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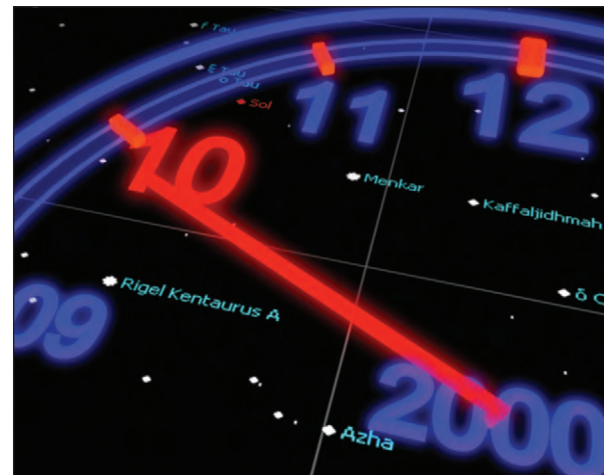
The noughties: a period of transition

As this decade draws to a close an obvious question comes to mind: has it been a successful period for the compound semiconductor industry? I'd have to argue for a yes, because I'm convinced that we are in much better shape than we were ten years ago, thanks to far greater diversity.

At the start of the millennium all the talk was of how the internet was going to revolutionize the world for ever. And this was undoubtedly good news for many, because the roll-out of supporting infrastructure was driving substantial shipments of pricey lasers and detectors, and giving these chip manufacturers excellent profit margins.

But as we all know, this over-hyped growth didn't last long, and when the internet bubble burst, it inflicted scars that remain to this day. Share prices tumbled – JDSU, for example, which peaked at over \$1000, now trades at low double-digits figures – and far more alarmingly, thousands lost their jobs. These events kicked-off a squeeze in profit margins that continues to this day, and a battle for survival of the fittest has ensued, with some companies merging with others in a bid to survive.

Fortunately, many of the chipmakers that serve the telecoms sector have turned to new revenue streams, such as sales to fiber laser manufacturers. But by far the biggest change in the noughties has been the rising sales of III-V chips to consumer electronics manufacturers, including producers of handsets. In the last ten years global cell phones shipment have rocketed from just over 400 million to more than a billion, and this has spurred the sales of LED and GaAs power amplifier makers. And although revenue generated from LED shipments to the handset sector has now peaked, new applications are starting to fuel further sales growth, such as backlighting units for LCD TVs.



Greater awareness in energy efficiency is also starting to play into our hands. Manufacturers of PC power supplies are switching from silicon diodes to SiC equivalents to boost efficiency, and the triple-junction solar cells that power satellites are starting to promise a competitive form of terrestrial power generation in sunnier climes.

Thanks to this greater diversity, coupled to strong penetration of III-V devices into consumer electronics, we're avoiding a really heavy battering in this credit crunch. The dot.com bubble has arguably taken more prisoners in the compound semiconductor industry than today's recession, and it seems that we're actually in a good position to enjoy strong business growth as we move forward. Hopefully we can grab all the opportunities that lay in store over the coming years.

Richard Stevenson PhD
Consultant Editor

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16 Tube lasers ready to light up
Differences in polarity, lattice constant and thermal expansion hamper the unification of compound semiconductor light emitting structures and silicon ICs. A team from McGill University have turned to a novel micro-tube laser architecture that suspends the device just above the wafer surface.

22 Combatting LED droop
Three themes dominated the latest nitride meeting: the cause of LED droop; the best approach to plugging the green gap; and the development of higher-quality, lower-cost native substrates.

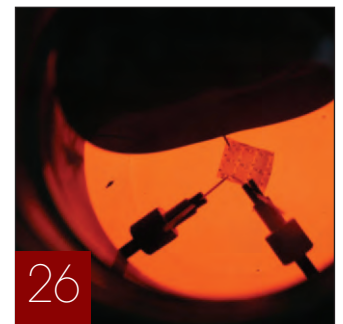
26 Pushing transistor and sensor limits
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It is something that should be a simple task but it is amazing how intricate the process can be.

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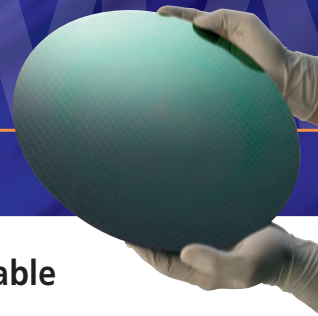
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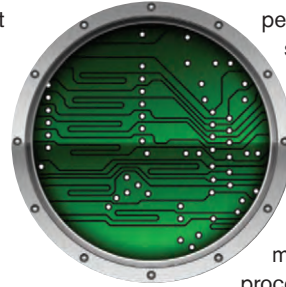
Has the industry reduced costs?

The EMC3D semiconductor equipment and materials consortium has extended its agreement in order to improve the industry further. Improvements in the compound semiconductor industry have been vital in reducing costs, it has been claimed.

From an original closing date of October 2009, the members of the international EMC3D semiconductor equipment and materials consortium have now extended their agreement to July 2011. Originally, the aims of the group were to commercialise

individual unit processes that could be implemented easily into a volume production environment and to enable a low overall cost of ownership (CoO) for 3D chip stacking.

Initial CoO targets were of \$200 (£122) per wafer, but EMC3D project director Paul Sibley noted that now fabs running iTSV can produce 3D-TSV devices at less than \$150



per unit. He commented: "Improved synchronization between the unit processes along with aggressive cost saving designs have been very successful at exceeding the consortium's original cost goals."

Equipment efficiency, reduced material expenses and simplified process flow have all been vital in lowering costs, Mr Sibley concluded. The group EMC3D was originally established in September 2006.

A LIFT for fibre lasers

LIFT - Leadership In Fibre Laser Technology, is a collaborative, large-scale integrated project funded by the NMP Directorate in the 7th Framework Programme of the European Commission. European industry today leads in industrial laser processing. Continuous innovation and adoption of novel technologies are required to maintain this position. Fibre lasers represent only 10% of an estimated market volume of 2 billion Euros worldwide for industrial lasers. The market share of fibre lasers is expected to double by 2010 and double again by 2013, when fibre lasers will account for more than 30% of all industrial lasers.

In order for Europe to advance its position as technology and manufacturing leader in industrial laser processing, it is imperative for European manufacturers to take the Leadership In Fibre laser Technologies. That is exactly the goal of the LIFT project. This project will establish an internationally

leading position for Europe in the science, application and production technologies of fibre lasers.

The consortium will develop innovative laser sources with intelligent beam delivery systems and dynamic beam manipulation, in continuous-wave, nanosecond pulsed, and ultra-short pulsed femtosecond laser sources, operating at power levels ranging into the kilowatt regime. LIFT will enable a greater market share for existing applications, create new application areas for manufacturing, and build a European network of components' suppliers and laser system manufacturers.

Demonstrations will show the potential of this technology in domains where there are large existing markets such as high-speed remote cutting and welding, medical diagnostics and treatment, TFT patterning or where there are potential markets such as



solar cell fabrication and cold ablation for ceramics manufacturing.

The results will bring radical advances in four important application areas:

- Laser Materials Processing
- Health Care Delivery
- Cost-Effective Manufacturing of Solar Cells for Renewable Energy
- Manufacturing of the next-generation of ICs with nanometre feature size.

Nanoscale semiconductors could get support from DNA

A team of researchers have developed a solution to address the industry challenge of organising carbon nanotubes into nanoscale electronic circuits which contain semiconductors. The researchers at the California Institute of Technology (Caltech) hoped that DNA origami could be used as 100 square nanometre construction bases for prototyping electronic circuits with semiconductors because of DNA's ability for self-assembly.

Researchers have been trying for a number of years to arrange single-wall carbon nanotubes with diameters of less than two nanometres into desirable geometric patterns. Single-wall carbon nanotubes are effective semiconductors.

"DNA is the perfect molecule for recognising other strands of DNA and single-stranded DNA also just happens to like sticking to carbon nanotubes," said

Si-ping Han, a theorist in materials science who is currently researching the interactions between carbon nanotubes and DNA at Caltech.

Researchers at Rice University discovered in 2003 that large numbers of pure carbon nanotube fibres could be dissolved in strong acidic solvents, a method which can help the materials become processed on an industrial scale.

Bio electric cross talk

IMEC has presented a microchip with microscopic nail structures that enable close communication between the electronics and biological cells. The new chip is a mass-producible, easy-to-use tool in electrophysiology research, for example for fundamental research on the functioning and dysfunctioning of the brain. Each micronail structure serves as a close contact-point for one cell, and contains an electrode that can very accurately record and trigger in real-time the electrical activity of an individual electrogenic cell in a network.

Electrogenic cells such as cardiomyocytes (heart cells) or neurons (brain cells) rely on electrical signals to communicate with one another. Knowledge of the electrical activity of these cells is essential to gain insights in the communication process of these cells, to unravel the cause of brain disorders such as Alzheimer's or Parkinson's disease, or validate the effect of drugs on cardiac cells in the struggle against cardiac diseases,

etc. IMEC's new micronail chip is the ideal instrument to study the communication mechanisms between cells.

The electrodes in IMEC's micronail chip are downsized to the size of cells and even smaller. They consist of tiny nail structures made of a metal stem covered with an oxide layer, and a conductive (e.g. gold or titaniumnitride) tip. When cells are applied on the chip surface, their cell membrane strongly engulfs the nail structures, thereby realizing an intimate contact with the electrode. This very close contact improves the signal-to-interference ratio enabling precise recording of electrical signals and electrical stimulation of single cells.

"We tackled several challenges to realize this micronail chip such as keeping the cells alive on the chip surface; combining the wet cell solution with the electronics underneath without destroying the electronics; guiding the cell growth so that the cell body is just on top of one individual electrode; and last



but not least: bring the cells as close as possible to the chip surface. Now, we have a unique instrument to record and interpret the signals of the neurons. We can also stimulate neurons and follow up the consequences to unravel the functioning of our brain," said Wolfgang Eberle, Group manager Bioelectronic systems.

Kris Verstreken, Director Bio-Nanoelectronics: "Little is known about the functioning of our brain. Where do emotions origin? How do we build up memories? Or what is the cause of brain diseases such as Parkinson's disease or Alzheimer's disease?"

Increasing IC density

A deeper understanding of the current flow at a nanometric scale is central to the development of modern molecular nanoelectronics, it has been asserted. The advance of miniaturisation of electronics has supported the manufacture of integrated circuits containing a greater density of semiconductors, allowing technology such as mobile telephones and handsets to become smaller and more efficient, Basque Research - the resource for scientific and technological research carried out in the Basque Country - noted.

It is important to comprehend how current will flow in future devices made up of many molecules. Research by Thomas Frederiksen, researcher at the University of the Basque Country, who discovered the characterisation of the electric current between two molecules. Research into the molecules known as C60 discovered that electric current does not flow well between two touching C60 molecules because the conductance of the pair is less than that of a single molecule by a factor of 100.

IQE awarded contract with TriQuint

IQE's New Jersey operation sub-contract Gallium Nitride (GaN) wafer products to TriQuint as part of an \$16.2 million Defence Advanced Research Projects Agency (DARPA) multi-year Gallium Nitride (GaN) R&D contract. The programme aims to advance GaN research and develop new generations of compound semiconductor circuits through the Nitride Electronic NeXt-Generation Technology (NEXT) program.

"GaN is already recognized for its ability to handle more power per square millimeter than other semiconductor technologies like gallium arsenide, and much more so than silicon. Yet even with the advances TriQuint has pioneered, today's analogue GaN technology has frequency and power limits. "NEXT circuits will be 'game-changing' technology that could radically improve performance in defence and aerospace applications like phased array radar and communications. NEXT calls for complex digital GaN circuits that also have very high breakdown voltages-something that silicon

can't do, and that is also beyond the scope of today's other semiconductor processes," said TriQuint's Principal Investigator, Senior Fellow Dr. Paul Saunier.

Alex Ceruzzi, VP and GM of IQE's New Jersey facility commented: "IQE and TriQuint have enjoyed a close relationship over many years and our role in this programme clearly demonstrates IQE's ability to provide world class materials across a broad RF product portfolio. "The four and half year NEXT programme lead by TriQuint will utilise IQE's GaN wafer product expertise with the ultimate aim of developing and producing advanced semiconductor chips with operating frequencies up to 500GHz."

IQE's New Jersey facility is a GaN HEMT epi foundry, and provides a complete portfolio of RF products. The Group's Gallium Nitride production capability was recently increased through the acquisition of UK-based NanoGan Limited announced earlier in October 2009.

Semiconductor researchers develop "fin-like" transistor from indium gallium arsenide

Semiconductor researchers at Purdue University are in the process of developing a new type of transistor which could enable engineers to create more compact and faster circuits.

The researchers have developed the new semiconductor which uses a "fin-like" structure - rather than the conventional flat design - made from indium-gallium-arsenide, by using atomic layer deposition technology.

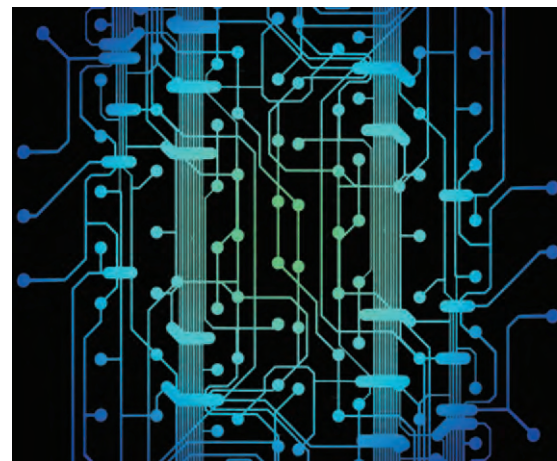
According to the higher education establishment, the new semiconductors could help the electronics industry meet the challenges set by Moore's law, which states that miniaturisation of components will allow the number of transistors on an integrated circuit to double roughly every

two years, without the circuit increasing in size.

However, it has become increasingly difficult to continue to miniaturise devices which are made out of conventional silicon, leading to suggestions that indium-gallium-arsenide could address this.

"As gate lengths are made smaller than 22 nanometres, the silicon dioxide insulator used in transistors fails to perform properly and is said to 'leak' electrical charge," the university noted.

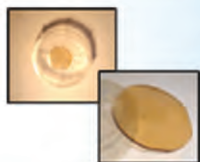
The Nano-Science Centre recently reported that combining the semiconductors gallium-indium-arsenide and indium arsenide in the same nanowire could enable more energy to be captured.



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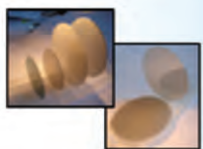


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What are the benefits of solid state lighting?

Solid state lighting offers a number of benefits over fluorescent or incandescent lamps.

Solid state lighting differs from fluorescent or incandescent lamps – which use filaments and gases in a glass bulb to create light – as it converts electricity to light through semiconductors.

Although light-emitting diodes (LEDs) were first developed over 40 years ago, so far they have primarily been used in devices such as torches and laser pointers.



they tend to be twice as bright.

Further benefits of LEDs include being safer – as they run on low voltage and tend not to heat up – being flexible thanks to their size and being more durable, as they are able to withstand vibrations. The Lighting Research Centre (LRC) noted: "LED lighting systems have already proved to be very effective in indicator applications where brightness, visibility and long-life are important, such as in exit signs and traffic signals."

However, research and development could well mean they are increasingly used in solid state lighting. Organic light-emitting diodes or polymer light-emitting diodes can also be used in the devices as well. Solid state lighting is often used in traffic lights and remote controls. The technology looks like it may revolutionise the lighting industry and there are many advantages of using compound semiconductors in such items.

LEDs can reduce operating costs as they have a longer life to incandescent light bulbs. While the latter option lasts an average of 1,000 hours, the former can provide 50,000 hours or more of life – and

According to the group, there are numerous possibilities where the items can be used in the future, such as lighting, under-shelf features, outdoor parking and step marking. It may be possible in the future for them to be used to cover entire walls and ceilings, as the technology becomes more advanced, the organisation concluded.

Recently, the LRC conducted research into understanding which factors affect the performance of standalone solar-powered LED lighting systems. It found that generally high irradiance, low temperature and maximum power point tracking controller can provide the fastest charging rates.

