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AIXTRON

November / December 2010
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The LEDs ultimate application

Despite my interest in new technology I'm anything but an early adopter. I prefer my music played through a well-engineered turntable, I have an ageing mobile that's rarely got enough juice to take a call and my TV sports a cathode ray tube.

But a few weeks ago I decided to invest in the lighting of the future, the LED-based light bulb. What's it like? Well, in a word, fantastic. It sends out a beautiful warm white light that puts the fluorescent bulbs in the house to shame and it needs just 8W to pump out enough lumens to be considered the equal of an 40 W incandescent bulb.

So am I on the verge of replacing all the light bulbs in the house with LED-based ones? No. Although that would mean that I'd never have to shop for light bulbs for another 15 years, this exercise would set me back a £1000!

Instead, I'll bide my time while the LED industry continues to chip away at the cost per lumen. The attack will come on two fronts: reducing the amount it costs to make an LED; and increasing the amount of light this chip produces.

In this issue, two features offer entirely different takes on how to pull the first of those levers.

A piece from Aixtron describes a holistic approach to doubling throughput of multi-wafer MOCVD reactors. It's no surprise that turning to bigger wafers delivers part of this gain, but there are also improvements associated with substantially reducing the 'down time' thanks to the introduction of a new ceiling plate.

A far more radical way to slash chip costs is to dispense with GaN and turn to a cheaper material. ZnO could fit the bill because it combines low cost with the promise of efficient emission and widespread availability of its constituents.

Today ZnO LEDs are confined to the lab, but they will be in the fab by the middle of this decade, according to the market analyst Nanomarkets. The key question is how well they will sell. My guess is that in ten years time my house, along with many of yours, will be lit by GaN-based LEDs. But maybe I'll have bought one ZnO version, just to see how it stacks up.

Richard Stevenson PhD
Consultant Editor



CSindustry awards2011

From backlighting TVs to empowering mobile devices and harnessing the sun's energy, compound semiconductor chips are playing an ever increasing role in modern life. This is set to continue, but who had the biggest breakthroughs over the last 12 months? Which pioneering companies from around the globe created the best opportunities for the compound semiconductor industry?

The CS Industry Awards will recognise the success and development along the entire value chain of the Compound Semiconductor industry from research to completed device. The Awards will focus on the people, processes and products that drive the industry forward. Compound Semiconductor has created the CS Industry Awards to recognise the vital individuals and companies that enable a company to achieve success in a competitive global market.

The categories represent key areas where challenge met innovation. The CS Industry Awards are a platform

that allows the compound semiconductor industry to judge and make their voices heard about the people and products and practises serving this industry.

The CS Industry Awards will remind us what is good about the industry – the people who drive it with their technical expertise and customer orientated perspectives.

Nominations are open to all companies, individuals and organisations within the CS industry and voting will occur through Compound Semiconductor online and print services.

Category One:

Substrates, & Material Award
Epiwafer Tool Award
Epiwafer Processing Award
Metrology, Test and Measurement Tool Award
Metrology, Test and Measurement Process Award
Device Design and Packaging Award

Category Two:

Most Innovative Device Award
Fab Management Award
R&D Award
Chip of the Year Award

The call for nominations will close on December 17th 2010

www.csawards.net/nominate

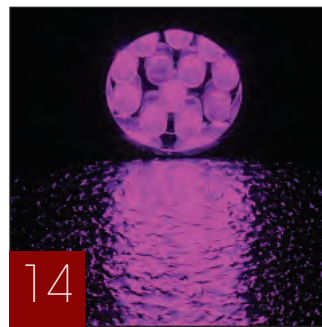
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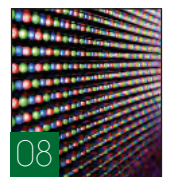
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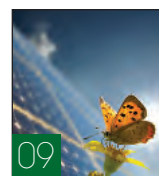
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Has gallium nitride found a way into the smart grid?

RESEARCHERS from the University of North Carolina, led by Jay Narayan have integrated gallium nitride with silicon as a material for electric grids. In light of this, the University of North Carolina is researching how to balance an increased energy demand with a more efficient means of delivery through "smart" grids.

The smart grid is a recent development in electrical engineering, which increases current distribution efficiency compared to traditional electric grids. However, with new technology comes the need for new material. Jay Narayan and John C. Fan have led a team of researchers for the past decade into the process of developing a way to "integrate" gallium nitride (GaN) onto silicon chips for the use of smart grids and other technologies.

Although storage capacity is limited, there is a large response on the industry's side to confront the problem. ABB, a multinational power technology company, has been looking into ways to improve storage technology. Despite being the leading company in the world for power technology, ABB has set up an outpost on Centennial Campus to research and enhance the present grid.

"You need the storage in order to charge up batteries when you can produce the energy,

so you can use the stored energy when it's not sunny, if you're using solar energy as an example," Le Tang, the VP and Head of the U.S. Corporate Research Center for ABB, said. "We are working on the interface of the renewable sources with the power grid. They don't naturally go together."

Narayan's goal is to be able to apply his new discoveries to the industry, especially for the "smart grid." He has been working closely with technology companies like ABB, Cree and Kopin to develop the connections necessary to make an impact with his new discoveries. Nevertheless, Narayan's focus is not limited to smart grids. He is first and foremost a materials scientist, so his main concern was to figure out a way to "marry" GaN to silicon.

Besides its use in smart grids, GaN can be used in various sorts of electronics, including LED lighting and high frequency communications for the military. The potential for savings is so great that the government has invested a plethora of resources into the research. Narayan has received much of his funding from the National Science Foundation (NSF), which has been an important contributor to smart grid research. The NSF has poured an additional \$18.5 million into the FREEDM Center on Centennial Campus, which is the centre for the smart grid research.

TriQuint receive NRL contract for GaAs MMICs

TriQuint Semiconductor, a RF products manufacturer and foundry services provider, has received a \$2 million contract from the U.S. Naval Research Laboratory (NRL) to develop S-band amplifiers with new benchmarks for noise floor, linearity and efficiency performance.



TriQuint was awarded the contract based on its expertise with GaAs and other technologies. The NRL (MMIC) contract will focus on low noise amplifiers and high power amplifiers (LNAs / HPAs).

"We're pleased the U.S. Navy has chosen TriQuint again for another program. It's exciting to explore another opportunity with the NRL that advances the state of the art," said Tony Balistreri, TriQuint Marketing Director.

Dow breaks ground in Korea

DOW ELECTRONIC MATERIALS, a business unit of The Dow Chemical Company has announced plans to build a new metalorganic precursor manufacturing plant in Cheonan, Korea. The construction of Dow Electronic Materials' new Korea plant is part of a multi-phase plan announced in June 2010 to expand TrimethylGallium (TMG) production capacity to meet the surging global demand for the material in the LED and related electronics markets.

The facility is expected to be operational in early 2011. Capacity expansion in the United States at existing facilities is also progressing as planned, with new capacity expected by the end of 2010 and continuing

through the first quarter of 2011. Total additional capacity resulting from the multi-phase plan is expected to be 60 metric tons per year.

"Meeting our customers' near-and long-term needs for high-quality materials continues to be a priority for us," said Joe Reiser, global business director, Metalorganic Technologies, Dow Electronic Materials.

TMG is a metalorganic chemical vapor deposition (MOCVD) precursor material that is critical to the manufacture of LEDs and other compound semiconductor devices. Exceptionally high-quality materials and precise delivery of metalorganic precursors are essential to building reliable LEDs.



SiGe BiCMOS technology

PLESSEY SEMICONDUCTORS has commenced the development of a 0.35 micron silicon germanium (SiGe) BiCMOS process technology on its 8-inch line at its Plymouth, England semiconductor manufacturing facility. As part of its strategy of developing its three core product lines of sensors, RF components and power

management devices it was decided that a bespoke SiGe BiCMOS process was required.

The products manufactured on this process will take advantage of having a 70GHz, 2.5V breakdown voltage architecture together with a 40GHz 5V breakdown

voltage architecture on the same substrate. Peter Osborne, Chief Technologist, said, "We have looked at SiGe bipolar and BiCMOS process technologies for some time and have developed processes for other fabs. We believe that our exceptional complementary bipolar processes on SiGe together with our 0.35 CMOS capability should provide a compelling platform from which Plessey can develop outstanding product lines."

GaAs & GaN based Amps to Overshoot Silicon

STRATEGY ANALYTICS predicts that the GaAs and GaN based MMIC and hybrid amplifier market is estimated to reach \$227 million in 2014. The global conversion from analog to digital broadcasting standards, which increases consumer demand for bandwidth, intensive applications and new services is driving strong growth in CATV.

The recently published Strategy Analytics GaAs and Compound Semiconductor (GaAs) data model, "CATV Infrastructure Amplifier Forecast 2009-2014," projects a 10% CAAGR from 2009 to 2014 for the hybrid and MMIC amplifiers used in CATV infrastructure.

This analysis shows a shift away from Silicon to GaAs and GaN-based amplifiers. Strategy Analytics projects GaAs hybrid and MMIC amplifiers to grow at a CAAGR of 21%, more than twice the market, to reach slightly more than \$160 million in 2014.

GaN hybrid amplifiers will enter the market in 2010 and grow strongly to reach nearly \$18 million by 2014. During this same time, Strategy Analytics forecasts that Silicon MMIC and hybrid amplifiers will decline with a negative CAAGR of 9% falling to \$49 million in 2014.

"CATV network infrastructure is no longer just television. It is central to the "triple-play" of voice, video and data," noted Eric Higham, Director of the Strategy Analytics GaAs Service. "As consumers adopt new bandwidth-intensive services, networks become more sophisticated to keep pace. This will encourage strong growth and attractive opportunities for amplifier suppliers in the industry."



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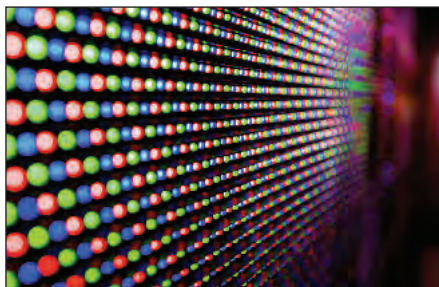
INNOVATIVE SOLUTIONS FOR SEMICONDUCTOR INDUSTRY

RIBER

6-Inch Full-Field Projection Exposure System

USHIO America, a provider of specialty and general illumination lighting solutions as a wholly owned subsidiary of USHIO Inc, today announced that the company has started marketing the world's first 6-inch full-field projection exposure system for manufacturing LED chips in the US.

USHIO successfully developed its new exposure system — model UX4-LEDs — that allows full-field exposure of 6-inch wafers while preventing wafer warpage or distortion, achieving a throughput enhancement of 300% compared with conventional stepper systems. The UX4-LEDs exposure system is based on the same platform as USHIO's field-proven UX series full-field projection exposure systems



for semiconductors, FPDs, printed-circuit boards and MEMS. USHIO already has installed more than 1,000 units of the UX series systems throughout the world.

"The UX4-LEDs projection exposure system is one of the most innovative items of LED manufacturing equipment today. Based on a

collection of our lighting-edge technologies that USHIO has fostered in its field-proven UX exposure system series, it is the world's first 6-inch wafer full-field projection exposure system. It will allow major LED manufacturers to dramatically increase their mass-production capacity while lowering their manufacturing cost," said Kenji Hamashima, President/CEO of USHIO America. "We are confident of introducing this new product into the US market and gaining top market share by reinforcing our sales and technical support forces. We expect to ship the first unit within this year, since several major LED manufactures have already been evaluating this system for mass-production."

EV GROUP announces 20%+ increase in revenue

EV GROUP today announced that the company witnessed a more than 20-percent increase in overall revenue during fiscal 2010, ended September 30. EVG attributes this growth, in large part, to continued demand for equipment used in advanced manufacturing of 3D ICs, CMOS image sensors and MEMS devices.

In fact, the company reports it has grown, on average, approximately 20 percent year-over-year since 2003—successfully avoiding a drop in order intake and revenue even in 2008 and 2009 despite the global economic recession. According to Hermann Waltl, EVG's executive sales and customer



support director, the company capitalizes on its technology and market leadership by continuously building upon its extensive experience in bringing new and innovative products to market. "It's been another solid year for our company and demonstrative of our continuous investment in R&D. We firmly believe that our strong emphasis on R&D provides us with an edge in supporting our customers' increasingly sophisticated manufacturing requirements.

As a result, we've witnessed continuous year-over-year growth since our inception in 1980—as well as expansion into key, high-growth markets, which has played a

significant role in allowing us to navigate through this cyclical economy." EVG also announced that its EVG770 Automated NIL Stepper won the prestigious fifth annual EuroAsia Semiconductor IC Industry Award in the category of back-end-of-line (BEOL) wafer processing.

The IC Industry award winners are voted by customers and users of the tools. This win points to the company's excellence in service and the technology prowess of the EVG770 system, which is designed for step-and-repeat large-area UV-nanoimprint lithography (UV-NIL) processes for various applications, including 3D ICs, MEMS and CMOS image sensors.

Aixtron Installs 2 MOCVD Systems

AIXTRON has installed two AIX 2800G4 HT 2 inch MOCVD tools at Jiangxi Changda, a new customer in the southern province of PR China. The new HB GaN LED growth reactors have been successfully installed and commissioned by the local Aixtron support team at the company's facility.

Lu Bo, Executive VP of Jiangxi Changda comments, "I have been impressed with the reputation of this equipment thus our team has been looking forward to the arrival of the new AIX 2800G4 HT MOCVD reactors. We need them to comply with our planned capacity increase as we manufacture more LEDs to meet the strongly growing demand. The Aixtron systems match our specification for process flexibility, thickness uniformity, doping, and

composition. We had a swift and efficient installation thanks to the Aixtron close local support and service."

Christian Geng, VP Greater China and General Manager at Aixtron Taiwan adds, "This is an important sale for Aixtron for several reasons: Jiangxi Changda is a subsidiary of Lattice Power Corporation in Nanchang, Jiangxi Province, which is one of our long-time customers and one of the first in China.

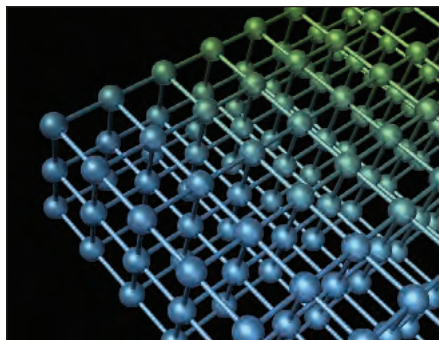
This company relies on several Aixtron MOCVD systems to develop and manufacture HB LEDs for full color displays. Lattice Power is also scaling up its R&D for the production of HB GaN LEDs on silicon substrate for even more cost efficient devices."

DTU Danchip to spearhead nanotube research

AIXTRON AG has announced a new order for a Black Magic Plasma Enhanced CVD (PECVD) system from DTU Danchip and DTU Nanotech at the Technical University of Denmark in Lyngby, Denmark.

The institution placed the order for a 4-inch configuration deposition system during the second quarter of 2010. Following delivery in the current quarter, it will be used for the growth of graphene and carbon nanotubes for a number of different applications, such as cell-microchip interfaces, lab-on-chip filters and other microfluidic components, transducers and electrodes. Several research groups covering physics, chemistry, lab-on-chip and lifescience subjects will use the new system.

Associate professor Peter Bøggild from DTU Nanotech comments, "We wanted a turnkey solution for graphene and carbon nanotubes. In our evaluation, the Black Magic system was indeed very mature and capable of large-scale, homogeneous production of these carbon nanomaterials in a reproducible manner. Since one of our main objectives is research for practical applications, reproducibility, reliability and scalability in addition to material quality are vital. Based on recommendations from trusted researchers and personal



experience, we have no doubt that the AIXTRON system will live up to our high expectations. In fact, we have a long line of users ready to use the Black Magic system."

Peter Bøggild received his Ph.D. degree at Copenhagen University in 1998 and is head of the Nanointegration research group at the DTU. He received the prestigious Danish award 'AEG Elektronprisen 2009' for his pioneering work on nano-tweezers and actuators, and has worked with carbon nanomaterial for many years.

The Danchip cleanroom contains a selection of state-of-the-art process equipment for lithography, etching, thermal processing, thin film deposition, packaging and characterisation, professionally maintained.

Exceptional y-on-y growth predicted for CIS/CIGS

MARKETSANDMARKETS report 'Thin Film PV- Advanced Technologies and Global Market (2008-2015)' says that the CIS/CIGS market is expected to grow with a maximum CAGR of 43.9% from 2010 to 2015. Low cost and optimum efficiency of thin film PV cells is driving the growth of the thin film PV in overall photovoltaic market, says MarketsandMarkets. The global thin film photovoltaic market is expected to grow from \$3,406 million in 2009 to \$19,422 million in 2015, at an estimated CAGR of 32.2% from 2010 to 2015.



The amorphous silicon market is currently contributing the maximum proportion to the total thin film PV market with growing opportunities.

Lesker Valves



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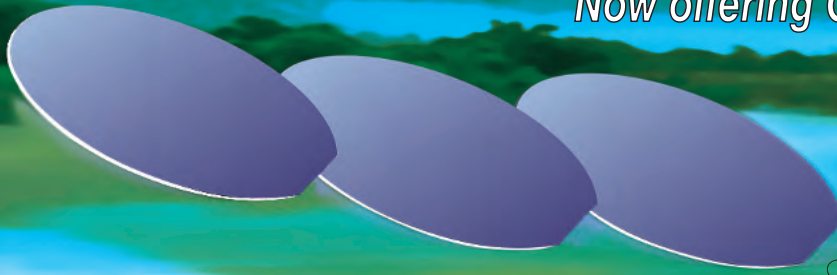
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CPV market is tipped for take-off

The concentrated photovoltaics industry should deliver massive growth over the next few years, according to market analyst **Carlos Márquez from CPV Today**. But this success requires recent installations to demonstrate that this technology can generate electricity reliably, while offering investors a good return on their money. Richard Stevenson reports.

For many people the recent economic downturn will be the toughest that they have ever lived through. While it may not have been as bad as the depression of the 1930s, when thousands and thousands queued on the streets for hours for food, many people have lost their job, seen the value of their investments plummet and are now facing a reduction in the services provided by their government, which is squeezing its belt.

It's not just individuals that have suffered over the last few years. Industry has also taken a battering, with the lack of available capital hitting the emerging technology sector hard. This includes the concentrated photovoltaics (CPV) sector, a fledgling industry that was widely tipped to take off in the days before the phrase "credit crunch" had been coined.

The lack of capital available to CPV start-ups has hampered their efforts to promote themselves; accelerate their research and development; and expand their manufacturing capacity. It has also been a contributing factor to acquisitions, such as that of Sol3G, which has gone under the wing on Abengoa Solar. In addition, capital constraints have led to postponement of some installations, including the world's biggest CPV deployment, a 154 MW project in Mildura, Australia. This was caused by a Chinese investor withdrawing funding from Solar Systems.

However, some of the CPV system builders have made progress over the last few years. Carlos Márquez, an analyst at CPV Today, points out that Concentrix scaled up in 2008, which was right in the middle of the whole credit storm. And at the start of this year Amonix announced that it aimed to increase its annual production capacity from 30 MW to 100 MW per annum. By the end of this year this US outfit may well have topped that figure, because this July it also signed a lease on a manufacturing facility in North Las Vegas, Nevada,



Concentrix Solar GmbH, a spin-off of Fraunhofer Institute for Solar Energy Systems, was founded in 2005 and is located in Freiburg, Germany. It expanded its production capacity in 2008, and is now actively pursuing a development of a 50 MW utility-scale power plant in the Western Cape, South Africa. Credit: Concentrix

creating nearly 300 jobs and the opportunity to add a further 150 MW of production capacity. Márquez believes that this hike in capacity will pay dividends, allowing Amonix to attain economies of scale.

It's not just the likes of Amonix that have a positive view of the future. Despite concerns over double-dipped recessions and very slow recovery rates, investors are

showing an increasing interest in CPV technology. Deployment of these systems is also on the up, and Márquez calculates that there has been more than 70 MW of new project announcements scheduled for 2010.

By far the biggest of these is a 59 MW installation in Taiwan that will be undertaken by Guascor Fotfin and Ya-Fei Green Energy. Once completed, this will be the largest CPV installation in the world. There have also been announcements of 1 MW projects by Concentrix Solar, Sol Focus and Opel, which will lead to CPV deployments in Questa, New Mexico, Victorville, California, and Portugal.

Looking further ahead, Márquez is tipping the industry for tremendous growth over the next few years, estimating that installations could approach 1 GW by 2016. However, he openly admits that there is a high degree of uncertainty in that headline figure.

Crunch time

Márquez believes that the future of CPV rests on the outcome of projects currently being deployed, which typically range in size from several hundred kilowatts to one megawatt. "These projects will set the track record for CPV. I think that the market will take off in terms of revenue if companies can prove that those projects have been successful; were built on-time, on-budget; produce an amount of electricity that they were meant to produce; and that they made investors a decent return."

It is possible that the CPV market could top the 1 GW mark by 2016 because Márquez has only considered deployments of grid-connected solar farms with an output of at least 500 kW. There are also opportunities for CPV systems to provide power for either companies, or for

rural communities that are not connected to their nation's electrical infrastructure. "Those installations require smaller capital costs, which makes them a good way for companies to get started and upgrade their technology," says Márquez.

If Márquez's prediction for a tremendous ramp in CPV system deployment happens, it should not put undue strain on this industry. That's because a good supply chain has fallen into place over the last few years. The vast majority of firms involved in CPV are specializing in one area, such as the manufacture of solar cells, the building of modules, or the construction of solar systems. "The only company that I am aware of that is completely integrated is Emcore," says Márquez.

Cell multiplication

One of the key components in every CPV system is the triple-junction solar cell. According to Márquez, no concerns have been reported regarding the reliability or performance of these cells, which are typically used with light concentration factors of 500. The thermal load on the cell is preventing progression to even higher concentrations, which promise a cut in electrical generation costs. However, there are ongoing efforts at improving thermal management, including research at IBM.

CPV system manufacturers now have far more sources for obtaining their triple-junction cells. For many years the choice was between two US suppliers, Emcore and Spectrolab, and the European photovoltaic manufacturer Azur Space Solar Power. Now the likes of Cyrium Technologies, Spire Semiconductor, Solar Junction, Microlink Devices, Arima and Sharp can be added to this growing list, which will soon be strengthened by III-V stalwarts RF Micro Devices and JDSU.

Márquez is adamant that increased competition will be good for the CPV industry. A couple of years ago there were fears that cell production would fail to keep pace with a sharp increase in demand for CPV systems. "With the new entrants I don't think that there is a chance that there is either going to be a shortage, or a situation where a few suppliers control the market."

