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State of substrates
Experts provide opinion

An Angel Business Communications publication
March 2010 Volume 16 Number 2

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Editor-in-Chief
David Ridsdale dr@angelbcl.co.uk
+44 (0)1923 690210

Consultant Editor
Richard Stevenson PhD richardstevenson@angelbc.co.uk
+44 (0)1291 629640

Director of SOLAR & IC Publishing
Jackie Cannon jc@angelbcl.co.uk
+44 (0)1923 690205

Account Handlers
Shehzad Munshi sm@angelbcl.co.uk
+44 (0)1923 690215
Tommy Beazley tb@angelbcl.co.uk
+44 (0)1923 690222

USA Representatives
Brun Media
Tom Brun
Tel: 724 539-2404
E: tbrun@brunmedia.com

Janice Jenkins
Tel: 724-929-3550
E: jjenkins@brunmedia.com

Design & Production Manager
Mitchell Gaynor mg@angelbcl.co.uk
+44 (0)1923 690214

Circulation Director
Jan Smoothy js@angelbcl.co.uk
+44 (0)1923 690200

Subscriptions Manager
Debbie Higham dh@angelbcl.co.uk
+44 (0)1923 690220

Chief Operating Officer
Stephen Whitehurst stephen@angelbc.co.uk
+44 (0)2476 718970

Directors
Stephen Whitehurst, Jan Smoothy
Bill Dunlop Uprichard

Published by
Angel Business Communications Ltd,
Hannay House, 39 Clarendon Road,
Watford, Herts WD17 1JA, UK
T: +44 (0)1923 690200
F: +44 (0)1923 690201

Angel Business Communications Ltd
Unit 6, Bow Court, Fletchworth Gate,
Burnsall Road, Coventry CV5 6SP
T: +44 (0)2476 718 970
F: +44 (0)2476 718 971

Compound Semiconductor is published eight times a year on a controlled circulation basis. Non-qualifying individuals can subscribe at: £105.00/€158 pa (UK & Europe), £138.00 pa (air mail), $198 pa (USA). Cover price £4.50.

US mailing information: Compound Semiconductor (ISSN 1096-598X) is published 8 times a year Jan/Feb, March, April/May, June, July, August/September, October, November/December for a subscription of $198 by Angel Business Communications Ltd, Hannay House, 39 Clarendon Road, Watford, Herts WD17 1JA, UK. Periodicals postage paid at Rahway, NJ. POSTMASTER: send address changes to: Compound Semiconductor, c/o Mercury International Ltd, 365 Blair Road, Avenel, NJ 07001

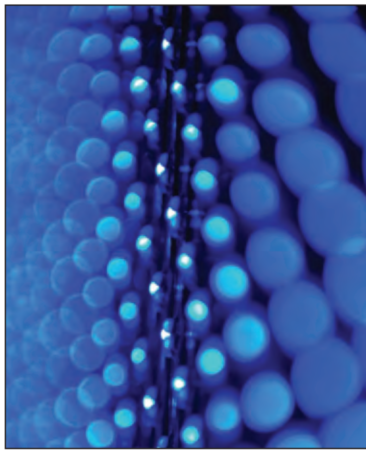
Printed by: Pensord Press.
ISSN 1096-598X

LEDs: the times, they are a changing

The LED industry is booming. Revenue started taking off at the back end of 2009, and it will rocket over the next few years.

Chipmakers are already reporting the effects of this uptake in demand. Cree recently posted record quarterly sales of almost $200 million, and it expects to follow this up with $215-225 million next time around. Meanwhile, Philips revealed that its LED sales have grown to 10 percent of its total revenue, and they are set to surpass its conventional lighting sales in five years.

MOCVD manufacturers are already getting in on the party, thanks to chipmakers expanding capacity to fulfill greater demand. Aixtron had the joy of informing the markets that it would exceed its own guidance, with record revenue and profits. And its rival, Veeco, announced that it was increasing its capacity for tool manufacturing to 45 reactors in the current quarter and 70 in the following one.



Sapphire substrate makers are also enjoying the spoils of the LED boom. Sales at Rubicon increased by almost 50 percent between the third and fourth quarters of 2009, and they are expected to grow by nearly another 25 percent in the first three months of this year.

In fact, the growth rates forecast within the industry are so rapid that they have even led to talk of material and tool shortages. In Yole Developpément's recent sapphire report, analyst Philippe Roussel warned of turbulent times in the second half of this year, before increases in sapphire production come on-line in early 2011. And analyst Munisamy Anandan from the Gerson Lehrman Group has claimed that there will be a shortage of MOCVD tools.

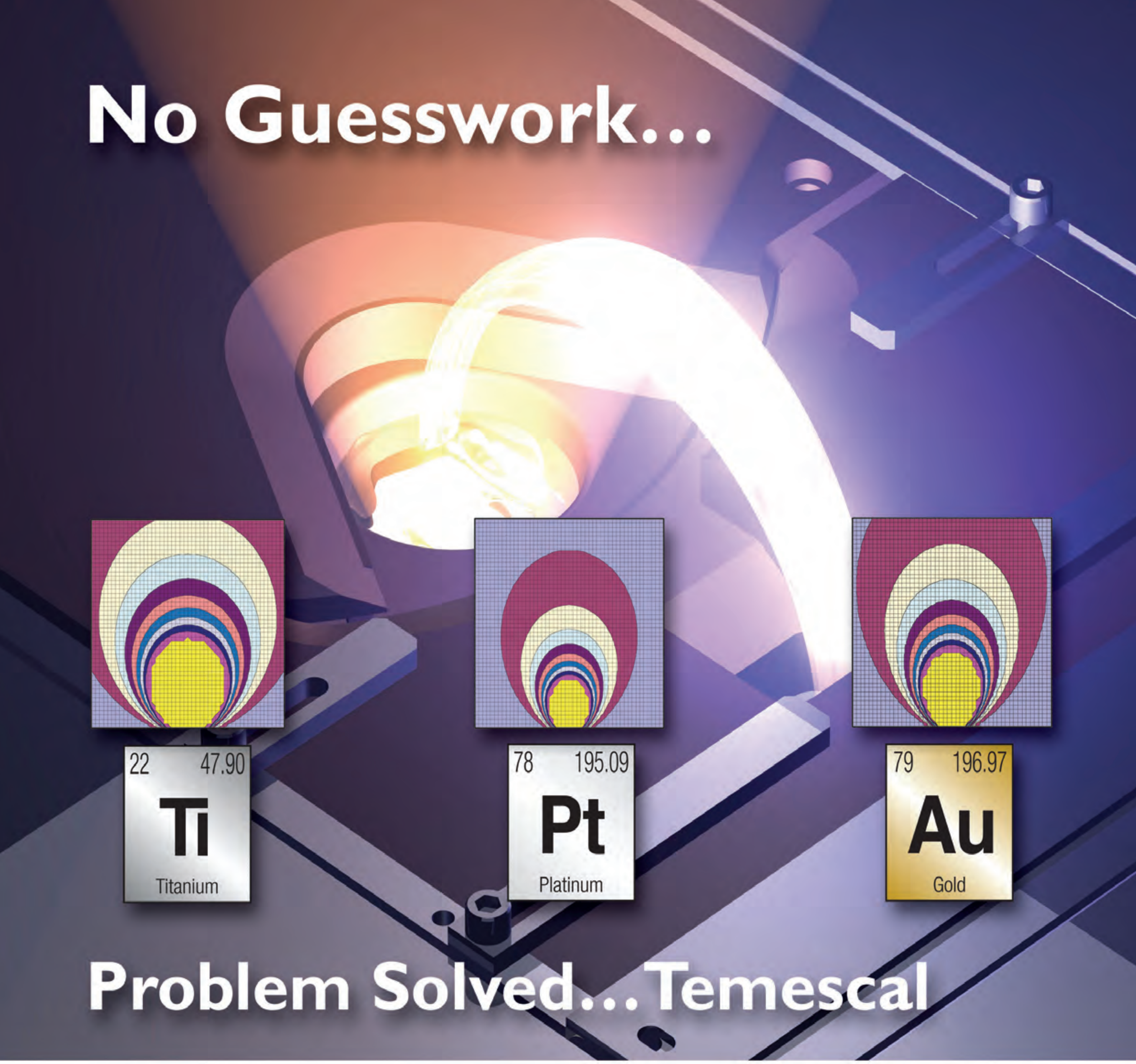
It will be interesting to see whether Anandan's prediction turns out to be right or wrong. But regardless of the outcome, if any company wants to have a crack at making some money as an MOCVD equipment supplier, then now must be the time to try.

One company that's already giving it a go is the heavyweight silicon equipment supplier Applied Materials. It has grabbed some government funding to develop a tool for LED growth, and industry sources tell me that it's already got two reactors out on test.

Success will be hard won, because III-V growth is far more complex than silicon deposition. But it is unlikely that Applied Materials will be daunted by the incredibly steep learning curve that it faces, because it can choose to devote a tremendous amount of resource to overcoming the problems that it comes across along the way.

Whether it succeeds of fails, we will be in for some exciting years ahead. And you can bet that this will not be the only large company from outside our industry that fancies a foray into the rapidly growing LED business. But we can be sure of one thing – the times, they are a changing.

Richard Stevenson PhD
Consultant Editor



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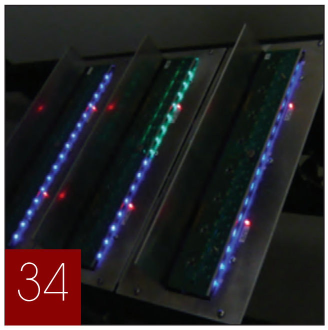

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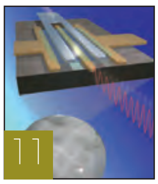


Front Cover designed by Mitchell Gaynor

TriQuint Semiconductor's GaAs technology

The GaAs technology used by TriQuint Semiconductor means it can meet the demands placed upon network operators of faster and more efficient broadband internet access via smartphones.

TriQuint Semiconductor has released the first products from its new, green and high efficiency TriPower portfolio of 3G/4G wireless base station radio frequency identification chips (RFICs), which will allow network operators to meet the demand of smartphones which enable broadband internet access.

Networks which are 3G and 4G have complex modulation requirements and cannot be delivered efficiently by legacy semiconductor technologies.

As such, TriQuint drew on its expertise of gallium arsenide (GaAs) and gallium nitride to name its GaAs heterojunction bipolar transistor (HV-HBT) technology as the best choice for high-power base station applications because of its reliability and efficiency.

Efficiency gains include reducing the electricity required to power network base station amplifiers, allowing operators to increase network speed and capacity.

Since the TriPower RFICs are designed using a high-voltage heterojunction bipolar transistor GaAs process, network operators and wireless base station manufacturers can make efficiency improvements while meeting the linearity requirements which 3G/4G cellular systems impose.

Larger amplifiers can be placed on to existing cell site towers with size and weight needing to be increase, while the higher-power amplifiers deliver quicker data rates to handset users.

This appears to be reflective of Moore's Law, which states that the number of transistors which can be placed on an integrated circuit without it needing to be increased in size approximately doubles every two years.

In order to show the telecommunications market of the advantages the TriQuint TG2H214120 120-watt devices, the organisation is showcasing the device family at the GSMA Mobile World Congress in Barcelona, Spain between February 15th and 18th.

Commenting on the importance of the event, Shane Smith, senior director of marketing for mobile devices at TriQuint Semiconductor, said: "As one of the telecommunications industry's largest tradeshows, GSMA Mobile World Congress is a great place to meet with customers and partners and other industry experts to hear about the latest trends, better understand the issues driving the mobile ecosystem and of course meet with customers to share technology roadmaps and understand their needs."

Mr Smith stated that he was confident that TriQuint would prove itself to be the "leading innovator in GaAs technologies" as the compound semiconductor operates more efficiently at higher breakdown voltages, while also being capable of exceeding 250 gigahertz.

TriQuint can therefore meet the high-frequency performance requirements of modern wireless solutions because of the breakdown voltages and high electron mobility of GaAs.

"Our products provide the RF solutions in today's mobile devices and the networks that deliver the voice, data and video to those devices. Our power amplifiers amplify intended signals while our filters eliminate unwanted signals," Mr Smith added.

The confidence of TriQuint in establishing itself as a compound semiconductor market leader could be reflected from a previous report by University of California at San Diego, which noted that TriPower devices deliver the best efficiency advantage.

Its GaAs HV-HBT technology was compared against other base station amplifier semiconductor technologies including silicon laterally diffused metal oxide semiconductor and found to be the leader - something Mr Smith understands sets TriQuint apart from its competitors

Valdez, Alaska, Joins Cree LED City Program

Cree has announced that the city of Valdez has joined the Cree LED City initiative, an international program that promotes the deployment of energy-efficient LED lighting. Valdez is in the process of converting all 343 street lights to LED technology.

As part of this project, city officials have negotiated a new, reduced billing rate with Copper Valley Electric Association for the LED street lights and will renegotiate its maintenance contract when it expires in 2011.

"We project we can achieve 45-percent or higher energy savings with the new BetaLED fixtures we are installing, compared with the high-pressure sodium lights we are replacing," said Mayor Bert Cottle. "As we look ahead and anticipate rising energy costs, investing in LED technology becomes even more attractive. Community feedback on the initial lights has been overwhelmingly positive. Valdez citizens like the quality and color of the new LED lights and they are happy about the projected energy and maintenance cost savings."

The BetaLED fixtures can be operated at three light levels. Initially, the fixtures will be operated at a higher setting for maximum light output during the winter months, when snow removal activities require high light levels. Going forward, city officials can choose to switch the lights to a lower operating level, depending on actual light-level requirements, which can potentially increase energy savings to 60 percent. The city replacied the first one-third of its streetlights in 2009 and expects to complete the conversion by 2011.

Cree Breaks 200 Lumen Per Watt Efficacy Barrier

Cree has announced another industry best reported efficacy record of 208 lumens per watt for a white power LED. This R&D result passes a significant milestone within the solid-state lighting industry as well as demonstrates Cree's relentless drive to increase the performance of its LEDs.

Cree's tests confirmed that the LED produced 208 lumens of light output and achieved 208 lumens per watt efficacy at a correlated colour temperature of 4579 K. The tests were conducted under standard LED test conditions at a drive current of 350 mA at room temperature.

"We have now broken the elusive 200-lumen-per-watt efficacy barrier for a single white power LED," said John Edmond, Cree co-founder and director of advanced optoelectronics. "This is a result of improvements in blue optical output power, lower operating voltage and higher conversion efficiency. We continue to push the envelope for the highest efficiency white lighting products in the marketplace."

While this level of performance is not yet available in Cree's production LEDs, Cree continues to lead the industry with the broadest family of high-performance LEDs.

Veeco states MOCVD will not be a bottleneck for HB LEDs

Veeco has spoken out about claims that a bottleneck of MOCVD tools will impact upon market demand for HB LEDs. It stated that not just any company can take away market share from Veeco should they be unable to meet demand.

Veeco Instruments recently announced its TurboDisc K465i gallium nitride (GaN) metal organic chemical vapour deposition system (MOCVD) to enable the production of high-brightness light-emitting diodes (HB LEDs).

The TurboDisc K465i combines the industry's highest productivity with the ability to deliver best-in-class LED yields which approach 90 percent, a development which Veeco believes further extends its lead in capital efficiency.

Jim Jenson, vice-president of the MOCVD/LED business unit at Veeco, explained that high-performance HB LEDs have more than 100 separate layers which need to be at the right thickness, purity, composition and crystalline quality.

The layers are grown in an epitaxial deposition process which uses MOCVD equipment. Gaseous compounds flow over heated substrates where they decompose and the constituent elements recombine to form the thin epitaxial layers. Capital efficiency is defined as the number of good wafers produced by the MOCVD system for each capital dollar invested.

Mr Jenson stated: "Veeco Instruments is systematically developing and introducing new MOCVD technologies with a goal to ultimately quadruple capital efficiency."

As HB LED efficiency increases, the number of the devices required to produce a target total lumens of output decreases. At the centre of the GaN MOCVD system is the Uniform FlowFlange, a patent pending technology which delivers superior alkyl and hydride flow pattern uniformity. Fast process optimisation on wafer sizes of up to eight inches, as well as a fast tool recovery time after maintenance, are two of the features of FlowFlange which allow for the LED industry's highest productivity.

High productivity of HB LEDs is currently at the centre of debate within the industry. Managing director of the Organic LED Association Barry Young stated that demand for HB LEDs will grow by 61 per cent in 2010 and suggested that current supply will not be able to keep up.

Mr Jenson said: "We are ramping capacity of MOCVD tool manufacturing, but also ramping our field service and support. And, we continue to invest in research and development to drive next-generation MOCVD tools."

However, the suggestion has been raised that should current suppliers be unable to keep up with HB LED demand then this could open up doors for other MOCVD tool makers to break the monopoly of Aixtron and Veeco. Indeed, Applied Materials is set to use funding granted by the US Department of Energy (DoE) to advance epi tools for GaN LED devices.

An advanced multichamber hybrid epitaxial growth system will also be used by Applied Materials for MOCVD.

