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Can zinc oxide light up the world?

A debut for the non-polar GaN VCSEL

Adding light to the GaN integrated circuit

Watt-class diode lasers in the blue and green

Guaranteeing a stable flow of MOCVD gases

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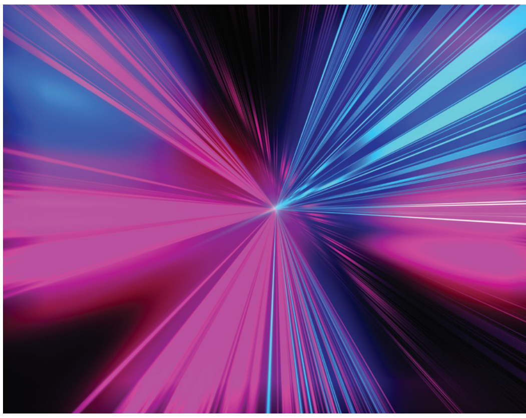
AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

Viewpoint

By Dr Richard Stevenson, Editor

A better plane for the GaN VCSEL



I EXPECT that for many of you are well-versed in the virtues of the VCSEL. You will know that it produces a desirable emission profile, offers on-wafer testing, and thanks to its small size, can be modulated at far faster speeds than its edge-emitting cousin.

But when it comes to GaN, the material needed to produce blue and green VCSELs, what are the merits of a non-polar design over the more conventional polar one?

If you can recall the benefits of a non-polar LED, you can probably take an educated guess. You would be right when arguing that the non-polar plane eliminates external electric fields, thereby allowing electrons and holes to come closer together, and ultimately enable a higher radiative efficiency. And you may also be able to point out that the thickness of the well can be increased without impacting electron-hole overlap, enabling a reduction in Auger recombination, a non-radiative process.

But there is another benefit that you may overlook – and I certainly did. If you switch from a polar plane to a non-polar one, this fixes the polarisation of the laser. And that's a big deal if you produce an array of VCSELs, because you can then create a source that is completely polarised in one direction. That's a very promising option for Li-Fi, as polarisation division multiplexing could enable a substantial hike in data transmission rates.

Non-polar VCSELs are certainly not ubiquitous. The only makers that I know of are a team at the Nakamura Lab at the University of California, Santa Barbara.

Those West-coast researchers have been developing these devices for several years, and have recently realised a new milestone: the first non-polar GaN VCSEL capable of continuous-wave emission (you can read the story of their success in the feature "Propelling the performance of non-polar GaN VCSELs", on page 48 of this issue).

Several of their innovations – such as the use of transparent tunnel junctions to inject carriers into the device while ensuring minimal optical loss, and photoelectrochemical etching to precisely define the length of the cavity – could also aid the developers of polar GaN VCSELs.

That's good news, because progress in GaN VCSELs on all fronts could enable red, GaAs-based VCSELs to be combined with green and blue GaN VCSELs, to form great light engines for full-colour projectors. What's more, due to the low power consumption of the VCSEL, these devices could be used in wearable displays.

So there's certainly motivation to drive progress – which in the case of the GaN VCSEL is never easy.

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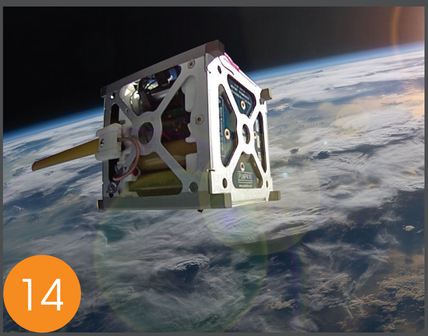


research review

Rohm is technology partner for Venturi Formula E

ROHM SEMICONDUCTOR has been official technology partner of the Venturi Formula E team since Season 3 (2016/2017), and now it has also become a global sponsor for the brand.

Formula E is the leading racing event for electric vehicles. The collaboration between Rohm and Venturi in Formula E highlights the key to success in the all-electric racing series – power management.

Venturi Automobiles is a pioneer in designing electric powertrains, which it supplies to the Venturi Formula E team. The challenge of Formula E is to find the most efficient way of using the energy provided by the battery and applying it on the road.

To do this, Venturi initiated a partnership with Rohm, who developed new power semiconductor technology using SiC, resulting in extremely low losses of power and higher temperature resistance for their inverter. Thus, Rohm and Venturi hope to gain an edge over the competition while also pushing forward the development of new technical solutions to increase power conversion efficiency.

Venturi Automobiles holds the FIA World Land Speed record for an all-electric vehicle. In 2016, the Venturi Buckeye Bullet 3 set the official top recorded speed achieved by an electrically-driven car of 549 km/h on the Bonneville Salt Flats in Utah.

As global sponsor for the brand, Rohm says it exemplifies its commitment to further development of power and energy management systems. Bringing SiC technology to Formula E and to e-mobility in general is an important step in changing drive technology.

Veeco, AMEC and SGL settle dispute

VEECO INSTRUMENTS, Advanced Micro-Fabrication Equipment (AMEC), and SGL Carbon SE (SGL), have mutually agreed to settle the pending litigation among the parties and to amicably resolve all pending disputes, including AMEC's lawsuit against Veeco before the Fujian High Court in China and Veeco's lawsuit against SGL before the US District Court for the Eastern District of New York. John R. Peeler, chairman and CEO of Veeco, commented: "I am pleased to report that we have reached a mutually agreed settlement of the pending IP disputes and we are back to normal business operations in our MOCVD business."

AMEC's Chairman and CEO, Gerald Yin, stated: "This settlement is a good example of how competitors can resolve IP matters for the benefit of their global customer base."
As part of the settlement, all legal actions worldwide (in court, patent offices and otherwise), between Veeco, AMEC and SGL, and their affiliates, will be dismissed and/or otherwise withdrawn. As a result, all business processes, including sales, service and importation, will be continued. Terms of the settlement were not disclosed.

Infineon, Cree agree long-term supply of SiC wafers

INFINEON TECHNOLOGIES and Cree have agreed on a strategic long-term supply agreement for the provision of SiC wafers. Infineon aims to broaden its offering of SiC products to address today's high-growth markets such as photovoltaic inverters and electro-mobility.

Since Infineon has already converted all its SiC manufacturing lines to the most advanced 150 mm SiC wafers, the agreement with Cree covers only this wafer diameter.

"We have known Cree for a long time as a strong and reliable partner with an excellent industry reputation," said Reinhard Ploss, CEO of Infineon. "Based on the secured long-term supply of SiC wafers, we strengthen our strategic growth areas in automotive and industrial power control. As a consequence, we will create additional value for our customers."

"Infineon is a longstanding, valuable commercial partner with an excellent reputation," said Gregg Lowe, CEO of Cree. "This agreement validates the quality of Cree's SiC wafer technology and our capacity expansion, as well as the accelerated adoption of SiC-based solutions that are critical to enabling faster, smaller, lighter and more powerful electronic systems."
Semiconductors based on SiC technology are the basis for most high-efficiency and disruptive system solutions in power conversion and in the electric car. The use of SiC-based power semiconductor solutions has shown a strong increase over the last years.

Compared to silicon-based power semiconductors, SiC devices provide higher energy savings and higher system density from size reduction of the passive components.
Over the next few years, in addition to electro-mobility and photovoltaic, SiC products will expand into application fields such as robotics, industrial power supplies, traction and variable speed drives.

Horticultural LED market: Is Amazon showing the way forward?

THE HORTICULTURAL LED lighting market reached almost $3.8 billion in 2017, currently driven mainly by greenhouse applications. But future growth may be dominated by new types of farming, according to Yole Développement and PISEO (both part of the Yole Group of companies).

In Yole's latest Horticultural LED Lighting report, greenhouse applications will not maintain their leadership in the mid and long term and are only the tip of the iceberg. Emerging applications, including urban farming, are likely to make the horticultural lighting market boom with a 16.4 percent CAGR between 2018 and 2023.

In this context, it is not surprising to discover Jeff Bezos' support for a vertical farms project in China. In a recent article, a journalist announced a 300 vertical farms project in China, supported by Amazon CEO Jeff Bezos and Alphabet Executive Chairman Eric Schmidt.

According to this article, a start-up named Plenty has raised more than $200 million, thanks to the Softbank Group and investment funds. Entering the Chinese market, Plenty hopes to tap into the country's growing demand for organic foods.

"Vertical farms, especially developed in cities, are probably the most relevant solution we found to produce fresh food and vegetables", comments Pierrick Boulay, technology & market analyst at Yole.

"The world population is growing and almost 80 percent of the world's population will live in cities and megacities by 2050. As a consequence, vertical farms will clearly be part of our future."

"LED technology is a key enabler for the development of the vertical farming industry", adds Joël Thomé, general manager at PISEO. "Thanks to optical radiation versatility, easier integration, and long-life span, crop yields under artificial LED lighting will increase dramatically."

Indoor farming should develop strongly in the largely urbanised Asian areas, especially in China, as this region faces severe soil and water pollution. The Plenty start-up is but one example.

Penetration of this market by Amazon and Alphabet is not an isolated example and must be strongly considered by others in the future. According to Yole and PISEO, the horticultural lighting market is expected to reach $17 billion by 2027 thanks to a boom in indoor and vertical farming applications. Such figures clearly highlight the attractiveness of this sector.

Amazon's new positioning confirms the added-value of vertical farms as an answer to the evolution of the world's population and food resources. But it is also strong confirmation of the diversification strategy of the giant Amazon in penetrating the whole foods grocery chain.

Advantech announces new GaN amplifier for radars

ADVANTECH WIRELESS has announced recently the release of its second generation GaN 1kW X-band pulse amplifier designed for Radar Systems. The new 1kW X-band Solid State Pulse Amplifier (SSPA) is fully integrated and operates over the band of 8.9 – 9.6 GHz.

Features include a duty cycle monitor and pulse width monitor to ensure trouble free operation. The SSPA is designed to replace ageing travelling wave tubes and Klystrons with advanced solid state technology. Second Generation GaN technology reduces power consumption and operating costs due to its very high reliability, according to the company. Because of the system's linearity, the amplifier also produces a cleaner pulse, resulting in better range and resolution of the radar system.

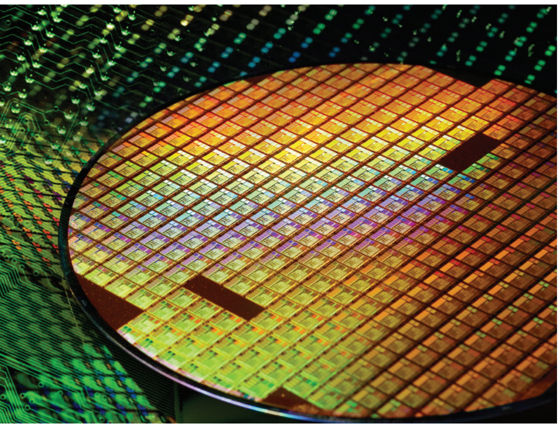
"The advantage of solid state design over tubes and klystron technology is that this technology is much better suited for mobile radar applications," said Cristi Damian, Advantech Wireless VP, business development.

"These new GaN based Solid State Pulse Amplifiers for Radars exhibit very high spectral purity, linearity, and low phase noise. The radar pulse processing allows for very high pulse fidelity and sharpness, which translates in longer ranges, and higher detection capabilities."

Macom and STMicroelectronics announce GaN collaboration

RF and microwave specialist Macom and the semiconductor giant STMicroelectronics have announced an agreement to develop GaN on Silicon wafers to be manufactured by ST for Macom's use across an array of RF applications.

While expanding Macom's source of supply, the agreement also grants to ST the right to manufacture and sell its own GaN-on-silicon products in RF markets outside of mobile phone, wireless basestation and related commercial telecom infrastructure applications.



Through this agreement, Macom expects to access increased Silicon wafer manufacturing capacity and improved cost structure that could displace incumbent silicon LDMOS and accelerate the adoption of GaN on Silicon in mainstream markets. ST and Macom have been working together for several years to bring GaN-on-silicon production up in ST's CMOS wafer fab.

As currently scheduled, sample production from ST is expected to begin in 2018. "This agreement punctuates our long journey of leading the RF industry's conversion to GaN-on-silicon technology. To date, Macom has refined and proven the merits of GaN-on-silicon using rather modest compound semiconductor factories, replicating and even exceeding the RF performance and reliability of expensive GaN on SiC alternative technology," said John Croteau, president and CEO, Macom.

"We expect this collaboration with ST to bring those GaN innovations to bear in a Silicon supply chain that can ultimately service the most demanding customers and applications. ST's scale and operational excellence in Silicon wafer manufacturing aims to unlock the potential to drive new RF power applications for Macom and ST as it delivers the economic breakthroughs necessary to expand the market for GaN-on-silicon," said Marco Monti, president of the Automotive and Discrete Product Group, STMicroelectronics.

"While expanding the opportunities for existing RF applications is appealing, we're even more excited about using GaN-on-silicon in new RF Energy applications, especially in automotive applications, such as plasma ignition for more efficient combustion in conventional engines, and in RF lighting applications, for more efficient and longer-lasting lighting systems."

"Once the $0.04/watt barrier for high power RF semiconductor devices is crossed, significant opportunities for the RF energy market may open up," said Eric Higham, director Advanced Semiconductor Applications Service at Strategy Analytics.

Higham continued, "Potential RF energy device shipments could be in the hundreds of millions for applications including commercial microwave cooking, automotive lighting and ignition, and plasma lighting, with sales reaching into the billions of dollars.

SPTS wins $37 million in orders from RF device makers

SPTS TECHNOLOGIES, an Orbotech company and a supplier of wafer processing solutions, has received approximately $37 million in orders for multiple etch and deposition systems from two GaAs foundry customers.

SPTS's Omega plasma etch, Delta PECVD, and Sigma PVD systems will be used to manufacture RF devices for 4G and emerging 5G wireless infrastructure and mobile device markets. Delivery of the systems is expected to be split between the first quarter and second quarter of 2018.

"Compound semiconductor electronic devices based on GaAs are the cornerstone of high speed wireless communications," stated Kevin Crofton, corporate executive VP at Orbotech and president of SPTS Technologies. "RF devices are entering another exciting phase of growth with the proliferation of 4G mobile communications and preparation for 5G. IDMs and foundries are looking to add capacity to existing fabs to meet the growing demand, while new entrants are establishing new lines to address future demand for the 5G rollout.

"Our lead customer has been at the forefront of GaAs foundry services for almost two decades, and their repeat orders are a testament to the production advantages that our etch and deposition solutions continue to deliver to their core business."

Power amplifiers (PAs) are among the most critical RF components in mobile communications and virtually all PAs in a modern smartphone are made from circuits built on GaAs semiconductors. Analysts are predicting that the growth of 4G communications, gigabit LTE (Long Term Evolution) and emerging 5G will be the growth engine to drive the RF GaAs device market from over $8.1 billion in 2017 to over $9 billion by 2021.

"Our latest forecast shows that PAs for cellular applications will continue to account for more than half of the RF GaAs device market," noted Eric Higham, director of the advanced semiconductor applications service at Strategy Analytics.

He added, "Despite smartphone growth slowing, the added complexity in mobile devices to support gigabit LTE and the emergence of 5G points to continuing growth in RF GaAs production."

ON Semi and Audi announce chip partnership

ON SEMICONDUCTOR has announced a strategic relationship with Audi following its selection to become part of the German car maker's Progressive Semiconductor Program (PSCP).

Audi's Progressive Semiconductor Program is designed to rapidly make the latest semiconductor technologies available in cars, while increasing reliability. An important part of it involves being in direct contact with the semiconductor manufacturers and working with them on joint development.

Automotive innovations have increasingly been enabled by semiconductor-based solutions – a trend set to continue due to sophisticated powertrain electrification, Advanced Driver Assistance Systems (ADAS) and the progression towards autonomous driving. ON Semiconductor has a range of image sensors, power management and connectivity devices for automated driving systems. It also has a portfolio of power solutions including modules and SiC/GaN wide-band gap devices designed for the development of next generation electric vehicles (EVs) and hybrid electric vehicles (HEVs).

"With semiconductors being so vital to recent and future developments on our vehicle platforms, we recognised that traditional automotive innovation cycles were no longer appropriate for keeping pace with consumer demand for exciting new technologies in all areas of the vehicle," said Thomas M. Mueller, head of electrics/electronics at Audi AG. "Partnering with a market leader like ON Semiconductor on our PSCP will provide the perfect framework for close collaboration and help speed the realisation of innovative, high-quality and highly efficient systems for our vehicles."

Twinning technique cuts SiC wafering costs

SILTECTRA has validated a breakthrough capability for its Cold Split, laser-based wafer-thinning technique for advanced substrates including SiC, GaN and sapphire.

Cold Split is claimed to outperform traditional grinding methods by thinning wafers to 100 μ and below in minutes, with virtually no material loss.

Now, using an adaptation known as twinning, Siltectra has demonstrated that Cold Split can reclaim substrate material generated (and previously wasted) during backside grinding, to create a second bonus wafer in the process. Siltectra validated the process by producing a GaN on SiC HEMT device on a split-off (or twinned) wafer at its new state-of-the-art facility in Dresden, Germany. The HEMT showed results that were superior to a non- Cold Split enabled HEMT when measured for CMP characterisation, as well as GaN epi, metal layer and gate layer outcomes.

Siltectra believes that the solution's combined advantages, which include fewer process steps, potentially lower equipment costs, and ultra-efficient use of substrate material, could reduce total device production costs by as much as 30 percent.

Leading integrated device manufacturers (IDMs) are now evaluating the technology.

HRL Labs to offer GaN MMIC foundry service

HRL LABORATORIES – a corporate research lab owned by Boeing and General Motors in the US– has announced a new shared foundry service, offering advanced millimetre-wave (mmW) GaN technology for fabrication of monolithic microwave integrated circuits (MMICs) through multi-project wafer (MPW) runs.

"Eligible customers will be able to design into our world-class, state-of-the-art mmW T3-GaN fabrication process and receive custom, tailored circuits for their specific applications at a price much lower than a dedicated foundry run," said Shawn Burnham, the HRL scientist in charge of the GaN foundry service. "They will be given access to a process design kit, which has already been used to demonstrate world-record power amplifier and low-noise amplifier performance."

HRL T3-GaN is a leading-edge mmW HEMT technology for applications such as next-generation high-data-rate wireless communications and high-resolution radar imaging.

HRL processes GaN wafers in a 10,000-square-foot ISO Class 4 cleanroom, and is a US Department of Defense Trusted Foundry. HRL will begin an open subscription period soon for customers with verified US government end-use of the foundry product.

For customers that do not want to perform custom MMIC designs themselves, HRL also continues to offer related T3-GaN MMIC design services to US Government customers, which could then be used on MPW runs.

HRL has over 25 years of experience designing MMICs from UHF to mmW, including low-noise amplifiers, power amplifiers, mixers, switches, attenuators, and phase shifters, and the expertise to package the fabricated MMICs.

Wolfspeed introduces next generation GaN HEMTs

WOLFSPEED, a Cree Company and a supplier of GaN-on-SiC HEMT and MMICs, has introduced a new series of 28 V GaN HEMTs RF power devices.

These new devices are capable of higher frequency operation to 8 GHz with increased efficiency and higher gain as well as high reliability. RF design engineers are now able to build more efficient broadband power amplifiers for commercial and military wireless communications and radar applications.

The new 28 V GaN HEMT devices are developed using Wolfspeed's 0.25 μm GaN-on-SiC process, and are designed with the same package footprint as the previous generation of 0.4 μm devices, making it possible for RF design engineers to use them as drop-in replacements for the earlier devices in existing designs.

Available as both packaged devices (CG2H400 Series) and bare die (CG2H800 Series), the new GaN HEMTs are said to deliver 33 percent higher frequency operation to 8 GHz (from 6 GHz), an additional 1.5-2.0 dB of gain, as well as a 5 - 10 percent boost in operating efficiency compared to Wolfspeed's earlier generation devices.

"By moving to our proven 0.25 μm process for these next-generation devices, we are able to deliver significant performance advantages to a wide range of customers while maintaining the superior reliability these types of applications require," said Jim Milligan, RF and microwave director, Wolfspeed.

"Offering these new devices in the same packages as our previous generation parts enables RF design engineers to quickly and easily boost the performance of their RF amplifiers."

The higher efficiency (up to 70 percent at PSAT) and higher bandwidth capability makes these devices ideal for an extensive range of RF power amplifier applications, including those for military communications systems, radar equipment (UHF, L-, S-, C-, and X-band), electronic warfare and electronic counter-measure systems, as well as commercial RF applications in the industrial, medical, and scientific band.

Deep UV LEDs have highest output power

DOWA ELECTRONICS MATERIALS has successfully developed a deep ultraviolet LED chip, which it says feature the world's highest output power of 90 mW, with a peak wavelength of 310 nm, and dimensions of 1 mm × 1 mm.

Deep ultraviolet lights with a wavelength of 310 nm are used for curing and skin therapy. Replacing conventional mercury and excimer lamps with these LEDs enables equipment to be smaller and mercury-free. With the advantages of long life time and power saving, this product is expected to find new applications.