LED semiconductors see uptake for solid-state lighting'

The semiconductor market is expected to further grow, with the light emitting diode (LED) industry enjoying greater financial security, it has been reported.

Over the past two months, three companies have raised almost \$800 million (£481 million) for LED development and the Has LED Lighting Reached a Tipping Point? report from Strategy Analytics said this indicates accelerated adoption of the semiconductor backlighting technology.

Furthermore, the financial support highlights a move towards solid-state lighting, with the company also noting backlogs for metalorganic chemical vapour deposition

(MOCVD) equipment - a technique for depositing thin layers of atoms on to a semiconductor wafer.

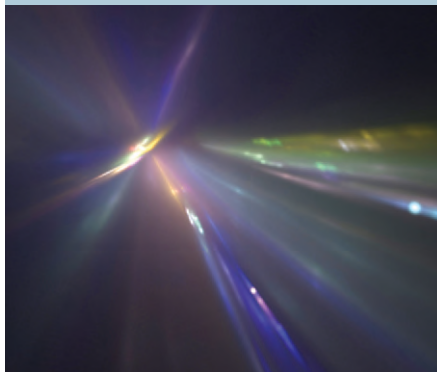
"LED-based backlighting has reached a tipping point where we expect to see significant acceleration of the market for LED-backlit liquid crystal display TVs from 2010 on," said Steve Entwistle, vice-president of Strategy Analytics' strategic technologies practice.

Using MOCVD enables a range of semiconductor photodetectors and lasers to be built as a number of layers can be built up each to a precisely controlled thickness to enable specific electrical and optical properties.?

Quantum dot technology 'experiences demand'

Quantum dot - or fluorescent nano-crystalline particle - maker Nanoco has reported that demand for the semiconductor technology is increasing, especially for use in solar cells and light-emitting diode (LED) backlighting. The particles can be used in cleantech applications such as next-generation photovoltaic cells and low-energy lighting, as well as for flatscreen televisions and biological marking.

LED lighting which includes quantum dots is 60 times more efficient than incandescent light bulbs and twice as efficient as mercury-discharge lighting, the company stated. As such, Nanoco has reported it is moving towards the mass production of quantum dots that do not contain heavy metals, because in order to expand the semiconductor market, there needs to be a move away from technology based on cadmium.



"The market has really started to move for us. We're working hard to meet the demand that seems to be mushrooming in front of us," chief executive Michael Edelman told Reuters.

Nanoco is the only manufacturer which can currently supply production quantities of such nanoparticles which do not use a regulated heavy metal. It recently announced it has signed a joint development agreement with a major Japanese electronics company to develop fluorescent nano-crystalline particles for use in liquid-crystal display televisions and LEDs.

OLED receives funding from Germany

Applied Materials, Merck KGaA and the Braunschweig University of Technology (TU-BS) has announced that they have been awarded a grant by Germany's Federal Ministry of Education and Research (BMBF) to develop processes to lower the cost of manufacturing organic light-emitting diode (OLED) lighting for general illumination applications. Applied will spearhead the three-year project, named Light InLine (LILi), joining forces with Merck, a leading manufacturer of high performance OLED materials and TU-BS, an internationally recognized center for OLED research. Work on the LILi project will be centered at Applied Materials' advanced development facility in Alzenau, Germany.

Fabricated on sheets of glass, OLED lighting tiles can emit white light that is brighter, more uniform and more energy efficient than fluorescent light fixtures, making them well-suited for ceiling lights in homes and offices. While a number of OLED products have been developed in recent years, challenges such as limited lifetime and high costs must be addressed for the technology to be widely adopted. The LILi project aims to address these challenges by developing large-area manufacturing using organic materials and efficient device design.

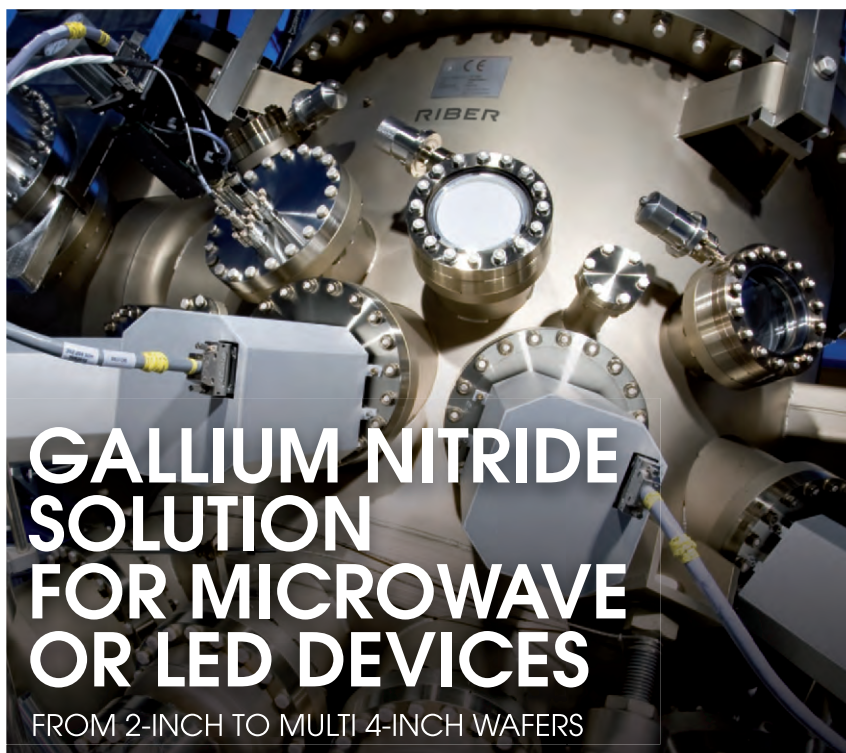
"Solid state lighting is an important component of an energy-efficient future," said Dr. Mark Pinto, senior vice president, corporate chief technology officer and general manager of Applied's Energy and Environmental Solutions Organization. "OLED technology aligns well with our equipment used for manufacturing flat panel displays. We've already delivered a system that is now in pilot manufacturing at a leading European lighting manufacturer. Through the LILi project, we expect to further optimize this technology to increase the quality and drive down the cost for OLED lighting applications."

"Merck has a wealth of experience in developing and scaling up the complex organic compounds that are essential for stable and cost-effective OLED manufacturing," said Dr. Udo Heider, vice president, Liquid Crystals/OLED, Merck KGaA.

"Innovation in OLED technology is one of the primary focuses of our institute," said

Professor Wolfgang Kowalsky from TU-BS. The total cost of the OLED project will amount to approximately €7.49 million, which includes €3.26 million to be provided by the German Federal Ministry of Education and Research and €4.23 million to be

contributed by the industry partners. The grant (FKZ 13N10611) is part of the BMBF's "OLED 2 – Organic Light Emitting Diodes - Phase 2" initiative, which seeks to support OLED research and encourage OLED manufacturing in Germany.



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Obducat takes part in EU project



OBUDUCAT has been invited to participate in the EU funded SMASH project. The project's purpose is to establish new materials and process technologies to be used in production of low-cost, power-efficient, white LED-light sources for the general lighting market.

SMASH is an EU funded project within the Seventh Framework Programme, FP 7. The project is coordinated by OSRAM Opto Semiconductors GmbH and brings together complementary expertise from across Europe. 14 partners will participate in the project.

"Our main focus within the SMASH project will be on stamp manufacturing and replication of nanostructures based on our proprietary IPS-STU nanoimprint lithography technology for high volume manufacturing", says Patrik Lundström, CEO, Obducat AB.

Key success factors for the broad penetration of LEDs into the general lighting market are: high power efficiency and low cost. The concept of SMASH is to establish disruptive approaches that exploit

nanostructured compound semiconductors to realize the key market factors of high efficiency and low cost. These will be achieved by epitaxial growth of LED structures on ultra-low defect nanostructured templates and by the development of LEDs based on nanorod emitters. These approaches will have large impact on manufacturing costs because they enable growth on large area, low cost substrates such as Silicon.

"Realizing these technologies will lead to a new generation of highly efficient and affordable LEDs, which enables the entrance to the general lighting market. That will keep Europe at the forefront of the energy-saving solid state lighting business and strengthen its position in the manufacturing supply chain and luminaire business", says Patrik Lundström.

UV laser for sapphire scribing in GaN LEDs

Coherent has announced a UV laser that could reduce the cost of micromachining tasks in areas like scribing sapphire substrates used in the fabrication of GaN LEDs.

The AVIA 355-5 is a Q-switched Nd:YVO4 laser that delivers 5W of 355 nm output at 50 kHz, and is suitable for operation at repetition rates of up to 150 kHz. Its combination of high repetition rate and short pulse length (less than 20 nsec at 5W)

enables a high throughput processing with minimal heat affected zone (HAZ).

The new UV laser is targeted as a cost effective, compact, OEM product that offers many of the features found on more powerful AVIA models. The laser also has an automated harmonic crystal shifter to maintain constant output power for greater than 20,000 hours and help reduce the cost of ownership. The AVIA 355-5 has been designed for easy integration with a



laser head measuring only 491 mm x 216 mm x 141 mm. The laser also delivers enhanced reliability and ease of maintenance.

AIXTRON receives order for MOCVD GaAs for LED

AIXTRON AG has announced that Changelight Co., Ltd has ordered an AIXTRON Planetary Reactor system for the production of Gallium Arsenide (GaAs) LED. The Changelight order is for an AIX 2600G3 system in the 49x2-inch wafer configuration. The tool was delivered in the third quarter 2009 to the company's state-of-the-art new facilities in Xiamen (Xiang An) Torch Industry Park of Fujian Province, China.

Mr. Deng Dian Ming, CEO of Changelight Co. Ltd., comments: "The AIX 2600G3 system is well known for its capabilities in respect to the mass production of GaAs LED. We are convinced that the system lives up to its reputation as regards throughput, uniformity and dependable production efficiency. We have been working closely with the local AIXTRON support team before and they have always been very responsive, thus we are looking

forward to further good cooperation.

Changelight is fully committed to the development and large-scale production of III-V-based optoelectronic devices. We have acquired the most advanced equipment for this application which will be used by our highly skilled technical team strongly being supported now by new staff members from the USA and Taiwan".

GreenVolts appoints technology veteran as CEO

GreenVolts, a concentrating photovoltaic (CPV) technology company, has announced that it has appointed David Gudmundson as President and Chief Executive Officer. Mr. Gudmundson comes to GreenVolts with more than 20 years of experience in senior management positions at leading technology companies, and a successful track record of growing both domestic and international market share and revenue. He has a deep working knowledge of all aspects of company operations, including sales and marketing, engineering, manufacturing, and finance.

Mr. Gudmundson assumes his role as President and CEO immediately, in place of interim CEO and former GreenVolts' CFO Gary Beasley, who is leaving to pursue a career in private equity. The company also announced today that it has relocated its headquarters from its startup offices in San Francisco to a state-of-the-art facility in Fremont, California.

"We are energized by having a world class executive like David leading the team at GreenVolts," said company Founder and Chairman Bob Cart. "David's management experience and strong leadership will help us scale the business while delivering on the great promise CPV holds for our customers."

Mr. Gudmundson has a proven history as a senior executive building teams, expanding market-share and revenue, and delivering upon aggressive measurable goals across a number of industries, including Networking, Optics, and Government and Defense. His experience spans the globe in the

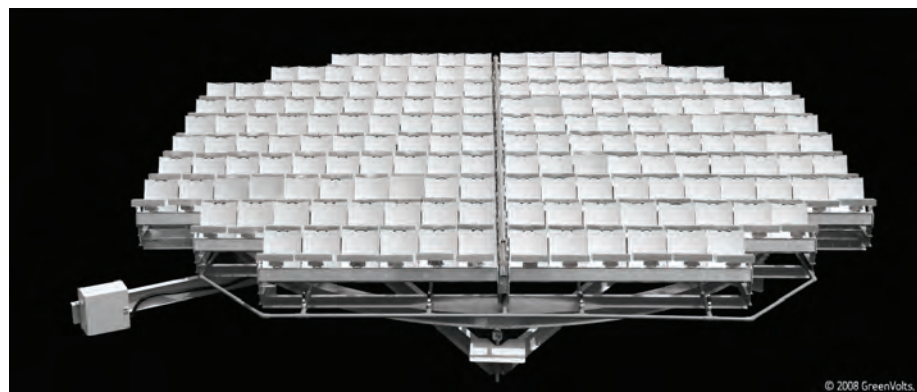
technology and engineering fields, working for companies such as JDSU and Cisco Systems.

In these roles, he has managed businesses with over \$1 Billion in total annual revenue, acquired and integrated a dozen companies, and led globally distributed organizations.

As President of JDSU's Optical Communications Product Group and a Corporate Executive VP, Mr. Gudmundson led a 3,000-person team to significantly increased profitability, revenue growth, and market share. In his role as Senior Vice President of Corporate Strategy, M&A and Marketing, he played a critical role in identifying and executing a number of acquisitions as well as a corporate restructuring that helped JDSU become a profitable portfolio company.

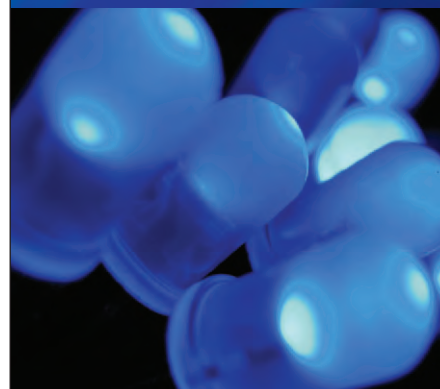
Prior, Mr. Gudmundson served as a Group Vice President and General Manager for Cisco Systems. He was a driving force behind Cisco's entry into both the access router and broadband markets, and he led the company's successful entry into the security server market.

GreenVolts' approach to concentrating photovoltaics has led to a power purchase agreement with Pacific Gas & Electric for a two-megawatt pilot facility in Northern California. GreenVolts has raised nearly \$45 Million in venture capital, including \$34 Million as part of a Series B round late last year. The company is also working with the National Renewable Energy Laboratory to optimize solar cells for concentrating photovoltaic systems.



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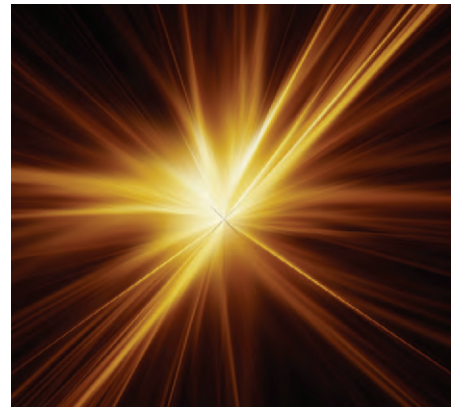
EMCORE Corporation has announced today that the company has been awarded a contract by Dutch Space of Leiden, The Netherlands to manufacture, test, and deliver the solar panels to power the Cygnus spacecraft being developed by Orbital Sciences Corporation for NASA's Commercial Resupply Service (CRS) project. With all options exercised the total value of the contract would be in excess of \$15 million.

Under the CRS project, Orbital will carry out eight pressurized space cargo missions beginning in early 2011 and running through 2015 to provide a U.S.-produced and-operated automated cargo delivery service to the International Space Station (ISS). An initial demonstration flight will be carried out as part of NASA's Commercial Orbital Transportation Services (COTS) project, which provided NASA incentives to the developing commercial launch services industry.

The solar panels to be delivered to Dutch Space will use EMCORE's ZTJ solar cells. With a sunlight-to-electricity conversion efficiency of 30%, the ZTJ solar cell is the highest performance space qualified multi-junction solar cell available in the world today.

Production of the solar panels will take place at EMCORE's state-of-the-art manufacturing facilities located in Albuquerque, New Mexico. Bart Reijnen, CEO of Dutch Space: "From our joint experience on NASA's Dawn interplanetary project, which included Orbital as the prime contractor, we know that collaborating with EMCORE results in first-class technology tailored to specific needs. Their contribution to the solar arrays for the Cygnus spacecrafts will provide the highest available efficiency, optimized for the mission."

Christopher Larocca, Chief Operating Officer of EMCORE stated, "This is a



significant award for EMCORE as this program will be powered by the most highly efficient space solar cells available today.

