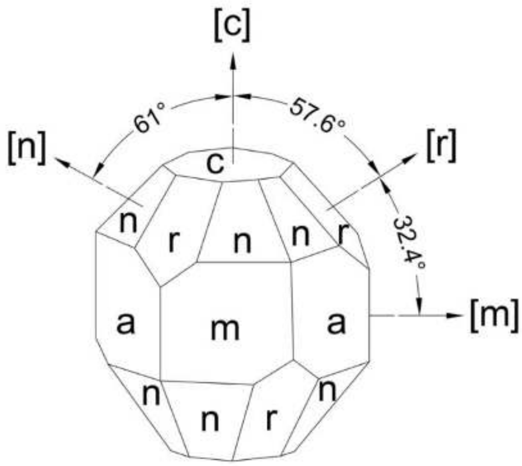
PROPERTIES AND APPLICATIONS OF SAPPHIRE

Sapphire is a tough optical material resistant to chemicals, scratching, and high pressure in many diverse environments and has exceptional transparency. Frequently it is the combination of two, or more, of its properties that make sapphire the only material available to solve complex engineering design problems. Below are some of the properties that set sapphire apart from all other optical materials:

- It has a high modulus of elasticity and high tensile strength that make it extremely wear, abrasion and impact resistant.
- It is an excellent electrical insulator because of its high dielectric constant.
- Due to the thermal stability of sapphire, it does not lose any of its mechanical and optical attributes when exposed to temperatures ranging from cryogenic to over 2000C degrees.
- The thermal conductivity is greater than other optical materials and most dielectrics.
- There is no surface damage or devitrification due to extreme thermal cycling.
- Unlike other optical materials, it does not sag or slump at very elevated temperatures.
- It is highly corrosion resistant and more resistant to corrosive chemicals than most other optical and non-optical hard materials.
- No solarization in high-radiation systems.
- Superior optical transmission span from UV to mid IR. (see Figure 2)

Sapphire has a hexagonal / rhombohedral structure, and there are properties that are dependent on the orientation of the crystal (Figure 1). Sapphire substrates are available in C, R, A, and M plane and random orientations. Random is the least expensive and is generally specified for non-critical optical or mechanical applications.

- C-plane sapphire is the strongest and most mechanically symmetric orientation. C-plane sapphire is usually specified for optical applications to eliminate the inherent birefringent properties of the crystal. Sapphire substrates are used to grow III-V and II-VI compounds such as GaN for blue LED and laser diodes. In addition, it is useful for infrared detector applications.
- A-plane sapphire substrates provide a uniform dielectric constant and high insulation for hybrid microelectronic applications. High Tc superconductors can be grown with a-plane Sapphire substrates.
- R-plane sapphire substrates are used for the hetero-epitaxial deposition of silicon for microelectronic IC applications. Sapphire is an excellent choice for hybrid substrates such as microwave ICs because of its high dielectric constant. In addition, when filmed with an epitaxial silicon process, high speed IC and pressure transducers can be created. Other applications are growing thallium, other superconducting components, high impedance resistors, and GaAs.
- M-plane and R-plane sapphire is used for growing non-polar/semi-polar plane epitaxial layers, which helps in improving luminescence efficiency. Hybrid microelectronics, microelectronic IC applications use sapphire substrates.



REPRESENTATION OF THE PRIMARY PLANES OF A SAPPHIRE CRYSTAL

Figure 1

Sapphire is, by far, the strongest, toughest, thermally shock resistant, and chemically inert opto-electronic material available. It is a far superior material to glass, fused silica, fused quartz, alumina and other ceramic materials, and is the material of choice for critical and demanding applications.

Fused silica has been utilized in many applications where sapphire would be better suited. Many times, the decision to use fused silica was strictly due to cost. While the cost of fused silica is less than sapphire, the cost of a material failure in a critical situation can result in expensive repairs, downtime, lost opportunities and other unforeseen problems.

The overall benefits of strength, durability, reliability and service span of sapphire components more than compensates for the material price differential. It should be noted that the raw material price differential between sapphire and fused silica is minimal for smaller parts and does not become a factor until large geometries are involved. We at Meller Optics have found that customers that have switched from use of fused silica to sapphire have realized significantly extended life cycles in harsh environments. This substantially reduces the costs associated with replacement of the components and system downtime.

