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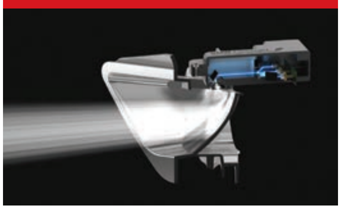
Inherent randomness contributes to green gap

Leaving California for the CS Institute, Cardiff

Strategies to build better, brighter LEDs

Lighting the world with ultraviolet GaN lasers



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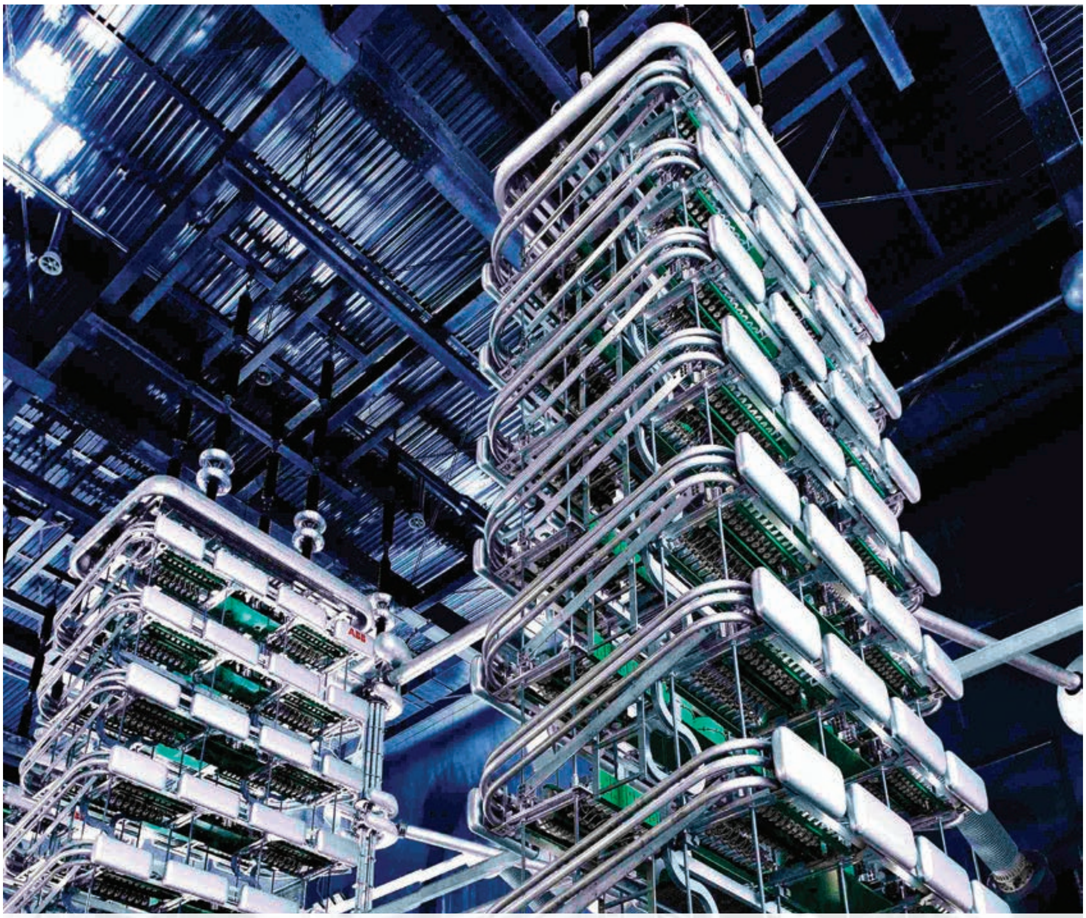

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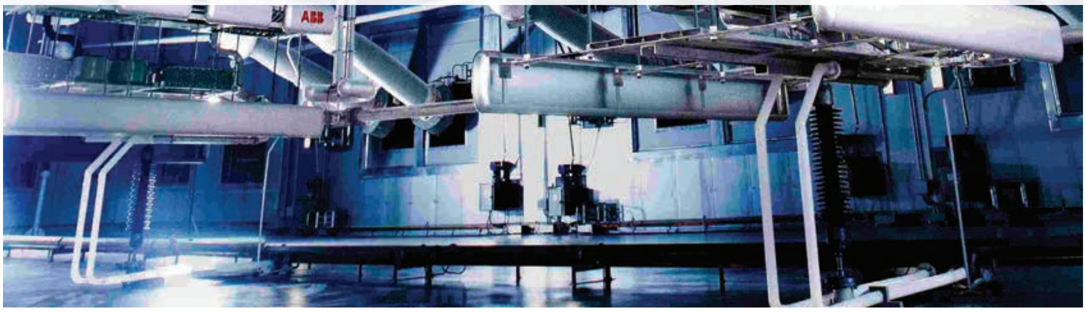

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Viewpoint

By Dr Richard Stevenson, Editor

Probability and the green gap

I BET that you know the basics of probability. I doubt you'd be duped by the argument that a coin that has landed 'heads' three times in a row is now odds-on to fall 'tails'. And you'll probably not raise an eyebrow when told that two children in a class share the same birthday (if there are more than 23 in the class, this is more likely than not).

However, maybe like me, you'll struggle to extend your grasp of probability to the configuration of atoms in the quantum well. If an InGaN quantum well with equal numbers of indium and gallium atoms has been grown, it's easy to think that along each lines of atoms, every other atom will be nitrogen, and in between them will alternate, in a perfect manner, indium and gallium.

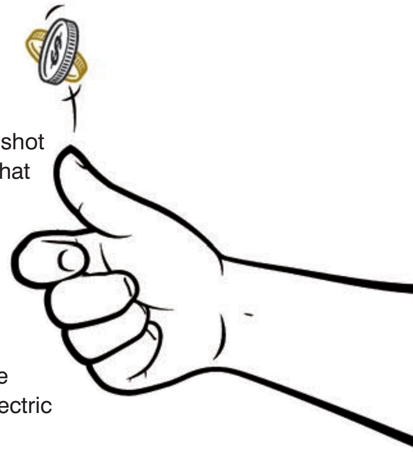
But that's not the case. Even if the growth is perfect, the arrangement of the indium and gallium atoms will have a degree of randomness, with the likelihood of distributions dictated by the laws of probability.

Why does this matter? Well, it has implications for the green gap – the decline in the quantum efficiency of the InGaN LED as its indium incorporation is increased and emission shifts from the blue to the green.

It is well known that the efficiency of this class of LED falls at longer wavelengths due to the quantum confined Stark effect. As indium content increases, internal electric fields within the active region strengthen, pulling electrons and holes further apart and diminishing the efficiency of radiative recombination.

This contributes to the green gap, but cannot account for all the reduction in efficiency with increasing wavelength. And that's where the atomic make-up of the quantum well comes in: according to calculations by researchers at the University of Rome 'Tor Vergata' and the STR Group, compositional fluctuations in the InGaN alloys contribute to the reduction in efficiency with increasing wavelength (see p.28 for details).

Calculations by this team have shown that the electrons and holes head to locations where the indium content is highest. However, due to their spatial separation, this happens independently, with wave functions for electrons and holes peaking at different positions. The upshot is an additional reduction in overlap that contributes to the green gap.



One of the next steps for the team is to extend their work to semi-polar and non-polar LEDs. It will be interesting to see if the distribution of atoms in the quantum well explain the green gap in these devices, where electric fields are weaker, or not even there.

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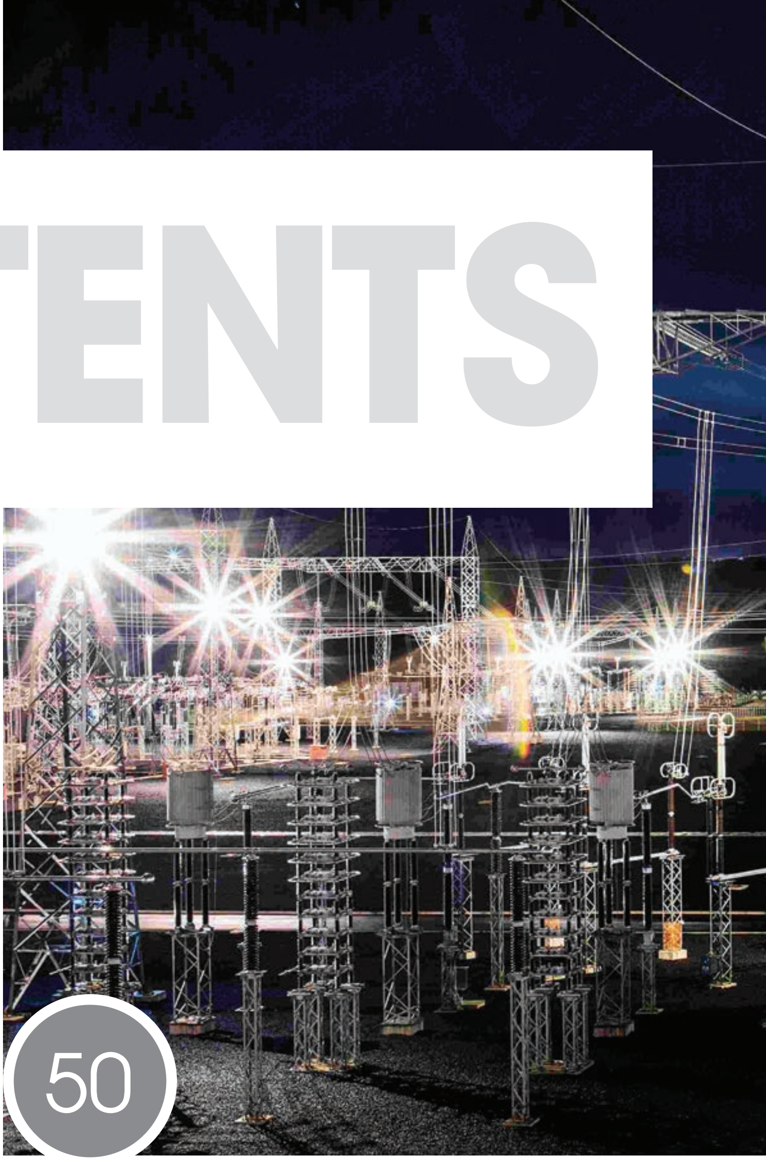

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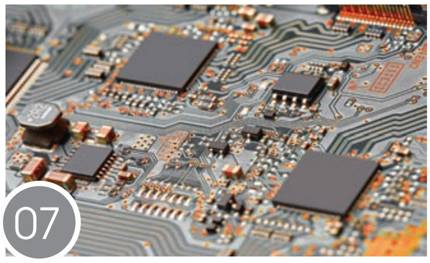

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Cree calls off Wolfspeed/Infineon deal

CREE has announced that it will terminate the definitive agreement to sell its Wolfspeed Power and RF division, which includes the SiC substrate business for power, RF and gemstone applications, to Infineon Technologies.

Cree and Infineon have been unable to identify alternatives which would address the national security concerns of the Committee on Foreign Investment in the United States (CFIUS), and thus, the proposed transaction will be terminated.

"We are disappointed that the Wolfspeed sale to Infineon could not be completed," stated Chuck Swoboda, Cree chairman and CEO. "Considering this development, we are going to shift our focus back to growing the Wolfspeed business. The Wolfspeed business has performed well this year as our customers have further realised the value of our unique technology and is on a great path as a part of Cree.

"The strength of our balance sheet and improving operating cash flow gives us the ability to invest in Wolfspeed, while continuing to pursue our LED and Lighting growth plans. We believe investing to grow all three businesses will create the most value for our shareholders."

Swoboda added: "I thank Dr. Ploss and the rest of the Infineon team for the significant amount of time and commitment they invested trying to successfully complete the transaction." The termination of this transaction with Infineon will trigger a termination fee of $12.5 million being paid to Cree.

Because of the transaction termination and Cree's decision to focus on running the Wolfspeed business, Wolfspeed will now be reported as a separate segment of Cree's continuing operations.

GaNonCMOS project to drive power integration densities

GERMAN PCB firm AT&S has announced that it is one of several organisations collaborating within a new Horizon 2020 EU Research and Innovation programme called GaNonCMOS, coordinated by Jean-Pierre Locquet from the Katholieke Universiteit Leuven (KUL).

Epigan, Fraunhofer, IBM Research, IHP, Tyndall National Institute, PNO Innovation, Recom, NXP Semiconductors and X-FAB Semiconductor are the other participants. The four-year project, launched in January 2017, aims to bring GaN power electronic materials, devices and systems to the next level of maturity by providing the most densely integrated materials to date. This will be realised by integrating GaN power switches with CMOS drivers using different integration schemes from the package level up to the chip level including wafer bonding between GaN on silicon(111) and CMOS on silicon (100) wafers.

The project aims to produce several demonstrators with GaN power switches and CMOS drivers, as well as new magnetic core materials that will enable switching frequencies up to 200 MHz. Combined with optimised embedded PCB technology, the developments should lead to new integrated power components for low-cost, high-reliability systems, according to AT&S.

Allos customer runs GaN-on-silicon epi technology on Aixtron and Veeco systems

ALLOS SEMICONDUCTORS has announced that its low leakage, doping-free 600 V HEMT GaN-on-silicon epiwafer technology is running in parallel on both Aixtron G5 and Veeco K465i reactors for a power electronics customer. The project requirements included developing customised interlayer and superlattice based epi structures with up to 7 μm total thickness for 150 and 200 mm wafer diameter. Additional project objectives were specified device-level parameters and establishing the epi process in the two different widely used reactors.

To have low leakage is one of the prerequisites in the industry to enable mass-market adoption of GaN-on-silicon for power electronic applications like power supplies and motor drives. Allos says its technology fulfills the required low vertical leakage current of less than 0.1 μA/mm² at 600 V and at the same time is using growth conditions optimised to reach Allos' high crystal quality without using carbon or other dopants to isolate the GaN.

Carbon doping became popular in the GaN-on-Si industry in recent years as it can be easily employed to increase isolation. Unfortunately, commonly used techniques to increase carbon levels are resulting in degradations in crystal quality. Allos shares the increasing concerns of industry experts that insufficient crystal quality can have severe negative side-effects on crucial performance and quality characteristics. Consequently, Allos has worked on novel ways to accomplish very low leakage without compromising the crystal quality.

The core of these innovations is growing high quality epilayers without doping. This is based on Allos' patented and proprietary growth techniques and epi structures. "Another concern many deciders are sharing with us is possible conflicts with incumbents who own strong IP around using carbon doping," says Allos' CMO Alexander Loesing.

"Avoiding such conflicts is another benefit of not using carbon," he adds. In the recent customer project, the same epi structures were successfully grown in both tools with very good and reproducible results, according to the company. These include crystal quality XRD FWHM values of 330 arcsec for (002) and 420 arcsec for (102), threading dislocation densities of 2 x 10^8 cm^{-2}, no meltback and no cracks on the entire wafer, tightly controlled bow of less than 30 μm for SEMI-standard thick wafers, mobility of 2000 cm^2/Vs and sheet resistance of 350 Ω/sq. A sheet resistance uniformity of 1.5 to 3 percent (std. dev.) was achieved, depending on the platform. Furthermore, all device-level requirements were met, low vertical leakage of < 0.1 μ A/mm². Beside these technical parameters the economic factors like consumption, yield, reliability, maintenance and throughput for each epi process have also been analysed.

"Allos' experience in installing its technology on many different reactor platforms and the robustness of our technology were essential in achieving the excellent results on the two hardware platforms in this project," says Atsushi Nishikawa, CTO of Allos. He adds: "However, for the first time the same epiwafer structures were grown in two alternative reactor types in parallel and the epiwafers were processed and characterised under equal conditions in the same facility. Based on hundreds of runs this provides a unique performance and cost comparison of MOCVD reactors to the customer. It also gives them all the information they need for choosing their future production platform."

Allos says that these strong results demonstrate that the choice of the right hardware is important but not paramount. In both reactors, superb crystal quality and very low leakage without carbon doping were achieved, and in both reactors, this was possible for interlayer and superlattice structures.

Monocrystal demonstrates 350 kg sapphire crystal

MONOCRYSTAL, a Russian firm specialising in growing and processing synthetic sapphire, recently demonstrated the world's first 350 kg KY (Kyropolous method) sapphire crystal. The 350 kg crystal is a part of Monocrystal's technological roadmap, aimed at enabling higher crystal uniformity, more efficient large diameter ingot throughput for LED, and size-sensitive optical applications.

Low bubble content, which is crucial for ultra-large sapphire products, has successfully been achieved with the 350 kg crystal, according to the company. Another objective of the roadmap is to move Monocrystal's sapphire supply reliability to a new level, which is now of paramount importance, since major LED makers are increasing their capacities. "Our ongoing 'Extra Large Stress Free' initiative is in response to challenging conditions on our main market: sapphire for LEDs. Extra-large crystals enable high crystal uniformity across a 6-inch wafer surface and guarantee uniform wavelength distribution. Our LED customers are able to ramp up their production securely, having Monocrystal as a reliable source," Monocrystal's CEO Oleg Kachalov commented.

"We also have received a very positive feedback from the non-LED market since the introduction of our extra-large crystals in 2015. Working closely with our partners, we have already enabled several promising large-size applications. We are confident that our new 350 kg crystals will allow greater flexibility of our customers' designs and further expand the scope of sapphire use," Monocrystal's VP sales Mikhail Berest added.

Osram IR LEDs used in organic response systems

ORGANIC RESPONSE Lighting Control Systems are designed to operate wide area lighting installations with maximum energy efficiency while still maintaining a high level of comfort. The key lies in a distributed intelligence, which enables the system to react to the presence of persons in the immediate vicinity, as well as to those further away.

The system has sensor nodes integrated in each luminaire, each of which comprises a motion sensor, an ambient light sensor and an infrared transmitter/ receiver pair for communication. The moment a sensor node detects occupancy, the luminaire reacts by putting out a predetermined light level.

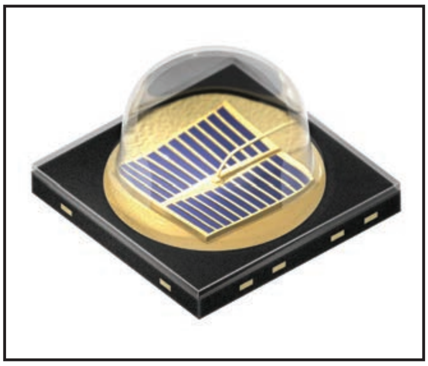
At the same time, it communicates that occupancy to its neighbours by emitting an infrared signal. Subsequently, the neighbouring sensor nodes respond by setting their luminaire to a predetermined light level appropriate to an occupant in that vicinity. They then also simultaneously relay another infrared signal to their own neighbours, informing them there is an occupant two light fittings away.

Ultimately, each sensor node 'knows' how close a person is and sets the luminaire to an appropriate brightness. In this way, it is not just the spot the person is in that is illuminated, but also adjacent areas. This also eliminates the sensation of literally stepping into darkness when entering currently unoccupied spaces. "We initially designed this emitter for infrared illumination and 3D camera applications. But with its high power, narrow emission angle and fast switching time it provides a great solution for optical communication, too," say JÜrg Heerlein, marketing manager Infrared at Osram Opto Semiconductors.

Dean Campbell-Smith, technical director at Organic Response reports: "While developing our product, we evaluated several options for the infrared LED component. However, considering the trust associated with the brand and the strength of their IR LED product, we decided to go with Osram. In the end, it turned out to be an excellent decision for us as it allowed us to address the varying requirements of our clients. We have enjoyed ongoing product support from Osram and have always been pleased with their ability to deliver."

Using light as a means of communication ensures that only luminaires within the person's field of vision are turned on while systems in neighbouring rooms, for instance, will not be triggered.

In case an office is reorganised, newly positioned walls will automatically block the infrared signal and thus adapt the system response automatically to any adjustments. In contrast to lighting



installation that require IDs assigned to each luminaire and which therefore need to be programmed, the organic response solution uses the adjustable range of the IR signal to address specific luminaires. It thus eliminates the need for programming during installation.

The infrared (IR) LED Oslon SFH 4725S provides enough optical power to ensure communication for all possible set ups. The IR LED is based on stack technology, which was developed by Osram to provide one chip with two emission centers, thereby doubling its output.

Driven at 1 A, the SFH 4725S yields 990 mW of optical power. Its narrow emission angle of ±45° results in a radiant intensity of 425 mW/sr. The emitted light has a wavelength of 940 nm, which is invisible to human eyes but a perfect match for the spectral sensitivity of silicon photodetectors.

Navitas produces first integrated half-bridge GaN power IC

NAVITAS SEMICONDUCTOR has announced a technology breakthrough with the introduction of the industry's first integrated half-bridge GaN Power IC. Half-bridge circuits are essential building blocks in power electronics, used in everything from smartphone chargers and laptop adapters, to TVs, solar panels, datacentres and electric vehicles.

Navitas' proprietary AllGaN half-bridge GaN power chip with iDrive monolithically integrates all the functions required to deliver switching speeds of up to 2 MHz and enable a dramatic reduction in size, cost and weight while delivering faster charging. Previously, older silicon-based half-bridge components suffered from slow switching and parasitic power losses, slowing speeds by up to 30 times, according to the company.

The first half-bridge GaN Power IC is the 650 V-rated NV6250, in a 6 mm x 8 mm QFN complete with dual drivers, level shifter, dual 560 mΩ power FETs, bootstrap circuit and extensive protection features. Low-power digital PWM inputs switch the half-bridge at all frequencies, with ease-of-use and layout flexibility for the power system designer. The NV6250 is compatible with a wide range of analogue and digital controllers from multiple IC partners. "This is an exciting time in the field of power electronics", explained Navitas CEO Gene Sheridan. "High-voltage, high-speed power systems are now commercially viable and will enable a new class of high-density, fast-charging and lower-cost power systems. Since Navitas first demonstrated the half-bridge at APEC 2015, we have worked closely with partners to create the next generation of adapters and chargers with breakthrough size and efficiency. Our earlier announcement of the AllGaN platform's JEDEC qualification demonstrates GaN's maturity and readiness" Sheridan added.

"The perennial difficulty with the half-bridge topology in high-frequency applications is how to power and control the high-side switch precisely, quickly and efficiently", said Milan M. Jovanovic, senior VP of R&D at Delta, a major power supply company. "By integrating the critical level-shifting, bootstrap, and dual-drive functions, all in Gallium Nitride, major practical challenges have been solved, paving the way for MHz high-voltage power systems."

"MIT has studied the opportunities and the limitations in high-frequency power converters for more than a decade", said David Perreault, leader of the MIT Power Electronics Research Group. "One key bottleneck in many designs has been the limitation in high-speed level shifting and driving of high-side devices. The introduction of high-voltage GaN Power ICs with integrated, high-speed drivers has tremendous potential in many applications. Congratulations, Navitas!" Perreault concluded.

Mitsubishi Develops Smallest SiC Inverter for HEVs

MITSUBISHI ELECTRIC has announced that it has developed a working model of an ultra-compact SiC inverter for hybrid electrical vehicles (HEVs) that is believed to be the world's smallest SiC of its type at just five litres volume.

It also is believed to offer the world's highest power density of 86 kVA / L for two-motor HEVs, thanks to incorporation of full-SiC power semiconductor modules that achieve superior heat dissipation. Commercialisation for HEVs, electrical vehicles (EVs), and others is expected sometime around 2021.

With fuel-efficiency regulations growing increasingly stringent, the new ultra-compact SiC inverter is expected to help meet the increasing demand for HEVs by reducing the amount of on-board space that must be allotted to electrical apparatus, such as inverters and motors.

To develop the inverter, Mitsubishi Electric says it created a superior heat dissipation structure that ensures long-term reliability by connecting the power semiconductor modules and heat sink with solder.

Going forward, Mitsubishi Electric will continue developing its super-compact SiC inverter for mass production, aiming for commercialization around 2021. This development has been partially supported by Japan's New Energy and Industrial Technology Development Organization (NEDO).

Thales to supply GaN-based transmitters to the danish navy

THALES has been awarded a contract by the Danish Defence Acquisition and Logistics Organisation for 14 GaN-based Continuous Wave Illumination (CWI) transmitters. These will be integrated in the current ESSM fire control systems on-board the Absalon and Iver Huitfeldt class vessels of the Royal Danish Navy.

The CWI transmitter is one of the key components in the fire control chain by providing the x-band signal to illuminate the threat and allow the Evolved Sea Sparrow Missile (ESSM), a medium-range, surface-to-air US missile, to 'home in' on the reflected signal. Thales's CWI transmitter uses state-of-the-art GaN technology and incorporates a proven missile waveform generator (MWFG) building block for high performance. The design is scalable to support emerging missile modes and threats.