We are proud to once again be part of an Orbital-led mission with Dutch Space as the solar array provider. This is a reformation of the team that successfully collaborated on NASA's DAWN mission, which is currently powering the spacecraft on its voyage to the Asteroid Belt. The CRS award builds on the successful heritage of DAWN and paves the way for more future partnerships with Dutch Space."

Thin-Film share of solar panel market to double

Thin-film solar cells are rapidly taking market share away from the established crystalline technology, with their portion of Photovoltaic (PV) wattage more than doubling by 2013, according to iSuppli Corp. Thin-film will grow to account for 31 percent of the global solar panel market in terms of watts by 2013, up from 14 percent in 2008.

"The market viability of thin-film has been solidly established by First Solar Inc. as it rockets to become the world's top solar panel maker this year, with more than a gigawatt of production," said Greg Sheppard, chief research officer for iSuppli.

Most solar panels are made of crystalline wafers with 180 to 230 microns of polysilicon. In contrast, thin-film panels are made by depositing multiple layers of other materials a few micrometers in thickness on a substrate.

The main tradeoff between the two technologies is efficiency versus cost per watt of electricity generation. Thin-film panels are less efficient at converting sunlight to electricity, but they also cost significantly less to make. At the same time

thin-film is at a disadvantage when installation space is limited, such as on a residential rooftop. A thin-film installation can take 15 percent to 40 percent more space to achieve the same total system wattage output as crystalline. This tends to limit its appeal in certain applications.

The average thin-film solar panel price is expected to decline to \$1.40 in 2010, down 17.6 percent from \$1.70 in 2009. Average prices for crystalline panels are expected to drop to \$2.00 in 2010, down 20 percent from \$2.50 this year.

Through 2012, crystalline prices will continue to close the thin-film pricing gap to some degree because its purveyors have deeper pockets and keep pouring on capital spending, technology R&D developments and manufacturing refinements, iSuppli expects.

Many types of thin-film PV technologies are available. Their efficiencies in converting light to electricity mostly hover at less than 10 percent, although some have lab results pushing into the mid-teens. Some of these technologies are what is known as single-

junction, where one diode is used. Recent developments use multiple junctions stacked on top of one another—also called tandem and triple junction—so that more parts of the spectrum can be absorbed using different combinations, or junctions, of material.

Most of these technologies rely on variants of Chemical Vapor Deposition (CVD), or screen printing, to deposit the layers of materials on various substrates, i.e., glass and various plastics. Some recent technologies employ variants of ink-jet printing to more quickly deposit the materials. Another accelerator of thin-film technology is the rising availability of turn-key production lines from companies such as Applied Materials, Oerlikon, and Centrotherm.

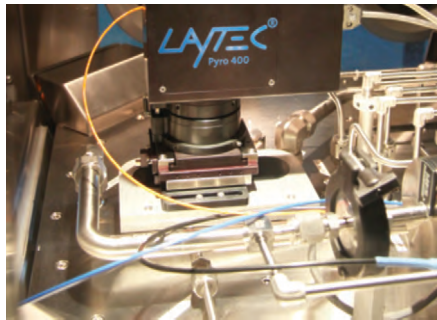
In spite of a greater than 50% drop in the contract price of polysilicon since last year, the market outlook for thin-film solar modules remains promising. iSuppli projects that thin-film based PV solar modules will grow to account for more than 30% of the total module market by 2013, up from 14% in 2008.

Real GaN temperature with Pyro 400

At the International Conference on Nitride Semiconductors (ICNS) in Korea in October LayTec presented a product, the Pyro 400, they claim is the first real solution for measuring the exact surface temperature of GaN layers.

Unlike conventional infrared pyrometry, which can only detect the susceptor surface temperature under sapphire or SiC wafers, Pyro 400 performs pyrometry at 400 nm. At this wavelength GaN emits light and makes it possible to measure its temperature.

At the ICNS Dr. Kolja Haberland of LayTec presented the results obtained during growth of GaN LED structures containing multi quantum wells (MQW). Pyro 400 monitored the temperature profile during a full revolution of the susceptor. The data



provides direct access to the GaN temperature distribution across each wafer in a planetary reactor.

Together with the complementary reflectance and curvature data measured by EpiCurve, the in-situ measurements give all important information needed to optimize uniformity and LED performance. The data

shows that wafer bowing causes changes in temperature distribution and proves that the center of concave bowed wafers is hotter.

Dr. Haberland also reported that the real surface temperature of GaN is sensitive to changes of carrier gas, rotation speed, and reactor pressure.

These deviations cannot be detected by conventional infrared pyrometry measurements at all.

There are no emissivity oscillations during GaN buffer growth, which makes Pyro 400 an ideal tool for temperature feed-back control application.

Pyro 400 provides a new quality of temperature measurement with an accuracy and will be of benefit in GaN based LED and laser production in the future.

Green GaN amplifier modules

RF Micro Devices has released the industry's first "green" gallium nitride (GaN) based CATV amplifier modules. The modules are designed for use as power doubler amplifiers in current and next generation CATV infrastructure applications.

The devices are hybrid power doubler amplifier modules designed to provide the final amplifier stage for CATV trunk amplifiers, line extenders, and optical nodes. The parts employ GaAs pHEMT and GaN HEMT die and operate from 45 MHz to 1000 MHz.

The performance of this new family of CATV amplifiers is on par with other industry-leading GaAs CATV Power Doublers, also supplied by RFMD, but with 20% lower current consumption (24V/380mA).

With these "green" energy-saving benefits, these products enable designers to fulfill growing requirements for lower energy consumption and assist network operators in their drive to reduce the overall cost of operating CATV networks. Reducing costs has always been a key goal for the industry as it ensures better and cheaper products.

Bob Van Buskirk, president of RFMD's Multi-Market Products Group (MPG), said, "Network operators worldwide are increasingly focused on reducing the energy costs of operating their wireless and wireline networks.

He continued, "RFMD's high-performance GaN technology satisfies the industry's drive for "green technology" by enabling advanced RF components and products that provide industry-leading power and operate at significantly lower power consumption levels."

Plasma-Therm announces etch system sale to III-V foundry

Plasma-Therm has announced the sale of a multi-module etch system to a major III-V foundry. To meet capacity requirements, the system is configured with three chambers for GaAs via etch process resulting in high productivity. Additionally, the VERSALINE ICP modules feature actively controlled source heating which enables a stable process environment and reduces downtime due to maintenance. These process modules incorporate fully

integrated EndpointWorks for accurate and repeatable endpoint process control.

"We are pleased to continue our expansion into the high production sector and demonstrate our process performance and superior cost of ownership," said Ed Ostan, Executive Vice President of Sales & Marketing at Plasma-Therm. "The modular approach of the VERSALINE platform offers versatility that meets customer

requirements from R&D through high volume production."

Plasma-Therm LLC is a U.S. based plasma process equipment supplier that serves various specialty markets including photomask, solid state lighting, thin film head and compound semiconductor. Plasma-Therm LLC has the largest installed etch equipment base in the GaAs wireless sector.



“For applications such as wavelength division multiplexing you need multiple, evenly spaced channels. One of the objectives of our research is to develop these multiple wavelength tube lasers.”

Zetian Mi, McGill University

Credit: Owen Egan

Tube lasers prepare to light up silicon circuits

Differences in polarity, lattice constant and thermal expansion hamper the unification of compound semiconductor light emitting structures and silicon ICs. But Zetian's Mi's team from McGill University can avoid all these issues by turning to a novel micro-tube laser architecture that suspends the device just above the wafer surface. **Richard Stevenson reports.**

Silicon has a major weakness. It's a lousy light emitter, and this means that it cannot be used to build monolithic ICs incorporating lasers or LEDs. So to address this Achilles heel, many researchers are trying to find ways to unify compound semiconductor light sources with silicon. If a cost-effective technology for high-volume manufacturing could be found, then many would welcome it. The electrical interconnects that are currently being used for chip-to-chip data transfer have very little headroom left, and switching to an optical approach would alleviate a looming bottleneck. In addition, silicon ICs with opto-electronic functionality could spur developments in biological sensing applications.

Efforts at developing III-V-on-silicon light sources go back a long way and progress has been hampered by several major differences between the two types of material. In fact, it might actually make more sense to keep them slightly apart, rather than putting these unhappy bedfellows together.

One researcher holding precisely that view is Zetian Mi from McGill University, Montreal. He is leading a team that's developing a free-standing tube laser that sits a few hundred nanometers above the silicon platform. This GaAs-based novel architecture promises to provide the circuit with a light source operating at incredibly fast modulation speeds, while consuming very little power.

Mi wants to keep the III-Vs and silicon apart due to their incompatibility – these materials have significant differences in polarity, lattice constant and thermal coefficients of expansion. "When you grow GaAs on silicon, in some regions the gallium atoms attach to silicon first, and in other regions arsenic attaches to silicon first. So as you grow more and more layers there will be a boundary, called the anti-phase domain boundary." This interface, which stems from differences in polarity, creates a high density of dislocations in the material, leading to a

leakage current path that causes local heating. These problems are compounded by defects that stem from strain in the epilayers caused by lattice mismatch. Some researchers, including those from Intel, sidestep these problems by growing lasers on a native platform, and then bonding their devices to silicon. But this approach cannot eliminate stresses that are caused by thermal expansion coefficient differences. What's more, this type of laser cannot be scaled to the sub-micron sizes needed for realizing ultra-low power consumption alongside modulation speeds of hundreds of GHz.

Mi's approach, which promises to deliver on all these fronts, begins by taking a GaAs substrate and depositing a strained structure with an active region onto it. The epitaxial layers are patterned into a U-shape, before a sacrificial layer is removed. The strain in the remaining structure causes it to roll into a tube, which can then be transferred to silicon with the aid of a solvent (see Figs. 1 and 2).

Micro-tube laser fabrication begins with the MBE growth of an epistructure that features two quantum dot layers embedded in a GaAs film
Credit: Owen Egan





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Scope & Topics; Contribution addressing materials, growth, processing, devices and applications of InP and related materials are welcome. Contributions addressing the use of other materials for traditional InP applications are also encouraged.

Topics of interest include, but are not limited to the followings.

Characterization and Bulk Materials (Dr. Kyoichi Kinoshita, JAXA)

Epitaxy (Prof. Yasufumi Fujiwara, Osaka Univ.)

Optoelectronics and Related Processing Technologies (Prof. Hiroshi Yasaka, Tohoku Univ.)

Electron Devices and Related Processing Technologies

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Tube pioneers

Mi did not invent micro-tube technology – this accolade goes to Victor Prinz from the Institute of Semiconductor Physics (Siberian Branch) at the Russian Academy of Sciences. He developed the technology for producing a micro-tube structure in the late 1990s and reported his results in 2000.

Since then trailblazing has transferred to Germany. Efforts by Oliver Schmidt and co-workers at the Max Planck Institute for Solid State Research in Stuttgart, along with Tobias Kipp's team at the University of Hamburg have led to an improved understanding of the formation of these structures, and observations of the optical emission from GaAs-based devices at very low temperatures and SiO₂/silicon heterostructures at room temperature. Mi's two recent, major contributions to this field are the demonstration of coherent emission - and ultimately lasing - from III-V micro-tubes; and the development of a process to transfer these structures onto a silicon substrate.

The McGill academic employs MBE for the growth of his epiwafers, which comprise a 50 nm-thick AlAs sacrificial layer, a 20 nm thick In_{0.18}Ga_{0.82}As layer, and a 30 nm thick GaAs cap that incorporates two In_{0.5}Ga_{0.5}As quantum dots layers. Some of these structures were grown in Pallab Bhattacharya's group at the University of Michigan, but Mi has plans to move production in-house after his team has conditioned a recently purchased MBE tool that is dedicated to arsenide deposition.

Mi says that his active region contains quantum dots, rather than quantum wells, because they offer superior carrier confinement. "The resulting near-discrete density of states promises both large gain and large differential gain for laser operation, compared to quantum wells." In addition, the dots provide strong carrier localization that greatly reduces non-radiative recombination associated with surface defects.

A U-shaped GaAs-based structure is defined by photolithography and subsequent etching into the InGaAs layer. Self-rolling of these epilayers is then initiated by selective etching of the AlAs sacrificial layer with hydrofluoric acid. This eventually leads to the formation of "fully released" quantum dot micro-tube structures on a GaAs substrate.

Other groups have already developed methods for the transfer of III-V devices onto alternative substrates, but Mi says that these processes are incompatible with his micro-tubes. "The reason that we don't use dry printing is that our structures are hollow and fragile, and you cannot press on the surface. Solution casting works very well, but you can't position these micro-tubes where you want to."

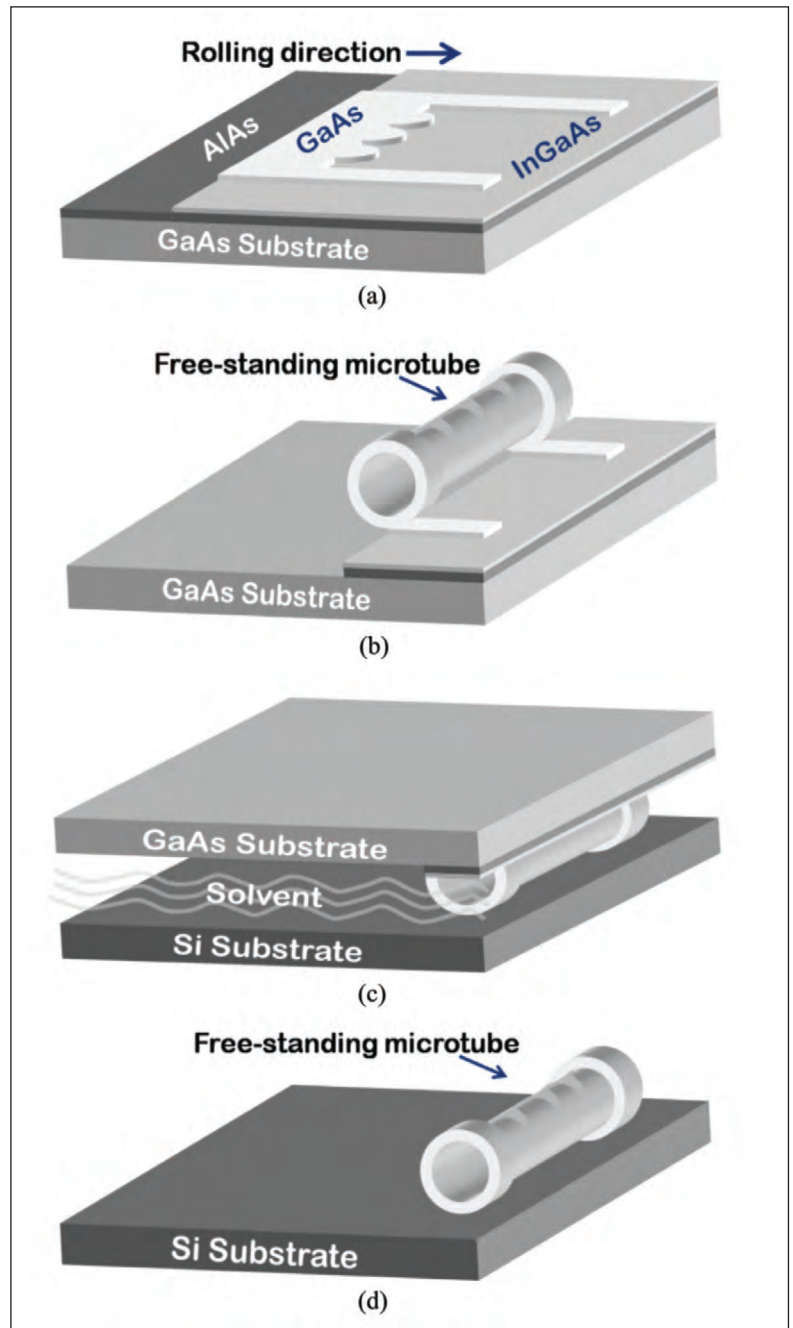


Figure 1: Fabrication of micro-tube lasers begins by taking a GaAs substrate, and using MBE to deposit a strained arsenide-based epistructure that features a quantum dot active region onto this platform. A U-shaped structure is etched into this surface (a), before the AlAs sacrificial layer is etched away. Strain drives the rolling-up of this structure to form a free-standing micro-tube (b), which can be transferred to a silicon surface in the presence of a solvent (c). The micro-tube binds to the silicon surface due to the gravitational force induced by the solvent in and around the tube (d)

Instead, the micro-tubes are directly transferred from the GaAs substrate to a silicon platform with the aid of a solvent. According to Mi, removal of the GaAs substrate creates freestanding micro-tubes that preferentially stay on silicon due to the gravitational force induced by the solvent in and around the tube. Solvent evaporation leaves the micro-tubes bound to silicon via a Van De Waals attraction. Mi believes that his micro-tube laser fabrication process has several strengths. "You combine the benefits of top-down and the bottom-up up processes. For

example, the tube diameter is determined by layer composition, and the wall thickness by the etching process." The fabrication process is also simple and controllable, says Mi, and it can produce incredibly smooth surfaces with a roughness that's determined by MBE growth.

