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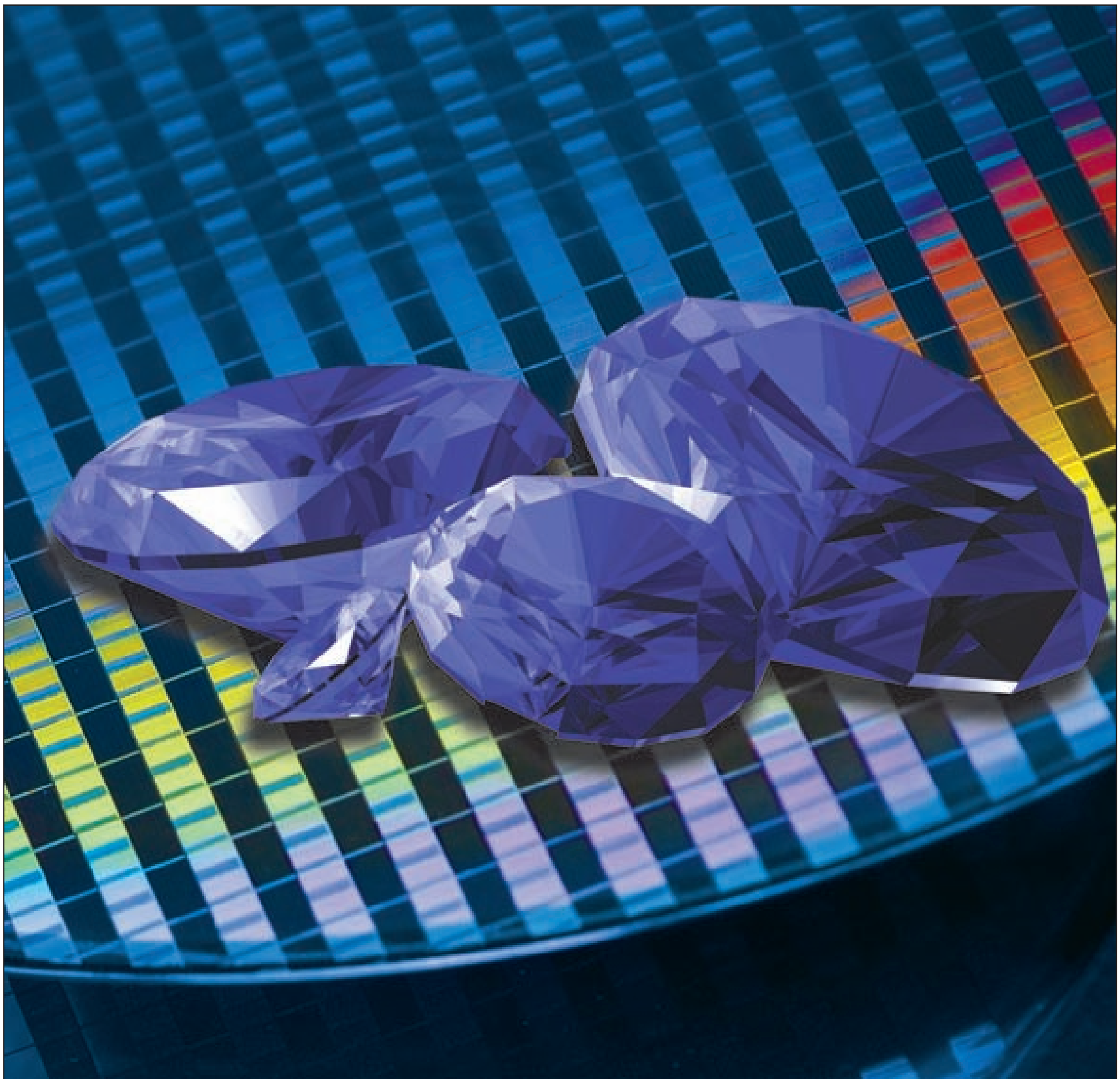
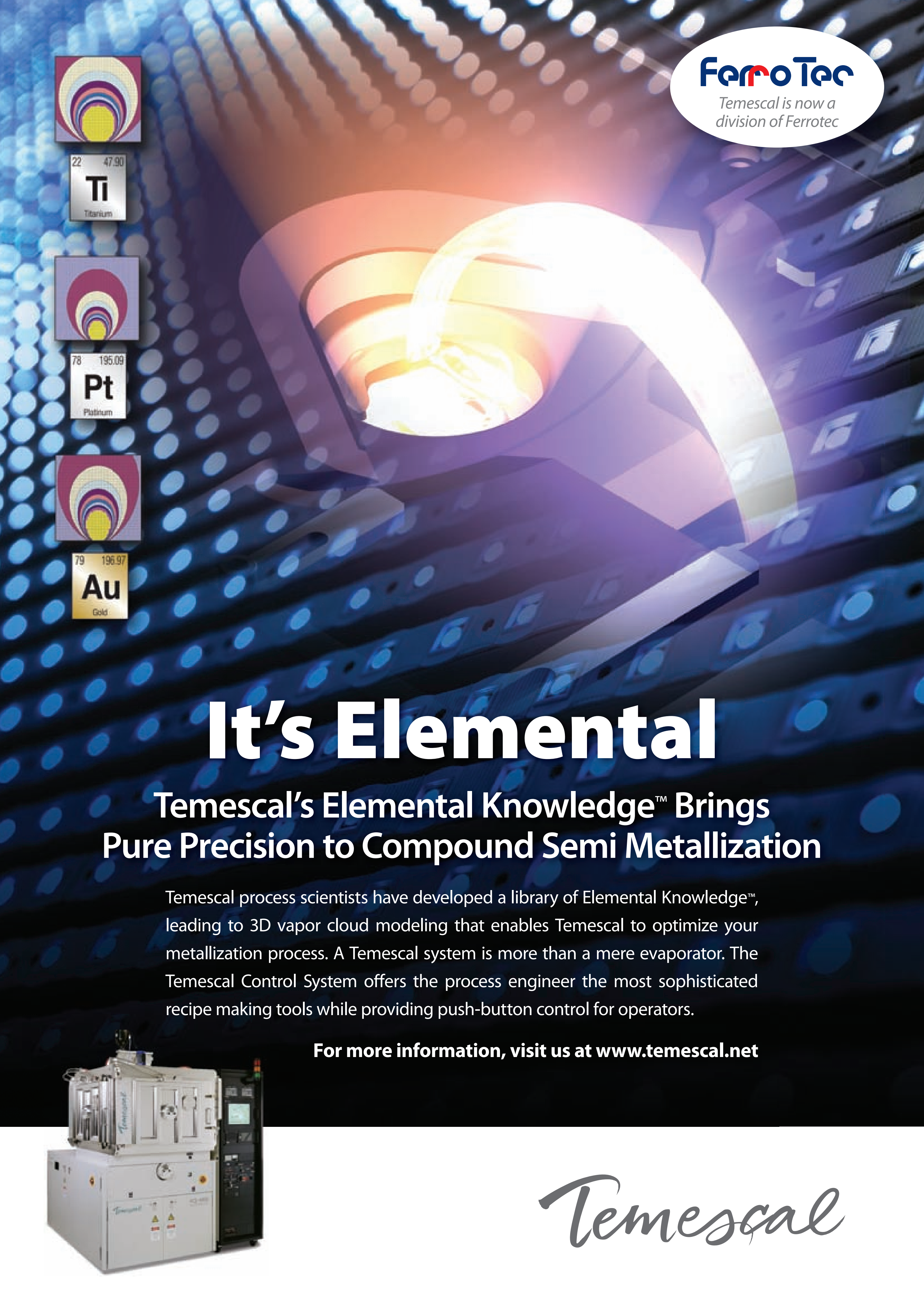


The right cut
Opportunities from new sapphire approach

An Angel Business Communications publication

April/May 2010 Volume 16 Number 3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Editor-in-Chief
David Ridsdale dr@angelbcl.co.uk
+44 (0)1923 690210

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

News Editor
Dr. Su Westwater suwestwater@angelbc.co.uk

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

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

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

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

Director of Logistics
Sharon Cowley sc@angelbcl.co.uk
+44 (0)1923 690200

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

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

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

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

Directors
Bill Dunlop Uprichard – CEO
Stephen Whitehurst – COO
Jan Smoothy – CFO
Haroon Malik, Jackie Cannon, Scott Adams, Sharon Cowley, Sukhi Bhadal

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

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

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Quantum cascade lasers shake off the R&D tag

The quantum cascade laser represents the pinnacle of bandgap engineering. By controlling of the thickness and composition of hundreds of very thin layers, engineers are able to tweak the wavefunctions of the electrons and holes that skitter through this structure, and ultimately fine-tune its emission.

Thanks to this control, quantum cascade lasers can span a range of wavelengths that are outside the grasp of their more conventional, III-V cousins. This includes vast swathes of the infrared spectrum with energies that can be used to probe the absorption lines of various gases, and far longer wavelengths close to a terahertz.

If powerful enough, easy-to-use and affordable quantum cascade lasers were available, then these sources would have a great chance of finding application in detecting gases, distracting heat-seeking missiles and aiding the construction of terahertz imaging systems. But for many years this class of laser, which was invented in the mid-1990s, has produced relatively feeble powers and been caged in a cryostat. But now the tide is turning …

In the Fall of 2008, this magazine covered the effort of Manijeh Razeghi's group at Northwestern University, which had realized continuous-wave outputs of more than one tenth of a Watt at room temperature.

Back then these researchers were starting to look at new devices geometries, such as those that incorporating a buried ridge. Initial efforts showed that refinements such as that could lead to outputs of several Watts. However, at that time of writing the output was multi-mode - no good for gas sensing.

More recently, the US firm Pranalytica has produced quantum cascade lasers that deliver several Watts at room temperature via single-mode emission. This advance has come through a radical change in the structure of the laser: a change in the way that phonons are used to help to drive electrons to their lowest energy level within the laser.

Like Razeghi and her co-workers, the team at Pranalytica have detailed their efforts in an exclusive feature for *Compound Semiconductor*. If you want to read about the details of this new type quantum cascade structure, and the performance that it has realized, you can find their feature on p. 22.

Richard Stevenson PhD
Consultant Editor

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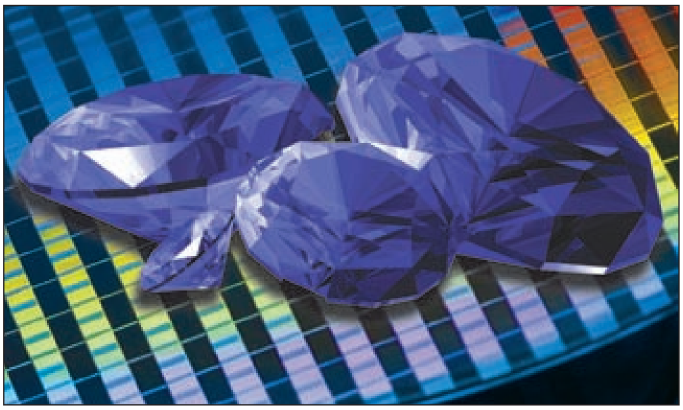


Flexible OLEDs from Fraunhofer

Low-cost, energy efficient lighting becomes tangible thanks to barrier coating systems for flexible OLEDs developed by Fraunhofer researchers. Organic light-emitting diodes (OLEDs) are nowadays synonymous with next generation lighting, which could replace common light-bulbs in a couple of years. They convert electricity very efficiently into light of high quality. However, existing OLEDs on the market are costly and mostly deposited on rigid materials such as glass.

Scientists from two Fraunhofer Institutes in Germany assembled flexible, large-area organic light-emitting diodes with barrier layer systems which are necessary for long device lifetimes. The Fraunhofer Institute for Photonic Microsystems IPMS and the Fraunhofer Institute for Electron Beam and Plasma Technology FEP for the first time manufactured a flexible OLED in a roll-to-roll production and encapsulated the device in a subsequent inline-process. This process design would allow the production in a single plant. The steps were developed in the frame of the project ROLLEX, funded by the German federal ministry of education and research (BMBF).

Professor Karl Leo, director of the Fraunhofer IPMS, confirms: “The successful assembly of an OLED in a roll-to-roll process means a breakthrough on the way to highly efficient and competitive devices. The project shows the capacity of Dresden as a focal point for organic electronics.”

A major component of flexible organic LEDs is the homogenous encapsulation of luminescent layers with transparent barrier layer systems. Permeation of only small amounts of humidity or oxygen shortens the lifetime of the devices drastically, which explains the strong need for barrier systems protecting the luminescent materials on a large area without defects.

However, the barrier layers should not absorb the emitted light and should not interfere with the colours of the light. The researchers of the Fraunhofer Institutes deposited OLED materials on a cheap aluminium foil in a roll-to-roll pilot plant, further encapsulated the luminescent foil with a barrier layer system, patented by the Fraunhofer FEP, without compromising its luminosity.

Dr. Christian May, head of the business unit, Organic Materials and Systems at the Fraunhofer IPMS stated, “Developing the flexible OLED, experience from both institutes has been united. We integrated the barrier layer systems from Fraunhofer FEP into technology of the IPMS.”

Dr. Nicolas Schiller, head of the business unit Coating of Flexible Products at the FEP adds, “The coating processes opens up potential to reduce costs.”

The technology developed marks a milestone towards industrial manufacturing of flexible OLEDs. Other devices, such as organic solar cells or memory systems, could be developed. The work is going to be continued in a larger consortium.

euroLED - Europe's leading event in Solid State Lighting!

This event will be the 7th annual euroLED consisting of conference, exhibition and gala dinner.

euroLED 2010 will continue to promote the global LED industry, developing themes of future lighting, intelligent energy and the influencers of the low carbon economy . This event supports future Birmingham Science Park Aston's focus on innovation to help drive the knowledge economy.

euroLED 2009 provided an impressive array of new approaches in solving technical challenges and 2010 is expected to offer much more. LED based technology is being increasingly viewed as significant segment within energy efficient "Clean Technology" sector, by addressing environmental issues.

The market had significant changes since 2009, with niche high value applications attracting collaborative R&D with products in illumination and lighting currently competing in a $2Bn market. Driving innovation forward in the LED industry are organisations such as Philips Lighting, OSRAM – Future Lighting - Everlight – Anglia – MARL – and Arrow all premier sponsors of euroLED 2010.
New to euroLED 2010 is the Conference Expert Panel, whose members have a wealth of commercial and technical expertise.

The Panel comprises Lee Bensley (Philips Lighting), Geoff Williams (Thorn Lighting), Jon Potter (Future Lighting), Dr Gareth Jones (PPE/KTN), Paul Drosihn (Arrow Lighting) and Dan Scott (Anglia Lighting).

The euroLED 2010 conference showcase current innovation; look forward to next generation products and also identify future development opportunities for the industry.

Key attractions:

- Conference showcases innovation for lighting industry with a highly respected Expert Panel.
- Extended exhibition space from 2009.

As well as the premier sponsors, euroLED exhibitors includes The Bergquist Company, Forge Europa, Carclo, Silica and Farnell.

On 9th June 2010 the industry will be invited to the Gala Dinner which attracted 220 international delegates last year.
ACDC will be showcasing their Double Decker LED Bus suitable for networking area for delegates.

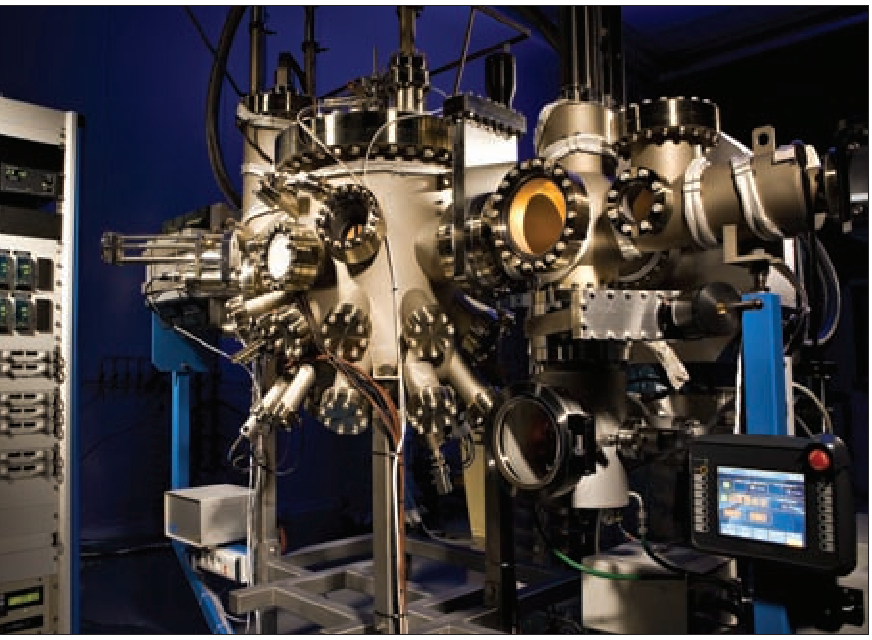
euroLED is being supported by The Lighting Industry Federation & The Lighting Association, who will be hosting seminars / workshops in the exhibition arena over the two days.

UKTI are supporting the show with a 1 to 1 meetings area for UK industries to discuss ambitions and strategic direction.

To participate in euroLED 2010, please visit the official euroLED website: www.euroLED.org.uk or contact Eve Gaut, euroLED Manager at eveg@bsp-a.com or on +44 (0) 121 250 3515.

Achieving GaN heights

Riber is a French company that has evolved into the leading suppliers of Molecular Beam Epitaxy (MBE) for the Gallium Nitride (GaN) industry. **Michel Picault, Marketing Director and Pierre Bouchaib, Sales Director of Riber** spoke to Compound Semiconductor about the outlook for the industry and for their company.



Q Riber states they are a world leader in MBE products. Why do you think this is true and will an increase in application demand for GaN encourage new players aiming for some of your market share?

A Riber is the world leader in MBE with more than 50% of the market share on a yearly basis with twice as many installed tools than the next competitor. This has been the case since MBE began in the 1970's. Riber's customer base is evenly distributed across global regions with around 30% in each. Riber offers the widest range of MBE systems covering diverse applications (IIIV, II VI, ZnO) and usages (R&D , pilot line and Production). We have preferred Ammonia Nitride production instead of RF plasma although we have such systems in the field. The Ammonia Nitride approach allows 3 to 5 times higher growth speeds which is crucial for a customer's costs. There are few competitors at present and Riber's experience makes it difficult for new players.

Q Why is GaN so important across such a wide range of communities eg LEDs, solar, community access television components (CATV)?

A GaN for LED is unique in its ability to produce blue light that can be converted to white light. GaN for CATV enables high power in a range of microwave frequency spectrums, for transmission across a wide band. GaN for Solar can capture green and blue light from the solar spectrum increasing the energy captured for higher currents in the PV cell. In RF and diode devices GaN can sustain high voltage for new devices required for power electronics in electrical or hybrid cars (900 volts). In any electrical car at least 5 to 7 heavy duty diodes or IC's made out of GaN are necessary.

Q what is Compact21 is and why was it funded by the European Community (EC)?

A Compact21 is a research laboratory working on MBE with a goal to improve manufacturing of monocrystaline films of compound semiconductor materials used in microwave, optoelectronic and sensing applications. Funding was received through a EC R&D programme because GaN is viewed as an enabler for future microwave and lasers devices.

Q Some industry analysts expect a bottleneck in MOCVD tools that may impact on the HB LED supply. Do you think this could be a problem in?

A There might be tensions in MOCVD supply, and some end-users might consider developing their own tools, but supply will ultimately catch-up demand.

Q Why is your MBE system more competitive than those produced by your rivals and what does 2010 hold for Riber?

A This depends upon application. For the GaN LED market, MOCVD is a better choice. Compared to other MBE systems our GaN Systems have proven to produce good GaN structures (Mainly in RF) over large substrate in a real production environment. We believe 2010 will be a good year in terms of R&D MBE Systems but also in production systems sales. We will continue to increase our MBE market while diversifying into breakthrough technologies such as OLED and CIGS for our effusion cells.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CIGS - Efficiences near 16%

A Japanese team of scientists have demonstrated the world's highest photovoltaic energy conversion efficiency among monolithically integrated flexible solar cell submodules (certified efficiency) of 15.9 % (aperture area: 75.7 cm^2) using a CIGS thin film (a solar cell material).

Lightweight and flexible solar cells are attracting attention as a key technology for wider use of photovoltaic power generation; we can expect wider applications because they can be installed even at locations where current solar cell panel modules cannot be installed. However, it was extremely difficult to obtain photovoltaic energy conversion efficiency higher than 10 % in a flexible solar cell module of an integrated structure.

They have worked on the technical challenges of alkali addition control and integration processes, and succeeded in drastically enhancing the photovoltaic energy conversion efficiency of an integrated-type flexible CIGS solar cell using a submodule-size substrate of the practical use level.

The result of this important study will be published in the 57th Spring Meeting, 2010, of The Japan Society of Applied Physics, held at Shonan Campus, Tokai University, in March , 2010, and at the 35th IEEE Photovoltaic Specialists Conference to be held in June, 2010 where the scientists wioll present their findings.

Cambrios and Ascent Announce collaboration on Solar Power

Ascent Solar Technologies is a developer of flexible thin-film photovoltaic modules while Cambrios uses nanotechnology to simplify electronic materials manufacturing processes and improve end-product performance. Ascent says it will investigate whether its Copper-Indium-Gallium-Selenium (CIGS) photovoltaics thin-film solar modules can be used with Cambrios' ClearOhm coatings. ClearOhm films produce a transparent, conductive film by wet processing are alleged to have improved properties by comparison to traditional transparent conductive oxides.

Although CIGS solar cells are not as efficient as crystalline silicon solar cells they are expected to be substantially cheaper due to the much lower material cost and potentially lower fabrication cost. Another advantage of CIGS over crystalline silicon is that they have a direct bandgap and thus require much thinner layers to absorb the same amount of light.

"Ascent Solar has very high efficiency CIGS solar cells so they are the perfect partner for this program," Cambrios Chief Executive Officer Michael Knapp said in a statement.

Leti shows off new CMOS laser

Letihas announced that it has demonstrated a fully CMOS-compatible laser source coupled to a silicon waveguide, a major milestone toward the WADIMOS project's goal of fabricating silicon photonics circuits in CMOS foundries.