Combining a high-quality AlN template with unique crystal growth technology, Dowa has been prepared for a mass production for deep ultraviolet LED chips, which boast the world's highest output power in the disinfection wavelength of 280 nm.

For the wavelength of 310 nm, combining this technology and the fine-structured sapphire substrate developed by Oji Holdings Corporation, Dowa proceeded to improve luminous efficiency, enabling a 20 percent higher output power compared to current products, resulting in an output power of 90 mW, the highest in the world for the wavelength of 310 nm. It will begin to mass-produce the newly developed deep ultraviolet LEDs with the wavelength of 310 nm in April 2018.

GaNFast chip is at the heart of smallest charger

NAVITAS SEMICONDUCTOR has announced what it believes is the world's smallest, fastest charging mobile adapter enabled by GaNFast power ICs.

The 27 W design delivers five times greater power than standard smartphone chargers and is twice the power density, according to the company.

The lightweight reference design has world-wide input voltage capability and a new Type C connector with USB-PD 3.0 and Qualcomm Quick Charge 4.0 features.

"The 27 W is another size and speed breakthrough for consumers enabled by GaNFast technology, and with Quick Charge 4.0 compliance, you can decrease the amount of time you spend tethered to an outlet giving your device 'five for five' – that's five hours of battery life from five minutes of charging" said Stephen Oliver, Navitas' vice president of sales and marketing.

"Now that the high-frequency power eco-system of GaNFast power ICs, new controllers, new magnetics and soft-switching topologies has been established, we'll see a wide-range of fast-charging, high density designs on the market."

Using a Navitas' high-speed, half-bridge GaNFast power IC in the advanced Active Clamp Flyback (ACF) topology, the 27 W reference design measures 39 x 37 x 16 mm (uncased) and achieves a power density of 1.2 W/cm^3 (19 W/in^3) uncased and 0.7 W/cm^3 (11 W/in^3) assuming a 2.5mm case thickness.

The 27 W design (NVE039) made its debut at the Applied Power Electronics Conference (APEC) March 5th in San Antonio, Texas.

Microchip to acquire Microsemi

MICROCHIP TECHNOLOGY, best known for its microcontroller range, will acquire Microsemi, a company focused on power, comms and defence semiconductors (including GaAs, GaN and SiC technologies), for $68.78 per share in cash.

The acquisition price represents a total equity value of about $8.35 billion, and a total enterprise value of about $10.15 billion, after accounting for Microsemi's cash and investments, net of debt, on its balance sheet at December 31, 2017.

"This transaction represents a compelling opportunity for Microsemi stockholders, employees and customers by combining the leading embedded control market position of Microchip Technology with the world class power, security, reliability and performance solutions from Microsemi," said James J. Peterson, chairman and CEO of Microsemi. "We are delighted to become part of Microchip Technology, a premier company in the semiconductor industry."

"We are delighted to welcome Microsemi to become part of the Microchip team and look forward to closing the transaction and working together to realise the benefits of a combined team pursuing a unified strategy. Even as we execute a very successful Microchip 2.0 strategy that is enabling organic revenue growth in the mid to high single digits, Microchip continues to view accretive acquisitions as a key strategy to deliver incremental growth and stockholder value" said Steve Sanghi, Chairman and CEO of Microchip.

"The Microsemi acquisition is the latest chapter of this strategy and will add further operational and customer scale to Microchip," added Sanghi.

Following the closing, the transaction is expected to be immediately accretive to Microchip's non-GAAP earnings per share. Based on currently available information, Microchip anticipates achieving an estimated $300 million in synergies in the third year after close of transaction.

Microchip plans to finance the transaction with approximately $1.6 billion of cash from the combined company balance sheets, approximately $3.0 billion from Microchip's existing line of credit, approximately $5.0 billion in new debt and $0.6 billion of a cash bridge loan.

The board of directors of each company has unanimously approved the acquisition. Subject to approval by Microsemi stockholders, customary regulatory approvals and other closing conditions, the transaction is expected to close in the second quarter of 2018.

Macom announces amplifiers for massive MIMO 5G

MACOM has announced its new MAGM series of GaN-on-silicon-based MMIC power amplifiers (PAs)for massive MIMO antenna systems targeted for 5G wireless basestation infrastructure.

Providing wideband performance simultaneously covering bands 42 and 43 with flat power and superior power efficiency compared to legacy LDMOS technology, Macom's new MAGM PA Series delivers GaN performance at LDMOS-like cost structures at scaled volume production levels in fully integrated MMIC packaging for simplified, cost-effective 5G basestation manufacturing.

MAGM Series MMIC PAs are specifically tailored for mainstream 5G basestation architectures, meeting and surpassing the power density and thermal requirements of 64-element massive MIMO antenna arrays, with a pathway to exceeding the performance of LDMOS technology, at scaled volume level production cost structures and supply capacities that can't be achieved with competing GaN-on-SiC technology.

Designed with Macom proprietary wideband circuit topology, the PAs meet the stringent. 5G TDD linearity requirement using off the shelf digital-pre-distortion (DPD) systems. Compared to earlier generation multichip-format GaN-on-silicon modules, costs are further lowered through a reduction in packaging and design complexity.

Leveraging this ideal performance and cost with the capacity scale manufacturing afforded by Macom's partnership with ST Microelectronics, Macom's GaN-on-silicon solutions are expected to be able to significantly improve customers' time to market.

"Macom's new MAGM Series PAs combine the unique performance and cost benefits inherent to GaN-on-silicon technology with the MMIC packaging efficiencies needed for commercial volume-scale 5G basestation manufacturing and deployment," said Amer Droubi, director product marketing, Macom.

"Our continuous innovation in this domain sets a strong foundation for next-generation multifunction GaN-on-Si MMICs targeted to enable fully-integrated front-end modules for massive MIMO 5G basestation architectures."

Ranovus to demo 200G quantum dot laser transceiver

RANOVUS, a start-up providing multi-terabit interconnects, has launched its 200G On-Board Optics and CFP2 optical transceiver solutions for 5G mobility and data centre interconnect (DCI) applications.

These are based on the company's multi-wavelength Quantum Dot Laser (QDL), ring resonator based silicon photonic (SiP) modulators, driver ICs as well as receiver building blocks.

Ranovus' products are now in lab trials with multiple optical networking equipment vendors, including ADVA Optical Networking which has worked with the company to demonstrate 400GB/s transmission over 80km.

"Our demonstration will feature transmission of 400Gb/s in an FSP 3000 CloudConnect terminal and over 80km of standard single mode fibre utilising our open line system," said Christoph Glingener, CTO/COO at ADVA.

"In partnership with Ranovus, we have made impressive progress to validate direct detect technology as an effective way for data centre operators to lower their cost per bit and improve energy efficiency."

The Quantum Dot Multi-Wavelength Laser (QD MWL) is a semiconductor laser that uses self-assembled quantum dots to generate multiple wavelengths simultaneously from a single device. A single QD MWL device can provide up to 96 wavelengths in the C-band alone, allowing for the replacement of 96 individual lasers in an equivalent system.

According to Ranovus, QD MWL based solutions allow for a much simpler and compact interface design, resulting in lower power consumption and better performance when compared to an equivalent solution having multiple discrete lasers and components.

The advantage of a QD MWL is its ability to provide multiple wavelengths simultaneously, each of which can be selected and used as a light source for data transmission at 25 Gb/s and beyond.

"In today's data driven economy, the unprecedented growth in the data traffic cannot be efficiently addressed in terms of cost and power by yesterday's technologies. We are very excited to bring the next generation of scalable and miniaturised multi-wavelength Quantum Dot Laser and Silicon Photonics platform technologies to support the data growth curve," said Hamid Arabzadeh, chairman and CEO at Ranovus.

"After a series of successful trials over the last year we are pleased to announce the general availability of our product portfolio that enables scalable multi-terabits bandwidth connectivity in form factors that consume less power and are at a third the cost of coherent and half the cost of other PAM4 direct detect transceivers per Gb/s."

"Our impressive product demonstration with ADVA includes transmission of live traffic over Ranovus' on-board optics integrated into the FSP 3000 400G terminal, as well as Ranovus' 200G CFP2 modules over the same physical layer for 80km of transmission distance." said Saeid Aramideh, co-founder and chief marketing & sales officer at Ranovus.

"We would like to extend our gratitude to the team at ADVA for their tremendous support and partnership over the years to bring our innovation to market deployment."

Ranovus was founded in Ottawa February 2012 and has received financing from leading venture capital firms including Azure Capital Partners, Deutsche Telekom Venture Funds, BDC Capital, OMERS Ventures, MaRS Investment Accelerator Fund, Export Development Canada, and funding from Sustainable Development Technology Canada.

Additional information about Ranovus can be found at www.ranovus.com

Small satellites, big business

As the small satellite space race takes off, Akash Systems is set to send GaN-on-diamond systems into orbit, reports Rebecca Pool

US-based CubeSat developer, Akash Systems, has started 2018 with a bang, raising a massive $3.1 million in seed funds to accelerate delivery of its shoebox-sized satellites, based on GaN-on-diamond RF power amplifiers.

The cash comes at a time when worldwide data demand is fast outstripping the bandwidth provided by today's satellite communications infrastructure. Meanwhile, technology advances have pushed satellite services beyond Internet, television and GPS navigation, unleashing imagery-rich and data-heavy applications from aeroplane tracking to pollution monitoring.

Crucially, CubeSats and other miniature satellites are already slashing the cost of commercial satellites. And GaN-on-diamond is set to take these plummeting prices even lower.

"Historically, satellite makers have required a very big satellite to provide kilowatts of power but now we can squeeze that tremendous amount of power into a CubeSat," says Akash Systems co-founder and chief executive Felix Ejeckam. "This means we can deliver new features and capabilities in a small satellite, which is a key reason satellite suppliers are switching over."

However, today's small satellites use GaN-on-SiC power amplifiers, which means power and speed come at a cost; heat. While such GaN-based HEMTs can ideally reach 40 W/mm RF power at frequencies of 10 GHz and more, thermal heating restricts power densities to some 10 W/mm. But GaN-on-diamond can make a difference.

According to Ejeckam, diamond, with its high thermal conductivity, removes the heat in an amplifier up to four times faster than any other substrate on the market today. And as the chief executive points out, today's satellite suppliers do not want to expend resources cooling power amplifiers.

"Today's satellite suppliers would like amplifiers that can operate at higher ambient temperatures without the need for cooling," he says. "[Using GaN-on-diamond], the logistics, heaviness and size of equipment that comes from having to cool an amplifier down simply goes away."

What's more, Ejeckam is adamant that the GaN-on-diamond power amplifiers that his company is already supplying to market do not cost more than the GaN-on-SiC equivalent.

"[GaN-on Diamond] devices are actually cheaper," he asserts. "We are happy to go with the prevailing dollars per watt, that a customer wants. And our amplifier is also smaller and has these additional benefits."

Indeed, in the months that Akash has been supplying its power amplifiers, demand has, as Ejeckam puts it, been 'overwhelming'.

"We cannot meet demand and literally cannot make enough power amplifiers," he says. "Everyone wants what we can make and more."

To get the full benefits of GaN-on-diamond, satellite suppliers are designing the power amplifiers into systems, rather than simply swapping these components with existing devices. And right now, demand is coming from suppliers of small, commercial low earth orbit (LEO) satellites as well as the manufacturers of larger geostationary satellites, keen to remain competitive.

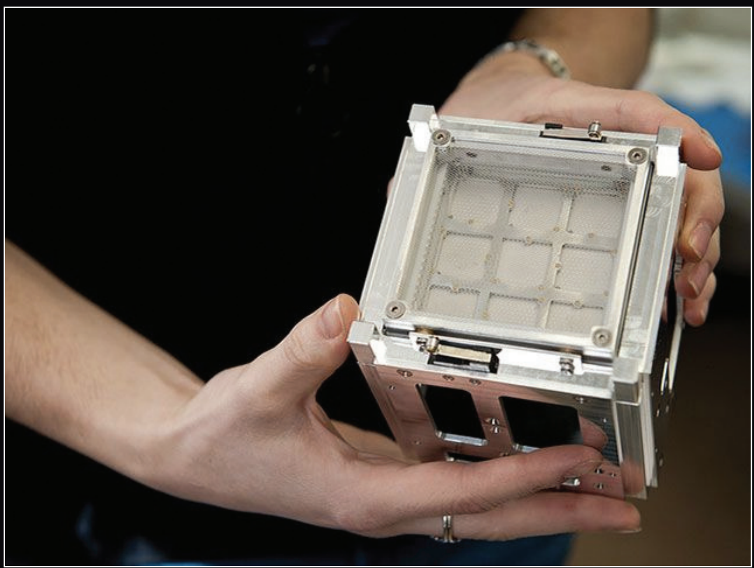
"The geo suppliers are feeling threatened by the LEO [companies] and want to make these satellites smaller, cheaper, more powerful and as effective as possible," points out Ejeckam. "Their existing business is not expected to decline, but [performance] requirements are getting tougher and tougher every year, so these suppliers are looking for new technologies."

"We cannot meet demand and literally cannot make enough power amplifiers.Everyone wants what we can make and more"

But Akash Systems' key challenge is to ramp up amplifier production to meet the burgeoning demand, while developing CubeSat systems that are scheduled to reach market next year. To this end, the company is working closely with foundries, and devices are being fabricated on 100 mm GaN-on-diamond wafers. As Ejeckam says: "We are still happy with 100 mm wafers."

But burgeoning demand or not, it's no secret that the marketplace for small satellites is crowded with more and more so-called space-start-ups getting ready to launch new systems. Figures from Nanosatellite – the world's largest database of small satellites – reveal that in 2016, launches came in at 88, rocketed to 295 in 2017 and are expected to reach 703 come 2023.

So how does Akash Systems intend to compete in this rapidly growing space? Ejeckam is blunt. "We have this underlying, fundamental technology that nobody has," he says. "This distinguishes us greatly from everyone else."



With its GaN-on-Diamond power amplifiers already in satellite markets, Akash Systems is currently developing CubeSats that are scheduled for delivery in 2019.

Move over silicon carbide

On the cusp of commercial production, Flosfia gets set to deliver the highest performing power semiconductor yet, reports Rebecca Pool

COMMERCIAL PRODUCTION of cheap and high performing gallium oxide power devices will take place later this year, if Kyoto University start-up, Flosfia, lives up to its latest promises.

Talking to *Compound Semiconductor*, vice president of marketing, Takuto Igawa, says: "We have a very good relationship with a domestic foundry, have started production and will see commercial production of our Schottky barrier diodes by the end of this year."

"We can't disclose details but this is a global foundry and our customers will be happy," he adds. "Operations will start on a domestic scale but we will expand production both physically and globally. We are seeking partners that can maximise our production capacity"

Flosfia impressed industry pundits in 2015 when it released its first corundum structured gallium oxide device. The 521 V Schottky barrier diode (SBD) had an on-resistance of 0.1 mΩcm^2, lower than that of any commercially-available SiC diode.

At the time, Flosfia director, Naonori Kurokawa claimed a 600 V 5 A SBD 'was almost ready'. And now, Igawa confirms these diodes are now good-to-go and ready to rival silicon and SiC counterparts.

"One of our first target markets will be the AC adapter for consumer use... and once we reach full-scale capacity on our production lines in 2020, we are highly confident that we will have also reached cost parity with silicon devices," he says.

Flosfia's intent to release its cool, new devices this year follows its latest funding round in which it bagged JPY 800 million – US$ 7.4 million – bringing total investment funds to a hefty JPY 2.26 billion (US$20.8 million). According to the company, that latest capital will be used to develop its production lines, at its partnering foundry, ready for imminent commercial manufacture.

And with its SBDs in production, Flosfia then intends to sample MOSFETs in 2019, with commercial production scheduled for 2020.

Perfecting the process

Flosfia's success hinges on its novel mist epitaxy CVD process, used to deposit dislocation-free layers of α-Ga_2O_3 onto 4-inch sapphire substrates. Here, a mist of metal compounds is injected into the reactor chamber, and this decomposes when it reaches the heated sapphire substrate to form gallium oxide layers.

As part of this, Flosfia co-founder, Shizuo Fujita, pioneered a 'lift-off' proprietary process to transfer the α-Ga_2O_3 layers onto a highly conductive metal support, alleviating thermal management issues and enabling operation at a lower temperature.

Crucially, this process has now been honed for the high throughput and easy-handling of wafers, and as Igawa asserts: "this process is included in commercial lines."

So with the process ready, and commercial production nigh, the future looks bright for Flosfia. In conjunction with its latest funding round, the company has also joined forces with Japan-based automotive systems supplier, Denso, to develop gallium oxide devices for power control units in hybrid and electric vehicles.

Alongside Mitsubishi Heavy Industries and Japan-based venture capital firms, Denso is a key investor in Flosfia, and according to Igawa, is keen to implement the company's diodes and MOSFETs in its power systems.

The Flosfia vice president will not be drawn on device performance specifications or any further detail, simply saying, 'we do not wish to cause confusion at this stage'. However, he also points out how both partners are keen to reduce the energy losses, cost, size and weight of inverters used in electrified vehicles.

"We are very, very interested in the automotive market," highlights Igawa. "We cannot discuss details but we can say we have mutually agreed to launch gallium oxide power systems for automotive applications by 2025."

Guaranteeing
stable, dependable sources

Richard Stevenson catches up with Steven Buerkel, President of Applied Energy Systems, and quizzes him on what it takes to be a successful provider of gas supply equipment to the compound semiconductor industry.

Q What do you believe to be the greatest accomplishment of Applied Energy Systems?

A It has been growing the company to a size where we have a very diverse and experienced engineering team. When we get these chemical delivery or gas challenges, we can immediately understand the challenges with regard to two-phase flow issues, heat of vaporisation issues, low vapour pressure problems, and that kind of thing. We have to be on top of all of that, because the III-V industry, and the compound semiconductor industry in general, is pushing the old frontiers in terms of chemical delivery and mass flow rates.

Q Do you have critical IP in gas delivery that is of significant benefit for the compound semiconductor industry?

A We are at the lower-technology end with regard to device manufacturing. How can we make sure that we can help our customers? By making sure that we do not generate any problems for them, or cause a gas or liquid delivery issue that could impact process performance. So we are continually reviewing our designs and software and implementing improvements.

There are things that we will be launching later this year, in terms of predictive analysis and self-diagnosis, to make sure that our customers don't have to reach out to us in a middle of a run because there is some issue with our equipment operation. Maybe there is a seat problem in a valve, maybe there is an unacceptable decay in the supplied pressure due to a component issue or a decay in the vapour pressure. So the idea is to catch that point of failure early on, so you can schedule maintenance, rather than shut down in the middle of a run. Perhaps through direct access to iPads or cell-phones, we will be able to notify facility engineers, so that they can make sure there are no problems supplying the chemicals and gases to the MOCVD tools.

I challenged my team as recently as this morning to generate a timeline for a new launch for this. I'm targeting Q3 this year. It's going to be rather transformational in our industry, but it requires a lot of R&D investment. But that's the way it has to be. Anybody can put a regulator on a cylinder and deliver 100 litres of helium a minute. That's not a technical challenge.

Q What are your customers looking for from you?

A They want us to deliver a product that will not cause any issues. We've been doing this for 30 years now, and I have a very experienced team. All of our customers know us, and an significant amount of our business is repeat business, because customers just have confidence in our product.

Q What is the key figures of merit when it comes to gas delivery for the compound semiconductor industry?

A It's maintaining flow rates, and making sure you have uninterrupted delivery issues. A lot of times we have to heat cylinders, maintain vapour pressures, and make sure we don't have two-phase flow issues.

We don't want anybody to make a phone call: Hey, Steve, we have a problem here. They are the things that I lose sleep over. Do I lose sleep a couple of nights a year? Possibly. But usually I'll find out that it's some anomaly, outside of our control.

Q I presume that one of the key moves that you see in the industry is companies moving to higher flow rates, so they can reduce growth times. Is one of your goals to help the chipmakers by being able to deliver faster rates of flow, but maintain that uniformity?

A I'm not sure of the market drivers, but with regard to new developments, this seems to be where we have on-going challenges. Larger flows, either supporting more tools with one source, flowing more for each tool, or runs becoming longer. We seem to be challenged every year with the higher flow rates on more-difficult-to-flow material.But we've gotten good at that. So I embrace that. We look at our Mollier charts, and make sure we don't have a risk for two-phase flow during adiabatic expansion, and all that kind of stuff.

Q You serve many different industries. Why is the compound semiconductor industry important to you?

A Well, first of all it is intriguing and very exciting. It's that excitement of watching the technology mature, develop and get pushed by price points and performance continuously. I don't even know when the race is going to end, but it's fascinating. Our company gets a great sense of pride and accomplishment helping our customers and delivering more than is expected. We provide direct access to all of our engineers.

It's also an industry I happen to know as I have worked since the mid-eighties with the MOCVD team at AT&T in Murray Hill and Crawford Hill, New Jersey, so I saw this excitement when they were developing the early technical breakthroughs.

Q You are based in Malvern, on the outskirts of Philadelphia. Is that a good location for your business?

