



Window of Opportunity

Industrial applications experts in the semiconductor and aeronautical fields are specifying single-crystal sapphire plates and windows over 14 in. in diameter for their product designs. In addition, the semiconductor community is scaling up the size of its silicon and gallium arsenide wafers. Subsequently, sapphire wafer carriers and other mechanical parts must follow in form.

The aerospace industry is now turning from non-sapphire to sapphire windows because of the material's robust nature and good optical properties. These new large-dimension standards required the scale-up of the heat exchange method (HEM)* of crystal growth, as well as fabrication processes to accommodate the new regime of components.

HEM-Grown Sapphire

In the HEM process, a single crystal sapphire seed is centered at the bottom of a crucible and loaded with broken pieces of sapphire called crackle. High-purity crackle ensures high optical transmis-

sion in the crystals. Once the crucible is loaded with crackle, it is placed on the heat exchanger in the HEM furnace. The furnace is evacuated and the charge is heated by the heating element. The heat exchanger is located under the crucible and provides a cool spot that prevents seed melt-out. After the stabilization of the molten sapphire charge and the appropriate solidification is achieved by controlling the heat input and the heat extraction.

The HEM process controls heat input and heat extraction without moving the crystal or crucible. After solidification is completed, the crucible is still in the heat zone. The furnace temperature is lowered below the solidification temperature and *in situ* annealing of the boule is achieved prior to a controlled cool-down to room temperature. *In situ* annealing of sapphire boules can thereafter be carried out after growth so that stresses introduced during the growth can be relieved and further multiplication reduced.

After the sapphire boule is grown and annealed, it is still sensitive to stresses due

► Large sapphire crystals are increasing in demand for many of today's industrial applications.

by Kurt Schmid, Chief Operating Officer, and Scott Cohen, Sales Engineer, Crystal Systems, Salem, Mass.

to temperature gradients imposed during the cool-down cycle. The cool-down cycle is therefore tailored to minimize these stresses. Competing crystal growth processes impart larger stresses on the crystal because the crystal is physically pulled or flowed away from the heat source, thereby creating larger temperature gradients.

The most unique aspect of the HEM system is its ability to control the heat input (melt the sapphire crackle) and also extract heat from the system (freeze or grow the sapphire). This control allows a thermal gradient to be developed in the chamber without mechanically moving or rotating the crystal, as other sapphire growth techniques require. Traditional sapphire growth techniques, such as Verneuil, Czochralski and edge-defined growth (EFG), can be limited in terms of outside diameter capability, orientation offerings, homogeneity, and bubble and inclusion formation.

HEM-grown sapphire is bottom-seeded, temperature-controlled and produced in a vacuum environment. The solidification

*Developed by Crystal Systems, Salem, Mass.

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process is such that impurities are the last to solidify; impurities migrate to the edges of the boule where they can be easily removed. The slow cool-down of the boule as part of the growth process creates an *in situ* anneal, which provides a pure and homogeneous sapphire.