WADIMOS is an EU-funded research project to demonstrate a photonic interconnect layer on CMOS. Leti's partners in the project, which is coordinated by Imec, include STMicroelectronics, MAPPER Lithography, the Lyon Institute of Nanotechnology (ILN) and the University of Trento.

Working with a circuit design from INL and Imec, Leti completed the specific process studies for the laser source to adapt and modify standard III-V materials process steps that would comply with a CMOS environment. Leti replaced gold-based metal contacts with a Ti/TiN/AlCu metal stack. WADIMOS partners at SPIE Photonics Europe 2010 in Brussels will present the results, April 12-16.

The enormous computing power of multi-processor systems and manufacturing tools being considered will require data transfer rates of more than 100Terabit/s.

These data rates may be needed on-chip, e.g. in multi-core processors, which are expected to require total on-chip data rates of up to 100TB/s by 2015, or off-chip, e.g. in short-distance data interconnects, requiring up to 100TB/s over a distance of 10-100 meters. Optical interconnects are the only viable technology for transmitting these amounts of data.

Besides a huge data rate, optical interconnects also allow for additional flexibility through the use of wavelength division multiplexing. This feature may be help realize more intelligent interconnect systems such as the optical network-on-chip system that the WADIMOS project also is studying.

WADIMOS, which is an abbreviation for Wavelength Division Multiplexed Photonic Layer on CMOS, will build a complex photonic interconnect layer incorporating multi-channel microsources, microdetectors and different advanced wavelength routing functions directly integrated with electronic driver circuits. It also will demonstrate the application of the electro-photonic ICs in an on-chip optical network and a terabit optical datalink.

GaN market 'poised for growth'

GaN products could soon see a growing demand for use in low-power applications. The market for gallium nitride (GaN) products could be set to take off in the months ahead due to an increasing demand for chips produced using this compound semiconductor.

With applications in mobile handsets, wireless communications, servers and notebooks, GaN-based chips are likely to see a significant boost in demand due to the low-power benefits they offer, Chip Design Mag reported in a recent blog by Ann Mutschler.

"The benefits of GaN in low power are density, efficiency and cost. Ultimately, it gives you a better trade-off for all three of those compared to silicon and the key is to make it below a certain cost threshold," commented Tim McDonald, vice-president of the emerging technologies group at International Rectifier.

Elsewhere, International Rectifier announced it has opened a new manufacturing facility in San Jose where it will be focusing on the production of GaN and silicon materials for use in space, aerospace, military and heavy-duty industrial applications.

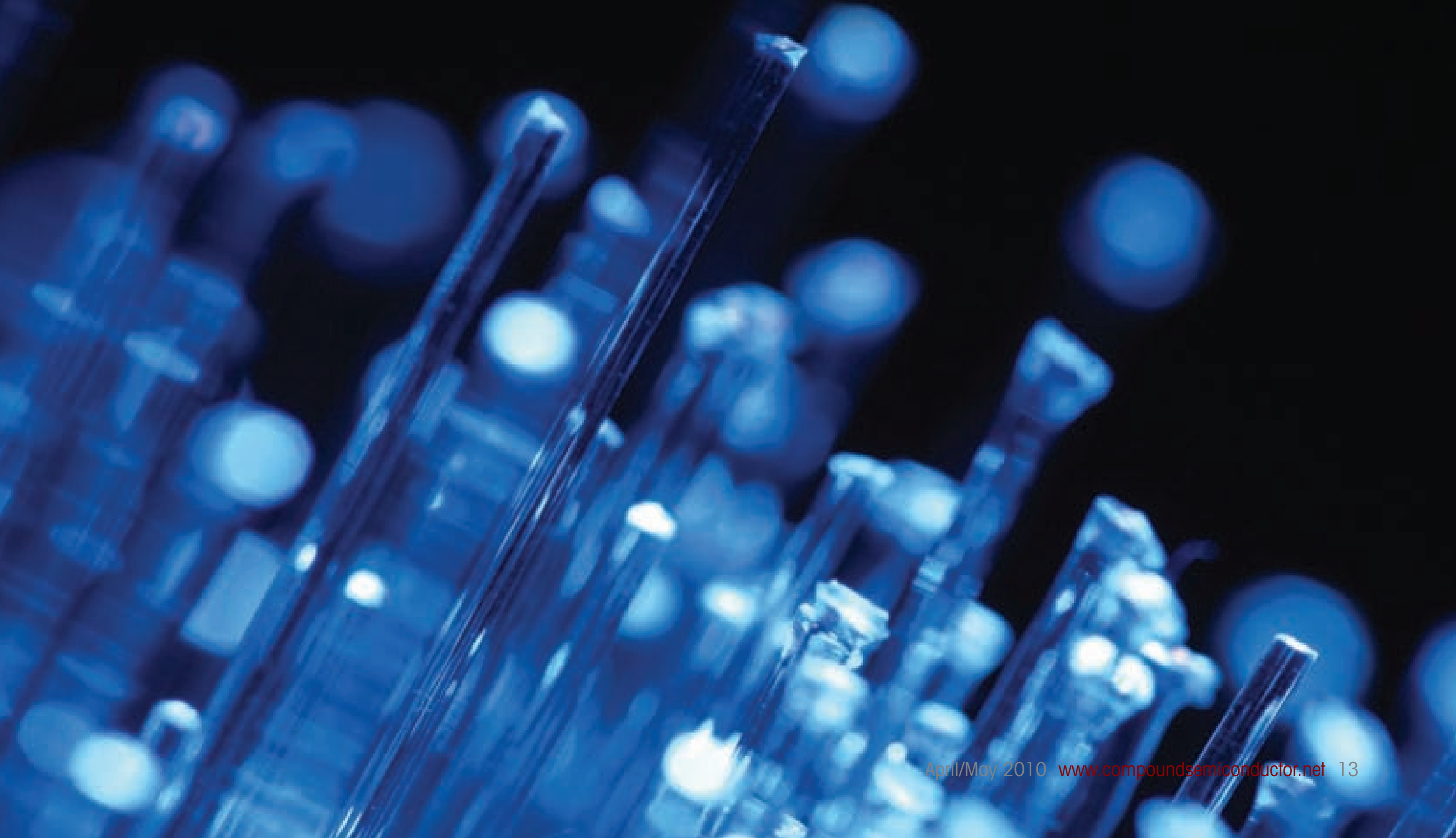
Optical switching: faster, smaller, and more frugal

Optical switches need to consume less power, cut their footprint and speed up if they are to stand a good chance of serving tomorrow's optical networks and PC infrastructure. One way to realize all this and more is to turn to switches that employ microdisk or photonic crystal lasers, according to a **European Research team.**

Network traffic is rising, driven in the main by a rise in internet traffic. This had led to an increase in the transmission of data-packets, which contain a header section with address information, plus a payload detailing information content.

To cope with increases in data transfer, system manufacturers are developing electronic packet switches. But these packet switches are a short-term fix: they are power hungry and they are not suited to scaling to higher bit rates. Turning to photonic packet switching could address these issues, and it has another benefit too – it is the only technology that can realize packet switching at ultrahigh bit rates.

Photonic packet switching could also aid other applications, particularly computing. Optical technology is already being deployed in ever-shorter links, and in the future there is a high likelihood that this will be used to boost the bandwidth and power efficiency in computers. The next step after this will be progression from simply the transportation of data in the optical domain to its manipulation too. This will deliver a massive pay-off, because it will eliminate the need for conversion between the electrical and optical domains. Thanks to the promise of optical switching in various applications, several research groups have been looking seriously at this technology for about a decade. During this time researchers have realized



one of the major weaknesses of all-optical packet switching is the omission of large optical random access memories, which are needed for buffering. Efforts have tended to focus on realizing buffering through various delay lines, such as slow-light waveguides, and re-circulating fiber loops. However, buffering times have to be relatively short if the signal is not to be degraded by attenuation or distortion. There are also concerns relating to the footprint and power consumption of delay-line-based buffers. This has led to the need to compromise between the different figures of merit. To make matters worse, other devices for optical switching and routing, such as wavelength converters, are usually based on one or more semiconductor optical amplifiers with a large power consumption and a substantial footprint. And to top it all, it is extremely difficult and unpractical to integrate several switches, delay line buffers, wavelength converters and gates together into practically useable photonic integrated circuits (PICs) for optical packet switching. However, despite these challenges, progress is being made, thanks in part to recent developments in heterogeneous integration of InP-based devices onto silicon-on-insulator (SOI) passive circuits, and small, low-power lasers that can be achieved using this approach.

Our European team is capitalizing on this success and developing low-power, small-footprint PICs for all-optical packet switching through a project called HISTORIC – heterogeneous InP-on-silicon technology for optical routing and logic. This program, which kicked off in July

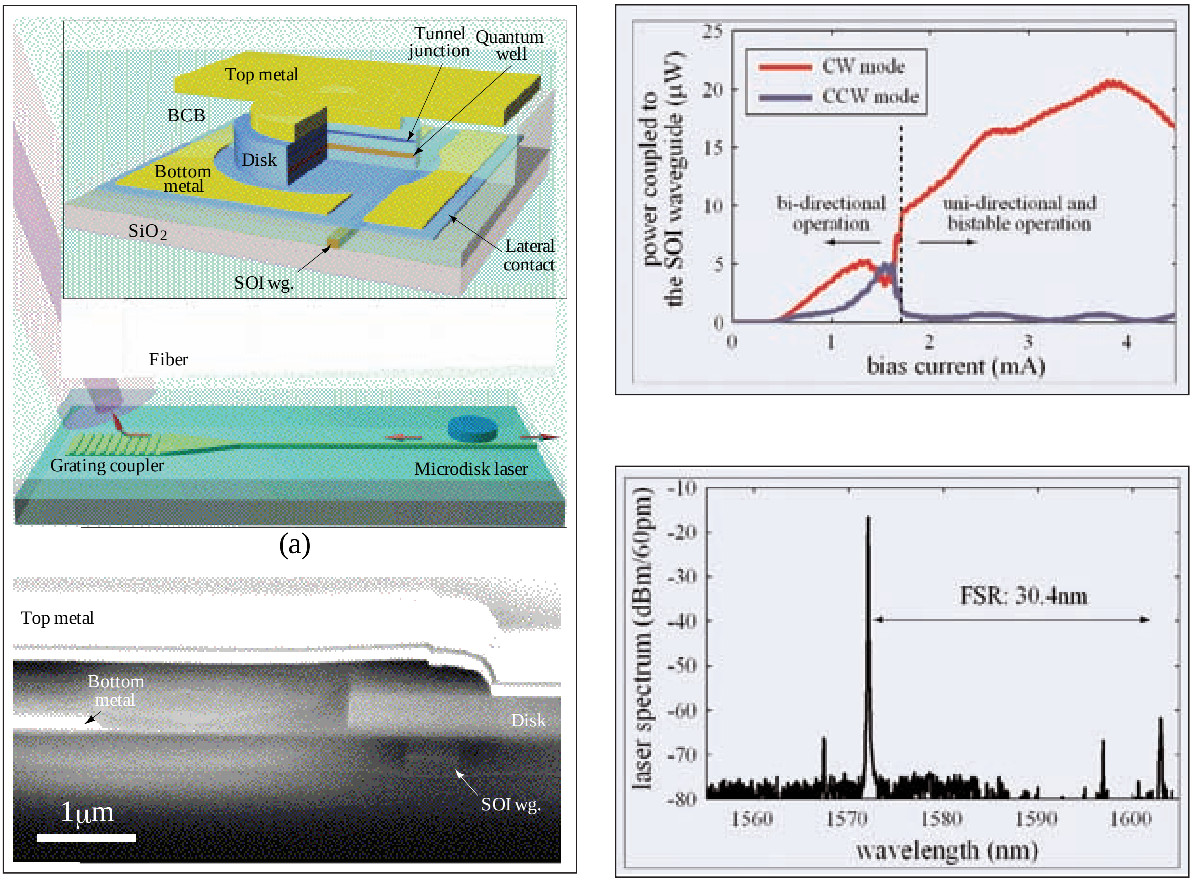


*Figure 1. Microdisk lasers could provide a key building block for next-generation optical switches that set a new benchmark for speed, low-power consumption, and a small footprint. These tiny lasers are united with silicon-on-insulator waveguides, with coupling provided by a grating coupler (a). A scanning electron microscopy image reveals the various layers in the structure (b). Light-voltage curves show the two competing modes produced by the microdisk laser, which has a 7.5 µm diameter (c). Lasing spectrum for the CW mode at a bias of 3.8 mA (d) . All powers are calculated inside the SOI waveguide by taking into account the coupling efficiency of the grating coupler. (From: L. Liu, et al,, 'An ultra-small, low power all-optical flip-flop memory on a silicon chip', Nature Photonics, ISSN , 1749-4885, **4** 182-187, March 2010)*

2008 and has 2.3 million Euros of funding from the European Union, is a two-pronged effort: PICs comprising microdisk lasers and resonators; and photonic-crystal-based lasers heterogeneously integrated onto SOI wafers and interconnected by silicon wire waveguides.

Four partners are involved in the project: imec-Ghent University, Belgium, which is acting as the coordinator; CNRS-LPN (Laboratory of Photonics and Nanostructures), France; the Technical University Eindhoven (TUe), the Netherlands; and IBM Zurich Research Labs, Switzerland. All partners are collaborating on the design of the PICs.

The fabrication and technological development of the microdisk-based PICs is taking place in the clean rooms of imec-Ghent University, while the facilities at CNRS-LPN and TUe are being used to create photonic crystal-based PICs. The PICs are to be used by IBM and the systems group at TUe to perform the systems experiments and evaluate the quality of various architectures.

For the individual building blocks, such as the all-optical flip-flops and gates, a footprint of less than 200 μm^2 is targeted. Scaling to these device dimensions should lead to record low switching times of tens of picoseconds and switching energies below 10 fJ.
Together with the small footprint and low propagation loss in the silicon wire waveguides, this promises to create optical packet switches with competitive speeds and very low power consumption.

Tiny lasers

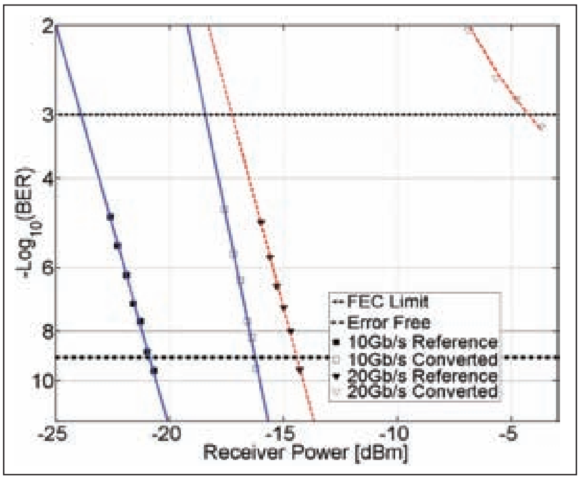


Figure 2. The microdisk laser wavelength converter has a higher bit-error-rate at 20 Gbit/s

Major strides in this direction were made in the first year of the project. This included the fabrication of 7.5 μm diameter, microdisk-lasers that form all-optical flip-flops, which were coupled to silicon wire waveguides (Fig. 1). This is the first electrically pumped, all-optical flip-flop on silicon fabricated using CMOS technology (a detailed report is provided in our *Nature Photonics* paper published earlier this year). Switching occurs between predominant clockwise and anticlockwise lasers modes, and can be realized with switching times and energies of just 60 ps and 1.8 fJ.

The threshold current of our microdisk lasers is only 0.33 mA. Between threshold and 1.7mA these lasers have two competing modes, but at a higher drive current they are

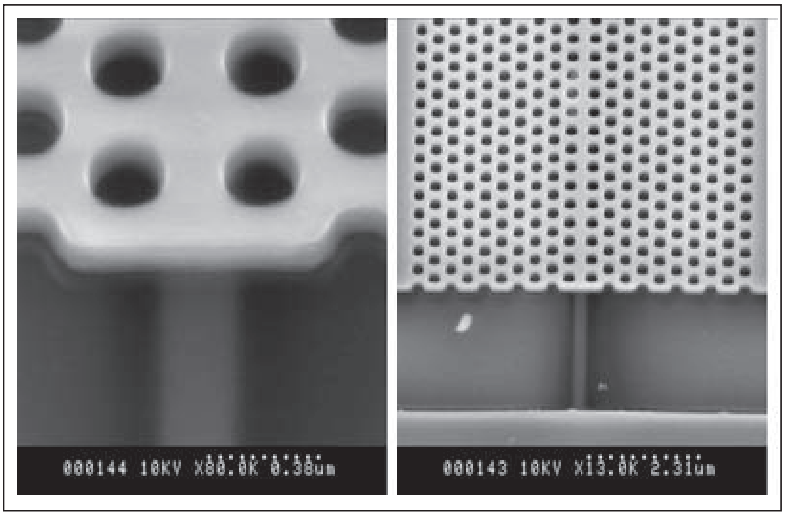


Figure 3. Scanning electron microscopy images show the alignment of the InP photonic crystal to the silicon waveguide

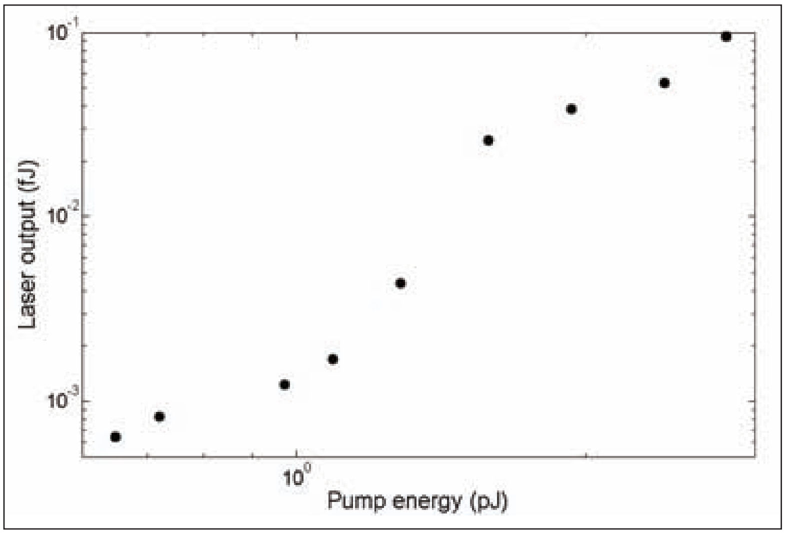


Figure 4. The photonic crystal laser can realize lasing via optical pumping

bi-stable (see Fig. 1). A further reduction of the threshold current and the operating current (at which bi-stability is obtained) should be possible by shrinking disk dimensions, increasing the current injection efficiency, and cutting the various reflections that lead to coupling between clockwise and counter clockwise modes.
The same disk lasers that are used as all-optical flip-flop memories have also been demonstrated as all-optical gates and all-optical wavelength converters, which currently operate at up to 20 Gbit/s. The small footprint and lower power consumption associated with microdisk lasers enables a new level of performance, in terms of Gbit/s/mW μm^2. The bit error rate for this technology is suitable for the target applications (see Fig. 2). At a 10 Gbit/s speed the converter operates error free, and at 20Gbit/s the bit error rate is below 10^{-3}, which is considered sufficient for systems employing forward error correction. All these results were presented in more detail at the 2010 Optical Fiber Communications Conference.
A further success of HISTORIC is the fabrication of the first InP-membrane photonic crystal laser heterogeneously integrated onto SOI. This novel device holds the key to a step-change in the performance of an all-optical flip-flop. Microdisk-laser-based, all-optical flip-flops promise to deliver power consumption below 1 mW, combined with switching energies of a few fJ and a footprint of just a few hundred microns squared. But equivalents based on photonic crystal lasers should realize power consumptions that are an order of magnitude lower, alongside a footprint of just a few tens of microns squared.

Efforts directed at fabricating photonic crystal lasers heterogeneously integrated onto SOI are being led by CNRS-LPN and TUe. LPN has so far concentrated on the coupling of photonic crystal lasers to photonic circuits implemented in SOI. Coupling is tough, due to the very small mode size of the photonic crystal lasers, but the first InP-based photonic crystal lasers heterogeneously integrated onto silicon-on-insulator have been demonstrated (see fig. 3).

Pumping the lasers with short pulses from a titanium-sapphire source produces lasing. Emission from the photonic crystal lasers was coupled evanescently into single-mode silicon waveguides (see fig. 4). Coupling to single mode fiber was, just as for the microdisk lasers, realized with surface grating couplers.

The TUe is focusing on electrical pumping of InP-membranes with a thickness of less than 200 nm. The key to this approach is micro-scale integration of active and passive components with a transparent, high-resistance layer. This layer is in the center of the membrane, outside the active region, and it acts as a current-blocking layer between the n and p-type contact layers. By employing a current-blocking layer everywhere except in the active region, it is possible to create an "electrical pin-hole" for funneling all the current flow through the region. This design enables the electrodes to be placed far enough from the laser cavity, with an efficient current injection in the active region.

Future goals for the HISTORIC project include: the fabrication and testing of PICs implementing combinatorial logic such as NAND, XOR, and other gates; and sequential logic such as D-latches or optical shift registers. IBM, TUe and IMEC have already conceived several inventive designs for all-optical logic circuits, making use of interconnect microdisk lasers and gates. These components should be ready within a matter of weeks, and will be tested extensively in the following months. If progress goes according to plan, this will pave the way for the realization of large-scale, low-power, small footprint PICs for all–optical packet switching and routing.

This article was written by the HISTORIC project team.

SiGe finds a fantastic home on sapphire

Sapphire can form the bedrock for the growth of relatively thick, single crystal epitaxial films of rhombohedral SiGe. This material has much higher carrier mobility than single crystal silicon, and could spur the development of ultra-fast chipsets, say **Yeonjoo Park and Sang Choi from NASA Langley Research Center.**

Band-gap engineering is one of the most important guidelines to design new semiconductor alloys and devices. For the last 60 years, two important semiconductor alloy engineering models were developed for band-gap engineering; the cubic crystal structure model shown in Figure 1-(a) and hexagonal crystal structure model shown in Figure 1-(b). The first cubic crystal model includes group IV semiconductors (Si,Ge,C) of diamond structure, and group III-V (GaAs, InP, etc.) and group II-VI (ZnSe, CdTe, etc.) semiconductors of cubic zinc-blende structure. The second hexagonal crystal model includes III-Nitride semiconductors (GaN, AlN, InGaN, etc.) and hexagonal SiC semiconductors.