Despite claims of a bottleneck of MOCVD tools, Mr Jenson said Veeco does not believe the availability of MOCVD systems will hold back the development of the LED industry. Veeco has previously reported that it would ramp the manufacture of MOCVD tools to a minimum of 45 in the first quarter of 2010, although should the market demand it this capacity can be increased.

But rather than Veeco increasing manufacture to meet market demand, will other companies simply not take its share of the MOCVD sector?

"While there is certainly the possibility that new entrants will come into the LED equipment space, MOCVD is an extremely complex process and Veeco believes there are significant barriers to entry in a market where technology know-how, customer relationships and proven production success are paramount," Mr Jenson asserted.

With Veeco also recently being awarded money from the DoE to advance its MOCVD technology to deliver a four-time reduction in the cost of epitaxial growth for LED devices, competition could be set to increase in the sector - or Veeco could take the lead.

Applied Materials receives DoE funding for GaN MOCVD system

The DoE has given £2.4 million in funding to Applied Materials so it can advance a GaN MOCVD system to make the manufacture of LEDs cheaper and more efficient.
Applied Materials has been awarded $3.9 million (£2.4 million) by the US Department of Energy (DoE) to develop manufacturing equipment and processes to reduce the costs associated with light emitting diode (LED) manufacturing.

The DoE announced $37.8 million from the American Recovery and Reinvestment Act to fund 17 high-efficiency solid-state lighting projects, which saw beneficiaries including Philips Lumileds, Veeco Instruments and Cree. Applied Materials is set to use the money to advance epi tools for Gallium Nitride (GaN) LED devices. An advanced multichamber hybrid epitaxial growth system for LED manufacturers will be developed, which has the potential to improve binning yield, increase the efficiency of LEDs and decrease operating costs.

The system will also be used for metalorganic chemical vapor deposition (MOCVD) and builds on the Applied Materials Centura platform which is used to grow high-quality, low-cost epitaxial wafers for silicon-based integrated circuits. Applied Materials' Centura MOCVD platform extends the capability of tungsten technology to 45 nanometre logic and 55 nanometre memory applications.

Commenting on the grant, the company said the funding, which is the first US government grant in lighting it has received, shows how the DoE understands that in order to see a broad adoption of LEDs, efficiency has to be improved.

Efficiency is improved, in part, because the platform enables low contact resistance (Rc) and tight Rc distribution. Low Rc makes LEDs efficient as more current can flow through a device during a given period, enabling it to shine brighter. With more energy being utilised for light, less is wasted on heat. A high loss of heat reduces the efficiency of electronic devices, making the expense/performance ratio less favourable.

GaN is commonly used in LEDs and has low sensitivity to ionising radiation, a property it shares with other group III nitrides. Transistors made from GaN can work at higher voltages and temperatures.

A recent IMS Research report stated that there is predicted to be a shortage in 2010 of 12-14 billion in-spec die, with this shortage expected to progress into 2013.

Barry Young, IMS Research senior consultant and MD of the Organic LED Association, explained: "Demand for HB LEDs is forecast to grow by 61 per cent in 2010 and supply is unlikely to keep up, creating an opportunity for new manufacturers and new tool makers."

LED market more valuable than conventional lighting

Philips executive Niels Haverkorn has revealed that for the first time, LED-based products made up more than ten per cent of the company's lighting sales during the fourth quarter of 2009.

Speaking to Reuters, he said that by 2015 LEDs will be more valuable then conventional lighting. Indeed, Philips estimates that the global lighting market will grow to more than €80 billion by 2015, although between six and eight per cent of the €45-50 billion sales seen in 2009 were made up of LEDs. As such, more than €4 billion (£3.5 billion) has been invested by Philips to help it defend its "world-leading position" as the producer of one in four of the world's lights, the news agency reported. In order to maintain this position it has increased its LED output to combat competition from Osram, Sharp, Samsung and Cree. Furthermore, Philips Lumileds has announced that it has implemented complete traceability for LUXEON power LED products and it can now pinpoint to the wafer level exactly how each of the hundreds of millions of LEDs were manufactured.

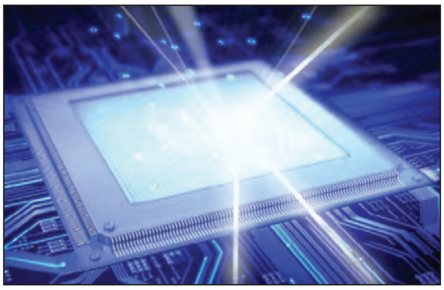
First germanium laser

MIT researchers have demonstrated the first laser built from germanium that can produce wavelengths of light useful for optical communication. It's also the first germanium laser to operate at room temperature. Unlike the materials typically used in lasers, germanium is easy to incorporate into existing processes for manufacturing silicon chips. So the result could prove an important step toward computers that move data – and maybe even perform calculations – using light instead of electricity. But more fundamentally, the researchers have shown that, contrary to prior belief, a class of materials called indirect-band-gap semiconductors can yield practical lasers.

As chips' computational capacity increases, they need higher-bandwidth connections to send data to memory. Conventional electrical connections will soon become impractical, because they'll require too much power to transport data at ever higher rates.

"The materials used in today's lasers, such as gallium arsenide, are "all tough fits," says Tremont Miao, a marketing director at Analog Devices. "They're all challenging integrations." As a consequence, the lasers have to be constructed separately and then grafted onto the chips. Moreover, gallium arsenide is more expensive than silicon.

Integrating germanium into the manufacturing process, however, is something that almost all major chip



manufacturers have already begun to do, since the addition of germanium increases the speed of silicon chips. Gallium arsenide, silicon, and germanium are all examples of semiconductors, the type of material used in virtually all modern electronics. Lasers made from semiconductors convert the energy of electrons – particles of charge – into photons – particles of light.

Semiconductors come in two varieties: those with direct band gaps, like gallium arsenide, and those with indirect band gaps, like germanium and silicon. According to Jurgen Michel, principal research associate in the Electronic Materials Research Group, "There was an opinion in the scientific area that indirect-band-gap semiconductors will never produce laser light.

In a forthcoming paper in the journal Optics Letters, Kimerling, Michel and three other researchers in the group – postdoc Jifeng Liu, the lead author on the paper, and grad students Xiaochen Sun and Rodolfo Camacho-Aguilera – describe how they coaxed excited germanium electrons into the higher-energy, photon-emitting state.

Their first strategy is a technique, common in chip manufacturing, called "doping," in which atoms of some other element are added to a semiconductor crystal. The group doped its germanium with phosphorous, which has five outer electrons. Germanium has only four outer electrons, "so each phosphorous gives us an extra electron," Kimerling says. The extra electron fills up the lower-energy state in the conduction band, causing excited electrons to, effectively, spill over into the higher-energy, photon-emitting state.

The second strategy was to lower the energy difference between the two conduction-band states so that excited electrons would be more likely to spill over into the photon-emitting state. The researchers did that by adapting another technique common in the chip industry: they "strained" the germanium. Both the silicon and the germanium were deposited at high temperatures. But silicon doesn't contract as much as germanium when it cools.

The atoms of the cooling germanium tried to maintain their alignment with the silicon atoms, so they ended up farther apart than they would ordinarily be. Changing the angle and length of the bonds between germanium atoms also changed the energies required to kick their electrons into the conduction band. "The ability to grow germanium on silicon is a discovery of this group," says Kimerling, "and the ability to control the strain of those germanium films on silicon is a discovery of this group."

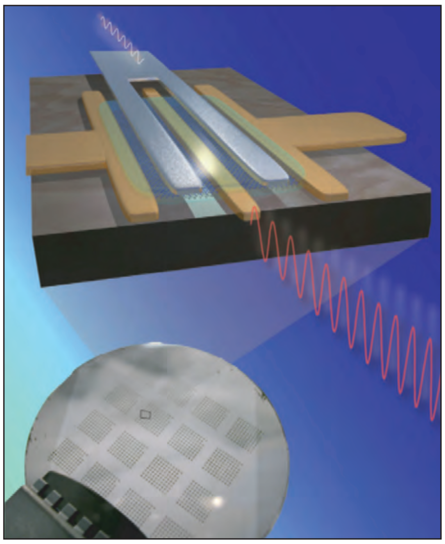
IBM Scientists Demonstrate World's Fastest Graphene Transistor

In a published paper in the magazine Science, IBM researchers demonstrated a radio-frequency graphene transistor with the highest cut-off frequency achieved so far for any graphene device - 100 billion cycles/second (100 GigaHertz).

This accomplishment is a key milestone for the Carbon Electronics for RF Applications (CERA) program funded by DARPA, in an effort to develop next-generation communication devices. The high frequency record was achieved using wafer-scale, epitaxially grown graphene using processing technology compatible to that used in advanced silicon device fabrication.

"A key advantage of graphene lies in the very high speeds in which electrons propagate, which is essential for achieving high-speed, high-performance next generation transistors," said Dr. T.C. Chen, vice president, Science and Technology, IBM Research.

Graphene is a single atom-thick layer of carbon atoms bonded in a hexagonal honeycomb-like arrangement. This two-dimensional form of carbon has unique electrical, optical, mechanical and thermal properties and its technological applications are being explored intensely.



Uniform and high-quality graphene wafers were synthesized by thermal decomposition of a silicon carbide (SiC) substrate. The graphene transistor itself utilized a metal top-gate architecture and a novel gate insulator stack involving a polymer and a high dielectric constant oxide. The gate length was modest, 240 nanometers, leaving plenty of space for further optimization of its performance by scaling down the gate length.

It is noteworthy that the frequency performance of the graphene device already exceeds the cut-off frequency of state-of-the-art silicon transistors of the same gate length (~ 40 GigaHertz). Similar performance was obtained from devices based on graphene obtained from natural graphite. Previously, the team had demonstrated graphene transistors with a cut-off frequency of 26 GigaHertz using flakes extracted from natural graphite.

Bulk GaN: Ammonothermal trumps HVPE

Today's GaN substrates are manufactured by a HVPE process that requires high temperatures and substantial reactor maintenance. Ammonothermal growth can address both these issues, while producing material with far fewer dislocations in a more efficient manner, says **Ammono's Robert Dwilinski, Roman Doradzinski and Marcin Zajac.**

GaN-based devices have an important role to play in the portfolio of energy-saving technologies making an ever-increasing impact on our world. LEDs based on this wide bandgap material can deliver incredibly efficient light emission, and nitride transistors are promising devices for efficient, high-power output at high frequencies.

Although nitride based devices are already capable of delivering an impressive performance, they are held back by the limited availability and high cost of a native substrate. Devices are usually built on sapphire, silicon and SiC, and heteroepitaxial growth of nitrides on these platforms leads to a high density of defects in these films. These result from a difference in lattice parameters and thermal expansion coefficients between the materials. What is needed by the industry is a bulk GaN substrate that can drive improvements in the efficiency of optoelectronic and high-temperature electronic devices, but does not cost the earth.

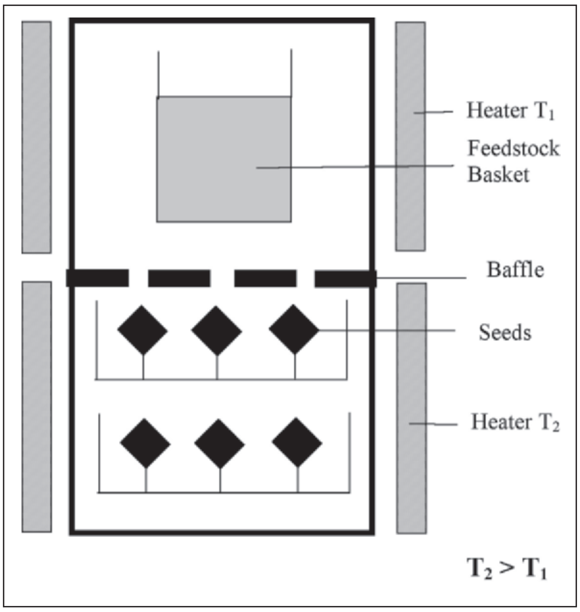


Fig.1. The ammothermal growth method involves temperature-driven transport of material from a GaN-based feedstock to another zone of the autoclave, which is filled with native seeds. The process takes place in a closed system, and nearly all of the feedstock material is converted into product

Developing a GaN substrate is very challenging, because it is impossible to use standard methods to grow a boule. The Czochralski and Bridgman techniques employed for GaAs manufacture are not applicable, because GaN decomposes into gallium and nitrogen gas.

It is possible to grow high-quality GaN crystals by combining high temperatures (of about 1500 °C) with extremely high nitrogen pressures (of the order of 15 kbar). But such high pressures prevent the use of large growth chambers. In addition, crystal seeds cannot be used, which imposes serious limitations on crystal size.

Other techniques have also been developed, including HVPE, a growth technology used for most of today's free-standing GaN substrate production. Although material produced by this technique is undeniably a commercial success - it has provided the bedrock for 405 nm lasers deployed in Blu-ray players - it suffers from a high dislocation density that stems from the use of non-native seeds. Even after the seed has separated, the free-standing HVPE GaN is still highly stressed and bowed.

Better quality material can be produced by a sodium-flux technique, which involves the growth of GaN crystals in a vessel containing a gallium-sodium mixed metal melt and pressurized nitrogen gas. However, there are still many

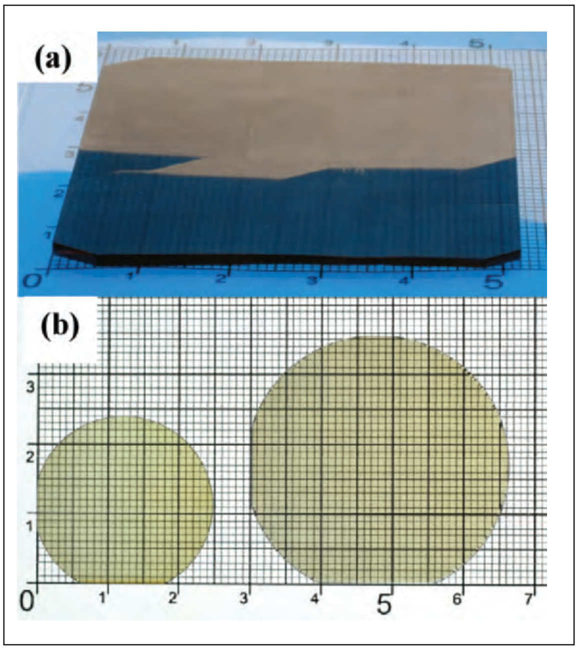


Fig.2. Ammono has produced 2-inch GaN seed crystals (a) and used them as seeds for growing crystals enabling manufacture of 2-inch substrates. The company currently sells 1-inch and 1.5-inch substrates. The electrical properties of the substrates can be carefully controlled, allowing the production of: n-type material with a hole concentration of $2x10^{19}$ cm^{-3} and a resistivity of 10^{-3} - 10^{-2} Ω cm; p-type material with an electron concentration of $2x10^{18}$ cm^{-3} and a resistivity of 10^{1} - 10^{2} Ω cm; and semi-insulating material with a resistivity of 10^{6} Ω cm - 10^{12} Ω cm

problems to solve, such as poor growth of seeds, heterogeneity, mosaicity and poor scalability.

Ammonothermal growth

At Ammono, a company which is based in Warsaw, Poland, we are pursuing a more promising technique involving convection-driven transport of an ammonia solution, followed by crystallization of GaN on native seed crystals. Advantages of our approach include growth in equilibrium conditions, growth in a closed system and scalability.

Our success in manufacturing GaN stems from long-term experience in ammonothermal crystallization of this material. Efforts in this direction can be traced back to the early 1990s, when two of us (Robert Dwilinski and Roman Doradzinski), plus Leszek Sierzputowski and Jerzy Garczynski built the first ammonothermal set-up for GaN synthesis at the Institute of Experimental Physics, at the University of Warsaw. The first breakthrough was the growth of micro-crystalline GaN powder by a chemical reaction between gallium and ammonia. Alkali-metal amides, such as $LiNH_2$ or KNH_2, were added into the reaction zone to play the role of mineralizers, highly increasing the reactivity of the solution.

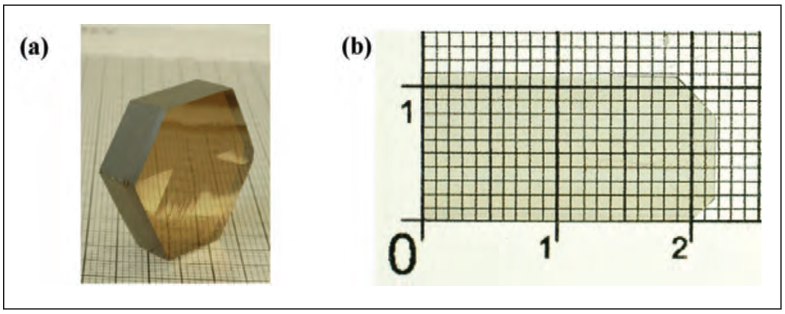
Growth at 550 °C and 5 kbar produced GaN crystals in the form of a wurtzite-type microcrystalline powder with grains up to 5 μm in size. This material revealed highly intensive photoluminescence with very sharp peaks of near band-edge emission accompanied with a weaker parasitic yellow band. These promising results sparked the formation of our company in 1999, renting at the very intial stage several labs owned by Polish government institutes. At this time we also started to collaborate with Nichia Corporation, Japan.

