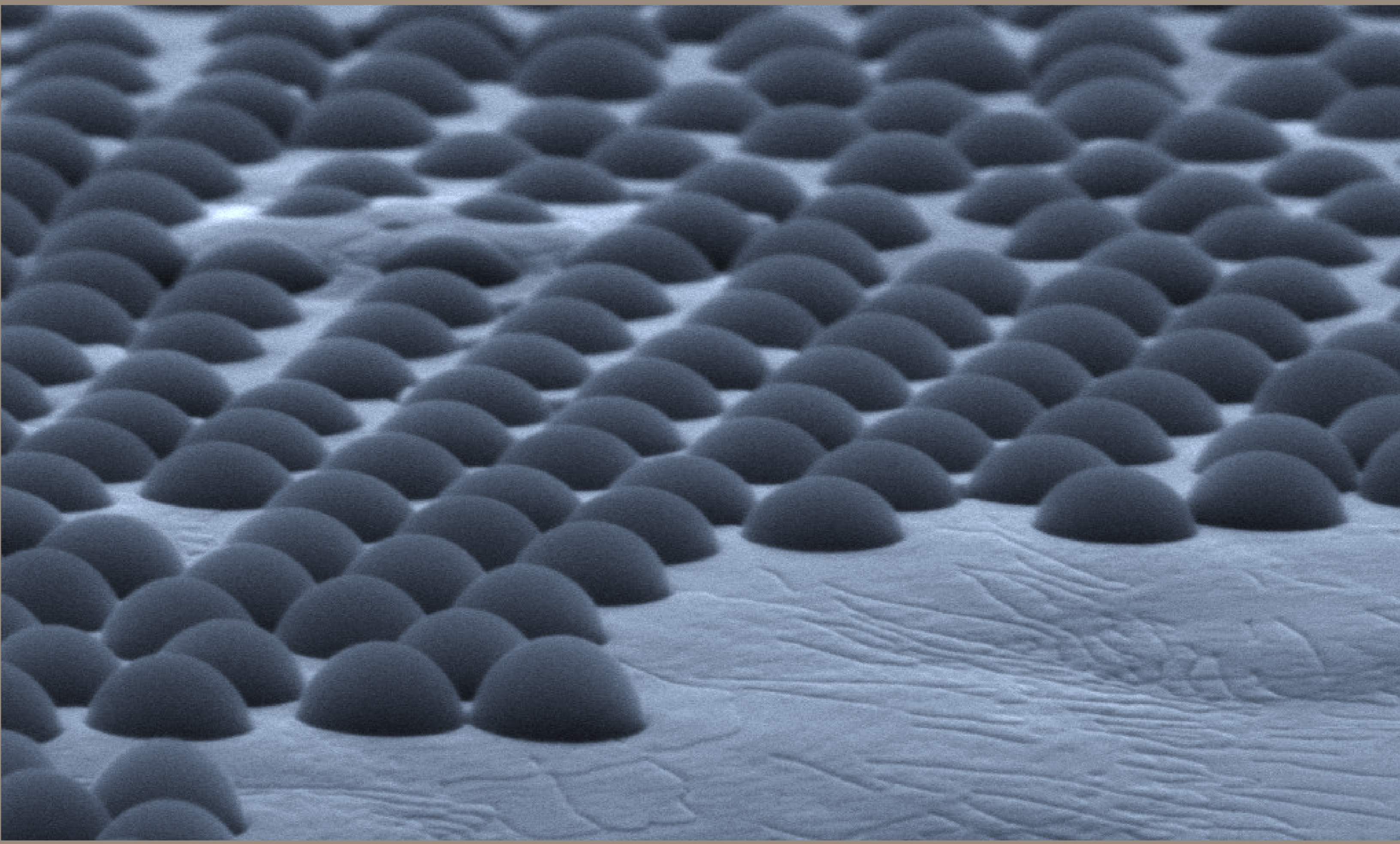
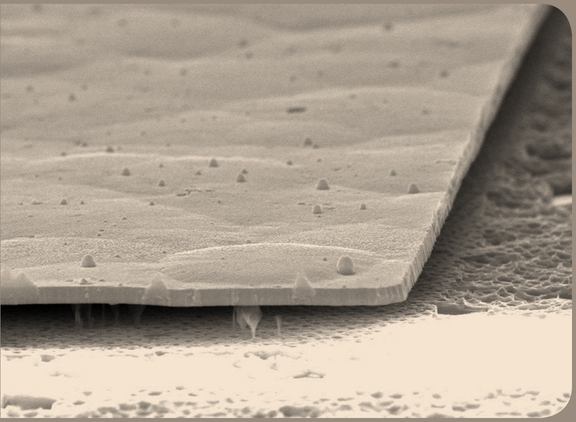
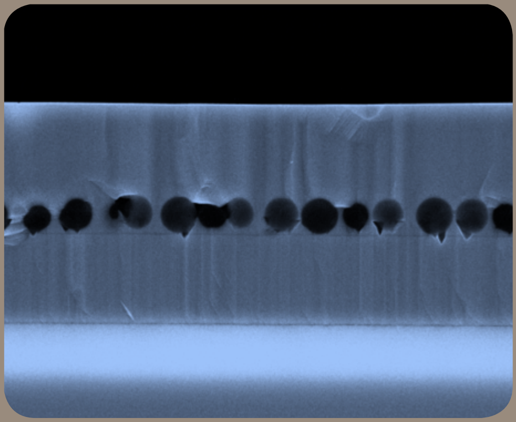
R&D 100 • 2013

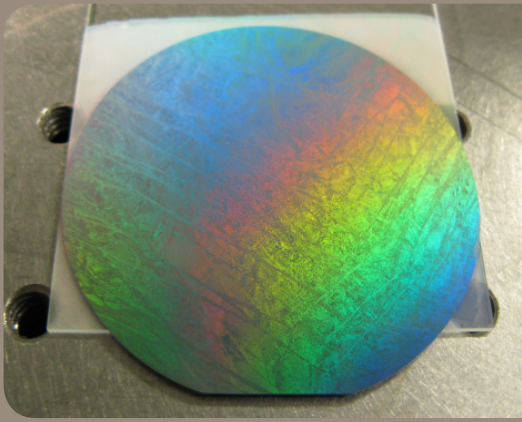
SAND2013-2414P

Microsphere-Templated Gallium Nitride (GaN)









Exceptional service in the national interest

Sandia National Laboratories

Microsphere-Templated Gallium Nitride (GaN)

1. Organization Contact Information

For associated video, **CLICK HERE**

A. Submitter/Product Developer

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B. Principal Developer Organization

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Sandia National Laboratories is the sole developer of the microsphere-templated GaN method in its entirety.