From emission to lasing

Mi has made rapid progress since he started developing micro-tube lasers following an appointment at McGill's Department of Electrical and Computer Engineering in September 2007. Optically pumped emission from his microcavities at 77K was realized in late 2008, and this year he has progressed to coherent emission at room temperature and finally lasing from these structures. Advances are the fruits of processing improvements resulting from ever greater familiarity with device fabrication.

The emission wavelengths produced by these tubes are governed by the lateral dimensions of the waveguide, and its associated whispering-gallery modes. This leads to multiple emission modes. The dominant lasing wavelengths produced by one of the most recent structures occur at 1194 nm, 1217 nm and 1241 nm, and there are also weaker, subsidiary peaks (see Fig 3).

If Mi's micro-tubes were perfect ring resonators, emission would be produced from every point in the tube. But these tubes have a starting and stopping edge that scatter light, and this dominates the emission because the rest of the structure is incredibly smooth. Light that emanates from these points rapidly diverges.

One of the promising aspects of Mi's approach is its very high yield. This is partly thanks to the simplicity of the process, which involves just one photolithographic step. Emission from the tubes may not be in the preferred direction, but this can be remedied by simply rotating them.

If these micro-tube lasers are to kick-on and enjoy commercial success, then they will have to be driven by an electrical source. "It is difficult to achieve high efficiency, electrically injected micro and nano-scale lasers, and making an electrical contact directly onto the free-standing laser without adversely affecting device performance is particularly challenging," admits Mi. "However, we have devised an approach and expect to achieve electrically injected devices within one year."

The spectral emission profile from these electrically pumped lasers is expected to feature multiple-emission lines that are already seen in optically pumped

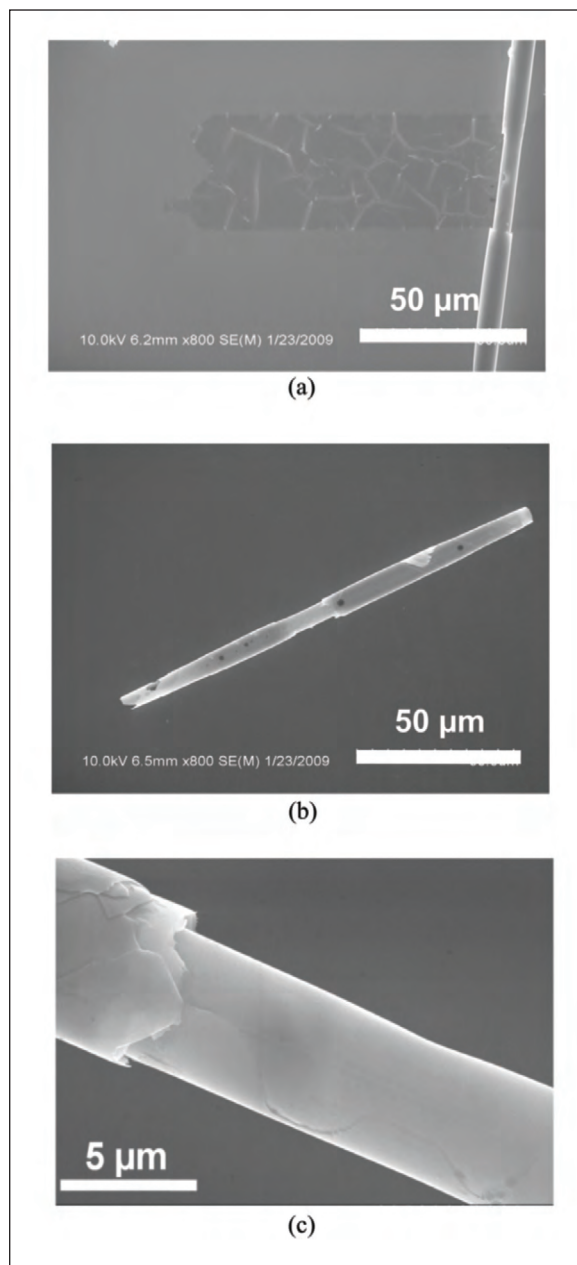


Figure 2: Scanning electron microscopy reveals the free-standing quantum dot micro-tube, and the etched GaAs mesa (a). This can be transferred to a silicon substrate (b). Closer inspection of the micro-tube reveals the sinusoidal geometry of its surface (c).

Mi and his team are clearly identifying and eliminating the barriers to commercializing their technology. Patent application filing is already underway through McGill University, and they have also initiated a collaboration with Reflex Photonics, a Montreal-based start up that is developing high-speed optical connections for semiconductor packaging and data transfer

counterparts. “For some applications you want a single wavelength, but for other applications, such as wavelength division multiplexing, you need multiple, evenly spaced channels”, explains Mi. “One of the objectives of our research is to develop these multiple wavelength tube lasers.”

Modulation speeds for these lasers are expected to be well over 40 GHz, and Mi believes that this can be increased to the terahertz range by scaling devices so that all of their dimensions are less than a micron. But he admits that realizing this goal will be particularly tough. Another aspect of his technology that he is looking to advance is the precision with which the micro-tube is positioned on the silicon surface.

The existing substrate-to-substrate transfer process cannot guarantee that the laser will be successfully

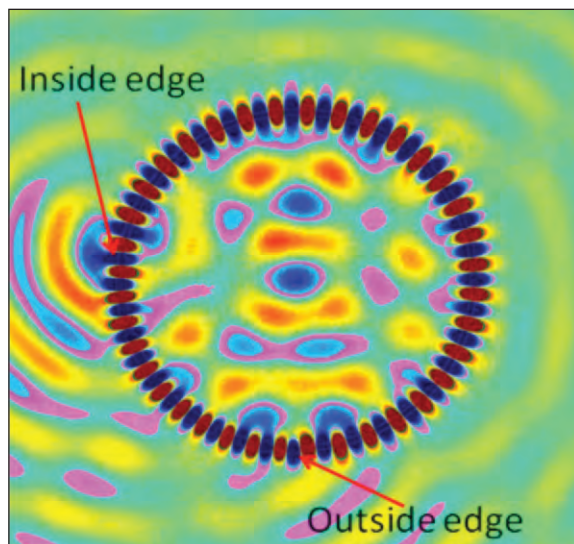


Figure 4. Zetian Mi's team have calculated the optical resonance modes for a rolled-up micro-tube with a 5.6 μm diameter and a wall thickness of 100 nm using a finite-difference time domain method

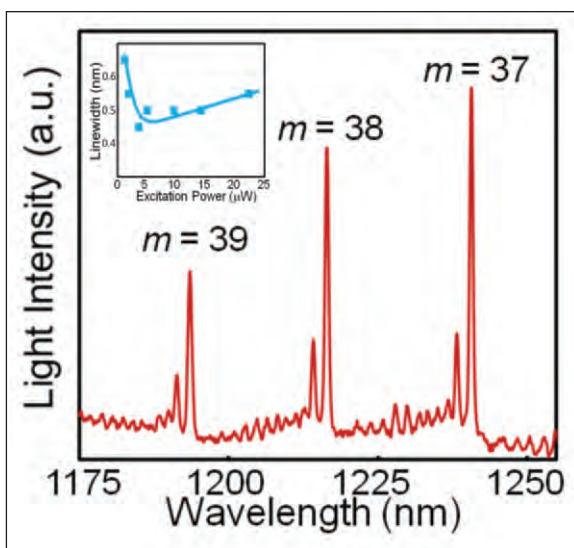


Figure 3: Optically pumping with 632.8 nm excitation from a HeNe laser produced three distinct lasing lines. The absorbed power for this measurement was about 23 μW

coupled to a waveguide on the silicon IC. But Mi's team is addressing this issue by developing a process to move the tubes on the silicon surface. And if the Van de Waals forces are not strong enough to lock them in position for a commercial product, then they can be bonded in place with passivation techniques.

Mi and his team are clearly identifying and eliminating the barriers to commercializing their technology. Patent application filing is already underway through McGill University, and they have also initiated a collaboration with Reflex Photonics, a Montreal-based start up that is developing high-speed optical connections for semiconductor packaging and data transfer.

So it may be that it is a novel, ring-based approach that will hold the key to a long and happy marriage between silicon ICs and III-V lasers.

Many ICNS-8 delegates decided to stay in the conference hotels, set in several acres of beautiful coastal gardens

LED droop continues to bamboozle researchers

Three themes dominated the discussions at the latest nitride meeting: the cause of LED droop; the best approach to plugging the green gap; and the development of higher-quality, lower-cost native substrates. **Cambridge University researcher Michelle Moram reports from Jeju Island, Korea.**

As a fast-growing and dynamic country, Korea was an ideal host for the most recent International Conference on Nitride Semiconductors (ICNS-8). This popularity of this conference series is clearly on the up: almost 1000 delegates flocked to the meeting, and 27 different industrial exhibitors made their way to Jeju Island from across the globe, continuing the trend of growth seen from previous conferences in Las Vegas (2007) and Bremen (2005).

Despite the recent economic recession, the leading LED manufacturers - such as Cree, Osram, Philips Lumileds, and Samsung - dominated the conference program presentations. Their strong presence also provided further evidence of the robust nature of the nitride-based device market, which is expected to grow strongly, thanks in part to the emergence of solid-state lighting (SSL). Similarly, sustained worldwide governmental support for the development of energy-efficient SSL ensured that a high proportion of European, American and Asian academics were able to attend.

Thanks to these shared goals and interests, it was no surprise to see that the majority of contributions from academia and industry focused on light-emitting devices. Key themes that emerged during the week were the unsolved problems of 'efficiency droop' and the 'green gap'.

Although LED efficiencies initially tend to rise with increasing current densities, they subsequently level off and then drop as the operating current increases. This 'roll-over' and the 'droop' that follows it are major obstacles to the development of high-efficiency, high-brightness LEDs for low-cost SSL. Unfortunately, while droop isn't such a problem for near-UV devices, it becomes increasingly important for longer-wavelength blue and green emitters, which contain high proportions of indium in the InGaN active regions of the device. This increase in indium content tends to be correlated with drastic reductions in device efficiencies even at the optimum operating current, limiting device performance as emission wavelengths move into the green and yellow spectral regions.

Unfortunately, coming from the other end of the spectrum, the efficiencies of AlInGaP devices - traditionally used to create red, yellow and orange emitters - also falls off as wavelengths shorten and move towards the green, hence the term 'green gap'. It's a gaping hole that desperately needs to be plugged, especially if devices such as green lasers for projection applications are to reach the market.

With this in mind, Steve DenBaars of the University of California, Santa Barbara (UCSB) opened the conference

with a plenary talk on devices made using semipolar and nonpolar crystal orientations, which can help reduce or eliminate the piezoelectric fields that plague conventional c-plane (polar) nitride devices. The audience was especially keen to hear his views on the best film orientation for making green laser diodes.

DenBaars began by recapping recent achievements throughout the globe. The leading successes on c-plane material are a 526 nm laser from Osram and 515 nm version from Nichia. For non-polar lasers, UCSB and Rohm are leading the way with lasing at around 492 nm and 500 nm, while Sumitomo Electric recently produced a 531 nm laser on the unusual semipolar 20 $\bar{2}1$ plane.

Thanks to the rapid pace of progress using all of these orientations, no clear winner has emerged just yet; however, DenBaars says that the alternative orientations do offer some significant advantages. For example, although incorporating high concentrations of indium is still difficult, the UCSB group has shown that the absence

Thanks to these shared goals and interests, it was no surprise to see that the majority of contributions from academia and industry focused on light-emitting devices. Key themes that emerged during the week were the unsolved problems of 'efficiency droop' and the 'green gap'

of fields across the light-emitting InGaN quantum wells allows them to be grown thicker, and this in turn enables the elimination of the AlGaN cladding layer. Getting rid of this layer is a big plus point, because it means that the growth time for a 492 nm blue m-plane laser can be slashed from 12 hours to just 2 hours. Additionally, LEDs grown on semipolar orientations - where indium incorporation is easier - could help close the green gap: UCSB's first unoptimized 562 nm LEDs showed a surprisingly high external quantum efficiency of 13.4 %.

Droop: the mysterious malady

However, UCSB's nonpolar and semipolar LEDs still showed unexplained efficiency droop, despite the reduction of piezoelectric fields. Summarising the debate on droop, Shugo Nitta from Toyoda Gosei discussed the possible candidate mechanisms: Auger recombination, related to high current densities; electron overflow from the active region; poor hole injection; polarisation effects,



Delegates could walk for just a few minutes from the conference to marvel at magnificent views of Jeju Island

which encourage carrier leakage; and problems related to defects and InGaN material composition.

Aurelien David confirmed Philips Lumileds' existing position on droop, presenting both electrical and luminescence measurements that could be explained in terms of a composition-independent Auger process. Consistent with this finding, many groups reported success by reducing carrier densities in the active region: the Fraunhofer Institute, Germany, opted for wide quantum wells and low dislocation densities, while Cree's "engineering solution" was to increase the chip area.

Taking a different approach, the group of Seong-Ju Park at Gwangju Institute of Science and Technology, which is working in association with Samsung LED, reduced droop by removing the AlGaN electron blocking layer that lies

At the packed rump discussion on this topic, most agreed that some loss mechanism occurred at high carrier densities, but the simple rate equation used to describe it might be inappropriate to describe all the complex, poorly understood recombination processes that seem to occur in the nitrides

between the InGaN quantum wells and the p-type layer. This improved hole injection efficiencies at high current densities. However, Fred Schubert from Rensselaer Polytechnic Institute showed that p-doped electron blocking layers allowed good hole injection, while compositional control could be used to reduce the polarisation mismatch between the LED's quantum wells and the barriers that separate them. This combination reduced the carrier leakage, thereby reducing droop.

However, the strong droop observed in UCSB's nonpolar LEDs suggested that polarisation couldn't be the whole story.

No matter what, there were no reports of droop-free LEDs, regardless of the active layer design, film orientation, defect densities or measurement temperature – leading Jong-In Shim of Hanyang University and many others came to the conclusion that droop must be intrinsic to III-nitride materials, although it wasn't clear why. At the packed rump discussion on this topic, most agreed that some loss mechanism occurred at high carrier densities, but the simple rate equation used to describe it might be inappropriate to describe all the complex, poorly understood recombination processes that seem to occur in the nitrides.

However, leading the discussion away from droop mechanisms, James Ibbetson of Cree said it was "time to move on from the name-calling" and instead think about "what comes next", arguing that high LED operating temperatures produced an equally important droop effect. Christian Fricke presented Osram's route towards better thermal management, involving drilling tiny holes in the chip and creating buried p-contacts, permitting uniform current injection and light extraction.

However, he also emphasised the need to control costs and to concentrate on LED reliability and light quality, rather than limiting the focus simply to high-brightness devices, which are not appropriate for every application.

Slashing LED costs

One way to reduce costs is to increase the substrate size, cutting down on the wasted edge material and thus boosting yields. However, it can be harder to get uniform layers on larger substrates, due to wafer bow. With an eye on future trends, Aixtron demonstrated a new reactor configuration for 6-inch wafers, capable of producing GaN-on-sapphire epilayers with a reproducible thickness uniformity of 1%. Building up to full devices, the University of Cambridge group presented 455 nm LEDs with a high internal quantum efficiency of 58 % fabricated on 6-inch silicon, while IMEC showed considerable progress with their green LEDs on 4-inch sapphire.

