High Purity Alumina (HPA) Enables Sustainable Production for the LED and Watch Industries

HPA transforms into the vital sapphire components integral to LED and watch cover production by enhancing its quality and sustainability. Environmental costs are in the focus of sapphire production, which can be minimised by using low-emission HPA produced by Advanced Energy Minerals/CA.

Fig. 1
Carrot produced in Verneuil process

Sapphire – a material with outstanding properties

Sapphire is a key component to our everyday life due to its transparency, scratch resistance, and high thermal conductivity.

These properties make it ideal for various uses, such as scratchproof windows, translucent ceramics and insulating layers for semiconductors. A sizeable quantity of sapphire is used to make jewellery and watches, where recent trends have lead to a higher demand from consumers for sustainable products.

Industrially produced synthetic sapphire is as hard as natural sapphire but more transparent as it lacks the trace elements that give gems their various hues. Marketed as "scratch resistant" or "virtually scratchproof", sapphire measures 9 on the Mohs scale of hardness, meaning that it can only be scratched by a harder substance such as diamond. Sapphire crystals are also fundamental to light-emitting diodes (LEDs), the small light sources that illuminate everything from our personal devices to our cities. Sapphire's transparency ensures there is no unimpeded light emission from the LED's underside.

Additionally, the high thermal conductivity of sapphire is vital for LEDs to ensure adequate heat dissipation during operation, which is necessary to prevent damage to the LED structure and maintain its lifespan and efficiency.

Lastly, superior electrical insulation properties allow it to effectively insulate the active parts of the LED from other components, reducing the risk of electrical short circuits.

Keywords
High Purity Alumina (HPA), sapphire, LED, watch cover

Sustainable sapphire production – using zero emission HPA

The industrial process to manufacture and customise sapphire takes place in three major steps.

1) Manufacturing high-purity alumina (aluminium oxide).
2) Crystallization of HPA at very high temperatures (~2050 °C) to form a raw crystal of synthetic sapphire.
3) Shaping and slicing of the crystal mass into pieces using diamond-coated saws. The resulting wafers are then ground and polished for the desired application.

These processes cause a severe carbon footprint. However, it can be reduced substantially at each step.

Manufacturing HPA starts with a mineral feedstock. If this feedstock is manufactured with hydropower as the only energy source, its only carbon impact occurs from the transportation. If the mineral source is close to the factory, this can be minimal or even brought to zero by compensation.

Such is the case for Advanced Energy Minerals (AEM) which manufactures HPA in Québec/CA; a region blessed by ubiquitous hydroelectric infrastructure utilising region-

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al feedstock produced predominantly with hydroelectric power.

The AEM factory was designed to minimise power consumption by using a patented chlorine leach crystallisation process. Local renewable sources, hydro and wind from Hydro Québec provide AEM's energy. The factory at Cap-Chat, northern Québec, neighbours the Le Nordais wind park with 133 turbines. Renewable utilisation was at 96 % and reached 100 % by the end of the year 2023. This reduced CO_2 emissions from less than 2 t of CO_2 per ton of HPA to practically zero. External auditors have further determined the complete LCA and concluded the following:

- Scope 1 is 0,00 CO_2 equ./kg alumina produced
- Scope 2 is 0,06 CO_2 equ./kg alumina produced
- Scope 3 is 0,70 CO_2 equ./kg alumina produced

The report is in accordance with the classification proposed by the Greenhouse Gas Protocol (GHG Protocol).

This is in strong contrast to alumina producers using the traditional alkoxide processes, who typically have very poor utilisation of renewables, which emits 12,3 t of CO_2 per ton of HPA. Other producers have a goal of reducing this by a factor of five, which is still very high. AEM has also a product line to deliver customised 4N (99,99 %) and 5N (99,999 %) purity compacted alumina monolithics to its customers. These ranges in size from pucks of a few grams to giant pucks of up to 21 kg. 4N HPA is typically employed for LED applications, while an even purer variant, 5N HPA, is used for optics.