We have learnt how to produce relatively large pieces of GaN by taking advantage of the chemical transport of ammonia solution in a temperature gradient. In 2003 we started selling GaN substrates, although these were not available on the open market at that time. Three years later we transferred to our own facility, an incredibly beneficial move that allowed us to design a laboratory and production and office facilities tailored to our specific needs. Two years ago we made a further investment, installing large-diameter autoclaves capable of simultaneous growth of many GaN crystals. The workforce has also increased, and today we have 50 highly trained staff.

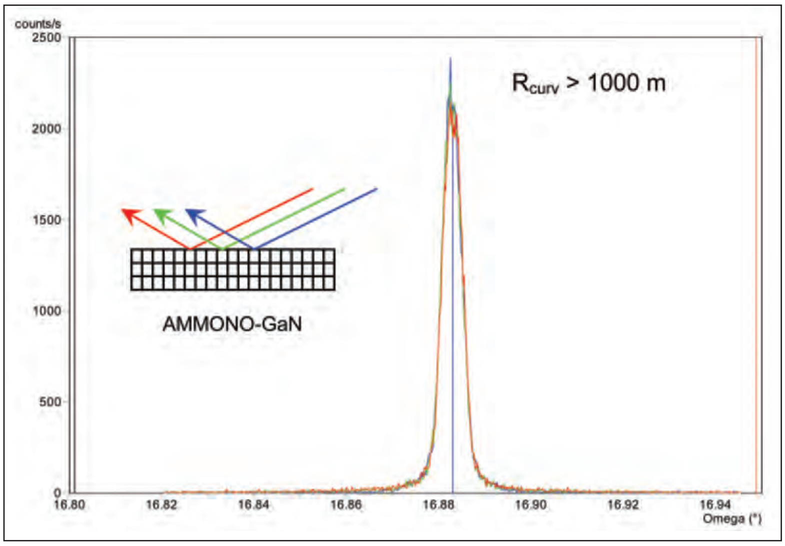
Thanks to refinement in our ammonothermal technology, we can now manufacture high-quality, bulk c-plane GaN seeds up to 2-inches in diameter with perfect crystalline quality. Recent additions to our product portfolio include non-polar m-plane, a-plane and semi-polar GaN substrates. These provide a platform for fabricating blue and green lasers and LEDs that are free from the strong internal electric fields hampering optoelectronic devices grown on conventional, polar surfaces.

The ammonothermal technique that we have adapted is an analogue of the hydrothermal technique used for commercial mass production of α-quartz. GaN-containing

Fig.3. m-plane non-polar GaN can be made by slicing material from a piece of 12 mm-thick, one-inch GaN. The non-polar substrate is 11 mm by 22 mm in size



feedstock is dissolved in one zone of the high-pressure autoclave, before being driven by a temperature gradient to a crystallization zone. Here, GaN crystallizes on native seeds thanks to the supersaturated solution (Fig. 1). Typical temperatures and pressures are 0.2- 0.5 GPa and 500 °C - 600 °C, respectively. Mineralizers are added to enhance the solubility of GaN in ammonia. Our growth technology is actually an ammonobasic version of the ammonothermal technique, with pure alkali metal or alkali metal amides such as $LiNH_2$, $NaNH_2$ or KNH_2 used to introduce NH_2^- ions into the solution. At the start of the previous decade we realized an unusual, but beneficial feature of this particular approach - the solubility of the solution decreases with increasing temperatures. The consequence is that soluble GaN can be transported from a low-temperature dissolution zone offering high solubility to a higher-temperature crystallization zone with lower solubility. To realize an efficient re-crystallization process with this approach, the high-temperature, seed-containing zone has to be placed below the low-temperature zone containing feedstock (see Fig. 1).



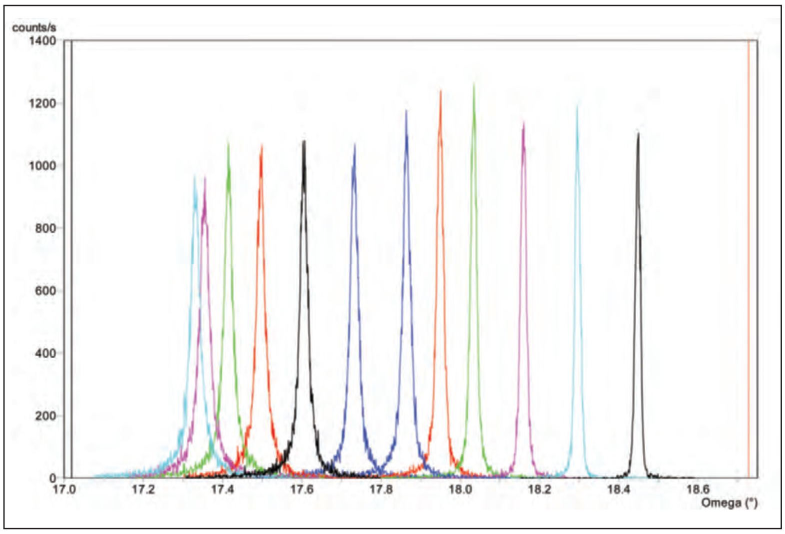


Fig 4a (top) and Fig 4b (above) X-ray diffraction shows that the ammonothermal method outperforms HVPE in terms of crystal quality. The typical radius of curvature is greater than 100 m (a), compared to values of just 2-12 m for HVPE grown crystals (b), as calculated from the angle position of the diffraction peaks measured along the wafer

Ammonothermal growth has several strengths: it enables growth of high-diameter, truly bulk seeds with perfect crystalline quality; it is highly controllable and reproducible at process temperatures of just 500-600°C and pressures of 0.2-0.5 GPa; and it is perfectly scalable with the size of the autoclaves. The dimensions of the autoclave are the only limit to the size of the crystal, and it is possible to grow hundreds of them in one run.

Further advantages are the conversion of almost all the feedstock material into the final product, thanks to the use of a closed system; relatively easy reactor maintenance; and growth that can be continued up to any thickness, because the crystal quality does not deteriorate as the process time is increased. The latter benefit holds the key to the growth of quality, non-polar substrates of any size.

In comparison, growth of GaN by HVPE is hampered by the use of non-native seeds, far higher growth temperatures of 1100°C, and the use of an open reactor rather than a closed system. The later weakness means that only a small fraction of the raw materials are converted into the product.

For example, just 5-15 percent of the flowing $GaCl_3$ incorporates gallium into the GaN crystal, which equates to wasting at least 85 percent of gallium. If HVPE reactors are used to grow GaN, then there is also the need to etch away parasitically nucleated crystals and regularly exchange elements, costly tasks that take time and impair productivity.

Material benefits

We manufacture 1-inch and 1.5-inch diameter, c-plane orientated, polished GaN substrates that have been sliced and round-shaped from a larger crystal. Our ammonothermal method allows scaling of substrate sizes, leading to production of 2-inch seed monocrystals (see Fig.2). We now plan to ramp the production and shipment of 2-inch GaN substrates to a high volume after building up a sufficient stock of seeds.

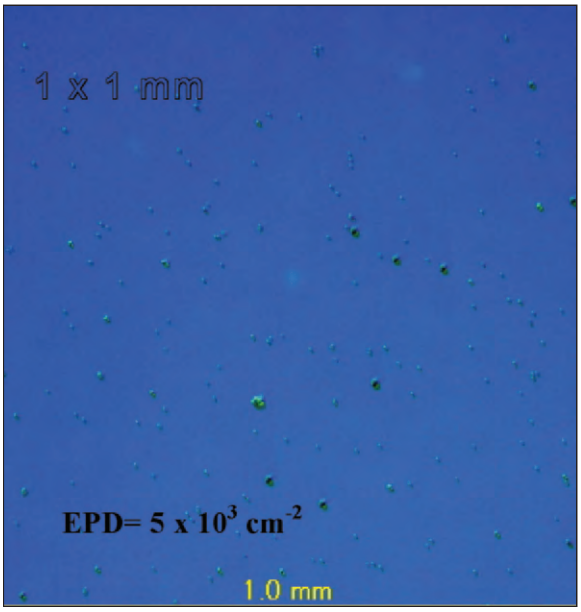


Fig.5. Etching experiments in molten potassium hydroxide (400°C, 5 min) reveal the incredibly low dislocation density in GaN produced by Ammono. Differential interference contrast micrographs show that the density of hexagonal pits, which results from increased etching rate at dislocations, is typically 5 x 10^3 cm^{-2}. It is believed that all defects were revealed at 400°C, because no new defects appeared during etching at a higher temperature of 520°C.

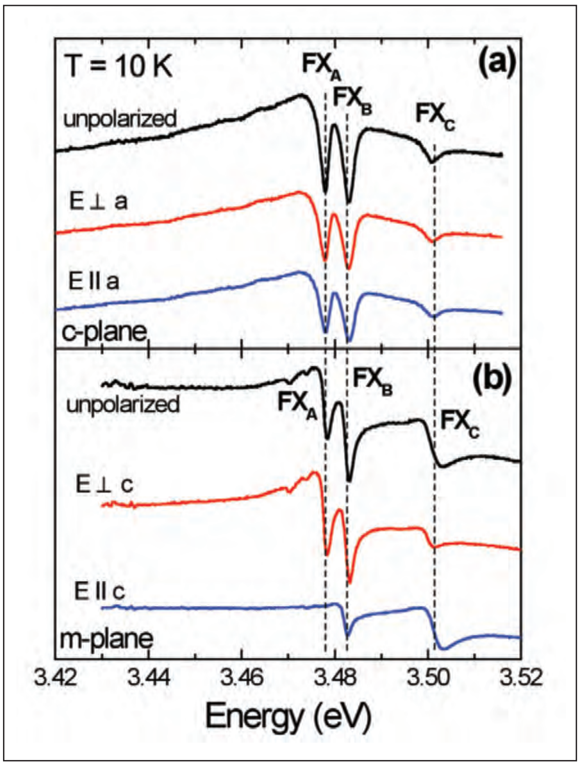


Fig.6. Reflectance spectra of GaN epilayers grown on Ammono's GaN polar substrate (a) and non-polar substrate (b) feature peaks due to free excitons A, B and C. Energy positions are typical for stress-free homoepitaxial layers. In the case of GaN epilayers deposited on non-polar m-plane substrates, the studied films exhibit free exciton lines that are very sensitive to the optical selection rules typical for hexagonal symmetry. A line completely disappears in E || c configuration, proving the truly non-polar character of these m-plane oriented GaN crystals. These crystals have an ideal hexagonal symmetry that is free from any local, structural imperfections that could destroy this symmetry and change the optical selection rules.

By slicing thick, 1-inch diameter GaN crystals, we have created non-polar substrates with a surface area of several square centimeters (see Figure 3). Semi-polar substrates, such as the (20$\bar{2}$1) orientation that has been used to make a green laser, can also be realized by this approach. We have set ourselves the target of producing the first 1-inch non-polar wafer in the near future.

Hall effect experiments and contactless methods have verified that it is possible to control the electrical properties of the substrates with appropriate doping to realize n-type, p-type and semi-insulating material. Tuning the electrical properties of our material will enable it to find application in both optoelectronic devices requiring a highly conductive platform, and HEMTs that must be grown on a semi-insulating substrate.

The exceptional crystallinity of our bulk material is revealed by X-ray rocking curve measurements that show a peak with a full width at half maximum (FWHM) of just 16 arcsec (Fig. 4), measured for the (0002) crystallographic plane (c-plane substrates), (10$\bar{1}$0) plane (non-polar substrates), and (20$\bar{2}$1) plane (semi-polar substrates (Fig. 4). Incredibly low values have also been obtained for appropriate asymmetric planes.

One of the downsides of GaN that has been produced by HVPE is its high internal stress, which leads to an unwanted curvature of the crystal planes. We have measured this bending by studying the systematic shift in the maxima of diffraction peaks on the Ω-axis (see Fig.4). This effect reflects the systematic change of the

Ammono GaN substrates ready to dispatch

inclination of the (0002) plane when moving along the measurement line. The X-ray data has been used to calculate a radius of curvature for HVPE-grown GaN of 2-12 m, which is at least three orders of magnitude smaller than that for ammonothermal GaN (see Fig. 4). In other words, the crystalline quailty of our GaN is extremely flat, indicating that there is very little built-in stress in our material. The high degree of crystallinity of this material allows it to be used as a seed for the growth of additional pieces of bulk GaN without any loss in the crystal quality of the product.

Although the dislocation density in HVPE-grown GaN continues to improve, typical values are still of the order of 10^6 cm^{-2}. This density is far higher than that for ammonothermal GaN - after etching the material in potassium hydroxide, hexagonal pits were observed by microscopy with a density of just 5 x 10^3 cm^{-2} (see Figure 5).

The combination of mechanical and chemical-mechanical polishing has created epi-ready surfaces that have provided a base for homo-epitaxial growth of thin films with excellent properties. Optical and X-ray measurements indicate that it is possible to grow strain-free homoepitaxial layers with excellent quality on our polar and non-polar substrates. Photoluminescence is dominated by an intensive, perfectly resolved excitonic structure that is uniform across the entire sample surface. The width of the bound exciton peak is just 0.3 meV.

Reflectance spectra reveal the truly non-polar character of m-plane oriented GaN (see Figure 6), and X-ray and microscopic measurements show that the resulting epitaxial layer has a high crystal quality with very few dislocations. The FWHM of the X-ray diffraction peak is just 22-25 arcsec, and the threading dislocation density is less than 5 x 10^4 cm^{-2}.

Although the ammonothermal growth rate is much lower than that for HVPE, its perfect scalability makes it by far the most promising method for high-volume manufacture of bulk GaN, partly because it is possible to produce hundreds of crystals in one run. Our next goals are further development and up-scaling of this method, plus the realization of lower operating costs by further automatization of the process.

If we can execute on this front, we will deliver lower-cost, higher-quality substrates than the HVPE-produced material on the market today. And that should ultimately lead to a hike in the performance of commercial, energy-saving, high-power optoelectronic and electronic devices.

GaN substrate manufacturer Ammono is headquartered in Warsaw, Poland, and has a production plant just outside the country's capital

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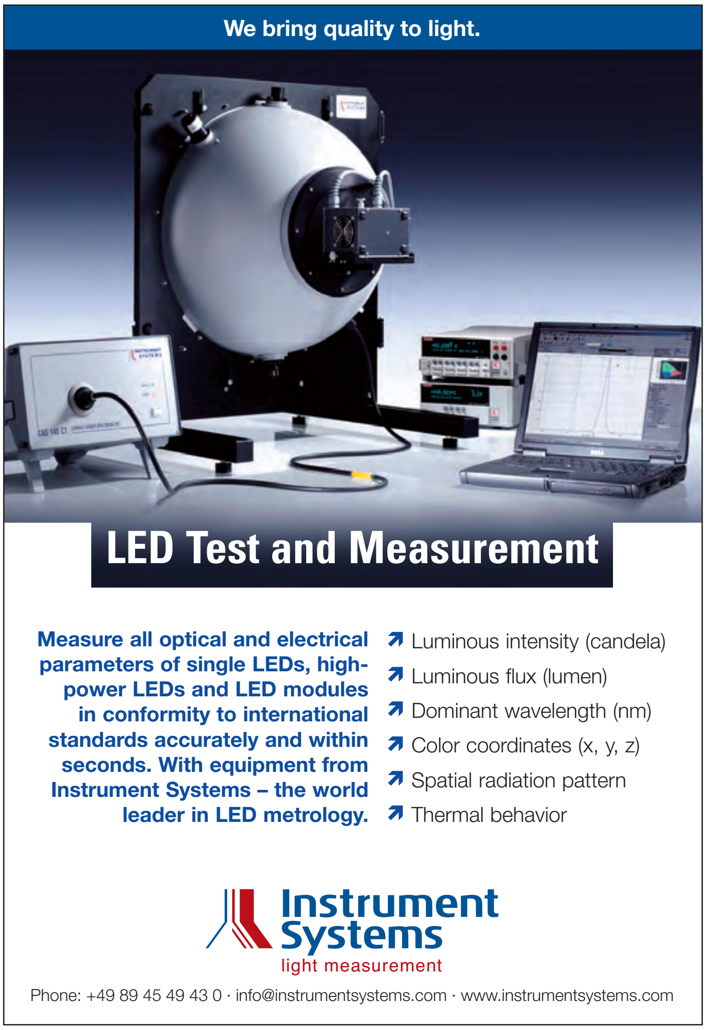
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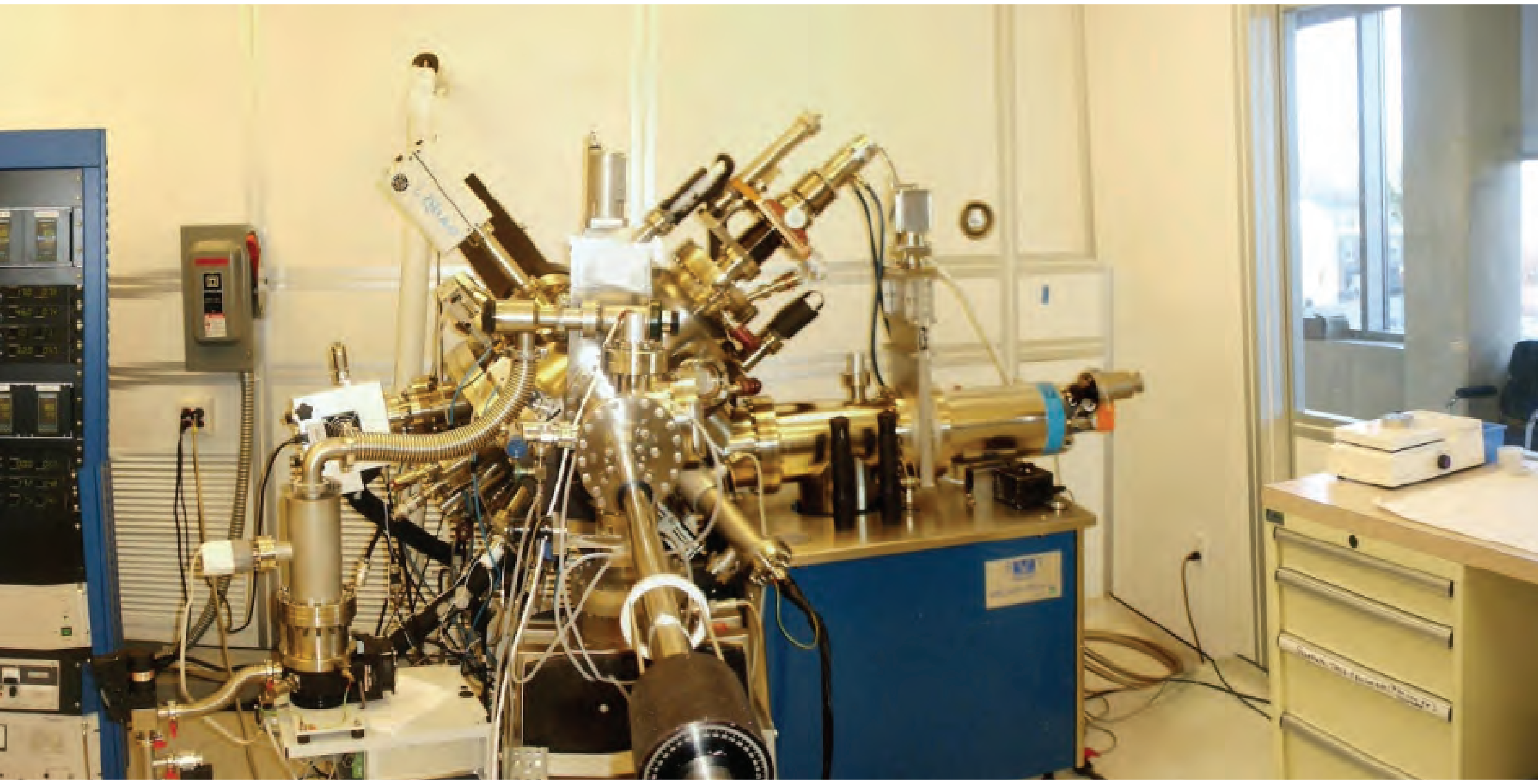
Shedding light on the mystery of LED droop