"The CWI transmitter is an important product in our strategy as it strengthens our ability to provide complete ESSM fire control solutions in the market," said Geert van der Molen, Thales' VP of surface radars and above water systems in the Netherlands.

The first delivery will be made mid-2019 and the last system will be delivered in 2021.

A second contract was signed for the sustainment support of the CWI systems until 2049.

Researchers achieve higher growth quality with GaN on SOI

WORKING with Okmetic Oy and the Polish ITME, researchers at Aalto University in Finland have shown that SOI (silicon on insulator) wafers are suitable for growing GaN layers, reducing defects and strain compared to silicon substrates. SOI wafers have a layer of silicon dioxide insulator sandwiched between two silicon layers to improve the capacitive and insulating characteristics of the wafer. "We used a standardised manufacturing process for comparing the wafer characteristics. GaN growth on SOI wafers produced a higher crystalline quality layer than on silicon wafers. In addition, the insulating layer in the SOI wafer improves breakdown characteristics, enabling the use of clearly higher voltages in power electronics. Similarly, in high frequency applications, the losses and crosstalk can be reduced", explains Jori Lemettinen, a doctoral candidate from the Department of Electronics and Nanoengineering. "GaN based components are becoming more common in power electronics and radio applications. The performance of GaN based devices can be improved by using a SOI wafer as the substrate", adds Research Fellow Sami Suihkonen.

Growth of GaN on a silicon substrate is challenging because of the difference between the materials' coefficients of thermal expansion and lattice constants. These limit the crystalline quality that can be achieved and the maximum possible thickness of the produced layer.

HexaTech and Osram announce AlN collaboration

HEXATECH, a US supplier of single crystal AlN substrates, has announced signing two strategic agreements with Osram Opto Semiconductors, of Regensburg, Germany.

The agreements include a long-term supply commitment for HexaTech's AlN substrates, direct support of HexaTech's 2-inch diameter substrate development program, as well as licensing of certain HexaTech intellectual property (IP). HexaTech has developed a valuable knowledge base for optoelectronic, high power and RF applications based on its proprietary AlN substrate material. The material is enabling long life UV-C LEDs for disinfection applications, deep UV lasers for biological threat detection, and high voltage power semiconductors for smart grid and efficient power conversion.

"We view this collaborative partnership with Osram as truly a win/win for both companies," stated HexaTech CEO John Goehrke. "By licensing our technology, Osram can accelerate their UV-C LED device development based on HexaTech's material, and we can focus on our core competency, supplying world-class AlN substrates." He added: "We're thrilled that Osram, a clear industry leader, recognises the

tremendous value our IP and substrates provide for UV-C applications, which once again demonstrates our belief that the best substrate material yields the best device performance." Hans-Juergen Lugauer, head of UV-LED research and development at Osram Opto Semiconductors remarked: "Through Osram's strategy of actively expanding our non-visible optoelectronic product portfolio into the UV-C wavelength range, we are poised to capitalise on this rapidly growing market segment."

He added: "Establishing a long-term strategic relationship with HexaTech, a recognised industry leader in the field of AlN, will allow us to develop highly efficient and reliable deep UV devices, positioning Osram as the dominant high performance optoelectronic technology provider from the deep ultraviolet through infrared wavelengths."

RF compound semiconductor revenue will grow

STRATEGY ANALYTICS Advanced Semiconductor Applications (ASA) service report, '*RF Compound Semiconductor Forecast and Outlook: 2016 - 2021'* indicates that while RF compound semiconductor revenue will grow to slightly more than $11 billion in 2021, GaAs devices will not be the driver for this revenue growth. Wireless applications have been the primary driver for GaAs device revenue growth, but this segment of the RF market will stagnate. Instead, revenue growth will come from strong adoption of InP, GaN and SiGe. Eric Higham, service director, Advanced Semiconductor Applications service commented: "GaAs will remain the dominant RF technology, but device revenue will flatten in this application." He added: "A slowdown in the wireless segment will open the door for the other RF compound semiconductor device technologies and additional market segments to really propel revenue growth." Asif Anwar, service director, Advanced Defense Systems service added: "The aerospace and defence market will be one of the bright spots for GaAs device revenue." He went on to say, "the increasing usage of GaAs and GaN devices in this segment will result in strong growth for RF compound semiconductor revenue."

Littelfuse increases investment in Monolith Semiconductor

LITTELFUSE, a US company focused on circuit protection and power control, has made an incremental $15 million investment in Monolith Semiconductor, a Texas-based start-up company developing SiC technology. SiC enables power devices to operate at higher switching frequencies versus conventional silicon. This allows inverters and motor drives to operate with significantly improved energy efficiency and reduced system cost.

"We are pleased to expand our partnership with Monolith's experienced team of SiC and power semiconductor experts," said Ian Highley, senior vice president and general manager, semiconductor products and chief technology officer for Littelfuse. "With the increasing needs to make power electronic devices that will be stronger and more efficient, we are excited about the opportunities this game-changing technology provides."

"Littelfuse has been a great partner with us as we move closer to the commercialization of our technology," said Sujit Banerjee, CEO of Monolith Semiconductor. "We are working closely with Littelfuse to position our combined portfolios to develop innovative solutions for our customers."

As a result of this additional investment, Littelfuse now has a majority ownership position in Monolith and will begin including Monolith in its operating financial results. Littelfuse previously announced that its first quarter 2017 earnings per share guidance included $0.03 of expense to fund development activities with Monolith Semiconductor. This additional investment is expected to reduce earnings per share by $0.09 across the second through fourth quarters of 2017. Under the terms of its agreement with Monolith Semiconductor, Littelfuse has committed to add to its investment once Monolith has achieved certain milestones.

II-VI EPIWORKS: BIGGER AND BOLDER

With rapid expansion underway, II-VI Epiworks is reaching out for growing VCSEL markets and more, reports Rebecca Pool.

LATE LAST YEAR, II-VI Epiworks, the epiwafer production arm of US-based photonics business, II-VI, announced it had 'broken ground' on its state-of-the-art production facility in Champaign Illinois.

II-VI acquired Epiworks alongside Anadigics in February 2016 to boost production capacity for semiconductor lasers and target up and coming VCSEL markets in sensing, consumer electronics and data centre applications. Clearly the Epiworks expansion – intended to quadruple Champaign capacity over the next three years – can only help.

"We want to build the world's leading state-of-the-art MOCVD factory and more capacity is a part of this," highlights II-VI Epiworks co-founder, David Ahmari.

"After the acquisition, II-VI immediately purchased three new MOCVD production tools," he adds. "These systems are now installed, and we are currently adding more cleanroom space to enable rapid production scaling over the next five years."

II-VI Epiworks is manufacturing III-V epitaxial wafers to target several markets including 3D sensing, already earmarked for massive growth by VCSEL manufacturers such as II-VI and Lumentum. Other key markets include photonics communications, industrial photonics and next-generation RF communications.

As part of this, Ahmari is adamant that the very latest wafer characterisation tools will be instrumental to success. Once complete, the Champaign expansion will provide standard capabilities, such as photoluminescence and photoreflectance wafer characterisation for VCSELs, as well as *in-situ* MOCVD monitoring, but new tools will also be available.

Ahmari won't yet be drawn on the types of tests that will be provided, but says: "We asked ourselves what direction is the industry heading, and can we build ourselves a characterisation capability with a set of unique tests that can be used to meet the challenges ahead?"

"So we have anticipated the new types of test that will enable the materials and devices of the future," he adds. "We will also be using automated steps in our epi-process and the infrastructure will be in place to enable the next generation of scaling."

But as the co-founder emphasises, the expanded facility will not just serve VCSELs, but also encompass high-power edge emitters, DFB lasers, photodetectors, HEMTs and more. And plans are in place to scale all wafer production from 3- and 4-inch platforms to 6-inch production.

"Most of our GaAs production volume is already on a six-inch wafer platform, but with the expansion, we'll have more of it," says Ahmari.

Global designs

Right now, II-VI Epiworks has a strong presence in the US, but looking to the future, the company will extend its global reach. According to Ahmari, the

wafer production business can take advantage of II-VI's global infrastructure, and will grow business aggressively in Asia Pacific.

"Foreign semiconductor companies are receiving strong financial backing from government or related entities, making them competitive from an equipment capacity standpoint, but in the end, the efficiency and output of the equipment is the key manufacturing differentiator, and it is our objective to stand apart with our leading epiwafer technology, facility and capacity," highlights Ahmari's colleague and fellow II-VI Epiworks co-founder, Quesnell Hartmann.

"We will combine that with the most advanced characterisation and strongest technical team in the world," he adds. "You can't just throw equipment at the challenges associated with epiwafer growth and scaling up production, but by having the best people, technology and yields, the rest falls into place."

Expansion of the facility is scheduled for completion by mid-2017 and new equipment will then be installed. Crucially, II-VI Epiworks is continuing to act as a global external foundry, with its primary business focusing on serving external customers rather than II-VI alone.

And as capacity scales, so will II-VI Epiworks' workforce. According to Ahmari, the company is set to hire engineers and technicians 'from PhD level through to equipment operators'.

"In early 2016, we employed 60 employees, but our hiring plan is very aggressive and in the relatively near future we expect to have grown our workforce to approximately 150 people," he says. "How quickly we recruit beyond this depends on exact business circumstances and how quickly manufacturing ramps."

II-VI Epiworks is ramping up manufacture of III-V epitaxial wafers to target several markets [II-VI Epiworks]

Commercialising **diamond GaN**

Can a multi-million pound UK project unlock Diamond-on-GaN's full potential, asks Rebecca Pool.

AS THE semiconductor industry's need for speed and energy efficiency continues unabated, global demand for the mighty GaN transistor is rising.

Thanks to high electron mobility and power density, GaN is the material of choice for RF electronics applications such as radar, satellite and electronic warfare.

But power comes at a price, and in this case, it's heat. While GaN-based HEMTs have reached stupendous RF power levels of up to 40 W/mm at frequencies exceeding 300 GHz, self-heating means devices can only be reliably operated to power densities of 10 W/mm. However, a UK-based multi-million pound research project now looks set to realise the full power potential of GaN by swapping the substrate from SiC to diamond and integrating novel cooling to boost power performance by up to a factor of six.

Launched early this year, *Integrated GaN-Diamond Microwave Electronics: From Materials, Transistors to MMICs* will develop GaN-on-diamond HEMTs and MMICs in a bid to banish the thermal management issues that limit current GaN electronics.

Diamond has an incredibly high thermal conductivity, and thanks to this property, a diamond substrate has the potential to boost heat spreading in a transistor by up to six times compared to the SiC equivalent. Project leader and physicist, Martin Kuball from the University of Bristol, has been developing GaN-on-diamond devices for several years, and is confident the time is now right to take the technology further.

"Many industrial partners want higher power microwave electronics devices but are limited mainly by heat extraction from the electronics." he says.

"We've been involved in many programs to develop GaN-on-diamond for this reason, and I now believe there is a huge opportunity for the UK to pull off a full integrated program here."

Indeed, the project, funded by UK-based Engineering and Physical Sciences Research Council (EPSRC), has attracted myriad industry players including MACOM, Plessey Semiconductors, IQE, Element Six, Logitech and the National Microelectronics Institute. The Universities of Bristol, Cardiff, Cambridge, Birmingham and Glasgow are all on board. And Kuball also highlights how aerospace interest is rising, bringing the European Space Agency, as well as Airbus Defence and Space aboard.

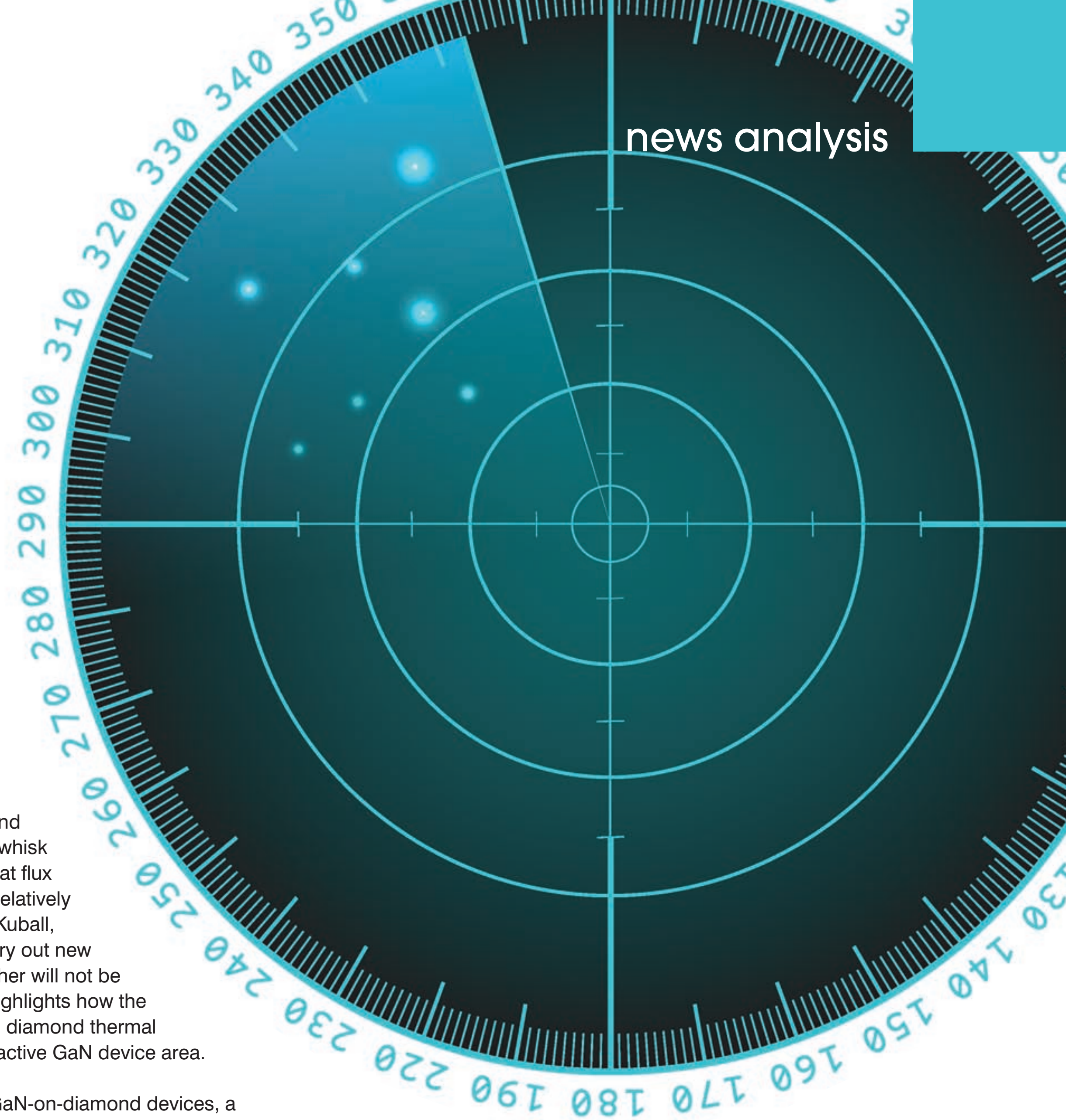
Crucially, many Europe-based industry players are concerned that the US International Traffic in Arms Regulation (ITAR), which controls the trade of defence-related products and services on the United States Munitions List, will restrict market access to state-of-the-art GaN microwave technology.

"I envision that a GaN-on-diamond MMIC would fall into ITER's strike, so getting this technology into Europe would involve a lot of paperwork and be very painful," says Kuball. "There are many challenges to tackle but by having control over the full supply chain, from epitaxy growth to application, we can more easily bring in new device design ideas."

Cooling chips

A key part of new device design is to incorporate novel cooling systems to the GaN-on-diamond chip. As part of a US Defense Advanced Research Agency programme – Intrachip/Interchip Enhanced Cooling (ICECool) – industry heavyweights Raytheon, Northrop Grumman and BAE Systems have already been devising different microelectronics cooling set-ups for such devices.

Raytheon, for one, has developed a systems of coolant-filled high-aspect ratio diamond microchannels that act as a heat exchange. These microchannels channels are positioned next to the known hot spots within a GaN-on-diamond MMIC to boost thermal performance.



Meanwhile, Northrop Grumman lines microchannels etched into the base of a GaN-on-SiC chip with a diamond coating. These channels whisk away heat and reduce heat flux by spreading it across a relatively large area. According to Kuball, the latest UK project will try out new approaches. The researcher will not be drawn on the detail but highlights how the project team will optimise diamond thermal conductivity close to the active GaN device area.

For example, in today's GaN-on-diamond devices, a thin dielectric layer is deposited onto the GaN surface to enable seeding and deposition of diamond onto the GaN. Unfortunately this GaN-dielectric-diamond interface has a poor thermal conductivity.

So, given this, Kuball and colleagues first hope to reduce thermal resistance by eliminating this seeding layer as well as optimising the nearby diamond grain structure. "Our team has some very good diamond growers, including researchers at the University of Cardiff and Bristol, and we believe we can avoid using this seeding layer," says Kuball. "This needs to be tested but we strongly believe we can do this."

In a similar vein to past US research, the team also intends to investigate the use of microfluidics, but this time, will introduce novel phase change materials into the channels to boost heat removal further. Kuball describes this as a 'dramatically more powerful approach than conventional microfluidics'.

"If you use a phase change material, additional energy is required for the phase change to take place, improving the heat-carrying capability of the liquid in the microchannel," he says.

According to Kuball, his team has a range of methods to introduce the microfluidic channels to the epitaxy layers, and adds: "We have a few other ideas on how to construct the walls of the microfluidic channels which are different to what has already been done."

So what now? Within the initial two years of this five-year project, Kuball hopes to have optimised epitaxy growth, developed the novel microfluidics, experimented with new design concepts and fabricated working devices. "We hope to have delivered a few early trial devices within year two," he adds.

And come the end of the project in 2021, he expects a fully optimised device to be in place and also hopes to have formed a spin-out company with industrial partners.

"We have a multitude of challenges to face from the seeding layer to the integration of the microfluidics. Also managing stresses and wafer bow is not going to be trivial," he says.

"But as I think is quite evident, I am very excited to be running this programme," he adds. "We have such a good team of industrial supporters and this is so critical when developing a new technology."

Taking the reins of the Institute for Compound Semiconductors

Leaving California for Cardiff is a price worth paying for taking the top job at the Institute for Compound Semiconductors

BY RICHARD STEVENSON

TAKE A NEW JOB FAR AWAY, and you should be prepared for a great deal of upheaval. Saying farewell to your colleagues and clearing your desk is only a small part of it. You will have to pack your belongings, move out of where you live and search for a new home. Your friendships will change, as those you bumped into day-by-day will now keep in touch via e-mail, calls and Facebook, and you will have to try and settle in a new location. And your family will face change, either because they go with you and face similar challenges, or because the steps taken to meet up with these loved ones will be very different from before.

This list of negatives grows even longer if you are the leader of an academic group. While the move to a new university may be enticing to you, it is unlikely to do so for those nearing the end of their PhD or their post-doctoral contract, so losing personnel is to be expected. If the move is overseas, then you should check the fine-print of your grants to determine the implications, while you get to grips with the funding process in your new country. And expect your research to be disrupted, whether you are packing up your lab and reassembling it, or buying, installing and setting up new equipment.

So, to outweigh this long list of inconveniences, a new job in a new country – and especially one that is an academic position – must have tremendous appeal. And in the case of Diana Huffaker, it certainly does. Early last year she left the sunny climes of California, where she had a great time heading the Integrated NanoMaterials Core Lab at UCLA, to far wetter

Wales, to take charge of the Institute for Compound Semiconductors in Cardiff.

Money has been a big factor behind the move of this incredibly hard-working 52-year-old. She has netted funding worth £10-11 million with her appointment of a Sêr Cymru chair that is backed by a Welsh government initiative.

Huffaker's move has also been motivated by the chance to play a key role in the setting up of the world's first ever compound semiconductor cluster. The pieces of the jigsaw are starting to fall into place, with industrially relevant, company-led research at the institute set to dovetail into activities at the Compound Semiconductor Centre, and the CS Catapult. Together, this trio will provide a wide range of services, from design, epitaxy, fabrication, packaging and basic research to prototyping and foundry production. Running alongside these activities will be the EPSRC Manufacturing Hub in Future Compound Semiconductors, which aims to bring UK academics and industry together.

Hiring and hiring

One of the Huffaker's leading priorities since arriving in Cardiff has been the putting together a top-notch team for the Institute. Combining moves within the university with hires from outside, she has assembled expertise that ranges from quantum technologies to energy harvesting/storage, III-N power and RF devices, and compound semiconductor MMICs (for more details, see "Leading lights at the Institute for Compound semiconductors").

The new facility for the Institute for Compound Semiconductors is being built on the main university campus, and should be open for business in the first quarter of 2019.

The line-up is not yet complete – there are another nine or ten appointments still to make. "They run from lecturer to senior lecturer, a couple of readers, and one more professor," says Huffaker.

A great deal of Huffaker's time is taken up with practical matters associated with the running of the Institute. She has been busy helping to put together a new business plan, a new financial model and a new strategic plan; deciding the terms of reference for the board; hiring an external committee; and selecting equipment for the facility.

The hope is that it will only be a matter of months before companies start to come to the Institute to seek solutions to their problems – and that this dialogue will start to shape the direction of the research. To help make this happen, the Institute is advertising for a Business Development Manager (BDM). "We've got a bid budget for a BDM, for travel and events," enthuses Huffaker.

Working with companies will come easily to this academic. That's partly because she has already been involved in two start-ups, and partly because the focus of her work has always been on addressing real-world problems, rather than blue-sky research. She has a track record that is built on successes with compound semiconductor nanostructures and lattice-mismatched materials, with highlights including: optical links for avalanche photodiodes, which are more efficient than the incumbent approach, thanks to the use of nanostructures; development of a very effective passivation technique that allows nanostructures to deliver their promise; and a process for growing antimonides on top of either silicon or GaAs. On top of this, she has promising results for photovoltaics and gamma-ray detection. "With all the popularity of modular, nuclear reactors, we are really starting to go after some of those applications."

A major milestone for the Institute for Compound Semiconductors will be its move into its new, purpose-built building next year. This central campus facility will have 13,500 ft^2 of space – including 11,000 ft^2 that is "clean" – and an area dedicated to packaging. Within this space there will be one line for processing material from a centimetre or so up to 4-inch, and another for 4-inch to 8-inch. Engineers will work on both these lines, using equipment from the same

A major milestone for the Institute for Compound Semiconductors will be its move into its new, purpose-built building in next year. This central campus facility will have 13,500 ft^2 of space – including 11,000 ft^2 that is "clean" – and an area dedicated to packaging

companies as much as possible, to ease the transition from development to production.

Huffaker's research is not on hold while she waits to move in. She's been busy building a full 4-inch line in a well-renovated facility within an existing university building. Members within her rapidly expanding group include an expert in MBE, another in MOCVD, and three post-doctoral fellow that are studying terahertz avalanche photodiodes, single-photon emitters and long-wave superlattice detectors.

Apart from one researcher that has come over from UCLA, Huffaker is having to build her team from scratch. But she has not abandoned her previous group. Instead, she has taken "leave of absence", and every two months she heads back there for a fortnight. As the group there inevitably dwindles, Huffaker is unlikely to keep up such a gruelling schedule, and will surely spend more of her time in Cardiff. That would allow her to devote ever-more energy into figuring out how to drive the success of the Institute for Compound Semiconductors, and help her to meet her goals for the next 12 months, which include: hiring the BDM; engaging with industrial partners and external academics to increase the usage of the 4-inch line, while understand their needs for the 8-inch line; and expanding the size of her own group.

Come summer 2018, Huffaker and all her co-workers at the Institute should get the keys to their new building and start moving in their tools. "We expect to open for business in the first quarter of 2019."

The hope is that this leads to jobs, with companies from Europe moving to Cardiff and new firms starting-up in the Welsh capital. "The mission really is cluster," enthuses Huffaker. "I hope that when people speak about Fraunhofers and imec, they will talk about the cluster as well."