The processes to convert HPA to sapphire all melt the alumina at a temperature above 2050 °C. This is followed by a slow cooling process that takes one to two weeks to create a crystal of sapphire. Because this is a relatively low-tech process, the crystal is not perfect. It can, however, be influenced by the quality of the HPA used and the dexterity of the furnace operator. Lower-purity HPA is used for LEDs.

The next level of purity finds application in watch covers. The highest quality HPA is transparent to deep UV due to its low titanium content. This makes it suitable for medical applications.

Crystallisation issues may also impact the final product quality and determine the final application. For instance, an LED device containing an imperfect and inhomogeneous sapphire component may experience decreased efficiency, a shorter lifespan, or a variation in emitted colour. In addition to HPA quality, the different sapphire growing processes yield crystals that are suitable for different applications.

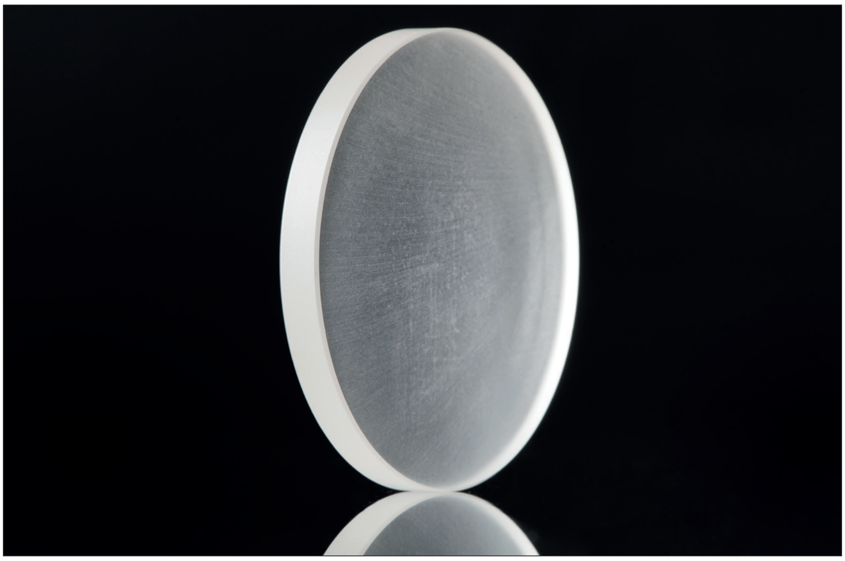

Fig. 2
Watch cover before cutting

Sapphire "carrots" for watch covers

Sapphire crystals for watch covers are traditionally grown with the Verneuil process. The result that awaits further processing is called a "carrot" in the trade (Fig. 1). It is close to a cylinder in form, approximately 15 cm high and 3–4 cm in diameter. Of course, this step has a typical energy requirement if not performed with green energy. The relevant CO_2 emission would be an average of 89 g/kWh for Switzerland, where environmental issues have a strong focus, or 475 g/kWh worldwide.

Because the crystal sapphire carrot has an imperfect form and contains defects, there will be substantial yield loss during the further processing steps. This loss can be minimised by generating a digital model of the carrot that is based on a 3D scan with specialised confocal tomography equipment.

It is worth noting that cutting and polishing sapphire is highly energy-consuming, as the material's exceptional hardness presents a significant challenge. The first step with yield loss is the scrapping of carrots after inspection and before further processing due to an unacceptable rate of defects. The yield from slicing the core into wafers and polishing them is 85 %. The result is an average combined yield of 28 % in the watch industry for a flat watch cover (Fig. 2). This will have a diameter ranging from 25–45 mm and a thickness from 1,6–6 mm. The typical weight is 4,6 g.

These steps can all be optimised with digital quality control from the Swiss company Scientific Visual. The company manufactures scanners for quality inspection of industrial crystals. Using these automated tools, individual steps can be optimised to avoid defects. For example, it prevents defective crystal parts from entering costly processing. In addition, by providing feedback to crystal growers, fewer crystals will have to be scrapped. The simulated form for the cylinder can be moved so that a minimum of defects remain in the physical carrot. Slicing can also be offset to bring defects between adjacent wafers. These steps all work to bring the yield for a flat cover to 34 %. For a domed watch cover, the improvement is from 4 % to 5 %, which is a 25 % improvement.