A Well, we are two hours from perhaps the world's largest MOCVD manufacturer. We work closely with them on whatever their new tools require, so we understand where the market is going. We've built some large, high-flow ammonia systems for some of their customers.

Q Are you facing competition from emerging companies in China, offering gas delivery? And if so, what will give you an edge over them?

A We had a presence in China for a while. It's very difficult for me. We're just 75 employees – we're not a multi-international, like Air Products, although we do have a strong presence in some countries with local representation such as India and Israel, and also ship to such countries as Turkey, Norway, Germany, Taiwan among others. I tried to develop a market in China, but it was difficult and I abandoned it to focus on the US, and on some other markets that are more accessible to us.

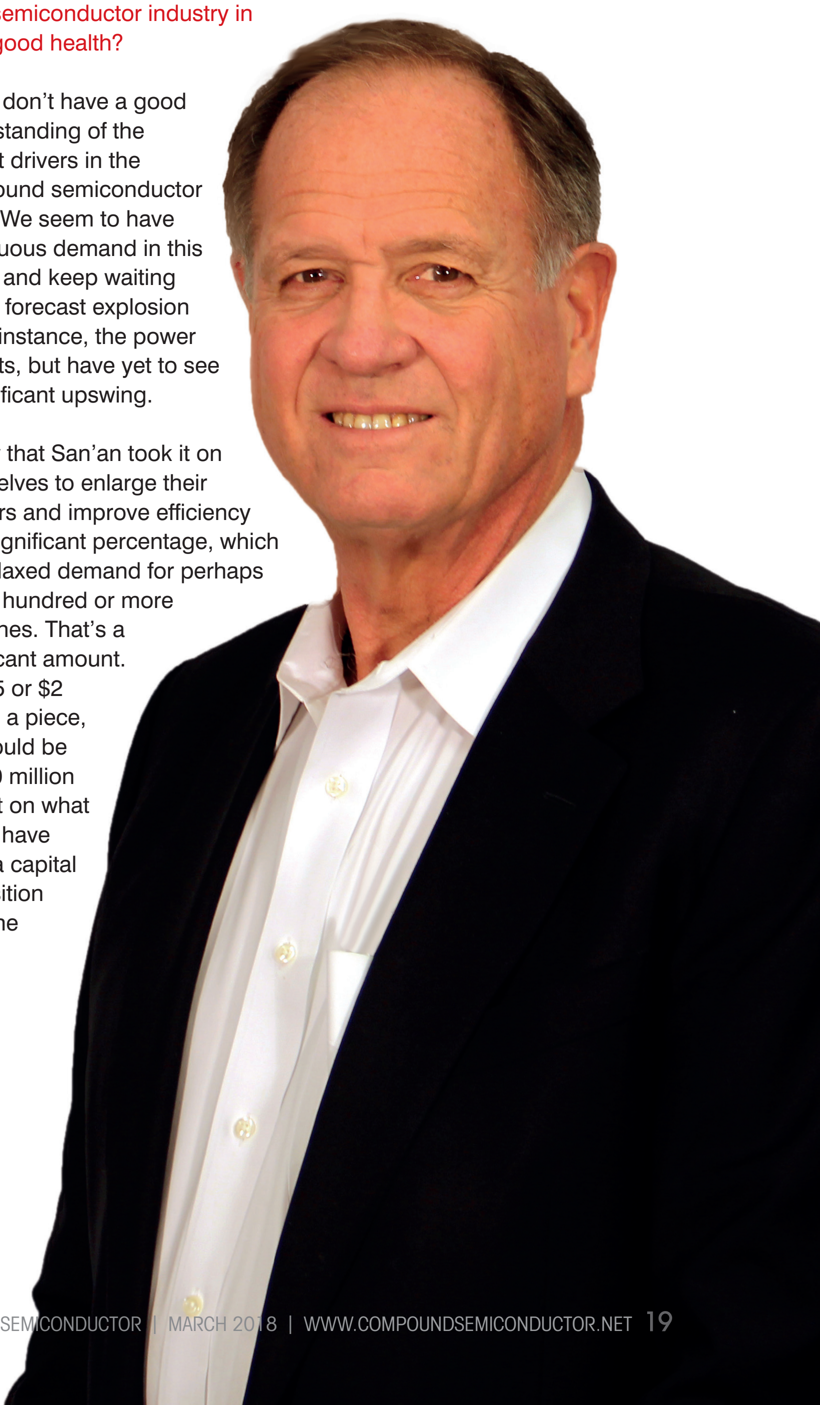
I don't see those products coming over here. But never say never.

Right now we're at capacity, and trying to find the right experienced talent to grow through 2020 and beyond. Experience is difficult to find so we are hiring younger engineers, and then mentor them for three to five years. It is difficult to increase capacity by 20 percent in a technical market.

Q From your perspective, is the compound semiconductor industry in good health?

A I don't have a good understanding of the market drivers in the compound semiconductor fields. We seem to have continuous demand in this sector and keep waiting for the forecast explosion in, for instance, the power markets, but have yet to see a significant upswing.

I know that San'an took it on themselves to enlarge their reactors and improve efficiency by a significant percentage, which has relaxed demand for perhaps fifty or hundred or more machines. That's a significant amount. At $1.5 or $2 million a piece, that could be a $200 million impact on what would have been a capital acquisition from the major



Steve Buerkel is President and sole stockholder of Applied Energy Systems. He took over the company in 1978, ten years after its founding, and has held the position of President of the company for 40 years.

Megaturion MultiCylinder Bulk NH_3 System.

supplier. Some of the laser guys are expanding. But that is just one tool here or a couple of tools there. It's not like a hundred tools in a new fab for LED manufacturing. The tool manufacturers have a better sense for the market growth here than I do.

Q How much interest are you seeing from the developers and producers of GaN power electronics?

A Power electronics is growing at double-digit compound annual growth rates in terms of devices, and we do have some of our customers in this market spending on facility capital improvements. But not as much as forecast. Two or three years ago, they were forecasting very large capital growth in this industry, and I haven't seen it.

One company said that two or three years ago that they were going to put in ten or fifteen reactors, and they put in one.

Q Are there any other sectors within the compound semiconductor industry that are showing significant promise?

A There are some solar cell companies doing some interesting things. One in California, owned by a Chinese parent, is growing III-V solar cells on large areas. They have very high flows of a very toxic liquefied gas, so the challenge there is understanding the thermodynamics, making sure we don't have any cylinder cross flows due to thermodynamic differences and some other operational risks. We know ammonia pretty well now. We supply equipment for anything up to 1000 litres a minute.

This two day event covers five themes

Speakers announced to date

Wrestling Market Share from Silicon Power Devices

What are the next opportunities for SiC? And how can GaN gain significant traction in the market place?

ANALYST

- **Richard Eden: IHS Markit** The SiC & GaN power semiconductor market: Forecasts and drivers

SPEAKERS

- **Felix Grawert: AIXTRON**
  Accelerated adoption of wide bandgap devices in automotive applications
- **Philip Zuk: Transphorm** Shifting gears: The "GaN-ification" of automobiles
- **Peter Friedrichs: Infineon** Exploiting the merits of GaN and SiC
- **Hiroyuki Handa: Panasonic** Trimming the losses in GaN GITs
- **Tamara Baksht: VisIC Technologies**
  High efficiency at high power density: realisation of GaN's promise for power electronics
- **Andy Sellars: Catapult** Accelerating the commercial application of compound semiconductors
- **Mohamed Alomari: IMS Chips**
  Fast-loop assessment of GaN/AlGaN epitaxial layers for power applications
- **Cem Basceri: Qromis**
  'Status updates: Volume manufacturing of high performance & scalable GaN power devices on 8-inch diameter QST platform'
- **Samantha Reese: National Renewable Energy Laboratory, USA**
  A techno-economics look at SiC WBG from wafer to motor drive
- **Phil Greene: Ferrotec**
  Efficient metal deposition with the Ferrotec UF6100 200mm lift-off evaporator
- **Sarah Okada: Revasum** Simplified SiC backside thinning
- **Mikko Soderlund: Beneq** High-capacity wafer-scale solutions for More than Moore Applications

- **Anoop Somanchi: KLA-Tencor**
  Defect inspection and process control solutions for compound semiconductor materials
- **Benoit Ravot: Nanometrics**
  Process control solutions to maximize yield in HVM for SiC and GaN power devices
- **Speaker TBC: Nanowin** Presentation Topic TBC

5G: Where are we and What's Next?

What form will 5G take? And how good will 5G be for GaAs and GaN?

ANALYST

- **Eric Higham: Strategy Analytics** Is 5G roll-out a certainty? And will it be good for GaAs and GaN?

SPEAKERS

- **Scott Vasquez: Qorvo** Building the industry's first 5G front-end
- **Liam Devlin: Plextek RFI** MMICs - what is needed to get mmWave 5G to work?
- **Marianne Germain: EpiGaN** GaN Material Solutions for 5G
- **Somit Joshi: Veeco**
  Enabling GaN RF and power electronics through innovative MOCVD and wet etch process technologies
- **Qing Wang: Sino Nitride Semiconductor**
  High-quality free standing substrates

Ramping Revenues from RF Devices

What are the opportunities for III-Vs in defense and civilian markets? Will higher frequencies open up new sales?

ANALYST

- **Asif Anwar: Strategy Analytics**
  Defense sector trends and the associated market outlook for compound semiconductors

SPEAKER

- **Nick Cataldo: Efficient Power Conversion** Wireless charging with GaN devices
- **Timothy Boles: MACOM** Industrializing RF GaN/S

Finding Solutions with Heterogenous Integration

Where will the growth of compound semiconductors on silicon deliver a fundamental change? And what are the tricks to ensure success?

ANALYST

- **Hong Lin : Yole Développement**
  Presentation TBC

SPEAKERS

- **Thomas Uhrmann: EV Group**
  Wafer bonding of compound semiconductors: Achieving desired interface properties
- **Jean-Pierre Locquet: GaNonCMOS EU Project**
  Dense integrating GaN power switches with CMOS drivers
- **Wolfgang Stolz: NAsP III-V**
  Building III/V-devices on CMOS-compatible Si (001)
- **Lars-Erik Wernersson: Lund University**
  Integrating III-V nanowires to advance CMOS system-on-a-chip technologies
- **Speaker TBC: Nanotronics**
  Topic TBC

LEDs: Magnifying Margins

Which sectors offer the best returns? Does the bottom line get the biggest benefit from streamlining manufacturing, or from optimising the chip?

ANALYST

- **Pars Mukish: Yole Développement**
  Revolutionising displays with MicroLEDs

SPEAKERS

- **Samuel Sonderegger: Attolight**
  Improving LED manufacturing by full wafer cathodoluminescence
- **Leon Baruah: Seoul Semiconductor**
  Improving LEDs with a Wafer Level Integrated Chip on PCB (WICOP) architecture
- **J.C.Chen: Ostendo Technologies**
  The monolithic full-colour LED and its applications
- **Keith Strickland: Plessey Semiconductors**
  Horticultural lighting offers growth opportunities

SiC: Going through the gears

There's a positive outlook for the SiC device market. Sales of Schottky barrier diodes are well-established, and shipments of the MOSFET are tipped to take off over the next three years

RICHARD STEVENSON REPORTS

Rohm is now providing full SiC power modules to the Venturi Formula E team. In Venturi's latest race car, the inverter is 43 percent smaller and 6 kg lighter than that of silicon-based predecessor used for the 2015/16 season.

The 16th February, 2017, could well go down in history as the most important day in the SiC industry. At that point in time, the US Committee on Foreign Investment barred Infineon from buying Wolfspeed.

If the acquisition had proceeded, an $850 million cash deal would have equipped the German power electronics manufacturer with an incredibly strong position within the SiC power device market. Not only would it have had more than half of all global sales, which approached $300 million in 2017, according to market analyst Yole Développement – it would have given the company the leading source of substrate production. Armed with this, it could influence the supply of material for all its rivals, and adopt a vertically integrated approach to its own chip production, using the cream of the substrates that it manufactured.

Unsurprisingly, many of Infineon's peers breathed a sigh of relief when the deal fell through.

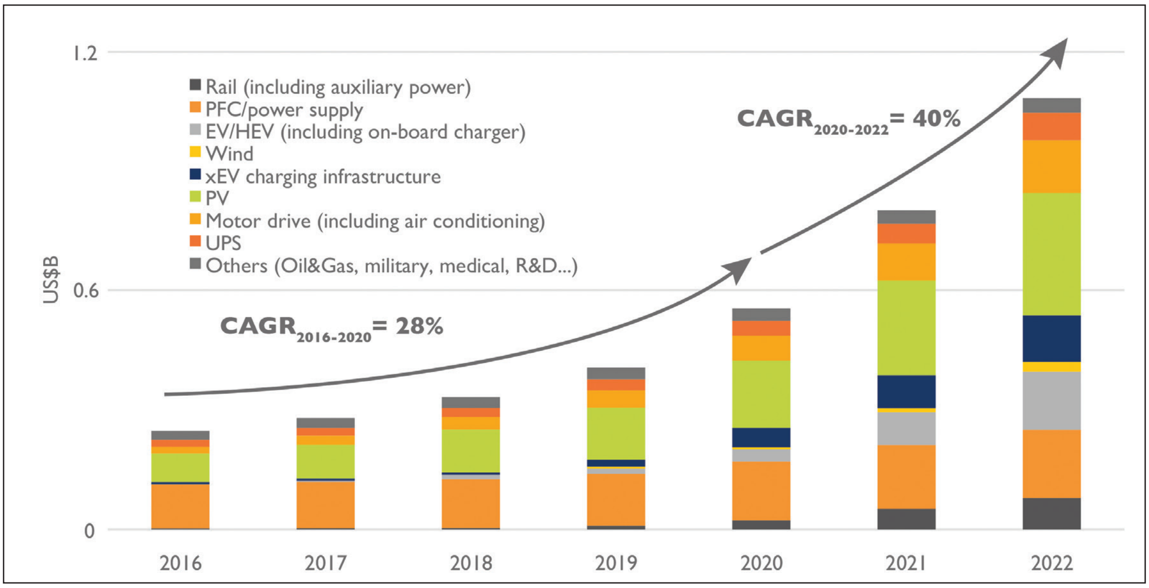
"The key competitors are happy," says Hong Lin, a technology and market analyst at Yole Développement. She believes that the failure of the acquisition has given competitors the space to develop. "That will give the end user a choice of different suppliers. When there is only one dominant supplier, that's not necessarily good for the market."

Dominating diodes

Even with the failure of the Infineon-Wolfspeed deal, there's not much space for the little guy. Sales are dominated by SiC Schottky barrier diodes, which currently account for more than 80 percent of the SiC power device market, according to Lin – and over half of those sales are going to Infineon and Wolfspeed.

The other two big players, Rohm Semiconductor and STMicrolectronics, are also big names in the power industry. "On-Semi have their products that they are launching, so they could be an important supplier in the future."

Infineon is the longest-serving manufacturer in this market, having introduced its first SiC Schottky barrier diode back in 2001. It is now offering a sixth



Yole Développement is predicting tremendous growth in the SiC market, led by a hike in MOSFET sales.

generation product. Gains between one generation and the next are more evolutionary, than revolutionary, according to Lin. She argues that this form of diode is now mature, although it is still improving in areas such as current handling and reliability – and the chip is getting smaller.

Lin says that the price of the diode has dropped significantly since its launch at the turn of the millennium. "In the past five years the price has dropped by 50 percent, but we think the pace will slow down a little bit, and be less than ten percent year by year."

Manufacturers of these Schottky diodes are keen to migrate production from a 4-inch to a 6-inch line. "However, there is still a short supply of 6-inch [substrates], so both of them are used," explains Lin.

The majority of diode sales are for products providing blocking voltages of 600 V, 1.2 kV and 1.7 kV. However, there are also products with a 3.3 kV rating. According to Lin, the primary application for 600 V SiC Schottky barrier diodes is in power factor correction circuits for power supplies. The diodes with the higher blocking voltages are used in photovoltaic inverters, and in powers supplies with higher ratings.

To reach even higher blocking voltages, needed for the engines of electric trains, some companies are developing SiC *p-n* diodes. The leader of this device is Wolfspeed. Note, however, that it's not easy to compare its technology with that of the leading companies in Japan. "Japanese companies mostly use SiC products for internal use, so even though they have this kind of product, they are not necessarily on the market," says Lin.

Mushrooming MOSFETs

Part of the motivation behind Infineon's attempt to purchase Wolfspeed is that it would have equipped the German outfit with a leading MOSFET technology. "Infineon have long-term experience in SiC, in general, but they are late for SiC MOSFET products," says Lin. "Their first product was released in 2016." Part of the reason for this is that Infineon spent many years pursuing the SiC JFET, only to discover that this product did not find favour with end users.

Wolfspeed and Rohm are currently the leaders for the SiC MOSFET. "But based on their client portfolio, and their understanding of power electronics, Infineon could quickly catch up," says Lin.

There are also some start-ups that are trying to enter this market. "They have some prototyping, but to go to mass production will be another issue," says Lin.

If start-ups are to enjoy any success, they will need to differentiate themselves from the established players. "I think they will try to use the foundry model," says Lin, who believes that this approach could lower production costs. "In terms of mass production – personally, I would like to say that the big companies have more advantages."

Many SiC MOSFETs manufacturers also make SiC diodes. "I think that customers try to buy products from the same manufacturers," says Lin, who adds that it is much more challenging to make a MOSFET.

She says that there are still concerns over the reliability of the SiC MOSFET. "For example, there are standards for silicon devices. For all wide bandgap devices – for SiC and for GaN – they don't have established standards. They still need some international co-working to develop standards."

There is also a need for more field testing of the SiC MOSFET. There are many prototypes, some of which are already in use, but very little data on the performance of these devices.

During the next few years Lin is tipping the sales of the SiC MOSFET to take off. "In the next two or three years, we will see SiC MOSFETs massively deployed. At the moment we are still on small-volume sales."

Due to the small volumes, SiC MOSFETs are currently manufactured on 4-inch SiC substrates. As these devices are more challenging to make than Schottky barrier diodes, there is more concern over substrate quality, which applied the brakes to the transition to 6-inch substrates, which are in short supply.

Prices for MOSFETs are falling fast, with this device is seeing traction in the market. Opportunities exist in the photovoltaic industry, and in on-board chargers for electric vehicles. For example, leading Chinese electric vehicle manufacturer BYD recently confirmed that it is using SiC in its on-board chargers. SiC is also hitting the headlines for its deployment in Formula Electric, with Rohm's SiC power devices slashing losses in the inverter, while offering the capability to operate at higher temperatures.

The rise of the module

In addition to discrete diodes and MOSFETs, the SiC power industry has a third source of revenue: SiC modules. It is a really small proportion of the market right now, but it is set to grow.

"There are lots of kinds of modules," explains Lin. "You have the old generation, using old IGBT packaging. And then you have a lot of innovative packaging designs, for example, Fuji Electric."

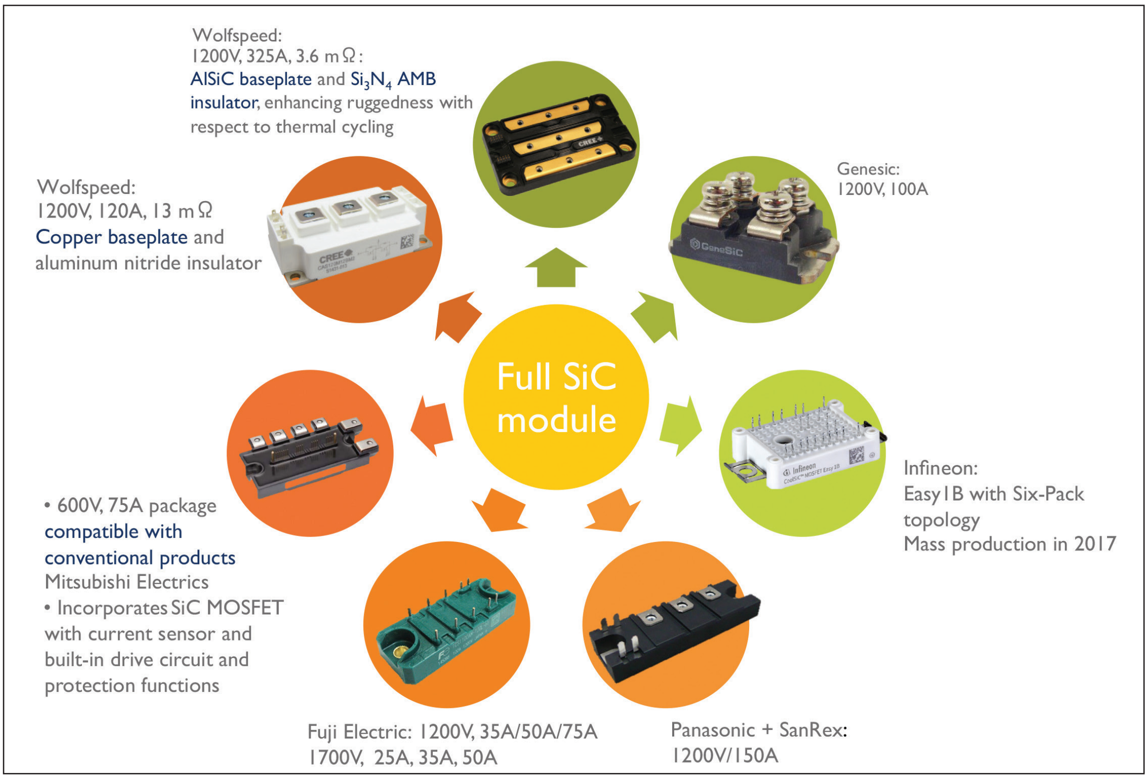
Customers are often seeking bespoke designs. They may involve new materials – producers are trying to maximise the performance of the SiC devices with the likes of new diode attach materials, different types of heat sink, and the placing of different materials around the diodes and transistors.