At a glance: The career of Professor Diana Huffaker

Current role
Director of the Institute for Compound Semiconductors

Previous positions
Director of the Integrated NanoMaterials Core Lab, UCLA
Faculty Member, University of New Mexico

Research interests
Directed and self-assembled nanostructure solid-state epitaxy

Optoelectronic devices including solar cells and III-V/silicon photonics

Honours and awards
2014 IEEE Distinguished Lecturer
2013 Fellow, The Optical Society
2010 SPIE, Nanotechnology Innovation Award
2008 DoD, National Security Science and Engineering Faculty Fellow
2008 IEEE, Fellow

Education
PhD, Material Sciences, University of Texas, Austin
MS, Material Sciences, University of Texas, Austin
BS, Engineering Physics, University of Arizona

Leading lights at the Institute for Compound semiconductors

Working with the head of the Institute of Compound Semiconductors, Professor Diana Huffaker, are:

Dr Daryl Beggs
Specialist in silicon photonics and photonic crystals, aiming to produce quantum photonic devices in compound semiconductor photonic integrated circuits

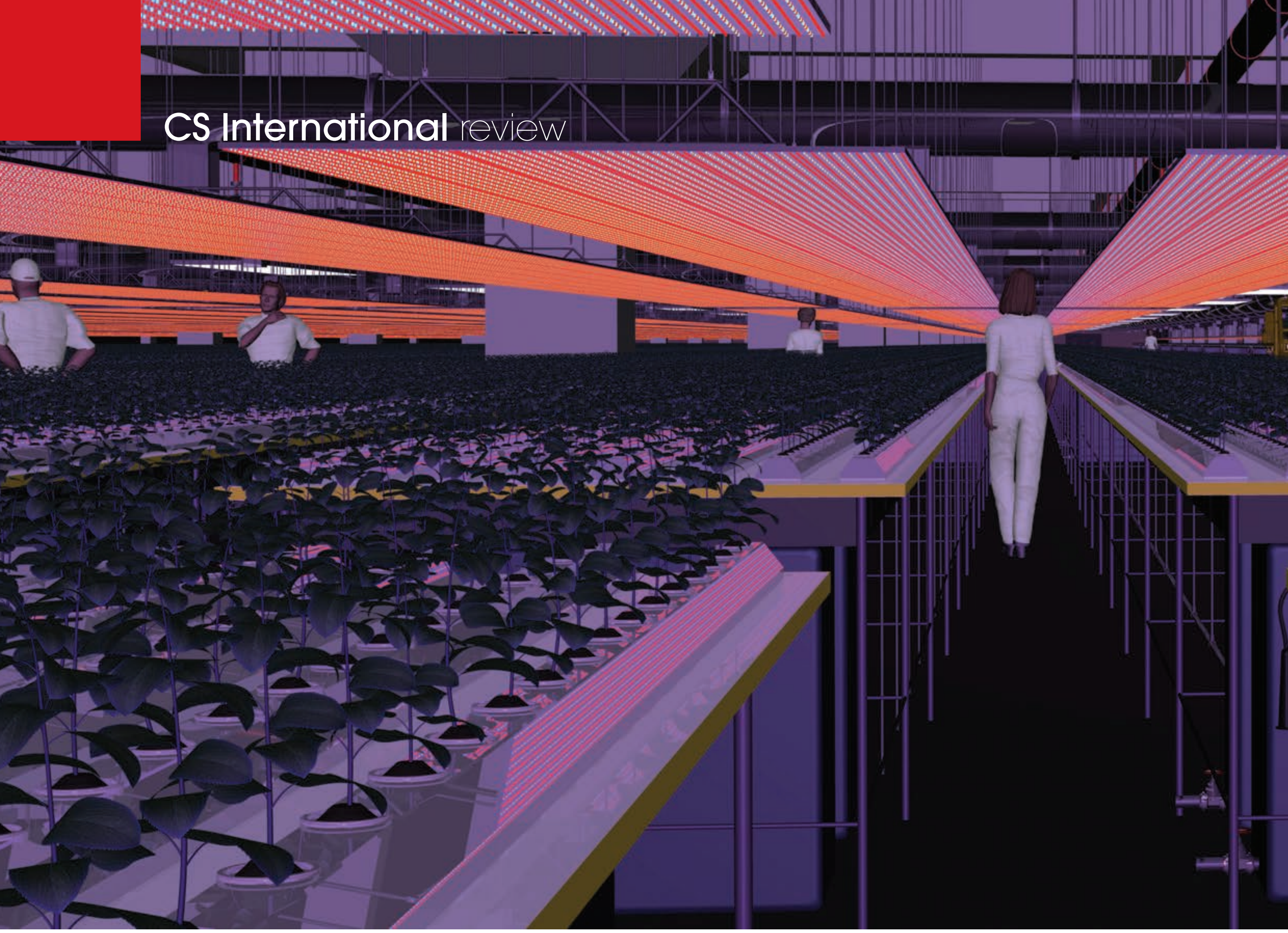
Dr Philip Buckle
Head of Condensed Matter and Photonics, School of Physics and Astronomy, with interest in developing devices with a InSb quantum well two-dimensional electron gas that can be used in the field of quantum communication

Prof. Sam Evan
Head of School of Engineering, with an interest in nanocomposites

Prof. Peter Smowton
Deputy Head of School and Director of Research with an interest in quantum dot lasers, high power emitters for photodynamic therapy, and the physics of InGaN-based LEDs

Prof. Matt Griffin
Head of the School of Physics and Astronomy, with an interest in far infrared and sub-millimetre astronomy and instrumentation

Dr Sudha Mokkapati
Specialist in manipulating interaction between light and compound semiconductor nanostructures, to enhance optoelectronic devices



Manufacturing LEDs:

Developing and exploiting an edge

Chipmakers are chasing better margins via greater economies of scale, carefully targeted product portfolios and superior device performance

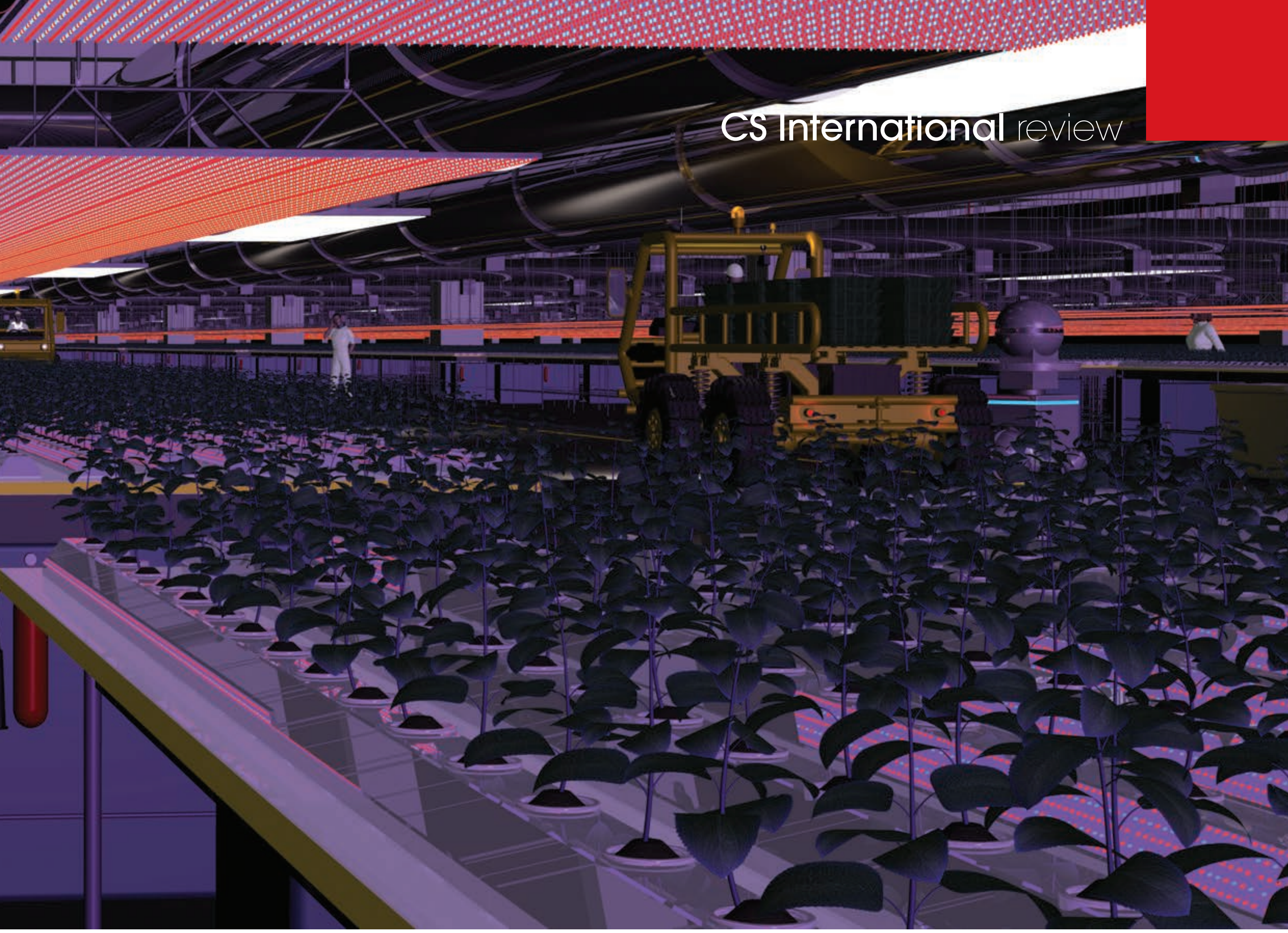
The LED industry is not in the greatest of health. Despite a slight rise in global revenue, market conditions are tough. Recent, severe price erosion is making it challenging to operating with good margins, and any LED chipmaker striving to do so will have to develop and exploiting an edge over its peers.

At the seventh CS International Conference, held in Brussels on 7-8 March, three of the world's biggest LED chipmakers offered an insight into how they are trying to succeed in today's market. The Chinese colossus Sanan Optoelectronics revealed its advantages when it comes to economies of scale, resulting from tremendous manufacturing capacity, while Philips Lumileds and Osram Opto Semiconductors, two industry stalwarts, explained how they are setting themselves apart from the chasing pack by producing devices with superior performance.

Colossal capacity

Delivering the keynote talk in the session *Optimising Light Emitters*, Sanan's Chief Technology Officer, Troy Hsu, began his presentation with a positive take on the LED lighting market, claiming: "There is lots of space for lighting growth in the next few years".

To back up this view, Hsu shared data from two market researchers. He said that Digitimes had forecast that the global LED lighting market would be



worth $24.6 billion in 2016, with this form of lighting having a penetration rate of 31 percent; and quoted reports from LEDinside, suggesting that the LED lighting market will grow from $29.6 billion in 2016 to $33.1 billion in 2017, when it will have a penetration rate of 52 percent.

This growth is good news, but note that increases in LED sales will be modest, and declining. LEDinside suggests that the LED market will grow by 4.2 percent from 2016 to 2017, before slowing to year-on-year growth of initially 2.6 percent, followed by 2.7 percent, 1.2 percent, and then a 0.1 percent decline.

Hsu discussed the expansion of LED manufacturing in China, and the dominance of Sanan. China's share of the global LED industry has rocketed from 27 percent in 2013 to 46 percent last year, with Sanan's share of this accounting for more than 55 percent.

This strong position requires substantial manufacturing capacity. Sanan certainly has that, with more than 6000 employees shared over four production sites that are equipped with the equivalent of 259 Veeco K465i MOCVD reactors.

Sanan's target is to have the greatest epi-capacity in the world, and it is certainly well on the way to that goal. In 2017, it plans to increase the number of MOCVD tools to more than 376, and it "maybe up to 400".

The capabilities of Sanan extend beyond visible LEDs to include the production of various substrates, infra-red, UV and microwave devices, and chips for optical communication. Backing up this activity are 640 global patents, plus another 571 that are pending.

To illustrate the great range of expertise at Sanan, Hsu described the company's core technology, in terms of epitaxy, substrates and devices for different material systems. The company has strength in GaN epitaxy, the production of sapphire and SiC substrates and the production of LEDs based on this; it has capabilities in GaAs epitaxy, the growth of GaAs and germanium substrates, and the fabrication of microwave devices and solar cells; and it has expertise in InP epitaxy, InP substrates and the production of devices for optical communications.

The LEDs produced by China's leading chipmaker span the deep UV to the infra-red: AlGaN-based devices emit at 260 nm to 280 nm, products based on AlInGaN cover 365 nm to 535 nm, AlGaInP chips extend from 564 nm to 618 nm, and AlInGaAs LEDs emit from 610 nm to 940 nm.

Sanan's portfolio is vast, due to the range of devices it produces at different wavelengths, and it is enjoying significant success in many sectors. It has 70 percent of the domestic market for lateral chips used for backlighting, along with 40 percent of the market

LEDs are ideal for horticultural lighting, combining high efficiency with the opportunity to target a spectral range. Sanan has a 30 percent share of the Chinese market for horticultural lighting.

for general lighting, which it serves with a variety of devices, including high-voltage variants. Hsu explained that these products, operating at 9 V, could be used to replace two or three die.

When it comes to displays, Sanan has a 70 percent share of the domestic market for indoor displays, and accounts for 50 percent of the outdoor display sector. According to Hsu, strengths of LEDs that serve this application include a high brightness in the green, a long reverse-bias operating lifetime and good immunity to electrostatic damage.

To cater for those that miss the warm glow of the incandescent bulb, Sanan has released a form of lateral device that it describes as its filament series. Chips have efficacies of 160 lm/W to 230 lm/W, and offer uniform dimming.

Bulbs based on filament LEDs have the look of an incandescent, but the efficiency of a solid-state source. Manufacturers of these tiny LEDs included Sanan.

Sanan has a very strong position in the domestic market for flip-chip LEDs. The company's high-brightness products, which can be used for automobile headlights and camera flash, have a lower forward voltage and higher light output than those of their rivals, claimed Hsu. The demand for this class of device is so high that a three-fold expansion in capacity is taking place during the start of this year.

The company also produces a range of vertical LEDs with powers of 1 W to 30 W. They are targeting projection, industrial, automotive and entertainment markets. These devices can handle current densities of up to 4 A mm^{-2}, and are available as white emitters with colour temperatures of 2700 K to 7000K, and single-colour emitters in the UV, blue, green, red, deep red and far red.

Within the UV range, Sanan produces devices that span the UVA (360 nm to 405 nm) and the UVC (265 nm to 300 nm). The former, which are claimed to deliver world-class performance and can be used for curing, zapping bugs and horticulture, include 280 nm devices that produce more than 30 mW at 350 mA. In the lab, devices are emitting 70 mW. Products with a 50 mW output are planned for release in the third quarter of this year.

Sanan's red, orange and yellow LEDs, which are based on the AlInGaP material system, are being use for outdoor displays, automotive lighting, and horticulture. It also produces AlGaAs-based, infra-red LEDs that can handle drive currents up to 1.5 A mm^{-2}, and are targeting surveillance systems, touch panels, vehicle night vision, medical equipment, iris recognition and data sensing.

At CS International 2017, Chief Technology Officer of Sanan, Troy Hsu (left), delivered the keynote talk in the session Optimising Light Emitters. He spoke about the company's expansion plans, which are claimed to transform the chipmaker into the biggest in the world. Speaking in the same session, Martin Behringer (centre), leader of chip research at Osram Opto Semiconductors, showed how improvements in crystal quality can combat droop, and Oleg Shchekin (right), Senior Director of Device Architecture, Technology Research and Development at Lumileds, discussed the role of the entendue in LED performance.

Summarising the efforts of the company, Hsu explained that Sanan will soon have the greatest capacity of any LED chipmaker in the world, thanks to a 70 percent expansion this year. The current focus is not on standard, visible LEDs, but those emitting in the UV and infra-red, as well as micro-devices and emitters for the automotive market.

Combatting droop

An insight into improving the performance of the LED was provided by Martin Behringer, leader of chip research at Osram Opto Semiconductors.

Behringer began his talk by pointing out that today's LEDs can have an internal quantum efficiency in excess of 85 percent at room-temperature. However, the efficiency peaks at a low current density – typically just a few A cm^{-2}. "We want to operate at a very high current density, and that's far away from the peak, so we lose ten to fifteen percent."

According to Behringer, this loss – known as droop – is well understood, being caused by Auger recombination. He argued that loss can be reduced by either: lowering the current density, via the introduction of new architectures; or increasing the crystal quality of the device. Using the latter approach, engineers at Osram have improved the internal quantum efficiency over the entire operating range, compared to devices from 2012 and 2015.

Another option for overcoming droop is to switch to the third dimension – that is, to produce LEDs from nanowires, which operate at lower current densities. Merits of this approach are not limited to increased efficiency, but extend to lower costs, optical and thermal benefits, an increased active area per wafer area, and the opportunity to use a close-coupled, micro-grain phosphor. What's more, as the emission size is equal to the chip size and the packages can be very small, the technology is scalable, as devices can be placed right up to one another in arrays.

Blue nanowire devices developed by Osram produce homogeneous emission, exhibit minor current crowding close to the current-spreading chips, and have an external quantum efficiency, estimated from wafer-level measurements, of 10 percent at 70 mA.

Like Sanan, Osram is keen to compete in the ultra-violet market. UVA LEDs are in development, producing wall plug efficiencies in excess of 50 percent at up to 1.5 A. These devices are capable of emitting 4.5 W mm^{-2} when driven at 3 A. In the deep UV, high-performance is far harder to realise, with Behringer listing challenges that include doping

Sanan's target is to have the greatest epi-capacity in the world, and it is certainly well on the way to that goal. In 2017, it plans to increase the number of LED tools to more than 376, and it "maybe up to 400". Its capabilities extend beyond visible LEDs to include the production of various substrates, infra-red, UV and microwave devices, and chips for optical communication

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aluminium-rich AlGaN, realising a high quantum efficiency, extracting most of the light out of the device, and ensuring its reliability.

One option for increasing the external quantum efficiency in all forms of LED is to stack quantum wells on top of one another, and insert tunnel junctions between them. Behringer explained that this promises to produce infra-red LEDs that combine an operating voltage of 1.7 V – far less than that of the battery – with an external quantum efficiency in excess of 100 percent, thanks to using each electron twice.

Profiling emission

Speaking within the same session, Oleg Shchekin, Senior Director of Device Architecture, Technology Research and Development at Lumileds, outlined approaches to deliver high efficiency at high power densities.

Shchekin began by highlighting the tremendous progress in LED efficiency, which has led to cool-white LED packages with efficacies of over 150 lm/W, and warm-white variants not that far behind.

According to data presented by Shchekin, retaining the conventional design, the phosphor-converted LED, would allow further gains in efficacy to around 240 lm/W. However, switching to a combination of a blue LED, a green phosphor, and a red LED would lift the ceiling to about 300 lm/W, while 350 lm/W might be possible by combining red, green, blue and amber LEDs.

Two classes of LED were discussed in detail: conventional mid-power LEDs, which have high extraction efficiency die, low operating power densities for a high efficiency, and a large reflective cup that reduces optical losses; and conventional high-power LEDs, which feature high-extraction thin-film flip-chip die, a highly reflective and thermally conductive sub-mount, and a die footprint of 2 mm^2 or more to maintain a high internal quantum efficiency.

"Unfortunately, not all light is useful," warned Shchekin, before going on to explain the concept of the entendue, which is the product of the emitting area of the source, the emission solid angle and the square of the refractive index.

The lower the entedue, the greater the freedom of the designer to optimise light utilisation and system size. Both conventional mid-power and high-power LEDs are poor is this regard, having a high entendue that stems from a large source area – and in the case of the latter device, also the silicone dome.

Superior structures for combining high-luminance with a low-etendue are chip-scale packages, and isolated thin-film flip chips and vertical thin-film chips. Challenges with these architectures include droop, due to the higher current densities.

Shchekin discussed approaches to combat droop associated with both the chip and the phosphor, and also technologies for increasing extraction efficiency (both are detailed in the feature "Strategies for better, brighter LEDs" on p.36").

It is clear from this talk, and those of Hsu and Behringer, that the leading LED makers are striving hard to improve the capability of their products, and widen their portfolio. Profits are harder to come by, but that's not stopping performance from increasing.

The lower the entedue, the greater the freedom of the designer to optimise light utilisation and system size. Both conventional mid-power and high-power LEDs are poor is this regard, having high a entendue that stems from a large source area – and in the case of the latter device, also the silicone dome.


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GETTING TO GRIPS WITH THE GREEN GAP

Compositional fluctuations in InGaN alloys are partly to blame for the dramatic drop in efficiency when moving from blue to green LEDs

BY MATTHIAS AUF DER MAUR FROM THE UNIVERSITY OF ROME 'TOR VERGATA' AND SERGEY YU KARPOV FROM STR GROUP

THE REVOLUTION in solid-state lighting is well underway. GaN-based LEDs are gaining an ever-greater share of the general lighting market, and LED lamps are on sale in many outlets, enabling them to slowly replace conventional light bulbs.

However, there are still some fundamental issues to be solved. One of these is why does the LED's quantum efficiency plummet when its emission is shifted from the blue to the green (see Figure 1). And another key question is why does the efficiency of this device, regardless of its wavelength, fall as the current that passes through it is cranked up.

It is important to realise that both of these issues, which are referred to as the green gap and droop, respectively, are not merely problems of an academic nature. Instead, they have far reaching consequences for LED-based technology and applications.

Take droop, for example. It is an impediment to ultra-efficient lighting, because applications such as generic illumination and car headlights require a high luminosity – and as luminosity is at most proportional to the drive current, high light intensity implies high current. So, when LEDs are used for white-lighting applications, they often have to operate at currents where droop is already significant, and this impairs the overall efficiency.

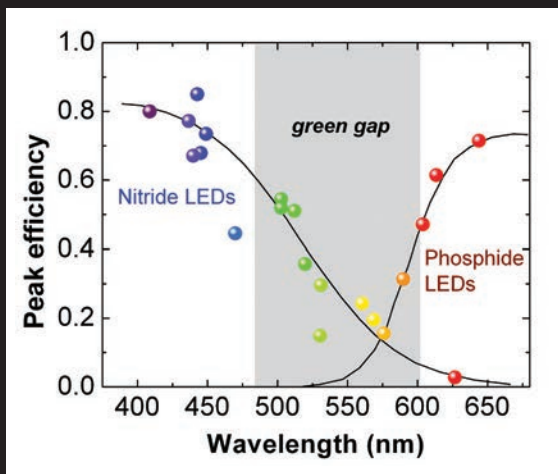

Figure 1. The dramatic drop in LED efficiency in the green and yellow is widely referred to as the 'green gap'. The plot of external quantum efficiency is based on reports for different commercial and research grade nitride and phosphide LEDs. The black lines are guides to the eye.

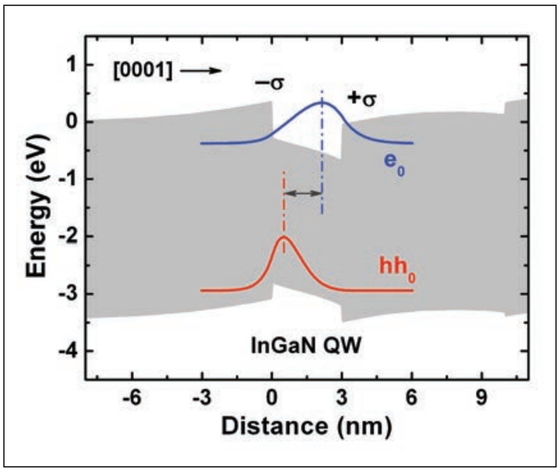

Figure 2. Electron (e_0) and hole (hh_0) ground-state wave functions (lines) in a polar InGaN single quantum well LED. The grey shadow indicates the band alignment in the structure. Here, the structure is grown along the [0001] crystal direction, coinciding with the wurtzite crystal's *c*-axis. $\pm\sigma$ indicate the effective surface charges originated from the polarization discontinuity. This induces an internal electric field in the quantum well that separates electrons and holes along the growth direction.

At first glance, the green gap appears to be far, far less of an issue than droop. After all, white LEDs generate their output by using a blue-emitting LED to pump a yellow-emitting phosphor, and the emission is combined. However, green LEDs are very relevant when trying to form a superior source of white light through the mixing of emission of differently coloured LEDs. This approach, which typically combines the output of red, green and blue LEDs – it has the moniker RGB – has two significant advantages over the incumbent technology: it eliminates phosphor conversion, which is hampered by an additional energy and thus efficiency loss; and thanks to the opportunity to control the single-colour components, it is possible to control the emission spectrum. The challenge is that to ensure an efficient RGB white-light source, a sufficiently efficient green LED with a wavelength in the very middle of the green gap must be adopted. Note that it's not an option to shift the emission of red LEDs to shorter wavelengths, as efficiency nosedives, due to a switch from a direct to an indirect bandgap. As efficient green LEDs based on any material system are not available, phosphor-converted white LEDs are used, as they currently outperform any direct mixing approach. But this could change by uncovering the origin of the green gap, which is in fact just as big an issue as droop.

Today, the consensus of opinion is that the primary contributor to droop is non-radiative Auger recombination. When it comes to the green gap, its origin remains a mystery. It is well-established that as AlGaInP-based LEDs shift to shorter wavelengths, efficiency falls, due to a hike in electron leakage into the *p*-side of the LED structure. This increases with current and operating temperature. With nitride LEDs, the finger points at changes in the active region, which requires an increase in indium content in the InGaN quantum wells to reach longer wavelengths. There is a large mismatch in lattice constant between the InN and GaN crystals that constitute the InGaN alloy, and this leads to the introduction of more defects. They have been blamed on an increase in non-radiative recombination.