Our team at NASA Langley Research Center proposed and proved that a third alloy engineering model - "rhombohedral-trigonal crystal model" - can be established between the cubic one and hexagonal one. A simple diagram of rhombohedral-trigonal crystal model is shown in Figure 1-(c). In details of the new model, a general cubic crystal is not only a special case of tetragonal crystal but also a special case of a rhombohedral crystal with inter-planar angle of 90°. When a cubic crystal is strained in the [111] direction, it becomes a rhombohedron. Thus, a cubic crystal belongs to a rhombohedral crystal group.

Additional mathematical transformation equation transforms any rhombohedral crystal into a trigonal crystal in hexagonal frame. Therefore, cubic crystals belong to a more general trigonal crystal group and the epitaxy between cubic crystals and trigonal crystals can be established not as an accidental coincidence-lattice-matching but as a fundamental crystal symmetry relation. Figure 1-(d) shows such an example of rhombohedrally aligned cubic SiGe on trigonal c-plane sapphire. The problem of this epitaxy is that two crystal structures which are twin to each other can be formed as shown in Figure 1-(e), the top view. This twin defect was a major problem in the rhombohedral epitaxy and has hindered further applications so far.

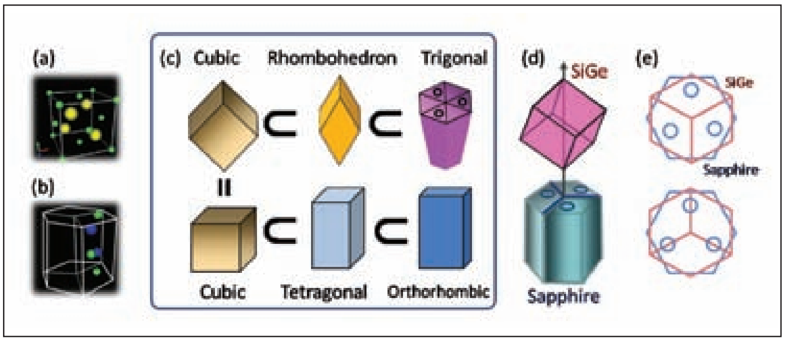


Figure 1. Crystal structure of (a) cubic zinc-blende or diamond structure, (b) hexagonal Wurtzite structure, (c) crystal symmetry group relation, (d) Rhombohedrally aligned SiGe on c-plane Sapphire, (e) two possible alignments of SiGe on trigonal c-plane Sapphire, twin to each other

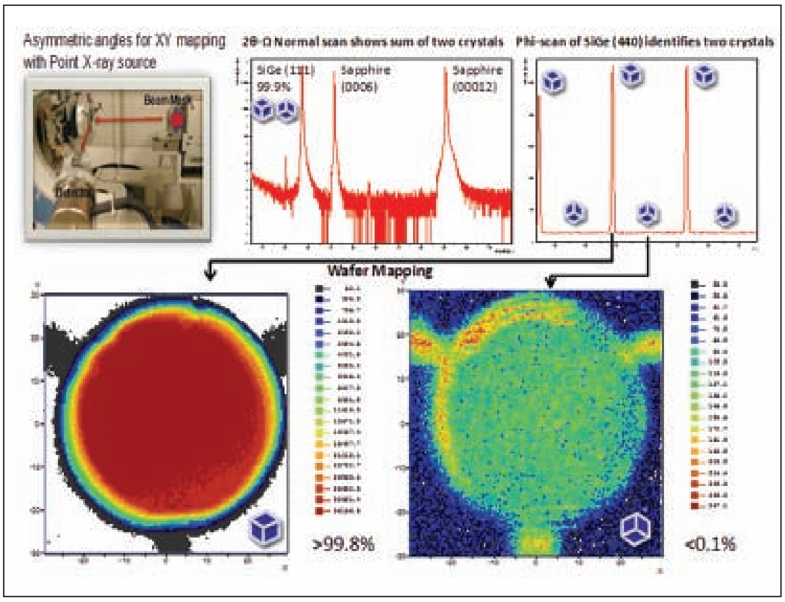


Figure 2. Innovative patented XRD methods characterize integral density and spatial distribution of twin defects

However, we found that optimized growth under new X-ray diffraction (XRD) characterization can eliminate twin defect and form single crystalline rhombohedral SiGe layer on c-plane sapphire in one of the crystal alignment of Figure 1-(e). This is because threefold symmetry of a trigonal crystal prefers one rhombohedrally aligned cubic crystal to the other. Thus, a symmetry breaking occurs between two cubic crystals that are rotated by 60° from each other, i.e. one cubic crystal becomes dominant and the other cubic crystal diminishes.

The discovery of super-hetero-epitaxy growth technology for rhombohedral single crystalline SiGe on c-plane sapphire was confirmed by the NASA-invented new XRD methods: (1) Total defect density measurement and (2) Spatial wafer mapping method (see further reading, patents pending 2, 4, and 5). Figure 2 shows the characterization results by XRD. Innovative XRD wafer mapping method shows spatial distribution of major single crystalline SiGe (99.8%) (Left image) and twin defect SiGe (0.1%) (Right image) that exist on the same sapphire wafer clipped by three plastic jaws outside. Twin crystal defect is reduced to below 0.1% and it exists only at the edge of a wafer. The successful development of rhombohedrally aligned SiGe has also led the inventors to construct a new hybrid bandgap engineering diagram with transformed lattice constants. In conventional cubic bandgap engineering diagram, the distance of [100] vector, i.e. lattice constant of a cube is used as coincidence lattice distance. On the other hand, conventional hexagonal bandgap engineering diagram uses the distance of basal plane basis vector as coincidence lattice distance. Direct comparison of the two lattice constants, one from the cubic crystal and the other from the hexagonal crystal is not very meaningful because it is an apples-to-oranges comparison although they are often plotted in one diagram. To the contrary, in rhombohedral super-hetero-epitaxy, three <2-20> vectors of cubic crystal that are perpendicular to [111] vector is making coincidence lattice matching with the combination of basal basis vectors of the trigonal crystal. Also, by adding another fact that hexagonal crystals can be epitaxially grown on trigonal crystals such as GaN on Sapphire with in-plane rotation, a combined ab-initio hybrid bandgap engineering diagram was developed and under test now.

Hundreds of new alloys and thousands of new device structures can be fabricated with rhombohedral-trigonal model because this epitaxial scheme is not only limited to SiGe on sapphire but can be extended to other cubic semiconductors on thousands of trigonal crystals in nature. It is expected that not all trigonal crystals can accommodate rhombohedrally aligned cubic crystals, but selected trigonal crystals that have enough difference of formation energies between two cubic crystals rotated by 60° can yield a single crystal epitaxial layer.

To identify other new materials within the rhombohedral super-hetero-epitaxy category, NASA scientists have selected a few candidate materials and they are developing the growth methods. Another benefit of rhombohedral super-hetero-epitaxy in addition to new hybrid crystal structure is that it has unprecedented lattice matching conditions that are different from cubic lattice matching. These new opportunities to create lattice matched and strained semiconductors are under study now. It is also interesting that a cubic semiconductor on trigonal substrate is strained from <1-10> directions and elongated or compressed along [111] direction so that it deforms into a rhombohedron shape while conventional cubic epitaxy creates tetragonal deformation by strains in <100> direction.

Many trigonal crystals are insulators like sapphire. Therefore, it is also possible to create SiGe on Insulator (SGOI) with a possible lattice matching condition. Tables 1 and 2 show how the key features of currently developing lattice matched SiGe on Insulator (LM-SGOI) under our research compare to existing products or technologies: The far right column of table 1 shows the NASA Langley developed SiGe material that is compatible with the conventional insulator silicon oxide. The compatibility of SiGe with the silicon oxide is a very important factor for wafer-based mass production. Table 2 shows the attainable speed of SiGe chipsets based on the gate length and the charge mobility. Lattice-matched SiGe widely opens a possibility of chipset speed improvement, while the single crystal silicon itself has its own intrinsic limit on speed even by miniaturized feature size. From this table, one can easily imagine the great impact of NASA Langley's rhombohedral lattice-matched silicon-germanium material on the new generation ultrafast chipset development.

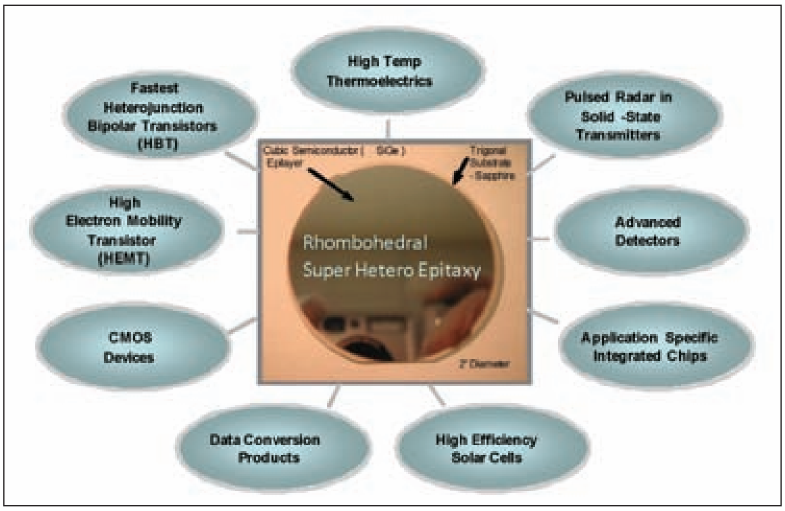


Figure 3. Applications of rhombohedral semiconductors on trigonal crystals

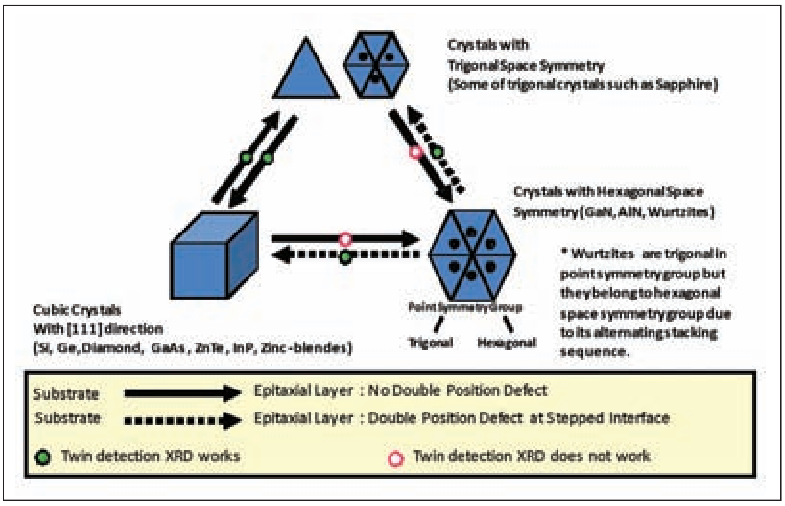


Figure 4. Inter-crystal-structure epitaxy possibility relations with applicability of twin detection XRD methods

NASA's rhombohedrally single crystal SiGe is the first of its kind ever achieved in the world. Therefore, there is no competition. The highly anticipated increase in charge mobility of the proposed materials technology is unique for the development of ultra fast chipsets. The lattice-matched SiGe is also complemented by silicon oxide as an insulator, unlike the arsenide, antimonide, or other compound semiconductors.

A proper insulation material like SiO_2 for lattice-matched SiGe allows fabrication of several hundreds of chips on a wafer basis. Compound semiconductors, such as zinc-blendes and Wurtzites, do not have proper insulators to allow mass production, instead of a single chip.

Another challenge is to incorporate higher germanium content into SiGe layer to raise carrier mobility. For example, the electron mobility of germanium is 4,000 $cm^2/V{\cdot}s$ while that of silicon is only 1,400 $cm^2/V{\cdot}s$. By providing a suitable substrate for SiGe layer, transistors of higher operation frequencies can be fabricated as shown in Table 2.

Ultra-CMOS

Rhombohedral semiconductors on trigonal substrates can improve the following products: Ultra fast Complementary Metal Oxide Semiconductor (CMOS) chipsets; Hetero-junction Bipolar Transistors (HBT); Thermo-Electric (TE) device; photo-voltaic solar cell device; advanced detectors; high frequency high power transmitters; and others as shown in Figure 3.

Before our research, trigonal crystal materials were not considered to be compatible with cubic semiconductors. The hybrid structure of rhombohedrally deformed cubic semiconductors and trigonal crystals create new opportunities to fabricate completely new single-crystal alloy structures for ultrafast semiconductor chip development beyond the silicon-based chip technology.

Since the NASA's rhombohedral SiGe can allow faster electron motion with higher germanium contents than single crystal silicon has, it will offer the development of ultrafast chipsets for numerous applications. In addition, hexagonal space symmetry materials can be grown on trigonal space symmetry materials such as GaN on c-plane sapphire.

We summarize the following inter-crystal-structure epitaxial relation between cubic [111] direction, trigonal [0001] direction, and hexagonal [0001] direction for further possibilities as shown in Figure 4. This diagram shows the possibility of epitaxial growth from underlying substrate material of one space symmetry group to an epitaxial layer of a different space symmetry group. A solid line means that it is possible to form a single crystal layer, and a dashed line means that double position defect creates huge difficulties to form a single crystal. A round green circle indicates that twin detection XRD methods can be applied and an empty circle means that twin detection XRD methods do not work.

Technology	Si	SOI / SGOI	SiGe on Si	NASA LaRC LM-SGOI
Fabrication	Single crystal ingot	Hydrogen crack	Gradient layer, super lattice	Lattice matched growth
Growth method	Czochralski	Wafer bonding	Epitaxial growth	Epitaxial growth
Lattice matched Ge content	0%	0%	0%	10% (current) and greater with new substrate
Ge content in strained layer before defects	0%	Usually 0~8%	Usually 0~8%	10 % Obtained 20 % Achievable
Ge content in relaxed layer	0% (Not available)	Could be up to 25% but contains severe defects	Could be up to 25% but contains severe defects	At least 35% achievable with no defects
Parasitic capacitance reduction	No	Yes	No	Yes
Growth of additional strained Si layer	No	No / Yes	Yes	Yes
Device	BJT, CMOS	BJT, CMOS / HBT, CMOS	HBT	HBT, CMOS
Improvement	Conventional Technology	High speed with insulating substrate	High speed (ultra thin SiGe lowers collector voltage of HBT)	High speed with thick & thin SiGe layer and insulating substrate. Higher device yield with lower defect

Table 1. Comparison of Si, SOI, SiGe on Si, and LM-SGOI technologies

	Carrier Mobility ($cm^2/V{\cdot}s$) at Dopant Density 10^{16} $/cm^3$		
Gate Length (nm)	1400 (Si)	2000 (SiGe)	3000 (SiGe)
commercial 360	18 GHz	25 GHz	38 GHz
commercial 180	36 GHz	51 GHz	77 GHz
commercial 90	72 GHz	102 GHz	154 GHz
commercial 45	144 GHz	205 GHz	308 GHz
12 (FinFET) (Experimental)	300 GHz	428 GHz	643 GHz

Table 2. Expected operation speed of a transistor with various mobilities and gate lengths

This research has won a R&D100 award in 2009 and it has double-edge impact as the world's first development of single crystalline rhombohedral SiGe semiconductors on trigonal substrates and opening the first window to hybrid crystal structure alloy engineering, namely, "Rhombohedral Hybrid Band-gap Engineering" with innovative XRD methods.

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QCLs take the leap from toys to tools

A revolutionary active region is the driver behind the record single-facet output powers emanating from **Pranalytica's** quantum cascade lasers (QCLs). This advance will spur the launch of compact, lightweight, multi-watt, mid-wave infrared lasers, say the company's **Richard Maulini, Arkadiy Lyakh, Alexei Tsekoun and Kumar Patel.**

QCLs are a novel class of laser that can plug critical gaps in the mid-wave and long-wave infrared spectral regions that are currently served by very few continuous wave (CW), room temperature solid-state sources. QCLs can operate in this spectral range because their emission is not based on conduction band to valence bands transitions that govern the emission of conventional laser diodes. Instead, they generate laser emission from transitions between confined intersubband states formed within a superlattice of alternating layers of materials with lower and higher bandgaps, known as quantum wells and barriers. The emission wavelength is then dictated by properties of the superlattice, such as the thickness of the wells and barriers, and this opens up a range of wavelengths that can be reached through bandgap engineering.

The fundamental idea behind the QCLs is not new and dates back to the early 1970s. However, practical realization of this device took nearly 25 years, due to the extreme demand that the laser structure puts on epitaxial quality. Even after the first working QCL was produced, this class of laser remained little more than a laboratory curiosity for a decade. Initial performance was poor, and the first generation of QCLs were available only in the form of individual chips, or chips on carrier assemblies. Consequently, integrating this class of laser into a system required expertise in QCL handling, powering and packaging. In addition, early designs had to be cooled to cryogenic temperatures - CW, room-temperature performance was only realized in 2002.

At Pranalytica, our mission has been to improve the performance of QCLs and their packaging, so that they can make the transition from laboratory devices to commercial lasers that can serve a host of applications. Thanks in part to funding from the US Defense Advanced Research Projects Agency, we have made significant strides in this direction, including a recent room-temperature demonstration of 3W, CW output from one single facet of a 4.6 μm laser. This record-breaking laser, which has a wall-plug efficiency of 13%, was the result of multiple advances that span the entire QCL production chain, from fundamental design of the active region through to thermal management of the chip.

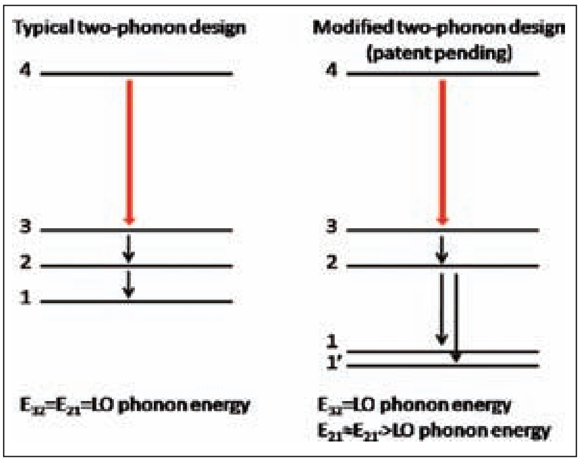


Fig.1. A typical QCL design employs a two-phonon active region. Longitudinal optical phonons are needed for transitions between levels 3 and 2, and 2 and 1 (left). Pranalytica uses an alternative approach with a non-resonant extraction active region that vastly increases the freedom of QCL design (right)

Beckoning applications

Thanks to these improvements, our QCLs are now attractive candidates for real world applications. In the defense market space, they are being explored for protection of military and civilian aircraft, and high-power handheld devices are being tested as target illuminators. In addition, several non-defense QCL applications are imminent, including free-space optical communications, ultra-sensitive trace-gas sensing based on photo-acoustic spectroscopy and other detection techniques and remote sensing.

There is no denying that it has taken the QCL community a long time to get to the stage where its lasers are commercially viable. That's partly because this class of laser has a relatively complex design, consisting of hundreds of superlattice layers, each with a thickness of just a few nanometers. Imperfections in the hetero-interfaces can cause undesirable carrier scattering, and in

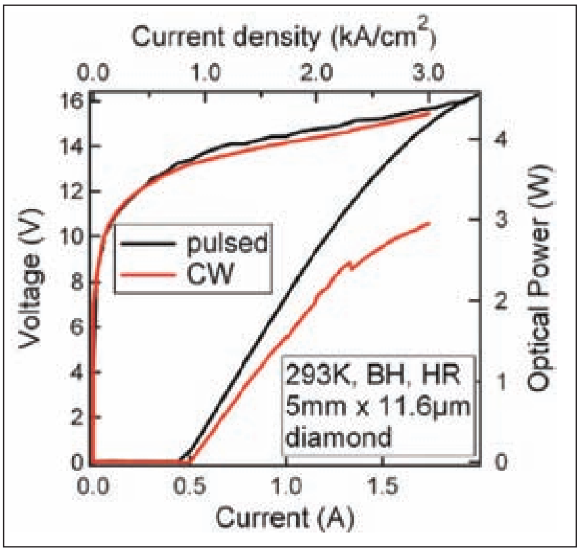


Fig. 2. Pranalytica's 4.6 µm QCLs feature a non-resonant extraction active region and can deliver a record-breaking CW output of 3W at 293 K

the worst case, distortion of the shape of a given quantum level, driving the design away from the optimum.

In addition, QCL performance can be compromised by small deviations in growth uniformity, both across the wafer and in the timings of the growth process. Since carriers traverse the superlattice structure sequentially, any thickness deviations within the structure will degrade device performance. So it is no surprise that advances in MBE held the key to practical realization of the first QCLs.

Most QCLs are made from a combination of InGaAs wells and InAlAs barriers, grown on an InP substrate. This material system is popular because it is well understood, thanks to its use in numerous telecom lasers. But that's not the only reason for selecting this particular material system – the pairing of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ is lattice-matched to InP, simplifying the epitaxial growth of very thick QCL structures. This combination produces a conduction band offset in excess of 0.5 eV, so it is possible to construct QCLs emitting at

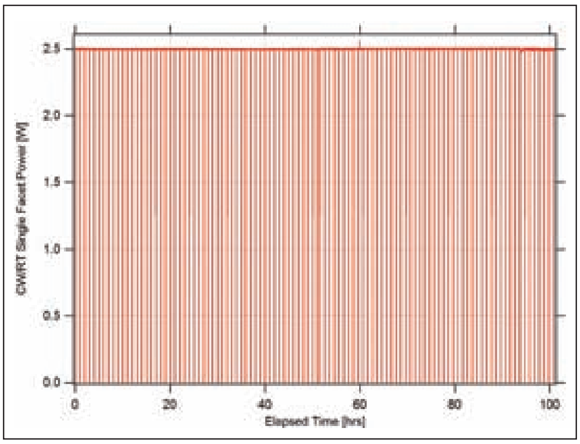


Fig.3: A robust facet coating has aided development of reliable, high-power mid-infrared QCLs. This includes 2.5W QCLs that show no signs of degradation during a 100-hour pre-delivery test

6 µm and beyond. Shorter wavelengths can be reached by increasing the depth of the quantum wells. A higher conduction band offset is then needed, which can be realized through increasing the indium concentration in InGaAs, along with the aluminum concentration in InAlAs. However, compositional adjustments pay the penalty of adding strain into the superlattice, because these ternary compositions are no longer lattice-matched to InP substrates. Strain can be partially ameliorated through careful selection of alternating compressively strained and tensile strained layers of appropriate thickness. By optimizing this approach, we have made record-breaking 4.6 µm lasers that contain about 1 percent strain.