An alternative route towards lowering costs is to increase LED efficiencies. This can be realized by reducing the high densities of dislocations – typically 10^8 cm^{-2} – that are produced when nitride films are grown on foreign substrates. While there were few surprises in this established area, the University of Cambridge did present data showing that dislocations could move and react within GaN films at growth temperatures, suggesting a future for suitably chosen annealing-based dislocation reduction processes.

Of course, low defect density bulk substrates would be an ideal solution to the dislocation problem, but their costs need to fall substantially. Fortunately, considerable progress towards commercially viable substrates is being made using several competing approaches: both the Chinese Academy of Sciences (with Suzhou Nanowin) and Unipress/TopGaN announced plans for mass production of substrates grown by hydride vapour phase epitaxy (HVPE), the latter using high-pressure solution growth on top of a HVPE-grown 'seed' crystal.

In contrast, Osaka University, Japan, announced breakthroughs in bulk GaN grown by the sodium-flux method, reporting inclusion-free 2-inch c-plane GaN wafers with dislocation densities of around $3 \times 10^4 \text{ cm}^{-2}$ and announcing their plans to scale up to 4-inch substrate production. However, the most impressive data came from the Polish company Ammono Ltd., who reported flat 2-inch c-plane GaN substrates grown by the ammonothermal method with dislocation densities as low as $5 \times 10^3 \text{ cm}^{-2}$. Despite the low growth rates associated with this method, high-volume production and commercial release of these 2-inch substrates is scheduled to occur, once a sufficient stock of seed crystals has been built up. All of these methods also have the potential to lead to the commercialisation of bulk nonpolar and semipolar GaN.

Additional progress on low defect density c-plane bulk AlN was also announced by several groups, including the Russian start-up Nitride Crystals, who reported the sublimation growth of c-plane AlN using AlN-on-SiC seeds in a tungsten crucible. The resulting 2-inch substrates have a 'block' structure that enables the realization of areas with dislocation densities as low as 10^2 cm^{-2} . Substrate sales will begin once seed crystal stock has been built up.

Although the availability of all large-area native substrates is currently limited and the cost is high, this route towards low defect density material looks set to be especially important for UV-LEDs. Although deep-UV LEDs were announced based on nonpolar (NTT Corporation), semipolar (University of South Carolina with NITEK) and c-plane (RIKEN and Sensor Electric) heteroepitaxial films,

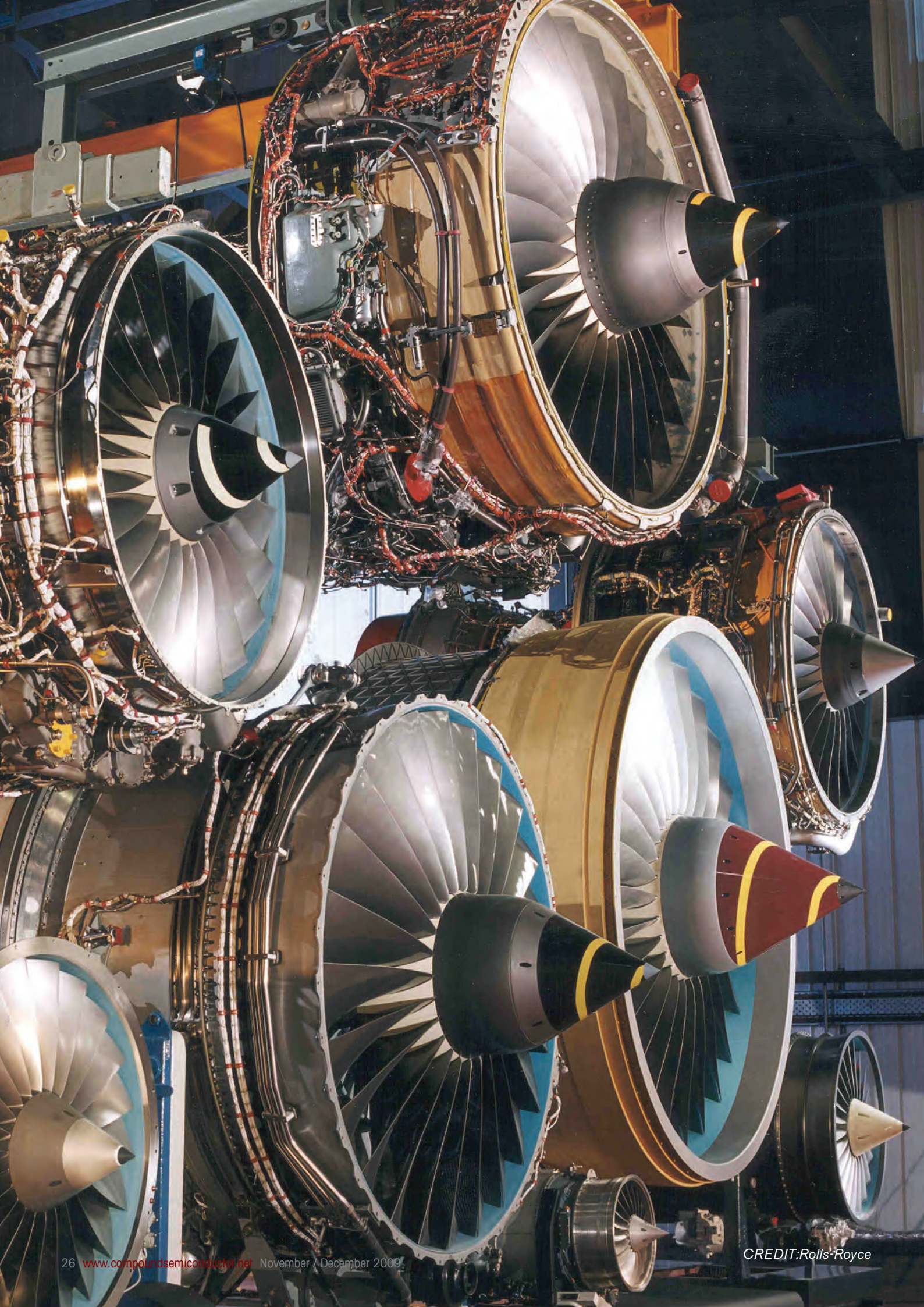
the high defect densities were linked to high forward voltages, low output powers and highly resistive p-type material. Elsewhere at ICNS-8, only modest progress was reported on the reduction of defect densities in heteroepitaxial AlGaIn and AlN films, which is needed for high external quantum efficiencies and output powers in the UV.

Low defect density, insulating GaN and AlN substrates are also promising for GaN-based electronics, as dislocations are thought to lead to high leakage currents and degradation in GaN-based HEMTs, which are used in high-frequency and power switching applications. Reflecting these concerns, many groups presented device reliability studies. One clear trend is towards the use of InAlN, and even InAlGaIn, in order to circumvent some of the strain and defect issues associated with AlGaIn-based transistors. New designs were also presented, including the 'normally-off' transistors based on nonpolar crystal orientations that were developed by Umesh Mishra's group at UCSB, while Cree announced a series of improvements to their high-power, high-frequency transistor range, bringing the prospect of high-power near-terahertz applications for the nitrides within reach.

It will be interesting to see how much progress is made on this front, and also on the quests for an understanding of the green gap and LED droop when the nitride community reconvenes for the ninth meeting of this series in Glasgow in 2011. If this meeting is anything like the previous affairs, it promises to be a have a real buzz about it.

The 8th International Conference on Nitride Semiconductor was held in Jeju International Convention Center, Jeju Island, Korea, between 18 and 23 October. 940 delegates from 35 countries attended this event





Europe turns to AlInN to push the limits of transistor and sensor performance

The European Commission is funding a multi-national project that aims to boost the performance of nitride-based transistors, pressure monitors and chemical sensors. Success could lead to creation of AlInN/GaN-based devices that probe the environment in jet engines, measure incredibly high pH levels, and deliver output powers of more than 1kW at 2 GHz. **Richard Stevenson investigates.**

The AlGaIn/GaN heterostructure has its pros and cons. Its strengths include the natural formation of a two-dimensional electron gas (2DEG) at its interface thanks to piezoelectric effects, which greatly simplifies HEMT fabrication. But this pairing also creates high epilayer strain that might impact reliability.

Turning to AlInN can eliminate this weakness. Switching to this ternary not only does away with stress, because it allows lattice-matching to GaN – it also leads to a superior 2DEG density. Thanks to far stronger spontaneous polarization, the AlInN/GaN heterojunction produces twice the charge density of its $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ cousin.

One team that is looking to exploit the strengths of AlInN is a European consortium called MORGaN – Materials for Robust Gallium Nitride. This three-year effort that kicked-off in November 2008 is backed by €9.2 million of funding from the European Commission, and involves 24 partners from 11 nations. One of its goals is the development of material for AlInN/GaN HEMTs that can deliver an output of 1 kW at 2 GHz, and another of its aims is the fabrication of chemical and pressure sensors that are based on the same material and can operate in very harsh environments.

If the program is successful, it could aid a very wide variety of applications. It could help the construction of high-power amplifiers based on AlInN HEMTs, which could be employed in radar systems and base-stations for mobile communications, or in power electronics for consumer applications. MORGaN could also lead to the development of pressure sensors capable of operating at temperatures of up to 700°C that could aid oil exploration, and help to determine the environment in automobile and jet engines. And robust chemical sensors could be fabricated in the project, which increase the pH detection

limit for a compound semiconductor device from 12 or 13 to values of 15 or more.

Producing devices capable of operating in these extreme conditions requires innovation on many fronts, and this is reflected in the wide range of activities in the MORGaN project. Efforts are being directed at the growth of nitrides on a variety of platforms; optimization of the growth of AlInN/GaN heterostructures; new sensor architectures; and radical packaging technologies that help devices to operate in these harsh environments.

One of the striking aspects of this effort is its incredibly broad agenda. That's because MORGaN is actually the amalgamation of two projects proposed to the European Commission. One was focused on the development of AlInN-based pressure and chemical sensors; and the other, a successor to a project called UltraGaIn, aimed to demonstrate AlInN HEMTs' appropriateness with microwave operations. All members of original UltraGaIn team are participating in the MORGaN project together with additional partners from sensor fields and advanced material manufacturing.



Switching from a AlGaIn/GaN HEMT to a InAlIn/GaN equivalent can increase the maximum operating temperature of the transistor from 800°C to 1000°C. Credit: MORGaN

Building on UltraGaN

"We got excellent results in UltraGaN. It was a major success," says Sylvain Delage, a researcher from the Alcatel-Thales III-V Laboratory in France who is now leading the MORGaN project. "In America they are now launching many projects using AlInN, based on all these results we obtained in UltraGaN." He claims that one of the highlights of this project was the demonstration of an AlInN/GaN HEMT working at 1000°C, which is 200°C higher than an AlGaIn-based equivalent. And another success was the realization of a continuous-wave output of more than 10 W/mm at 10 GHz, alongside a power-added efficiency of 56 percent.

These results were produced with a very simple, normally-on transistor architecture that is now being employed in the MORGaN project. By lattice-matching the AlInN/GaN heterostructure, it is possible to form a 2DEG with properties that are independent of the thickness of the ternary layer. "That means that we can make a HEMT with about 3 nm of AlIn," claims Delage. This allows a metal gate to change the surface potential of the material, and opens the door to the fabrication of a normally-off transistor, because the Schottky contact removes the 2DEG below it.

Producing AlInN/GaN heterostructures is challenging, because the ternary tends to phase separate and it is difficult to form a high-quality interface between the two materials. So to overcome these barriers to high-quality AlInN growth, four strong epitaxial partners were set loose on these issues: the MOCVD toolmaker Aixtron, Germany; EPFL (Ecole Polytechnique Fédérale de Lausanne), Switzerland; the Alcatel-Thales III-V lab, France; and FORTH (Foundation for Research and Technology – Hellas), Greece. Between them, they have one MBE reactor, which has provided excellent results for AlN growth to demonstrate an AlN/GaN HEMT, and three MOCVD tools, which have produced the better InAlN/GaN device results. The UltraGaN project used sapphire substrate for heterostructure optimization, while best power demonstrations were obtained on SiC substrates thanks to their superior high thermal conductivity.

Below and below right: F-cubic can produce various 3-D structures with a high-precision, ink-jet printing technique. This includes a set of chess pieces, and packages for housing AlInN-based devices operating at very high temperatures. Credit: fcubic



These teams - plus the University of Bath, England - are now focusing on the development of growth technologies for realizing high-quality InAlN/GaN heterostructures on a variety of platforms. These include composites

that feature diamond, an incredibly efficient heat spreader. Some progress has already been made, including the deposition of relatively smooth epitaxial layers directly on all three orientations of the material.

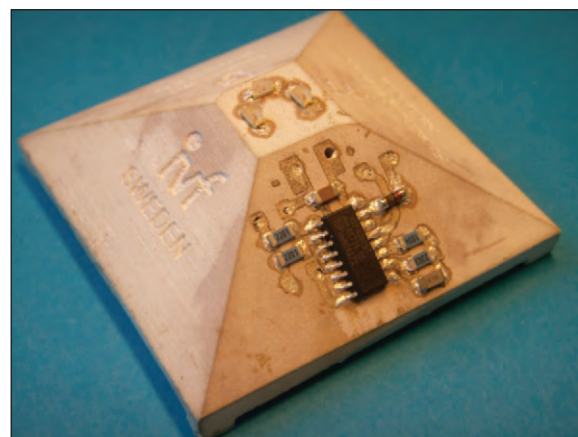
Sensing the environment

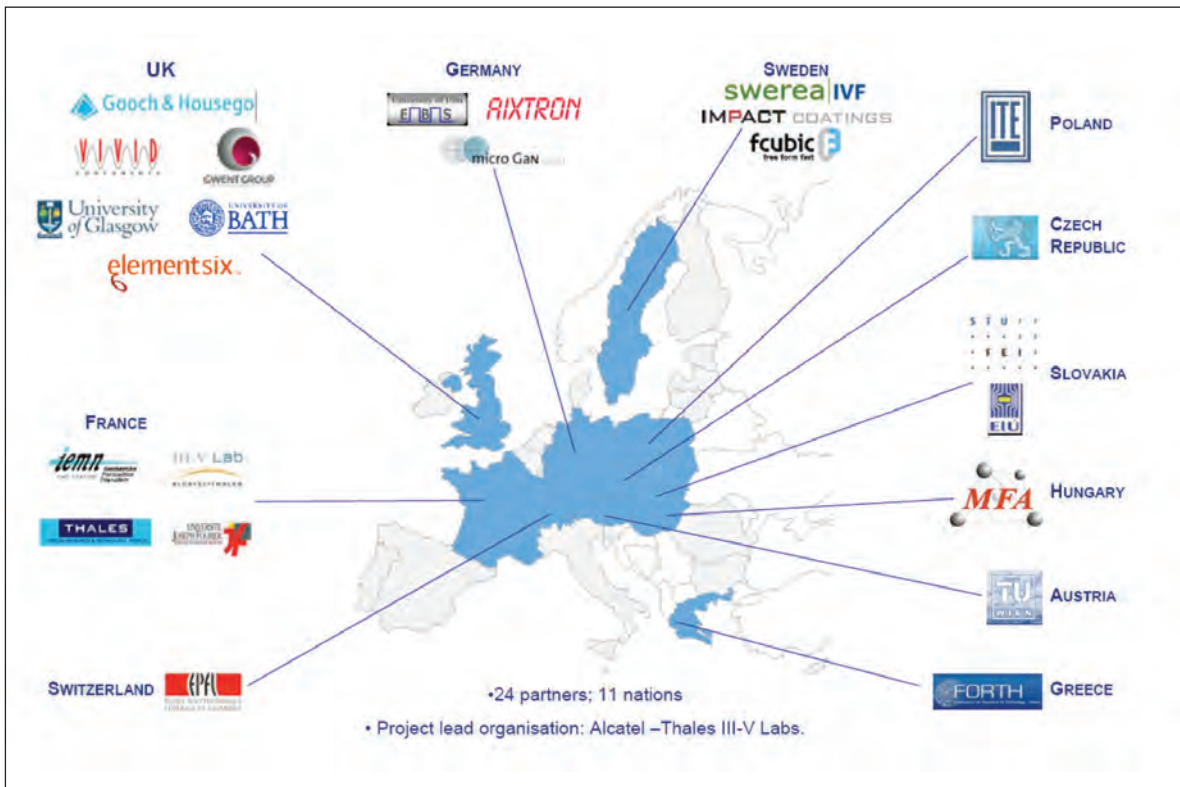
Other partners in MORGaN are developing sensors that employ an AlInN HEMT to measure values of pH or pressure. HEMTs can reveal levels of acidity, because liquids impinging on the surface alter the chemical potential within the device, leading to a variation in current flow through the transistor. And measurements of pressure are possible, because the piezoelectric nature of the material means that strain impacts the concentration of the 2DEG. Variations can be determined with great precision by connecting this HEMT to three others in a Wheatstone bridge configuration.

