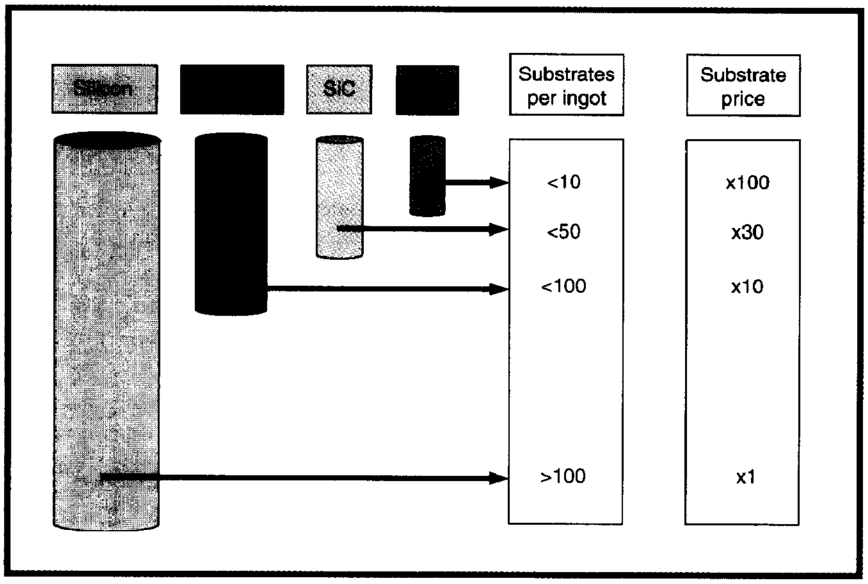
Roy Szweda
Associate Editor

**2002 has seen a resurgence of interest in the development of GaN single crystal substrates. The number of companies in the field has grown and they are at last receiving major funding to help them overcome the next hurdles. The impetus behind this lies in the shortcomings of the sapphire-based technologies currently in use. There is still a question mark against the commercial viability of pure GaN wafers when and if they will ever match the market need for low-price materials.**

# Successors to sapphire in the GaN market

It has been six years since the first III-nitride violet laser. While such devices are now commercially available from Nichia and have found their way into a growing range of applications, these devices still fall short of the requirements of volume products such as all-digital re-recordable next-generation DVD on both a commercial and technical basis. Each device still costs one hundred times more than a red laser of the same power. This is due in part to the fact that production volume remains tiny and yet their lifetime and stability are far from being good enough.

*Figure 1. This generalised schematic is intended to illustrate the relative importance of substrate technologies for gallium nitride today and tomorrow. Obviously, silicon ingot technology is highly advanced compared to virtually all others. It can provide larger substrates at lower unit prices while the bulk GaN processes are currently at a much earlier state of development and yield much fewer of the much more expensive substrates. The synthetic sapphire crystals that underpin today's III-nitride businesses and which are available in sizes ranging from 2- to 4-in, yield substrate products somewhere in between these two extremes.*
*Source: Elsevier Advanced Technology 'Gallium Nitride & Related Wide Bandgap Materials & Devices: A Market & Technology Overview' 3rd Edition now in preparation.*




When one mentions bulk GaN one of the groups that automatically springs to mind is the Polish Academy of Science's Unipress. Having worked for many years furthering the high pressure growth of GaN crystals, this year they took the step to full-scale commerciality via the new start-up, TopGaN. Mike Leszczynski who is Head of the Nitrides Epitaxy Lab told TFR that, "I'm convinced that blue and violet laser diodes of powers higher than 50 mW can be only constructed using material with dislocation density smaller than $10^4$ $cm^{-2}$ and with no lateral strains. People tend to forget, for example, that ELOG structures have very large lateral strains".

"This search is being driven by the fact that nitride layers grown on sapphire suffer from high defect density - due to the large lattice mismatch between sapphire and GaN - from a large thermal expansion mismatch - one of the causes of device layer cracking - and from poor thermal conductivity."