Growing Larger Crystals

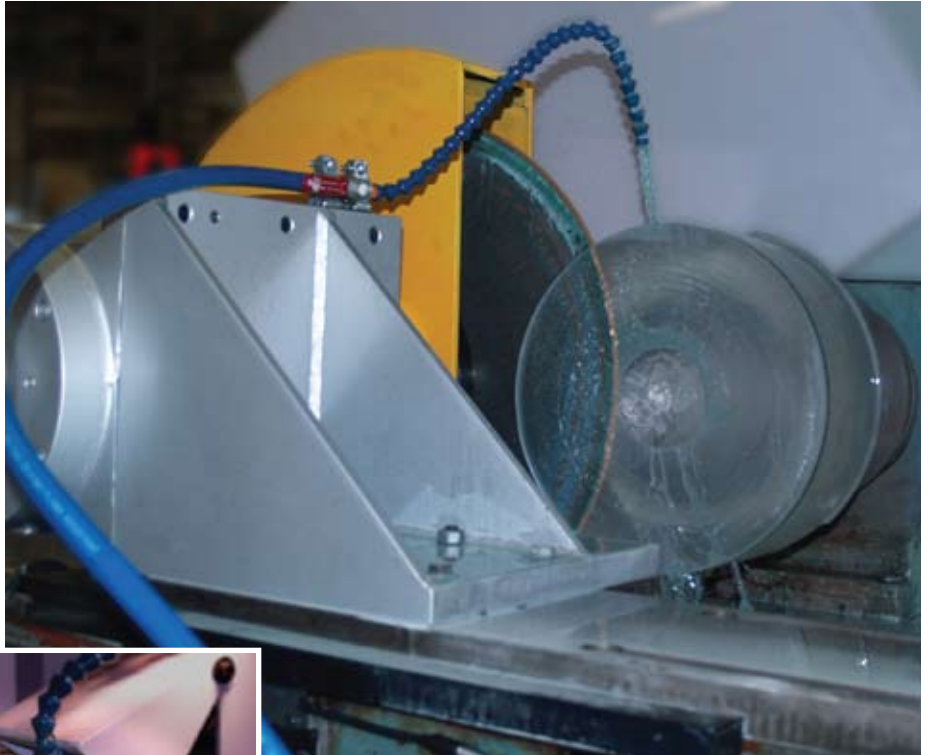
The HEM growth method recently underwent extensive engineering to adopt the same growth conditions used to produce high-quality 13-in. crystals for the newly introduced 15-in. crystals. The environmental sensing of the interior of the crystal chambers was upgraded with the most sensitive and robust technology available. This increased sensitivity to the environment inside the chamber allows new sapphire growth programs to be developed that have further increased crystalline quality. It is now possible to produce 15-in. crystals with higher-quality sapphire than any other competing growth method.

An additional benefit of the updated HEM growth method is that furnace upgrades were engineered to minimize electricity consumption. The high efficiency of the HEM furnaces has become one of the most important economic factors in offering cost-effective components. The large crystals yield high volumes of sapphire material, which has allowed a highly commercialized sapphire production line to be established.

Figure 1 shows an 11-in. plate that was taken from a 15-in. crystal. The window was polished with a standard polishing process, and the transmitted wave front error is $\lambda/10$ peak to valley (PV) or $\lambda/40$ root means square (RMS). Most traditional processes could not support these values without compensating through corrective polishing techniques.

Aerospace Applications

Demand for large sapphire windows is increasing sharply in the aerospace industry. Airplanes and unmanned aerial vehicles (UAVs) feature advanced reconnaissance systems and other large-view ports that sapphire is well-suited for. Sapphire is also increasingly viewed as a window material upgrade to zinc



When sapphire is grown without stress and fabricated using low-damage processes, the result is a high-performance material that will operate in environments that most materials would not survive.

sulfide (ZnS), fused silica and magnesium fluoride (MgF_2) for these airborne applications because of the flexibility it affords in terms of sizes, mechanical properties and wide transmission range. These parameters, along with the availability of 15-in. diameter sizes, give the material a real advantage over other optical materials. Furthermore, HEM sapphire can support excellent optical wave front values of λ over 10 (1/10th TWE, P-V).

One of the primary advantages of sapphire over traditional materials is its greater strength in terms of tensile, knoop hardness, and rain and sand erosion. Sapphire's high values in these areas allow for the fabrication of thinner, lighter windows. The reduction of total aircraft weight is always among the top objectives of aeronautical engineers, and thin sapphire windows have the ability to reduce overall payload while increasing the strength of the interface between the environment and the underlying systems.

The polished sapphire surface also offers high durability to rain and sand erosion. High-speed travel of the systems on aircraft results in contact with rain, sand and bugs on the active optical surfaces. The sapphire windows maintain surface figure and roughness to accurately transmit the respective lasers or light through the surfaces after continued exposure to the sand and rain particle impacts. Sapphire material accomplishes this goal and is thus used extensively on today's reconnaissance, targeting and missile systems.