Utilization of sapphire to replace fused silica has the following benefits:

- Sapphire has a Knoop hardness of 2200 vs. 460 for Fused Silica (Scratch Resistance – mechanically second only to diamond)
- Sapphire has a strength of 400 Megapascals vs. 60 Megapascals for Fused Silica (Survivability)
- Sapphire will transmit further into the mid-wave infrared region than Fused Silica (Improved Transmission)
- Sapphire windows can maintain the highest temperature rating of all optical materials and withstand considerably higher temperatures in both oxidizing and inert atmospheres than fused silica, with zero degradation. Fused silica will degrade and devitrify over time at temperatures almost half the maximum operating temperature of sapphire.

Physical properties of Sapphire and Fused Silica		
	SAPPHIRE	**FUSED SILICA**
Density (g/cm^3)	3.98	2.20
Tensile strength (PSI)	60,000	7,000
Hardness (Mohs)	9	5.5 - 6.5
Compressive Strength (PSI))	300,000	160,000
Melting Point	2050°C	1715°C
Poisson Ratio	.17	.28

Figure 2

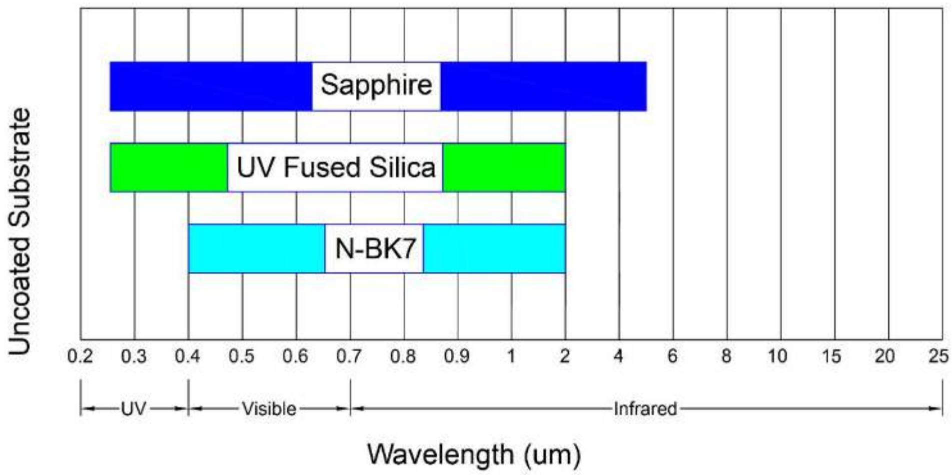


Figure 3

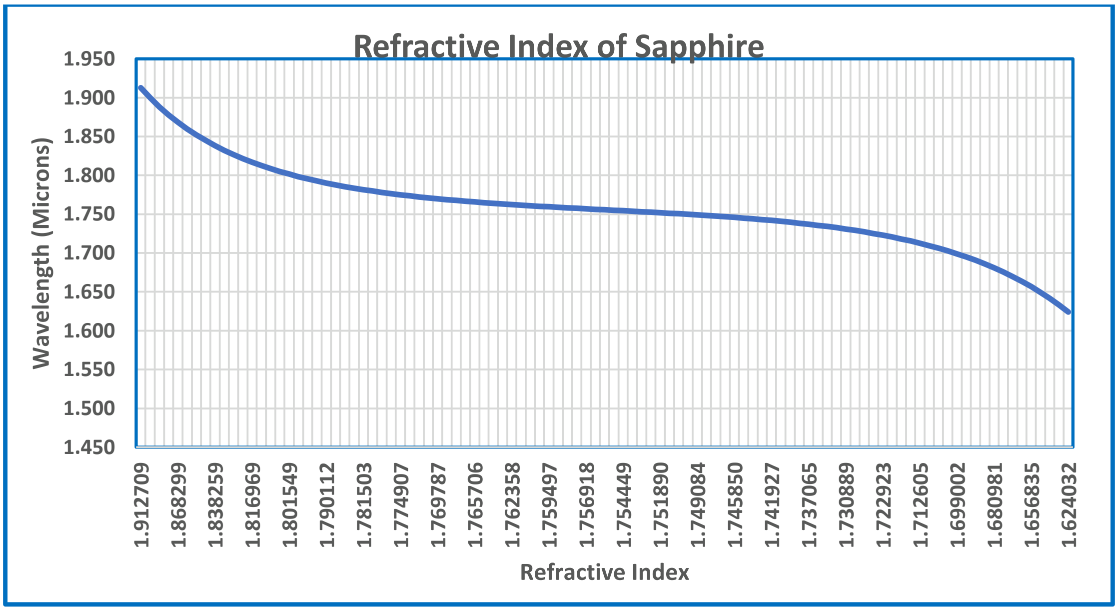


Figure 4

APPLICATIONS FOR SAPPHIRE

Sapphire Windows and Lenses

The toughness, durability, clarity and broad spectral range of sapphire is why it can be used in just about any application calling for windows and/or lenses. Sapphire windows and lenses can withstand considerably higher temperatures than the closest runner up material, fused silica, with zero degradation. Fused silica will degrade and devitrify over time at temperatures almost half the maximum operating temperature of sapphire. Sapphire maintains the highest temperature rating of all optical materials in both oxidizing and inert atmospheres. Here are just some of the ways that sapphire windows and lenses are commonly used:

- Ideally suited for protecting cameras, detectors, sensors, and even telescopes in outer space.
- Viewing windows on furnaces due to its capability to withstand extremely high temperatures.
- Sapphire cell windows are used in centrifuges as they can withstand the extreme speed and transmit infrared light to observe as necessary.
- Protective windows on many types of lasers due to its ability to withstand laser damage.
- A sapphire window can be exposed to extreme abradants such as sand and particulates with minimal effect on the clarity of the window. This makes sapphire windows the ideal material for a variety of applications such as: Aerospace windows, downhole and drilling vision systems, inspection windows, watch crystals and gun sights.
