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## Improving the thermal management of UV LEDs

## How can quantum dots generate more sales?

## Perfecting the vertical GaN power device

## Could this be the world's most agile III-V fab?

## Hybrid PICs target tomorrow's networks


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# Viewpoint

By Dr Richard Stevenson, Editor

# Reaching for the skies

When searching for improvement, there are times when it is not clear what the approach should be. But in other situations, one knows what to do – but the challenge is how to do it successfully.

It is the latter state of affairs that confronts the developers of ultra-high efficiency solar cells. Everyone knows that the route to improving efficiency is to add more junctions. However, how to triumph with this approach is far from easy.

A leading option for increasing efficiency is to add high-energy junctions to the existing three- or four-junction designs. For this to be beneficial, it is critical that the new junctions are of high crystal quality, so that they deliver a worthwhile contribution to the performance of the device.

One candidate for covering higher energies is the pairing of InGaAsP quantum wells and InGaP quantum barriers. Working together, this pairing can yield a superlattice structure with a bandgap that may be tuned from 1.5 eV to 1.8 eV.

This approach is not new. In fact, it has been pursued since the 1980s, using strain-balanced structures. However, those heterostructures are inefficient at absorbing light, with external quantum efficiency pegged back to about 25 percent.

A breakthrough can come from the switch to lattice-matching. That's just been done by a team from the North Carolina State University and the National Renewable Energy Laboratory, and it has enabled the external quantum efficiency to rocket to over 65 percent (to discover the details of this effort, turn to p 58).

An encouraging feature of this technology is its high degree of versatility. During the last few years, efforts around the globe to improve solar cell efficiency have involved various approaches, including devices grown on germanium, dilute nitrides grown on GaAs, and wafer bonding techniques. The good news is that lattice-matched superlattices based on the combination of InGaAsP and InGaP are compatible with all of these.

Let's not get carried away, though. I don't expect this technology to revive the market for terrestrial solar cells any time soon. That sector is in the doldrums, and its re-emergence might take decades.

But I think it this technology could have an impact in space. Efficiency is very highly valued in that domain, and if these lattice-matched cells can deliver high levels of reliability that are demanded out there, this technology could well be a winner.


**Editor** Richard Stevenson richardstevenson@angelbc.com +44 (0)1291 629640
**Contributing Editor** Rebecca Pool editorial@rebeccapool.com
**News Editor** Christine Evans-Pughe chrise-p@dircon.co.uk
**Sales Executive** Jessica Harrison jessica.harrison@angelbc.com +44 (0)2476 718209
**USA Representatives** Tom Brun Brun Media tbrun@brunmedia.com +001 724 539-2404
Janice Jenkins jjenkins@brunmedia.com +001 724-929-3550
**Publisher** Jackie Cannon jackie.cannon@angelbc.com +44 (0)1923 690205
**Director of Logistics** Sharon Cowley sharon.cowley@angelbc.com +44 (0)1923 690200
**Design & Production Manager** Mitch Gaynor mitch.gaynor@angelbc.com +44 (0)1923 690214

**Circulation Director** Jan Smoothy jan.smoothy@angelbc.com +44 (0)1923 690200
**Chief Executive Officer** Stephen Whitehurst stephen.whitehurst@angelbc.com +44 (0)2476 718970
**Directors** Bill Dunlop Uprichard – EC, Stephen Whitehurst – CEO, Jan Smoothy – CFO, Jackie Cannon, Scott Adams, Sharon Cowley, Sukhi Bhadal, Jason Holloway

**Published by** Angel Business Communications Ltd, Hannay House, 39 Clarendon Road, Watford, Herts WD17 1JA, UK. T: +44 (0)1923 690200 E: ask@angelbc.com

**Accounts & Multi Media** Angel Business Communications Ltd, Unit 6, Bow Court, Fletchworth Gate, Burnsall Road, Coventry CV5 6SP, UK. T: +44 (0)2476 718 970 E: info@angelbc.com



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# Infineon to sell Welsh Fab to Neptune 6

INFINEON has signed a definitive agreement under which Neptune 6 will acquire IR Newport Ltd, a subsidiary fab based in Newport, Wales. Neptune 6 is a newly founded private company that intends to operate the Newport site under the name Newport Wafer Fab Ltd.

Both parties expect to conclude the deal by the end of September 2017. Infineon and Neptune 6 have also entered into a two-year supply agreement ensuring a mutually smooth transition phase.

Infineon inherited the Newport facility when it bought International Rectifier in 2015, at which time Infineon said the site would either be sold or closed in 2017. With Neptune 6 Infineon has now found a buyer that can use the factory and ensure a viable future for production and jobs.

Jochen Hanebeck, member of the management board operations at Infineon Technologies AG, said: "I am convinced that with Neptune 6 we have found the right partner who will secure production and jobs in Newport. Knowing we would have to part with the Newport site, it was my personal concern to make sure it will be in good hands. I am also delighted that the solution we have found now enables us to support our customers even better and more flexibly.

"The transfer of the fab is a major step in consolidating our frontend manufacturing


footprint after the acquisition of International Rectifier. I would like to express my sincere thanks to Neptune 6, the Welsh Government and above all to the committed employees at the Newport facility who have always excelled by their enormous commitment and expert knowledge."

Steve Berry, the legal director of Neptune 6 Ltd, commented: "The Newport site, which comes with a skilled workforce of highly reliable and very experienced people, is extremely well placed to contribute to the rapidly emerging International Compound Semiconductor Cluster of South Wales. The fab is very well equipped to act as a globally competitive chip foundry, and Newport Wafer Fab Ltd. will be highly complementary to the existing semiconductor expertise in the region."

On behalf of the Newport Wafer Fab team, Steve Berry expressed his gratitude to the involved parties, including Infineon, HSBC Bank and the Welsh Government for facilitating the transaction. "The success of the transaction means that Newport Wafer Fab can provide the employees, the region and the UK with a very bright future in high volume advanced semiconductor chip manufacturing," Berry said.

Welsh Cabinet Secretary for Economy and Infrastructure Ken Skates said: "I am delighted that the Welsh Government has been able to support a deal to save the Newport site and the jobs of the people employed there. The closure of the site in Newport would have been a major setback for the local and national economy and would greatly detract from the substantial investments made to establish Wales as a global centre for Advanced Compound Semiconductor technologies."

As Skates underpinned, the site would form a key part of the Compound Semiconductor Cluster over the coming years: "The cluster will make a significant contribution to the future of the Welsh economy and support many global companies based here, such as Airbus, GD, Sony and GE. The synergies this can deliver will contribute to increased skills levels in the region and will attract further technology businesses to Wales. Highly-skilled technology roles, such as these retained in Newport, are of significant value to our economy and vital to ensure Wales capitalises on the growth of the digital economy."

# Mitsubishi reports record efficiency for SiC MOSFET

MITSUBISHI ELECTRIC has developed a SiC MOSFET with what is believed to be the world's highest power efficiency of a device of its type. It is designed to be installed in power modules, and does not require a high-speed protection circuit to interrupt supply when excess current is detected.

Mitsubishi reported the development at the 2017 International Conference on SiC and Related Materials (ICSCRM 2017), held in Washington, DC.

The superior reliability and efficiency of the new device is the result of a new proprietary source structure. In conventional MOSFETs, the source area is formed as a single region. However, Mitsubishi Electric has introduced an additional region in the source area to control the source series resistance of the SiC-MOSFET.

Adopting this structure reduces the incidence of excessive current flows caused by short circuits. As a result, on the general short-circuit time used for silicon power semiconductor devices, the on-resistance of the SiC-MOSFET is reduced by 40 percent at room temperature, and power loss by more than 20 percent, compared to conventional SiC-MOSFET devices. A simplified circuit design allows the technology to be applied across SiC-MOSFETs with various voltage ratings. Tried and tested circuit technology is used to protect silicon components from damage in the event of short-circuits, and can be applied to existing SiC-MOSFETs without any need for modification. This guarantees easy implementation of protective functionality in power electronics equipment using SiC-MOSFETs.

Mitsubishi believes that the new device could help improve the reliability and energy efficiency of power electronics equipment used in a very wide range of applications such as home electronics, industrial machinery and railway operation.

# Finnish start-up raises €450k for III-V passivation process

COMPTEK SOLUTIONS OY, a Finnish start-up, has announced the completion of €450k funding-round to support commercialisation of its technology for radically reducing (up to 98 percent) the surface defects on III-V materials. The round was led by Inventure, a Nordic venture capital fund. Timo Toikkanen and several other business angels and industry experts also participated.

Compound semiconductor materials tend to oxidise very quickly during the manufacturing process, leading to a much lower performance level than what could be achieved. Comptek tackles this problem with a novel process, discovered and patented by the founders, giving the industry a new tool to push the efficiency of compound semiconductor devices to the next level. With the proceedings of the investment, Comptek is setting up a laboratory with a clean room and custom made reactors with which to make commercial samples. The company is currently involved in a couple of trial agreements with big companies in the optoelectronic and RF sectors.

"With our technology, branded as Kontrox, we are giving compound semiconductor producers the means to push the boundaries of power efficiency much further. This is of extreme importance in booming markets, such as electrical cars, self-driving cars, or VR/AR, where the demands for functionality optimization and power savings are critical. We have already achieved the unprecedented levels of performance for some materials and raised the interest of some of the biggest companies in the space worldwide", says Vicente Calvo Alonso, CEO of Comptek Solutions.

Timo Tirkkonen, partner at Inventure comments: "We are very impressed of what the team have achieved so far. The proprietary technology developed by Comptek shows a tremendous increase in performance and quality in the compound semiconductor process. We believe that the technology will be a crucial part of the next-generation semiconductor products."

# Navitas GaN ICs shrink laptop adapters

NAVITAS SEMICONDUCTOR has announced what it believes is the world's smallest 65 W USB-PD (Type C) adapter reference design, to keep pace with the dramatic size and weight reductions in laptop designs over the last ten years.

High-frequency, high-efficiency AllGaN Power ICs are used to deliver 65W in only 45 cm$^3$ and only 60 g in weight by minimising the size, weight and cost of transformers, filters and heatsinks. By contract, existing silicon-based designs can require 100-115cm$^3$ and weigh over 300 g, according to the company. The NVE028A reference design achieves its small size (51 x 43 x 20.5 mm cased) and breakthrough power density (1.5 W/cm$^3$ cased) using simple, standard, low-cost manufacturing techniques.

"Finally, a laptop adapter is thin and light - like the laptop it charges – and at a great price", said Stephen Oliver, the company's vice president of sales & marketing. "Power designers have been faced with several, conflicting industry challenges, from new USB Type C connectivity and USB PD (Power Delivery) output compliance to statutory energy efficiency standards and the ever-present issue of cost. Navitas GaN Power ICs deliver the simultaneous achievements of high-speed operation and high efficiency to enable a single system design that meets all of those challenges – at the same or lower cost than old, slow silicon designs".

The new NVE028A reference design uses GaN Power ICs in an active clamp flyback (ACF) topology running three to four times faster and with 40 percent lower loss than typical adapter designs, to deliver smaller size and reduced costs. The design is fully compliant with European CoC Tier 2 and US DoE Level VI efficiency standards, in addition to reaching peak efficiencies of over 94 percent at full load. "This is a major achievement in adapter design", said Mark Dehong Xu, president of the China Power Supply Society (CPSS) and director of the Institute of Power Electronics, Zhejiang University. "I think China Power Supply manufactures have been looking for wide-band-gap components like this, to further increase the power supply's efficiency and power density to satisfy the requirement of customers".

"Since we introduced the AllGaN platform at APEC'16, Navitas has announced single and half-bridge GaN Power ICs, the world's smallest 150 W adapter, and now the world's smallest, fully-compliant 65 W USB-PD design", said Gene Sheridan, Navitas CEO.

"This is the flexible, high-performance, cost-effective platform that meets and exceeds the targets of the mobile and consumer charger markets".

# BluGlass, Griffith University and IMCR work on next Gen GaN transistors

AUSTRALIAN technology innovator, BluGlass is working with Griffith University and the Innovative Manufacturing Cooperative Research Centre (IMCRC) to deliver next generation GaN transistors for power electronics.

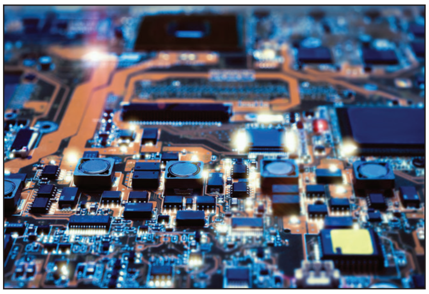
BluGlass will be leading the two-year, $600,000 cash investment (inclusive of a $300,000 grant from the IMCRC) research project to develop high performance normally off GaN HEMTs, that promise a positive and stable threshold voltage, low on-resistance and high breakdown field.

The project aims to combines two Australian enabling technologies – BluGlass' deposition technology called Remote Plasma Chemical Vapour Deposition (RPCVD), a low temperature approach for the manufacture of semiconductor materials, and Griffith University's Queensland Microtechnology Facility (QMF) Atomically Smooth SiC on large silicon wafers.

"Today, electronics manufacturers face high cost barriers for higher performing materials," said BluGlass managing director Giles Bourne. "The research project aims to overcome those industry challenges."

"Silicon is incredibly cheap and traditionally difficult to displace despite the performance advantages of other materials such as GaN. BluGlass' deposition technology, RPCVD operates at temperatures hundreds of degrees cooler than the current industry incumbent technology. This offers electronics manufacturers many advantages, including higher performance, lower cost throughputs and the ability to deposit on lower cost substrate such as silicon."

Bourne also stated that the ability to produce fail-safe, normally off devices will be critical for widespread adoption of GaN transistors. "Our unique low



temperature deposition of the *p*-GaN gate is required to enable high performance normally off devices, and this has significant commercial implications, not only for BluGlass but for the Australian power electronics industry."

Griffith University's QMF atomically smooth SiC on large silicon wafers provides a chemical barrier and template for the epitaxial growth of nitride layers that helps to address the challenges of defects and long-term device reliability.

Senior deputy vice chancellor Ned Pankhurst said the funding showed Griffith University's expertise in the nanotechnology field and its reputation as international leaders in the industry. "Griffith welcomes this innovative partnership which highlights the university's commitment to advancing technology through industry collaborations, further establishing us as world-leaders in cutting-edge technology and translational research," he said.

Throughout the project, which is co-funded by IMCRC (a not-for-profit, independent cooperative research centre), BluGlass will work closely with Griffith University's QMF and access their process and test equipment, infrastructure, device knowledge and resources to develop and optimise HEMT devices.

IMCRC managing director and CEO David Chuter said that this project has the potential of creating high value IP and industry transformative enabling foundry technologies which could lead to the generation of a local semiconductor wafer economy.

# SUPER8 project to develop 200GBps optical transceiver

THE COMPOUND SEMICONDUCTOR CENTRE (CSC) – a Joint Venture between Cardiff University and IQE Plc – has announced the award of a £1.1 million collaborative R&D project under the recent InnovateUK Emerging and Enabling Technologies Call. Project SUPER8: (A scalable 200Gb/s Super-thermal, 8 channel Coarse WDM architecture) will focus on the development of new ultra-high speed transceiver platform to service the enormous growth market in optical data communications in hyper-scale Cloud datacentres.

The consortium comprising CSC (Cardiff), Kaiam (Livingston) and Compound Semiconductor Technologies (Glasgow) will collaborate to deliver a commercial grade solution with the target of transfer to high volume manufacturing in a timescale of 30 months.
CSC Project Lead, Wyn Meredith commented: "The adoption of cloud services, video on demand and emerging IoT services are driving a massively expanding global data bandwidth demand.

The UK is already a major player in the supply of high performance compound semiconductor materials and components that underpin the global communications network. However, next generation high capacity networks will require higher transmission rate, lower cost transceiver solutions. This project will deliver an 'all UK' developed and manufactured solution which leverages world class compound semiconductor materials and device expertise at CSC and CST with Kaiam's highly innovative Photonic Integrated Circuit technology."

CSC was founded in 2015 as a Joint Venture between Cardiff University and IQE Plc, with the mission of accelerating commercialisation of Compound Semiconductor Materials and Device Research.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# JEDEC set standards for wide bandgap semiconductors

JEDEC Solid State Technology Association, the standards development organisation, has formed a new JEDEC committee: JC-70 Wide Bandgap Power Electronic Conversion Semiconductors. Led by interim chairs from Infineon, Texas Instruments, and Wolfspeed, a Cree Company, the new JC-70 committee will initially have two subcommittees: GaN and SiC and focus on Reliability and Qualification Procedures; Datasheet Elements and Parameters; and Test and Characterisation Methods.

JC-70's first committee meeting will be co-located with the 5th IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA), on October 30, 2017 in Albuquerque, NM. JEDEC meetings are open to committee members and invited guests only, and interested companies worldwide are welcome to join JEDEC to participate in this important standardization effort.

"The formation of the JC-70 committee is part of an ongoing effort within JEDEC to extend our standards setting expertise to new technologies to meet market demands. We welcome all interested companies to participate in the development of open industry standards within JEDEC."

SiC and GaN are the most mature wide bandgap (WBG) power semiconductor materials and offer immense potential for enabling higher performance, more compact, and energy efficient power systems. "WBG GaN and SiC technologies are poised to benefit from the development of standards focused on quality and reliability, datasheets, and test methods," said Tim McDonald, senior director, GaN applications and marketing at Infineon Technologies.

During an industry conference in the spring of 2016, a working group of industry experts was formed. Designated as GaNSPEC DWG, it began laying the necessary groundwork for the development of standards for GaN.

JEDEC began providing logistical support to the group shortly thereafter. "To meet the demand of today's energy and product requirements, this team is helping to create the mature industry infrastructure that customers need to design power supplies," said Stephanie Watts Butler, technology innovation architect at Texas Instruments. "The broad academic and industry participation is indicative of the importance of wide bandgap for complying with these requirements."

GaNSPEC DWG was soon joined by a counterpart: the SiCSPEC working group. The two groups grew to almost 50 device manufacturers, equipment manufacturers, technology creators, academic representatives, and government labs from the US, Europe, and Asia.

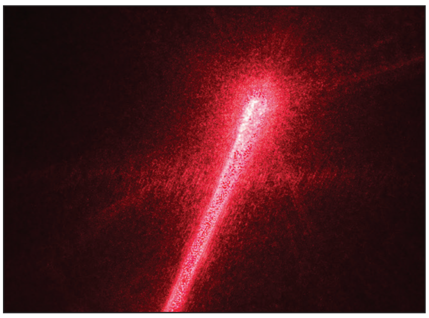
"Our consensus is that JEDEC is the logical home for the continuation of these efforts in a public forum, and the team is delighted to invite industry participation in this new JEDEC committee," said Jeff Casady, business development & programs manager from Wolfspeed, a Cree Company. "Creating clear, universal standards is a key step in advancing the adoption of wide bandgap technologies. These new parameters will enable users to design SiC and GaN devices into the systems of tomorrow, thus creating a more energy efficient future."

John Kelly, JEDEC President, added, "The formation of the JC-70 committee is part of an ongoing effort within JEDEC to extend our standards setting expertise to new technologies to meet market demands. We welcome all interested companies to participate in the development of open industry standards within JEDEC."

# II-VI launches laser bars for directed energy weapons

II-VI, a provider of high-power semiconductor laser components, has announced the commercial availability of its industry actively cooled laser bars, emitting 200 W of continuous wave power with greater than 60 percent efficiency. These laser bars enable multi-kilowatt vertical stacks to optically pump neodymium-doped solid-state lasers, including in below-freezing environments.

"With these bars we are capable of building stacks with more than 7 kilowatts of output power," said Karlheinz Gulden, general manager, II-VI Laser Enterprise. "It's a significant achievement that adds to our 20-year legacy of GaAs laser technology platform development."
Next generation directed energy weapon systems require increased mobility and operation at extreme ambient temperatures. II-VI's new laser bars



are said to offer an unprecedented combination of power, efficiency and polarisation purity. They enable diode-pumped solid state laser designs employed in new directed energy weapon systems to achieve optimum size, weight and energy efficiency.

The use of an ethylene-glycol coolant makes the II-VI laser bars commercially unique in their ability to operate in extremely low temperature conditions such as in airborne vehicles and withstand storage temperatures as low as -40°C. II-VI's new laser diode-bars, with demonstrated continuous wave output of up to 275 W, are rated for continuous wave output of 200 W in operation. The laser bars can be stacked to optically pump multi-kilowatt solid-state lasers. They also feature a proprietary hard solder technology designed to withstand high power pulsed operation with excellent reliability.

With short operating wavelengths in the 8xx nm regime, the laser-bar stacks are also effective in direct diode laser systems to process metals such as copper, bronze, brass, stainless steel and aluminum that are otherwise highly reflective to the longer wavelengths of typical industrial lasers.

# AXT completes purchase of Chinese facility in Dingxing

AXT, a manufacturer of compound semiconductor substrates, has completed the purchase of its new manufacturing facility in the city of Dingxing in the People's Republic of China.

Dingxing, located in the province of Hebei and under the jurisdiction of the prefecture-level city of Baoding, is approximately a 90-minute drive south of the company's current Beijing location. The new site, which features space for expansion, currently has three existing buildings, which comprise approximately 140,000 sq. feet of manufacturing space, and 50,000 sq. feet designated for offices and dormitories.