C. Principal/Primary Investigator, Developer, Inventor, or Team Leader

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2. Product Information

A. Product Name

Microsphere-Templated Gallium Nitride (GaN)

B. Generic Description of Product

Microsphere-templated GaN is an innovative and inexpensive technique for growing and removing high-quality GaN from foreign and native substrates.

B. Product Photo

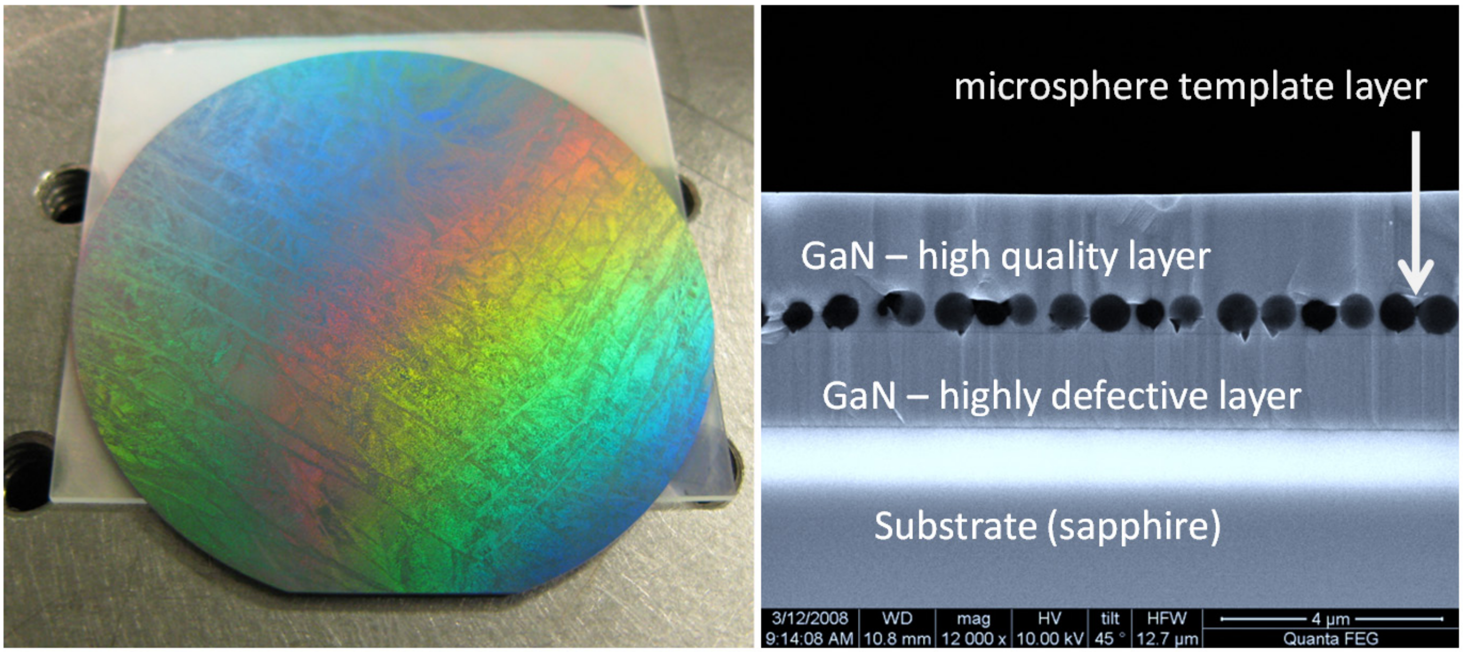


Figure 1. Left: 2-inch Si wafer covered by a silica microsphere template. Right: Growth of high-quality GaN layer through microsphere template on a sapphire substrate.

3. Executive Summary

Light-emitting diode (LED), or solid-state, lighting represents the largest revolution in lighting technology since the invention of the incandescent light bulb. Its widespread adoption, however, has been hindered by high costs. Sandia's microsphere-templated GaN is an innovative, versatile, and inexpensive technique that addresses current key limitations of the LED manufacturing process driving these high costs. The microsphere-templated GaN process uses inexpensively deposited silica microspheres that help reduce defects and cracking and allow for the subsequent removal of GaN from the growth substrate by way of a simple wet-etch process. In this manner, microsphere-templated GaN not only enables the growth of high-quality GaN-based LEDs and improved manufacturing yields of native bulk GaN substrates, but it does so at considerably reduced costs.

4. Introduction Date

Sandia's microsphere-templated GaN growth and lift-off technique was made available for licensing on November 27, 2012 (see Sandia National Laboratories Intellectual Property Licensing Portal on "Microsphere Templated Gallium Nitride Growth and Liftoff").

5. Previous R&D 100 Entry

This product has not been entered previously in the R&D 100 awards competition.

6. Product Price

The estimated cost of the microsphere-templated GaN process is estimated to be \$0.40/cm^2 of wafer area for smaller wafer sizes in limited production volumes, including consumables and processing costs. Using larger wafer sizes (e.g., 6 inches) and production volumes, the cost could be reduced to less than \$0.20/cm^2. This cost is insignificant considering that the added value from employing the technique ranges from about \$4/cm^2 for LED wafers to more than \$30/cm^2 for bulk GaN substrates.

7. Patents

U.S. Patent Application 12/388,103, "Low-Dislocation-Density Epitaxial Layers Grown by Defect Filtering by Self-Assembled Layers of Spheres," George T. Wang and Qiming Li, Sandia National Laboratories. Filed February 18, 2009.

U.S. Patent Application 13/113,123, "Method of Fabricating Low-Dislocation-Density Epitaxially Grown Films with Textured Surfaces," Qiming Li and George T. Wang, Sandia National Laboratories. Filed May 23, 2011.

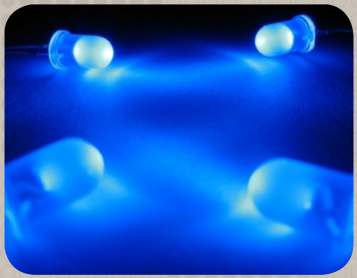
8. Product Description

What Does Microsphere-Templated GaN Do?

