COMPOUND SEMICONDUCTOR

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Insights into gallium oxide growth

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INSIDE

News, Analysis, Features, Editorial View, Research Review and much more

ELECTRICITY FROM HEAT

III-V thermophotovoltaics hold the key to highly efficient energy storage everywhere

IMPROVING DETECTION

Adding a sprinkling of bismuth to GaAs drives down the noise of avalanche photodiodes

AUDIOPHILE AMPLIFICATION

Exceptional switching characteristics of GaN underpin a new era in high-fidelity amplification

VIEWPOINT

By Dr Richard Stevenson, Editor

Hearing the difference

All of us want to bask in the gains provided by the introduction of compound semiconductor devices, or improvements to these chips. But it's rare that we actually get to do this. For example, although we know that the modulation rate for the VCSEL is increasing, and this benefits datacoms, we don't get to feel this progress first hand; and while we know that the introduction of SiC electronics to power supplies trims energy losses, these savings are not tangible.

Up until very recently, my delights in the benefits wrought by compound semiconductor devices focused on LED lighting. My LED headtorch was so much better than its predecessor, weighing far less and having a far longer battery life. And I felt really good when investing in LED-based bulbs that rid me of the dilemma of choosing between a light source that produced great colour quality, but more heat than light (the incandescent); and the more frugal option that cast horrible hues, often failed to work with a dimmer switch, and took several minutes to work up to full brightness (the compact fluorescent).

Over the last few months I have had the chance to revel in another benefit brought by compound semiconductor devices. GaN is just starting to replace silicon in audio amplifiers, and over the last couple of months I have had the opportunity to evaluate a great example of this new breed, a pair of monoblocks produced by Orchard Audio (a feature on why this company uses GaN starts on p. 28).

Even before I had swapped Orchard's monoblocks for my cherished, silicon-based power amp, I could appreciate some of the benefits of the nascent technology. Rather than manoeuvring large, potentially back-breaking units into my rack, I could position each of these minimalist monoblocks with ease. And when I plugged them in, the units remained cold to a touch; certainly a welcome feature as energy bills soar.

But what about the sound, the characteristic that obviously matters most? Well, these miniature marvels certainly pack a punch, driving my floorstanders with ease to cast a wide soundstage, while producing plenty of base. But the GaN-based monoblocks did fall short of my power amp in one regard – note, though, that my unit retails for nearly four times the price, so it's hardly surprising that I have found one area for improvement. Compared with my far more expensive amp, Orchard's monoblocks don't have a richness of tone with plucked strings and great vocalists. However, I should point out that if you have never enjoyed this aspect of musical production, you'll not miss it.

Despite my nit-picking, I'm really happy that Orchard is winning fans. After all, isn't it great that our industry is helping to bring a smile to many faces.

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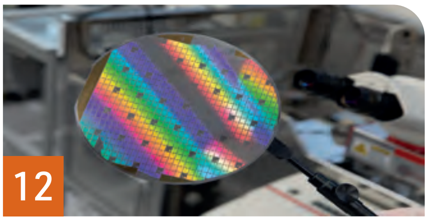

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BelGaN Group acquires Onsemi Belgium fab

BELGAN GROUP BV has completed the acquisition of all shares of On Semiconductor Belgium BV from the Onsemi group. The site in Oudenaarde (pictured right) will be transformed from silicon to GaN.

BelGaN aims to become a leading 6-inch and 8-inch GaN automotive semiconductor foundry in Europe. Part of its vision is to develop a growing ecosystem in Europe and beyond for GaN-based chips and power electronics with applications, amongst others, in EV, mobile, industrial, data centre and renewable energy markets. This is well aligned with the European ambition for greater chip autonomy (European Chips Act) and a carbon-neutral society (Green Deal).

"After starting my career in Bell Labs with a Doctoral Fellowship 30 years ago, I have witnessed the success and growth of Silicon Valley by commercializing Bell Labs inventions", said Alan Zhou, CEO of BelGaN BV. "I envision an opportunity of a lifetime to build the 'GaN Valley' in Belgium by leveraging Imec's next-generation GaN power device innovations with BelGaN team's more than ten years of GaN technologies development and more than thirty years of automotive semiconductor manufacturing experiences".