Comparative studies have unveiled an LED architecture for realizing negligible droop: Employ a non-polar design with an electron blocking layer to abolish carrier spillover and a gallium-doped ZnO p-contact to eliminate current crowding, say a team of researchers from **Virginia Commonwealth University and Kyma Technologies.**

Increasing sales in the LED market have been driven by improvements in chip performance that have enabled these devices to target new applications. These blue, violet and green emitters - which can also emit white light when used in combination with yellow dye - have already generated billions of dollars through lighting the keypads and displays of handsets, and they are now starting to generate additional revenue through deployment in the backlights of TVs, car headlights and general illumination.

Replacing the light bulb with an LED has been identified as a very important, long-term goal within this industry. Tremendous progress has already made, but one of the issues that remains is the realization of very high efficiencies at high current densities. According to early reports, LEDs tend to produce their peak external quantum efficiency (EQE) at current densities below 50 A/cm^2 (a current density that corresponds to a drive current of 500 mA for a 1 mm x 1mm chip), and monotonically decreases thereafter. This decrease in efficiency, which has been given the moniker “droop”, even occurs when the LED is driven with a low duty cycle, pulsed current that prevents device heating.

The origin of droop is attracting tremendous interest from researchers in industry and academia, including our team from Virginia Commonwealth University and Kyma Technologies Inc. Our studies have led us to conclude that one of the strongest candidates for droop is electron overflow - or spillover – that is caused by asymmetric carrier injection that stems from far more electrons being pumped into the device than holes.



Semiconductor growth facilities at Virginia Commonwealth University

Is Auger to blame?

Many ideas have been proposed for the cause of LED droop, and there is currently no consensus behind its origin. One of the first explanations for LED droop was carrier loss due to Auger recombination, a non-radiative process involving the interaction of an electron, a hole and a third carrier. Researchers at Lumileds deduced an Auger coefficient of 1.4-2.0 x 10^{-30}cm^6/s for quasi-bulk InGaN layers by fitting a recombination rate equation to photoluminescence data.

In 2009, computational scientists at the University of California, Santa Barbara, calculated an Auger recombination coefficient of 2x10^{-30}cm^6/s that emanated from the presence of a 2.5 eV upper conduction band. Interestingly, these simulations indicated that Auger recombination would be effective only in a narrow range of wavelengths around 500nm (~2.5 eV).

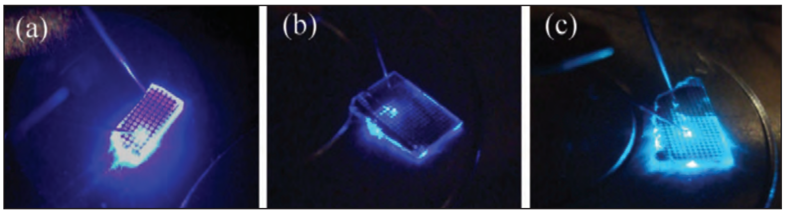
Other theoretical work, however, disagrees with the claim that Auger recombination is the dominant cause of droop. Efforts led by Jörg Hader, a University of Arizona theorist, led to a far smaller Auger coefficient of 3.5x10^{-34}cm^6/s. This calculation employed fully microscopic many-body models, and concluded that intrinsic Auger recombination should not be the major mechanism for the efficiency loss.

More recently, a publication by Han-Youl Ryu and co-workers from Inha University and Hanyang University, Korea, cast further doubt on whether Auger recombination can account for LED droop. These researchers found that in order to account for the large efficiency droop in LEDs, the required Auger coefficient is too large to be reasonable. It would have to be in the range of 10^{-27}-10^{-24} cm^{6}s^{-1}, at least three orders of magnitude higher than the other reported values. The implication of their work is that Auger recombination is insufficient to solely explain the droop in InGaN LEDs.

Resonant photoexcitation has been used by several research groups that are trying to fathom the origin of LED droop. This measurement involves the probing of samples with a laser that is tuned to ensure photon absorption in the quantum wells only. Equal numbers of electrons and holes are formed in the wells, and it is possible to then determine the proportion of carriers recombining radiatively and non-radiatively. The efficiency degradation has not been observed at carrier generation rates comparable to electrical injection levels, indicating that efficiency degradation is most likely to be an electrical problem. It might be related to the carrier injection, transport, or leakage processes.

Our team believes that LED droop stems from electron overflow, which we also refer to as spillover. This is caused by relatively low hole injection, which may combine with the poor transport of this carrier resulting from its large effective mass. The term "spillover electrons" refers to the electrons that escape the active region without any form of recombination, and tend to wind up recombining in the p-GaN region or the p-contact. In this p-doped region carrier lifetime is incredibly short, due to magnesium doping. Our hypothesis is supported by our efforts that show the mitigation of the efficiency degradation in LEDs with thinner barriers.

The vast majority of studies on LED droop have been restricted to investigations of conventional, polar devices. In comparison, we have carried out a wider investigation, and looked at the effect of a p-type electron blocking layer



m-plane non-polar LEDs emitting at (a) 400nm (near ultraviolet), (b) 440nm (blue) and (c) 490nm (blue-green) at a DC current density of about 100 Acm^{-2}. The LEDs were grown on nonpolar m-plane GaN substrates provided by Kyma Tech. Inc.

(EBL) in InGaN LEDs on both c-plane sapphire and non-polar m-plane bulk GaN substrates. Regardless of the polarity of the growth platform, the omission of the EBL leads to a reduction in the electroluminescence intensity by a factor of four to five (see Fig. 1).

We have also performed resonant optical excitation measurements on all of these LEDs using a laser that excites the carriers into the quantum wells only. This series of experiments, which were performed at a range of excitation intensities, show that the EBL has essentially no impact on the internal quantum efficiency of the LED.

This suggests that the lower electroluminescence intensity for the LEDs without an EBL has its genesis in carrier spillover (i.e., electron overflow triggered by poor hole injection, among others, and poor hole transport inside the multi-quantum well region).

It is also worth noting that substantial carrier spillover occurs in both non-polar and polar devices that do not have an EBL. This suggests that the polarization charge is not a major factor responsible for the efficiency degradation observed, particularly at high injection levels.

Current crowding

At the recent MRS Fall meeting that was held in Boston we announced that an additional efficiency droop could result from current crowding. This would mainly affect LEDs with lateral current conduction in the p-contact/epilayer region. We found that the design of the contact architecture is not the only factor affecting droop – the choice of p-contact materials also plays an important role.

We arrived at these conclusions after comparing the performance of LEDs with a gallium-doped ZnO (GZO) contact, and those with a semi-transparent Ni/Au (5nm/5nm) contact. The results revealed two major benefits of the GZO contact compared to the metal one: an increase in light extraction by almost a factor of two,

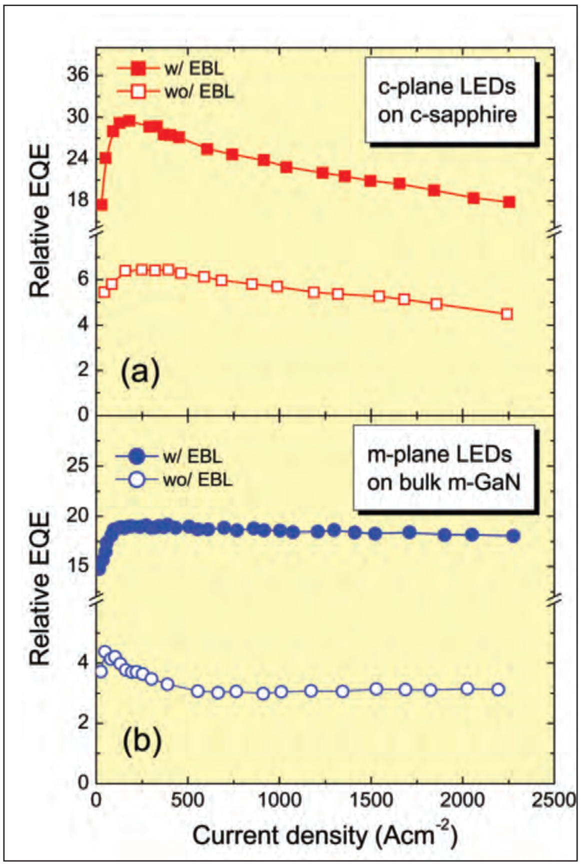


Figure 1. Relative EQE for (a) c-plane LEDs on c-plane sapphire and (b) m-plane LEDs on bulk m-GaN with and without an EBL measured under pulsed current. Except the inclusion of the EBL, all the LEDs have the same structure: MQWs with 6 periods of 2nm $In_{0.14}Ga_{0.86}N$ wells and 12nm $In_{0.01}Ga_{0.99}N$ barriers. All of the LEDs used for this particular study have an emission wavelength of about 400-410 nm. For both c-plane and m-plane varieties the EL intensity from the LEDs with EBLs is higher by 4-5 times than that from respective LEDs without EBLs. The m-plane LED with EBL shows almost negligible efficiency droop (about 5 percent) up to a current density of 2250 Acm^{-2}, compared to about a 40 percent droop for the c-plane LED with EBL

thanks to far greater light transmittance through the contact; and a significant reduction in droop. The device with the GZO contact had a droop of about 27 percent up to 3500 Acm^{-2}, compared to a droop of about 37 percent for the LED with the thin Ni/Au contact.

The reduction in droop is caused by elimination of current crowding. This crowding is responsible for the non-uniform light emission seen in LEDs with a Ni/Au contact driven at high current densities. When devices with a GZO contact are driven equally hard, they produce uniform emission.

Junction heating can also contribute to the efficiency droop at high currents. This can be combated by surrounding the chip with a heat-extracting package, an approach that is already well developed by the leading players in the LED industry. One of the consequences of junction heating is a decline in internal quantum efficiency that results from an enhancement in non-radiative processes, including Shockley-Read-Hall recombination. Heating can also degrade contacts, leading to an increase in series resistance that drives down quantum efficiency and power conversion efficiency.

Our studies also show that m-plane LEDs can outperform their conventional counterparts. They produce higher electroluminescence intensity, and the efficiency droop with increasing current is smaller than it is for c-plane, polar LEDs (see Fig. 2).

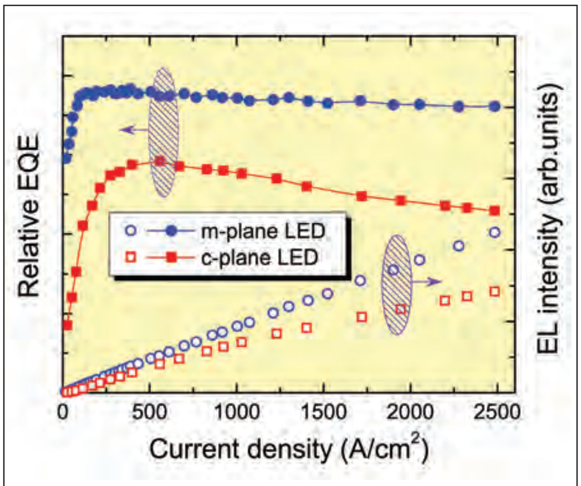


Figure 2. Relative external quantum efficiency and integrated EL intensity of the m-plane LED on m-plane bulk GaN substrate and the reference LED on c-plane bulk GaN as a function of pulsed injection current density. The LEDs used for this study have an emission wavelength of about 400-410 nm. Both samples have the same device structure (MQW active region with 2 nm $In_{0.14}Ga_{0.86}N$ quantum wells, 12 nm $In_{0.01}Ga_{0.99}N$ barriers, and p-$Al_{0.15}Ga_{0.85}N$ electron blocking layers. The 12 nm barriers were chosen to demonstrate efficiency droop on c-plane)

The MOCVD reactor at Virginia Commonwealth University has been used for the InGaN-based LED study. This custom-designed system utilizes a gas delivery system manufactured by Emcore Corporation and a vertical deposition chamber, equipped with an in-situ reflectance monitor that enables the measurement and control of film thickness during epitaxy

Possible explanations to account for the negligible droop in m-plane LEDs are enhanced hole carrier concentration and lighter holes in m-plane orientation, leading to enhanced hole transport throughout the active region, and the lack of a polarization-induced field. But whatever the cause, the combination of a high quantum efficiency and its retention at high current densities makes the m-plane LED a very promising candidate for general lighting.

The work at Virginia Commonwealth University is supported by grants from the Air Force Office (ARO) of Scientific Research and the National Science Foundation. Partial support by ARO under Phase II W911NF-07-C-0099 contract for non-polar bulk development at Kyma Technologies, Inc., is acknowledged. The study of the GZO contact is partially supported by a grant from the Department of Energy, Basic Energy Sciences, through a subcontract from the University of Wisconsin.

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The lowdown on substrates

Leading market analysts offer their take on the health of the GaAs, SiC, GaN and InP substrate markets, and predict how these sectors will evolve over the next few years. **Richard Stevenson reports.**

Asif Anwar, Director of the GaAs and Compound Semiconductors Technologies (GaAs) Program at Strategy Analytics, is the author of several market reports that include: *GaAs Industry Forecast 2008-2013* and *InP Bulk Substrates Market 2007-2012*. Here he provides an insight into the trends in the GaAs and InP substrate markets.

Q How has the market for semi-insulating GaAs substrates, which are the starting point for making power amplifiers for handsets, been affected by the current economic storm?

A In the final quarter of 2008 handset manufacturers stopped buying power amplifiers, and the power amplifier manufacturers stopped buying substrates. There was also very minimal business in Q1 of 2009, but there was an upturn in the second quarter, and the second half of the year was actually quite strong for substrate manufacturers.

In terms of overall volume – and we haven't got actual survey results yet - our modeling suggests a 2 percent increase in volume year-on-year. So even in a down year, manufacturers still managed to hold their own, if nothing else.

Q How do you see revenue in this substrate sector evolving over the next five years?

A We are forecasting a 5 percent compound annual growth rate in terms of revenue. The key driver remains the multi-mode, multi-band handset. Over the next three to five years we will see the real emergence of 3G, 3.5G (HSPA) and LTE.

Q Who are the big substrate manufacturers in this market?

A The four key manufacturers are Sumitomo Electric, Freiberger, AXT and Hitachi Cable.

Q Is AXT continuing to grab market share from its competitors?