The existing structures will enable the company to move more quickly to production. AXT has already begun to prepare the site for GaAs substrate manufacturing, and is planning for a staged relocation of its GaAs equipment and personnel throughout 2017 and 2018, pursuant to its relocation plan. Initial qualification substrates are expected to be available in the fourth calendar quarter of 2017.

The company expects to have production-level quantities from both its current site in Beijing and the new Dingxing site for a period of time, and then gradually increase production volume at the new site.

AXT has acquired a total of approximately 18.8 acres and expects to increase manufacturing capacity at the new location as needed to meet customer requirements. In addition, AXT will continue to evaluate the potential timing of relocation of its InP and germanium substrate manufacturing, which is expected to remain at the Beijing facility while the relocation of its gallium arsenide business is completed.

"Securing the location of our new facility is a positive step for AXT," said Morris Young, CEO. "We have worked closely and collaboratively with both local and central government authorities in China

to fulfill the government's request for the relocation of our GaAs production, while ensuring that we can continue to serve the needs of our customers and support the growth of our business.

"This step underscores the desire of all parties involved to make our relocation a success. I want to thank the city officials of Dingxing and Baoding for welcoming AXT to this site."

Young continued: "With its relative close proximity to our current facility, its existing manufacturing space, and its room for expansion, we believe our new location positions us for both a successful and efficient relocation of our GaAs business, as well as the expansion of our capacity as current and emerging applications for our technology increase customer demand. Our goal is to make our new location a world-class manufacturing facility and a showcase of our capabilities for customers and investors."

Wilson Lin, chief operating officer, said, "Our dedicated manufacturing and operations teams have been working diligently over the past year to prepare for a smooth and efficient transition for our customers.

"We are committed to supporting their requirements from our current location, while providing an efficient qualification process and transition plan for the new facility. I am confident that we have a highly skilled team in place, and the deep executive experience and oversight to ensure our success."

# Norstel develops low defect 150 mm SiC substrates

NORSTEL AB, Sweden, has announces the successful development of low defect density 150 mm SiC *n-type* substrates. "With a micropipe density below 0.2 $cm^{-2}$ and a Threading Screw Dislocation density below 500 $cm^{-2}$, our first 150 mm conductive 4H SiC substrates demonstrate our commitment to quality as an enabler for high yield device processing" says Alexandre Ellison, CTO of Norstel AB.

The company states that it has prioritised wafer quality over time to get to the next wafer size. As a result, emphasis was given in R&D to first decrease the dislocation density in the SiC wafers prior to diameter expansion from 100 mm to 150 mm. First 150 mm customer samples will be available by 1st quarter 2018.

Ronald Vogel, CCO of Norstel, summarizes: "Our SiC Perfection development program performed in the recent years has enabled us to achieve a leading position in terms of high quality SiC wafers.

"We now have achieved to preserve the high quality during the expansion to 150 mm. In light of the growing market demand for SiC-based energy efficient power electronics solutions in applications like PVs, EVs/HEVs, charging infrastructure, trains, energy storage and many more the SiC device and module industry scales up to meet such demand.

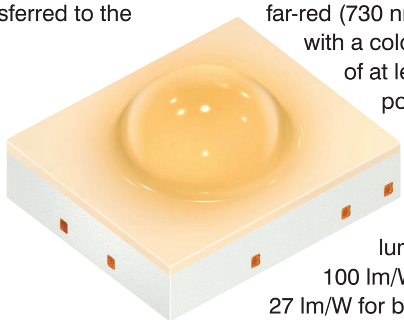
"Larger diameter and lower defect SiC wafers will enable them to increase production efficiency, device yields and volume supply capability to meet their customers' expectations."

# Osram launches new mid-power LED range

OSRAM OPTO SEMICONDUCTORS has announced the Osconiq product line, a mid-power LED family that will cover professional applications including linear and area lighting, high and low bay lighting and street lighting.

The familiar Duris P products, which are currently being used for these applications, will be transferred to the new Osconiq line.

The first member of the new family is the Osconiq P 2226 which features an epoxy package, surface-emitting chip and robust silicone.



The different versions of the 2226 are said to be particularly durable and resistant to corrosion.
They have the same footprints as the previous Duris P 5 series, namely 2.2 mm x 2.6 mm x 1.25 mm, which means they are interchangeable and can be integrated in existing systems.

The small dimensions of the Osconiq P 2226 enable more LEDs with the same or with different colours to be integrated in customer applications to achieve optimum homogeneous color mixing results.

These features make the LEDs ideal for outdoor applications such as horticultural and architectural lighting and also for indoor lighting systems such as those installed in restaurants and hotels.
The Osconiq P 2226 is available in the following colour versions: deep blue (450 nm), blue (465 nm), true green (525 nm), yellow"(595 nm) red (623 nm), far-red (730 nm), and ultra-white with a colour rendering index of at least 60. This mid-power LED offers the usual outstanding performance.

For example, the luminous efficacy is 100 lm/W for the red version, 27 lm/W for blue and 92 lm/W for true green.

The LEDs are designed to be used in professional indoor and outdoor applications where monochromatic colours are required. The LED also offers a large bandwidth of operating points. If required, it can be operated with a flexible range of currents.

While the binning current of 100 mA provides a competitive luminous flux at outstanding efficacy, the Osconiq P 2226 can be driven up to 250 mA, when clients need especially strong light.

# MBE award for CCNY's Maria Tamargo

NEW YORK chemistry professor Maria Tamargo has won the 2017 MBE Innovator Award for her work in "advancing the growth of wide bandgap II-VI semiconductors by molecular beam epitaxy and demonstrating their unique physical properties and potential novel device applications.' The North American MBE Advisory Board will present the award at the North American MBE Conference (NAMBE) in Galveston, Texas, in October. Tamargo will receive a $3,000 prize, a plaque and the opportunity to give an invited talk at the NAMBE Conference.

Established in 2004, this international award recognises individuals whose innovative work has significantly advanced the field of molecular beam epitaxy. Recipients are highly distinguished scientists whose inventive work must have had/or continue to have a significant impact on the advancement of MBE technology. In addition to her faculty position in City College's Division of Science, Tamargo is director of the National Science Foundation's CREST Center for Interface Design and Engineered Assembly of Low-dimensional Systems, known as IDEALS.

# Ascatron introduces first 3DSiC power products

ASCATRON, a spin-out from the Swedish research centre Acreo, is now providing next generation SiC power semiconductors using its proprietary 3DSiC technology.

With a background in producing advanced SiC epi material, Ascatron has recently transformed from a service provider to a device product company. The first products available for customer testing are diodes rated to 1200 V, 1700 V and 10k V. MOSFET switches are under development and will be introduced 2018.

"We have developed a unique material technology that makes it possible to fully use the potential of SiC to handle very high power with minimal losses, while maintaining the reliability of silicon", says Adolf Schöner, CTO of Ascatron. "We call it 3DSiC and is based on our expertise in producing advanced SiC epitaxy material. The technology has the potential to lower the losses up to 30 percent compared to conventional solutions".

The 3DSiC technology enables a modular design of Ascatron product line. Each device is divided in a high voltage module related to the desired voltage class, and a low voltage part for each type of component. Combination of different modules gives a wide range of products.

"Our business target is to be highly trusted and innovative supplier of SiC semiconductors for power electronics in industry, automotive and energy", says Christian Vieider, CEO of Ascatron. "We foresee a period of technology change when shifting from silicon to SiC and target to take part in such industry consolidation".

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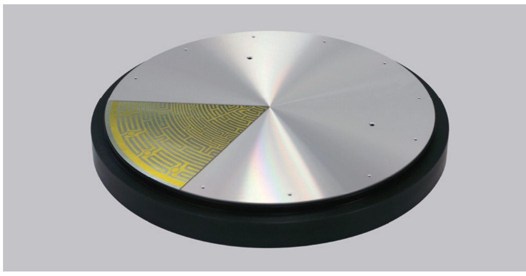

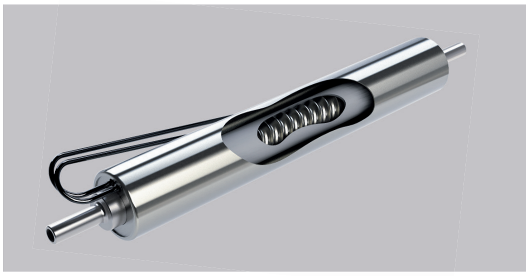

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# European Consortium completes VCSEL project

PHILIPS PHOTONICS, a maker of VCSELs, has announced the successful completion of its 'VIDaP' project (VCSEL Pilot Line for Illumination, Datacom and Power Applications), a €23 million project jointly sponsored by the German Federal Ministry of Education and Research (BMBF) and the EU, and executed under the umbrella of the European ECSEL program.

Since its inception in 2014, the project has focused on making significant advancements in highly automated manufacturing, bringing VCSEL production to the same level of maturity as the LED industry. Philips Photonics led the project. Other partners were IQE Ltd, STMicroelectronics, Sidel, SICK AG, Mellanox Technologies Ltd, and the Technical University of Eindhoven. Global revenues for the VCSEL market currently stand at several hundred million, and are expected to swell to above $1 billion in 2022.

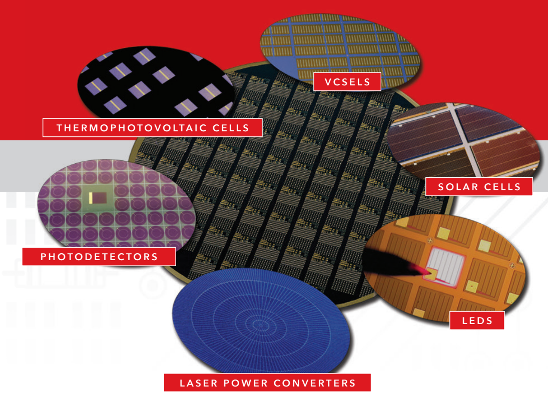
Prior to the project, VCSELs were only manufactured in small quantities, with largely non-automated processes. Now, Philips and its consortium partners have successfully demonstrated the capability to manufacture VCSELs to the same standards as other high volume semiconductor components. The capability will help to unlock the potential of new solutions such as high speed data transmission, 3D recognition, optical sensors such as Lidar and digital industrial thermal processes, whilst significantly reducing the size of sensors and energy consumption in data centres and thermal industrial processes. Following the announcement last year that Philips was expanding and doubling the capacity of its laser-diode facility in Ulm, Philips has produced a cumulative 700 million VCSELs. This fast growth in demand has triggered follow-up investments that will lead to another doubling of capacity by early 2018. The expansion of the facility in Ulm is also on track to be completed by the end of 2017, as scheduled.

"With the digital revolution firmly underway, the market need for VCSELs is rapidly accelerating. Anticipating this demand, over the past few years we have invested consistently in research, product development and efficient manufacturing processes," said Joseph Pankert, general manager, Philips Photonics. "Today, our products are widely used in data centres, smartphones and a number of industrial applications, with the advancements brought about by the project helping to secure Philips a leading European position in this growing segment of optoelectronics."

# Oxford PV founder awarded Citation Laureate

OXFORD PHOTOVOLTAICS, a developer of perovskite solar cells, has announced that Henry Snaith, the company's co-founder and chief scientific officer has been selected for a 2017 Clarivate Citation Laureate.

Snaith has been recognised for his advancements in the field of chemistry, specifically for his contribution to the discovery and application of perovskite materials to achieve efficient energy conversion, alongside Tsutomu Miyasaka and Nam-Gyu Park, also pioneers in this area. "Citation Laureates are scientists and economists whose publications have been cited so often by their colleagues – and thus who have been so influential – that they are forecast as potential recipients of the Nobel Prize in this year or in the future" commented Jessica Turner, global head of the Scientific and Academic Research business at Clarivate Analytics. "In 15 years, 43 Citation Laureates have gone on to receive Nobel honours. We are delighted to congratulate Henry on being selected for a Citation Laureate. This independent validation demonstrates the considerable progress that has been made in developing perovskite as a disruptive solar cell technology," said Frank Averdung, CEO, at Oxford PV.

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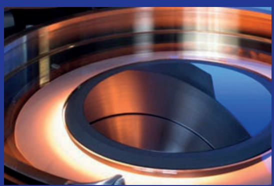  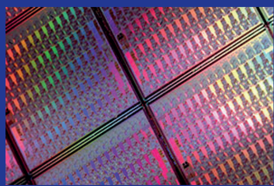  

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# **Blazing** ambition

Crystal growth furnace manufacturer, GTAT, has a solution that could see the price of SiC substrates plummet, reports Rebecca Pool.

FOLLOWING decades of development, SiC devices are finally gaining traction. Across the board, manufacturers of power supplies, photovoltaic inverters, and now plug-in vehicles, are testing or prototyping blisteringly fast and highly efficient SiC devices.

And the latest market forecasts from France-based Yole Developpement estimate the total SiC device market will top $1 billion come 2022, with compound annual growth rate reaching 40 percent from 2020 to 2022.

For US-based crystal growth and polysilicon technology supplier, GT Advanced Technologies, these market developments spell good news.

Emerging from bankruptcy following a fractured sapphire furnace supply contract with consumer electronics goliath Apple, the reorganised GTAT is targeting the solar industry with its equipment, amongst other markets. And, right now, it is touting a repeatable process for producing high-quality 6-inch SiC boules.

GTAT chief executive, Greg Knight, claims GTAT is the only supplier of both the equipment and a robust process to manufacture SiC boules for 6-inch wafers

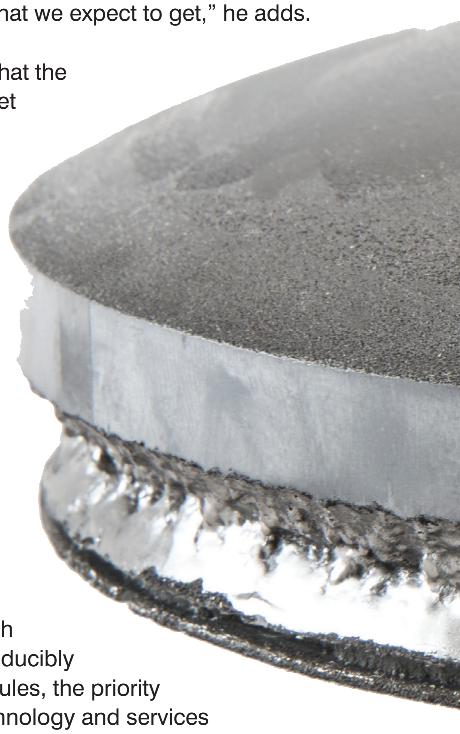
"For several years, we have been aggressively pursuing and have now established a stable, high-yield, robust 6-inch process," highlights GTAT's chief executive, Greg Knight. "This follows extensive thermal modelling, process development as well as switching from non-silicon carbide seeds to full silicon carbide seeds."

The process includes the company's 'SiClone' SiC sublimation furnace, related process technology and the all-important graphite hot zone, instrumental to reproducible, high-quality crystal growth.

Crucially, Knight is certain his company's process is ready to grow high yielding 6-inch boules that will compete, on quality, with 4-inch boules.

The chief executive won't be drawn on yield figures but as he puts it: "Getting the correct hot zone design and process were absolutely critical, and then the biggest challenge has been to reliably grow the boule over and over again, but this is what we are able to do."

"I'm not implying we have 100 percent yield but every time we open the furnace we're getting boules of the geometry and size that we expect to get," he adds.



Knight is confident that the time is right to market the company's SiC manufacturing solution, highlighting how much of the world's production remains captive, limiting supply and keeping prices high.

However, he hopes his company's approach will boost SiC semiconductor supply and drive costs down. And with a process that reproducibly produces quality boules, the priority is to get GTAT's technology and services into the market so manufacturers have access to an 'appropriately priced' 6-inch substrate.

"There are six-inch fabs out there that need this material and end up paying very high prices to get it," he says. "Our goal is to get the selling price of high-quality 6-inch wafers down so that downstream, fabs get the economic benefit of going to the larger substrate, and with our process, yield and hot-zone cost, we're ready to reach this now."

"We're very good at developing the necessary equipment, including optimising the furnace hot zone so it yields a good boule," he adds. "We're able to do this and reduce hot zone costs, so the [overall] cost is going to come down astronomically."

Indeed, today the cost of a 6-inch SiC wafer currently comes in at around $1500, while Knight believes, even now, this figure should be closer to $1000. As he highlights: "We have already identified a roadmap to get epi-ready wafer manufacturing costs down to around $300."

"Companies such as Cree are seeing a big uptake in the demand for SiC [technology], so when you see these businesses heavily investing in SiC, that is the biggest signal that the market growth is real," he adds.

Right now, Knight reckons GTAT is the only supplier of both the equipment and a robust process to produce SiC boules for 6-inch wafers, with the competition offering, as he puts it, a non-optimised baseline recipe. He also believes large markets for GTAT's equipment exist in Asia, including China, Taiwan and Korea, as well as the US, with key applications including PV inverters, electric vehicles alongside on-board electronics and charging stations.

"It has really been a tough transition for substrate providers; the move from four- to six-inch wafers is not so simple, especially for silicon carbide," he says. "But if the fabs have a six-inch substrate that is priced appropriately, six-inch production will increase, yields and demand will rise, costs will come down."


6-inch SiC boule grown in a SiClone 200 furnaces; the boule has been annealed and shaped.

# II-VI GROWING THE SIX INCH MARKET

A healthy mix of expansion and acquisitions looks set to secure II-VI's place in burgeoning compound semiconductor markets, reports Rebecca Pool

AS US-BASED II-VI steadily delivers transceivers, optical subsystems lasers and more, research analysts have predicted healthy year-on-year growth of more than 14 percent.

For the optics and photonics firm, buoyant times follow a swift string of acquisitions including Anadigics and Epiworks in 2016, as well as significant epiwafer expansion of its production facility in Champaign Illinois, US.

Signalling clear growth intentions, II-VI also acquired a UK-based compound semiconductor wafer fab from Kaiam, US, in late summer this year.

The Newton Aycliffe facility was originally built by Fujitsu in the 1990s to manufacture silicon memory chips. Several sales later – with Kaiam holding onto the facility for mere months – the plant has been steadily churning out GaAs transistors.

But as Gaurang Shah, senior vice president at II-VI, points out, the facility has the potential to manufacture so much more.

"This is a world class facility that can service many growth markets and we will be able to develop and differentiate many technologies and provide customers with the capacity they need to grow business," he says.

"The shell and current general facilities of the plant alone at least double our current capacity, but the infrastructure is there for us to grow this even more and become a significant player in the compound semiconductor market," he adds.

According to Shah, key growth applications include 3D sensing, already earmarked for considerable growth by many VCSEL manufacturers, as well as 5G wireless infrastructure and high-speed data centres.

VCSELs will remain as important as ever to II-VI, but Shah reckons future production options at Newton Aycliffe could include InP photonic integrated circuits as well as RF devices based GaAs and GaN-on-SiC materials.

"VCSELs are a key growth area for us but the real purpose of the acquisition is to make the world's most agile compound semiconductor fab," he says. "We want to put several different technologies here as the facility is large enough and also has the capacity to handle this; our growth will go well beyond VCSELs."


Photo credit: Kaiam

Given that 6-inch epi-wafer production is underway at II-VI's rapidly expanding MOCVD facility at Champaign Illinois, the Newton Aycliffe plant is expected to operate on a 6-inch platform as well.

As Shah tells *Compound Semiconductor*, the equipment at Newton Aycliffe is in good shape, and includes an Aixtron G4 MOCVD reactor for in-house epitaxial production.

"We intend to move quickly and aggressively with our plans to roll-out the technologies that we have targeted for the site" highlights Shah. "We expect to produce initial samples of at least one or two of these technologies within a year and reach qualification within the next 24 months."

Right now, Newton Aycliffe is home to a workforce of about 100 employees. According to Shah, the 'quality of the talent here is very high'. And as he adds: "This world class fab has some very good people, and as production increases, we expect to expand this workforce."

## Partnership prospects

In the meantime, II-VI is also in the process of putting together a formal working relationship with the facility's previous owner. California-based Kaiam's core business is transceivers for telecom and datacom markets, so II-VI could provide key components as well as finished epi-wafers to the firm.

Indeed, Kaiam's chief executive, Bardi Pezeshki, is upbeat about such prospects. As he tells *Compound Semiconductor*, the facility has an 80 percent to 20 percent split with 6-inch GaAs, and InP production.

His firm's interests are primarily centred on the latter, InP production, but news of 6-inch production availability stirred up significant industry interest.

"A number of companies approached us to use the six inch line for various applications with Kaiam providing foundry services," he says. "This quickly morphed into a number of offers for the whole factory and potentially the new owner providing foundry services for InP."

"The reverse relationship made a lot more sense than Kaiam becoming a foundry for the larger six inch line," he adds.

According to Pezeshki, Kaiam is now using the $80 million cash from its sale to expand its transceiver line and develop next-generation device production. And for Shah, with Newton Aycliffe in tow, II-VI's prospects for growth are certain, as indeed, analysts predict.

"The world of compound semiconductors is very capacity-constrained at the moment so we see huge opportunities here," he says. "We will develop products that are applicable to global markets and this really allows us to expand our business."

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### ANALYST

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

### SPEAKERS

- **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

## 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

- **Zhen Zong: Yole Développement**
  Presentation title to be announced.