LEDs as required for solid-state white lamps, the other principal high volume market target for III-nitrides, may also ultimately depend on the availability of better substrates: "The situation with UV emitters is even more dramatic. When one deals with material that is indium-free it must be perfect from a crystal point of view. Therefore, much money will have to be spent to get good substrates for the GaN epitaxy. Perhaps surprisingly, it may turn out that the GaN crystals grown at high pressure such as those grown by Unipress/TopGaN or Japan Energy, General Electric, et al., turn out to be cheaper than those grown in by the highly sophisticated methods such as double ELOG, MOVPE + HVPE, etc. that are now used to get material of a comparable quality. I think that at first one should have a good technology and still nobody has."

The need arises from the shortcomings of III-nitride layers grown on dissimilar substrates such as sapphire. These have the disadvantages, e.g. their high defect density which is due to a large lattice mismatch between sapphire and III-nitrides (see Figure 3).

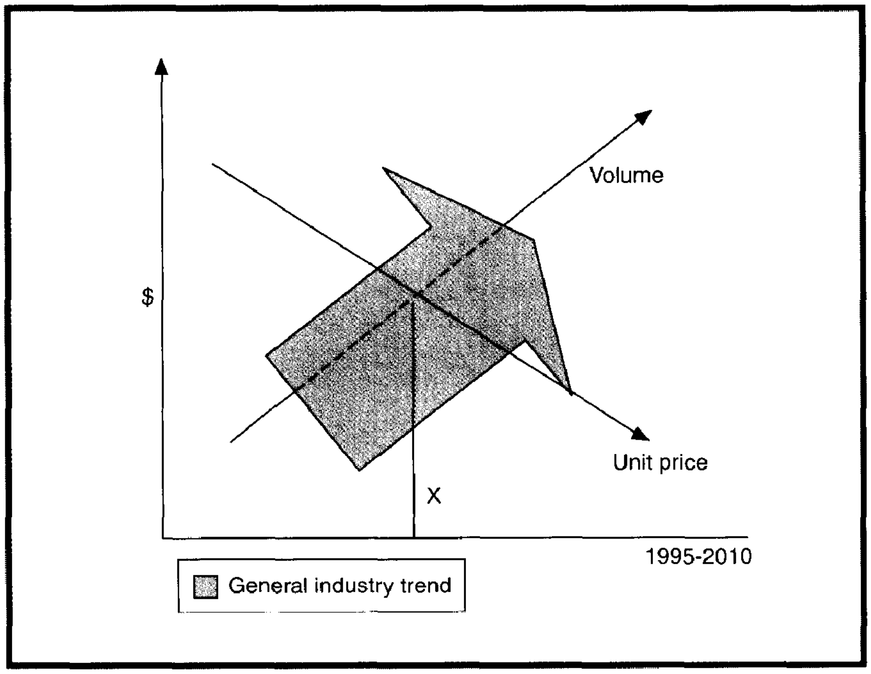



*Figure 2. This generalised schematic illustrates the progression of the gallium nitride substrate market over the 1995-2010 period. It follows the traditional trend of unit price having to fall drastically as the market gets underway and volume applications come into play. Point X represents the turning point for the market when this occurs is a subject of considerable speculation and could fall at any time in the next decade depending on how successful the main players can overcome the technical obstacles.*
*Source: Elsevier Advanced Technology 'Gallium Nitride & Related Wide Bandgap Materials & Devices: A Market & Technology Overview' 3rd Edition now in preparation.*

## Commercial offerings

Although this article is mainly about GaN substrates, AlN also has commercial possibilities. This derives from its crystal and chemical compatibility with GaN and the $Al_xGa_{1-x}N$ alloys. Of considerable interest for power devices is the fact that the thermal conductivity of AlN is ten times that of sapphire and almost double that of GaN.

To demonstrate the efficacy of AlN, the Palo Alto Research Center (PARC) fabricated the world's first UVLED on AlN. Built on substrate material supplied by Crystal IS, the LED structure consisted of a GaN/AlGaN MQW active region with emission wavelength near 360 nm.

