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Opportunities for Sapphire

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Executive Summary

Sapphire has emerged as a versatile material useful to a range of industries in many varied applications including LEDs, optical and RFICs. Sapphire has a number of physical attributes that make it suitable for a wide range of end markets including its hardness and resistance to physical damage and chemical erosion. This white paper will examine the markets that leverage sapphire including emerging markets and evolving applications, key market trends and the migration to large diameter sapphire wafers.

LEDs are the largest end market for sapphire. Within that market the major end applications are general lighting and LCD backlighting. Other noteworthy LED market segments include signage and automotive. Most vendors have a standard manufacturing process used for LEDs for several or all applications and do not consider substrate demand by application. However, the advantages of sapphire do vary by application. For example, lighting, industrial and automotive benefit from the long life which is relatively less critical for LEDs for mobile handsets and notebooks which prioritize high brightness and low power consumption.

While most LEDs have been and are produced on 2-inch and 4-inch wafers, there is currently a migration to 6-inch wafers at some leading manufacturers. Today, approximately 7% of industry capacity (by area) is believed to be at 6-inch.

Overview of the Role of Sapphire in the LED Market

In the LED production process, sapphire is used as the substrate onto which the chemicals that will become the emitting layer of the LED are deposited as a vapor. Most LEDs today are produced on a sapphire substrate.

Sapphire is a crystal that is grown by single crystal technology, after >99.5% pure Al_2O_3 (alumina) is melted at a temperature higher than 2300ºC and then slowly cooled. Its hardness (9 on the Mohs scale of mineral hardness which is harder than steel) and a high melting point of 2050ºC make sapphire very appropriate as a substrate for GaN, which is deposited at a high temperature. Further, it is resistant to erosion by oxygen or alkali, which is helpful in the LED manufacturing process, providing strong resistance against a variety of processes during production such as wet etching.

For the LED market in particular, the lattice mismatch (to GaN) is not substantial and the number of defects produced is at a satisfactory, manageable level. With sapphire, it is possible to achieve good quality LED chips with good light output and reliability, and, importantly, to minimize the lattice mismatch (relating to differing thermal expansion coefficients of substrate vs. the epitaxial layer). Such lattice mismatch causes cracks and offsets between the substrate

and epitaxial layers as well as other heat transfer and stress issues that reduce the quality and lifespan of the LED. Other alternative substrates either have difficulty with thermal matching (which would typically require adding a buffer layer) or some other difficulties that add extra cost, allowing sapphire to continue to dominate the LED substrate market.

Demand Side Analysis

Overview

Sapphire's quality and cost enable it to be a suitable substrate for all applications, indeed for cost, quality and reliability it is currently the only choice for most manufacturers. LED manufacturers widely believe that sapphire's physical characteristics are important for LED production in general, and often do not consider substrates on a "by application" basis.

Economies of scale also offer some benefit to consolidating all of a company's production on a certain substrate rather than changing the substrate used for some applications, especially since LED manufacturers are often not fully aware of the end application use at the production stage.

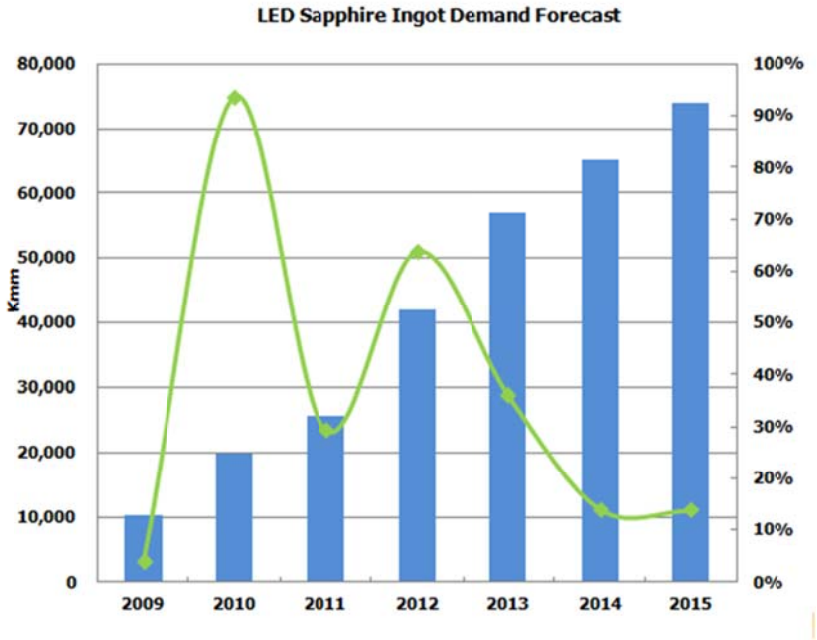
This white paper investigates how sapphire demand might vary based on the end application of the LED. The ultimate use of the LED – handset, TV, lighting – has no impact on sapphire demand. Growth of the end markets and tech developments within the LED industry are key drivers in sapphire demand.