Since the mid-20th century, LEDs have been among the forerunners fueling modern-day advancements in technology, particularly in lighting and electronic displays. Today's blue, green, and white LEDs are made from stacked, single crystalline, GaN-based layers grown by chemical vapor deposition. Ideally, in

order to achieve the highest performance and efficiency, these GaN-based LEDs would be grown on native GaN substrates. However, due to the cost and lack of availability of bulk GaN substrates, current GaN-based LEDs are grown on top of "foreign" sapphire, silicon (Si), or silicon carbide (SiC) substrates, which causes GaN-based LEDs to suffer from a large number of structural defects that ultimately limit LED power, efficiency, and long-term reliability.

To overcome the limitations imposed by using foreign substrates in the production of high-quality GaN-based devices, Sandia National Laboratories' George Wang and Qiming Li have developed an innovative technique — microsphere-templated GaN. This technique employs layers of self-assembled silica microspheres that first act as a strain and defect control layer and then as a sacrificial layer to allow the growth and removal of high-quality GaN layers and native substrates, enabling low-cost and high-power LEDs.



Principal Advantages of Microsphere-Templated GaN

The microsphere-templated GaN process provides three primary advantages that address the critical limitations associated with the current industry-standard LED epitaxial growth and device packaging process. The first advantage to using microsphere-templated GaN is the unique capability of the silica microspheres to filter out structural defects during growth on foreign substrates, such as sapphire and Si. The result is higher quality GaN that increases the power and performance of GaN-based LEDs, while keeping substrate costs low.

The second advantage to using microsphere-templated GaN is the capability to lift off GaN-based devices and films using a selective wet etch to dissolve the silica microspheres. Typically, lift-off of GaN LEDs is done so that the device can be transferred and bonded to a more thermally and electrically conductive substrate during packaging. However, current LED industry laser lift-off methods are not only costly, since they involve a serial process that requires expensive equipment, but they are also limited to substrates like sapphire that do not absorb the laser. In contrast, by using microsphere-templated GaN, multiple wafers can be etched in parallel in an inexpensive acid bath, and the process is compatible with any substrate, including Si, SiC, and GaN. Following lift-off, the microsphere-templated GaN process can be repeated using recycled substrates to culture new, high-performance GaN-based LEDs or substrates, providing an additional cost savings.

Sandia's microsphere-templated GaN technique can also be applied to lower the cost of native bulk GaN substrates. Previous attempts to use GaN substrates for the growth of ultra-high performance LEDs and power electronics have been stymied by the fact that GaN substrates are extremely expensive (greater than $1,600 per 2-inch GaN wafer versus about $10 for a 2-inch sapphire wafer) and are not readily available in large quantities. A key reason for the limited availability and high cost is that manufacturing yields of GaN substrates fall below 20 percent as a result of strain-induced cracking from growing a thick GaN substrate (typically a few hundred microns thick) on foreign "seed" substrates, like sapphire.

With the microsphere-templated GaN process, the microspheres act as a strain-relief and structurally weak, "sacrificial" separation layer to detach the thick GaN layer from the underlying foreign substrate prior to the cooling down stage, where cracking occurs. This results in improved GaN yields that can reduce manufacturing costs by an estimated four times or greater than current industry standards, which would significantly improve the commercial viability of and enable the widespread use of native GaN substrates. Likewise, Si substrates, which are currently being evaluated by the industry as a lower-cost alternative to sapphire, also suffer from cracking caused by the large thermal mismatch between GaN and Si. Therefore, the microsphere-templated GaN process can also be applied to improve the viability of large area Si substrates as ultra-low cost LED growth substrates.

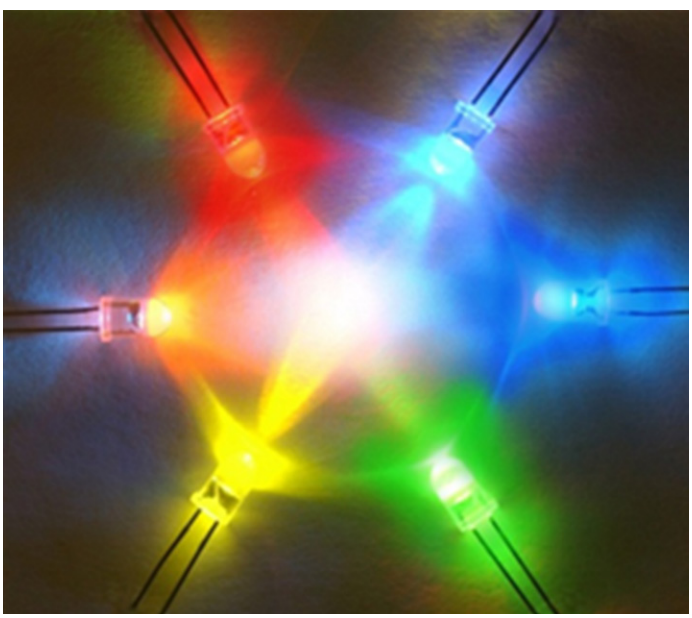


Photo courtesy of E. Fred Schubert of Rensselaer Polytechnic Institute.

Impacts and Benefits to the GaN and LED Market

White-light LEDs represent a new form of solid-state lighting that offers substantial energy savings and new functionalities, leading to a smarter, "greener" version of lighting. Despite its advantages and consumer approval of the technology, high costs have prevented widespread adoption of solid-state lighting. Sandia's microsphere-templated GaN provides multiple solutions for enabling lower cost, high-performance LEDs using either foreign or native substrates. Given its higher yields and significantly reduced cost compared to current methods, Sandia's microsphere-templated GaN process may pave the way for GaN substrates to become a widespread and commercially viable solution for high-performance LEDs and other GaN-based devices. In fact, by enabling LEDs on native GaN substrates, it is estimated that the amount of light per LED chip could be increased by 5 to 10 times, which would lower the overall cost of LED lighting considerably and accelerate its adoption.

According to U.S. Department of Energy estimates, the cumulative energy savings between 2010 and 2030 from solid-state lighting could total approximately 2,700 terawatt-hours, representing approximately $250 billion at today's energy prices. This energy savings could also reduce greenhouse gas emissions by 1.8 billion metric tons of carbon. Considering that the GaN-based LED market totaled about $8 billion in 2011 and is projected to grow to double-digit rates in 2013 and 2014, the potential economic impact of microsphere-templated GaN is quite significant.