A Yes. Over the past couple of years they have managed to come back from being a company that was out of the running, and re-establish themselves as a viable supplier. Our most recent numbers suggest that they have overtaken Hitachi Cable, in terms of commercial supply of substrates. Obviously the situation is cloudy if you take the overall market, because companies like Hitachi Cable also have captive demand. But in 2008 the rankings in the commercial market were Freiberger, Sumitomo Electric, AXT and then Hitachi Cable.

Q Different technologies are used for substrate manufacturing. Is a winning approach emerging?

Right: Feature-rich hand-held wireless devices, such as Research in Motion's range of Blackberry products, have a high content of GaAs electronics. This is helping to spur the growth of GaAs substrate sales

A The industry has now settled on two main manufacturing technologies – LEC (liquid encapsulation Czochralski), and VGF (vertical gradient freeze), which is also referred to as VB (vertical Bridgman). Sumitomo Electric is almost exclusively using VB, AXT is exclusively using VGF, Freiberger has a mix of both, and Hitachi Cable is almost exclusively using LEC. So what has happened is that VGF or VB technologies have taken control of the market. This has been driven by the use of VGF for the production of HBT technologies, which form the bedrock for power amplifier production.

PHEMT manufacturers typically use LEC-based substrates. PHEMT is still a volume market, especially for the switch side. For higher frequency applications, for example, such as point-to-point mm-wave radios, PHEMT technology is used for power amplifier functions.

Q What size of semi-insulating GaAs substrate is used for the majority of manufacturing?

A 6-inch is the dominant diameter now by far now - it started to take over the market in 2005. We've seen some of the larger players move to this size over the last few years. RFMD has converted to 6-inch and bought the Filtronic fab that has a 6-inch line, and Skyworks has done a partial conversion to 6-inch. You also have WIN Semiconductor, TriQuint, and Anadigics high-volume-manufacturing on 6-inch.

There are still players working on 4-inch platforms in Europe, Japan, and the US. But overall, 4 inch is only about 27 percent of the total market, and the bulk of the remainder is 6-inch.

Q Are substrate prices falling?

A There is pricing pressure across the whole supply chain, including substrate vendors. They are seeing average price declines of around 4 to 5 percent year-on-year for the pricing of their substrates. The actual pricing depends on individual relationships, the size of the contract, and how much volume companies are buying.

Q Do you think that the GaAs chipmakers will move to a 200 mm platform by the end of this decade?

If we see 8-inch manufacturing, it's probably going to come in through the foundry route as opposed to the IDMs (independent device manufacturers). It makes sense for them – the larger the diameter that they can get and produce, the more cost effective it is for them, whereas for an IDM, they have to invest significantly in new equipment, new infrastructure, and then a 5-10 year cycle that equipment has to be amortized over and depreciated. I don't see any of the major GaAs manufacturers, the IDMs, making that kind of investment.

Looking forward, the multi-mode, multi-band approach might be replaced by broadband power amplifiers. If that was the case the actual potential demand for power amplifiers, in terms of volume, would start to drop, and have a knock-on effect on how many substrates are needed.

Q How would you describe the current semi-conducting GaAs substrate market that serves LED manufacturers?

A It is quite healthy. The LED market has seen resurgence, but the thing to remember is that LEDs aren't exclusively based around GaAs technology. The primary technology coming into play right now is GaN-based LEDs. But having said that, we expect to see about a 4 percent compound annual growth rate for semi-conducting GaAs substrates over the next four to five years. And LED manufacturing is going to be about 30-40 percent of that demand.

Q What applications will drive the semiconducting GaAs market over the next few years?

In terms of volume demand, the market is going to be driven by LEDs. And what's going to drive that is the flat panel display market. Your mainstream TVs will have edge-lit or back-lit white, nitride-based LEDs, but then you have premium models that have red, green and blue lighting. The red LEDs are grown on GaAs substrates.

We have also modeled in a growth market for solar. What you have to bare in mind is that the bulk of III-V concentrating photovoltaic production has typically been on germanium substrates. However, there are efforts to grow III-V solar cells on GaAs as well. There will be some impressive compound annual growth rates, but I would not expect solar to represent more than 10 percent of the market in the next four or five years, as far as volume is concerned.

Q Is the manufacturing leader board for semiconducting GaAs similar to that for semi-insulating GaAs?

A We see some of the same names, but the market tends to be dominated by the Japanese companies, such as Sumitomo Electric, Mitsubishi Chemical, and Hitachi Cable – those are the market leaders. Other Japanese companies include Dowa. AXT and Freiberger are behind the larger Japanese suppliers.

Q What is the dominant substrate size for sales of semiconducting GaAs?

A It is still 2-inch, but you are seeing larger diameters moving forwards. Right now we see 2-inch representing about 40 percent, but there has been a move towards larger diameter substrates over the past couple of years, and that growth will continue. We expect that by the 2013-2014 timeframe, 3-inch and 4-inch will represent over 70 percent of semiconducting substrate demand.

Q Moving on to InP, how would you describe this market?

A It is in a fairly healthy state. There is going to be strong growth for semiconducting InP bulk substrates, resulting from the fiber-optics market. On the optoelectronic side, InP demand is driven by photo-detectors and transmission lasers.

On the semi-insulating side, it's the same market driver – fiber optics. However, the overall volumes are a bit lower, because the devices manufactured on this substrate are analog ICs such as TIAs (trans-impedance amplifiers) and laser drivers. The penetration of that technology is dependent on 40 G and 100G growth moving forwards. And those are still emerging markets, so that is why the microelectronics market is a bit slower. But it is still going to see significant growth. We are forecasting for InP, in terms of dollar value, a compound annual growth rate of over 47 percent over the next four to five years.

Q Who are the leading manufacturers of InP substrates?

A The Japanese are dominating that segment. Companies such as Sumitomo Electric and Nikko Materials are in the lead, but AXT is also a significant supplier of InP. Other providers include the French company InPACT. There is also IQE subsidiary Wafer Technology, though they now seem to be focusing on more esoteric substrates.

Philippe Roussel from Yole Développement has been taking a close look at the SiC substrate market for several years. He has authored several reports, including *SiC market 2010: a 10-year projection*. He offers his take on the SiC substrate market.

Q How would you describe the state of the current SiC substrate market? Has it been rocked by recession?

A I would say that the market was quite flat in 2009 compared to 2008. In 2009 the market for all SiC substrates, including semi-insulating and all the R&D substrates, was $48 million, and in 2007 it was $47 million. In terms of volumes we saw an increase in sales, but there was also an erosion of prices.

Q The SiC market can be sub-divided into semiconducting and semi-insulating material, and 4H and 6H polytypes. What are the types of devices grown on each of these platforms?

A To be frank, we should no more speak of 4H and 6H polytypes, because most of the products today are made on 4H. Even Cree is manufacturing everything on 4H SiC.

So the most important divide is between semi-insulating verses semiconducting SiC. Semi-insulating SiC is only used for RF applications. Conductive substrates are used for LEDs, power electronics, and MEMs, but the later application is a very small market.

Q Some manufacturers of SiC substrates use their material for manufacturing their own chips. For example, Cree produces LEDs on its own substrates. In terms of volume, how does the total internal market compare in size to that of the merchant market?

A We have tried to simulate Cree's captive SiC consumption and translate it into a value. In 2008 this was in the range of $235 million. The merchant market was only $47 million, so peanuts in comparison.

But it was very tricky to get a real number, because it is hard to estimate the internal costs of Cree wafers. Our actual figure is probably wrong, but Cree's captive market will probably be somewhere within the range of two-to-three hundred million dollars.

Q How quickly will SiC market revenues grow over the next few years, and what will drive this growth?

Right: The development of a reliable SiC transistor could lead to the deployment of SiC electronics in hybrid electric vehicles. If this happens, it will fuel an increase in SiC substrate sales

The substrate business is linked to the device business, and it will be boosted by the launch of the transistor. We believe that the MOSFET will start volume consumption somewhere between 2013 and 2014

A The substrate business is linked to the device business, and it will be boosted by the launch of the transistor. We believe that the MOSFET will start volume consumption somewhere between 2013 and 2014.

This is the inflection point for us. If the transistor is introduced in the market place in 2010 it will take one to three years before the system makers will implement it, validate it and make all qualification processes. We expect the substrate business to reach $350 million by 2019.

Q Who are the leading manufacturers of SiC substrates?

A It's no surprise that Cree is leading the business. But their market share is decreasing year after year. In 2008, Cree had a little bit more than half the market share of the merchant market.

The two big challengers were II-VI and SiCrystal. In 2010 we are expecting to see Dow Corning take-off, and this will further decrease Cree's market share.

Q Are SiC substrate makers using different techniques to produce their material?

A Most of them are using sublimation from powder. Only Norstel is using high-temperature CVD. Sumitomo has an interesting liquid phase epitaxy technology, but it's not in production.

If we consider the market situation, then 95 percent of material is made using sublimation. Most of the newcomers are starting with sublimation, so the dominance of this technique will probably continue.

Q Are there still issues of SiC material quality, or is this now behind us?

A I think that only Cree is able to produce zero micropipe material. Their challengers are working on that. There are very good results with dislocation densities of less than one per square centimeter. So the dislocation density is under control. The next challenge is the Basal plane dislocations. If these dislocations are in the raw material, then they can degrade the quality of the epilayers.

Q How do sales of 2-inch, 3-inch and 4-inch substrates compare?

A The split is currently moving from 3-inch to 4-inch. In power electronics production, in 2009, it was 80 percent on 4-inch, versus 20 percent on 3-inch and 2-inch. And 2-inch is less than 2 percent now.

6-inch is expected by a lot of players. Its introduction will depend on Cree, because it has announced a 6-inch substrate for 2010. But nobody has seen any real 6-inch material yet. Due to the qualification time – one to one-and-a-half years – we don't expect to see 6-inch in production until 2012. Its success depends on the price.

Q I've heard that it's more expensive to make products on 4-inch substrates than 3-inch equivalents?

A That's not true. It was true during the introduction of the first samples, but not any more. The cost-per-square-inch is now less with 4-inch material if you buy in volume - an order of 50 to 100 substrates or more. But an R&D lab will pay more by a factor of four or five.

Q What is the trend of the average selling price of SiC substrates for high volume orders?

A It's a bit like in the PC world. You always pay the same price, but you get something better every year. The typical price for a volume order from a large substrate manufacturer is $1000-$1200 per substrate. This was the price for 2-inch SiC seven or eight years ago, for 3-inch four years ago, and now for 4-inch.

Q Do you see any changes in the number of players in the SiC market over the next few years?

A We don't see a lot of incomers. The market size is not big enough to sustain any new companies to enter. And I expect one or two established SiC substrate manufacturers to disappear, because they have to live until 2013 with quite low-volume products. I don't think that there is enough room for all of them, so the weaker will disappear.

Strategies Unlimited is well known for it analysis of the LED market. In addition, it covers the GaN substrate market, with reports co-written by Bob Steele and consultant Hank Rodeen. These authors, which wrote *GaN Substrates: Performance Comparisons and Market Assessment – 2009,* offer a view on the GaN market.

Q How would you describe the state of the GaN substrate market?

A In 2008 it was just over $100 million. We haven't tabulated the number for 2009, but we don't think that market would have been much bigger. Demand is driven mainly by lasers for Blu-ray players and the Sony PlayStation 3. The Nintendo Wii has been so popular, and PlayStation 3 sales may have suffered from a combination of this and the recession.

Q How will the market evolve over the next few years?

A We forecast a compound annual growth rate for sales of about 10 percent through to 2013, and by then the market will be worth about $190 million. The unit volume will increase by about 20 percent per year, but there will be attrition in price. The market will be driven mainly by lasers, but there might be some small demand for electronic devices. We don't foresee any demand for LEDs. We've looked at this carefully, and talked to people, researchers are getting outstanding lab results on sapphire and SiC. Cree announced 186 lm/W [at 350 mA] from a lab device in the last 6 months. The price of GaN is higher than sapphire, or even SiC, and it would be very difficult to envisage a hike in LED performance that's commensurate with that difference in price.

GaN substrates are predominantly used to make 405 nm lasers for reading Blu-ray discs. This technology features in the Sony Plastation3

Q Who are the big players in the GaN substrate market?

A The leader for GaN sales is Sumitomo Electric, and they have about 80 percent of the business. They are the major exponent of HVPE, which involves the growth of thick layers of GaN onto another substrate. They were using GaAs to put GaN on, but we had heard that they were changing. They are shipping volume, and most of their volume is 2-inch.

Others producing HVPE-grown GaN substrates are: Kyma Technologies; TDI, which is now part of Oxford Instruments; Lumilog; Hitachi Cable; Mitsubishi Chemical; Samsung Corning; and TopGaN. A lot of GaN that's produced is sold as rectangles, or squares that are typically 15 mm by 15 mm, or 25 mm by 25 mm in size. But these are difficult to process into volume, and anyone going into business should target a 2-inch disc.

Q The US and Europe are way behind Japan in terms of GaN producers. Will this change?

A We don't have any reason to think it will. In Europe and the US there aren't any large companies involved in GaN. When the big companies – Sumitomo, Mitsubishi, and Hitachi Cable – want to be serious in the business, they have the resources and the needs to do it. Most of the others are start-ups, or small operations. One exception is the Korean firm Samsung Corning, which has enough resources to strongly pursue this market if it wants to.

The other factor is who makes the lasers. It's Japanese companies, mainly Sony, but Nichia and a few others. Historically speaking, Japanese companies have relied on other Japanese companies to be their suppliers. So our guess is that Japan will dominates GaN manufacturing for the foreseeable future, unless someone else comes up with something that is so much better. However, there are some larger companies in the US with substantial resources and infrastructure that are doing R&D on GaN substrates under the radar. They may well be able to compete with the major Japanese players in the future.

Q What other methods are being used to produce GaN substrates?

A In addition to HVPE, which can give defect densities close to 10^4 or 10^5 per square centimeter, you have ammonothermal growth. There are three suppliers – Ammono, Mitsubishi Chemical, and Sixpoint Materials, which is a spin-off out of the University of California, Santa Barbara - but none of them have very large volume. The defect densities depend on the type of seed, and they run in the range of 10^4 or 10^5 per square centimeter.

Then you have the high-temperature, high-pressure (HTHP) approach, which is the ultimate from the standpoint of low defect density. But it's also the ultimate in terms of price. We don't think any crystals are made, except by happenstance, that are any bigger than 0.6 or 0.7 inches in diameter.

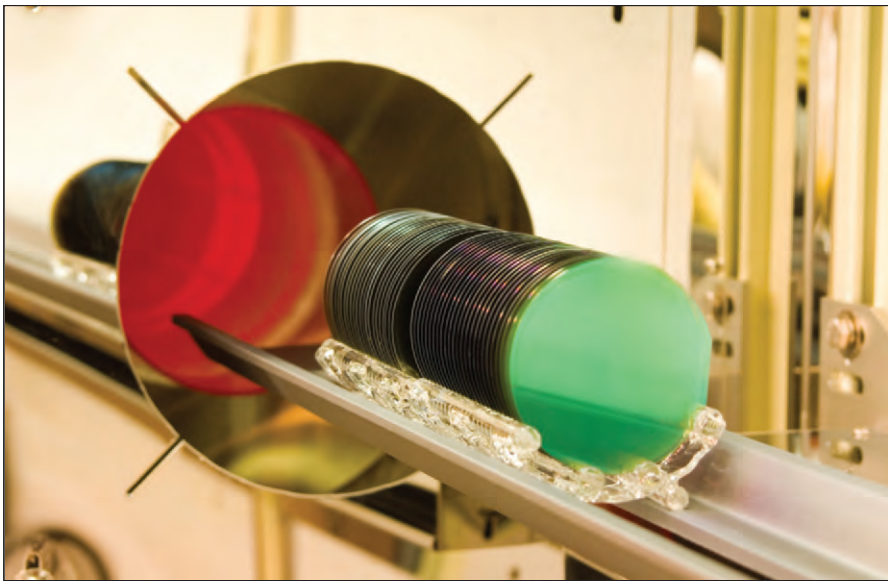
The leading companies, as far as capability is concerned, are: TopGaN; TDI; and A. F. Ioffe Physical Technical Institute in Russia, which is a research organization that ships stuff out for evaluation.

If you use a HPHT approach with a HPHT seed that starts out with a defect density of 10^2 per square centimetre, then you can produce some pretty good material. It's an approach that a lot of people would take. They would get the best material that they could and get the best price that they could on it, while realizing that it's not practical for manufacture until the price came down.

But they could demonstrate their capability, carry out device characterization, and generate a lot of meaningful data from the standpoint of performance. They will say: here's where we are going to be – all we need is a good price and availability.

Q Although GaN substrates are far more expensive than silicon, sapphire and even SiC, they do provide a superior platform for making low defect density epiwafers. Do they also improve device lifetimes?

A The reliability issues for devices on GaN substrates may well become apparent on devices operating at high power and high temperature. However, there has not been sufficient testing and evaluation at this stage to know just how big a difference in reliability that GaN substrates might make.



Cree is by far the biggest seller of SiC substrates, and it also uses this material as the basis for its own LED production

Q I've heard that a typical price for a piece of 2-inch GaN is $5000. Is that correct?