Triple-junction solar cell costs should fall thanks to greater competition between their manufacturers. In turn, this

Sol Focus is winning contracts for larger and larger CPV deployments. In 2008 it completed a 200 kW installation in Puertollano, Castilla-La Mancha, Spain, and this year it finished a 1 MW facility in Victor Valley College in Victorville, California. While many CPV system manufacturers use Fresnel lenses to focus the sun's rays, Sol Focus prefers to use mirrors for this purpose. Credit: Sol Focus



should help to reduce system costs, but it will not make a huge impact. To really drive down the cost of CPV systems requires a significant cut in the cost of the tracker, which is the most expensive component.

The high cost of these trackers, which tend to be a dual axis design, stems from the level of engineering employed to create an incredibly precise tool for focusing the light onto the cell. What's needed, according to Márquez, is the introduction of "clever optics" that will cut costs by allowing tracking systems to be less precise without compromising performance; easier and cheaper to manufacture; and easier to repair and maintain.

Lenses or mirrors?

The tracker adjusts the angle of the modules that contain either mirrors or Fresnel lenses for focusing light onto the cells. Of these two technologies, the latter is becoming increasingly popular. "It is tried and tested. It does the job, and there is a good supply of lenses," says Márquez.

A choice of lenses will help to reduce the CPV systems' cost, which can be measured in several ways. Calculating the cost-per-Watt is a very common approach throughout the solar industry, but one that Márquez dislikes, because it ignores the lifetime of the system.

"The lifetime cost of the system is more important than the cost-per-Watt installed," argues Márquez. In his opinion, a system that is more expensive on a cost-per-Watt basis but produces more electricity and lasts for 40 years is likely to yield more profit than a cheaper system that fails after 20 years. "The cost of energy is probably a more useful metric."

On that basis, a CPV system already offers the cheapest way to generate electricity in some parts of the world. On islands such as Hawaii most of the electricity is currently produced by diesel generators, a relatively expensive way to generate power.

Most people don't live in such remote locations, however — burning coal produces most of the electricity consumed by humanity. Today this electricity generating process is significantly cheaper than that associated with CPV systems, but this margin does not have to be eliminated to make the greener technology an attractive option for some companies. That's because the utilities have to make a profit. If a company can install a CPV system on its grounds, and the cost of the electricity produced is comparable to the price it pays the utility, then it may decide to invest in this technology.



This summer Amonix completed its 240 kW CPV system deployment at the River Mountains Water Treatment Facility, Nevada. Recent efforts by this company also include a substantial expansion to its manufacturing capacity. Credit: Amonix.

It is expected that there will come a time when CPV reaches grid parity in most places. Márquez expects that to take four to five years, by which time the generating costs of a typical CPV system will be around \$0.08/kWhr.

As electricity generating costs for CPV systems fall and deployment rockets, many of the 35 or so system manufacturers in this sector will flourish. But it will probably not be a wonderful time for all. "In the solar industry in general there seems to be a trend for larger, more established companies acquiring smaller companies with specialist technologies," says Márquez. "I think we will see that happening in CPV as well."

● Carlos Márquez is the author of *The Concentrated Photovoltaics Industry Report 2010*. See www.cpvtoday.com/cpv-report

"In the solar industry in general there seems to be a trend for larger, more established companies acquiring smaller companies with specialist technologies. I think we will see that happening in CPV as well." Carlos Márquez, CPV Today

LEDs: ZnO prepares to leap from lab to fab

A dozen or so companies are developing ultraviolet and white LEDs for market. In two to four years time products will launch and kick-on to net over \$400 million by 2015, according to NanoMarkets analyst Lawrence Gasman. **Richard Stevenson investigates.**



As a material for making LEDs, ZnO has loads to recommend it. It is cheap, non-toxic, and chemically stable; it is incredibly well understood; it can emit light very efficiently; and it is capable of making devices that span the ultraviolet to the infrared. However, despite all its promise, the ZnO LED has failed to make any commercial impact. That is partly because material issues have hampered device development — realizing p-type doping in this material has been a major challenge, and there have also been differences of opinion over the design of the active region needed to yield a light-emitting device.

While these issues have undoubtedly hampered the progress of the ZnO LED, they are not the primary reason why this device is still confined to the lab, according to Lawrence Gasman, Principal Analyst at the market research firm NanoMarkets. He believes that if a large firm had financed a major effort at commercializing ZnO LEDs, they could have ironed-out the technical issues in just a year or so.

"I see the obstacles as being on the business side," says Gasman, who points out that winning venture capital investment for novel semiconductor businesses is far, far harder than it was before the credit crunch. However, that's not to say that there is no funding for ZnO LED development. This device has 'green' credentials, and some start-ups have won funding on the back of that attribute.

Gasman expects the first ZnO LEDs to hit the market in two to four years time. "The LED market is slated to grow very fast now, and if ZnO can knock off a segment of that market in a time starting in three or four years from now, then that [sub-section of the] market can be very substantial." He believes that ZnO LEDs will make an impact and net \$415 million in 2015. That will make this device the biggest earner for ZnO, which will also be used to build transistors and provide a transparent, conductive oxide for displays and photovoltaics (see box "The great versatility of ZnO").

Starting with ultraviolet

The pioneers of ZnO LED manufacture will begin by making ultraviolet emitters. This is the simplest form of the device to produce, because ZnO's bandgap is 3.3 eV.

"The market for [ultraviolet lighting] is not huge, but it's a good place to start, because you are not completely reliant on the whims of everyday consumers," claims Gasman. Today lamps with fairly short lifetimes are the most common providers of ultraviolet emission, which is used for water purification and medical treatments. ZnO LEDs promise to be a far more reliable source.

Another reason why ZnO LED makers will target the

ultraviolet market first is that it will allow them to get their businesses off of the ground without having to compete with huge, well-established GaN chipmakers. "If you are in the UV business, you are talking about a much more modest supply chain [than the general illumination business], which a small firm could conquer with a couple of decent sales guys and a business development guy," says Gasman.

Once the ZnO LED manufacturers have enjoyed some success in this market, they will add phosphors to their devices to produce white emitters. These promise to be cheaper than the GaN incumbents, which are starting to penetrate general lighting but need to drop in price to fuel the rapid adoption of this technology.

"The hope is that ZnO will give a range of colors that are more attractive than CFLs and GaN LEDs," says Gasman. This could help to spur the sales of these ZnO emitters, because, according to Gasman, many people have the perception that GaN-based LEDs produce a cold and harsh form of white light. "The companies that are working on ZnO LEDs claim that you can get better color quality from these LEDs."

According to Gasman, another strength of the ZnO LED is the abundance of its constituents: "There is plenty of nitrogen around, but maybe there is some constraint on gallium. Remember that there has been a dance between cost and supply of indium, for indium tin oxide." Although incredibly small amounts of indium tin oxide are needed to make a display, billions and billions of screens are made every year.

One difficulty facing the pioneers of any innovative technology is the reluctance of potential customers who may be suspicious of adopting the new materials. However, this should not be a major issue for the ZnO pioneers. "Samsung has announced using carbon nanotubes for backlighting and displays, and they are actually producing that now," says Gasman. He is also aware of companies working with silicon quantum dots, and he sees ZnO as just another emerging material in this sector.

According to Gasman, there might be up to a dozen companies working towards the commercialization of ZnO LEDs. They tend to keep a very, very low profile. "In some cases they are funded by famous names," says Gasman.

The progress of all of these firms is held back by the materials and processing equipment. One issue is that there are only about ten producers of crystalline ZnO, and the substrate sizes produced by them are too small for mass production. For example, the material offered by the Atlanta-based firm Cermet is either shipped as 10 mm by 10 mm squares, or 25 mm-diameter circular substrates.

Although ZnO LED developers would prefer to manufacture their devices on native substrates, partly because this should offer the best route to high quality material, these firms might begin by using sapphire. The difference in lattice constant between ZnO and GaN is only a few percent and both materials share the wurtzite crystal structure, so many of the challenges of growing these wide bandgap materials on sapphire are similar.

ZnO LED developers are yet to reach a consensus on the best deposition technique for epitaxial growth of the heterostructure. For many of these firms, optimization of the growth technology, which will form a key part of their intellectual property, is their overriding goal.

It is possible to buy commercial ZnO deposition tools, such as the range of MOCVD reactors made by Structured Materials Industries of Piscataway, NJ, that feature high-speed rotating discs. These Spin CVD tools – which are available as single wafer, 1-inch or 2-inch tools, or multi-wafer variants capable of accommodating up to 38 wafers with a 2-inch diameter – employ a uniformly heated deposition plane and are capable of growth rates of 10-20 nm/minute (for more details see “Nitride LEDs get brighter with transparent ZnO contacts,” *Compound Semiconductor* September 2007, p. 14).

However, according to Gasman, many ZnO developers are not buying commercial tools and using them off of the shelf. Instead, they are either building their own tools or adapting commercial ones. In some cases, they are also pioneering novel forms of growth. For example, ZnO device specialist MOXtronics, which is based in Columbia, MO, has developed a hybrid beam deposition

“The great versatility of ZnO”

Interest in ZnO is on the rise. According to the research firm Nanomarkets, which is based in Glen Allen, Virginia there has been a flurry of patent activity over the last few years. What’s more, sales of ZnO device and coatings are now set to take off, more than tripling to \$1.3 billion in 2015 and hitting \$2.3 billion by 2017. A significant proportion of this revenue will come from the sale of LEDs.

However, ZnO will be increasingly used as a low-cost electrode and conductive coating in displays, lighting and photovoltaic applications. There is also interest in ZnO thin-film transistors, and ZnO-based power electronics.

process that it claimed to be comparable to MBE. The unique features of this MBE-related approach are a ZnO plasma source, which is produced by illuminating a polycrystalline target with either a pulsed laser or an electron beam, and a high-pressure, oxygen plasma created by a radio-frequency oxygen generator.

Another issue that ZnO LED developers might be struggling with is the design of the active region. Some researchers are employing a homojunction, while others are considering which pairing of materials is best for forming the active region. Some of the early work on ZnO light emitting structures involved the combination of ZnO and MgZnO, but more recent research has shown that this ternary tends to phase separate when the magnesium content exceeds 33 percent, due to differences in crystal structure – MgO is cubic. One promising alternative is BeZnO, which shares the hexagonal crystal structure of ZnO.

There is no doubt that all these ZnO developers face an up-hill task. However, they will be motivated by the dream of creating cheaper, high quality ultraviolet and white LEDs. And if companies in the supply chain can share their vision and play their part, then many of the manufacturing issues will fade away. For example, although the crystalline ZnO substrates available today are too small for high volume manufacture, the technique to produce them, hydrothermal growth, is well established and churns out tones and tones of quartz every year. If such efforts to scale up ZnO are applied alongside other activities to improve the supply chain, then maybe the solid-state lighting revolution will turn out to be a two-pronged affair: GaN LEDs and their ZnO cousins.

- Lawrence Gasman is the author of the report *Zinc Oxide Markets, 2010 and beyond*.



AlN: can it become a universal substrate for III-nitrides?

Physical vapor transport can produce high-quality 2-inch AlN crystals with low dislocation densities. Substrates sliced from these crystals provide an ideal platform for the growth of ultraviolet LEDs, lasers and RF devices, says a team from **Nitride Crystals**.

III-nitrides are undoubtedly a remarkable family of semiconductors. Unlike their semiconductor cousins, high-quality films of this material can be grown on almost any substrate - sapphire, silicon and even glass.

However, despite their propensity for forming single crystals on practically anything, no III-nitrides occur naturally. Consequently, there has been continuing interest in manufacturing a native, single crystal substrate for these nitrides since the first demonstration of epitaxial growth of GaN by HVPE in 1969 by Paul Maruska and co-workers at RCA Sarnoff. Over the intervening decades nitride devices have kicked on to demonstrate unexpectedly good performance characteristics despite high dislocation densities. Blue LEDs, for example, can realize excellent reliability and power at dislocation densities of $5 \times 10^9/\text{cm}^2$, a value that would kill light emission in their GaAs and InP longer wavelength cousins. However, in general, semiconductor devices have shown highest performance on low-defect native substrates, so there is no reason to suspect that the III-nitrides, even with their unique growth habit, will be any different.

There are three options for native substrates: AlN, GaN and InN. To date, no one has produced bulk crystal InN; GaN has been grown from solution at high pressure; and AlN has been produced using relatively straightforward physical vapor transport (sublimation). Another strength of AlN is that it is the most promising universal substrate for epitaxy of a wide variety of nitride devices, including LEDs, lasers, RF and surface acoustic wave (SAW) devices. Of all the III-nitrides, it has the largest bandgap; highest thermal conductivity, breakdown electric field and SAW velocity; and the smallest *a*-lattice parameter. What's more, deposition of high-quality epilayers on this platform is relatively easy, because all AlInGaN compositions are in compression when grown on AlN, thus minimizing cracking probability.

However, although the PVT process used to grow true bulk AlN crystals was first identified by Glen Slack and co-workers at GE Research Lab more than 35 years ago,

it has proven extraordinarily difficult to grow large diameter, low-defect crystals, even with well established experience in SiC growth. Initially, there was little interest in scaling crystal dimensions of AlN, but this has now changed thanks to the dramatic success of the nitrides.

Today, a handful of companies have reported success in developing at least small, high-quality AlN substrates. These include the US firms Crystal IS, Hexatech and Fairfield Semiconductor; the Japanese materials specialist Sumitomo Electric Industries; the German outfit CrystAlN; and ourselves, Nitride Crystals, which has bases in both the US and Russia. To our knowledge, we, along with Fairchild, are the only companies shipping AlN substrates on a commercial basis. We focus on sales of round substrates, while Fairchild ships 10 mm squares. Of the other players, CrystAlN has recently entered the market, and Crystal IS and Hexatech have reportedly established internal production of AlGaN devices such as deep UV LEDs. Perhaps the fact that both Crystal IS and Hexatech have decided to focus their AlN wafer manufacturing toward their own device products is the clearest indication of the potential importance of that material.

Our approach to operating in the AlN substrate and device market is based on this belief: The AlN substrate and device markets will never be significant unless major device players and substrate manufacturers adopt the technology. Therefore, we place no restrictions on how

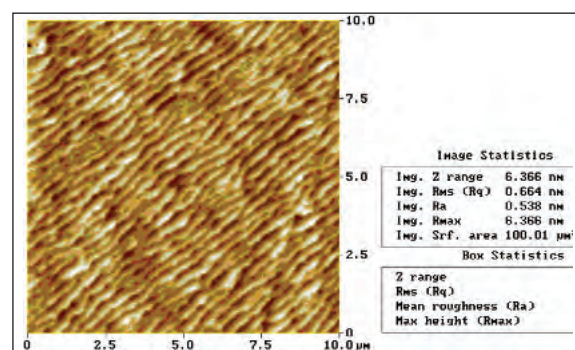


Figure 1 AlGaN epitaxy on AlN

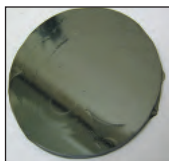


Figure 2 Thick, micropipe-free 60 mm diameter 6H-SiC seed

our customers use our AlN substrates. Production of our substrates has been governed by two major factors: nitride epitaxy on sapphire has a dislocation density of $5 \times 10^7 - 5 \times 10^8/\text{cm}^2$, yet LED performance is excellent; and commercial manufacturers of optical devices need 2-inch wafers as a minimum size. Taking these factors into account, we have set ourselves the goal of scaling our wafer capability to 2-inch diameter as quickly as possible while maintaining quality that is “good enough.” What is our take on “good enough”? That the density of substrate dislocations is three-to-six orders of magnitude lower than that of epitaxy on sapphire.

We have developed production technology for delivering a range of 15 mm diameter AlN crystals and epi-ready substrates, which can be shipped with the aluminum face epi-ready polished, and the nitrogen-face polished or fine lapped, with US flats. All variants have excellent crystallinity, low dislocation density, high UV transparency and high resistivity. This is borne out by X-ray diffraction maps that show that the single peaks of the best substrates have a full-width half maximum less than 100 arcsec in both asymmetric and symmetric scans. These substrates provide a foundation for growing high-quality AlGaIn layers (see Figure 1). We have also recently shown that it is possible to produce larger crystals - we have achieved fully mono-crystalline 2-inch diameter AlN by using low defect SiC seeds that we also grow by PVT.

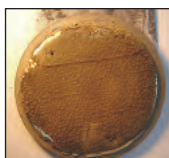


Figure 3 AlN layer separated from SiC seed and attached to crucible lid

Scaling to 2-inch

Early in our AlN development we realized that AlN can be successfully seeded by PVT on SiC. The growing AlN-and-SiC seed forms a solid solution. Near the interface the concentration of silicon and carbon in AlN can be higher than 5 percent, giving rise to conductive AlN; however, the concentration of these two elements falls rapidly with distance from the interface, where resistivity is far higher. Second-generation (grown on AlN seeds) AlN has resistivity in excess of 5×10^{11} Ohm-cm. We have not studied the effects of silicon concentrations of more than 5 percent in AlN, but on the basis of the seed growths we speculate that it will be possible to make conductive AlN (or perhaps more correctly AlSiN?).

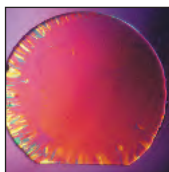


Figure 4 A crossed polarizer photo of a typical wafer. The edge striations have not been fully removed by diameter grinding

A micropipe-free, low dislocation seed is required only for the initial growth of a thick AlN layer. Figure 2 shows the initial micropipe-free 6H-SiC seed. Once this thin AlN layer is separated from the SiC, it is then employed for the growth of the AlN bulk crystal. Figure 3 shows the AlN layer separated from the SiC seed and attached to the crucible lid. The pattern of cracks that heal during bulk growth attests to the high quality of the AlN seed layer.

Typically, as shown in Figure 3, the seeds used to produce 2-inch AlN have a diameter that is much larger. This removes edge striations and defects that occur during growth. The high quality of this material is revealed by the lack of features in crossed-polarizer images (see figure 4). Before the AlN crystals are ground to 2-inch diameter, they are used as seeds for fabricating AlN material of this size.

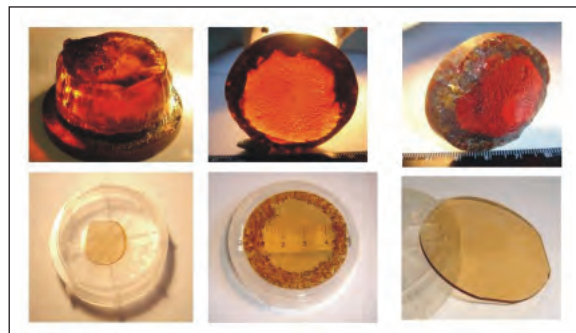


Figure 5 Evolution of AlN crystals and substrates from 15 mm to 2-inch diameter

AlN sublimation issues

Our outfit, just like the team at CrystAlN, has extensive expertise in the growth of bulk single crystal SiC. However, despite this background, scaling up the growth process to 2-inch has been surprisingly difficult. Unlike SiC, AlN dissociates congruently into aluminum and nitrogen gas; however, aluminum vapor at high temperature is extremely reactive and forms lower-temperature eutectics with many materials that would be otherwise inert. To deal with these issues, we use TaC crucibles, which is a process that Hexatech and CrystAlN have also reportedly adopted. These crucibles are employed for the growth of the initial thick layer of AlN in a graphite system. A combination of TaC and tungsten crucibles, along with tungsten reactors, is then used for growth of bulk crystals. The historical evolution of our AlN crystals from 15 mm diameter to 2-inch diameter is illustrated in Figure 5. In an intermediate phase, the single crystal center was surrounded by a polycrystal ring as we expanded the micropipe-free SiC seeds. Recently, however, we have progressed to the production of fully mono-crystalline material.

There are wide variations in the reports of optimum growth conditions for AlN. Hexatech reports that they achieve very high quality crystal growth only on the

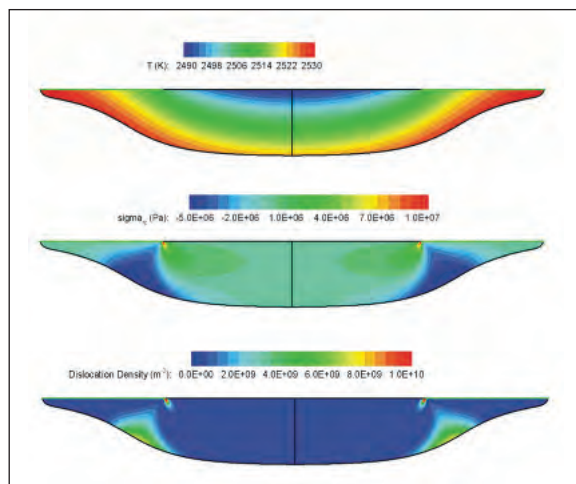


Figure 6 VirtualReactor simulation of crystal growth

nitrogen-face and only at temperature of 2600 °C. On the other hand, we are able to grow “good enough” AlN crystals on the aluminum-face or nitrogen-face at relatively low temperatures, ranging from 1950 °C to 2050 °C, using a near atmospheric pressure N₂.

We utilize the VirtualReactor-AlN code from Soft-Impact to model growth conditions in detail. Figure 6 shows an example of a VR simulation of crystal growth.

Making substrates

For AlN substrate production, crystals are separated from seed holders and the head cropped off, before being ground to a 2-inch diameter and oriented by X-ray. Both major and minor US-convention flats are ground into the crystal. The round crystal is mounted to a slicing fixture and the mis-orientation angle of the substrates is fixed with X-rays, before a multi-wire diamond saw slices the crystal into wafers. The sliced wafers are lapped as needed and then subjected to chemical mechanical polishing (CMP). Finally, the wafer is cleaned and packaged in a nitrogen atmosphere.

We have developed our own CMP final polishing for the production of seed substrates; however, final polishing of the AlN substrates can be made by Novasic (France) on request. Novasic has established a unique, industry-recognized polishing capability for hard materials such as sapphire, SiC and AlN.

Characterization data, such X-ray diffraction and atomic force microscopy (AFM) measurements, is typically collected on the wafers after cleaning. A good assessment of the wafer production process is revealed by the quality of the epitaxy. Mapping of the surface topography with an AFM reveals the absence of scratches in the epi-layer, attesting to the quality of the CMP.

The dislocation density of the majority of crystals is in the range 1×10^4 to $1 \times 10^5/\text{cm}^2$ (see Figure 7). This meets our criterion of “good enough.” The ultimate test of the substrate quality is epitaxy growth and device performance. UVA LEDs grown on AlN substrates can show a four-fold efficiency improvement over those grown on sapphire; however, to date, deep UV LEDs made by Crystal IS on their AlN substrates have not shown remarkably improved efficiency. This may be due to factors such as impurities rather than crystal quality.