One company that's leading the development of both types of sensors is a start-up called MicroGaN, which spun out of the University of Ulm in 2002. The company has already developed GaN-on-silicon cantilever structures that are 200-400 μm wide, and 1 mm in length, and GaN actors, where cantilevers can be moved by electrical stimulation.

The new cantilever design will provide superior performance at high temperatures, according to MicroGaN's Ulrich Heinle. MicroGaN and its partners will need to develop new processing steps for these elevated temperatures. "Traditional ohmic contacts are based on titanium and aluminum, and these are not practical for temperatures above 500°C," says Heinle, who explains that a partner is working on copper-based contacts. Another issue is that the current produced by this type of sensor is not stable at 600°C, and researchers are working to try to understand the degradation mechanisms and devise ways to address them.

The GaN-on-silicon cantilevers that MicroGaN has made tend to bend slightly under no external pressure, due to





MicroGaN is receiving over €9 million of funding from the European Commission through a seventh framework program that has the theme of nanosciences, nanotechnologies, materials and new production technologies

the internal stresses in the GaN film. "Due to the stress, the cantilever will bend downwards, and this can be 50 μm to 20 μm , depending on the structure," says Heinle. One way to address this issue is to introduce double-clamped structures that are better at coping with any initial stresses in the material.

The University of Bath is developing a process for producing nitride films on silicon substrates with incredibly low levels of stress. Their approach - pioneered by the academic Wang Nang Wang - involves a nanoscale lateral overgrowth technique that begins with the formation of an array of nano-columns on a GaN template. Adjusting the growth conditions can then lead to the coalescence of the GaN nano-columns into a continuous planar film of a low-stress, high-quality semiconductor.

The Bath team is looking to extend this concept to the growth of thin membranes of GaN clamped either at all edges or along just one edge. In the latter configuration the structure will resemble a microscopic cantilever grown out from the semiconductor surface. "When released these cantilevers will sense applied forces by the piezoelectric effect as they bend," explains Duncan Allsopp, a researcher at Bath University. "We have already demonstrated the growth of short, stubby cantilevers and we are now extending our research to clamped membrane structures to act as pressure

sensors." The Bath team has designed a photolithographic mask and is now optimizing the geometry of these epitaxially grown cantilever and membrane sensors. "Once the geometry is optimized, our collaborators in the MORGaN program will be able to design the most appropriate transducer. We are getting close to that stage now."

Diamond platforms

A team of suppliers of high-performance, diamond-base substrates is underpinning much of the effort in the MORGaN project. Diamond promises to be a great foundation for these devices, thanks to its incredibly high thermal conductivity of typically $2000 \text{ Wm}^{-1}\text{K}^{-1}$. This enables it to act as a very efficient heat spreader that rapidly sucks the heat away from the localized hot spots within devices.

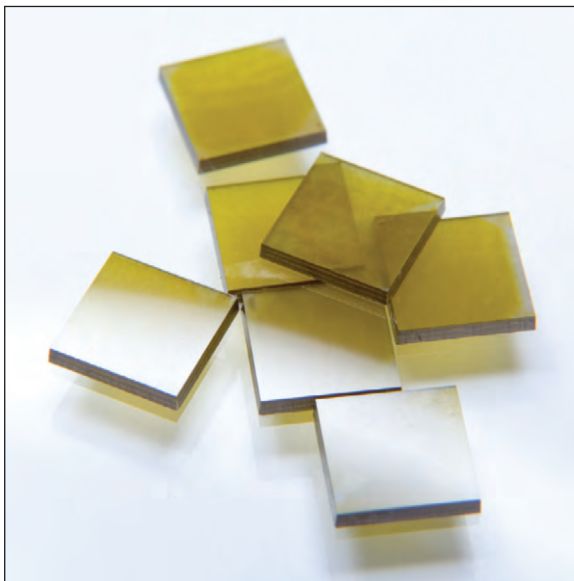
Providing funding for this aspect of the program might raise a few eyebrows, because the epitaxial teams could simply import the diamond composite wafers that are under development by firms such as sp3 Diamond Technologies and Group 4 Labs. However, the Element Six R&D Operations Manager Geoff Scarsbrook, who is heading-up this part of the MORGaN project, says that funding of diamond-based substrates is justifiable, because the technology is far from mature: "Whilst the benefits of incorporating a diamond layer are well understood, the optimum technology for integrating the

Work on the substrate is currently focused on thinning of the silicon layer, in order to stop the silicon from acting as a thermal barrier, and to provide a good interface for nitride deposition

diamond into the high-power GaN device technology is still under development". He believes that the approaches of others have strengths and weaknesses, and he is confident that Element Six can make a significant contribution, because it is at the leading edge of all aspects of diamond technology. In addition, Scarsbrook suggests that there is a secondary reason for the funding of substrate development - it could lead to an internal supplier of these products for Europe.

Element Six provides partners in the MORGaN project with a variety of diamond-based substrates. These players have the option of growing directly onto single crystalline or poly-crystalline substrates, or depositing their epilayers on a diamond-on-silicon composite. A third option is also available – post-growth bonding of the epilayers to diamond.

Scarsbrook says that all three approaches face the same challenge - managing the strain that is generated at the interface. This arises from the significant differences in thermal expansion coefficients of the materials involved. Element Six produces single crystal diamond by a high-temperature, high-pressure process (HPHT) that involves



Element Six can produce pieces of diamond by a high-pressure, high-temperature technique.
CREDIT: Element Six

temperatures of 1400-1600°C and pressures 5-6 GPa, and also by CVD, which offers greater control of purity. For MORGaN the company is developing and supplying both single crystal and polycrystalline diamond substrates produced by the CVD route, as well as some HPHT single crystal. One of the key questions that MORGaN will address is whether it is possible to deposit device quality single crystal GaN on polycrystalline diamond.

CVD is also used to make diamond-silicon composites. The diamond layer can have as many as three roles to play in this type of substrate, according to Scarsbrook: it has to act as a heat spreader; it may be needed to provide some mechanical strength, either for processing steps, or in the final device; and it has to provide a backplane to the device. "This backplane is positioned on the opposite side of a dielectric, and the appropriate distance – which determines the thickness of the diamond – is around 100 µm."

This substrate is produced by CVD deposition of diamond on silicon. Element Six can produce 4-inch wafers by this route, but it is only shipping a 2-inch version to its partners in the project at present, because this size is compatible with the majority of processing tools used in the MORGaN effort. Work on the substrate is currently focused on thinning of the silicon layer, in order to stop the silicon from acting as a thermal barrier, and to provide a good interface for nitride deposition.

Putting together a good package

If the sensors and transistors that are developed in the MORGaN project are to reach their true potential, then they need to be housed in well-designed packages delivering excellent thermal management capabilities. Several partners are working towards that particular goal, including f cubic from Sweden. This start-up uses a combination of high-precision ink-jet printing and elevated temperatures to produce three-dimensional packages from a diverse range of materials, including stainless steel, titanium, and silver. Delage says that this approach can make relatively large packages, and it is compatible with medium-sized markets requiring up to 10,000 pieces, making it suitable for microwave product manufacture.

Solders used in these packages must also withstand high temperatures. The Swedish firm Impact Coatings is active in this area, and it has developed a new refractory metal with a very good sheet resistance that can operate at 1000°C.

So it seems that MORGaN has an answer to every potential problem associated with developing AlInN-based devices for extreme conditions. This should serve them well in their quest to raise the performance bar of nitride sensors and transistors during the remaining two years of this project.

Heating a Wafer – How Difficult Can it Be?

Temperature uniformity in wafer processing has always been an area requiring accurate measurement and control in silicon based manufacturing. With new materials and scaling challenges the need for temperature control has increased to the point that any deviation from requirements can lead to manufacturing failure. **Thomas Kupiszewski** of **Watlow** discusses how thermal design analysis is used in improving existing processes and even extending the life of equipment.

Among the many processes involved in fabricating integrated circuits, it is deposition and dry etch which levy some of the most stringent requirements on the temperature uniformity of wafer heaters. Both chemical vapor deposition and planar plasma etch often stand out as the most demanding applications of “superuniformity” solutions to the wafer heating problem, reference Figure 1. Common to such processes is the need for a pedestal heater which supports and transfers thermal energy to a target substrate while maintaining surface temperature and flatness profiles within acceptable limits over the life of the equipment.

This article presents a case study examining the development of a rather unconventional pedestal heater to address an unusual confluence of thermal and structural requirements which proved to be highly coupled and conflicted. The problem presented here was the modification of a legacy pedestal heater design for a new application with an increased process heat load. The legacy heater configuration was characterized by a concentric, dual control zone layout of spiraled heating elements embedded in an aluminum casting.

This product was supported on a bi-metallic shaft as depicted in the left half of Figure 2. In the new

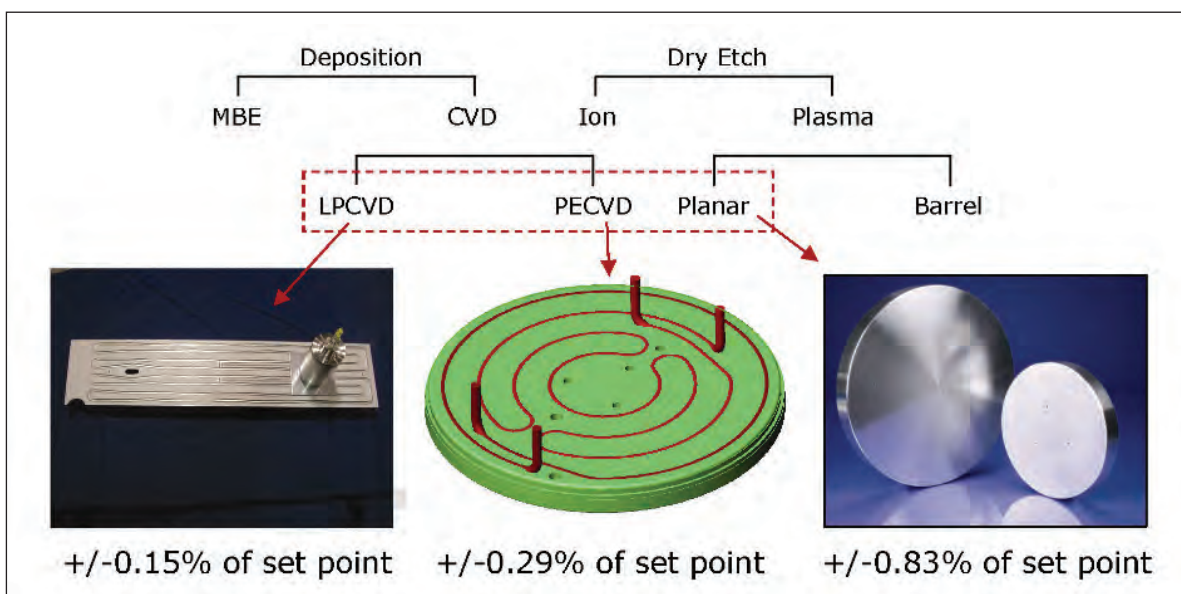


Fig. 1 Application domain for “super-uniformity” heating solutions. Optimized with the aid of realistic computer modeling and simulation, Watlow pedestal heaters have exhibited impressive temperature uniformity performance in fielded systems

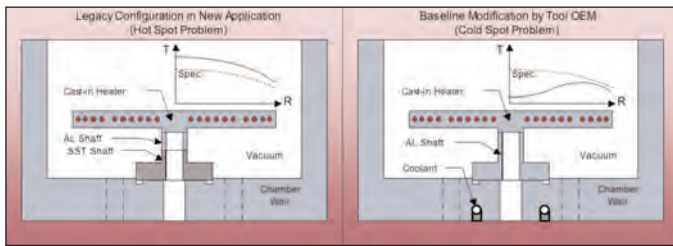


Fig. 2 Comparison of the legacy pedestal heater (left) versus the water-cooled variant (right). New process requirements imposed on an old design became highly problematic for achieving temperature uniformity goals

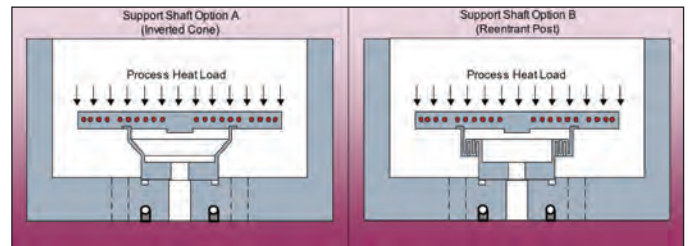


Fig. 3 Comparison of alternative solutions. Leveraged by computer aided engineering (CAE) resources, an iterative virtual prototyping effort rapidly identified, refined and verified the preferred embodiment

application, however, the heat transmission performance of the shaft became detrimental to temperature uniformity. Because the stainless steel end of the shaft was so effective at impeding heat conduction to the chamber floor, the excess process heat load manifested itself as an unacceptable hot spot at the center of the heater. The right half of Figure 2 depicts the attempted workaround. This design consisted of eliminating the stainless steel spool piece, extending the aluminum end of the shaft down to the chamber floor and actively cooling the chamber floor so the vacuum seal temperature would remain within safe bounds. Unfortunately, the net heat sinking effect of these changes caused an unacceptable cold spot.

Challenges

The following considerations framed the issue set for re-optimizing the baseline, all-aluminum design:

1. Accommodation of multiple operating modes. The excess process heat load scenarios ranged from 0 to approximately 1000 watts, depending on which condition was in play. For the maximum heat load condition, maintaining temperature uniformity proved to be highly problematic with a center-mounted, all-aluminum shaft. To improve uniformity, the radial temperature distribution would have to be “re-balanced” by moving the shaft mounting location closer to midway between the pedestal center and its outside diameter.

2. Thermal stress. For shafts which attach to the heater near the radial midpoint, there was concern about thermal stresses being high at the shaft weld joint locations because of a macroscopic thermal strain effect known as coning, whereby the warm end of the shaft expands more than the cool end.

3. Constraints. In addition to uniformity remediation and thermal stress mitigation, the design improvement effort would have to account for numerous constraints. These constraints included the bending limitations of sheathed heating elements, nichrome (NiCr) wire watt density limitations, shaft manufacturability, heater “castability,” welding limitations, construction material limitations, and a 50°C (122°F) design margin for the o-ring sealing the shaft bottom flange.

Solution Approach

The leading design options which emerged from concept ideation are illustrated in Figure 3. The inverted cone (Option A) was preferred from a relative ease-of-manufacturing perspective.