Lin expects that in the high-voltage market, sales of modules will be very strong. "For 1.2 kV and above, the module will be dominant. That's not the case at the moment, because the module is very expensive."

She believes that the leading suppliers of modules may differ from those that dominate diode and transistor sales. Wolfspeed acquired APEI in 2015 to enhance its module design capability, but the company does not have that much experience in module design and manufacture compared to leading modules players. Due to this, Lin expects this sector to be led by those that do, such as Mitsubishi, Fuji Electric and Infineon.

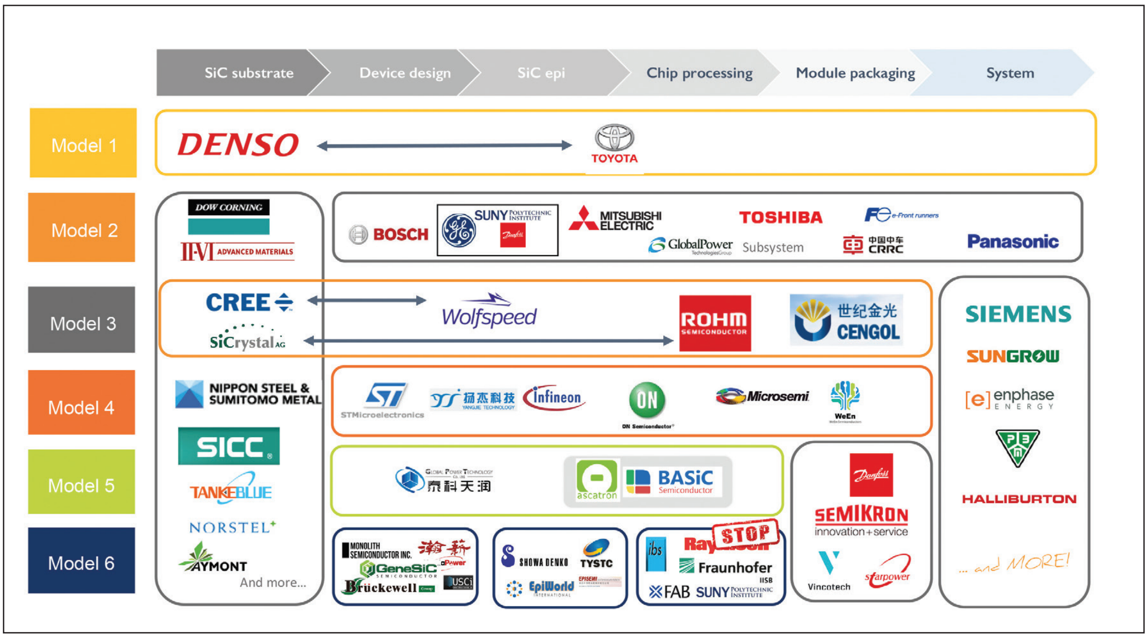
One threat to the success of SiC sales is the rival wide bandgap semiconductor, GaN, which can form devices on silicon substrates. This combination has the potential to lower the cost of wide bandgap power electronics, and stymie sales of SiC devices. However, Lin doesn't expect this to happen anytime soon.

"For the diode side, SiC is quite well established," says Lin. "The SiC MOSFET, for 1.2 kV and above, GaN is not challenging at all." She believes that GaN



SiC modules, which currently account for a very small proportion of the SiC market, come in wide variety of formats.

Many different modules are used for the production of SiC Schottky barrier diodes. The information provided in his graphic is not exhaustive. All business models are detailed and analysed in the Yole report: *Power SiC 2017: Materials, Devices, Modules, and Applications.*



could provide some competition to the SiC MOSFET in the 650 V range, but argues that SiC is more mature. "I don't think in the next five years GaN will take over SiC devices."

Instead, she expects SiC to take market share from silicon in the power device market. SiC sales are predicted to grow fast, with an estimated compound annual growth rate of 28 percent.

- More insight into the status of the SiC market may be found in the Yole Développement report *Power SiC 2017: Materials, Devices, Modules, and Applications*

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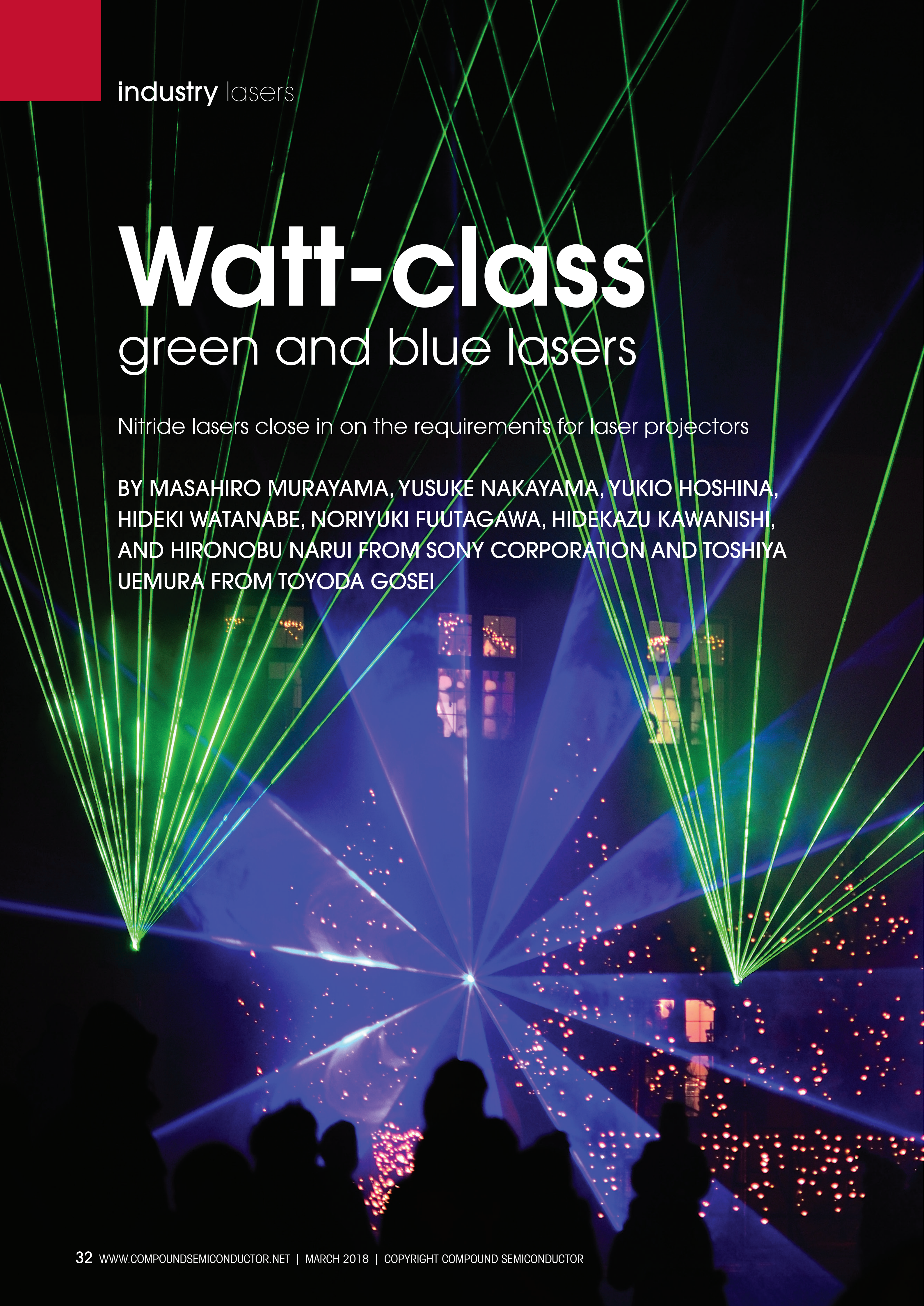

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green and blue lasers

Nitride lasers close in on the requirements for laser projectors

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SINCE MAKING ITS DEBUT in the 1990s, the GaN-based laser has made great strides in its output power, spectral coverage and reliability. Due to all these improvements, this class of device has found deployment as a 405 nm source for reading Blu-ray discs, and more recently, as a phosphor pump for directional lights, including car headlights.

More success is still to come. Sales of blue GaN lasers for automobile headlights are set to climb, and this device – plus its green cousin – are destined to provide key components in full-colour laser projectors. Efforts to expand spectral coverage even further are also starting to bear fruit, with emission spreading to the red and ultraviolet.

Arguably, of all the applications that nitride lasers can serve, the one with the most promise is that of the laser projector. For this application, light sources based on lasers have several advantages over conventional lamps and LEDs, including high brightness, high colour reproducibility, small size, and a long lifetime.

To exploit these excellent characteristics, various products are being developed, including head-mounted displays, mobile projectors, business and home projectors and digital cinema projectors.

As displays get larger, the demand for high-output lasers increases. High-brightness projectors require lasers with an output of one Watt of more.

One of the key figures of merit for the projector is its luminance. Today, this is typically several thousands to tens of thousands of lumens, realised by employing tens to hundreds of blue lasers. To reduce this number, which could cut costs and trim the size of the light source module, the power produced by the laser must increase.

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Ideally, increases in power would be accompanied by a hike in efficiency. Do this and it is possible to reduce the tremendous amount of heat generated by high-power lasers, and ease the demands placed on the special cooling mechanism needed to prevent overheating.

Another desirable attribute for these lasers is an emission wavelength that enables the light engine to meet the next standard for colour space, set to be adopted for future 8 K displays: the ITU-R Recommendation BT.2020. This standard provides a far wider pallet of colours than the current one, and will offer the ultimate video experience (the BT.2020 covers almost 100 percent of Pointer's gamut of real world colours that humans can see, compared to 74.4 percent for BT.709).

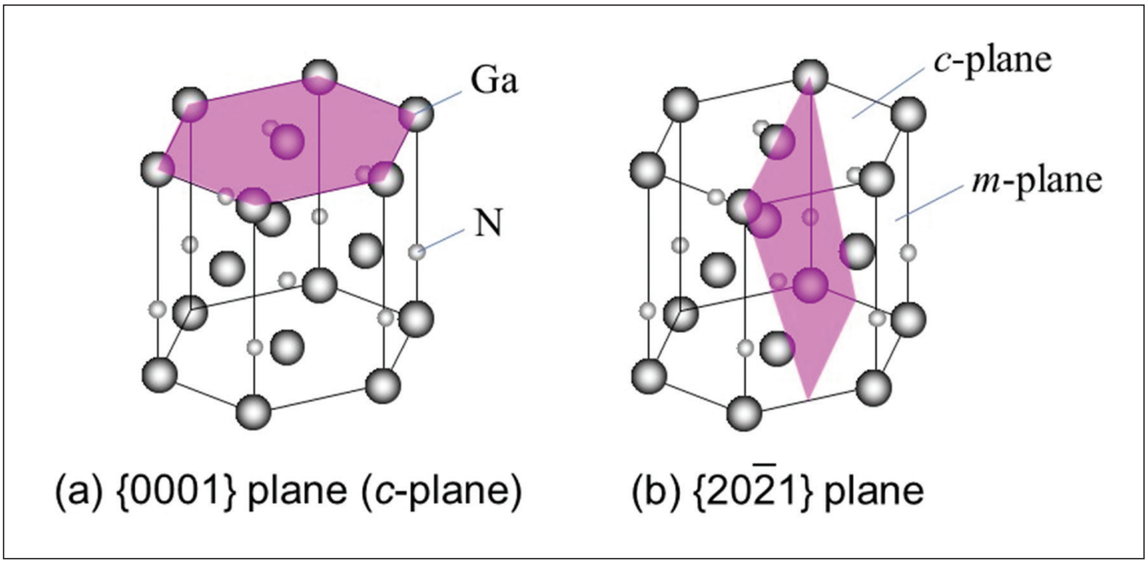


Figure 1. Switching from the *c*-plane to the {20$\bar{2}$1} plane in GaN enhances the performance of green or longer-wavelength light-emitting devices, due to the combination of a weaker piezoelectric field and good indium incorporation.

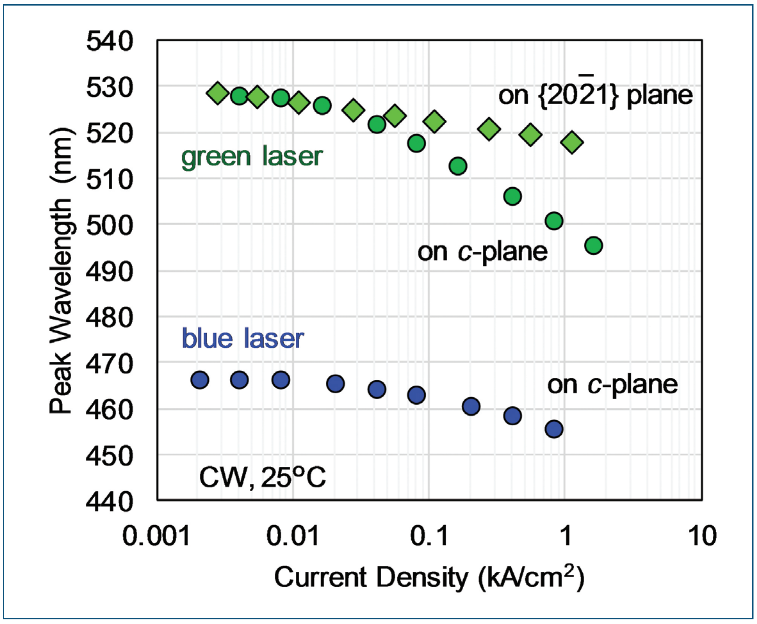


Figure 2. Dependence of electroluminescence peak wavelength on current density for a blue laser fabricated on the *c*-plane, a green laser fabricated on the *c*-plane, and a green laser fabricated on the {20$\bar{2}$1} plane. For each laser, the operating current was increased gradually up to near the threshold value. Clearly, there is a much larger blue shift for the green laser fabricated on the *c*-plane than for the blue laser. This suggests that the piezoelectric field and indium inhomogeneity in the InGaN active layer increase at longer wavelengths. On the other hand, the blue shift for the green laser fabricated on the {20$\bar{2}$1} plane is smaller than that for the laser fabricated on the *c*-plane.

To fully satisfy the BT.2020 standard, monochromatic red, green and blue light sources are required that sit on the spectral locus. One option is to use quantum dot phosphors. However, to realise high colour purity and high efficiency, cadmium-based quantum dots must be employed, and they have the drawback of being harmful to the human body.

Alternative forms of dots that are free from cadmium are under development, but lagging in efficiency. Consequently, it is the view of our team from Sony Corporation and Toyoda Gosei that red, green and blue lasers offer the best solution as light sources for next-generation displays that meet the BT.2020 standard.

Device makers

Two of the pioneers of high-power, GaN-based lasers are Nichia and Osram Opto Semiconductors. Using the c-plane of GaN, Nichia has reported an output power of almost 5 W for a 455 nm blue laser and 1 W for a 525 nm green laser, while Osram has announced a 450 nm blue laser producing 3.5 W. These results are impressive, but to fully satisfy the BT.2020 standard, the lasers need to emit longer wavelengths – such as 467 nm in the blue and 532 nm in the green. These are the targets that our team is pursuing, as we develop high-power, high-efficiency lasers.

We have had success in this endeavour, which we partly attribute to the use of semi-polar planes. We select the orientation {20$\bar{2}$1} – it is tilted by 75° from the *c*-plane toward the *m*-plane (see Figure 1).

Calculations suggest the piezoelectric field in material grown on this plane is only about one-third of that for the c-plane. That implies a substantial reduction in the strength of the electric field, and the promise of a significant boost to the performance of light-emitting devices. That's because the weaker the field, the greater the overlap of electron and hole wavefunctions in the well, and the greater the likelihood of radiative recombination.

What's more, when InGaN quantum wells are fabricated on the {20$\bar{2}$1} plane, rather the *c*-plane, the indium distribution and well thickness are more uniform. Both these features can lead to a further hike in radiative performance.

We can see the benefits of the semi-polar {20$\bar{2}$1} in our devices, which we grown by MOCVD. Measurements confirm that green lasers grown on that semi-polar plane have a far smaller blue shift with increasing current than their conventional cousins (see Figure 2). That's because c-plane lasers are plagued by a stronger piezoelectric field and a greater variation in indium distribution within the quantum well.

We take the level of performance of our green lasers even higher by employing an indium tin oxide (ITO) top contact for the *p*-side electrode (see Figure 3). To ensure a good contact to the *p*-type layer, this oxide is deposited on the ridge and then annealed.

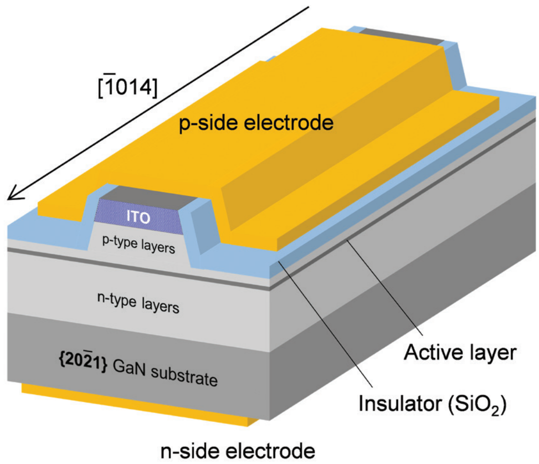


Figure 3. Sony's green lasers are formed by using MOCVD to deposit a GaN-based epitaxial stack on a {20$\bar{2}$1} GaN substrate. ITO is used on top of the ridge. The stripe orientation is parallel to the [$\bar{1}$014] axis.

One of the benefits of turning to ITO is that it can improve the optical performance of the laser. Its refractive index, typically 2.0, is much lower than that of the active region, allowing it to contribute to the optical cladding and ultimately ensure good vertical optical confinement. Thanks to this, a trimming of the thickness of the high-resistivity *p*-type AlGaN cladding layer may follow, leading to a lower device resistance. On top of these gains, internal loss, typically 1 cm^{-1} or less, is lower than it would have been when using a highly absorptive metal contact.

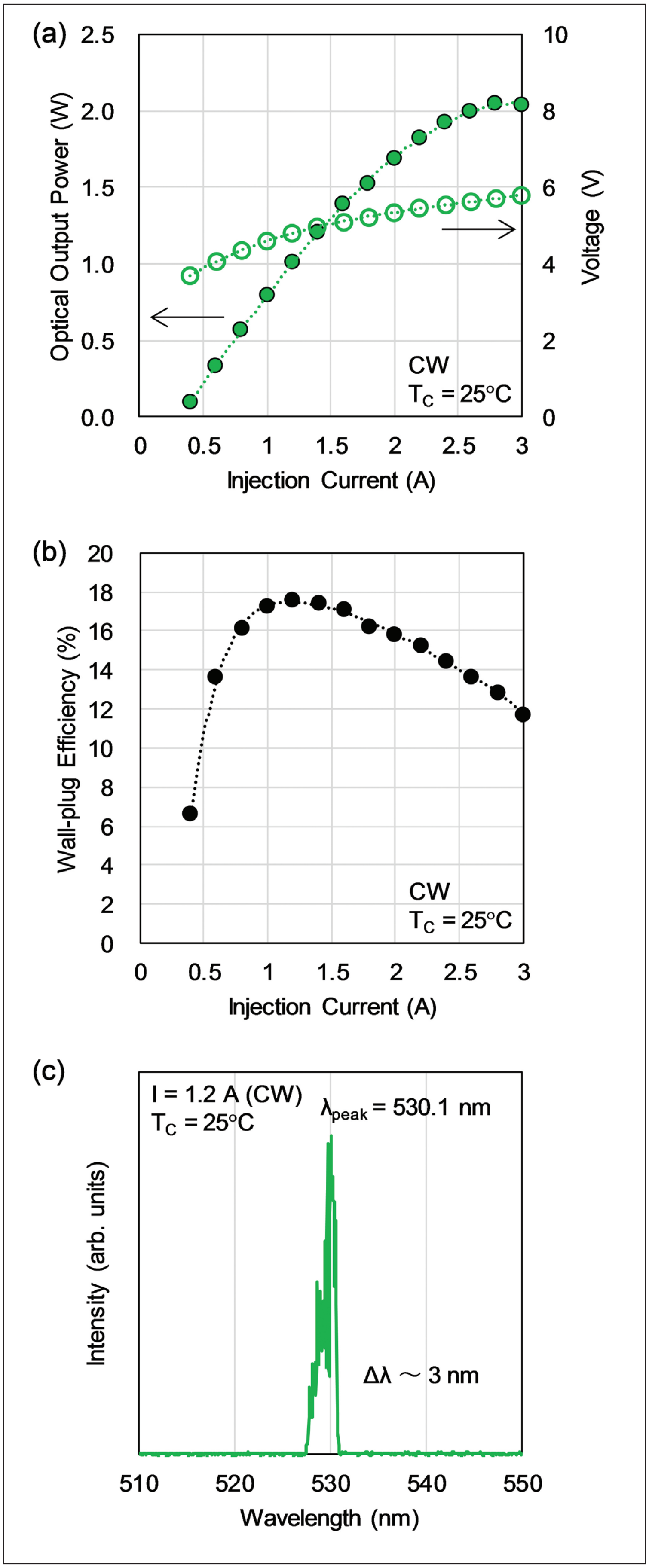
Armed with ITO contacts and a semi-polar plane, our green lasers produce an optical output in excess of 2 W – that is the highest value reported to date for a green laser (see Figure 4). The wall-plug efficiency for this device can reach 17.5 percent.