Figure 1: LED Sapphire Ingot Demand (source: DisplayBank)

The market has shown growing demand since 2010 with an expansion of the LED/LCD TV market and the growth of applications such as general lighting.

Green line indicates rate of growth per year

Key: Demand in thousands of millimeters of two-inch equivalent sapphire



The amount of sapphire required is linked primarily to the die size and wafer thickness. A general lighting LED would typically have a larger die size than an LED for mobile handset backlighting and so more sapphire would on average be used to create one unit LED for lighting than one unit for mobile. However for a given die size, the amount of substrate required would be the same irrespective of the application (given equivalence of other factors, such as wafer size).

It was found, from research with both LED and sapphire companies, that there is little specific demand for certain sapphire attributes depending on the end application. LED companies do not normally require any difference in the substrate material used because of the application. Ultimately, in the longer term, companies that use different substrates for different applications would have additional complexity in the production process and quality control and more limited economies of scale. It is therefore thought that companies will prefer only one substrate in the future for most or all of their production.

However it should be noted that some applications, such as general lighting, do have a higher quality demand in terms of consistent light quality than others, such as architectural lighting or toys. This could mean that quality is demanded more in all processes throughout the production in these cases. Other exceptions to the general rule that substrate demand does not relate to the end application usage will be discussed later.

Application Summary

To understand market demand, it is critical to understand each of the four major LED end markets: general lighting; backlighting/consumer electronics; signage; and automotive.

General Lighting is the biggest future market for LED revenue, and in 2012 is provisionally anticipated to have been larger than the TV market for the first time, although it will still be lower than the whole backlighting market (which includes monitors, notebooks and TVs). Lighting LEDs are often require larger die size (although not always), higher power and brightness than other applications, which puts this market nearer to the cutting edge of technology.

Philips LED Light Bulb

The lighting market is characterized by a widely fragmented customer base and regionally-oriented markets. Here, the new technology of LEDs meets an older and more established industry. In the lighting market, white GaN based LEDs dominate, with other types, e.g. red AlInGaP, accounting for only a small portion of the market. Lifetime, reliability, brightness and color quality are the critical factors. Major packaged LED vendors to this market include Cree (which, uniquely, uses silicon carbide substrates), Lumileds, Nichia, OSRAM Opto, Samsung and Seoul Semiconductor.

The Apple iPhone 5 features LED backlighting, silicon-on-sapphire chip, and a sapphire lens cover.

Consumer Electronics applications are characterized by the use of white LEDs of medium brightness and die size. Blue and other LEDs (e.g. AlInGaP) can also be used in some applications. GaN-based LEDs certainly dominate, particularly in LCD backlighting, although other LED types can be used in some consumer applications. Low cost is most important for these LEDs, but certain product specifications must also be met. Reliability over a long lifetime is less important in this area, especially for certain applications such as mobile phone handsets which have a relatively short life. Major packaged LED players in this application include Nichia, Citizen, Toyoda Gosei, Everlight, and many others.

Signage (including large LED displays) is characterized by the use of RGB multi-chip LEDs for video walls. These products can be many square meters in size costing hundreds of thousands or millions of dollars. In addition, traffic signals and channel letters (large three dimensional hollow letters) are lit by internal LEDs. The overall die sizes are thought to be mid-size, less bright than lighting but brighter than basic indication. Both AlInGaP and GaN/InGaN dies are used. Major packaged LED vendors include Nichia and Cree.

