | 2.198 |
| 10.6 | 2.192 | 11.0 | 2.186 | 11.4 | 2.18 |
| 11.8 | 2.173 | 12.2 | 2.167 | 12.6 | 2.159 |
| 13.0 | 2.152 | 13.4 | 2.143 | 13.8 | 2.135 |
| 14.2 | 2.126 | 14.6 | 2.116 | 15.0 | 2.106 |
| 15.4 | 2.095 | 15.8 | 2.084 | 16.2 | 2.072 |
| 16.6 | 2.059 | 17.0 | 2.045 | 17.4 | 2.03 |
| 17.8 | 2.015 | 18.2 | 1.998 | | |



## Zinc Sulphide Multispectral (ZnS)



Zinc Sulphide is produced by synthesis from Zinc vapour and $H_2S$ gas, forming as sheets on a graphite substrate. Zinc Sulphide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Multispectral grade is then Hot Isostatically Pressed (HIP) to improve the mid IR transmission and produce the visibly clear form. Single crystal ZnS is available, but is not common.

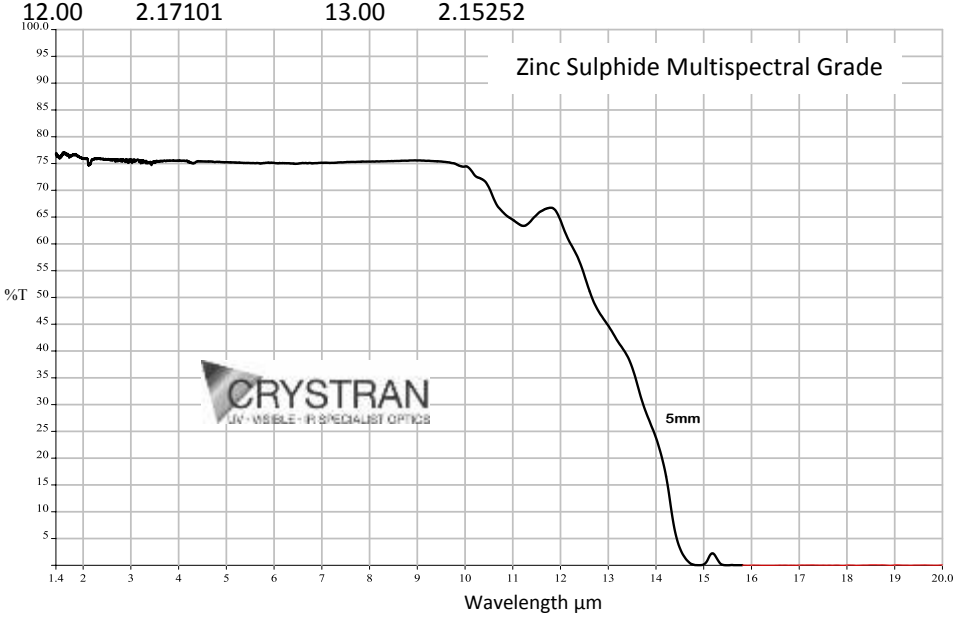
**APPLICATIONS:** ZnS Multispectral (water-clear) is used for IR windows and lenses in the thermal band (8 to 14µm) where maximum transmission and lowest absorption is required. Also selected for use where visible alignment is an advantage.

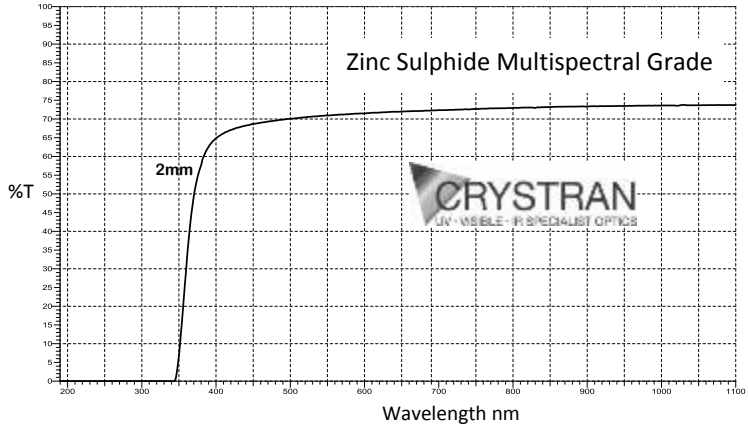
| | |
|---|---|
| Transmission Range | 0.37 to 13.5µm |
| Refractive Index | 2.20084 at 10µm |
| Reflection Loss | 24.7% at 10µm (2 surfaces) |
| Absorption Coefficient | 0.0006 $cm^{-1}$ at 3.8µm |
| Reststrahlen Peak | 30.5µm |
| dn/dT | +38.7 x $10^{-6}$ $K^{-1}$ at 3.39µm |
| dn/dµ = 0 | n/a |
| Density | 4.09 g/cc |
| Melting Point | 1827°C *See notes below |
| Thermal Conductivity | 27.2 W $m^{-1}$ $K^{-1}$ at 298K |
| Thermal Expansion | 6.5 x $10^{-6}$ $K^{-1}$ at 273K |
| Hardness | Knoop 240 with 50g indenter |
| Specific Heat Capacity | 515 J $Kg^{-1}$ $K^{-1}$ |
| Dielectric Constant | 88 |
| Youngs Modulus (E) | 74.5 GPa |
| Shear Modulus (G) | n/a |
| Bulk Modulus (K) | n/a |
| Elastic Coefficients | Not Available |
| Apparent Elastic Limit | 68.9 MPa (10,000 psi) |
| Poisson Ratio | 0.28 |
| Solubility | 65 x $10^{-6}$ g/100g water |
| Molecular Weight | 97.43 |
| Class/Structure | HIP polycrystalline cubic, ZnS, F42m |