Marnix Tack, CTO and VP Business Development at BelGaN, states: "GaN is a new generation of semiconductor material for power devices that enables more energy-efficient and faster charging, higher power density and greater energy savings for mobile, industrial, electrical vehicle and renewable energy markets. The global market for GaN power chips is currently estimated at around $100 million per year and is expected to accelerate to more than $1 billion per year within the next five years".

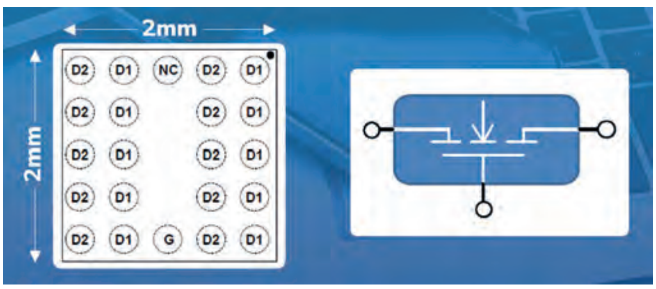
Rob Willems, general manager and VP Operations of BelGaN BV, noted: "We are proud to announce the start of BelGaN, a new and exciting chapter in the history of our semiconductor company in Belgium. The 400+ current employees will remain on board. In addition, BelGaN is planning to expand and hire a variety of extra profiles from operators to engineers. GaN power chips will be a game changer in the electric automotive and many other sectors and an important step towards a more sustainable future."

Innoscience delivers GaN HEMT for mobile handsets

CHINESE GaN company Innoscience has announced the INN40W08, a 40 V bi-directional GaN-on-silicon enhancement mode HEMT for mobile devices, including laptops and cellular phones. The INN40W08 HEMT has been developed using the company's InnoGaN technology.

Denis Marcon, general manager of Innoscience Europe and marketing manager for the USA and Europe, remarked: "GaN technology has been adopted by manufacturers of mobile phone chargers over the last couple of years to deliver increased power and shrink device size. However, Innoscience's significant breakthrough now makes it possible to introduce GaN HEMTs into mobile phone handsets as well, increasing efficiency and performance. With Innoscience's huge available capacity, we provide the secure supply chain that customers nowadays expect."

Featuring a bi-directional blocking capability, the new INN40W08 GaN HEMTs have an on-resistance of 7.8 mΩ. This is achieved by a patented strain enhancement layer technology, which reduces sheet resistance by 66 percent. Gate charge is typically 12.7 nC. The 5 by 5 grid wafer level chip scale package measures 2 mm by 2 mm. The small footprint enables INN40W08 GaN HEMTs to be integrated inside mobile phones. Applications include high side load switching, over-voltage protection in a smart phone's USB port and multiple power supplies including chargers and adapters. In over-voltage-protection systems, the technology can replace two silicon MOSFETs with one InnoGaN (or BiGaN) transistor.



Ams Osram introduces next-generation projected lighting

PROJECTED LIGHT is the latest optical effect to be used to brand a car's interaction with the driver and passengers. Tiny assemblies of LEDs and micro-lenses embedded in the wing mirror, door sills and elsewhere project light patterns on to the road or pavement, producing effects such as the 'welcome light carpet' – the car's optical 'hello' to the driver when the wireless key fob comes into range.

Ams Osram has recently revealed that it is now developing the next generation of the technology: semi-dynamic light projection, opening up new creative possibilities to car makers.

Projected light technology has to achieve extreme miniaturisation, so that the entire projection system can easily be accommodated in unused space, such as the underside of the wing mirrors or the door sills. It also needs to provide a sharp, well focused rendering of a pattern, symbol, or graphic artifact such as a logo.

Individual lens features, each measured in fractions of a millimetre, can be sculpted individually to produce the pattern required in the application when light is projected through the array, forming an ellipse on the 'image plane' – the surface on which the graphic is displayed, such as a pavement or roadway.

Until now, the technology has only been capable of projecting static images on to the image plane. The latest innovation from Ams Osram enables semi-dynamic projected lighting.

Here, a segmented micro-lens array works in combination with four collimators split by an optical separator, with four independently steerable LED light sources.