### SPEAKERS

- **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

## 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

- **Roger Hall: Qorvo**
  Building the industry's first 5G front-end
- **Liam Devlin: Plextek RFI**
  MMICs - what is needed to get mmWave 5G to work?

## 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

- **Andreas Weisl: 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

## 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





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# Setting a new benchmark for brightness

## Reducing thermal lensing boosts brightness of broad-area laser bars

BY CHRISTIAN LAUER FROM OSRAM OPTO SEMICONDUCTORS

FOR ANY MANUFACTURER, the ideal product is one that increases its share in a growing market. That's the case for the high-power laser diode, which serves a variety of applications from pumping fibre lasers to laser cutting and welding. It lies at the heart of fibre lasers and fibre-coupled diode lasers, which are taking market share from carbon dioxide and flashlamp-pumped, solid-state lasers, thanks to compelling attributes that include lower operating costs, greater efficiency and a smaller form factor.

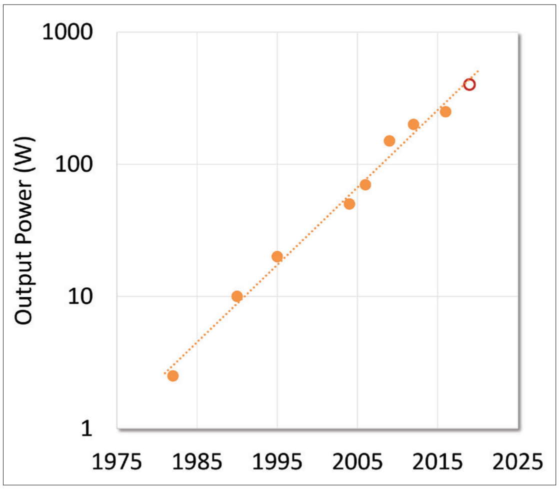


Figure 1. Osram's high-power diode laser products have undergone a tremendous increase in output power since the 1970s.

Commercial opportunities for the high-power laser diode are increasing, driven by new additive manufacturing techniques, such as laser metal deposition, laser metal fusion and laser sintering. These laser-based technologies are laying the foundation for automated, and thus cost-effective, production of a handful of parts – and in some cases single entities. Rapid growth for additive manufacturing systems is predicted, due to the move towards digitalized, highly connected smart factories. In Germany this new era in manufacturing is known as Industry 4.0.

As Industry 4.0 takes off, the deployment of high-power diode lasers will become even more widespread, placing cost under an even more intense spotlight. This scrutiny will crank up the pressure on the bang-per-buck of all the components, including the most important of all, the laser diode.

In fibre lasers, laser diodes tend to be in the form of broad-area laser bars – these comprise several wide emitters and deliver a very high optical power. CW outputs of hundreds of watts to a few kilowatts are possible, using industrial diode lasers based on multi-bar stacks.

One option for lowering the cost of the fibre laser

Left: High-performance diode lasers are playing an increasingly important role in materials processing, for example in welding and cutting. Semiconductor laser diodes with high beam quality and brightness have the potential to significantly reduce the cost of these systems.

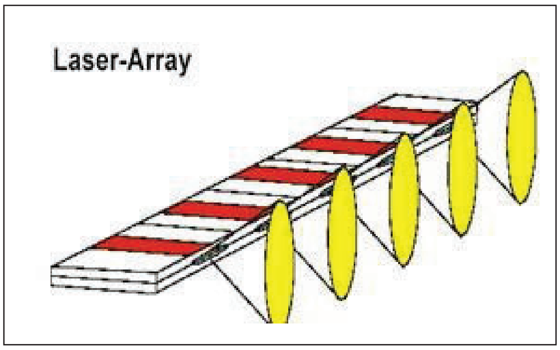


Figure 2. A highly elliptic beam is produced by individual laser diodes and the emitters of a laser bar.

system is to increase the output power and the efficiency of the laser diode, and ultimately trim the number of chips. Success in this endeavour would have additional benefits, as it would simplify cooling and reduce the complexity associated with the coupling of the laser beam into the fibres. Further gains could result from improvements to the beam quality of laser diodes, as this can increase the coupling efficiency into the fibres.

## Material processing

At Osram Opto Semiconductors of Regensburg, Germany, we are making progress on all these fronts, and are setting a new benchmark for brightness, a figure of merit that is critical to evaluating the capability of a laser when deployed in a fibre-laser system.

Our efforts draw on more than 40 years of experience in producing and developing infrared laser diodes and laser bars based in AlGaInAs and GaInP, two

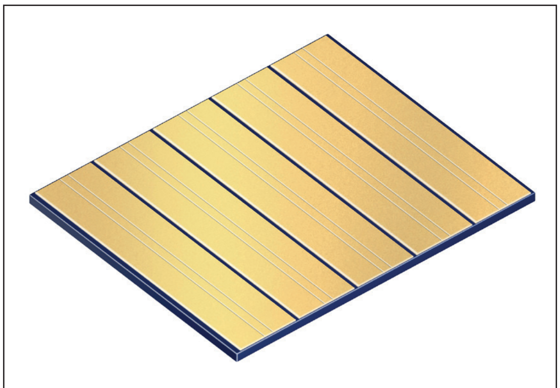

Figure 3. Osram's SPL BF98-40-5 laser bar was specifically developed for efficient coupling of light into fibres.

alloys that can deliver emission at around 1 μm, an ideal wavelength for materials processing (see Figure 1). Since the 1970s, the output of our lasers has increased from just a few watts to 250 W, with the efficiency of power conversion climbing to now exceed 60 percent. Further improvements will follow: by 2020 we expect to produce 400 W laser diodes with an efficiency of more than 70 percent.

Increasing power and efficiency are not our only objectives – we are also improving the beam quality of the laser, because this determines how efficiently light is coupled into a fibre. Today, our efforts are focused on a mini-bar, known as the tailored bar, or T-bar for short. This architecture has been developed to support a relatively recent move by manufacturers of high-power diode lasers; namely, designing a laser bar for a certain type of fibre, to reduce the complexity of the light incoupling optics. With a wavelength of 976 nm, our T-bar is specifically designed to pump ytterbium-doped fibre lasers.

Beam quality is a measure of how well a laser beam can be focused. It is defined by the product of the divergence half-angle and the radius of the beam in the focus point, known as the beam parameter product (BPP). Note that the beam quality is closely connected to the brightness of the laser, that is, its optical output per unit of area and solid angle. To realise a high brightness, a high proportion of the light emitted by the laser has to be coupled into a fibre in an efficient manner.

The beam quality of the laser decreases with its output power, thus setting an upper limit to the suitable output power of the whole system. Or, in other words, if a laser system is to operate as cost-efficiently as possible, the optimum beam quality for each fibre must be realized with the highest possible optical power.

Coupling the output from a laser diode into a fibre is not that easy. Ideally, the beam would be circular. However, it is actually elliptical (see Figure 2). This means that the beam parameter product of the laser diode has different values in the vertical and the lateral directions (referred to as the fast and slow axes, respectively). Along the fast axis, the beam angle is typically 40°, while it is just approximately 10° along the slow axis.

The tremendous difference in the beam divergence along the fast and slow axes stems from the geometry of the active region: it is just a few microns thick, but around 100 μm wide. Due to these dimensions, in the vertical direction the standing light wave in the resonator develops just one optical mode and provides diffraction-limited output, enabling easy coupling, while in the lateral direction there are a large number of higher order modes and the emission exceeds the diffraction limit by far. Trimming the width of the emitter could cut the number of modes, but the

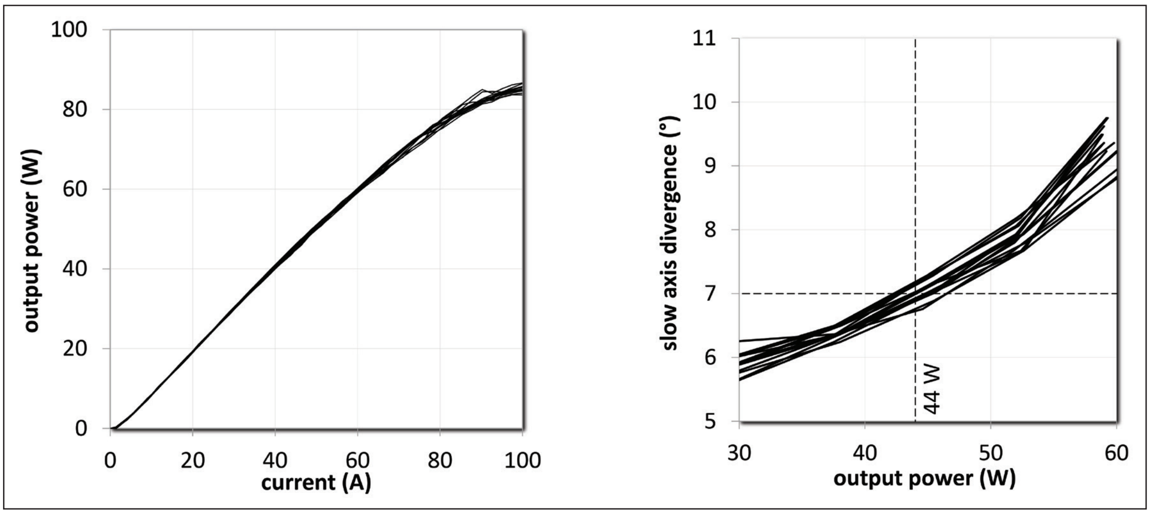


Figure 4. (a) Characteristics of Osram's SPL BF98-40-5 bar. Up to approximately 70 A, the output power remains linear with the current at a slope of around 1.08 W/A. Efficiency exceeds 60 percent up to 65W. (b) Dependence of the lateral beam angle, and thus beam quality, on output power. The target value of 7° or 15.5 mm-mrad is achieved at 44 W. This corresponds to a brightness of 2.8 W/(mm-mrad).

price to pay for this is a cut in output power. However, optimisation is still possible, and great strides could be made, as today's values for beam quality fall far short of what is theoretically possible. In the vertical direction it is a different story as this "optimisation" is inherent to the vertical waveguide design.

We have optimised the design of our T-bar – the SPL BF98-40-5 – for coupling into fibres with a diameter of 200 µm. However, the development of this chip, as well as the measurements on it, can be directly applied to other designs of laser diodes.

Our T-bar chip is 5 mm wide, 4 mm long and comprises five 100-µm-wide emitters, arranged side by side in parallel (see Figure 3). The fill factor, that is the percentage of space taken up by the emitters over the entire edge area, is only 10 percent. The advantage of using a small fill factor is it largely avoids thermal crosstalk between the emitters.

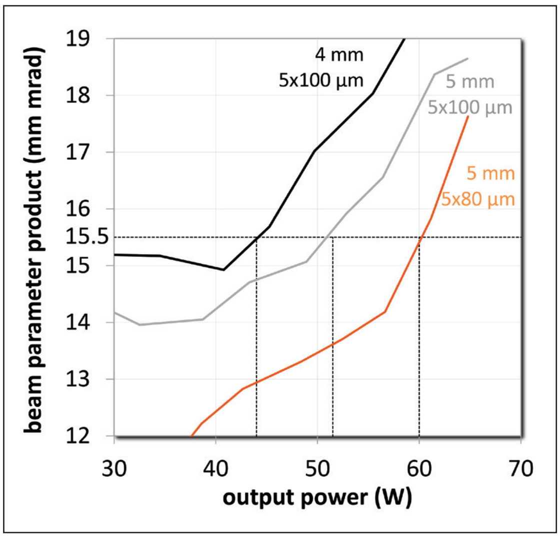


Figure 5. Increase in optical output power for a beam parameter product of 15.5 mm-mrad, based on the SPL BF98-40-5 (black), with a longer resonator (grey) and with narrower emitters (orange).

To keep the operating temperature of our device as low as possible, we hard-soldered it, using a gold-tin alloy, to copper-tungsten sub-mounts with microchannel coolers. A common weakness for the edge-emitting laser is the mirrors on the facets, which are exposed to very high power densities. However, this is not an issue for our chip, as there are no signs of catastrophic optical damage, even at a current of 100 A (see Figure 4 (a)).

When the current is this high, our device is hampered by thermal roll-over. In this regime, the chip is so hot that any further increases in current do not lead to a higher output, but just impair efficiency. Due to this, lasers are typically operated well below the thermal rollover point. For the SPL BF98-40-5, operation at an output power of below 65 W is to be recommended, as this produces a power conversion efficiency in excess of 60 percent.

The optimal beam parameter product for the laser is governed by the value for the corresponding fibre. The fibre we are using has a core diameter of 200 µm, a numerical aperture of 0.22, and a beam parameter product 22 mm-mrad.

Based on the latter value, we calculate that the most efficient optical incoupling will occur when our laser has a beam parameter product of 15.5 mm-mrad. This corresponds to a lateral divergence angle of 7° – at this angle, the beam area contains 95 percent of the output power.

Measurements on our T-bar laser show that the target value of 7°, or 15.5 mm-mrad, is reached at 44 W (see Figure 4 (b)), resulting in a brightness of 2.8 W/(mm-mrad). Crank up the power beyond this and beam divergence increases, preventing full coupling of the light from the bar into the fibre. We

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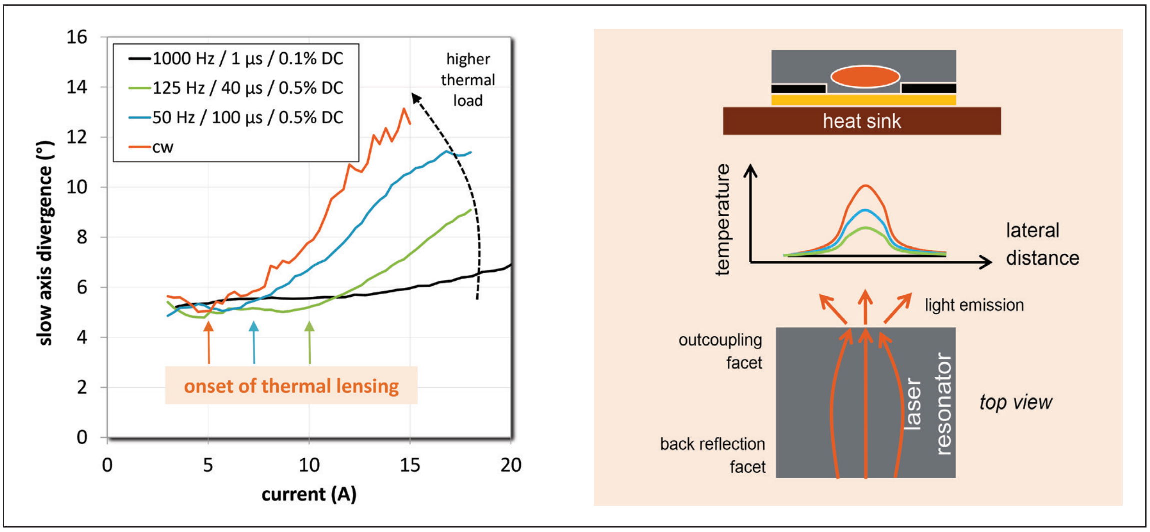



Figure 6. Thermal lensing of a single emitter as a function of pulse length and current.

can conclude from this observation that it is the beam quality of the chip that limits the efficiency of the entire system.

## Longer resonators, narrower emitters

We can be sure that it is the beam quality that is holding back system efficiency, because extensive reliability tests show that chips can deliver significantly higher output powers while maintaining long lifetimes. Our goal, therefore, is clear: to increase beam quality or vice versa achieving a higher output power at the beam parameter product of 15.5 mm-mrad.

Efforts have kicked-off with an increase in the length of the resonator from 4 mm to 5 mm. Switching to the larger chip enhances heat dissipation, and ultimately allows the laser to operate at a cooler temperature while its current is maintained. Thanks to this refinement, the output power at 15.5 mm-mrad increases to 52 W, and the resulting brightness improves to 3.4 W/(mm-mrad).

We have focused our attention on thermal lensing, which is associated with a lateral gradient in the refractive index. This occurs because there are electrical resistances and optical losses present during device operation that cause the active region to heat up, heat to flow to the heat sink, and a non-uniform temperature profile to appear across the chip

Our second modification to the T-bar laser has led to a reduction in the number of high lateral modes. As the number of these modes increases with the width of the emitter, we made it narrower, trimming it from 100 µm to 80 µm. This enabled an output of 60 W and a brightness of 3.9 W/(mm-mrad) at 15.5 mm-mrad (see Figure 5).

Unfortunately, the lengthening of the resonator and the reduction in the emitter width don't just lead to a substantial increase in output power at 15.5 mm-mrad. They also have undesirable consequences: they increase chip size, due to the introduction of a longer resonator, and this increases costs; and a narrowing of the emitter increases the power and current densities within the chip, raising reliability concerns. One upshot is that additional quality tests are needed to ensure safe operation at maximum operating conditions.

## Trimming thermal lensing

These downsides have prompted us to search for a way to improve the beam quality while retaining the standard chip geometry, which is the 4 mm resonator length and 100 µm emitter width.

We have focused our attention on thermal lensing, which is associated with a lateral gradient in the refractive index. This occurs because there are electrical resistances and optical losses present during device operation that cause the active region to heat up, heat to flow to the heat sink, and a non-uniform temperature profile to appear across the chip.

The lateral gradient in the refractive index resulting from the non-uniform temperature profile causes the diffraction of light beams towards the centre of the emitter, resulting in a large number of lateral modes and a higher divergence angle.

Measurements on our T-bars reveal the impact of current and pulse length on thermal lensing (see Figure 6). With very short pulses the chip barely heats up and the beam angle remains more or less constant as current increases. Lengthen the pulses, however, and higher beam angles are seen at higher currents. When the pulse lasts forever – in other words, the device is operated in CW mode – the beam angle starts increasing at just 5 A. So, for a bar with five emitters, the threshold is only 25 A.

Turning to a new chip structure has reduced the lateral temperature gradient in the active region, reduced the divergence angles, and delivered a clear drop in the beam parameter product at a given output power (see Figure 7). What this means is that our laser can now deliver about 15 percent more power for the same beam parameter product. For the target value of 15.5 mm-mrad, the optical power has increased to 50 W and the brightness hits 3.22 W/(mm-mrad).

Today we are manufacturing extremely efficient, bright laser bars for coupling into fibres. These bars, which combine a high brightness of just under 3 W/(mm-mrad) with an efficiency of over 60 percent, can improve the overall system performance of industrial fibre and diode lasers. Thanks to this, costs are lower, as they employ fewer chips that require less cooling.

One promising option for increasing the performance in the future is to reduce thermal lensing. This will open the door to further increase in the output power at a given beam quality, while not compromising chip cost or reliability.

We have already achieved promising results with this approach, and over the next few years we will optimise this technology and transfer it to the production stage. Our goal is to take optical power to a new high while maintaining high beam quality, so that diode laser systems are more cost-efficient than ever before.

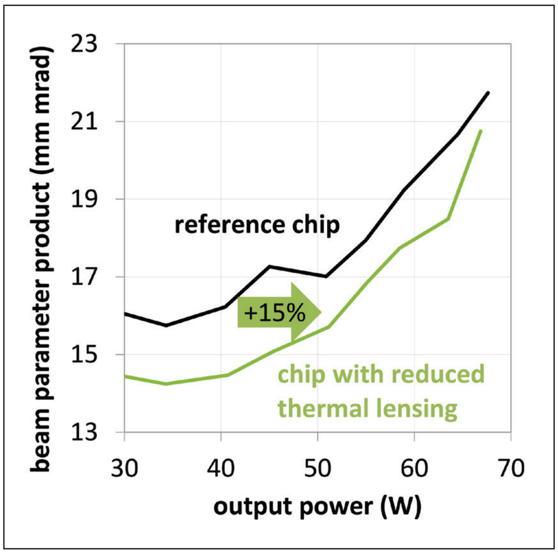



Figure 7. Reducing thermal lensing increases the optical power by around 15 percent at a constant lateral beam parameter product.

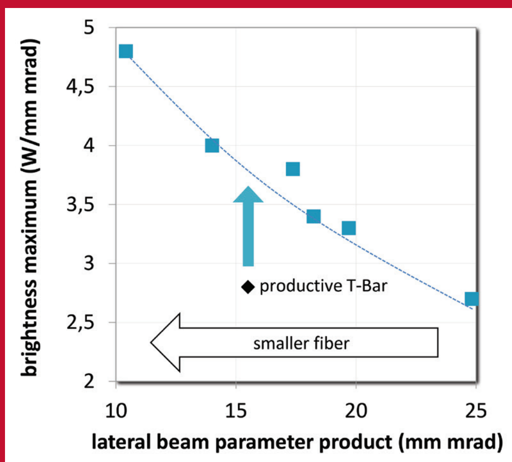
## Maximising brightness

IN AN R&D study, researchers at Osram have tried to maximise the lateral brightness at a low beam parameter product. The reward for that higher brightness is the coupling of more light into the fibre. For efficient coupling into small diameter fibres, low beam parameter products are a pre-requisite.

For this effort, researchers at Osram worked with a T-bar laser with a 5 mm resonator length. Improving the beam shaping of the chip has led to enhanced beam parameter products.

