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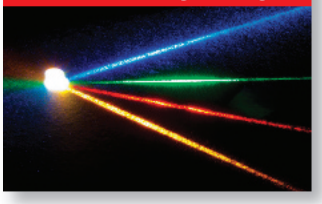
The promise of lasers for lighting

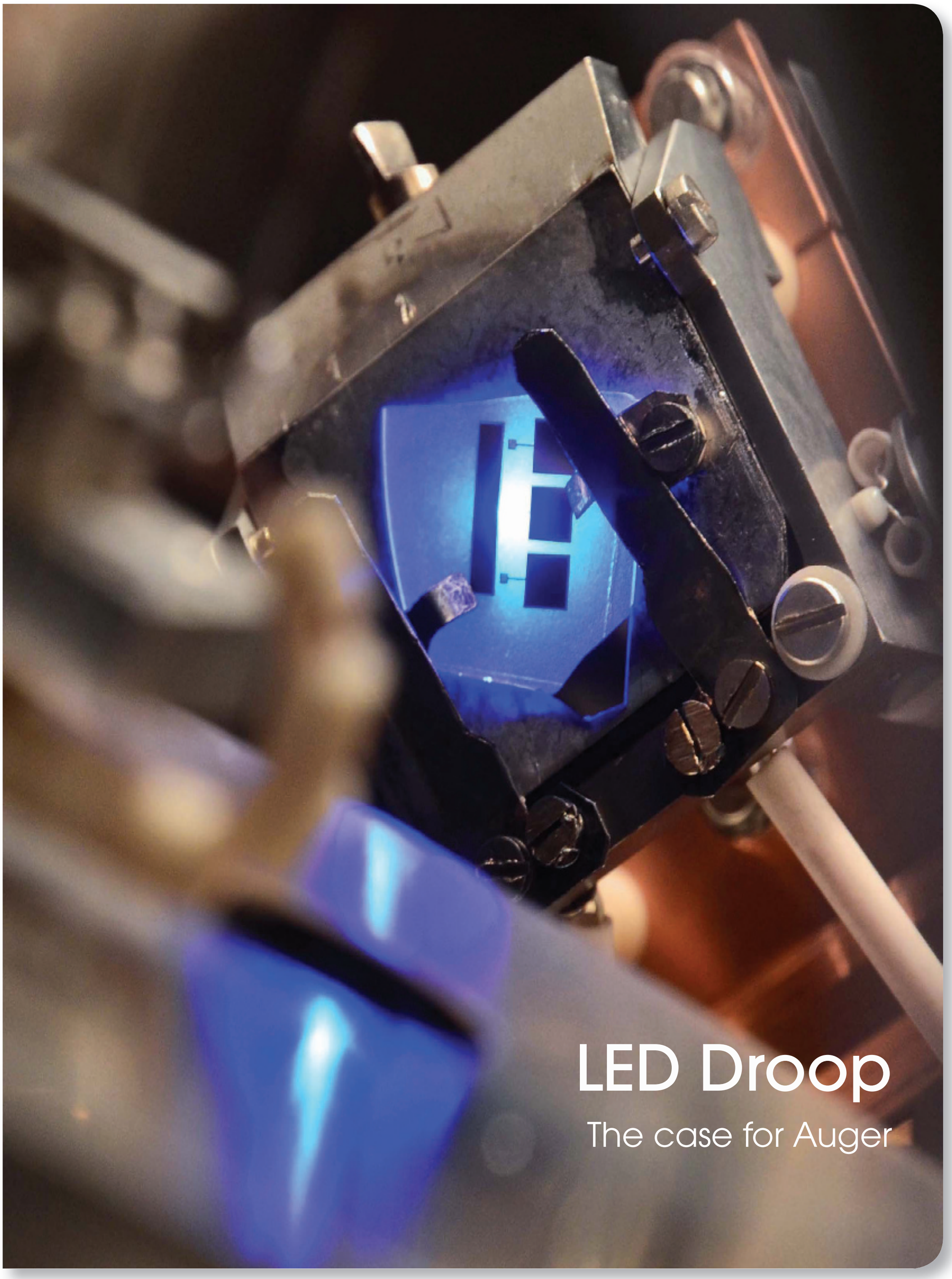


Fourth junction aids PV efficiency

Silicon industry's call for III-Vs

Cutting costs with novel LEDs

Optics: Going for vertical integration



LED Droop

The case for Auger

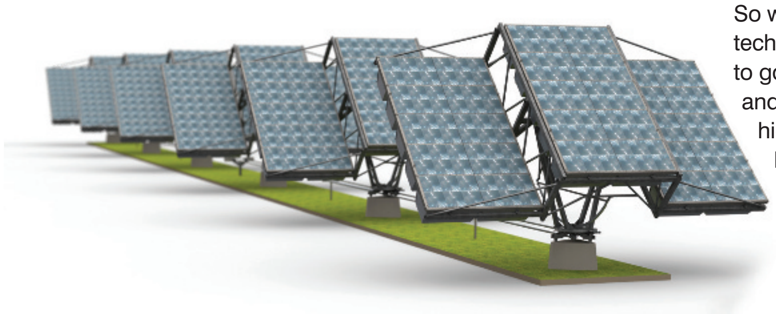
editorialview

by Dr Richard Stevenson, Editor

CPV: The future lies with France

AS US MAKERS of concentrating photovoltaic (CPV) systems fall by the wayside, France has taken over as the new powerhouse. It's shocking development, given all the US companies that had set themselves up to tap into this market. Take GreenVolts, a company that promised to prove the viability of this technology in 2009 with the installation of a 2 MW system. It folded three years later, around the same time that Amonix scaled back operations, to leave SolFocus as the leading CPV systems maker in the US. This firm struggled on, but finally closed this September.

Such developments are clearly bad news for the leading US multi - junction cell makers. And rubbing salt into their wounds, none of them now have the bragging rights for the world's most efficient solar cell, which has been built by engineers at Soitec.



This French outfit, working in partnership with other European institutions, has been pioneering the development of four-junction cells. Such a device structure will be difficult to replicate by rivals, because it is produced using a combination of wafer bonding and proprietary SmartCut technology (see "Wafer bonding creates record-breaking four junction cell" on p36).

It is now only a matter of time before this cell technology ends up in the company's CPV systems, which have won contracts for deployment in various locations, including Saudi Arabia, Madagascar and California. Soitec, however, should not be the sole beneficiary from these high-efficiency cells– they will also aid French start-up Heliotrop. Founded in 2009, it has been deploying CPV systems domestically, and also in Portugal and Morocco (see "CPV: The French Focus" on p18).

So why is Heliotrop still going and Soitec pursuing this technology while US rivals have folded? Well, it is all down to government backing. In 2011, the French Environment and Energy Management Agency invested €44 million in high-concentrating photovoltaics, including €16 million for Heliotrop. I, for one, hope that Heliotrop and Soitec use this cash very wisely and become a success stories for CPV. For I fear that if they don't, triple-junction cells may never make a meaningful contribution to world's electricity generation.

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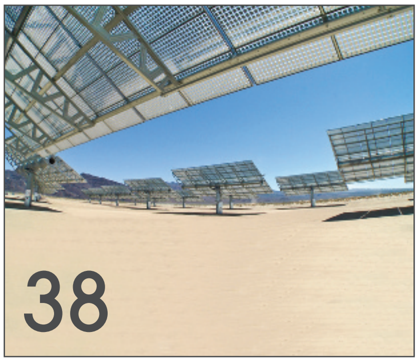

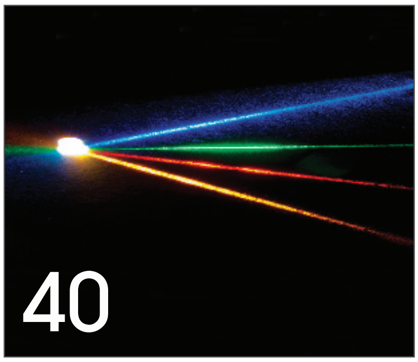

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Ammono wins European Space Agency funding

A CONTRACT has been granted to Ammono by the European Space Agency, with the aim of developing GaN substrates dedicated for space applications. Gallium nitride is a key material for boosting the performance of space related electronics. One of its main advantages is a strong robustness against ionising radiation effects which can degrade the performance of electronics in space and reduce their operating life-time.

The higher power density and higher efficiency offered by GaN allows miniaturisation of electronic payloads, leading to reduced mass and volume of electronics systems launched in space. Last but not least, compared with today's generation of space electronics based on GaAs, GaN makes it possible to operate devices at higher frequencies and higher power, which is essential for long distance space communications.

The main electronics application areas are in transistors for RF communication and DC-DC power conversion applications. However, a new promising application is also in the area of GaN based solar cells since they allow the possibility to generate more energy from a square centimetre than offered by existing solutions.

For space applications the material quality is of extreme importance. Ammono-GaN substrates, which the firm says have the best quality currently available on the open market, have an extremely low dislocation density.

This characteristic can potentially improve the reliability of devices which is important for space applications. Ammono-GaN is therefore ideally suited to provide the high performance requirements of space applications and is the first step towards the design of a novel generation of space electronics.

Multiple plasma systems being installed at Chinese university

OXFORD INSTRUMENTS is currently installing several PlasmaPro plasma etch and deposition tools at the Nanotechnology Centre at the University of Science and Technology of China (USTC) to facilitate their fundamental research in micro- and nano-scale technology.

Zhu Xuelin comments, "USTC has a very strong background in the fields of nanoscale science and engineering. The Nanotechnology Centre recently ordered a PlasmaPro100 ICP380 system for silicon etching, a PlasmaPro80 RIE advanced etching tool for SiO2 and SiNx etching, in addition to a PlasmaPro100 PECVD system for SiO2 and SiNx deposition from Oxford Instruments." He adds, "These systems will be used to replicate and form various nanostructures on wafers, which is highly critical in several nanoscale science fields including quantum physics, quantum information, nano-materials and nano-chemistry. We chose Oxford Instruments tools as they could provide the multiple leading edge technologies, excellent process flexibility and capabilities, backed by the effective customer support offering that USTC expects."

"As a leading plasma etch and deposition tool manufacturer, one of our key advantages is that we offer a wide range of R&D process and system solutions, making us the ideal provider to research institutes worldwide," says David Haynes, Sales and Marketing Director at Oxford Instruments.

II-VI Laser Enterprise ships 200 millionth VCSEL

SWISS BASED II-VI Laser Enterprise GmbH, a subsidiary of II-VI Incorporated, has shipped its 200 millionth VCSEL since 2008.

This is another milestone achievement for the volume supplier of VCSELs which are used in consumer electronics applications such as optical finger navigation, laser computer mouse, and active optical cables.

The optical characteristics of VCSELs such as low beam divergence, small wavelength shift over temperature, narrow spectral line width and high speed modulation properties make them the ideal light sources for advanced sensing, communication and illumination applications in mobile devices. VCSELs can be produced cost-competitively by utilising high throughput wafer scale manufacturing and testing processes. II-VI Laser Enterprise's expertise is in optimising VCSEL design to provide the required combination of performance, reliability and cost advantages to demanding high volume markets.

In addition, II-VI Laser Enterprise has added high power VCSELs to complement its product portfolio geared at high volume consumer electronics markets. The company is sampling high power VCSELs for sensing and illumination applications. The single die lasers emit more than 10mW at 850nm.

The replication of the same die on a 2D-array is enabling to reach up to 2W optical power at 850nm for illumination of larger volumes that can be required in sensing applications such as in time-of-flight. II-VI Laser Enterprise GmbH is a provider of 980nm single mode pumps, high power laser diode and VCSEL solutions.

BluGlass brings MOCVD reactor online

AUSTRALIAN Cleantech company BluGlass Limited has increased its operational capacity with the successful commissioning of a former production MOCVD system at the company's Silverwater facility.

BluGlass has commissioned a Thomas Swan MOCVD system capable of producing 19 x 2 inch (or 5 x 4 inch or up to a single 8 inch) LED wafer(s) in a single growth run.

The MOCVD system has now been commissioned and qualified to grow the multi-quantum well (MQW) base structures required for the demonstration of the Brighter LEDs milestone. This milestone involves demonstrating LED performance improvement by growing low temperature RPCVD *p*-GaN on top of MOCVD grown multi-quantum wells.

InGaN quantum wells are prone to degradation at elevated temperatures in the subsequent MOCVD grown *p*-GaN process steps, resulting in a loss of LED brightness. Growing the *p*-GaN layer at lower temperatures with RPCVD instead of MOCVD should reduce the MQW degradation, hence resulting in a brighter LED.

The company's Chief Technology Officer says, "This system will give BluGlass control of the whole LED structure required for the company to demonstrate an LED performance lift with RPCVD grown p-GaN on MOCVD grown wafers.

The key focus of having both MOCVD and RPCVD capability under one roof will be to demonstrate a successful integration of RPCVD and MOCVD to obtain better light output. In addition, it will assist in the performance comparison of the two technologies."

A second MOCVD system recently arrived at the Silverwater facility which will be installed and reconfigured as an RPCVD system. This will enable the company to further accelerate the RPCVD development and will also assist in demonstrating the scalability of the RPCVD technology from its current 7 x 2 inch deposition capability to a 19 x 2 inch (or up to a single 8 inch) wafer deposition capability. The commissioning of these new tools will now enable multiple programmes (including GaN on silicon) to proceed simultaneously at the Silverwater facility.

BluGlass will also target revenue generation by producing wafer templates as an early market point to boost acceptance of RPCVD technology by building credibility in the market place.

BluGlass CEO, Giles Bourne says, "This is an important step forward for the company. Having multiple programmes in place simultaneously will significantly expedite our technology progress. Our primary goal remains now to demonstrate that low temperature RPCVD has the ability to produce brighter LEDs".

He continues, "This new MOCVD resource will enable us to simplify this development process by giving the technology team full flexibility of MOCVD run cycles, but also by eliminating the lead-time required to obtain templates from overseas suppliers."

SemiLEDs unveils 10W integrated RGBW LED

SEMILEDs Corporation is releasing the 10-Watt M63 RGBW integrated 6363 LED. The 4-channel M63 RGBW delivers over 410 total lumens of combined red, green, blue and white light output. The compact 6.3mm x 6.3mm dimensions enable the M63 RGBW to fit in a wide range of colour-changing applications, including entertainment, large scale displays, and colour-adjustable luminaires for building façade.

"The M63 RGBW demonstrates a new level of LED product integration from SemiLEDs," comments Ilkan Cokgor, Executive VP of Sales and Marketing for SemiLEDs. "By combining three colours, plus an independent phosphor-coated white emitter, onto a single LED package, customers will be able to better optimise the optical and thermal properties of their design, while minimising the manufacturing complexities of their luminaires or large scale displays.

The integrated package is the first to bring together SemiLEDs vertical, white chip, and ceramic packaging technologies. Measuring just 6.3mm on a side (39.7 square mm/0.06 square inches), the compact multi-colour LED opens the door to arrays with cumulative lumen-densities in excess of 6000 lumens per square inch.

Beyond just the size and potential for high-lumen densities, the square footprint also greatly simplifies colour mixing and integration with secondary optics, including narrow beam spotlights which benefit from the symmetry and depend upon minimised source sizes.

When compared to a strictly RGB source, the addition of discrete white to the colour changing LED architecture enables a broader spectrum and more natural white palette to be projected. The white source in the M63 RGB delivers 100 lumens per watt at a correlated colour temperature (CCT) of 6300K to 8000K. By its nature, an RGBW LED should include a cool-white source to complement the additive nature of the colours in the integrated device.

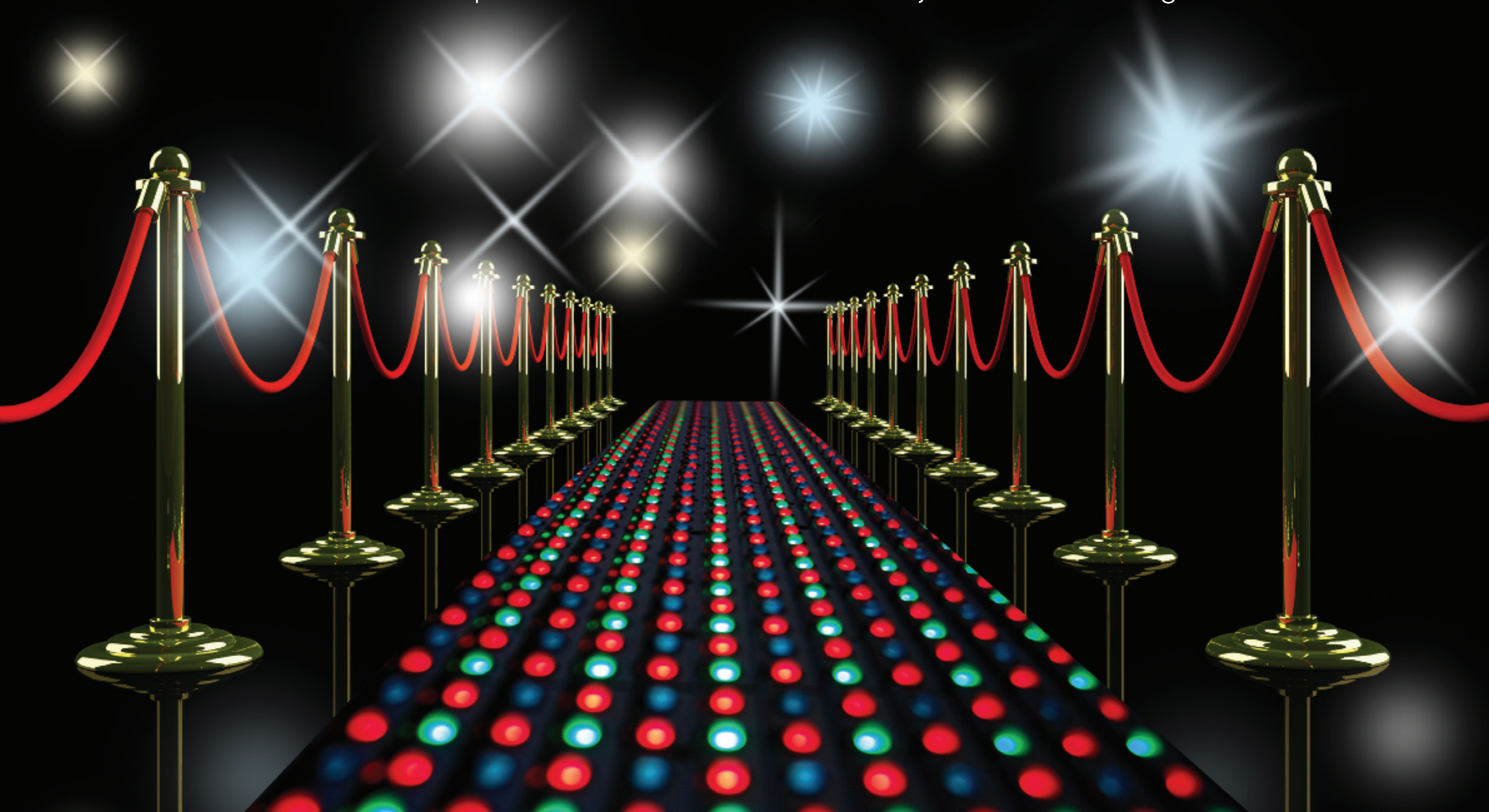
Excelitas expands with acquisition

EXCELITAS TECHNOLOGIES, which specialises in delivering innovative, customised optoelectronics to OEMs seeking high-performance technology solutions, has acquired Lumen Dynamics. Lumen Dynamics is a privately-held volume manufacturer of lamp and LED-based UV curing and fluorescence illumination systems.

"Lumen Dynamics' technology and innovative product portfolio complement Excelitas' existing suite of specialty lighting products," says David Nislick, Chief Executive Officer, Excelitas Technologies. "With the addition of Lumen Dynamics' expertise in UV curing, Excelitas is now poised to expand our penetration of the high growth UV curing markets and address an even wider range of demanding medical and industrial applications."

Headquartered in Ontario, Canada and founded in 1984, Lumen Dynamics is focused on advancing UV system technology while continuously improving its contribution towards environmental sustainability. It offers a comprehensive suite of products under high profile OmniCure and X-Cite brands.

The combined companies will deliver an expanded range of customized fibre optic UV and LED solutions and specialty lighting products for OEMs.



EVG reveals non-contact lithography tool for photonics

EV GROUP (EVG), a supplier of wafer bonding and lithography equipment has introduced the EVG PHABLE exposure system, which is designed specifically for manufacturing photonic components.

Leveraging EVG's expertise in photolithography, the EVG PHABLE system incorporates a unique contactless lithography mask-based approach that enables full-field, high-resolution and cost-efficient micro- and nanopatterning of passive and active photonic components, such as patterned structures on LED wafers, in high-throughput production environments. The EVG PHABLE exposure system is the first fully-automated production equipment to feature PHABLE ("photonics enabler") technology from Eulitha AG, a pioneer in lithography tools based in Villigen PSI, Switzerland.

Integrating Eulitha's full-field exposure technology with EVG's nanolithography production platform provides a unique solution for the automated fabrication of photonic nanostructures.

The EVG PHABLE system combines the low cost-of-ownership, ease-of-use and non-contact capabilities of proximity lithography with the sub-micron resolution of lithography steppers to provide low-cost automated fabrication of photonic patterns over large areas. This makes it ideally suited for patterned sapphire substrates (PSS) or to enhance the light extraction (and thus the efficiency) of LED devices. The EVG PHABLE system includes a unique Displacement Talbot Lithography approach that enables it to produce features ranging from three microns down to 200 nm with effectively no depth-of-focus limitation or stitching effects that can arise from using steppers on substrates with rather poor total thickness variation.

As a result, it can be used to pattern substrates up to six inches in diameter in a single exposure step. This approach also enables the EVG PHABLE system to maintain consistently high patterning throughput independent of the size of the processed wafer, as well as maintain very large exposure gaps (up to several hundreds of microns) between the mask and wafer, thereby avoiding process-related mask contamination.

"We are excited to enter the commercialization phase of our collaboration with Eulitha," states Hermann Waltl, executive sales and customer support director at EV Group. "The EVG PHABLE system broadens EVG's micro- and nanopatterning process portfolio, providing a unique, very cost-efficient solution to our customers in the LED, optics and photonics markets. The novel equipment clearly demonstrates the synergies of our respective technologies."

The EVG PHABLE system can produce both one-dimensional patterns, such as lines and spaces, as well as two-dimensional patterns, such as hexagonal or square lattices.

Thus, it supports a variety of approaches to enhance the light extraction from LEDs. These include LED surface structuring, PSS, photonic crystal applications, nanowire LEDs and optical gratings. The system can also be configured for photovoltaic, optics or biomedical manufacturing applications.

Eulitha AG is a spin-off company of the Paul Scherrer Institute, Switzerland. It specialises in the development of innovative lithographic technologies for applications in optoelectronics, photonics, biotechnology, and data storage.

It produces and markets nano-patterned wafers and templates using its unique EUV interference method and state-of-the-art e-beam lithography tools. PHABLE is the brand name of its new photolithography platform, which includes exposure tools and wafer patterning services.

Osram LED offers better light in the operating theatre rooms

WHEN IT LAUNCHES the new Osram Ostar Medical, Osram Opto Semiconductors will be introducing the first LED component with a high colour-rendering index (CRI) of 95 and the possibility of adjusting the temperature of the colour white.

This makes it ideal for medical applications - for instance in operating rooms, where a precisely controlled chromaticity coordinate and high natural colour rendering are crucial.

The new Osram Ostar Medical incorporates thin-film chip technology and comprises four different LED chips in the colours warm white, ultra white, verde (green) and amber (red). This permits customers to set the shade of white emitted by the LED according to their individual requirements within a colour temperature range of between 3,700 and 5,000 Kelvin - and at a high overall CRI of 95.

Thermal resistance (Rth) is 1.8K/W and typical brightness is around 180 lm at 4,000 K and about 325 lm at 5,000 K. This combination of precise chromaticity coordinate control and excellent CRI is particularly important for lighting in the medical sector. When optimised for the red spectrum (RaR9), the CRI remains at around 95 so that red shades are particularly true-to-life - ideal for light systems in operating rooms.

With a footprint of just 5.9 mm x 4.8 mm and a housing height of 1.2 mm, the design of the Osram Ostar Medical is very compact. Indeed, it is only about one-quarter as high as the components ordinarily used.

The product owes its compact design to the flat, antireflex-coated glass cover with which the LED is equipped instead of the usual lens.

The high CRI, even for shades of red, and the precise control of the chromaticity coordinate make the Osram Ostar Medical the ideal LED for medical lighting (Photo: Osram).

"Compact luminaires prevail in the modern medical lighting sector and the low height of the new Ostar Medical makes it the ideal product," explains Wolfgang Schnabel, who is in charge of marketing the product at Osram Opto Semiconductors. "The component is standardised, which means that customers can use the commonly available lenses."

Soraa expands US GaN LED manufacturing

SORAA, a developer of GaN on GaN LED technology, will open a new semiconductor fabrication plant in Buffalo, New York.

In partnership with the State of New York, the company will construct a new state-of-the-art GaN on GaN LED fabrication facility that will employ hundreds of workers. The new facility is projected to be operational in 2015. Soraa currently operates an LED fabrication plant in Fremont, California, one of only a few in the U.S.

"We chose Buffalo as the best location for our new fabrication facility based on several factors, including the innovative high-tech vision and strategy of Governor Cuomo; the ability to attract some of the best and brightest scientists and engineers in the world; and the capacity to tightly control the product quality and intellectual property around our LEDs through our partnership with the SUNY College of Nanoscale Science and Engineering," says Tom Caulfield, President and COO of Soraa.

He adds, "With the new facility, our LED lighting capabilities will be refined and expanded, product innovation will accelerate, and light quality and efficiency will continue to improve."

"Under the largest investment in our Buffalo Billion initiative, we are building a state-of-the-art campus to house high-tech and advanced manufacturing companies that will create hundreds of jobs and leverage over a billion dollars in private investment for Western New York," Governor Cuomo says. "Today, we welcome world-renowned high-tech company Soraa to Buffalo - an affirmation that Buffalo is back and better than ever.

