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Notes on Sapphire

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Sapphire has been suggested by Ron Drever for use as an optical substrate material. Single crystal sapphire has thermal and mechanical properties which make it preferable to fused silica and other amorphous materials in some respects. This memo reviews what I have learned about the advantages and disadvantages of sapphire.

1 Physical properties of sapphire

Sapphire is aluminum oxide, Al_2O_3. It is grown as a single crystal, of hexagonal crystal structure, and is transparent in the visible and near infrared. Table 1 lists some of the properties of sapphire.[1]

The thermal and mechanical properties of sapphire are very attractive. A current dilemma in the use of fused silica involves thermal distortion, both physical distortion resulting in change of mirror figure, and refractive distortion resulting in a non-uniform refractive index and a focusing effect. The dn/dt of sapphire is a little bigger than that of fused silica ($1.3 \times 10^{-5}/°C$ as opposed to $1.2 \times 10^{-5}/°C$), but the thermal conductivity of sapphire is 17 times larger, so for a given thermal absorption, the temperature gradients in sapphire will be much smaller. Similarly, the thermal expansion coefficient of sapphire is about twice that of fused silica, but the higher thermal conductivity should still result in less thermal disfigurement. Also, the thermal expansion effect is less important than the dn/dt effect.

A significant disadvantage of sapphire is its intrinsic birefringence. While it is possible to cut the boule so that the optic axis is parallel to the extraordinary axis, there is still some chance that the birefringence will result in some wavefront distortion. If the surface of the optic has a significant curvature, then the wavefront cannot be everywhere perpendicular to the extraordinary axis, and even in a planar blank, the required wedge angle may be bit of a problem. The effect of birefringence in sapphire requires further analysis.

The refractive homogeneity of sapphire is slightly better than that of glass.[2]

[1] Gentilman, et. al., **Comparison of ALON and Sapphire Windows for HEDI**, to be published, 1989, also AIP and OSA Handbooks.

[2] Hal Bennett, private communication.

The inhomogeneity of birefringence is not known.

Sapphire Al_2O_3	
Optical properties	
Refractive index	1.774 (o-ray @ 0.5μ)
	1.755 (o-ray @ 1.0μ)
	e-ray 0.008 smaller
dn/dt	1.3×10^{-5} /°C
Absorption at 5μ	0.92 cm^{-1}
Scatter at 0.63μ	0.02 cm^{-1}
Mechanical properties	
Density	3.98 g/cc
Flexural strength	400 MPa
Knoop hardness	2200 kg/mm^2
Poisson ratio	0.27
Young's modulus	379 GPa
Thermal properties	
Melting point	2040 °C
Thermal expansion	8.8×10^{-6}/°K (30-1000°C)
Thermal conductivity	24 W/m·°K

Table 1. Properties of Sapphire

The value of the thermal conductivity of sapphire is a little bit of a question. The unpublished paper of Gentilman et. al. lists it as 24 W/m·°K. Bob Spero used the value of 35 W/m·°K at the January LIGO engineering meeting. Another reference[3] lists it as 25.1 W/m·°K parallel to the c-axis and 23.0 W/m·°K perpendicular to the c-axis at room temperature. But, depending upon the method of preparation, it lists thermal conductivities for Al_2O_3 as low as 2.6 W/m·°K and as high as 46 W/m·°K.

2 Availability of Sapphire

At present, the most homogeneous sapphire is grown in the Heat Exchanger Method, invented by Crystal Systems, Inc., of Salem, Massachusetts. While the boules which they grow are large enough for a LIGO mirror (8 inch diameter by 4 inch thick), they have never been asked for a single piece that large. At present, it would be very difficult to obtain an optically homogeneous piece of this size.

I was permitted to examine a sapphire window at Zygo Corporation. The piece was rectangular, about 10 inches by 4 inches, and about 3/8 inch thick. To the eye, it looked quite homogeneous, except for a cluster of bubbles near one edge. When viewed through an interferometer, it appeared to be homogeneous to better than a fringe throughout most of its cross-section, but it had one

[3] Touloukian, et. al., **Thermophysical Properties of Matter.**

glaring inclusion through the middle, parallel to the four inch edge. I was told by one of Zygo's senior opticians that this is typical. He speculated that the boule of material may be inhomogeneous in its center, near the seed. If true, this may be a problem, because a truly homogeneous LIGO mirror would then have to be cut from a boule more than twice its diameter, and these have not yet been grown.

3 Figure and Polish of Sapphire

Great advances have been made in the ability to polish sapphire in the last several years. Sapphire is much harder than fused silica. It takes longer to polish, it is more labor intensive, it is harder on the polishing machines, and it cannot be polished in one step, as fused silica can. Nevertheless, surface figures of $\lambda/20$ are achievable, and microroughnesses of about one angstrom r.m.s. have been achieved, and one half angstrom is believed to be achievable without much difficulty.[4]

4 Sapphire-like Materials

There is interest among star warriors in finding a sapphire-like material that can be made cheaply and in large pieces. Two such materials which are often mentioned are aluminum oxynitride and spinel. Aluminum oxynitride, made by Raytheon under the trade name ALON, is a polycrystalline material with the approximate composition $Al_{23}O_{27}N_5$. It is fabricated using a powder processing technique and has an isotropic cubic crystal structure. Spinel is also fabricated via powder processing. Its composition is $MgAl_2O_4$. Both materials are afflicted with severe bulk scattering problems, and neither is suitable for a LIGO mirror. Progress in improving the homogeneity of these materials is likely to be slow in coming.[5] Nevertheless, we should keep an eye on these materials, because efforts are being made in industry to make them more optically uniform.

5 Cost

Quotes for sapphire blanks from Crystal Systems are as follows: For a one inch diameter by 0.375 inch thick Hemex 0 plano-concave blank with one meter radius of curvature, 3 parts for $660 each or 5 parts for $512 each. Surfaces would be 20/10 scratch/dig. The planar surface would be flat to one-half fringe, and the concave surface good to two fringes in power and one fringe in irregularity. Hemex 0 is the highest grade of homogeneity from Crystal Systems. For a four

[4] David Valentine, Zygo Corporation, private communication.

[5] Richard Gentilman, Raytheon, private communication. David Valentine, Zygo, private communication. Hal Bennett, private communication.

inch diameter by two inch thick piece with a three inch clear aperture, the quote is \$9803. The surfaces would be flat to $\lambda/10$ with a scratch/dig of 10/5. Estimated times of delivery are 12 weeks for the small parts and 16 weeks for the large.