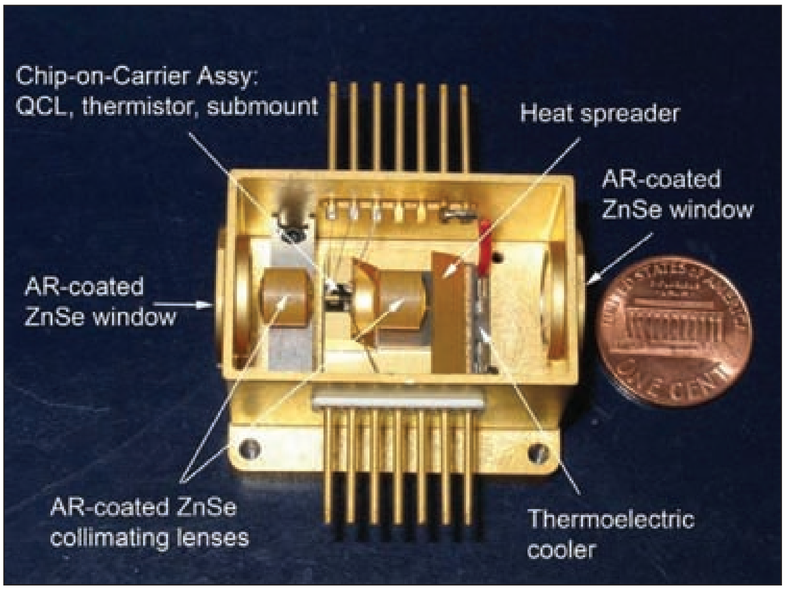
The leading materials candidates for wavelengths shorter than about 3.8 µm are III-V antimonides, which have larger conduction band offsets. Present efforts have focussed on either the InGaAs/AlAsSb or InAs/AlSb systems. QCLs built from these pairings of materials hold significant promise for short wavelength emission, but room-temperature, CW performance is yet to be realized.

Superior active regions

QCLs are unipolar devices, with emission governed by intersubband transitions that do not depend on the intrinsic properties of the material, but rather on the thickness and depth of the quantum wells and barriers that make up the gain medium. The challenge for designers of QCLs is to simultaneously optimize all the quantum cascade structure parameters influencing laser performance.

Most of today's QCLs are designed using the two-phonon resonance approach (see Fig.1). The lower laser level 3 is depopulated by two consecutive non-radiative transitions to the levels 2 and 1, which are each spaced by roughly the longitudinal optical (LO) phonon energy E_{LO} in the material (In the case of InGaAs, E_{LO} is about 35 meV). With this design, the lower laser level is rapidly depopulated, thanks to fast resonant, phonon-assisted scattering. But this advantage has to be weighed against the shackles of the two-phonon QCL design. Once the two phonon resonance condition is met, there are not sufficient degrees of freedom remaining in the design to optimize its other aspects. For example, with this design it is difficult to increase the energy spacing E_{54} between the upper laser level 4 and the active region level 5, which ultimately suppresses parasitic carrier injection into the latter state.

We have regained design flexibility for the QCL by removing the two-phonon resonance condition and turning to a non-resonant extraction approach. Our design replaces a single, resonant final state with several closely spaced final states separated from the state above by substantially more than E_{LO}. Even though the transition to each of the new final states is slower than that in the resonant case, carrier lifetime in the state above is



QCLs can be mounted in butterfly packages containing thermoelectric coolers and collimation optics

reduced thanks to the introduction of several parallel extraction paths.

MBE or MOCVD?

The first QCLs were produced by MBE, a technique that is adept at producing precise growth of thin layers with abrupt heterointerfaces. This form of epitaxy dominated the growth of QCLs for a decade, but notable improvements to MOCVD technology during the 1990s have enabled process engineers to now have a choice of deposition techniques. MOCVD's potential advantages include a faster growth rate - a particular cost advantage for the very thick QCL structures - and nominally lower reactor maintenance.

The first MOCVD-grown QCL was demonstrated in 2005 by researchers at the University of Sheffield, UK, and since then this approach has been gaining traction. As of today there is no consensus in the QCL field regarding fundamental superiority of MBE or MOCVD, and we keep an open mind, producing lasers with both techniques.

We have produced a portfolio of high-quality, QCL epi-structures for emission in the medium-wave infrared by optimizing our growth process for strained structures containing hundreds of nanometer-thick layers. QCL quality is normally assessed through measurements of the spontaneous emission spectrum's full-width at half-maximum: our 4.6 µm structures have a value of just 26 meV at room temperature, 20 percent less than that of previous growths of the same design.

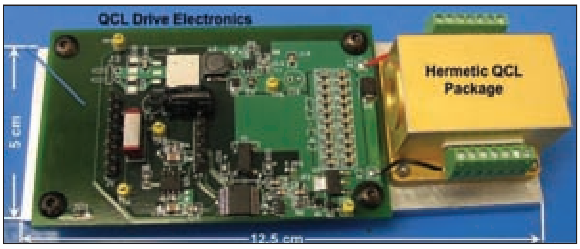
To simplify systems integration of our QCLs, we have developed advanced, high-reliability, self-contained packages that employ well-proven telecom practices. These require only electrical power and heat sinking to operate.

QCLs run in CW mode generate a substantial amount of heat – typically 10 MW/cm^3 – and we have addressed these thermal issues with a buried-heterostructure geometry. The epitaxial laser structure is etched to form near-vertical ridges defining the side-walls of the laser cavity, and valleys are overgrown with a material providing superior thermal conductivity to that of the active region superlattice. This additional material, MOCVD-deposited iron-doped InP in the case of InGaAs/InAlAs QCLs, is transparent to the lasing wavelength and electrically insulating. At the package level, we have pioneered the use of epi-side mounting of QCLs for efficient thermal management. Thanks to optimized thermal management, we have realized a ratio of pulsed-to-CW output power of just 1.5 for a 3W QCL attached to a diamond submount. This type of submount is widely used to report results, because it is very efficient at extracting heat from QCLs, but its thermal expansion mismatch to the thermal expansion of the QCL material impairs long-term reliability. In the case of diamond substrates, to prevent damage to the laser, QCLs are soldered to the submounts with soft indium solder, but this leads to solder electro-migration at high temperatures and/or high currents densities.

We circumvent all these issues by: utilizing AlN submounts with a thermal coefficient similar to that of the laser; bonding the submount to the QCL with hard AuSn solder; and optimizing device geometry and facet coatings for room-temperature, CW operation. This has enabled a maximum CW output of 2.9W at 293K. We have also studied the performance of our QCLs without thermoelectric cooling (often called "uncooled" operation) and found that they produce a maximum average power of 1.2W, and a CW power in excess of 1W. Recently, thanks to further improvements in thermal management, we have raised the bar for average power output for "uncooled" operation to 2.0W.

It is worth noting that our output power and wallplug efficiency figures are given for single-ended emission. As with all edge-emitting semiconductor lasers, as-cleaved QCLs emit light equally from both facets, and many researchers report the combined output from both facets as the output power. But the vast majority of applications demand single-ended output, a requirement that is fulfilled by depositing a high reflectivity coating on one of the facets. This is a daunting task for high-power QCLs – optical power density on the facet of a 2W laser can exceed 10 MW/cm^2. However, we have risen to the challenge of producing a reliability coating operating in the mid-infrared and developed QCLs emitting 1W or more that can deliver many thousands of hours of degradation-free operation (see Fig.3).

To facilitate the integration of our QCL chips into various applications and ensure long-term reliability, these devices are installed into custom-designed butterfly type packages containing a thermoelectric cooler and collimation optics.



Output powers in excess of 1W can be produced from an uncooled package (left). A table-top variant has also been produced (above). This version can also drive the laser with pulses exhibiting rise and fall times of less than 5 ns

This complete system, which is hermetically sealed in nitrogen atmosphere, is very compact – its mass is less than 100 g and it has a volume below 50 cm^3. An additional appeal of these hermetic packages is that by providing a well-defined electrical and optical system interface, they free system designers from needing to become QCL experts, thereby dramatically reducing the risk and time for developing QCL applications.

Some applications require higher powers, and to meet these needs we have developed specially packaged, cryogenic QCLs that deliver a CW output in excess of 7W at 80K. However, the increase in the output power of this chip has the downside of a more expensive, larger and heavier system.

Any systems integrator requires infrastructure in addition to the laser package, including drive electronics and package thermal management. These tasks for room-temperature, CW QCLs are challenging, because this class of laser requires significantly higher drive voltages (12-16V) than its diode cousin, as well as a more capable form of external thermal management. To reduce the barrier to entry for QCL system integration, we have developed appropriate drivers, heatsinks and controllers that represent the entirety of equipment necessary for operating a QCL in a customer's system. Such systems, which are now commercially available in several different versions with a CW output power in excess of 2.5W, should help to unlock the door to deployment of lasers for protection of military and civilian aircraft, gas sensing, and a host of other important applications.

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Pranalytica manufactures commercial, turn-key, high-power QCL systems that operate off standard AC power and can deliver CW output powers in excess of 2.5W (above). The laser head houses the QCL and its thermal management system, and a controller provides all of the necessary supply, command, control and safety functionality. This version can deliver more than 2W of collimated radiation at 4.6 µm. For applications requiring projection of the QCL beam over several kilometers, the laser head can be coupled to an external objective (right)

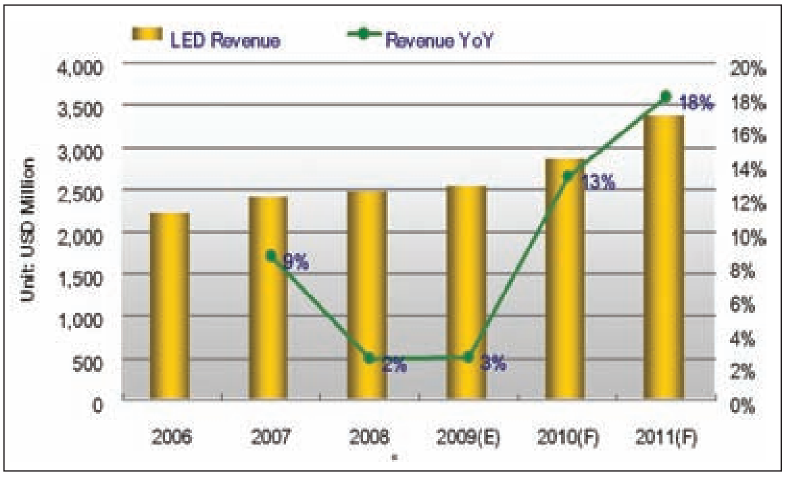
LED-backlit displays and street lighting fuel Taiwan's LED growth

Tawian's LED industry has weathered the global economic storm, and it is now recovering fast thanks to increased deployment of this chip in street lighting and display backlights. **The Photonic Industry and Technology Development Association (PIDA)** details the transformation.

The financial crisis brought a global downturn at the very beginning of 2009 that led to a slowdown of market development and a decline in revenue generated by Taiwan's LED industry. However, strong demand from LED TVs is reviving the industry beyond expectation. It is thought that revenue from Taiwan's LED industry hit NTD 80 billion ($ 2.5 billion) in 2009, which is 3 percent higher than it was for the previous year. And PIDA analysts predict that the LED industry will do even better in 2010, with the year-on-year revenue growth of 13 percent.

The leading application for Taiwan's LED products is mobile phones, with a 37 percent share of total revenue, followed by electronic devices, accounting for 32 percent. The market share taken by these two applications slightly shrank in 2009, due to rising revenues in signs/displays and illumination. The former accounts for more than 20 percent of LED sales, and has delivered 5 percent revenue growth compared with 2008, while the share of LED illumination has increased from 5 percent in 2008 to 7 percent in 2009. PIDA's analysts forecast continued growth for the next few years generated by the deployment of LEDs in signs/ displays and illumination.

Taiwan's LED revenue was flat towards the end of the noughties, but it will pick up over the next few years. Credit: PIDA

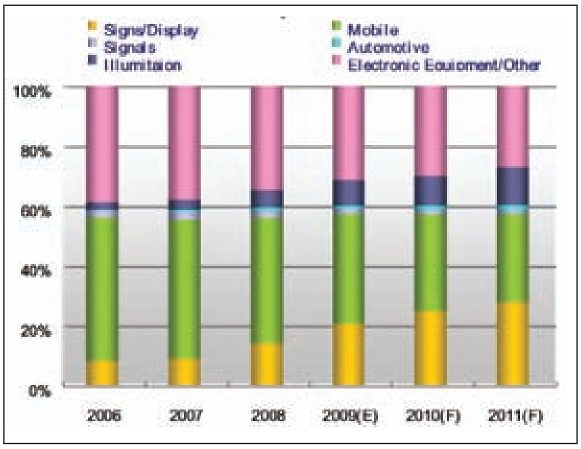


In 2009, LED streetlights and LED-backlit TVs (or LED TVs, the term coined by Samsung) were the applications that attracted the most interest in Taiwan's LED industry. Regarding LED streetlights, the government collaborated with several industry players to set up three demonstration areas in Taipei city. Later, in June 2009, the Cross-straits LED Forum provided a prime opportunity for a Taiwanese LED player to install a demonstration involving about 1.4 million street lamps in 21 major cities in China. Taiwan-based chipmakers are believed to benefit from China's insufficient domestic production of LED chips.

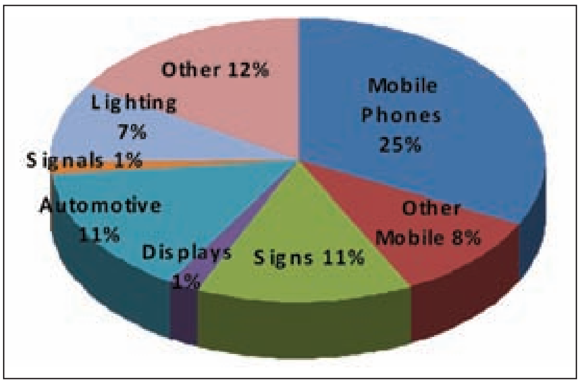
LED TVs have taken off beyond industry players' expectation, and sold half a million units within a hundred days, triggering a battle to launch LED TV among brand name companies including Sony, LG, Sharp, and Toshiba, who are all vying for market share. This has increased demand for LEDs, benefiting Taiwan's chipmakers and packagers. For example, sales at Taiwan's largest LED chipmaker, Epistar, have been growing since summer 2009, and in January 2010 they hit NTD 1.3 billion, more than double that for January of the previous year. Another leading LED player, Formosa Epitaxy, has also seen its revenue increase recently. In February 2010 sales hit NTD 203 million. The company has installed 43 MOCVD reactors since the fourth quarter of 2009, and it will add another 55 this year that will give the firm a year-on-year increase in capacity of 40 percent.

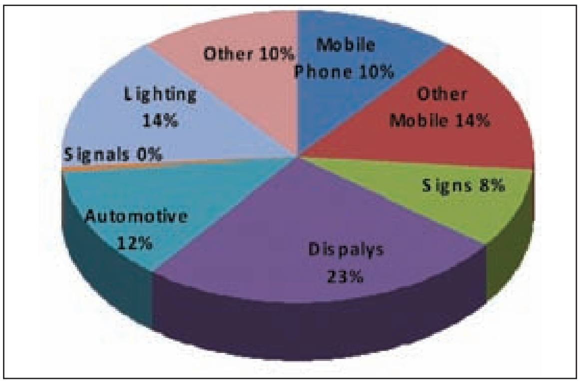
Government-backed growth

In order to reflect the industry's need to commercialize the LED, as well as to put into effect the Energy-Saving and



The proportion of Taiwan's LED production deployed in signs and displays will rise during the first few years of this decade. Credit: PIDA





Market analyst Strategies Unlimited predicts that the proportion of LEDs used for displays will grow substantially from 2009 (top) to 2012 (bottom)

Carbon-Reduction Action Plan, Taiwan's central and local governments collaborated with a number of industry players. This led to an announcement in December 2008 to set up three exclusive demonstration areas, making it abundantly clear that the government wants to nurture the LED industry.

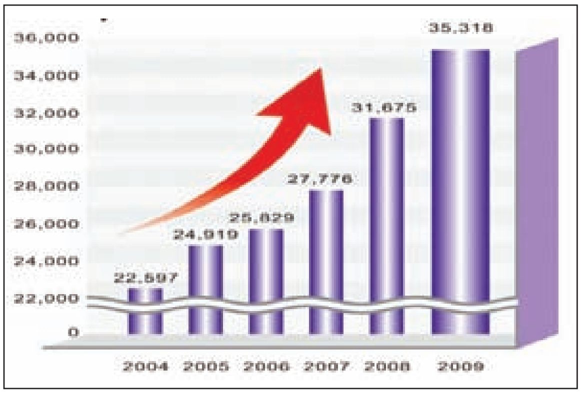
The three demonstration areas are located in Taipei city and include 228 Peace Park, Fuzhou Street and Nanyiang Street and its neighborhood. In 228 Peace Park, an LED lighting landscape, plus a garden control system and accessories, were adopted to showcase the impressive grand sight down at Kaidagelan Boulevard. Around Fuzhou Street, LED outdoor street bulbs were used to light up the roadway. In the neighborhood of Nanyiang Street LED lighting fixture were designed to beam down on the paving.

According to Chii-Ming Yiin, Taiwan's Minister of Economic Affairs, with years of subsidization from the government plus advanced technology improvement from business initiatives, the long-anticipated third revolution in lighting has arrived. Minister Yiin also claimed that Taiwan is leading the world in terms of LED production by volume, and it can drive the industry growth that began last year. What the government aims to contribute to this development is to draw up a well-arranged plan, including national standards, enactment of regulations, and innovation awards programs.

In addition, according to Taipei City Government - one of the cities on the island that invests a great deal of money and effort in driving the environmental protection activities - the exclusive demonstration can act as a catalyst that spurs more effective follow-up commitments to energy-saving. Mayor Longbing Hao acknowledged that global warming is getting worse and will cause a great deal of harm, but this state of affairs can be mitigated if governments throughout the world, including Taipei, develop measures to reduce greenhouse gas emissions. In Mayor Hao's expectation, more than 140,000 incandescent streetlamps in Taipei city will soon be replaced with power-saving, LED-based bulbs.

According to LEDinside, an independent industry research institute based in Taiwan, the nation's streetlight market offer a potential business opportunity valued at around NT $40-50 billion for local LED firms. The

According to Chii-Ming Yiin, Taiwan's Minister of Economic Affairs, with years of subsidization from the government plus advanced technology improvement from business initiatives, the long-anticipated third revolution in lighting has arrived



The number of attendees at LED Lighting Taiwan has risen rapidly over the last few years

government earmarked NT $200-300 million to install LED streetlights in 2009. LEDinside also predicted that Taiwanese LED firms that specialized in packaging, including Unity Opto Technology Co., Ltd, Bright LED Electronics Corp., and Foxsemicon Integrated Technology Inc., will benefit from the plan.

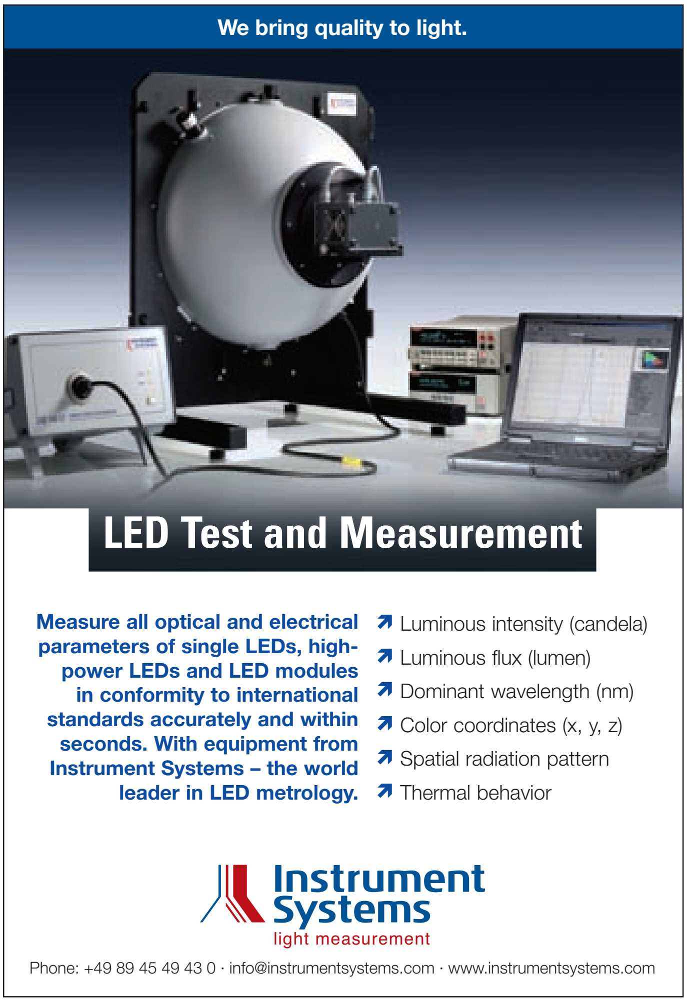
Given the wide range of activities needed to implement the production of LED-based systems for new applications, collaboration across the industry is widely accepted as the right way to go. Two companies expected to produce LED chips for this effort are: Epistar Corporation, which is located in the central city of Hsin-chu and is developing and manufacturing high brightness LED products by applying its own proprietary MOCVD technology; and Formosa Epitaxy Incorporation, a Taoyuan-based manufacturer of InGaN LED wafers and chips that is offering InGaN blue, green, and near-UV LED products.

On the packaging side, players that join the project include Lite-On Technology Corp., a well-established LED firm that will help to build a fully integrated supply chain of LEDs among Taiwanese high-tech heavyweights, along with companies such as: Alliance Optotek Corporation, a solid-state lighting solution provider for lighting industries; China Electric Mfg. Corporation, an own-branded lighting company supplying a full range of products including LED and Solar Energy lighting systems; and Lustrous Technology Ltd, a leading COB packaging technology company.