With this chip, the beam parameter product for power outputs up to 30 W has fallen to just 8 mm-mrad, enabling coupling to very small diameter fibres and corresponding to 3.75 W/(mm-mrad). At 50 W, this figure rises to 10.4 W/(mm-mrad) and the resulting brightness approaches 4.8 W/(mm-mrad). This is believed to be among the highest brightness values ever recorded for a broad-area laser diode, and is more than 60 percent higher than those of Osram's current T-bar products.

Power conversion efficiency of the chips peaks at 67 percent and consistently exceeds 60 percent up to 45 W. The new chips do, however, have higher power and current densities. Due to this, reliability tests are underway to ascertain the maximum admissible operating conditions.




An optimized chip design results in brightness levels of up to 4.8 W/(mm-mrad) with lower beam parameter products. This represents one of the highest levels ever recorded for broad-area laser diodes.

# Nitrides

## Strategies to boost performance

Presentations at the twelfth International Conference on Nitride Semiconductors offered an insight into strategies for improving the performance of UV LEDs, lasers and various forms of transistor

BY JEAN-YVES DUBOZ FROM CRHEA-CNRS


The Palais des Congrès et de la Musique hosted the 12th International Conference on Nitride Semiconductors. This venue, also known as the Strasbourg Convention Centre, was built in the 1970s and has undergone a major facelift in the last few years.

THERE IS NO DOUBT that a material system that has been used to manufacture countless devices for more than two decades is a success. But that does not mean that the devices have been commoditised, or that the material system is fully understood.

That's the state of affairs for GaN-based devices. While myriad LEDs and lasers have been shipped, netting billions of dollars, many questions remain that cover many bases. These questions are related to optoelectronic, RF and power devices, and to material properties and growth mechanisms.

Anyone wishing to hear the latest views on any of these matters should have attended this year's International Conference on Nitride Semiconductors, held in the historic city of Strasbourg during several rather wet days at the end of July. If they made the trip, they would have had the chance to talk to more than 800 delegates from all over the globe that met together in the Palais des Congrès et de la Musique. Many made the trip from Asia, which accounted for 43 percent of attendees, including 20 percent from Japan, while Europe contributed 42 percent and the US 12 percent.

Chris Van de Walle from UCSB provided a beautiful opening talk to this biannual meeting with a didactic overview of GaN material and its specific properties.

The west-coast academic championed the need for a proper reference for calculating the spontaneous polarization in nitrides – it is a key feature of these materials, and one that plays a critical role in device behaviour. Van de Walle also discussed droop, the decline in LED efficiency at high drive currents. He stressed the importance of the Auger effect, which he believes has been underestimated by many authors. In addition, he explained how non-radiative recombination on point defects can be enhanced by the excited states of defect levels.

Echoing some of these themes in the final plenary talk on the closing day, Slatko Sitar from North Carolina State University highlighted the importance of point defects in AlGaN. These imperfections increase non-radiative recombination, leading to a reduction of UV LED efficiency. According to Sitar, it is the growth mode that governs the population of these point defects, which can take the form of either intentional or residual doping.

Sitar also explained why intermediate AlGaN phases appear during the growth of AlGaN epilayers on AlN substrates. He pointed out that this low dislocation system allows the observation of a kinetically driven phase separation on the surface, which occurs due to strain. The extent of the separation depends on the temperature, growth rate and off-cut angle of the substrate.

During the conference many other groups reported results rela ted to these additional AlGaN phases. However, in most cases they arose in more dislocated systems, where surface kinetics are obscured by the effect of dislocations.

One of the highlights of the material session was the presentation by Bastien Bonef from UCSB, who showed both the beauty and the limitation of atom probe tomography. He argued that contrary to popular belief, atom probe tomography cannot be quantitative, unless it involves the use of a reference sample. Bonef also pointed out that the exact – and largely unknown – shape of the sample directly impacts the topology of the reconstructed profile.

Another talk in this session, given by Al Balushi from Pennsylvania State University, revealed that it is possible to form a two-dimensional layer of GaN between a SiC substrate and a graphene layer obtained thereon with a migration-enhanced encapsulation method. This is a triumph for GaN, as it can now replicate what has been accomplished with its BN cousin. It is not yet clear what applications may benefit from two-dimensional GaN, but its very high bandgap of 4.8 eV suggests that it has great promise in the UV. By undertaking precise transmission electron microscopy measurements, Balushi and co-workers observed how gallium atoms intercalate between graphene and the SiC, before reacting with ammonia to form a thin GaN layer with R3m symmetry.

## Improvements in the visible...

Although academics dominated the conference, there

were plenty of presentations from those in industry. They included plenary speaker Guillaume Arthuis, President of BBRight, a French-based developer of laser projection technologies. Arthuis argued that lasers can revolutionise movie projection by lowering the power consumption compared to filtered xenon lamps. What's more, lasers can simplify 3D projection, and by separating the light source from the digital light projector, they can yield simpler, cheaper, and more reliable systems in movie theatres. However, the downside of laser projection is speckle, stemming from the high degree of coherence of the laser. Addressing this issue is not easy – so far the best solution, which is far from ideal, is to shake the screen.

Arthius will have been pleased to hear talks at the meeting describing recent improvements in visible semiconductor laser performance. Masahiro Murayama from Sony Corporation announced that the company's green lasers can now deliver a 1 W CW output at 530 nm, under a drive current of 1 A. This laser has a wall plug efficiency of 17 percent, and an estimated lifetime of over 20,000 hours. Another pioneer of powerful green lasers is Osram Opto Semiconductors. Spokesman for that company, Harald König, told delegates that its green 517 nm lasers can now produce 120 mW at 200 mA, with a wall plug efficiency of 11 percent. Increase the wavelength to 532 nm and wall plug efficiency falls to 6.5 percent.

Other developments in visible nitride emitters included impressive results on green VCSELs by a team including Xin Zhang, who is affiliated to Xiamen University. Zhang described a surface-emitting device that produced CW, room-temperature emission at 560 nm with a threshold of 780 A $cm^{-2}$. Meanwhile, Czesław Skierbiszewsk, from TopGaN and the Institute of High Pressure Physics at the Polish Academy of Sciences, revealed the use of tunnel junctions in MBE-grown blue lasers. These devices demonstrated a slope efficiency of 0.85 W/A. Erin Young from UCSB is pursuing the same goal of improving the laser slope efficiency by introducing a tunnel junction in her blue edge-emitting lasers and VCSELs. With this modification she obtained a seven-fold increase in the power produced by the VCSEL.

Moving further to the red, Yasufumi Fujiwara from Osaka University revealed that the addition of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europium to the nitride quantum well enables a shift in emission to longer wavelengths. He and his co-workers fabricated red LEDs that produce 1.2 mW at 621 nm under a drive current of 20 mW. These results correspond to an external quantum efficiency of 3 percent. Higher efficiencies are possible, suggested Fujiwara, by optimising the incorporation site of europium so that it enhances energy transfer between this element and the GaN lattice.

An even more exotic approach to increasing the emission wavelength of nitride materials is to incorporate antimony into the active region during MBE growth. Zetian Mi, now at Michigan University, is leading a team exploring this approach. He told delegates that incorporating just 1 percent of antimony can shift emission to 600 nm. He explained that while changes to indium content merely impact the conduction band, the addition of antimony pushes up the valence band. Confirmation of these findings could unlock the door to new designs of nitride optoelectronic devices.

## ... and the UV

The performance of nitride devices is also improving in the UV. For LEDs operating in this spectral domain, many groups are exploring the trade-off between a good light extraction, by employing a *p*-AlGaN contact layer, and realising good carrier injection with a *p*-GaN contact layer. Both options lead to a similar wall plug efficiency: it is about 10 percent at 275 nm. RIKEN chief scientist Hideki Hirayama showed that this wall plug efficiency can be achieved with an AlGaN top contact, leading to an external quantum efficiency of 20 percent. With the alternative approach of the GaN contact, results reported in recent academic literature show that although the external quantum efficiency is just 10 percent, the lower bias results in a similar wall plug efficiency.


Going to even shorter wavelengths causes efficiency to plummet. According to Leo Schowalter, Chief Technology Officer at Crystal IS, efficiency halves for every shortening of wavelength by 5 nm. This rule of thumb is backed up by his report of an external quantum efficiency of about 0.3 percent at 239 nm, for a 1.8 mW LED, and the claim of a 4 percent external quantum efficiency by Akira Hirano from UV Craftfory, for a 260 nm LED.

Modifications to the standard device architectures are producing exciting results in the UV. Zetian Mi spoke about the use of AlN nanowires, which realise extraordinarily high levels of *p*-type doping, thanks to strain relaxation. Using this approach, his group has produced 239 nm lasers and 207 nm LEDs. Adding a tunnel-junction is another modification that shows promise. Siddharth Rajan from The Ohio State University revealed the successes of his group with this approach, including an on-wafer wall plug efficiency of 1 percent for a 287 nm device operated at 12 V.

An even more novel approach, described by Thomas Wunderer from PARC of Pan Alto, CA, is to replace electrical injection with electron-beam pumping. This approach enabled lasing action at 387 nm; and also emission at 246 nm, with a power of 230 mW, using pumping with a 4.5 mA current and a 12 kV accelerating voltage. For the shorter wavelength, wall plug efficiency is 0.4 percent.

Progress in LEDs and lasers continues to be driven by a combination of experimental efforts and theoretical work – together they can lead to new insights. At this year's ICNS, Aurélien David, Senior Principal Scientist at Soraa, gave new insights into the physics of LEDs within the framework of the well-known *ABC* model, which describes the various recombination mechanisms for the device. David explained that the *A*, *B* and *C* coefficients all depend on current, and revealed that with this modification it is possible to produce a very good fit to experimental data. Meanwhile, Gerhard Klimeck, an academic at Purdue University, explained that it is possible to correctly describe the transport in LEDs with a full quantum model that is based on a non-equilibrium Green function.

When talking about nitrides, one does not necessarily think about quantum optics. However, nitrides are good candidates for fabricating true single-photon emitters working at room temperature. Good results have been obtained by Yasuhiko Arakawa's group from the University of Tokyo. Spokesman for this team, Mark Holmes, detailed quasi perfect, single-photon emitters ($g^2(0) = 0.02$). These were obtained by working at a low temperature (10K), and by exploiting the quantum-dot like fluctuations in GaN quantum wells.

Further highlights from this session that covered optical devices included: the use of LEDs in high bandwidth communication and positioning, described in a talk by Phil Dawson from the University of Manchester; a presentation from Qian Sun from Sinano detailing a CW, room-temperature laser grown on silicon, as well as photonic circuits – including an emitter, guides and detector – made with this material system; and in a similar vein, the talk by Fabrice Semond from the University Côte d'Azur, describing an optically pumped microdisk laser grown on silicon that emits from 275 nm to 470 nm.

Another advance, reported by Moti Katz from Soreq NRC, Israel, was a transition at 1.8 μm associated with strong coupling. This is commonly observed with interband transitions, but in this case it resulted from intersubband transitions, observed in both transmission and in the photocurrent from a quantum cascade detector.

## Power devices

Although GaN power devices are not generating the sales of their LED cousins today, revenues are rising, and the potential for further growth is very promising. One of the leaders of device production is Infineon Technologies, and at ICNS-12 Thomas Detzel, the firm's Senior Manager for GaN Technology Development, closed the conference with a historical and technical comparison of the capabilities of GaN and silicon for power applications. In his plenary talk, he argued that the fundamental advantage brought by the nitrides over silicon is the combination of a lower on-state resistance ($R_{DSON}$) and a negligible recovery charge. Thanks to these attributes, GaN devices can go faster while consuming less power. That does not mean, however, that silicon devices are doomed. Detzel believes that it will take some time before GaN can take significant market share in the power arena, and he expects GaN to coexist with silicon for a long time, rather than replacing the incumbent.

Within the electronic session, the focus was on power electronics, and in particular established horizontal FETs and emerging vertical transistors, plus Schottky diodes. However, there were also reports on RF devices, including those with vertical structures.

– its addition propelled the breakdown voltage from 775 V to 1600 V. However, reaching an on-resistance of just 1.8 mΩ $cm^{-2}$ required a slight sacrifice to this figure. Oka and co-workers have formed switching circuits formed from the FETs and GaN Schottky diodes with a switching time of just 20 ns, and switching energies for turn-on and turn-off of 12 μJ and 90 μJ, respectively.

Those attending ICNS-12 will be aware of the move to higher frequencies for applications and circuits. GaN technology could serve here: Rüdiger Quay from Fraunhofer IAF and Kozo Makiyama from Fujitsu both argued that point-to-point communication at 84 GHz could benefit from this wide bandgap technology. However, José Jimenez, a Fellow of Device Physics at Qorvo, warned that GaN still suffers from a lack a linearity and a lack of reproducibility in this characteristic. In his opinion, based on existing performance, GaN has limited capability to replace GaAs.

Another highlight of the electronic session was the presentation by Grace Xing from Cornell University.

The talks in this session revealed two trends in nitride electronics: a move to more vertical devices; and the use of nanotechnology to provide better control of the electric field in the gate region

At the gathering in Strasbourg, researchers described the development of devices with classical and quantum transport. Examples of the former include finFETs pursued by Tomás Palacios' group at MIT and fin MOSFETs fabricated by Maher Tahhan and co-workers at UCSB, while the latter includes the tunneling hot electron transistor, described by Siddharth Rajan from The Ohio State University.

The talks in this session revealed two trends in nitride electronics: a move to more vertical devices; and the use of nanotechnology to provide better control of the electric field in the gate region. A group pioneering the latter is that of Elison Matioli and co-workers from EPFL. Using slanted tri-gate structures, they realised breakdown voltages of up to 1.8 kV.

Another move within the power electronics community is to grow GaN devices on a native substrate. Tohru Oka from Toyoda Gosei described efforts in this direction, including the fabrication of a Schottky diode with a lateral field plate that had a breakdown voltage, at 1 mA $cm^{-2}$, of 770 V. The recovery time for this diode is just 50 ns, a value far less than that for equivalents made from silicon and SiC.

Oka revealed that the field played a crucial role in realising a high breakdown voltage in the MOSFET

Xing reported convincing results on resonant tunneling diodes grown by MBE on GaN substrates. She observed clear, stable and repeatable negative differential resistance at current densities ranging from a few to 180 kA $cm^{-2}$. This indicates that there is tunnel transport through fundamental and excited states in a thin GaN well in between two AlN barriers. This negative differential resistance led to oscillations at 300 MHz when the diode was inserted into a resonant circuit. In addition, impact ionization was observed, likely due to high-energy ballistic electrons crossing the outer GaN region of the structure.

More reports on GaN transistors and other devices will be given at the next ICNS, held in Seattle in July 2019, and chaired by Alan Doolittle from Georgia Tech. For researchers that can't wait that long to hear and discuss developments in the nitrides, one option is the International Workshop on Nitride Semiconductors, which will be held next year in Kanazawa, Japan, in mid-November.

**Further reading**
http://www.european-mrs.com/meetings/icns-12/icns-12-topics

# Improving the thermal management of UVC LEDs

UVC LED technology will revolutionise how we disinfect our homes, hospitals and workplaces. But before this can happen, engineers need a better way to remove heat from their designs

BY JOHN CAFFERKEY FROM CAMBRIDGE NANOTHERM

OVER THE YEARS mankind has come up with a variety of methods for sterilising objects, surfaces and consumables; from heating, to the use of chemicals, to dehydration.

It has long been understood that natural sunlight can act as a sterilising agent, albeit a relatively weak one. Experiments in the late 19th century demonstrated that water left for a long period in sufficiently direct sunlight would remain free of bacterial growth.

It was later discovered that the cause of this sterilising effect was the ultraviolet C-band (UVC) light present in natural sunlight. Today we can generate UVC artificially, and with a much greater intensity than is present in ordinary sunlight. Such UVC-emitting devices can provide a highly effective means of sterilising different materials.

All UVC disinfection devices, regardless of their size or specific technology, work on the same basic principle: UVC devices emit light in the 'germicidal range' of 200 nm to 280 nm, a spectral domain that literally 'breaks apart' the genomes of bacteria, rendering the bacteria inert and therefore sterilising any surface the UVC light irradiates.

There are many advantages to the use of UVC to sterilise materials. You can avoid the use of toxic or corrosive sterilising chemicals, which can leave toxic by-products. This makes UVC ideal for applications such as municipal-scale water sterilisation, or any situation where the use of chemicals might be either hazardous or less thorough.

UVC is a better option for tackling chlorine-resistant pathogens such as giardia and cryptosporidium. It may also present the best way to disinfect hard-to-reach areas, or surfaces that will stain or otherwise react upon contact with cleaning chemicals. And regardless of the cost of buying UVC equipment, in many situations UVC can allow companies to reduce the long-term overheads involved in training staff in the use of hazardous chemicals, emergency planning, risk management and insurance.

## Issues with traditional UVC technology

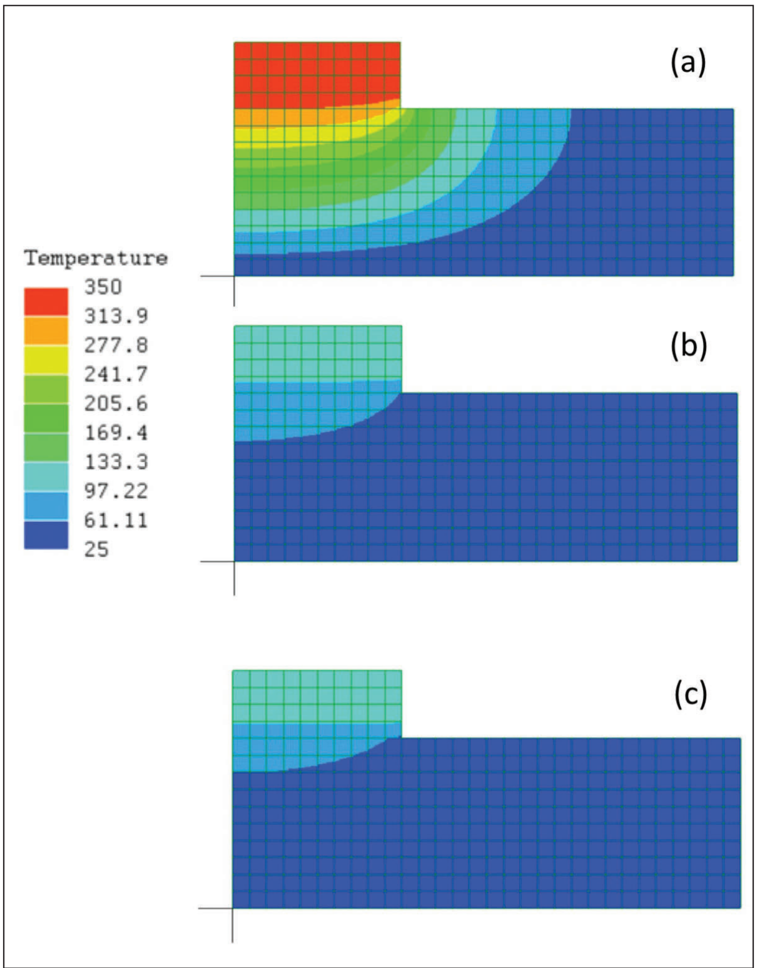
One of the factors that has restricted the spread of UVC technology so far has been the reliance on mercury vapour lamps. These are superb for certain applications, being bright, efficient and lasting for a long time. On the other hand they're expensive, fragile and they contain toxic mercury, which restricts the number of applications in which they can be used and demands a closed recycling scheme.

Mercury vapour lamps are well-suited to applications such as municipal water sanitation, for example, where they are commonly used. Here, the relatively high costs of the bulbs can be justified, size isn't much of an issue, and engineers can be on site quickly to manage any breakages.

More importantly, the chances of the public being exposed to toxic substances in the event of a breakage are practically non-existent. But for all the same reasons, mercury vapour lamps aren't suitable for smaller, more portable devices, or in consumer applications where the lamps might be easily broken.

## Opportunities for LEDs

Advances in LED technology have reached a point that UV LEDs are not only possible, but are becoming an increasingly attractive option for a range of applications.




Thermal modelling highlights that $Al_2O_3$ (a) fails to deal with the challenge presented by a UV LED. Nanotherm's DMS solution (b) copes with the challenge admirably, and is practically identical to the thermal performance of AlN. This result is to be expected, given that the thermal conductivities of $Al_2O_3$, Nanotherm DMS and AlN are 25 W/mK, 150 W/mK and 170 W/mK, respectively. Calculations were based a '¼ model', to exploit the symmetry, and considered materials that were homogeneous and thermally isotropic. Die are 150 μm-thick x 1 mm per side (hence 500 um shown), the solder joint is 50 μm-thick, and the substrate is 500 μm-thick x 6 mm per side (hence 1.5 mm shown). The lower surface of heat sink is fixed at 25 °C. It is assumed that there is a balanced rate of heat generation in the die and removal from the lower surface of the heat sink.

UVC LEDs are more cost effective than mercury lamps for certain applications – and are becoming more cost effective all the time. What's more, UVC LEDs are much smaller, more robust, require less power, can be turned on instantaneously (with no warm-up time), and do not contain significant amounts of hazardous chemicals.

According to industry analysts Yole Développement, UVC LEDs will need to drop to a price point of around \$1–\$4/mW before they are adopted by the mass market. As a result the UVC LED industry has been focused on reducing costs. As processes have improved, prices have fallen by eight to ten times in recent years. The ultimate aim is to get to the point where UVC LEDs cost around \$1 per mW. At the same time the industry has focused on creating higher-performing devices (with a power output of greater than 10 mW per package) that last significantly longer.