However, due to lingering concerns about thermal stress, the radial bellows alternative known as a reentrant post (Option B) was developed in parallel as a fallback. To advance a suitable design into production prototyping, Watlow began by detailing 20 solid model versions

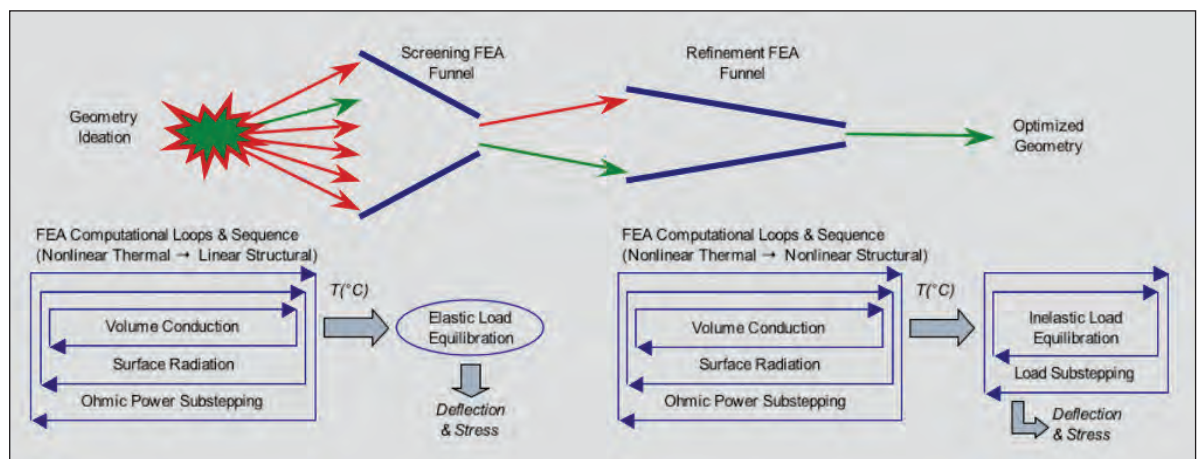


Fig. 4 FEA-driven, rapid virtual prototyping to identify the preferred shaft design

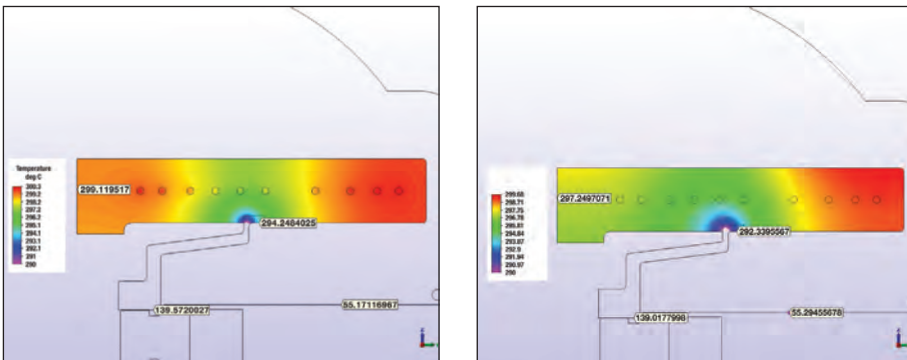


Fig. 5 Thermal FEA result comparison for the zero process heat load (top) and maximum process heat load (bottom). The predicted uniformity indicates the promise of an order of magnitude improvement relative to the baseline depicted in

spanning the aforementioned two geometries. These versions were funneled down to a final embodiment through the two-stage, multi-physics finite element analysis (FEA) process depicted in Figure 4.

This process was comprehensive in scope, accounting for all heat conduction paths subjected to the process heat generation and radiation and convection boundary conditions established in the chamber, as well as the coupled inelastic thermal strains and associated stresses in the entire pedestal heater subassembly.

Outcome

As a result of numerous FEA simulations, one of the originally-conceptualized versions of the inverted cone geometry ultimately emerged as the preferred shaft redesign alternative for improving the pedestal heater's uniformity.

The illustrative thermal FEA result case presented in Figure 5 suggests the theoretical feasibility of a one percent surface temperature uniformity goal for a hypothetical process scenario. The inelastic thermo-mechanical FEA results verified the reentrant post was superior in terms of

thermal performance and long-term structural robustness.

However, the inverted cone provided the best overall combination of temperature uniformity, stress margins and manufacturability (lathe operation only versus lathe and mill or weld for the reentrant post).

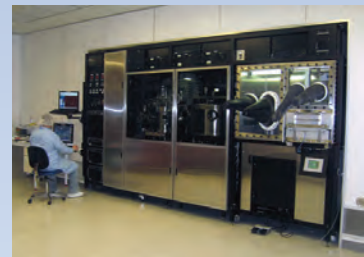
Although the results also indicated the top weld joint might undergo significant creep deformation as the temperature exposure time approached 10,000 hours, the 70 percent higher yield stress limit at the 100 hour mark was large enough for the inverted cone to retain adequate elasticity during thermal cycling intervals more representative of actual use. Heating a wafer to achieve a surface temperature "super-uniformity" approaching one percent of the application set point temperature is not trivial from the heater design perspective.

Comprehensive, FEA informed trade studies accounting for coupled physics effects, design and manufacturing rules, as well as material limits are beneficial to achieving aggressive performance goals, particularly when legacy components are being considered for retrofitting into next generation systems.



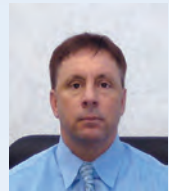
Thomas Kupiszewski is a design analysis expert with more than 23 years experience in developing and manufacturing custom electric equipment for cryogenic and high temperature applications. Kupiszewski holds a bachelor's degree in Engineering and Applied Science from the California Institute of Technology and a master's degree in mechanical engineering from the University of Wisconsin-Madison.

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Superluminescent diodes have an eye for diagnosis

Superluminescent diodes have been the poor relative of the photonics toolkit for many years. But Optical Coherence Tomography promises to change that, and quantum dot superluminescent diodes have the potential to be the ideal technology for this application, says **Mark Hopkinson** from the **University of Sheffield, UK**.

Healthcare costs are in the spotlight. The US is wrestling with the proposed introduction of universal access and many other countries are looking at the financial burden of their burgeoning state-run systems.

Reducing the cost of diagnosis and improving treatment efficiency are areas of major focus. One of the largest increases in costs in recent years has been the use of diagnostic imaging tools such as ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI), access to which can cost several thousand dollars per examination. Diagnostic imaging based on relatively low cost photonics could be the answer in some applications.

Whilst not a direct replacement for tools like MRI, near surface photonic imaging techniques can have an important place within certain diagnostic schemes. Even for internal imaging where the lack of light penetration can be an issue, there is much invention to be gained using optical probes to bring the source light into the region to be interrogated. Furthermore, if the applications are intended to be used for diagnosis in vitro rather than in vivo, these restrictions are considerably relaxed, since then specimens can be prepared in which penetration depth is not an issue.

Non-contact near surface imaging of the skin or eye using Optical Coherence Tomography (OCT) is an example of a technique that has become popular both in the lab and in the clinic. It has gained considerable favour for its potential to provide two and three-dimensional real-time images of biological tissues with micron-like resolution. The technique can be described as an optical analog to ultrasound in which light is used instead to probe the variation of reflected light as a function of depth. Combined with areal scanning it is relatively easy to obtain useful cross sectional images of skin and tissue.

The basis of OCT is low-coherence interferometry in which a broadband source illuminates a Michelson interferometer. The system is very easy to implement in fibre and the ideal sources for such applications are the edge-emitting superluminescent diodes. The axial resolution of such systems is inversely proportional to the bandwidth of the source, which explains the strong desire for broadband sources.

Aside from fibre optic test equipment, the edge-emitting superluminescent diode has served relatively few applications over the years. But this device may well have found its niche as a broadband source in the near infrared (800-1300nm), the wavelength range most suited to the

OCT application. Companies such as Exalos, Superlum, and Inphenix have emerged as suppliers of sources for the emerging OCT supply chain. Yet these products are generally based on InP or GaAs-based quantum well technology, and realising a significantly wide broadband output from this class of device is very challenging. However following the lead from researchers in EPFL, who were later to found Exalos, we became interested in exploiting the properties of quantum dots for such applications and have been working on these devices within the European FP6 project 'Nano-UB sources' together with OCT technology partners.

Indium Gallium Arsenide quantum dots (QD's) have many useful properties for this application. They are naturally broadband, exhibiting a statistical variation in size and shape within a typical ensemble. In addition, under increasing carrier injection the QD ground state can saturate in favour of emission from a first, or subsequent excited states. Combining just the ground and first excited state (GS and ES) emissions can give a broadband output of typically around 100nm.

But there are two complicating factors. Firstly efforts have to be introduced to reduce the dip between emission states otherwise a multiple peaked image results in multiple or 'ghost' OCT images. This is done by introducing a variation into some of the quantum dot layers in the structure to progressively shift (or 'chirp') the emission. In the MBE growth that is carried out at the University of Sheffield, this is achieved by varying a structural parameter, usually the position of the QD within a surrounding quantum well.

The second problem with quantum dot structures is the relatively low gain. Gain values of 20-40cm⁻¹ are typical of multi-quantum dot active layers whilst a single InGaAs/InP

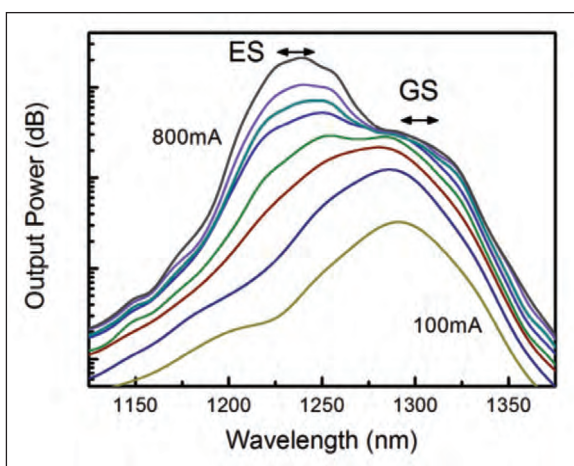


Figure 2: Spectral evolution of superluminescent diode output as a function of injection current

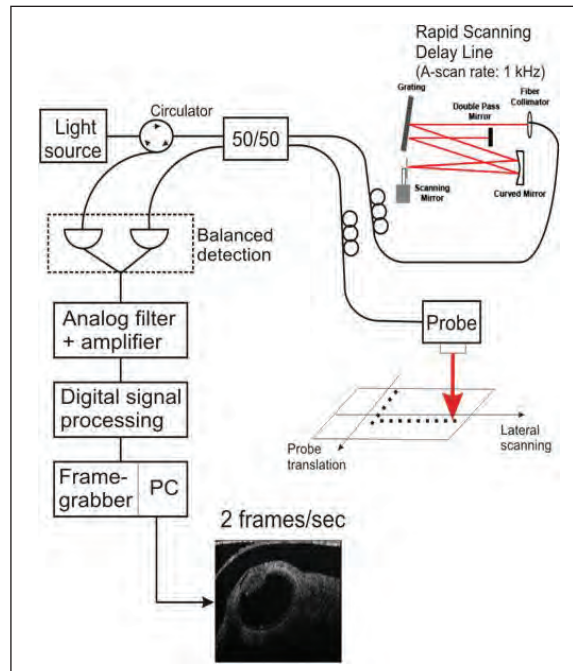


Figure 1: Optical Coherence Tomography Schematic

quantum well can offer 50-100cm⁻¹. Despite this, it is relatively easy to obtain low threshold and high power output from QD lasers because the losses can also be very low.

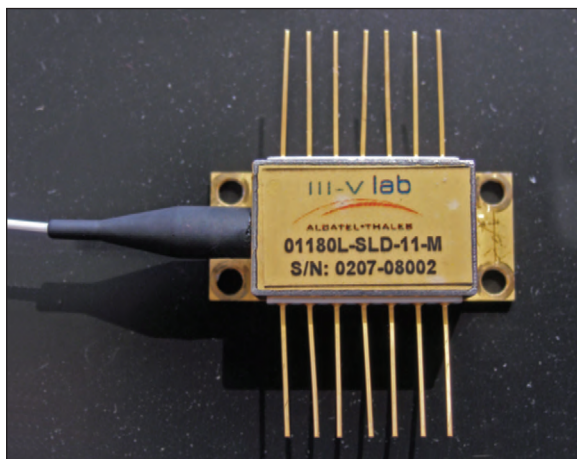
However the same is not true of superluminescent diodes which operate on single-pass amplification of spontaneous emission, rather than multi-pass feedback to induce stimulated emission. A quantum dot superluminescent diode is therefore a long device (typically 4-6mm) in comparison to a laser diode (1-2mm) and it needs to operate under higher injection and therefore higher thermal loading.

Project partners Alcatel-Thales III-V lab and Opticap Ltd have fabricated and packaged superluminescent diodes targeting two wavelengths, one an established market segment around 1300nm and one at the shorter wavelength of 1050nm which is more suitable for ophthalmology.

Output powers (ex-facet) of up to 160mW and bandwidths of 115nm have been observed, although it is hard to obtain high power and broad bandwidth at the same time. For the more commercially viable 1050nm devices, a more typical result would be the measurement of 130mW ex-facet and 65mW ex-fibre packaged from a device exhibiting ~70nm bandwidth. Such a device was exhibited by Alcatel-Thales III-V lab at the Munich CLEO-Europe meeting in 2009. The QD technology is very competitive against any other alternatives at this less developed wavelength.

Development of compact fibre-optic OCT diagnostic tools based on III-V quantum dot superluminescent diode sources has been undertaken by colleagues at the technical University of Denmark and the University of Cardiff. Two major markets exist within dermatology and ophthalmology, for which high power and broad bandwidth sources can give unprecedented enhancement in the ability to resolve the structural morphology of human tissue

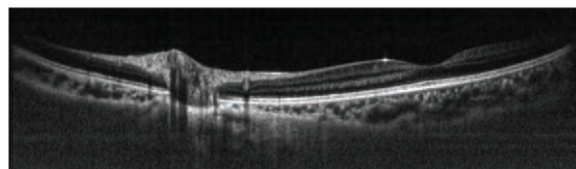
Figure 3: Fibre coupled superluminescent diode module developed by Alcatel-Thales III-V lab with project partners



Development of compact fibre-optic OCT diagnostic tools based on III-V quantum dot superluminescent diode sources has been undertaken by colleagues at the technical University of Denmark and the University of Cardiff. Two major markets exist within dermatology and ophthalmology, for which high power and broad bandwidth sources can give unprecedented enhancement in the ability to resolve the structural morphology of human tissue.

In one such example, a 3D OCT image of normal human retina, made up of 512 individual cross-sectional scans is shown right, together with that of a single scan below. The image shows the fovea (to the right), peripheral parts of the optic disc (to the left) and has good depth penetration into the retina as a consequence of the 1060nm centre wavelength of the source.

So what next for OCT? The medical advances are clear: in the hands of qualified medical clinicians, the technique is already playing a role in early-state cancer diagnosis in skin and in the monitoring of ocular diseases that are the world's leading causes of blindness. But the technology does not stand still and neither do the source requirements. Attention is now turning to high speed OCT scanning performed by a tuneable laser source rather than the movement of an interferometer mirror. Low cost,



widely sweeping sources need to be developed. Furthermore the benefits of multispectral imaging are now being realised by imaging with a linear array or even full 2D cameras. So as the application moves on, perhaps the simple superluminescent diode has had its day already. However broadband gain materials, such as quantum dots will play an important role in future devices for this application.

With thanks to project partners Peter Andersen, Wolfgang Drexler and Michel Krakowski. Interested researchers are encouraged to visit the website <http://www.nano-ub-sources.org> for further information.

It's been a roller coaster year for AkzoNobel's High Purity Metalorganics division. Orders in the first quarter were incredibly weak, but the return of a burgeoning LED industry and great solar prospects are strongly reviving the business.

Richard Stevenson talks to Michiel Floor, AkzoNobel's global business manager of these products, about this division's change in fortunes and other recent developments.

Rocketing LED manufacture spurs AkzoNobel's metalorganics division

Q The end of 2008 was a really tough time for substrate suppliers. Did your experience echo theirs?

A Our business was running strongly in 2008 until it fell off a cliff in mid-November. In the month after we felt the impact of low operating rates at many of our customers. They keep quite significant stocks of our products, and decided to live off this before re-ordering.

We had to quickly reduce costs wherever possible. One of our advantages is that we produce our metal-organic sources at a large plant in Texas, near Houston, and this is shared with our larger metalorganic manufacturing organization that sells metal alkyls to the polymer and pharmaceutical industries. That business suffered much less than ours, and we shared resources and reduced our cost base temporarily.

In the crisis - which lasted well into at least the second quarter of 2009 - we used the time to refocus on our own technology and manufacturing, and made good progress to start preparing for the growth that would come as the industry picked up.

Q How have sales from the high-purity metalorganics (HPMO) division fared since then?