However, this explanation is flawed: recent experimental evidence rules out defects as a main cause of the green gap. Experiments undertaken by researchers at Osram Opto Semiconductors GmbH and the Technical University of Berlin on high-quality LEDs with different colours show that that the defect-related recombination coefficient is roughly constant from blue to green. Green LEDs have a lower efficiency, however, indicating that other effects must be behind the green gap.

What is beyond doubt is that increasing the indium content in the quantum well increases the internal electric field due to the presence of strong spontaneous and piezoelectric polarization fields in III-nitride wurtzite crystal structures. This electric field pulls apart the electrons and holes in the quantum well, pushing the former towards one InGaN/GaN interface, and driving the latter to the other (see Figure 2). This phenomena, known as the quantum confined Stark effect, reduces the overlap of electron and hole wave

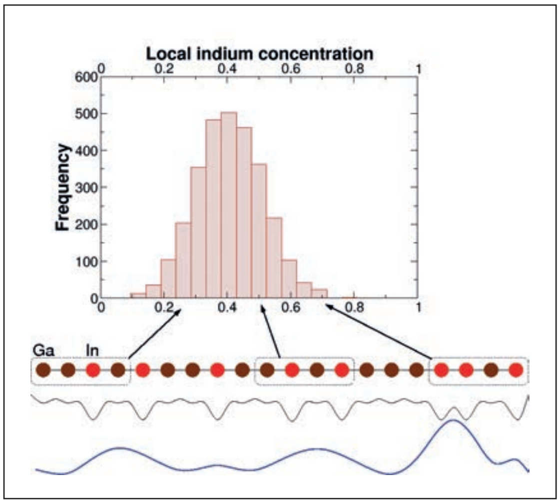

Figure 3. The statistical distribution of the local indium concentration (top panel) is obtained by counting atoms in small control volumes of defined size, shown schematically in the one-dimensional random gallium-indium sequence. Different control volumes give different local concentration, and the random atomic disorder produces a random potential landscape seen by the carriers (black curve), so that the envelope of the wave functions (blue curve) become inhomogeneous, with fluctuations that are correlated with the atomic disorder.

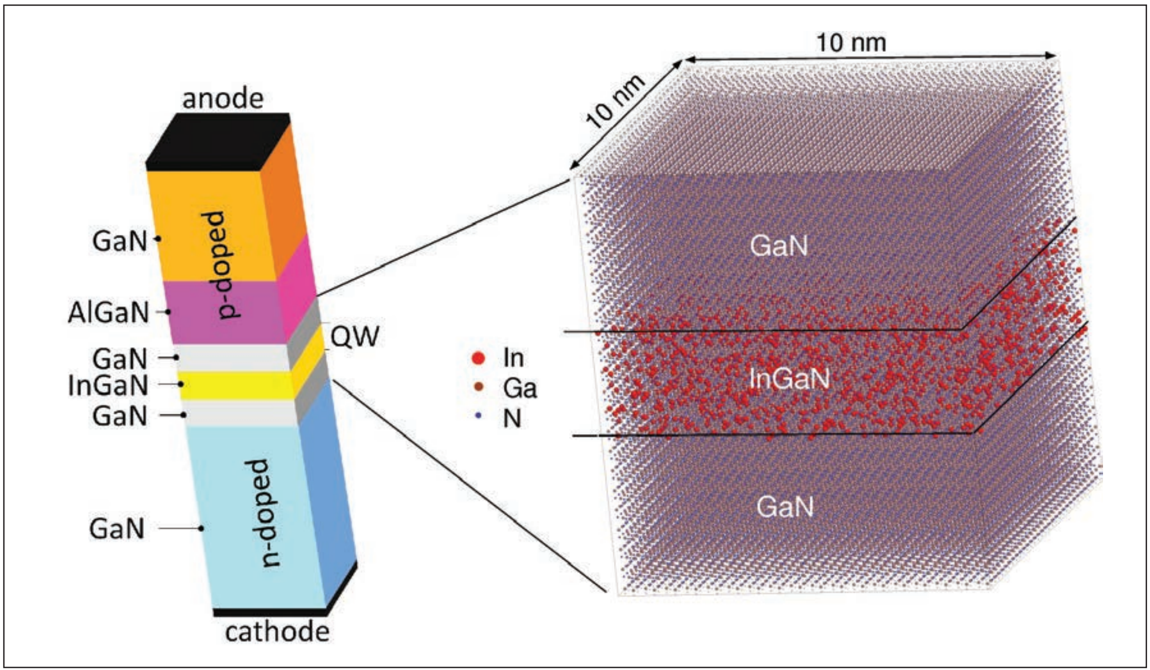

Figure 4. The single quantum well LED structure that is analyzed: The InGaN quantum well (QW) is sandwiched between *n*- and *p*-type doped GaN layers, and an AlGaN layer follows the active region to block electrons from reaching the *p*-doped region. The 3 nm-thick QW and 4 nm of the surrounding GaN barriers has been modeled atomistically with random structures, as shown on the right. The randomly distributed indium atoms are highlighted as red dots. A 10 nm by 10 nm section of the quantum well has been simulated. This corresponding to roughly 100,000 atoms.

functions as the indium content in the well increases. As the radiative recombination rate and the optical emission are proportional to this overlap, they fall, along with the efficiency, as wavelength increases.

When this reduction in efficiency with wavelength is measured, it is significantly larger than one would expect from the quantum confined Stark effect. So other factors must be at play – a view supported by experiments with non-polar nitride LEDs. These devices have no built-in fields, so they are not expected to have a green gap. But they do.

Statistical variations

One explanation for the missing piece to this conundrum is random statistical fluctuations in the InGaN alloy composition, which lead to subtle effects in the electronic structure of the material. Such fluctuations are present in even the best quality material with a completely homogeneous composition, since the exact position of every single indium atom in the GaN host material is governed by statistics. The situation mirrors the classical experiment of drawing, on several occasions, a certain number of balls from a pot filled with many white and black balls: you know that the mean number of white balls that you pull out should equal the ratio of white to black ones, but the exact number will fluctuate from experiment to experiment.

Going back to the InGaN alloy, the implication is that there is a statistical spread in the local InGaN composition obtained by counting indium and gallium atoms (see Figure 3 for an illustration). So, there will be spatial fluctuations on the atomic scale in the energy landscape experienced by electrons and holes. In turn, this will lead to a spread in the energy levels of the electronic states, spatial inhomogeneity in the wave functions, and, as will be shown below, a reduction in the photon emission rate.

One question naturally arises: can these atomic-scale fluctuations have a measureable impact on macroscopic device performance, and ultimately contribute to the green gap or droop? We have been seeking an answer to this in our investigations at the University of Rome 'Tor Vergata' and the STR Group. We know that today's experimental methods are incapable of uncovering the effect of atomic-scale alloy fluctuations on electronic and optical properties, so we have used theoretical calculations to consider their possible contribution to the green gap and droop.

The most natural way to study the influence of atomic scale features is by atomistic models, which explicitly use the detailed information on the atomic structure of the device, such as atomic species and positions. But the downside of this approach is that these atomistic simulation models can be computationally quite demanding, because simulated structures can contain hundreds of thousands of atoms or more.

A reasonable compromise is to use an empirical tight-binding model. For these calculations, we construct electronic wave functions from a linear combination of atomic orbitals, and only account for interactions between nearest neighbour atoms. This model is 'empirical', because the parameters are obtained by fitting to the known band structures of bulk materials. The strength of such a model is that it combines reasonable computational efficiency with the ability to treat random atomic structures – and it is such a structure that lies at the heart of the matter.

We began by considering the effect of random compositional fluctuations on the maximum LED efficiency. To do this, we employed standard simulation models, and evaluated realistic LED structures under operating conditions near the efficiency maximum. We then constructed statistical sets of random atomistic structures, with efforts restricted to just the relevant part of the LED, which obviously includes the quantum well with randomly distributed indium atoms (see Figure 4).

By using a classical valence force field method, we could then calculate exact atomic positions. After this, we projected the electrostatic potential obtained formerly in the device simulation onto the atomic positions and constructed the tight-binding Hamiltonian – and then from this, we obtained the energies and wave functions of a subset of all electron and hole states via an efficient implementation of an eigenvalue solver, using modern graphics processing units. Finally, from the electron and hole states, we calculated the radiative recombination rate and the carrier densities. To determine the impact of LED performance on wavelength, we performed these calculations for different indium contents between 15 percent and 35 percent, and for each of those, we considered several dozen random samples, each with a different random distribution of indium atoms. Taking this approach allowed us to extract the statistical mean values for both the radiative recombination rate and the carrier densities.

For comparison, we repeated the calculations, but this time we ignored the random structure of the alloy. In this case, we treated InGaN as an effective medium, with effective parameters for the construction of the tight-binding Hamiltonian. This approach is comparable to that adopted for a standard device simulation, where electronic states are calculated using a continuous effective medium approximation.

It is immediately apparent from these simulations that the energies of electron and hole states are not the same in every randomly disordered sample. Instead, they show statistical scattering. This state of affairs is also seen in the momentum matrix elements, which are the most relevant quantities for radiative recombination. This insight indicates a variation of electron-hole wave function overlap from sample to sample, which will surely impact the final emission efficiency.

What's more, comparing these results with those employing an effective medium approximation reveals that the inclusion of compositional fluctuations reduces the momentum matrix elements, and that the reduction becomes stronger for higher indium content that equates to longer wavelengths. This implies that the effective medium based models tend to overestimate the radiative recombination rate, and thus the efficiency.

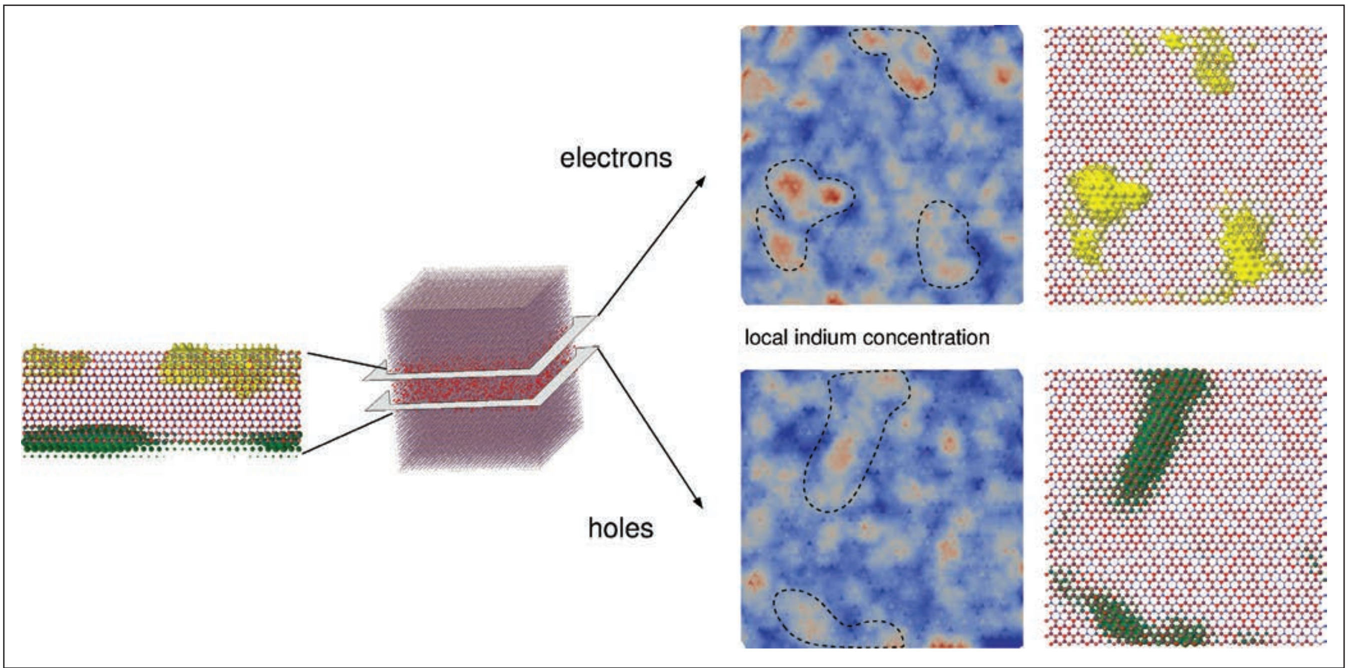

Figure 5. In the plane of the quantum well, the electron and hole wave functions that are represented by yellow and green in the figure, respectively, have their maximum where the local indium concentration is highest (see panels on the right). The side view on the left shows the vertical spatial carrier separation along the quantum well thickness. Electrons and holes are separated by the quantum-confined Stark effect.

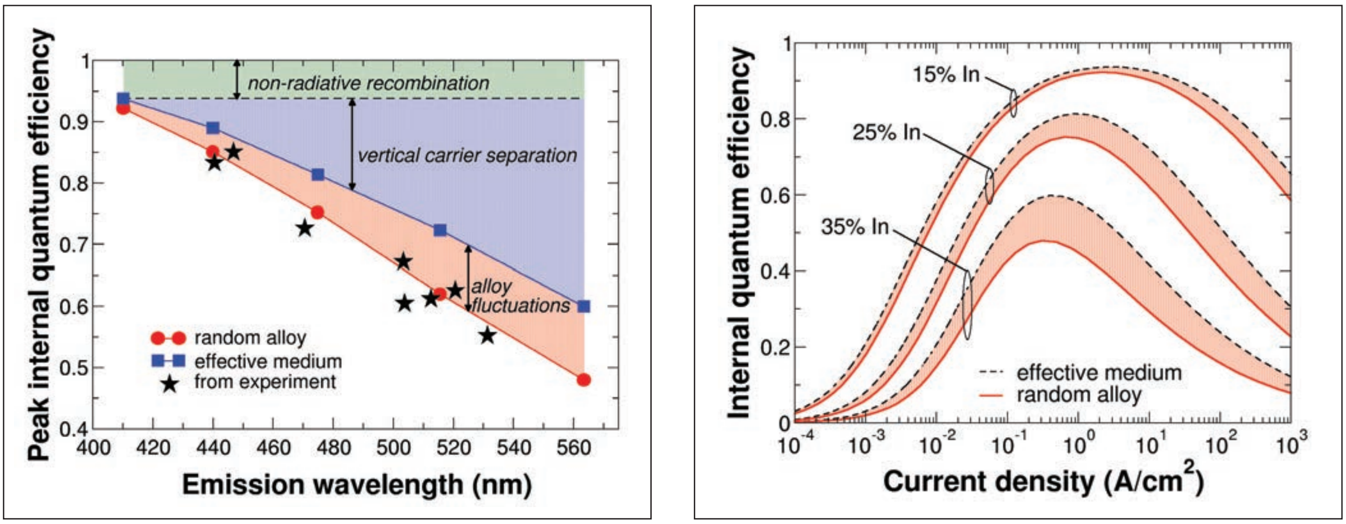

Figure 6 Left panel: Peak internal quantum efficiency for different emission wavelengths, due to differences in indium content, assuming constant non-radiative recombination constants borrowed from [2]. The model, which includes random alloy fluctuations, accurately reproduces the wavelength dependence of the internal quantum efficiency obtained by using the measured radiative recombination parameter. Alloy fluctuations contribute up to 30 percent of the green gap. Right panel: IQE as a function of current density for different indium contents. Compared to the model based on the effective medium approximation, random alloy fluctuations decrease peak efficiency and tend to slightly increase droop.

Implications of fluctuations

It's easy to intuitively grasp the implication of the simulations by looking at the wavefunctions of the electron and hole ground states, and relating them to the local indium concentration. Both the electron and hole wavefunctions accumulate at the peaks in the indium concentration on the relevant atomic planes in the quantum well (see Figure 5). So, to put it another way, electrons and holes head to where more indium is present. However, due to their spatial separation in the growth direction, this happens largely independently, with wave functions for electrons and holes peaking at different positions in the quantum well plane. The upshot is an additional reduction of overlap.

Even more interesting than this qualitative insight are comparisons with actual measured data. To do this, we have compared our results for the effective radiative recombination parameter with those extracted experimentally on high-quality, single-quantum-well LEDs emitting at different wavelengths [2]. What we find encouraging is that our theoretical prediction for the wavelength-dependency of the peak LED efficiency accurately matches that obtained with experimental parameters (see Figure 6). If, on the other hand, compositional fluctuations are neglected, they will predict a smaller reduction in efficiency [1]. This is a strong indication that random compositional fluctuations play a critical role in the green gap.

We have also pursued a semi-empirical simulation [4,5]. With this approach, we assume that electrons are completely delocalised in the conduction band and holes are strongly localised by composition fluctuations in a bulk InGaN alloy. This difference between the two types of charge carrier results from the far higher effective mass for holes than electrons. Unlike the atomistic model, the strength of carrier localisation is controlled by the hole localisation energy as a fitting parameter.

One of the strengths of this semi-empirical model is that it provides a good fit to the spectral dependencies of both the radiative and the Auger recombination coefficients reported by the team from Osram and the University of Ulm [2] – so it ultimately provides an insight into the efficiency drop in the green gap (see Figure 7). However, this model overestimates the absolute values of the coefficients because it neglects the effects of polarization fields. Yet, despite this discrepancy, it is still able to highlight the crucial impact of carrier localisation on both radiative and Auger recombination in InGaN-based LEDs. It is this phenomenon that plays a role in the green gap.

A good test of any model is whether it can explain temperature-dependent behaviour. Recent measurements have revealed that radiative recombination coefficients show an anomalous increase with temperature [4], which can be attributed neither to bulk materials nor to quantum wells (Figure 8). Now an explanation is needed that offers a natural interpretation, in terms of carriers localised by compositional fluctuations, using both the semi-empirical model [4] and atomistic simulations.

Have our efforts finally laid bare the nature of the green gap? Well, not just yet – there is still much work to be done. What we can say is that we have

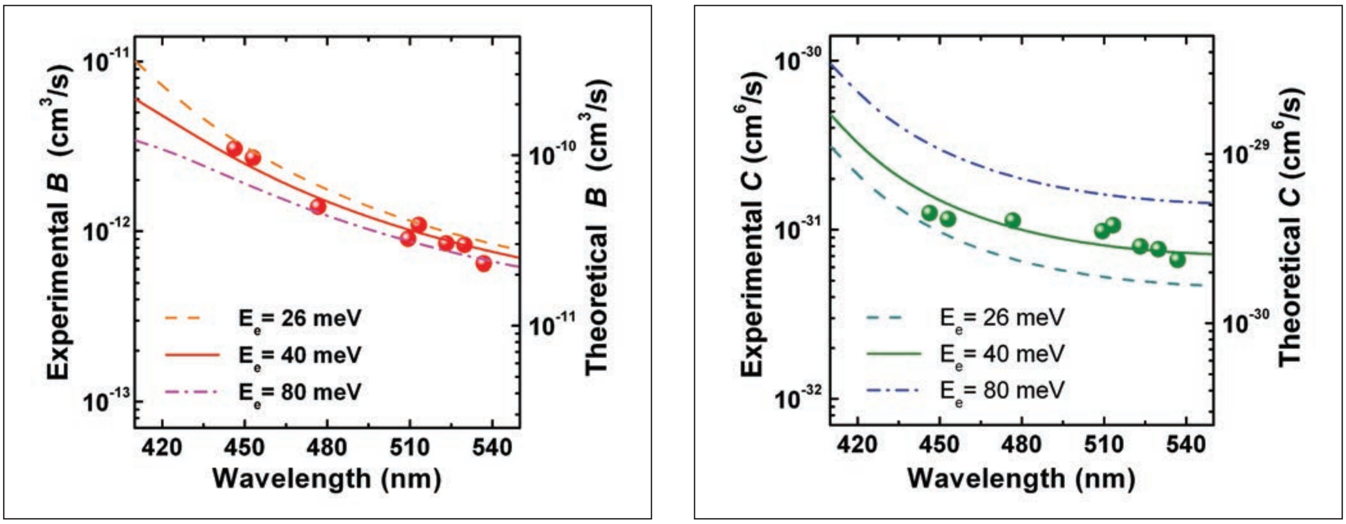

Figure 7. Spectral dependency of the radiative (B, left panel) and Auger (C, right panel) recombination coefficients from measurements [2] (balls) and from the semi-empirical model (lines), estimated for different electron energies E_e .

undoubtedly reached a better understanding of the role of random alloy fluctuations and associated carrier localisation, and we are now confident that they play an important role in the green gap. We know that statistical compositional fluctuations are present in even in the best quantum well with highly homogeneous InGaN composition, and this results in a fundamental limitation for the efficiency of long-wavelength nitride LEDs. So, it is not possible to overcome the green gap through technology optimization. However, if there is indium clustering in InGaN quantum wells – this may arise due to non-optimal growth conditions and processes – the efficiency will plummet faster as the emission lengthens from blue to green and yellow.

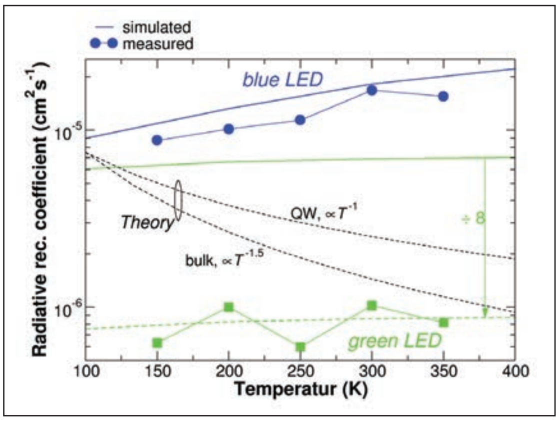

Figure 8. Temperature dependence of the radiative recombination coefficient in blue and green multi-quantum-well LEDs measured in [4] (symbols). The atomistic simulation accounting for compositional fluctuations (solid lines) reproduces qualitatively the observations (the simulated values for the green LED have been divided by a factor of 8 to match the range of measured values), while conventional theory predicts the opposite trend both for bulk materials and quantum wells (dashed lines).

The closing of the green gap will require a more detailed, quantitative understanding of the effects of alloy composition fluctuations. Heading the list of issues that must be clarified in future is the effect of alloy fluctuations on the efficiency of green non-polar and semi-polar LEDs, as the electron and hole localisation in these devices is no longer spatially uncorrelated, thanks to the absence or severe reduction in the quantum confined Stark effect. From a practical perspective, there is also great interest in understanding the influence of compositional fluctuations on the emission spectra, and the impact of indium clustering on the optical spectra.

The authors thank Alessandro Pecchia (Consiglio Nazionale delle Ricerche), Gabriele Penazzi (University of Bremen), and Walter Rodrigues and Aldo Di Carlo (University of Rome 'Tor Vergata') for their important contributions to the atomistic simulations. The FP7 project NEWLED is acknowledged for funding.

Further reading

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Strategies for better brighter LEDs

Diminishing droop and enhancing extraction efficiency help to build better, brighter LEDs

BY ASHISH TANDON, TONI LOPEZ, OLEG SHCHEKIN, ISAAC WILDESON, PARIJAT DEB, HENRY CHOY AND JY BHARDWAJ FROM LUMILEDS

THE LED is a highly versatile device which has transformed solid state lighting in the last decade. This device is best known for its high efficiency and long lifetime, which have helped to drive its adoption in general lighting. The efficiency has continued to improve at an astounding pace, which is resulting in accelerated adoption as well as reducing cost, by not only reducing the LED count for a given application, but also reducing hardware system costs, by allowing the use of smaller heat sinks and direct attachment to board. This efficiency gain also allows high luminance die shrink that enables a new class of applications based on densely packed arrays to create an addressable matrix that is well-suited for automotive headlight dynamic beam steering. The inherent high speed switching of InGaN LEDs makes them ideal for visible light communications or LiFi, which can be dual function alongside lighting.

The wide penetration of LEDs into various markets has been enabled by massive strides in blue LED wall-plug efficiency, white conversion efficiency and the ability to precisely tailor and control the colour point. In this article, our team from Lumileds, San Jose, CA, discusses the technology breakdown for LEDs and compares different architectures, thus highlighting opportunities for future improvements. In the following sections we cover various aspects: White LED efficiency breakdown pareto – typical losses (ranges); epitaxial considerations for high-power LED multi-layer stacks – internal quantum efficiency versus droop trade-off, polar versus semi-polar versus non-polar GaN; carrier spreading and light extraction in devices – patterned substrates; die architecture comparison; photo-thermal quenching of phosphors; and we conclude with some ideas for next-generation LEDs.