This project marks a giant step forward in our Buffalo Billion strategy, transforming a once vacant property into a development ready site that will create good-paying permanent jobs, make Buffalo an international hub for innovation, and attract more businesses from around the world. Today, Buffalo is truly on the move."

In 2007, a team of engineering and semiconductor professors - Shuji Nakamura, Steven DenBaars, founder of Nitres and James Speck of U.C. Santa Barbara's College of Engineering came together and made a bet on an LED technology platform completely different than current industry practice, a technology most industry experts at the time considered to be impossible to execute.

Soraa bet that GaN on GaN LEDs would produce more light per area of LED and be more cost-effective than technology based on other foreign substrates like sapphire or silicon carbide. This strategy ran against every trend in the LED industry.

But they say the bet paid off. Today, the company claim its LEDs emit more light per LED material than any other LED, handle more electric current per area than any other LED, and the company's crystals are up to a thousand times more precise than any other LED crystal.

Spectrolab III-V solar cell beats own record with 38.8% efficiency

BOEING subsidiary Spectrolab has set a new world record by producing a solar cell that converted 38.8 percent of solar energy into electricity, more than any other ground-based solar cell not using concentrated sunlight. The U.S. Department of Energy's National Renewable Energy Laboratory in Golden, Colorado, verified the new record, which beats Spectrolab's own previous world record by 1 percent.

"Improving solar cell manufacturing technology is at the core of what we do at Spectrolab," says Spectrolab President Troy Dawson. "We will continue to innovate new ways to achieve even better results."

Spectrolab manufactured the high-efficiency multi-junction solar cell, which was developed from new Boeing semiconductor bonding technology. This solar cell technology could be used to power high-power spacecraft and unmanned aerial vehicles.

Spectrolab, part of Boeing Defence, Space & Security, is a merchant supplier of high-efficiency multi-junction solar cells and panels for concentrated photovoltaic and spacecraft power systems, in addition to being the a provider of airborne searchlights.

Material is key for device development

ELECTRONIC APPLICATIONS, such as Schottky diodes, transistors, etc., require high-quality single-crystalline CVD diamond, which has superior characteristics such as high carrier mobility, long carrier lifetimes, high breakdown fields and high thermal conductivity. High quality low-defect diamond wafers produced from diamond crystal made by High-Pressure High-Temperature (HPHT) method are only a few mm in size. In comparison, the competing semiconductor materials such as SiC are already available in wafer sizes up to 150 mm.

For future diamond-based active devices, it is crucial to increase the wafer size to above 2-inch with the defect density 100 cm^{-2} and below. Different approaches to achieve free-standing wafers from thick diamond films are under development. A mosaic type method is currently approaching 2-inch wafer size, but the defect density needs to be reduced. According to Yole's technology roadmap for single crystal diamond wafers, low-defect 2-inch wafers could be commercially available around 2016 - 2017. The Microwave-enhanced Chemical Vapour Deposition (MWCVD) approach for crystal growth is more promising than HPHT, because of its potential for scaling. Yole also says MWCVD is the most promising technique for thin-film growth. High-quality thick diamond films can be grown by homoepitaxy on single-crystal diamond wafers. The heteroepitaxy of diamond on iridium enables diamond films of up to 4-inches in size, but further development is needed to obtain a well-controlled and reproducible manufacturing process.

Besides the technology challenges related to single-wafer material manufacturing, electronic applications of diamond in electronics are heavily hampered by the fact that *n*-type doping is still relatively difficult to achieve due to the lack of an efficient donor. As *p*-type doping of normally insulating diamond can now be reliably achieved using boron, many activities have been focused upon the fabrication of unipolar devices. The first expected active diamond power devices will be Schottky diodes.

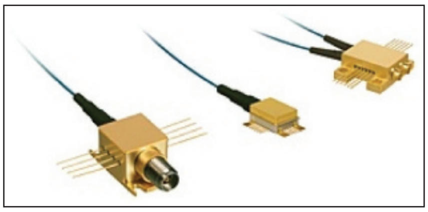
Although polycrystalline films have inferior electric and thermal properties compared to single crystal material, they are available in larger dimensions and at lower costs. Yole says they are used mainly in applications as heat spreaders (and many non-electronic applications, such as optical windows, etc.). Future cost decrease and performance improvement of diamond films relies strongly on the CVD equipment used. Therefore a strong effort from equipment makers like Cornes Technologies (Seki Diamond), Element Six, Plassys-Bestek, sp3 Diamond Technologies… is focused on the development of CVD reactors with a larger deposition area, higher growth rate, lower electricity consumption and better film quality. An "integration" of diamond film directly into a wafer (used for the fabrication of electronic and opto devices as done for instance in Group4 Labs' GaN-on-Diamond approach) has great potential to reduce the cost of heat management solutions for high-power and high-frequency applications.

Advanced Photonix wins multimillion dollar contract

PICOMETRIX, LLC has successfully completed its annual negotiations to supply high-speed optical receivers to a leading OEM telecom systems customer.

The firm's high speed optical receivers address the entire range of 10 Gbps and 40 Gbps applications utilising its proprietary III-V PIN and APD photodiodes. Bandwidths range from 2 GHz to 60 GHz and cover wavelengths from 700 nm to 1650 nm. The 2014 commitment includes the full suite of Picometrix's 100G products, including the new CR-100D with integrated variable optical attenuator (VOA), designed for 100G long haul communications in dense wavelength division multiplexing (DWDM) systems which utilise DP-QPSK and DP-BPSK modulation.

The innovative CR-100D receiver is designed to increase dynamic range, as well as improve optical signal-to-noise ratio (OSNR) performance. The receiver spans the entire extended C and L band wavelengths and can be used in "colourless" coherent networks that enable service providers to better manage network capacity. Colourless capabilities allow communication equipment to utilize any wavelength for any port at the add/drop site. This allows for faster data throughput and lower costs per bit transport, both of which are big concerns for the industry.



"Once again we are pleased to have successfully concluded our 2014 negotiations with an important tier 1 customer to supply our 100G products, including our new CR-100D with VOA," says Robin (Rob) Risser, COO of API and General Manager of Picometrix. Risser continues, "We highly value our strong relationship and close collaboration with this strategic customer and their commitment to work with us this past year as our advanced procurement and engineering teams solved difficult supply chain disruptions in our 100G product offerings in the first half of 2103."

"The demand for 100G coherent equipment is in its early growth stage as bandwidth intensive applications like full motion video and social media place demands on the networks infrastructure. Virtually every carrier is deploying, or plans to deploy, 100G systems into the Long Haul and Metro markets over the next several years and we plan to participate in this growth with our current and future 100G product offerings," Risser concludes.

Hittite expands GaN MMIC power amp

HITTITE MICROWAVE CORPORATION has revealed a new GaN MMIC power amplifier product. The company says the device offers significant performance, size and durability advantages for communications, test instrumentation and radar systems

Operating in the 6 to 18 GHz frequency range, the HMC7149 is a 10W GaN MMIC Power Amplifier (PA) which typically provides 20 dB of small signal gain and +40 dBm of saturated output power. The amplifier draws 680 mA quiescent current from a +28V DC supply and features RF I/Os that are matched to 50 Ω for ease of use. The device, pictured above, also offers high output power capability, a compact die size and simplified biasing, which make it ideal for integration into high power density Multi-Chip-Module (MCM) and subsystem applications.

The HMC7149 is Hittite's fifth GaN MMIC amplifier to be released during 2013, along with the previously released 2-6 GHz, 25W HMC1086, HMC1086F10 and the 2-20 GHz, 8W HMC1087 and HMC1087F10 amplifiers.All five GaN MMIC power amplifiers complement Hittite's extensive line of microwave power amplifiers which provide continuous frequency coverage from 0.01 to 86 GHz.

Earlier market entry to secure better position in future markets

THE DIFFERENTIATION between diamond material suppliers is mainly due to technology. Although many players are today able to supply diamond materials, only a few of them can supply a high quality material providing higher differentiation compared to lower performance but also less-costly non-diamond alternatives. Actually, less than three companies per material type can consistently deliver high quality products. Many players have significant R&D activities underway to develop new products and access dedicated R&D funding, as well as to hold any technological advantages they have over the competition.

The recent acquisition of Group4 Labs by Element Six (a member of De Beers Group) indicates the trend to maintain the key technologies within a select group of players, providing them a well-established position in the diamond material market. As learned from history, the development and optimization of diamond technologies is complex and takes many years. During this period, the historical diamond players will acquire a significant technological and IP advantage which may be hard for new players to overcome and make it nearly impossible to enter the market in the future.

The developers/manufacturers of high-performance devices such as high-power and high-frequency devices and high-power optoelectronics rely on the reproducible supply of high-quality materials. Leading European and Japanese companies, especially those involved in the power electronic business are still quite conservative with regard to using diamond-based devices. This provides an opportunity for other companies which may take leadership. in this market segment.

Vertical LEDs ready for market

After nearly a decade of development, Glo's nanowire LEDs are slated to reach market early next year. Compound Semiconductor talks to Glo chief technology officer, Nathan Gardner, to find out more.

THEY'VE BEEN A LONG TIME COMING, but early next year high brightness nanowire LEDs, manufactured by Glo, should be commercially available. Following nearly a decade of post-research development – the Sweden-based Lund University spin-out was founded in 2005 – Glo's 3D LEDs look ready to challenge existing planar LEDs.

"We already have products in customers' hands and expect to start shipping in the next couple of quarters," says Nathan Gardner, chief technology officer of Glo-USA. "We expect to offer better green LEDs than planar devices as well as a higher performing blue LED. Red nanowire devices will follow so we will have an RGB solution all based on the nitride semiconductor system."

But why the focus on nanowires? Compared with conventional planar LED heterostructures, these vertical 3D structures promise several advantages. For starters, growing vertical nanowires onto a substrate prevents the accumulation of wafer stresses that takes place when planar layers are deposited instead. Here, differences in each material's coefficient of expansion lead to lattice mismatches during fabrication and a wafer wrought with defects that degrade device yields and performance.

What's more, the vertical structures boost light output efficiency, thanks to the large surface-to-volume ratios, and are compatible with low-cost, large-area silicon substrates.

> "To date, Glo has focused on fabricating LEDs on sapphire substrates. And while Gardner asserts the nanowire LED manufacture is compatible with large area silicon substrates, the company's efforts will remain focused on sapphire for the foreseeable future."

As Gardner explains, Glo's LEDs comprise vertically aligned GaN nanowire arrays, grown via MOCVD, over a selective-area growth mask deposited on a GaN/sapphire template. Holes in the mask, imprinted via lithography and dry-etched, guide nanowire growth.

The actual diode structure consists of an InGaN active region, deposited on the m-plane sidewalls of the *n*-type GaN nanowire core. This active region is followed by a *p*-type AlGaN layer, *p*-type GaN and a heavily doped *p*-type GaN contact layer.

"TEM analysis shows the dislocations existing in the *n*-type GaN template rarely propagate into the nanowire," he says. "[And so] the active region is deposited on a defect-free *m*-plane template."

Glo hasn't publicly released technical specifications – this information is only provided under a non-disclosure agreement to customers that are sampling devices – but Gardner claims overall performance of green and blue devices is on par with today's commercial planar devices.

"The peak quantum efficiencies of our green devices are within 10 percent of the commercially available green peak efficiencies while the internal quantum efficiency of our blue LED is equivalent to the state-of-the-art planar commercial blue [device]," he says. "And the reliability data from the devices show they meet normal customer requirements."

To date, Glo has focused on fabricating LEDs on sapphire substrates. And while Gardner asserts the nanowire LED manufacture is compatible with large area silicon substrates, the company's efforts will remain focused on sapphire for the foreseeable future.

"The nanowire device structure in general is quite amenable to being fabricated on large area silicon substrates, and compared to planar structures, we do not have the complexity and cost of growing a buffer layer," he says. "But the companies manufacturing planar LEDs don't perceive silicon as being advantageous from a cost perspective until 8-inch diameters are reached. So once volumes increase and should the demand come, then we will look at silicon."

Quality or cost?

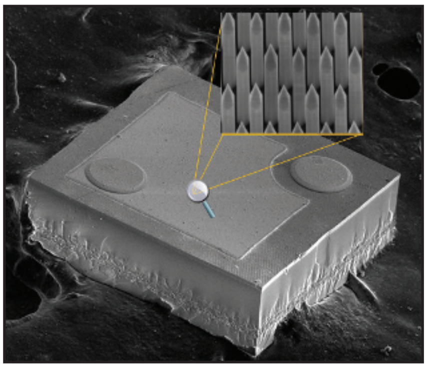
In March this year, the US-based nanowire LED developer, Aledia, and Glo's closest rival, unveiled prototype microwire GaN-on-silicon LEDs fabricated on 8-inch silicon wafers. Customer samples are expected early 2014.

At the time, chief executive, Giorgio Anania, told *Compound Semiconductor* that the LEDs could be grown three times faster than planar GaN LEDs, would probably cost around four times less than conventional devices, but his company would not be targeting high performance markets.

"Initially we will not offer the best Lumens per Watt, but many applications do not need this, what they really need is best lumens per dollar," he said.

Clearly Glo is taking a different tack. Gardner states his company's nanowire device manufacturing speeds are comparable with those of planar LEDs, and for the time being, so is the cost.

"Eventually, devices could be cheaper than planar but we don't think we will offer such a solution in the next year to year-and-a-half," he says. "Our tactic has always been to use the nanowire topology for LEDs as a platform to generate breakthrough performance across all colours of the visible spectrum. Our real aspiration is to exceed the performance of planar."



A scanning electron micrograph of a Glo chip showing individual nanowires

WITH ITS LACK OF direct solar irradiance, France does not leap out as being a prime site for a concentrated photovoltaic power (CPV) plant. But with the nation's government pouring millions into CPV projects, local player Heliotrop is proof that, in this case, it pays to be French.

In 2011, the French Environment and Energy Management Agency (ADEME) awarded the CPV manufacturer, some €16 million as part of its €44 million HCPV 1024 Soleils project that aims to demonstrate CPV on a utility scale. Then in 2012, solar power operators using Heliotrop's system won contracts from the Commission de Régulation de L'Energie (CRE) worth tens of millions of Euros, to build 29 MW of CPV plant.

"CPV is important to France," says Heliotrop co-founder and chief executive, Paul Bellavoine. "Heliotrop has research and development, and a manufacturing plant in France, while Soitec has its headquarters in France. Between the two companies, the French government has decided to foster CPV development."

Heliotrop's prime focus is on France right now, with Bellavoine saying: "Most of our projects are large-scale projects in France to be rolled out in 2014 and it will be hard to start large-scale projects up abroad before these are fully up and running."

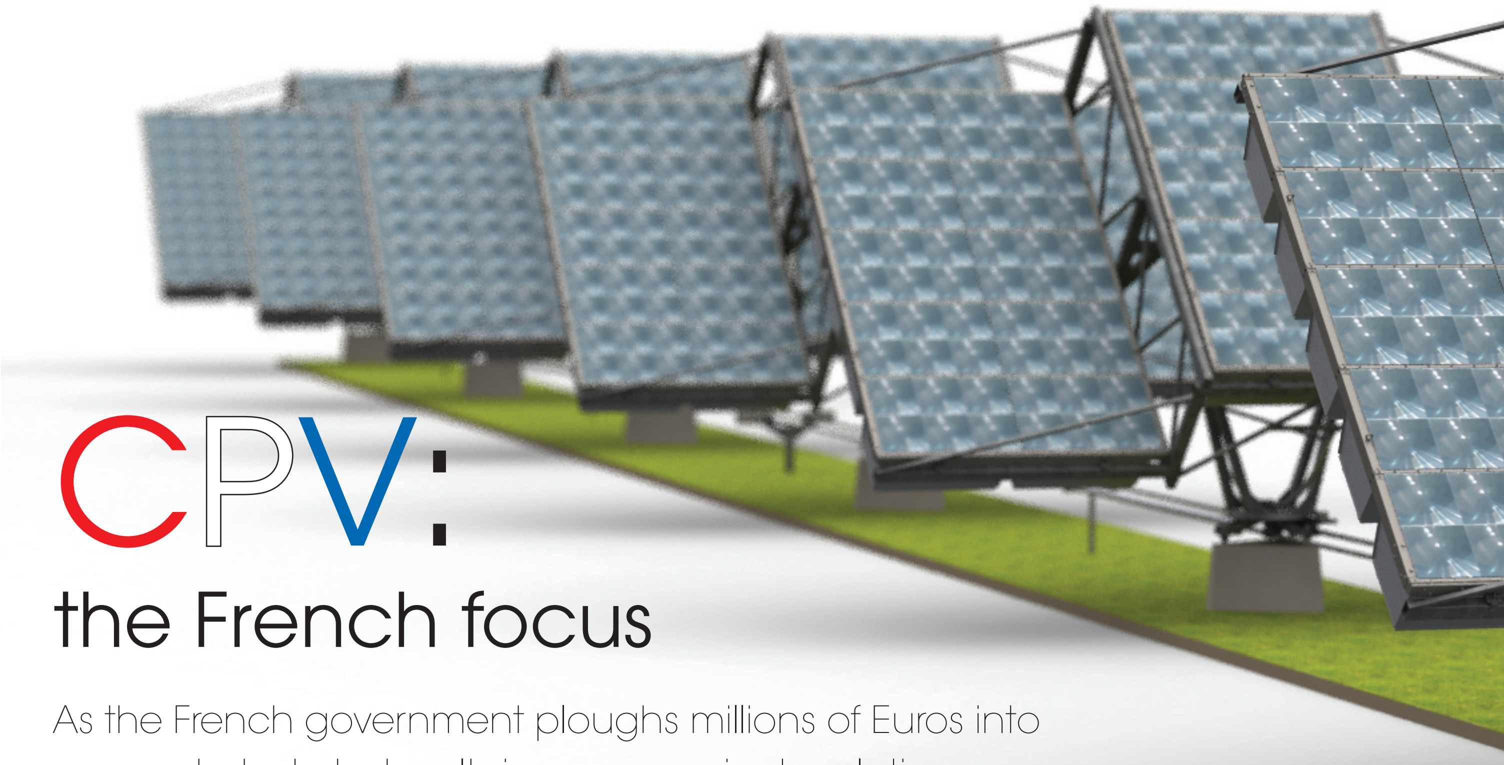
But thanks, at least in part, to its hefty government backing Heliotrop has also deployed CPV units in Portugal and Morocco, as well as more recently bagging a contract with Mexico Sonora State to build several megawatts of CPV plant. So what exactly has the company developed?

With an efficiency just over 30 percent, Heliotrop's CPV systems are based on III-V triple junction solar cells, comprising layers of Ge-InGaAs-InGaP, with a 40 percent efficiency. Current module costs are not public information but Bellavoine claims the high concentration level of 1024 suns, twinned with accurate design optimised for mass manufacture gives a low cost per watt.

"At such high concentrations, heat dissipation can be a problem but we have done a lot of work with our dual-step dissipater to avoid this," he says. "Mechanical tolerances are another issue as you really need to have a system that is very well aligned."

"We have been working with manufacturers from the automotive industry who are brilliant," he adds. "We've followed their methodologies from the grade of aluminium to use, to the robots used on their manufacturing lines; and everything is very standard, low cost and highly reliable."

According to the chief executive, the



CPV: the French focus

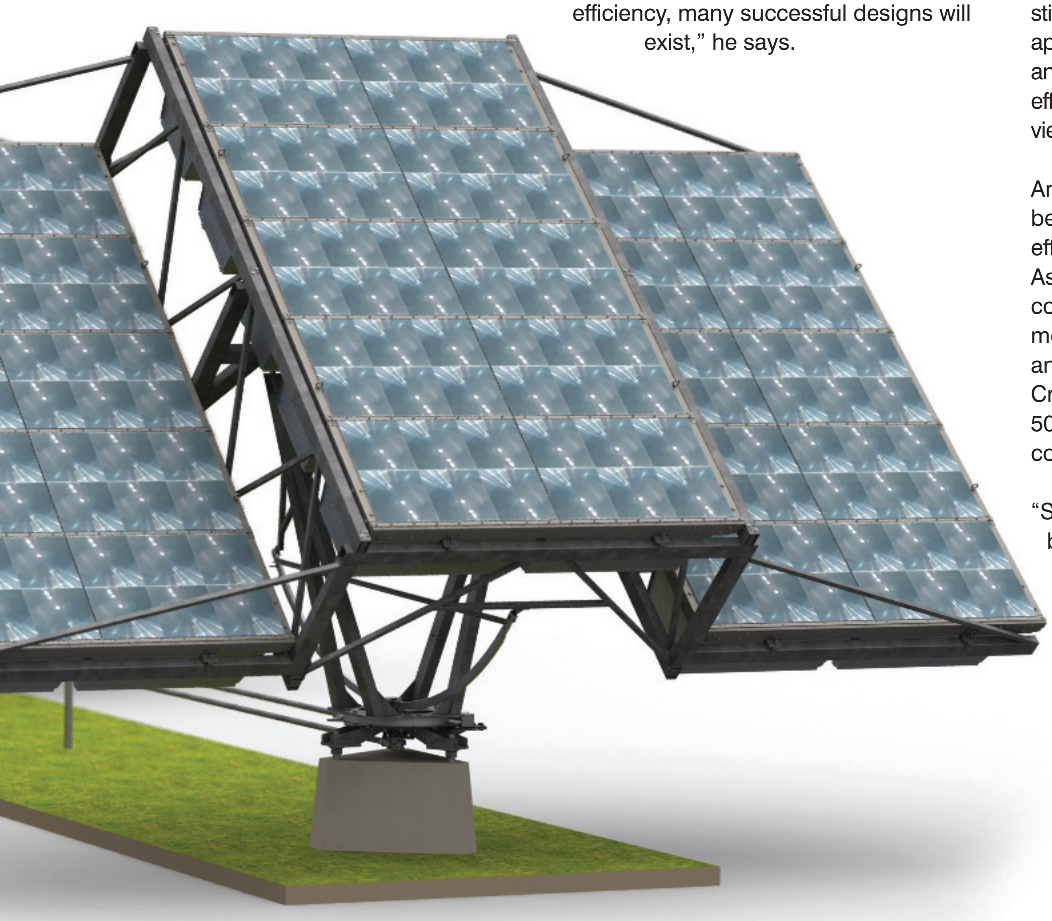
As the French government ploughs millions of Euros into concentrated photovoltaic power projects, relative newcomer, Heliotrop, is reaping the rewards.

company will announce a higher system efficiency in the coming months, and come 2020, its systems will have hit at least 40percent efficiency. While these efficiency gains will partly come from optical design and manufacturing quality, the biggest emphasis, by far, is on the solar cell.

"For the last decade, triple junction cells have gained 1 percent efficiency every year, so we are very confident that some cells will be more than 47 percent efficient by 2020, and this will give us a model efficiency above 40 percent," he says. "We take a multi-sourcing approach which gives us the opportunity to get the best cell all the time."

And while Bellavoine remains tight-lipped on which cell manufacturers supply his solar cells, he is confident, at least for this his CPV systems, multi-junction cells will remain the cell architecture of choice. "The maximum critical efficiency for a multi-junction cell is 80 percent and today we are at 40 percent. There are metamorphic, inverted metamorphic and already fourth junction designs. As long as we remain below 50 percent efficiency, many successful designs will exist," he says.

Heliotrop Concentrated Photovoltaic technology promises to produce electricity that is competitive with all other energy sources at between 6 and 10 cent/kWh



"But in the next five to ten years, once we reach 50 percent efficiency, we will probably add more junctions, maybe move to five junctions. Right now we are still in the comfort zone so many different approaches will work. Beyond this, any researcher working on a very high efficiency cell will have his or her own view."

And Bellavoine is certain the market will be using cells with at least a 50 percent efficiency in the relatively near future. As he highlights, cell efficiency has continued to increase with 'almost no money, no investment, just a few labs and research teams around the world'. Crucially, he believes hitting the 50 percent cell efficiency milestone, could trigger CPV market growth.

"Silicon is still less expensive than CPV but at some point very soon we will be at parity with silicon PV. When efficiency increases from 40 percent to 50 percent, model costs will decrease by about 25 percent, as, for example, we will need fewer trackers," he says.

"There is this big race against silicon PV, but silicon technology has already achieved all its mass production and efficiency gains, and progress is now very slow."

New GaN centre to drive devices to market

Germany-based researchers and industry players join forces to commercialise GaN-on-GaN research.

THANKS TO A WEIGHTY €1.6 million in funds from the German Saxony State government, Dresden Technical University spin-off, NaMLab, and GaN substrate developer, Freiberg Compound Materials, have just launched a GaN research laboratory. Drawing on this and additional funds from the German research ministry, the Gallium Nitride Centre researchers will now collaborate with colleagues at the Freiberg University of Mining and Technology to drive GaN-on-GaN optoelectronics and power electronics to commercial markets.

"We don't claim that we're going to compete on cost with GaN-on-silicon," says Thomas Mikolajick, scientific director at NaMLab. "But we want to go into performance corners and special applications where you really need a low defect density."

NaMLab is known for its strong device development while keeping a close eye on commercial applications. However, Mikolajick is keen to highlight how the organisation will now be working closely with Freiberg Compound Materials on materials growth.

"We're going to make high quality GaN substrates," he asserts. "We're going to start with two inch wafers to raise quality and throughput levels to commercial standards, and then we will bring costs down by moving to larger diameters."

The partners will use HVPE to grow GaN substrates, growing a thick GaN layer on a template that will later be removed,leaving the boule from which to slice GaN wafers.

"I can't be specific but we are using a template as the starting process, and we are not looking at ammonothermal growth," says Mikolajick.

"The challenge will be to make the GaN as thick as possible, so we can get a lot of wafers."

According to Mikolajick, his team will first develop high quality GaN substrates for laser applications, but more applications will follow.

"Maybe we'll even aim for high brightness LEDs with a high current density where you cannot get the necessary reliability from substrates with many defects," he says. "But general lighting applications are not on our roadmap as we wouldn't get to market for cost reasons."

The team is also looking to develop vertical power devices, although Mikolajick admits this is very much research in progress right now. In past projects, NaMLab has defined a front-up process flow for planar GaN MIS-HEMTs, but as part of the Saxony GaN Research Centre will now explore new architectures.