Lighting may be the future for LEDs, but today revenue is driven by chip deployment in other applications, ranging from cell phones to large-sized products such as notebooks, TVs and monitors. Large-sized display backlighting should become the largest LED application market in near future, according to PIDA. LED application in displays will soar from 1 percent in 2009 to 23 percent in 2012, bringing a strong growth in the LED market.

Thanks to the low cost associated with LED backlights in small-sized displays, this technology that combines high efficiencies with low weight has enjoyed substantial success in small-sized products. The technology is now starting to be deployed in large panels (not including netbooks), with shipments reaching 79.8 million units. The penetration rate was 18 percent in 2009, a four-fold growth compared with the previous year. In total, the penetration rate of LED back-lit notebooks leapt from 11 percent in 2008 to 51 percent in 2009, becoming the strongest driver of growth of LED backlit modules in large-sized panels. Concerning LCD TV, the penetration

Rising sales of LED backlights for LCD TVs are driving strong growth of Taiwan's LED industry. Firms involved in the supply chain include: LED TV panel makers AUO, CMO, CPT; LED TV brand names Amstran, BenQ, CMO; LED chip makers Epistar, Formosa Epitaxy, Tekcore, Huga, Optotech, Lextar, Chi Mei Lighting; LED packagers Unity Opto, Everlight, Harvatek, LiteOn, LHTC, Wellypower; and LED lead frame producer I-Chiun Credit: Samsung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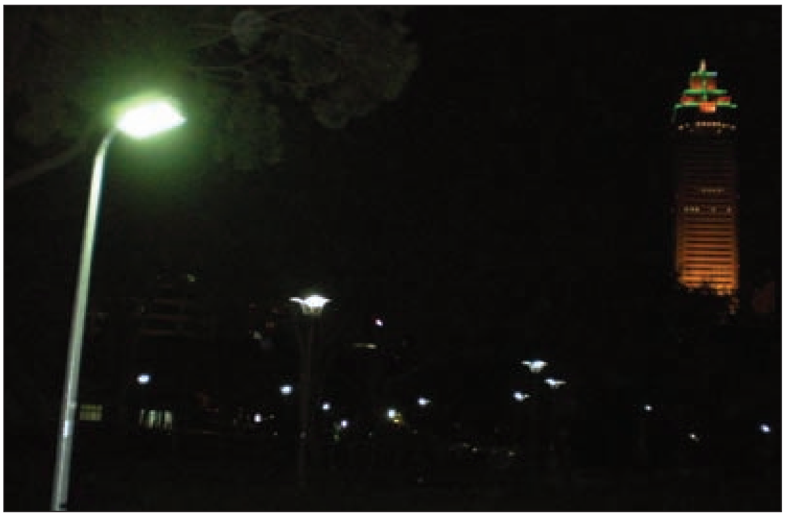


LED Street Lights in 228 Peace Park. Credit PIDA

rate of the LED back-lit versions has grown from 0.5 percent in 2008 to 2.5 percent in 2009, and LED-lit monitors might be over 2 million in 2009 with the penetration rate at 1.6 percent.

Taiwan, being the most powerful LED manufacturing engine in the world, is well known for its integrated and comprehensive LED industry supply chain. In order to reflect the trend and the bright performance of Taiwan's LED industry, LED Lighting Taiwan 2010, scheduled to be held from June 9th to 11th 2010, will not only bring the most updated developments and features of Taiwan's LED industry - it will also showcase the synergy between local and global LED manufacturers, and how this synergy can help to create business opportunities.

This year show organizer PIDA has launched a global marketing initiative to boost the visibility of this exposition. PIDA is going to arrange official visiting activities, such as cooperating with Science Parks, meeting with international delegates from Germany, UK and the Republic of Ireland, and organizations such OITDA and JLEDS to enhance the cooperation between the local and global LED industry. PIDA also cooperates with overseas Taiwan trade offices/foreign trade offices to market the green image of LED Lighting Taiwan. In addition, the international technical and trade press will be out in force, helping to give more exposure to the show.

Apart from the exhibition itself, PIDA also presents special events such as the Opening Ceremony, Outstanding Photonics Product Award, Welcome Reception Party, Exhibitors' Seminar, and Business Match Meeting to help promote this annual event. In 2009, LED leaders including Nichia, Cree, Dow Corning, Panasonic, Seoul Semiconductor, Optotech, Everlight, Genius Electronic Optical and LiteOn attended this photonic event and made it a success. Top tier providers will be at LED Lighting Taiwan again this year.

LED Lighting Taiwan 2010, with the strong commitment and support from both local and world-class LED manufacturers, promises to help boost the industry's vitality, as well as stimulate the business. Thanks to the efforts from all participants at the show, LED Lighting Taiwan 2010 will create win-win opportunities for everyone and bring tremendous success to the LED industry.

Taiwan's Top 10 LED Backlight Module Manufacturers

Coretronic Coporation
Radiant Opto-Electronics Corporation
Forhouse Corporation
Nano Electro-Optical Technology (Nano-Op)
Kenmos Technology
Forward Electronics Co., Ltd
Chi Lin Technology Co., Ltd
Global Lighting Technologies, Inc.
K-Bridge Electronics Co., Ltd
Precisions (L) Corp

Millions of LED street lights are being deployed in Taiwan. The supply chain involves: LED chips from BridgeLux, Cree, Epistar, Formosa Epitaxy, Nichia, Osram, SemiLEDs; LED packages from Everlight, LiteOn, AOT, Bright, Harvatek, Lustrous; LED thermal modules from TTIC, CCI, AVC, Neng Tyi, Lustrous, NeoPac Opto, Advanced Thermal Devices, AuguX; LED lamp poles from Toalux, Everready Precision; and LED street lamp systems from FITI, NeoPac Opto, Bright LED, TTIC, Advanced Thermal Devices, Harvatek, LEOTEK, Delta, TGI, Unity Opto, Neo-Neon, Tatung, Genius, Topco, Anteya, Yeong Li, Alliance Optotek, AuguX, Everlight

Optimising LED manufacturing

LED manufacturers seek new methods to reduce manufacturing costs and improve productivity in an increasingly demanding market. **Tom Pierson, Ranju Arya, Columbine Robinson of KLA-Tencor Corporation** discuss how epitaxy process control can result in improved MOCVD uptime and overall yield. Challenges that can be assisted with inline inspection techniques.

To meet the requirements of demanding new market applications such as LCD backlighting and general lighting, light emitting diode (LED) manufacturers must slash costs and boost fab productivity. Inline inspection will be critical in that effort, speeding the fab ramp process and increasing production yields. In the front end wafer semiconductor process, epitaxial layer defects in particular can account for as much as 50% of the total wafer level yield budget. The KLA-Tencor's Candela surface inspection system is designed for the inspection needs of the LED industry and can capture a wide variety of mission-critical substrate and epitaxial defects. Full implementation of inline inspection and statistical process control (SPC) could cut yield loss from epi defects in half while significantly increasing the metal-organic chemical vapour deposition (MOCVD) reactor uptime.

Inline inspection for LED process

LED performance is defined by optical characteristics such as efficiency, brightness, and colour quality, which depend on the composition and structure of the device layer. The industry currently uses photoluminescence, reflectance measurements, x-ray diffraction, and similar analytical techniques to monitor wavelength, film thickness uniformity, material composition, and other metrics tied to optical performance and parametric yield. In addition, the industry is seeing increasing adoption of automated inspection tools for monitoring and control of epitaxial defects. Epi defects are known to impact the electrical and optical properties of LED devices as well as limiting reliability and lifetime. Functional yields can vary from batch to batch – typical yields at full wafer test (FWT) can range from 60% to above 90% depending on chip design, material defects, and fabrication process

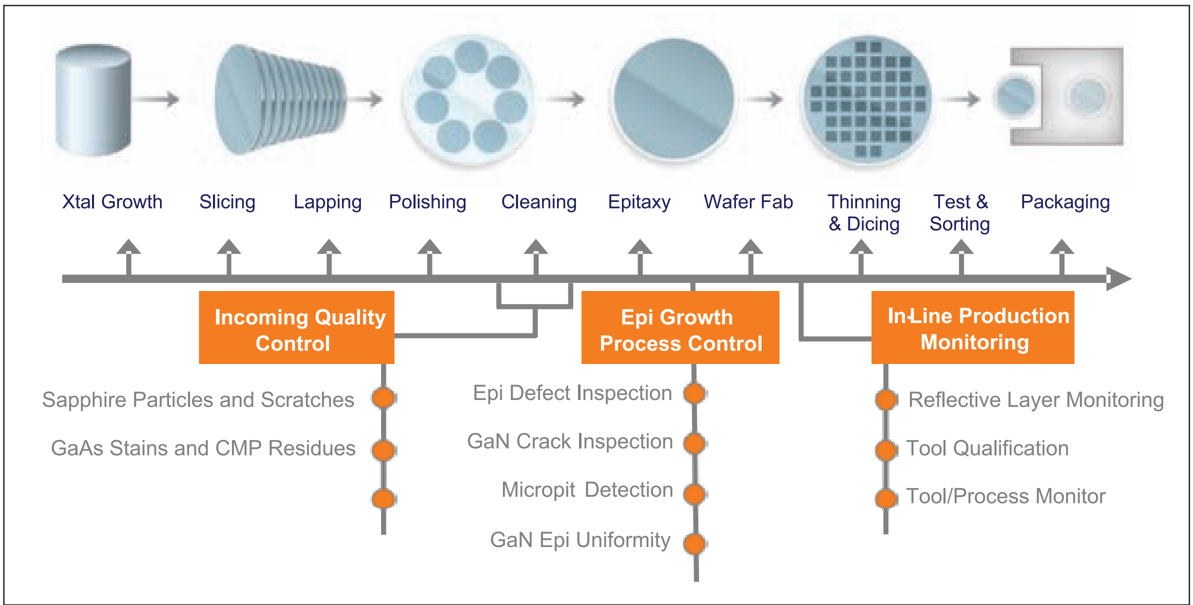


Figure 1: Key inspection points in the LED manufacturing process

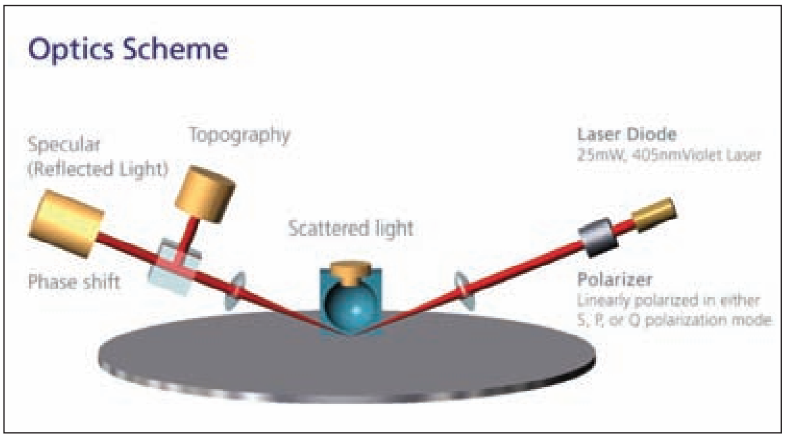
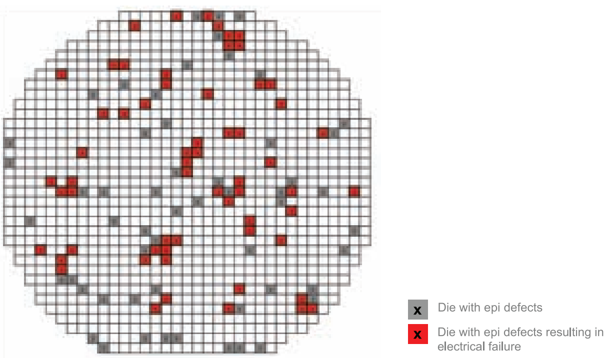


Figure 2: Candela design with multi-channel analysis to detect and classify a wide range of mission-critical defects

variations. Epitaxial layer defects in particular can account for as much as 50% of the total wafer level yield budget. Industry leaders who use automated inspection to monitor defect densities within wafer, wafer-to-wafer, and batch-to-batch estimate that optimal inspection practices can reduce the yield impact of material defects and offer significantly higher yields.

Key inspection points across the front-end process include before and after cleaning and final preparation of substrates, and after deposition of the epitaxial layer (Figure 1). If a yield crash occurs, having data from multiple inspection points greatly simplifies the root cause analysis and helps prevent misguided process adjustments. There is no need to alter MOCVD process parameters when the underlying problem can be traced to incoming substrate quality.



Correlation of Epi Defects to LED Device Yield (Sample A)

	# of Die	# of FAILED Die	% Yield Loss
Die WITH epi defects	117	61	52.1%
Die without epi defects	893	94	10.5%
Total Die	1010	155	15.3%

KILL RATIO 52.1%
% of die with epi defects which resulted in electrical failure

Figure 3: Correlation of epi defects to LED device yield

Epi defect correlation

KLA-Tencor's inline inspection system is designed specifically for the defect inspection requirements of the LED industry. The optical design uses multi-channel detection technology to measure the scatter, reflectivity, phase shift, and topographic variations across the transparent substrate surface (Figure 2). Multiple measurements are made enabling production grade throughput and 100% surface coverage.

After scanning, the analysis software extracts defects from the background signal, classifies them by defect type, and reports defect parameters and locations. For example, during inspection of polished sapphire substrates, the inspection recipe may include particles, scratches, pits, slurry residues and stains. Typical GaN-epitaxial layer defects include particles, scratches, micropits, microcracks, crescents, circles, hexagon bumps, and other topographic defects.

An analysis grid can be set to match the die dimensions, allowing correlations between individual defects and final wafer test results. For example, Figure 3 shows the influence of epi defects on device performance. In this study, the device die grid was overlaid on the Candela defect map and pass/fail criteria was set based on known killer defects (i.e. epi pits, crescents, hexagon bumps, and topography clusters). It is important to note that surface particles were omitted from the pass/fail criteria as surface particles are added and removed many times throughout processing.

After device fabrication, FWT electrical probe data was collected. Failed die were defined as those with a reverse leakage current greater than 1mA indicating a short of the device p-n junction. The corresponding yield map was overlaid with the Candela defect map to demonstrate the correlation between epi defects and LED device yield. Dies with known killer epi defects had a 52.1% failure rate (or kill ratio) at electrical testing, while dies without epi defects had only a 10.5% failure rate. Thus, dies with killer epi defects had a 5X greater probability of failure than those without defects.

Figure 4 shows the bar graph of the yield loss for the samples in this study. From the correlation investigation, total yield loss can be partitioned into "epi defect induced yield loss" and "other sources of yield loss." Other sources of yield loss include fabrication induced defects, particle and handling contamination, etc. The total yield loss after FWT for the three LED wafers analyzed was 15.3%, 17.5%, and 14.3% of which 6.0%, 7.2%, and 5.5%, respectively, could be attributed to epi defects. In this example, the epi defect induced yield loss represents roughly 40% of the total yield loss budget.

Best Known Methods (BKMs)

Manual inspection techniques are inadequate for full wafer coverage and do not provide detection and classification results in a quantitative and repeatable manner. At best, manual inspection techniques might detect a rise in defectivity due to a major process excursion, but they will miss a transient increase in the severity of specific killer defects such as pits or hexagon bumps. Such minor excursions, subtle increases in killer defect densities, are virtually undetectable through manual inspection techniques, but can account for a substantial fraction of total yield loss.

Figure 5 shows the value of automated inspection for early detection of an epi reactor excursion of epi pits known to short the device p-n junction. The upper portion of the figure illustrates a minor excursion which goes undetected by manual inspection. A typical fab cycle through FWT is two to three weeks. Thus, for a manufacturer running at 20,000 wafer starts per month (WSPM) the feedback loop does not occur until the wafers reach electrical FWT. In the case of a two-week fab cycle, a minor excursion would expose 10,000 wafers to increased defect densities and increased yield loss. The lower portion of Figure 5 illustrates how automated inspection isolates the defect excursion.

Corrective actions quickly reduce defectivity levels to within process control limits. Fewer wafers are exposed to killer defects, reducing incremental yield loss. Early detection of excursions through automated inspection translates to millions of dollars in savings each year for LED chip makers. The cost of the MOCVD epitaxial layer is also an important contributor to overall device cost. MOCVD equipment accounts for about 65% of the capital cost of an LED fab (source: Bank of America Merrill Lynch Global Research, 2009). Maximizing the uptime and productivity of these systems is critical. Leading LED manufacturers use Candela defect data to implement SPC monitoring on each MOCVD reactor, thereby providing a rapid control loop should the defect density of a given reactor exceed process control limits.

Substrate and epi-layer defects

Common defects on sapphire substrates include particles, pits, scratches and CMP process stains. Substrate pits are known to cause GaN epi defects. Sapphire substrate stains are a root cause of localized areas of GaN epi roughness, where underlying high densities of atomic crystal dislocations can short device p-n junctions. Figure 6 illustrates the cause-and-effect of substrate stains on subsequent GaN-epi growth.

Automated inspection of incoming substrates verifies substrate quality. With clear pass/fail criteria,

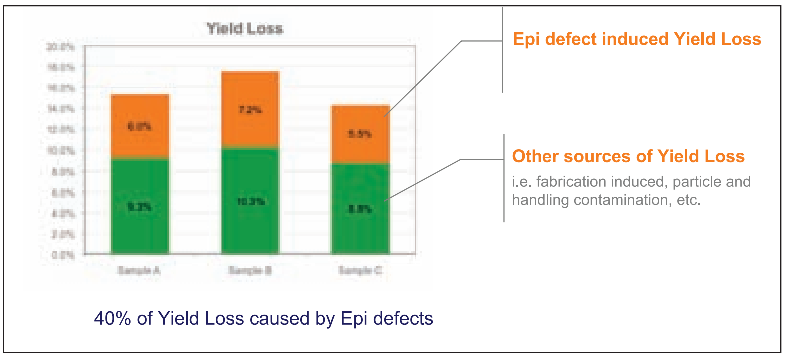


Figure 4: Sample yield Loss

manufacturers can more readily set and enforce material quality specifications, raising both yield and overall device performance.

MOCVD processes produce a variety of GaN epi defects; common yield-impacting defects include hexagonal pits and bumps, crescents, circles, and other topographic defects. In addition to such device killers, GaN epi cracks are also known to be a significant reliability killer. As LEDs make their way into higher-end applications such as LCD backlighting, automotive, and general lighting, field reliability and LED performance longevity are of critical importance.

GaN epi cracks can be extremely problematic to LED makers as these defects cannot be screened at FWT or final probe test and only later result in field failures and expensive recalls.

Figures 7.a and 7.b illustrate Candela inspection images for GaN epi morphology and epi crack defects. These defects can be readily detected and classified in the output defect map.

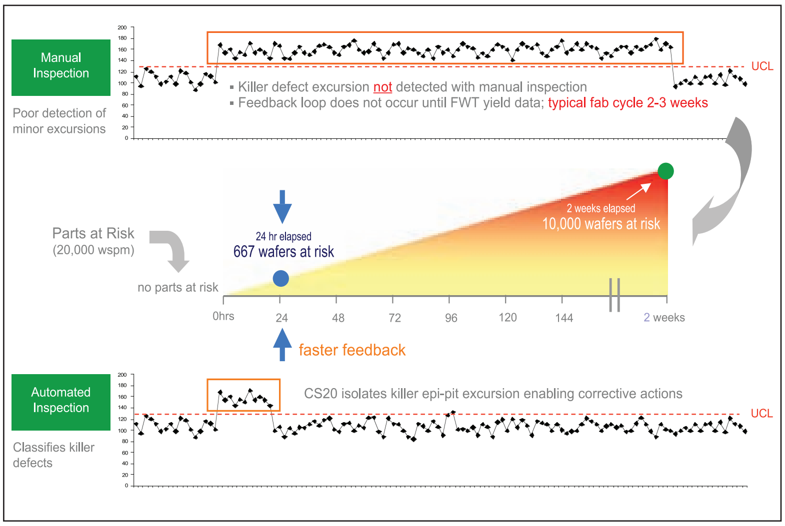


Figure 5: The value of automated inspection for early detection of an epi reactor excursion of epi pits

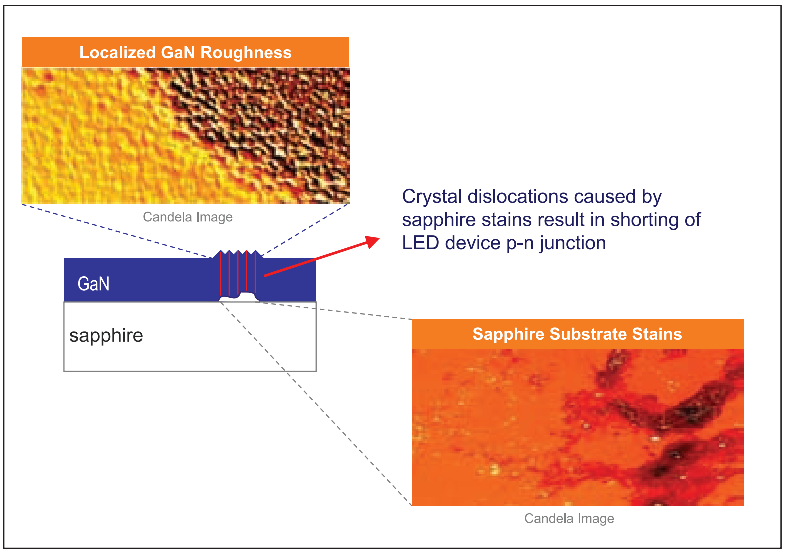


Figure 6: Impact of substrate stains on GaN-epi

Improving yield

Inline inspection delivers ROI by helping to improve yield, minimize process excursions, and increase MOCVD uptime. Inline defect inspection, combined with SPC monitoring, provides a rapid feedback loop for tuning reactor growth parameters and correcting process problems. If these interventions keep epi defectivity within control limits there is less need for preventive maintenance procedures and their associated downtime.

Figure 8 illustrates a timeline representative of the evolution of process control improvements and benefits derived from automated inline inspection. The x-axis begins at time = 0, i.e. the point in time when an LED fab implements automated inspection with production SPC monitoring. Figure 8 summarizes the three key economic benefits derived from automated inspection with SPC:

1. Killer defect reduction from process improvement.
When production-grade automated inspection is first implemented, defect levels are high with wide run-to-run tolerances. Quantitative and methodical inspection results provide engineers with the necessary data to design experiments aimed to reduce epi defectivity and improve production yields. On average, LED makers will achieve a 2-3% improvement in FWT yield within the first 6 months of ownership.