Additional Applications for Microsphere-Templated GaN

Beyond high-brightness, GaN-based LEDs is a plethora of additional technologies that stand to benefit from the use of GaN substrates and Sandia's microsphere-templated GaN technique, including blue and green laser diodes, high-speed electronics, and high-power electronics. Revenue for GaN power electronics is forecasted to grow by a compound annual growth rate of over 60 percent over the next 10 years to $1.8 billion by the end of 2022. Thus, the potential technological, environmental, and market impact of microsphere-templated GaN is almost limitless.

9. Technology Description

How Microsphere-Templated GaN Works

Sandia's microsphere-templated GaN process uses one or more layers of commercially available silica (SiO_2) microspheres that are coated onto a substrate. The substrate can either be a bulk GaN substrate or a thin GaN or aluminum nitride (AlN) layer that has been previously deposited onto a foreign substrate, typically sapphire or Si. The microsphere layers act as a defect and crack-mitigation template as well as a sacrificial layer, enabling both the growth and removal of high-quality GaN-based LEDs and bulk GaN substrates.

As shown in Figure 2, silica microspheres are first deposited onto the substrate prior to growth in a controlled, layer-by-layer fashion using a commercially available dip-coater known as a Langmuir-Blodgett trough. GaN is then grown using conventional methods, such as metal organic chemical vapor deposition,

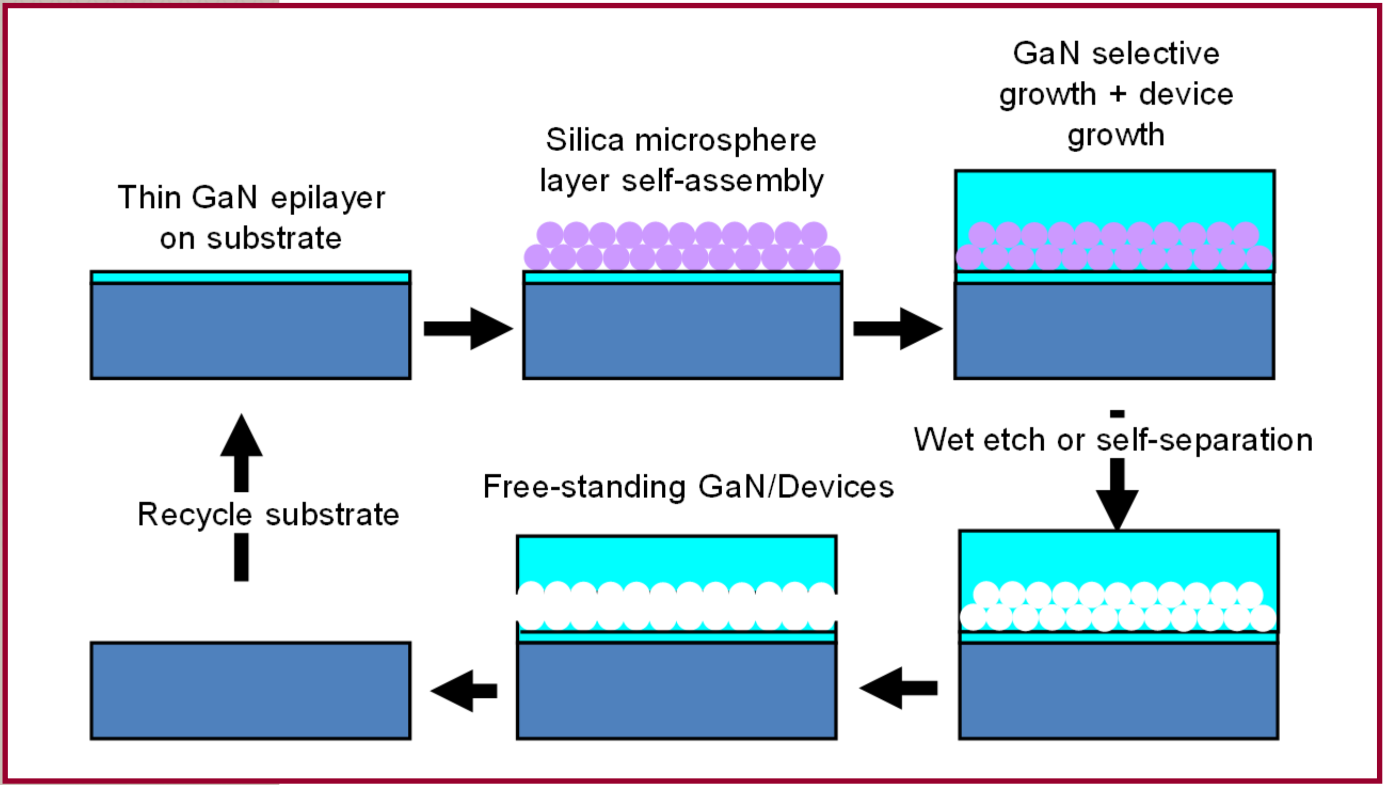


Figure 2. Microsphere-templated GaN growth and lift-off process.

through this microsphere template and allowed to coalesce, or reform, back into a smooth, continuous film. Due to the defect-blocking properties of the microsphere template, the number of structural defects in the GaN is greatly reduced. Once the GaN layer has been established, an LED structure can then be grown on this high-quality GaN layer. Alternatively, a thick GaN substrate can be grown on the microsphere template, which acts as a porous strain control layer that reduces the amount of cracking caused by the thick GaN layer on the foreign growth substrate. Finally, the GaN-based LED or substrate can be lifted off of the original substrate by wet etching away the silica microspheres, which does not affect the GaN.