These green lasers are offering many of the attributes that are valued for laser displays. Emitting at 530 nm, they can help to meet the BT.2020 standard. In addition, they can deliver a long-term stable output power of approximately 1 W; and they have an estimated lifetime of more than 20,000 hours at a case temperature of 60°C, which is typically the minimum required lifetime for laser display applications. Encouragingly, these impressive results are not the limit of what is possible, and an even higher level of performance is to be expected, following refinement to the growth conditions and optimisation of the structure of the epitaxial layers.

Better blues

Like their green cousins, we produce our blue lasers by MOCVD growth on GaN substrates; and we use ITO electrodes, which contribute to the optical cladding. However, as the shorter wavelength diminishes the benefits of the semi-polar plane, we use *c*-plane GaN as the foundation for these sources.

Driven at 3 A, our 465 nm lasers deliver an optical output of up to 5.2 W and a wall-plug efficiency of 37.0 percent (see Figure 5). Note that these are the highest values reported within this spectral domain. This laser provides a pure blue light source for meeting the BT.2020 specification, and it is capable of



Right: Figure 4. Optical and electrical characteristics of Sony's green lasers. The output power and forward voltage are plotted in Figure 4(a) as a function of injection current under CW operation at 25°C. An output power of approximately 1 W was obtained at 1.2 A, and the maximum output power was 2 W, which is the highest value reported to date. The wall-plug efficiency, plotted in Figure 4(b), was calculated to be 17.5 percent at 1.2 A, which is also the highest value reported to date. Under an operating current of 1.2 A at 25°C, the lasing spectrum shown in Figure 4(c) exhibited a peak at 530 nm, which is suitable for laser display applications meeting the BT.2020 standard.

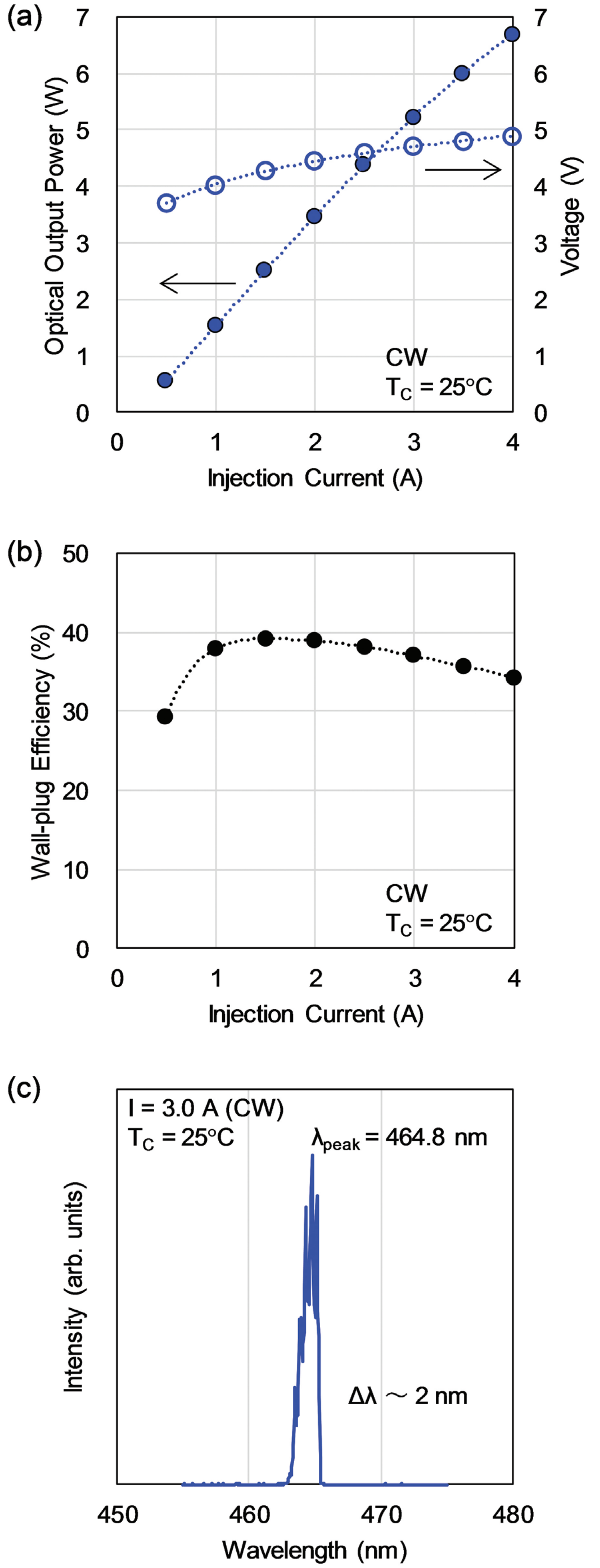


Figure 5. Optical and electrical characteristics of a Sony blue laser under CW operation at 25°C. The output power and wall-plug efficiency, shown in Figures 5(a) and 5(b), were 5.2 W and 37.0 percent, respectively, at a current of 3.0 A. The lasing spectrum, shown in Figure 5(c), had a peak at a wavelength of 465 nm, which is also suitable for laser display applications that meet the BT.2020 specifications, similar to the green laser with a wavelength of 530 nm.

long-term stable operation. Its lifetime is estimated to exceed 20,000 hours at a case temperature of 60°C.

We have also produced blue lasers that emit at 445 nm. They deliver a slightly superior performance, thanks to a reduction in the strength of the piezoelectric field and improved crystallinity. Driven at 3 A, these devices can produce 5.7 W at a wall-plug efficiency of 41.3 percent.

The shorter wavelength of these sources makes them suitable for phosphor excitation. They could be used in car headlamps, or in laser phosphor projectors.

Upping the power

Demand for higher-output, higher-efficiency laser diodes shows no sign of abating; thus, there is the desire for further improvement in these areas. While an output power of around 1 W in the green is a big improvement compared with what was possible a few years ago, it still fails to satisfy market demand, falling short of the excellent value of 5 W achievable with blue lasers. Consequently, there is urgent demand for a higher-power green laser. To address this, we are focusing on: increasing internal quantum efficiency of this device, to improve the light output with current; and reducing internal loss, as this will lead to a higher output power and wall-plug efficiency.

It is worth noting that while the wall-plug efficiency of high-power lasers emitting in the green and blue has been improving in recent years, these devices still fall short of the figures for the LED cousins. It may take several years for lasers catch up and overtake, but when they do, it will open the door to a large market share for lasers in display and lighting applications.

Further reading

M. Murayama *et al*. Physica Status Solidi A 2017, 1700513

This two day event covers five themes (Speakers announced to date)

Refining the PIC: Achieving the Next Milestone in Performance

What are the leading approaches for integrating key building blocks at the chip-level and how can we bring together electronics and photonics more efficiently?

SPEAKERS

- **Michael Lebby: Lightwave Logic**
  Scalable PIC platforms: The impact of using polymer PICs for 100 and 400Gbps datacom applications
- **Wim Bogaerts: Ghent University/imec**
  Programmable photonic ICs: making optical devices more versatile
- **Tan Yong Tsong: Institute of Microelectronics**
  Coupling electronics and photonics – promising paths for device-makers to explore
- **Sasan Fathpour: CREOL, The College of Optics & Photonics**
  Silicon photonics beyond silicon-on-insulator - emerging solutions for integrated photonics
- **Yvain Thonnart: CEA-Leti**
  Integrating photonic building blocks towards complete electro-optical computing
- **Shinji Matsuo: NTT Photonics**
  III-V membrane lasers on silicon for datacom and computercom applications

Delivering the goods: Advances in PIC Manufacturing

What are the latest tools and techniques that can be deployed in the fab? And what are the options when it comes to evaluating the output?

SPEAKERS

- **Jessie Rosenberg: IBM**
  Inline wafer-scale photonic testing to boost PIC manufacturing efficiency
- **Graham Reed: CORNERSTONE**
  CORNERSTONE: Silicon photonics fabrication capability based on DUV lithography
- **Michael Geiselmann: LIGENTEC**
  Silicon nitride for new PIC applications
- **Florent Gardillou: Teem Photonics**
  Photonics on glass : The ioNext PIC platform
- **Arne Leinse: LioniX International**
  Silicon nitride based TriPleX PIC modules in a broad range of applications
- **Henk Bulthuis: Kaiam Corporation**
  Vertical integration: bringing key elements together to match PICs to the market
- **Scott Jordan, Physik Instrumente**
  99% alignment cost reduction through novel parallel technology – An enabler for SiP production economics
- **Ignazio Piacentini, FiconTEC**
  Better and faster assembly and testing: recent advances and innovations in automated manufacturing equipment

Moving the Data: PICs for Cloud Computing and Telecoms

Data centres and networks need smart solutions to manage the sharp growth in traffic. What can integrated photonics bring to the table and how can developers make sure their products appeal to key customers?

SPEAKERS

- **Vincent Zeng: Facebook**
  PIC opportunities for datacentres
- **Yuichi Nakamura: NEC Corporation**
  Big data analysis - a golden opportunity for silicon photonics
- **Martin Schell: Fraunhofer HHI**
  The Zettabyte is not enough: Volume handling for InP, silicon photonics, and hybrid photonic integration
- **Radha Nagarajan: Inphi**
  Silicon Photonics for distributed data centre interconnects
- **Weiming Yao: JePPIX/PITC**
  III-V photonic integrated circuits for telecoms and beyond
- **Peter Winzer: Nokia Bell Labs**
  Massive array integration and the need for a holistic digital/analog optics/electronics co-design
- **Eric Mounier: Yole Développement**
  Data centre technology - the big PICture, opportunities for energy efficient photonics
- **Ruth Houbertz: Multiphoton Optics**
  Quo vadis – Industrial high-precision 3D printing
- **Eli Arad: Colorchip**
  Emerging integrated optics: An approach to high-volume manufacturing

PIC Design, Simulation and Packaging: A Blueprint for Future Success

How can we implement ideas faster and what needs to be considered to keep the final device cost on track?

SPEAKERS

- **Peter O'Brien: Tyndall National Institute** PIXAPP – Open Access Opportunities for Advanced PIC Packaging
- **Robert Scarmozzino: Synopsys** PIC Design: From concept to manufacture
- **Christopher Cone: Mentor Graphics** From schematic to layout – overcoming today's PIC design challenges
- **André Richter: VPIphotonics** Scalable design of integrated photonic and optoelectronic circuits
- **Pieter Dumon: Luceda Photonics** Moving the edges in PIC process design kits
- **Twan Korthorst: PhoeniX Software** Driving the PIC revolution

PIC Horizons: New and Emerging Applications for Integrated Photonics

How can developers capitalize on opportunities for optical platforms in growth areas such as medical diagnostics, industrial sensing and biological analysis?

SPEAKERS

- **Milan Mashanovitch: Freedom Photonics**
  Low size, weight and power (SWaP) instruments for sensing applications - cutting edge PICs
- **Sascha Geidel: Fraunhofer ENAS**
  Adding the 'tech' to biotech - opportunities for photonic integrated circuits
- **Andrew Sparks: Analog Devices**
  Lidar for autonomous driving: Key technological opportunities

Panel: Has Silicon Photonics got the Required Scalability to Displace InP?

Silicon photonics has attracted the interest of many in large corporations, SMEs, and academics as a potential replacement to the incumbent PIC technology InP. Given these conditions, the question remains to ask if SiP can be truly scalable towards $1/Gbps at 400Gbps data rates and above (for any distance)?

Bert Jan Offrein – IBM
Di Liang - Hewlett Packard Enterprise
Robert Blum – Intel
Sean Anderson – Cisco

Panel: High volume and high performance opportunities for PICs

Will transceivers ever achieve super high volumes to allow scalability in cost and performance, and if so, what would be the common large volume platforms, and more specifically, what would be the transceiver format/form factor?

Drew Nelson – IQE
William Ring – POET Technologies
Philip Gadd – Intel
Peter Winzer – Nokia Bell Labs

Can ZnO light up the world?

Will it be possible to overcome doping issues in ZnO, and unleash the potential of LEDs and lasers made from this material system?

BY FAIZ RAHMAN FROM OHIO UNIVERSITY

GaN has provided the foundation for the success of blue lasers, blue LEDs and, by extension, white LEDs as well. It is this material system that is underpinning the success of entire solid-state lighting industry of today.

There is little doubt that GaN will retain its role as the de-facto material for generating blue, violet and long-wavelength ultraviolet radiation. Its technology, from both a material and process standpoint, has matured to a point where GaN-based light-emitting devices have become commodity products – widely available and very affordable. While transforming the lighting industry, they have undergone two decades of refinement, and now, by widespread consensus, they have reached the pinnacle of perfection. In the coming years, further improvements will be realised in the various metrics that characterise these optoelectronic devices. However, the resulting performance gains will be, at best, very modest. What's needed to take the performance of solid-state devices to an entirely new level is a new material system, possibly accompanied by new device architectures.

That's a route that has often been taken within the semiconductor industry. A study of its history showcases the transformation in performance that can be realised with new materials. Back in the early 1960s, the microelectronics industry made great headway when switching from germanium to silicon. And more recently, further progress has resulted from the emergence of GaAs as a semiconductor of choice for building extremely fast devices.

It is possible that a similar development could take place in optoelectronics, by replacing GaN with a II-oxide compound semiconductor: ZnO (see figure 1). Its potential for making semiconductor light-emitters that outperform those made from GaN has been known for several decades. However, unlocking its promise and realising practical ZnO-based devices has been far from easy. In the remainder of this article, we shall consider why that is the case, review the present status of development of ZnO-based LEDs, and examine the challenges that remain to develop commercially viable devices.

GaN versus ZnO

The best place to start is to compare ZnO and GaN – and to focus on the properties that are relevant to making high-performance LEDs. Roughly speaking, ZnO has superior optoelectronic properties to GaN, but it is impaired by its mechanical characteristics (see Table 1). These differences account for the love-hate relationship researchers have had with ZnO for more than two decades.

One key difference between these two wide bandgap materials is that GaN is harder and less susceptible to point defects, while ZnO is soft and prone to defects, such as vacancies and interstitials. This characteristic of ZnO is easy to see when in either powder or crystal form, and heated to temperatures that are high enough to change its colour from white to yellow. This thermochromic change is due to an increase in oxygen vacancies.

ZnO has the upper hand when it comes to exciton binding energies. In this oxide the exciton binding energy is very high, enabling brighter, more efficient light emitters. Another string to its bow is its lower refractive index, leading to a reduction in light entrapment within the device.

Additional, noteworthy advantages of ZnO include the availability of bulk wafers (see figure 2), ease of etching – both dry and wet – and simple techniques for producing *n*-type (donor-doped) material. What's more, a ZnO LED can be constructed entirely from this material – that is, the substrate, buffer, *n*- and *p*-type layers, the active recombination layer and the current spreading layer can all be made of ZnO. This is not the case with GaN LEDs.

Taken together, the material advantages of ZnO can simplify device processing, and can contribute to low-cost production of ZnO-based electronics and optoelectronics. LEDs made from ZnO have the potential to be cheaper than their GaN cousins, and outperform them, while ZnO laser diodes promise to exhibit narrower line widths and a lower threshold

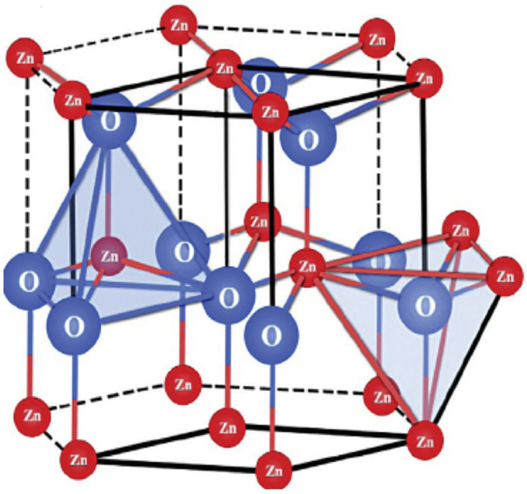


Figure 1. Lattice structure of hexagonal (Wurtzite) ZnO, showing Zn^{2+} ions (red) and O^{2-} ions (blue). This structure can be regarded as composed of Zn-centred and O-centred tetrahedra, as shown.

current. And last but by no means least, ZnO could provide an easier, cheaper route to making mid- and deep-UV light-emitting devices – an area where III-nitride devices have not been particularly successful to date.

Doping challenges

The potential performance advantages of ZnO over GaN have spurred a substantial research effort into the development of LEDs made from this oxide. Several aspects of ZnO growth and process technology require further work, but the show-stopper is establishing a method to make stable, hole-rich ZnO. Due to this weakness, most attention has been directed at developing techniques for effective *p*-type doping of ZnO.

Those working in the area will be aware of two rules of thumb: the wider the bandgap, the harder it is to dope; and *p*-type doping is more challenging than *n*-type doping (ZnTe is the notable exception, being easier to dope *p*-type).

ZnO adheres to both these trends, and it is much easier to dope with donors than acceptors. This limitation hampered the development of GaN devices, until practical techniques for preparing *p*-type GaN were developed in Japan. History appears to now be repeating itself with ZnO.

Table 1. Properties of ZnO and GaN

Property	ZnO	GaN
Lattice constant	3.25 Å	3.19 Å
Density	5.6 g/cm^3	6.2 g/cm^3
Band gap (300 K)	3.37 eV (Direct)	3.4 (Direct)
Refractive index (D line)	2.0041	2.4290
Exciton binding energy	~60 meV	~24 meV
Hardness	Low	High
Dry etching	Easy	Easy
Wet etching	Easy	Difficult
Ease of defect formation	High	Low

For this oxide, *p*-type doping is not only hampered by a wide band gap. There is also the impediment that when ZnO is undoped, it exhibits *n*-type conductivity, arising from the presence of naturally-occurring defects. The most notable of these, which are easily formed, are oxygen vacancies – that is, oxygen atoms that are not sitting in their usual positions on the crystal lattice. These defects give rise to donor energy levels close to the conduction band edge of ZnO. The intrinsic *n*-type behaviour that results leads to a substantial electron-mediated conductivity. It is so great that it allows ZnO and lightly aluminium-doped ZnO to be used as transparent conductors in applications such as transparent touch screens.

If a technique for the *p*-type doping of ZnO is to be viable, it must counter the material's natural *n*-type character and flood it with holes. Almost all the conceivable approaches have been tried, including spin-on doping, gaseous diffusion, ion implantation and plasma-phase doping (for a good review that provides a starting point for understanding the contemporary material challenges with the ZnO family of materials, see the paper by Kozuka, Tsukazaki and Kawasaki, given in the Further Reading section).

Obvious starting points for trying to realise *p*-type ZnO are to substitute group-I elements for zinc sites, or to substitute group-V elements for oxygen sites. However, despite much effort in this direction, it is still very tricky to realise acceptor-doping in this oxide semiconductor. Controlling the doping level is very challenging, because there is the need to compensate for the native *n*-type character before generating any holes. Complicating matters even further, the hole population of ZnO is drained by the continuous formation of additional electrically-active defects and defect complexes.

Hopes were raised when nitrogen-doped ZnO appeared to be a very promising candidates for creating *p*-type ZnO epilayers. However, this form of doped ZnO failed to fulfil its early promise. Nitrogen-doped material was found to be unstable at higher temperatures, and nitrogen atoms were found to suffer from limited dopant solubility in ZnO. But the good news is that while it is difficult to achieve very high hole concentrations, material with a hole number density of around 10^{18} cm^{-3} can be prepared without much difficulty.

A parallel issue is maintaining a stable hole population. Often, the number of holes diminishes over time, due to thermodynamics. Defect complex formation takes place, gradually draining *p*-doped ZnO of extrinsic charge carriers, and robbing any device of the holes that it needs to deliver its potential operating efficiency.

