Advanced Optical Materials For Use In Protective Windows And Transparent Armor

Choosing the proper material depends on forces experienced by the part, required wavelength range of the optics, overall weight envelope of the platform, and other design constraints.

By Drew T. Haven

Peak performance of sensitive optics and protection of our warfighters are critical to modern warfare. For sensitive optics, this includes protection of the optic itself and proper design of its enclosure, with the appropriate material, to limit wave-front distortion of the source. For protection of the warfighter, transparent armor (TA) designed with transparent ceramics has enabled solutions capable of providing higher levels of threat protection at greatly reduced weights and thicknesses.

Such materials allow TA to be incorporated into lightweight platforms where glass-only TA has been considered too bulky. This article surveys a range of optical materials that can be used in harsh and battlefield environments, comparing and contrasting their properties and manufacturing readiness for use in both sensitive optics and TA applications.

Sensitive optics used in military sensors and surveillance systems face a host of harsh environments. To protect these sensitive components and ensure continuous, long-term operation, they often are protected by an external window. Although this practice would seem straightforward, the end design has to have high optical transmittance with minimal wave-front distortion while withstanding some of the harshest operating conditions imaginable. Thus, materials used must have:

- High fracture toughness, to avoid breaking under impact
- High flexure strength, to avoid bending and distorting the wave-front
- High hardness, to limit abrasion and scratching
- Low density, to reduce weight
- Very high transmission in the desired operating range

These criteria limit the number of feasible materials, and often, the design plays out as a compromise between durability (high strength and hardness) and optical transmission range (UV to MWIR, or Visible to LWIR). The most common materials used in this space are listed in Table 1. The list includes sapphire, aluminum oxynitride (AlON), spinel, zinc sulfide (ZnS), and zinc sulfide that's been through a hot isostatic pressing process (ZnS HIP'ed), which improves transmission.

A primary design concern of electro-optic windows in military applications is force exerted on the window. This includes both large-area forces (for example, an aircraft will exert significant wind resistance, maneuvering, and landing forces on the entire window) and small-scale "micro" level forces (such as impact from rain and sand). To withstand the former, the window must be sufficiently thick, and the enclosure sufficiently robust, to ensure that there is minimal

Table 1. Selected material properties; values from [1, 2, 3, 4, 5, 6, 7, 8]. **All sample thicknesses under 7mm.

	Sapphire	**Aluminum Oxynitride**	**Spinel**	**ZnS**	**ZnS HIP'ed**
Fracture Toughness (MPa $m^{1/2}$)	2	2	1.5	.8	1
Flexural Strength (MPa)	300-1,000	300-700	170	84-103	50-60
Knoop Hardness (kg/mm^2)	2,200	1,800	1,650	210-240	150-160
Young's Modulus (GPa)	344	320	276	74.5	85.5
Density (g/cm^3)	3.97	3.69	3.58	4.08	4.09
Approx. Transmission Limit (μm)	0.15-6	0.22-6	0.25-6.5	0.5-14.7	0.35-14.5
**Transmission (>70%, μm)	0.2-5	0.3-4.7	0.4-5.3	None	0.35-10
**Transmission (>80%, μm)	0.25-4.7	0.35-4.3	0.4-5	None	None
Index of Refraction @ approx. 0.7 μm	1.760	1.787	1.711	2.332	2.331

deflection of the window and enclosure. Performance in the latter scenario requires a window with sufficient hardness to avoid erosion on the outside face. Poor performance dealing with either of these categories — large- and small-scale forces — will increase wave-front distortion of the target signal.

As depicted in Table 1, transparent ceramics most ably satisfy these extreme design requirements as they possess high hardness, high flexure strength, and high fracture toughness. Although it is possible to design around the limitations of ZnS, the task requires a much thicker window to meet the same design criteria and, often, a hard coating — such as aluminum gallium phosphide (AlGaP) or a diamond-like carbon coating — to improve abrasion resistance. Such a window is much heavier and must be replaced after a set number of service hours as its surface deteriorates. Thus, unless a broadband transmission range that extends into the LWIR is absolutely required, it is usually preferable to use the transparent ceramics in conditions where high forces will be experienced.

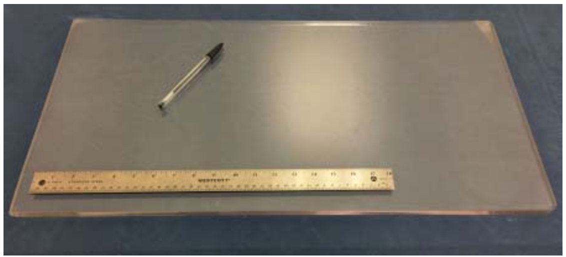

Figure 1. A sheet of EFG sapphire measuring 26 x 14 x 0.5 in^3

A second design criterion is window size and shape. Large sheet sapphire, of the kind typically used for EOIR windows, usually is grown through an edge-defined film-fed growth (EFG) process. EFG can be used to grow large, flat sheets or windows with small radii of curvature (Figure 1). Sapphire also can be grown to significant sizes via both the heat exchanger method and Kyropoulos (boule sapphire), or by new technologies being developed to grow large sheets (up to 14" x 20" optical windows and one 18" x 36" blank have been produced [9, 10]; however, maximum area sizes for boule typically are smaller, and the new sheet technology remains in its infancy.