The micro-lens components are produced as wafer-level optics using technologies and equipment common to the semiconductor industry. The precision and miniaturisation possible when producing wafer-level optics is extraordinary: optic-to-optic alignment is of the scale of ±5µm, and optics-to-mechanics alignment is ±30µm.

Toshiba launches SiC MOSFET modules

TOSHIBA has launched two SiC MOSFET dual modules. The MG600Q2YMS3 has a voltage rating of 1200 V and drain current rating of 600 A; and the MG400V2YMS3 has a voltage rating of 1700 V and drain current rating of 400 A.

The first Toshiba products with these voltage ratings, they join the previously released MG800FXF2YMS3 in a lineup of 1200 V, 1700 V and 3300 V devices.

The latest modules have mounting compatibility with widely used silicon IGBT modules. Their low energy loss characteristics meet needs for higher efficiency and size reductions in industrial equipment, such as converters and inverters for railway vehicles, and renewable energy power generation systems.

Applications include inverters and converters for railway vehicles, renewable energy power generation systems, motor control equipment, and high frequency DC-DC converters.

Infineon announces SiC module for streetcars

INFINEON TECHNOLOGIES is launching power semiconductors with CoolSiC MOSFET and .XT technology in the XHP 2 package – which it says is tailored specifically for requirements of rail services including trams and streetcars.

The XHP 2 power module from Infineon has already been used in a joint field test conducted by Siemens Mobility and Stadtwerke München.

An Avenio streetcar in Munich was equipped with these power modules and tested in passenger service for a year, covering around 65,000 km.

Siemens Mobility concluded that this use of power semiconductors based on SiC had made it possible to reduce the energy consumption of streetcars by ten percent. At the same time, it was also possible to significantly reduce engine noise during operation.

"Innovative semiconductor solutions for rail technology are an important driver for green mobility. The successful field test with streetcars in Munich demonstrates the benefits of SiC technology for manufacturers, rail operators, and residents," said Peter Wawer, president of Infineon's Industrial Power Control Division.

The tests were carried out under the European development and research project PINTA and are part of the extensive European research and innovation initiative Shift2Rail, which aims to create a sustainable European rail system through targeted investments.

Implementing SiC in power modules for traction propulsion systems can also pose major challenges: in addition to an efficient and very robust SiC chip, packages that allow high switching speeds are required, as well as interconnection technologies that enable a long service life.

These are precisely the features offered by Infineon's power module: since trains accelerate and decelerate frequently, the power cycles for semiconductors in rail applications are very demanding. The constant temperature fluctuations stress the interconnection technology. Infineon's .XT technology provides a solution to this challenge. T

Transphorm to uplist on Nasdaq

GaN COMPANY Transphorm has announced that its common stock has been approved for listing on the Nasdaq Capital Market.

Trading on Nasdaq started on February 22, 2022, with shares continuing to trade under the ticker symbol TGAN.

Commenting on the announcement, Primit Parikh, president and co-founder of Transphorm, stated: "Our uplisting to Nasdaq is a significant milestone for Transphorm and is a testament to the dedication and hard work of the Transphorm team, as well as our strong co-operation with our valued customers and partners to build one of the leading GaN companies in the world."

Parikh added: "This uplisting should raise the visibility of Transphorm in the capital markets and allow for increased sponsorship from worldwide institutional investors as well as increased liquidity in the trading volume of our stock."

Umesh Mishra, CTO and co-founder of Transphorm, commented, "This achievement and recognition represents a key benchmark for both GaN and Transphorm. With our world-leading innovations in GaN and robust IP portfolio of more than 1,000 patents, we are proud to be a world leader in GaN power conversion, which is the next large market for GaN since GaN LEDs and GaN RF transistors."

The company recently announced that product revenue increased sequentially for an eighth consecutive quarter and grew 220 percent year-over-year to a quarterly record of $3.6 million. In December 2021, Transphorm shipped over one million SuperGaN Gen IV FETs for 45 W to 300 W power adapter and fast charger applications.