For deep UV LEDs the transparency of the AlN substrate is particularly important. Due to its 6.02 eV bandgap AlN should be transparent down to nearly 200 nm. However, early substrates, even though optically almost colorless, had a rather sharp transmission cut off near 300 nm. Positron annihilation spectroscopy indicates that the main defect in AlN crystals may be an aluminum vacancy complexed with oxygen. This defect has an absorption feature in the blue that gives AlN crystals their usual orange/yellow color. But, it does not normally affect the UV absorption. Other impurities are likely to be responsible for the low energy cut off. This is confirmed, at least for

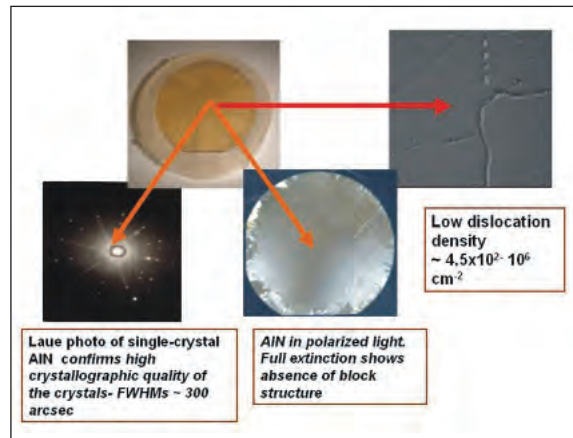


Figure 7 AlN characterization

our growth, since increased pre-purification of the AlN source powder leads to a shorter cut-off. Indeed with the cleanest source materials the cut-off is typically just 205 nm.

AlN Applications

AlN substrates have already been used for a wide variety of devices. Excellent performance of RF structures grown on this platform has been reported; however, these devices are not expected to become commercially important until 4-inch diameter AlN becomes available. Using the SiC seeding process AlN could be scaled to 4-inch diameter in a rather straightforward manner. Crystal IS has reported deep UV LEDs on AlN and shown that thick, fully strained pseudomorphic layers of AlGaIn can be grown on this foundation. Meanwhile, SAW devices have been made by a variety of groups on AlN. This gives great promise for AlN as a universal substrate for III-nitrides.

The quest to obtain a 2-inch diameter AlN substrate has been pursued for many years. Our efforts have yielded material of this size with a dislocation density that is three-to-six orders of magnitude lower than that associated with epitaxy on sapphire. The many users of this substrate have obtained excellent epitaxial results, which are realized without the need for special buffer layers. While AlN forms an unavoidable oxide layer, simple procedures can remove any residual oxide.

Today the pricing of AlN is similar to that of SiC when it was first commercialized. But AlN prices will drop as sales increase. Substrates made from both these wide bandgap materials should have similar production costs in years to come. Since AlN is UV transparent, it may be usable in laser lift-off, although to date no publication of such results has been made. This could reduce the cost of AlN to that of repolishing, making it competitive with sapphire, GaAs and GaP, despite its greater initial cost.

Further reading

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What next for the Compound Semiconductor Industry?

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Klaus H. Ploog

Pioneer of Molecular Beam Epitaxy (MBE) Keynote Speaker

Topic: What next for the Compound Semiconductor Industry?

Klaus H. Ploog is one of the pioneers of molecular beam epitaxy (MBE), a versatile tool to fabricate semiconductor and metal nanostructures. The MBE technique has been established in the early 1970s, i.e. long before the hype on "Nano" started to dominate the world wide research funding policies in the late 1990s.

Using molecular beam epitaxy, he has designed and fabricated numerous new semiconductor and magnetic nanostructures that showed unique quantum size effects.

These man-made nanostructures have led to a number of novel device concepts, including high-electronmobility transistors (HEMTs), quantum well and quantum dot lasers, quantum cascade lasers, etc.

His research achievements have been published in more than 1500 papers in international refereed journals, and he has received several prestigious awards. His current interest for the subject of sustainable energy concepts has emerged from his research on Group-III Nitrides for solid-state lighting beginning in 1995, where he has paved the way for more efficient blue, green and violet GaN-based LEDs by using non-polar epitaxial layers and heterostructures.

Dr. Petteri Uusimaa

President, Modulight

Topic: How to make a state-of-the-art visible red laser, what its specs are, and what new markets it can target

Prior to joining Modulight Dr Petteri held numerous manager positions in international research projects in which he managed relations to international funding companies as well as was the principal scientist in the programs. Since 1997 Petteri has been managing semiconductor sales to multinational companies and acted as a President & CEO of Modulight since incorporating the company in 2000. Dr. Petteri Uusimaa has a PhD in semiconductor physics from Tampere University of Technology (TUT).

Jan-Gustav Werthen, Ph.D.

Senior Director, Photovoltaics
JDSU

Topic: The urgency for the world to make power grids digital (smart grids) and photovoltaic developments for electricity production from solar.

Jan-Gustav Werthen brings more than 26 years of technology experience to JDSU. As senior director of Photovoltaics, Jan drives overall business and product development that includes power-over-fiber products and solar CPV cells. Jan joined JDSU in 2005 as part of the

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acquisition of company that he founded called Photonic Power Systems, Inc. From 1992 – 2005, Jan was CEO of Photonic Power Systems, where he built a semiconductor device and subsystems organization from the ground up and grew sales over \$1 million annually, addressing worldwide markets.

Prior to running his own company, Jan held management positions at companies such as VS Corporation, an early player in the fiber-to-the-home market, Varian Associates, and Xerox. Jan received his Ph.D. and M.S. in Materials Science and Engineering from Stanford University.

Jeff Shealy

**Division Vice President
RFMD**

Topic: Role of GaN RF Power Technology for Tomorrow's Commercial and Defense Wireless Applications

Jeff Shealy is vice president of the Infrastructure Product Line at RFMD, where he is responsible for strategic planning and execution of the corporate infrastructure strategy. Dr. Shealy was a principle founder of RF Nitro Communications, Inc., where he served as president and CEO until RFMD acquired the company in October 2001. Dr. Shealy is a Howard Hughes Doctoral Fellow and has held positions at Hughes Research Labs and Hughes Network Systems. He received his MBA from the Babcock School of Business at Wake Forest University and he holds a Ph.D. in electrical engineering from the University of California at Santa Barbara. Dr. Shealy is a member of the IEEE Electron Device Society.

Dr Otto Berger

**Corporate Advanced Technology Director
TriQuint Semiconductor, Inc**

Topic: 3G/4G requirements for wireless systems and the role GaAs and GaN devices will play in meeting these requirements

Dr. Otto Berger is TriQuint's Corporate Advanced Technology Director, overseeing the company's portfolio of acoustic technologies, 150mm GaAs process developments and advanced packaging techniques at TriQuint Munich, Germany. He leads innovation developments in these fields to evolve TriQuint technology for future product generations. Dr. Berger began his professional career at Siemens Semiconductor and moved to TriQuint in 2002 through the acquisition of Infineon's GaAs business. He has worked in various roles in process development, product engineering and fab

management within the GaAs field for more than 20 years. Dr. Berger received his PhD degree in physics from the University of Muenster, Germany.

Marc Rocchi

CEO, OMMIC

Topic: What's needed from GaAs and GaN for tomorrow's wireless

Marc Rocchi received his degree in Electrical Engineering and Solid State Physics from the Ecole Supérieure d'Electricité de Paris in 1972. In 1976, he joined the Philips Research Lab in France to work on the design of high-speed digital GaAs circuits and in 1983, he became head of the GaAs RFIC department. In 1988, he moved to Philips semiconductors in Eindhoven to lead the CMOS process and characterization group as part of the 1Mbit SRAM project. Since 1990 he has successively been general manager of Philips Microwave Limeil and CEO of OMMIC. He is now Chairman of the board of directors of OMMIC.

Alexander Bachmann

**Marketing Engineer
OSRAM Opto Semiconductors GmbH**

Topic: Recent Progress on Green InGaN Laser Diode Development at OSRAM Opto Semiconductors

After the studies in physics, Alexander Bachmann worked on the development of electrically pumped vertical-cavity surface-emitting laser diodes at the Walter Schottky Institut of the Technical University of Munich. Emitting in the near- to mid-infrared spectral region, these devices are perfect light sources for trace gas sensing applications. In 2010 he joined OSRAM Opto Semiconductors for the marketing of visible lasers for pico projectors. With first products already being available on the market, a huge market growth is expected for the next years, driving the development of blue and particularly green laser diodes.

Dr. Michael Fiebig

**Director Marketing and Business Development Solid State Lighting
OSRAM Opto Semiconductors GmbH**

Topic: What are the success factors for the deployment of Solid State Lighting?

Dr. Michael Fiebig gained his PhD in Physics at the University of Hanover in 1998. During his doctoral thesis he worked on Diode-pumped solid-state-lasers in the



Klaus H. Ploog



Dr. Petteri Uusimaa



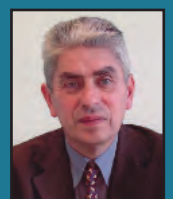
Jan-Gustav Werthen, Ph.D.



Jeff Shealy



Dr. Otto Berger



Marc Rocchi



Alexander
Bachmann

spectral region at 2 μ m for medical applications. In 1998 he joined Lambda Physics as Product Manager for Excimer Lasers for display and industrial applications. From 2001 he joined OOSRAM Opto Semiconductors and was heading the Marketing segment for Consumer and Communication until 2008. Since 2008 he is leading the Marketing and Business Development in the business segment Solid State Lighting at OSRAM Opto Semiconductors.



Dr. Michael
Fiebig

Dr. Markus Behet
Europe Business Development Manager
Dow Corning Compound Semiconductor

Topic: SiC Advances for Power Electronic Applications

Dr. Markus Behet received his PhD in Electrical Engineering and Semiconductor Physics from the Technical University Aachen in 1995. From 1995 - 1998 he was R&D Manager for epitaxial growth and device processing of advanced III/V Semiconductors for High Frequency and Infrared Laser applications at IMEC in Leuven/Belgium. In 1999 – 2002 he joined Siemens Semiconductor and later Infineon Technologies where he was responsible for Business Development and Marketing of GaAs mmW products and foundry projects.



Dr. Markus
Behet

From 2002 - 2010 he held several Marketing and Sales positions for GaAs handset, foundry and mmW markets at TriQuint Semiconductor. In 2010 he joined Dow Corning as Development Manager for SiC based Compound Semiconductor Solutions.



Dr. Ulf Meiners

Dr. Ulf Meiners
Chief Technical Officer, UMS

Mark Murphy
Director Marketing, RF Power & Base, NXP
Topic: High performance compound semiconductors for infrastructure, automotive and defense applications

Ulf Meiners received the Ph.D. in physics from the Technische Universität Munich, Germany and has been working in the compound semiconductor domain since more than 20 years. He is the Chief Technical Officer of the UMS group and the Technical Managing Director of UMS GmbH, Germany.



Mark Murphy

Mark Murphy received a BEng in Electrical and Information Eng from Queens University Belfast and has been working in the semiconductor industry for more than 20 years. First at Analog Devices, followed by Philips & is currently at NXP where he is the Marketing Director for the Product Line "RF Power & Base Stations".



Mats Reimark

Mats Reimark
CEO, TranSiC

Topic: How will SiC power devices help getting a greener planet

Mats Reimark has been a director in international organizations for more than 10 years. He is, since May 2009, CEO at TranSiC AB a company specializing in development and manufacturing of bipolar transistors in Silicon Carbide. Prior to joining TranSiC Mats has had a long career at GM with assignments such as Director Hybrid Powertrain Engineering Europe, Chief Engineer Technology at Fiat-GM Powertrain and Director Engine and Controls Engineering SAAB.

Dr. Philippe Roussel
Project manager Power Electronics and Compound Semiconductors
Yole Développement

Topic: GaN power electronics: Market forecasts and industry status

Yole Développement (www.yole.fr) is a market research and strategy consulting company based in Lyon, France.

Dr Philippe Roussel has headed the Compound Semiconductors division since 1998. Yole produces numerous market reports and is currently publishing their analysis of the SiC, GaN, AlN, Sapphire power and RF device as well as high-brightness LED markets. Dr. Philippe ROUSSEL is graduated from the University of LYON in Electronics and Microelectronics. He was granted a Ph-D in Integrated Electronics Systems from the Applied Sciences National Institute (INSA) in LYON.

He is working at YOLE DEVELOPEMENT since 1998 and is leading the techno-economical market analysis in the fields of Compound Semiconductors and Power Electronics at materials, equipment and devices level.

Scott Parker
Executive Vice President Sales and Marcom
Oclaro, Inc

Topic: Future Proofing Networks with 100 Gigabit Optics

Mr. Parker was previously with Avonex Corporation, most recently serving as the Company's Senior Vice President of Sales. Prior to joining Avonex, Mr. Parker held senior management positions at two start-up companies funded by Sequoia Capital. Previously, Mr. Parker served as Senior Vice President of Sales and Marketing for JDS

Uniphase where he integrated the sales and customer service teams from numerous acquisitions. He also held sales and general manager positions at VLSI, National Semiconductor and Intel. Mr. Parker earned an M.B.A and bachelor's degree in marketing from the University of Utah.

Dr. Ertugrul Sönmez
Business Development
MicroGaN GmbH

Topic: Efficient High-Voltage GaN Devices and ICs for Next Generation Power Management Solutions

Ertugrul received his Diplom-Ingenieur degrees in electrical engineering from University of Ulm, in 1998. In 1998, he joined the department of Electron Devices and Circuits as a member of the scientific staff, earning the Doktor-Ingenieur degree in 2007. His main fields of research were compact silicon bipolar transistor modeling and analog RF MMIC design at 24GHz. He has authored and co-authored more than 40 publications and conference contributions.

In March 2005, he joined ATMELO Germany GmbH in Heilbronn as Marketing Manager, to be responsible for the world wide UWB RFID product line. In June 2005, he joined TES Electronic Solutions GmbH in Stuttgart, a service provider of ATMELO Germany GmbH. His main activities were to lead the ultra wide band MMIC design.

In December 2006, he has been called by MicroGaN GmbH as the strategic Business Developer to bring in his experience in semiconductors and markets.

Roy Blunt
SEMI International Compound Standards

Topic: Standardisation in compound semiconductors - an essential step for furthering the efficiency & profitability of the industry.

Roy Blunt graduated from Imperial College London in 1969 and joined Plessey Research Caswell Ltd., where he worked on a variety of R&D projects before becoming part of the GaAs IC pilot production team and developing a particular interest in compound semiconductor characterisation techniques (metrology).

In 1988 he left Plessey to become part of the founding team of Epitaxial Products International Ltd in Cardiff - now IQE (Europe) Ltd.

He has been involved in standards work since the early 1980s and was a co-founder and, for many years, co-

chairman of the SEMI European Compound Semiconductor Technical Committee which has been very active in standards development both on its own and in co-ordination with the North American and Japanese SEMI Compound Semiconductor committees.

Dr Mike Cooke
Chief Technology Officer
Oxford Instruments Plasma Technology

Topic: Batch and single wafer processing strategies for HBLEDs

Dr Mike Cooke joined Oxford Instruments Plasma Technology in 1992. As Chief Technology Officer, he leads the team of expert development technologists responsible for developments such as PEALD and scaling plasma tools towards 450mm.

Dr. Thomas Uhrmann
Business Development Manager
EV Group (EVG)

Topic: Engineered Substrates for future compound semiconductor devices

Thomas Uhrmann is Business Development Manager for Compound Semiconductors and Si-based Power Devices at EV Group (EVG). In his current role, he is responsible to introduce and manage technological innovations for the fabrication of high-brightness light emitting diodes (HB-LEDs) at EVG.

Uhrmann holds an engineering degree in mechatronics from the University of Applied Sciences in Regensburg and a PhD in microelectronics from Vienna University of Technology. Uhrmann authored and co-authored several papers on semiconductor diode structures, micro or nanomagnetism and related areas.

Mike Czerniak
Product Marketing Manager, Exhaust Gas Management
Edwards

Topic: GaN - meeting emissions regulations

Mike Czerniak received his PhD at Manchester University, and started as a scientist at Philips' UK laboratories before moving to its fab in Nijmegen, working on compound semiconductor applications. He was in marketing at Cambridge Instruments and VG Semicon; he is now the product marketing manager of the Exhaust Gas Management Division of Edwards, Clevedon, North Somerset BS21 6TH, UK



Dr. Philippe
Roussel



Scott Parker



Dr. Ertugrul
Sönmez



Roy Blunt



Dr. Mike Cooke



Dr. Thomas
Uhrmann



Mike Czerniak

Liquid delivery system for high volume NH₃ usage in the proliferation of low cost LEDs

The use of LEDs is already widespread in consumer electronics, appliances, and other products. Single LEDs are seemingly ubiquitous; LED assemblies are widely used in mobile electronics, computer displays, and televisions. We can expect that LEDs will spread through industrial lighting and into the general lighting of our homes. **By Ryan Clement and Robin Gardiner, at MATHESON.**

The growth has occurred quickly. The shift in manufacturing scale, from niche production to high volume /low unit cost processing, is well underway. Along with it, fabricators are engaging in a complete review of all aspects of the supply chain. At the focal point, naturally, is production process technology. Purchase a backlit TV, and the LED unit assembly can be 28% of the costs . An estimated 25 million LED backlit TV's will be built this year with as many as 500 LEDs per panel. It is expected that this application alone will have a growth rate of 10-15 % through to 2013/2014. Replace an old bulb today with LED technology and as much as 40% of the price you pay is cost of materials . With a potential of 100 billion additional LEDs by 2020, manufacturers are eager for improvements that impact their total cost by reducing production downtime, product variability, and waste.

Ammonia delivery and its pivotal role in the LED fabrication process

Ammonia (NH₃) is one of the primary gases used in high volume for MOCVD growth of gallium nitride (GaN) films used to make LEDs. Consequently, NH₃ is being used at increased rates and in increased quantities that parallel the rapid expansion of production.

At the outset, and until recently, cylinder-based delivery systems were used to deliver NH₃ to the GaN MOCVD reactors. Today, as the manufacturers have been adding reactors to keep up with LED demand, it has become clear that bulk NH₃ supplies are required.

Weaknesses of conventional bulk delivery

Conventional Bulk Specialty Gas System (BSGS) exhibit limitations in three critical areas:

1. Output flow rate is limited, which in turn limits the number of reactors that a BSGS can serve;
2. The bulk liquid supply becomes increasingly contaminated by water (and other impurities) as it is being depleted. This results in variable demands on external purification, and, more importantly, in a significant residual volume of contaminated liquid ammonia that is below spec and must be discarded.
3. Safety and performance considerations involved with heating a large volume of NH₃ grow more complicated as the size of the BSGS vessel is increased.

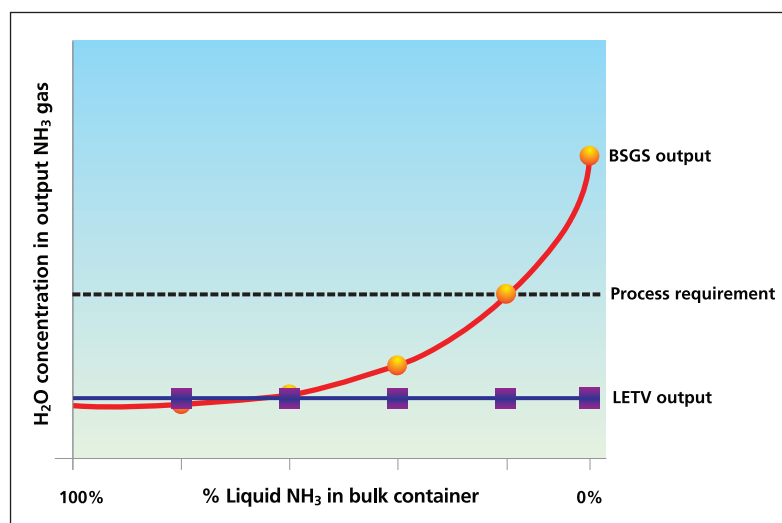


Figure 1. Representation of the increasing water contamination of NH₃ gas output in standard bulk supply systems and LETV systems. Impurities are easier to remedy when they are stable; LETV impurity level is essentially flat throughout the depletion of the bulk supply

These disadvantages are basic and severely limiting. The need for higher productivity in LED production is a real-world requirement. Overcoming any the limits of flow rate scalability, bulk material contamination, waste, performance, and safety would be a positive step. Overcoming them all would be a breakthrough.

A newer approach to bulk ammonia supply, Liquid Extraction and Total Vaporization (LETV) is the breakthrough technology that overcomes all of the weaknesses of conventional BSGS systems. First, we will describe the detail of the BSGS limitations; after which we will provide a description of the LETV technology and its advantages.

Flow limitations in conventional bulk delivery systems

A conventional BSGS is comprised of a bulk container and a gas piping system. Liquid NH_3 vapourises within the bulk container and is piped to the point of use as a gas. Limitations associated with heat control of the bulk container (explained below) constrain the size of the bulk container, and impose limitations on liquid ammonia surface area – in turn limiting the flow capacity, and constraining the scalability of the system.

So, even with a bulk delivery system in place, fabricators who continue to expand by the addition of multiple GaN reactors place consequent additional burdens on their NH_3 delivery systems, and face the need to deploy additional BSGS systems.

Impurity issues with BSGS

The mechanism employed in a conventional BSGS is, in effect, a single plate distillation. As with all distillations, the composition of what remains inside the container changes over time. As the ammonia is consumed, the concentration of impurities increases. Under process conditions, the overall composition of the bulk supply can change to the extent that it no longer meets the specifications required, and its use must be terminated. Depending upon process requirements and end-user SOP, the unusable supply can be as much as 20% of the original volume; this is an obvious and immediate target for cost reduction.

Wasted supply is not the only problem. Water is a common impurity for ammonia, and oxygen is the cause of critical defects related to LED brightness. As described above, as the NH_3 is consumed, the concentration of impurities increases. Well before the point at which the ammonia supply is rendered completely unusable, the drift in moisture contamination from the BSGS is a process variable that impacts product quality (see Figure 1).

Removal of moisture and impurities from the exiting gas is possible, but because the moisture and impurity content changes dynamically as the bulk supply is consumed, purification under these changing conditions represents a challenge to most purification systems. The resulting

inconsistency in the quality of the gaseous ammonia output can lead to process and product variability.

Heating the bulk container

An additional complication is that a conventional BSGS requires that heat be applied to either to the entire bulk NH_3 supply or to the liquid surface through microwave technology in order to induce vaporization and to maintain the required flow rates.