The Audi A8 features LED headlights.

The **automotive** market has a wide range of applications including basic indicator lights available for less than $0.01 so there is a wide range of quality required depending on the end application. Most LEDs used in the automotive sector, particularly for the exterior of the vehicle, have to be qualified to an industry or government standard and need to have high quality and reliability which are more important than low cost. A long lifetime is also important in this application. Exterior lighting requires red, white and yellow LEDs and interior lighting requires a wide range of colors although there has been a trend towards white LEDs over the last several years. Major packaged LED vendors to this market are OSRAM Opto, Lumileds and Nichia.

Sapphire Demand by Application

Although most people generally believe there is little link between LED application and type of sapphire substrate, not everyone agrees. For example, applications where long lifetime and reliability are required, such as automotive, industrial and lighting, customers could specify more durable LEDs relying on the physical advantages of sapphire in terms of thermal matching and stable LED devices. Silicon could be more successful in smaller, dimmer die used in consumer applications with shorter lifetimes. One respondent commented that temperature resistance, history, reliability, yield and quality are particularly valuable advantages for sapphire-based LEDs when used in general lighting.

Sapphire's quality advantages might make it harder for alternative substrates like silicon to challenge. Silicon may be used initially for lower quality LEDs (such as signage and indication) in some cases according to sources. Sapphire's advantages are particularly important for high quality products while lower cost and lower quality products may be where silicon makes inroads.

General lighting has to be the main focus for any future improvements or changes to substrates as the backlighting and display markets reach their saturation points. Characteristics required in LEDs for lighting applications

include a high junction temperature and a good heat path. According to some sources, it is thought that sapphire-based LEDs can more easily reach a higher junction temperature (compared to silicon, but not compared to silicon carbide). Sapphire is helpful in lighting to produce high quality LEDs at a reasonable cost, and there is a correlation between sapphire characteristics, such as a good thermal matching coefficient with GaN, and LED quality and reliability. Further, the lighting industry will require some proof and history of a product which sapphire can offer; something less important with shorter-lived consumer products.

Lighting uses larger dies which are more challenging to produce, so again the history, reliability and quality of sapphire are beneficial here. However, it is worth noting that lighting die size is trending to smaller sizes.

New patterned sapphire substrates, where LED chip manufacturers etch a pattern into the sapphire substrate before beginning the MOCVD process, improve performance which some consider more valuable for lighting where performance is paramount –although it adds cost. In other applications, such as mobile handsets and other backlighting, patterned sapphire substrates would likely not be considered because of the lower overall LED cost, smaller profit margin and lower required brightness.

However, there is not much linkage between application demand and sapphire's specific characteristics. In lighting, it is worth noting that Cree, the number one player in the market, uses silicon carbide and is fully focused on lighting. We believe the two things are not thought to be connected; Cree uses silicon carbide for historical reasons and is focused on lighting for separate, strategic reasons.

The automotive sector is conservative and slow to react. It prefers to use qualified parts known to be reliable and to have been rigorously tested. While LEDs produced from silicon might be the same part to the same specification, there may be an argument for sticking to existing production processes (using sapphire for example) to ensure continuity and longevity and not take risks. A stable supply is also considered important. However, as automotive only represents about 10% of the LED market, it is worth noting that production process decisions (such as whether or not to use sapphire) may be made based on the larger backlighting and lighting markets and applied to all of a company's supply chain, rather than evaluated on an application by application basis.

In the consumer sector in particular, and in all sectors to some extent, cost is probably the most important factor. Most LED vendors sell into diverse applications, rather than focusing heavily on one sector or another. Therefore, production process decisions do not tend to be linked to one application.

Trends in Each End Market

From 2014, most LED markets will be either saturated or smaller compared to the total LED market. Excluding lighting, the rest of the LED market will decline. Meanwhile, the general lighting portion of the market will grow as current penetration rates are low (still single digit). Lighting should ensure continued solid demand for substrate material from the LED industry for some years.

The advantages of LEDs in general lighting, therefore, are all beneficial to the future demand for sapphire. These benefits include the energy saving potential (saving both carbon emissions and running cost), the long lifetime and reliability and associated lower maintenance costs.