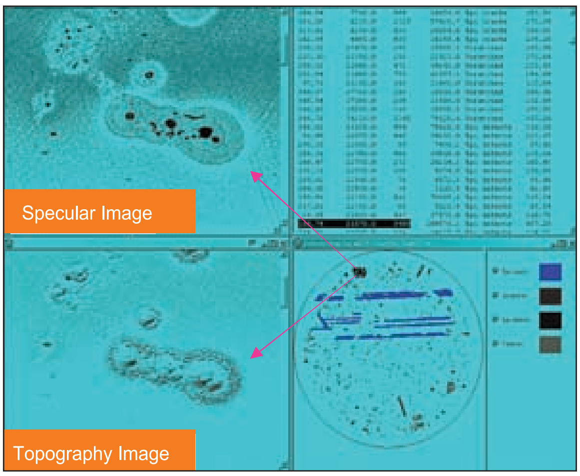
2. Fewer production lots exposed to yield loss from minor excursions.
Once baseline defect levels are established, control limits are put in place to monitor each MOCVD reactor. Defect inspection provides a feedback loop for corrective actions on MOCVD process parameters. Inspection sampling rates are typically 100% in order to address within-wafer, wafer-to-wafer, and run-to-run trends. Reduced exposure to minor excursions – which may last for weeks, or even months – is the most common economic gain realized by LED device manufacturers.

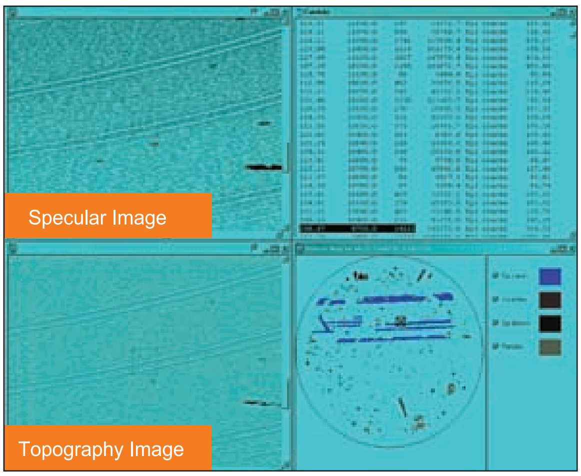
3. Prevention of minor excursions from becoming major excursions.
Defect inspection not only provides a feedback loop to minimize the impact of minor excursions, but also helps to prevent minor excursions from becoming major excursions thereby improving MOCVD uptime and overall productivity.

These three components of value are the key drivers for implementation of automated inline inspection. Reducing killer defect densities results in yield improvement while defect density SPC results in less exposure to minor excursions and increased MOCVD uptime. Leading LED manufacturers worldwide have demonstrated that the value derived from automated inspection translates to millions of dollars in savings each year.

Conclusions

Epi defects in the bottleneck MOCVD process are frequent yield killers and account for roughly half of the





Above left: Figure 7.a: Candela specular and topography images of typical epi topography defects
Above right: Figure 7.b: Candela specular and topography images of typical epi crack defects

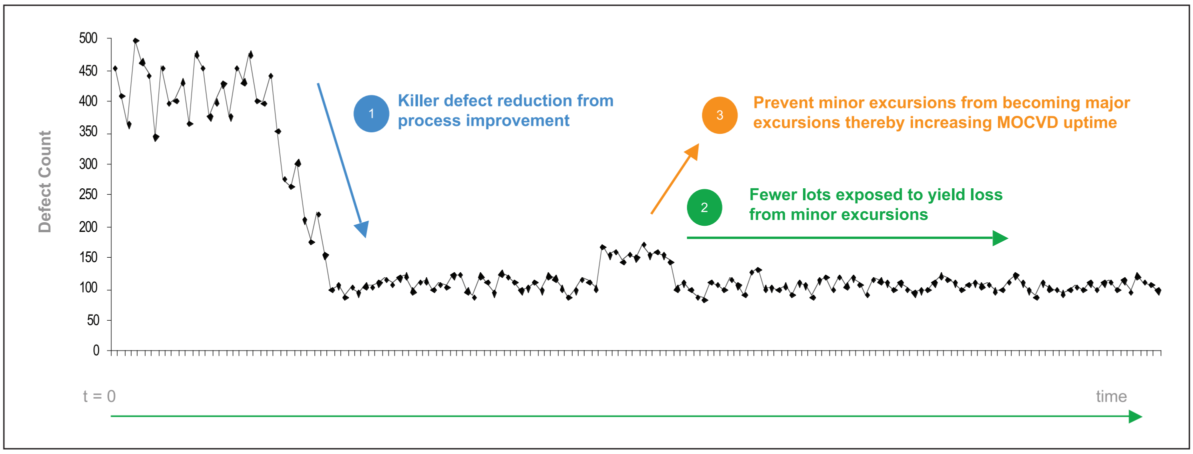


Figure 8: Key value drivers of automated inline inspection

total wafer level yield budget. Implementation of inline inspection and SPC monitoring of the MOCVD process could cut the yield loss from epi defects in half.

These yield and productivity (MOCVD uptime) enhancements are achieved through killer defect reduction, early detection and prevention of minor and major excursion trends. KLA-Tencor's Candela surface inspection system allows comprehensive inspection and control of epi process and helps LED manufacturers realize this multi-million dollar yield opportunity.

Improved LED production with integrated vacuum and abatement

Companies seek to constantly improve their production methods. HBLED manufacturers are faced with many challenges including vacuum and abatement. **Mike Czerniak**, Product Marketing Manager, Exhaust Gas Management at **Edwards** discusses the benefits of combustion based abatement technology.

The technology used to manufacture high brightness LEDs (HBLEDs) made from gallium nitride (GaN) has developed rapidly over the last dozen years, and market growth has continued, despite the current economic slowdown. This is a combination of developments in LED technology, the size and contrast benefits LEDs offer in flat panel applications and adesire by both governments and individual consumers around the world to reduce energy consumption due to concerns about global warming.

Current market opportunities driving the expansion in LED production already include laptop computers, as well as liquid crystal displays (LCD) backlighting used in LED TVs and automotive applications. The LED consumer lighting market is also showing growth as LED efficiency has increased to over 100 lumens per watt. For LED technology to become truly competitive in mass-market applications, however, it must still achieve even greater reductions in the initial cost per lumen.

LED manufacturers hope to achieve this cost reduction through economy of scale that comes with high volume production. Increasing production is dependent upon demand. LED manufacturing strategies are focused on addressing the technical aspects of high-volume production, while also minimizing both the capital expenditures and operating costs of production equipment.

Figure 1: HBLEDs are replacing incandescent bulbs in automobiles.

As manufacturing processes scale to higher volumes, the relative contribution of variable costs to cost-of-ownership (CoO) often grows as fixed costs are distributed over the increased volume of production. In addition, ramping LED volume production also increases the demands on both vacuum and abatement systems, which must handle higher volumes of production gases or manufacturing by-products, respectively.

The GaN compound semiconductor manufacturing processes used to produce LEDs require large flows of hydrogen and ammonia. Because of the small size of the hydrogen molecule, this gas is difficult to pump, especially in high volumes. At the same time, depending on the abatement technology in use, ammonia can produce solid by-products during the waste removal process that tend to clog the bath, recirculation pump and drain pipes in conventional wet scrubbers, requiring them to be cleaned every month or two, during which time the production tools are idle, reducing productivity and increasing tool CoO.

This article discusses the pumping and abatement requirements needed to accommodate the use of hydrogen and ammonia in HBLED production, and highlights an abatement technology that can significantly reduce manufacturing cost of ownership. It also presents a new approach to implementing vacuum and abatement systems within a process tool that can help to further reduce system CoO.

Vacuum Pumping

Pumping hydrogen, regardless of the process involved, presents certain challenges because of the gas's small molecular size and low viscosity, which is approximately half that of nitrogen. While these characteristics are not an issue when

Figure 2: Edwards' iXH dry vacuum pump has been specifically designed to handle the high volumes of ammonia and hydrogen involved in HBLED production

pumping at low pressures, they become a problem when the gas is compressed towards atmospheric pressure in a vacuum pump. At these pressures, due to its low viscosity, hydrogen tends to leak back through pump clearances, reducing the effective pumping speed. Hydrogen also has a much higher thermal conductivity (seven times greater) than heavier gases such as nitrogen. As a result, systems pumping hydrogen typically have a different thermal profile and different component dimensions than those pumping nitrogen. A pump optimized to deal with hydrogen ideally operates with clearances set to account for the thermal properties of the gas, and integrates a progressive nitrogen purge capacity to offset the challenges of pumping this lighter gas at higher pressures. Finally, since hydrogen is flammable if mixed with an oxidant such as air, the pump exhaust must be appropriately managed to avoid ignition.

As mentioned earlier, pumps used in the metalorganic chemical vapor-phase deposition (MOCVD) processes used to manufacture LEDs also handle high volumes of ammonia. This means they must be highly corrosive-resistant. Modular dry pumps have proven to address the challenges of pumping both ammonia and hydrogen in a production environment, while also offering potential CoO savings. Edward's iXH pump (Fig. 2), for example, has been specifically designed to meet the challenges associated with pumping high volumes of ammonia and hydrogen with enhanced purge flow, temperature-controlled operating range, light gas performance and corrosive resistance and improved powder handling. In addition, Edwards' pumps incorporate a unique, proprietary seal technology that helps to prevent ammonia leaks. These capabilities reduce maintenance intervals and extend pump life, thereby helping to reduce overall tool CoO. The vacuum pump offers further CoO savings through reduced energy consumption.

Exhaust Gas Abatement

In LED manufacturing, the extraction, safe handling and disposal of gases from MOCVD processes significantly contribute to manufacturing CoO. The conventional approach to exhaust gas management uses a wet scrubbing technology that adds significant costs to the manufacturing process in terms of energy use, water consumption and treatment.

Combustion-based abatement offers an attractive alternative to wet scrubbing. While capital costs are approximately the same, combustion-based abatement systems offer greatly reduced operating costs, as illustrated in Figure 3. Their large input flow capability, typically equivalent to three to five process tool exhausts, eliminates capacity constraints and helps minimize capital expenditures. At the same time, their use of the exhaust gases as the main fuel in the abatement process significantly reduces energy costs. In addition, innovative reaction chemistries minimize the formation of unwanted by-products such as nitrogen oxides (NOx), a regulated emission, or ammonium solids, which require increased system maintenance downtime, thereby reducing tool productivity.

The wet scrubbing technology typically used in the GaN MOCVD process essentially bubbles the gases through a tub of water where they are absorbed. This process, however, does not remove hydrogen, which is the most common waste gas produced in the MOCVD process. While hydrogen emissions are not regulated, allowing the gas to be vented directly into the

Abatement System	**SG3000**	**Wet**
No. tools per abatement system	6	3
Fresh water cost	$0	$4,505
Waste water cost	$0	$0
Power cost	$4,505	$751
Nat. gas cost	$2,147	$0
H2 cost	$501	$0
CDA cost	$0	$0
H2SO4 dosing cost	$0	$1,430
NH3-N treatment by Gas striping tower	$0	$751
Value of Ammonium sulphate recovered from gas stripping	$0	-$2,893
Heat recovery	-$20,000	$0
N2 Cost	$158	$158
GaNcat cartridges/year	$0	$0
GaNcat Cartridges disposal costs/year	$0	$0
Potential value of heat recovered from exhaust gas	$0	
Total Utility Cost	**-$12,689**	**$4,702**

Figure 3: Cost Comparison of Operating Costs for Combustion-Based Systems vs. Wet Scrub Abatement Systems

atmosphere, there is a slight, but potential danger that static electricity could ignite the hydrogen during the abatement process, causing an explosion and fire.

The second most common gas produced as a by-product of the MOCVD process is ammonia. While water scrubbing can eliminate this gas, there is a danger, when hard water (water containing calcium or magnesium salts) is used, that the ammonia will react with the salts in the water producing ammonium solids. Hard water occurs anywhere that mountain run-off is a major source of water, which constitutes a large portion of the globe. As mentioned earlier, these ammonia solids can build up in the system, thereby increasing maintenance requirements and increasing CoO.

Combustion-based abatement technology solves both these problems by burning the exhaust gases in a controlled way. (Figure 4 provides a schematic of a typical four-stage combustion abatement system.) The only outside energy required is that to operate a small pilot light, similar to the ones used in home gas furnaces or stoves. Not only does this approach eliminate the hydrogen safety issue and the maintenance problem caused by ammonium solids, it offers significant reductions in energy costs compared to wet scrub technology.

In addition, the combustion-based system is air cooled, with the air flow being generated by the house extraction system. This air-cooled design ensures that combustion by-products are efficiently transported from the system to the factory central scrubber or dust filter. An air-cooled system eliminates many of the fixed and operating costs associated with a wet process, including the cost of the water itself, the capital and operating costs associated with water pumps, the energy to run them and water treatment costs. Air-cooled systems are also simpler in design and have fewer moving parts. As a result, maintenance intervals are increased, while maintenance times and spares inventory requirements are reduced, all of which helps to further reduce system CoO.

When burning ammonia in a combustion-based abatement system, there is always the danger of creating NOx emissions, which are strictly regulated in most regions of the world. Edwards' Atlas and Spectra G (Fig. 5) abatement systems avoid this danger by using a proprietary process that carefully controls the oxidation of the gases being burned to minimize NOx emissions.

In addition to the benefits of combustion-based exhaust systems in terms of safety, lower CoO and reduced environmental concerns, combustion-based abatement technology has a well-established track record for reliability. Hundreds of combustion-based exhaust abatement systems are deployed at a variety of companies in the semiconductor, flat panel and solar cell industries. The efficiency of its gas treatment process has been field-tested and meets the most stringent air emission regulations in Europe, the United States and Asia. It is currently experiencing a high rate of adoption by leading LED manufacturers world wide.

An Integrated Solution

The benefits of integrating related subsystems in a manufacturing tool has been proven in a variety of industries, such as semiconductor and flat panel manufacturing, to help reduce overall manufacturing CoO in a variety of ways. For example the combined vacuum and exhaust management systems provide enhanced safety, process tool compatibility, minimum footprint and reduced CoO. In addition, since they are housed in a single extracted cabinet with a single utility connection, these integrated systems provide a highly cost-effective means of providing protection should leakage occur.

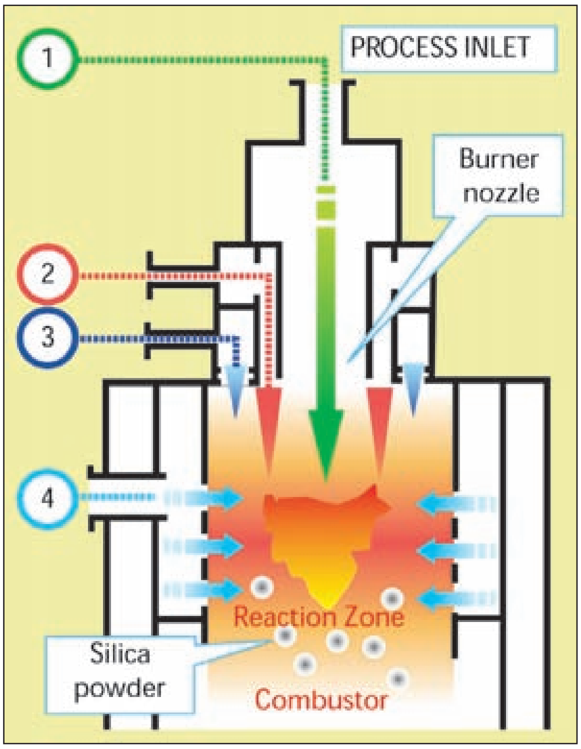


Figure 4: Four Stage Combustion

Using an integrated vacuum pump and abatement system, such as Edwards' Zenith system can reduce installation time by up to 70 percent, cut installation costs by over 60 percent and eliminate over 50 percent of facilities connections. Overall capital expenditures are also significantly reduced. In the case of phosphide MOCVD, the Zenith also significantly improves the safety when dealing with toxic gases like phosphine and arsine.

Author Biography:
M.R. Czerniak, Product Marketing Manager, Exhaust Gas Management, Edwards.

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

SemiLEDs: Vertical architecture boosts LED performance

Combining a metallic foundation with a vertical current path creates an LED that prevents current crowding, realizes excellent thermal management, and delivers the high efficacies and long lifetimes needed for general illumination, says **SemiLEDs' Trung Doan.**

GaN-based LEDs are already serving many applications. They are illuminating mobile phone keypads, backlighting LCD displays, generating camera flash, and providing the red and green components in full-color outdoor displays. With recent breakthroughs in efficiency and cost, high-brightness, high-power versions of this device are starting to gain traction in general lighting.

The general lighting market promises to be very lucrative, but success in this sector requires low-cost manufacture of LEDs with excellent thermal management, efficacy, and reliability. Managing the heat generated by the LED is critical, because increases in junction temperature shorten device lifetime and cut efficacy – a 20 degree C rise in junction temperature drives down output power by at least 5 percent. An efficacy greater than 100 lm/W is also needed if LED products are to offer a viable alternative to incumbent lighting technologies. And these solid-state devices must also deliver a reliability of 20,000 hours under continuous operation and have a cost of ownerships that exceeds 200 lumens per dollar.

At SemiLEDs we have developed an LED that can meet all these criteria. Our firm, which is headquartered in the US and has chip fabrication facilities in Hsinchu Science Park, Taiwan, released an I-core LED in December 2009 that is capable of very high levels of performance, thanks to its vertical device architecture and metal alloy base.

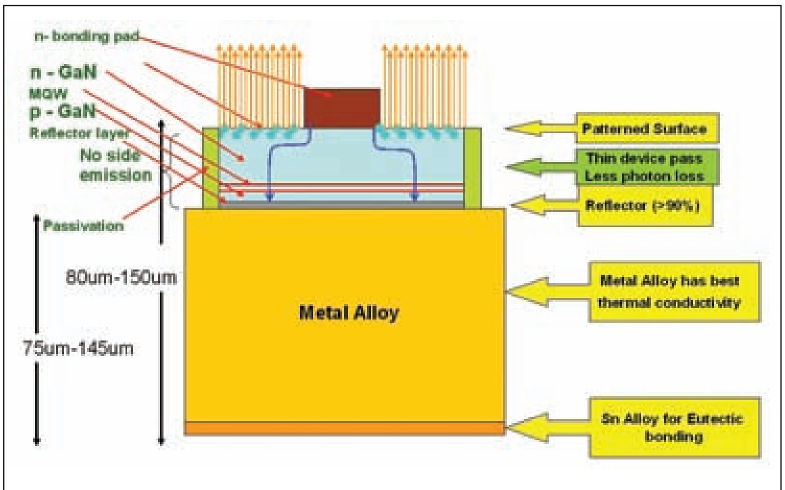
The I-core shares the vertical LED (VLED) structure of all our products. It consists of: a mirror, directly deposited on copper alloy that acts as an anode and reflector; a 0.2 µm thick p-GaN/p-AlGaN layer; an InGaN/GaN multiple quantum well active region; and a 4 µm thick n-GaN layer (see Figure 1). The n-surface is patterned to enhance the light extraction. One benefit of this novel architecture is that it avoids the current crowding issues that plague conventional LEDs, because current can pass vertically from the anode to the cathode. Additional strengths are that the photons generated in the active layer can escape without passing through any semi-transparent conductive contact layer, and the extraction efficiency is improved with the mirror, which is highly reflective at visible wavelengths. Thanks to this design, our LEDs trap far less light than typical, large LEDs on sapphire.

Copper alloy vs sapphire

Our VLEDs have excellent thermal management that stems from the copper alloy foundation. The thermal conductivity of this metal, 400W/mK, is far higher than that of any substrate currently used for LEDs – it is more than ten times that of sapphire - and this gives our devices superior heat dissipation through the chip and out of the heat sink. This leads to a lower junction temperature and ultimately a higher-efficacy, longer-lasting device.

Conventional LEDs are also hampered by the location of the n- and p-type electrode pads. Both these pads are located on the same side as sapphire, an electrical insulator. Device processing involves the removal of p-GaN and the active region to expose the n-GaN layer on which the n-pad is deposited. The downside of all this processing is that it cuts the total emission area of the device.

Figure 1: SemiLEDs' devices employ a vertical conduction geometry and feature a metal alloy foundation. The metal alloy is highly reflective, and can boost the light extraction efficiency of the LED



A further weakness of the conventional device architecture is associated with its routing of the current through the chip (see Figure 2). As current passes from the anode to the cathode it spreads laterally along the n-GaN layer. This causes current crowding underneath the n-pad, which increases serial dynamic resistance and operating voltage, and ultimately impairs LED efficacy. Conventional GaN-on-sapphire LEDs can also be hampered by a lack of current spreading in the p-GaN layer, due to its low conductivity.