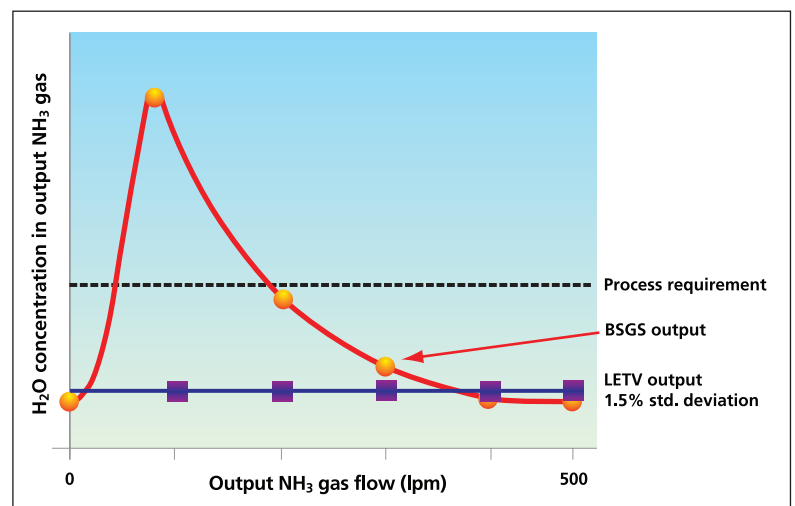
The application of heat to ammonia presents control problems as well as safety risks. Heating any size vessel poses a control problem, because the amount of heat must be continuously monitored and adjusted as the container is emptied in order to maintain the delivered gas at a constant flow.

Larger vessels respond to temperature changes more slowly, and are difficult to control with precision. Larger vessels also pose a larger safety risk when electric heaters and microwave energy are present. Smaller vessels reduce the control problem, but suffer the obvious disadvantage of low capacity. Large or small, vessels of any size present a temperature control problem. In the quest for capacity, there are practical limits to the size of a bulk liquid NH_3 container that can be efficiently and safely heated.

Phase change dynamics and moisture

NH_3 has a high latent heat of vaporization and keeping the phase change continuous and controlled in the face of varying demand from the process is non trivial. From a conventional BSGS the concentration of the water impurities increases with exiting gas flow rate; it reaches a maximum; then declines. This behavior is a result of the combined effects of thermodynamics, fluid dynamics and heat transfer. As smooth evaporation occurs, an increase in moisture develops at the NH_3 liquid-vapor interface. Surface enrichment increases with an increased flow rate and therefore the moisture concentration increases (see Figure 2).

Figure 2. Representation of contamination profiles as a function of gas output flow rate. Flow rate changes are to be expected in a real-world production setting – variable contamination as a function of flow rate is a real-world problem.



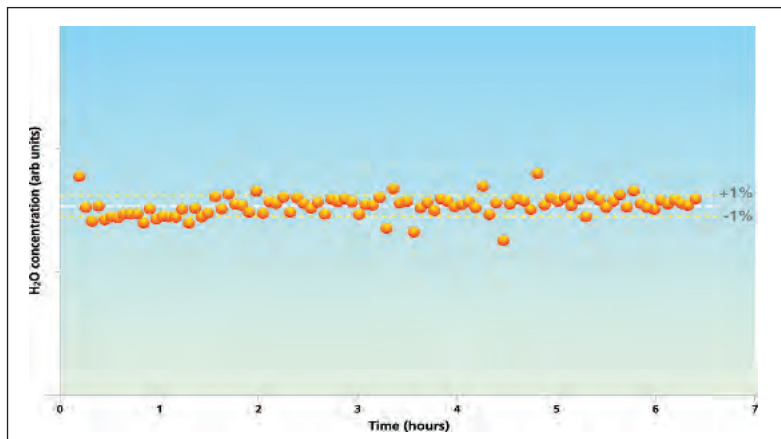


Figure 3 – Output from liquid delivery system and NH₃ vaporizer at 250 slpm, showing no change in moisture concentration as the bulk supply is consumed

At a certain flow rate, boiling becomes vigorous enough to disrupt and mix the liquid-vapor interface which starts to lower the surface enrichment of moisture. At high flow rate, a film boiling regime develops and heavy mixing is found within the container. As a result, the surface enrichment is not capable of developing; and a lower moisture level is observed.

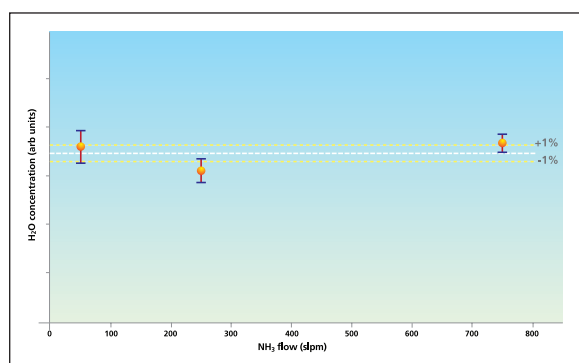
In the real-world setting of LED production, reactors and processes start and stop requiring on-the-fly changes in demand for gaseous NH₃. Under this circumstance, levels of moisture will always vary in the output flow of conventional NH₃ delivery systems - a result of fundamental physical properties of NH₃ with H₂O contamination no matter what the purity.

In the final analysis, the instability and variability of the vaporization process in the typical BSGS presents barriers for the development of a repeatable, high volume production process.

Liquid extraction and total vaporization (LETV)

LETV technology circumvents the problems observed with gas phase delivery from a bulk supply. In a critical departure from conventional BSGS technology, LETV technology isolates the storage vessel from the vaporization process. The design concept is to push liquid from a bulk container to an external vaporizer. In doing so, the system is able to achieve total vaporization of the NH₃ while maintaining constant temperature, pressure and therefore flow.

Figure 4. Gaseous NH₃ purity extracting then vaporizing a UHP liquid source – changes in flow rate over time do not impact purity of output



The vaporizer is isolated from the bulk supply, therefore vaporization conditions are constant, and are easier to control – and the process is, by definition, a safer one.

- The flow rate limitations of existing designs due to heat flux limitations are not present in the LETV. Everything that reaches the vaporizer is vaporized and there is no “concentration effect” on impurities in the bulk container.
- The flow rate from a single LETV system vaporizer is easily increased to support 50 GaN MOCVD reactors with flow rates up to 5,000 slpm achievable by adjusting the heat flux.
- The LETV technology overcomes the problem of moisture impurity spikes and drift through the life of the entire bulk container and across a wide range of flows.

Because vaporization is isolated as a separate and controlled step, and because all of the liquid NH₃ is vaporized and exits the system, the stability of moisture levels in NH₃ delivered by the LETV is better than 2% across a widely varied flow rate range, and throughout the depletion life of the bulk supply.

LETV: No increase in water contamination during bulk supply depletion

The stability of moisture contamination in NH₃ is represented in Figure 3. The moisture content was constant as the bulk vessel was depleted. There was no “concentration effect” of impurities as the supply was consumed. The standard deviation in the data was less than 1%.

Tests of the LETV technology have shown that the standard deviation was less than 2% even when the flow rate was changed, and regardless of the liquid volume in the bulk container. In fact, LETV is so effective throughout the depletion of the bulk container that the amount of wasted bulk NH₃ is limited only by the extent to which the bulk vessel and dip tube enable the emptying of the bulk supply.

LETV: Purity of gas supply from UHP liquid bulk supply

In conventional BSGS designs the concentration of water contamination will increase as the bulk supply is consumed (to a point where the bulk supply becomes unusable). In an LETV system the purity of the gas output is wholly dependent upon the purity of the bulk supply – and the impurity profiles of both the bulk liquid and the gas output remain essentially flat during use. Maintaining UHP performance from source to delivery is a high demand on any liquid/gas delivery system.

For NH₃ with 100 ppb moisture levels in liquid phase the effect of the drying down of the tubing is important in the

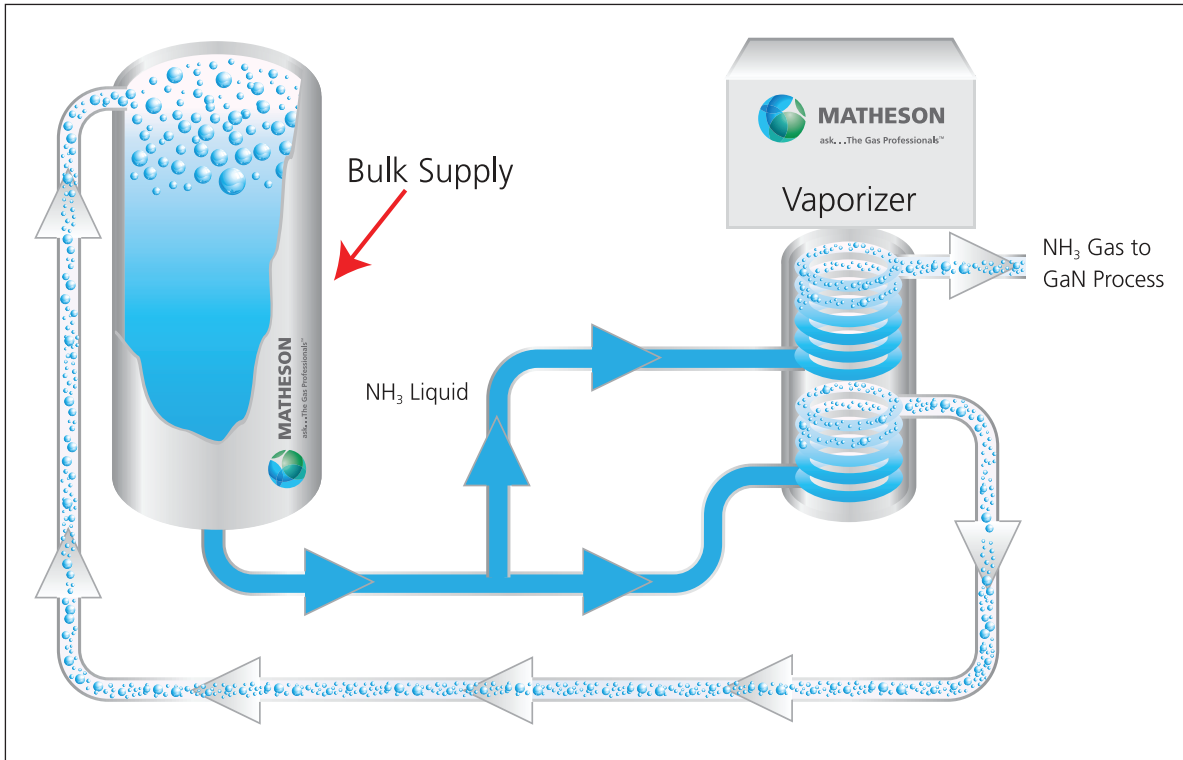


Figure 5. Graphic representation of LETV system, illustrating isolation of the vaporizer from the bulk supply

effort to monitor the LETV performance at such low levels of moisture. The results are given in Figure 4 and for flow rates of 50, 250, and 750 slpm show that the moisture contamination levels can be expected to remain close to constant across a wide range of flow rates, even with a UHP source.

Figure 4 clearly demonstrates that LETV technology is capable of delivering gas phase ammonia with consistent moisture content that is equivalent to the moisture impurity level in the liquid phase supply. Notably, this was demonstrated even after abrupt changes in NH_3 flow rate, mirroring “real world” conditions used by high volume LED manufacturers.

Summary

Conventional BSGS systems vaporize NH_3 in the bulk supply container, and subsequently transfer the gaseous NH_3 to the point of use. Systems of this design have limitations in terms of impurity levels in the gas phase delivery, constancy of impurity levels, capacity, maximum

flow rate, and safety. In such systems, water contamination can be such a problem that as much as 20% of the bulk supply is wasted.

Liquid Extraction and Total Vaporization (LETV) technology isolates the storage vessel from the vaporization step. This enables better control of the vaporization process – even at high flow rates.

LETV technology also removes the limitation on the size of the bulk container. At the same time, LETV technology eliminates the “concentration effect” on impurities, which virtually eliminates waste. The amount of NH_3 that can be removed from the bulk container approaches 100% and is limited only by the bulk container design and the access to the liquid phase contents.

LETV technology-based systems reduce capital expenditures by being scalable; can increase yields by eliminating variations in source gas; and reduce variable costs by increasing material utilization.

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Getting ready for a mature HB LED industry

The fast moving HB LED sector is starting discussions to consider the kinds of consistent materials characterization, testing protocols, tool interoperability, or other common practices that typically enable a mature high volume industry, reports **Paula Doe from SEMI**.

Driven by rapid progress in technology, fast growth in display backlighting markets, and a potentially huge market for general lighting about to come, the high brightness LED sector is hurtling towards becoming a more mature volume manufacturing industry within the next few years. Though companies will of course maintain their unique core processes, the mature high volume manufacturing business will also require some changes, towards efficient supply chain management, towards more automation and towards more emphasis on tuning a controllable manufacturing process for consistent high yields.

"The industry is maturing very fast, much faster than the IC industry did, as it can learn from that experience," says Iain Black, Philips Lumileds VP of Worldwide Manufacturing Engineering & Innovation. "This is becoming a serious business. In the future we expect that with a smaller number of key players and a consolidating supply base, some of the custom variation will have to come out of industry. That will require standards, and they will need to be defined early enough to avoid delaying the development of the market, perhaps not in 2011, but certainly sooner rather than later."

Some industry leaders are gathering to start to discuss these issues at the first meeting of the newly formed SEMI North American HB LED Standards Committee November 11 in San Jose, California. The group is led by

Black; Bill Quinn, chief technologist for MOCVD at Veeco Instruments; and Chris Moore, CEO of Semilab USA. SEMI invites participation from all interested parties. Parallel activities are expected to follow with committees in Europe, Taiwan and Japan.

"I see standards as somewhat inevitable," adds Black, noting that it won't be realistic to keep using all bespoke materials. "So it's important to be involved in the process to have some input. It's time to get the conversation started around what might be possible."

Finding common ground

One key area of common ground is the characterization of incoming materials. This could begin with consistent measurement of purity for chemicals and benchmarks for LED grade materials like indium, gallium, metal hydrides, and packaging materials, which all differ a bit from supplier to supplier. This might not be too difficult because there are a limited number of suppliers.

Wafer standards are more challenging, with multiple different diameters and substrate materials in production employing radically different processes, so some argue that even agreeing on a common thickness for 150 mm sapphire wafers is unlikely. But others counter that one thinner ~1 mm standard for those who thin the wafer down and prefer a thinner substrate, and another thicker ~1.3 mm standard for those who remove the epi layer and prefer a thicker substrate, could probably handle most production needs while doing away with much of the individual customization.

Even a few more standard products would allow efficient supply chain management, letting both wafer users and suppliers stock products and buy and sell off the shelf, and to deal with multiple sources in times of shortage. It would also allow tool suppliers to improve process measurement and control. The timing could be good for the fast transition about to come in substrate diameter.

Tool hardware specifications may be another area of common ground, as susceptors, graphite and SiC from different vendors aren't the same, and measurements of conditions in the tool aren't measured the same way across suppliers, so results can't be compared.

Better binning

Metrology and test is another key area for potential gain from consensus on best practice. As the HB LED sector matures and moves from the realm of the development engineer to the manufacturing engineer it will begin to move away from its current focus on volume. The focus will shift to control of the established manufacturing process, and to greater attention to the operational benefits of yield, identifying and tracking yield issues as

"Standards need to focus on the leading edge, 6-inch wafers, 6-inch cassettes, and some sort of wafer or carrier-level identification for traceability as the basics to enable automation", Clint Harris, Brooks Automation

early in the process as possible. But the process is currently hindered by everyone measuring different things in different ways.

To measure something as basic as wavelength uniformity on the wafer, for example, some LED makers use electroluminescence tests, others use photoluminescence tests, some measure peak wavelength, and others measure dominant wavelength — and all of those give different results.

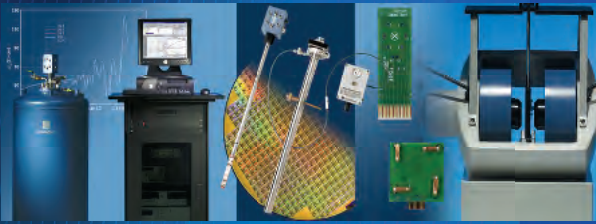
"If everyone could agree on one of those measures as best practice, it would get everyone talking about the same issues," argues Veeco's Quinn. "If everyone measured things the same way, it would be easier for the epi guys and the rest of the fab suppliers to improve the process for everyone. The potential to improve yields with standard testing and feedback is huge. It's definitely not too early to start talking about standards."

"Every company's fixturing is different, and will give different results," concurs Dan Morrow, president of Op-Test, citing the difference between probe tests and integrating spheres, and multiple different set ups for each. Morrow suggests that common testing protocols — like standards for thermal junction temperature management during production test — would give makers more useful feedback for process control, and make spec sheet data more useful and meaningful for both LED makers and their customers.

Morrow suggests the traditional transformed CIE XY photometric measurements of what the eye sees, from the traditional lighting industry, may not give precise enough data of what energies are at what wavelengths to drive yield improvements and guarantee that things that look the same really are the same. Spectral power distribution may be the more useful data to improve the production process. "Few are using process control feedback yet, but big players are coming into the market and I expect that will bring big changes," he adds.

Wafer level test systems are still largely a custom business, points out Mark Cejer, Keithley Instruments director of marketing. He notes that the different degrees of precision in color uniformity needed even for edge-lit versus back-array television backlights applications, to say

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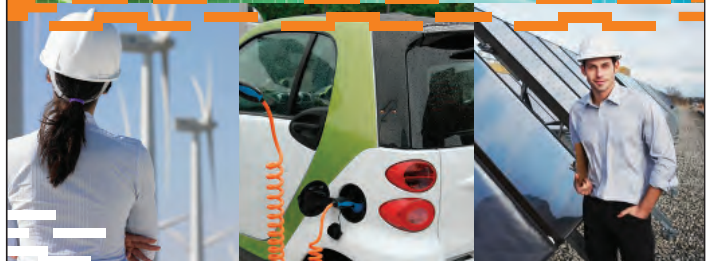


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nothing of automobile lights versus cell phone displays, all requiring different tradeoffs of complexity and costs. So LED makers tend to put together their own systems of source-measure units, probers, spectrometers and custom software, or have a local systems integrator do so. To make it even more complex, companies are also going to larger devices, or to multiple-device die cut from the original wafer, which require higher voltages or currents and shorter pulses for testing.

"We have to remain flexible to all these different ways of doing things because there are no established methods for test yet," says Cejer. "But the relentless price pressures will drive the industry towards efficiency, and if we put our heads together maybe we can do it efficiently."

Going forward, one solution might be finding enough correlation to characterize optical quality from only electrical tests, at least in some applications where the trade-offs were acceptable. Metrology and test are also easier for LED makers to talk about with suppliers. There is no advantage in not being able to measure things, so no one loses if a company works with a supplier to develop technology to test things that can't be tested now.

Materials, substrates, automation and metrology are usually the first areas to standardize as an industry matures, says Semilab's Chris Moore, noting the accelerating speed with which some other sectors have moved up to consistent volume manufacture. The solar industry, which also differentiates on process IP, was skeptical of manufacturing standards only a few years ago. However, it has now embraced standards with amazing rapidity, compared to the slow and painful process of the IC and LCD sectors before. Now two years in to starting standards discussions, there are some 400 photovoltaic industry experts working to facilitate efficient volume manufacture. This team is starting by coming to a consensus on the best measurement methodology for purity and setting benchmarks to define PV grade materials, and agreeing on carrier and equipment interfaces to facilitate automation. First agreement on defining consistent characteristics of solar grade silicon was reached in only three meetings over one year. They've reached consensus on 12 standards so far, with another 6 expected to be published by the end of the year, and more than a dozen more under development.

Automation

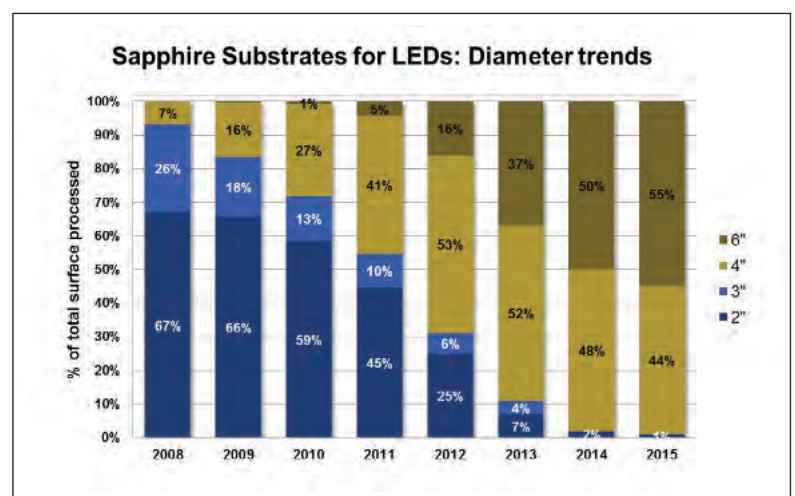
Though small wafers, cheap labor and long batch processes have limited the need for automation so far, the LED industry is transitioning to more and more automation as it moves to larger wafers and higher volumes. Robotic wafer handling, automated glove boxes, interbay automation, mini-environments and standardized carriers such as SMIFS are all technologies that will become pervasive in LED fabs of the future, argues Clint Haris, Senior Vice President of the Systems Solution group at Brooks Automation. He points out that LED makers are starting to look towards automation to improve yields and traceability. "The industry is rapidly evolving from manual

operation to fully automated factories," he says, noting that the LED industry has seen change in the last five years that took 40 years in the semiconductor industry. "Things are moving so quickly, standards need to focus on the leading edge, 6-inch wafers, 6-inch cassettes, and some sort of wafer or carrier-level identification for traceability as the basics to enable automation."

"Automation always increases yield," points out Quinn, noting that Veeco has found that when its experienced technicians instead of its interns load the tools, yields are improved by as much as 50 percent. Automation also may enable a faster ramp to volume than finding or developing all the qualified operators and engineers to run all the new epi reactors now out in the field. Though HB LED manufacturing is unlikely to move to the expensive full automated materials handling required for the heavy cassettes of 300 mm semiconductor wafers, it is likely to move towards the semiconductor automation of the 200 mm generation of the 1990s.

Automating data collection, analysis and even correction will also be key to getting more die into the bins that bring high margins, notes Applied Materials' Phil Walker, global product manager for automation products. "We need to get the data out of the tool and metrology, and linked to the right wafer to be able improve bin yields," he says, pointing to the potential for tracking the parameters of the production process, mining the data for the root cause of defects, and making needed adjustments to the tool as soon as possible.