MIT Lincoln Lab nears construction of compound semiconductor facility

WORK IS EXPECTED to start in the next couple of months on a long planned $279 million project to build a Compound Semiconductor Laboratory – Microsystem Integration Facility (CSL-MIF) at MIT Lincoln Laboratory in the US.

The project is funded by the US Air Force military construction (MILCON) program, under the direction of US Army Corps of Engineers (USACE), who will manage the building of the 160,000-square-foot, three-story facility. Lincoln Laboratory will install and calibrate the facility's fabrication equipment. Of the 160,000 square feet, 35,000 will be high-end clean room space.

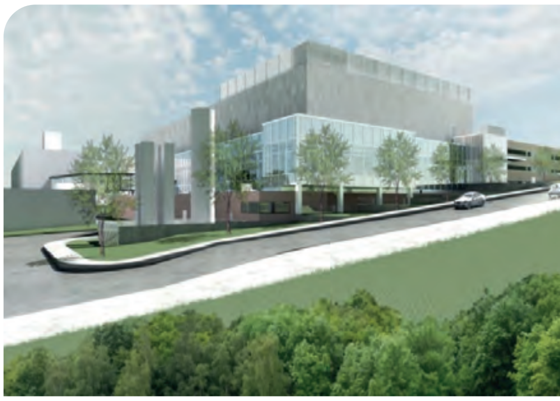
The CSL-MIF building project has been over a decade in the making. In 2014, the US Department of Defense acknowledged a critical need for Lincoln Laboratory facility modernisation, and the CSL-MIF was one of two MILCON building projects. The second building project programmed for MILCON funding is a new Engineering Prototyping Facility (EPF) for establishing advanced fabrication and integration laboratories for large system prototypes. Together, the CSL-MIF and EPF make up a larger facility modernisation effort called the West Laboratory Project.

"The CSL-MIF will enable the most advanced microelectronics research and prototyping in critically important national security areas for decades to come. We look forward to the many technology advances that will be developed through the combination of this new laboratory and our outstanding staff," says Lincoln Laboratory director Eric Evans.

When finished, the CSL-MIF will enable scientists and engineers to grow, fabricate, and characterise compound semiconductors and package specialised heterogeneously integrated electronic prototypes.

Technologies of focus will include 3D-integrated focal plane arrays for scientific imaging and surveillance, integrated electro-optical systems for space-based optical communication, superconducting microsystems for integrating quantum information bits (qubits), and advanced 3D-ladar imaging systems.

The capabilities of the CSL-MIF will be complementary to those of the laboratory's existing Microelectronics



Laboratory (ML), the US government's most advanced silicon-based research and advanced prototyping fabrication facility.

"The combination of the new CSL-MIF with our existing ML infrastructure will be a powerful and differentiating resource for the laboratory in the advanced microelectronics area. The two facilities together will allow us to explore and demonstrate complex heterogeneously integrated microsystems that could not be realized without access to the capabilities provided by these two specialised facilities," says Craig Keast, associate head of the the laboratory's Advanced Technology Division and technical lead on the CSL-MIF project.

Nuburu gets extra growth capital

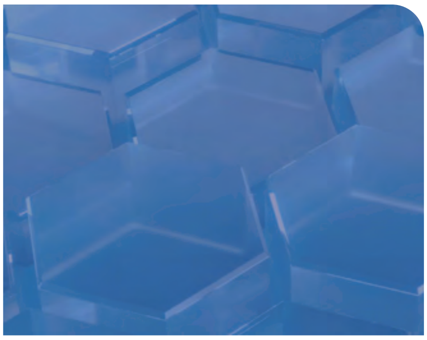
THE US BLUE LASER COMPANY Nuburu has announced that it has raised additional growth capital at a valuation of approximately $350 million. The company has also brought on experienced technology executive, Brian Faircloth, as chief operating officer, and promoted Andrew Dodd to VP of Global Sales to boost commercialisation efforts for its revolutionary industrial blue laser technology.

Existing investors Anzu Partners, Grapha Holdings, and Thomas Wilson participated in the funding round that will be utilized to expand Nuburu's presence across its target markets, including automotive, aerospace, consumer electronics and defense.

Nuburu's blue laser technology brings breakthrough speed and quality improvements to welding and metal 3D printing of copper, aluminium and other reflective metals to increase productivity for manufacturers globally.