The Science Behind Microsphere-Templated GaN

Microsphere-templated GaN uses a Langmuir-Blodgett self-assembly process to control the packing and arrangement of the microspheres and the number of layers deposited. The silica microspheres are first treated with an organic ligand to make their surfaces hydrophobic. During the Langmuir-Blodgett dip-coating process, the monodisperse silica microspheres self-assemble into a single layer on the substrate with a close-packed hexagonal lattice. Figure 3 shows a template comprised of three layers of silica microspheres coated onto a sapphire substrate by three sequential dips. The microsphere template has a porous structure due to the interconnected air spaces between the spheres, which allows for GaN to grow

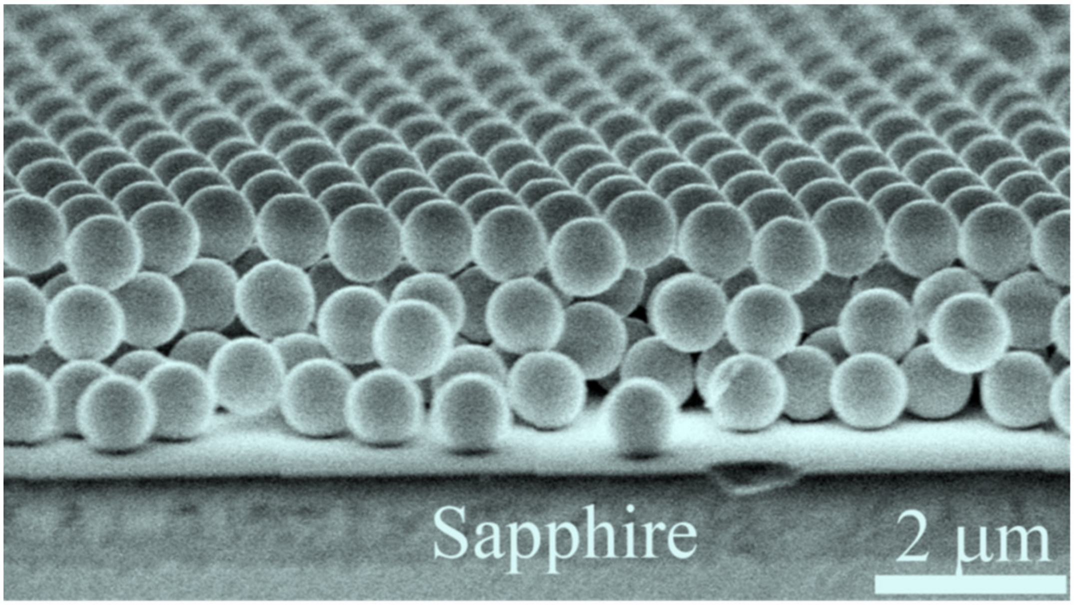


Figure 3. Growth and separation template consisting of three layers of close-packed microspheres on a sapphire substrate.

through the spaces in the microsphere template. The microsphere size, which typically ranges from 0.1 to 3.0 microns in diameter, and the number of layers can be varied depending on the desired application. For example, when using foreign substrates, larger spheres enable greater defect reduction but require longer GaN growth times. For the growth of bulk GaN substrates, multiple layers of smaller spheres are desired to provide greater strain relief and to induce self-separation. The process is easily scalable to large wafer sizes (8 inches and above).

The growth of GaN layers on foreign substrates causes the formation of large clusters of vertically propagating line defects due to differences in the crystal lattice spacing between the two materials. These defects, known as threading dislocations, result in decreased LED efficiency and power. As a result, LED chip manufacturers seek to reduce these defects to as low a density as possible. In the microsphere-templated GaN process, the microspheres serve to directly block and filter out threading dislocations, which prevents their propagation in the new GaN layer that forms over the microsphere layers and upon which the LED device is grown (Figure 4). The result is a microsphere-templated GaN layer with a defect density that is more than 10 times lower than commercial GaN films grown on sapphire substrates, and more than 100 hundred times lower than GaN grown on Si substrates.

Microsphere-Templated GaN Separation Benefits

In current industry laser lift-off techniques, an ultraviolet (UV) laser is used to

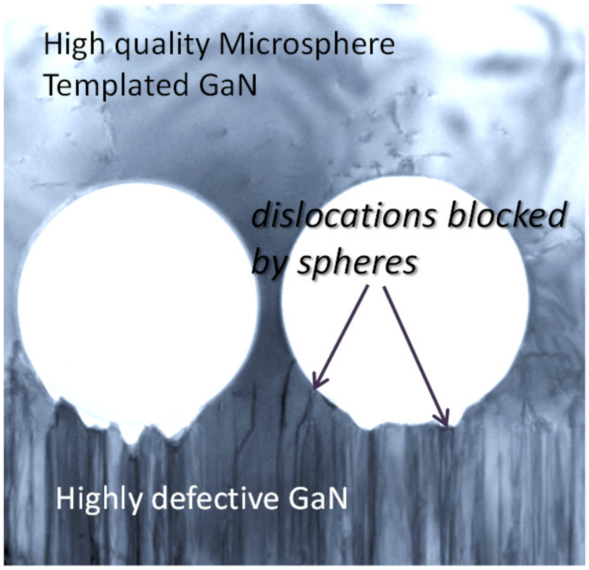


Figure 4. Transmission electron microscope image showing dislocations (dark lines) being bent and blocked by the microsphere template.

irradiate through a transparent substrate, typically sapphire. The laser energy then gets absorbed by the GaN and causes a thin GaN layer to decompose, resulting in delamination. Unfortunately, this method does not work to separate GaN films from GaN, SiC, or Si substrates since these substrates absorb the laser.

Compared to the laser lift-off method, Sandia's microsphere-templated technique provides a much cheaper and broader range of separation alternatives from different types of substrates. For example, the silica microsphere template can be dissolved using a selective wet etch, such as hydrofluoric acid, that does not attack the GaN surface (Figure 5), thereby allowing GaN films to be removed from