"We also need the software to compare tools and tune them to match those that provide the best performance," he added. "The first step to unlocking hidden performance is collecting the data and understanding it."



HB LEDs production is fast transitioning to larger wafer diameters, moving to mass adoption of 4-inch (actually 100 mm) wafers next year, and to 6-inch (150 mm) within a few years, as the better use of reactor carrier real estate and reduced edge losses can increase throughput by as much as 30 percent, and allow use of the other semiconductor equipment available at 6-inch.

Source: Yole Développement Sapphire Market 2010 Q4 Update



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Manufacturing photonic LEDs with photolithography

Due to a very small depth of focus, standard photolithography techniques have insufficient fidelity for defining photonic crystal structures on LED epiwafers. But high-quality, large-scale patterning is possible by turning to a novel self-imaging photolithography technique, say **Harun Solak, Christian Dais and Francis Clube from Eulitha.**

The introduction of light extraction techniques has spurred an increase in GaN LED efficiency. That's because this type of technology can prevent a high proportion of light being trapped and eventually absorbed in the high refractive index semiconductor layers where emission is generated.

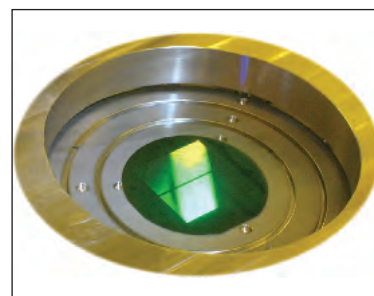
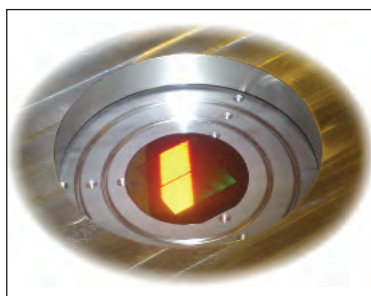
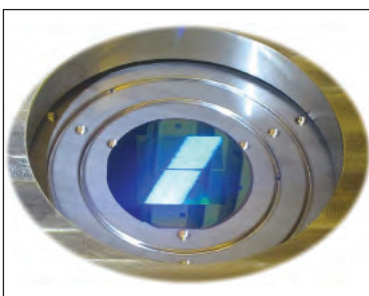
One of the most effective light extraction technologies involves etching regular arrays of holes into the emitting surface. Such photonic crystal structures cut the proportion of light propagating within the guided modes of the high index dielectric layer, and channel more emission out of the structure. Indeed, some of the highest performing devices have been created in this way by researchers at manufacturers such as Philips Lumileds and Osram. In addition, there are highly successful commercial products employing this concept, such as the series of Phlatlight LEDs from Luminus Devices.

There are many different ways to incorporate photonic crystal structures into LEDs. Arguably the most straightforward is the etching of a hole structure into the top layer, leaving air holes that can extend into the active region. Other approaches include incorporating a lower index dielectric - such as silicon dioxide - as pillars in GaN, or patterning the substrate with a photonic crystal structure.

Adding a photonic crystal pattern influences light emission in two ways: overall extraction increases by a factor of two-to-three; and the emission profile changes, becoming more concentrated around the surface normal. This enhanced directionality of the emission results in a brighter LED, which is especially important for applications where the light needs to be further guided, collimated or focused. Through careful design of the photonic crystal structure it is possible to tailor the LED's emission pattern to the target application. Electromagnetic simulation codes are one tool for realizing this. They can determine the effect of parameters such as the period or lattice symmetry.

An alternative, popular practice within the industry for boosting efficiency is roughening or texturing of the LED surface. This introduces facets at different angles, making it easier for light to escape from the chip. One downside of this approach is that it offers no gain or control over the directionality of the emitted light. What's more, by turning to an optimized and highly controlled photonic crystal pattern instead of a textured surface, it may be possible to increase the process and emission reproducibility across chips and wafers, leading to higher production yields.

Despite the research programs being undertaken by major manufacturers and their published results, the application of photonic crystals to LEDs has not yet been adopted



Photographs of a 600 nm period hexagonal pattern on a 2-inch wafer

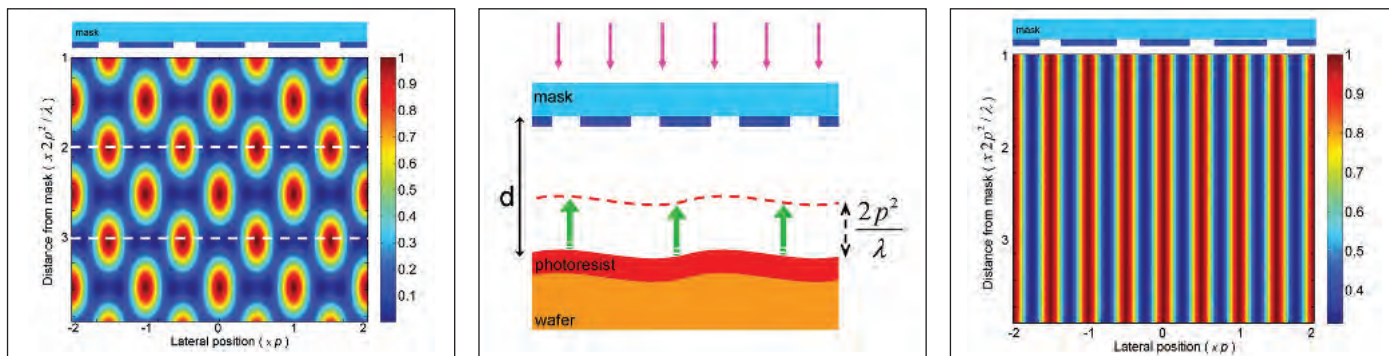


Figure 1 (a) Calculated image produced by a linear diffraction grating illuminated with monochromatic collimated light. The dashed lines show two of the self-image planes. (b) Diagram illustrating the PHABLE concept. (c) Resultant image obtained with the innovative method showing the invariance along the longitudinal direction and hence elimination of the DOF limitation faced in conventional photolithography

extensively by this industry. That's primarily because this approach is believed to add substantial complexity and cost to the lithographic process required for the fabrication.

Printing versus optics

Photonic crystals designed for light extraction from GaN-based LEDs typically have a lattice period of 300-600 nm. The lattice symmetry is usually hexagonal, although other geometries such as square grids are also considered. In order to realize such patterns, holes as small as 100 nm in diameter need to be printed on LED wafers. This rules out proximity (or contact) photolithography, which has a minimum resolution of about 500 nm. And features of this size are only possible in contact mode, where damage to the mask and process yield are both serious issues.

Another optical method is holographic lithography, which involves interfering of two or more mutually coherent beams to obtain periodic structures. Resolution is not an issue for this UV method, but it is unsuitable for high volume production processes because the optical configuration has to be modified to realize different patterns. In addition, this approach requires a strict control of the environment to maintain stable fringe patterns.

Nanoimprint lithography (NIL) has been proposed as a suitable technique for high-volume manufacture of

photonic LEDs because it promises to combine sufficient resolution with high throughput. Some manufacturers have indeed adopted this technique, and all main Nanoimprint tool providers now advertise equipment specially targeting this application. However, the NIL approach faces considerable challenges: process difficulty, cost and throughput. These difficulties are partly caused by the non-flatness of LED wafers and the particulate contamination commonly found on their surfaces. There are ways to circumvent this problem, but they add to process complexity, which ultimately increases cost. Meanwhile, deep UV lithography, as used by the IC industry, is not considered to be a viable option due to its prohibitively high cost. In addition, there are depth-of-focus problems associated with printing high-resolution patterns onto non-flat LED wafers.

Staying focused

At Eulitha, a start-up founded in 2006 in the canton Aargau of Switzerland, we have developed a proprietary technology to address this important manufacturing roadblock. Our technology that is known as PHABLE - a shortening of "photonics enabler" - is a mask-based photolithographic technology that takes full advantage of standard photolithography infrastructure such as photoresists and associated processes. It enables fabrication of periodic structures required for photonic applications, such as arrays of holes arranged on hexagonal or square lattices, or linear gratings with sub-100 nm resolution. The unique property of PHABLE is that it forms an optical image with a very large depth of focus (DOF), which means that it is not a problem to print high-resolution patterns onto non-flat surfaces, such as LED wafers.

Self-imaging of gratings (or the Talbot effect) is a well-known phenomenon where a mask with a periodic structure (grating) is illuminated with monochromatic collimated light to form images of the grating at periodic distances after it. These so-called self-images have a DOF that scales with the square of the pattern period. A typical DOF value for a pattern period of 400 nm, illuminated with 365 nm light, is 50 nm. This value is so small that it

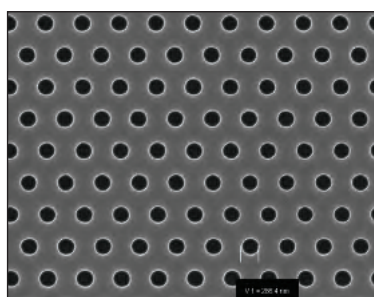
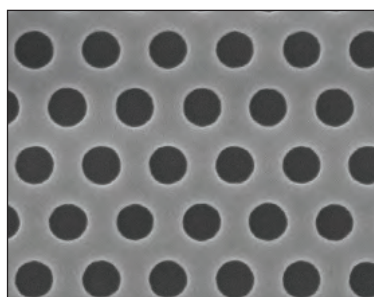
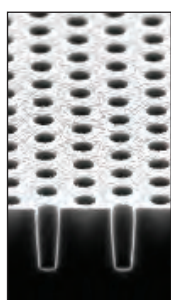


Figure 2 SEM images of photonic patterns with hexagonal symmetry. (Bottom left) Pattern in photoresist with 500 nm pitch. (Right) and (Top left) Top-down and cross-section images of 600 nm-period hexagonal hole array etched to a depth of about 800 nm in silicon

prevents use of non-flat substrates or sufficiently thick photoresists, and requires very precise positioning and alignment of the wafer with respect to the mask. While there have been many demonstrations and research studies, up until now the limited DOF has prevented application of this method in industrial fabrication, especially for high-resolution structures. The PHABLE technology promises to lift this restriction.

In order to explain the principle behind this new technology, we show the intensity distribution and self-image planes formed behind a linear grating in Figure 1a. According to the conventional method, the photoresist-coated substrate is precisely positioned at one of these self-image planes to record the pattern which has a DOF smaller than $p^2/2\lambda$, where p is the pattern period and λ is the wavelength. In the PHABLE method the wafer is not kept stationary at a self-image plane. Instead, it is moved toward the wafer by a full Talbot period ($p^2/2\lambda$) to record an integral or average image (Figure 1b).

The resultant image is shown in Figure 1c. This image is also periodic along the lateral direction but, interestingly, is not sensitive to the starting distance of the wafer from the mask. Therefore the image has effectively no DOF limitation. A further advantage is that the printed pattern has half the period of the grating in the mask, therefore a resolution gain is achieved with respect to the mask.

To ensure a reliable and reproducible lithographic process, the contrast of the aerial image has to be high enough so that the non-linear response of a photoresist converts the image into a binary pattern. An inspection of the calculated image in Figure 1c reveals a peak-to-valley intensity ratio of about three – this is ample contrast for photoresist exposure. In general, simulations show that images obtained with this method have high contrast, which is supported by the experimental results presented below.

Any pattern you like

This principle illustrated in Figure 1 is applicable to both one-dimensional patterns, such as lines and spaces, and two-dimensional patterns, such as hexagonal or square lattices. Examples of patterns printed using this method are shown in Figure 2. A hexagonal pattern of holes with 500 nm period printed in photoresist is seen in Figure 2a, and top-down and cross-section images of a hexagonal array of holes with 600 nm period etched in a silicon wafer are shown in Figures 2b and 2c, respectively. Exposures were performed with a PHABLE tool using collimated UV light and a standard photoresist. In each case the wafer was displaced over one Talbot period during exposure to print large-area patterns over 2-inch wafers.

Evaluation of the printed structures showed that good uniformity and reproducibility were obtained despite an uneven gap and large resist thickness, proving that the pattern is indeed insensitive to the distance between the mask and the wafer. The large gap between the mask and the wafer ensures a practically unlimited lifetime for the masks.

Since PHABLE is a mask-based photolithography method, printing a different pattern simply requires a change of mask. What's more, many different patterns can be simultaneously printed on a single chip or a wafer in much the same way as different circuits are printed on silicon wafers. The limiting resolution of the printed features depends on the wavelength of the light used, with the smallest period being close to half the wavelength.

PHABLE is ideally suited for patterning LED wafers because of its non-contact nature and ability to print over large topographical features and on non-flat surfaces. Photonic nanostructures can be created on LED surfaces after epitaxial deposition steps or on sapphire substrates before the device layers are grown. Relatively thick standard photoresists can be used, such as those with a thickness of 0.5-1.0 μm . This enables etching into semiconductor layers without the added complexity or cost of hard masks, such as SiO_2 . Photonic crystal patterns with various different periods, orientations or symmetries can be incorporated on individual chips to effectively tailor and control the distribution of light emission. The high reproducibility and uniformity of the lithographically produced patterns can improve yield and reduce the costs associated with binning products with large performance variations.

Other emerging technologies also stand to benefit from this innovative photonic patterning technology. For example, lithographic patterning for nanowire-based LEDs and photovoltaic devices can be accomplished with PHABLE. Heteroepitaxy on patterned silicon substrates and epitaxial lateral overgrowth for Blu-ray laser production are other potential applications. Wire-grid polarizers needed in both LCD displays and projectors are other areas where this technology can make a strong impact.

The PHABLE technology enables low-cost fabrication of photonic patterns. The time-tested approach of a mask-based UV exposure and its associated infrastructure will ensure a smooth adoption of this approach. In particular, there is no requirement to invent or develop new materials. Standard photoresists with optimized resolution and etch properties are available from multiple vendors. The infrastructure for mask fabrication is also already in place. This means that the HB-LED and other industries can rely on the usual, well-established sources for the required consumables and a low-cost process for realizing their photonic nanostructures.

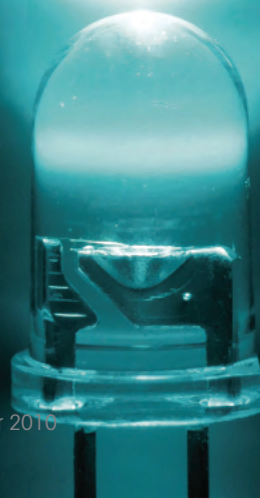
We are now offering samples and wafer batch processing services to companies and researchers developing nanostructure-based products, who are interested in taking advantage of this breakthrough technology. We are also currently offering laboratory lithography tools for 2-inch to 4-inch wafers that are suitable for product development. High-volume production tools with throughput in excess of 100 wafer-per-hour will be made available to manufacturers in the near future. Many future photonic devices will shine even brighter with the introduction of our proprietary technology.

Further reading

Jonathan J. Wierer *et al*, Nature Photonics, (2009)
K Bergeneck *et al*, IEEE J. of Quantum Electronics, (2009)
F. Rahman, Optics and Photonics News, (2009)

Turning 6-inch GaN LED manufacturing into reality

Substantial reductions in chip production costs will spur the uptake of LED-based solid-state lighting. One way to do this is to start to manufacture these emitters with multi-wafer 6-inch tools that set a new benchmark for reproducibility, argues **Aixtron's Rainer Beccard**.



The LED business is booming. These chips are generating attractive cash flows from backlighting the screens of netbooks, lap tops and TVs and this solid-state device is about to break into lucrative new territory: general illumination. The leading LED manufacturers have had their eyes firmly fixed on this goal for many years and their dream is now turning into reality, thanks to the release of the first commercial lighting products.

At Aixtron, which is based in Aachen, Germany, we have a strong track record in supporting the tremendous progress of LED manufacturers. Our effort has focused on continuous improvement in the throughput of MOCVD reactors, echoing the developments of other toolmakers in the silicon industry.

Our first design of MOCVD reactor for growing GaN-based LED epistuctures accommodated 2-inch substrates, and over the years we have unveiled reactors that can house more wafers with larger diameters. This effort has culminated in our release of the future-proof Aixtron AIX G5 HT earlier this year. This tool offers simultaneous deposition of GaN and its related alloys on eight 6-inch wafers, the size that many LED chipmakers will look to migrate to over the next few years. In addition, this reactor can be configured for the growth of multiple 8-inch wafers.

The economies of scale realized by changing to a 6-inch process are obvious: better utilization of the MOCVD reactor area; less edge exclusion; more efficient handling; and better precursor utilization in the epitaxial process. However, it is not possible to produce high-quality, 6-inch LED epiwafers by simply taking established processes and applying them to these larger wafers. That's because such large wafers create their own challenges due to their size, weight, and thickness, and the entire MOCVD environment has to be designed to suit them. In addition, the MOCVD tool must be capable of high yields and fast cycle times, as otherwise this would negate the productivity advantage gained by the migration to large wafers.

We considered these issues when we defined our requirements for our 6-inch MOCVD tool. We decided that the reactor must be capable of producing epiwafers with uniformity high enough to translate to an overall gain in yield over previous generations of MOCVD tools. For the same reason, we had to build a reactor that set a new benchmark for wafer-to-wafer, run-to-run and tool-to-tool reproducibility.

To maximize throughput, our reactor would have to operate without cleaning and baking between growth runs. In addition, we set out to build a tool that required very little preventative maintenance, generated very few particles, and was highly automated. For example, customers had to have the option of buying a version of this tool with automatic loading and unloading.

Our flagship reactor, the AIX G5 HT, fulfills all these goals by realizing stable, reproducible and uniform growth processes on wafers up to 8-inch in diameter (see Figure 1). While designing this reactor, we paid careful consideration to the two fundamental aspects that determine the capabilities and performance of any MOCVD reactor: the thermal conditions; and the gas flow dynamics and chemical reactions, in both the gas phase and the solid phase.

Minimizing temperature variations

The AIX G5 HT features a novel type of gas injector that introduces perfectly laminar gas flows into the reactor. This condition can be realized at high growth pressures (close to atmospheric pressure) and growth rates of up to 30 $\mu\text{m/hr}$. Thanks to this approach, uniform gas phase depletion occurs for all wafer sizes.

One pre-requisite for the growth of high-quality epiwafers is excellent temperature uniformity across the wafer — deviations must be less than 1 °C. This must be realized for both the low temperatures associated with multi-quantum well (MQW) growth, and the far higher temperatures employed for growth of the other regions of the LED.

To realize the excellent temperature uniformity that holds the key to uniform film deposition, we employ our proprietary Planetary Reactor design that features on all of our multi-wafer tools. The satellite disks that hold the wafers rotate individually on a rotating planet disk, which is heated by an RF coil. For large wafer sizes such as 6-inch, this principle leads to an inherent advantage for the subsequent backend process. This stems from the high degree of rotational symmetry associated with the temperature distribution on the satellite, and the wafer that it supports.

To improve reactor performance even further, we have optimized the design of the RF coil and the satellite disk. Thanks to this, our tool delivers unprecedented levels of uniformity on 6-inch wafers.

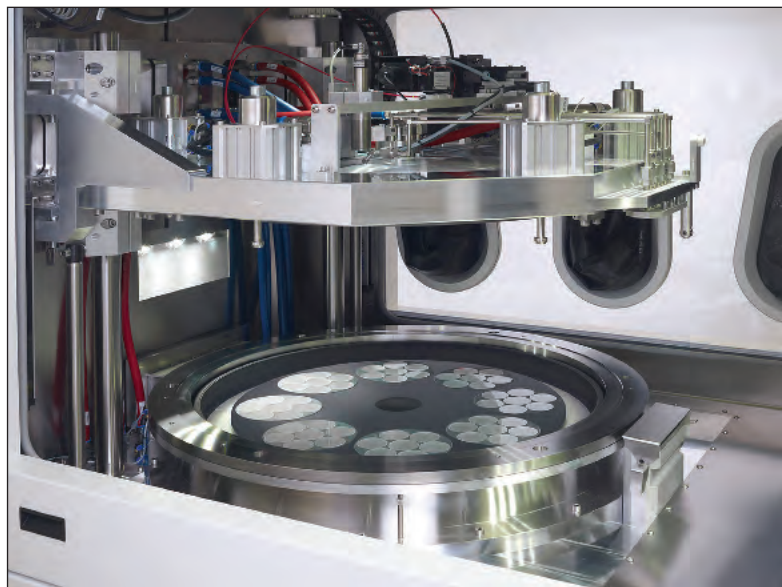
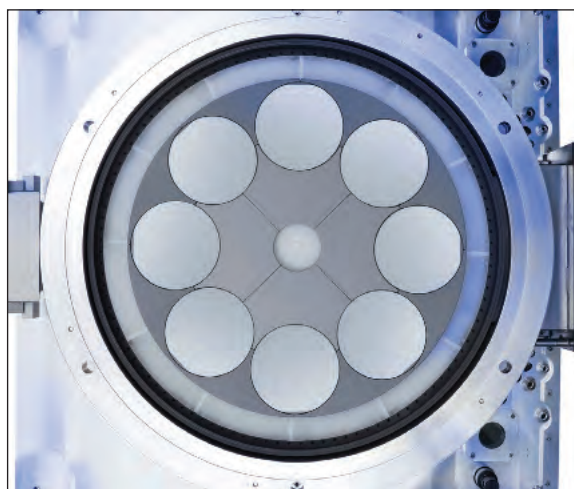


Figure 1. Aixtron G5 HT Planetary Reactor in 56 x 2-inch configuration (above). Top view of this reactor in 8 x 6-inch configuration (right). The tool can also be configured for 4-inch and 8-inch wafers



Unfortunately, complete absence of temperature variations on the satellite disk is no guarantee of highly uniform film deposition. That's because there are differences in the lattice constants and thermal expansion coefficients of the sapphire substrate and the nitride-based LED heterostructure. Strain that results affects all wafers, although the bowing that it causes gets more pronounced as wafer size increases.

Needless to say, bowing is an impediment to uniform LED properties. To prevent this, it is possible to deposit the epiwafers on thick sapphire substrates (above 1 mm), employ *in situ* curvature measurements to monitor and correct for bow, and last but not least, insert special layer stacks into the LED heterostructure that minimizes bow. Armed with these techniques, it is possible to realize

excellent photoluminescence uniformities using the 8 x 6-inch configuration of the G5 reactor.

This high level of uniformity leads to great yield figures. Based on the above uniformity data, an exact calculation of the area yield shows that more than 98 percent of the wafer area is in a 5 nm bin.