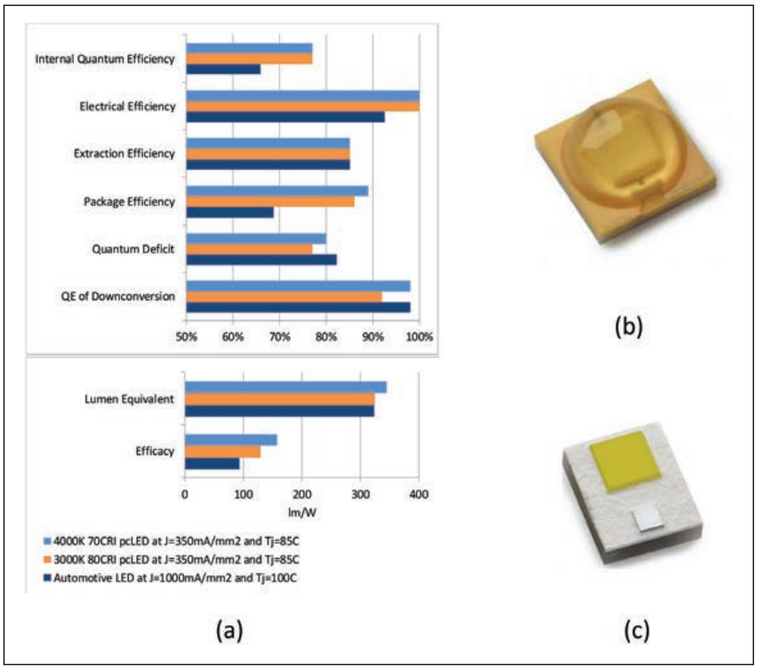

Figure 1: (a) Breakdown of efficacy components for typical cool white, warm white phosphor-converted high power illumination LEDs at J = 350 mA/mm^2 and T_j = 85 °C, as well as for a typical high power automotive front-lighting LED at J = 1000 mA/mm^2 and T_j = 100 °C; (b) a typical high power general illumination LED; (c) a typical high power automotive lighting LED. With these products, the package is constructed for efficient dissipation of heat and extraction of light. To ensure this, the phosphor is positioned in proximity to the emitting surfaces of the pump LED chip, with the latter placed on a ceramic sub-mount and encapsulated in a silicone dome. Note that high power automotive LEDs are designed with emphasis on source brightness. Such LEDs feature pump chips with high extraction efficiency, ceramic sub-mount and proximity phosphor, but forgo using domes to keep source étendue small at the expense of package efficiency.

Excelling in efficacy

The luminous efficacy of an LED – essentially a measure of efficiency, evaluated in terms of the response of the human eye – is commonly represented by the product of four factors: the internal quantum efficiency of carrier recombination in the active region; the extraction efficiency of photons in the blue LED; the electrical efficiency of the injection of carriers into the active region; and the efficiency of converting blue photons into the desired LED spectrum. In Figure 1, typical values for all these efficiencies are given for two classes of LED, a typical InGaN-based device for high-power illumination and an automotive LED. Note that in this figure the conversion efficiency is sub-divided into: the package efficiency; the Stokes shift penalty, which is referred to as the quantum deficit; the luminous equivalent of the emission spectrum; and the quantum efficiency of down conversion by phosphors.

A quick glance at that breakdown reveals that the internal quantum efficiency of the multi-layer epi stack offers the greatest potential for improvement. Addressing this is not trivial, because it involves combatting droop within the active region. Next on the list are the extraction efficiencies out of the pump chip and the package.

In some instances, an area of concern is the quantum efficiency of the down-conversion of blue light by the phosphor materials. This can be very high, but may decline at high drive currents, due to photo-thermal quenching. The loss can be a significant impediment in devices designed to have a high colour rendering or warm colour temperatures, because they require red nitride phosphors that quench more easily.

Combatting droop

As LED luminance requirements rise, operating current densities are increasing, with traditional values of typically 35 A cm^{-2} extending to 100 A cm^{-2} or more. This change has a profound impact on epitaxy, as the focus for increasing the internal quantum efficiency at 100 A cm^{-2} differs significantly from that at current densities of 10-20 A cm^{-2}.

At the lower current densities, increases in internal quantum efficiency come from material quality improvements. That's because Shockley-Read-Hall recombination dominates at low current.

In stark contrast, when LEDs are driven harder, the focus has to be directed at combatting droop, which is the reduction in internal quantum efficiency with increasing current density. Today, there is widespread support for Auger recombination as the dominant cause of droop in state of the art industry devices [2-3]. Auger losses are significant at high drive currents, due to the increasing carrier densities within the quantum wells, which bolster the likelihood of this three-particle recombination process.

An obvious candidate for mitigating Auger recombination is the introduction of active regions with more wells, as this promises to reduce the carrier density in each of them. But this has limited success. Asymmetry in electron and hole effective masses results in the carrier density in the *p*-side of the active region being higher than it is in the *n*-side, and that leads to variation in carrier recombination. So adding quantum wells produces diminishing returns – and then none at all.

A far better approach is to use band structure engineering. This can promote better carrier distribution and ensure a lower carrier density per quantum well. Accomplish this and the operating point for the device is higher on the efficiency curve (see Figure 2).

Although active regions designed for low droop are generally able to realise an even distribution of carriers amongst the quantum wells, they do so at the expense of material quality – and this increases non-radiative Shockley-Read-Hall recombination. Often, it is the increase in the indium content in the low-droop active region designs that contribute to the degradation in material quality. Clearly, an optimal LED must combine

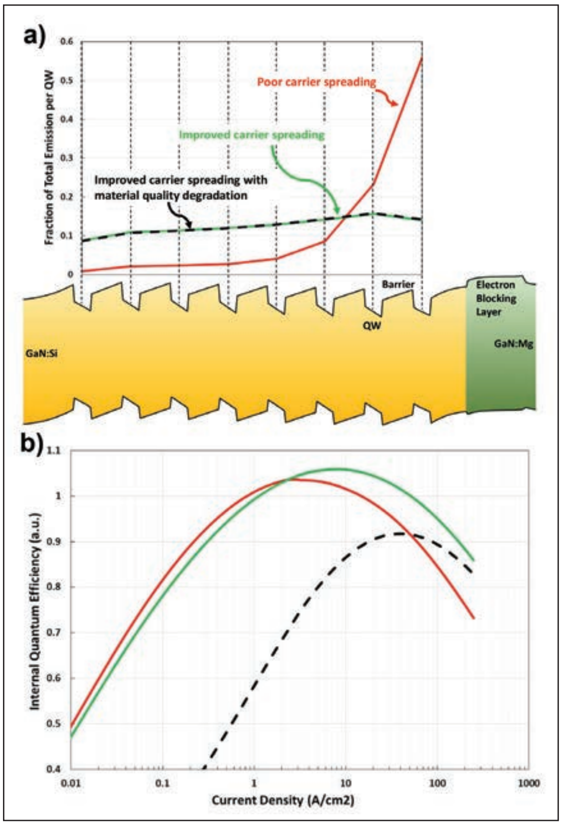

Figure 2. One-dimensional device simulations of LED active regions with different carrier distributions and material quality (a), and corresponding internal quantum efficiency (IQE) curves (b). The different scenarios of carrier spreading and material quality are achieved by adjusting the input heterostructure design and non-radiative recombination lifetimes, respectively, into the simulation. Moving from a poor carrier spreading structure (red lines) to an improved carrier spreading structure, but with poorer material quality (black dashed lines), provides gain at only very high current densities. In comparison, an improved carrier spreading structure with no material quality degradation (green lines) offers significant high current gains over the poor carrier spreading baseline.

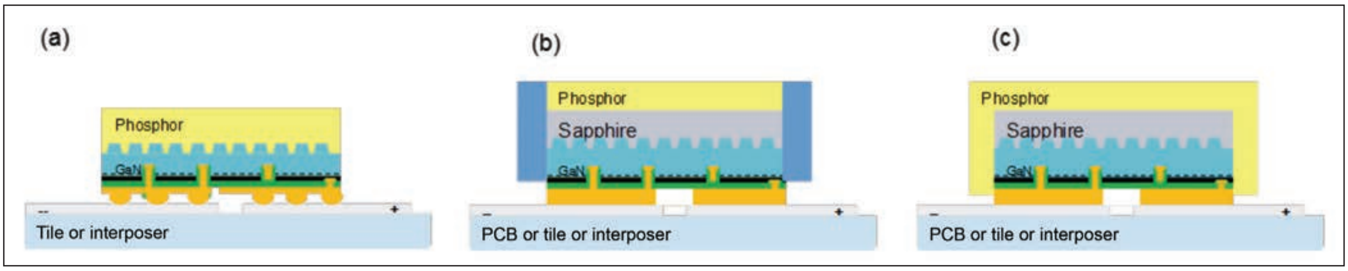

Figure 3. A comparison of thin-film (TF) and flip-chip (FC) designs: (a) thin film, (b) flip-chip based single-side low étendue emitter, (c) flip-chip based five-side emitter. Note that the drawings are not to scale: the epitaxial growth is typically 5-10 μm, the phosphor layer typically ranges from 40 μm to 100 um, and the sapphire thickness is 100-200 μm.

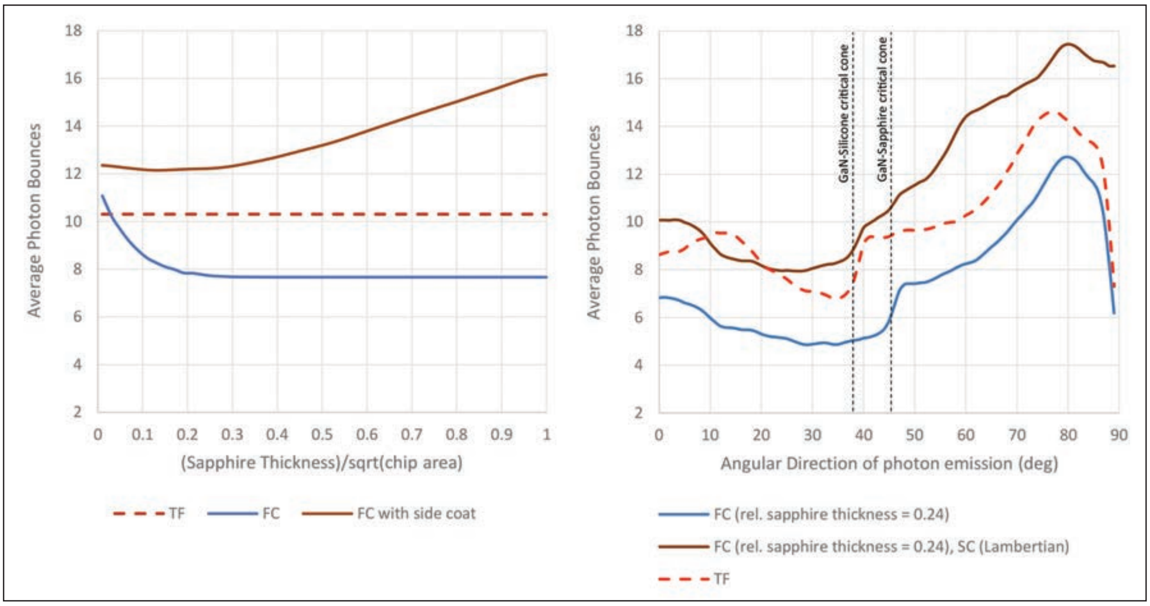

Figure 4. Simulated average photon bounces of various chip designs as a function of relative sapphire thickness (left plot) and angular direction of photon emission (right plot), in the case of a relative sapphire thickness of 0.2. Normal incidence is described as 'Angle 0deg'. Side coat is assumed to reflect light according to a Lambertian function. Photon bounces are computed using the number of average round trips for a pump photon before it can escape with a probability in excess of 99 percent. The model computes the out-coupling of monochromatic light of a bare die in silicone ($n=1.55$, typical phosphor matrix). All designs, including the thin-film, feature the same surface-scattering characteristics, corresponding to typical patterned sapphire structures. Light emission from the active region in the left plot considers the dipolar angular radiation nature of the band transitions and the wave interference with a near metal reflector.

combatting droop with high material quality that ensures a low Shockley-Read-Hall recombination (see Figure 2 for details)

Another option for negating droop is to increase the radiative recombination rate via greater overlap of electron and hole wave functions. Today's LEDs are produced on the c-plane and plagued by internal electric fields, which pull apart the electrons and holes and impair radiative recombination. Improvements are promised by switching to semi- and non-polar substrates that would reduce or eliminate polarization-induced electric fields within the active region. Benefits are not limited to a higher radiative recombination, but extend to a reduction in Auger recombination rates at higher drive current, thanks to the intrinsically lower quantum well carrier density that stems from the shorter radiative lifetimes. What's more, as the carrier overlap constraints on the quantum well thickness are far weaker in semi- and non-polar devices than in their conventional cousins, wells can be thicker, driving Auger recombination even lower.

Fulfilling all this promise is not easy. Today, semi- and non-polar devices are held back by their short non-radiative recombination lifetimes, and substrates are very pricey, with no commercial volumes. In addition, although progress is being made on these alternative crystal orientations, they are chasing a moving target, as performance of *c*-plane, high-current devices continues to improve, thanks to refinements in carrier spreading and material quality.

Enhancing extraction

One route to optimizing the light extraction in modern, high-power LEDs involves reducing the number of pump photon bounces – that is, the number of round trips that a pump photon typically undergoes inside the die cavity before it escapes – and cutting the pump absorption within the die cavity.

These two key characteristics – the number of pump photon bounces and the pump absorption – can be markedly different in two common architectures: the flip-chip and the thin-film (see Figure 3 for diagrams of the device architectures). Thin-film designs provide a smaller source size, and they are preferred in highly directional applications, whereas flip-chip designs allow direct attach onto boards, without the use of an interposer. Common to both are high current densities and a low thermal resistance, which enables high density arrays.

In addition to these two designs, there is a third, which is a variant of the flip chip: it redirects photons through the top side of the die by blocking the sides of the sapphire substrate (see Figure 3 (b)). Merits of this design include: a smaller source size and tighter angular radiation pattern, leading to a smaller étendue; a more efficient coupling efficiency; and greater flexibility in design.

Judged in terms of photon bounces, both of the flip chip designs, which have a strong dependence on sapphire thickness, outperform the thin-film architecture (see Figure 4). With the flip-chip geometry, the sapphire needs to be thick enough to prevent a high number of photon bounces – for example, at least 100 μm for a 1 mm^2 chip.

There are two characteristics of flip-chip architectures that lead to a significant reduction in the number of bounces, thereby facilitating extraction. The first is the reduced index contrast at the escape GaN surface relative to the thin-film, due to the high refractive index of sapphire. And the second is that once light has transitioned into the sapphire cavity, it can propagate out through the side-walls, thus reducing back scattering into the GaN area. For a typical sapphire thicknesses, side-wall radiation may account for 30 percent to 40 percent of the extracted power (see Figure 5).

One downside of this geometry is that the potential flux gain goes hand-in-hand with a hike in the étendue, which increases proportionally with the effective emitting area. Coating the sides of the flip-chip die with highly reflective scattering material, such as a TiO_2-loaded silicone, can minimise the étendue by ensuring single top-surface emission that maximizes luminance levels. However, the price to pay is inferior light extraction, particularly at high sapphire thickness levels when using highly scattering coating materials.

In general, the number of photons bounces depends on the angular direction of photon emission from the active region, and is highest for angles near grazing incidence. But the relationship between angle and photon bounces is not simple, with valley curves appearing between 15° and 40°. This feature is seen in all three designs of the LED, and is associated with the complex transmission characteristics of the patterned sapphire surface interface. As will be shown later (see Figure 9), such transmission does not necessarily peak at normal incidence, and may do so at a significantly different value. Note that for higher photon emission angles, the average number of photon bounces takes a sudden step-up, coinciding with the critical angles of either the GaN-sapphire or the GaN-silicone interface. Side-coating of the chip has a significant impact on the number of photon bounces.

For a flip-chip die without a side-coat, the bounce number increases rapidly at higher angles around the GaN-sapphire critical angle as opposed to that for GaN-silicone. This is consistent with our understanding, as any total internal reflection at the sapphire-silicone top surface will have a second

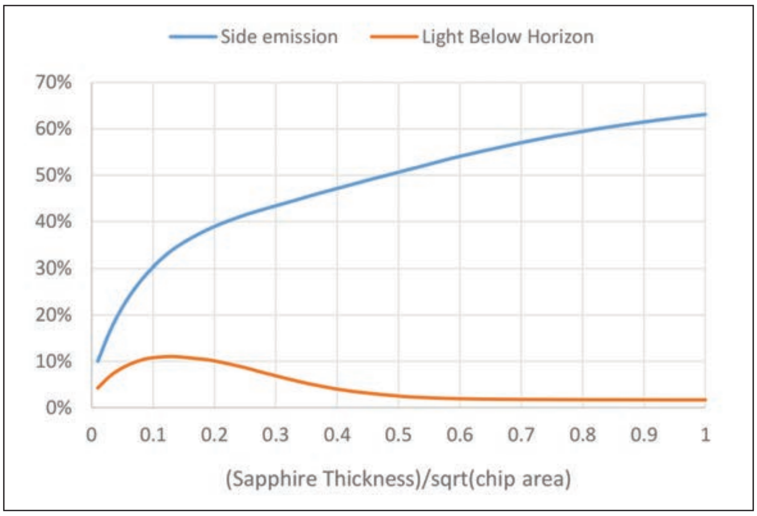

Figure 5. Simulated sapphire thickness dependence of side emission and light below the horizon relative to total output pump power in a flip-chip design. Simulations assume 10 percent mirror absorption without additional chip losses. Model computes the out-coupling of monochromatic light of a bare die in silicone (n=1.55). Light emission from the active region considers the dipolar angular radiation nature of the band transitions and the wave interference with a near metal reflector. All designs, including the thin-film, feature the same surface scattering characteristics, corresponding to typical patterned sapphire structures.

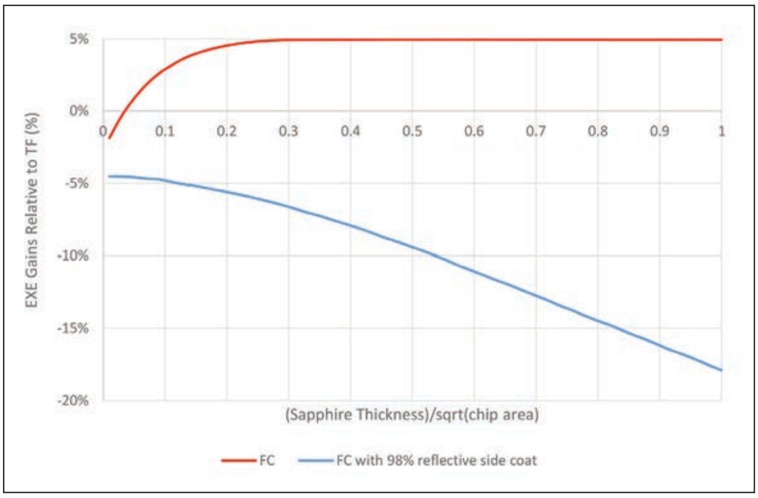

Figure 6. Simulated external extraction efficiency gains for flip-chip designs relative to that of the thin-film architectures. It is assumed that there is the same chip absorption, surface scattering and active region emission characteristics. See captions from Figure 4 and 5 for further details.

Architecture	Pros	Cons
TF (e.g. TFFC, VTF)	Low étendue	Requires sub-mount
FC	Reduced photon bounces	Light below horizon
FC with side-coat	Low étendue	High photon bounces

Table 1. Summary of potential pros and cons of thin-film (TF) and flip-chip (FC) architectures regarding light out-coupling characteristics.

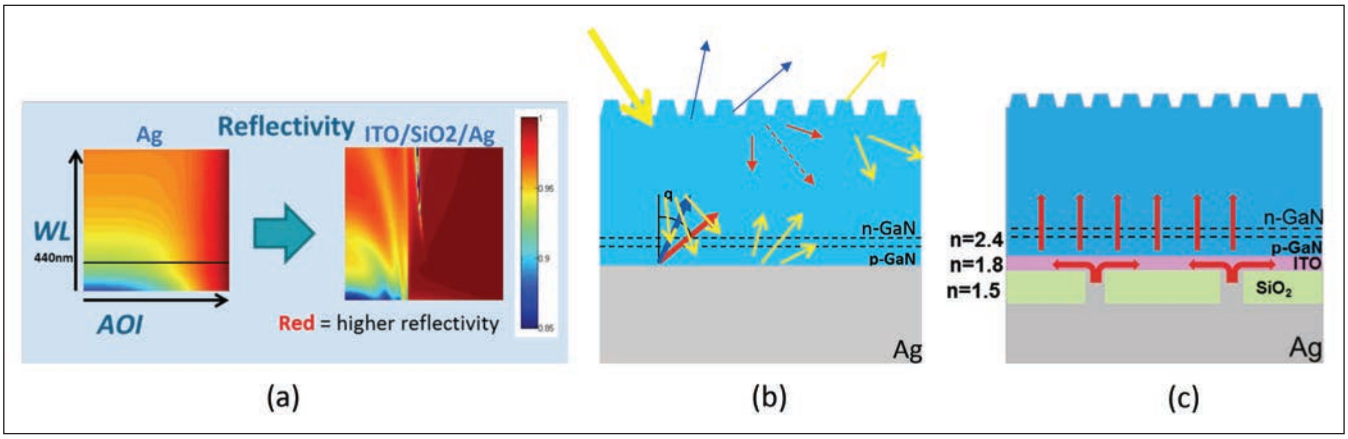

Figure 7. (a) Simulated reflectivity as a function of wavelength and angle of incidence for a GaN/Ag contact compared to a GaN/ITO/SiO_2/Ag contact. The reflectivity plots clearly indicate the advantages of the composite contact, especially at higher angles of incidence; (b) representation of photon scattering inside the die; (c) representation of current injection and spreading in a composite contact.

chance to escape from the sapphire side-walls. Side-coating the flip-chip die is a game changer, leading to a hike in back-scattering into the GaN, with the consequent increase of bounces shifting to lower angles near the GaN-silicone critical angle.

The extraction efficiency from the different types of designs can be explained within this framework (see Figure 6, which plots the gain in extraction efficiency for the flip chip design, compared with that for the thin-film architecture). For the flip-chip, extraction improves rapidly with sapphire thickness up to a relative a thickness level of around 0.25, and then it reaches a plateau. Side-coating is detrimental, failing to deliver any increase in extraction efficiency, even if the coating is considered lossless. When poorly reflecting coatings are used in conjunction with high sapphire thicknesses, extraction efficiencies may plummet.

For outright efficiency, the five-side emitting flip-chip excels, because the sapphire cavity can reduce the interaction of the backscattered light with the lossy areas of the chip. However, the net reflectance gain over the thin-film designs may only be significant for relatively high sapphire thicknesses. Typically, it must be well above 0.1, in consistency with the dependency on the number of bounces.

Our approach to improving light extraction focuses on reducing pump absorption. For the flip-chip, attenuation of the recirculating pumped radiation as it propagates inside the die cavity is typically 7 percent per round trip. This leads to an extraction efficiency of around 85 percent when there are, on average, eight photon bounces.

The greatest contributor to this absorption is the GaN-

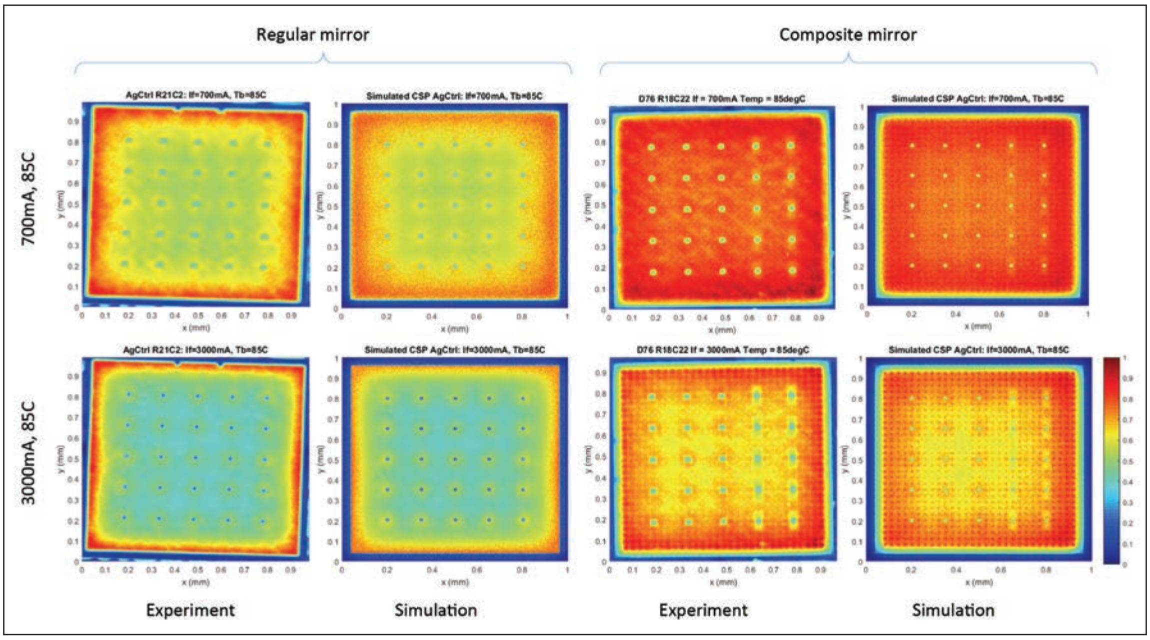

Figure 8. Normalized simulated and experimental near-field surface brightness images of regular and composite mirror schemes at 700 mA and 3000 mA drive operation. The optical model offers accurate predictions, which enable a thorough study, design and optimization of the composite mirror.