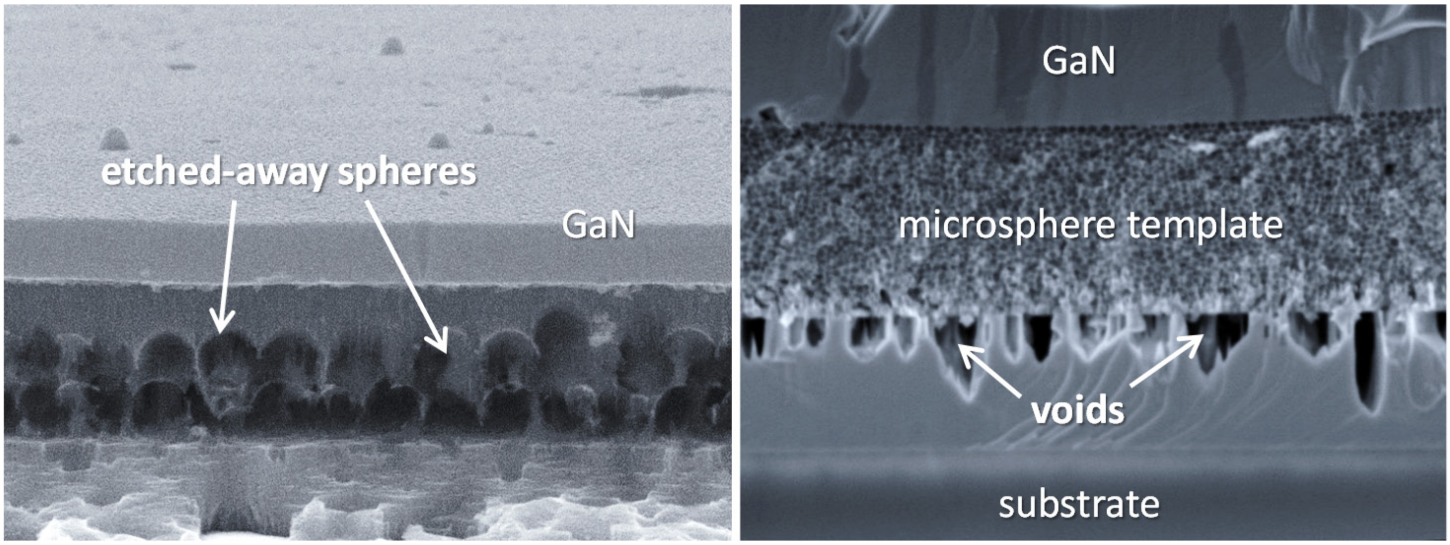


Figure 5. Left: Microsphere-templated GaN layer following removal of the silica microspheres by wet etching. Right: Void-filled layer for crack reduction and void-assisted mechanical separation of thick GaN layer/substrate.

GaN, Si, or SiC substrates. For thick GaN layers grown for subsequent use as native freestanding substrates, a strain-induced fracture of the brittle microsphere template can be used to separate the GaN from the growth substrate. This process is assisted by the formation of voids below the silica microsphere template during growth, allowing for mechanical self-separation due to the structurally-weak, void-filled underlayer. This reduces stress-induced cracking when the GaN cools down to room temperature, which is caused by the lattice and thermal mismatch of the GaN layer and foreign substrate, greatly improving the yield of native GaN substrates.

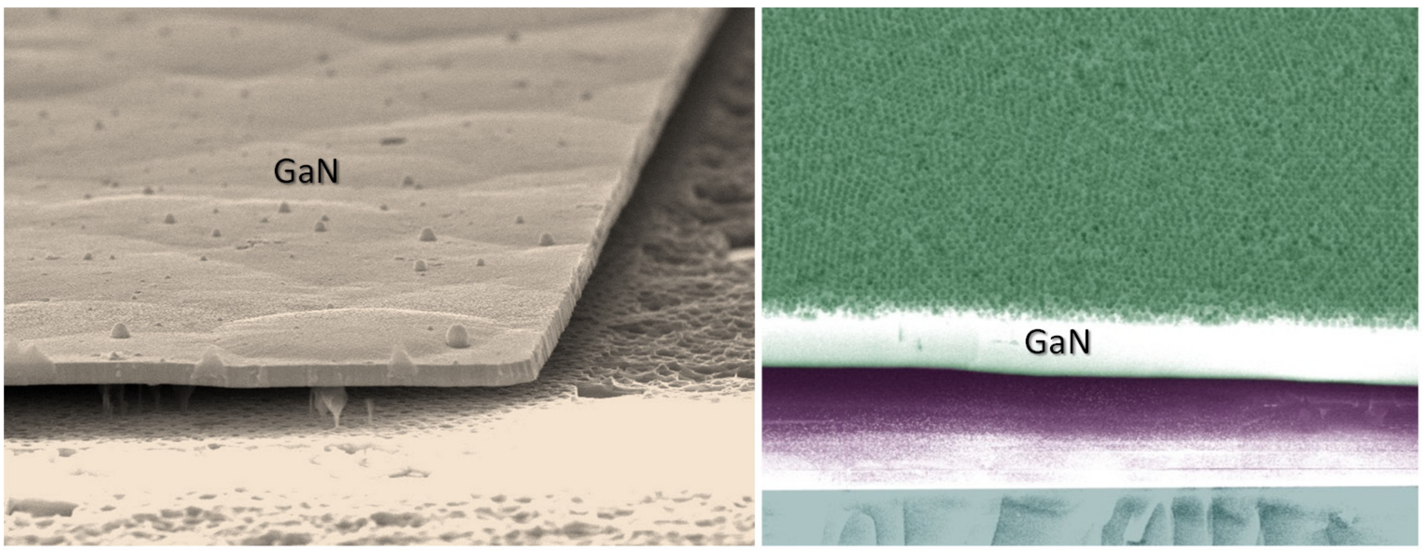


Figure 6. Left: Free-standing GaN mesa approximately 1.5 microns thick following wet etching of microsphere template. Right: Flipped-over, free-standing GaN film, approximately 10 microns thick, showing the inverted microsphere surface texturing for enhanced LED light extraction.

An additional benefit to Sandia's microsphere-templated GaN lift-off technique is the inherent surface texturing of the GaN LED. As seen in Figure 6, etching away the microsphere template leaves behind an inverted sphere surface morphology that prevents light trapping in the device caused by total internal reflection. This unique surface morphology inherently enhances light extraction, and hence LED performance, without the need for further chemical or chemical-mechanical roughening of the surface typically used in commercial LEDs.

10. Product Comparison

Currently, there are no commercially available equivalents to Sandia's microsphere-templated GaN technique. This versatile method provides low-cost solutions to three critical limitations inherent in the current LED manufacturing

Table 1. Comparison matrix of microsphere-templated GaN to other growth and removal methods by application.

Application: Low-Defect Density GaN			
Method	**Defect Density**	**Estimated Cost (2-inch wafer)**	
GaN Epilayer on Sapphire	Medium–High	$40	
Microsphere-Templated GaN	Low	$75	
Epitaxial Lateral Overgrowth (ELO)	Low	>$1,000	
Bulk GaN Substrate Growth	Low–Very Low	>$1,600	
Application: Lift-Off			
Method	**Processing Speed**	**Compatible Substrates**	**Equipment and Maintenance Costs**
Microsphere-Templated GaN	Fast (parallel)	Any	Very low $
Laser Lift-Off	Slow (serial)	Sapphire	Very high $$$$
Application: Native (Bulk) GaN Substrates			
Method	**Yield**	**Estimated Cost (2-inch GaN wafer)**	
Microsphere-Templated GaN	70%	<$400	
Self-Separation from Substrate	10–20%	>$1,600	
Laser Lift-Off or Other Separation Methods	10–20%	>$1,600	

process: low-defect density GaN epitaxial layer (epilayer) growth on foreign substrates, laser lift-off method, and native GaN substrate production. Table 1 compares the microsphere-templated GaN process to the current methods for each area.