- A supported sapphire window can be taken to 1950C with no change to its shape and minimal reduction to mechanical performance. Sapphire windows are the perfect material for high temperature combustion chambers, gas processing and lamp shields.
- Sapphire windows are the ideal material for pyrometry. They transmit a wide range of wavelengths while safely isolating hot zones up to 2000C from external room temperature observation, making sapphire windows the ideal sight window for furnaces and high temperature processing equipment.
- Sapphire is the material of choice for windows that are designed for high-pressure applications in unmanned underwater surveillance vehicles (AUV and UUV).
- Lenses can be fabricated in concave, convex, meniscus and aspherical configurations for use in telescopes, FLIR, thermal imaging systems and sensors, missiles, and related vision systems.
- Sapphire lenses for robotic systems that function in extreme environments that resist scratching, high pressures, and high temperatures.
- Medical and dental tools that require UV sterilization, curing and IR thermal processing are typical applications where sapphire windows are appropriate.

Optical Domes and 360-Degree Viewing Windows

Sapphire Optical Domes and 360 Degree Windows, with a hardness second only to diamond, are highly resistant to fast moving dirt, sand, and saltwater, and can withstand 10,000 psi and 1,000°C. They exhibit 99% transmission from the UV to IR when A/R coated on both sides and up to 85% transmission uncoated. These components provide front surface protection for high-speed missile guidance systems, panoramic image masts, viewports, and other front surface optics requirements. Sapphire Optical Domes, windows and lenses are also ideal for providing front surface protection in gimbaled systems.

Extreme Applications

Because of all the superior properties of Sapphire, it is unmatched in its ability to function and survive in extreme conditions. Military, Research, Undersea, Space, and Drone applications requiring robust and ultra-clear protective optics that have one or more of the following conditions to contend with:

- Fast Moving Sand or Abrasive Particulates
- Salt Water
- Algae Growth
- High Pressures
- High Vacuum
- Radiation
- Outer Space

Sapphire can be finished to a smooth, scratch-free polished surface that inhibits algae growth and adherence of films and microorganisms in liquid environments. Perfect for submersibles, AUV, UUV, and other deep water undersea applications.

Sapphire is well suited for all types of laser weapon systems, high power microwave, and other applications requiring extremely flat and robust optics.