Ag interface. One way to address this weakness is to switch to a composite structure, formed by interposing a sufficiently thick, low-index oxide layer between the metal and the semiconductor (see Figure 7). Selecting SiO_2 prevents light incident within a critical cone angle of approximately 40° from interacting with the metallization. The reflector loss contribution can then fall from 50 percent to just 20 percent, according to our simulations.

Superior current spreading also results from the composite structure, as it is possible to ensure that injection into the active region predominantly takes place away from the *n*-GaN vias (see Figure 8). This is especially beneficial under high drive conditions.

The three-layer mirror is not without fault: weaknesses include additional absorption in the ITO layer, a reduction in enhancement of the internal quantum efficiency associated with the Purcell effect, and a more pronounced angular side emission from the active region. It is challenging to uncover the sweet spot with all these factors at play, and to help in this endeavour we use our proprietary advanced multi-physics models and design tools. An example of our efforts with this high accuracy approach is shown in Figure 8.

Another measure taken to increase light out-coupling via a reduction in the number of photon bounces is to optimize the scattering features associated with patterned sapphire substrates. If plain sapphire were used, this would be detrimental on two fronts. Firstly, there would be a lowering of the optical transmittance at the exit surface in the angular range of maximum incident radiation, which is closer to grazing than normal incidence. And secondly, there would be a reduction in the cancelation of guided modes, due to light becoming specular-reflected rather than diffracted.

Using wave optics, we have simulated the external extraction efficiency from a typical patterned sapphire texture design. These calculations, which uncover the impact of diffraction optics, reveal that sub-micron features only produce modest enhancements in light out-coupling. What's needed are micron-size features that can optimize scattering and transmission characteristics at the surface interface (see Figure 9).

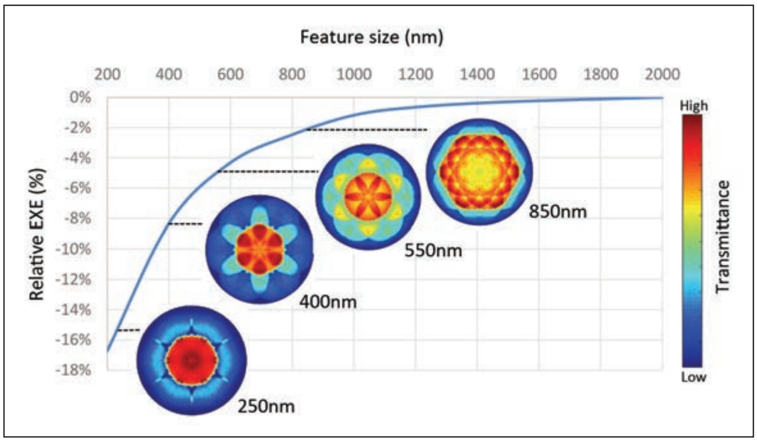

Figure 9. Influence of the patterned sapphire feature size on external extraction efficiency in a flip-chip architecture. Inset represents simulated transmission characteristics of various size periodic gratings at the semiconductor interface as a function of the angle of incidence (polar and azimuth in k-space coordinates). Transmission increases at higher polar angles (i.e. wider exit cone) as feature size increases, thus improving extraction.

Diminishing phosphor droop

Mirroring the reduction in internal quantum efficiency of the InGaN active regions, the quantum efficiency of the luminescence in phosphors decreases non-linearly with excitation density. However, the extent of photo-quenching varies between phosphors, being strongly pronounced in Eu^{2+} doped nitride red phosphors, and far weaker in the yellow-emitting Ce-doped aluminium garnets. The level of quenching also depends on temperature. For the Eu^{2+} doped nitride red phosphors, the efficiency decrease has a quadratic dependence on the concentration of excited europium activators. For warm-white, high-power LEDs requiring a red-emitting phosphor to produce the necessary colour temperature, photo-thermal quenching can account for a quarter of the total drop in efficiency with increasing drive current. This is a major impediment to the brightness of white LEDs.

A true fix for photo-thermal quenching can only come from innovation at phosphor material level. But while we wait, practical approaches can be taken to mitigate this effect, such as optimizing the converter and introducing different architecture. The key is to minimize the concentration of excited activators in the phosphor, while meeting the requirements for LED performance.

One option is to lower the activator concentration at the material level. Take this route and a larger volume of material is needed to convert a desired fraction of pump light. In high brightness applications, where lateral source dimensions are kept to a minimum, the upshot is the need for thicker converting layers above the LED pump chip. This is bad news if the phosphors are embedded in silicones, because thicker converting layers lead to greater scattering of photons back into the chip, as well as higher phosphor operating temperatures. Fortunately, switching to ceramic phosphors can trim scattering while increasing thermal conductivity. It may also be possible to increase the converting volume laterally, if the source étendue can be relaxed for a given application.

Examples of practical approaches to reduce photo-thermal quenching include: mid-power LED architectures, where a small die is immersed in a large volume of phosphor slurry; and remote phosphors,

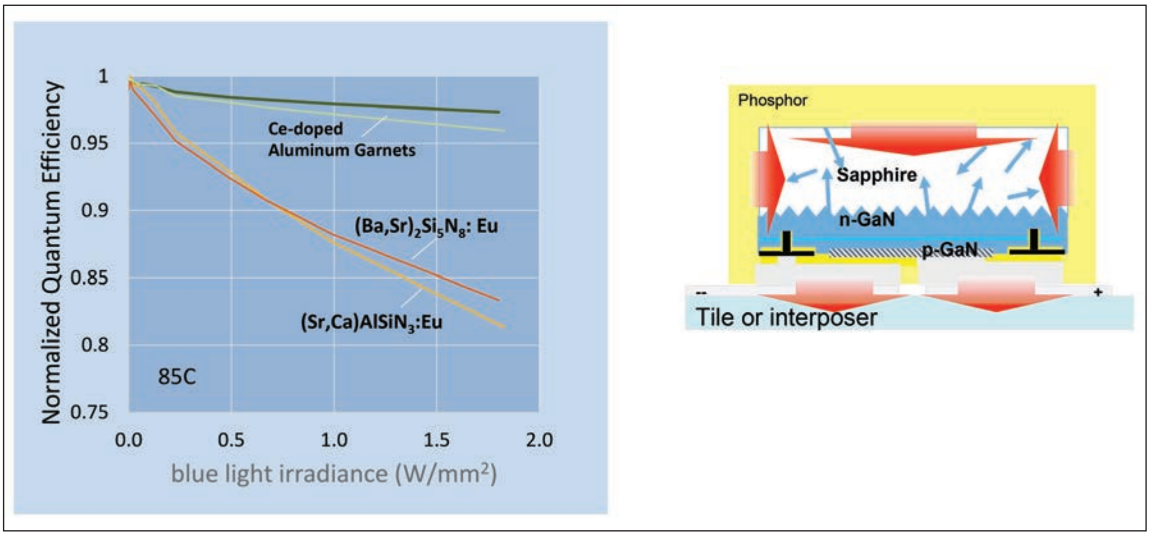

Figure 10. Photo-quenching of different phosphor systems as a function of blue flux. The adjoining illustration highlights the interaction of phosphor with the die in flip-chip architectures. Note that a larger phosphor area and efficient heat sinking can greatly reduce the impact of photothermal quenching.

where a large area of phosphor is illuminated by pump LEDs. In both cases, the emitting area of the optical source increases, hampering its capability to address high-luminance applications.

A workable compromise is found in a form of flip-chip that has a sapphire substrate coated with phosphor on multiple sides. By taking this tack, phosphor heatsinking extends over a larger area, lowering the excitation density and slashing the photo-quenching (see Figure 10).

What next?

Efforts at improving the performance of the LED will continue to focus on increasing the internal quantum efficiency of epitaxy structures, boosting the extraction efficiency and photo-conversion efficiency of the die and package, and refining the emission spectra of the phosphors. For high-brightness, low étendue architectures, additional challenges may come from photothermal quenching of phosphors and a significant reduction in package efficiency. Some of the advances in LED performance will be driven by improvements in basic technology, while others will stem from superior practical design choices for specific applications.

A promising technology for increasing the internal quantum efficiency in high-luminance LEDs – beyond improving the carrier distribution within the quantum wells – is to introduce tunnel junctions. This opens the door to the vertical stacking of LED active regions on top of each other in a single device. Tunnel junction LEDs are capable of producing the desired luminance at a lower current density than their single junction incumbents, thereby allowing each quantum well in the stack to operate at a higher internal quantum efficiency.

Another refinement to the LED might be the introduction of narrow band phosphors, which could be quantum dots. They would enhance the emission efficiency, while improving colour gamut and colour saturation. What's more, these new phosphors could cut the difference in efficiency between domed and un-domed devices. That's important, because efficient un-domed devices hold the key to reduced emitter size, high luminance, closely packed dense array applications of the future.

The architecture of the LED is another avenue that could be explored for improving device performance. Today's thin-film devices are desired for their smaller étendue, while flip-chip structures excel in extraction efficiency and attach flexibility. System architects will always have to weigh up the pros and cons of every design, before picking between them by considering the most crucial metric for a particular product.

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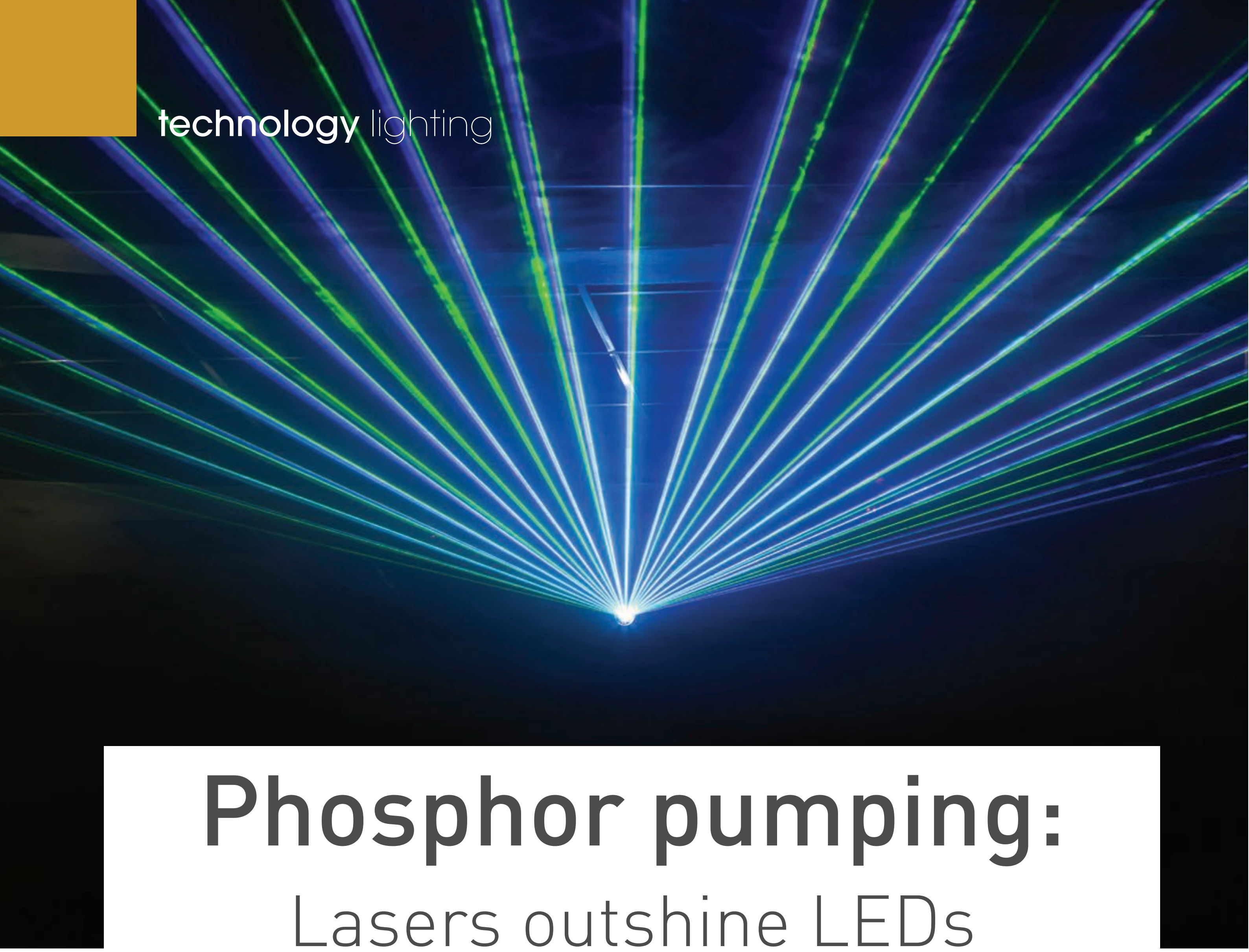

Phosphor pumping: Lasers outshine LEDs

For phosphor-pumped white-light sources, switching from LEDs to lasers increases efficiency, lengthens lifetime and yields highly collimated beams

BY FAIZ RAHMAN FROM OHIO UNIVERSITY

THE WHITE-EMITTING LED is a flawed gem. Its many strengths, including its robustness, high efficiency, long lifetime and ability to hit full brightness in an instant, have enabled it to wrestle market share from incandescents and fluorescents. But cranking up the current through this chip compromises efficiency, due to a mysterious malady known as droop; and as the die gets hotter, efficiency plummets even further.

One solution to both these impediments is to use a laser, rather than a short-wavelength-emitting LED, to pump the phosphor and generate white light via colour mixing. Attributes of the laser-based approach include immunity from droop and reduced thermal heating – increases in temperature are far lower than those of LEDs. Laser pumping is also practical, as devices emitting in the near UV are easily available, and can effectively serve in this role.

The evolution from LED-pumping to laser-pumping will not take place overnight. Instead, LED-based luminaires are destined to remain the principal means of generating white light for the foreseeable future. However, laser-diode-based solid-state lighting systems are already gaining ground in high brightness lighting applications, and are now commercially available from several manufacturers.

A driving force behind the development of laser-diode-pumped luminaires has been the promise of avoiding the LED efficiency droop. That's not the only benefit, however. With the exception Soraa and possibly a few others, the chips used by the makers of LED sources do not contain wavelengths shorter than about 450 nm. So, when these low-cost LEDs with a peak wavelength of 450-460 nm are adopted for phosphor pumping, the sources that result are deficient in the violet part of the spectrum.

This limitation can be avoided with white lamps that employ 405 nm violet-emitting laser diodes. These devices are cheap, highly efficient, and already mass-produced for the optical data storage market. Armed with short wavelength phosphor pumping, the spectral output is richer, the spectral coverage greater, and the colour-rendering index higher than it is with a typical LED-pumped white-light source (see Figure 1 for a chromaticity diagram, which contains a chromaticity point for a laser diode-pumped white light lamp).

In many cases, even more important than the quality of the white light is the quantity. And judged in this manner, the laser diode-pumped source literally shines. Intense light from the laser produces very strong phosphor pumping and equally intense light emission. This allows the pairing of laser diodes and appropriate phosphors to form ideal high-intensity light sources that are suitable for architectural lighting, searchlights and automobile headlights. Another attribute of laser-based sources is their directional nature, as they emit a concentrated low-divergence light beam.

The merits of the laser-pumped light source have not escaped the notice of automobile manufacturers – several of them are actively working on laser-powered headlamps for their high-end models. Just as it was with the penetration of LED lighting in the automobile sector, it is premium-quality vehicles that are leading the way, including some models by BMW (see Figure 2).

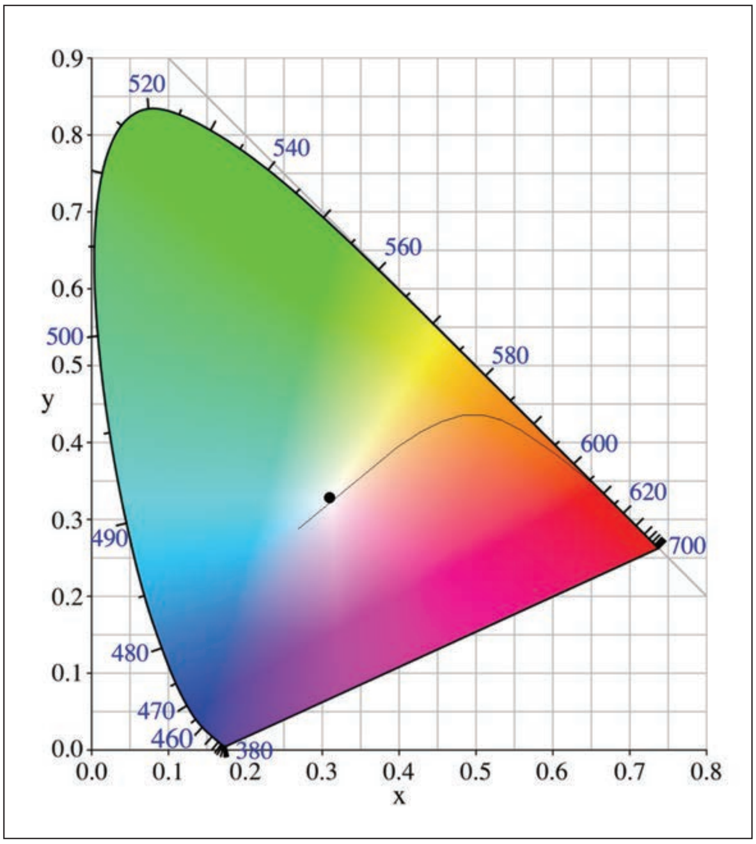

Figure 1. The chromaticity point of light from a laser diode-pumped, white-light lamp is almost neutral (x = 0.3305, y = 0.3309), attesting to the spectral richness of the light source. The black line inside the diagram is the Planckian locus.

Laser-pumping architectures

A different arrangement is required when a laser diode, rather than an LED, is used to pump the phosphor. It is no longer possible to simply deposit a phosphor on top of the pump device, due to the directional nature of laser radiation and its high intensity. Instead, more involved optical arrangements are needed, such as the combination of phosphor plates and reflectors, or the use of a phosphor-coated integrating sphere (see Figure 3).

For both these approaches, more than one diode may be used for pumping, so long as a suitable technique is employed for combining the multiple laser beams. This means that there is no upper limit on the optical power available from a laser-pumped light module. An additional advantage of any remote pumping architecture is that the phosphor does not sit on a hot component. This prevents the phosphor from heating up substantially during operation, greatly prolonging its life.

A relatively simple approach for laser pumping is to

All of the strengths of white-light sources produced by laser pumping must be weighed against their limitations. Just like lamps based on LEDs, the emission contains two distinct components: down-converted light from the phosphor, and the residual un-converted laser light

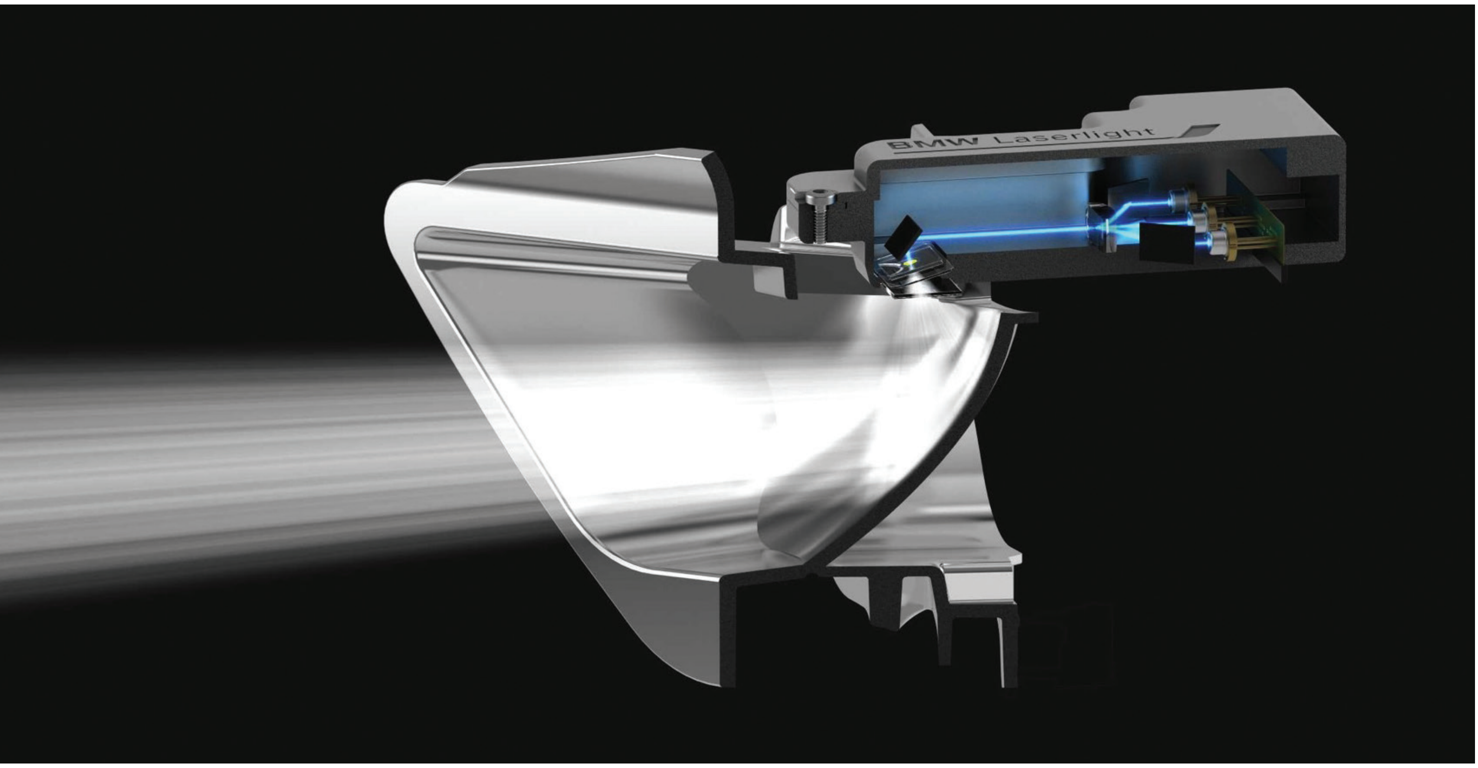

Figure 2.
A BMW laser-based headlamp features individual laser diodes, a beam combiner, phosphor target and reflector assembly.

direct the laser at a phosphor plate and collimate the resultant radiation with a reflector (see Figure 3 (a)). However, it is more efficient, in terms of optical power conversion, to use a phosphor-coated integrating sphere (see Figure 3 (b)).

Other arrangements may be adopted, depending on whether a low-power or high-power light source is required. For example, small luminaires can use a beam expansion lens to pump the entirety of the phosphor plate. Such an approach is illustrated in Figure 4: it depicts a ray trace simulation for a single pass-through lamp.

All of the strengths of white-light sources produced by laser pumping must be weighed against their limitations. Just like lamps based on LEDs, the emission contains two distinct components: down-converted light from the phosphor, and the residual un-converted laser light. However, with a laser, the big difference is intrinsic coherence, which results in speckle – a visible pattern of light and dark spots that appear on any illuminated surface.