** Zinc Sulphide oxidizes significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Sulphide windows should not be used above 250°C in normal atmosphere.*

## Zinc Sulphide Multispectral (ZnS)

| µm | No | µm | No | µm | No |
|---|---|---|---|---|---|
| 0.4047 | 2.54515 | 0.4358 | 2.48918 | 0.4678 | 2.44915 |
| 0.480 | 2.43691 | 0.5086 | 2.41279 | 0.5461 | 2.38838 |
| 0.5876 | 2.36789 | 0.6438 | 2.34731 | 0.6678 | 2.34033 |
| 0.7065 | 2.33073 | 0.780 | 2.31669 | 0.7948 | 2.31438 |
| 0.8521 | 2.30659 | 0.8943 | 2.30183 | 1.014 | 2.29165 |
| 1.1287 | 2.28485 | 1.5296 | 2.27191 | 2.0581 | 2.26442 |
| 3.000 | 2.25772 | 3.500 | 2.25498 | 4.000 | 2.25231 |
| 4.500 | 2.24955 | 5.000 | 2.24661 | 8.000 | 2.22334 |
| 9.000 | 2.22334 | 10.00 | 2.20084 | 11.25 | 2.18317 |
| 12.00 | 2.17101 | 13.00 | 2.15252 | | |



## Fundamental Constants

An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2014 adjustment.

| Quantity | Symbol | Value | Uncert |
|---|---|---|---|
| Speed of light in vacuum | $c$, $c_o$ | 299 792 458 m $s^{-1}$ | (exact) |
| Magnetic constant | $\mu_o$ | $4\pi \times 10^{-7}$ N $A^{-2}$ | (exact) |
| Electric constant $1/\mu_o c^2$ | $\varepsilon_o$ | $8.854\ 187\ 817... \times 10^{-12}$ F $m^{-1}$ | (exact) |
| Gravitational Constant | $G$ | $6.674\ 08(31) \times 10^{-11}$ $m^3$ $kg^{-1}$ $s^{-2}$ | $4.7\times10^{-5}$ |
| Planck constant | $h$ | $6.626\ 070040(81) \times 10^{-34}$ J s | $1.2\times10^{-8}$ |
| $h/2\pi$ | $\hbar$ | $1.054\ 571\ 800(13) \times 10^{-34}$ J s | $1.2\times10^{-8}$ |
| Elementary charge | $e$ | $1.602\ 176\ 6208(98) \times 10^{-19}$ C | $6.1\times10^{-9}$ |
| Magnetic flux quantum $h/2e$ | $\phi_o$ | $2.067\ 833\ 831(13) \times 10^{-15}$ Wb | $6.1\times10^{-9}$ |
| Conductance quantum $2e^2/h$ | $G_o$ | $7.748\ 091\ 7310(18) \times 10^{-5}$ S | $2.3\times10^{-10}$ |
| Electron mass | $m_e$ | $9.109\ 383\ 56(11) \times 10^{-31}$ kg | $1.2\times10^{-8}$ |
| Proton mass | $m_p$ | $1.672\ 621\ 898(21) \times 10^{-27}$ kg | $1.2\times10^{-8}$ |
| Fine-structure const $e^2/4\pi\varepsilon_o\hbar c$ | $\alpha$ | $7.297\ 352\ 5664(17) \times 10^{-3}$ | $2.3\times10^{-10}$ |
| Inverse fine-structure constant | $\alpha^{-1}$ | 137.035 999 139(31) | $2.3\times10^{-10}$ |
| Rydberg constant $\alpha^2 m_e c/2h$ | $R\infty$ | 10 973 731.568 508(65) $m^{-1}$ | $5.9\times10^{-12}$ |
| Avogadro constant | $N_A$, $L$ | $6.022\ 140857(74) \times 10^{23}$ $mol^{-1}$ | $1.2\times10^{-8}$ |
| Faraday constant $N_A e$ | $F$ | 96 485.33289(59) C $mol^{-1}$ | $6.2\times10^{-9}$ |
| Molar gas constant | $R$ | 8.314 459 8(48) J $mol^{-1}$ $K^{-1}$ | $5.7\times10^{-7}$ |
| Boltzmann constant $R/N_A$ | $k$ | $1.380\ 648\ 52(79) \times 10^{-23}$ J $K^{-1}$ | $5.7\times10^{-7}$ |
| Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3c^2$ | $\sigma$ | $5.670\ 367(13) \times 10^{-8}$ W $m^{-2}$ $K^{-4}$ | $2.3\times10^{-6}$ |