As costs reduce, UVC LEDs have fallen to an acceptable price for a wider range of applications.

UVC LEDs will enable a brave new world of disinfection devices. The small size of UVC LEDs, combined with their safety and low power draw, mean that we may well see UVC disinfection embedded in everyday consumer items such as baby feeding bottles, or in toothbrush holders — enabling these items to be automatically disinfected at the point of use. UVC could also be integrated into handheld cleaning devices, which users could sweep over surfaces, keyboards, mobile phones and more to sterilise them, or into 'self-sterilising' water bottles and medical equipment.

However, in order to realise the full potential of the UVC LED market, one of the remaining hurdles manufacturers have to overcome is that of thermal management.

## The thermal challenge

While incandescent bulbs are able to radiate and convect heat directly into the air, this is not an option for LEDs. UVC LED die measure only a few millimetres along each side, so these chips present too small a surface area to the air for any appreciable cooling by convection. The temperature of each chip is also too low to radiate a significant amount of heat.

The only effective way to remove heat from a UVC LED is by conducting this energy through the materials of the die itself, through the submount and PCB to a heatsink and then to the ambient atmosphere.

In the case of a visible light LED, this problem is usually addressed by mounting the LED on a metal-clad PCB (MCPCB). Generally aluminium is used due to its good ratio of thermal conductivity to cost. This is then topped with a layer of epoxy resin, which acts as a dielectric, electrically isolating the aluminium from the copper circuit layer above.

One major problem, however, is that UV light degrades organic substances such as epoxy. Secondly, the overall thermal performance of such a stack is simply inadequate for the particularly aggressive thermal demands of UVC LEDs.

Traditionally, this has caused designers to turn to ceramics. Designers can choose between two types of ceramic: aluminium nitride (AlN) or alumina ($Al_2O_3$). Of these, only AlN (at around 140-170 W/mK) is thermally conductive enough to suit UVC LED applications.

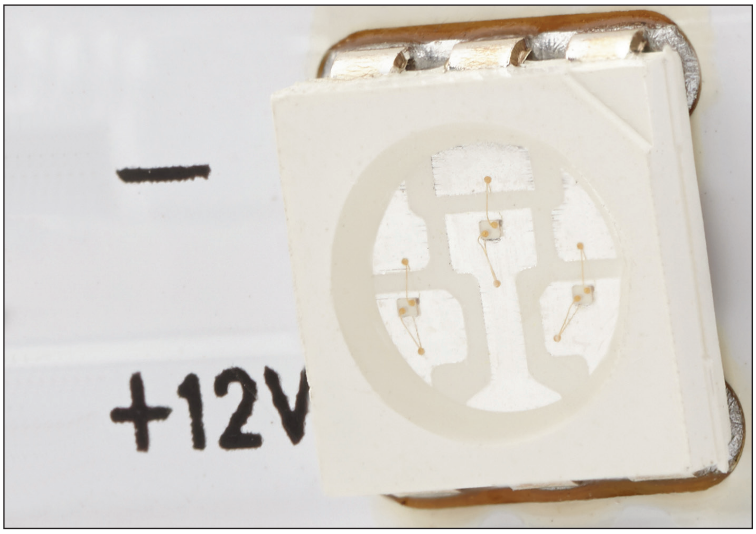
However, AlN is also expensive and only available in small tiles. Also, ceramic circuit boards are brittle, making them hard to machine, impractical for screw-mounting, and unsuited to more rugged applications.

At Cambridge Nanotherm in Haverhill, UK, we have developed a patented process (involving electro-chemical oxidation – our 'ECO' process) that enables designers to take advantage of the best properties of both MCPCBs and ceramic solutions.

Our approach is to convert the surface of a sheet of aluminium into an alumina ($Al_2O_3$) ceramic, which acts as the dielectric layer. The thickness of this layer can be tightly controlled to just tens of microns thick. This thinness means that the relative thermal inefficiency of $Al_2O_3$ ceases to be an issue – the ceramic dielectric layer that we create is so thin that heat is conducted through it efficiently.

To increase the thermal conductivity of the overall stack even further, the circuit layer is then 'sputtered' onto this nanoceramic dielectric using a 'thin-film' process. Essentially the atoms of copper are 'fired' at the board, wedding them to the board at the atomic level, ensuring maximum thermal efficiency.

The result is an MCPCB-like board with a composite thermal conductivity of 150 W/mK (perfect for UVC LED applications and comparable to AlN) but which is also mechanically robust and can fit within existing MCPCB production processes. Easy machineability and high yields, combined with the low cost of aluminium, make our solution cost effective. And with




no epoxy in use, there is nothing for the UV light to degrade.

The boom in LED UVC disinfection has started, and will have major implications for everyone. Manufacturers are creating completely new types of UVC products that will change how the process of disinfection is approached, making it easier to render objects, surfaces and substances safe.

In order to reach this point, however, designers will have to reconsider how they approach the thermal challenges of UVC devices at the board level. Fortunately new technologies are being developed that make UVC LED products a commercial reality.

## Why is heat such an issue for UV LEDs?

THERMAL MANAGEMENT presents a challenge for all LEDs. However, as the wavelength of light moves up the electromagnetic spectrum, the external quantum efficiency (EQE) drops. This is particularly notable in the UV spectrum where EQE drops from around 40 percent for UVA (380 nm) to just a few percent for UVC (260 nm). Whilst EQE is somewhat outside of the remit of this article it helps to frame the thermal management requirements that will need to be dealt with by the module substrate.

EQE is a product of three factors: internal quantum efficiency (IQE), electron injection efficiency (EIE), and light extraction efficiency (LEE).

New approaches to improving IQE are underway with the use of bulk AlN and AlN-on-sapphire substrates. Bulk AlN substrates are pure AlN wafers which are used instead of sapphire as the base of the epitaxy process. Bulk AlN has a lower defect density in the epitaxial layer which increases IQE. Bulk AlN is also one of the few materials capable of transmitting light below 280 nm, potentially opening up new device structures.

EIE improvements involving quantum tunnelling are exploring ways to cut the resistance and improve the electrical efficiency of the AlGaN/InGaN layers. Whilst there's positive work underway, turning the theory into a commercial reality is far from certain.

There are a number of approaches to improving LEE underway ranging from using flip-chip technology to nanowires and novel chip geometries.

However, while there is significant research and development underway to address EQE at a chip level, the fundamental fact is that, today, the higher the wavelength the less efficient the chip. This means in order to get a useful amount of light out of the chip it needs a lot of power to be put in. This produces a lot of excess heat that needs to be removed from the LED to keep the junction under its maximum operating temperature.

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## 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
- **Luis Henrique Hecker de Carvalho: BrPhotonics**
  Converging photonics and microelectronics: applying advanced technologies to ramp up PIC performance
- **Tan Yong Tsong: Institute of Microelectronics**
  Coupling electronics and photonics – promising paths for device-makers to explore
- **Radha Nagarajan: Inphi**
  Highly integrated silicon photonics to push PICs to the next level
- **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

## 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**

- **Katharine Schmidtke: 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
- **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

## 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
- **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

## 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**
  Putting liquid crystal waveguides in the fast lane automotive applications for PICs

## 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
- **Jack Xu: Finisar**
  Meeting the challenge of producing PICs at high-volume
- **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

**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 Transceiver 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?

**Aref Chowdhury – Nokia**
**Drew Nelson – IQE**
**Katharine Schmidtke – Facebook**
**Vipul Bhatt – Finisar**

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# HYBRID PICS TARGET TOMORROW'S COMMUNICATION NETWORKS

Uniting III-Vs with silicon CMOS enables the fabrication of ground-breaking, low-cost lasers for access/metropolitan networks and datacentres

BY DAVID CARRARA AND GUANG-HUA DUAN FROM III-V LAB AND SEGOLENE OLIVER FROM CEA LETI

THE LAST DECADE has witnessed an explosion in bandwidth demand on telecommunication and data communication networks. This has been driven by an uptake in smartphones, and the introduction of online services such as Youtube, Netflix, Google and Facebook. But this is just the beginning: 4k and 8k video streaming are the emerging new standards; data traffic for the smartphone will soon exceed that for the computer; and due to the growth of the Internet-of-Things, more objects are going to be connected to one another. Given this shift in the landscape, it is clear that bandwidth demands are going to increase drastically over the coming years, straining different layers within the communication networks.

Two of the key segments in this infrastructure are the datacentre and the access/metropolitan networks. The former deals with the data we 'consume' from all over the world, while the latter provides links that allow us to access all that data from our homes and offices. In addition, access/metropolitan networks enable data transmission within a city or a local region.

Both the datacentre and the access/metropolitan networks are very different from long haul networks. They are much more sensitive to the cost, and the photonic components that are adopted have to be manufactured in far higher volumes.

To address this pair of requirements, the III-V Lab in Palaiseau, in partnership with CEA Leti in Grenoble, has developed a wafer-bonding approach that can form low-cost, efficient photonic integrated circuits (PICs) by uniting high-performance III-Vs with mature CMOS silicon. Armed with that approach for enabling the bonding of various types of III-V wafers on silicon, we have produced lasers that set a new benchmark for tunability and spectral purity, and fabricated the first silicon Mach Zehnder Modulator that is integrated with a tunable hybrid III-V/silicon laser.

## Marrying two materials

At the heart of our approach is the marriage of the two main platforms in the semiconductor industry: silicon and III-V.

The former, the 'mother' of modern electronics, is renowned for its really low cost, allied to it suitability for very large-volume production. But there is more to it than just that: silicon, working in tandem with its native oxide, can form compact passive optical elements with very good optical performances. Even modulators and detectors can be directly fabricated within this platform. However, one key component remains elusive – the laser.

Production of the laser is routine with a III-V semiconductor platform – and this can also be

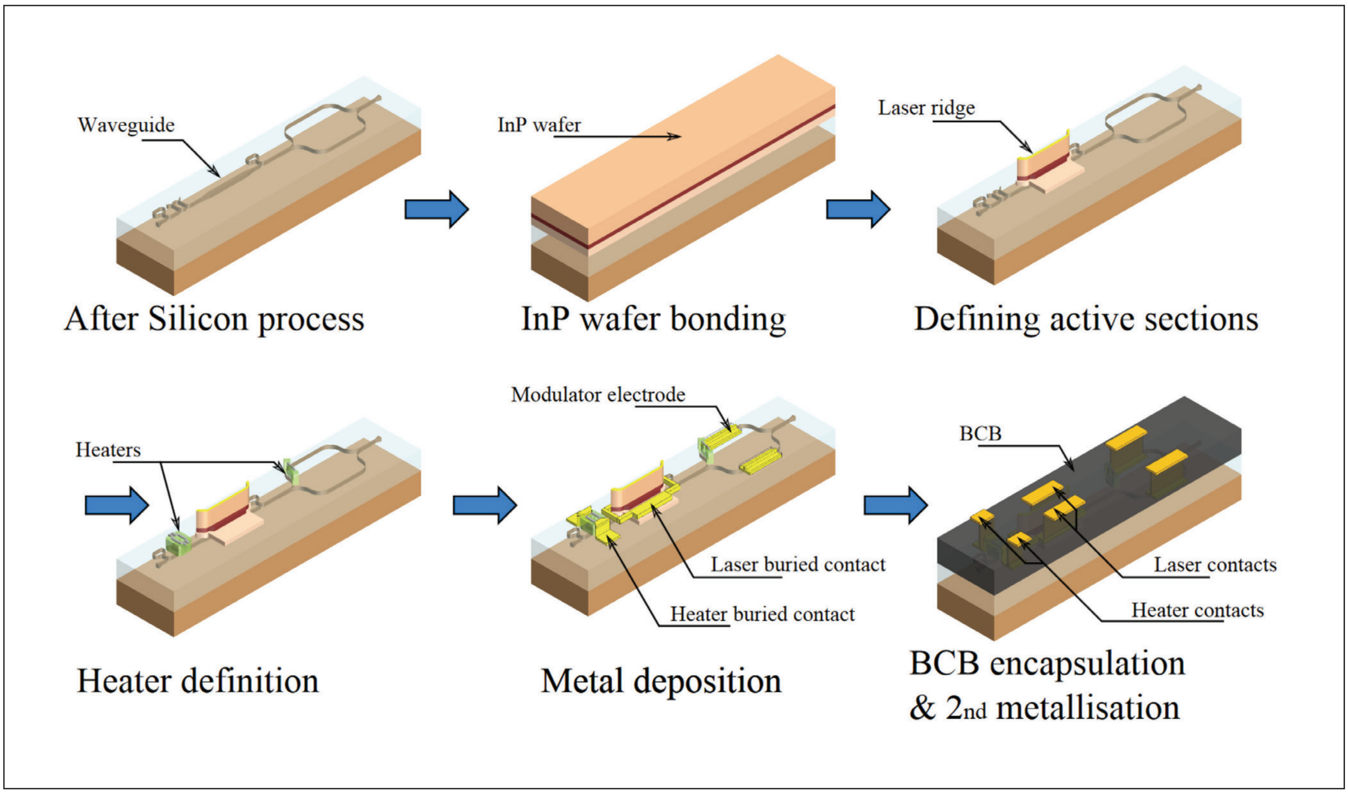


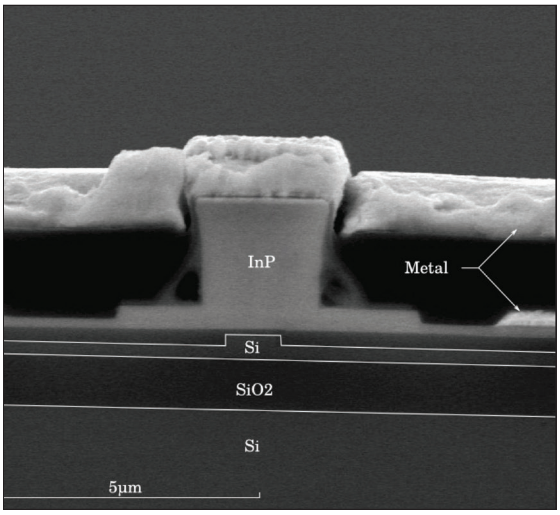

Figure 1. The different steps used in the hybrid III-V/silicon process.

used to manufacture high-performance light detectors, modulators and amplifiers. However, these components have high production costs, due to smaller volumes within this industry and the less mature processes it employs.

By exploiting the advantages of both platforms, we have developed a hybrid technology that could unlock the door to the manufacture of low-cost, very high-performance PICs in high volume.

Device fabrication begins by taking 200 mm SOI wafers with a silicon top layer of typically 440 nm and using a hard mask technique to define different waveguide levels. A first partial etch of 220 nm, using a combination of deep UV lithography at 193 nm and reactive ion-etching, forms rib waveguides that are optimized for coupling with III-V waveguides – they are aligned on top of the silicon waveguides in a latter step. Additional etching steps form the passive circuitry, which includes strip waveguides, Bragg reflectors, filters and vertical-output couplers.

After physical structures were defined, selective dopant implantation creates *p-n* and *p-i-n* junctions in silicon and germanium. Finally, a high density plasma deposition process encapsulates the surface with an oxide. This oxide is planarized with a chemical-mechanical process to ensure a flat, smooth interface – a pre-requisite for a good molecular bonding with the III-V wafer.



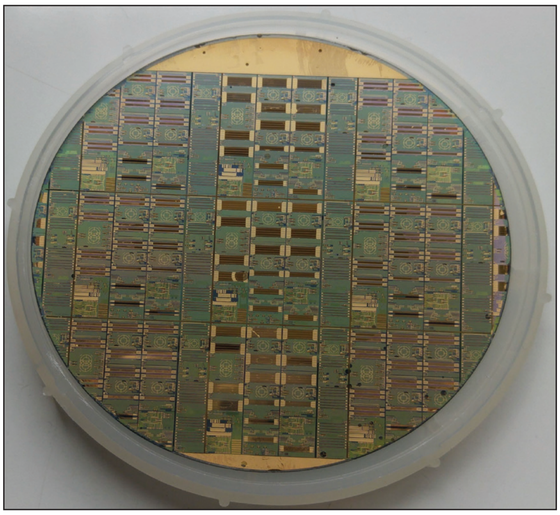



Figure 2. A wafer at the end of the III-V process (right) and a scanning electron microscopy cross-section of an active III-V section showing the alignment of the III-V waveguide and the silicon waveguide (left).

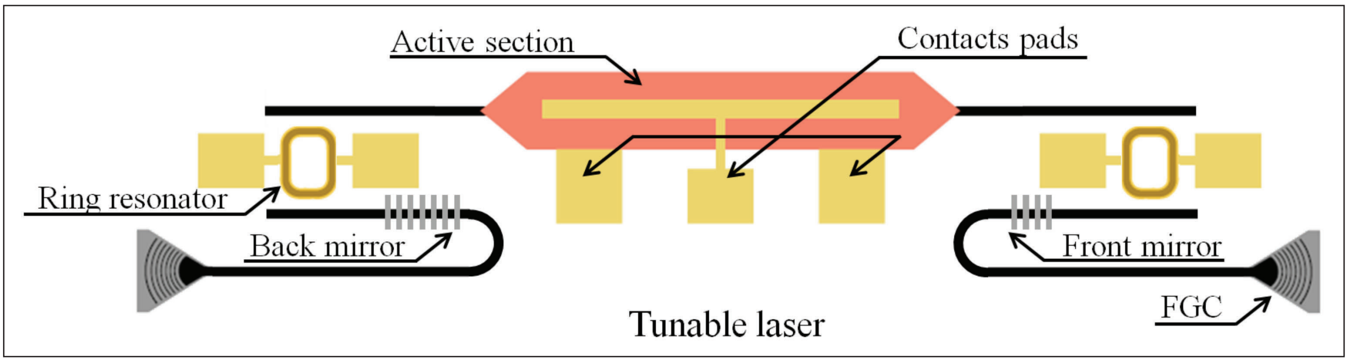



Figure 3. A hybrid III-V/silicon double ring laser provides temperature-dependent tuneable emission.

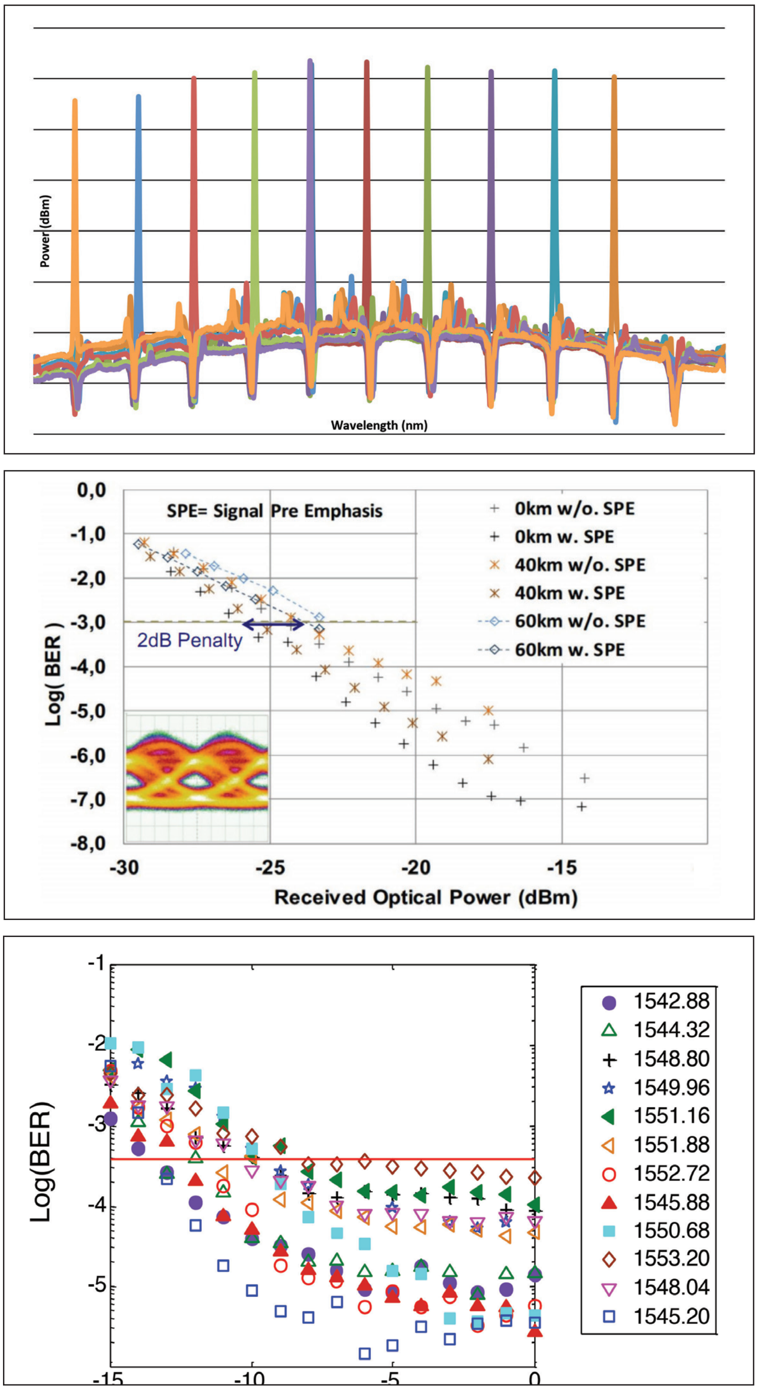
In parallel, we grow inverted III-V heterostructures on III-V substrates that have a diameter of either 2-inch, 3-inch or 4-inch. Optimised growth conditions ensure a defect-free surface that enables good quality wafer bonding and ultimately a high performance from the laser.