Weaknesses associated with GaN-on-sapphire LEDs, such as current crowding issues and the low thermal conductivity of the substrate (which is typically 100 μm thick) force conventional LEDs to operate under low current density conditions in order to prevent thermal problems. This hampers the application of conventional GaN LEDs on sapphire, especially high-power versions used for required for solid-state lighting applications. Current crowding is not an issue in our VLEDs, because the current travels vertically from the bottom anode to the top cathode (see Figure 3). This path slashes the serial dynamic resistance compared to conventional LEDs on sapphire. In addition, n-GaN has much higher conductivity

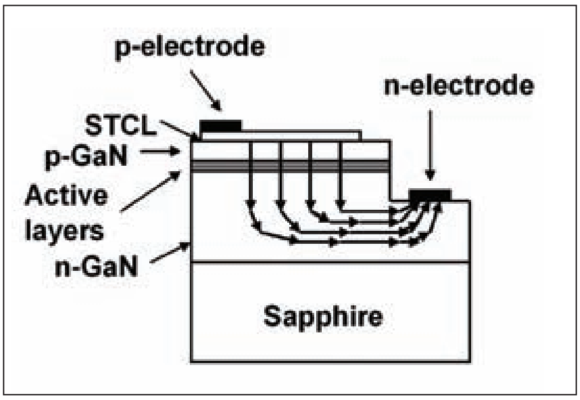


Figure 2: One of the weaknesses of conventional LEDs on sapphire is their lateral conduction path between the n- and p-type electrodes. This increase the resistance in the device, thereby increasing the LED's operating voltage and reducing its efficiency

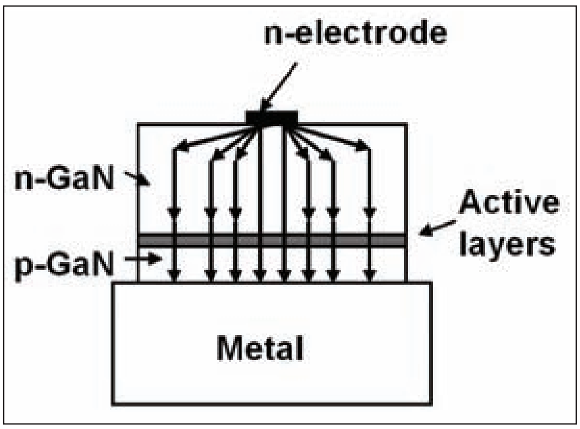


Figure 3: One of the strengths of SemiLEDs device architecture is the vertical conduction path that abolishes current crowding

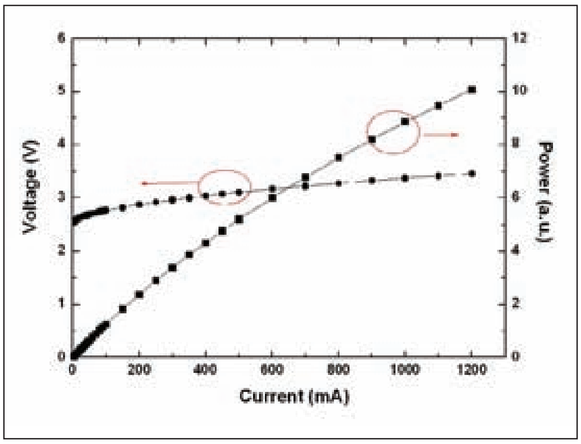


Fig.4 Even at very high drive currents, the operating voltage of SemiLEDs I-core LED is well below 4V

than its p-type cousin, and this enables sufficient current spreading – there is no need to resort to a semi-transparent conductive layer.

Avoiding the use of this semi-transparent layer reduces light absorption in the device, thereby boosting LED output, and the excellent current spreading in the n-type layer opens the door to scaling chip dimensions without impacting efficiency.

LEDs with a vertical architecture can generate heat in the active region and at the metal contact, and dissipate this energy through the p-type GaN interface. However, we have found that heat extraction can be even faster if the thin p-type GaN (~0.2 μm) layer is directly laid on the layers of a high thermal conductivity metal alloy. Thanks to faster heat dissipation, it is possible to realize the high drive currents needed for LEDs targeting solid-state lighting applications.

Electrode design

The efficacy of any LED depends on its electrode arrangement, because this affects how light can escape from the top surface of the n-GaN layer. In our devices, we employ an n-electrode pattern that takes into account the current spreading of the n-GaN layer. We have found that each n-electrode line can spread the current over 250 μm. The electrode design for our I-core LED differs from the first-generation devices, and improves light extraction and brightness. Thanks to higher conductivity in the n-GaN layer, the total area covered by the electrode can be reduced, leading to less light being blocked by this structure. On top of this increase in brightness, the latest design offers a high degree of compatibility with single and double wire bonds.

The efficacy benchmark for LED targeting conventional lighting is 100 lm/W, and our I-Core device is more than capable of this – it can deliver 120 lm/W at a drive current of 350 mA, which corresponds to a forward

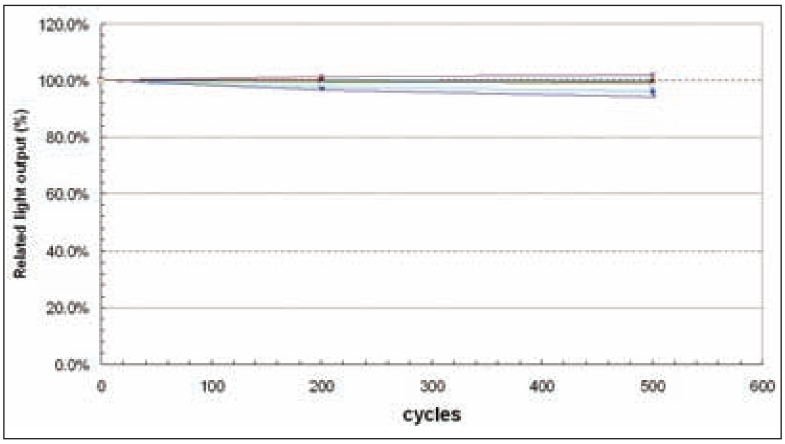


Figure 5: SemiLEDs latest LEDs are more robust than previous products. Output fell by less than 5 percent during a 2,000 hour burn in test at junction temperature of 115±10 degrees C

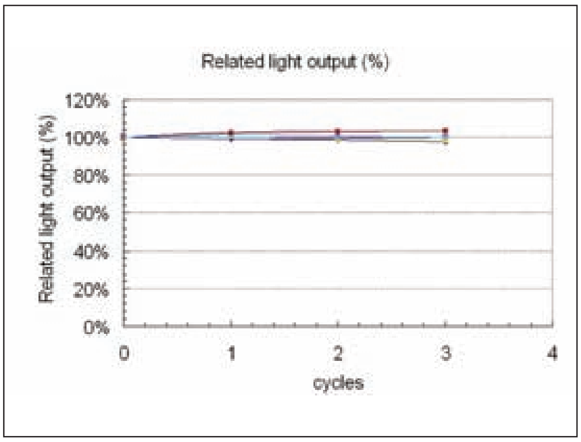


Figure 6: The reliability of packaged VLED chips in light output power after 3 times reflow

voltage is only 3.0V. This performance is realized by housing the device in a white LED package. When designing our I-core LED, we did more than just focus on optimizing the brightness of the chip – we also strived to improve reliability. Assessments were made by placing the chip in a SMD package with silicone capsulation, and testing this entity in a closed space with a stable ambient temperature. The device was mounted on a PCB and driven at 350 mA, and we calculated that its junction temperature was 115±10 degrees C. These tests showed that the light output fell by less than 5 percent, even after a burn-in test of 2,000 hours. In real life applications at room temperature, no degradation of light output has been observed so far.

The excellent reliability of our I-core LED, which builds on the performance of earlier products, is also evident from the results of our thermal shock tests. These tests involved assessments of packaged LEDs held at temperatures ranging from –40 degrees C (15min) to 125 degrees C (15min). After 500 cycles of high and low temperature aging, our packaged I-core LEDs showed: no obvious degradation of the light output power; a typical forward voltage shift of less than 1 percent for a 350 mA drive current; and no leakage current at -5 V.

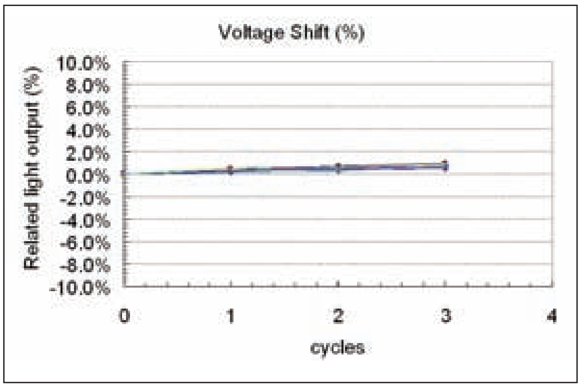
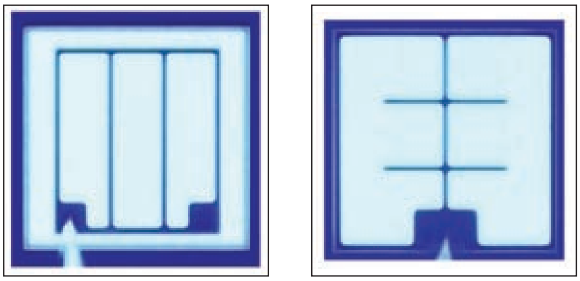


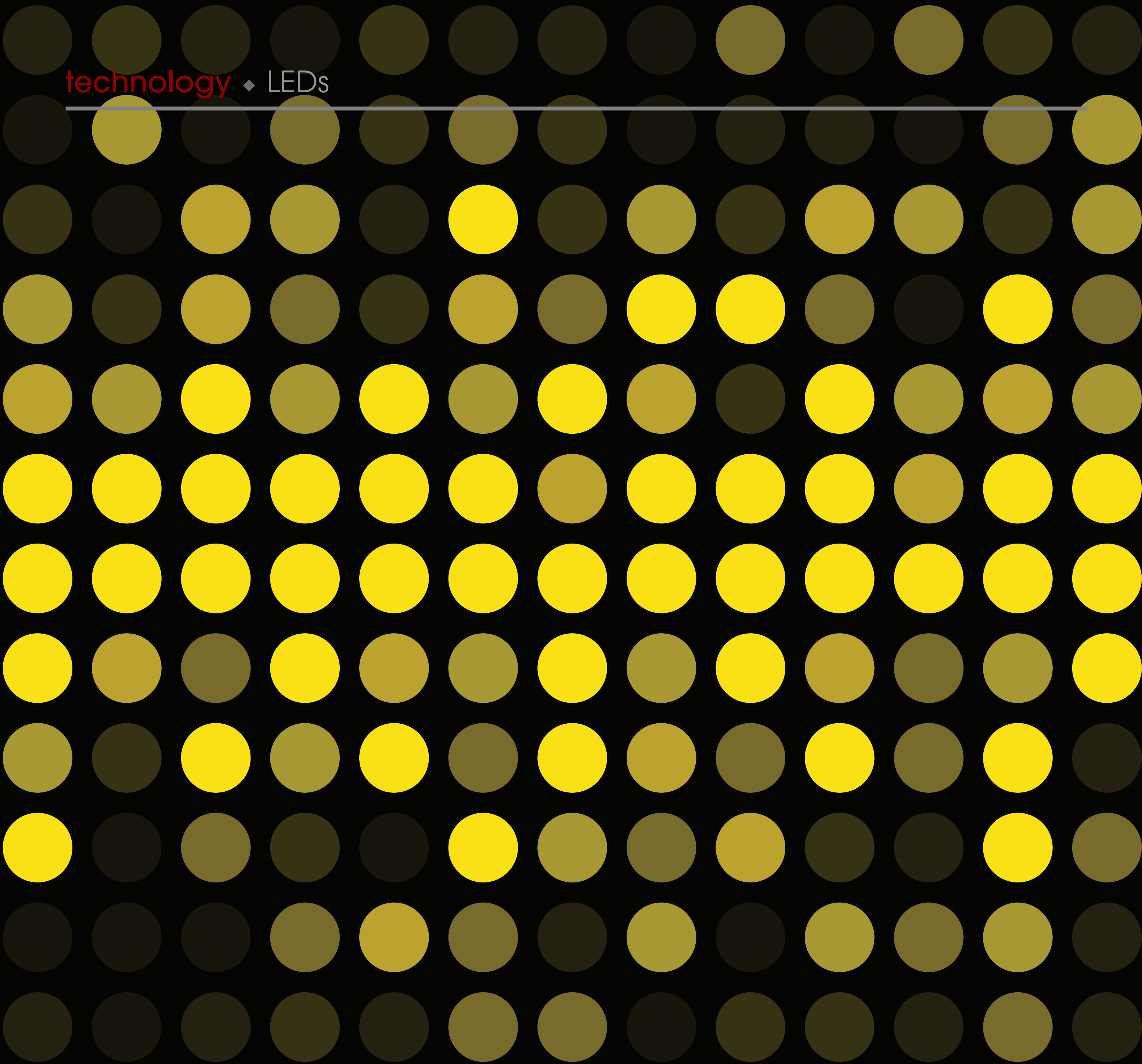
Figure 7: The reliability of packaged I-core LEDs in operation voltage at 350mA after 3 times reflow

Our packaged I-core LEDs are capable of operating in harsh environments, such as desert conditions or on the outside of an airplane. Figure 6 shows the reliability of packaged I-core chips and light output power after subjected to three times reflow cycle testing, a process that involves heating the device from ambient to around 250 degrees C, and then cooling it at up to 6 degrres C per second. The light output remains steady at 100 percent throughout these cycles. Figure 7 shows that the packaged I-core LEDs show no operation voltage failures after three times reflow cycle testing.

When we designed our I-core LED, we addressed all the major issues that are currently facing high power LEDs. Our latest product is not only the most reliable device that we have ever made – it is also significantly brighter. This is partly the result of a robust design that delivers far high light extraction, and also a consequence of a superior epitaxial structure that delivers a higher internal efficiency. Another key strength of the I-core is the patented, proprietary MvpLED technology on which it is based, which features a vertical structure with a copper alloy base that provides multiple benefits over conventional LEDs on sapphire. Thanks to all these strengths, we believe that the I-core is well-positioned to be at the forefront of the solid-state lighting revolution.



SemiLEDs has improved the electrode geometry of its LEDs. The electrodes in the previous generation of devices (left) covered a higher proportion of the chip area than the I-Core LED (right), and this led to higher light absorption



Seren promises brighter, cheaper LEDs

A UK start-up is claiming to have developed a novel device treatment technology that paves the way for the manufacture of brighter, lower-cost LEDs.
Richard Stevenson investigates.

General illumination offers by far the most lucrative market for the white LED. But if this nitride-based device is to grab significant market share from incandescents and compact fluorescent lamps, then its output will have to increase and production costs fall.

One company that claims to have a technology that can do just this is a little known UK start-up called Seren Photonics. This University of Sheffield spin-off, which takes its name from the Welsh word for star, has an intriguing, low-cost device treatment that is claimed to boost light output by increasing extraction efficiency and internal quantum efficiency.

"We combine fundamental physics and device technology to achieve a new type of device," says Tao Wang, the technical director and the current driving force behind the company's technology. Exactly how the company increases its LED output is a bit of a mystery, because Wang is not prepared to go into specifics at this stage. That's a shame for everyone with an interest in the inner workings of LED chips, but Wang's tight-lipped approach is understandable: although Seren has filed for a key patent, it is yet to be granted. But when it is, Wang assures us that he will lift the veil and publish a series of papers detailing the technology.

Nitride veteran

Wang's interest in the nitrides goes back a long way, and before he came to the UK he spent five years working at the Nitride Semiconductor Organization in Tokushima, Japan. During his time at this company, which is spin-off of the local university, he focused on epitaxial growth technology. While he was there he yearned for the freedom associated with an academic career, and in 2002 he took a lectureship at the University of Sheffield. "Sheffield has good facilities, and allows me to have my own group," explains Wang.

When he arrived at Sheffield he began by focusing on improving the epitaxial quality of ultraviolet LED structures. "The UV LED is much more sensitive to dislocation density than the blue or the green. We wanted to use a different, novel technology to improve the crystal quality by reducing the dislocation density."

The standard approach to forming these structures involves a process known as two step growth: deposition of a low-temperature GaN nucleation layer; followed by growth of a thick GaN layer and then the main structure at a higher temperature. "There are a number of issues relating to that two step growth, particularly for the UV LED," explains Wang. "For example, there are strong external absorption issues, a cracking issue, and there's another major point – [Shuji] Nakumura's patent. You can't get around that."

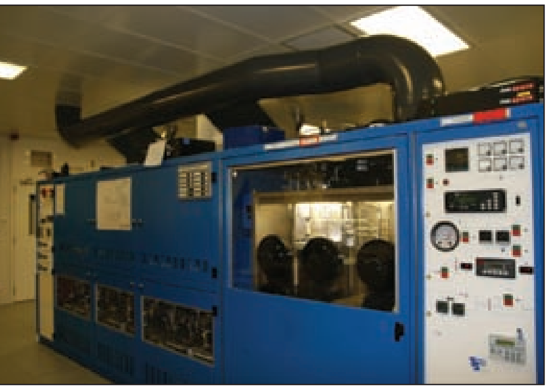
Wang and his team explored a different route to nitride growth based on a high-temperature, AlN buffer. Although this technology was developed for UV LEDs, it can be used to improve the crystal quality of any form of nitride device.

According to Wang, there are several advantages associated with the high-temperature AlN buffer approach, including freedom regarding the thickness of this AlN layer – it just needs to be smooth. Further gains for LED production including a massive reduction in the density of dislocations, particularly the screw type. Evidence for this is provided by X-ray rocking-curve measurements, and transmission electron microscopy.

While Wang was developing his process for improving UV LED material quality, he started to think about a new way to process devices. The technology that underpins Seren Photonics was underway. "The idea started in 2004, and we did some preliminary work in July 2007, which is directly related to the IP technology that Seren has," explains Wang.

Getting going

When researchers at most universities think about starting a company, they have to go out and try and win funding themselves. At Sheffield, though, things are a quite different indeed. In 2005, this university gave the rights for all of its university-owned research to Fusion IP, which has been supporting Seren Photonics since its inception in December 2009.



Seren Photonics has access to growth facilities at the EPSRC National Centre for III-V Technologies in Sheffield

Seren is currently led by managing director, Carl Griffiths, who has experience in the III-V industry, having previously worked for the Welsh instrumentation firm ORS. Griffiths has a very wide experience in marketing and management, according to Wang, plus good expertise in demonstrating the company's LEDs to potential customers. Seren also has a chairman, Peter Grant, who is the director of Fusion IP, plus an employee in charge of financing.

Funding for the development of Seren Photonics' technology partly comes from Fusion IP and another, undisclosed company. In addition, efforts can be supported by some of the research grants that Wang receives from the Engineering and Physical Sciences Research Council (EPSRC). It's hard to put an exact figure on total funding, but Wang estimates that it is about £0.5 million, which is enough to support two post-docs that are developing Seren's technology. More investment in the company could follow shortly – several companies have been in contact, and this may lead to further funding for Seren, or the sharing of its technology with other chipmakers.

Today the devices are fabricated at the EPSRC National Centre for III-V Technologies, and Seren just has to pay the costs of accessing these facilities. Measurements of the devices that are produced are performed in Wang's lab, which is equipped with tools for measuring LED photoluminescence, electrical behavior, and light output. The only part of LED fabrication that cannot be performed by Wang's team is the packaging of the chip. "Eventually we'll have to do this, but at this moment we would like to make a collaboration with a company that does packaging."

So today's evaluations are based on bare chips. They have found that their treatment of 0.3 mm by 0.3 mm chips driven at 20 mA leads to a doubling of light output, while plotoluminescence intensity undergoes a massive hike, increasing by a factor of 6-10.

Wang claims that his treatment can not only boost LED output – it can also cut the cost-per-lumen of these emitters. He argues that his process is compatible with LED epiwafers of reasonable material quality. When treated with his process, he claims that they can outperform LEDs made with the very best material. "With Nichia, the crystal quality is high, but the cost is also high. Our idea is to use standard, commercially available epiwafers – not the best available."

Obviously, lowering the cost-per-lumen by this approach is only possible if the treatment process per wafer is cheaper than the difference in price between the highest quality epiwafers and standard equivalents. Wang claims that this is the case. He says that his treatment technology requires just a few processing steps, and these can be performed with the existing equipment found in chipmakers' manufacturing facilities, so there are no concerns over high capital expenditure.

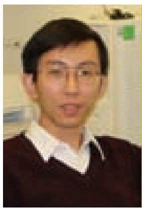
LEDs deployed for general lighting applications are driven at high current densities, and their performance is hampered by droop. This phenomenon, which is attracting tremendous debate over its origin, causes a decline in external quantum efficiency as drive current increases. Wang says that his treated devices are less susceptible to droop, because they are able to deliver an equivalent light output at lower drive current.

One key question concerning Wang's treatment is whether it could deliver a doubling of the output of all forms of chip. Cree recently reported a lab device delivering over 200 lm/W, and other researchers have claimed that the theoretical efficiency limit for LEDs is just over 300 lm/W. The implication is that a doubling of light output from Cree's chip is impossible. However, Wang argues that theoretical efficiency figures can be misleading. "The theoretical value for the limit depends on a lot of factors. I've heard a talk that says 480 lm/W. It's unclear – nobody knows."

Chipmakers are a secretive bunch, and it is possible that one of them may already be using a process like that developed by Wang to boost LED output. But Wang thinks that this is unlikely. He argues that his process is not related to improving epitaxial quality, which is the path of progress pursued by the leading chipmakers, such as Nichia and Cree. But to be on the safe side, Wang and his colleagues have employed experts to trawl through the patent literature on their behalf. This turned up nothing that encroaches on Seren's technology.

Even if Seren's IP is safe for year to come, it would be tough for this start-up to take on the big chipmakers. However, that is not the plan for the company – it wants to license its technology to these firms, and work with them. To this end, over the next twelve months the Sheffield spin-out is aiming to attract more funding from companies that are interested in sharing its technology. Armed with this cash, it will then develop better devices for sampling.

Seren's technology is still it its infancy, and it will be interesting to see how much progress can be made over the next few years. "Currently we don't know what is the limit that we can have – it could be ten times higher, it could be twenty times higher," enthuses Wang. But even if it's only half as good as that, then Seren is destined for success, because its technology will play a key part in the development of brighter LEDs for general lighting.



Tao Wang is a Reader in Semiconductor Materials and Devices and an EPSRC Advanced Research Fellow

LED has competition for lighting

There is a lot of hope for LED in general lighting applications but the race is far from won with competing technologies also claiming a stake in this lucrative market. **Thomas P. Pearsall**, General Secretary of European Photonics Industry Consortium (EPIC) asks what will it take for LEDs to succeed against competing solutions.

Almost everyone knows that HB-LEDs offer a new source of lighting with lower energy consumption and longer lifetime. LEDs are now mass-manufactured and sold on a commercial basis. They are the preferred solution for many important lighting applications. A major exception is general lighting applications in home and business applications, which together account for more than 66% (Light's Labour's Lost, IEA, 2006, p.35) of the electrical consumption for lighting.

The three main areas where attention is needed in order of priority are marketing, manufacturing cost reduction and performance improvement. LED lighting solutions are more expensive than all other commercial alternatives on a euro-per-lumen basis. LEDs can be sold today in high-end luminaires where the unique performance and appearance of LEDs can contribute to the added value. Two examples are automobiles and backlighting for flat-panel displays. However, the lighting industry has chosen to aim instead at low-end bulb replacement. LED solutions are not cost-competitive for this market segment. In our opinion this marketing strategy needs modification.