"Vertical GaN MOSFETs and HEMTs have been proposed in literature, and we are currently thinking of integrating a HEMT into a vertical configuration," he says. "This is also on our roadmap, but is still a vision."

Silicon origins

Still, vision or not, the new GaN Centre is hardly starting from scratch. NaMLab was originally set up as a joint venture between TUD and Infineon Technologies memory products, later to become memory giant Qimonda, Germany. NaMLab's first years were spent focusing on developing high-κ dielectrics for capacitors in dynamic random access memories. But then Qimonda filed for bankruptcy in 2009, and NaMLab started looking for new markets to apply its device expertise.

Come 2010, the organisation had teamed up with Freiberg Compound Materials, with a view to accelerating the development of GaN substrates by providing its industrial partner with feedback on device performance.

"Originally we were silicon guys, with our biggest knowledge being how to integrate semiconductor devices into silicon," explains Mikolajick. "We'd done a lot of work on integrating high-κ dielectrics into capacitors and transistors but discovered that GaN [businesses] were also interested in integrating [these materials]."

The organisation has since worked closely with various partners on GaN HEMT processes as well as novel device development, and is now keen to swiftly turn research results into commercial applications.

Mikolajick will not be drawn on when the first real application will surface, giving several years as a ball park figure, but says: "At the end of the day, if you want to sell something, you have to understand what happens after processing and make sure you can fabricate good devices. We make simple, but complete devices where you can see the entire fabrication process."

And he is confident the strong focus on device integration will bring more GaN-on-GaN devices to market.

"You know in Germany, this is not a natural way for a research organisation to work; hand in hand with product development and commercialisation," he says. "But we are working very closely with Freiberg Compound Materials, and this is an important part of founding our research centre in Freiberg."

II-VI lays out **Oclaro** plans

Following its Oclaro acquisition, II-VI intends to simplify operations, re-think manufacturing and pursue new products.

IN SEPTEMBER THIS YEAR, Oclaro sold its Switzerland subsidiary, including GaAs fabrication facility and associated laser businesses, to materials and optoelectronics business, II-VI, for $115 million.

Oclaro chief executive, Greg Dougherty, described the move as "an important first step in our plan to restructure", but equity analysts have since downgraded the optical communications developer's share rating, citing 'daunting operational challenges' ahead.

Meanwhile, the sale represents the second deal between the two companies. II-VI bought Oclaro's thin film filter business and interleaver product line in late 2012, after a spate of acquisitions including photonic design business, Photop, tunable optical device developer, Aegis Lightwave and advanced ceramic materials developer, M Cubed Technologies.

This latest acquisition furnishes II-VI with the necessary GaAs semiconductor technology to manufacture high power laser diodes, VCSELs and 980 nm pump lasers alongside a related research and development facility in Tucson, US. And as chief financial officer, Craig Creaturo asserts, his company is retaining all related employees.

"This includes 200 workers at the Zurich operation, all people at Tucson as well as around twenty individuals throughout Oclaro that we identified as supporting this business," he says.

As part of the deal, II-VI also acquired the MOCVD reactors for growing GaAs epitaxial layers at Oclaro's UK fabrication facility, formerly owned by Plessey Caswell. "All the GaAs wafers that [the Swiss business] use today are coming from Caswell in the UK, so this will continue for the foreseeable future," says Creaturo. "But in the longer term it will be logical to move these into the Zurich operation. This will not be an immediate move, it needs to be planned out from logistical, regulatory and environment standpoints."

And while Oclaro is continuing the back-end manufacturing of the 980 nm pump and some high power laser diode products at its Shenzhen facility in China, this could also change. Right now, Oclaro is supplying these products to II-VI under a manufacturing services agreement, but as Creaturo says: "We have options internally as to where to take these product lines.

We're currently studying each one and will make the right decisions as to what to do with each going forward. We have large-scale operations in Asia and will possibly be using those in the future," he adds.

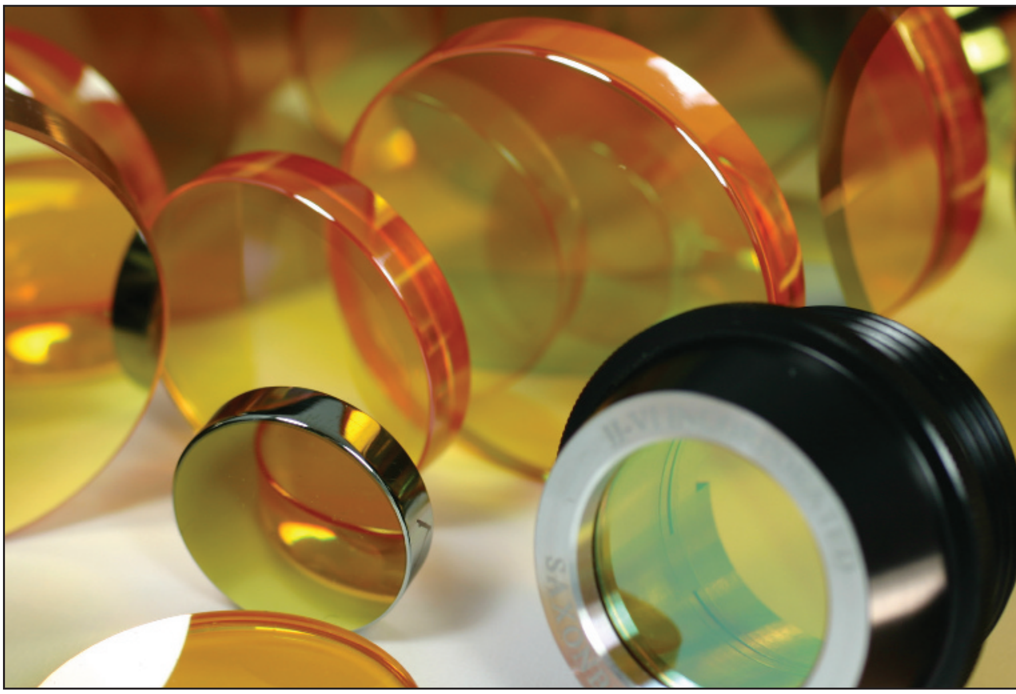
And it is this attitude that lies at the heart of II-VI's business strategy. Take a look at the structure of II-VI and you will see the business is incredibly vertically integrated. The company develops, refines and manufactures myriad materials, components and products primarily for industrial, optical communications and military markets as well as photovoltaic, medical and aerospace applications.

Zinc selenide for infrared laser optics, silicon carbide for high power electronics, bismuth telluride for thermoelectric coolers, optical channel monitors for reconfigurable optical networks, microchip lasers, optoelectronic modules, optical couplers for telecoms; the list of products is exhausting.

"We believe in vertical integration and having the materials expertise," says Creaturo. "We control the cost and quality along all lines, we're not so dependent on other [suppliers] and we're pretty self-sufficient in our manufacturing approach.This goes all the way back to having materials-centric businesses and controlling the raw material input as much as we can," he adds.

But vertical integration or not, can II-VI really turn the latest Oclaro sale into a commercially solid entity? Indeed, some business analysts recently suggested that II-VI had entered "overbought territory", advising investors to sell shares.

Creaturo remains confident. He asserts high power lasers and the 980 nm pump lasers will remain the backbone of the business, but highlights how the Zurich team will now have the financial backing to explore new opportunities in say, sensing for consumer electronics.



Vertically integrated: II-VI provides synthetic crystal materials growth, optics fabrication, electronics component manufacture and more.

Meanwhile he is also adamant his company can simplify Oclaro's operations, and, for example, has spotted 'a lot of synergies' with products from II-VI's Photop business.

"We believe many components here will now be used to manufacture the high powered lasers and 980 nm pump lasers that Oclaro was manufacturing," he says. Convinced more opportunities will emerge with time, he adds: "In a typical acquisition, we might add global sales and manufacturing, crystal growth expertise or our global offshore manufacturing footprint. We buy a healthy growing business, and we are usually able to make it better."

> "In a typical acquisition, we might add global sales and manufacturing, crystal growth expertise or our global offshore manufacturing footprint. We buy a healthy growing business, and we are usually able to make it better"

Antimonide ambitions

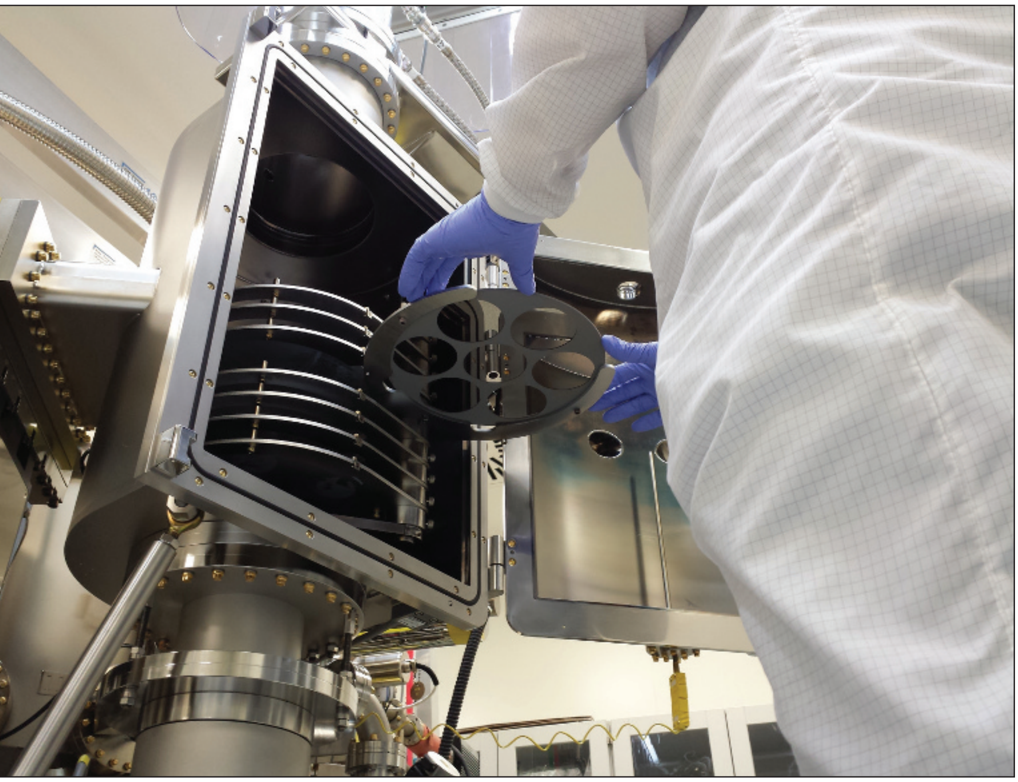
As antimonide laser diode manufacturer, Brolis Semiconductor, readies for market, Compound Semiconductor, quizzes co-founder Augstinas Vizbaras on the secret of his start-up's success.

FOR A COMPANY that opened its doors just two years ago, Brolis Semiconductors has made stunning progress. Manufacturing antimonide laser diodes on 3-inch GaSb substrates, and offering MBE growth of structures based on the AlGaInAsSb materials system, the Lithuanian business has bagged millions in European Investment funds and is ramping production for mass market.

"We have a lab dedicated to the MBE of antimonides as well as a research and development line for laser diode testing and packaging, which is what we are expanding," explains chief operating officer, Augus tinas Vizbaras.

"Right now our devices are demonstrating a high performance, but to bring these products to market we really need to optimise the yields and benchmark the products ourselves."

Brolis Semiconductors was launched in 2011 by the Vizbaras brothers; Brolis means brother in Lithuanian. The eldest, Dominykas, responsible for attracting the healthy venture funds, heads up the business as chief executive, while twins Kristijonas and Augustinas step in as chief technology officer and chief operating officer. Each twin researched III-V materials at the Germany-based Walter Schottky Institut, Technische Universitat Munchen, with Kristijonas studying MBE of arsenides and antimonides for GaSb lasers. Meanwhile Augustinas focused on long-wavelength semiconductor lasers, quantum-cascade lasers and III-V devices, publishing paper after paper with laser diode and quantum cascade laser pioneers, Markus-Christian Amann, TUM, and Mikhail Belkin, the University of Texas at Austin.



Brolis Semiconductor is currently expanding its facilities to ramp laser diode production

Today, the now nine-strong outfit has just received €1.6 million – bringing its research and development investment to €6.5 million – and is rapidly expanding its laser diode facilities and product line. A Veeco MBE production system was installed late last year and as Augustinas Vizbaras highlights, the latest expansion plans include more clean room space and automated instruments for lasers.

"We will add tools so we can bring our pilot devices very close to market," says Vizbaras. "We intend to increase volumes and will produce not just tens of chips but hundreds and maybe thousands."

As the chief operating officer points out, manufacturers of long wavelength antimonide lasers, such as m2k-laser and nanoplus, are still 'relatively small companies, based in small facilities, using small MBE reactors and turning out relatively few chips'. But the Vizbaras brothers want more.

"In larger markets, such as industrial gas sensing, the large consortia developing systems for these applications will require tens of thousands, and even hundreds of thousands, of laser diodes," says Augustinas Vizbaras. "We really need to work to show that this technology has the potential to go to mass market."

And herein lies the stumbling block. While III-V diode lasers based on GaSb nicely plug the gap in the mid-infrared spectrum, between the 1.7 μm end of InP-based lasers to the short-wavelength 4.2 μm end of quantum cascade lasers, materials issues have hampered progress. GaSb, the typical antimonide laser substrate, has a larger lattice constant than GaAs and InP, with a bandgap energy of 0.726 eV, corresponding to 1.7 μm. Missing out on the fibre-optic rush to InP-based lasers, researchers have since pushed antimonide lasers to reach longer and longer wavelengths for applications such as molecular sensing and spectroscopy.

However, at longer wavelengths Auger decay and free-carrier absorption ramp up, draining optical amplification. Still, researchers worldwide have persevered, focusing on materials development and fabricating novel structures to combat these effects. Today, commercial laser diodes emitting at 2.2 μm are available with research groups reporting continuous-wave, room temperature operation at 3 μm and beyond.

But still many remain unsure over the commercial viability of these lasers. "If you look at the literature, many research papers say this material just isn't homogeneous and the [devices] aren't reliable," says Vizbaras. "But we do not see this in our materials and we firmly believe our products will not suffer from reliability issues. However, reliability takes a lot to time to evaluate so we will be doing this on large batches of devices."

In the interim, Vizbaras claims that the company can manufacture lasers emitting from 1.8 μm to nearly 4.0 μm at room temperature. Indeed, Brolis recently delivered continuous wave, single-mode 2.1 μm laser diodes that offer output powers of more than 160 mW at 20 °C as well as multi-mode continuous wave 2.1 μm devices with more than 500 mW power at 20°C.

"It may be too early to say, but our present testing indicates we should be able to benchmark [our devices] at a 10,000 hour lifetime," he adds. "I believe this is what the industry needs."

The Vizbaras brothers and founders of Brolis Semiconductor hope to manufacture antimonide laser diodes for commercial markets in the next year and a half

"In larger markets, such as industrial gas sensing, the large consortia developing systems for these applications will require tens of thousands, and even hundreds of thousands, of laser diodes. We really need to work to show that this technology has the potential to go to mass market"

Materials matter

So what is behind the rapid rise of Brolis Semiconductor? In less than 9 months the brothers set up their fab from scratch and have amply demonstrated high brightness, Watt-level continuous wave pilot devices with 24 percent wall-plug efficiency. They now reckon devices will reach commercial markets in around a year and a half.

Vizbaras thinks a key advantage is keeping technologies in-house. "This allows for a much more rapid turnaround than when you out-source manufacturing," he says. "Also, our MBE business is a commodity business and is running well, being a major cash flow generator for us at the moment."

But without a doubt, the company's core competence has to be the brothers' strong materials and device development background.

"In my opinion, the problems [with antimonide lasers] come from an insufficient knowledge of the materials, and how to control and grow them," says Vizbaras. "But we are very confident of the material quality that we can get from our reactor, which we can then covert into laser diodes. Our performance figures are excellent and we we do not see any problems that could differentiate us from GaN and InP-based devices."

Wide Bandgap RF Devices

GaN and SiC have a great set of attributes that make them very promising materials for producing RF devices. But are they now fulfilling their potential and netting substantial sales?

Keynote presentation: Andrew Barnes
Overview of GaN reliability improvement activities at the European Space Agency

Chris Horton
Enabling material solutions for GaN in the RF arena

Mike Mallinger
Microsemi's SiC for long-range radar

Marc Rocchi
100nm GaN/Si mmW foundry service and MMICs

Solar

Triple-junction solar cell efficiencies are increasing steadily. Will this help to spur rapid growth in the concentrating photovoltaic sector, or will it be more valued by those requiring a power source for satellites?

Keynote presentation: Vijit Sabnis
Setting a new benchmark for space solar cell performance

Rainer Krause - Soitec
Wafer bonded 4-junction GaInP/GaAs//GaInAsP/ GaInAs high performing concentrator solar cells

LEDs

LEDs are the dominant source for backlighting screens of all size. So, to penetrate new markets and grow revenues, can chipmakers now trim the cost-per-lumen of the LED or equip the device with additional features?

Keynote presentation: Young Soo Park
Slashing LED costs with 200 mm silicon substrates

William Henry
Applications and opportunities for MicroLED emitters

Pallavi Madakasira
LED light bulbs: When and how will the lighting of tomorrow become the lighting of today

Ulrich Steegmueller
Success factors in the increasingly competitive LED ecosystem

David Kepniss, Director of Sales and Marketing
Sub part-per-billion analysis of high purity hydrogen - process improvement applications with the HEMS™ analyzer

Continues on next page

Front Ends for Mobile Devices

Handset front-ends are becoming more complex, due to an ever-increasing number of bands used for mobile communication. Will this trend play into the hands of GaAs chipmakers? Or is silicon CMOS technology going to grab market share?

Keynote presentation: Jeremy Hendy
Envelope tracking - transforming the performance of CMOS and GaAs PAs

Asif Anwar
Coming full circle - will Si CMOS burst the GaAs bubble?

Thomas Meier
GaAs & Silicon: Co-existence in a wireless world

Brendan Timmins
Minimizing the cost of precious metals used in compound semiconductors

Dr Dirk Schumann, CSO/CTO
Waterbased stripping innovation for wafer stripping and metal lift-off

Wolfram Drescher, CEO
"Cold split" – A simple thinning and wafering process technique

Power Electronics

Silicon has dominated the power electronic market for decades, but wide bandgap semiconductors will soon replace this material. What's the primary role for SiC, and where will GaN feature?

Keynote presentation: Ming Su
Can SiC or GaN power the next-generation hybrid electric vehicle drive systems?

Keynote presentation: Mike Briere
Pioneering GaN on Si power devices on large diameter substrates

Philippe Roussel
Vertical integration vs outsourcing in the wide bandgap sector

Marcus Behet
SiC and GaN/Si for power electronics – niche forever?

Denis Marcon
200mm GaN-on-Si CMOS compatible platform

Kolja Haberland
Advanced in-situ growth monitoring for gan based power electronics on silicon

Integration of CMOS and III-Vs

Silicon is running out of steam, and the future is widely tipped to be high-mobility channels made from germanium and III-Vs. But how will these materials be introduced in the world's leading silicon foundries?

Keynote presentation: Dr Jean Fompeyrine
Co-integration of III-V and Ge CMOS
IBM

Dr. Thorsten Matthias
Direct wafer bonding: Enabling technology for future photonic and electronic integration
EVG

Shinichi Takagi — The University of Tokyo
III-V and germanium FET technologies on Si platform

Aaron Thean
Beyond silicon CMOS: Transforming transistors with heterogeneous material integration
imec

Selection of companies also presenting include:

EpiGaN, evatec, GT Advanced Technologies, Oxford Instruments, KLA Tencor, SAFC Hitech, Siltectra, Temescal

Platinum Sponsors

evatec, EVG, GT Advanced Technologies, KLA Tencor, LayTec, Oxford Instruments, S3Alliance, Siltectra, SAFC Hitech, Temescal, Yole Développement

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Networking Reception — Indium Corporation

Delegate Bag — TriQuint

Lanyard — Dow Electronic Materials

Portfolio — rfmd

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Please visit **www.cs-international.net/register.php** to secure your place

CS INTERNATIONAL CONFERENCE

Connecting the leading compound semiconductor industry insiders

Strong uptake of Google glasses could help to spur demand for higher-performance microprocessors, and consequently drive the introduction of new materials for transistor channels

Maintaining Moore's Law:

The role of III-Vs as a logical successor

If reductions in the dimensions of the transistor are going to go hand-in-hand with increases in its performance and a trimming of its power consumption, silicon channels will have to be replaced with higher mobility materials, such as III-Vs. But will this happen, and if so, when? What has to be done to usher in these new materials? And if III-Vs are to make an impact in microprocessors, will they be there to stay? Richard Stevenson puts these questions, plus several more, to analyst Dean Freeman from Gartner Research.

Q Will silicon CMOS prevail for many decades? Or are there barriers to scaling with silicon?

A I think you've got to help the silicon. Silicon as a template is going to be what we use for a long time, but the gate material is probably going to evolve. We've gone from a planar, metal oxide and silicon semiconductor to a high-κ, metal gate transistor. You are probably going to get to the point where you have some sort of compound semiconductor as part of the gate material.

You can probably shrink silicon down to the 4-nanometre technology node and even shrink the transistor further than that. The question is how much power is it going to take to turn the transistor off and keep it off. Based on the technology and the way we understand it now, you're going to have a very leaky device for anything made out of silicon.

Guys from Soitec are saying that they can help out a little bit, but there is only so much that leaks through the bottom of the transistor. You also have leaks from the source to the drain, and from the substrate into the gate. So you eventually end up at a point where you just have to have so much power that it is not economical to run the device. Many years ago Patrick Gelsinger [CEO of VMware] showed the slide that we will go from having an iron on our lap to a nuclear power plant on our lap. That will continue to happen with new materials. However, [the extent of this heating] depends on what type of material you get in the gate, as well as what you can do to keep the leakage at a minimum as you continue to shrink the devices.

Q Do many within the silicon industry believe that other materials are needed for the channel?

A Right now, a lot of different materials are being looked at for the channel. You've got germanium for the pFET, indium antimonide arsenide for the nFET; you've also got graphene and nanotubes being looked at; and you have folks looking at different types of silicon nanowires. So there are a lot of different irons in the fire.

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The question is this: When we get down to the point where we can no longer make the high-κ metal gate transistor work, what is next? What can we manufacture at a reasonable cost so we can keep providing faster-working devices at a lower cost?

Q One of the most radical changes in the history of the silicon industry is the move in the last few years from a planar device to one with a fin protruding out of the surface. If new materials are introduced, will they be in the form of finFETs, or could we see a return to planar devices?

A It depends on the mobility of the device. One advantage of a fin device is that you get so much higher mobility, because you have gone from having just one surface that the electrons can pass through to what I call two-and-a-half, based on the height and width. This basically doubles the mobility of the device.

If we get something such as indium antimonide phosphide or graphene, which both have a really high mobility, it is possible that we could go back to a planar device. That would ease some of the manufacturing difficulties a little bit. But it's likely that the fin is here to stay, provided that the fabs can continue to manufacture it. That has to do with lithography and etching.

Q If III-Vs and germanium are to make an impact, when do you believe this will be?

A The rumour is that germanium is going to show up at the Intel 10 nanometre technology node. So, that will show up at what the foundry is now calling the 7 nanometre technology node. So you will probably see the III-V materials at the Intel 7 nanometre technology node. You could see the foundries try to accelerate this, but Intel, from a research and development perspective, is significantly ahead of most of the foundries.

Samsung's and Global Foundries' ace-in-the-hole is the work that they have got going with IBM – IBM has been playing with weird materials for a long time. I don't think that they'd be able to leapfrog Intel, but they could potentially introduce a III-V transistor in a very similar timeframe. However, when would the foundries be able to economically push that out to their customers?

Q One of the challenges with III-Vs is uniting them with silicon in a manner that could be deployed in high-volume, high-yield foundries. imec is pioneering the growth of III-Vs in trenches formed in silicon wafers, while IBM is looking at a wafer-bonding approach. Are there other promising options?

A It appears that you can grow nanowires, either in a vertical or a horizontal direction. You could drop a trench in, put your catalyst on the side, and then grow these nanowires across a trench. That means that you've got a gate-all-around process. I think that's one of the more probable techniques that you'll see come out. [That's because] if you are growing directly on silicon, without the catalyst, you have to start with a buffer layer, so you get the right crystal structure. It appears that you can grow a pretty good nanowire – with the right characteristics – across that trench, without any significant preparation. The only problems are getting the right angle for the nanowires, and making sure that they haven't gone wild. You want something that's nice and orderly, verses something that looks like a bunch of earthworms. That's the technique that they need to iron into perfection.

I haven't confirmed this, but I've heard that although you can grow the nanowires vertically, you can't make a device out of them, because you can't do the source-drain properly. This is unfortunate, because growing the nanowires vertically would be the easiest. But if we look at Intel's technology roadmap, we have 6 years or so until they need to be in production, so we could figure something out between now and then.

Q Are the equipment manufacturers gearing up for any move to introducing III-Vs into the channel?

A Aixtron and Veeco are talking and making noise about this, and Applied Materials and ASMI are looking at it closely, because it is the next epitaxial material that we are going to have to look at. The University of Illinois has been playing with this stuff for years, and they've been working with Intel. And you've got IQE: They're making noise about this, and are capable of doing this as a bulk epitaxial film.

The problem is that there is a lot of risk. You are looking at something that is six years away from production, and you don't want to jump on the bandwagon with too much money in your pocket.

It was easier with silicon. The move to the high-κ metal gate was a very obvious transition. People had been working with the high-κ's since the 1980s, and everyone knew that you had to make the transition. However, if you take a look at the companies that jumped on-board from a dielectric perspective, there were really only Genus and ASMI, and it took a long time for that move to become economically feasible for them. So the equipment manufacturers are approaching it with a great deal of caution. They want to make sure they do it right, verses doing it several times.

Q If we do move to a III-V channel, it will have implications for other parts of the transistor, such as a new gate stack. Is that going to introduce difficulties?