Other advantages include the style/branding factor of being the new technology, form factor (the small size of LED components compared to other light sources) and dimmability of LEDs. LEDs hold other advantages over CFL lighting including the fact that LEDs reach maximum light output quickly and LED lighting does not include hazardous metals like mercury.

There are no trends over time that will significantly change the demand for substrate specifically, however, as yields improve over time, less sapphire will be required for all applications. However, the migration to larger diameter wafers will require thicker wafers and therefore more sapphire material.

In the backlighting market, major trends that will affect demand, and therefore sapphire demand, are market penetration and LEDs per device. The market penetration has increased recently and this is boosting sapphire demand. While some applications, such as mobile handsets and laptops/notebooks, are already at 100% penetration, TVs and monitors will not achieve full penetration until 2014 and thus have more growth potential. After that, the market will be saturated and will grow in line with overall shipments of devices and panels.

As LED lighting evolves, a number of changes to light guides, overall display brightness, and improvements in LED efficiency have steadily led to a decrease in LEDs per device and this has limited the market growth. However, the new iPad took an opposite position, introducing a new display that was both brighter and with higher resolution, more than doubling the number of LEDs used for the same display area. If this becomes a trend, it will be a big benefit for the LED and the sapphire industry.

The signage market has matured, so changes to demand as a result of trends are less likely.

In the automotive market, a similar situation is true. Major trends include the adoption of LEDs for headlights and new regulations mandating daytime running lights in EU countries. However, these will have a minimal effect on the overall market. Another trend is the fast growth of smaller vehicles in Asian countries including China and India. This would cause quite a large increase in the overall number of vehicles sold (although a smaller percentage increase for the LED market, as smaller, low cost vehicles use fewer LEDs per vehicle).

Migration of LED Producers to Six-inch Wafer Substrates

Like the semiconductor industry, LED manufacturers have begun to leverage the cost efficiencies of large diameter substrates. LED manufacturers have been making progress in migrating to 6-inch wafers. During the production process, the use of, say, 2-inch wafers, means more wasted space between wafers and more edge loss. So 6-inch enables a more efficient production process resulting in a lower LED cost. However there are still challenges to overcome in producing a good quality reliable die as well as process challenges in LED manufacturing such as laser lift off. In addition, new tools are required at certain process steps such as etching and testing which add costs and will slow movement to 6-inch given the current weak environment in the LED industry and world economy. However, larger size wafers may be more of a fit with existing manufacturing process and expertise at semiconductor companies which can lead to overall cost savings on a large scale.

Typically major LED players are already at 4-inch and moving to 6-inch, and this is common in Taiwan, Japan and the West. However some smaller players, particularly in China, do not even have a plan to consider moving to 6-inch – almost all of them currently operate at 2-inch.This is due to a lack of available technical expertise within the industry in China.

Six-inch wafers already exist today (2012) with a modest share. It is expected that this share will become very significant by 2016 with several LED companies estimating an industry share of 30-40%, although this could change as new market entrants from China mature. Share will be much higher in Korea, Europe, USA and Japan, but much lower in China where the technical skill and experience required at the large wafer sizes is often absent as the LED industry there is less mature.

LED companies, sapphire companies and other industry insiders believe and agree that the advantage of using larger wafers is to obtain a lower cost, but the disadvantage is the difficulty and challenges of fabrication with a more immature process. Difficulties include the bending/warping of wafers and the possibility of breakage.

Sapphire, rather than competing solutions, has the early lead at 6-inch. Ultimately the move to 6-inch should reduce costs and assist the LED lighting market to move to the next stage of adoption.

Six-inch MOCVD reactor shipments in 2011 ranged by quarter from 0% to 7%, with 7% in Q1’12 and about 10% expected for the rest of 2012. However many reactors in this time frame have been purchased by newer entrants in China, which only have the capability to produce at 2-inch. For first and second tier players, there is a much higher fraction of 6-inch now for new MOCVD shipments. Overall, industry capacity, including all machines in use today many of which were installed some years ago, is currently just over 1% by number of wafers or 7% by area share. This will grow only slowly due to the many Chinese players that have entered the market and are ramping up at 2-inch, however at top tier players the change will be faster in some cases.