As will be shown here, there are more companies than ever in the business of commercialising bulk GaN products. Figure 1 illustrates the relative importance of today's and tomorrow's substrate technologies: silicon, sapphire and bulk GaN. These are really the main contenders although SiC will continue to be important and sit somewhere between sapphire and GaN as regards utility and unit wafer price.

Then in Figure 2 the progression of the GaN substrate market over the 1995-2010 period is shown. Unit price is going to have to fall drastically before the market can truly get underway and volume applications can come into play.

To begin the overview of substrate players, Cermet is an interesting company which has looked at a number of sapphire alternatives. Cermet, via BMDO- and DOD-funded projects uses a pressurized RF induction melting process to produce GaN single crystal after proving the processes utility with AlN. Now the company, which had success with AlN and ZnO (it offers a lattice match within 2% of GaN) has a Phase I SBIR project to show if it is feasible to grow high quality 5 mm boules of GaN single crystal using a novel physical vapour transport technique. Here a gallium-containing vapour is crystallized on a seed in a nitrogen-containing atmosphere so as to form the GaN boules.

Moreover, each substrate technology will likely have particular application for one or more device types. For example, sapphire will continue to be near-ideal for low- to mid-brightness LEDs and because of its high thermal conductivity and other qualities SiC will be good for high-power devices.

Already, researchers and companies worldwide are beginning to develop opto- and micro-electronic devices to exploit homoepitaxial growth on GaN monocrystalline substrates. Opinions differ on the respective merits of the technologies and companies are continuing to back heteroepitaxy. Not so long ago, RF Nitro Communications, Inc., completed what it described as the world's first GaN 4-inch wafer pilot line. This is the

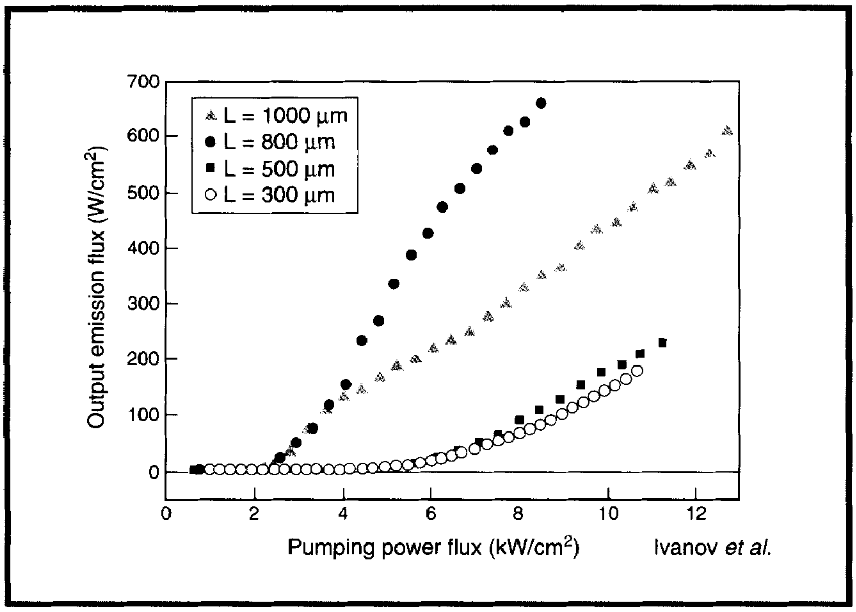
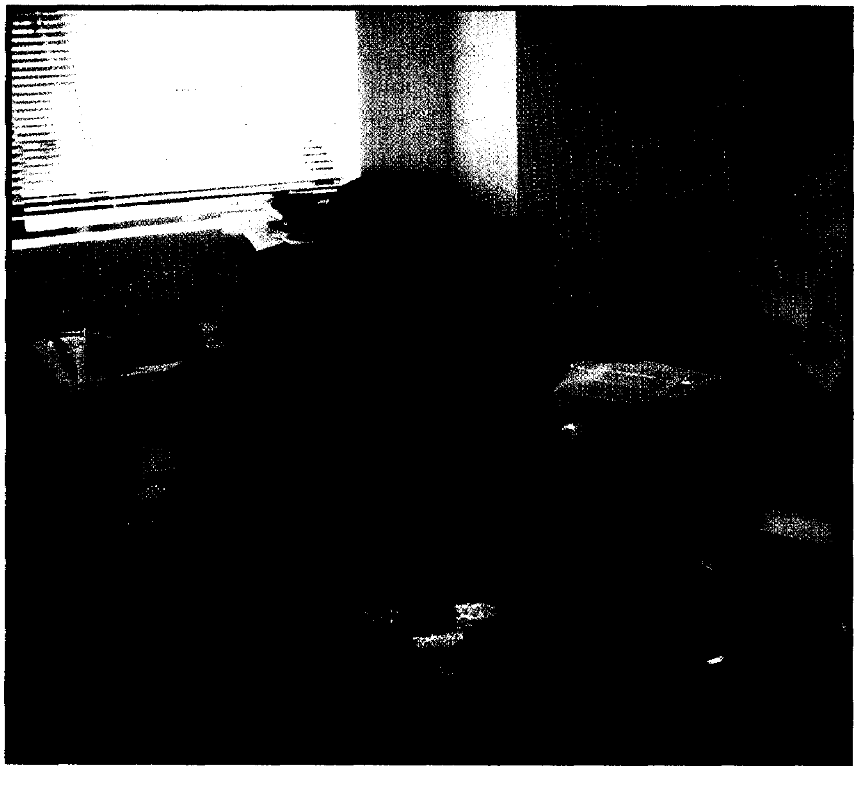