A Not really, because you are still going to use some form of dielectric. If I grow my indium-antimony-based material, I will probably still use a high-κ dielectric and I just have to make sure that my interfaces work OK. Actually, my interfaces will probably be better with indium antimony than they are with silicon dioxide. With silicon dioxide, if any oxygen diffuses, I get a thicker or a lower-k dielectric.

It is possible that we could go to a kinder and gentler high-κ dielectric, such as alumina, or zirconium, instead of hafnium.

Q There will be concerns within the silicon industry that III-Vs could lead to arsenic contamination within the lines. How big are these concerns?

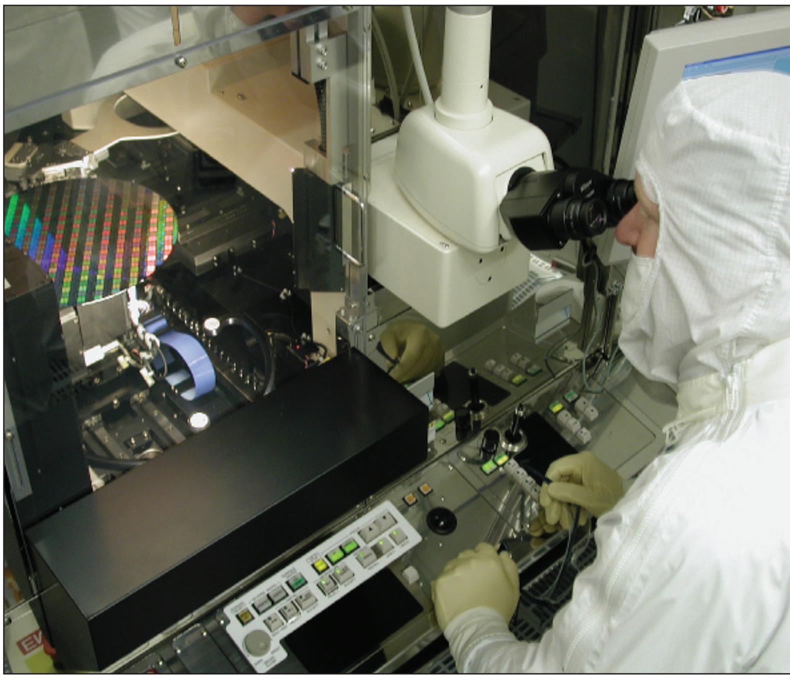
A You already use arsenic, antimony and phosphorous as implant dopants in certain applications. So it's not a huge concern. You build a special room for it and take precautions.

Q Are there other concerns that those in the silicon fabs have?

A I don't think we are far enough along yet for those concerns to have manifested themselves. As Intel would say, we are still in path finding.

With germanium, you are going to have new process techniques. You are going to etch it slightly differently, you are going to have to deposit it slightly differently, and it's a lower temperature process, so you will have to adapt to those new materials, just like we had to adapt to the high-κ metal gate process.

With an indium antimony arsenide process, you'll have to be careful not to crank your temperature up too much, or you'll loose some of the favourable dopants and you could shift your threshold voltage as a result of out-gasing of one of those III-V materials.



Right: Intel leads the way with the development of new materials and processes to maintain the march of Moore's law. The company is tipped to introduce germanium at its 10 nm node, and possibly follow this up with III-Vs at the 7 nm node. Credit: Intel.

Q How long could III-Vs make an impact for?

A That's very hard to say. My guess is that it is hard to conceive that you would go through all the work it would take to introduce a new material for just one generation. I think that's part of the concern that is going into the decision-making process. The one great thing about the indium antimony scheme is that this is the second fastest material in the world, behind graphene and carbon nanotubes. So you could probably get two-to-three generations out of it.

A big question is how much further can we shrink what I call conventional process technology? Right now, everything is 'you dep, you print, you etch'. We have a pretty clear path to 7 nanometres, and there we will probably see our first III-V materials.

Once we go beyond 7 nanometres it gets a little fuzzier. We are adding new materials, we've got some challenges with lithography, and it's not as clear what we have to do to get the power-performance that we've been used to for the last 40 years.

Once you start to get down to 5 nanometres or 3 nanometres, you are probably going to have to see self-assembly introduced for the very small features. You will also have some difficulties in the metallisation scheme. An engineer might be saying that they've got this transistor that is fantastic, but its copper metallisation doesn't work fast enough and its resistance is too high.

Aside from having to deal with the transistor, you have to deal with the interconnect as you move down to these smaller and smaller technology nodes. There is some thinking about how to get around this, with graphene and carbon nanotubes, and doing some different things with the copper interconnect, but it will be challenging.

Q Is the future of the channel the biggest challenge facing the silicon industry, or is it the scaling of lithography?

A I think it depends on who you talk to. EUV is a huge challenge. We know we can do 7 nanometres with optical lithography – it just gets very expensive. Now, when EUV comes on-board, it reduces the expense of lithography. But once we get past 7 nanometres to 5 nanometres, you then have to start playing some of the same tricks with EUV that you were playing with optical lithography, such as proximity correction, so the lithography costs begin to go up again.

Historically, we've had about a 30 percent cost decline per node, and a 30 percent shrink in silicon, with the cost falling as a result of shrinking the silicon. If we continue to stay on that curve, we'll continue to shrink, but if lithography costs are going up, and transistor material costs are going up, that curve starts to tick up. If you don't get the performance that you're looking for, you have to start to question the economics: Is the speed you're getting out of the device worth going to the next node?

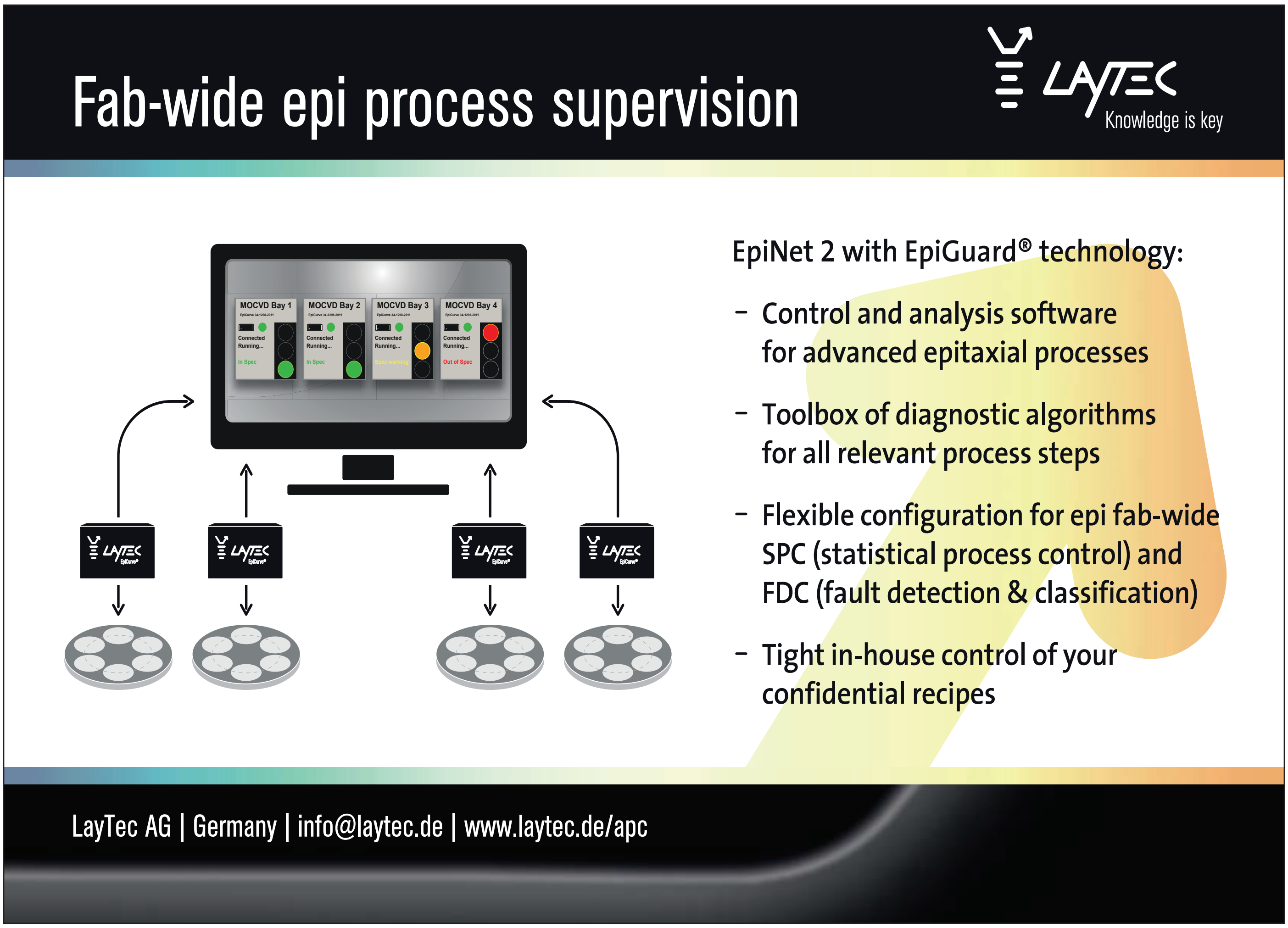
Q So is it not obvious that scaling will continue forever?

A There is grumbling at the foundries that they are not getting the power-performance curves that they need, or historically have gotten. This is why the foundries are trying to jump to the finFET at 20 nanometres as quickly as they can to get back on the power-performance curve. I think you have to look at whether we can continue to stay on that curve. If I can get a newer gadget that can work faster every three years, I'm probably going to continue to spend money on it. If I can't do it, we'll be in the PC doldrums we are now, with consumers saying: 'I used to buy a new PC every three years, but this one works fine. So maybe I'll just upgrade the screen, so it's a little bit bigger and a little bit brighter, and I'll make do with what I have. I have enough storage and it's fast enough for what I'm doing, and until Microsoft will not support my operating system, I can continue to live. I use it for content creation, so I don't need the speed, because I'm using my iPhone, my iPad or my tablet for my content absorption, and my PC is a secondary unit for content absorption.'

Tablets are still going pretty strong, but you are starting to see the application fatigue that has been out there in the cell phone. The high-end cell phones aren't selling. Parents have finally come to the realisation: Why am I buying my child a $200 iPhone when I can give them the 4S for free, or I can get them a cheap Android for free and just pay the monthly fee.

The newness has worn off. But if I am able to, say, take that cell phone and shrink that into a Google glasses or a watch, then I'll not carry a cell phone with me any more. I'll have something else for my visual, whether it's the glasses or watch, and everything is voice recognition, because my processors are fast enough to do that and understand what I say, even if I have a terrible ascent or don't speak clearly. Then, maybe we'll continue to drive the new applications or the new toy harder and faster. But if we don't hit those price points, we're not going to continue to drive those killer applications.

Dean Freeman, Research Vice-President at Gartner Research, is part of the Semiconductor Equipment, Manufacturing, and Materials service in the Semiconductors group. He is responsible for market research and analysis of semiconductor equipment and trends in IC manufacturing techniques, as well as emerging semiconductor technology, which includes nanotechnology, LEDs and printed electronics. Freeman has almost three decades of experience in the semiconductor industry, having worked with Texas Instruments, Lam Research, FSI International and Watkins-Johnson's Semiconductor Equipment Group.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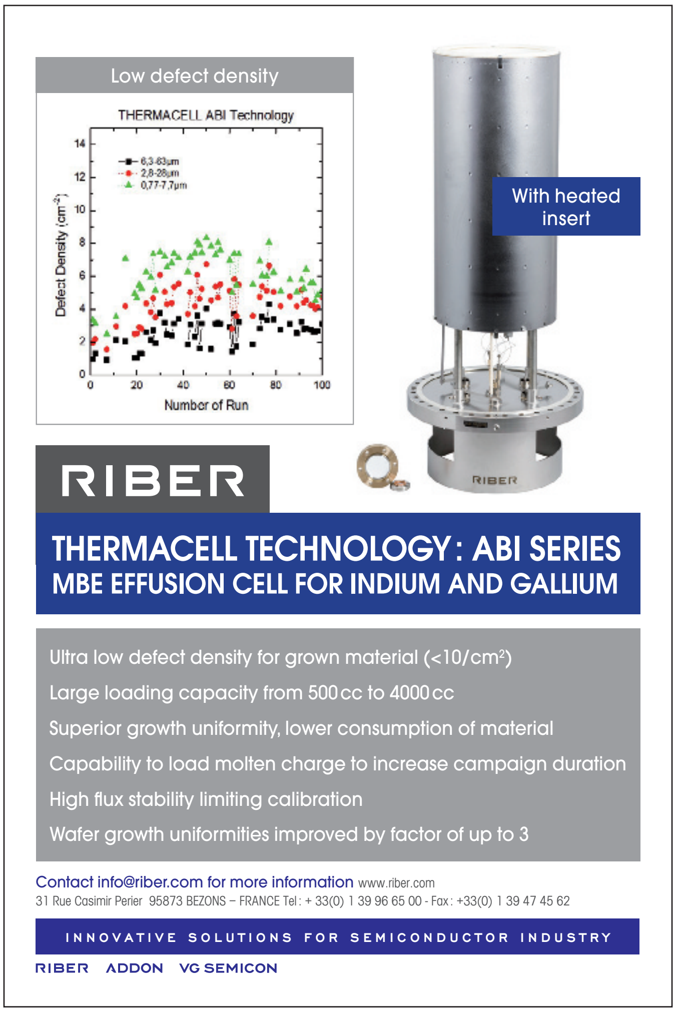
Low defect density
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2,8-28µm
0,77-7,7µm
Defect Density (cm⁻²)
Number of Run
With heated insert
RIBER
THERMACELL TECHNOLOGY : ABI SERIES
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Wafer bonding creates record-breaking **four-junction cell**

To prevent the formation of efficiency sapping defects, conventional multi-junction cells are built with lattice-matched materials. But this restriction can be lifted with wafer-bonding, which enables the fabrication of a four-junction cell with record-breaking efficiency, say Rainer Krause and Bruno Ghyselen from Soitec and Frank Dimroth from the Fraunhofer Institute for Solar Energy Systems.

CONCENTRATING PHOTOVOLTAICS (CPV) involves the generation of electricity through the focusing of sunlight onto solar cells.

At Soitec of Bernin, France, we are one of the world's leading manufacturers of this class of solar system. We manufacture modules that use Fresnel lenses to focus sunlight onto cells at a concentration of over 500 suns and we are analysing optical concentrators that would allow us to increase further the concentration level with the same degree of reliability (see Figure 1). To ensure that these modules generate as much energy as possible, they are mounted on tracking systems that follow the sun's position in the sky from dawn to dusk. Such systems are deployed on solar farms, and deliver their best returns in locations with bright sunshine (regions said to have a high value for Direct Normal Irradiation, or DNI).

We are currently making our systems more competitive by working on different elements of the system. On the solar cell side, by teaming up with researchers from Fraunhofer ISE and CEA-Leti, we are running a programme to take cell efficiency to a new level. Our new devices feature four junctions – one more than the traditional multi-junction cell – bringing the achievable maximum efficiency to around 50 percent. On the way to hitting this level of performance, in 2013 we raised the world record for efficiency to 44.7 percent by uniting a top tandem cell of GaInP and GaAs with a bottom tandem cell made from GaInAsP and GaInAs.

We are by no means the only multi-junction cell manufacturer or developer that has devoted a great deal of effort to improving device efficiency. That's because gains in efficiency can lead to significant reductions in the levelised cost of energy.

Before we unveiled our ground-breaking device, increases in the record for efficiency – which have recently increased by about one percent a year – resulted from refinements to the conventional triple-junction cell. In its standard form (see Figure 2), it comprises a germanium (0.7 eV) bottom junction and middle and top junctions of GaAs (1.4 eV) and GaInP (1.9 eV).

Several firms, including AZUR-Space in Germany, and Boeing-Spectrolab and Emcore in the United States, manufacture this incumbent design using mature, high-yield industrial production processes. Such devices are deployed in commercial systems, where they can reach efficiencies of 41 percent [1, 2].

Features of the standard device include two terminals – a front contact and a backside contact – and the connection of the three cells in series, so that a single voltage is delivered at the cell level. The epitaxial structure of the multi-junction cell is usually formed by MOCVD. There are limits to what is possible with this approach, due to epitaxy and lattice matching, and if the material quality is not high, charge carrier recombination can impair device performance. So, to optimise the efficiency of the cell, it is crucial to carefully balance the characteristics of every junction, so that they work well together.

Increasing efficiency

Two well-known routes exist for improving the efficiency of multi-junction cells. One is to fine-tune its absorption profile, so that the contribution from every junction combines to propel the overall efficiency to a new high. And there is also a more ambitious approach: To add additional junctions, starting with a move from three to four.

We are not alone in targeting a four-junction device with cells operating at the optimum bandgap energies of 1.9 eV, 1.4 eV, 1.1 eV and 0.7 eV. It has been demonstrated that it is possible to reach these energies by introducing dilute nitrides, such as GaInNAs, into the conventional GaInP/GaAs/Ge stack [3]. Meanwhile, researchers at NREL followed by other industrial groups, have proposed the use of an inverted metamorphic four-junction solar cell [4].

Our approach is different. While the number of junctions and the choice for their energies remain basically the same, a totally different and key technological step is added to the epitaxy tool box: wafer-bonding. The concept of applying wafer bonding in this arena is not completely new [5, 6]. However, we are the first to use this to form, at full wafer level, cells with an efficiency that exceeds every triple-junction device. Introducing wafer bonding has enabled the marriage of lattice-mismatched materials without the creation of dislocations, so GaAs and InP can be united.

To join materials such as these, two crystal structures must be brought together to form covalent bonds at the interface. Success demands that materials are carefully prepared, and their surface roughness is low. Once these conditions are met, it is possible to yield multi-junction solar cells based on defect-free material.

Wafer bonding

We have developed a specific wafer-bonding process for uniting InP- and GaAs-based materials to form a transparent, electrically conductive

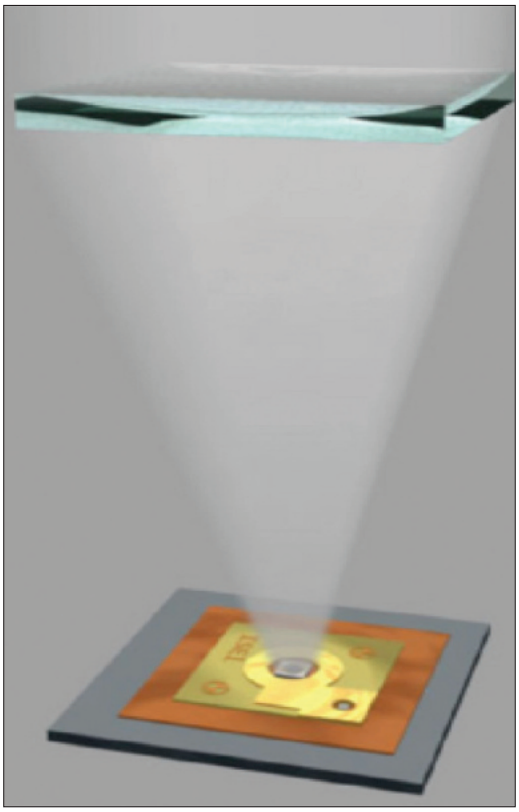


Figure 1. Soitec's concentrating photovoltaic modules employ high efficiency III-V multi-junction solar cells, a Fresnel lens array with a relatively small aperture, and glass for the front cover and bottom plate

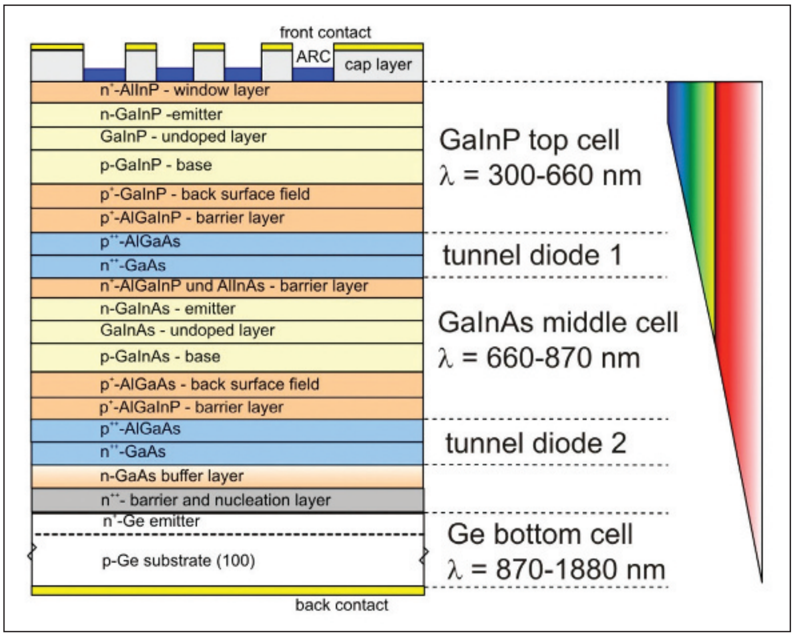


Figure 2. A state-of-the-art triple junction solar cell features a bottom junction made from germanium, and additional junctions based on GaInAs and GaInP

design. In our case, bonding is not restricted to bulk wafers, but includes ternary and quaternary epilayers, thereby enabling an incredibly wide choice of optimum materials.

InP bulk material is more expensive than GaAs or germanium wafers, but this is not a stumbling block for us, because we can leverage our Smart Cut technology, which we have used in volume manufacturing for more than a decade. Armed with this, we use only a very thin layer of initial material, and can consequently re-use the InP substrate many times. Once a thin layer of InP has been extracted from the substrate, it can be transferred to many different types of carrier. This led us to introduce the acronym 'InPOX' as a generic name for 'InP-on-X', where X can include silicon, GaAs, germanium and sapphire.

An example of this is the transfer of a 0.5 μm-thick layer of InP to 100 mm sapphire. Working with partners at Fraunhofer ISE and CEA-Leti, we have used our Smart Cut technology in conjunction with direct wafer bonding and III-V epitaxial growth to produce a record-breaking four-junction cell. Our collaborators contribute expertise associated with III-V material growth, fabrication of engineered substrates and epitaxial lift-off and bonding techniques.

The device that resulted features a bottom GaInAs junction with a bandgap of 0.7 eV, overlaid with GaInAsP, GaAs and GaInP cells with bandgaps of 1.0 eV, 1.4 eV and 1.9 eV, respectively (see Figure 3). Features of this photovoltaic include low shading losses, which results from front metal contacts with a finger width of 5 μm, and a double layer anti-reflection coating that ensures minimal reflection.

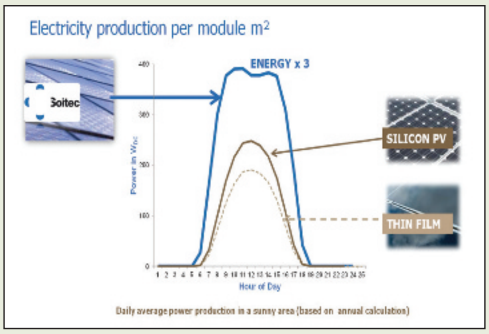
Using 100 mm substrates, cells with an area of 5.2 mm^2 have been processed and characterised to form four active junctions. Development of the fabrication process revealed approaches for dramatically increasing the yield of good solar cells, and this helped us to produce wafers with a yield of functional devices in excess of 95 percent (see Figure 4 for images of finished cells, at wafer level and after die separation).

Our partners at the Fraunhofer ISE CalLab measured our cell's quantum efficiencies and current-voltage characteristics under one-sun AM1.5d (1000 W/m^2, 25 °C) standard test conditions using a spectrally adjustable solar simulator. To determine performance under concentration, a Xenon Flash simulator with adjustable distance between the flash bulb and the measurement plane illuminated the devices.

The strengths of CPV

Concentrating photovoltaic systems are already cost-competitive in very sunny climes, and in these locations there are several reasons for turning to this form of energy generation. For example, aside from the tiny solar cells located at the focal points of the lenses, the production of a CPV system generally employs low-cost materials, such as glass or silicone, and involves fully automated mass-production conditions.

Another attribute of CPV is that the record-breaking cells not only outperform their rivals at room temperature, but exhibit a far slower decline in efficiency with temperature, as well as much less aging degradation. What's more, mounting of these cells in tracker systems leads to a more constant power output curve throughout the day (see figure), resulting in not only more energy harvested, but also a higher energy production during peak hours – when it is most valuable. On top of all these arguments, which are associated with the levelised cost-of-energy, there are environmental considerations, such as the small physical footprint of CPV, its absence of water consumption, high levels of recycling, and the opportunity for dual land use with agriculture or animals.