A worthwhile analysis of yield must not be restricted to a single wafer – it must consider wafer-to-wafer uniformity and reproducibility. To deliver on both these fronts, we have devoted substantial effort to optimizing the design of the reactor and the materials that it is built from. On top of this, we have made further gains by controlling the temperature of each individual wafer.

To realize individual temperature control, the temperature from the top of each satellite is measured with a pyrometric device. The gas flow of the gas-foil rotation drive of each satellite is then adjusted accordingly, bringing the temperature of the wafer back to its desired value.

Keep on running

Reproducibility is a key issue in high volume manufacturing environments employing many identical MOCVD tools running standardized growth recipes. If high yields are to be realized day-in, day-out, then every reactor must deliver exactly the same performance and results from one run to the next without any re-calibration.

We have analyzed the root causes of non-stability in various MOCVD systems and determined that they are predominantly related to small temperature drifts in the reactor set-up. Consequently, with our G5 reactor we have strived for a design with inherent temperature stability. One of the key features of this particular reactor is its novel graphite ceiling plate. In the Planetary Reactor designs, the ceiling plate defines the upper thermal boundary of the reactor. Even though it is not actively heated, it does influence the reactor's thermal management.

The great strength of the new graphite ceiling is that its emissivity is unaffected by the deposition of materials onto its surface. This means that the thermal properties of the reactor are fixed, rather than depending of the number of growth runs already performed. This results in unprecedented reproducibility of all LED properties, from run to run and between different reactors.

Another route to increasing productivity of an MOCVD system is to reduce its cycle times. The G5 reactor excels in this regard. Not only does it enable very high growth rates that cut material deposition times – it also has very

In more quantitative terms, the throughput of the AIX G5 HT is more than double that of the previous MOCVD tool generation, thanks to the combination of larger capacity, large wafers and shorter cycle time

short times associated with the non-growth processes that form part of the production run.

These gains stem predominantly from the introduction of the graphite ceiling. As noted before, this ceiling plate does not have to be frequently exchanged to ensure thermal stability, because there is absolutely no thermal drift. What's more, the process conditions used for the ceiling mean that any deposits create a very solid film. This is stable, does not peel off and never generates particles, so there is no need whatsoever to exchange or clean the ceiling between LED growth runs. Additionally, there is no need for *in situ* bakes, conditioning runs, or exchange of any reactor parts.

The upshot of all of this is that growth runs can be performed continuously, without interruption. This slashes "downtime" associated with cleaning and maintenance. In more quantitative terms, the throughput of the AIX G5 HT is more than double that of the previous MOCVD tool generation, thanks to the combination of larger capacity, large wafers and shorter cycle time.

Avoiding human contact

The features associated with the G5 will appeal to many of the bigger LED manufacturers, including those having a history in the silicon or display business environment. Many of these firms will lead the transition from small wafer sizes to 6-inch wafers, and are likely to view automation as a pre-requisite for unlocking the full potential of large substrates.

From a yield point of view, manual wafer handling carries an inherent risk of error. Over time this diminishes yield, with larger wafers leading to bigger losses than smaller ones. Consequently, the advantages associated with automation for manufacturing on 6-inch wafers heavily outweigh any downsides, especially once the cut in the non-productive cycle time of the MOCVD tool is accounted for.

Our incorporation of automation on the G5 tool has been realized without making any compromise to the performance of the MOCVD reactor or its processes. The transfer module, which provides automated loading, is very reliable and simple to use. A robotic system accesses the reactor through a gate valve, picks up a satellite disk together with the wafer, and then replaces it

with another satellite disk housing a fresh substrate. It only takes a few minutes to exchange a complete reactor load, a process that is performed after only a short cooling phase (hot load capability). The satellites housing the epiwafers are taken away and unloaded and reloaded while the G5 starts its next MOCVD growth run.

It is possible to operate a single G5 reactor with a transfer system. However, to cut overall capital expenditure and save space, if an LED chipmaker has several of these MOCVD units, they can share transfer systems.

The light ahead

Over the next few years there will be major changes in LED manufacturing. The emergence of solid-state lighting will encourage many leading LED chipmakers to increase production capacity, and prompt heavyweights in other industries to enter this sector. This will lead to bigger LED fabs, which will start to resemble the silicon foundries.

These bigger fabs will focus efforts on rapidly improving throughput and productivity, which will include the introduction of 6-inch LED processes. Sapphire substrates of that size are already available, and are complemented by the latest MOCVD tools, such as our AIX G5 HT. Whether this is configured as an automated tool or as an MOCVD cluster tool, it will easily meet the foreseeable throughput, cost, performance and yield requirements of the coming years.

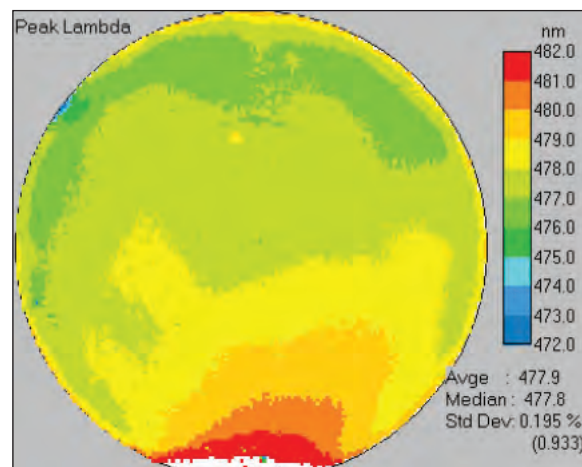


Figure 2. Photoluminescence map of a typical LED multi-quantum well. Standard deviation across the entire 6-inch wafer (no edge-exclusion) is 0.9 nm

Dots deliver beautiful whites

An ensemble of spatially distributed III-nitride quantum dots can produce the broad, visible emission that is desirable for ambient lighting and the growth of crops, says **Soh Chew Beng, Chua Soo Jin and Liu Wei from the Singapore Institute of Materials Research and Engineering.**

GaN-based LEDs have made tremendous progress in the last decade. In particular, the high-brightness, phosphor-coated white variety has come on in leaps and bounds, and it is now starting to penetrate solid-state lighting. In this market it offers a far more efficient alternative to the incandescent bulbs that are being phased out in many countries through government legislation, and it does not employ the toxic materials used in compact fluorescent bulbs.

However, light generated by phosphor-coated LEDs is far from perfect. Its color-rendering index is inferior to that of a compact fluorescent, there are production yield issues,

and the phosphor coating tends to degrade with usage, leading to unwanted changes in the spectral output of this lighting source.

Shifts in emission profile are a major impediment to the deployment of LEDs for in-door ambient lighting and horticultural lighting for eco-conscious greenhouse and indoor growers. To mimic sunlight and enable plants to perform photosynthesis, it is essential for horticulture lighting to have dominant peak wavelengths at 430-460 nm and 650-700 nm, the spectral ranges where Chlorophyll-A and B have the highest responsivity. If strong emission can be produced at these wavelengths,



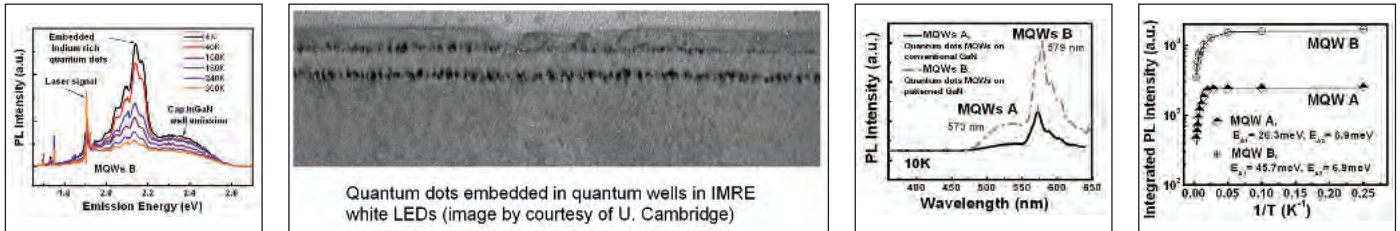


Figure 1 (Far left) Temperature varying PL spectra for MQWs B; with embedded quantum dots on nano-ELO GaN substrate (Left) Cross-section TEM images showing the quantum dots incorporation in InGaN/GaN quantum wells. (Right) Low temperature PL spectra of the InGaN/GaN multiple quantum wells at 10K; MQWs A and B on GaN and nano-ELO GaN template with indium rich nanostructures incorporation in InGaN/GaN MQWs. (Far right) Arrhenius plot for determination of activation energy of MQWs

LEDs can then tap into the horticultural lighting market that currently uses sources such as the HID lamp, which has low conversion efficiency and only outputs a small proportion of its emission spectrum in the ranges useful for photosynthesis.

At Singapore Institute of Materials Research and Engineering – which is a member of the Agency for Science, Technology and Research (A*STAR) – we are developing light sources for horticultural and ambient lighting. These feature a long broad spectrum in the yellow to red regime, plus a narrow blue emission peak.

To produce this form of emission, we have developed a novel technique for incorporating quantum dots (QDs) into LEDs that can tune their emission spectrum. These QDs, which are embedded in the multiple quantum wells of an LED, are clearly visible in transmission electron microscopy images. They produce an internal quantum efficiency of 40 percent, according to photoluminescence measurements at 4K and 300K with an excitation source at 325 nm (Figure 1).

Ambient sources

Incorporation of quantum dots into the active layers of devices yields two major advantages over the conventional InGaN well: It increases the recombination efficiency of the emitting layer, thanks to the strong exciton binding energy and large band-offsets; and it reduces the electroluminescence shift due to superior carrier confinement in three dimensional space.

While many researchers have turned to QDs to make a narrow linewidth source, we have taken an entirely different tack, using them to create a broad emission spectrum that covers 450 - 750 nm and mimics daylight. To make such a source requires the fabrication of dots with a broad range of sizes, which we realize by variations in growth temperature and trimethylgallium flow (see Figure 2).

Our white LED is based on dual-stacked InGaN/GaN multiple quantum wells with QDs embedded in one of the

multi-quantum wells. The lower part of the structure comprises long-wavelength-emitting, indium-rich QDs incorporated in quantum wells and the upper set features cyan-green emitting multiple quantum wells. By controlling growth temperature and the precursor flows, we can realize LEDs with many different shades of white.

LED performance has been evaluated with current-voltage and electroluminescence tests. These measurements revealed that there is minimal change in the LED emission peak as injection current increases from 100 mA to 280 mA – it shifts by just 5 nm. This suggests that the piezoelectric field effect does not have a major influence on the energy levels of QDs embedded in quantum wells.

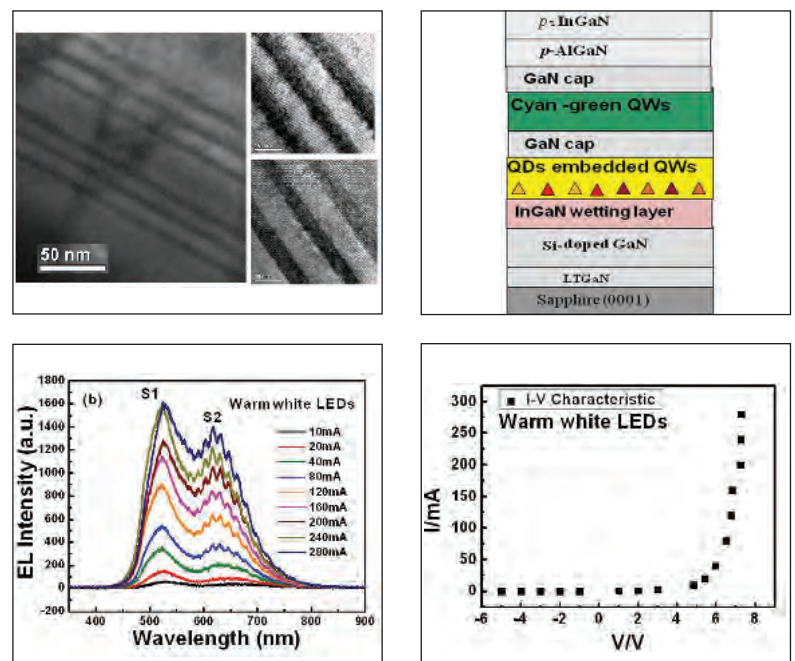


Figure 2 (Top left) TEM images of the dual stacked MQWs in quantum dots incorporating white LEDs. (Top right) Sample structures of the LEDs. (Bottom left) Electroluminescence spectra of a packaged warm white LEDs (Bottom right) I-V curve of the LEDs

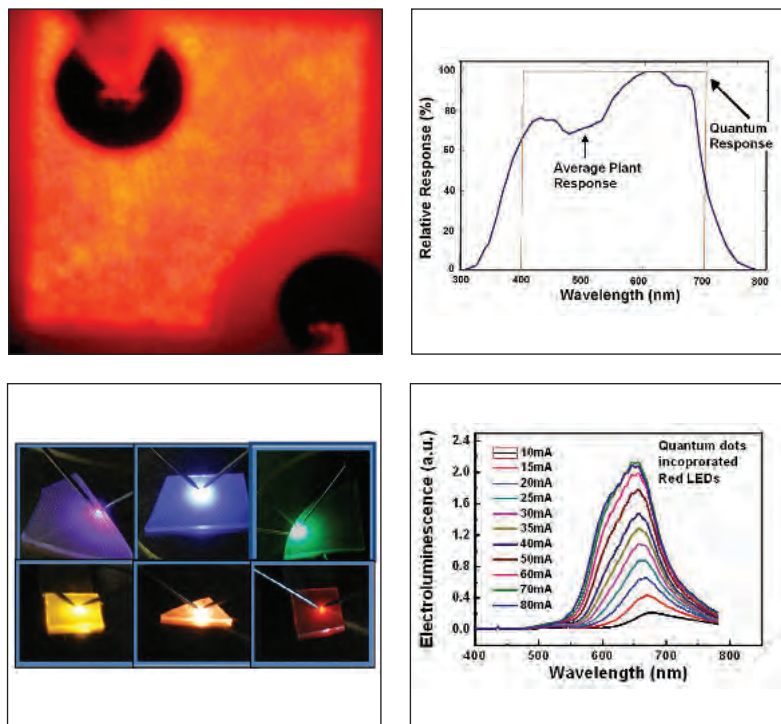


Figure 3 (Top left) Electroluminescence of quantum dot incorporated red LEDs (Top right) The relative quantum efficiency curves as determined by the average plants response for photosynthesis. The red box shows the quantum (PPF) response when all photons are weighted equally between 400 nm to 700 nm. PPF overestimate the photosynthetic value of photons between 400 nm to about 550 nm (from McCree, 1972a). (Bottom Left) Processed LEDs at wafer level with violet to green obtained from conventional InGaN/GaN MQWs while yellow to red from quantum dots incorporating MQWs (bottom right) EL from QD LEDs

Graphing light output as a function of injection current shows that droop is more prevalent in conventional LEDs than it is in our novel emitters. This characteristic makes our QD-based LEDs attractive candidates for high-power device applications.

LEDs for horticulture

Studies have shown that ultraviolet and far red radiation is better for driving photosynthesis than green emission. Against the backdrop of efforts to reduce carbon dioxide footprints, greenhouse growers are exploring different combination of lighting for effective vegetation and flowering during different stages of the plant's growth cycles.

However, the different type of materials used for growth of UV LEDs (III-nitrides) and red LEDs (III-arsenides) will pose a reliability issue for LED lighting units for horticulture. What's more, the integrated

electroluminescence spectrum tends to deviate from its optimum profile after a period of use.

We believe that our novel LEDs that incorporate QDs can address these issues. Our red-emitting versions – which have dominant emission peak at 652 nm with a full-width half maximum of 200 meV – display minimal shift in wavelength with increasing injection current and can cover the longer wavelength (far red) emission required by plants for photosynthesis. Combining this output with the violet/blue emission from conventional InGaN/GaN LEDs enables the production of a lighting source that covers the whole photosynthetic response of plants.

Despite the favorable characteristic and properties of QDs, this system has its limitation. When these dots are incorporated into LEDs they tend to suffer from out-diffusion into the surrounding matrix of InGaN wells and GaN barriers during the growth of high temperature p-type GaN and chamber annealing for magnesium activation.

We have investigated the extent of this degradation and found that it is possible to prevent out-diffusion by capping the structure with an AlN layer. This is possible thanks to the low mobility of AlN adatoms on the film surface at a low growth temperature of typically 780 °C and formation of stable Al-N bonds. Aluminum also possesses a lower vapor pressure than indium, which effectively reduces the diffusion length of subsequent indium deposited on the first quantum well layer. In turn, this increases the quantum dot density at the second quantum wells.

Another benefit of the addition of a stable thin AlN encapsulation layer is a reduction of piezoelectric polarization charge accumulation at the interface to the compressively strained InGaN well. This lowers the blue shift of emission wavelength with injection current.

Getting the light out

To improve the efficiency of LEDs and maximize their energy saving potential, chip manufacturers and researchers are looking into ways to resolve efficiency droop and improve light extraction. We are going down this road too, and have developed the cheap patterning technique using nanosphere lithography. This involves polystyrene nanospheres, anodized alumina oxide and UV-enhanced electrochemical etching to generate nanoporous GaN.

Our phosphor-free, apple-white LEDs unite a dual stack of InGaN/GaN multiple quantum wells. The lower set contains long-wavelength-emitting, indium-rich nanostructures incorporated in quantum wells, and the upper set comprises cyan-green emitting multiple quantum wells. The LEDs were grown on a nano-epitaxially lateral overgrown (nano-ELO) GaN template,

While our QD LEDs enjoy the advantages associated with zero dimensional structures, such as strong confinement of excitons and color tuning via size control, they are held back by restrictions in the choice of growth temperatures for the top p-type GaN layer

which was formed through re-growth of embedded GaN nanopillars over a SiO₂ film. The SiO₂ film was patterned by carrying out ICP etching with an anodic aluminum oxide mask featuring an array of holes that were 125 nm in diameter and spaced 250 nm apart.

Anodization of aluminum film or foil using various acids and applied voltages produces hole arrays with diameters ranging from 60 nm to 200 nm. This serves as a natural surface patterning technique. The periodicity of the embedded array of GaN nanopillars enhanced light extraction of the LEDs by 34 percent.

Higher gains of 50 percent or more should be possible by improving internal quantum efficiency through reductions of threading dislocations and stress relaxation. This is a realistic goal, because the separation between dislocation lines is about 200 nm for a GaN sample with a dislocation density of 10⁹ cm⁻². Since in our case the diameter of the holes is just 125 nm, it should be possible to prevent many of the threading dislocations from further propagation and annihilate them at the SiO₂ mask via bending at the GaN-SiO₂ interface.

While our QD LEDs enjoy the advantages associated with zero dimensional structures, such as strong confinement of excitons and color tuning via size and composition control, they are held back by restrictions in the choice of growth temperatures for the top p-type GaN layer. The AlN encapsulation layer can reduce the indium out-diffusion from quantum dots, but it cannot eliminate it. So we are currently exploring alternative techniques, such as the implantation of acceptor into p-type GaN, followed by laser annealing for activation.

Another goal of ours is to develop vertical quantum dot LEDs. This could be realized by either an existing laser lift-off technique or electrochemical wet etching of our embedded sacrificial SiO₂ film in surface patterning. A patterned n-face GaN aids light extraction, bringing us a step closer to achieving high brightness QD LEDs.

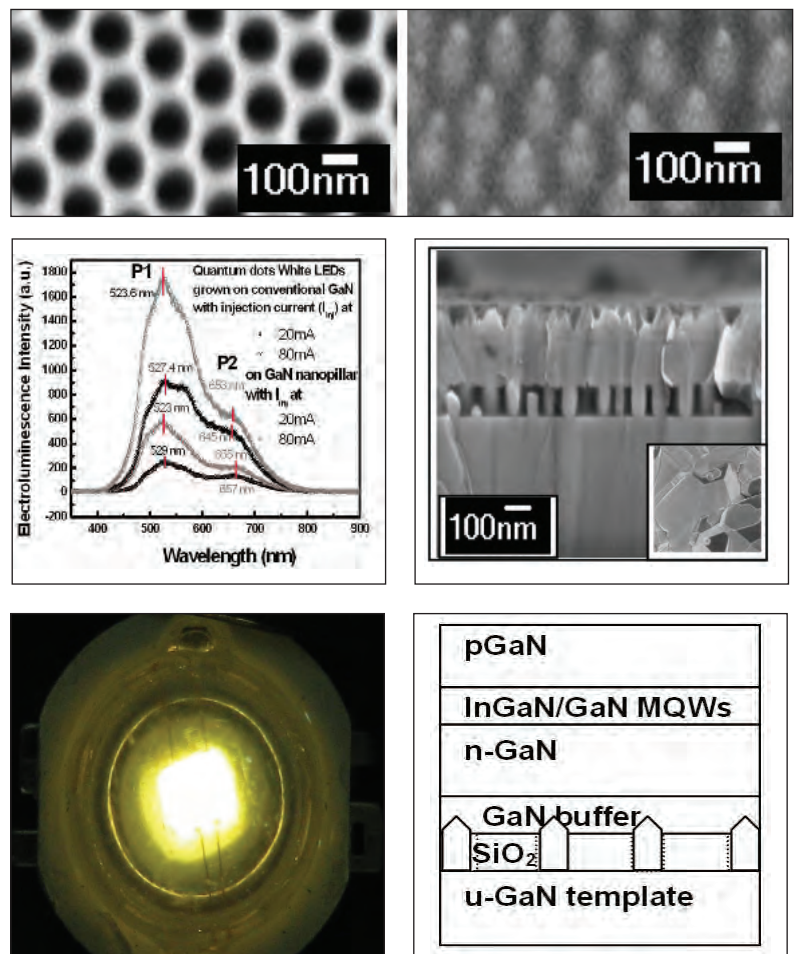


Figure 4 (Top) SEM image of the anodized alumina oxide mask used to pattern a hole array on SiO₂ and GaN nanopillars grown from SiO₂ layer (Middle left) Electroluminescence spectra of quantum dots LEDs grown on GaN nanopillars (with nanohole array of SiO₂ mask) and conventional GaN (Middle right) cross-section SEM image of overgrown GaN buffer layer (Bottom left) Images of packaged apple white LEDs chip with GaN epitaxy overgrown on the GaN nanopillars (Bottom right) sample structures for the apple white LEDs

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LEDs and lasers are the big success stories of the III-nitride field. Thanks to the tremendous growth in device revenue, sales of nitride chips are now only eclipsed by those made from silicon. In the research community these light emitting devices are also hot, having taken up a prominent position on the conference circuit, including dominance of the two big biannual nitride gatherings: the International Workshop on Nitride semiconductors (IWN) and International Conference on Nitride Semiconductors (ICNS).