*Figure 3. Latest results for optical pumping measurement on homoepitaxially grown layers from the Polish Academy of Sciences, Unipress/TopGaN.*

company which was acquired by RF Micro Devices, one of the world's leading MMIC product manufacturers last year.

"Large-diameter sapphire costs approximately $100 per substrate and GaN-on-sapphire offers superior insulating properties, lower defect density, higher frequency performance, and superior power performance over GaN-on-silicon approaches," said Dr. Joseph Smart, VP of Advanced Materials, "SiC substrates are expensive, but GaN-on-SiC offers the ultimate combination of frequency and power performance for high power applications."

*Figure 4. GaN pioneer Professor Shuji Nakamura holds a sapphire crystal but is now working on bulk single crystal GaN at UCSB.*



## USA strong in GaN

Technologies and Devices International, Inc., based in Maryland reckons it has made the industry's first true GaN bulk substrate. It is sampling boules and polished wafers measuring 1.5-in (35 mm) in diameter. "The performance and lifetimes of all GaN-based device designs will be significantly enhanced by using bulk GaN versus GaN layers grown epitaxially on non-native substrates such as SiC or sapphire. To date, those have been our industry's only alternatives," said Vladimir A. Dmitriev, President and CEO of TDI.

TDI's process and progress have received significant support thus far from the US Department of Defense's Office of Naval Research, BMDO and other US government funding sources. Tangential technical development has come from a variety of research and development teaming efforts with especially noteworthy research and educational institutions and government labs, including Cornell University, NRL, and NIST in the USA, and Erlangen University in Germany.

As is becoming clear the US is once again becoming a focus for bulk crystal growth. University research spawned another of the wide bandgap semiconductor pioneers, Cree, Inc., and now seems to be generating many of the players which will be important in any future bulk GaN market. Interestingly, this so far has not involved the principal III-V substrate makers such as M/A-Com Inc. However, AXT Inc., has developed a HVPE process for growing thick films of GaN on sapphire in work with the University of California at Berkeley.

Kyma Technologies Inc., announced shipment of what it said at the time was the industry's first single-crystal 2-in GaN substrates to a 'major device manufacturer' (unidentified). The single-crystal GaN substrates were 500 microns thick with over 90% usable area for device processing. They are N-type and have an X-ray-scan (002) of less than 300 arc-seconds. It is currently developing 4-in substrates.