**Non-SI units accepted for use with the SI**

| | | | |
|---|---|---|---|
| Electron volt: (e/C) J | eV | $1.602\ 176\ 620\ 8(98) \times 10^{-19}$ J | $6.1\times10^{-9}$ |
| (unified) atomic mass unit $\frac{1}{12}$ m ($^{12}$C) | u | $1.660\ 539\ 040(20) \times 10^{-27}$ kg | $1.2\times10^{-8}$ |

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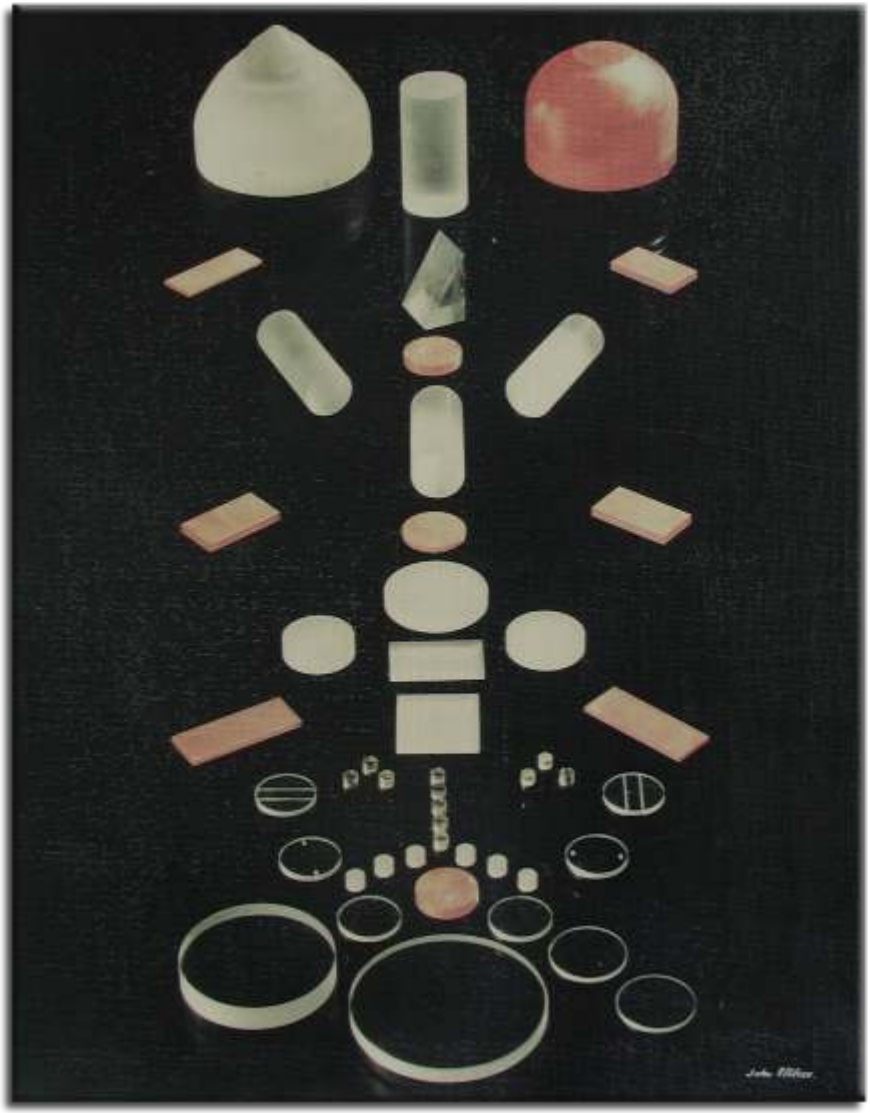
CODATA Recommended Values of the Fundamental Physical Constants: 2014
Peter J. Mohr, Barry N. Taylor, and David B. Newell, NIST, USA (25/06/2015)



*Original photograph of crystals and crystal products by John Etches 1983*

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