Effect of low-emission HPA from AEM for watch cover production is considerable. In the worst-case scenario, HPA emits 12,3 g of CO_2 per g of HPA. Manufacturing the flat watch cover emits: 12,3 g× 4,6 g/0,28 yield = 202 g and the domed watch cover emits: 12,3 g × 4,6 g/0,04 yield = 1400 g. The use of current low-emission HPA and digital quality control reduces these values to 20 g and 138 g, respectively. This is even before zero-emission HPA eliminates the cost completely, if not the wastage.

Sapphire "boules" for LEDs

The production of synthetic sapphire crystals, known as "boules", from HPA powder or monoliths is a complex process where size matters (Fig. 3). Sapphire boules serve as the starting material for thin wafers (250–150 µm) that later become LED substrates during production.

The diameter of the finished LED wafers is determined by the size of the boules. This diameter can range from 2" (almost obsolete now) to 6–8" (common today) to 12" (future standard). Competition requires growing larger boules, which is more economically viable. For context, a 90 kg boule that accommodates an 8" core diameter, has a bottom diameter of 30 cm and stands at 45 cm tall. The largest sapphire boule produced at the time of writing is 800 kg and measures 70–80 cm tall. It was manufactured in China.

Growing such boules demands precision, expertise, and time. The LED sapphire is often produced using the Kyropoulos growth method, which allows the largest crystals of the highest quality to be produced. The process begins with a slightly imperfect sapphire seed coming into contact with high purity alumina melt at around 2050 °C. As the crystal grows, it is surrounded by the melt and continues to grow until its surface reaches the crucible walls and gets lifted to restart the growth cycle.

This method allows crystallisation at low temperature gradients, resulting in lower thermal stresses in the crystal. For a 90 kg boule, the process takes 17 days – 8,5 days to grow the crystal and another 8,5 days to cool it down, and for 800 kg it is far more than a month.

Sustainability is also a key component of this process, as the crystal-growing furnace can consume 200 kW of electricity or even more. Sapphire manufacturer Alox Technology, based in Washouga/US, uses hydroelectric power from the nearby Columbia River for crystal growth.

This highlights how the LED industry not only produces products with low power consumption but also promotes environmental sustainability.

In order for the boule to become a LED substrate, it must first be processed into a core, or "cored". But before that, it must be ensured that the parts of the boule volume that are used for wafer production are free of defects such as small bubbles, cracks, and impurities. This is where the company Scientific Visual from Switzerland come in, offering advanced crystal inspection equipment.

After coring, the extracted cylinders are "wafered" into thin slices that are about 300–800 µm thick, depending on the diameter. Sapphire has a hardness just below that of diamond, so diamond saws and considerable energy is used for cutting and wafering. The wafers are then further refined through processes such as grinding and polishing to prepare them for the next phase of their life in an LED.

After the rigorous process of inspecting and cutting, the sapphire boule is transformed into thin wafers that serve as the LED epitaxy. Each wafer is placed in a chamber heated to 900 °C to grow the light-emitting layers on it, taking advantage of the sapphire's high-temperature stability.

With that miniaturisation, the industry is facing stricter standards for the final products. This ripple effect on the end products gets to the first production steps, such as high purity alumina production. A close relative of the LED, the miniLED, is characterised by its smaller size. A miniLED measures between 100–200 µm on a side, which, while smaller than a typical LED, still packs a powerful punch in terms of brightness and efficiency.

The future of display technology is often associated with microLEDs. Although they currently find a home primarily in high-end displays due to their high production costs, their potential is immense.