When working with InP-based semiconductors, the III-V region of our PICs consists of: a *p*-doped InGaAs contact layer; a *p*-doped InP cladding layer; typically six InGaAsP quantum wells, surrounded by two InGaAsP separate confinement heterostructure layers; and an *n*-doped InP layer. Molecular bonding unites these III-V wafers, epitaxial layer down, to the processed SOI wafers. Subsequent wet etching removes the III-V substrate, prior to laser dicing around the III-V wafers. This yields smaller wafers that are easier to process in a III-V fabrication plant.

To define the different active sections of our III-V structure, we employ a combination of UV photolithography at 402 nm, selective wet etching, and reactive-ion etching with a mixture of hydrogen gas and methane (see Figure 1). Electrical contact pads and resistors are added by photolithography, followed by evaporation and sputtering of metals. After this we spin-coat a passivation layer of BCB, and then deposit a second metallic layer – an alloy of titanium, platinum and gold – to access the electrical pads through etched vias. Electro-optic characterisation of these components may be carried out directly on wafer, using the integrated vertical-grating couplers etched directly on the SOI wafers (see Figure 2).

## Access/metropolitain networks...

One potential application for our devices is in access networks. Today time-division multiplexing is used to create a data transmission rate of 1 Gbits/s, with




Right: Top, Middle & Bottom:
Figure 4. (a) Superimposed laser spectra for different currents injected into one heater, at 20°C. (b) Measured bit error rates for different lengths of fibre with a typical eye diagram for back-to-back 10 Gbits/s transmission. (c) Measured bit error rates for various wavelengths after 10 km of propagation in single-mode fibre under 21.4 Gbits/s non return-to-zero modulation.

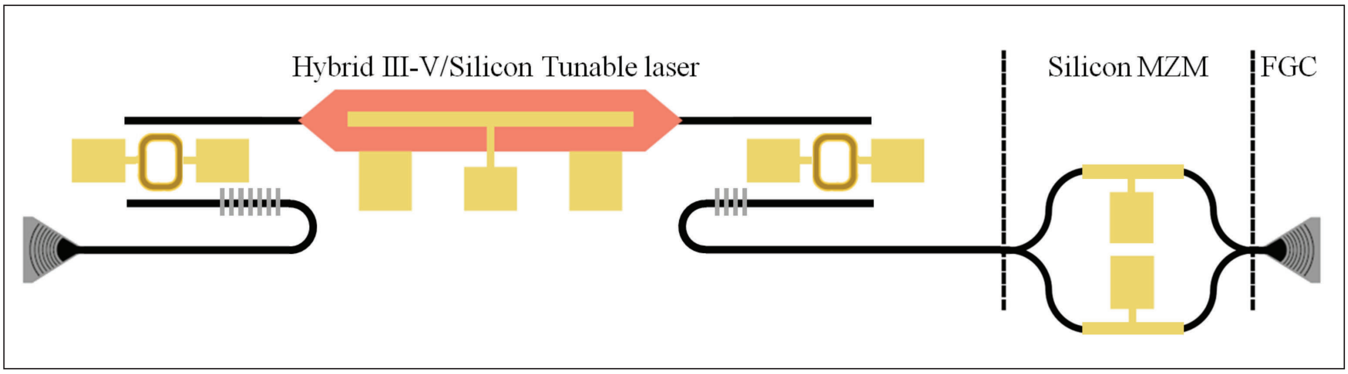



Figure 5. Integrating a silicon Mach-Zehnder modulator with a hybrid III-V/silicon tuneable laser increases the modulation speed.

just one wavelength shared between the users. But the future standard, NG-PON2, will incorporate wavelength-division multiplexing, by exploiting four wavelengths operating at 2.5-10 Gbits/s. Benefits of this move include a far higher bandwidth, enhanced flexibility and a new pricing policy.

A key element in every NG-PON2 network is a device that emits at different wavelength channels (up to 16 channels with 100 GHz channel spacing) and modulates light at 10 Gbits/s. As such a device will be embedded in each individual user internet box, rather than being shared by other users, it must be low in cost and available in high volume.

Our tuneable lasers fulfil these requirements (see Figure 3). They feature: an InP-based gain section, adiabatic tapers for the modal transfer between III-V and silicon waveguides; mirrors, etched in the SOI, on both sides of the cavity; and a double ring filtering system. By exploiting the Vernier effect, the two ring resonators can select a specific, unique Fabry Pérot mode of the cavity; and by heating the rings – by means of small metal heaters on the top of the ring resonators – the emission wavelength is easy to tune.

These lasers break new ground, delivering a tunability over 45 nm combined with a side-mode suppression ratio in excess of 40 dB (see Figure 4(a)). Thanks to these attributes, the devices demonstrate good quality transmission up to 60 km at 10.3 Gbit/s, according to measurements with a $2^{31}$-1 pseudorandom binary sequence (see Figure 4(b)). Shorten the transmission distance to 10 km, and ten wavelengths are possible at 21.4 Gbit/s (see Figure 4(c)).

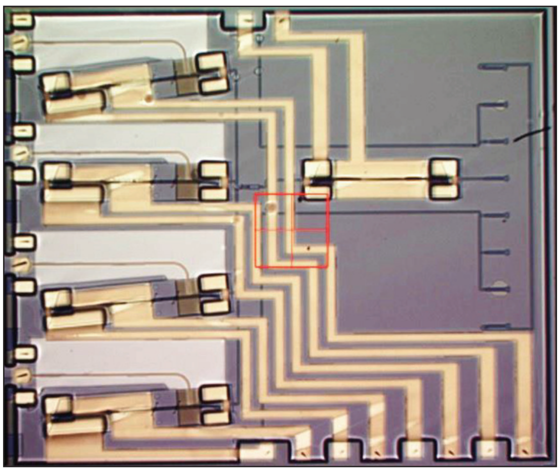


Figure 6. A 4x25 Gbits/s wavelength division multiplexing transmitter meets the requirements for 100 GbE.

Based on these results, it is clear to see that our hybrid III-V/silicon tuneable lasers have great potential for NG-PON2 networks. They meet the requirements for 2.5 Gbits/s, and they are close to fulfilling them at 10 Gbits/s. More importantly, according to published work, they are the only devices providing 16 wavelength channels with 100 GHz channel spacing. Note that a similar ring-resonator approach was also demonstrated for a tuneable receiver.

To enhance the modulation speed, we have pioneered integrated direct modulation of the laser section with an external silicon modulator. This allows us to realise operation at 25 Gbits/s by combining a tuneable hybrid III-V/silicon laser, which is similar to those previously described, with a silicon Mach Zehnder modulator and an optical output coupler (see Figure 5). Modulation efficiency, expressed as $V\pi L\pi$, is around 2.2 V.cm, while the 3 dB modulation bandwidth exceeds 15 GHz. These results showcase the potential of our hybrid III-V/silicon integration technology for fabricating low-cost, tuneable transmitters for metropolitan networks with advanced modulation formats.

## ... and datacentres

Due to the dramatic increase in global data centre traffic – Cisco Systems expects it to more than treble between 2015 and 2020 – the Ethernet standard is expected to shift from 25 GbE to 100 GbE. The new standard could be accomplished by combining four transmitters, emitting at a different wavelengths and modulating at 25 Gbits/s.

To comply with this new standard, which will include a low cost requirement, we have developed a 4 x 25 wavelength-division multiplexing transmitter with our hybrid III-V/silicon process. This transmitter integrates four distributed feedback lasers, each emitting a different wavelength around 1.3 μm. Channel separation is 4.5 nm, corresponding to an 800 GHz wavelength-division multiplexing grid.

Within these components, each laser is integrated with an electro-absorption modulator. A multi-mode interferometer coupler combines the light exiting all four modulators, and directs this into a unique output waveguide. Here power is increased with a semiconductor optical amplifier. A vertical coupler, etched at the end of the waveguide, enhances the output from this chip (see Figure 6).

Using a pseudorandom binary sequence generator, this transmitter has produced bit error rates of just $10^{-9}$ and $5 \times 10^{-5}$ at 25 Gbits/s and 32 Gbits/s, respectively. Under a modulation voltage of just 0.9 V peak-to-peak, and at a bias voltage of -0.6 V, the measured eye diagram is clearly opened at 32 Gbits/s (see Figure 7).

These results show that our III-V/SOI transmitter PICs are a promising solution for datacentres that require low-cost, high-volume integrated wavelength-division multiplexing transmitters operating at 100 Gbits/s. These devices, as well as those suitable for NG-PON2, demonstrate that our PICs can combine affordability with low energy consumption and a small footprint. As they are suitable for high-volume manufacture, they are excellent candidates for meeting the stringent needs of datacentre and access/metropolitan networks.

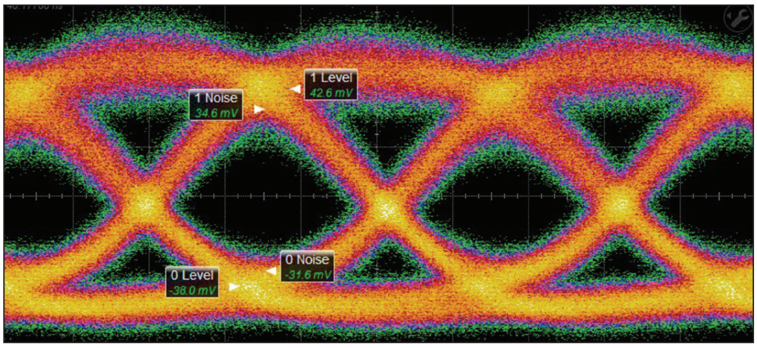



Figure 7. An eye diagram of one arm of the wavelength-division multiplexing transmitter at 32 Gbits/s with an extinction ratio of 6.7 dB. This measurement showcases the potential of this technology for datacentre applications.

**Further reading**

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# GaN power devices:

## Perfecting the vertical architecture

Optimised trenches and fins enable the production of vertical, normally-off GaN power transistors with low epitaxial costs and high blocking voltages

BY YUHAO ZHANG, MIN SUN AND TOMÁS PALACIOS FROM MASSACHUSETTS INSTITUTE OF TECHNOLOGY

GaN IS TIPPED to revolutionise the power electronics industry. It promises to trim the losses in power conversion circuits, and could drive a 10 percent reduction in global power consumption. What's more, thanks to its capability to handle far higher power densities that today's devices, it could trim the size, weight and cost of power systems.

Initially, the development of GaN power devices focused on a lateral geometry. Recently, however, there has been a growing interest in vertical architectures. Merits of this geometry include: the capability of realising high breakdown voltage and current levels, without having to enlarge chip size; a superior reliability, resulting from the shift in the peak electric field from the surface to the bulk of the device; and a simplification of thermal management, compared with lateral devices. Thanks to these attributes, vertical GaN devices are the most likely contenders to combine currents in excess of 100 A with voltages of more than 600 V – the typical requirements for many medium and high power applications, such as electric vehicles and renewable energy processing.

One of the challenges facing vertical GaN power devices – like their lateral cousins – is the realisation of normally-off operation. That's not the only issue, however: many vertical devices require *p*-type GaN or epitaxial regrowth. That's not easy, as compared to *n*-type GaN, the *p*-type variant has a low ratio for the acceptor activation and a far lower carrier mobility. And if epitaxial regrowth is needed, this greatly increases the complexity and cost of device fabrication.

To overcome these difficulties, our team at the Massachusetts Institute of Technology has developed a novel GaN-based vertical power device that features trench and fin structures, and avoids the growth of *p*-type material.

## Enabling normally-off devices

Trench structures are key building blocks in many modern GaN vertical devices. For example, they have been recently used in trench metal-insulator-semiconductor barrier Schottky rectifiers, where they shield the high electric field at the Schottky contact (see Figure 1 (a)). The addition of the trench greatly enhances the reverse blocking characteristics of the GaN Schottky rectifier by delivering a doubling of the breakdown voltage and a slashing of the leakage current at high reverse biases by a factor of $10^4$.

Normally-off GaN transistors have also benefited from the addition of trenches. They include one of the most widely used vertical transistor architectures, the current-aperture vertical electron transistor. This normally-on device combines the high conductivity of a two-dimensional electron gas channel at the AlGaN/GaN heterojunction with the improved field distribution of a vertical structure. Normally-off operation is possible by switching to a trenched semi-polar gate (see Figure 1(b)).

Another transistor architecture that benefits from the introduction of the trench is the vertical GaN MOSFET. This modification allows it to combine a normally-off operation with a low on-resistance (see Figure 1(c)).

## Perfecting trench fabrication

Trench etching and corner rounding are two of the key technologies for making high-quality trenches in high-voltage vertical GaN devices. As the trench corners typically coincide with the location of the peak electric field, and are therefore the most 'vulnerable' spots for breakdown, their smoothness is highly valued. If there are any rough surfaces or sharp corners in these trenches, electric-field crowding can occur, leading to device preliminary breakdown.

Good results are not possible with the conventional corner rounding process technology that is used for silicon and SiC devices. That's because the high temperatures – annealing is undertaken at more than 1000 ˚C – deteriorate GaN material quality and device performance.

To prevent this from happening, we have developed a damage-free corner rounding technology for GaN that works at only 85 ˚C. It involves a wet chemical treatment, with a tetra-methyl-ammonium hydroxide etching, followed by a piranha clean. By etching the sidewall along the *m*-planes and *a*-planes, the

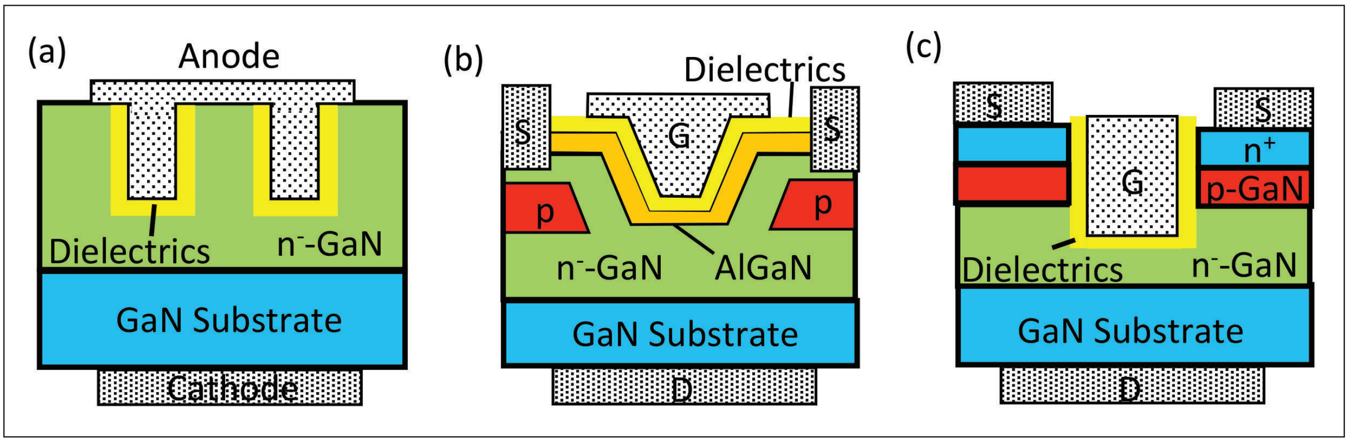


Figure 1. Trench structures can feature in various vertical GaN power devices, including: (a) metal-insulator-semiconductor barrier Schottky rectifiers, (b) current aperture vertical electron transistors, and (c) MOSFETs.

hydroxide eliminates surface damage caused by dry etching, before the etching residues are effectively removed by a piranha clean (see Figure 2 (a), (b) and (c)).

We are able to control the shape of the trench by tuning the dry etching conditions and applying the rounding process. We know from TCAD simulation and experimental study that we want to form a flat-bottom rounded trench, because this is the most effective profile for spreading the electric field distribution, and thus provides the best blocking characteristics (see Figure 2(d)-(e)).

Improvement in the blocking capability of trench structures is possible through the addition of advanced structures that shift the peak electric field away from trench corners/bottoms and towards the bulk semiconductor region. Success can result from the incorporation of implanted field rings, or the introduction of carbon-doped GaN/*p*-GaN hybrid blocking layers near the trench bottoms.

## A debut: the vertical GaN fin MOSFET

In trench-based vertical power transistors, the semiconductor regions between the trenches provide the channel for the field-effect transistors. For the current-aperture vertical electron transistor and the MOSFET, realising normally-off operation requires, in the channel region, complicated epitaxial regrowth or *p*-type GaN layers. Both options are undesirable: the re-growth step significantly increases the cost and

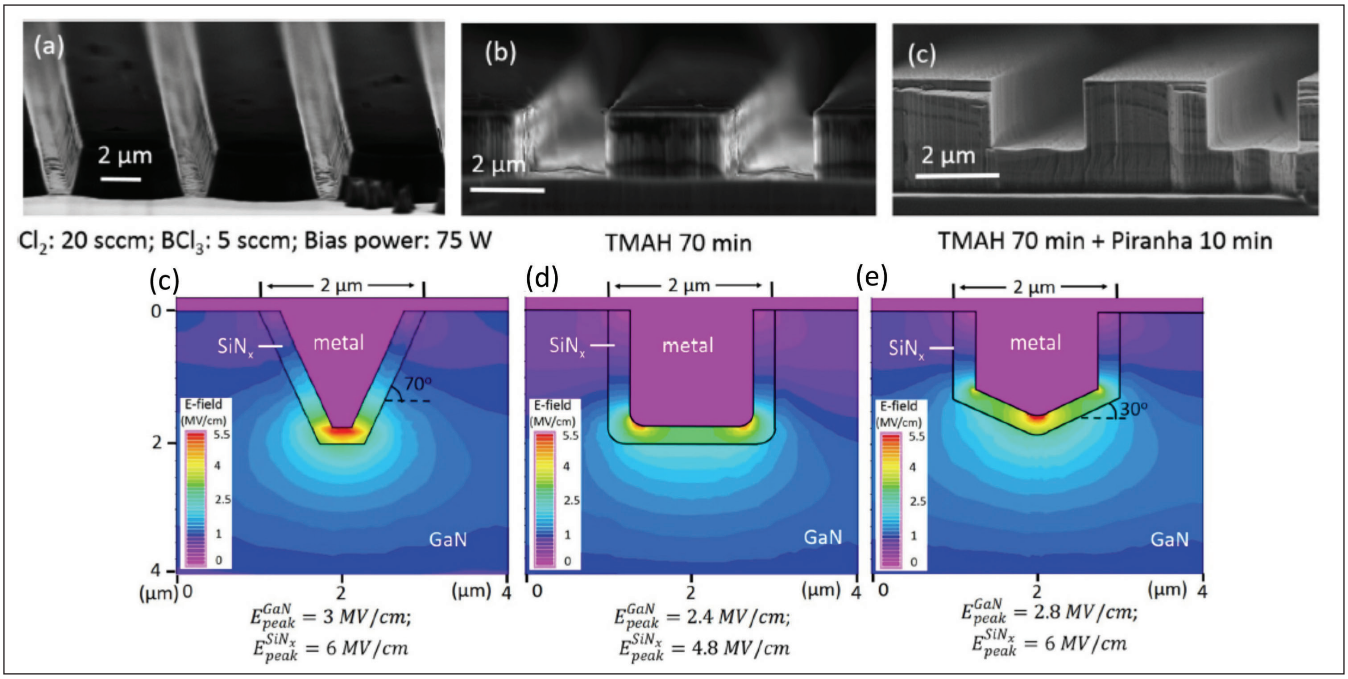


Figure 2 (a)-(c) Cross-sectional scanning electron microscopy images of trench structures right after dry etching, with a following tetra-methyl-ammonium hydroxide wet etching, and an additional piranha clean. (c)-(e) Simulated electric field distribution in the trench-based device unit-cells with three different trench shapes.