The downsides of speckle should not be overestimated. As well as being a distraction, it has a negative effect on visual perception, hampering

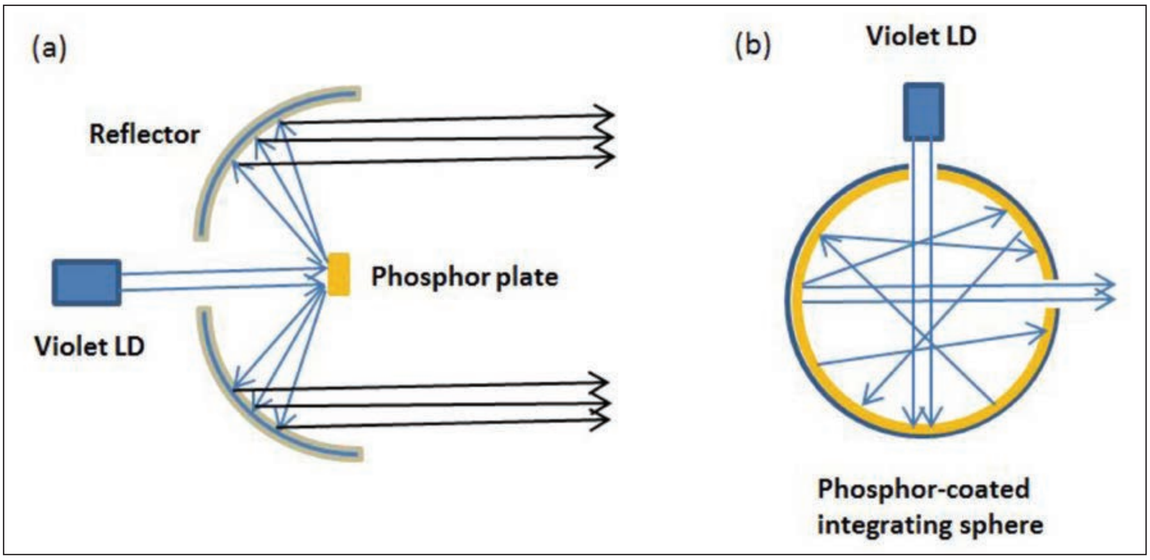

Figure 3.
Typical optical setups for laser diode pumping of wavelength down-conversion phosphors.

the detection of fine spatial detail in illuminated objects. Tests have shown that speckle decreases visual acuity by up to 40 percent, and reduces the ability to perceive high and low spatial frequencies. These issues are part of the reason why direct laser illumination has never caught on.

Note that with laser projectors, the coherence of the laser light is reduced by elaborate means – this tames speckle to acceptable levels. But it reaches even lower levels with laser-illuminated phosphors. In this case, the speckle is so small that it can be completely neglected. That's primarily because good lamp design ensures that the majority of the laser light is converted to longer wavelengths that do not show speckle. However, an additional boon is that the residual laser light shows very little speckle, thanks to a reduction in its coherence when it undergoes multiple scattering as it passes through the phosphor layer. The upshot of the phosphor-pumped laser system is intense, colour-rich, speckle-free light that is superior to that produced by an LED luminaire.

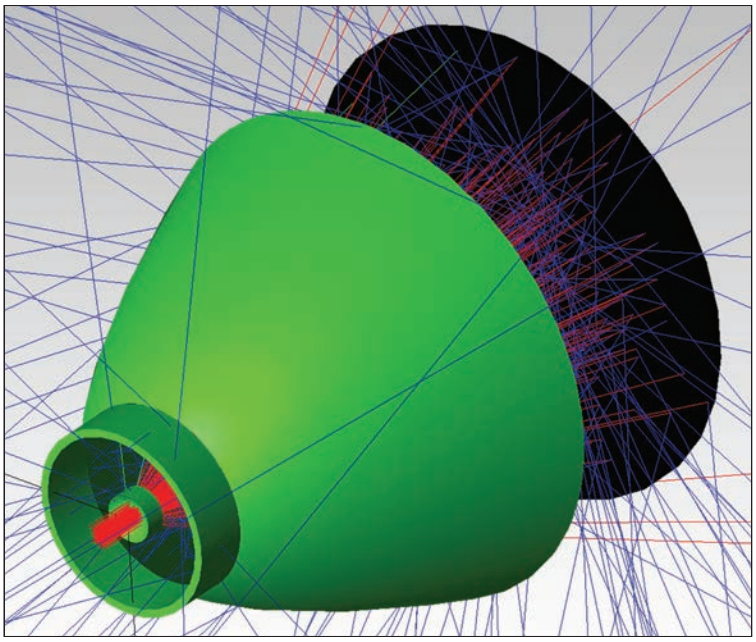

Figure 4. An efficient pumping arrangement for a small laser-pumped lamp. Pump light (red beam) enters from the left, passes through a concave beam expansion lens, expands to the diameter of the phosphor-coated glass plate on the right and is incident on the silicone-bound phosphor layer. The down-converted light is shown as a collection of blue rays. The phosphor plate, deliberately shown as opaque, is detached from the green reflector. This allows the trajectory of light rays inside the reflector envelope to be seen. In an actual lamp the phosphor plate, a piece of transparent glass that allows light to escape outwards, is sealed to the reflector rim. Very few rays are back-reflected towards the laser module to the left (not shown).

Pros and cons

The greatest downsides of the laser-pumped, white-light source are associated with the diode. First and foremost, this chip is much pricier than the LED. Despite the maturity that stems from its widespread adoption in data storage applications, for an equivalent level of light emission, the laser diode is far more expensive than the LED. Due to this high cost, laser-pumped phosphor systems are pricy, restricting their deployment to specialised, non-cost-sensitive lighting applications.

One strength of laser-pumped lighting systems is that they can span a wide range of output powers. Commercial laser diodes have power ratings that range from a few milliwatts to several watts, and even more powerful sources can be formed by combining the output of several lasers. However, this is detrimental to the longevity of the system. That's because diode lifetimes are inferior to those of LEDs, especially when they are operated at high drive currents. The shorter lifetimes can be traced back to the tiny, pre-existing crystal dislocations in the laser structures. These imperfections multiply greatly when the device is driven at high power levels. Running in this manner leads to the gradual formation of extensive dislocation networks, called dark line defects. They act as sites of non-radiative recombination, reducing the light output from the device. The diode's brightness diminishes over time, and the output of light source pumped by it falls, until it is so low that it is not of any use.

Encouragingly, as the maturity of the laser diode has increased, the severity of this problem has diminished – but it is yet to be eliminated. Helping to address this issue has been a shift to native GaN substrates for epitaxial growth, because this trims the number of interfacial threading dislocations and increases the lifetime of the laser diodes.

The other sticking point to adoption of laser-based white lighting, the high cost, may come down through economies of scale. This will open up new markets for violet and near-UV laser diodes; opportunities that were unforeseen only a few years ago. While LED lighting is undoubtedly in the ascendancy today, watch out for laser-based systems in the years that follow.

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A critical look at the SiC, high-voltage MOSFET

Merits of the high-voltage SiC MOSFET include low switching losses and a high operating temperature. But is this transistor sufficiently rugged and reliable for widespread deployment?

BY MUNAF RAHIMO FROM ABB SWITZERLAND LTD SEMICONDUCTORS

FOR DECADES, silicon devices have dominated the power electronics market. They have maintained pole position through tremendous advances in the starting material quality, in the techniques used for process fabrication, and in the architecture of the device.

However, silicon is not the perfect power electronics material: its inherent material properties are notably inferior to those of wide-bandgap materials. This has spurred the research and development of SiC devices, which deliver superior performance. Advantages include a wider range of voltage ratings, lower losses and higher operating temperatures.

These attributes are welcomed by designers of electrical systems, because they enable increased operating efficiencies and higher current densities, frequencies and temperatures. Savings that result from all these attributes are not only measured in terms of energy, but extend to the cost, weight and size of the unit, thanks to the opportunity to downsize the semiconductor content, the cooling system and the passive components/magnetics.

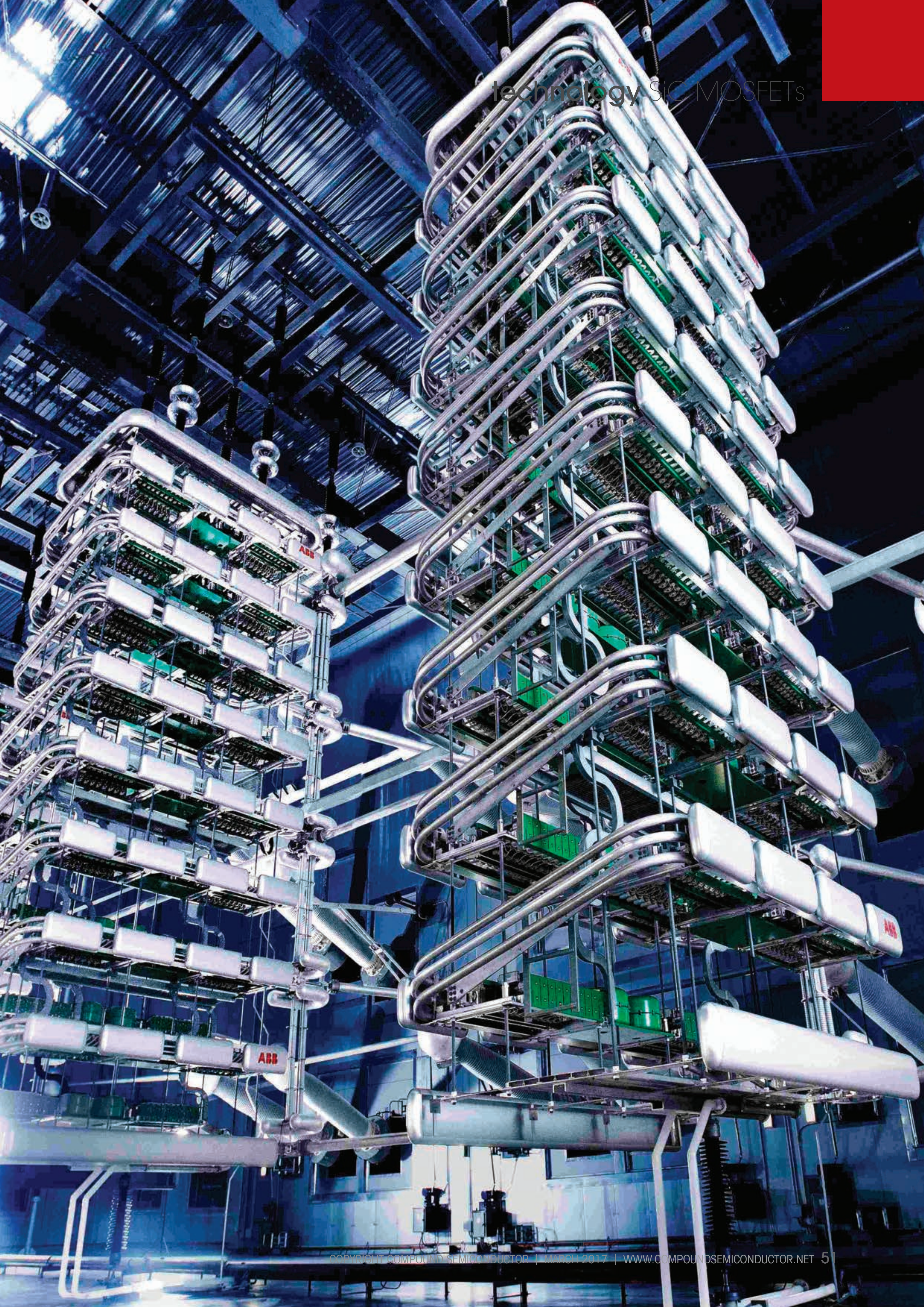
The first SiC device to hit the market was the SiC-based Schottky barrier diode (SBD). Launched in the early 2000s, it initially sported ratings below 1200 V. It can be purchased as a discrete component, or as part of a hybrid module, where it is paired with silicon IGBTs. Many low power inverters have been built with these devices, including those that serve the solar PV market.

More recently, the SiC power device portfolio has expanded through the launch of SiC MOSFETs with ratings below 1700 V (see Figure 1). These transistors are available as discretes, and also as full SiC MOSFET modules.

Many of the leading producers of SiC MOSFETs are now trying to increase the voltage rating of the devices to 3.3 kV and beyond (see Figure 2 for an example of the capability of these devices). This move has the potential to provide similar improvements to those in the lower power range. However, these MOSFETs will be targeting different applications with megawatt powers, such as: grid systems, both HVDC and FACTS; railway traction converters; medium-voltage industrial drives; and high-power renewable energy conversion and storage.

Megawatt requirements

The majority of the high-power applications in the megawatt range are based on a voltage source converter (VSC) topology, and operate at switching frequencies below 2 kHz. Today, at the heart of these systems are high-voltage silicon switches, such as IGBTs and IGCTs, and diodes with voltage ratings up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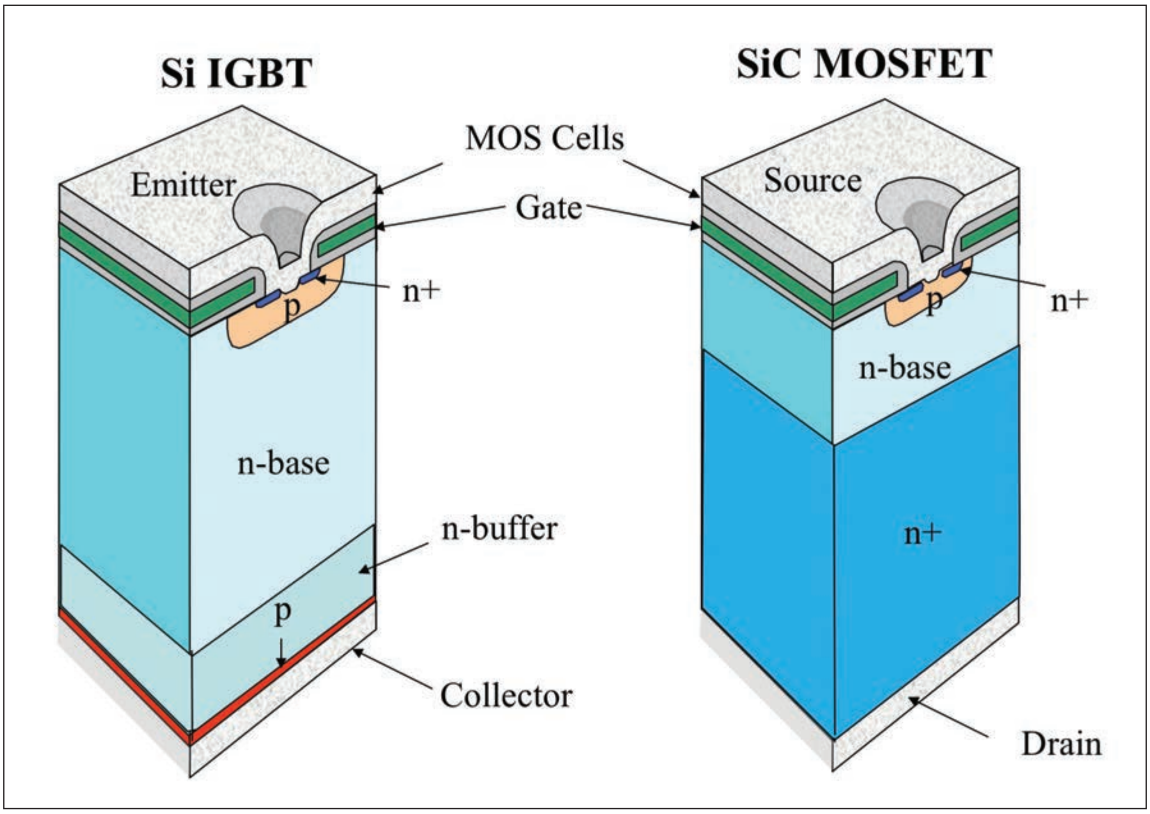

Figure 1. The silicon IGBT dominates the power switching market, but faces increasing competition from SiC MOSFETs.

to 6.5 kV (see Figure 3). The capability of all these devices continues to increase, with evolutionary steps on silicon device/package technologies providing continual improvements in system performance, reliability and cost.

Traditionally, depending on the requirements of the particular application and optimum performance-to-cost ratio, VSC-based applications adopt either a two-level (see Figure 4) or three-level topology (note that the level refers to the number of output voltages). With this technology, the route to higher voltages is the series connection of many devices. HVDC systems adopt this approach.

An important trend in recent years, which has been seen in many grid system and industrial drive applications, is to turn to multi-level topologies. This allows operation at much lower frequencies, such as below 300 Hz, and results in very low losses and far higher power levels.

One consequence of having a wide range of high-power applications is that it leads to differences in specifications, including those for power handling, efficiency and cost. Design engineers must carefully select from many available device and package solutions to satisfy the requirements of a particular application. However, there is some common ground, as all high-power applications share a design-in practice that is best described as a meticulous and relatively slow process. The focus is on the overall performance and reliability, rather than just considering basic power ratings and associated loss calculations.

At the global power technology giant ABB, we have extensive experience in evaluating the requirements for power electronics for mainstream, megawatt applications. In the remainder of this article we will detail the key characteristics for power electronics in general, before considering and evaluating the opportunities for the SiC MOSFET in the high power range.

The primary considerations for power electronics for megawatt applications may be divided into three categories: the power density handling capability; the capability for controllable, soft switching; and ruggedness, fault-handling and reliability. Devices that handle high powers should ideally exhibit low conduction and switching losses, a low thermal resistance, and the ability to operate at high temperatures while not compromising reliability.

When it comes to the second category, controllable and soft switching, there needs to be a soft-controllable turn-off that is accomplished with low overshoot voltages and minimal EMI levels, and a control of the turn-on that addresses transients while minimizing losses. The third category – ruggedness, fault-handling and reliability – involves considerations of the safe operating area associated with the turn-off current, fault-handling issues that include the short-circuit capability of IGBTs and surge current limitations of diodes, and reliability requirements associated with: current and voltage sharing, for devices arranged in parallel and series; stable conduction; and stable blocking performance.

While considering all of these issues, design engineers must also evaluate the attributes of the package. There is a shift towards more compact packages, which combine a higher packaging density with low parasitic elements and the opportunity to optimize the electrical layout. Additional trends are the development of more powerful packages, judged in terms of current, voltage and temperature handling capabilities, and reliability to temperature and power cycling.

If a power semiconductor is to be designed into a high-power application, it must fulfil every one of the requirements detailed above. Given this condition, it is our view that SiC MOSFETs must overcome a number of challenges, which depend on the specific application, before they offer strong competition to the well-established, and still improving, silicon devices.

SiC MOSFETs: Pros and cons

While there is still work to do, there is no question that unipolar SiC devices, and in particular the SiC MOSFET and SBD, are the most promising options for voltage ratings of up to 10 kV. Measurements on devices show that for voltages of up to 10 kV, drastic reductions in switching losses are realized in conjunction with low conduction losses, even at high temperatures. From a practical perspective, this is encouraging, because the voltage-controlled gate drive needed for the SiC MOSFET is similar to that for the widely adopted IGBT.

Lagging behind, in terms of performance, are high-voltage SiC bipolar devices, such as *p-i-n* diodes, IGBTs and thyristors. They are all impaired by high on-state losses, which stem from the built-in voltage that is inherent in the *p-n* junction: it exceeds 2 V. Making matters worse, SiC bipolar devices are plagued by forward-voltage degradation, which can be traced to crystal staking faults that materialise during device conduction.

Given this state of affairs, it is clear that there is a compelling case to focus on just SiC MOSFETs and SBDs. Here, there is increasing interest in running the SiC MOSFET in diode-mode operation. That's because of the ease in implementing a gate drive for the MOSFET conduction during freewheeling mode, the low reverse recovery losses, and the resulting lower costs associated with extra SiC diodes. We believe that for high-power applications, this approach offers a perfect opportunity. To understand why, consider our following analysis.

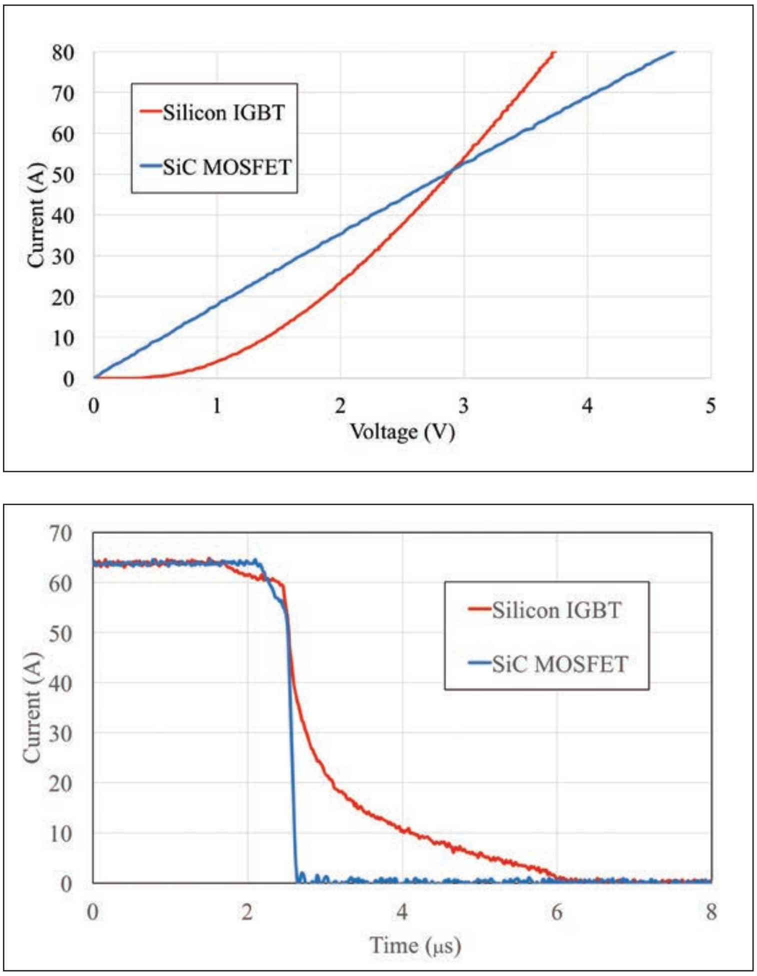

Figure 2.Rohm is one of the pioneers of the high-voltage SiC MOSFET. Its performance is compared to a IGBT produced by ABB.

Handling the power

As power devices improve, they trim the overall losses. This enables an increase in power density, and the opportunity to boost system efficiency. For both silicon IGBTs and SiC MOSFETs, realising this requires the optimisation of the channel density, resistance, MOS cell pitch and device thickness. The key difference between the two transistors is that: with the silicon IGBT, there is also the need to fine-tune the excess carrier enhancement in the base region; while with the unipolar SiC MOSFET, efforts must be directed at lowering the on-resistance via judicious selection of the doping and the thickness of the base region.

For higher voltage devices, the loss component is more prominent, strengthening the case for SiC. Assuming a similar conduction loss at typical nominal currents, compared to the silicon diode, the SiC MOSFET delivers a total reduction of more than 75 percent in switch-mode switching losses, while providing negligible diode recovery losses. The low

overall losses of the SiC MOSFET make it an attractive candidate for many mainstream applications that utilize different topologies operating below 2 kHz.

Another advantage of the SiC MOSFET over both the silicon IGBT and diode is the absence of a built-in voltage. This equips the SiC MOSFET with the potential to cut losses with each technological improvement – an accomplishment that is beyond the reach of silicon devices.

Armed with this attribute, the SiC MOSFET is an attractive option for modern multi-level topologies that require low conduction losses. Furthermore, the SiC MOSFET low conduction losses at low currents are actually very attractive in many applications, including FACTS/STATCOM and urban traction, where a large percentage of losses are dissipated in sub-load or idle conditions.

A well-known strength of wide bandgap materials is their superior thermal properties to silicon. However, this advantage has minimal impact, because the thermal resistance is largely dominated by the device area, packaging and cooling. Making more of a difference is the low leakage current at high temperatures, because this allows SiC devices to operate beyond 200°C.

One of the limitations of the SiC MOSFET is the packaging technologies employed, including the encapsulation materials and joining techniques. Reliability is held back, just as it is for packaged silicon devices. Consequently, the majority of system improvements that come from simplified cooling stem from the lower losses of SiC devices. Note, however, that there is also a weakness afflicting the SiC MOSFET at elevated temperatures, associated with its strong positive temperature coefficient. Due to this, conduction losses increase at higher temperatures, and have to be addressed by increasing the device area – an approach that adds to chip costs.