Finally, it is often a challenge to realise an ohmic metal contact to *p*-type ZnO. All devices require low specific resistance ohmic contacts, and ZnO throws up its own challenges, which can only be solved through proper optimization of contact metallization.

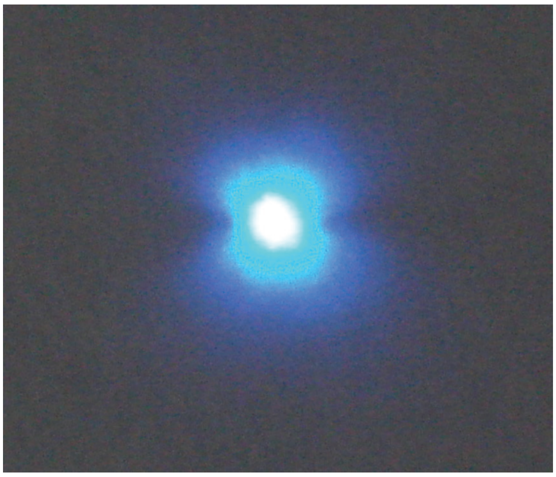
In short, if ZnO is to work as a feasible material for *p*-*n*-junction-based devices, commercial techniques must be developed that can produce a relatively large concentration of holes in ZnO that is stable over time – and accessible through practical metallization schemes.

ZnO and GaN?

Efforts at developing ZnO LEDs can be sub-divided into those associated with developing homojunction LEDs, and those pioneering heterojunction variants. Note that the term 'homojunction' is not applied that strictly within the ZnO comunity: although these LEDs have ZnO-only *p*-*n* junctions, they may contain ternary and even quaternary alloys, such as MgZnO and BeMgZnO, to make very high quality charge confinement structures. Meanwhile, heterojunction LEDs are defined as those that pair ZnO with another suitable family of semiconductor materials – usually the nitrides, in the form of GaN. One of the merits of combining *n*-type ZnO with the likes of *p*-type GaN is that it sidesteps the issue of poor *p*-type doping in ZnO, to create a promising *p*-*n* junction across a dissimilar material boundary.

Over the years, many academic and corporate research labs have demonstrated both homojunction and heterojunction LEDs. They have typical diode current-voltage characteristics, with forward voltage drops of around 4 V. Initially, these LEDs were only capable of a weak output at cryogenic temperatures, but now they can produce good optical output power at room temperature.

Like their GaN cousins, homojunction ZnO LEDs are formed by MOCVD. By incorporating various ZnO-based alloys, emission can be tuned from 350 nm to 420 nm, but output is the most intense at around 360 nm. Note that a weak broad yellow-green luminescence is often seen in these devices, attributed to background defects.



Light emission from an experimental homojunction ZnO LED. The central most luminous region appears white due to over-exposure.

Comparatively more effort has been devoted to fabricating heterojunction ZnO LEDs. Pairing ZnO with GaN makes a lot of sense, given that both have hexagonal structures, and their lattice constants differ by only 1.8 percent. These heterojunction devices are actually easier to fabricate, because they can be grown by techniques such as pulsed laser deposition and RF magnetron sputtering.

However, these devices are not fulfilling their promise. Emission often emanates from the non-ZnO component, defeating the purpose of drawing on the superior excitonic properties of ZnO. Nevertheless, these efforts have been useful, because building ZnO LEDs from dissimilar materials has taught the device makers a great deal about carrier confinement and carrier dynamics in ZnO-based devices.

Another type of ZnO-based LED that has been developed is that based on nanowires. This class of devices promise far better carrier and photon

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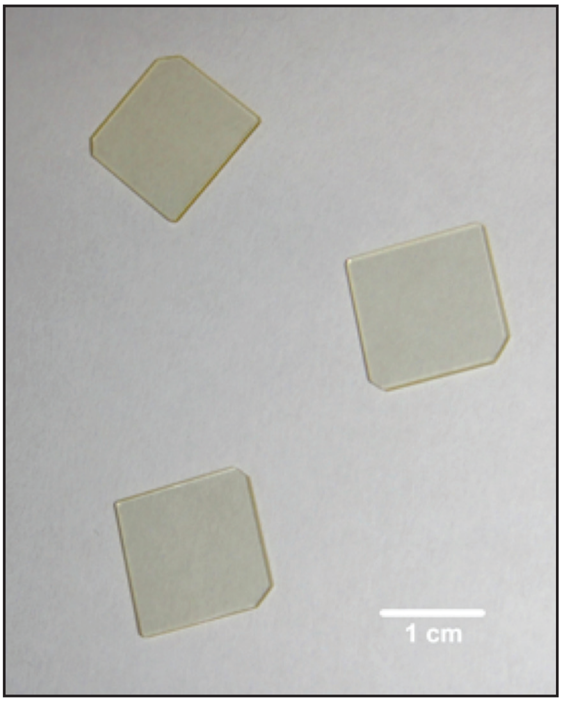

Commercial, hydrothermally-grown, un-doped ZnO wafers.

confinement; resulting in more efficient operation. Techniques such as hydrothermal growth and spray pyrolysis have yielded LEDs with an active region for carrier recombination that consists of a dense agglomeration of ZnO nanowires with diameters typically between 100 nm and 200 nm.

Getting the light out

When LEDs are made from wide bandgap materials, such as GaN and ZnO, their high refractive indices lead to the trapping of a substantial proportion of light within the device. To make the LEDs brighter, the confined light must be extracted – this is often accomplished by roughening the top surface of the chip.

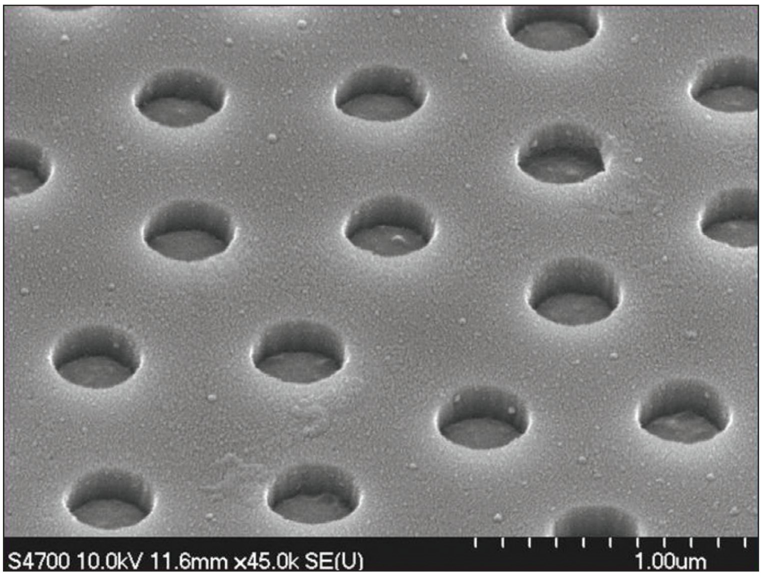

Figure 2. Typical photonic crystal structure etched on GaN surface. Very similar structures can also be fabricated on ZnO surfaces.

A similar approach, yielding better results, involves etching a regular pattern of shallow holes on the emitting face of an LED. This structure, known as a photonic crystal (see Figure 2), can extract a large proportion of the light that would be total internally reflected within the LED.

For commercial GaN LEDs, the brightness is often boosted by surface roughening and the introduction of photonic crystals. ZnO, if anything, it is even more amenable than GaN to surface structuring for the fabrication of light extracting structures. The ease with which this oxide can be etched makes it very simple to produce rough texturing and photonic crystal structures on ZnO LED surfaces, further enhancing their brightness.

The promise of ZnO as an optoelectronic material is not limited to LEDs, but extends to blue, violet and ultraviolet laser diodes. Making short wavelength semiconductor lasers is not easy, but the higher exciton binding energy found in ZnO can be a major asset. Thanks to this, ZnO semiconductor laser diodes can be brighter and more efficient than their GaN counterparts. Furthermore, they have the potential to be low threshold devices, operating with low power consumption.

Due to more exacting requirements on materials for making diode lasers, ZnO-based lasers trail their LED counterparts. However, once LEDs based on ZnO make their commercial debut, lasers will not be far behind.

So what are the prospects for ZnO LEDs and lasers? While progress has been slow, it cannot be disputed that a great deal of work over the years has led to a much better understanding of doping dynamics in this material. This progress, combined with a favourable commercial outlook, is sustaining the research momentum. Armed with this knowledge, devices could hit the market within a few years, once an industrially-accepted method for *p*-type doping is in place. Commercialisation is also hampered by longevity issues, which result from poorly understood carrier dynamics in ZnO. Address this with further research, and the dawn of the launch of ZnO bipolar devices will be in sight.

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The world's first CW non-polar GaN VCSEL

Polarization-locked arrays of violet, blue and green lasers are now on the horizon, thanks to the first demonstration of non-polar GaN VCSELs delivering continuous-wave operation

BY CHARLES FORMAN, STEVEN DENBAARS AND SHUJI NAKAMURA FROM THE SOLID STATE LIGHTING & ENERGY ELECTRONICS CENTER AT UNIVERSITY OF CALIFORNIA, SANTA BARBARA

THE VCSEL has many desirable attributes. Sporting a far smaller size than its edge-emitting cousins (see Figure 1), it is capable of higher modulation speeds for data communication, and lower power consumption, which is ideal for battery-powered devices. Its only significant drawback is its relatively low output power, but this can be overcome by arranging these devices in densely-packed, two-dimensional arrays.

VCSEL production is now well established. Leading the way are infrared VCSELs based on the GaAs family, which have been capable of CW operation since the late 1980s and were commercialised in the 1990s. These devices have replaced edge-emitters in computer mice and laser printers, and are now being deployed in mobile phones. In the latter application, Finisar is enjoying tremendous success, having just been awarded $390 million to increase its R&D and production of VCSELs, which are key components in the iPhone X TrueDepth camera and AirPod proximity sensor.

Finisar's success could be just the tip of the iceberg for VCSEL manufacturers. Today, this market is limited to red and infrared emission, using GaAs- and InP-based VCSELs. But if the spectral domain could expand to encompass blue, green and short-wavelength sources, VCSELs could start to penetrate a whole world of untapped applications in display, illumination, and sensing technology.

Combining red VCSELs with those emitting in the green and blue could create full-colour light engines for displays and projectors, while the low power of all these sources makes them ideal for portable electronics, such as wearable displays. In addition, VCSELs could be deployed in laser-based lighting, and in Li-Fi, where they could provide even faster modulation speeds than edge-emitters, which are already hundreds of times faster than LEDs, enabling a hike in data transfer rates.

At the Nakamura Lab at the University of California, Santa Barbara, we are taking important strides in this direction: we have demonstrated the world's first non-polar GaN-based VCSEL that is capable of lasing under continuous-wave (CW) operation. This is a significant breakthrough because non-polar VCSELs offer many advantages over their polar cousins, including: an absence of polarization-related electric fields in the active region that can improve radiative efficiency; and anisotropic gain, which enables the fabrication of arrays that provide a fully polarized emission source. The latter attribute increases the opportunities for the GaN VCSEL, by opening up applications ranging from optical sensing to increased data transmission rates via polarization division multiplexing.

GaN VCSEL progress

Progress in GaN VCSELs has not been easy. 12 years elapsed between Nakamura's report of the first blue laser in 1996 and the unveiling of the first electrically pumped GaN VCSEL, by Tien-Chang Lu and colleagues from National Chiao Tung University (NCTU). Even a decade on from that first great success, just eight research groups have successfully demonstrated an electrically-injected, GaN-based VCSEL.

Understand the difficulties associated with making a GaN VCSEL, and it is easy to appreciate this apparent

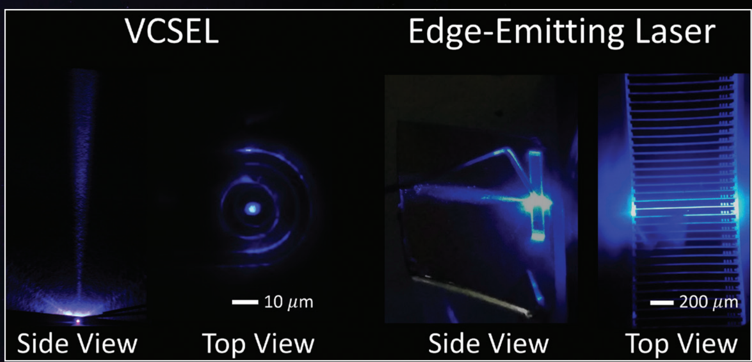

Figure 1. Violet GaN VCSEL (left) and blue edge-emitting laser (right) under electrical injection. In comparison to edge-emitters, VCSELs have many merits: orders of magnitude smaller active volumes, lower thresholds for lasing with lower power consumption, high-speed modulation, 2D arraying capability, on-wafer testing, circular output beam with low divergence, higher spectral purity, and ability for single-longitudinal mode operation.

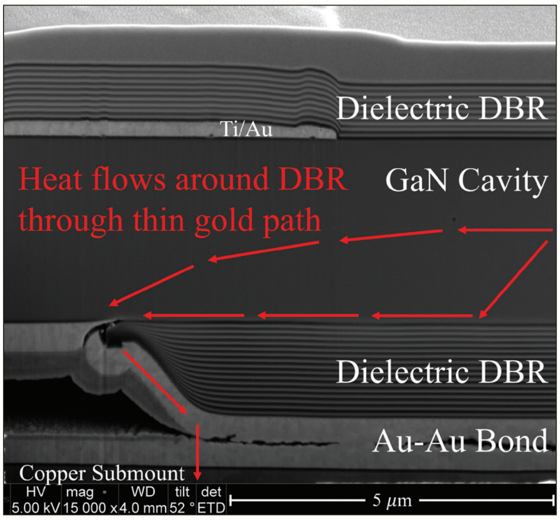

Figure 2. Focused ion-beam cross-sectional scanning electron microscopy revealed problems with earlier GaN VCSELs. The thermally insulating bottom DBR forces heat to flow through a thin gold path toward the flip-chip substrate. The thermal performance is further impaired by cracks in this thin metal that form during the Au-Au flip-chip bond.

lack of progress. Due to an extremely short gain path length of typically 10-30 nm, this class of laser requires a pair of mirrors with a reflectivity in excess of 99 percent. It's a requirement that is relatively easy to fulfil for GaAs VCSELs, wherein mirrors can be formed from alternating, lattice-matched layers of doped, quarter-wavelength-thick GaAs and AlGaAs – a pairing that creates electrically conductive epitaxial distributed Bragg reflectors (DBRs). However, with a GaN-based VCSEL, fully epitaxial DBRs have not been an option. There have been several growth challenges, along with difficulty activating *p*-GaN that is buried below epitaxial layers.

Instead, teams have produced VCSELs with either two sets of dielectric DBRs or a hybrid design with a bottom epitaxial DBR; however, even the growth of just one epitaxial DBR is challenging, due to a lattice mismatch between AlGaN and GaN that leads to cracking.

One team that has had success with the latter approach is that of Tetsuya Takeuchi and co-workers at Meijo University. Using lattice-matched, *n*-type conducting layers of AlInN and GaN, they have made a mirror with the required level of reflectivity. However, this requires 46 pairs of AlInN and GaN, due to the low index contrast. Consequently, it's a lengthy growth process, demanding precise thickness control to match the peak reflectance with the lasing wavelength.

The more common approach is to sandwich the active region between two sets of dielectric DBR mirrors. Typical combinations, such as the pairing of SiO_2 and Ta_2O_5, are relatively easy to deposit using e-beam deposition or sputtering. What's more, thanks to higher index contrast, this class of DBR requires a relatively smaller number of mirror pairs – and it has a much wider high-reflectivity stopband, easing alignment with the lasing wavelength.

However, it's not all smooth sailing with a dual-dielectric DBR design. Mirrors have to be deposited on both sides of the device, within a few microns of the active region. One way to do this, adopted by Tatsushi Hamaguchi and researchers at Sony, is epitaxial lateral overgrowth on top of a previously-deposited dielectric DBR on GaN. VCSELs produced in this manner, which feature an ion implanted aperture, can produce more than 1 mW, which is one of the highest reported peak output powers for this class of device. However, although epitaxial lateral overgrowth is promising, it is a sophisticated technique with several growth challenges.

An alternative approach, avoiding lateral overgrowth, is the creation of dual-dielectric DBRs with a flip-chip design. In this case, the price to pay is an increase in the complexity of the fabrication steps, including the need for flip-chip bonding to a submount and the removal of the growth substrate to access the *n*-side of the device. Conventional polishing and thinning is one option for removing the growth substrate. However, controlling VCSEL cavity length is challenging – and this is critical to device performance, because it impacts the electromagnetic standing wave field within the cavity.

We take a different tack to remove the growth substrate, using photoelectrochemical etching to selectively etch a sacrificial multi-quantum well. This enables precise control over cavity layer thicknesses and ultimately allows us to accomplish a key goal in VCSEL design: maximizing the gain enhancement factor. Success results from aligning the active region with the optical field standing-wave peak, which increases the confinement factor and helps decrease the threshold for lasing. Even higher levels of performance are possible by trimming optical

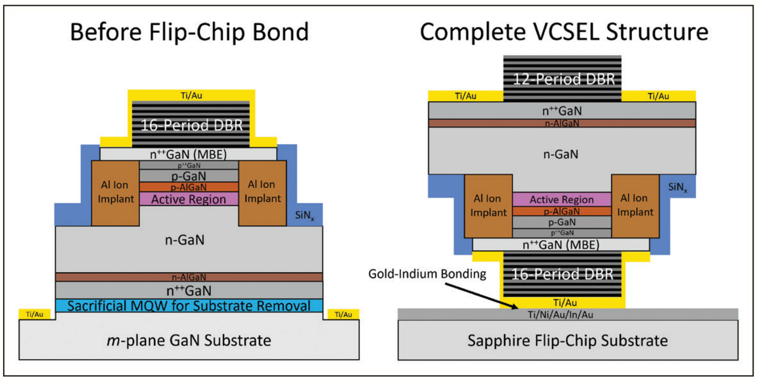

Figure 3. The dual-dielectric DBR GaN VCSEL with an ion implanted current aperture and tunnel junction intracavity contact, which reduces internal losses compared to ITO. The structure prior to the flip-chip bond is shown on the left. Photoelectrochemical etching of a sacrificial multiple quantum well enables precise cavity length control when removing the *m*-plane GaN substrate.

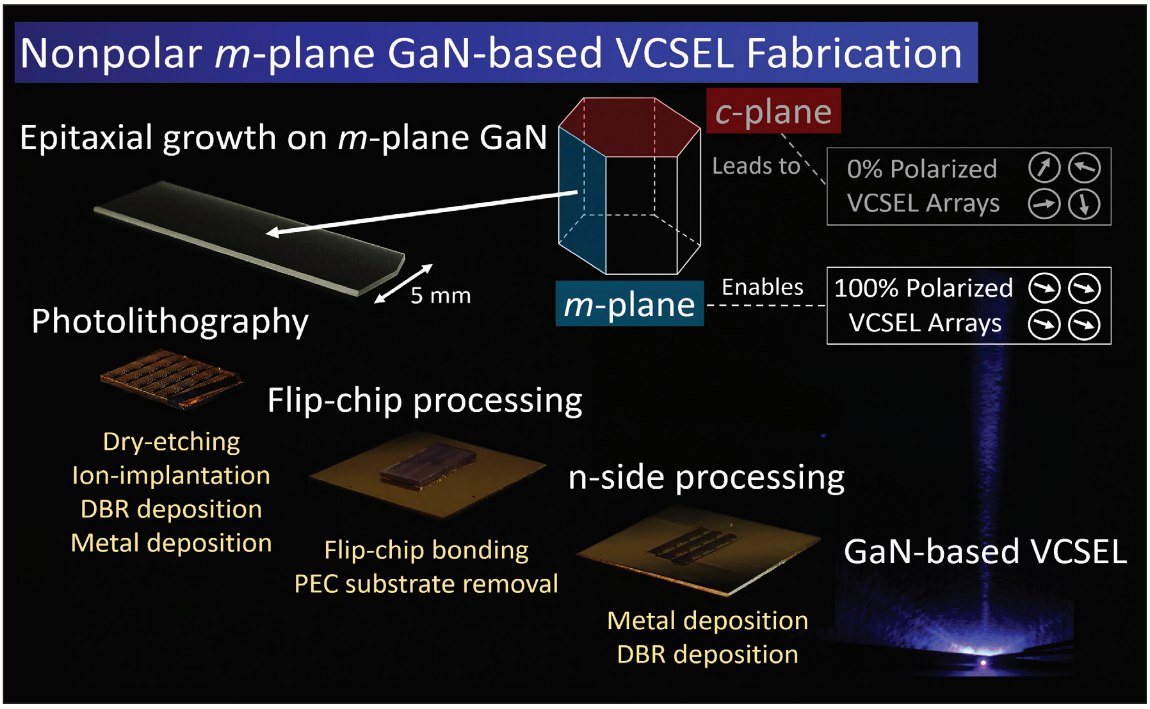

Figure 4. Summary of nonpolar *m*-plane GaN VCSEL fabrication. While c-plane GaN VCSELs are polarized in random directions, *m*-plane GaN VCSELs are consistently polarized in the a-direction, leading to VCSEL arrays with a 100 percent polarization ratio.

absorption. To realise this, layers with higher levels of optical loss, such as ITO and highly-doped layers, have to be aligned with standing-wave nulls.