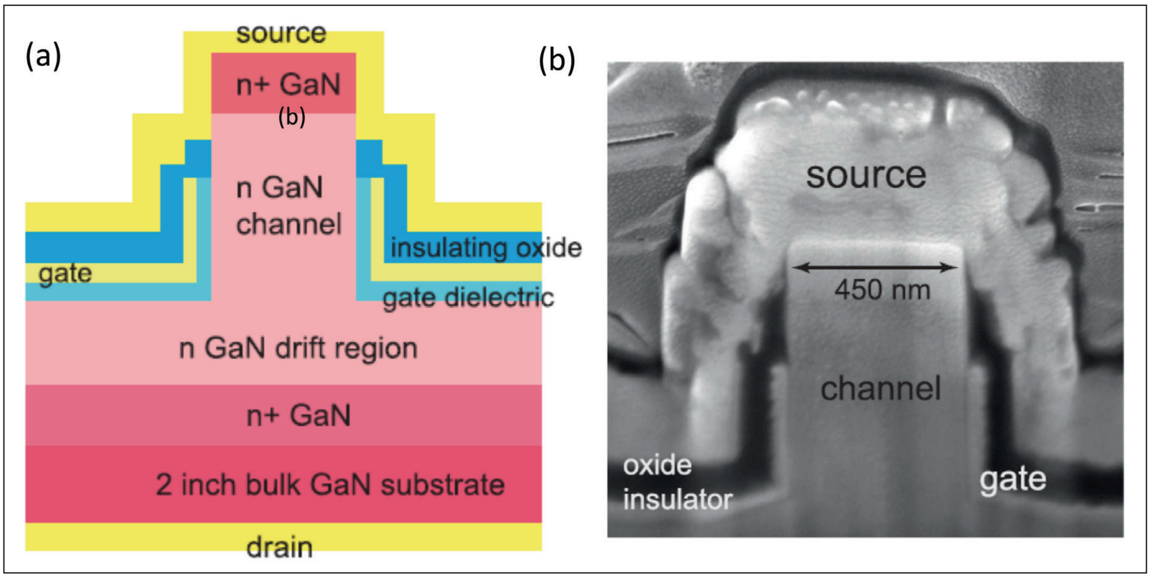


Figure 3 (a) MIT's novel vertical GaN fin MOSFET architecture. (b) cross-sectional scanning electron microscopy image of a fabricated fin device with a 450 nm channel width.

complexity of device fabrication; and adding *p*-type material produces transport properties that are far from ideal, because the mobility of the electrons in the inverted *p*-type GaN channel is typically at least 50 times lower than that in the *n*-type GaN regions, leading to high device on-resistance.

Addressing these challenges is our GaN vertical fin MOSFET (see Figure 3). This ground-breaking design consists of only *n*-type layers of GaN, thereby eliminating the need for material regrowth or *p*-GaN layers. With this device geometry, current is controlled through narrow, fin-shaped vertical *n*-type GaN channels that are surrounded by gate metal electrodes.

When our device is held at zero gate bias, electrons in the fin channels are depleted, due to the work function difference between the gate metal and GaN. We select a fin width below 500 nm, because this ensures that the depletion regions induced by the two free surfaces of the fin merge, leading to full depletion of the fin channel and ultimately normally-off transistor operation.

We are able to control the threshold voltage of these transistors by changing the fin width, and we have reported values in excess of 1.5 V. Another attribute of our transistors is the high mobility in the fin channel, thanks to the smooth sidewalls that are produced by the facet-dependent trench formation and corner rounding process.

Following optimisation, our GaN vertical fin MOSFETs produced: an on-resistance of just 0.36 $m\Omega\cdot cm^2$ for a blocking voltage of 800 V, with forward current in excess of $10^4$ A $cm^{-2}$; and a leakage current of only $10^{-5}$ A $cm^{-2}$ at a reverse bias of 600-800 V.

More recently we have achieved even better results. Through continuous optimisation of electric field engineering and the fabrication process, we have demonstrated a blocking voltage of 1200 V with an on-resistance of 0.2 $m\Omega\cdot cm^2$. These results will be published these results will be presented in the 2017 International Electron Devices Meeting (IEDM) this December in San Francisco.

These impressive characteristics show that our design, which incorporates recent innovations on GaN trenches and fins, can pave the way to a new generation of vertical GaN power transistors that feature low epitaxial cost, excellent blocking capability and normally-off operation. That makes these vertical power devices very promising candidates for extending the reach of GaN devices into high-voltage, high-current power electronics.

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# Increasing market penetration of the **quantum dot**

Can quantum dots flourish in telecom lasers, LIDAR and quantum communication?

BY DIETER BIMBERG FROM INSTITUTE FOR SOLID STATE PHYSICS, TECHNICAL UNIVERSITY BERLIN

THE MOST promising gain material for photonic devices is the quantum dot. Armed with an array of these nanostructures, devices have the potential to combine great temperature stability with high efficiency. This allows quantum dot lasers to target a wide variety of applications, ranging from the automotive sector to access networks.

But where did this revolution start? And where do we stand today? Read on to hear a story of errors and recent breakthroughs.

The advent of semiconductor nanostructure photonics can be traced back to 1976, when researchers Ray Dingle and Chuck Henry, working at Bell Labs, were awarded a US patent entitled *Quantum effects in heterostructure lasers*. In this patent they argued that threshold current can plummet by an order of magnitude with every 'reduction of dimensionality' – that is, with the move from three-dimensional material to double heterostructure lasers; and again with progression to two dimensional materials, as found in quantum well lasers; and eventually to one dimensional materials, which would lie at the heart of quantum wire lasers.

Since this proclamation by the Bells Labs' duo in the mid 70s, much progress has been made. Today, the production of semiconductor lasers is dominated by heterostructure designs featuring quantum wells. Manufacture is relatively easy, using well-established steps that include the epitaxial growth of a structure that is an extension of the double heterostructure. Three layers are replaced with five or more, allowing the gain layer to have a thickness of the order of nanometres. Separate confinement for the optical modes results from fine tuning the combined thickness of the well and the layers surrounding it.

Note, however, that a move from wells to wires has never taken off. Fabricating the latter is complex, with this class of device proving unreliable and failing to fulfil its promise.

Interestingly, the ultimate level of confinement, provided by zero-dimensional structures that are referred to as dots, did not get a mention in the Bell Labs patent. But it did ten years on, in a seminal paper by Yasuharu Suematsu and co-workers from the Tokyo Institute of Technology. This group evaluated the potential of GaAs and InP lasers with reduced dimensionality, and predicted tremendous improvements in gain and threshold current density with the switch from three-dimensional lasers to 'quantum box' lasers, how they called them.

Experimental work from that era also highlighted the promise of lower-dimensional structures. As far back as 1982, Yasuhiko Arakawa and Hiroyuki Sakaki witnessed a lowering of threshold current with increased confinement. They observed this when studying quantum well lasers in increasingly high magnetic fields that reduced the temperature dependence of the threshold current. They correctly attributed this behaviour to increasing carrier localization.

At that time, work on lower dimensional structures was restricted to lattice-matched structures, because this condition was considered imperative for fabricating dislocation-free heterostructures. Due to this limitation, efforts focused on the combination of lithography and epitaxy to form lattice-matched, quantum box lasers, which are now known as quantum dot lasers. Even after seven years of development, the best devices were not that impressive, having to overcome huge threshold current densities to deliver a pulsed mode output when cooled to 77 K.

## Self-organised success

A new dawn arrived in the early 1990s, with the re-writing of the rulebook for the production of quantum dot structures. At that time, researchers found that the deposition of a few monolayers of non-lattice matched material led to the formation of similar sized pyramids that were coherent – that is, defect-free (see Figure 1). These pyramids, with dimensions of nanometres, present self-organised quantum dots.

This class of dots may be grown by just modifying conventional semiconductor epitaxial processes. With both MBE and MOCVD, engineers have turned to previously undiscovered growth regimes to produce defect-free strained layers. By avoiding electron-beam lithography, production is simpler and cheaper. The dots that result have size- and shape-dependent electronic and optical properties, including their emission wavelength.

With these self-organised dots, efficient recombination is possible at 1.3 μm by inserting InAs quantum dots in GaAs. This combination provides an alternative to the InP material system for the near-infrared. Encouragingly, the material gain for these InAs quantum dots is orders of magnitude higher than that for the bulk form of this material. As the dot layers can easily be stacked on one another many times, modal gain can be comparable, or even exceed, that of stacked quantum wells.

Note that when quantum dots are said to be self-similar, that does not implying that they are identical. Adjacent dots do not have exactly the same number of atoms, or identical interfaces. However, they do have similar shapes, and thus symmetry properties. Entropy accounts for the differences, which are actually a benefit for almost all device applications.

For a single quantum dot, its density of states is described by a delta-function. This is replicated in its emission line shape (see Figure 2), which shows temperature-dependent Lorentzian broadening.

With a collection of dots, slight differences in the emission wavelength of individual dots impact the overall emission profile. Consider, for example, the active area of a 100 μm-wide, 1 mm long edge-emitting laser. If the density of dots is $10^{11}$ per square centimetre, then the active area will have around $10^8$ non-interacting dots, each emitting at a very slightly different wavelength. Emission produced by the laser will be the superposition of that produced by each of the dots, and well described by a Gaussian shaped envelope with a typical a half width of between 30 meV and 100 meV, depending on growth conditions. Thanks to this Gaussian broadening, mode-locked quantum dot lasers can produce femtosecond pulses, and semiconductor optical amplifiers can provide ultra-fast, multiple-wavelength amplification without cross-talk.

Measurements on the first generation of lasers with stacked quantum dot layers revealed device

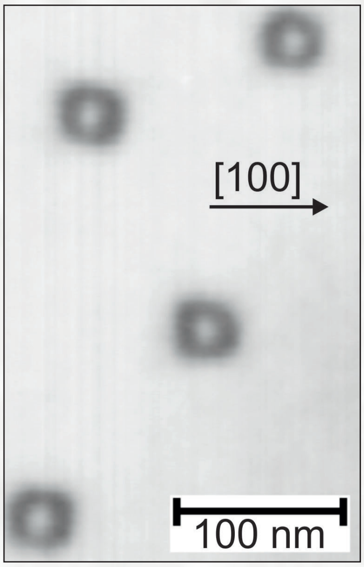


Figure 1. High-resolution, top-view, transmission electron microscopy image of a layer of InAs/GaAs quantum dots, showing four pyramidal dots. The basis of the pyramids are oriented parallel to [100] directions of the semiconductor. Taken from a chapter by D. Bimberg in *Optical Fiber Telecommunications* ed. by I.P. Kaminov, T. Li and A.E.Willner, Elsevier (2008) and D.Bimberg and U.W. Pohl, Materials Today **14** 388 (2011)

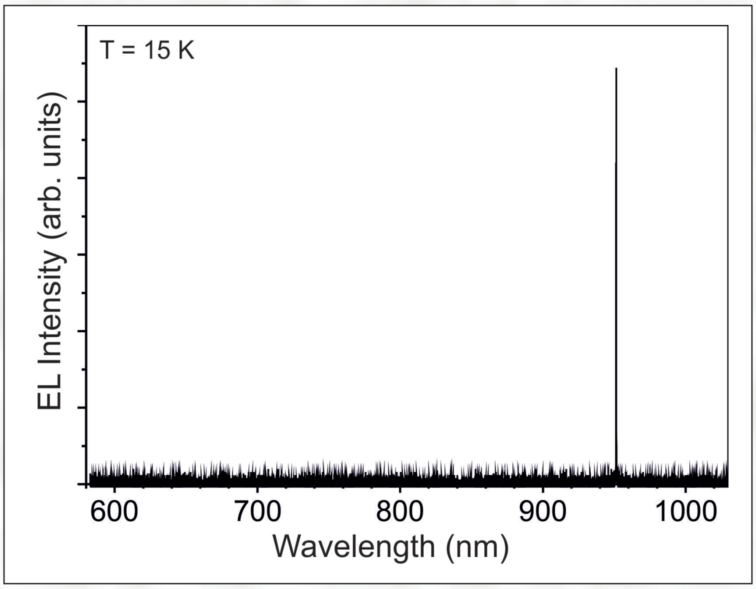


Figure 2. Electroluminescence, delta-function-like spectrum of a single quantum dot embedded in a *p-i-n* diode (see Figure 6). Emission consists of a superposition of two polarized emission lines a few hundred microelectronvolts apart, which are not resolved in this picture. It is remarkable, that across a range of 400 nm only the emission of this single QD is observed. Taken from W. Unrau and D. Bimberg, Laser and Photonics Review **8** 276 (2014)

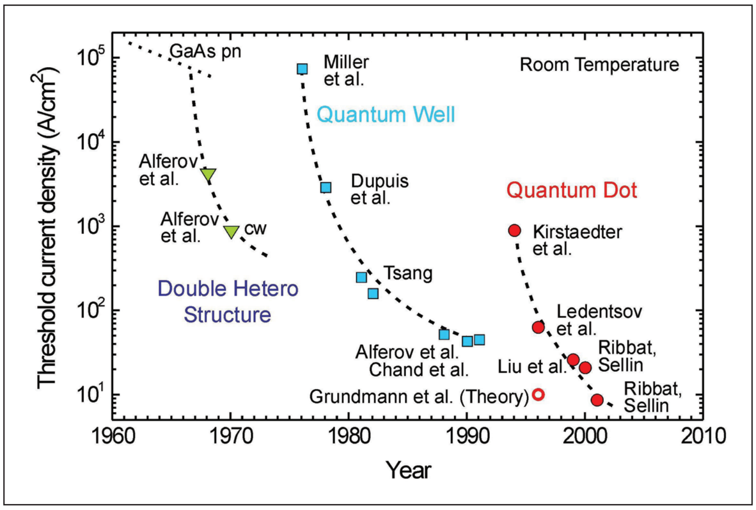


Figure 3. The threshold current density of diode lasers falls by four orders of magnitude when moving from homojunction to heterojunction, quantum well and finally to quantum dot based structures. Taken from a chapter by D. Bimberg in *Optical Fiber Telecommunications* ed. by I.P. Kaminov, T. Li and A.E. Willner, Elsevier (2008) and D.Bimberg and U.W. Pohl, Materials Today **14** 388 (2011)

properties that were far superior to those of quantum well lasers. In addition, these results were superior to those expected – a rare occurrence in device development.

A key figure of merit for the semiconductor laser is its threshold current density. This has decreased over many decades. By 2001, quantum dot layers were leading the way, setting a new benchmark of less than 10 A $cm^{-2}$ /dot layer (see Figure 3).

Placing dots within quantum wells can yield a particularly strong device performance. When combined with an appropriate scheme for *p*-type doping, lasers can exhibit a temperature-independence threshold current density at temperatures of up to about 70°C. In such devices, there is complete decoupling between the gain of the quantum dots and the index of refraction of the light guiding layer. That's possible because the total number of carriers residing in the dots is many orders of magnitude smaller than the number of carriers residing in the carrier reservoir.

One of the strengths of this type of laser is that it is capable of ultra-fast gain recovery following gain depletion, thanks to the very fast down scattering of carriers from the reservoir to dots via an Auger effect. Another merit of the device is that gain and phase modulation can be carried out independently, enabling higher-order modulation schemes. Bit rates of 100 Gbit/s or more are possible.

Additional attributes of the quantum dot laser are that it: increases coupling efficiency into a fibre by suppressing filamentation of the transverse ground mode of the edge-emitting laser; increases radiation hardness; lowers facet overheating, raising the level for catastrophic optical mirror damage; and enhances the stability for external optical feedback by more than 20 dB, leading to the elimination of optical isolators in fibre-based systems.

It may raise an eyebrow to hear that billions of quantum dot photonic devices have already been sold and used. However, these devices are not made with the arsenide or phosphide material systems – they are based on GaN. In GaN-based lasers and LEDs, the InGaN wells are thin and highly strained, giving rise to formation of localisation centres. While these dots have been largely been formed inadvertently, they provide the fundamental advantages associated with quantum dot based photonic devices, enabling the commercial breakthroughs of these device classes.

## Aiding the networks

The challenge is to now replicate this success with GaAs- and InP-based nanodevices. Up until very recently, this seemed unlikely, due to a lack of 'pull' from a market that had no interest in changing a winning formula: the InP-based quantum well laser. But the situation is now changing, due to demand for sources increasing, and a pressure to cut prices. This scenario is playing out particularly strongly in the market for fibre-to-the-home systems, which are being installed in huge quantities in all industrialized countries, and are the final point in metropolitan and access networks.

Within fibre-optic networks, installation of metropolitan area network traffic hardware is tipped to grow far faster than it is in long-haul networks. This means that there will be a rapid increase in the number, diversity and complexity of photonic devices serving these networks that operate at around 1.3 µm.

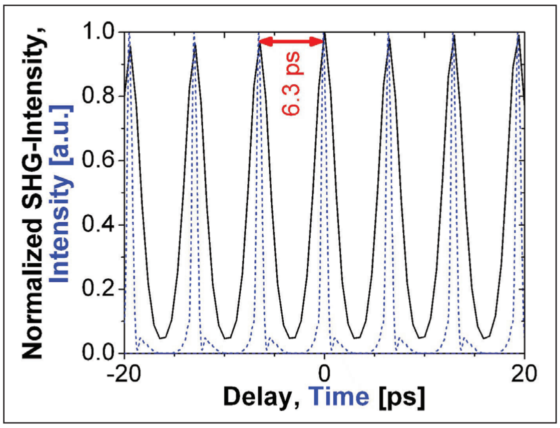


Figure 4. Repetition rate of a chirp-compensated QD mode-locked laser pulse comb at 160 GHz using an optical time division multiplexer, second-harmonic generation autocorrelation measurement (black) and corresponding pulse comb (blue). Taken from a chapter by D. Bimberg in *Optical Fiber Telecommunications* ed. by I.P. Kaminov, T. Li and A.E. Willner, Elsevier (2008) and D. Bimberg and U.W. Pohl, Materials Today **14** 388 (2011)

Controlling the power consumption and cost of the networks will require a sea-change in how the photonic systems are put together. One option for driving success is to turn to InAs/GaAs quantum dot-based photonic modules, because these outperform all the alternatives. They are more energy efficient, more temperature stable, far cheaper, and have merits not found in higher-dimensional devices.

A backbone for these high bit-rate optical communication networks is the mode-locked laser, which can emit electrical and optical pulse trains. This device can be used to make an optical clock, and when paired with a modulator, it can form a transmitter for optical time-division multiplexing systems. Further uses for the mode-locked laser exist in other fields of communications, such as multi-carrier generation and all-optical sampling. Meanwhile, in terahertz and photonics radio-over-fibre systems, mode-locked lasers can simplify source architectures.

The lowest cost mode-locked lasers are passive. Savings result from easily adding a saturable absorber into the cavity. This absorber, like the gain section, is simply direct-current biased. One of the merits of the addition of the absorber is that it ensures a self-start of mode-locking, without the need for an external radio-frequency reference source. When saturable absorbers are paired with 1.3 μm lasers, recovery is typically just 700 fs under large bias. This enables the generation of sub-picosecond pulses with low timing jitter at frequencies beyond 80 GHz. Repetition rates of 160 GHz were presented by multiplexing (see Figure 4).

In state-of-the-art access networks and metropolitan networks there are up to 40 wavelength channels, each carrying a data stream of typically 10 Gbit/s. This is set to increase to 40 Gbit/s in the very near future. Links in next-generation optical networks will cover longer distances, and accommodate far more customers. To compensate for the additional losses caused by the extended reach, and to cater for an increase in customer numbers, the networks will have to be equipped with optical amplifiers.

These amplifiers will have to fulfil many requirements. They will have to support multiple modulation formats and multi-level intensity-coded and phase-coded formats – and they will have to support multi-wavelength channel amplification, which includes the need for no channel crosstalk and wavelength switching. On top of this, they will need to have a low energy consumption, to minimise the carbon footprint, and a low cost to reduce capital investment.

Addressing these requirements are semiconductor optical amplifiers. They are low-cost, high-volume products that trim power consumption, have a very small footprint, produce a broader gain spectra, and ease integration into photonic integrated circuits. Advantages of amplifiers made from dots, rather than wells, include far faster carrier dynamics and the

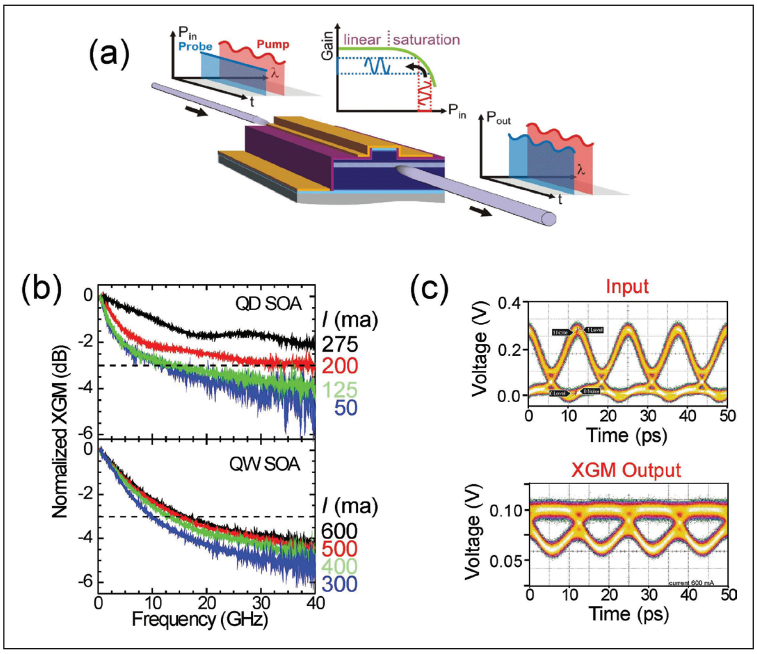


Figure 5. Cross-gain modulation of a semiconductor optical amplifier (SOA). (a) Operation principle: a strong, modulated pump signal ($P_{in}$, red) drives the SOA into the saturation regime. Consequently, the SOA gain is also modulated. The modulation pattern can be transferred to a weak CW probe pulse at another wavelength ($P_{in}$, blue), yielding an inverted modulation pattern on the probe signal in the output ($P_{out}$, blue). (b) Efficiency of the cross-gain modulation of a QD SOA (top) and a conventional QW SOA (bottom). The 3dB bandwidth of the QD SOA marked by the horizontal line can be tuned to beyond 40 GHz at high injection current. (c) Wavelength up-conversion using cross-gain modulation of a QD SOA and a pseudorandom RZ-OOK- modulation. Top: input eye diagram of a 80 Gb/s signal at 1292 nm wavelength, bottom: upconverted output signal at 1300 nm.