A $5000 is the number we used in 2008, but we've heard that the laser price has been pushed down, and this has had a knock-on effect on substrate prices. Lasers cost $15-20 in 2008, and we've heard that they have been as low as $6-8 in the past year. However, Sony is the dominant supplier of lasers, and it supplies itself. In Japan you have very vertically integrated companies, and money is made at the system level. So the component side gets squeezed to provide as low a price as possible for the system people. On the other hand, the component business has to make money too. I suspect that the prices have come down, because substrates are a huge percentage of the cost of the laser.

Q Are any companies developing 3-inch GaN substrates?

A We don't believe so. At this point we don't think that there is a huge driving force to go to 3-inch, because you can, in principle, get 5,000 lasers off a two-inch wafer. Laser volumes are just 15-20 million per year, which is very low to compared to LEDs, which are over 50 billion per year. However, even though there is not a large demand at the moment, Sumitomo and others could fairly readily scale up to 3-inch if necessary.

The reliability issues for devices on GaN substrates may well become apparent on devices operating at high power and high temperature. However, there has not been sufficient testing and evaluation at this stage to know just how big a difference in reliability that GaN substrates might make

Multiple applications beckon for UV LEDs

Brighter, more powerful and longer lasting UV LEDs promise to offer a viable alternative to UV lamps used to purify air and water, treat skin diseases, aid forensic investigations and combat forgery. **Dave Birtalan** details the opportunities for a cost-effective, solid-state device.

UV electromagnetic radiation is used in a variety of applications, such as: germicidal air and water purification, surface disinfection, currency validation, medical, military, industrial (photo-chemical) curing, printing, instrumentation, effect lighting and forensic analysis. The market for UV equipment of all types is conservatively estimated at over $5 billion. The predominate method used to produce UV electromagnetic radiation today is based on tube technology developed nearly 100 years ago. Though UV lamps are able to generate considerably higher power output levels than today's existing UV LEDs there are several drawbacks of UV lamps such as:

- Mechanically, lamps are fragile and susceptible to breakage.
- Mercury based lamps are environmentally unfriendly, incorporating RoHS material.
- UV lamps have a short working life spans defined in hundreds to thousands of hours.
- Medium/high pressure UV lamps operate at very high temperatures (600-900 °C); in applications such as photo-chemical curing the high temperature can pose a problem for the polymer and/or the substrate material being photo-chemically cured.
- UV lamps are prone to gas leaking from the tube due to thermal stress cracking the glass to metal seals in the tube or the glass itself. Lamp explosion is possible in medium and high pressure lamps.
- UV lamps are susceptible to temperature variation. Depending on the manufacturer, low pressure lamps have an optimum output with an ambient temperature of 25 to 30°C. Above or below this optimum temperature range will reduce the UV output; amalgam type UV lamps can be used to somewhat reduce the temperature effect.

The emerging UV LED technology has an opportunity in the coming years to provide a competitive technology in a manner similar to ongoing events in solid-state lighting using visible LEDs. UV LEDs will be an enabling technology in the future to drive new innovative applications.

Spanning the UV

The ultraviolet spectrum lies between the visible light range the human eye is able to detect and x-rays as shown in Table 1. The term Ultraviolet refers to all electromagnetic radiation with wavelengths in the range of 10 to 400 nanometers. In addition, there are several classifications inside of the UV range: UV-A (315-400 nm), UV-B (280-315 nm), UV-C (200-280 nm) and Vacuum UV (10-200) nm.

Wavelengths in the UV-A range are used for currency validation, industrial curing, phototherapy, and for forensic / analytical instruments. UV-A wavelengths from 315 to 345 nm are used for sun tanning and are a suspected cause for premature aging of human skin. UV wavelengths below 385-390nm can not be detected by the human eye; therefore it is essential to take precaution to protect your eyes and skin when working with UV light sources.

The UV-B range is more hazardous than UV-A, and it is largely responsible for sunburn. It is used in forensic and analytical instruments and for the more recent narrow band UV-B phototherapy skin treatments for Psoriasis (308-311nm). UV-B does not penetrate as deeply in the skin as UV-A, however, the deadliest types of skin cancer (malignant melanomas) start in the epidermis, an upper layer of the skin. UV-B is largely blamed for these cancers although shorter UV-A wavelengths are considered possibly cancer-causing as well.

The UV-C range refers to shorter UV wavelengths, which is sometimes referred to as the Deep UV Range.

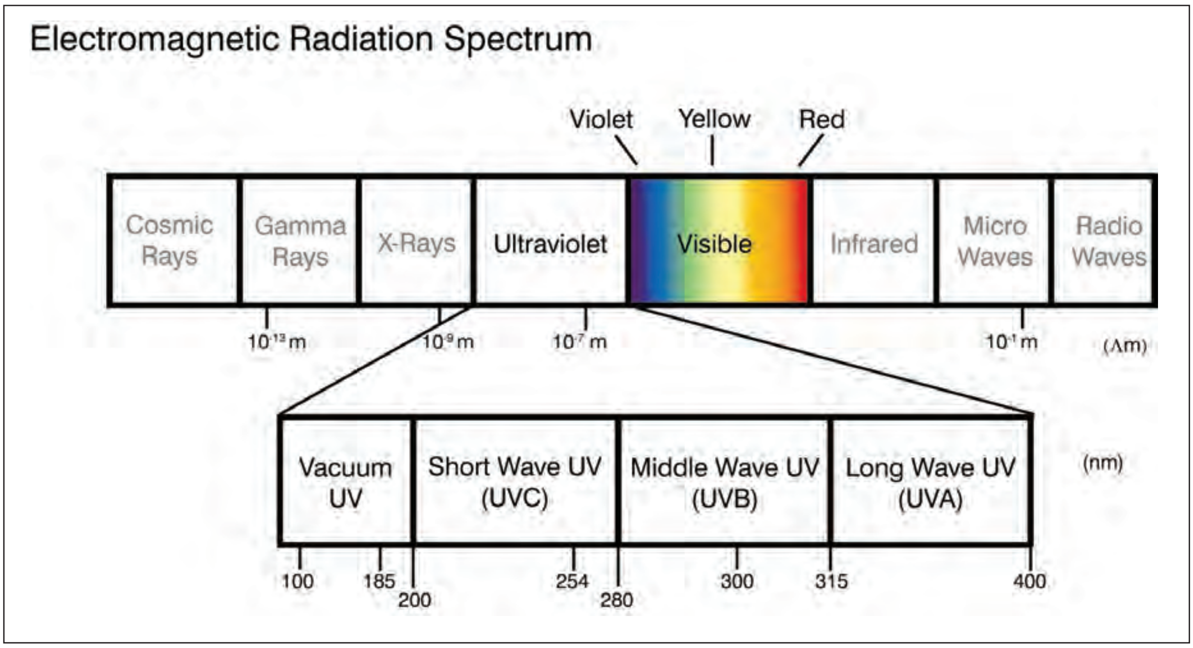


Table 1 Electromagnetic Wavelength Spectrum including Ultraviolet>> The various classifications of UV radiation used in the selected applications discussed in this article

Wavelengths in this range, especially from the low 200's to about 275 nm, are especially damaging to microorganism's DNA. UV-C is often used for germicidal applications for water, air and surface decontaminations. The earth's atmosphere absorbs most of the UV-C radiated by the sun.

Vacuum UV has the shortest wavelengths and highest energy level and is absorbed by the atmosphere. Strong absorption of vacuum UV in the Earth's atmosphere is due to the presence of oxygen. Semiconductor photolithography processes seek to use shorter UV wavelengths for the next generation of smaller IC chips.

Killing germs

UV germicidal technology has been established in Europe for nearly 100 years, and the first use of UV light to disinfect drinking water occurred in 1910 in France using mercury based lamps as the UV-C light source. Around the same time, UV-C light from mercury based lamps was being used to disinfect the air of pathogens such as tuberculosis. These applications were based upon the key discovery in 1877 by Dr. Arthur Downes and Thomas P. Blunt of the germicidal properties of direct sunlight. They correctly identified the increasing germicidal effectiveness (ability to inactivate pathogens) with shorter electromagnetic wavelengths (from visible blue, to violet and then to ultraviolet electromagnetic wavelengths).

More recently, the U.S. Environmental Protection Agency (EPA) has recognized the use of ultraviolet electromagnetic radiation as a proven technology to inactivate pathogenic microorganisms without forming regulated chlorinated disinfection byproducts in public water supplies. UV can also be used to disinfect surfaces and is used in the food, beverage, medical and semiconductor industries to deliver a sterile environment. The next section will review how UV electromagnetic radiation accomplishes these germicidal effects starting with a very brief review of biology.

All living organisms contain nucleic acids, the two most commonly known are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The former provides the genetic code information for all living organisms to develop and function, and the latter facilitates translating the genetic information of DNA into proteins. Generally, DNA is a double stranded helix structure as shown in the "before section" of Figure 1. The individual rungs of the DNA ladder shown in Figure 1 are made up of Nucleotides. The Nucleotides for DNA have nitrogenous bases of adenine, cytosine, guanine and thymine and the Nucleotides for RNA have bases that consist of adenine, cytosine, guanine and uracil.

Nucleic acids (DNA and RNA) readily absorb UV electromagnetic radiation, especially in the range of 240nm to 290nm. The UV absorption in DNA peaks around 260nm which is very close to the primary emission line of a low pressure mercury lamp at 253.7nm. Further examination showed that nucleic acids in DNA absorb 10 to 20 times the amount of UV electromagnetic radiations as equal weights of the protein component of DNA; whereas the sugar and phosphate components of DNA do not absorb UV above 210nm. It should also be noted that both the rate and peak absorption occurs at different levels for each of the Nucleotides of DNA (adenine, cytosine, guanine and thymine) and the pyrimidines

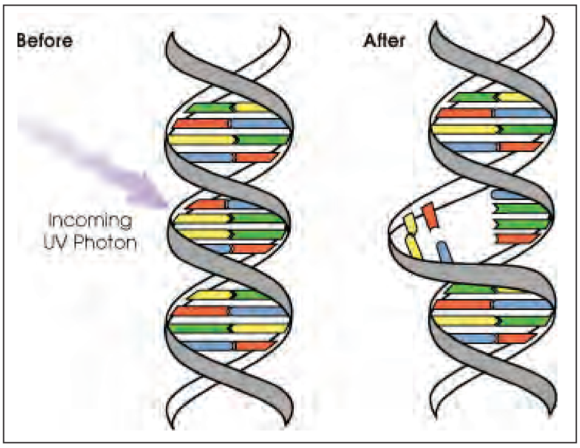


Figure 1. A normal strand of DNA before exposure to UV-B. A cell damaged by UV-B exposure with an incorrect DNA repair will become inactivated and unable to reproduce. Credit: Courtesy of David Herring and NASA

portion (thymine and cystosine) have been shown to be much more sensitive to UV electromagnetic radiation. Three possible pyrimidine dimers that can be formed in DNA are (thymine-thymine, cystosine-cystosine, and thymine-cystosine). The absorption of UV light by nucleic acid (3 types of pyrimidine dimers) is what leads to alterations in the genetic material; the smallest of which can ultimately lead to the death of a living organism. A microorganism that can not replicate is not capable of infecting a host.

The earth has been exposed to UV-B for millions of years; in some cases UV has performed a helpful role in forming the essential Vitamin D and likewise a harmful role in causing sunburn, skin cancer and cataracts. Ultraviolet electromagnetic radiation harms DNA in different ways.

An illustration describing one method how UV can alter DNA is shown in the "after UV-B" exposure portion of Figure 1. In this common damage event, adjacent bases bond with each other instead of across the nucleotide ladder. This creates a bulge and the distorted DNA molecule does not function properly. If the distorted DNA molecule can not produce the correct proteins the cell can die. Over millions of years, living cells have adapted to an environment exposed to UV-B electromagnetic radiation and have evolved by sending an enzyme in an attempt to repair the damaged DNA. These enzyme driven microbial repairs can be derived from light energy (photo-repair) or chemical energy (dark repair). However, as the time for UV exposure increases for the cell; the risk for an incorrect DNA repair increases as well.

Exposure of DNA to a higher energy level UV-C light source coupled with the fact that this is where the DNA peaks in absorbing UV energy (240nm to 290nm) will result in even greater levels of molecular damage. DNA with increased levels of disruption to cellular processes due to incorrect repairs is more likely to be inactivated and possibly die. High energy UV-C radiation from a typical low pressure mercury lamp emitting at 253.7 nm is very effective at inactivating viruses, bacteria, mold and protozoa that can be harmful to humans. Some extremely lethal pathogens like anthrax, typhoid fever, diphtheria, cholera, dysentery, salmonella and tuberculosis can be inactivated at energy levels measured in millijoules per square centimeter.

Many health officials worldwide are concerned with the potentially pandemic situations posed by the avian influenza virus (H5N1), more commonly known as Bird Flu. Health officials take steps to develop a vaccine before any major outbreak occurs, though there was difficulty with production for the Swine flu vaccine this year. The effects of the SARS virus from a few years ago on the worldwide economy and resulting loss of life are only part of the reason for these preemptive actions.

The worldwide Spanish Flu influenza (H1N1 virus) pandemic that occurred between1918-1920 is shown in Figure 2. The Spanish Flu mortality estimates ranged upwards of 5% of the human population (50-100 million) people being killed and infecting up to 400 million people world-wide at the time. A greater portion of the Spanish Flu deaths occurred in healthy young adults than normally is associated with influenza, in as little as one to two days. The Avian "Bird Flu" is a more virulent influenza strain with high fatality rates. If one considers the greater travel speeds and higher amount of international travel of today when compared to 1918; the pandemic concerns appear to be warranted. UV radiation can inactivate and kill the Avian Flu virus and measures can be taken to install UV systems in hospitals, office buildings, planes and homes to minimize the spread of a pandemic influenza. As the relative size of the target organism increases, generally so will the amount of UV electromagnetic radiation required to cause disruption to cellular processes.

The amount of UV required to inactivate a specific target organism involves many different factors in addition to the relative size of the target. The specific DNA chemical composition and accordingly the amount of UV absorption will vary between the DNA of a virus, bacteria, mold or protozoan. The different rate of UV absorption in DNA is based on the Nucleotides of DNA (adenine, cytosine, guanine and thymine) and the pyrimidines portion (thymine

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and cystosine) have different rates of UV absorption. The particular shape of the microorganism will help determine the specific amount of UV required to damage the cell. Possible shapes include but are not limited to being spherical, spiral, rod-like or filamentous and should also include other construction factors (cyst).

Ultraviolet radiation must be able to strike the microorganism in order to inactivate the target which is challenging in a very large UV air or water treatment system. Scattering can also be a factor, when the size of the target microorganism is much less than that of the UV wavelength then Rayleigh scattering is present. When the target microorganism is larger than the wavelength then empirical adjustments are generally made to account for this including the shape of the target microorganism (rod-like versus spherical). Harmful microorganisms can withstand considerably more UV radiation in water than in dry air. Consequently, higher dosage levels are required to kill the exact same type of pathogen in water than in air.

The largest UV disinfecting water treatment facility in the world is being implemented for the city of New York. The New York City UV water treatment facility is designed to process up to 2.2 billion gallons per day and serves over 9 million consumers daily. The UV disinfection treatment facility will cost on-quarter of what a comparable filtration plant would cost and it will require approximately one-tenth of the space.

The UV treatment facility will be comprised of 56 separate processing units capable of disinfecting 50 mgd (million gallons per day) under worst-case conditions. The city adopted a very conservative (higher) UV dose of $40mJ/cm^3$ that will insure a 99.9999% UV kill rate for the deadly Cryptosporidium protozoa. The contact time to inactivate microorganisms and disinfect the water is approximately 20-30 seconds in a single pass.

UVC water treatment can be used in a variety of applications to disinfect water for drinking, processing wastewater, in pools and spas, beverages and industrial processing. Industrial processing would include ultra pure water for pharmaceutical, cosmetic & semiconductor industries and for obscure applications like maritime ballast water and eliminating sulfate-reducing bacteria in offshore oil drilling. According to 2007 statistics from the American Water Works Association, there are more than 2,000 UV drinking water treatment systems operating in Europe and over 1,000 UV systems in the United States.