So it is not surprising that advances in the performance of blue, green, white and UV light emitters played a leading role in many of the presentations at the recent IWN 2010 meeting. However, this gathering had a noticeably different feel – one that reflected its growing maturity, which has been buoyed by the increasing diversity of III-N devices and their applications. This shift in outlook revealed itself in the vibrancy of newly added workshop sessions on power switching transistors, RF systems, and

photovoltaics and energy harvesting. And it was also there in a more subtle form at the handful of social events. There nitride researchers mingled with attendees from mainstream silicon companies such as International Rectifier, National Semiconductor, and Applied Materials.

The meeting kicked off with a plenary talk by Jim Speck from the University of California, Santa Barbara (UCSB) on the growth, characterization and performance of various light emitters. Key results from his discussions included continuous-wave results on *m*-plane laser diodes operating at 459 nm with 4.1 KA/cm² threshold current density and a 9.8 V threshold voltage. He also detailed the challenges for growing on various non-polar and semi-polar planes and justified UCSB's present focus on semipolar (20 $\bar{2}$ 1), pointing to the higher indium incorporation on this plane and the results it has produced: 516 nm lasing and 528 nm LEDs. The collection of invited talks on the first two days also included a presentation given by one of Speck's

IWN showcases the diversity of III-nitrides

While LEDs still dominate the IWN meetings, there is a growing interest in nitrides for transistors, detectors, solar cells and water-splitting devices, reports **W. Alan Doolittle from Georgia Institute of Technology.**



colleagues from UCSB, the computational scientist Chris Van de Walle. He offered a new insight into an old topic, the source of yellow luminescence from carbon impurities. In addition, he described recent efforts to computationally quantify the strength of direct Auger recombination and a newly suggested process - phonon-assisted Auger. Both of these processes have a potentially important role to play in LED droop.

Delegates were also treated to an insightful presentation by Eva Monroy from CEA Grenoble, France of MBE grown inter-sub-band (ISB) detectors, which included impressive TEM images. Detector results included operation well into the near IR region at 1.5 μm , the first observation of ISB absorption covering the entire mid-IR range from 1.5 to 10 μm and a demonstration of ISB absorption in the far IR at 9 meV. The audience was clearly impressed by efforts that not only married state-of-the-art growth, TEM and quantum mechanical sophistication, but also provided a glimpse into the possible future of III-Nitrides.

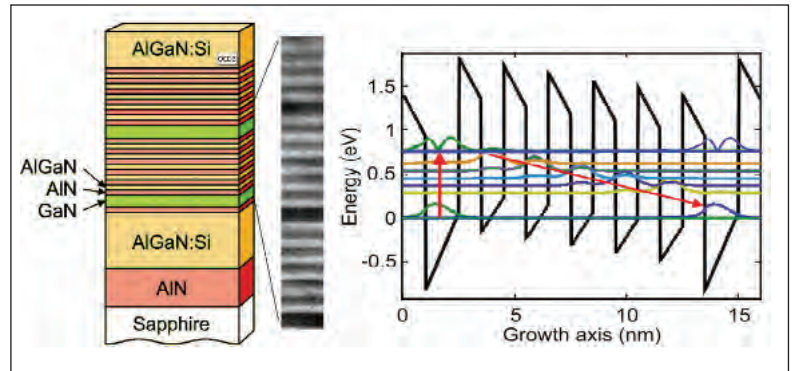
An update of activities at the start-up Nitek was provided by Vinod Adivarahan. He revealed that the University of South Carolina spin-off, Nitek, has produced pixelated single chip LEDs operating at 280 nm with 53 mW output and hybrid/multi-chip versions with a 233 mW output at room temperature. These power levels are suitable for sterilization, UV curing and biological detection applications.

Nitride transistors

Tomas Palacios from MIT provided further evidence for the increased diversity of the III-Nitride field. In an invited talk he argued that GaN is an ideal transistor for mm- and sub-mm wave applications, before backing up his claim with a description of transistors with an f_T of 225 GHz and an f_{max} of 300 GHz, and an outline of pathways to terahertz frequencies. Palacios then set the stage for parallel sessions later that week, which focused on the rapidly emerging "low hanging fruit" that is the GaN-on-silicon power electronics market. This should be a significant percentage of the well established \$ 20-40 billion silicon power device market.

Another scientist accepting the invitation to speak at the conference was Masaaki Kuzuhara from University of Fukui, Japan, who also spoke about nitride transistors. He detailed the high-temperature operation of AlGaIn channelled transistors with aluminum concentrations in excess of 50 percent. These outperformed variants with a GaIn channel at high temperature, opening up yet another transistor market for III-Nitrides.

Enrique Calleja Pardo from UP Madrid, Spain delivered a brilliant overview of the now well-understood mechanisms for nano-rod nucleation and growth. Pardo said that this field is "fully matured", and backed up this claim by



showcasing the research of H. Sekiguchi and his co-workers (see *Appl. Phys. Lett.* **96** 231104 (2010)), which details the fabrication and characterization of a full color range of nano-rod-based LEDs and many other equally impressive devices. After the opening two days of invited sessions delegates were presented with a mind-numbing smörgåsbord of choices stretching out over two days of parallel sessions. Words cannot do justice to the number of choices available.

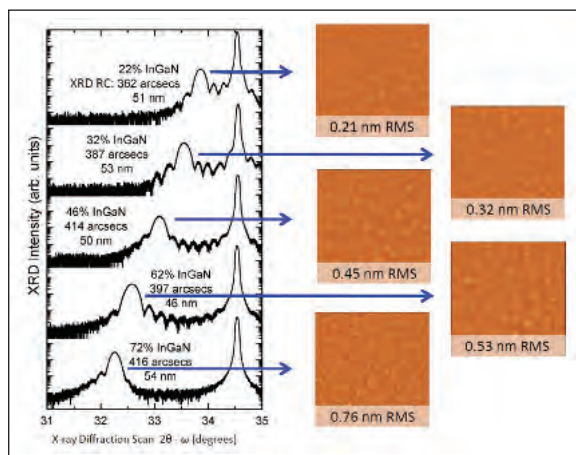
The statistics gives a flavor, however - 385 talks and 240 posters in two days that spanned epitaxial growth; bulk crystal growth; optical, electronic and magnetic properties; device processing and fabrication technologies; defect characterization and structural analysis; theory and simulation; nanostructures; light emitting devices; electron transport devices; sensors and MEMS; plus a newly added session in photovoltaics and energy harvesting. This new session included a score of talks on photovoltaics and solar-induced water splitting.

Figure 1. Example of an inter-sub-band detector and quantum well design presented by Eva Monroy from CEA Grenoble, France. Structures covering the near, mid and far IR regions were demonstrated

IWNS facts and figures

The International Workshop on Nitride Semiconductors 2010 was held in Tampa, Florida, from 19 to 24 September. Attendance at the meeting exceeded the previous IWN (2008) in Montreux by almost 15 percent, with 793 delegates making their way there from all over the world. 305 delegates were from North America, 255 from Asia and 204 from Europe. Following in the footsteps on previous IWN meetings, the conference started with two days of invited plenary talks, followed by two days of parallel sessions, before concluding with a mix of two plenary talks, late news, and reviews of the workshops. The traditional workshop themes, such as those of epitaxy, RF transistors and nanostructures sessions, were added to this time around, thanks to the introduction of sessions on power switching transistors, RF systems, and photovoltaics and energy harvesting.

Figure 2. X-ray diffraction spectra and AFM images for MME grown InGaN throughout the miscibility gap showing single phase materials with excellent surface morphology, MBE derived techniques presented by Michael Moseley from Georgia Institute of Technology



Attendance was healthy, and some invited sessions were standing room only. They were not there to hear good news, however, but to wrestle with one of the weaknesses of nitride devices. The unavoidable truth is that today all InGaN photovoltaic results are abysmal single digit efficiencies. This poor showing stems from phase separation issues within InGaN that limit the practically achievable device energy bandgap to portions of the solar spectrum with minimal radiation. The upshot is low efficiencies.

One possible route to overcoming these issues was revealed in an invited talk by Christiana Honsberg from the Arizona State University. She presented some intriguing new results, attained in collaboration with student Michael Moseley from Georgia Institute of Technology, which outlined growth methods that can completely eliminate phase separation. Similar growth techniques have been used by Chris Boney's team from the University of Houston, and have yielded respectable currents but at lower than expected voltages. Water-splitting talks highlighted challenges with surface stability against photo-electrochemical etching. The results realized to date are highly dependent on surface treatments and measurement methodology. Several speakers also pointed out that a successful photo-electrochemical process would need to include a method for separating hydrogen and oxygen. This topic was largely outside the focus of the session.

MBE: down but not out

During the IWN meeting there was an intriguing subtle undercurrent that spontaneously emerged throughout the meeting: a resurgence in promising MBE results, particularly regarding the growth of InGaN based devices. Evidence of this resurgence could be found in the talk given by Moseley from Georgia Institute of Technology, which detailed the control of phase separation throughout the entire miscibility gap using Metal Modulated Epitaxy (MME). It was also present in Chris Boney's InGaN solar cell award winner poster, the ultra-high growth rate results from the Los Alamos National Laboratory group using their scalable ENABLE process, and also in Christina Honsberg's descriptions of the impact MME would have on InGaN photovoltaics. What's more, MBE featured in

the promising nitrogen polar green LEDs reported by the Ohio State University group in the late news session and the encouragingly high hole concentration presented by student Jonathan Lowder and co-workers at Georgia Tech. Last, but by no means least, in the closing invited talk LED pioneer Hiroshi Amano pointed out that MBE and its related variants are capable of accomplishing things that other technologies struggle to achieve. While it is too early to determine if any of these new reports will manifest into manufacturable products, IWN 2010 did highlight the promise of alternative growth technologies in a field where MOCVD dominates.

On the last day of the conference, just like the first, conference chairs Christian Wetzal and Asif Kahn gave tribute to honorary chair, Isamu Akasaki from Meijo University, Japan, for his pioneering work and leadership in the Nitride community. Fittingly, it was announced that the next IWN meeting will be held on October 14-19, 2012, at Sapporo, Japan. Hiroshi Amano from Nagoya University is taking the role of executive committee chair, with Yoichi Kawakami from Kyoto University serving as program committee chair. If the III-nitride field continues to grow at the current rate, the famous beer gardens of Sapporo that are close to the meeting will be drained dry by hordes of thirsty "Nitridors".

Rump sessions in Tampa

To maintain the workshop nature of IWN, the conference organizing committee added five rump sessions to the IWN meeting. These sessions, which gave the audience a chance to pose questions to a panel of invited experts, were highly successful with attendance bursting out of many rooms. Discussions were lively, and in some cases, playfully controversial. The rump sessions covered:

- **III-N on silicon:** the best of two amazing semiconductors, which focused on how the integration with silicon enables new opportunities (and challenges) for III-N semiconductors in power electronics, optoelectronics and energy
- **III-N challenges for RF electronics:** which revolved around scaling, speed and reliability issues for pushing the 'standard' HEMT performance
- **Ideal III-nitride substrate technology:** a discussion on getting the right balance between cost of the substrate and its quality, which can enhance device performance
- **LED IQE roadmap:** from 70 percent to 90 percent, which looked at all the issues relating to increased efficiency
- **III-N nanowires:** a debate on the fundamental issues regarding growth, doping, and novel applications.

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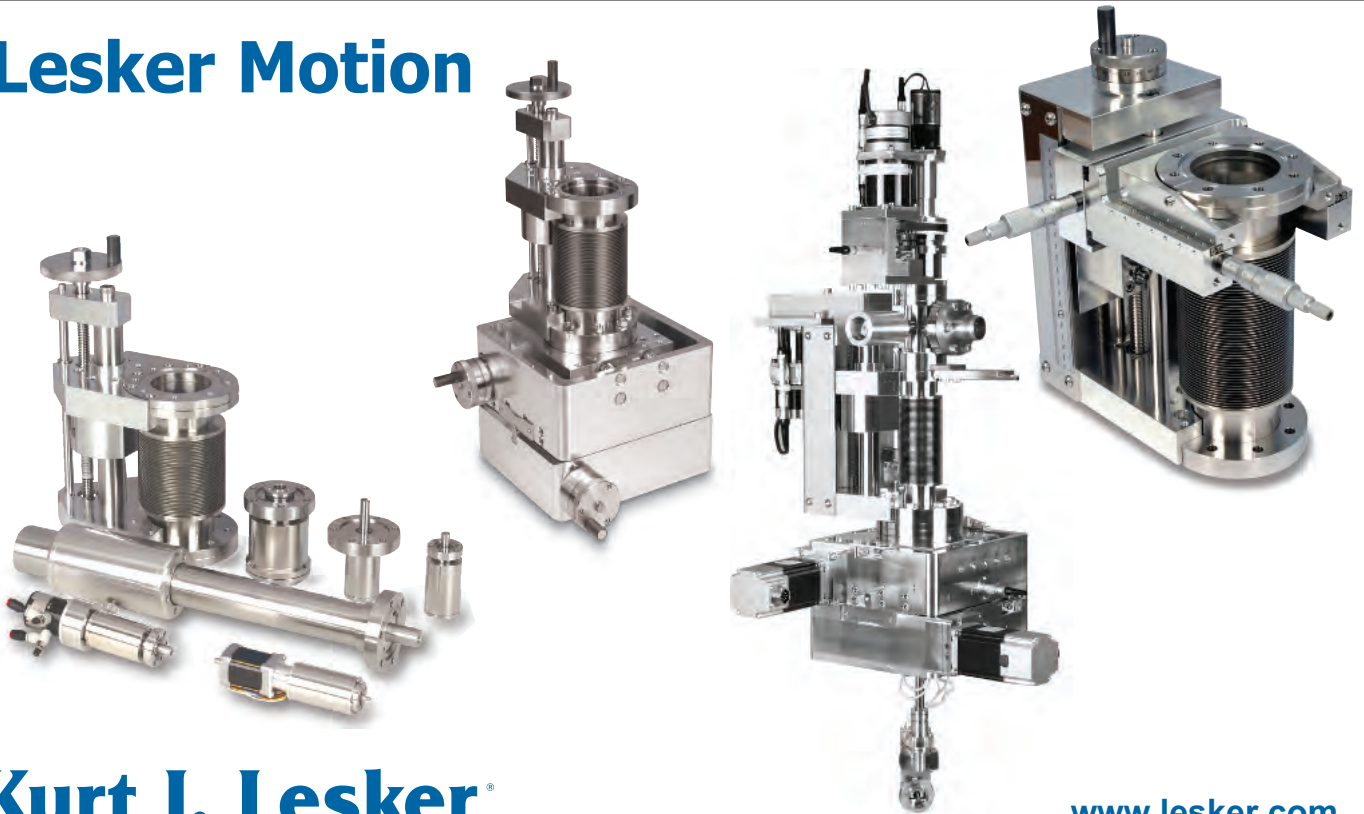
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The transistor laser: a radical, revolutionary device

There are tremendous differences between the laser and the transistor, but it is possible to draw their attributes together by building a transistor laser. This novel device that produces its electrical and optical outputs simultaneously promises to revolutionize data transfer, enabling new architectures capable of operating at incredibly high bit rates, says **Milton Feng from the University of Illinois, Urbana-Champaign.**

The semiconductor industry rakes in billions and dollars from the manufacture of devices invented way back in the middle of the twentieth century. With the benefit of hindsight it is clear that the most important of them all is the transistor, a device invented by John Bardeen and Walter Brattain in 1947, which has been the key building block in the development of microelectronics, integrated circuits, consumer electronics, and the computer industry. Not far behind the transistor is the visible LED, made for the first time by Nick Holonyak in 1962, and the laser diode, independently invented in that same year by Holonyak and Robert Hall. These two optoelectronic devices have provided a great foundation for revolutionizing display, lighting, and information technology.

Although the performance of all these devices has come on in leaps and bounds over the intervening decades, none can simultaneously deliver an electrical signal and a laser output. The invention of such device had to wait until 2004, when I, Milton Feng, in partnership with co-worker Holonyak, produced the world's first transistor laser.

This revolutionary semiconductor device that offers three-port operation – an electrical input, an electrical output and an optical laser output (see Figure 1) – has the potential to make important contributions to integrated photonic and electronic integrated circuits, the computer industry and new information technology. Amongst these many promises, it is capable of redefining the approach made to the transfer of digital data. Today, PCs operate solely in the electrical domain, and hooking up to the internet requires an infrastructure involving transmitters and receivers that can provide an interface with the optical domain. The transistor laser, however, is capable of performing all these functions itself. One of its roles could be to act as an optical interconnect that could allow incredibly fast data flow to and from memory chips, graphics processors and microprocessors.

Our transistor laser, which emits infrared light, is a modified, high-speed HBT with a quantum well in its base region. In conventional high-speed HBTs, which inevitably operate at a high current density, the base provides the pathway for electrons to travel from the emitter to the collector. In our device, the quantum well in the heavily-doped base traps some of these electrons, which diminishes the transistors gain, but allows this device to realize radiative recombination between holes and electrons. Thanks to the geometry of our device – the chip has cleaved facets that act as mirrors – the light that is emitted is bounded by a cavity, enabling stimulated emission, one hallmarks of a laser.

Our first transistor laser needed to be cooled with liquid nitrogen. But a year later it could be run at room temperatures, thanks to improvements in MOCVD growth

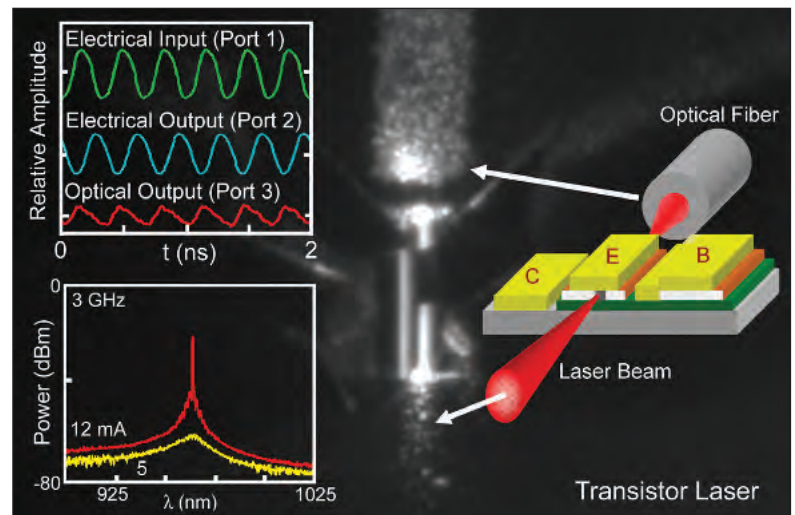


Fig. 1 Three-port operation of the transistor laser provides an electrical input (port 1), an electrical output (port 2) and an optical laser output (port 3).

and the design of the quantum well. Since then we have focused on improving the quality of light output from our transistor laser and understanding its electrical behavior.

Revolutionary modulation speeds

One of the really encouraging attributes of our transistor laser is its incredibly fast radiative recombination lifetime: it is below 30 ps. This can spur the direct-modulation bandwidth in an LED to 10 GHz, and to 100 GHz in a laser. The far higher bandwidth will accelerate the deployment of LEDs and lasers in optoelectronic interconnects and open the door to a new generation of high-performance, electronic-photonic integrated circuits.

Traditional laser diodes suffer from a resonance peak in the frequency response. To combat this, resonance compensation circuits are included in transistor laser driver circuits. Our transistor lasers, however, do not have to contend with this thanks to a shift in the carrier-photon damping ratio and elimination of the resonance peak. Thanks to these attributes, our laser transistors could be used to build an ultra-low power transmitter and array for 100 Gbit/s Ethernet and optical interconnect applications. In addition to the high speeds, there is also the possibility to tap into our device's non-linear characteristics, and exploit flexible signal mixing and processing.

An additional weakness of the conventional laser is a pulsation or "ripple" in its output. This phenomenon is well understood. It was observed in 1959 in masers under certain pump conditions, and has been studied in detail by the researchers Statz and deMars. They explained its occurrence in the 1960s by studying the transient solution of a pair of coupled carrier-photon rate equations

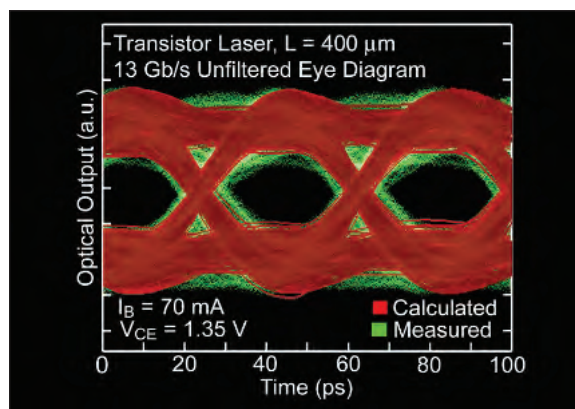
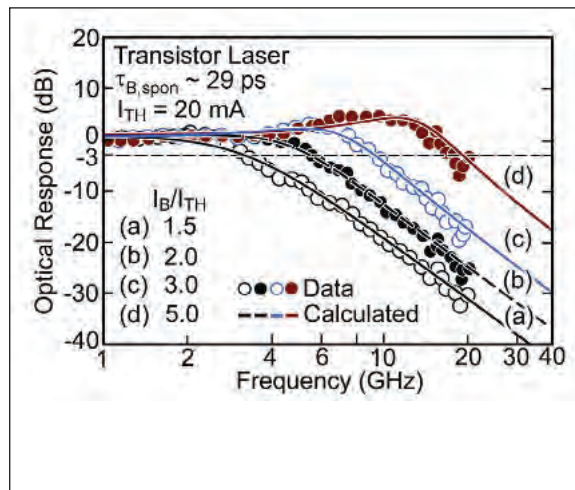


Figure 2. (a, top) Bandwidth (20 GHz) (b, above) Eye diagram (13.5 Gbit/s)

“fast” recombining carriers favored (see Figure 2). It follows that it is possible that the intrinsic spontaneous recombination time in the base of the transistor can be “clamped” at the same order of magnitude as the quantum well base region transit time, typically 10 ps.

We have studied the behavior of our transistor laser in more detail by considering its small-signal linear optical response. A damping factor is included in our calculations. One insight gained from this effort is there are at least three approaches to reducing the resonance peak: speeding the base spontaneous recombination lifetime; increasing the natural resonance of the system; and reducing the ratio between the base current and the threshold current. Analysis also reveals that it is possible to realize a “critically damped” condition that eliminates carrier-photon resonance.