Microsphere-Templated GaN versus Other GaN Growth Methods

The ultimate performance of LEDs is directly related to the GaN dislocation density on which the LEDs are grown. Compared to the standard GaN epitaxial layer (epilayer) growth on sapphire, the microsphere-templated GaN process produces material with approximately 10 times lower dislocation density (mid-10^7 per cm^2 versus mid-10^8 per cm^2). The improvement is even more drastic when compared with GaN epilayer growth on Si substrates, which produces material in the 10^9 per cm^2 range. As a result, the microsphere-templated GaN process enables the production of higher power LEDs that yield higher average selling prices.

Epitaxial lateral overgrowth (ELO) methods are currently employed to produce GaN epilayers on sapphire with similar dislocation densities to microsphere-templated GaN (mid-10^7 per cm^2 range). However, due to the processing complexity of ELO methods, the cost of a 2-inch ELO-grown GaN epilayer on a sapphire wafer is greater than $1,000. Moreover, ELO methods produce only thin strips (tens of microns) of high-quality GaN material, which limits the usable device area. The thin strips of useable area are also too narrow for the larger die sizes of high-power LED chips (greater than or equal to 1 millimeter), which is why ELO templates are limited to edge-emitting laser diodes. With microsphere-templated GaN, the entire wafer consists of low-dislocation density GaN, meaning that there are no unusable areas. Thus, microsphere-templated GaN provides a superior product compared to ELO at less than a tenth of the cost.

Microsphere-Templated GaN versus Laser Lift-Off for Device Removal

Currently, the laser lift-off method is the industry standard for removing GaN LEDs from a growth substrate so that the LEDs can be bonded to more thermally and electrically conductive substrates for packaging. However, this method is both slow and costly, since it is a serial process in which a laser rasters over the wafer using expensive (multi-million dollar) capital equipment that comes with high maintenance costs. In comparison, the microspheres in the microsphere-templated GaN method act as a separation layer that can simply be selectively wet etched away, resulting in the removal of grown LEDs. This is an inexpensive batch process where multiple wafers can be simultaneously processed, with minimal capital equipment costs (e.g., an acid bath).

Microsphere-Templated GaN versus Current Bulk GaN Substrate Production Methods

Bulk GaN substrates represent the ultimate solution for the growth of high-power LEDs and power devices. This process involves GaN substrates being grown as thick GaN layers on seed substrates, such as sapphire, and then subsequently separated as a freestanding GaN substrate. Cracking of the GaN layer occurs during the cool-down stage following growth, resulting in less than 20 percent yields. Current methods to reduce cracking, such as laser lift-off before the cool-down stage, have not been able to increase yields significantly as evidenced by the continued high price and limited availability of GaN substrates. With the microsphere-templated GaN process, void-assisted separation enabled by the high void-fraction of the structurally weak microsphere template greatly reduces cracking and dramatically improves yields.

Kyma Technologies, the sole U.S. provider of bulk GaN substrates, expects to be able to increase manufacturing capacity by a staggering 1,750 percent by licensing and adopting the microsphere-templated GaN process, which will decrease growth cycle times from 15 hours to 3 hours and increase yields from below 20 percent to 70 percent (see Appendix C). This will yield more than four times a reduction in GaN substrate manufacturing costs in the near term and decrease GaN selling prices to below $400 (from more than $1,600 currently). With further scale-up and development, Kyma expects the microsphere-templated GaN process to enable production of bulk GaN substrates with a target cost of only $10. This would help usher in a new age of ultra-high performance, low-cost LEDs grown on native GaN substrates and create a viable U.S.-based industry for GaN substrate manufacturing.

Limitations of Microsphere-Templated GaN

Microsphere-templated GaN is a versatile technique with many potential applications. As such, the exact process needs to be customized and optimized depending on the application. For example, the ideal parameters of the microsphere template, such as the sphere size and number of sphere layers, may differ significantly depending on whether defect reduction is the end goal or if lift-off is the priority application. Therefore, some development work is needed to maximize the benefits of microsphere-templated GaN to the end-user's requirements.

11. Summary

Despite its unconventional nature, Sandia's microsphere-templated GaN is not a case of innovation for innovation's sake. Microsphere-templated GaN provides real solutions to difficult challenges in the LED lighting industry and makes possible what was previously impossible or too expensive using other techniques. With the microsphere-templated GaN process, current LED manufacturing methods requiring the use of expensive and complex processes and equipment can now be replaced by simple, inexpensive wet-bench processes and equipment. This allows for high-quality GaN material to be produced at previously unachievable costs, thereby enabling higher performance and lower cost LEDs and bulk GaN substrates.

The versatility of the microsphere-templated GaN technique is its greatest strength. One LED manufacturer may prefer to employ it to reduce defect densities and grow higher performance LED chips that command higher market prices. Another manufacturer may be more interested in using microsphere-templated GaN as a cheaper alternative to the laser lift-off method to transfer the LED chips to a metal substrate for device packaging. A provider of bulk GaN substrates may use the technique to increase manufacturing yields to greatly reduce GaN substrate production costs. Thus, microsphere-templated GaN can provide multiple low-cost solutions to different end users and applications.

The potential commercial impact of microsphere-templated GaN is also considerable. In 2012, the packaged market for LEDs totaled $13.7 billion, which is projected to increase significantly in the years to come. Furthermore, GaN-based power electronics may represent an even larger future market than LEDs, which would benefit from the low-cost native GaN substrates made possible by microsphere-templated GaN. In fact, microsphere-templated GaN is such a technological game-changer for bulk GaN substrate production that it may enable the growth of a viable U.S.-based GaN substrate manufacturing industry. Additionally, microsphere-templated GaN can have a substantial beneficial environmental impact. Microsphere-templated GaN can accelerate the use of solid-state lighting by reducing the cost of high-performance LED lighting, which is the primary barrier for adoption. Upon widespread adoption by individual consumers and businesses, energy-efficient, solid-state lighting will save billions of dollars in electricity usage, while significantly reducing natural resource consumption and greenhouse gas emissions.

12. Affirmation

By submitting this entry to *R&D Magazine* I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. I affirm that I have read the instructions and entry notes and agree to the rules specified in those sections.