There are additional challenges associated with dielectric DBRs, which stem from their electrically and thermally insulating nature. As current injection is not possible through non-conductive DBRs, carriers need to be injected from the edges of the aperture, and the device needs to be designed so that current can spread toward the centre of the cavity. However, uniform current injection is not easy as *p*-type GaN has a notoriously low conductivity – typically around 1 Ω^{-1} cm^{-1} – inhibiting lateral current injection.

One of our innovations is to inject carriers into the device with an MBE-grown, relatively transparent tunnel junction and current spreading layer. This is superior to the more common approach of employing an intracavity, current-spreading layer made from ITO. That's because this oxide is flawed: it is not completely transparent at blue and violet wavelengths, and it degrades VCSEL performance due to significant optical loss, even when ITO is placed at the null of the optical standing-wave.

A non-polar design

In addition to the promise of higher radiative efficiency, which we championed earlier in this article, non-polar GaN VCSELs offer the opportunity to employ thicker wells without reduced radiative efficiency, and anisotropic gain that leads to a 100 percent polarization ratio for *m*-plane VCSELs. While individual *c*-plane VCSELs are polarized in random directions, *m*-plane VCSELs are consistently polarized along the *a*-direction, opening the door to 100 percent polarization-locked VCSEL arrays.

Another crucial advantage of the non-polar *m*-plane of GaN is that it is compatible with our photoelectrochemical etching technique. During this process, ultraviolet light creates photogenerated holes in the sacrificial wells that oxidize the surface and dissolve in a potassium hydroxide solution. Note that our etching technique cannot be applied to *c*-plane VCSELs because potassium hydroxide roughens the nitrogen-face GaN – this is not acceptable, because it would cause severe scattering loss on the *n*-side.

Significant cost savings may also result from our etching process. Bulk GaN substrates are pricey, but because they are removed from the device, it is possible that they could be reused for the next batch of VCSELs.

Our first milestone in non-polar VCSELs came in 2012, when Casey Holder demonstrated a device with a dielectric current aperture and an ITO intracavity

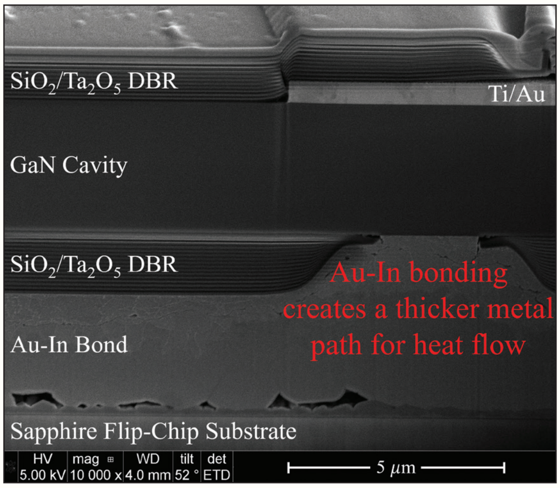

Figure 5. Focused ion-beam cross-sectional scanning electron microscopy image of a GaN VCSEL utilizing Au-In bonding to create a much thicker metal path for heat flow. This scheme for superior thermal management led to the first demonstration of CW operation for non-polar GaN VCSELs.

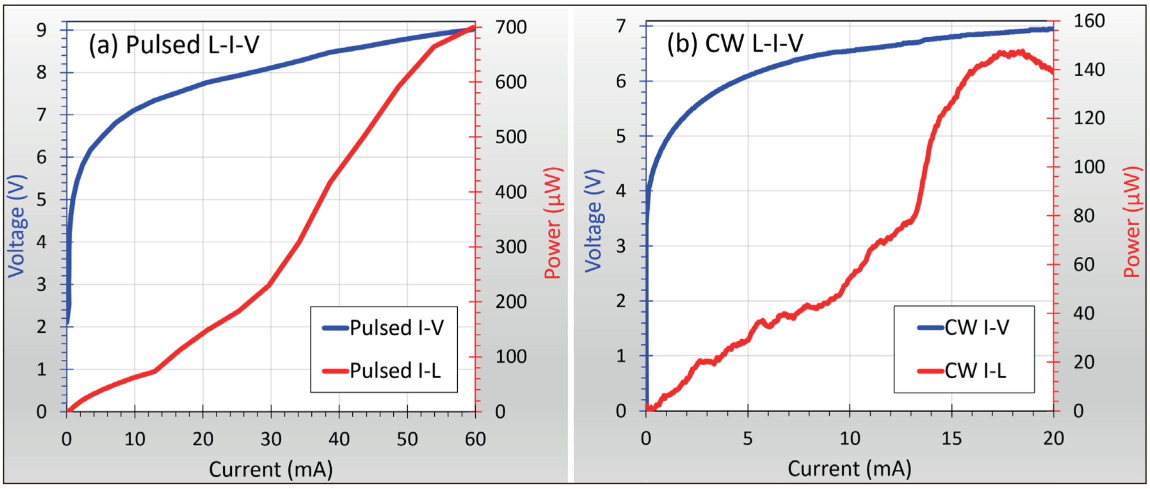

Figure 6. Current, light and voltage characteristics of a 6 μm aperture diameter VCSEL with a 23 λ cavity length (a) under pulsed operation and (b) under CW operation. This is the first demonstration of CW operation for nonpolar GaN VCSELs. CW lasing was stable for over 20 minutes of continuous testing. The threshold current was 12 mA under pulsed operation and 10 mA under CW operation.

contact. Refinements followed, led by John Leonard, who introduced three new GaN VCSEL designs, featuring ion implanted current apertures, tunnel junction intracavity contacts (replacing ITO), and photoelectrochemically etched air-gap apertures. Ion implantation produced the best results for current confinement, and has been adopted by Sony, featuring in devices reported in 2016.

From this era, our most impressive performance came from a VCSEL with an aluminium-ion-implanted current aperture and an MBE-grown, GaN-based tunnel junction intracavity contact. This device delivered a pulsed peak output power of 0.5 mW, but could not lase under CW operation.

Failure to provide CW operation stems from a bottom-side dielectric DBR that is thermally-insulating, and thus inhibits downward heat flow. Heat is extracted from the device by flowing it around the bottom DBR through a thin gold contact that leads to the flip-chip substrate. Unfortunately, the heat transferring capabilities of this gold contact are compromised by cracks and voids within it – they are exposed by scanning electron microscopy of cross-sections, prepared by a focused ion-beam (see Figure 2).

The origin of these imperfections is the high-temperature, high-pressure process used to unite gold-coated surfaces by thermocompression, flip-chip bonding. Damage extends to the devices, which have low yield and are plagued by cracks. To address this, we bond gold to indium, to create the first non-polar VCSELs that are capable of CW operation.

Making VCSELs

We produce our latest generation of VCSELs (see Figure 3) by taking *m*-plane GaN substrates with an intentional -1° miscut in the *c*-direction, loading them into an MOCVD chamber, and growing a 1.2 μm-thick *n*-GaN template, followed by a sacrificial multiple quantum well, 26 nm of n^{++} GaN, 15 nm of *n*-AlGaN, 3.2 μm of *n*-GaN, an active region with two 14 nm-thick InGaN quantum wells separated by a 1 nm-thick GaN barrier, 5 nm of *p*-AlGaN, 60 nm of *p*-GaN, and 14 nm of p^{++}GaN.

After dry etching past the active region to create a mesa, we use aluminium ion implantation to form the current aperture, before turning to Erin Young's expertise with ammonia MBE to grow an *n*-GaN tunnel junction and current spreading layer. This involves depositing a 40 nm-thick layer of n^{++}GaN, followed by 62 nm of *n*-GaN and 40 nm n^{++}GaN. To help smoothen the surface and ultimately reduce VCSEL scattering loss, we add a non-incorporating indium surfactant to the growth process. SiN is then deposited, so that the sidewall of the active region is protected during subsequent photoelectrochemical etching.

The next steps are the addition of a 16-period SiO_2/Ta_2O_5 DBR, followed by a deeper dry etch to expose the sacrificial multiple quantum well. After this, a Ti/Au *p*-contact metal is deposited conformally around the DBR, before this structure is flip-chip bonded to a sapphire substrate coated with an indium-rich alloy of indium and gold. Fabrication of the VCSEL is completed (see Figure 4) by using a potassium hydroxide solution, alongside 390 nm excitation from an LED array, to photoelectrochemically etch the sacrificial multiple quantum well, before adding a Ti/Au *n*-electrode, followed by a 12-period SiO_2/Ta_2O_5 DBR. Note that a rough residue forms after photoelectrochemical etching, which is removed by swabbing in Tergitol detergent.

Combining a relatively thick, indium-rich gold-indium alloy on the flip-chip substrate with gold atop the device on the GaN substrate produces a big improvement in thermal performance – and ultimately enables CW operation. The gold-indium system is ideal for flip-chip bonding, because it has a unique low-temperature liquid phase that occurs above 156 °C for gold-indium alloys with an indium content of more than 54 percent, in terms of weight. This enables flip-chip bonding at much lower temperatures and pressures than bonding between gold surfaces, leading to improved yield with significantly fewer cracked devices. While previous devices had a thin metal pathway for heat transport, gold-indium bonding completely embedded the bottom-side DBR in metal (see Figure 5), greatly improving thermal performance, according to COMSOL simulations.

Last, but not least, the thermal capabilities of the device are further improved by increasing the GaN cavity length from 7 λ to 23 λ. This lowers the active region temperature as heat can spread throughout a thicker thermally-conductive GaN cavity.

CW operation

We have produced VCSELs with 6 μm and 8 μm aperture diameters that deliver CW operation with stable lasing for more than 20 minutes. For the device with the 6 μm aperture, peak output power is 150 μW under CW operation, and 700 μW under pulsed operation (see Figure 6). Meanwhile, for a variant with a 10 μm aperture, peak output can exceed 1 mW, which is approximately double that from previous non-polar GaN VCSELs. We attribute this superiority to a longer cavity length, which aids mode alignment at higher current densities, thanks to a reduction in the longitudinal mode spacing.

The emission wavelength red-shifts with drive current. The peak in spontaneous emission occurs at 403 nm, and lasing initially appears at 406 nm and 412 nm under pulsed operation above the threshold current of 12 mA. Even when driven in pulsed mode, the peak gain red-shifts at higher currents, due to heating, with a dominating 419 nm lasing mode emerging above 33 mA. As this longer-wavelength mode appears, differential efficiency increases from 0.3 percent to 0.8 percent. We attribute this to lower absorption, a reduction in scattering loss, and lower mirror reflectivity at longer wavelengths.

Stronger lasing at longer wavelengths also results in an interesting phenomenon: the threshold current uncharacteristically decreases to around 10 mA under CW operation, due to the higher temperature red-shifting the peak gain, resulting in longer wavelength modes emerging at lower currents. An example of this is that the high-intensity 419 nm mode appears above 33 mA under pulsed operation, while the 420 nm mode appears much earlier, at 15.1 mA, under CW operation (see Figure 7).

This red-shifting of the gain spectra offers an insight into the VCSEL operating temperature. Measuring the red-shift in peak spontaneous emission under CW operation suggests a VCSEL operating temperature of 163 °C at 15 mA and a thermal impedance of 1400 °C/W. Both these values compare favourably with thermal simulations.

Close inspection of the emission from the device reveals that lasing is centred within the aperture, appearing as the fundamental transverse mode above threshold (see Figure 1). This is a significant improvement compared with previous *m*-plane VCSELs, which typically exhibit filamentary lasing – that is, random lasing spots appearing in the aperture. We are still in the process of confirming the reasoning behind this improvement. It may be related to the removal of a rough oxide layer, generated during photoelectrochemical etching.

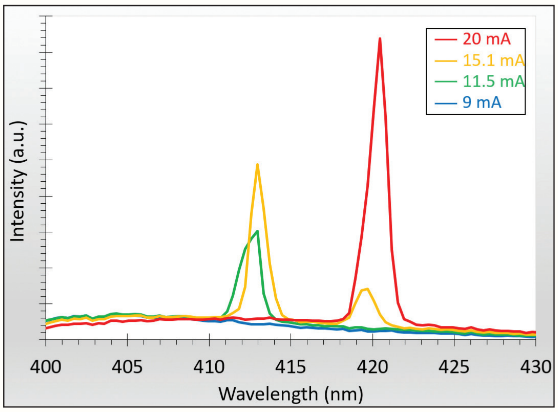

Figure 7. Emission spectrum at various current injection levels for a 6 μm aperture diameter VCSEL with a 23λ cavity length under CW operation. Under pulsed operation, lasing modes appeared at 406 nm, 412 nm, and 419 nm. Under CW operation, the redshifted peak gain resulted in only two lasing wavelengths at 413 nm and 420 nm. The peak gain redshifted with increasing current and longer-wavelength modes increased while shorter-wavelength modes decreased in intensity.

Our work is in its infancy, and we are sure that non-polar VCSELs can deliver far higher levels of performance. Refinements could include switching from sapphire for the flip-chip substrate to a more thermally conductive material, such as copper or SiC. An increase in output power should follow, allowing the device to take another step towards commercialisation, and the promise of significant sales in many markets.

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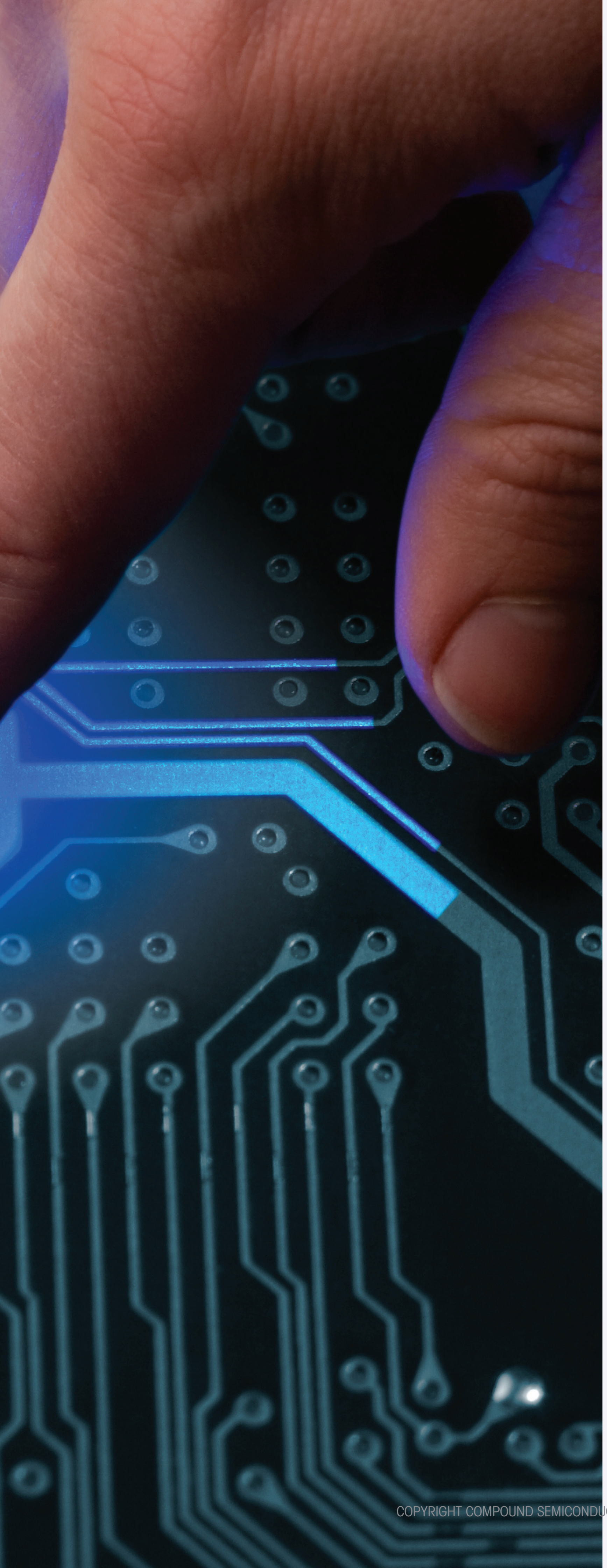
Making monolithic integrated systems with GaN

GaN produces great LEDs, lasers and transistors. Just imagine the possibilities when two or more of these classes of devices are united on the same chip

BY HOI WAI CHOI, WAI YUEN FU, KWAI HEI LI AND YUK FAI CHEUNG FROM THE UNIVERSITY OF HONG KONG



technology integration

GaN has breathed new life into LEDs. This wide bandgap material has propelled the status of this device from indicator lights to illumination lamps that are pushing incandescent lamps to the brink of existence, while slashing carbon footprints. And the penetration of this device still has further to go, due to rising sales of LEDs that combine GaN with AlGaN, rather than InGaN, the key material for visible emission. This alternative alloy widens the bandgap, enabling the production of devices stretching into the ultraviolet, which can be used to disinfect air, water and surfaces. There is also the cousin of the GaN LED, the GaN laser. It is already being widely used in high-density optical storage, commonly known as BluRay.

Following in the footsteps of these optoelectronic devices is an electronic industry based on the same family of materials. Their great intrinsic material properties has led the GaN HEMT to be widely touted as the next generation of power electronic device. Further commercial success may follow from other types of GaN device, including microelectromechanical systems and resonators, which are both under development.

In hindsight, it would have been better to develop the broad portfolio of GaN devices along similar lines. But that's not been the case. Instead, devices have often been developed individually, due to the lack of a common structure or platform. Nevertheless, optoelectronics and electronics often go hand-in-hand; an LED requires an electronic driver for stable operation, and this driver is built from electronic components. So it is clear that the GaN platform can become even more useful, functional and efficient when multiple components are tightly integrated to form an integrated system, just like that found with silicon ICs (see Figure 1, which illustrates this concept).

Let's begin by considering photonic integrated systems. A promising building block for these is the LED, which combines high quantum efficiencies with fast response times, making it suitable for transmitting signals at high speeds. However, the LED needs to be paired – on the same chip – with a photodetector capable of detecting the light that it emits. Although the GaN epitaxial layer underneath the active region is capable of making a good photodetector, this would not detect visible light. To address this, a thick InGaN layer may be grown over the LED structure to provide light absorption. However, there is a penalty to pay – an increase in the complexity of the process flow.

To avoid this stumbling block, our team at Hong Kong University adopts a different approach, using multiple quantum wells to detect the light that is emitted by this active region. There is much merit in this idea, given luminescence and absorption are complementary optical processes.

With this approach, the detection sensitivity depends on the relative shift between emission and absorption spectra, which is known as the Stokes shift. Despite this

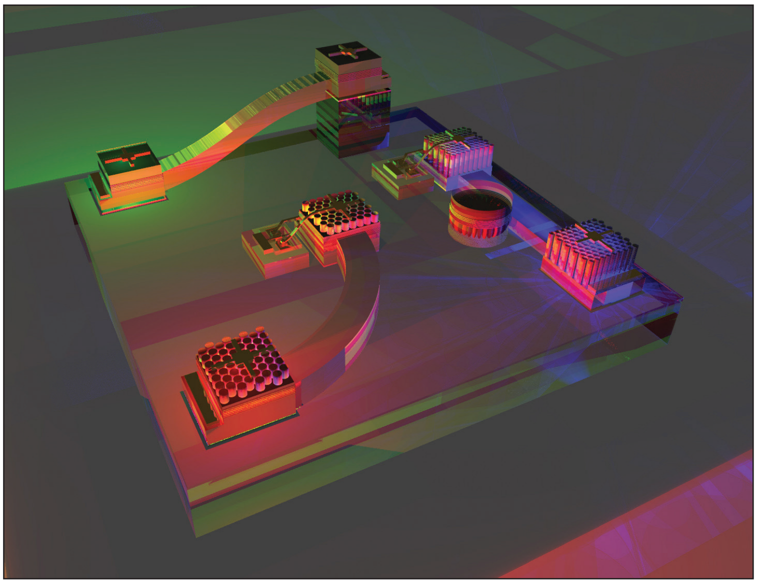


Figure 1. GaN has the potential to make very powerful ICs, by integrating lasers, LEDs and transistors on a single chip.

limitation, typical InGaN/GaN multiple quantum wells can still have a spectral overlap between 20 nm and 30 nm.

As our detectors are positioned adjacent to the LEDs, we can use them to monitor the light output intensity. We have found that the fluctuations and variations in the photocurrent that is generated track those of the light output remarkably well. By using the photocurrent as a feedback signal, we can realise a constant light output intensity, via adjustments in the drive current.

Many applications could benefit from this technology for forming intensity-stabilized emitters. Such sources are needed for optical spectroscopy and fluorescence imaging, and for the calibration of detectors. What's more, intensity stabilisation could ensure stable colour chromaticity in white-light sources formed from red, green and blue LEDs.