The small-signal linear optical response of our device has been calculated for spontaneous recombination lifetimes of 2, 10, 50 and 250 ps. For these calculations we have assumed a photon lifetime of 2.5 ps and a value of five for the ratio of base current to threshold current.

In addition, we have measured and fitted an optical frequency response to our transistor laser. This highlights the absence of carrier-photon resonance, which results from the “fast” base spontaneous recombination lifetime. In agreement with our model, there is a slight resonance in the output of our laser, which is less than 3 dB and only seen at higher bias. What is pleasing is that a resonance-free response of the tilted-charge transistor laser is observed at a range of biases: (a) $I_B = 30$ mA; (b) 40 mA; (c) 60 mA; and (d) 100 mA.

It is worth noting that the Statz and deMars coupled carrier-photon equations do not include parasitic charging delays. To cater for this, we have developed a physically based transistor model, which includes parasitic charging delays to predict microwave frequency response and digital eye-diagrams.

A consequence of the multi-port capability of the transistor laser is the need to re-formulate Kirchoff’s law, which is widely used to analyze and design conventional circuits. In order to cater for our transistor laser, this law must include energy conservation, and not simply current and charge. We have recently done just this, and published a paper detailing these efforts in the *Journal of Applied Physics*. Our novel transistor laser clearly holds great promise. It is still early days, but what is clear is that this multi-port structure offers a vast improvement in topological and device-to-device system design freedom. Thanks in part to these attributes, it promises to offer a leap in the performance of electrical-optical integrated circuits that is impossible to conceive with either the transistor, or even more limited two-terminal diode.

• This work is sponsored by DARPA and ARO

describing the dynamical interaction between population inversion and cavity electromagnetic energy.

The unwanted self-resonance seen in these masers also plagues today’s laser diodes used for data communication. Here it causes a hike in the bit error rate, which is countered with expensive, complex peripheral circuits. Typically passive low-pass filters, such as Bessel filters with a fixed cut-off frequency, are employed to “filter out” the resonance frequencies. But this addition comes with a big performance penalty: it restricts the laser’s transmission bandwidth to below its resonant frequency.

One of the great strengths of our novel, three-port device is that it can produce resonance-free semiconductor laser behavior. This stems from the incredibly fast base spontaneous recombination lifetime, which is typically just 29 ps. To realize this we use an approach that would fail in today’s workhorse for data communication, the p-i-n double heterojunction laser. This involves building a structure that tilts the injected carriers and diffuses them across a thin, oppositely doped quantum-well base active region. Slowly recombining carriers are removed, and

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Removing strain promises to boost detector performance

Quantum dot infrared photodetectors suffer from strain in their nanostructures that culminates in various performance-degrading defects. However, many of these defects can be avoided by turning to a novel, strain-free growth method based on the deposition of droplets, says **Jiang Wu from University of Arkansas Fayetteville**.

Infrared photodetectors continue to attract a great deal of interest thanks to the numerous applications that they can serve. These detectors can be used for night vision, optical communication, target identification, fire fighting, medical diagnostics and surveillance.

The first infrared photodetectors that appeared on the market were fabricated from materials with a narrow bandgap, such as lead salt, $\text{InAs}_{1-x}\text{Sb}_x$, and $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ (MCT). Detectors fabricated from these alloys have experienced a great deal of success and they are still selling today. However, they are plagued with growth-related issues, which has stimulated the development of intersubband quantum infrared photodetectors. During the last two decades, infrared photodetectors based on quantum wells and quantum dots have undergone dramatic development. Of the two types, the quantum dot infrared photodetector is the more promising due to intrinsic advantages associated with three-dimensional confinement. These include sensitivity to normal incidence radiation and high temperature operation.

One exciting aspect of the quantum dot infrared photodetector (QDIPs) is its potential to combine high resolution with multicolor detection capability. Traditionally these types of detector are fabricated from either InAs or InGaAs quantum dots. Coherent nanoscale islands are generally formed when a certain amount of $\text{In}(\text{Ga})\text{As}$ is deposited on the $(\text{Al})\text{GaAs}$ surface. However, other lattice-mismatched materials have been investigated as well.

Quantum dots are formed by a growth procedure known as Stranski–Krastanov (S-K) growth. Transformation from a two-dimensional growth mode to a three-dimensional one depends on the strain of deposited materials. The inevitable strain arising in S-K quantum dots introduces various defects, including long stacking faults, short stacking faults and dislocations. These defects impair the

optical and electronic properties of QDIPs and are one of the biggest factors behind their low quantum efficiency.

At the University of Arkansas Fayetteville we employ a novel growth process for producing strain-free dots: droplet epitaxy. This approach separately supplies source elements. Generally growth begins by forming nanosize droplets of group V materials. These structures are crystallized by group III vapor transforming droplets to yield a process that creates semiconductor nanostructures.

One of the great strengths of the droplet epitaxy approach is its versatility. It can construct quantum dot pairs, quantum molecules, quantum rings and nanoholes. In all cases, these tiny structures are free from strain, which is promising for the fabrication of high-performance devices. The QDIPs that we are developing feature strain-free

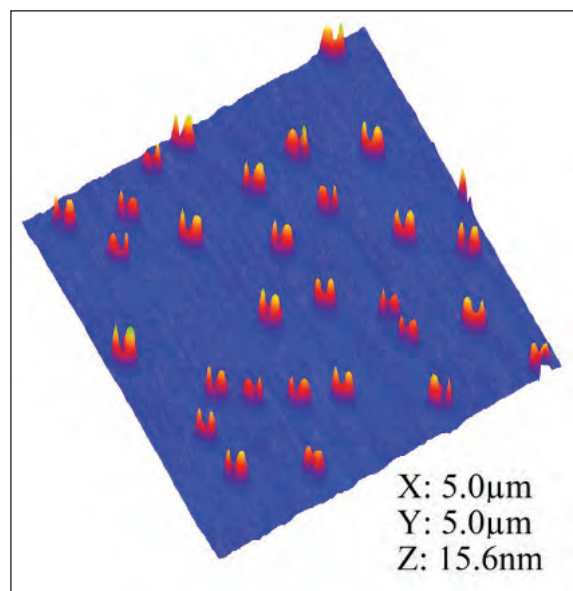
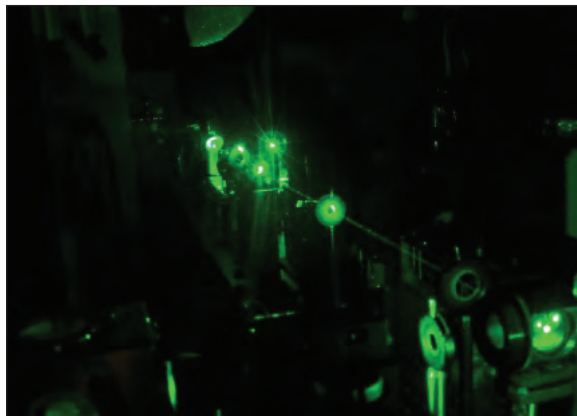


Figure 1. Atomic force microscopy image of quantum dot pairs grown by high temperature droplet epitaxy

Figure 2:
Probing with a green laser source unveils some of the characteristics of the quantum dots



GaAs/AlGaAs quantum dot pairs, which are grown on a (100) semi-insulating GaAs substrate by MBE. Typically the sample structure is a n-i-n photoconductor.

A 0.5 μm n-type GaAs layer with silicon doped to $2 \times 10^{18} \text{ cm}^{-3}$ is grown at 580 $^{\circ}\text{C}$ as the bottom contact layer. On top of this we deposit an active region containing 10 periods of GaAs/AlGaAs quantum dot pairs. Due to the strain-free property in future we could incorporate more periods to improve absorption and in turn increase the responsivity of our detectors. After the active region we deposit a 300 nm n-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ window layer that is silicon-doped to $3 \times 10^{18} \text{ cm}^{-3}$, followed by a 5 nm silicon-doped GaAs layer for making the top ohmic contact. The thin cap also prevents oxidation of AlGaAs.

Our efforts involve droplet epitaxy at temperatures in the region of 550 $^{\circ}\text{C}$. Droplet epitaxy is normally performed at low temperatures, but higher temperatures cut defects, leading to higher quality materials.

We have studied the morphology of our samples with an atomic force microscope (see Figure 1). The images that were acquired reveal that the two quantum dots are laterally aligned along the [011] direction. This is because of the anisotropic surface diffusion coefficient of gallium adatoms. The density of the quantum dot pair is $1.3 \times 10^8 \text{ cm}^{-2}$, their average height is about 9 nm, and their base diameters range from 150 nm to 200 nm.

To understand our sample's optical properties we have investigated its photoluminescence (PL) using 532 nm excitation from a Nd: YAG laser. Time-resolved PL has been performed by combining this excitation with that from a 750 nm mode-locked Ti: sapphire laser producing 2 ps pulses at an optical pulse train of 76 MHz (see Figure 2). PL spectra are taken at a low temperature, typically 10 K. For the continuous wave PL, various excitation powers were applied and ground and excited energy levels identified from PL spectra. PL decay transients were measured for detection wavelengths of 810 nm.

Time-resolved PL reveals two components to electron

relaxation: a slow decay time typically ranging from 0.3-0.7 ns; and a fast decay time of around ~ 100 ps. The relatively long PL decay time indicates that the quantum dots have good optical properties.

To probe the energy levels, we performed PL excitation and visible-near IR photoconductivity measurements. PL excitation revealed multiple peaks and confirmed the excited states observed from PL spectra. Meanwhile, the photoconductivity spectra uncovered possible energy level transitions. Under different bias voltages, the optoelectronic transition could be tuned, thanks to state-filling taking place as electron injection changes.

We have used photolithography to fabricate photodetectors from these quantum-dot-pair samples. The area of a single pixel is $500 \mu\text{m} \times 500 \mu\text{m}$. The pixels exhibit dark current densities of $5.6 \times 10^{-5} \text{ A/cm}^2$ at 80 K and $5.76 \times 10^{-5} \text{ A/cm}^2$ at 300 K. These low values are a highly desired attribute in high performance infrared photodetectors.

Further insights into the optical characteristics of our samples have been garnered by studying their mid-infrared (MIR) photoresponse spectra with an FTIR spectrometer, using a normal incidence configuration and a MIR source. These measurements reveal a broadband mid infrared photoresponse spanning 3.0 – 8.0 μm . This wavelength range is of great interest due to the transmission window of the atmosphere. The main photoresponse intensity peak is measured at 5.5 μm (225 meV), corresponding to intersubband transitions in quantum dot pairs. These measurements also reveal a large full width at half maximum (FWHM) in the photoresponse spectrum. This is about 2.1 μm when the detector is biased at 0.4 V.

Due to a large spectral width and relatively large energy separation, the photoresponse includes a contribution from bound-to-continuum transitions. Due to the easy tuning of nanostructures by droplet epitaxy, a multicolor detector can be achieved in a single device. For example, dual sized quantum dot pairs can be employed to detect two distinct wavelengths. Despite the very low density of quantum dot pairs in the device, there is a MIR photoresponse at 80 K. Simply increasing the nanostructure density can dramatically increase this response. The density of quantum dot pairs incorporated in our device is about two orders of magnitude lower than the typical density of In(Ga)As quantum dot detectors.

Given a higher density of quantum dots, this type of detector is expected to achieve state-of-the-art performance. Also, thanks to the flexibility of the growth technique, the energy levels can be easily engineered to detect long-wave infrared light, far infrared light, and even terahertz light besides MIR light. These strain-free nanostructures may also find application in other optoelectronic devices such as lasers and solar cells.

Further reading

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Navy unveils novel HBT

RESEARCHERS at the Naval Research Laboratory in Washington DC claim to have produced the first InAlAsSb/InGaSb DHBTs with an InAsSb emitter and sub-collector.

Introduction of this ternary emitter has led to significant improvements in DC and RF performance. This transistor, which is based on materials with a 6.2 Angstrom lattice constant, has a collector current density of 1.9×10^5 A/cm², a breakdown voltage in excess of 2.5 V, and values for the cut-off frequency and maximum oscillation frequency of 59 GHz and 34 GHz, respectively.

According to corresponding author James Champlain, these results show that this particular DHBT could serve many applications demanding low powers, high frequency performance, or both. Examples include deployment in A-to-D and D-to-A converters; ultra-linear low-noise amplifiers; and radar and imaging systems, especially those operating at terahertz frequencies.

One of the strengths of the team's transistor is its low power consumption, which is a major plus point in battery-powered, portable applications.

"Reduction of battery weight and extended lifetime are critical in applications where weight and space are limited, such as space-based applications," says Champlain. "Alternatively, in large distributed systems, such as some large phased array or imaging applications where power must be distributed to each cell of the system, reduced power consumption is critical in achieving practical applications."

Solid-source MBE was used to form the DBHT epistuctures that included a complex buffer (see figure for details). Standard processing and e-beam lithography techniques formed transistors from these epiwafers with a $2 \times 10 \mu\text{m}^2$ emitter.

Characterization revealed base and collector ideality factors of 1.5 and 1.0, respectively. Series resistance was relatively low, thanks to the introduction of the InAsSb emitter and sub-collector layers.

Champlain says that the team will now work on improving DHBT performance through modifications to the device's design layout and its material structure. This could involve reducing the area of the device, which should

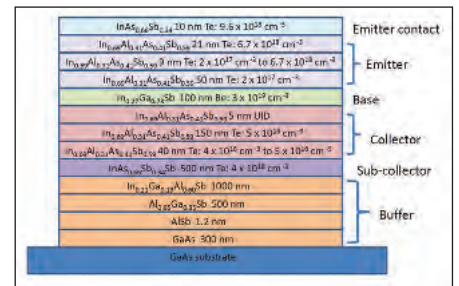


Figure caption: The DHBTs incorporate InAs_{0.66}Sb_{0.34} layers that have "superb" transport properties, and can provide an extremely low contact resistance when used for n-type contacts.

cut capacitance. Optimizing the selection of III-V layers offers another opportunity to increase transistor performance.

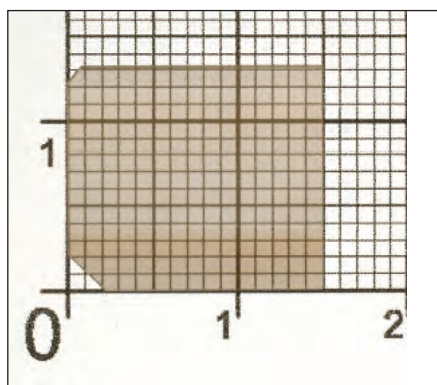
"Currently the device's design includes a quaternary collector," explains Champlain. "Classically, mixed alloys, such as ternaries and quaternaries, have poor thermal conductivity compared to binary alloys. Therefore, alternative collector designs and/or process technologies, such as substrate transfer, may be needed to capture the full benefit of these devices."

J.G. Champlain et al. *Elec. Lett.* 1333 46 (2010)

Ammonothermal yields high-quality semi-polar GaN

POLISH GaN substrate manufacturer Ammono has unveiled characteristics of its semi-polar (20 $\bar{2}$ 1) substrates. This cut of GaN is a promising candidate for the production of green lasers. Last summer, engineers at Sumitomo produced a 531 nm edge-emitter by exploiting the relatively high indium incorporation in InGaN quantum wells grown on this plane, plus the built-in electric fields that push emission to longer wavelengths.

Working in partnership with Wroclaw University of Technology, Poland, Ammono has employed X-ray diffraction to probe its semi-polar material that is produced in a high-pressure ammonia solution. X-ray diffraction rocking curves on pieces of (20 $\bar{2}$ 1) GaN, which has a typical dislocation density of 5×10^3 cm⁻² and a radius of curvature in excess of 100 m, produce a full width at half maximum of just 17 and 21 arcsec for the (20 $\bar{2}$ 1) and (20 $\bar{2}$ 0) peaks. "The best crystallographic properties and the lowest dislocation



Ammono is pioneering ammonothermal growth of semi-polar and polar GaN

density may suggest the best semi-polar GaN ever produced," says Ammono president Robert Dwilinski.

Contactless electroreflectance has also been used to study semi-polar (20 $\bar{2}$ 1) GaN. "With this technique, instead of measuring

the optical reflectance of the material, the derivative with respect to a modulating electric field is evaluated," explains Dwilinski. This measurement yielded a sharp, strong resonance peak at 3.4 eV, indicating that the sample had both good optical properties and a good surface.

The piece of semi-polar GaN studied by the Polish researchers had dimensions of 9 mm by 12 mm. But far larger sizes should be possible, given that Ammono has already produced 1-inch GaN non-polar crystals that can yield semi-polar substrates of at least that size. Today the Polish company sells 10 mm x 10 mm, 10 mm x 20 mm and 13 mm x 15 mm substrates. "We will work to increasing the size of our semi-polar substrates to 1-inch in 2011," says Dwilinski.

"This size is not available on the commercial market, and is hardly achievable by HVPE."

R. Kucharski et al. *Appl. Phys Express* 3 101001 (2010)

VCSELS retain speeds at high temperatures

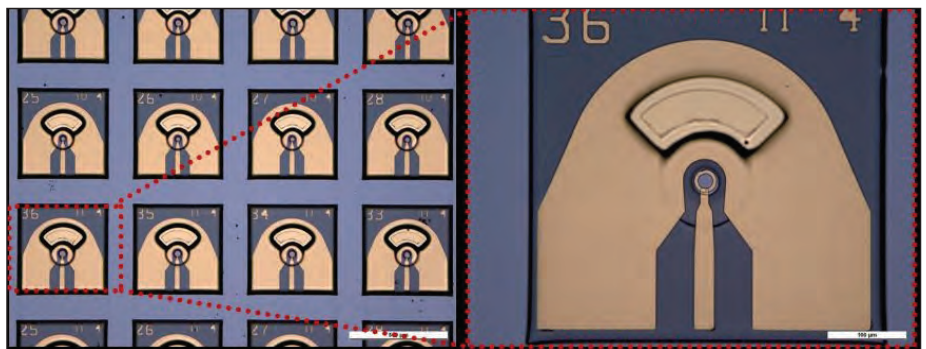
A GERMAN team claims to have broken the record for data transmission from an oxide-confined 980 nm VCSEL operating at 85 °C. Their device, which is capable of 25 Gbit/s operation at that elevated temperature, is an ideal source for very short optical links in high performance computers, according to the researchers from the Technical University of Berlin and VI Systems.

“Since temperatures inside computers are as high as 85 °C, or even higher, good temperature stability is indispensable for robust, inexpensive optical links,” says Dieter Bimberg, head of the research team at the Technical University of Berlin.

Today 850 nm is the standard wavelength for short-reach optical links and local and storage-area networks, but Bimberg believes there is a strong case for 980 nm sources in all these applications.

“980 nm has the crucial advantage of transparency of the GaAs substrate, so one can easily realize bottom-emitting devices, increasing and simplifying packaging density. This is very important, for example, in the case of a large number of VCSELS for parallel optical links.”

VCSELS are fabricated via MOCVD growth



The 980 nm VCSELS produced by researchers at the Technical University of Berlin and VI Systems have bit error rates at 25 Gbit/s of less than 10^{-12} .

of an epistructure containing 24 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ and $\text{Al}_{0.90}\text{Ga}_{0.10}\text{As}$ layers for the bottom mirror, and 37 pairs for the top mirror. Sandwiched between these mirrors is an active region with five compressively strained $\text{In}_{0.21}\text{Ga}_{0.79}\text{As}$ quantum wells that are 4.2 nm thick, which are interlaced with 6 nm thick $\text{GaAs}_{0.88}\text{P}_{0.12}$ tensile strained barriers.

Selective wet etching forms two 30 nm-thick $\text{Al}_{0.96}\text{Ga}_{0.02}\text{As}$ oxide apertures positioned just above the microcavity, in the field intensity nodes in the first two periods of the upper mirror.

Output from this 10 μm -diameter oxide aperture VCSEL is 4.3 mW at 20 °C, falling

to 2.6 mW at 85 °C. This relatively small reduction in power stems from an intentional red-shift detuning of 15 nm between the quantum well gain peak and the cavity resonance.

Future targets for the team are to speed the 980 nm VCSELS to 40 Gbit/s and maintain this rate at 100 °C. “We will use an optimized active region to improve the temperature stability even further, and an optimized cavity design to increase the speed beyond 25 Gbit/s,” reveals Bimberg.

A. Mutig *et al.* *Appl. Phys. Lett.* **97** 151101 (2010)

Modeling questions Auger’s contribution to droop

CURVE fitting with the standard equation for carrier recombination in an LED shows that Auger recombination cannot, by itself, account for droop, the decline in device efficiency at high drive currents. That’s the claim of a partnership between Rensselaer Polytechnic Institute (RPI), Sandia National Laboratories and Samsung LED.

Their effort involved fabricating a range of LEDs with varying numbers of quantum wells, device areas and quantum efficiencies; measuring external quantum efficiency at a range of currents; and fitting the data with the well-known “ABC” equation for carrier recombination. This equation describes non-radiative recombination at defects by a term that is proportional to the carrier concentration, and uses quadratic and cubic variants to cater for radiative and Auger recombination, respectively.

“It is impossible for us to just use the ABC model and get a good fit,” explains team member Fred Schubert from RPI, who says that the team’s experiment indicates that there are contributions from second order, third order and fourth order terms caused by carrier leakage. “Some of the samples have significant fourth order contributions.”

Inserting additional terms in the carrier recombination model has enabled the US-Korean partnership to fit the experimental data far better. To realize a good fit at all drive currents, it began by matching the ABC model to the data at low current densities. “This part of the curve is not in question,” says Schubert. “Everybody agrees that there is Shockley-Reed-Hall recombination and radiative recombination.”

Curve fitting was then extended to higher currents, where droop plays a significant

role. Here they found that at current densities of 111 A/cm² the higher-than-third order terms contribute 13 percent or more to the total recombination rate.

Using their model, the team extracted an coefficient for third order processes of $8 \times 10^{-29} \text{ cm}^6 \text{ s}^{-1}$ for the LEDs, which is comparable to values obtained by other experimentalists, but far higher than those determined by first-principle theoretical calculations for Auger recombination.

The researchers point out that this striking difference could be due to one component of carrier leakage that, like Auger recombination, is proportional to the cube of the carrier density.

Q. Dai *et al.* *Appl. Phys. Lett.* **97** 133507 (2010)

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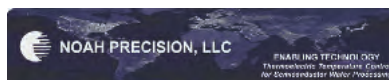
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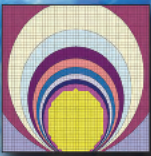
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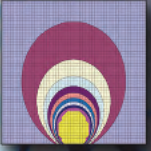
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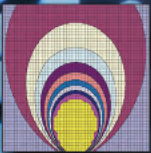
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