By mounting solar modules on a system that tracks the position of the sun in the sky from dawn until dusk, CPV systems generate significant levels of electricity throughout the day

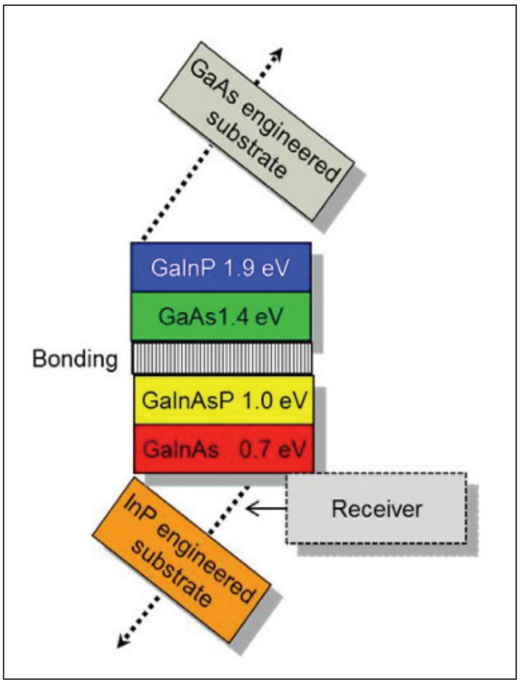
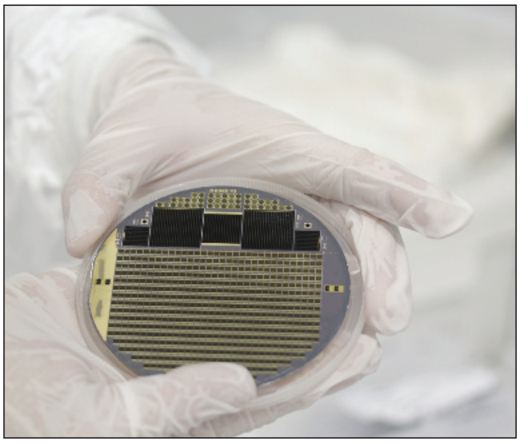


Figure 3. Fabrication of Soitec's four-junction cell involves wafer-bonding and substrate removal



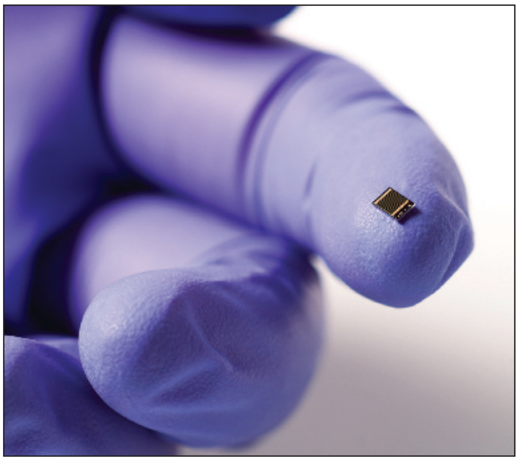


Figure 4: Soitec's cell at wafer level (a) and after die separation (b)

A three-dimensional laser microscope enabled an accurate measurement for mesa edge, and thus an accurate value for the efficiency of these small area concentrator solar cells [7].

Measurements revealed that the peak quantum efficiency for all four cells is well above 85 percent, and that device efficiency hits 44.7 percent at 297 suns. Even at 1000 suns there is no indication of a breakdown in peak tunnel current density, while the high fill-factor of 86.5 percent at this concentration indicates a moderate resistance of the bond interface, which operates well up to current densities of several A cm^{-2}.

We know that it is possible to deliver even higher efficiencies from our four-junction cell. Our plan is to realise this, and efforts at improving device structures are already underway, directed at the optimisation of sub-cell characteristics and further material quality improvement. In the longer term, this will help to trim the generating costs associated with concentrating photovoltaics and empower this technology to displace other types of cell.

The authors acknowledge the contributing work from the CEA Leti team in Grenoble France and the laboratory work of the Fraunhofer ISE team in Freiburg. Also acknowledged is the contributing work from Helmotltz-Zentrum in Berlin. This program is supported by the French Environment and Energy Management Agency (ADEME) through the "Investissements d'Avenir", pending European Commission notification agreement.

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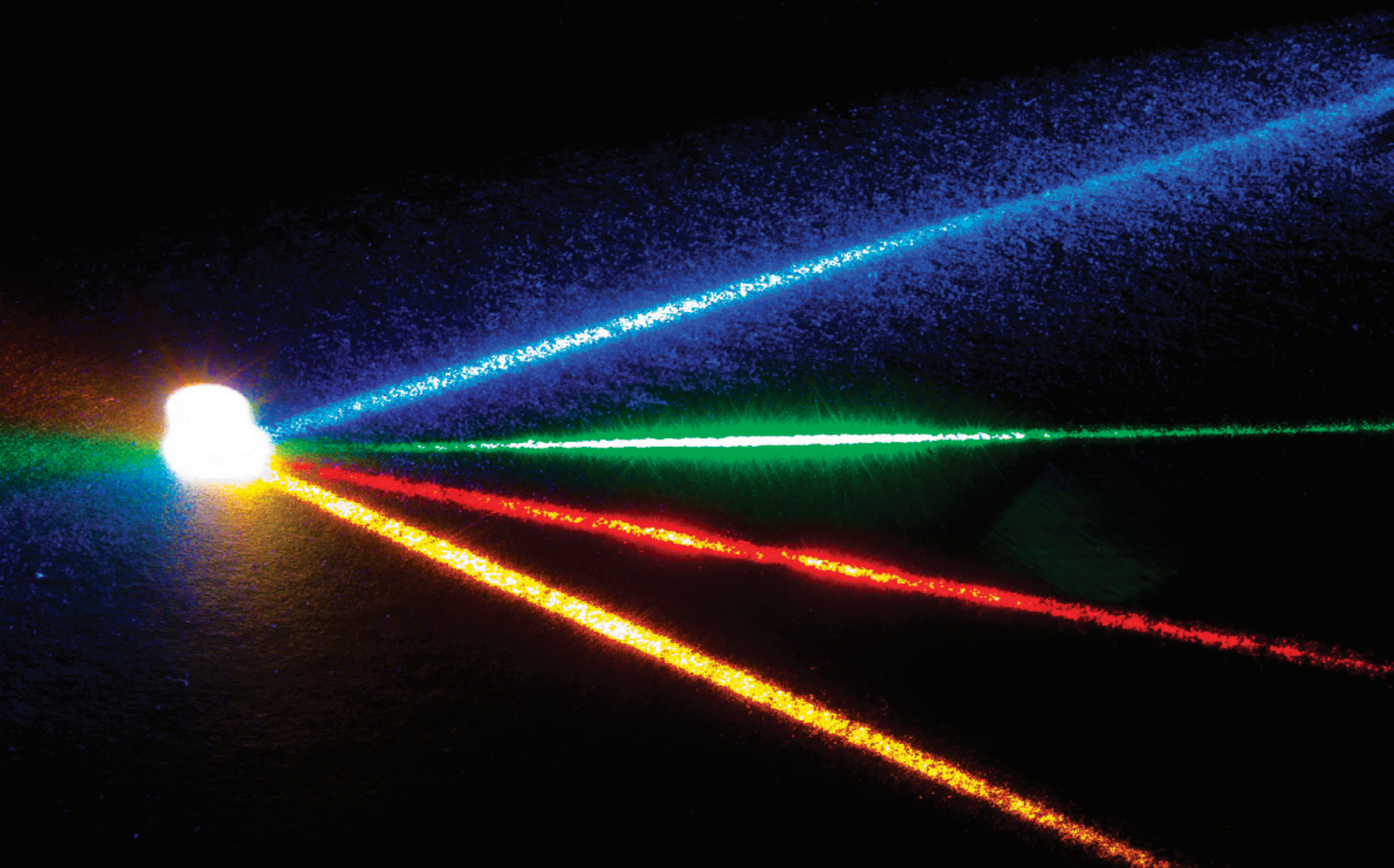
Combining the light from four lasers emitting at different wavelengths can produce a white light source. Very high efficiencies are promised, but are not possible today due to the low efficiency of sources emitting in the green and red. Credit: Randy Montoya.



Solid-state lighting:

Are laser diodes the logical successors to LEDs?

It is expensive to manufacture a GaN laser, and its peak efficiency is not that impressive. So why is this device, rather than the LED, being touted as the future of solid-state lighting?

RICHARD STEVENSON investigates.

If I asked you what you wanted from the bulb of tomorrow, incredibly high efficiency would probably top your list. Not far behind would be a low purchase price and a long lifetime, and you might also value a product delivering directional light and a manufacturing process that treads lightly on the environment.

One bulb ticking quite a few of these boxes is that based on the LED. This form of lighting is the leader in the efficiency stakes, it is free of mercury, and it excels in reliability, lasting 25 times as long as an incandescent and more than twice that of a compact fluorescent. But this bulb is not fault-free. Its light is challenging to direct, its retail price puts many off investing in solid-state technology, and its efficiency is not head-and-shoulders above that of some sources.

The high price of the LED bulb and an efficacy that is good, rather than great, are both consequences of LED droop – the mysterious malady that causes a decline in efficiency at higher drive currents. If droop did not exist, bulbs could operate at more than 200 lumens-per-Watt while being driven from a handful of tiny LED chips running at incredibly high drive currents. Such bulbs would be cheap to make, not just because of the minimal amount of semiconductor material in them, but because high LED efficiencies simplify heat sinking.

Unfortunately, it's hard to see this vision of cheap, ultra-efficient LED bulbs becoming a reality. Droop is an intrinsic weakness of the LED, and while it is possible to push out its impact to higher current densities, it seems that it will always be sapping efficiencies at really high drive currents. So, what is needed is an alternative way forward, possibly a device that provides a similar level of reliability to the LED, but doesn't suffer from droop. And, in an ideal world, it delivers directional light.

Come to think of it, doesn't this device already exist? Researchers Jonathan Wierer and Jeffrey Tsao certainly think so – they are even arguing that laser diodes are the logical choice for the future of lighting. Along with Dmitry Sizov from Corning, they have recently published a paper in *Laser & Photonics Reviews* detailing calculations that show the tremendous promise of this form of lighting.

Using lasers for lighting will raise a few eyebrows: After all, aren't they too expensive? Aren't they too inefficient? And how can these monochromatic sources produce a high-quality white light source? Well, as we are about to see, such concerns are not showstoppers: Lasers actually have the potential to be cheap enough and sufficiently efficient to produce very affordable, high quality lighting.

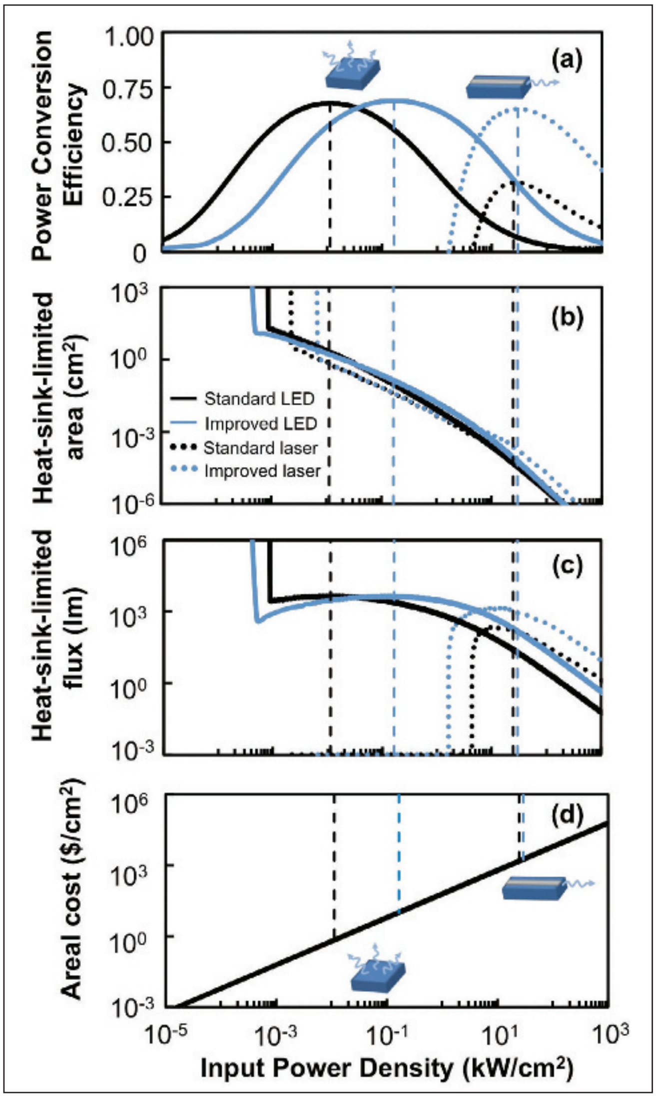


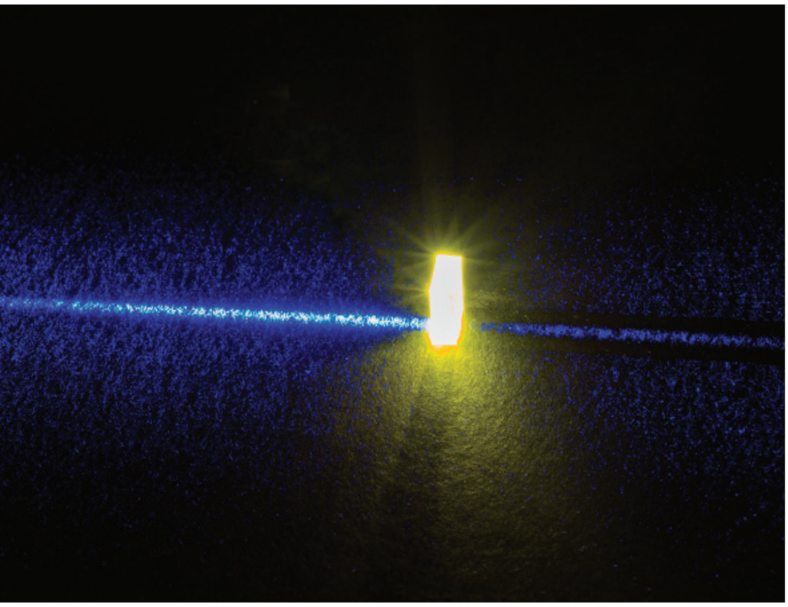
Figure 1. (a) The power conversion efficiency of LEDs peaks at a far lower current density than that of a laser. Today, the peak efficiency of an LED is much higher than that of a laser, but if lasers improve, this performance gap will shrink. (b) The higher the current density in lasers and LEDs, the smaller the chip must be to prevent overheating. (c)The heat-sink limited flux is determined by the current density running through the device, its power conversion efficiency and its maximum size. (d) The maximum acceptable manufacturing cost for a laser chip for solid-state lighting is far higher than that for an LED, thanks to the far higher current density of operation

How many lasers?

The scientists from Sandia have been considering novel approaches to lighting for many years. Back in 2007, their calculations revealed that efficacies of 408 lm/W, combined with a colour-rendering index of more than 90, are possible by combining four narrowband sources. These calculations were for line-widths of 1 nm and emission at 463 nm, 530 nm, 573 nm and 614 nm.

Unfortunately, building an efficient lighting system based on this approach is a long way off. Although it has been possible for some time to deliver a reasonably efficient output from a narrowband-emitting blue laser, efficiency plummets at longer wavelengths, similar to the LED. This weakness, known as the green gap, occurs because, as more indium is added to the InGaN quantum well to push its emission to longer wavelengths, two unwanted effects occur: material quality diminishes; and there is an increase in the strength of the internal electric fields in the LED, which pull apart electrons and holes and impair efficient radiative recombination.

The answer is not to turn to the AlGaInP material system, even for the red source. Although this quaternary enables the manufacture of efficient lasers at around 650 nm – the spectral



One way to form white light is to pump a yellow-emitting phosphor with blue emission from a laser. Credit: Randy Montoya

region used for DVD players and recorders – efficiency rapidly falls at the shorter wavelengths necessary for solid-state lighting, due to plummeting carrier confinement in the quantum wells. So if efficient green, yellow and red lasers are to exist, progress needs to be made with III-nitride materials. This should happen, but it will take time, so Tsao and Wierer are proposing an interim step: pumping a phosphor with a blue laser.

Constructing a white-light source in this manner is not a new idea. Back in 1962, Nick Holonyak, co-inventor of the laser diode, speculated on the development of the laser as a practical light source. Fast-forward to 2007, and at the Photonics West meeting in San Jose Nichia's engineers demonstrated such a product, a white light source formed by coupling a GaN laser into a fibre that had a phosphor coated to the other end. And, more recently, BMW announced that it is developing headlights based on GaN lasers, which can deliver directional beams that would be hard to create with LEDs.

The discouraging news is that Nichia no longer markets the fibre laser white-light product. Tsao argues that it does not follow, however, that this implies that laser-based lighting is fundamentally flawed: "I think Nichia was just a little bit early. Back then lasers were not as efficient as they are now, and even now they are not efficient enough."

Today, blue-emitting lasers have a power conversion efficiency of up to 30 percent, while state-of-the-art LEDs can hit 70 percent. So it appears that lasers are well behind at the moment. But these figures don't tell the full story. A fundamental weakness of the LED is that its peak efficiency occurs at a very low current density, typically around 1 Acm^{-2}. If LED light bulbs were to operate in that regime numerous chips would be required to produce enough light, and total chip costs would be exorbitant. Thus, the current density through the devices that are deployed commercially is cranked up to ten-to-twenty times this value, where droop kicks in.

The origin of droop

Although the cause of this efficiency-sapping malady is highly controversial, Wierer is adamant that it is the result of Auger recombination. "[Auger] has been measured in five or six different ways, and it seems like the values that people are measuring for that recombination are converging on a certain number." Alternative theories for droop, such as electron leakage and carrier leakage, just don't cut it with Wierer: "Every time I read a paper that suggests a mechanism that is not Auger, I can shoot holes in it."

However, even if it turns out that Wierer and all those in the Auger camp are wrong about the cause of droop, it would not alter the key message from this study – that lasers, rather than LEDs, are the most promising devices for solid-state lighting. That's because whatever causes droop drives down efficiency at very high current densities and ultimately allows lasers to operate more efficiently in this regime.

Although lasers are impaired by Auger recombination, carrier-density-related parasitic recombination losses are 'clamped' once the current density is high enough to induce lasing. That's because, beyond threshold, additional current density is determined not by the clamped radiative (due to spontaneous emission) and non-radiative recombination. Instead, it depends on recombination due to stimulated emission and an increase in the density of cavity photons.

Nonetheless, by assigning droop to Auger processes, a set of self-consistent equations can be employed to describe the behaviour of both classes of device. "I've always been a big believer that you can look at LEDs and learn something about lasers, and vice-versa," says Wierer. "The devices are related, because some of their operations are similar. The laser diode before threshold is just a spontaneous emitter, so it has got to behave like an LED, even though it is in a cavity."

Although lasers are not plagued by droop, they are impaired by another significant loss mechanism at high drive currents – resistive heating, which is proportional to both resistance and the square of the current. "[This loss] is normally more severe than it is in LEDs because of geometry– the laser diode normally has a smaller area, so you are trying to force current through a smaller area," says Wierer.

Predicting the future

To gauge how profound an impact the laser can make in lighting, it's important to not just consider the performance that the laser and the LED deliver today, but what they will be capable of tomorrow. Wierer and his co-workers have tried to anticipate similar degrees of improvement to both classes of device by using a set of self-consistent equations and considering probable refinements to today's state-of-the-art emitters.

For the LED, the baseline device chosen by the team was a Philips-Lumileds Luxeon Rebel royal-blue LED. This high-performance, thin-film chip features a silver mirror contact to the *p*-region and a roughened *n*-type surface that enables an extraction efficiency of 80 percent. The active region of this device is unknown, so the theorists took an 'educated guess' – three quantum wells with a thickness of 2.5 nm.

Calculations for an 'improved' LED indicate what might be possible in the future. With the improved LED, Auger loss is trimmed by reducing carrier densities in a non-polar LED with 20 wells that exhibits one-quarter of the resistance and one-tenth of the mirror loss of today's device.

Calculations for the efficiency of the standard laser are based on a design with the same active region as the standard LED. Characterisation of this laser indicates an internal loss of 6 cm^{-1}, a modal gain coefficient of 23.9 cm^{-1} and an inhomogeneous line broadening of 30 meV. Meanwhile, the 'fully improved' laser is non-polar; its mirror loss and internal loss are ten times and four times lower, respectively; the inhomogeneous line width is just 20 meV; and optical confinement is four times higher.

Plotting power conversion efficiency for the improved LED and laser as a function of input power density shows that, at really high input powers, the laser is more efficient (see Figure 1a). However, if the performance of the LED improves while that of the laser stands still, this gap could shrink fast.

Thermal limitations

One significant downside of driving devices harder is that it leads to greater chip heating. In a light bulb, the temperature of the light-emitting chip cannot exceed a certain value, so this places an upper limit on the input power density. Wierer and his co-theorists have considered the case where chips are attached to a simple (not 'super-expensive) heat sink, the maximum temperature rise is limited to 55 °C and the ambient temperature is 25 °C. Modelling shows that the dimensions of the LED can be orders of magnitude larger than that of the laser at peak efficiency (see Figure 1b).

Armed with details of the maximum size of the device, plus values for the input power density and the power conversion efficiency, the team went on to calculate the maximum light output at peak efficiency from the chip.

> "What really matters is this: The acceptable cost for ecenomical solid-state lighting. And judged against that metric, the laser is the clear winner, because it has a much higher allowable areal cost than the LED."

This is just 130 lumens for a state of-the-art laser, but 4200 lumens for an LED (see Figure 1c). "[With an LED], you are driving it at lower powers compared to the laser, so you are getting much less light per square centimetre – but you can make the chip much bigger, so you win," says Wierer.

However, he is quick to point out that you don't win by that much. "It's not like the laser is so tiny you can't get any light out of it." This difference in maximum lumen output will decrease as devices improve. With an LED, the improvements in device design will lead to higher power density (at peak efficiency), leading to a modest decrease in heat-sink-limited chip area and a modest decrease in maximum output (or heat-sink-limited flux) to 4600 lumens. But for the laser, the heat-sink-limited chip flux will increase, spurring white light output to 1050 lumens at peak efficiency.

Although the LED can deliver more light than the laser, that finding on its own could lead to erroneous conclusions regarding the future of solid-state lighting. For what really matters is this: The acceptable chip cost for economical solid-state lighting. And judged against that metric, the laser is the clear winner, because it has a much higher allowable areal cost than the LED (see Figure 1d).

"Because you are getting so much light per square centimetre [with a laser], you can make the chip really expensive," explains Tsao. In his view, cheap solid-state lighting is far more feasible with a laser than with really low-cost LEDs made on silicon. "GaN-on-silicon was touted to be the thing because it is so cheap, but it's not that cheap on a per-lumen-output basis."

Although no one is currently making laser-based light bulbs, Soraa of California has made what Wierer describes as "the next logical step" by producing GaN LEDs on native substrates and driving them at higher current densities. " [Soraa's] LEDs operate at around 400 nm, not in the blue, because droop is less there", says Weirer, adding that this allows them to run at higher current densities.

Where are we today?

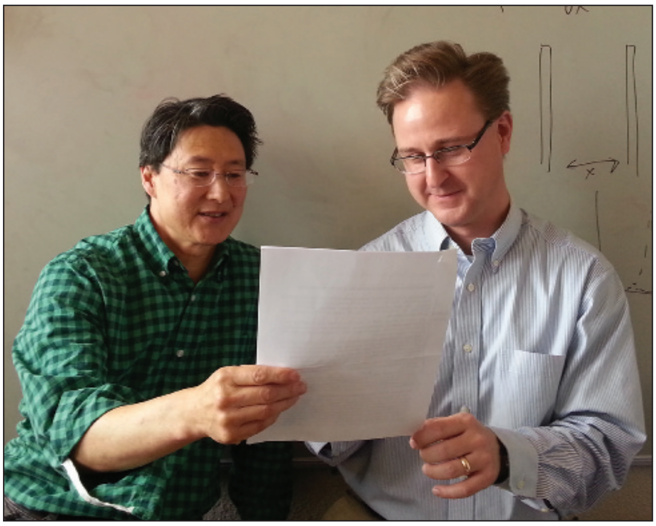
When the scientists from Sandia calculated the acceptable chip-cost-per-unit-area, they included a figure for the ratio between the capital cost of light and its operating cost. With established forms of lighting, this ratio is one-sixth, and that is the value that the theorists have employed."There is nothing magic about it, and maybe it will not be one-sixth in future, but one-sixth is already pretty cheap," says Tsao.

How do today's solid-state lamps compare to that one-to-six ratio? Well, the Cree 60 W bulb that puts out 800 lumens and retails for just under $13 is not that far away. It draws 9.5 W, and if it were used for 20,000 hours, it would run up an electricity bill of $19. That means that if its retail price could fall to just over $3, it would hit the traditional ratio.

Reducing the price tag to this level will require trimming the costs of all the bulb's components. Opportunities for cost reductions vary. There is more potential to slash costs for chips than there is for more mature parts. Given this state of affairs, the scientists have assumed that when LEDs make a big impact in lighting, they will account for just 10 percent of total bulb costs – a far lower proportion than they do today. Although it seems that LED bulbs can be competitive, laser-based variants promises to be even more attractive, because they can not only cut chip costs, but also boost efficiency. Does that mean that the consumer would actually be willing to pay more for a laser-based bulb, rather than an LED-based one, due to the energy savings? Ironically, no, at least in the long term, explains Tsao: "You are going to be willing to pay less, because you want the purchase price to be smaller than the price of the fuel." So, a switch to laser based lighting should lead to a fall in the price of the bulb, which is actually what one would expect, based on the one-to-six ratio.

This situation sounds great for the general public. However, it is not necessarily going to happen, and it will hinge on a substantial increase in the efficiency of the laser, so that it can displace the LED within the bulb. "And it's not just efficiency for electricity consumption," says Tsao,"but efficiency that is so high that it makes heat-sinking easier. That is a big potential factor in how to get your package costs down."

If this happens, the producers of lasers that can hit these high efficiencies should see rocketing sales, as will suppliers of GaN substrates. But not everyone in the III-V industry will be a winner. "This would be a disaster for equipment manufacturers," admits Tsao. "There might be some yield problems at the beginning, but you will not need very many tools."



Above: Jonathan Wierer and Jeffrey Tsao from Sandia National Laboratories have modelled the performance of lasers and LEDs and determined that the former holds more promise for low-cost, solid-state lighting. (Credit: Mike Coltrin) Right: Dmitry Sizov from Corning is the third member of the team that is revealing the promise of laser-based solid-state lighting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A biased LED emits blue photons and electrons in the UHV chamber (photo credit: Ph. Lavialle, Ecole Polytechnique)

LED droop:
Overwhelming evidence for Auger

At the heart of the debate over the origin of droop is the question Auger or not Auger? Circumstantial evidence for Auger has been mounting, and now this is joined by a 'smoking gun', the observation of hot Auger electrons in electro-emission. Detailing their novel experiment and its interpretation are a UCSB-Ecole Polytechnique partnership involving Claude Weisbuch, James Speck, Justin Iveland, Marco Piccardo, Lucio Martinelli and Jacques Peretti.

DROOP IS THE GREATEST IMPEDIMENT to affordable, highly efficient solid-state lighting. This mysterious malady, which drives down the efficiency of GaN LEDs as the current through them is cranked up, is behind the high total chip costs within the bulb and an efficiency that is only a little better than that of a compact fluorescent.