InfraRed Countermeasure Systems (IRCM)

Sapphire aerospace windows protect onboard imaging, sensing and targeting systems while allowing broadband transmission for; Forward Looking Infra-Red (FLIR) systems, targeting systems, sight windows, and Reconnaissance and surveillance systems.

Microwave-RF

Sapphire can support products ranging from plasma applicator tubes and plasma injector nozzles to RF transparent waveguide barriers. Sapphire can be used for microwave applications, from the heating of food products, and plasma generation, to radome systems. Due to sapphire's RF transparency, thermal conductivity, and high-temperature resistance, it is the ideal material of choice for products that require resistance to radiation damage in high-power microwave applications

Sapphire Waveplates

Sapphire waveplates are a unique alternative to crystalline quartz for rugged visible and IR polarization control components. Sapphire is a tough birefringent material that has useful transmission from .25 to 4.7 microns. Sapphire transmission is >98% in this wavelength region with AR coatings on two sides. It is intrinsically hard (Mohs 9) and will withstand harsh chemical environments. Sapphire waveplates are available in half wave and quarter wave in both zero order and multiple order configurations. Because sapphire can be made thinner that its quartz counterpart, ultra-precise lower order waveplates can be fabricated; thereby reducing the errors in higher order plates. Sapphire waveplates are ideal for use in high power IR and Visible lasers where applications may include:

- Creation of circular polarization from linear or linear polarization from circular
- Reflection suppression when used with a polarizer
- Optical pumping and ellipsometry
- Rotation of the plane of polarization in a laser
- Electro-optics modulation
- Visible ratio beam splitter when used with a polarizing cube
- Dual wavelength designs

Miscellaneous

- Sapphire transmits in the UV - visible - IR wavelengths, making ideal for Ablation Procedures and Cosmetic Laser Dermatology.
- Sapphire is radiolucent; ideal for use in CT, MRI and other X-ray intraoperative imaging procedures, resulting in clear imagery, allowing enhanced diagnostic capability. Its high thermal conductivity allows for enhanced cooling for laser procedures.
- Excimer Laser technology is used in photolithography, pulse laser deposition, laser ablation, eye surgery and in dye laser applications. Sapphire's thermal conductivity and electrical insulator properties make it the ideal material in use as pre-ionizer corona tubes. Replacing alumina corona tubes with sapphire tubes will increase productivity and lower cost of operation.
- Sapphire is compatible with Ultraviolet, Visible and mid-wave infrared sensors (UV-VIS-MWIR), and laser range-finding, spot tracking systems.
- Ground vehicles and aircraft need protection to stop high-velocity projectiles. Sapphire protection is 50% thinner and lighter than glass alternatives while providing the same kinetic energy or stopping power performance and it offers better abrasion and chemical resistance.
- Sapphire can be used for standoffs in high temperature furnace systems. Sapphire remains dimensionally stable up to 1700C.
- Sapphire flats and wear parts are used in applications in which wear is a problem. Systems like canning machines, slide plates, V-blocks, flat bearings and pushers utilize sapphire flats and blocks to extend the lifetime of the equipment and reduce downtime.
- Sapphire rods and tubes are so chemically and bio-inert, they are the perfect materials for medical, pharmaceutical, semiconductor and other applications where maintaining purity and health is critical.
- Due to the extreme chemical resistance of sapphire tubes and rods at high temperatures, a sapphire tube is the ideal choice for plasma chambers and sapphire lamp applications.
- Only hot caustic salts can etch sapphire rods and sapphire tubes. All other solvents, acids and caustics have no effect on sapphire, including molten metals. This property allows for safe, chemically pure chemical handling and processing.

MELLER OPTICS PRODUCTS

Meller Optics Standard Quality Sapphire MSW Series Windows have high transmission, temperature stability and low cost. These windows are manufactured to the following specifications:

- Material Quality: Infrared Grade
- Crystallographic Orientation: Random or c-Plane
- Diameter Tolerance:
    - 0.250” Diameters up to 1.250” Diameters = +/-.002”
    - 1.375” Diameters up to 2.000” Diameters = +/-.004”
- Thickness Tolerance:
    - 0.250” Diameters up to 1.250” Diameters = +/-.002”
    - 1.375” Diameters up to 2.000” Diameters = +/-.004”
- Parallelism:
    - 0.250” Diameters up to 0.375” Diameters = 10 Arc Minutes Maximum
    - 0.500” Diameters up to 0.750” Diameters = 5 Arc Minutes Maximum
    - 1.000” Diameters up to 2.000” Diameters = 3 Arc Minutes Maximum