All of the UV water treatment facilities that have been discussed are based on UV lamps. UV-C LED power output levels are at present several orders of magnitude lower than needed to inactivate microorganisms. However, in the coming years, improved LED chip design coupled with higher density packaging and improved thermal management will make inroads. Water treatment applications for UV LEDs is unique since the high volume of flowing water in the systems could utilize the water to

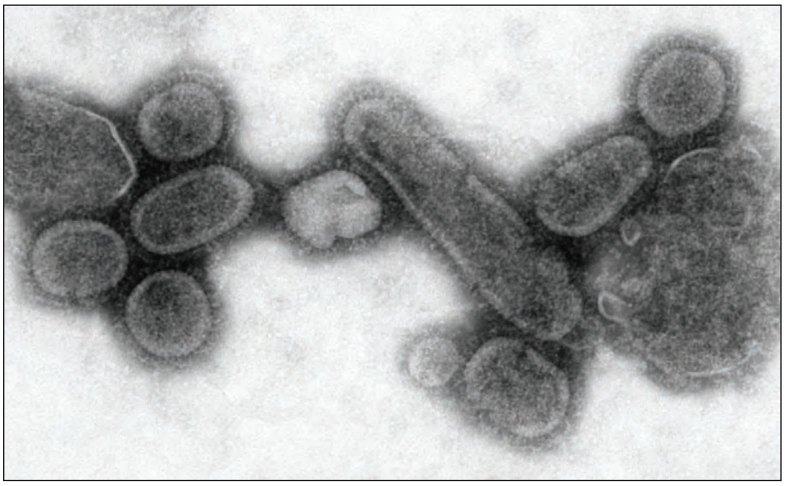


Figure 2 Recreated 1918 Spanish Flu Influenza Virus, Courtesy of the CDC>> The Spanish Flu Pandemic of 1918, an H1N1 virus strain, caused the death of at least 50 million people. The recreated Spanish Flu strain can be inactivated with UV radiation

remove a significant portion of the heat generated in the LEDs. As mentioned earlier, low pressure UVC lamps operate best at a wall temperature of approximately 40°C and begin to lose efficiency at a temperature below –or-above 40°C. HVAC systems also could utilize the high velocity cool air to enhance the LED performance.

Treating psoriasis

Another major use for UV Technology is Phototherapy to treat Psoriasis and other skin conditions. Phototherapy describes a broad range for medical treatment using light. Psoriasis is a persistent and chronic skin disease which has a tendency to be genetically inherited. Psoriasis can range from a small localized area to covering the entire body and can be treated with UV-A or UV-B wavelengths. UV-A is done in conjunction with a photosensitizing agent which allows for a lower UV dose to be used. After several treatments, improvement can be seen in as little as 3 weeks with maintenance therapy thereafter. UV dental applications include curing (UV-A to Blue Visible LED) for cavity fillings, brightening and UV-C for toothbrush and medical instrument sterilization.

The medical analytical instrument market also utilizes UV light sources in fluorescence spectroscopy and ultraviolet-visible spectroscopy. Fluorescence spectroscopy is a type of electromagnetic spectroscopy which analyzes the fluorescence emitted from a sample being irradiated and evaluated. The light source is generally UV to excite the electrons in the specimen to emit light of a lower energy level usually in the visible spectrum. In fluorescence spectroscopy, the sample is excited, by absorbing the higher energy UV light, causing the sample to move from its ground electronic state to one of the various vibrational states in the excited electronic state. Analysis of the emission spectrum will permit the identification of the substance (chemical compound, tumor, food processing).

Figure 3: Currency anti-counterfeiting measures incorporate UV threads imbedded into a currency in order to validate the authenticity and quickly detect forgeries. The currency is illuminated with a 365nm UV LED.

Fluorescence spectroscopy is also used in forensics and chemical research fields. Ultraviolet-visible spectroscopy (UV/ VIS) uses multiple wavelengths of light in the visible, ultraviolet and near infrared ranges. The absorbance of light in a solution is directly proportional to the solution's concentration (Beer-Lambert Law).

UV light sources are fundamental tools for forensic investigative work. The US Department of Justice in the Revised Processing Guide for Developing Latent Fingerprints which includes UV light sources for all types of surfaces (porous & non-porous) issued the FBI Laboratory Division in 2000. UV light sources have vastly improved collecting human DNA evidence (oils, amino acids, blood) at a crime scene by making the evidence highly visible to investigators. UV light can also be used by police to discover former wounds, bite marks and bruises not revealed by the visible spectrum for up to 6 to 9 months after the injury was inflicted that would not otherwise be visible.

Exposing counterfeits

Protecting the integrity of paper currency and other important financial documents such as stock and bond certificates against counterfeiting is fundamental to a sound monetary system. The United States Treasury Department and specifically the Secret Service Bureau was established in 1865 by Congress for the purpose of controlling counterfeiting. The mission was to prevent and prosecute counterfeiting activity and thus maintain the public's confidence in the nation's currency. Over the years many different features were used to deter counterfeiting US currency. In 1861, the first circulation of paper money issued by the federal government occurred to finance the Civil War. These non-interest bearing demand bills were green in color and the popular nickname "greenbacks" has been in use since that time. Many additional anti-counterfeiting measures have been taken since the first currency bills were issued such as the paper texture, paper weight, imbedded fibers, intricate images and serial numbers. Stock and bond certificates also adopted these same features.

The US Treasury Department has recently completed the security upgrade of US currency that was initiated with the twenty dollar bill in 2003 and completed with the release of the five dollar bill in 2008. The new anti-counterfeiting measures implemented include watermarks, new colors, micro printing and a security thread that emit a different color under ultraviolet radiation based on the specific denomination. The color coded stripe can be seen by holding the bill in front of a strong source of white light. However, when illuminated with UV-A light, the security thread glows a bright: Blue-$5, Orange-$10, Green-$20, Yellow-$50 and Red-$100 bill. Figure 3 shows US and British currency illuminated with fluorescent lighting and also with 365nm UV-A light emitted from UV LEDs in a dark room.

UV-A LEDs are now being investigated as replacements for mercury based UV tubes. US passports and many credit cards have implemented UV threads and materials in their anti-counterfeiting efforts. A very practical application is to include a UV-A LED emitter into a cell phone allowing consumers to conveniently validate the integrity of their currency. These measures will greatly increase both the technical challenge and financial costs to forge currency and financial instruments; thus maintaining the integrity and validity of the world-wide monetary system.

The material presented in this feature is based on one of the chapters from the recent book: Optoelectronics: Infrared-Visible-Ultraviolet Devices and Applications. This publication that was launched late last year expands on the groundbreaking work of its 1987 predecessor.

The second edition is fully revised to reflect current developments and practical considerations for those working in the field. Claimed to be a comprehensive mini-encyclopedia, this treatise reviews essential semiconductor fundamentals, including device physics, from an optoelectronic industry perspective.

The co-editor of this book, Dave Birtalan, began his career at General Electric's Semiconductor Division and held various engineering, product marketing and sales management positions involving Optoelectronics, MOSFETs, and Laser Diodes including working on the Strategic Defense Initiative Program. He received his bachelor of science in electrical engineering from Penn State University and conducted his graduate studies at Syracuse University. In addition, he has held leadership positions with the Mitsubishi-General Electric power semiconductor joint venture, Vishay Telefunken and TT electronics involving RF, LEDs, ICs, IrDC and Sensor products. He can be reached at: **dbirtalan@aol.com**

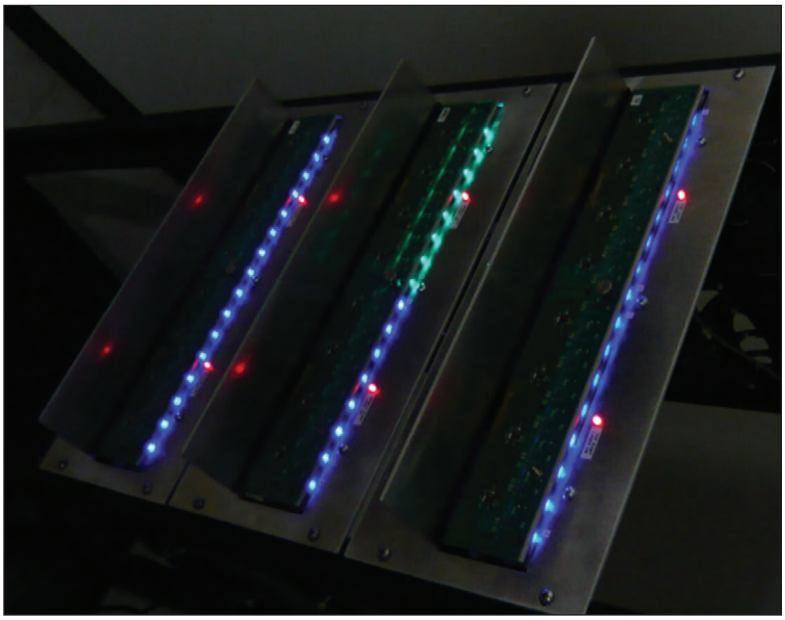
Kaai takes laser productions to new planes

Defense, medical, instrumentation and display markets are all hankering after affordable blue and green lasers based on a single semiconductor chip. Kaai aims to satisfy this demand with a portfolio of devices grown on semi-polar and non-polar planes. **Richard Stevenson investigates.**

A small start-up grabbed headlines at this year's Consuming Electronics Show (CES) with a claim for the longest wavelength, continuous-wave (CW) nitride laser. And there is good reason to believe that this firm will remain in the spotlight of the technical press for the rest of the year, because it plans to imminently launch on to the market what could well be the first violet, blue and green nitride lasers built on semi-polar and non-polar planes.

The name of this firm – Kaai – may not ring any bells, but its founders are certainly familiar. They are the University of California, Santa Barbara academics Shuji Nakamura, Stephen DenBaars and Jim Speck, who formed this spin-off shortly after collaborating to give the world its first ever non-polar laser.

Kaai is testing the reliability of its blue and green lasers. Blue lasers have already showed lifetimes of up to 5000 hours



This triumvirate hit that particular milestone on 29 January 2007, and then went on to further develop the technology, file patents, and lay the foundations needed to launch a spin-off company. It all came together in early 2008, and during the last two years the team at Kaai has been busy assembling a fabrication facility capable of everything from epitaxial growth through to finished products, and putting this resource to good use by developing a laser portfolio.

For most of that time the company has been operating in stealth mode. "Our view is that seeing is believing," explains Paul Rudy, VP of Marketing and Sales. "Once we could physically show the laser to people, and once we had a road map for commercialization, we thought that it was the right time to go public." He believes that the visible laser market has suffered from tremendous hype surrounding low-cost green sources, which are typically based on second harmonic generation (SHG), and he hopes that Kaai can combat any lingering skepticism by under promising and over delivering.

At CES Kaai unveiled a 523 nm CW laser delivering 2-3 mW, and since then it has also reported a 521 nm, 9 mW laser plus a 525 nm device producing 6 mW. Other devices in the company's portfolio include a "world class" 405 nm CW device with a single-mode output of 0.5W and a wall-plug efficiency of 25 percent, and a 450 nm, single-mode laser that is also claimed to deliver world-class powers and efficiencies.

Although this is a very impressive set of results, Kaai's longest wavelength laser, which emits at 525 nm, is still a few nanometers short of Sumitomo's record. Last summer this Japanese company reported 531 nm emission from a device driven in pulsed mode with a duty cycle of 0.5 percent. However, Rudy points out that there is a major difference between running a laser in a low-duty-cycle pulsed mode and operating it continuously: "The first step to creating a diode laser is to get lasing in pulsed mode, which is generally one-tenth of a percent duty cycle. It's an important step, but in that regime the devices are not very useful." Although some applications do employ pulse-driven lasers, their duty cycle is in a completely different regime - typically 30-40 percent, according to Rudy. Getting the devices to operate in this regime - or to deliver a CW output - requires a significant reduction in operating voltage alongside a hike in efficiency.

Building a team

Company founders Nakamura, Speck and DenBaars all spend about a day a week at Kaai, which is located in Goleta, a small city 8 miles west of Santa Barbara. The company's future is now in the hands of Richard Craig, a CEO with a strong track record in growing the revenue of III-V start-ups. "He was CEO of Santur and grew that company from zero to $100 million, and executive VP of SDL, from the very early days until the acquisition by JDSU," explains Rudy. Craig has put together a team of about 25 staff, including veterans involved with engineering, marketing and business development.

Laser diode expertise within Kaai's ranks includes experience in the manufacture of both AlGaAs-based and InP-based lasers. In addition, Craig has also signed-up some former UCSB researchers, including James Raring, director of engineering, who were quick to jump at the chance to commercialize the technology that they had helped to create. Finance is in the hands of a finance start-up expert, who is a Silicon Valley start-up veteran, and business development is lead by Rudy, who can draw on his experience gained by a decade at Coherent, followed by a few years at QPC Lasers.

Start-ups needs more than just great technology, and securing the financial backing needed to bring ideas to market can be particularly tricky in the current economic climate. But Kaai has made very light weather of this challenge, thanks to a great relationship with venture capitalist Kholsa Ventures. "My understanding is that the Santa Barbara group and the Khosla group had been following one another's work, and [early 2008] was just the right time to form the company," says Rudy. Once a deal had been struck, the fabrication of the facility followed very quickly, and the company was making lasers by summer 2008.

Different foundations

Switching growth from the polar planes used by today's leading semiconductor laser manufacturers to semi-polar and non-polar ones that Kaai is exploiting is reported to deliver several benefits: either the elimination or substantial reduction of internal electric fields that hamper light emission; the opportunity to increase quantum well thickness and introduce new structures for light guiding; and the potential to cut laser growth times.

Rudy thinks that all of these gains are beneficial, but says that the biggest one of all is the far greater choice of device design. "That design freedom may be on different architectures, it could be on different materials – there's just a lot more freedom across the board." Kaai's engineers are already exploiting these advantages, and seeing higher efficiencies and powers from their single-mode lasers. Their efforts to date also indicate that yields for non-polar and semi-polar devices will

Kaai's portfolio of blue and green lasers can target many different markets, including displays, such as Laser TVs. Credit: Mitsubishi

One of the major choices facing Kaai's engineering team is whether to work with a non-polar substrate for a particular laser design, or select a semi-polar plane

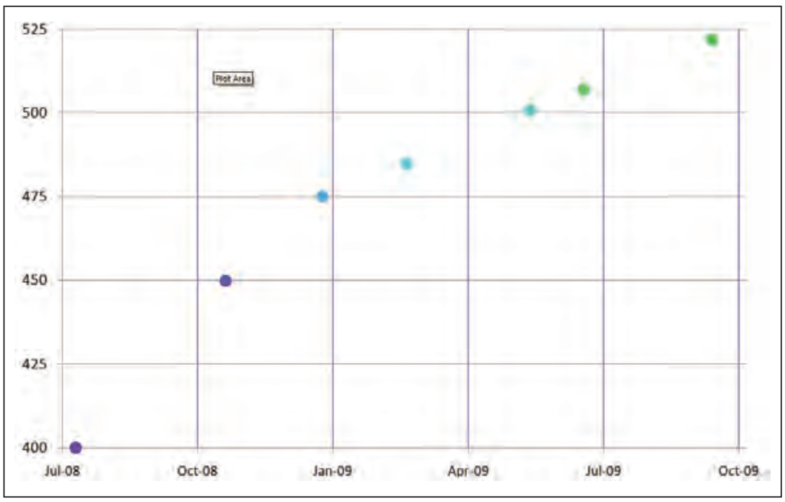
Kaai recently came out of stealth mode after developing CW, single-mode green lasers. These include a 6 mW laser at 525 nm, and a 9 mW version at 521 nm

be better than those for conventional nitride lasers. One of the major choices facing Kaai's engineering team is whether to work with a non-polar substrate for a particular laser design, or select a semi-polar plane. And if they select the latter, then there is the question of which particular plane. Rudy, however, is not divulging any secrets relating to that key decision-making process: "As a small company with great ambition to grow and commercialize this technology, we'll be keeping a lot of cards to our chest."

Up until now, most of the pioneering work on non-polar and semi-polar devices has been carried out using substrates that are no bigger than a fingernail. This is not a barrier to trailblazing researchers, but it is a significant headache for anyone wishing to manufacture lasers in reasonable volume. This issue surrounding substrates was a big concern when the company was founded, but it now has a solution, which it is keeping under wraps. "I think [that the issues surrounding substrates] are a major barrier to entry for folks that want to enter this market and don't know their way around, and don't understand the technology," says Rudy.

Multiple markets

The potential markets for Kaai's products can be divided into existing markets currently served by other classes of laser, and new opportunities serving emerging applications. Markets that are buying blue and green lasers today include defense, biomedical, therapeutic medical, industrial and instrumentation, and these could all benefit from the lower cost that a single chip laser promises to deliver.



Since its launch in early 2008, Kaai has made rapid progress in extending the wavelength of its nitride lasers

"Some segments may be elastic and the world doesn't know that yet, because it's tough to explore that potential opportunity if you've got a three stage laser with an infrared pump and two crystals," says Rudy.

Another opportunity for Kaai's lasers exists in specialty lighting that demands high spatial brightness. Even a niche in that very large market is substantial. And on top of that, non-polar and semi-polar lasers could be used in laser displays, such as laser TV and pico projectors.

"The pico side has a lot of potential," says Rudy. "SHG lasers have some technology out there, but manufacturers don't seem to be in a position to ramp production."

Kaai's long-term commercial success could rely on a strong patent portfolioto to protect the company's IP. This US start-up has addressed this issue by licensing critical technology from UCSB, and then moving on to establish its own patent portfolio. "All the founders, as well as the many folks that have come onboard, are really aware of how to build IP portfolios in this space," says Rudy. "It's a big area of attention for us."

Kaai has set itself several short-term goals, including the sampling of products in the first half of this year, followed by production in the latter half. In 2011 it will aim to ramp production, grow volume, and work hard to fulfill customer expectations. The plan is to offer both blue and green lasers, and the company is particularly excited about applications requiring both types of source.

One area of focus for the company is optimizing the efficiency of its 525 nm lasers, because potential customers are telling Kaai that 525nm is "green enough". They say that they would rather start to receive product at that wavelength, than wait for the next generation 532 nm source to be developed. But in the longer term Kaai wants to extend the wavelength range of its products.