If, for a moment, I could be taken to a world where droop did not exist, you could have LEDs in bulbs delivering efficacies of more than 200 lumens-per-Watt; and they could do this at very high current densities, trimming total chip costs. What's more, heatsinks could shrink, for gains in efficiency spawn a reduction in device heating.

To try and realise this dream, many researchers throughout the world have been trying to understand and combat droop. This phenomenon was first reported by engineers at Nichia, and detailed analysis followed at Lumileds, where a claim that Auger recombination is responsible for droop emerged in 2007. This non-radiative process, which limits the efficiency in telecommunication lasers and ultra-high efficiency solar cells, involves the interaction of three carriers – two electrons and a hole, or two holes and an electron – with one promoted to a higher energy state.

Since Lumileds' made its claim that Auger recombination causes droop, several alternative theories have been put forward to account for this energy-sapping mechanism. They include electron leakage out of the active region and non-radiative defect recombination, which is activated by increased carrier concentrations. To try and bring this debate to an end, our team from the University of California, Santa Barbara, and Ecole Polytechnique, France, have performed a novel, insightful experiment that provides irrefutable evidence that Auger is the cause of droop.

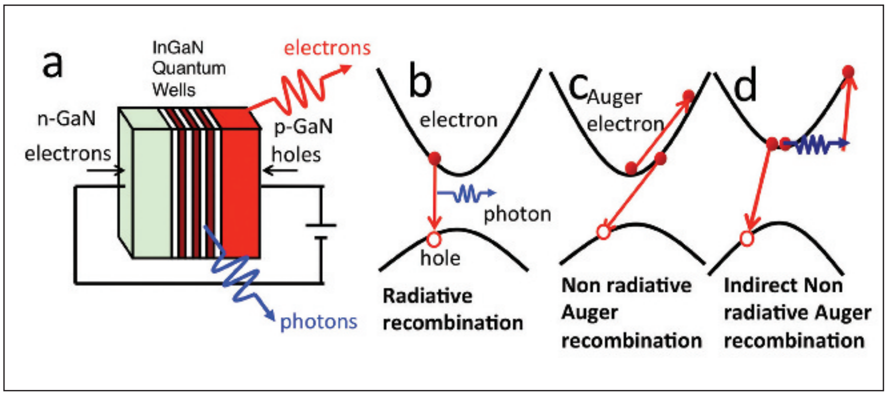


Figure 1: (a) An LED under current injection. Electrons and holes recombine radiatively in the active quantum wells by emitting photons (b); Shown in (a) is also electron emission in vacuum which only occurs when the LEDs have a specially treated *p*-type GaN surface (by Cesium deposition); (c) The principle of the non-radiative Auger effect in semiconductors: an electron-hole pair recombines by exciting another electron to a high kinetic energy. (d) Schematics of the phonon-assisted Auger effect where a phonon (lattice excitation) supplies momentum to the Auger electron, increasing the transition rate

Our experiment, which reveals the presence of Auger-generated carriers within the LED, is very challenging to perform. It requires measurements of the kinetic energy of the electrons using an experiment reminiscent of the photoelectric effect, discovered by Hertz in 1887 and explained by Einstein in 1905. In addition, the experiment demands excellent levels of surface cleaning, ultrahigh vacuum conditions, and a high degree of energy resolution for measuring the electrons emitted from an LED into a vacuum. Many universities do not have the facilities to carry out such an experiment, but we can at Ecole Polytechnique, one of the world's leading centres for electron emission spectroscopy, using LEDs made by Taiwanese chipmaker Walsin Lihwa and prepared for the experiment at UCSB.

How are mechanisms usually identified?

Our approach is remarkably different from that of most analysis of the droop phenomena. The mainstream approach is to curve fit the well-known *ABC* model, which was first used by Lumileds to describe the effect of the Auger process on the external quantum efficiency. Variations in the carrier recombination rate as a function of carrier density (n) are expressed as $An + Bn^2 + Cn^3$. (In this expression, A is the Shockley-Read-Hall non-radiative recombination coefficient, B is the bimolecular radiative recombination coefficient and the Cn^3 term describes Auger recombination.) Two approaches can be taken with this *ABC* model. One is to calculate the external quantum efficiency as a function of current density, and compare it with experimental values. In order to do this, you have to know the values of the *ABC* coefficients and make the assumption that light extraction efficiency and carrier injection efficiency in the quantum wells do not vary with injected current.

The other option, which is more common, is to analyse experimental plots of external quantum efficiency versus current density, and then fit *ABC* values. The value for the B coefficient can be obtained by either measuring the recombination lifetime, or calculating it from first-principles, which is an approach taken for instance by Joerg Hader from The University of Arizona and his co-workers.

If you use the *ABC* model, you have to accept two fundamental limitations of this approach. One of them, first pointed out by researchers at Lumileds, is that the *ABC* coefficients are not constant, but vary with current density. This occurs because at high carrier concentrations, polarization fields in the quantum wells are screened; and there is also an inhomogeneous distribution of carriers caused by current crowding.

The upshot is that it is not feasible to accurately describe the recombination mechanisms present in the LED with *ABC* values that do not depend on the current density, and consequently it is impossible to unambiguously identify any mechanism responsible for droop with this approach. The second major drawback associated with analysis based on the *ABC* model is that this approach only provides a fit of experimental efficiency data. Consequently, it only gives an indication of the cause of droop: it is not a direct physical observation of any recombination process occurring within the LED.

To make the ABC model compatible with other mechanisms for droop, some researchers have replaced Cn^3 with a more complex term, $Cf(n)$, that allows a different functional dependence. Meanwhile, others have added terms to represent carrier localization effects occurring above a carrier density threshold, or added terms to account for the leakage current. By adding new terms and fitting plots of external quantum efficiency as a function of carrier density

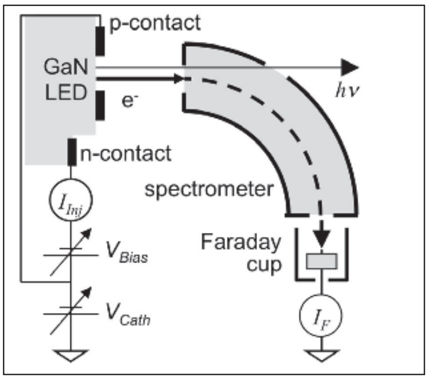


Figure 2. In the novel experiment by researchers from UCSB and Ecole Polytechnique, electrons are ejected into vacuum from a forward-biased LED. The kinetic energy of the electrons is analyzed in a cylindrical electrostatic deflector

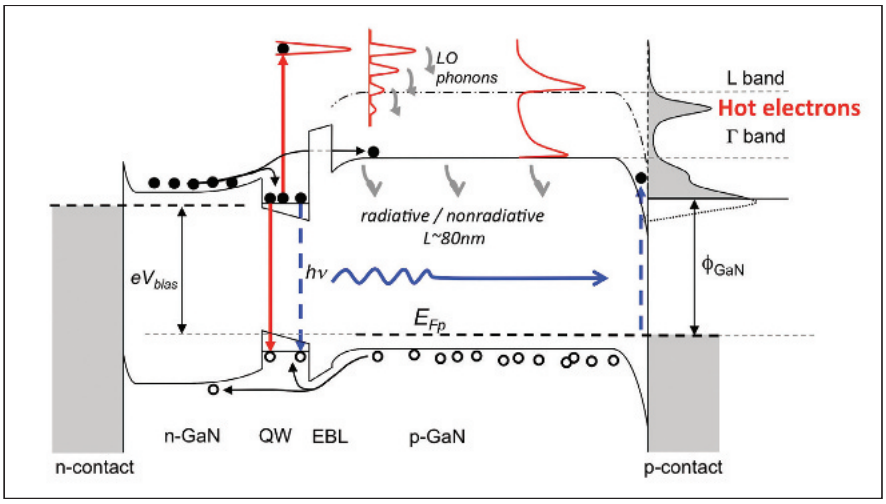


Figure 3. Emission of electrons from an LED in a vacuum: electrons originate from the active region, the quantum well (marked QW), with some high-energy ('hot') electrons generated by the Auger effect. They give rise to high-energy peaks in the energy distribution of electrons emitted in vacuum

for different LED designs or operating temperatures, these researchers, through their empirical approaches, will inevitably invoke other mechanisms than Auger for explaining droop.

Support for Auger

At the LED chipmakers Lumileds and Osram, researchers have provided further support for Auger as the cause of droop. Their efforts go beyond fitting of the *ABC* model, and involve photoluminescence and electroluminescence measurements. One of the merits of photoluminescence is that it allows droop to be observed under direct excitation within the quantum wells – this measurement may be made with no applied bias, or by applying a bias to induce flatband conditions. By configuring the bandstructure within the LED in this manner, carrier escape and

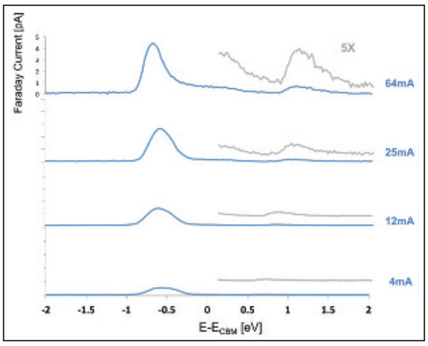


Figure 4: Energy distribution curves, with respect to the bottom of the bulk conduction band minimum (ECBM), of electro-emitted electrons for different injection currents (the base line of each spectrum was shifted). When increasing injected current, high-energy peaks appear around 0.2 eV and 1.2 eV, signalling generation of hot carriers in the structure

leakage cannot take place, but droop is still observed. What's more, there is a perfect similarity between the behaviour measured by photoluminescence and electroluminescence, including carrier lifetimes. This led the researchers to conclude that Auger is the culprit for droop under LED electrical operation, because it is then related to a mechanism that is internal to the wells.

More recently, researchers at Osram have fabricated a structure with a range of wells emitting at different wavelengths. Photoluminescence from this structure reveals hot carrier generation that is attributed to the Auger effect (see the feature on p.52 for a full account of this work).

In addition to all these experimental efforts, the theoretical group at UCSB, which is led by Chris Van de Walle, has provided further support for Auger as the cause of droop. Calculations by this team show a high rate for the indirect Auger effect.

However, despite this mounting support for Auger as the cause of droop, the origin of this mysterious malady is still hotly debated. There are other experimental explanations for droop, also based on circumstantial evidence, that have some merit, while determining the precise experimental value for the *C* coefficient is hampering progress. Obtaining a precise value for *C* is tricky, due to uncertainty in injected electron and hole densities, the number of wells that are involved in radiative recombination, carrier localization effects, and practical issues such as current crowding near *n*-type and *p*-type contacts.

The smoking gun

The debate on droop should soon be over, however, because our experiment provides overwhelming evidence that Auger is the cause of droop. Our approach is not that dissimilar to that of the US physicist Robert Millikan, who in 1914 measured the kinetic energy of electrons escaping from a metal as a function of exciting energy of incident photons. Since then, one of the leading approaches to determining the energy of electrons within materials is to photo-emit them, and measure their energies.

Our approach differs slightly from this, as rather than firing photons at the LED to liberate electrons, we forward-bias our commercial LED and measure consequent electron emission (see Figures 2 and 3). The active region contains eight wells, and a high proportion of the electrons and holes that are injected into them will undergo radiative recombination. However, at a high injection current density, a fraction of the carriers injected into the wells with the highest carrier density will recombine by an Auger process and will generate electrons with a high kinetic energy. According to the work of Van de Walle's group, the most likely Auger process that will take place is an indirect one, with momentum conservation provided

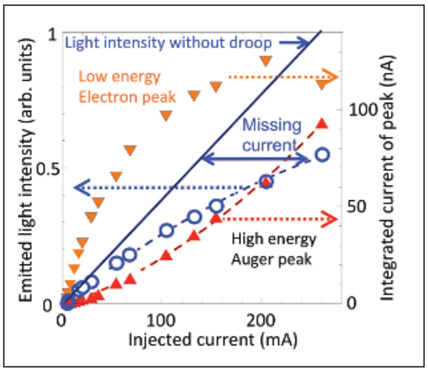


Figure 5: Plots of the current integrated over the high electron energy peak and of the optical output power as a function of the injected current. The straight line is the expected optical output power in the absence of efficiency droop, obtained by a linear extrapolation from the maximum internal quantum efficiency (IQE) value. The droop current is the difference between the actual injected current and the current that would give the same optical output if the maximum IQE had been conserved. This supplementary current is the droop current

What are the arguments of those not convinced?

IN OUR OPINION, these experimental results are the long-awaited 'smoking gun' evidence that Auger recombination is the dominant cause of LED droop. However, not everyone is convinced, and a handful of researchers have voiced concerns over these results and their interpretation [1-5].

Researchers who are skeptical that an Auger mechanism causes droop claim that the measured Auger coefficient might be too large compared to theoretical values, and that the behaviour with temperature is not perfectly represented. However, it is worth noting that theorists are still to reach a consensus on what the value of the *C* coefficient should be, and that there are large fundamental imprecisions in its experimental determination which arise from carrier density inhomogeneities – both in plane and in the perpendicular direction – and their variation with injected current.

One theoretical group is arguing that it should not be possible to see Auger-generated hot electrons escaping in vacuum, due to their calculated ultrafast electron energy relaxation [1-4]. These researchers claim that the hot electrons observed outside of the device are the result of electron acceleration in the surface electric field. But this acceleration cannot raise the total energy of electrons above the bulk conduction band minimum. Why? For the same reason that a stone rolling downhill can gain kinetic energy, but never raise its total energy above its initial energy.

Another critic, Fred Schubert from Rensselear Polytechnic Institute, argues that droop is due to carrier leakage [1-3]. This finding is based on the strong injection regime reached in *his* LEDs, according to his measurements and analysis. But in our devices, due to the very high doping (greater than 10^{20} cm^{-3}) of the *p*-type region (see Figure 3), the electric field is of the order of 100 V/cm. This field, which is typical of that found in commercial LEDs, is very far from inducing strong injection and its resulting carrier leakage.

Concerns have also been voiced that the hot electrons that we observe might be photo-created by LED light. However, if these hot electrons were formed by direct excitation at 450 nm, they would have to result from two-photon absorption from the valence band. Very few hot electrons would be formed in this way, because it tends to require intensities of many megawatts cm^{-2}, many orders of magnitude higher than the light intensities at the surface of our LEDs. It is also unlikely that hot electrons are formed by two-step photo-creation, which is the absorption of an LED photon by an electrically injected electron. The absorption probability is in the region of 10^{-4} in the quantum wells, the surface band-bending region and the *p*-doped layer, when determined using known and calculated free electron absorption coefficients in the 10-20 cm^{-1} range for LED carrier densities of around 10^{18} cm^{-2}.

Recently, researchers at the University of Southern California claim to have identified a new mechanism for free carrier absorption that is much larger than any previously predicted or observed [5]. This team have argued that this effect can both account for droop and our observation of hot electrons. We feel that one weakness of this work is that the mechanism is based on the analysis of differential, picosecond, pump-probe transmission measurements, hitherto analysed in terms of modified interband transitions, not conduction intraband transitions.

If such phenomenon could account for sizeable losses in LEDs, where electrons only travel a few tens of nanometres across quantum wells, would not the associated losses for laser modes propagating several hundred microns along such high loss materials (where the carrier density is even higher) prevent laser action?

To directly address these criticisms – and to assess the possibility of LED-light-induced hot electron emission – we performed measurements under LED biasing and also under external laser light excitation. The latter condition mimics LED internal emission. We were able to single-out the electron emission from the laser by chopping, and detecting in-phase, the electron emission. We found that we could only detect thermalized photoemission, so the maximum contribution provided by photocreated hot electrons is 0.4 percent, based on our current counting statistic limitations of the total hot electron current.

Reference
[1] *Physics Today* July 2013, p. 12
[2] IEEE *Spectrum*, http://spectrum.ieee.org/semiconductors/optoelectronics/a-definitive-explanation-for-led-droop
[3] *Compound Semiconductor* http://www.compoundsemiconductor.net/csc/news-details.php?id=19736706
[4] F. Bertazzi *et. al.* http://arxiv.org/pdf/1305.2512.pdf
[5] D. Dapkus *et. al.* Appl. Phys. Lett. **103** 041123 (2013)

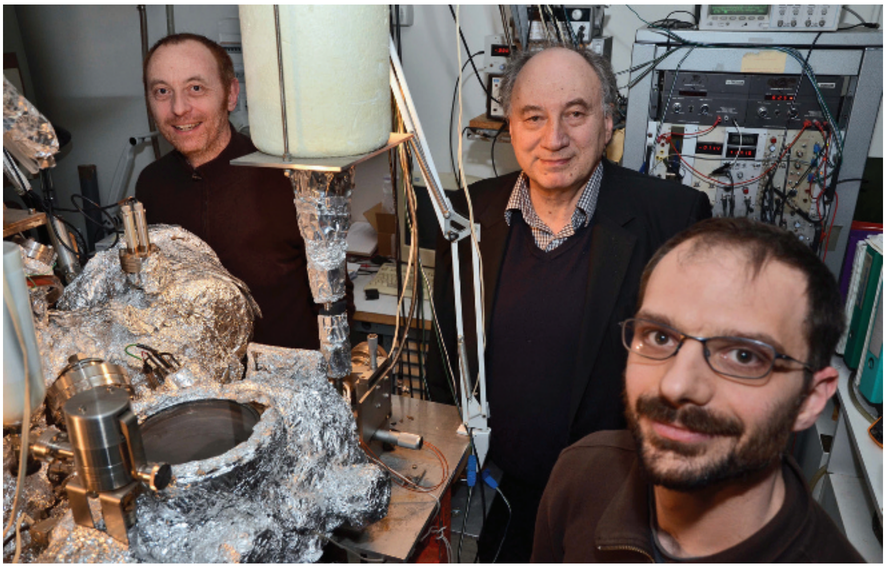
by phonon emission or absorption (see Figure 1d). In our experiment, electrons with various energies, including energetic Auger electrons, reach the surface and are emitted into vacuum (see Figure 3). Since the energy distribution of electrons in vacuum is the same as that of electrons impinging at the LED-vacuum interface, measurements of the energy of these electrons provide evidence of Auger electrons, so long as some of the Auger electrons reaching the surface sustain a significant fraction of their high initial energy. To make sure that all thermalized electrons can escape the LED, we treat its *p*-type surface with cesium, enabling activation to negative affinity. One of the downsides of this treatment is that it rules out annealing of the contacts, so the *p*-contact is non-Ohmic.

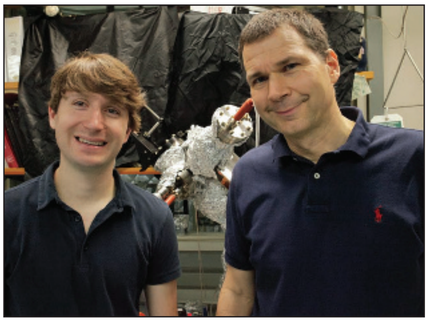
Armed with this modified device, when we crank up the current through our LED, we are able to observe higher energy peaks in the vacuum-emitted electrons (see Figure 4).

Since no other mechanism can generate hot electrons in the structure, these high-energy peaks represent a clear and direct signature for Auger recombination.

In their transit towards the surface, the Auger electrons will lose some kinetic energy. Fortunately, a number of them lose their energy cascading down in a so-called 'side' conduction band (satellite valley), which has a long energy memory time (the 'L' band in Figure 3). A peak is observed at this energy, reminiscent of the high energy of the original Auger electrons.

Additional, highly compelling evidence that Auger is the cause of droop is the emergence of these high-energy peaks at exactly the same time that droop kicks in with current (see Figure 5). We can even show that the magnitude of the droop current – the supplementary current needed to reach a given light output in the absence of droop – has a linear relationship with the integrated, high-energy, vacuum-current intensity (see Figure 6). Based on these findings, it is highly unlikely that a mechanism other than Auger can account for droop. All alternative mechanisms proposed so far do not have the same cubic dependence on carrier density as the Auger-related current, and any new theories for droop are unlikely to





Above: Measurements of the energies of electrons emitted by the LED in vacuum were carried out in the CNRS-Ecole Polytechnique Laboratory of Condensed Matter Physics (photo credit: Ph. Lavialle, Ecole Polytechnique)

Left: Justin Iveland (left) and James Speck (right) are the part of the team based at UCSB. Iveland prepared the samples, and went to CNRS-Ecole Polytechnique to help with the measurement of these LEDs. Credit: UCSB

How do the various materials and structures compare?

AMONGST the leading manufacturers of state-of-the-art *c*-plane GaN-based LEDs that discuss the origin of droop publicly – the likes of Osram, Lumileds and Soraa – the consensus is that Auger is the dominant mechanism for diminishing efficiency with increasing drive current.

Alternative mechanisms, meanwhile, emanate from academic labs. So might these differing views simply stem from differences in the quality of the LEDs under investigation?

One way to answer this question would be to carry out a round-robin analysis of droop on high-performance LEDs. Unfortunately, however, there are yet to be any reports of such an investigation.

What is clear is that after years of optimisation of growth quality, fabrication technology, metals contacting and so on, high-quality commercial grade materials used to make LEDs have probably reached optimal efficiencies for the particular crystal orientation and active region design. Refinements have resulted from optimization of quantum well materials, barriers, layer architectures and so on, through recipes that often are unpublished and kept in secrecy.

Two examples highlighting the extent of this optimisation, and how state-of-the-art LEDs have evolved and improved beyond recognition, are the advances associated with: determining the optimal number of wells within the structure, and the continual improvement in the device's material quality.

The high number of wells in today's state-of-the-art LEDs will raise some eyebrows, given the challenge of injecting holes uniformly throughout this structure. Although companies do not publish the details of their active regions, it is known that they use between five and twelve wells in their LEDs. Since un-injected wells lead to inefficient carrier injection, substantial emission must be coming from the entire active region.

Turning to material quality, it has been argued that when defect densities, such as dislocations and various point defects, are high, it is possible to account for droop with a conjecture based on carrier localisation. The argument put forward is that at a low carrier density, compositional or interface fluctuations localise the carriers, leading to efficient emission; but as the current is cranked up, a higher proportion of carriers diffuse to non-radiative centres, and external quantum efficiency falls.

The magnitude of non-radiative emission is associated with the *A* coefficient in the *ABC* model. Its value is diminishing all the time, as witnessed by the spectacular improvements in the external quantum efficiency of blue LEDs. At the turn of the millennium, these efficiencies were below 20 percent, but now the figure is nearer 80 percent [Mukai 1999, Krames 2000, and Narukawa 2010]. Since extraction efficiency has doubled during this time frame to 90 percent, the peak internal quantum efficiency must have shot up from 45 percent to 90 percent, and the *A* coefficient will have plummeted by a factor of about 100.

satisfy these conditions precisely. So, in short, we believe that our experiment provides the most compelling evidence to date that Auger recombination is the dominant origin for droop in state-of-the-art, nitride-based LEDs. In the future, through judicious device design, we plan to use this tool to compare active region designs, including those with various quantum well and quantum barrier thicknesses and differing electron barriers and doping crystal plane orientations. All these efforts are focused on reducing droop.

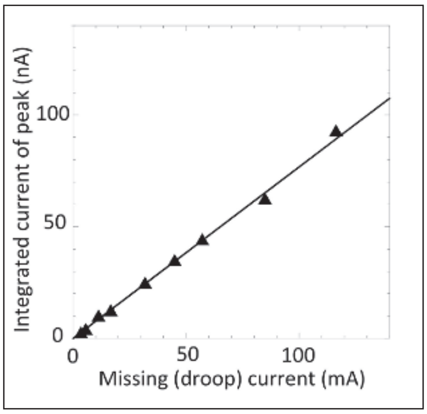


Figure 6: Plot of the integrated current over the high electron energy peaks as a function of the droop current resulting from the generation of Auger electrons. The simultaneous onset of droop current and Auger electron generation, and their linear dependence, indicate a common origin. Other droop mechanisms are highly unlikely to account for this observation, because they do not scale with carrier density as Auger electrons do (as the cube of the carrier density)

Further reading

A detailed account of the experiment described in this feature can be found in the paper:

J. Iveland *et. al.* Phys. Rev. Lett. **110** 177406 (2013)

Other measurements of Auger recombination are detailed in the following papers:

Y. C. Shen *et. al.* Appl. Phys. Lett. **91** 141101 (2007)
A David and M. J. Grundmann Appl. Phys. Lett. **97** 033501 (2010)
M. Binder *et. al.* Appl. Phys. Lett. **103** 071108 (2013)
A. Laubsch *et. al.* Phys. Status Solidi C **6** S913 – S916 (2009)

Reviews of alternative mechanisms of droop are offered here:

G. Verzellesi *et. al.* J. Appl. Phys. **114** 071101 (2013)
V. Avrutin *et. al.* 050809 J. Vac. Sci. Technol. A **31** 050809 (2013)
J. Cho *et. al.* Laser Photonics Rev. **7** 408 (2013)
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Photoluminescence pinpoints Auger as the cause of LED droop

The debate on droop has been enriched by compelling evidence that Auger is to blame. Strong support for this includes our novel experimental data that shows that carriers produced in a green quantum well interact via Auger processes to generate higher energy carriers, which populate and recombine in an ultraviolet well, explain Michael Binder, Bastian Galler, Roland Zeisel and Anna Nirschl from Osram Opto Semiconductors.

A REVOLUTION IN LIGHTING has just begun. Individuals and businesses are now buying LED lamps, thanks to their great attributes. These solid-state sources can span a wide range of lumen outputs; they produce a colour quality that has improved dramatically in recent years to a level that now rivals that produced by halogen lamps; and they deliver lifetimes and efficiencies that are superior to most conventional sources. So why, given all these wonderful characteristics, isn't a battalion of LEDs now found at the heart of every installed light source?