Superior switching

Unipolar devices are a concern with regard to their switching characteristics. This is blamed on oscillatory behaviour during switching transients, originating from the absence of excess carriers. Bipolar devices, in contrast, are known for softer characteristics. However, while there is truth in these views – and it is important to develop low inductive packages and circuits – the SiC MOSFET benefits from adjustments

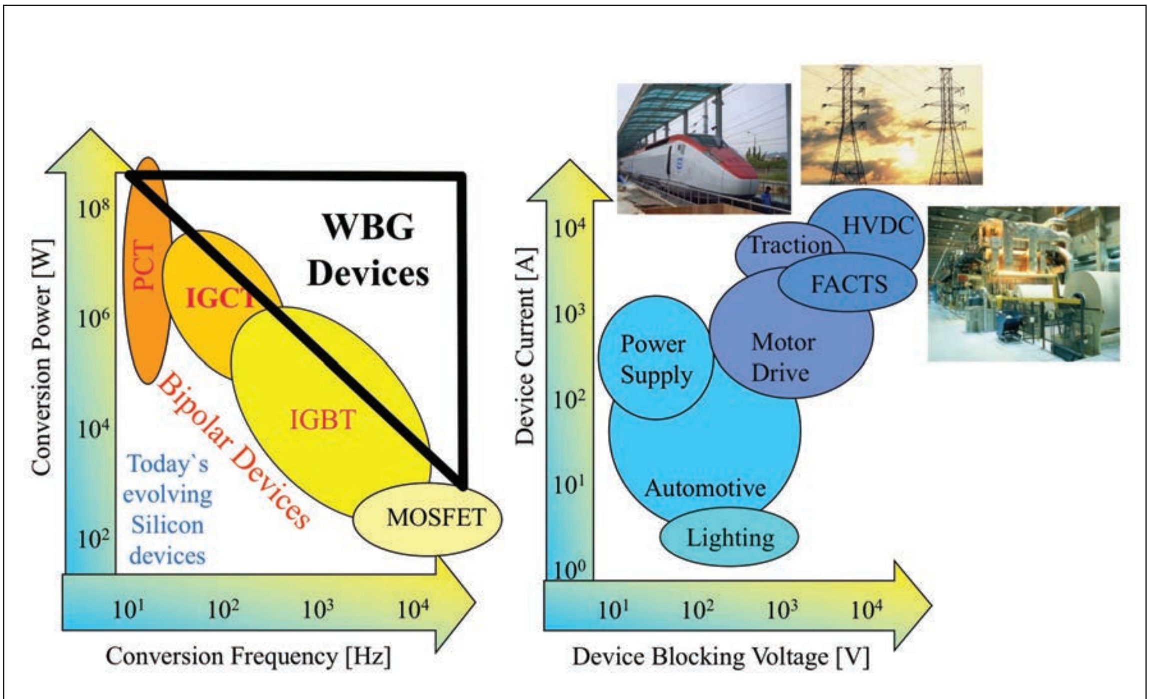

Figure 3. SiC devices are targeting various applications in the high-power semiconductor market that are currently served by a portfolio of silicon products.

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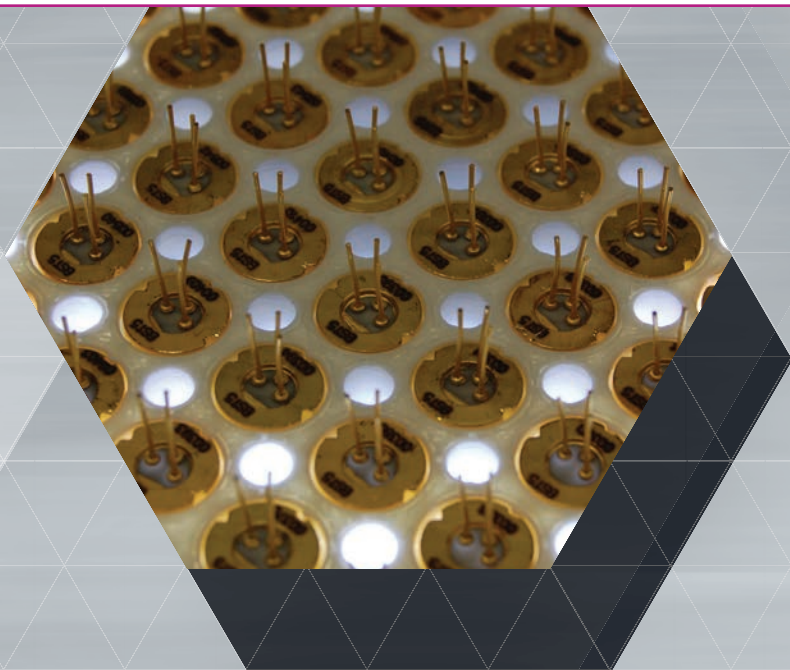
- 50 -100 mW CW output
- Single - TE00 mode
- 2100 nm, 2300 nm, 2450 nm
- >20 % WPE
- Ultra - low input power



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BEYOND-STATE-OF-THE-ART TECHNOLOGY FOR INFRARED APPLICATIONS in the gate drive set-up, with the greatest gains coming from optimisation of the turn-off gate resistor.

Although a higher gate value increases the energy consumed in the off-state, losses are still far lower than for those with an IGBT. So, system performance in high-power applications is enhanced significantly, due to the substantial reduction in losses.

Additional virtues of the SiC MOSFET are that it responds well during turn-on, and when doing so, it produces far lower energy losses than the silicon IGBT. These benefits come from the low reverse-recovery peak current, and the ability to ramp down the voltage very fast during switching.

Ruggedness, reliability and fault-handling

For high-power applications, ruggedness, reliability and fault-handling all play a major role during the design-in phase of power devices. For SiC MOSFETs, these requirements could be the stumbling block to their introduction in the high-voltage range.

One of the strengths of the SiC MOSFET is its substantial safe-operating-area during turn-off. Due to the unipolar nature of this device, it does not suffer from a dynamic avalanche limitation that impairs safe-operating area capability – note that this does hamper the silicon IGBT. What's more, the SiC MOSFET has a higher junction built-in voltage, so, compared to its silicon cousin, it has extra protection against parasitic *n-p-n* transistor failure modes during switching. Due to these characteristics, much higher currents are needed to forward bias the *n*-source, due to the higher built-in voltage of the wide bandgap material. In turn,

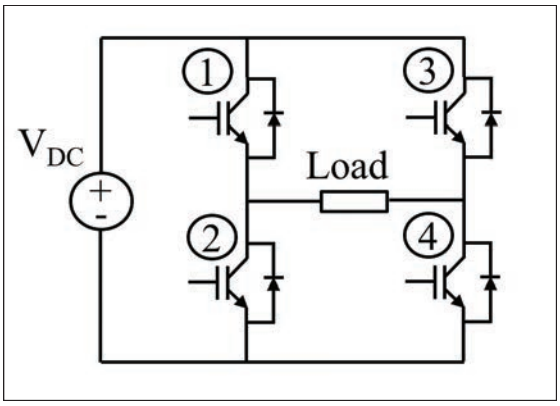


Figure 4. A typical voltage-source-converter H-Bridge with four IGBTs and diodes.

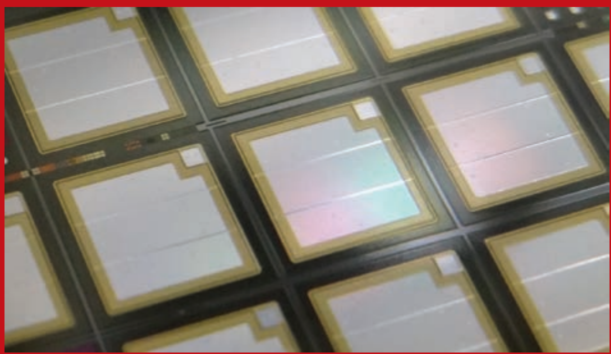
there is a potential improvement in safe-operating-area capability.

When it comes to fault handling, one of the key performance requirements for high-voltage applications, SiC MOSFETs are yet to reach the required levels, so there is a need to either improve device capabilities, or alternatively, employ new solutions at the system/gate drive level.

Encouragingly, low-voltage SiC MOSFETs have already some capability of withstanding short circuit conditions. But there is a need to employ new gate drive conditions to limit the pulse durations, because these devices have high short-circuit levels – and this leads to higher thermal stress, due to the high MOS cell densities that are used to ensure a low

SiC developments at ABB

Engineers and scientists at the corporate research centre of ABB, located in Switzerland, have been developing SiC devices and packages. In addition, the team has been prototyping advanced forms of packaging, with emphasis on realising an optimum switching performance. The primary focus of all this effort has been the development of next-generation components targeting the medium-to-high power segments. ABB has a strong market position, especially in grid systems, traction and industrial applications.



SiC device and package (LinPak) developments at ABB target high power applications.

on-resistance. The downside is that improvements to short-circuit capability will come at the expense of increases in conduction losses, which are considerable in high-voltage devices.

With respect to diode surge current capability, there is a need to accommodate a high current, which is up to ten times the nominal current for different pulse durations. When the SiC MOSFET is utilized in diode mode as discussed earlier, the integrated *p-i-n* diode is better suited to providing the required surge current capability than a separate unipolar diode, due to the lower conduction losses at such high currents.

Concerns over reliability must consider how the SiC MOSFET is deployed within the circuit. If it is used in a parallel configuration involving many chips in a high current module, the device's strong positive temperature coefficient and its low temperature dependency on the switching losses should ensure good current sharing. If it is used in series, there should also be no major issues, thanks to low leakage current levels and little dependency on increasing temperatures. The greatest challenges are to realise low levels of voltage changes with time, and minimal oscillations. This is accomplished by reducing the stray inductances and optimizing the gate drive parameters, as they can influence the voltage sharing of series-connected devices during switching events.

Another key characteristic of semiconductor devices is their stability over time. This is evaluated with standard qualification tests. SiC MOSFETs suffer from higher electric fields at the MOS cell, so to combat this, developers of these devices have optimized processes and material preparation techniques to ensure a low shift in the gate parameters, such as the threshold voltage. An additional concern is a shift in the on-state forward voltage. As the SiC MOSFET *p-i-n* diode will be functional during reverse recovery switching and in surge events, the device will be flooded with excess carriers (bipolar mode), which could produce stacking faults that lead to shifts in the forward voltage drop.

In addition, there are major concerns associated with the stability of the blocking behaviour of the SiC MOSFET. To ensure stability, there is a need to increase the protection of the device through superior junction termination/passivation designs, and the introduction of better packages, which provide extra protection against harsh environmental conditions, such as high humidity and temperature variations.

To increase cost competiveness with silicon, SiC manufacturers have capitalized on the wide bandgap properties and shrunk the junction termination region, so that they can maximize the usable active area. The downside is that the electric fields outside the semiconductor bulk material, such as those in the passivation layers and package filling materials, are higher than those in silicon. What's needed are optimum chip designs and packaging materials for SiC device protection.

A further consideration is to prevent failures that are induced by cosmic rays. This is possible through optimisation of the thickness and doping levels of the base region. Getting this just right is essential, as it will impact the conduction losses associated with the on-resistance.

In short, while there is no doubt that the high-voltage SiC MOSFET has tremendous promise to deliver substantial efficiency savings, alongside reductions in the weight, size and cost of power systems, today doubts remain over the reliability, ruggedness and fault-handling capability of these wide bandgap transistors.

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Asymmetry accelerates InP-based HEMT

Transistors with a drain-side recess enhance terahertz performance

Thanks to an asymmetric gate recess, researchers at Fujitsu have produced a HEMT capable of record-breaking frequencies for its relatively long gate length.

The team's InAlAs/InGaAs HEMT, which has a 75 nm gate length and an extended drain-side recess, has a maximum oscillation frequency of 1.3 THz.

This high-speed HEMT is an attractive candidate for various millimetre and terahertz applications – including radio communication systems, imagers and radio astronomy – because it combines low-noise characteristics with an impressive performance at high frequencies.

Spokesman for the Fujitsu team, Tsuyoshi Takahashi, says that they are developing these devices for downloading data at gigabit rates over short distances. This will involve transmission at 300 GHz.

Takahashi and co-workers used gate lengths of 75 nm to investigate the impact of asymmetric HEMTs because device reproducibility is far higher than it would be with gate lengths of 50 nm or less.

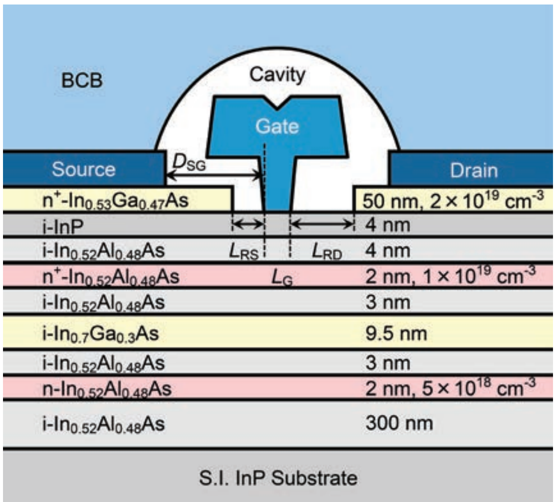
"A long gate length is very effective in preventing the top gate from peeling off, resulting in a high yield in gate electrode fabrication," explains Takahashi.

He points out that the benefits of an asymmetric recess are already well-known in GaAs-based power FETs and HEMTs, where this architecture leads to enhanced power output characteristics. The breakdown voltage increases, due to asymmetry, and there is also an improvement in RF characteristics, thanks to a trimming of the gate-to-drain capacitance.

Another feature of the Fujitsu device is its double-side-doping above and below the channel layer. This reduces the internal built-in field in the channel region, leading to a reduction in the drain output capacitance and a hike in the maximum oscillation frequency.

The team produced their devices, which incorporate a 4 nm-thick, intrinsically doped InP etch stop layer and an *n*-type InGaAs cap, on 3-inch InP substrates (see Figure for details of the structure). Removal of the cap enabled measurements of sheet carrier density and electron Hall mobility – values were 2.3 x 10^{12} cm^{-2} and 11,300 $cm^2 V^{-1} s^{-1}$, respectively.

Electron beam lithography defined the gate recess and the gate regions. The formation of the gate recess, produced by selective wet etching, allows fabrication of an asymmetric gate, because it is possible to change the drain-side recess independently of the source-side recess length.



Fujitsu's InP HEMT produces a record maximum oscillation frequency for its gate length, L_G. The asymmetry in the structure results from a difference between the drain-side recess length, L_{RD}, and the source-side recess length, L_{RS}. The distance between the source and gate is labelled D_{SG}.

To passivate the device, the researchers turned to CVD to enshroud the cavity in a 30 nm-thick SiN layer, before coating the transistor's surface with benzocyclobutene (see Figure).

Measurements on HEMTs with a 75 nm gate length and a source-side recess of 70 nm showed a hike in maximum oscillation frequency from 462 GHz to 1.08 THz when extending the drain side recess from 70 nm to 250 nm. This gain came at the expense of a slight decrease in the maximum cut-off frequency, which dropped from 378 GHz to 313 GHz.

To increase the maximum oscillation frequency, Takahashi and co-workers trimmed the distance between the source and drain electrodes from 0.8 μm to 0.3 μm, and optimised the biasing conditions. Employing a drain-source voltage of 1.0 V and a gate-source voltage of 0 V, the maximum oscillation frequency hit 1.3 THz, according to extrapolation of the unilateral gain of the HEMT.

The team claims that 1.3 THz is a record for a HEMT with a relatively long gate length of 75 nm. They believe 1.5 THz or more is possible with gate lengths of 50 nm or less.

Takahashi and his colleagues are now planning to make an integrated circuit operating at more than 300 GHz.

Reference
T. Takahashi *et. al.*
Appl. Phys. Express **10** 024102 (2017)

Increasing the gain of solar-blind detectors

Avalanche photodiodes can deliver superior performance by uniting a dual-period distributed Bragg reflector with a novel five-layer active region

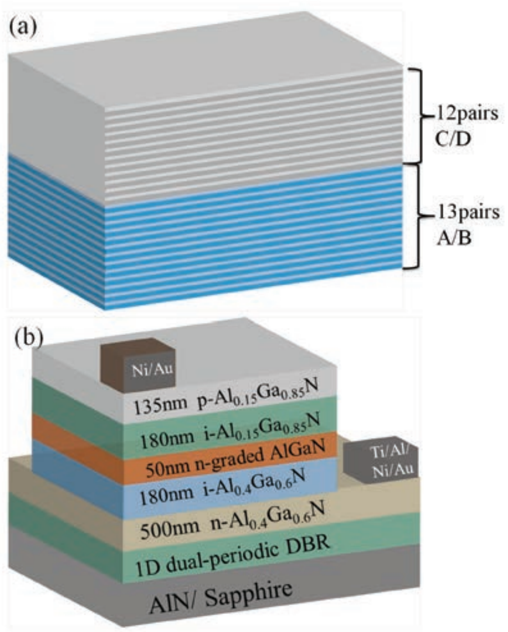
SIMULATIONS suggest that the performance of solar-blind avalanche photodiodes (APDs) can hit a new high when distributed Bragg reflectors work in tandem with separate absorption and multiplication regions.

"Our idea not only improves solar blind spectral responsivity, but can also reduce the avalanche breakdown of the APDs," claims Guofeng Yang, spokesman for the team from Jiangnan University, China. A low avalanche breakdown is favourable, because the device must operate above this voltage.

The team's detector, which is calculated to deliver a spectral responsivity of 0.184 A/W at 284 nm and produce a breakdown voltage of 65 V, could be used for missile plume sensing, flame detection, environmental monitoring, chemical and biological agent detection and covert space-to-space communications.

These applications create a civilian domestic market for solar blind detectors worth several billion Yuan, according to Yang. "The military market is much larger than the civilian market, but an accurate value cannot be evaluated."

Incorporating distributed Bragg reflectors into APDs is not a new idea. These mirrors are established optical filters for improving solar-blind performance – and when they are inserted between a sapphire substrate and an *n*-type layer, they also serve as a buffer layer, improving the quality of AlGaN.



Improvements in the performance of the APD come from the use of a dual-period DBR and a five-layer active region with separate absorption and multiplication sections.

One significant drawback of conventional single-period distributed Bragg reflectors used in APDs is their narrow stop-band. This is not wide enough to limit the response of the spectrum in the solar-blind region.

To tackle this weakness, the team is pioneering a new archirecture, a dual period distributed Bragg reflector. This is formed from 13 pairs of 40.5 nm-thick AlN and 26.5 nm-thick $Al_{0.55}Ga_{0.45}N$, followed by 12 pairs of 40.5 nm-thick $Al_{0.64}Ga_{0.36}N$ and 26.5 nm-thick $Al_{0.77}In_{0.23}N$. This is compared with a more conventional design, but one that produces a wider stop band than usual (this reference has a distributed Bragg reflector formed from 25 pairs of $AlN/Al_{0.55}Ga_{0.45}N$).

Using the software COMSOL, simulations suggest that both the reflectors retain a reflectivity in excess of 90 percent across a stop band that is about 40 nm wide and spans 294 nm to 337 nm. This is capable of filtering the incident light outside the solar-blind region.

The downside of the single-period distributed Bragg reflector is its very large lattice mis-match. This leads to cracking, rough interfaces, and a spectrum with very sharp fluctuations on both sides of the stop band.

Yang and his colleagues turned to Atlas Silvaco software to assess the optoelectronic performance of their APDs, and judge the benefits of their novel distributed Bragg reflector and their innovative separate absorption and multiplication regions.

Simulations showed that the device with a single-period distributed Bragg reflector suffers from sharp fluctuations within the reflectance profile that impair detection. This feature is not present in the device with the dual-period distributed Bragg reflector, which has a spectral responsivity at 284 nm that is 2.8 percent higher.

Further improvements in key characteristics results from replacing the conventional APD structure – a 50 nm-thick *n*-type charge layer, 180 nm-thick multiplication layer, and a 135 nm-thick *p*-type layer all formed from $Al_{0.4}Ga_{0.6}N$ – with the five-layer structure shown in the figure. Avalanche breakdown falls from 75.5 V to 64.5 V, while the maximum gain at these voltages increases from 1.3×10^5 to 4.6×10^6.

Reference

C. Yao *et. al.* Appl. Phys. Express **10** 034302 (2017)

Sputtering superior GaN

When it comes to forming GaN films with a high conductivity, pulsed sputtering deposition trumps the incumbent growth technology, MOCVD

A TEAM from Japan is claiming that silicon-doped GaN formed from sputtering outperforms that grown by MOCVD, in terms of several important electrical and optical characteristics.

Unlike GaN grown by MOCVD, that produced by sputtering is free from carbon and hydrogen, and it can sport a resistivity that is comparable with that of transparent conductive oxides, such as indium tin oxide.

That's makes silicon-doped GaN a very attractive candidate for fabricating GaN-based power devices and growing epitaxial transparent electrode material for III-N lasers and LEDs, argues the team from the University of Tokyo, and from PRESTO and ACCEL, divisions of the Japan Science and Technology Agency.

To demonstrate the virtues of PVD-grown, silicon-doped GaN films, the researchers deposited 1 μm-thick layers on a variety of substrates. Using pulsed magnetron sputtering sources in an atmosphere of nitrogen and argon, the researchers formed films with a variety of doping levels. Lightly-doped silicon samples with a silicon concentration below 1 x 10^{17} cm^{-3} were formed on iron-doped bulk GaN substrates, which were prepared by HVPE and had a threading dislocation density of typically 10^6 cm^{-3}. Meanwhile, layers with silicon concentrations from more than 1 x 10^{17} cm^{-3} to 2 x 10^{20} cm^{-3} were deposited on iron-doped GaN-on-sapphire that had been prepared by MOCVD.

To determine the mobility in their samples, the team fabricated van der Pauw structures. Using photolithography and reactive ion etching with an inductively coupled plasma, samples were processed into cloverleaf structures. Deposition of a Ti/Al/Ti/Au stack added Ohmic contacts.

Room-temperature Hall effect measurements revealed an increase in electron mobility with a reduction in silicon doping concentration, reaching 1008 cm^2 V^{-1} s^{-1} for an electron concentration of 1.5 x 10^{16} cm^{-3}. However, even at an electron concentration as high as 2 x 10^{20} cm^{-3}, electron mobility is 110 cm^2 V^{-1} s^{-1}.

The team noted in its paper that there are no previous reports of the fabrication of such a highly conductive silicon-doped GaN material by MOCVD. Measurements on samples with doping in excess of 8 x 10^{18} cm^{-3} reveal almost no variation in electron concentration between temperatures of 77 K and 300 K. The researchers also found that almost all the silicon atoms were active as *n*-type dopants in GaN, even for a doping concentration as high as 2 x 10^{20} cm^{-3}. It is argued that this shows that the growth process produces negligible, if any, undesirable SiN.

Pulsed sputtering deposition produces GaN films with a resistivity comparable to indium tin oxide.

When the doping level is below 1 x 10^{17} cm^{-3}, samples exhibit a temperature-dependent electron concentration. This behaviour can be well fitted under a charge neutrality condition as a non-degenerate *n*-type semiconductor.

Reflection high-energy electron diffraction offers an insight into the growth process. A clear streaky pattern is observed, indicative of a two-dimensional growth mode.

Further evidence for this growth mode comes from atomic force microscopy of a 5 μm by 5 μm sample area. Scans reveal an atomically flat step-and-terrace structure with a terrace width of about 1 μm. On these terraces the root-mean-square surface roughness is just 0.5 nm.

Calculations of electron mobility as a function of temperature – that consider the interaction of electrons with impurities, lattice defects and lattice vibrations – indicate that this is limited by optical phonon scattering at room-temperature. However, if the sample is cooled to below 200K, ionised impurity scattering dominates.

These findings reveal that reducing the concentration of compensating acceptors could increase the electron mobility in GaN formed by pulsed scattering deposition. A high-quality bulk GaN substrate provides an additional hike, as the highest low-temperature mobility comes from a sample grown on a substrate with a dislocation density of just 5 x 10^5 cm^{-2}.

Reference

Y. Arakawa *et. al.*
Appl. Phys. Lett. **110** 042103 (2017)

VENDOR VIEW Proton Site

On-site hydrogen generation: smart choice to improve process results

Hydrogen is widely used to support a variety of industrial applications worldwide, due to its ability to meet the specific needs of high purity industrial applications, ranging from semiconductor manufacturing and epitaxy to heat treating and materials processing.

Relying heavily on hydrogen to maintain process results, many operations personnel are responsible for evaluating which gas supply method will best suit their operation. Over time, this task can become daunting, because as businesses grow, increasing amounts of hydrogen are needed to satisfy elevated levels of production demand. This spike in hydrogen usage has translated into a collection of issues for facility operation.

Hassles such as inefficient production practices, fire permit restrictions, space limitations, increased costs, dangerous hydrogen storage and handling can make gas sourcing especially problematic.

Offering clear advantages over older, conventional methods of hydrogen supply such as delivered gas, dissociated ammonia and exo or endo gas, hydrogen generated on-site is a drier and safer alternative. A high performance solution to suit businesses small and large, on-site gas generators satisfy demand by producing hydrogen at its point of use with no inventory of flammable or poisonous gas. Hydrogen generation systems are easy to permit, easy to install, and operate automatically. Market data shows more and more stakeholders are making the switch to gas generators, eliminating the need for delivery and storage of hazardous gases within the industry.

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