In general lighting applications, customers do not buy technology. They purchase performance and pay attention to cost. Since LEDs are efficient, operating costs are low, and the cost of ownership is essentially the cost of acquisition. The cost of LED "light bulbs" in euros per lumen needs to decline by 75% before they can be competitive with existing fluorescent alternatives. On the other hand, there is market space for a higher-priced, higher-functionality "smart LED" luminaires which could not be challenged by fluorescent solutions.

Manufacturing costs for LEDs will come down. The Haitz Law learning-curve predicts that the cost per lumen will be 50% lower by the time the current generation of compact fluorescent lamps (CFL) burns out. Cost reductions for general lighting will come from photonic integration, manufacture on larger substrates, optimisation of chip size, reduction in current density, improvement in wavelength conversion technologies, and better packaging for thermal, electrical and optical management. A reduction of 75% in costs within five years seems to us to be within reach.

Figure 1. LEDs have a way to go before becoming the number one lighting choice

A competitive lamp for general lighting should produce about 600 to 1000 lumens. Commercially available LED lamps do not yet reach this level of emission. There is a lot of space inside the "light bulb" housing, and redesign of LED lamps can make use of this space to incorporate arrays of LEDs that operate at the maximum efficacy point, rather than at maximum brightness. More engineering work is needed to develop phosphor technologies that are highly reproducible with colour temperatures and which do not age.

These advances would make sensible standardization possible, so that commercially available lamps correspond to accepted levels of performance both in terms of light

An excellent example is the mobile phone. How many owners of this widely used instrument know that there is a modulation-doped mobility-enhanced GaAs transistor inside that exploits quantum mechanics to reduce noise and power consumption? (answer: fewer than one in one million). The features that have assured the success of mobile phones are performance, appearance, ease of use, acquisition cost, reliability, etc

emission and performance over lifetime. Such standards would give a boost to sales on one hand, and prevent the market space from contamination by cheap, underperforming imitations.

Marketing HB LEDs

An important principle to retain is that practically no one is willing to pay more for a product just because it exploits new or exotic technology. Few people understand or care that some of the world's most skilled scientists and engineers have toiled for years to develop technology into a product.

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Appearance

In the case of general lighting, there are two ways to present any light source. Either it is incorporated in a luminaire, or it is sold as a replacement bulb. The appearance factor of these two presentations is radically different. Lighting fixtures with attractive appearance are sold for hundreds of euros. On the other hand, the appearance factor of a GLS lightbulb is nearly zero, although there is a familiarity feature, as it is about 100 years old. Cost of acquisition can be traded off in exchange for appearance, as Apple has demonstrated with the i-Phone. HB-LED lamps, with a high acquisition cost, can be successfully marketed as part of an expensive luminaire. Examples of expensive luminaires are automobiles, LED-LCD television, building illumination, etc. As detailed below, these are exactly the areas where HB-LED lighting has strong market penetration.

HB-LED Marketing successes

This short list is not exhaustive, and illustrates how the HB-LED can be used successfully as a permanent, non-replaceable lighting system in a luminaire that will be discarded and replaced periodically for other reasons. Periodic replacement helps to ensure a continuing market for LED lighting. The HB-LED is chosen because of its performance in the application. The LEDs represent a small part of the cost of the luminaire.

- **Automotive lighting**
  HB-LEDs combine high-brightness, low-power consumption, long lifetime, attractive full-colour design capability. A challenge: reach optical power of 1000 lumens from a single chip.
- **LED Backlighting of LCD displays**
  This is the fastest-growing market segment for HB LEDs, LED backlight panels come in two different designs: edge-illumination and area illumination. Coloured RGB LEDs are used along with white LEDs. 2-d area illumination enables enhanced contrast and lower power consumption.The volume leading application is backlighting of LCD screens for PCs. This market will saturate around 2012 when all PC screens will be LED backlit. The volumes for television displays will continue to grow through 2015 when this market is expected also to saturate. Samsung is the leading adopter and investor fo this application.
- **Surgical Lighting**
  LED lamps are a lighting source for surgical theatres that does not "cook" the organs under operation. A challenge: marketing needs to assure that LEDs lamp design can produce the same colour temperature and colour rendering from lamp to lamp and from theatre to theatre and over time. Consistent colour balance and rendition are key to the surgeon's identification of diseased/damaged tissue.
- **Architectural and Outdoor Lighting**
  LEDs projection lighting opens up a new dimension in architecture. There are increasing examples of lighting that defines new facades, effectively replacing architecture. No other source combines luminance and access to the full colour palette. Outdoor street lighting

benefits from the fast and simple turn-on of LED lamps to implement lighting-on-demand. A challenge: can it be shown that outdoor lamps with a good CRI actually require less luminance and less power compared to a low-CRI lamp (like sodium vapour) to achieve the same lighting perception?

The lighting customer pays two costs: acquisition and operation. The LED has a relatively high cost of acquisition compared to other lighting solutions, while the cost of operation is the lowest. At the moment of purchase, the cost of acquisition is clearly displayed, but there is little or no information about the cost of operation. It is no wonder that customers overwhelmingly choose the lighting source with the lowest cost of acquisition. Consumers may be willing to pay a higher cost of acquisition if they can justify the expense. A pleasing appearance, new and useful functionality as well as overall cost payback in 3 to 5 years makes the proposition attractive.

Lighting manufacturers have uniformly decided to manufacture and market LEDs in the form of GLS bulbs and halogen lamps. This decision removes the appearance factor from pricing. They have also decided not to introduce new functionality (such as wireless control from a mobile phone). This decision removes the functionality factor from pricing. As a result, the adoption of LED lighting will depend only on the payback period. Since the payback period is variable, depending on usage and electricity tariffs, a precise number cannot be printed on the package, so the customer has no information. In our opinion this marketing strategy will lead to disappointing results and slower than necessary takeup for LEDs.

In the scenario below we show the payback calculation for three scenarios, comparing an incandescent lamp, a CFL and an LED. The parameters used were taken from commercial products on sale in the largest department store in Paris, France, one that specialises in hardware, lamps and lighting. We assume that the lamps are used for 1000 hours per year, and that the cost of electricity is 12 euro cents per kWh. Pay-back time assuming that the incandescent is replaced every year, and the CFL is replaced after 5 years:

The first result is that the CFL gives a positive result on a cost of ownership basis in the third year. In this simple model, the LED is not a cost-effective alternative to the CFL. The break-even point for the LED relative to incandescent lamps occurs at 7 years, and if account is taken of the interest that could be earned on the initial saving, the break-even point occurs after year 10. The example illustrates that LED lighting is still too expensive to be competitive in general lighting applications, if cost of ownership is the only criterion.

In the second scenario below, we consider how much the cost of LEDs needs to be reduced in order to achieve payback within 5 years time. All payback calculations are estimates, and depend on local conditions of application as well as the acquisition and operating costs of lamps. For example, in Canada (and other northern countries), the incandescent light bulb is an helpful heating source as well as an inefficient lighting source. Replacement of incandescent lighting by CFL requires additional "operational costs" to supplement heating needs. In Mediterranean countries, the heat generated incandescent lighting is a negative. Use of air conditioning to evacuate this heat is part of the "operational cost" of incandescent lighting.

This simple model suggests that an LED lamp could be priced only a few euros more than a CFL in order to be cost-competitive in general lighting applications. Similar conclusions have been reached by Cleantech Approach, who have carried out a more detailed study, Solid-State Lighting Benchmark Analysis : Pricing Lifetime costs, and Payback that estimates payback times for LED lighting replacement for many applications. The conclusion of this study, with which we are in agreement, is that LED lighting is not yet cost competitive with compact fluorescent lighting (CFL).

pay back		YEAR									
		1	2	3	4	5	6	7	8	9	10
10 lumens/watt	Incandescent	5.1	10.2	15.3	20.4	25.5	30.6	35.7	40.8	45.9	51
40 lumens/W	CFL	11	11.8	12.6	13.4	14.2	23	23.8	24.6	25.4	26.2
80 lumens/watt	LED	35	35.42	35.8	36.3	36.7	37.1	37.5	37.9	38.4	38.8

pay back		YEAR									
		1	2	3	4	5	6	7	8	9	10
10 lumens/watt	Incandescent	5.1	10.2	15.3	20.4	25.5	30.6	35.7	40.8	45.9	51
40 lumens/W	CFL	11	11.8	12.6	13.4	14.2	23	23.8	24.6	25.4	26.2
80 lumens/watt	LED	13.0	13.4	13.8	14.3	14.7	15.1	15.5	15.9	16.4	16.8

Figure 2. Lighting product display in a neighbourhood supermarket. The red and orange ovals identify incandescent and halogen while the green shows fluorescent. The lamps are primarily by Philips and Osram.

Incandescent lightbulbs will soon be a thing of the past. As they burn out, they will be replaced. The halogen lamp, which looks like an incandescent, and gives off the same quality of light and heat, is a possible replacement proposed by major lamp manufacturers. They are three times more expensive than incandescent bulbs, but last only twice as long. Many consumers may understand that this is an even more expensive choice. It is probable that most of the 12 billion lamp sockets world-wide, which now contain incandescent lamps, will be filled by CFL when the incandescent bulb burns out. Since the CFL lasts for 5 to 8 years, this sets the time by which manufacturers should have a competitively priced product. As another example, I visited a neighbourhood store where I am likely to go to buy a lamp. Space on the shelves is precious, and allotted only to products that sell. In figure 2 you can see that the lighting display is crowded, with 70% of the product space given to incandescent technologies and 30% to CFL. There were no LED lamps on display in this location.

Manufacturing cost reduction

The current application space for general lighting involving point sources like light bulbs, consists of 12 billion sockets (see Light's Labours Lost, IEA, 2006). As incandescent lighting is being phased out, these sockets are being filled by principally by CFL replacements with a lifetime of 5 to 8 years. This lifetime creates a potential opening for LED general lighting sources. During the next five years, the costs of LED solutions need to drop by about 70% in order to reach competitive pricing levels.

The Haitz Laws observe trends in LED performance and cost. Currently the cost per lumen is dropping at about 10% per year. Extrapolating, using this rate tells us that we could expect a 40% overall cost reduction in 5 years due to "standard" ingenuity. Examples of improvements of this type would be:

- Processing on larger substrates
- Increasing chip size
- Lower cost, higher throughput laser lithography
- Reduction in current density to reduce losses from droop, and improve efficacy
- Optimise production for high yield
- Higher performance phosphors
- Filling the light-bulb form factor
- Innovations in thermal management
- Simplification of the electrical power interface

The Haitz Laws also tell us that disruptive concepts will be needed. These may be based on continuous processing of LEDs, new synthetic substrates and alternatives to phosphors for wavelength conversion that would yield strictly repeatable colour temperature. The third key element in cost reduction will come from standards. Standards bring important cost reductions from manufacturers, while raising appeal for consumers. Many engineers are working on standards for LEDs. There are international bodies like the CIE, as well as national ones such as Energy Star in the United States. A feature of a good standard is its relevance to the application under consideration. Standards for automotive lighting are not the same as general lighting.

Conclusion

Following the ban on incandescent lamps for general lighting, LEDs will not capture this opportunity because there are not yet units that deliver performance at competitive pricing. The space will be filled by CFL and to some measure by halogen lighting substitutes. LEDs manufacturers will have a second opportunity to replace CFL lamps approaching the end of their product life. Manufacturers should achieve something like a 70% reduction in pricing over the next five years in order to capture this opportunity.

Standard learning-curve improvements will not be enough to reach this ambitious target. Substantial disruptive invention will be needed. Large LED manufacturers have also major investments in the competing technologies, and will continue to exploit the lighting solutions that generate the best return on investment. However, if the pricing of LEDs and CFL lamps becomes similar, there may be a chance to implement a ban on fluorescent lighting as a way to limit mercury proliferation in the environment. Finding a future for LEDs in the general lighting market depends on a complex mixture of elements most of which need substantial improvements: marketing, manufacturing methods, performance, technology and standards, being the most important.

LED droop: Lumileds strengthens Auger case

Philips Lumileds has gathered further evidence to support its claim that Auger recombination is the primary cause of LED droop, the decline in a device's external quantum efficiency at higher drive currents.

Researchers Aurélien David and Michael Grundmann determined that droop is correlated to a shortening of the non-radiative lifetime after studying a 430 nm GaN LED featuring a double heterostructure with a 15 nm thick InGaN layer. "The non-radiative lifetime is quantitatively compatible with Auger scattering, which supports Auger as being this non-radiative mechanism," explains David.

Although the data presented by Lumileds is in quantitative agreement with Auger scattering, it is still possible that droop is caused by another mechanism. The origin of droop is highly controversial, and many different theories for its cause have been put forward over the last few years.

One alternative explanation for droop is interband absorption, which, like Auger scattering, is a non-radiative process that depends on a cubic power law related to the carrier density. However, David and Grundmann argue that interband absorption is related to optical re-absorption, and is strongly influenced by geometric factors. Droop, however, appears to have a universal, geometry-independent behavior.

Another explanation for droop is based on energetic carriers flying over the active region. However, the Lumileds' researchers say that this can now be ruled out, because this process would not influence the lifetime of the carriers trapped in the active region. They have shown that this lifetime shortens at higher current densities.

One scenario that they cannot rule out is carrier capture and escape. However, they believe that this is unlikely, because there is no reason why this process should depend on the cube of the carrier density.

Probing the sample

Lumileds' latest work on droop has focused on determining the evolution of radiative and non-radiative lifetimes by measuring the differential carrier lifetimes in LEDs, and combining this data with an internal quantum efficiency measurement that gave a peak value of 65 percent.

To determine differential carrier lifetimes, the researchers fabricated vertically injected LEDs, and drove them with 3 μs pulses to avoid device heating. A small, AC voltage was superimposed onto this series of pulses, and this provided a probe for the lifetime measurement.

By assuming perfect injection efficiency, the researchers calculated carrier density, and then the radiative and non-radiative lifetimes.

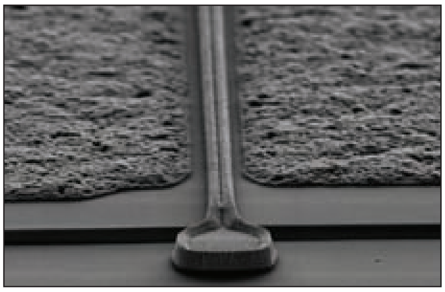
They found that the non-radiative contribution to the lifetime decreases as current increases, indicating the onset of an additional non-radiative process. At high current densities the radiative lifetime saturates, due to a process known as phase-space filling.

The researchers then compared their data with the standard model for the recombination rate, which involves the sum of: Shockley-Read-Hall recombination; radiative, bimolecular recombination; and an Auger process that depends on the cube of the carrier density. This model provided an excellent fit to the experimental data, and produced a value for the Auger coefficient of 10^{-29} cm^6 s^{-1}.

A. David et al. Appl. Phys. Lett. ***96*** *103504 (2010)*

Swiss speed AlInN HEMTs

A Swiss partnership between Colombo Bolognesi's group at ETH-Zürich and Nicolas Grandjean's group at EPFL have broken the speed record for AlInN/GaN HEMTs. When deposited on SiC, their devices can deliver a current gain cut-off frequency (f_T) of 144 GHz, an extrinsic transconductance of 480 mS/mm and a maximum current density of 1.84 A/mm. Silicon offers a cheaper, but inferior foundation that leads to a f_T of 113 GHz.



The AlInN/GaN HEMT fabricated by ETH Zürich and EPFL features Ni/Au T-shaped 100 nm gates. Credit: ETH Zurich

AlInN/GaN HEMTs promise faster speeds than their AlGaN/GaN cousins, but until now they have lagged a long way behind. "Our work has closed the gap for 100 nm gate lengths, presumably thanks to progress in the crystal quality of AlInN/GaN materials," explains Bolognesi.

He claims that the AlInN/GaN HEMT has the potential to outperform its AlGaN/GaN equivalent because its heterostructure can realize a higher channel electron density with a thin top barrier. "This allows one to place the gate electrode closer to the channel and thereby maintain a better electrostatic control of the transistor, so as to minimize the so-called 'short-channel effects' that curtail performance in shorter gate devices." Thanks to the combination of small gate-to-channel distance and a high electron density in the channel, these transistors can realize very high transconductances, and ultimately higher cut-off frequencies.

One of the weaknesses of the team's AlInN/GaN HEMT is its residual gate leakage, which prevents complete channel pinch-off at source-drain voltages above 3V. The source of this leakage might be caused by tunneling through the barrier, or leakage through either dislocation cores or the surface of the structure.

"If the gate leakage problem can be fixed, it will be interesting to explore how these devices behave in power applications," says Bolognesi. Another target for the partnership is the optimization of the epitaxial and device fabrication processes. "And of course, we are interested in finding out just how fast we can make these devices go."

H. Sun et al. IEEE Electron Device Lett. ***31*** *292 (2010)*

Complex barrier boosts UV output

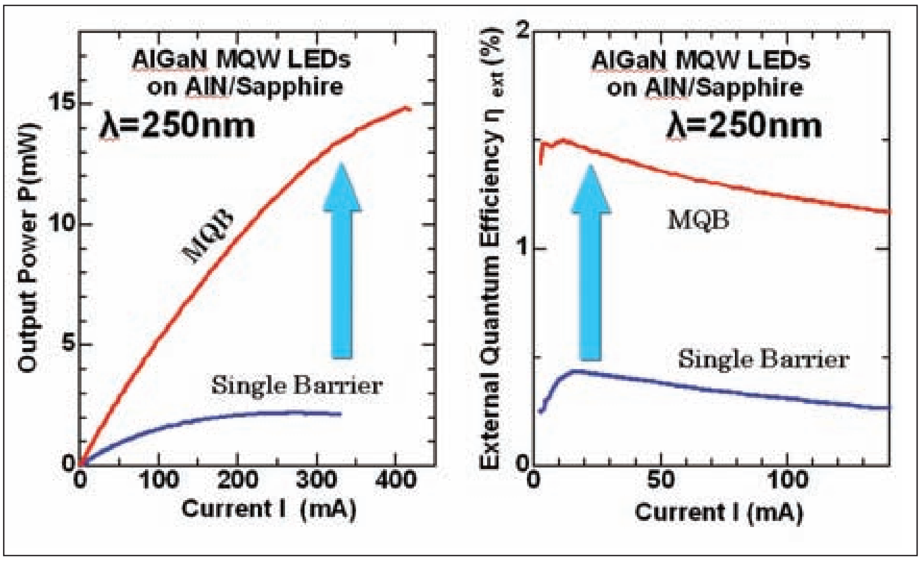
Japanese researchers have developed a complex electron-blocking region that can increase electron injection and deliver a massive hike in ultraviolet LED output.

Switching from a conventional single barrier to a multi-quantum barrier led to a seven-fold increase in the output of a 250 nm LED. The latter device delivered a maximum output of 15 mW, and a peak external quantum efficiency of 1.5 percent.

The team of researchers from RIKEN, Saitama, and CREST estimate that the modification to the barrier increased electron injection efficiency from 22 percent to 75 percent. Low injection efficiency - which results from a combination of electron leakage from the active region into the p-type layers, and low hole concentration in AlGaN layers with an aluminum content of 70 percent or more – is a major factor limiting the output of ultraviolet LEDs.

Lead author Hideki Hirayama told *Compound Semiconductor* that the team selected the thickness of the barrier and valley layers in their multi-quantum barrier to enhance its electron reflection. Calculations suggest that the effective height of the barrier is two-to-three times that of a single barrier.

Low-pressure MOCVD was used to grow the ultraviolet LED structure on a low-threading-dislocation density AlN buffer that was 3.4 µm thick, and had an "edge-type" dislocation density of 7×10^8 cm^{-2}.



The multi-quantum barrier has increased the output power and the external quantum efficiency of ultra-violet LEDs.

The ultraviolet LED structure consisted of: a 2 µm-thick, silicon doped $Al_{0.77}Ga_{0.23}N$ buffer; a three layer multiple quantum well with 1.5 nm undoped $Al_{0.62}Ga_{0.38}N$ wells and 6 nm $Al_{0.77}Ga_{0.23}N$ barriers; a 25 nm-thick undoped $Al_{0.77}Ga_{0.23}N$ barrier; a five layer multi-quantum barrier with 4 nm-thick, magnesium-doped $Al_{0.95}Ga_{0.05}N$ barriers and 5 nm-thick magnesium-doped $Al_{0.77}Ga_{0.23}N$ inter layers; a 25 nm-thick, magnesium-doped $Al_{0.77}Ga_{0.23}N$ layer; and a 60 nm-thick, magnesium-doped contact layer. Both electrodes were made from Ni/Au, and the p-type electrode was 300 µm x 300 µm.

The LED described in the Japanese team's paper had an operating voltage of 32 V at 20 mA current. According to Hirayama, this high voltage stems from the 1 mm separation between the two electrodes. They have now reduced this distance with a flip-chip device geometry, and the operating voltage has plummeted to just 8V.

Improvements in light extraction efficiency are now on the agenda. The latest devices extract just eight percent of the light, and the team plans to improve this figure by a factor of five.

H. Hirayama et al. Appl. Phys. Express **3** 031002 (2010)
http://www.riken.go.jp/r-world/info/release/press/2010/100225/index.html

Double barrier increases MOSFET mobility

Scientists from the University of Texas at Austin have broken the channel mobility record for an inversion-type/accumulation-type III-V MOSFET.

The key to realizing a mobility of 4729 cm^2/Vs was the addition of an $InP/In_{0.52}Al_{0.48}As$ barrier on top of the transistor. This addition reduces the chance of electrons spilling over from the channel to the barrier, where mobility is compromised.

A higher mobility of 5500 cm^2/Vs has been reported in an III-V MOSHEMTs-like structure, which has channel electrons provided by a silicon δ-doping layer, rather than a gate bias. However, realizing this higher mobility comes at the expense of fabricating a more complicated structure, according to team-member Jack Lee.

The University of Texas researchers could further increase the channel mobility of their devices by increasing the thickness of their InP layer in the barrier beyond 5 nm."But we have not tried [this] because the short channel effect would be much more severe," says Lee. " In our work we used long channel devices [with a length of 20 µm], where short channel effects are not a problem."

The team now plans to work on devices with new channel layers, such as InAs, which promise even higher mobility. "We will also measure effective channel mobility for III-V MOSFETs at different temperatures, and find scattering mechanisms that influence channel mobility," says Lee.

H. Zhao et al. Appl. Phys. Lett. ***96*** *102101 (2010)*