George T. Wang

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APPENDICES

Appendix A: Development Team Information

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Appendix C: Letter of Support

kyma
the new wave in nitrides
www.kymatech.com • www.galliumnitride.com

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March 12, 2013

R&D 100 Award Judging Committee
R&D Magazine

Subject: Letter of Support for Sandia's Microsphere-Templated Gallium Nitride

Dear Madam/Sir,

I am pleased to present this letter of support for the "Microsphere-Templated Gallium Nitride" 2013 R&D 100 award application. This novel technique, developed by George Wang and Qiming Li at Sandia National Laboratories, holds terrific promise for advancement of the state of the art of several products in the Gallium Nitride (GaN) industry that are critical for next generation power efficiency applications.

Kyma is currently the only company in the US that manufactures and sells GaN substrates. As Kyma's longest running employee (10 years), I have participated in countless development meetings, attended dozens of conferences, and visited hundreds of customers that were all focused on the singular task of bringing GaN to market in higher volumes and at lower costs. While some aspects of GaN technology have had tremendous advances in the past decade, the availability of inexpensive high quality GaN has not improved by the same leaps and bounds. The core roadblock to advancing the state of the art is the lack of availability of inexpensive, high quality GaN seed crystals that can be used to make inexpensive GaN wafers. The root cause of the availability issue is that current seed production processes have poor yields (<20%) and long process cycle times (1 day). A typical crystal growth system can therefore produce a seed crystal only once every 1-2 weeks, which causes dreadfully slow innovation cycles.

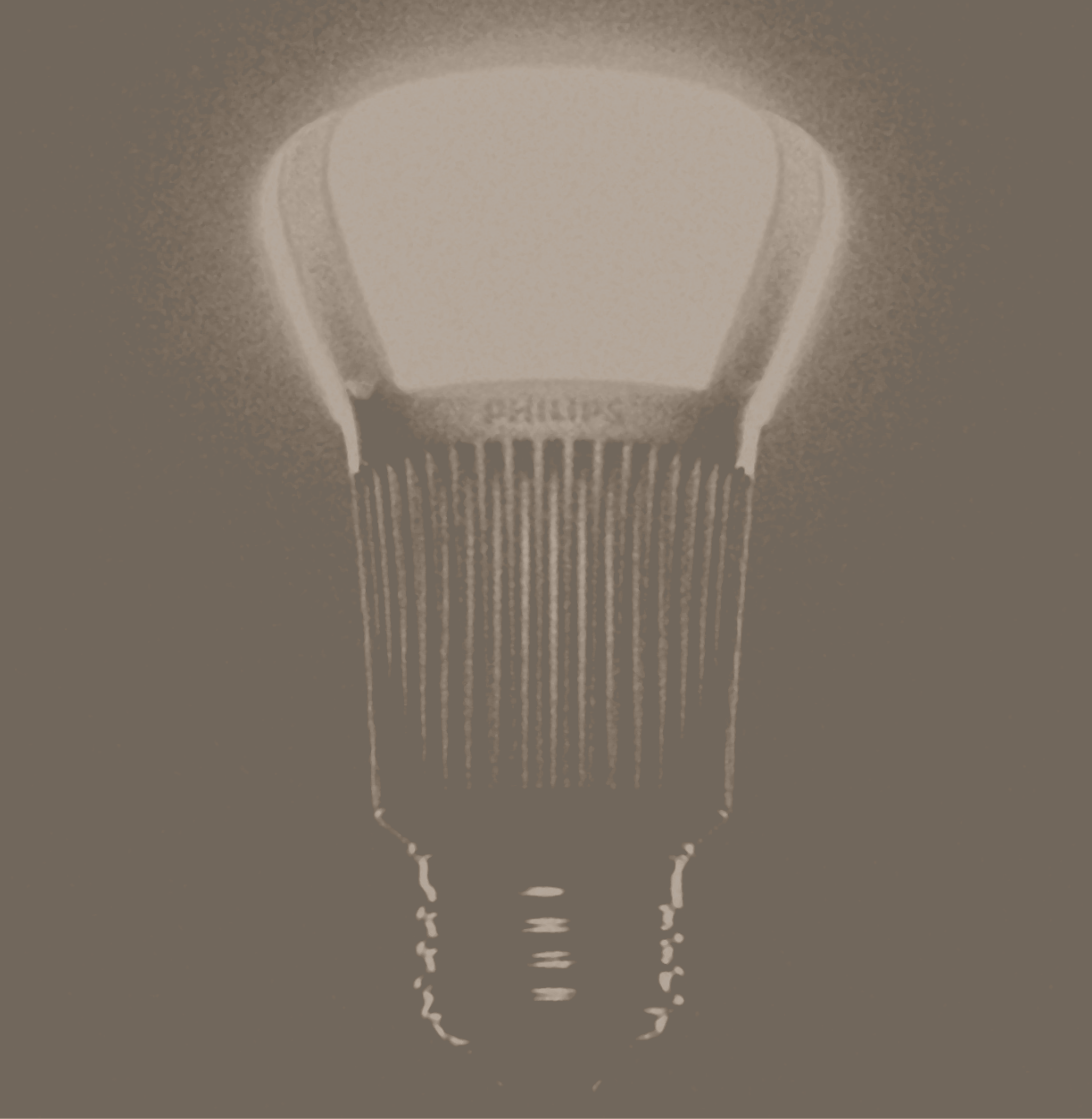
The technology that George and Qiming have developed cuts directly to the root of the yield and cycle time problem. The microsphere layer enhances the yield of seed crystal production and does so in a crystal growth run that is 3 hours long, instead of 15 hours long. Even if the yield does not increase, a single crystal growth tool's capacity is increased by 500%. Including modest yield assumptions (70%), this increases the capacity by 1750%. The huge increase in seed crystals will enable GaN wafers to be sold at substantially lower cost (<$500) and substantially higher volumes; several per day instead of 1 per week or two. Further evolution of these crystal growth processes will enable Kyma to target $10 per wafer, which is only possible with the Microsphere enabled seed wafer production process.

Our interest in this technology is so keen that Kyma has already proposed to, and obtained funding from the Department of Energy SBIR program to focus substantial effort on moving our experimentation plans forward. We are negotiating a license with Sandia and are also putting a funding vehicle in place for George and Qiming to continue with the advances they have already achieved to date. It is truly exciting to see such a technology become available for use in the US during a time of such need for our industry!

Sincerely,

Edward Preble

Edward Preble
Chief Marketing Officer, Kyma Technologies, Inc.



Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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