"My sense is that customers may want another 5 to 10 nm to get to 532 nm," says Rudy, who admitted that progress from 520 nm onwards is particularly challenging.

In addition, the company will direct efforts at increasing the power and efficiency of its lasers. If it executes on all these fronts, then the success that follows will change the perception of non-polar and semi-polar lasers from just interesting devices for the lab to a commercially competitive technology.

AXT benefits from a buoyant compound semiconductor market

Substrates sales will increase, argues **AXT's John Cerilli,** thanks to the combination of increasing GaAs content in mobile products, a resurgent LED industry and the beginnings of a terrestrial concentrating photovoltaic market.

Q How would you describe the current state of the business?

A This is an exciting time for AXT. The continued recovery that is taking place in the worldwide macro-economic environment, coupled with advancements in technology in the end markets that we serve, is creating new opportunities for our products. Further, our successful customer qualifications over the last several years are allowing us to supply, either directly or indirectly, to nearly every major customer in our space. We are very pleased to see this continued diversification of our customer and revenue base as well as many positive trends in our markets that highlight our competitive advantages and are likely to provide further opportunities in the months and years ahead.

Q Are sales of semi-insulating GaAs picking up?

A Yes, we have definitely seen a pick-up. The wireless device market that uses our semi-insulating GaAs substrates continues to strengthen. This growth is fueled by increasing demand for a new generation of smart phones and other sophisticated internet-connected devices, such as netbooks, that support more advanced features and access to a host of new web-based applications and services.

In addition to strong unit sales of these devices, we are also benefiting from the fact that these devices require performance levels that are substantially higher than previous generations and therefore utilize more power amplifiers and switches. This results in a higher content of GaAs substrates per unit. The increasing popularity of these devices coupled with the significant worldwide investment in the advanced networks to support them, indicates that this market has long-term growth potential.

Q Is your growth in semi-insulating GaAs substrates just a reflection of a growing market for these products, or are you taking market share from your rivals?

A In the last several years, our market share in this area has increased from the mid-single digits to more than 20 percent through our strong focus on quality, consistency and customer service. As we continue to grow, we are uniquely positioned to accommodate the increasing demand.

With our manufacturing based in China, we have adequate space and facilities to expand our capacity as needed. In fact, since 2006, we have more than tripled our 6-inch GaAs capacity and can continue to expand as new qualifications and increasing demand require greater production volume. Further, lower labor costs and our ability to build our own crystal growth equipment allow us to grow our business far more cost-effectively than our competitors.

Our facility is now one of the largest compound semiconductor substrate manufacturing facilities in the world, and in 2010 we will begin a new initiative to further upgrade and modernize our factory to enhance our capabilities and our efficiency.

Q You also produce semi-conducting GaAs substrates for LED manufacture. Is this market also growing?

A Absolutely. We continue to see signs of recovery, driven by improved demand from applications such as automotive lighting, and signage and display. In fact, in the third quarter, sales of 2-inch, 3-inch and 4-inch semiconducting gallium arsenide made up nearly half of our total gallium arsenide revenues. In addition to growth from our current customer base, we are also qualifying for a number of new emerging LED applications that require specific substrate characteristics and therefore, are less subject to competitive pressures.

We believe that there are many such opportunities for us and we are focusing our engineering teams on optimizing our products to match the requirements of these applications. We are also encouraged to see continued emphasis, particularly in Europe and Asia, on the use of

About the author….John J. Cerilli is the Vice President of Global Sales and Marketing for AXT, Inc. and has been with the company since 2005. He currently manages AXT's business in NE Asia. He has worked in the semiconductor / compound semiconductor industry since 1976.

LEDs in a variety of lighting applications, such as street and traffic lights as well as the development of a commercially viable LED light bulb. We believe that the LED market represents tremendous opportunity for us in the coming years.

Q AXT also produces germanium substrates. What is the dominant application for this product?

A The majority of interest for germanium substrates continues to be for satellite solar cell applications and in expectation of increasing demand across our customer base, we are adding substantial capacity for germanium substrates.

We are also qualifying for the emerging terrestrial solar cell market, where the volumes could be substantially higher when terrestrial applications achieve the cost structure and efficiency to gain wider adoption. We believe that as this market develops, our technology will provide important differentiators from our competition. AXT is the only germanium substrate supplier to offer vertical gradient freeze (VGF)-based technology, a process that we were the first to commercialize more than 20 years ago. Our close collaboration with our customers has revealed that our VGF technology produces germanium substrates with higher mechanical strength and better surface morphology than competing technologies. These characteristics are particularly important in the development of 6-inch germanium substrates, as larger diameter substrates are more prone to breakage.

Our customers are showing strong interest in our development of a larger diameter germanium substrate, particularly for terrestrial applications. Larger wafers would help to lower the cost of producing solar cells, making the technology more commercially viable. AXT has an advantage with tremendous expertise in large-diameter substrate production, as we were one of the first manufacturers to introduce 6-inch GaAs substrates in our industry. This is a major R&D initiative for us and we are committed to being a technology leader in next-generation energy solutions.

Q You have several joint ventures with raw materials companies. What are the benefits of this?

A We believe that our raw material joint ventures are providing us with unique advantages in terms of the cost structure for our critical materials as well as the availability to secure enough materials to accommodate our customer requirements. These five joint ventures, located primarily in the Nanjing and Beijing areas in China, were established between 1999 and 2001, and supply nearly all of the critical raw materials used to manufacture our products, including gallium, arsenic, and germanium metal, as well as pyrolytic boron nitride (pBN) and boron oxide (B_2O_3). With relatively small investments, we have reaped tremendous financial and strategic rewards. We will continue to explore opportunities to expand our joint venture portfolio, both for current and new materials.

Q You also manufacture InP substrates. How is this market faring?

A The InP substrate market is largely driven by fiber optics, which has been down for several years. Our sales in this area today are not a significant contributor to our total revenue but they are steady and profitable. Further, we produce an outstanding product for this market and will continue to support our customers and engage in new qualification opportunities as they arise.

Q Some researchers have published reports that suggest that the low reserves of several raw materials needed for the manufacture of III-V substrates, such as indium, are a cause for concern. Do you agree?

A No, we have not received any information to date that would support this theory.

Q Do you plan to expand your business, by introducing sapphire, SiC or GaN substrates?

A We are always investigating new materials such as these and others. However, our current focus for expansion is the addition of capacity in strategic areas, such as larger diameter gallium arsenide, the development of differentiated products for emerging applications within the LED market, the development of 6-inch germanium substrates for terrestrial applications and the addition of joint ventures to round out our raw materials portfolio. These expansion initiatives reflect the demand that we are seeing from our customers and their long-term product and technology roadmaps.

Q How would you sum up where you are today?

A This is an encouraging time for AXT. We are seeing renewed growth across all of the primary markets we serve, fueled by long-term positive trends in wireless devices, LED lighting and photovoltaics. We have been successful in our diversification efforts with key qualifications of new customers and new applications that are strategically important to AXT. We are excited to see our hard work resulting in ramping production volumes and higher revenues. Further, careful and conservative management of our business has resulted in the return of our company to profitability, giving us a solid financial foundation for our continued success.

Our strategic and competitive, sustainable advantages clearly illustrate that AXT has a very bright future ahead.

Triple layer barriers combat LED droop

Switching from a simple quantum barrier to multiplayer variant can boost internal quantum efficiency at high drive currents by cutting the polarization within an LED and impeding current overflow.

Replacing the conventional InGaN barrier in a blue, nitride LED with a composite made from InGaN and GaN can reduce droop, the reduction in efficiency at high current densities.

That's the claim of a partnership led by Samsung LED company, which involves contributions from researchers at Pohang University of Science and Technology, Korea, and Rensselaer Polytechnic Institute (RPI), New York.

The origin of LED droop remains highly controversial, but RPI's Fred Schubert, a co-author of the paper, believes that it stems from polarization fields across the quantum wells. These fields increase the likelihood of electrons jumping across the well and undergoing non-radiative recombination in the LED's p-type region.

A few years ago Schubert's team demonstrated that AlInGaN and InGaN barriers can both reduce LED droop when they are polarization-matched to InGaN quantum wells.

However, it is difficult to grow high-quality epi-structures that incorporate either of these materials. High-crystalline-quality AlInGaN is difficult to realize, because the optimal growth conditions for incorporating indium are very different to those for adding aluminum.

InGaN often tends to form rough surfaces, so using barriers and wells made from this ternary film can lead to poor crystalline quality in the active region.

The Samsung-led team has sidestepped both of these issues with a three layer, $In_{0.1}Ga_{0.9}N/GaN/In_{0.1}Ga_{0.9}N$ barrier that offers a better surface for quantum well growth. Atomic force microscopy studies have verified the high quality surface produced with the triple-layer barrier.

The morphology of a multi-quantum-well structure containing five wells separated by this type of barrier is similar to that of a control sample with GaN barriers (see figure). And in both cases the surface contains the steps needed for growing high-quality p-type cladding layers.

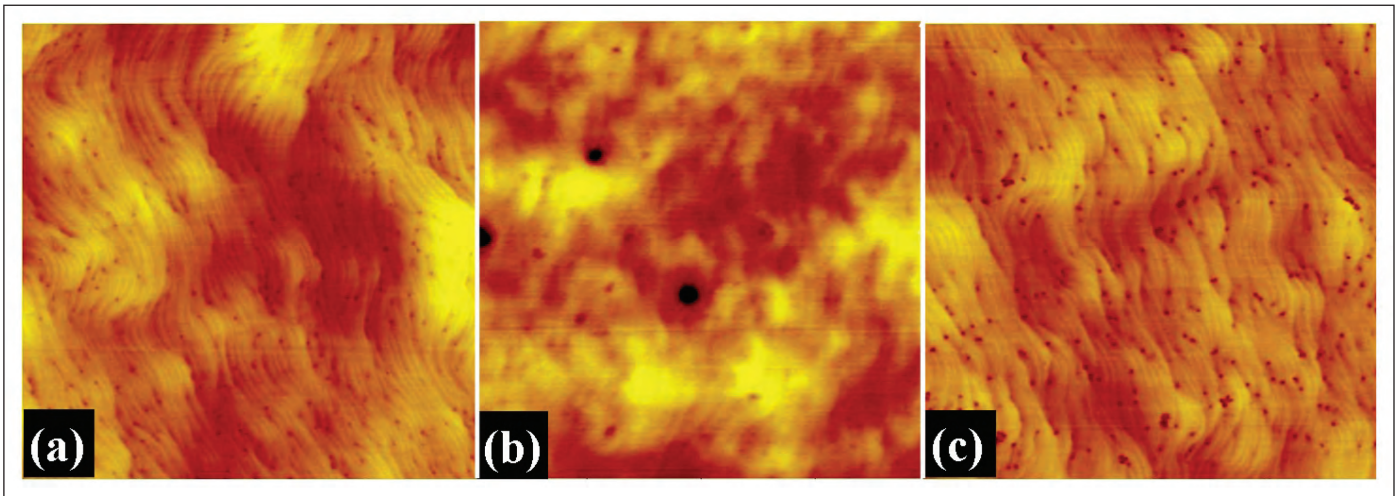
Four LED structures were produced in the study, each with seven quantum wells: a reference device with six GaN barriers; structures with two and four multi-layer barriers next to the p-side; and an LED with only triple-layer barriers. Corresponding author Hun Jae Chung from Samsung said that it took quite a while to find the best growth conditions - in terms of composition and thickness - for each layer of the multi-layer barrier structures.

"However, once this is done, we found that growth time did not increase much, and in some cases, it decreased slightly."

Reduced polarization in the novel structure was confirmed by time-resolved photoluminescence measurements, which revealed that this device had 19 percent lower polarization than a conventional LED.

Optical measurements revealed that increasing the number multi-layer barriers led to an increase in external quantum efficiency. Driven at a current density of 35 mA cm^{-2}, equating to 350 mA for a 1 mm x 1mm chip, the output from the best device was 37 percent higher than that of the standard LED.

H. J. Chung et al. Appl. Phys. Lett. **95** 241109 (2009)



Atomic force microscopy has been employed to compare the surfaces of three LED structures that do not contain any p-type layers: conventional structures with GaN barriers (a); a variant with $In_{0.1}Ga_{0.9}N$ barriers (b); and a novel structure with $In_{0.1}Ga_{0.9}N/GaN/In_{0.1}Ga_{0.9}N$ barriers (c). Structures (a) and (c)are broadly similar, but (b) contains pits with a depth of 10 nm that would hamper quantum well emission. Image Credit: SAMSUNG

SopSiC offers a base for low noise amplification

Researchers in France and Germany have built a nitride-based low-noise amplifier on Soitec's SoPSiC substrate that has a noise figure of just 0.12 dB.

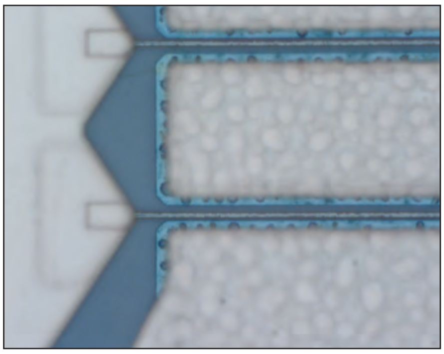
Lead-author Virginie Hoel from the University of Lille says that the amplifier has a similar noise figure to an equivalent device built on SiC, but is significantly cheaper thanks to the use of a composite substrate. SopSiC substrates are made by transferring a thin layer of single-crystal SiC onto a thick SiC polycrystalline wafer.

The team's nitride-based devices are able to withstand higher input powers than GaAs pHEMTs that are also used for low-noise amplification.

"Because the transistor can withstand high input power, it is possible to remove or simplify the input protection circuit in radar systems, such as S-band radars," explains Hoel. "Consequently, the design is simplified and a lower cost can be expected."

The researchers fabricated their devices by growing an AlGaN buffer, a 1.8 µm-thick GaN channel, and a 24 nm-thick, unintentionally doped barrier on a 2-inch SoPSiC substrate.

This material, which had a dislocation density of 10^9 cm^{-2}, was processed into 0.25 µm, T-shaped gate transistors with standard processing steps.



Low-noise amplifiers based on AlGaN/GaN HEMTs and grown on SoPSiC substrates could combine robustness, low noise and affordability. Credit: University of Lille

Characterization of a 2 x 140 x 0.25 µm transistor revealed a maximum drain-source current of 714 mA/mm at 5V, and an extrinsic maximum transconductance of 208 mS/mm.

The AlGaN/GaN HEMT had a current-gain cut-off frequency of 23 GHz, and a unilateral gain cut-off frequency of 58 GHz. The low noise figure of 0.12 dB was realized at a gate-source voltage of –3.5V, and a drain-source current of 203 mA/mm. These conditions produced 14.8 dB of gain.

V. Hoel et al. Elect. Lett. **46** 84 (2010)

Dots degrade solar cell

A European partnership between researchers at the Institute of Solar Energy in Madrid and the University of Glasgow has solved the mystery of why a class of intermediate band solar cells has relatively poor efficiency. According to the team, the addition of dots into the cells degrades the performance of this host.

Intermediate band solar cells are promising photovoltaics, because they have a theoretical efficiency of 63 percent, 22 percent higher than the limit for a conventional single cell. This higher theoretical efficiency stems from two processes that can be used to generate electricity. Electrons can either be promoted directly into the conduction band from the valence band, or via the intermediate band, through the absorption of two photons.

Researchers at Glasgow fabricated a range of intermediate band solar cells containing Strankski-Krastanov quantum dots. The current-voltage characteristics were measured at concentrations of up to 1000 suns. They found that the novel structures had an inferior efficiency to a conventional single-cell device, which was used as a control. Theorists at the Institute of Solar Energy modeled these cells with a circuit containing photocurrent generators and diodes. Fitting the model to the data revealed that additional quantum dots produced considerable deterioration of the cell.

"The remedy to this could be the introduction of strain compensating layers," says Antoni Marti from the Institute of Solar Energy.

A. Luque et al. Appl. Phys. Lett. **96** 013501 (2010)

Sumitomo: Semi-polar planes make better wells

Sumitomo has unveiled further characteristics relating to its record-breaking green lasers grown on a semi-polar plane.

Time-resolved photoluminescence studies on these devices - which have been grown by MOCVD on substrates with a threading dislocation density below 10^6 cm^{-2} – reveal the superior uniformity of the active region compared to a conventional nitride laser.

Measurements identified a localization energy for carriers/excitons in the laser's active region of 15.1 meV. This is about one-third of the value for green InGaN quantum wells grown on the c-plane. This indicates that the semi-polar plane is better for carrier delocalization, and that it should lead to the fabrication of lasers with lower threshold currents and higher slope efficiencies.

Sumitomo's engineers have also studied the polarization characteristics of InGaN quantum wells on semi-polar substrates over the 400-550 nm wavelength range. Increases in wavelength produce an increase in the polarization ratio. The team measured this ratio and concluded that a laser stripe perpendicular to the a-axis is best for green laser diodes.

M. Funato et al. Appl. Phys. Express **3** 021002 (2010)
T. Kyono et al. Appl. Phys. Express **3** 011003 (2010)