Photonic circuits

As LEDs are omni-directional emitters, light-guiding offers the only feasible means of optical transmission. The good news is that GaN, with its high refractive index, is ideal for forming waveguides with air as the surrounding medium. To ensure optimal coupling, waveguides should be physically connected to the emitters and detectors. The top and side facets of the etched waveguides provide excellent optical confinement, thanks to an interface with air. However, there can still be severe leakage through the bottom of the device, which interfaces with the substrate.

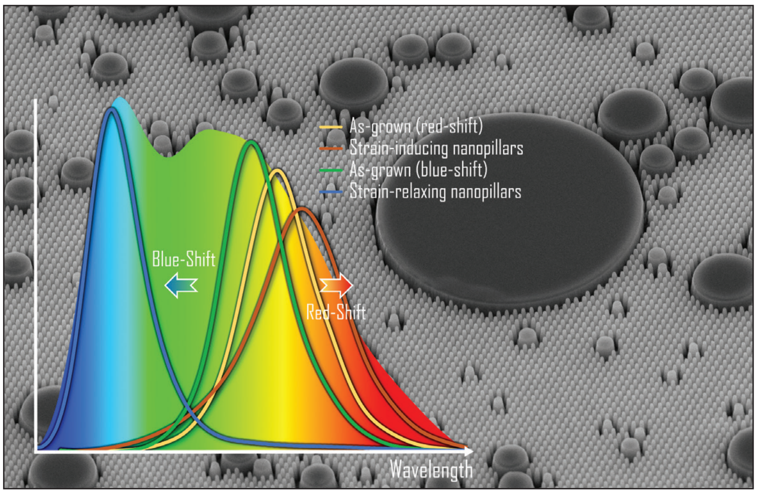


Figure 2. The combination of strain and the scaling of the dimensions of the emitter enables blue-shifting and red-shifting of the emission wavelength.

Several solutions have been proposed to overcome this problem. If the substrate is made from silicon, a wet-etch undercut process can selectively remove material from underneath the waveguide to form air-suspended waveguides. This approach can draw on the technique that we developed to promote optical confinement in suspended GaN microdisks. Note, however, that this technology cannot be applied to LEDs with a substrate made from sapphire, which is the more common platform for this device. In this case, a selective laser lift-off process can remove the substrate underneath the waveguide.

So, in short, regardless of whether GaN LEDs are formed in silicon or sapphire, there are processes that can generate suspended and even flexible waveguides, enabling optical transmission across multiple planes on the chip.

To see how quickly signals can be transmitted from the emitter to the detector, via the waveguide, we applied a pseudo-random binary sequence signal to our LED and detected the transmitted optical signal with our multi-quantum well photodetector. An oscilloscope, monitoring the photocurrent, produces a widely open eye diagram for signals up to 250 Mbits/s, and determines that the response time of the system is less than a few nanoseconds. Far faster rates beyond GBits/s should be within reach by switching the modulation scheme to one that is more sophisticated, such as OFDM.

In monolithic systems, single-wavelength transmission is to be expected, because the emission wavelengths of the multi-quantum wells are not tuneable. But that doesn't have to be the case. Due to significant lattice and thermal mismatch, the combination of InGaN wells and GaN barriers creates a highly-strained active region, particularly at longer emission wavelengths, and this offers a viable way of wavelength tuning.

Efforts are aided by dimensional downsizing, which can blue-shift emission wavelengths, due to strain-relaxation. Reducing dimensions below 100 nm blue-shifts emission by as much as 80 nm, turning green emitters into blue ones, and enabling controllable, multi-wavelength emission from a single wafer. It is also possible to go the other way. Introducing strain into the active region by nano-structuring produces a red-shift in emission wavelength. In this case, the wells themselves are not structured; instead it is the nanostructures formed right on top of them. Due to strain relaxation in the overlaying nanostructures, the wells are compressed laterally by inducing a tensile strain vertically.

Using this approach, we have recorded spectral red-shifts of more than 15 nm, propelling the emission wavelength from 572 nm in the as-grown structure to 589 nm. Given the challenge of realising red-light emission in active regions formed from InGaN wells and GaN barriers, our approach offers much promise as an alternative route for producing red-light InGaN LEDs, especially when such LEDs are to be monolithically-integrated with LEDs of other wavelengths.

Obviously, we didn't develop wavelength tuning by strain manipulation for multiple wavelength monolithic sources. Instead, the motivation for developing this technology was the creation of full-colour displays and monolithic white-light emitters, an attractive alternative to sources that include phosphors.

During this effort, we found that structuring the active region of an LED into an array of multi-dimensioned structures, with sizes ranging from tens of nanometres to several microns, can produce a spectrum that is broad enough to yield white light. The extent of strain relaxation and induction governs the wavelength tuning range. For example, an array of nanostructures and microstructures with dimensions ranging from 50 nm to 5 μm is capable of providing a spectral width of 148 nm and a colour rendering index of 61 (see Figure 2).

This technology can also be used to form full-colour monolithic displays from a combination of wavelength-adjusted pixels. The starting point is an LED wafer with green-emitting quantum wells. Blue and red pixels are then formed by introducing strain-relaxed and strain-induced elements respectively (see Figure 3). Note that the creation of red, green and blue pixels on the same chip is a very attractive approach to realising full-colour LED displays, which are currently constructed using pick-and-place solutions – they face several limitations, including pixel dimensions and pitches, yields and costs.

Adding electronics

So far, we have discussed the monolithic integration of optoelectronic and photonic components. Even greater rewards could come from the integration of electronic components, as this would greatly enhance the functionalities of the integrated systems.

Some success has already been realised. Kei May Lau's group at Hong Kong University of Science and Technology has reported extensively on the integration of GaN LEDs and HEMTs; and we have combined optoelectronic devices with MOSFETs, a form of transistor that is easier to introduce in the manufacturing process.

Initially, we developed Schottky-barrier MOSFETs to overcome potential issues associated with the shrinking of silicon devices. However, it turns out that those concerns can be resolved - at least for now. Nevertheless, such devices, sporting metallic sources and drains, remain attractive for GaN materials,

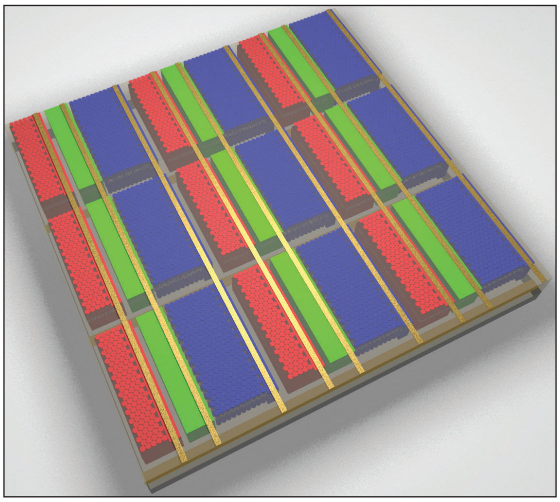


Figure 3. Full-colour displays could be created by taking a wafer designed for green LEDs and using strain and dimensional constraints to introduce structures with red- and blue-emitting regions.

because they eliminate the need for source and drain doping. Instead, the roles of the *p-n* junctions are fulfilled by metal-semiconductor Schottky junctions. This approach has great versatility, as both *p*-channel and *n*-channel transistors can be formed on the *n*-GaN and *p*-GaN layers of the LED wafer.

The normally-off transistors that we produce, which have high switching speeds, are an ideal building block for the integration of digital circuits onto the integrated system. For instance, placing these transistors (and capacitors) adjacent to the pixels in a monolithic display enables active-matrix addressing without relying on off-chip components. The upshot is a better-performing, more robust system.

Our work showcases the promise of monolithic integration of a diverse range of optoelectronic, photonic and electronic devices and components onto a typical GaN LED wafer. The list of devices we have developed is certainly not exhaustive, however. For instance, whispering-gallery mode microdisks can be integrated on-chip for various detection or sensing applications through modifications of the resonance conditions, and GaN-based MEMs can be used as actuators via the piezoelectric effect. So further work is needed to fully exploit the capability of this monolithic platform, so that it can deliver significant enhancements to the functionalities and performances of today's systems that are formed from heterogeneous integration.

Further reading

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- C. Feng *et al.* ACS Photonics **3** 1294 (2016)




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UV LEDs: Slashing costs with sputtering

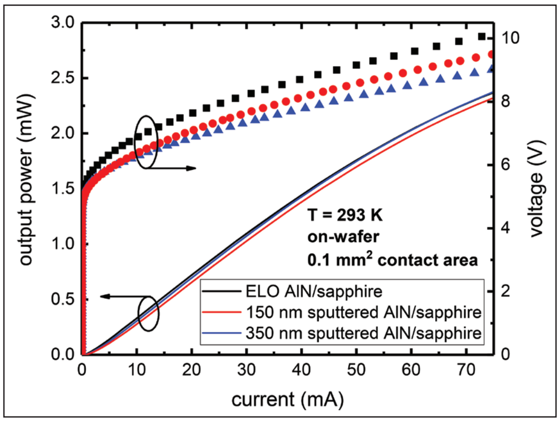
Annealing sputtered films of AlN reduces the cost of making a deep UV LED while retraining its performance

LEDs that emit in the deep UV are expensive to produce, because they have to be grown on AlN-on-sapphire templates that are formed using photolithography, etching and a second MOCVD step.

But the costs of device production could plummet, while LED performance is maintained, by growing these LEDs on sputtered, high-temperature annealed AlN-on-sapphire, according to a partnership between researchers in Germany and Japan.

"The cost reduction is very significant," claims Norman Susilo from TU Berlin. "Sputtering of AlN and high-temperature annealing can be operated at low cost, high volume and hopefully with a high reproducibility – which we will investigate in the future."

By bringing down chip costs, this effort could help to accelerate the deployment of UVC LEDs in medical diagnostics, gas sensing, biochemical agent detection and water disinfection.



Annealing can slash the cost of deep UV LEDs while retaining their efficiency.

The researchers from TU Berlin, the Ferdinand-Braun-Institute, Evatec and Mie University, Japan, formed their novel, low-cost templates by placing 2-inch sapphire substrates in an Evatec Clusterline tool and heating them to 700 °C under an argon-nitrogen atmosphere. AlN layers with a thickness of 150 nm and 350 nm were sputtered onto sapphire at a growth rate of 0.4 nm/s. Both structures were then annealed at 1700 °C, before MOCVD added a 400 nm-thick layer of AlN.

High-resolution X-ray diffraction on samples before and after annealing revealed that this step produced a remarkable decrease in the twist component of the sputtered layers.

Susilo says that the costs of purchasing a sputtering tool could be avoided, as annealing also works with MOCVD-grown layers. "However, sputtering might provide a lower cost in the long run." For many chip fabrication lines, this will not be an issue, as they will already have sputtering tools that they can utilize.

To compare the performance of devices formed on the two novel templates with those made on a more conventional foundation, the researchers also produced far thicker templates via epitaxial layer overgrowth. After using MOCVD to deposit 500 nm of AlN on sapphire, they turned to photolithography and etching to form stripes in the epilayer, before adding more AlN to create a template with a 6 μm-thick AlN layer.

On all three forms of template, the team deposited UV LED structures with an intended emission wavelength of 268 nm.

"To our understanding, the heterostructure is fairly standard," says Susilo. "However, as manufacturers do not publish their structures, it is hard to say what is standard in their point of view."

Estimates of the threading dislocation density, crucial to the performance of deep UV LEDs, were obtained from values of the full-width at half-maximum of rocking curves obtained from X-ray diffraction measurements. Those values revealed that increasing the thickness of the annealed layer cut the threading dislocation density from 2×10^9 cm^{-2} to 7.2×10^8 cm^{-2}. The latter figure is better than that for the 6 μm-thick AlN layer, which has a value of 1.1×10^9 cm^{-2}.

On-wafer measurements at a drive current of 20 mA revealed output powers of 0.65 mW, 0.70 mW and 0.72 mW for LEDs formed on templates featuring 150 nm of sputtered AlN, 350 nm of sputtered AlN, and 6 μm of MOCVD-grown AlN, respectively. These output powers correspond to external quantum efficiencies of 0.70 percent, 0.75 percent and 0.78 percent, respectively.

Susilo says that the team is now processing devices for flip-chip mounting and packaging. "Since it is a more elaborate process, it will take a little more time, but we expect first results from that fairly soon."

An additional goal for the team is to establish the technology of sputtered, high-temperature annealed AlN as a standard template in its growth processes. "This will take time, as the stability of the whole process chain, from the sputtering and annealing to life time testing, needs to be evaluated," says Susilo.

Reference

N. Susilo *et al*. Appl. Phys. Lett. **112** 041110 (2018)

Tunnel-junctions turbocharge microLEDs

Replacing transparent conductive oxides with tunnel junctions can increase performance while simplifying design

RESEARCHERS AT THE UNIVERSITY OF CALIFORNIA, Santa Barbara, have improved the performance of microLEDs via the addition of tunnel-junctions. Using this design, microLEDs have a higher efficiency and are less prone to droop.

The success of this team will catch the eye of many companies, which view this form of LED as the key to making more efficient, brighter, higher resolution displays.

In UCSB's microLEDs, the tunnel junctions replace a transparent conductive oxide and *p*-GaN, a pairing that enhances current spreading across the device, but increases electrical and optical losses.

Additional benefits of the tunnel-junction are a simplification of the nanofabrication process and an opportunity to introduce new designs.

"By using a tunnel junction, a common *n*-contact may be used, thus eliminating a separate *p*-contact metal deposition," explains David Hwang, spokesman for the team.

According to him, yet another merit of LEDs with tunnel-junctions is that they allow the use of low resistance, *n*-contact mirrors. For GaN-based LEDs, aluminium is a great choice for making these mirrors "A standard *p*-type mirror is a silver-based mirror, which has many issues, including silver migration and tarnishing, which affects the reliability of the mirror," explains Hwang.

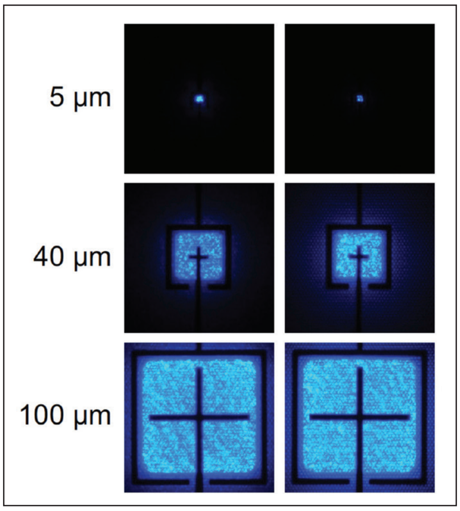
The team produced a range of square-shaped microLEDs, with sides varying in length from 5 μm to 100 μm. Tunnel-junctions were formed on top of a structure that featured an active region with six quantum wells and an electron-blocking layer.

To fabricate the tunnel junction, the researchers took the MOCVD-grown epiwafers that had been capped with a heavily doped *p*-GaN layer and removed excessive magnesium from the surface with ultra-violet ozone and hydrofluoric acid treatments. Wafers were then returned to the MOCVD chamber, where a 10 nm-thick, heavily *n*-type doped layer of GaN was added, followed by a 400 nm-thick *n*-type current spreading layer, and a 10 nm-thick *n*-GaN contact.

Silicon tetrachloride etching defined the dimensions of the microLEDs, before annealing for 30 minutes at 700 °C drove out hydrogen to activate *p*-GaN. To improve light extraction, omni-directional reflectors were added by ion beam deposition. The addition of *n*-metal contacts and wire-bonding pads completed device fabrication. To evaluate the performance of these devices, microLEDs with a 130 nm-thick, indium-tin oxide layer were also produced.

Current-voltage measurements revealed that the operating voltage for the devices with tunnel junctions is higher than that for those with ITO – the minimum penalty is 0.6 V.

"The penalty is not a record, but is encouraging for only MOCVD-grown tunnel junctions," says Hwang.



Close inspection of electroluminescence images show that as devices with a tunnel-junction (right) get larger, they have a higher proportion of dark areas. These regions result from incomplete activation.

This voltage penalty increases with the dimensions of the microLED. Using circular transmission line model measurements, the team have traced the origin of this penalty to the tunnel-junction barrier and *p*-GaN. It is possible that in larger devices, some of the *p*-GaN has not been activated by lateral diffusion.

Supporting this hypothesis are electroluminescence images, which have a higher proportion of dark areas in larger LEDs (see Figure). It is thought that the dark areas, which are not completely activated, have higher tunnel-junction barriers, due to an increased depletion width, and a higher resistance within the *p*-GaN layer.

Peak values for the external quantum efficiency of tunnel-junction microLEDs are 31 percent to 34 percent, compared with just 25 percent for the ITO-based control.

Tunnel-junction LEDs are also less susceptible to droop. For these devices, the reduction in efficiency from its peak value to that at a current density of 50 A cm^{-2} is between 6 and 10 percent, compared to 12 percent to 16 percent for the conventional control.

Hwang says that the team will now work on optimising its design, with a focus placed on lowering the operating voltage. "The biggest issue is the re-passivation of *p*-GaN with hydrogen, and we have some ideas on how to approach limiting this passivation."

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D. Hwang *et al.* Appl. Phys. Express **11** 012102 (2018)

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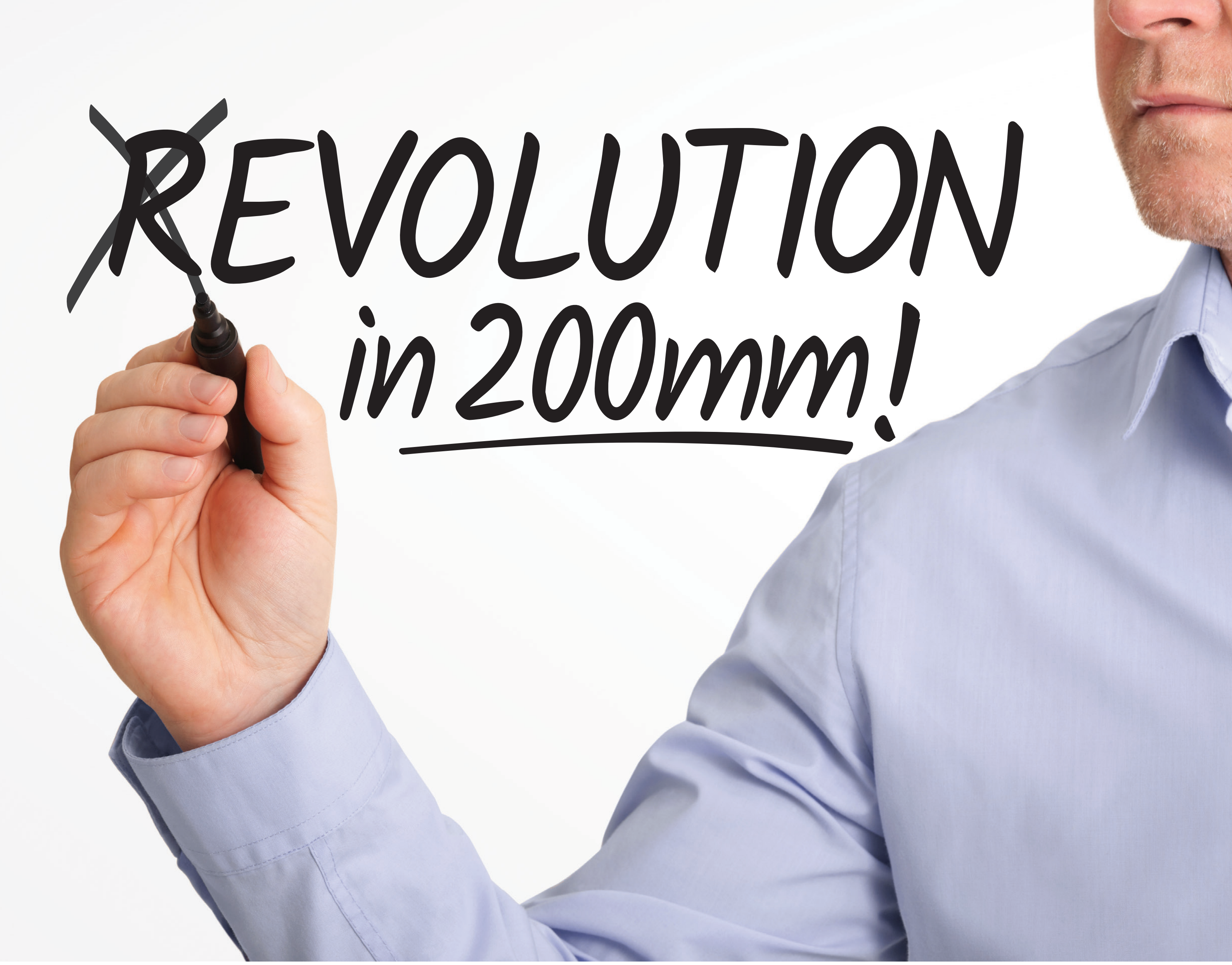

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