Advanced Technology Materials, Inc., (ATMI) is another US company which is perfecting materials based around monocrystalline GaN. A while ago it received a Phase II award to produce commercially viable, large area, low defect density GaN substrates. It had already demonstrated that the approach, based on its HVPE growth of GaN boules, was viable. The combined approach for Phase II outlines the use of ATMI's own GaN seed crystals with a goal to produce at least 2-in diameter wafers from 10 mm long boules.

Nevertheless, perhaps the most important boost for the credibility of bulk GaN has been the III-nitride pioneer Shuji Nakamura's ERATO Award (see Figure 4). Having almost single-handedly established the business, he is now further investigating nitride crystals at UCSB. Amongst the research areas announced were preparation of bulk crystals of GaN. Some might say that he is not a crystal pulling expert relying on ready-made sapphire substrates for his LED and laser devices. Earlier, he taught himself the necessary MOCVD and related techniques so you can be sure he will just as quickly master other processes.

## European start-ups

So far there are relatively few GaN substrate developers in Europe. Until fairly recently, Unipress/TopGaN was the only one. As usual, much of what there is has been developed by universities and like the earlier Polish example, in France, Lumilog has gained exclusive worldwide rights to a breakthrough technology for the production of very high quality GaN substrates. Founded in December last year and basically Europe's first nitride foundry, it is headed by Pierre Gibart, Jean-Pierre Faurie and Bernard Beaumont from CHREA-CNRS and is located in the Technological Park of Sophia Antipolis on the French Riviera.

Using a proprietary process, Lumilog produces ELOG (Epitaxial Lateral Overgrown GaN) wafers on 2-in sapphire where very low dislocations density between stripes are achieved. It is also involved in the development of bulk free-standing GaN substrates. Meanwhile, Lumilog is establishing GaN-on-sapphire epi production facilities. Current production is provided by a 3 x 2-in wafers MOVPE reactor with a new reactor due by year-end.

## Asian interests

Of course, Japanese companies are also keen to not lose the lead in III-nitrides. In June, Sumitomo Electric Industries said it had begun sampling low-dislocation GaN substrates. It says it is working to mass-produce these for the 'Blu-ray Disc' optical video recording technology. The new substrate has regions of low dislocation densities that are about 500 μm in diameter. The dislocation densities in these regions range from 10,000 to 100,000, which is 100,000 times less than the dislocation density of conventional GaN epitaxial layers on sapphire substrates, it said.

SEI developed the world's first 2-inch GaN wafer two years ago using a unique GaN substrate fabrication process, called the "dislocation elimination by epitaxial growth with inverse-pyramidal pits" (DEEP) technique. This technique reduced dislocations by forming inverse-pyramidal pits on the surface of the crystal. However, SEI has developed a technique that not only controls the regions where dislocations are concentrated, but also extends the low-dislocation density areas. Sumitomo forecasts the production of low-dislocation GaN substrates to reach 300 per month by April 2003.

In the parallel field of SiC development, a new company Hoya Advanced Semiconductor Technologies was formed so as to develop and produce cubic 3C-SiC.

So far, despite high level of interest in III-nitrides for LEDs in Taiwan, commercial advances in bulk substrates have been thin on the ground. A novel alternative approach comes from Advanced Epitaxy Technology (AET) involving bonding GaN-on-sapphire LED wafers onto GaAs which it says gives good yields.

Called "Virtual-chip Bonding" (VB) technology, AET moves one step on from the fairly common practice of removing the sapphire from the GaN active layers. It has then been able to create a simplified fabrication method for blue LEDs by bonding the GaN device to a GaAs substrate. Nevertheless, AET is also being funded by Taiwan's Ministry of Economic Affairs for GaN substrate R&D planning to have commercialised these by the end of next year.

***"This search is being driven by the fact that nitride layers grown on sapphire suffer from high defect density - due to the large lattice mismatch between sapphire and GaN."***

Mike Leszczynski, Head of the Nitrides Epitaxy Lab TopGaN.