It is believed that LG, Lumileds, OSRAM Opto and Cree are some of the main suppliers transferring some, much or all of their production to 6-inch, using sapphire.

The movement to 6-inch is an overall industry decision, however, with a particular focus on the future lighting market where costs need to be driven down to enable adoption.

Emerging Markets for Sapphire

RFIC/SoS (Silicon on sapphire)

The market for sapphire as a substrate for RFICs (radio frequency integrated circuits) is perhaps an order of magnitude less than the LED market. This comparison may change over time, however, because SoS RFICs are a disruptive technology that only recently (2011/2012) became widely specified in smart phones and other mobile devices, taking share from traditional GaAs chipsets. Thus the growth rate of sapphire in the SoS application should be higher than the growth rate of sapphire for LEDs. Peregrine Semiconductor, who owns the patents for SoS technology, is currently the only customer for sapphire in this market. Peregrine developed their SoS technology on 6-inch sapphire wafers, and because their platform is CMOS, they could be a candidate for early adoption of 8-inch sapphire wafers.

SoS RFIC chips deliver high RF performance with low power consumption, a small form factor, and significantly reduced crosstalk in antenna applications. The sapphire substrate, which is highly insulating, contributes to many of these benefits including speed, low power consumption and better isolation. Another advantage of sapphire in SoS is that it is environmentally friendly compared with GaAs-based devices using arsenic materials.

Peregrine announced in February 2012 that they had shipped more than a billion CMOS-on-sapphire RFICs. If SoS RFICs win broad-based adoption in additional applications and end-use markets, growth of demand for sapphire substrates in this market would accelerate.

Optical Windows and Industrial (Lenses, Sensors and Power Devices)

It is worth noting that sapphire can also be used in other markets such as lenses, sensors and power devices. In these markets, the high performance and cost advantages of sapphire can also be advantageous. In optical markets, sapphire's transparency has been cited as an advantage and sapphire can be optimized for transmission in the ultraviolet and infrared regions as well as the visible spectrum. Another advantage for sapphire in optical and industrial markets is also its durability and resistance to damage from heat, chemicals or physical abrasion. End markets for optical products include defense,

surveillance, medical and others.

In manufacturing processes, there may be other opportunities for sapphire. The hard nature of sapphire is suitable for precise processes, while the durability to physical and chemical wear is also advantageous.

While it is difficult to quantify the market size for all the areas considered in this section, these other markets are small in comparison to the LED end market (perhaps several times lower or an order of magnitude lower) despite a wide range of applications. However, it may be possible for higher percentage growth than for the LED market as these other areas may offer significant opportunity.

Alternative Substrates

LED manufacturers have been on the lookout for alternatives to sapphire as a substrate. GaN and ZnO can be used as substrates, but the costs are high. Silicon is still in the developmental stage as there are issues with LED die quality and thermal expansion coefficients that require the additional cost and complexity of a buffer layer. There are no other likely alternate candidate materials. It is expected that either sapphire will continue to dominate in the future, silicon will take over, or there will be a mixture. Many people view the mid- to long-term prospects for silicon as an LED substrate as good.

By 2013 it is expected that Bridgelux will be in mass production on silicon with Toshiba as a partner. Most other top manufacturers also have ongoing developmental efforts or research and development. By 2015 silicon may have a notable share of the market for the first time; it is thought that 6-inch or 8-inch could be where the battle between silicon and sapphire is most likely.

Conclusion

Sapphire has emerged as a versatile material in a range of industries for many varied applications. Sapphire's inherent physical attributes for durability, light transmission, chemical inertness and thermal insulation make it desirable for many markets for applications in LEDs optical windows, lenses and covers to semiconductor applications in smart phones and other consumer devices.

At the moment, these advantages are critical. Every LED company we spoke to during the research for this paper purchases sapphire and benefits for the superior yields and quality. Substrate demand in 2012 is estimated at 42 million 2-inch equivalent wafers (TIE) and expected to grow to 57 million TIE in 2013 by market research firm Displaybank. As the lighting market grows into a more significant segment and larger, thicker wafers are utilized, sapphire demand will accelerate given the larger die size utilized resulting in a forecast four successive years of 30%+ annual growth (by 2inch TIE in sapphire demand). The forecast accounts for the varying thickness of larger wafers.