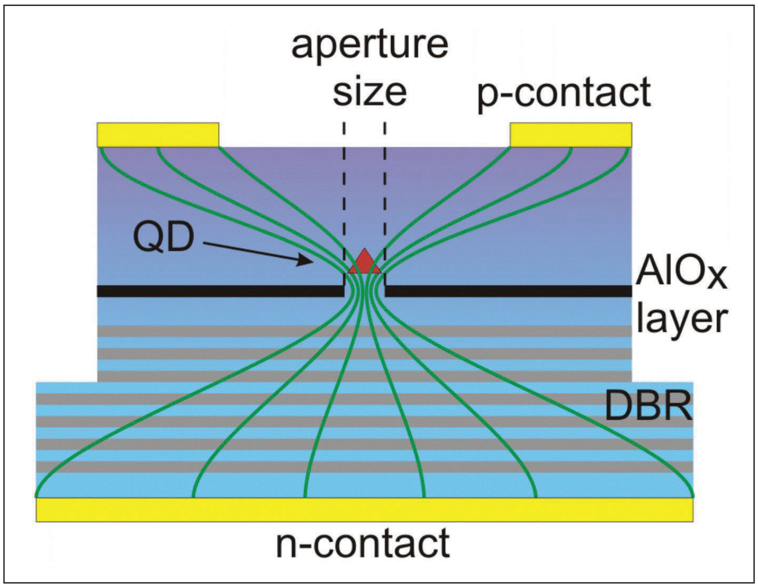


Figure 6. Cross section of a single electrically driven q-bit emitter showing the QD-position, aperture size and current flow. Taken from W. Unrau and D. Bimberg, Laser and Photonics Review **8** 276 (2014)

decoupling of gain and phase dynamics. Thanks to the fast gain dynamics, semiconductor optical amplifiers based on quantum dots have realised single and multi-channel amplification of intensity-coded signals at symbol rates of up to 80 GBd. Even higher symbol rates of up to 320 GBd were shown together with the single and multi-channel all-optical wavelength conversion of intensity-coded signals.

## Looking to LIDAR

To improve safety during the day and night, and when or driving in heavy rain, more and more cars are being fitted with systems based on light detection and ranging (LIDAR). They currently feature multiple quantum well lasers, emitting elliptical, high-power pulses with a typical width of 100 ns and a wavelength of around 905 nm. The pulses dictate the need for complex, costly, optical focusing and scanning systems and temperature stabilization technologies.

A superior alternative for scanning the road are inexpensive, temperature-stable quantum dot lasers that emit between 1260 nm and 1310 nm and are based on the inexpensive GaAs material system. Moving from 905 nm to these longer wavelengths lifts the ceiling on output power for satisfying safety class 1 regulations – it increases by 20 times – and shifts emission to within the window for maximum transmission within air. What's more, these quantum dot sources can be combined with novel laser structures to produce a round far field without having to resort to complex optics.

## Quantum communication

Another commercial opportunity for the quantum dot laser is as the source of a single-photon emitter for data encryption in quantum communication. In this application, which is the ultimate form of secure communication, the emitter must emit just a single polarized photon on demand. For bridging longer distances, it must also serve in a repeater, emitting exactly one pair of entangled photons.

The single quantum dot lasers that could serve this application must form deterministic integrated light sources with non-classical emission characteristics. Major steps have been made towards these requirements, including the fabrication of *p-i-n* diode structures with spatially localized quantum dots that employ a metal aperture for spatial filtering.

One noteworthy breakthrough has been the individual addressing of a single dot, by confining the current path (see Figure 4). To accomplish this, an oxide aperture with a small opening is positioned in close proximity, just below a dot. Quantum-bit repetition rates of up to 1 GHz are produced with this approach.

As we can see, the success story of nanostructured, infrared photonic devices has only just started. The time is now ripe to conquer huge additional markets.

I am indebted to Dr. S. Rodt for his help with the figures.

**Further reading**

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# GaN lasers: Understanding degradation

## Electrically driven diffusion is an issue for MOCVD-grown lasers, but not for their MBE-grown cousins

A MAJOR DISTINCTION between GaN lasers grown by MBE, and those formed by MOCVD, is that they differ in their degradation mechanisms. That's the key finding of a study by researchers from Warsaw-based institutions Unipress and TopGaN.

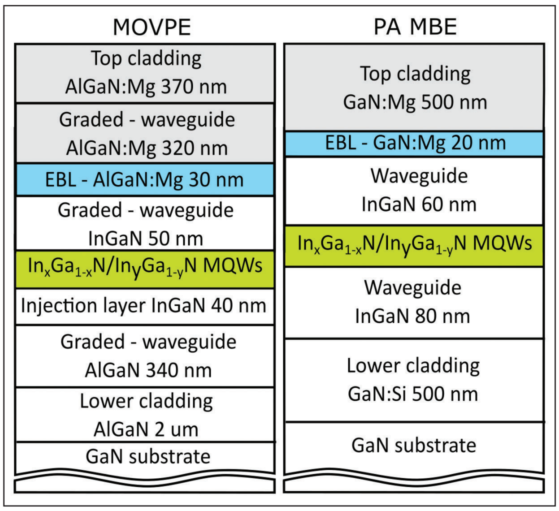
According to team spokesperson, Agata Bojarska, their study shows that the presence of hydrogen in MOCVD-grown lasers lies behind the degradation of these devices.

She believes that this insight could help to improve the performance of MOCVD-grown lasers, which are deployed in BluRay players, white-light laser sources in car headlights, and digital light projectors.

For the MBE-grown lasers used in the study, measurements on devices revealed a lifetime in excess of 50,000 hours. "It is definitely the best result for nitride MBE-grown laser diodes," says Bojarska, "but I believe that some of the Nichia and Osram MOCVD-grown lasers can achieve similar lifetimes."

One of the conclusions of the study is that MBE-grown lasers have the promise of even longer lifetimes, thanks to the absence of one of the degradation mechanisms found in MOCVD-grown lasers."However, MBE devices have other issues that need to be addressed before one can say that they are better," admits Bojarska.

To study degradation in MBE and MOCVD grown lasers, the researchers also fabricated both types of device on bulk GaN substrates formed by ammonothermal synthesis. Bojarska describes the MOCVD-grown devices as "relatively conventional", and points out that those grown by MBE are a little unusual, as they are free from aluminium. "However, the aluminium composition should not affect device lifetime."




Studies on lasers grown by MOCVD and MBE highlight the downside of hydrogen incorporation.

The researchers defined the degradation rate as the change in optical power over time. Mirroring the findings of studies by other groups, the MOCVD-grown lasers were found to have a linear dependence on degradation as a function of drive current. According to Bojarska and co-workers, this suggests that electrically driven diffusion is behind laser degradation. In comparison, for MBE-grown lasers, the degradation rate shows little or no dependence on drive current.

A second experiment by the team involved measuring the influence of temperature on degradation rate. Lasers were operated at a constant optical power of 25 mW, and heated to increase the temperature in 5 °C steps. These measurements allowed the researchers to calculate that the activation energy that is associated with the thermal degradation of MOCVD-grown lasers is typically just 0.4 eV, while for MBE-grown lasers it is far higher. This indicates that the aging mechanism for MOCVD-grown lasers is more sensitive to changes in temperature than the mechanism for the MBE-grown cousins.

To account for the differences in the degradation of the two classes of laser, the team considered the difference in growth, which lead to a vast difference in hydrogen incorporation in the *p*-doped layer. Secondary ion mass spectrometry measurements showed that the level of hydrogen in MOCVD-grown devices is proportional to the magnesium concentration – while in MBE-grown lasers, there is no correlation.

Hydrogen can easily migrate through the *p*-type layers, and may be partially responsible for the aging of the lasers, because it is an electro-diffusive element.

Degradation by diffusion due to threading dislocations – a popular mechanism for explaining the deterioration in device performance with time – can be ruled out: according to the team, the dislocation density in both types of lasers is too low for this to be a concern.

The team will now try to optimise its MBE-grown lasers by investigating new architectures, such as tunnel-junction laser diodes and distributed feedback lasers.

### Reference

A. Bojarska *et al.* Appl. Phys. Express **10** 091001 (2017)

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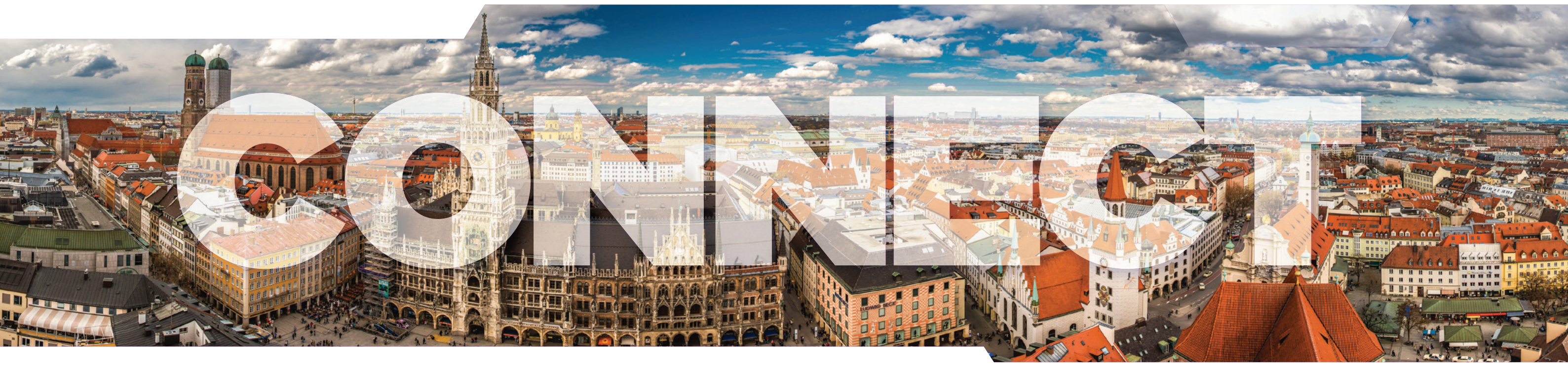


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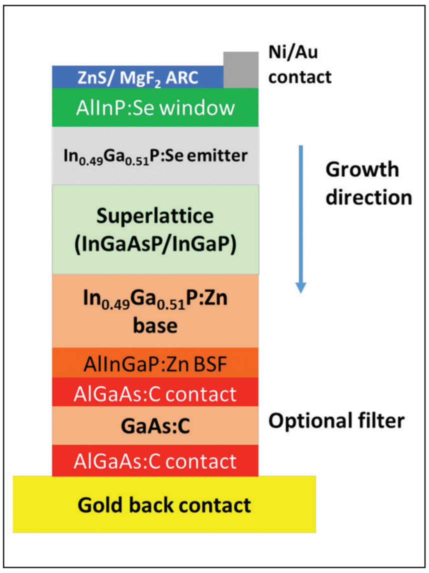
# Better junctions for solar cells

Latticed-matched superlattices of InGaAsP and InGaP promise to take multi-junction solar cell efficiency to a new high




The lattice-matched superlattice structures feature an optional GaAs filter.

TO PROPEL multi-junction solar cells to far higher efficiencies, the number of junctions has to increase from the three or four used today to five or six.

One option for doing this is to take an existing solar cell architecture and add an InGaP *n-i-p* structure with an intrinsic region formed from multiple InGaAsP wells and InGaP barriers.

Strained-balanced forms of this structure, which have been explored since the 1980s and enable the tuning of the effective bandgap from 1.5 eV to 1.8 eV, are plagued by inefficient light absorption that pegs back external quantum efficiency to around 25 percent. But efficiency can now hit more than 65 percent, thanks to the recent development of lattice-matched variants by a team from North Carolina State University and the National Renewable Energy Laboratory in Colorado.

Spokesperson for the team, Salah Bedair, says that its technology could be used in terrestrial cells and those that serve in space.

Another virtue of the technology is its compatibility with a wide range of material systems. "Our work was done on GaAs, but this structure can also be grown on germanium and dilute nitrides," says Bedair. Yet another option is the bonding to silicon solar cells to form high efficiency tandem devices.

Switching from a strain-balanced structure to a lattice-matched variant has enabled the team to increase the thickness of the absorbing InGaAsP wells. A further boost to light absorption has come from an increase in the proportion of the depletion region occupied by the wells – and this has also improved carrier collection.

Additional improvements have resulted from: etching off the GaAs substrate and adding a back-surface reflector, to double the optical path length; and reducing background doping – and thereby increasing the depletion region – with a judicious choice of precursors.

Bedair and co-workers have produced a range of *n-i-p* solar cells structures. These were grown inverted to allow the etching of the GaAs substrate, followed by the deposition of a gold back surface reflector. Some of the portfolio of devices feature a 1.2 μm-thick GaAs filter, which absorbs photons in the 1.4-1.85 eV range that are not absorbed by the wells in their first pass.

Devices produced by the team include a 20-period structure with 7 nm-thick wells and 3.2 nm-thick barriers; a variant with 40 periods; and a 100-period structure with the pairing of 5.5 nm-thick wells and 2.5 nm-thick barriers. The latter had thinner wells and barriers to reduce accumulated stress.

Testing under one sun with an AM1.5 spectra revealed that the gold back-surface reflector boosts short-circuit current density by 65 percent, 50 percent and 30 percent in devices with 20, 40 and 100 wells, respectively. The team believes that the structure with the fewest wells has the greatest benefit, because of its 'optical thinness' and its weak absorption of long-wavelength photons.

The most impressive results come from a 100-period device with a gold back-surface reflector and an anti-reflection coating. This design produces a short-circuit current density of 20.5 mA $cm^{-2}$, an open-circuit voltage of 1.126 V, a fill factor of 72 percent, and a solar conversion efficiency of 14.7 percent.

According to the team, the short-circuit current density is 26 percent higher than that of a standard InGaP cell, due to sub-bandgap absorption by the quantum wells. They believe that the fill-factor is not that high, and it could exceed 80 percent by improving interface quality. This could be accomplished by optimising gas switching and other growth parameters.

Another figure of merit for evaluating the cell is the bandgap offset voltage: it is the difference between the band gap and the open-circuit voltage. "The smaller the value, the better the material quality," argues Bedair. The team's devices have a typical band offset voltage of about 0.4 eV, a value that is claimed to indicate high internal and external radiative efficiencies.

Bedair believes that the technology could also aid the development of tuneable light-emitting devices. "We are considering this at the moment."

## Reference

I. Sayed *et al.* Appl. Phys. Lett. **111** 082107 (2017)

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# Accelerating GaN growth

A gallium evaporator made from a porosity-controlled ceramic holds the key to very high GaN growth rates

THE GROWTH of sales of GaN power devices is held back by the absence of low-cost, large diameter, high-quality bulk GaN substrates. Today, the commercial production of GaN substrates produces material that is expensive, limited in size and availability. But that could all change, thanks to the speeding up of a novel gas process developed by a team at Toyota Central R&D Labs.

This team from Japan has just delivered a five-fold hike in growth rate by replacing a conventional crucible with a porosity-controlled TaC ceramic that provides a significant increase in the surface area of the gallium source.

GaN is grown by the team's halogen-free vapour phase epitaxy process, through the reaction of evaporated gallium and ammonia.

As hydrogen gas is the only by-product, growth runs can be longer than they are by HVPE, which is cut short by the generation of ammonium ash.

A fast, low-cost GaN growth process could help GaN power electronics to grab market share from the incumbent silicon devices

When the team were using a crucible for the GaN source, heating to 1590 K produced a gallium evaporation efficiency of only 30 percent.

Although higher efficiencies were possible by increasing the temperature and decreasing the pressure, these options were not pursued, as they would compromise the reliability and durability of the reactor components.


Instead, the team have focused on increasing the evaporation rate with the introduction of a fin-shaped evaporator, which uses a capillary force to draw molten gallium through pores of the TaC ceramic.

TaC ceramics with pores that have diameters of 1-10 $\mu$m and a relatively high porosity of 2-5 percent formed the building material for two evaporators: one with eight radially aligned fins with an outer diameter of 30 mm and a height of 36.5 mm; and a second with six fins with an outer diameter of 35 mm and a height of 36.5 mm.

Growth rates of 481 $\mu$m/hour and 764 $\mu$m/hour were realised with the eight-fin and six-fin reactors, respectively. These values equate to an increase in GaN growth rate by a factor of 3.5 and 5.5, respectively.

One implication of these values is that the growth rate is not just determined by the surface area: the evaporators have surface areas that are almost identical, but their growth rates are markedly different.

The researchers also note that the level of the increase in growth rate is very similar to that for the increase in feed rate, indicating that it is the gallium feed rate that limits the growth rate for GaN. The feed rate is limited by the local saturation of gallium vapour pressure.

To avoid this limitation, the team have concluded that the evaporator should be designed so that the fins cover the entire nitrogen flow channel in a manner that does not lead to a local saturation of the gallium vapour pressure.

Efficiency of evaporation with the six-fin evaporator is estimated to be about 80 percent, a value that is believed to be very close to the practical limit.

The growth conditions at very high growth rates still need to be improved, as they currently lead to the creation of polycrystalline regions.

That's not the case when growing at around 200 $\mu$m/hour. In this regime, the GaN layer is mostly a single crystal, with relatively high quality, according to X-ray diffraction measurements.

## Reference

D. Nakamura *et al.* Apply Phys. Express **10** 095503 (2017)

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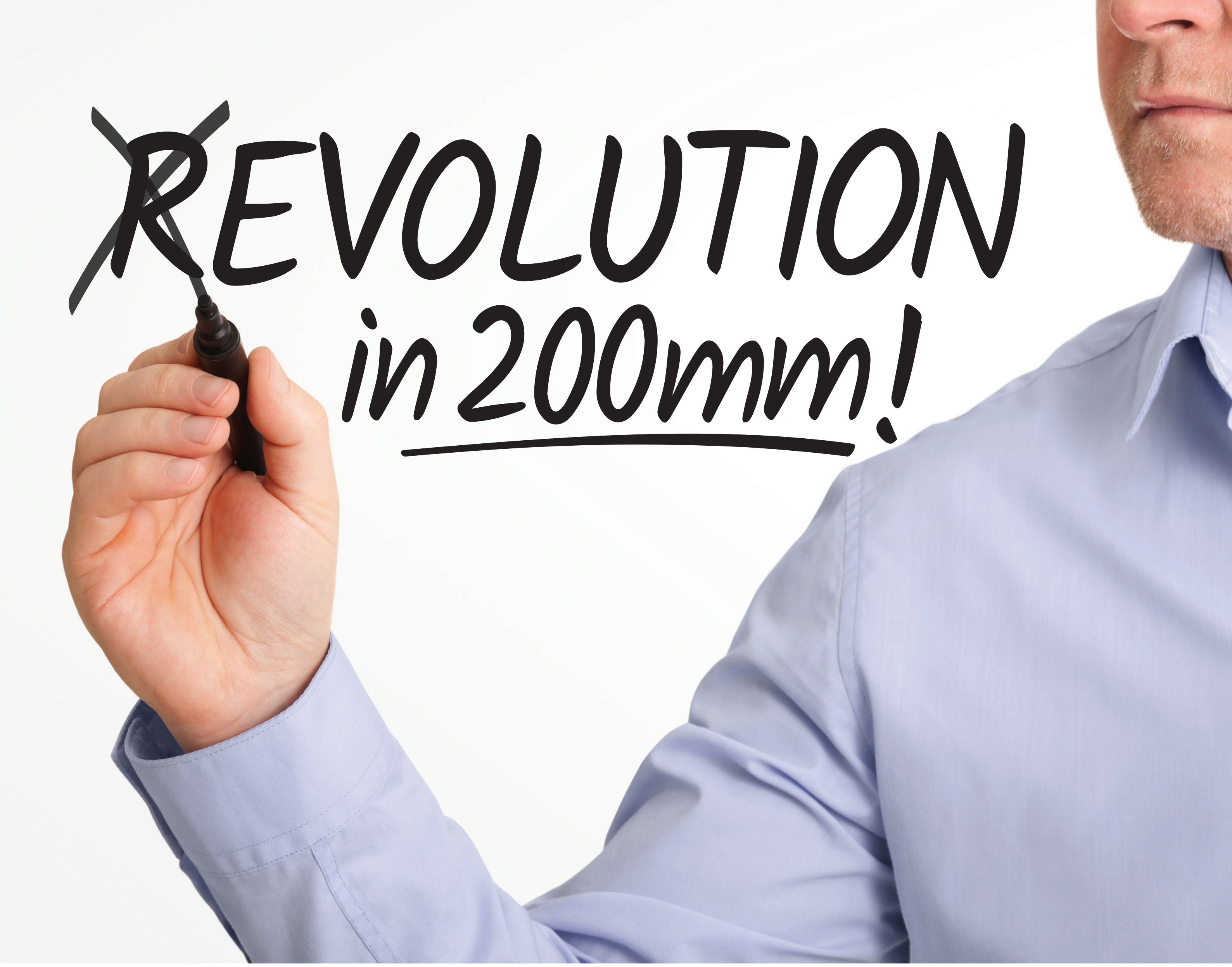


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