***"We believe GaN to be a disruptive and revolutionary technology in wireless infrastructure applications.... GaN power transistors exhibit power density approximately ten times greater than conventional GaAs power transistor processes and approximately 100x greater than Si. Using GaN, base station PAs may be built to operate at very high voltages and at higher efficiency and better linearity than existing designs using LDMOS technology,"***

**William Pratt, chairman and CTO of RF Micro Devices.**

## Silicon alternatives

As any perusal of the patents being awarded in the area of GaN R&D, will show there is no shortage of alternative approaches to heteroepitaxy. Sapphire will hold sway for at least another three years and most of these alternatives will prove no more than an interesting technical exercise. Sapphire is highly resistive so will suit microelectronic applications but not pn junction devices such as LEDs and lasers. So we can expect some divergence in the marketplace as it continues to evolve.

The one exception will of course be silicon. As more and more articles in this magazine show, there is a trend towards making silicon the 'universal substrate'. New types of epitaxy are opening up previously unimagined possibilities for opto- as well as micro-electronic devices.

GaN-on-Si has been demonstrated by numerous laboratories around the world. For example, workers at the Otto-von-Guericke Universität Magdeburg in Germany have shown bright blue to orange PL emission from high-quality InGaN/GaN MQWs on Si(111) substrates.

Most recently, at the International Workshop on Nitrides conference in Aachen, Germany in July, workers from the RWTH (Aachen), Stepanov Institute of Physics (Minsk) and Aixtron AG presented the first optically-pumped violet laser diode based on InGaN/GaN using a silicon substrate. The 447 nm laser has a maximum operating temperature of 420K, a low threshold to achieve lasing at 270 $kW/cm^2$ and an output power of 8 W. This is a performance close to that of diode lasers grown on much more expensive sapphire and SiC substrates, the group says, adding that the results achieved on bulk GaN are more than 100 times better.

This kind of heteroepitaxy has also been making commercial progress with one or two commercial enterprises. In particular, Nitronex has shown the possibilities for devices which can exploit the price advantages of silicon which costs one-tenth that of sapphire. Its 'SIGANTIC' growth technique enables deposition of GaN-on-silicon with no problems with these differences in thermal expansion coefficients or lattice mismatch. The low-defect density process is called PENDEO and the resulting production platform technology is called SIGANTIC, which comes from GaN-on-Si, plus "gigantic."

Of course it requires special techniques to be developed before GaN-on-silicon structures can be made into working devices. GaN has a lattice mismatch with silicon of the order of 17% but more importantly their respective difference in the coefficient of expansion is 100%. Silicon is also not appropriate to some opto devices because it shows strong absorption at the short wavelengths.

## No clear winner yet

As shown here there is no doubt that if it can be made to work, the single crystal GaN substrate could be the key to III-nitrides matching their potential in lasers, white LEDs and power transistors. With the first tranche of the device market established there is a lot of incentive to move on to a homo-epitaxial process basis. Having made some profits the market players will have to plough some of this back so as to bring on what is still a relatively immature bulk growth technology.

Each company has a process with a unique mix of characteristics and is championing its own brand as having the best chance of success. According to tradition, some consolidation will not be unexpected as no one approach has a clear lead over its competitors. In some respects the industry will have to hope that when the best method does become clear it can be widely taken up, let market forces come into play and drive the market upwards.

From this point in time the target would appear to be the 2-inch diameter wafer. This is the cornerstone of the opto industry and would be a reasonable objective given that it will be mainly a discrete device market.

However, the markets where GaN is ultimately going to have to excel are very price sensitive. At the present rate of development it is going to take a long time before market-ready low price substrates are available in the requisite quantities. In extremis, the only way the industry will succeed is to develop processes based on silicon. Some industry observers, however, caution that this too is highly unproven and higher process costs could outweigh any advantage from cheaper substrates. All of these things will matter little provided the requisite technical funding is available. If the will is there then it looks like it will simply be a matter of time before GaN crystal substrates come into their own.