AlON and spinel are green formed from powders, and then HIP'ed to create a near-fully dense and transparent window, while ZnS is formed through chemical vapor deposition (CVD). Both green forming from powders and the CVD process enable the manufacture of windows with complex geometry, such as domes and ogives, as well as flat pieces that are (theoretically) limited in size only by the scale of the HIP'ing and CVD equipment.

However, due to the nature of the manufacturing process for AlON and spinel, any variation in powder purity, powder size, or density after green forming or HIP'ing can lead to variations in transmission and index homogeneity. As a result, both maximum achievable size and volume production capability are limited (Table 2).

As of this writing, and to the best of the author's knowledge, only sapphire has been used in large-volume production for large-area windows in fielded platforms, such as the F-35 Joint Strike Fighter (Figure 2).

Figure 2. Electro-Optical Targeting System (EOTS) for the F-35 Joint Strike Fighter. The sensitive optical equipment is protected by a pod comprising six sheets of sapphire.

Moving on to TA, two key properties stand out in successful defense against any particular threat level: as stated by M. Grujicic et. al., [11] "To maximize the [strike face] material's contribution to the projectile defeat in the dwell stage, materials with a good combination of high stiffness (as measured by Young's modulus) and high inelastic deformation resistance … should be selected." Thus, high stiffness and hardness are critical, and by utilizing a material possessing these properties in the strike face layer, one is able to significantly reduce the weight and thickness (compared to traditionally produced, glass-only TA) of glass needed to defeat a specific threat level. Therefore, as TA, ZnS falls out of the discussion entirely, and we are left with the transparent ceramics sapphire, AlON, and spinel.

In traditional TA systems, the armor is composed of many layers of glass, laminated together with a polymer backing.

Table 2. Maximum known sizes of EOIR windows and whether each has seen volume production for this application. Sizes and production information based on author knowledge at time of publication and data sheets, where available.

	EFG Sapphire	**Boule Sapphire**	**AlON**	**Spinel**	**ZnS**
Maximum Area (in)	14x26	14x14 or ~20" Ø	18x35	12x12	36x36
Volume produced at sizes less than 144 in^2	Yes	Yes	Yes	No	Yes
Volume produced at sizes greater than 144 in^2	Yes	No	No	No	No

Such systems are designed to slow/deflect the incoming projectile to the point where it no longer has the kinetic energy to penetrate the back of the laminate system. With transparent ceramic used as the strike face, the high stiffness and high hardness change the interaction with the projectile, resulting in its breaking apart, or being "defeated." The effect is particularly pronounced with hardened armor-piercing projectiles (Figure 3).


Figure 3. Before (left) and after (right): a 7.62x54R B32 API round impact versus a sapphire strike face

The net result when using a transparent ceramic strike face is that a substantial amount of glass can be removed from the overall armor system, significantly reducing weight and thickness. In many cases, the weight savings can be over 50 percent.

In addition to weight and thickness reductions, there are two other important benefits to using a transparent ceramic-based TA system. The first is increased transmission in both visible and infrared (IR) wavelengths, where the attenuation due to glass will decrease as a function of the total thickness removed from the system. This is described in the following equation:

$$I(y)=I_0e^{-ay}$$

where $I(y)$ is the final irradiance, I_0 is the initial irradiance, a is the attenuation coefficient, and y is the thickness.[8, 12]

The second benefit is that scratching and pitting are nearly eliminated from the armor, owing to the high hardness of the transparent ceramic strike face. Such defects can reduce visibility over time as they accumulate, and they are also known to cause "flares" when operating night vision equipment, reducing warfighter situational awareness. The net result is an abrasion-resistant window with transmission performance exceeding the U.S. Armor Transparent Purchase Description (ATPD) requirements.

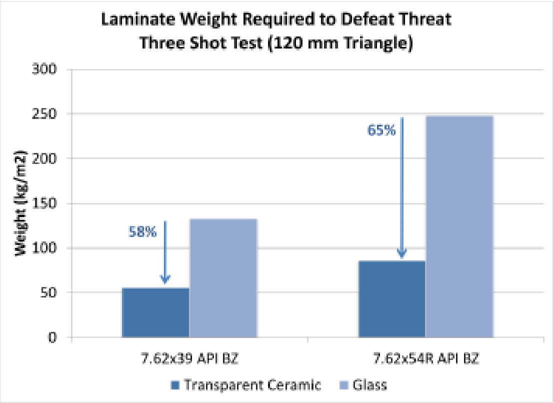

Figure 4. Weight reductions for transparent ceramic (sapphire)-based armor vs. traditional glass armor for STANAG 2 (7.62x36 API BZ) and STANAG 3 (7.62x54R API BZ) threat levels

Although all transparent ceramics have similar performance characteristics, overall size and volume manufacturing of large sheets need to be considered during the design process. As of this writing, the choice essentially is between AlON and sapphire, as the size and manufacturing maturity of spinel is limited. Between AlON and sapphire, AlON is capable of providing larger panels, but only large-sheet sapphire has been produced in volume for fielded transparent armor applications, as seen with the M142 "HIMARS" and M270A1 mobile artillery platforms.

Ultimately, choosing the proper material for IR windows and transparent armor depends on the requirements of the final application. Forces experienced by the part, the wavelength range required of the optics, overall weight envelope of the platform, and other design constraints are paramount. Small-scale systems or specialty platforms produced in small numbers will have the choice of just about any material. However, when designing for large-scale production, material manufacturability and maturity cannot be discounted. ■

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