A We saw extremely slow demand in the first quarter, but visibility recovered by the end of this period. Then orders came in, and we started shipping products again, but this was quite well into the second quarter 2009. The first signs of recovery, as always, were in Asia, and we started shipping products to them in May. I think it's remarkable how the LED industry has turned itself around. We talked to our customers in the first quarter - many were working part time, having reductions in labor force, and so on, and capacity was down in the 30-40 percent utilization level. Now most of our customers are buying new machines, and we've worked hard to get our share on the new tools. What we feel - based on what our customers tell us and what we hear from the tool vendors, Aixtron and Veeco - is that this trend will continue well into 2010 and very likely beyond.

Over the last few years AkzoNobel has increased the size of its metalorganic bubblers. Recent additions include a 20 Kg trimethyl gallium bubbler





Q Are sales to LED chipmakers a big part of your business?

A Yes, LEDs are by far the biggest market globally for any player in this industry. The other important markets for AkzoNobel are III-V solar cells, certain laser technologies, and a broader customer base of various device types.

Q Do you expect the company's metalorganics business to continue to thrive?

A I'm pretty excited about the outlook for the next few years. Strong demand in the backlit LED sector will continue. When the technology eventually reaches maturity and the market reaches saturation level, demand might level off again, but that is at least several years away because these technologies are still new. Products for netbook and laptop PCs are where the penetration is greatest, but these portable devices have a lot of potential for further growth. LED TVs are just beginning, and by the time the backlit sector has matured, the general lighting market will be much closer than it currently is. This will provide longer-term growth.

Q Are there local competitors to your metalorganic business in Asia, which are invisible on a global scale? And if they do exist, do they take a large chunk of their domestic markets?

A There are several local competitors in Japan, and there is also one Chinese competitor. Japan is a large market for LED production, and laser production is also very significant there. So they have, to an extent, a local supply of MO sources from their own companies.

We compete with these companies on a local basis. The way that we do this is to leverage our strengths from the manufacturing technologies that we have, and the scale of our operations.

Q Metal-organic suppliers are sandwiched between chipmakers demanding steadily falling prices, and a fluctuating materials market. How do you cope?

A We are, in a way, squeezed between what our raw material suppliers demand and what our chipmakers can afford, and the chip market is highly competitive with prices falling. However, as a chemical producer we have to strive for having a financial return that enables us to keep investing in the product line and keep extending our large bubbler fleet, so that we can support the future growth of customers and the industry. We need a certain return to keep our business viable.

Of course, the market demands high-quality, reliable products at competitive pricing to support growth in the LED industry. So what we've been doing over the past few years – and are still doing – is trying as aggressively as possible to control all our costs. But at some point you reach an asymptote, where not much can be squeezed out of the system any more. So the bottom line is that if our raw material costs increase – and the raw material costs are not an insignificant part of our total costs – then that needs to be reflected in the pricing of our products. This is not always easy, of course.

Q Some researchers have written papers that claim that the reserves of some metals, such as gallium and indium, will be depleted within a few years. What's your view on this?

A We are not as worried as the authors of the papers. We have looked at this at a corporate level, where we monitor all the key raw materials, and in the MO business, we approach this by working as closely as possible with our suppliers.

In the overall consumption of gallium and indium, the production of MO sources is a very small segment. This doesn't say anything about future capacity, but we are an almost insignificant part of total consumption. Take indium, for example. One of its largest uses is as a precursor for indium tin oxide layers in thin-film panels.

There are future uses of these chemicals that could have an impact, such as some of the solar technologies that are based on gallium and indium, and that could put pressure on the supply chain. We don't see that right

now, but it's an area that we continue to watch very closely.

Q What's your take on the terrestrial solar market?

A I think the terrestrial III-V solar cell market is real - there have been several projects underway, for example in Spain and Australia. This sector has continued to grow through the deepest part of the economic crisis, but it has been affected by difficulties to get financing. There are some delays in these projects, so momentum needs to be regained. What I see going forward is that III-V terrestrial will have its spot among the other solar cell technologies, and as it advances, it will need to compete on a cost per Watt basis with them.

Over the past couple of years competing technologies have developed that are based on traditional silicon solar cells - where we are not particularly active - and in thin films, which is basically glass that is coated with either an active layer of CIGS (copper indium gallium selenide), micro-crystalline silicon or amorphous silicon. This is an area of growth for us.

These panels always require conductive oxide layers that should be transparent to light - the so-called TCO-layer - and one of the technologies that can be used for this is based on zinc oxide. This can be applied by sputtering.

However, it is better to use an MOCVD process based on diethyl-zinc, because this gives a superior layer structure, particularly in the scattering of light into the active layer. We have become a major supplier of high purity "DEZn TCO" to this industry, which can use up to 20 tonnes per customer per year. That's a challenge. They want semiconductor-grade quality at bulk chemical pricing.

Q So are III-V chipmakers still your largest business?

A Right now they are, but the thin-film solar industry is about to take off. Many of these customers are in a ramp-up phase, and it will quite soon overtake the MO-III segment. It doesn't mean that we will neglect the MO-III part of the business - it is still very important, and there are technology synergies in the way we service both markets.

Q Silicon chipmakers are now looking to other materials to maintain the march of Moore's Law. Is this a market for you?

A We reassessed our business strategy in the middle of 2008, and we decided to focus on MO-III sources and dopants for the III-V industry, as well as DEZn for thin-film solar. We produce titanium, hafnium and zirconium metallocene-type chemicals in a plant in The Netherlands, but we have decided to not actively pursue the silicon market.

Q Environmental awareness of chemical pollution is greater than ever before. Does this affect the way you go about your business?

A AkzoNobel's approach is that sustainability offers us a business case to discriminate ourselves. At the corporate level this is getting significant attention. More specifically, in the HP MO business, our major impact on the environment is in the way in which we produce these chemicals. We see that there are actual benefits from producing these chemicals in the larger scale metal-alkyls production environment. We can maximize production synergies there, and we are well integrated with the raw materials, which is always efficient from an environmental point of view. We are also connected to the grid in the plant that provides pollution prevention and recycling systems.

Q Replacing an empty metalorganic source with a fresh one is a potentially dangerous activity. Are you working to reduce the chances of this process leading to a potentially lethal accident?

A Safety has always been AkzoNobel's number one priority and this is not about to change. We set firm targets for all of our businesses and continuously audit our operations. In the HP MO area we try to do as much safety education and training as possible on a one-on-one basis with our customers. We had a program to investigate which type of glove is most resistant to small droplets of MO sources. We found that leather gloves are by far the best to wear, which was not the industry practice. They provide chemical resistivity and thermal insulation.

What I feel myself, coming from my earlier jobs in AkzoNobel's bulk metal alkyl side of the business, is that

AkzoNobel's bubbler range includes Hiperquad and Hiperloop systems for TMIn (Trimethyl Indium) delivery that have a very stable flow and very high source utilization



What we've been doing quite actively over the last few years is to develop several larger style bubblers. We introduced a 7.3 Kg TMGa (Trimethyl Gallium) bubbler four or five years ago, which is offered with a heat exchanger that can be put in the existing cabinet of the tool. That bubbler brought us quite a lot of success

in this industry we still have a way to go in recognizing the hazards of these chemicals. To some extent clean room practices that are important for dust control conflict with what you would like to see from a metal alkyl safety perspective. If we transfer metal alkyls at our plant, we wear aluminized suits. This may seem overdone, but it is the only thing that really protects you against leakages. Of course, we handle larger amounts, but this practice hasn't really progressed into that of our users.

Q There seems a trend towards the production of larger and larger bubblers. Do you agree?

A That is absolutely true. What we've been doing quite actively over the last few years is to develop several larger style bubblers. We introduced a 7.3 Kg TMGa (Trimethyl Gallium) bubbler four or five years ago, which is offered with a heat exchanger that can be put in the existing cabinet of the tool. That bubbler brought us quite a lot of success.

We have now taken this one step further with the recent introduction of a 20 Kg bubbler. This can be used either in a central delivery set up, or directly in the tool, so we also adapted our heat-exchanger to fit this larger bubbler.

As the bubbler gets bigger, it gets harder to fit it into the cabinet. But we are working with a company called Noah Precision, which offers advanced thermo-electric chillers. They have a very small footprint, they avoid the use of the traditional open water baths, and they deliver very good temperature control with low maintenance. What we try and do with our new, larger-scale bubblers, is to offer the option that our customer buys it with a customized chiller. This enables them to put even larger bubblers in the cabinet.

There is also a growing interest in bulk central delivery systems, particularly in new fabs. We are able to offer such systems to our customers, building on our experience with bulk delivery of DEZn TCO.

Q What do else your customers want from you?

A If we focus on the LED sector, then our customers want to grow their LED business, which operates in a competitive environment. They need a very reliable supply of the MO sources, and quality consistency is also important. We believe that our relatively large batch sizes help in providing relatively good quality consistency.

In the end, pricing is always high on the agenda, and our major task is to keep supplying these chemicals at competitive prices. However, we also keep investing in bubbler innovations. We have the Hiperquad and Hiperloop systems for TMIn (Trimethyl Indium) delivery, that have a very stable flow and very high source utilization.

Typically, the TMIn flow drops off after 80 percent consumption. With these systems - which can increase the contact time between the carrier gas and the TMIn - the bubbler can be used up to 98 percent, and only then does it drop off. In that range we now offer two bigger sizes: 750g and 1500g.

An addition is a Hiperflo bubbler, a liquid bubbler technology that builds on the TMIn bubbler technology. We enhance the flow out of the bubbler, so it gives higher source utilization, and it allows faster growth, which is especially evident in lower vapor pressure sources like TEGa (Triethyl Gallium).



Michiel Floor, AkzoNobel's Global Business Manager for high-purity metalorganics, has a doctorate from Delft University, NL, in Chemical Technology.

He has been with AkzoNobel for 20 years, and first worked in metalorganics research and development at the Deventer labs in NL.

He has helped to market and develop the company's catalysts and metal organics, and has previously held the position of Commercial Manager in organic peroxides and polymer additives



Powerful infrared lasers promise a simpler, lightweight alternative to the systems for launching multiple flares, which is the current approach for deflecting heat-seeking anti-aircraft missiles. CREDIT: US Marine Corps

Pranalytica's novel design pushes up mid IR laser power

US researchers claim to have broken the record for the single facet output power from a quantum cascade laser (QCL).

The team from Pranalytica, Harvard University, and the University of California, Los Angeles, has fabricated a 4.6 μm QCL with a non-resonant extraction design that delivered 3W at 293K. The laser, which incorporates a highly strained InGaAs/AlInAs active region, produced a peak wall-plug efficiency of 12.7 percent.

Funding from the Defense Advanced Research Projects Agency (DARPA) assisted the development of this laser, which could aid directed infrared countermeasures, such as deflecting heat-seeking missiles. In addition, this QCL could aid free space optical communications and provide a battery-powered source for infrared target illumination.

Corresponding author Kumar Patel, who is Pranalytica's CEO, explains that the team's design differs from the majority of today's QCLs, which employ a two-phonon resonance approach. In this more common design, a radiative electron transition between upper and lower laser levels is followed by two consecutive, non-radiative transitions involving resonant interaction with longitudinal optical phonons.

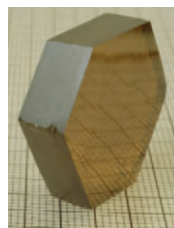
Patel says that this two-resonance condition leads to very fast removal of electrons from the lower laser level, preventing electrons backscattering into it. Stopping this from happening is beneficial, because it prevents a decrease in population inversion that would degrade laser performance. However, the penalty paid by this design is its lack of flexibility, because layer thicknesses in the active region are dictated by the resonance condition and the desired laser transition energy.

Pranalytica overcomes this weakness with a non-resonant extraction approach that uses parallel non-resonant transitions to realize fast carrier extraction from the lower laser level. Non-resonant transitions are slower than the resonant one, but multiple paths mean that the total lifetime in the lower laser level is essentially the same.

Two major benefits result from the non-resonant design, according to Patel: it enables higher continuous-wave output powers and wall-plug efficiencies; and it allows greater freedom in QCL design, which can also lead to improved performance. The researchers have also been

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Ammono produces hexagonal GaN crystals with excellent optical quality by the ammonothermal method.

Credit: Ammono

developing a low-reflectivity, Al_2O_3 coating for one of the facets, in order to increase wall plug efficiency. This adjustment, alongside the introduction of longer cavities, has led to the fabrication of a 1.1W QCL mounted on AlN that does not require cooling.

Micro-pixelated lamp combats current crowding

Nitek and Asif Khan's group at the University of South Carolina have fabricated a 42 mW lamp emitting at 280 nm.

This ultraviolet lamp is a promising source for air and water purification and polymer curing. "42 mW is certainly enough to purify water at the tap at a rate of about a gallon per minute," says Khan.

One of the challenges of making the chip was to overcome lateral current crowding, and this was addressed with a monolithic chip that contains 1600 micropixels, each with a diameter of 20 μm . Driven at an output power of 22 mW, this lamp has a lifetime of over 1500 hours.

Khan says that the team should be able to double the output power of the chip by optimizing the surface roughening of the chip.

Ammonothermal approach yields non-polar substrates

A Polish partnership has employed an ammonothermal growth method to produce non-polar GaN substrates with incredibly low threading dislocation densities (TDDs).

Development of high-quality non-polar substrates is seen as an important goal in the nitride community, because it enables the fabrication of optoelectronic devices that are free from the large internal electric fields that hamper electron-hole recombination in conventional LEDs and lasers.

Led by the Warsaw firm Ammono, this Polish team has produced m-plane substrates up to 11 mm by 22 mm in size that have a TDD below $5 \times 10^4 \text{ cm}^{-2}$. These substrates have fewer defects and are slightly larger in size than typical pieces produced by the leading commercial supplier of m-plane GaN, Mitsubishi Chemical, which produces its material by HVPE.

Ammono's substrate production begins by dissolving GaN-containing feedstock in ammonia in one zone of a high-pressure autoclave. A temperature gradient drives material to a second zone, leading to crystallization of GaN on native seeds, due to supersaturation of the solution. Measurements indicate that the quality of Ammono's material is excellent: X-ray diffraction spectra have peaks with a full-width half maximum below 20 arc seconds; optical microscopy reveals that the TDD in the

substrates and a 2 μm thick GaN epilayer deposited on them is below $5 \times 10^4 \text{ cm}^{-2}$; optical excitation experiments produce strong emission at 3.4 eV, indicating good optical quality; and reflectance measurements reveal the strong hexagonal symmetry of the crystals.

This ammonothermal approach also has the edge over HVPE in terms of the growth process, according to Ammono's Robert Dwilinski: "In HVPE, gases are flowing through the open reactor and only a small fraction of the raw materials is converted into the product. But with the ammonothermal method, thanks to recrystallization of polycrystalline GaN feedstock in a closed system, almost 100 percent of the raw material can be converted into the final product."

Dwilinski says that other strengths of the ammonothermal approach include lower growth temperatures that reduce energy consumption, easier reactor maintenance, and the scaleable nature of the process, which means that it is possible to grow hundreds of crystals in one run.

Ammono aims to lead the world in the development of ever-larger high-quality, non-polar substrates. "We can easily keep this position because our growth method can be scaled up to any thickness," says Dwilinski.

Calculations confirm the benefit of semi-polar planes for green emitters

Calculations by a US researcher have revealed why semi-polar planes of gallium nitride offer the best platform for growing green semiconductor lasers.

John Northrop from the Palo Alto Research Center performed first-principles calculations based on the chemical potential, which show that indium will incorporate in higher concentrations on the semi-polar (11 $\bar{2}$ 2) surface than the non-polar (10 $\bar{1}$ 0) surface.

Northrop says that he considered the chemical potential - which is the free-energy per atom for an atomic species - because it allows comparisons of energy between surfaces that have differing numbers of atoms.

He reached his conclusions by employing "fairly complex" code developed at the Fritz Haber Institute, Berlin, and calculating the indium chemical potential of (11 $\bar{2}$ 2) and (10 $\bar{1}$ 0) layers with various degrees of indium incorporation. These calculations included a low hydrogen chemical potential, a condition that is typically found in an MOCVD growth chamber.

So far, the longest emission wavelength for a nitride laser has been realized on the (20 $\bar{2}$ 1) plane.

Northrop is interested in these results that were produced by Sumitomo, but he has not performed calculations for that particular plane.

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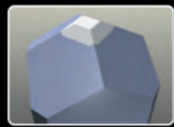
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