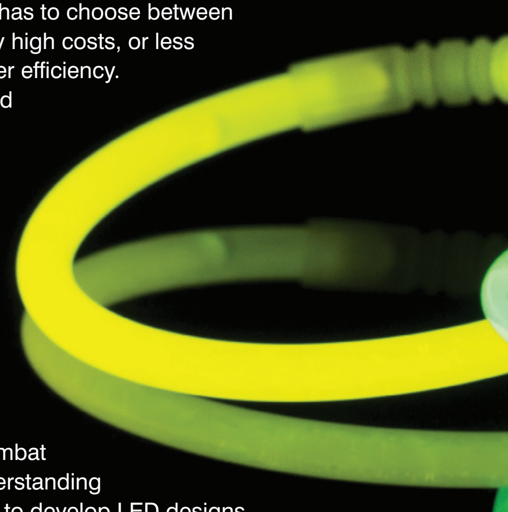
Well, as always, many answers could be given. And in this case, one of them is quite simple: The costs are still too high to be widely accepted in the consumer market.

To understand the reason for this, one must take a close look into the physics of the LED. One of its features is that its light output depends on its drive current, so doubling its current does not produce an increase in brightness by the same factor. Instead, in many classes of LED, the brightness increase is lower than this – and particularly so for InGaN-based devices, where the effect is known as droop.

For most classes of LED, it is pretty clear which physical effect is behind the rollover in efficiency. For example, in short wavelength InGaAlP-based LEDs, greater carrier overflow is behind the fall in efficiency at increasing drive currents. But with InGaN-based LEDs, the rather unspecific term 'droop' is used, because the root cause for this phenomenon has not been discovered, despite intensive research into this subject for many years.

The droop behavior in a typical blue-emitting LED produces a sub-linear rise in light output as a function of drive current (see Figure 1). The decrease in efficiency that results is often shown in plots of the external quantum efficiency versus drive current. Typically, efficiency peaks at about 20 mA for a chip with dimensions of 1 mm by 1 mm, and drops at higher currents. In addition, efficiency decreases at lower currents. However, this is not a major concern, because it corresponds to current densities that are well below those that would be used in a typical high-brightness LED. These devices often operate at current densities of around 40 A/cm^2, which, as can be seen from Figure 1, is a regime where the device efficiency is significantly below its peak value.

So why not simply drive the LED at the current density that produces the peak external quantum efficiency? Well, because in order to target the same light output, the area of the chip will have to increase by an order of magnitude, but because the cost of the chip scales with its size – and the chip is a major cost contributor to the device – this would result in more expensive LEDs. So one has to choose between very efficient LEDs at very high costs, or less expensive LEDs with lower efficiency. Fortunately, there is a third alternative, which is to address droop. This will allow the chip size to be reduced without losing efficiency, and it will ultimately enable cost to be brought down, speeding penetration of the LED into the general lighting market.



By far the best way to combat droop is to begin by understanding its origin, and then go on to develop LED designs that are not plagued by this malady. This approach sounds straightforward, but it is not – getting to the bottom of droop is far from easy. Over time, a handful of hypotheses have been developed to account for droop, and this has led to various physical models based on the likes of carrier leakage by overflow, defect-mediated losses and Auger recombination (these are illustrated in Figure 2). Some researchers have even drawn on the combination of hypotheses and blamed droop on mechanisms such as Auger-enhanced leakage.

Leading theories

With the model that focuses on defect-mediated loss, the quantum well can be compared to a pot that is not watertight, but has holes in its wall. When water is poured in, it remains within the pot until its level reaches that of the holes. Then, at that point, the water starts to leaks through them, causing filling efficiency to fall.

The leakage-via-defects model can be explained in a similar way, with charge carriers staying in the well when the carrier concentration is low. But when current density increases and carrier concentration rises, the defects in the quantum well become active, behaving as non-radiative recombination centres. Those supporting this view believe that these defects are probably V-pits, which are named after their apparent shape in a cross-sectional view of the crystal. It is argued that V-pits are surrounded by a repulsive potential, which hinders carriers to reach them and recombine there. However, this potential is surpassed as carrier density increases, enabling the activation of V-pits as recombination centres.

Charge carrier overflow can also be explained with the water-in-the-pot metaphor. This time the pot is tilted, so part of the water jet flows beside the pot and fails to contribute to its filling. It is also possible to imagine that if the water is flowing fast, it enters into the pot with such an impact that it splashes out again. Translating this behaviour to that for the LED suggests that the injection efficiency diminishes, due to charge carriers overflowing the quantum wells without recombining radiatively.

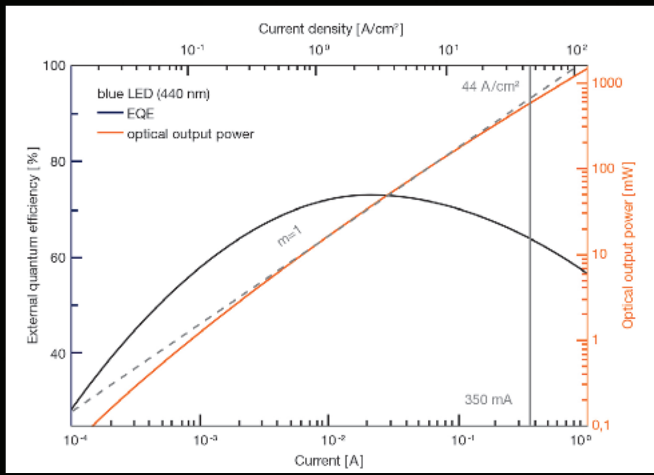
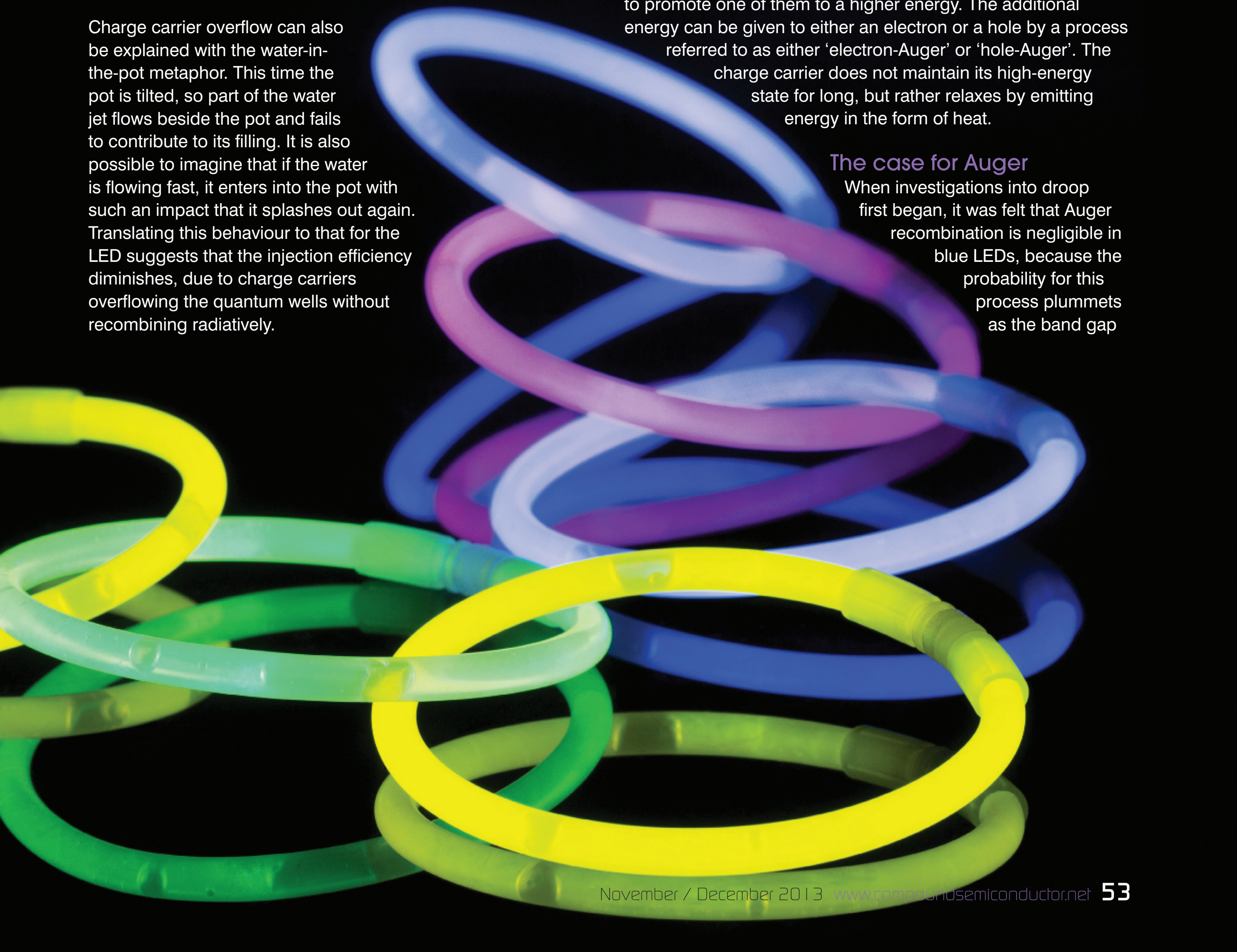


Figure 1: Current dependency of the optical output power (red) and the external quantum efficiency (EQE, blue) of a typical blue-emitting LED. At operating conditions (350 mA), the light output increases sub-linearly with increasing input power, which can be seen in comparison to the linear function plotted in grey. The associated decrease in EQE towards high currents is commonly known as droop

The third popular explanation for droop, Auger recombination, involves a process associated with the interaction of carriers to promote one of them to a higher energy. The additional energy can be given to either an electron or a hole by a process referred to as either 'electron-Auger' or 'hole-Auger'. The charge carrier does not maintain its high-energy state for long, but rather relaxes by emitting energy in the form of heat.

The case for Auger

When investigations into droop first began, it was felt that Auger recombination is negligible in blue LEDs, because the probability for this process plummets as the band gap



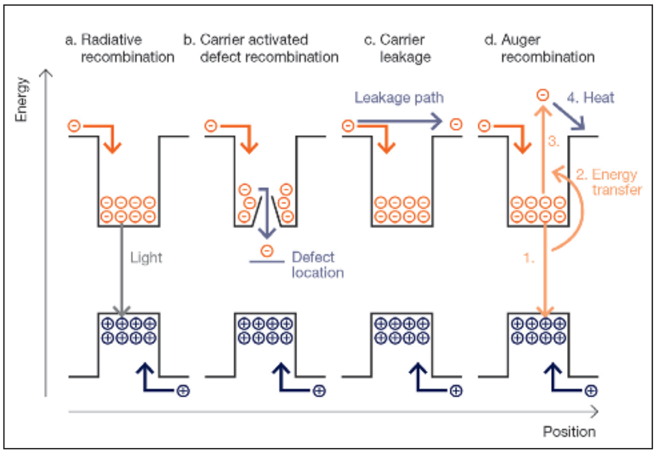


Figure 2: An illustration of light generation in comparison to proposed droop mechanisms: a) One electron recombines with one hole and the energy is released via a photon (light) b) Self-screening of defects from quantum well carriers (here electrons); once a certain density is reached the carriers overcome the potential barrier and recombine non-radiatively c) Carriers (here electrons) overflow the quantum well(s) and do not contribute to the light generation d) Energy transfer from non-radiative recombination of electron with hole to a third charge carrier (here an electron)

increases. However, when researchers carried out detailed simulations – which yielded higher Auger coefficients by taking into account phonon interactions and alloy fluctuations – it appeared that Auger recombination could be the dominating factor for LED droop. Efforts to build more accurate models for the LED continue to this day.

Experimental investigations to identify the role of Auger have also become increasing sophisticated. Earlier this year a partnership between researchers at the University of California, Santa Barbara, and Ecole Polytechnique observed high-energy electrons from an electrically driven LED. Their interpretation of these interesting experimental results, which are currently subject to controversial discussion, is that the high-energy electrons are the result of an electron-Auger process (see feature on p.46 of this issue for further details).

One of the reasons why the debate on droop has gone on for so long is that not only is it challenging to distinguish between electron leakage and Auger recombination, but these processes can be coupled. In addition, it is possible to reproduce the droop curve with models based on leakage and Auger recombination, and the Auger carriers that are generated within the LED have a high enough energy to overcome barriers and thus contribute to leakage.

To try and distinguish between injection and Auger loss, our team at Osram Opto Semiconductors devised an experiment that can exclude leakage by exciting the carriers directly in the quantum well. Our approach, like that of the UCSB-Ecole Polytechnique collaboration, exploits the fact that the Auger process generates highly energetic charge carriers (they are also known as 'hot' carriers). However, in our independent work, we employ a novel structure that converts these hot carriers into highly energetic light. The central idea of our approach is to capture hot carriers with a tailored quantum well, and record the spectral output that results from their recombination and subsequent photon emission. To carry out this experiment, we measure the photoluminescence emitted by an InGaN-based structure containing neighbouring ultraviolet (UV) and green quantum wells (see Figure 3). We pump this heterostructure with a blue laser, so absorption only occurs in the green wells.

If we use a low intensity laser beam and generate a low carrier density, we can neglect Auger processes and should only expect to see green emission; but if the intensity of the optical pumping is sufficient to create a carrier density comparable to that found in the droop regime, hot carriers should be created via Auger recombination, before they are captured by the UV wells, which act as detectors. So, in other words, if there is luminescence from the UV wells, it will prove that Auger recombination is taking place in the green-emitting wells, and thus in an LED. One great merit of this photoluminescence-based approach is that no macroscopic electric fields are present in the structure. Consequently, it is possible to rule out the generation of hot carriers by transport-related effects.

Experimental evidence

Our expertise associated with the growth of InGaN LEDs enables us to fabricate structures with high material quality. That's essential, because if the crystal quality is poor, other non-radiative processes are stronger than droop. After fine-tuning our experimental set-up, we acquired our first photoluminescence spectra, which exhibited the expected UV peak (see Figure 4). This was a breakthrough: It was the first time we had detected highly energetic charge carriers generated in an InGaN-based structure under resonant photoluminescence excitation. What's more, the intensity of the UV light was even higher than we had expected.

It is obviously important to rule out that the UV emission stems from artefacts arising from the green wells. To do this, we measured the photoluminescence spectra produced by our pair of reference samples, which contained solely green or UV wells. Emission from these samples did not feature a high-energy peak, implying that the high-energy peak in our structure with green and UV wells did not originate from artefacts from either the green wells or from direct excitation of the UV wells via two-photon absorption. Thermal effects and free carrier absorption were also ruled out with further experiments, leading us to conclude that only Auger processes could provide a full,

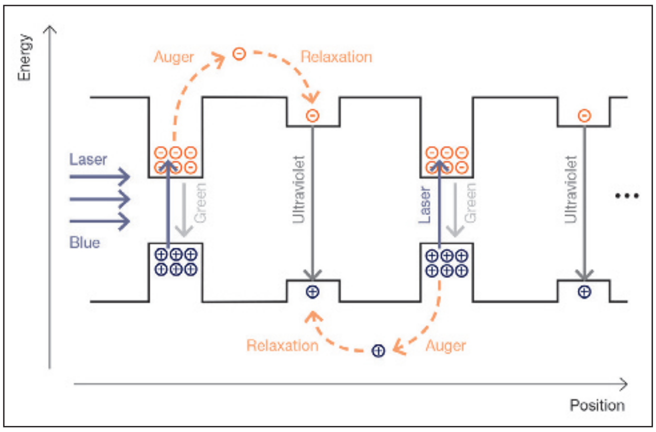


Figure 3: The approach taken by scientists at Osram to visualize Auger processes and correlate them to the droop. Ultraviolet quantum wells are used to capture hot carriers generated by Auger processes. Luminescence from the UV wells can be attributed to Auger recombination taking place in the drooping green wells

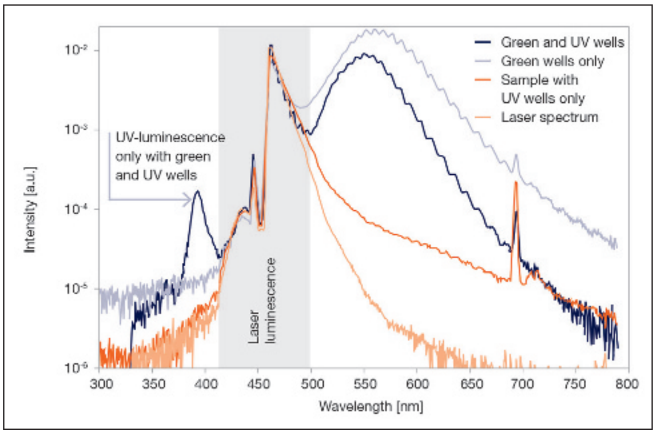


Figure 4: A blue laser excites a sample containing neighbouring green and ultraviolet wells up to charge carrier densities where droop occurs. The resulting spectra reveal the expected green emission, plus luminescence originating from the UV wells. Since the UV luminescence is only present in structures where green and UV wells are combined, its origin must be Auger processes in the green wells

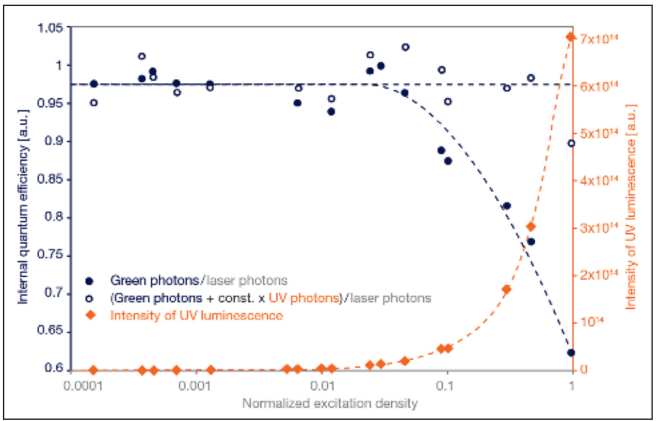


Figure 5: A measure for the internal quantum efficiency of the green wells is given by the ratio between detected green photons and exciting laser photons. Towards higher excitation density, where droop occurs, a steep rise in UV luminescence was observed. This was ascribed to Auger processes

consistent explanation of the data. Our experiment also offered a unique insight into the nature of Auger recombination. Since luminescence requires both carrier types in the UV quantum wells, our experiment reveals that the rates for electron-Auger and hole-Auger processes are both relevant.

Although we had detected the presence of Auger, we had yet to determine if it was the main contributor to droop. Could it just be a feature that is present and detectable, but one that does not play a significant role in the efficiency of the LED? To answer this key question, we took a closer look at the correlation between Auger processes, represented by UV luminescence, and charge carriers lost to the droop mechanism. This led us to observe a steep rise in UV intensity towards the excitation densities where droop occurs (see Figure 5). We note that droop and UV emission scale with the cube of the charge carrier density in the green well, implying that the number of green photons lost to the droop phenomena is directly proportional to the rate of emitted UV photons. Armed with this relationship, we could also prove that at least 1 percent of all lost charge carriers can be attributed to the Auger effect.

At first glance, this value of 1 percent seems very low, and it certainly doesn't follow that Auger is the sole cause of droop. But care is needed in interpreting this result. After thinking carefully about generation and recombination processes going on in this experiment, we can offer a sound argument that Auger is playing a dominant role in the behaviour of an LED. First, it is obvious that most Auger charge carriers, which are generated in the green quantum wells, will not be captured by the UV wells – instead, they will relax back into the energetically favourable green wells. So it is reasonable to assume that only a small fraction of them reach the UV wells. In addition, since every electron needs a hole to emit a UV photon, any discrepancy in the Auger generation rates for holes and electrons will diminish detection efficiency. Taking both of these factors into account, we conclude that the intensity of the detected UV emission strongly suggests that the Auger effect is the dominant cause of droop.

Developing a fully quantitative understanding of the contributions of Auger recombination to droop will require determination of electron- and hole-Auger rates. We have looked into this, and have just published a paper in *Applied Physics Express* showing that the transfer of energy to an electron, rather than a hole, is the more common process. This finding is in stark contrast to the claims of leading theorists, which conclude that the hole Auger process is stronger. Another question that remains is why Auger recombination should play such a prominent role in wide-bandgap materials, such as GaN and its related alloys. Theoretical work points to phonons and/or alloy fluctuations, which facilitate momentum conservation and allow high Auger rates. However, no experimental results have been published related to these conjectures.

From a practical point of view, our findings let us draw one very important conclusion: LED development must now focus on structures that extenuate the impact of the Auger effect and disregard other hypotheses. This finding is tremendously valuable, because epitaxial structures have a vast number of degrees of freedom, and it is very helpful to know that at least some of them have limited potential to mitigate the impact of droop. At present, the best practical measures for reducing the Auger effect are still to be uncovered. However, they will be revealed in further, detailed engineering and scientific work. This will help to define droop more and more, enabling the manufacture of brighter LEDs and ultimately the accelerated adoption of solid-state lighting.

Further reading:

J. Iveland et. al. Phys. Rev. Lett. **110** 177406 (2013)
M. Binder et. al. Appl. Phys. Lett. **103** 071108 (2013)
A. Hangleiter et. al. Phys. Rev. Lett. **95** 127402 (2005)
Y. C. Shen et. Al. Appl. Phys. Lett. **91** 141101 (2007)
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R. Vaxenburg et. al. Appl. Phys. Lett. **102** 031120 (2013)
B. Galler et. al. Appl. Phys. Express **6** 112101 (2013)

Uniting the strengths of LEDs and lasers

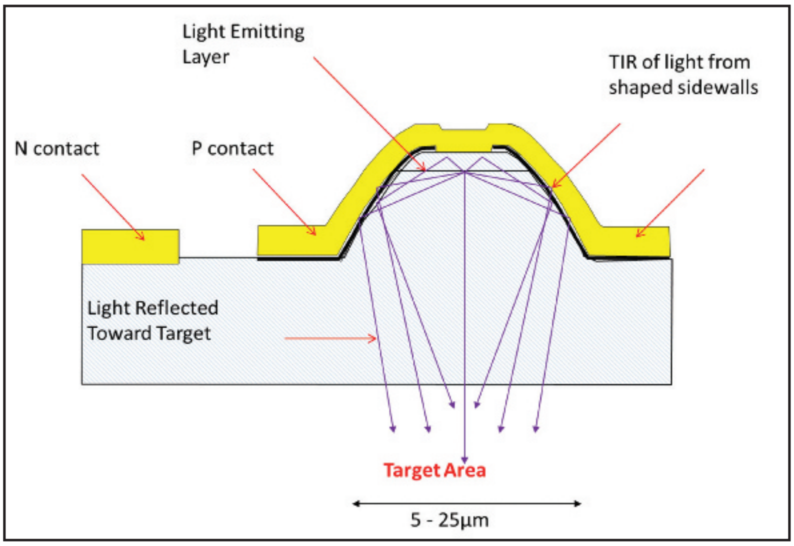
Optical designers are keen to combine the high-intensity, directional output of a laser with the low cost and broad spectral output of an LED. These wishes can now be fulfilled, due to the development of a novel LED featuring a parabolic mirror, claims Bill Henry from InfiniLED.

THANKS TO ADVANCES in medical science, we hope that we can be cured from many of the conditions that proved fatal to our grandparents. But we know that these gains are not cheap – modern, cutting-edge medical treatments can be incredibly expensive, and may cost even more in future.

To try and prevent the costs from becoming exorbitant, the medical industry is developing an increasing number of portable diagnostic and point-of-care devices. These can be used at the patient's bedside, enabling faster, cheaper treatment.

At the heart of many of these pieces of medical equipment is an optical system. Its role is to illuminate a sample, before recording the information obtained from light reflecting or re-emitted from this target. It is an approach that can monitor and diagnose an increasing range of conditions, including HIV and diabetes. The optical engineers designing these systems must decide how to control and manipulate the light, while dealing with optical aberrations, interference and losses. What's more, they have to make a critical decision: What should they use as the light source? Get this wrong and the consequences can be significant.

Figure 1: Schematic of a MicroLED emitter



Two options for the light source are the LED and the laser. They are often treated as separate species, serving applications that rarely overlap. Engineers tend to select an LED when they either need a broad spectral output, have to drive a device at a low current, are working to a tight budget, or must construct a highly portable product. But if they need to control the beam angle or employ a high light intensity, they select a laser. But the latter source has complications, such as wavelength drift and speckle. Another vitally important consideration facing the designer of any optical system is the étendue – in simple terms this is the ability of the system to effectively capture and use the light that is generated (a more formal definition is that, when viewed from the target area, the étendue is the product of the size of the light source and the angle it subtends). Often the étendue dictates system efficiency, making it critical to match the étendue of the system with the properties of the light source.

Unfortunately, engineers do not always heed this warning. Sometimes they are not able to, because the choice of source is dictated by other considerations, such as limits for power consumption, spectral output or emission wavelength. However, when these considerations take precedence, efficiency suffers, due to the low proportion of light captured within the system. Knock-on effects include additional costs and increased power requirements, both of which hinder the design of new and improved medical products.

A hybrid structure

At InifiniLED of Cork, Ireland, we have pioneered a new class of device that combines the merits of the LED and the laser. It's called a MicroLED and its design can be optimised to match the étendue of a given system to ensure maximum performance.

Our novel emitter can aid the designers of bedside and point-of-care medical equipment delivering simple, fast and accurate tests. Such systems employ markers for diseases that can be identified using fluorescence measurement techniques – which are both highly sensitive and accurate. Up until now, the optical control required for such systems has confined these tests to primarily laboratory settings, but the efficiency, collimation and form factor of our MicroLEDs enables the miniaturisation of these systems. Armed with our devices, it will be possible to test for a wide range of analytes, thanks to the flexibility of the emitters – in both wavelength and illumination area – and our unique geometry that will allow for the integration of additional components with the chip, such as filters and polarisers. This will further reduce system complexity.

The high intensity collimated output of our MicroLED means that it is also suitable for free space and fibre-coupled data transmission. What's more, it can also be used to make more efficient, tiny displays and LED print-heads.

All these applications are possible with an emitter that shares many of the attributes of a conventional LED, because it is built with standard LED materials and has the spectral profile, flexibility and reliability of this class of device. However, our MicroLED features a unique light-controlling structure, which is integrated onto the device during fabrication. This gives it characteristics associated with a laser, such as high light intensity and a collimated output. By modifying the design, it is possible to control the emission spectrum to target a particular figure for full-width half maximum.