- Surface Flatness:
    - 0.020” Thicknesses = Uncontrolled
    - 0.040” Thicknesses up to 0.125” Thicknesses = 10 Waves per Inch @ 633 nanometers
- Surface Quality: 80-50 per MIL-PRF-13830
- Clear Aperture: Central 80% of Diameter Face

These windows are ideal in high volume applications such as:

- High Intensity UV Lamps
- Endoscopic Components
- Medical and Industrial Gas Analysis and Monitoring
- Furnace Viewports
- Visible and Near IR Windows and Cover Slides
- Photodiodes

Meller Optics Precision Quality Sapphire MSPW Series Windows are designed for more demanding optical applications where image quality and birefringence effects are important. The raw material has negligible lattice distortion and is oriented with the optical axis normal to the faces to minimize the inherent birefringent properties of single crystal sapphire. These windows are manufactured to the following specifications:

- Material Quality: Optical Grade, produce by either the Kyropoulos Method or Heat Exchange Method
- Crystallographic Orientation: c-Plane
- Diameter Tolerance: + 0.00mm / - 0.10mm
- Thickness Tolerance: + / - 0.10mm
- Parallelism: 10 Arc Seconds Maximum
- Transmitted Wavefront Error: 1/4 Wave Maximum P-V @ 633 Nanometers
- Surface Quality: 20-10 per MIL-PRF-13830
- Clear Aperture: Central 85% of Diameter Face

Typical applications include:

- Imaging optics
- Polarization sensitive optics
- Short wavelength (UV) optics
- Focusing optics and reticles
- Refractometer windows

Meller Optics High-Precision Quality Sapphire MSLW Series Windows are designed for use in critical optical and laser applications where image quality and birefringence effects are important. The raw material has negligible lattice distortion and is oriented with the optical axis normal to the faces to minimize the inherent birefringent properties of single crystal sapphire. Flatness and surface finish are optimized to provide for the least amount of error in the transmitted wavefront. These windows are manufactured to the following specifications:

- Material Quality: Optical Grade, produce by either the Kyropoulos Method or Heat Exchange Method

- Crystallographic Orientation: c-Plane
- Diameter Tolerance: + 0.00mm / - 0.10mm
- Thickness Tolerance: + / - 0.10mm
- Parallelism: 2 Arc Seconds Maximum
- Transmitted Wavefront Error: 1/4 Wave Maximum P-V @ 633 nanometers
- Surface Quality: 10-5 per MIL-PRF-13830
- Clear Aperture: Central 90% of Diameter Face

Typical applications include:

- Laser Mirrors
- Laser Beam Splitters
- Laser Output Couplers
- Imaging Optics
- Optical Flats and Etalons

Meller Optics Sapphire MSB Series Precision Balls are inventoried in a wide array of sizes. Meller Sapphire and Ruby Balls are single crystal materials with zero porosity, that are chemically inert and extremely resistant to abrasion, heat, and high pressure. They are ideal for use in instruments, metering equipment, and other precision mechanisms where low friction bearings, long-life, and dimensional accuracy are important. Suited for orifice applications up to 50,000 psi and numerous bearing applications, Meller Sapphire and Ruby Balls have a 2,000°C melting point, 0.2 coefficient-of-friction, and a refraction index of 1.76 microns at 20°C, and are non-magnetic. These spheres are manufactured to A.F.B.M.A. Grade 25 standards and are also available in Ruby for enhanced visibility. The basic diameter tolerance is +/-0.0001" with a sphericity tolerance of 0.000025" and a diameter tolerance of +/-0.000025" on spheres from the same lot. MSB Series spheres can be used as:

- Ball Bearings
- Spacers in Metrology Applications
- In Check Valves
- In Piston Valve Seats
- In Flow Meters
- In Bar Code Readers
- In Fiber Optic Assemblies
- The spheres can also be ground and polished to a specific diameter and center thickness to make and inexpensive plano-convex lenses.