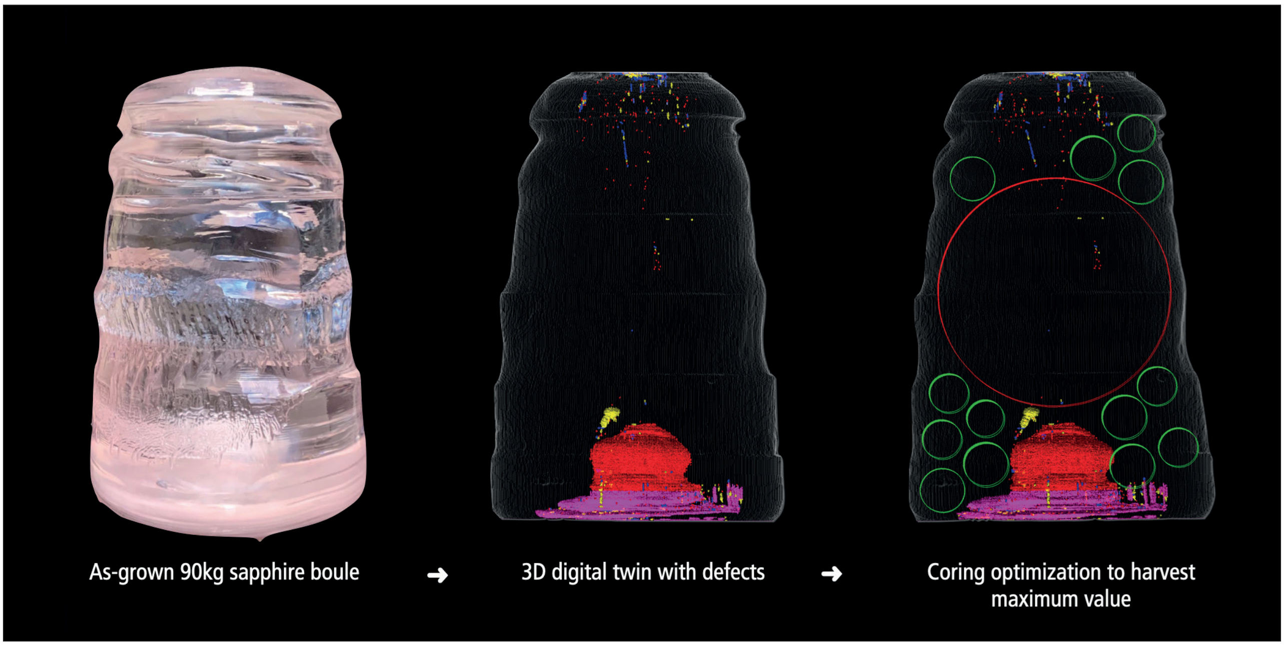

Fig. 3
Simulation of boules formation

Market forecast for sapphire and HPA – Green Alliance for Sapphire

The LED industry is a dynamic and rapidly evolving field, with new technologies and applications emerging regularly. As the demand for more efficient, brighter, and smaller light sources continues to grow, the role of HPA and sapphire in the LED industry will only become more critical.

In 2022, the projected total volume of high purity alumina was approx 35 000 t, with a substantial 30 000 t designated for LED production. Looking ahead to 2025, the demand for HPA is expected to rise to 58 000 t, with LEDs accounting for a significant 49 000 t, or an impressive 84 % of the total. By 2028, the demand for LEDs is forecasted to reach a remarkable 85 000 t.

In essence, LEDs have been and will continue to be, a crucial market for HPA, even as new applications emerge and other markets expand.

As for sapphire, the global market for these crystals attained a value of USD 903,3 million in 2021, according to the IMARC Group. They anticipate this figure to escalate to USD 2471,4 million by 2027, with a CAGR of 18,5 % during the period from 2022 to 2027.

With this growth potential it is relevant to watch the carbon foot print of the processes involved.

A project called Green Alliance for Sapphire, is a kind of consortium of companies active along the sapphire glass value chain that acknowledge that sapphire is not a sustainable product and its production causes significative carbon emissions. Moreover, the partners in the alliance are committed to working to bring to the market a more sustainable sapphire, and by doing so, contributing to the decarbonization of the industry. For AEM it is important to be in this network.

References

[1] OPTEL Carbon footprint assessment report for Advanced Energy (upon request)

[2] The Innovation Platform issue 14, www.innovationnewsnetwork.com

[3] The Innovation Platform issue 15, www.innovationnewsnetwork.com