Our device's light-controlling structure is based on a parabolic reflector that surrounds the light-generating region and controls the emitted light at the site of light generation (see Figure 1). We have found that this approach is far more efficient than using external optics to control the properties of the light escaping from the chip. With conventional, high-performance LEDs, the large difference between the refractive index of GaN and air is a major impediment to high light

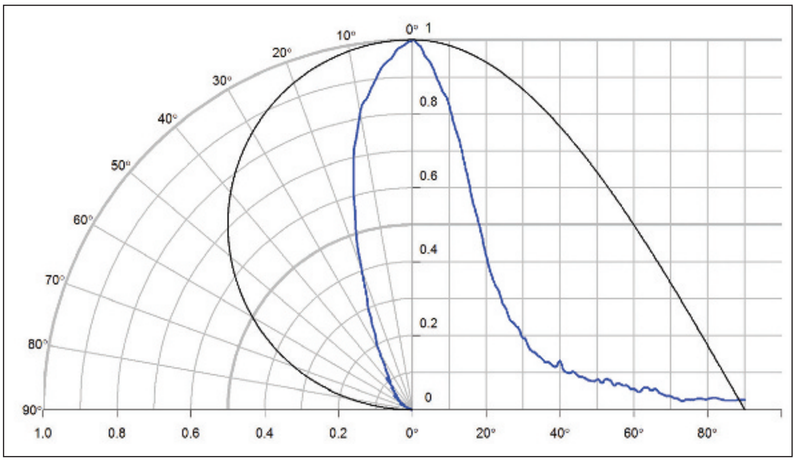


Figure 2: Far-field emission pattern from a MicroLED pixel directly from the chip (blue). The equivalent spectrum from a standard LED is shown in black

extraction efficiency. But with our device, we are able to use this significant difference in refractive index as an asset: It enables incredibly low light loss associated with the total internal reflection processes.

Reflections guide light from the sidewalls of a parabolic structure and focus it towards the extraction surface. Accurate shaping of the sidewalls ensures that a high proportion of the light reaching the exit surface is propagating perpendicular to the interface, leading to minimal back-reflections, high light extraction efficiency and a controlled beam profile. Extracting most of the light through a single surface simplifies the optical design of the full system. In addition, it reduces the number of processing steps to make this chip. With our approach, we differ from that employed by many LED manufacturers – they roughen the surface of the devices they make to overcome back reflections and trapping losses. Although this

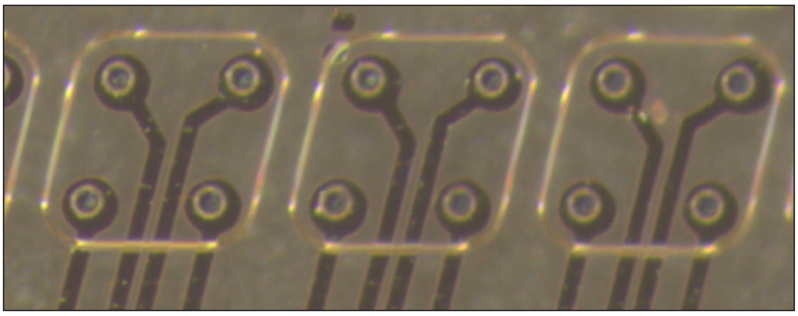


Figure 3: Individually addressable MicroLED pixels as presented at NIP28 conference

step increases the amount of light escaping from the chip, it also results in uncontrolled light emitted in all directions. With our approach, light extraction efficiency (power efficiency) through a single face of the MicroLED can be up to 50 percent – that's four times higher than that extracted through a single surface of a standard LED chip. This translates to a tremendous increase in the amount of light that can be used within a system.

One key attribute of the MicroLED is that it enables light generation to be controlled at the source. The active area of this device can be tailored to a specific application, and if the area of interest is 500 μm^2 or less, a single pixel can be employed. This approach ensures optimal power efficiency, because minimal light is wasted. Note that if the target area is larger, a cluster of emitters can be used that are packed closely together and driven in parallel.

Device characteristics

Our MicroLED's far-field emission profile has a full-width half-maximum of typically $\pm 30°$ – half that of the radiation pattern from a standard LED. We continue to make improvements in the control of light that exits these devices, and it is now possible for us to provide an emission profile with a divergence angle of less than $\pm 3°$. To improve the performance of our MicroLEDs, they are designed to be housed in a flip-chip package, with the light-generating layer positioned close to the heat-sink. By considering thermal management in the design, these emitters can be driven at high current densities without significant internal heating, enabling them to be used for applications demanding very high light intensity. For example, an output of 1 mW can be produced by a single MicroLED pixel with a 20 μm-wide emission area. This equates to a power density exceeding 300 W/cm^2, which is common for lasers, but not LEDs. The MicroLED not only operates in this regime, but can do so over a wide range of wavelengths.

Using a micro LED for machine vision or detection can increase system lifetime. This is possible by producing more useable and less stray light

Thanks to the small active area of the MicroLED, it has a low device capacitance, so can switch at very high speeds. This makes the device optimal for optical communication applications. Measurements performed at Tyndall National Institute have revealed data transfer rates in our green MicroLEDs in excess of 500 Mbit/s. This result sets a new record for transfer rates using a green LED-based source, which is attractive for plastic optical fibre data transmission, thanks to low attenuation at these wavelengths that enables longer transmission distances. Switching speeds of less than a nanosecond have also been observed, and we anticipate transfer rates of over 1 Gbit/s following appropriate optimisation.

One-dimensional and two-dimensional arrays can be formed with our MicroLEDs. Collimation at the source means that it is possible to distinguish the light emitted from individual pixels, and there is minimal cross-talk between them. The packaging technology selected for the source determines how close the LEDs can be packed together; a high density of MicroLEDs is possible with a range of packaging techniques, including direct bonding to CMOS or appropriate heat-sinked packages.

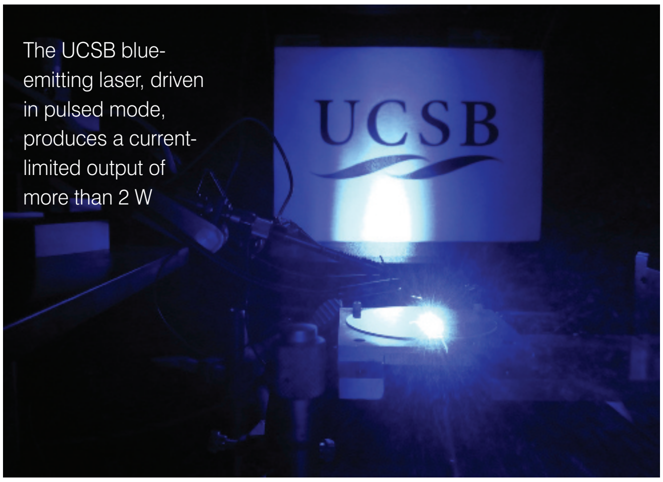
Targeting applications

By producing single MicroLEDs, plus clusters and arrays of these emitters, we are able to target many applications. Single pixels, which have an emitter diameter of 5-20 μm and offer high power efficiency, can be used for scanning and position sensing. These tiny devices are cheaper and more frugal than lasers, and when combined with integrated components, can produce patterns, shapes or images in the area of interest. Combining the MicroLEDs to form clusters enables the illumination of larger areas. Using such a source for machine vision or detection can increase system lifetime. This is possible by producing more useable and less stray light. By optimising the size of the emission area and the emission angle, all the light can be collected within the system. When MicroLEDs are deployed, component count can fall, because there is no need to mask and shape the light, and this ultimately leads to a simpler, cheaper system.

Addressable arrays can also be formed with MicroLEDs (see Figure 3 for example). Two-dimensional variants could be used for pico-projectors or near-to-the-eye displays. The addressable array takes on the roles of both the light source and the imaging engine, eliminating the need for a liquid crystal display or digital mirror device, leading to a lower system cost and trimmed power consumption.Whether these MicroLEDs are used by themselves, or in clusters or arrays, they have similar drive characteristics to LEDs. This means that they do not require complex control electronics or heat sinking, and effective operating lifetimes are 50,000 hours. Manufacture of these devices uses LED-type materials and processing, so the MicroLED benefits from the economies of scale available within this industry. This enables the light source to be affordable, giving it every opportunity for success in applications benefitting from efficient delivery of light by an optical system.

Blue semi-polar laser catches the performance of incumbents

A blue-emitting laser grown on the $(20\bar{2}\bar{1})$ plane delivers efficient emission at high current densities, highlighting the potential of laser-based solid-state lighting



The UCSB blue-emitting laser, driven in pulsed mode, produces a current-limited output of more than 2 W

RESEARCHERS at the University of California, Santa Barbara (UCSB), have produced a blue-emitting semi-polar laser that is claimed to deliver a similar level of performance to state-of-the-art, conventional equivalents. And in future, according to these researchers, this class of laser should exceed the performance of the conventional lasers grown on the *c*-plane, thanks to a trimming of the polarization-related electric fields that hamper efficiency in the active region.

The team's 454 nm laser, which is built on a $(20\bar{2}\bar{1})$ GaN substrate provided by Mitsubishi Chemical Corporation, emits 2.15 W of optical power at an external quantum efficiency of 39 percent.

Another attractive attribute of this laser is that it can operate efficiently at a very high current density of 28.1 kA cm^{-2}. This value underlines the potential of low-cost, laser-based solid-state lighting using chips that are driven hard and emit at very high power densities.

"We believe that lasers will play a strong role in future display and directional lighting applications such as headlights," argues team member Jim Speck.

Fabricating lasers on semi-polar planes, rather than the *c*-plane, opens up the possibility to use thicker quantum wells, due to a reduction in internal electric fields within the heterostructure. High modal confinement is then possible without the need for AlGaN cladding layers, which limit laser reliability and the level at which catastrophic optical mirror damage occurs.

The laser fabricated by the team is free from an AlGaN cladding layer. Sandwiched between 13.5 nm-thick barriers, it has four $In_{0.2}Ga_{0.8}N$ wells that are not particularly thick – they are just 4.5 nm wide.

"In our future research, we will definitely explore wider quantum wells, as well as many other aspects of the active region design," says Speck. "InGaN quantum wells on semi-polar planes, such as $(20\bar{2}\bar{1})$, have very low electrical field at blue emission wavelengths, as demonstrated in our LED work on $(20\bar{2}\bar{1})$ and by simple Schrodinger-Poisson/drift-diffusion solvers."

According to first-principles calculations by Chris Van de Walle's group as UCSB, the biggest contribution to modal loss in InGaN-based lasers is phonon-assisted absorption by acceptor-bound holes. This loss increases with magnesium doping density, and to reduce its impact on the semi-polar laser, the team has moved the locations for high magnesium doping away from the centre of the optical mode.

Magnesium doping is just 7.5×10^{17} cm^{-3} in the 60 nm-thick $In_{0.06}Ga_{0.94}N$ waveguide and 1.5×10^{18} cm^{-3} in the 200 nm-thick cladding. A 400 nm-thick cladding with a 7.5×10^{18} cm^{-3} magnesium doping level sits on top of this, followed by a 20 nm-thick magnesium-doped contact (1×10^{20} cm^{-3}).

Reactive ion etching formed 900 μm-long ridge waveguide lasers with a cavity width of 8 μm. Polishing these chips created smooth facets, before a high-reflectivity coating based on eight quarter-wavelength-thick layers of SiO_2 and Ta_2O_5 was applied to the back facet and the front-facet received an anti-reflection coating based on the same pairing of materials.

Measurements of laser performance were taken with an on-wafer probe, with the device driven with a 1 percent duty cycle – pulses with a 1 μs width, provided at a repetition rate of 10 kHz.

Maximum output power for the laser, 2.15 W, occurred at a drive current of 2.02 A. Even higher powers are possible, since the current delivered by the power supply limited the laser's output, and the increases in current applied to the device produced a monotonic increase in its external quantum efficiency.

One weakness of the laser is its operating voltage: Threshold is 9.0 V, rising to 18.7 V at peak output power. These high voltages are a result of the high series resistance – after turn-on it is 6 Ω – and they stem from a high *p*-contact resistance. The team say that its laser could be improved by trimming its electrical resistance and cutting internal loss.

A. Pourhashemi *et. al.*
App. Phys. Lett. **103** 151112 (2013)

Uncovering the secrets of high-performance green lasers

Photoluminescence exposes improvements within the quantum well

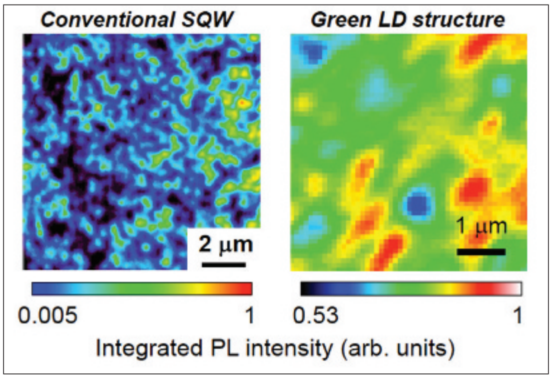
GREEN-EMITTING *c*-plane lasers have rapidly advanced from nowhere in recent years. Prior to 2009 such a device didn't exist, and since then performance has leapt from a 515 nm laser emitting 5 mW to a 525 nm, 1.01 W source. Although the driving force behind these improvements has been something of a mystery, secrets are now unravelling, thanks to research by a team from Kyoto University, Japan, and Nichia Corporation.

This partnership has shown that the strong performance of today's best lasers – such as the 1.01 W, 525 nm laser reported by Nichia in late 2012, which has a threshold current density of 1.68 kA cm^{-2} and a wall-plug efficiency of 14.1 percent – could stem from a very low level of potential distributions in the active region.

"Potential fluctuations generally broaden gain spectra and as a consequence reduce maximum gain, which makes lasing difficult because gain cannot overcome loss," explains Mitsuru Funato from Kyoto University. It is likely that these fluctuations result from variations in the InGaN composition within the quantum well.

To study the level of fluctuations in state-of-the-art green lasers, the team have used optical techniques to scrutinise a laser structure grown by engineers at Nichia. This MOCVD-grown heterostructure was not intentionally doped with the likes of silicon and magnesium to make it easier to assess its fundamental optical properties. However, insights into its potential lasing characteristics were uncovered through the fabrication of an identical structure with *p*-type and *n*-type doping. This lased at 512 nm, and had a threshold current density of just 2.75 kA cm^{-2}.

Several characteristics of the undoped structure were compared with that of a typical green-emitting InGaN/GaN quantum well of yesteryear – a 'conventional' structure that produced a photoluminescence (PL) spectra, but was of insufficient material quality for making a laser. Based on PL spectra at 7K and room temperature, the undoped structure has an internal quantum efficiency of 27.5 percent at 295 K.



Photoluminescence intensity uniformity is far higher in the active regions of state-of-the-art green lasers, than the green-emitting structures of yesteryear

By curve fitting these spectra, the researchers revealed that, at low temperatures, the full width half-maximum for the PL is 70 meV and the Stokes shift is 60 meV. They believe that these very low values indicate that the inhomogeneous broadening in the state-of-the-art structure is remarkably suppressed compared with that in the wells of the conventional structure.

Microscopic PL measurements were performed on both types of sample to determine spatial inhomogeneity. Many bright spots were present in the intensity map produced for the conventional sample. Dislocation density in this structure is 2 x 10^8 cm^{-2}, and the density of bright spots is far higher than this (see Figure), so the team concluded that potential fluctuations are responsible for the inhomogeneity. In contrast, the microscopic PL measurements on the undoped structure show uniform fluorescence.

To probe this sample more rigorously, the researchers turned to confocal microscopy, uncovering islands with dimensions of typically less than a micron. They found variations in intensity from 53 percent to 100 percent, which is far smaller than that seen in the conventional structure, where intensity fluctuations can vary by more than 90 percent.

Emission wavelengths were also far more uniform in the undoped structure. The peak wavelength in this sample varies from 536.9 nm to 539.5 nm, while that produced by a typical green-emitting InGaN/GaN well from several years ago had a emission wavelength variation exceeding 15 nm. The team has also carried out time-resolved photoluminescence measurements. They revealed a recombination lifetime for the undoped structure of 68 ns.

Armed with this broad range of measurements on the undoped structure, the researchers went on to determine that the composition of the well is 28 ± 2 percent and its thickness is 2.5 ± 0.27 nm (9 ± 1 monolayers). This indicates that the undoped well is thinner than its conventional counterpart, and its indium composition is higher. A thinner well has its advantages, because it increases the radiative recombination efficiency by reducing the impact of electric fields resulting from piezoelectric polarisation. However, it is possible that a thinner well reduces optical confinement, due to its smaller volume.

Fabricating a high-quality, indium-rich well will not have been easy. "To achieve high indium composition, the growth temperature must be lowered, which degrades crystal quality," explains Funato. This can mean that growth pits appear in the InGaN films, which can incorporate unintentional impurities or defects that act as deep carrier trap centres.

The team will now measure gain in laser diodes featuring intentional doping.

M. Funato *et. al.*
Appl. Phys. Express **6** 111002 (2013)

Composite oxide promises to aid III-V MOSFETs

A high-performance gate dielectric can be formed with a stack of interleaving La_2O_3 and HfO_2 layers that are subsequently annealed at 500 °C.

PROGRESS of III-V MOSFETs, which are tipped to play a major role in extending Moore's Law well beyond the 10 nm node, is held back by the lack of a high-quality gate dielectric. But recent work by a partnership between engineers at National Chiao Tung University in Taiwan, Tokyo University, and TMSC, shows that a composite oxide made from the pairing of La_2O_3 and HfO_2 could address this weakness.

Interleaving 0.8 nm-thick films of both these oxides to form a stack on InGaAs has created a metal-oxide-semiconductor (MOS) capacitor with a high capacitance, low leakage current and relatively few interface traps.

The attractive attributes of La_2O_3 have been known for some time. It has a comparable dielectric constant to HfO_2, the oxide that the silicon industry uses today for making its leading chips, but has a higher temperature for recrystallization. Films that are amorphous, rather than crystalline, are preferable for dielectrics, because they have a higher dielectric constant and thus enable a lower leakage current.

However, growth of La_2O_3 on InGaAs does have a downside: It leads to strong inter-diffusion between these two materials after post-deposition annealing. So a diffusion barrier needs to be inserted. And according to the Taiwan-Japan team, HfO_2 is a very good candidate, because it has a high-energy bandgap and can demonstrate inversion behaviour with InGaAs.

To test the capability of the pairing of La_2O_3 and HfO_2 on InGaAs, the team used molecular beam deposition to form a series of MOS capacitors, which were subjected to different annealing temperatures.

"Molecular beam deposition is an ultra-high vacuum system," says Edward Chang from National Chiao Tung University, Taiwan, who explains that the oxides were deposited by electron-beam evaporation.

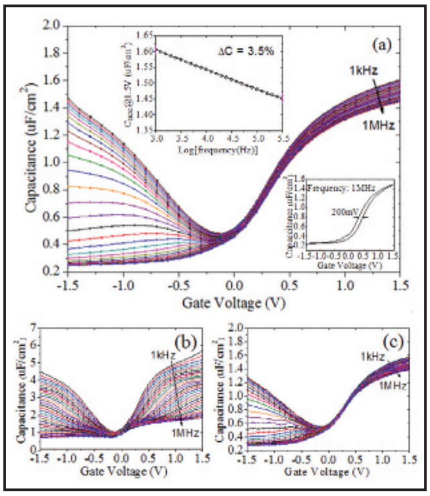
Surface cleaning occurred prior to oxide deposition on the 100 nm-thick film of *n*-type $In_{0.53}Ga_{0.47}As$. Wafers were cleaned in 4 percent HCl for 3 minutes, before they were dipped in $(NH_4)_2S$ for 30 minutes.

Wafers were then transferred to the molecular beam deposition tool, and five layers of 0.8 nm-thick HfO_2, interlaced with 0.8 nm-thick La_2O_3, were grown at 300 °C. Epiwafers were subsequently annealed in nitrogen gas for 5 minutes at either 400 °C, 500 °C or 550 °C, before a Ni/Au gate contact and a Au/Ge/Ni/Au back contact were added.

Photoelectron spectroscopy revealed compositional and interfacial properties of the epitaxial stacks. Increasing the annealing temperature was found to: reduced the number of As-As bonds; decrease the number of oxides associated with arsenic, gallium and indium; and increase the amount of La_2O_3 at an annealing temperature of 500 °C.

Oxide levels are thought to decrease at higher temperatures, due to the conversion of As-O, Ga-O and In-O bonds to InAs, GaAs and La_2O_3. However, cranking up the annealing temperature from 500 °C to 550 °C has a downside, leading to an increase in oxides associated with arsenic, gallium and indium, which occur due to diffusion of these atoms into the oxide layers.

Plots of capacitance as a function of voltage were obtained for devices formed at all three annealing temperatures (see Figure). The device formed by annealing at 400 °C shows abnormal accumulation capacitance at lower frequencies, which is thought to result from a higher leakage current and a higher density of traps at the interface. These are not issues for the device formed by annealing at 500 °C, which has superior electrical characteristics compared to the control – an 8 nm film of HfO_2 on $In_{0.53}Ga_{0.47}As$.



Capacitance-voltage plots for the InGaAs MOS-capacitor with a composite oxide built from five interleaved layers of 0.8 nm-thick La_2O_3 and 0.8 nm-thick HfO_2. Annealing temperatures varied from 400 °C (a) to 500 °C (b) and 550 °C (c)

The capacitance equivalent thickness – the thickness to produce the same capacitance as 1 nm of SiO_2 – is 2.2 nm for the device with the composite oxide, compared to 2.7 nm for HfO_2. What's more, compared to this control, frequency dispersion is lower, falling from 5.1 percent to 3.5 percent.

Annealing temperature impacts the density of interface traps, which fell with increasing temperature, plummeting from more than 10^{13} cm^{-2} eV^{-1} at 400 °C to 7 x 10^{11} cm^{-2} eV^{-1} at 500 °C. A higher annealing temperature of 550 °C did not lead to a further cut in the density of interface traps – instead this figure increased to 9 x 10^{11} cm^{-2} eV^{-1}. In comparison, the control sample had a interface trap density of 2.4 x 10^{12} cm^{-2} eV^{-1}.

The next goal for the team is to use this composite oxide to fabricate a MOSFET and a MOSHEMT.

Y. C. Lin *et. al.*
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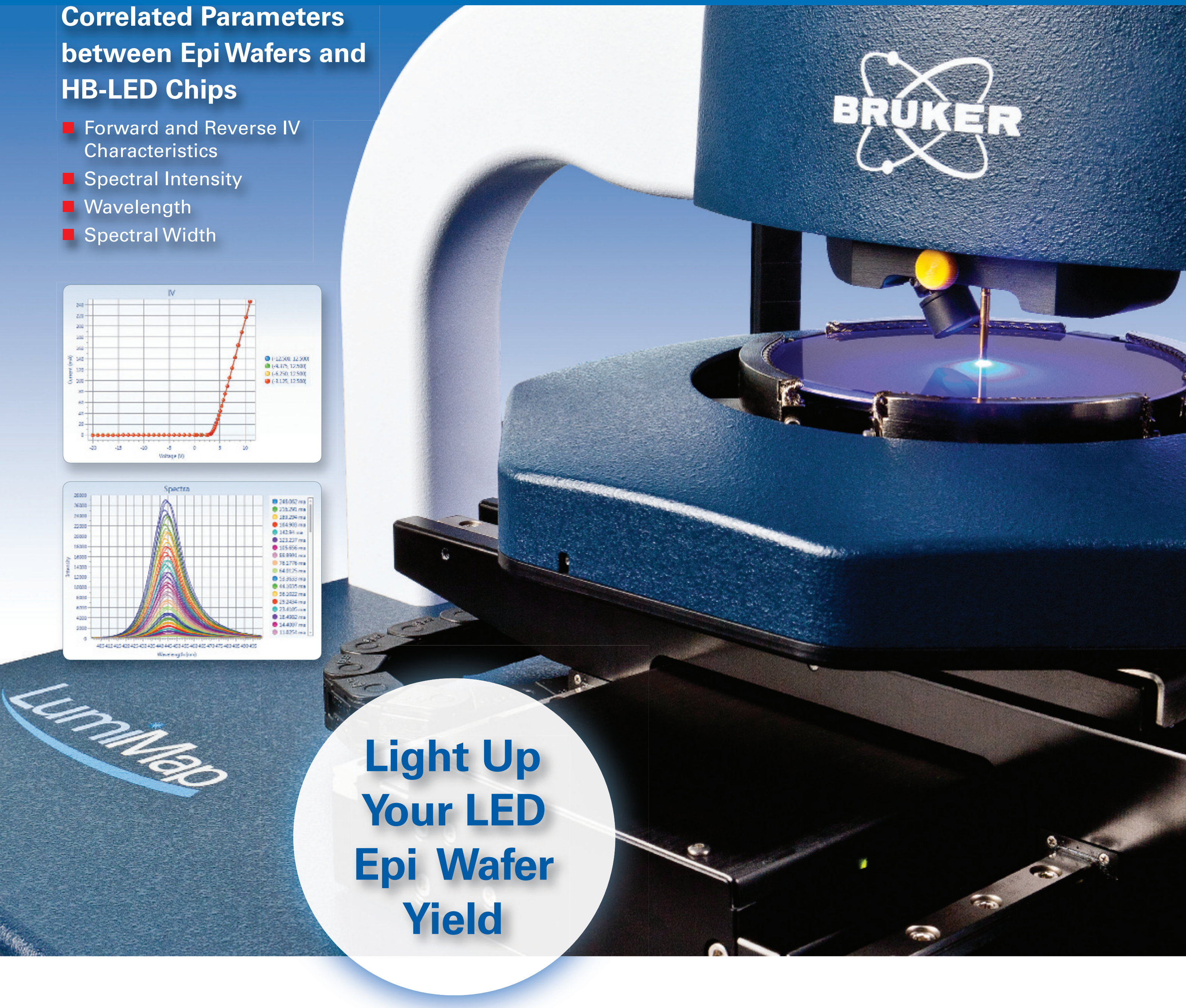

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