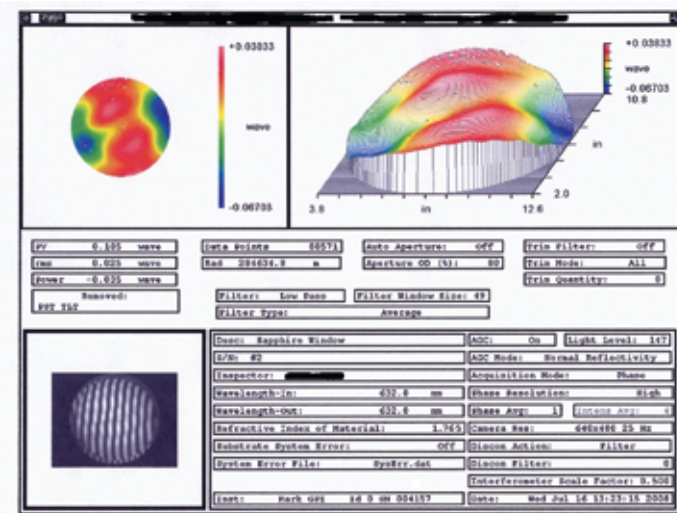


Figure 1. Interferogram of an 11-in. plate that was taken from a 15-in. crystal.

The wide spectral range of sapphire lends itself to housing many different types of instruments behind a common window. FLIR systems, infrared detectors, laser trackers and target designators can operate behind a single large sapphire or a set of sapphire windows. In addition, sapphire has a wide spectral range (220 nm to 5 um) from the vacuum ultraviolet (VUV) up through the mid-wave infrared region (mid-IR). The ability to utilize one optical element that can accommodate the many systems decreases the complexity of the overall optical design.

Mechanical Opportunities

Mechanical sapphire applications, including semiconductor wafer carriers, wear parts, nozzles, bearings, tubes and many other components, are also being specified to larger dimensions. The driving force behind sapphire in the semiconductor area is its inertness in harsh environments. Sapphire material has an operating temperature of over 1800°C without out-gassing or decay. Sapphire components can be installed in semiconductor equipment without worrying about lifetimes or the possibility of contaminating the chamber environment.

Other mechanical applications, such as liquid chromatography, require well-annealed and low-stressed material. HEM sapphire is low-stressed because of the anneal cycle used during the crystal growth cycle. Fabrication processes after growth are low-damage to ensure that no subsurface damage or micro-fracturing exists in the components. These machining tasks require each step of the final shaping process to leave a part free of defects, which are very hard to remove once they are introduced. When sapphire is grown without stress and fabricated using low-damage processes, the result is a high-

performance material that will operate in environments that most materials would not survive.

Fabrication Efficiencies

The fabrication of large sapphire components requires very good cutting efficiencies and low-damage processes. The diamond wheels must be well dressed and the cutting rates adjusted to allow absolute “free cutting” without any deflection of the blade. Equipment has been modified to achieve the dual task of slicing faster without damaging the material; capabilities include slicing 24-in. diameter crystals with masses exceeding 150 kgs. The ability to handle and process large sapphire efficiently with little kerf or yield loss is important as sizes are scaled up.

The use of fixed diamond wire slicing technology is required to maintain economies of scale while slicing high volumes of components to a common size. Proprietary methods have been designed to achieve high cutting rates with low damage using fixed diamond plated on wire. Fixed abrasive slicing technology (FAST) allows many parts to be autonomously sliced to a lapped finish without damage.** The FAST systems were scaled-up to accommodate slicing of large blanks over 8 in. in diameter. These larger components are gaining momentum in the LED, SOS and wafer carrier markets.

The migration from ID slicing and diamond slurry slicing to FAST slicing is bringing down processing costs and allowing larger throughputs due to the elimination of extra grinding steps. The surface roughness at less than 1 um Ra for parts processed on the FAST system is comparable to that for parts processed in a double-side lapping operation. The “as sliced” parts can be polished or final-shaped to the finish dimensions, thereby eliminating any surface grinding requirements. The removal of the grinding step eliminates the potential for sub-surface damage and decreases component cost.

Bigger and Better

The aerospace and mechanical markets for sapphire are growing, along with the actual component sizes within these markets. Low-energy-use, large crystal production and efficient manufacturing are increasingly necessary factors to support continued growth in the sapphire aerospace and mechanical markets. The HEM crystal growth method and FAST slicing technology complement each other to produce high-quality sapphire components at low costs. 🌐

For additional information regarding sapphire for industrial applications, contact Crystal Systems, 27 Congress St., Salem, MA 01970; (978) 745-0088; fax (978) 744-5059; sales@crystalsystems.com; or visit www.crystalsystems.com.

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quality, purity, consistency**

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