New COO Brian Faircloth brings over twenty years of operations, engineering, and marketing experience scaling high-tech companies in the laser and energy industries.

Prior to joining Nuburu, Faircloth spent nearly 13 years as a technical leader at high-power laser company, ForoEnergy,



where he served as VP of engineering and as CTO. During his tenure, he managed R&D and engineering of high-power laser and optics development for oil, gas and geothermal applications.

Earlier in his career, he held executive and director roles at leading laser technology companies, Nuvonyx and Coherent. Faircloth holds master's degrees in electrical engineering and applied physics from Washington University in St. Louis and Six Sigma from Villanova, as well as master certificates in business management and marketing from Tulane.

"Nuburu's blue laser technology brings improvements in metal processing, unlocking critical advantages to manufacturers across industries," said Faircloth. "I am thrilled to be joining the team during this period of growth and look forward to using my industry expertise to further commercialize this technology."

Andrew Dodd, a 30-year veteran of the laser development and material processing industries, joined Nuburu in 2019 as the North American Market Development Manager and has recently been promoted to Vice President of Global Sales as the company enters this new growth phase.

Dodd has been instrumental to laying the foundations for commercial expansion since joining Nuburu and brings significant global sales leadership and a strong track record from his tenures at GSI Lumonics, Amada WeldTech, and BLM Group North America.

"As electrification and advances in manufacturing drive growth in our target markets, this capital infusion, appointment of Faircloth as COO and Dodd's promotion to VP of Global Sales ensures continued momentum for Nuburu," said Mark Zediker, CEO, co-founder, and chairman at Nuburu. "Looking ahead, we are focused on growing our customer base, expanding our distribution channels, accelerating development of our ultra-high brightness product family and scaling our manufacturing operations to meet demand globally."

IVWorks acquires French GaN wafer business

SOUTH KOREAN GaN epi-wafer startup, IVWorks, has acquired the GaN wafer business of Saint-Gobain, a French company that designs, manufactures and distributes materials and services for the construction and industrial markets.

IVWorks is the sole South Korean enterprise specialising in semiconductor materials that has successfully mass-produced GaN epi-wafers of 4-, 6-, and 8-inch. It has to its credit the in-house development of the world's first epi-wafer production technology integrated with an artificial intelligence production system. The pioneering start-up has also recently installed a 12-inch production facility, for the first time in South Korea.

CEO Young-Kyun Noh of IVWorks said: "Recently, the use of GaN power devices is increasing significantly in all electronic products due to their advantages in terms of energy efficiency, and interest in GaN is high in the EV applications, a new market area.

Noh added: "Based on this acquisition, we will be able to expand our product portfolio by supplying GaN-on-GaN epi-wafers in high-power application fields and compete with SiC materials in the EV market."

II-VI qualifies SiC MOSFETs for cars and extends GE relationship

II-VI Incorporated has announced that it has qualified its 1200 V SiC MOSFET platform to the Automotive Electronics Council AEC-Q101 standard, exceeding it to 200°C. II-VI is also expanding its relationship with GE by signing a three-year technology access agreement (TAA) with GE Research to gain access to the Lab's world-class SiC module technology and team of experts to accelerate customer design-in engagement activities.

"This qualification represents an important milestone that allows us to begin ramping up our commercial activities for devices in the industrial motor and renewable-energy markets, while in parallel, initiating longer-term design-in activities in the electric vehicle market," said Sohail Khan, executive VP, New Ventures & Wide-Bandgap Electronics Technologies.

"The licensing of GE's technology in 2020 allowed us to achieve our qualification milestone ahead of schedule. The technology access agreement will strengthen our relationship with GE and further accelerate our time to market as we continue to execute on our previously announced plan to grow by investing $1 billion in capacity and innovation for our silicon carbide platform over the next ten years."

The TAA with GE Research expands the relationship with GE by building on an earlier agreement in which II-VI licensed GE's technology to manufacture SiC devices and modules for power electronics.

The TAA will involve about a dozen of GE Research's SiC device and systems experts and test facilities, which will be dedicated to the next phase of the commercialization of II-VI's SiC devices and modules.

"We're excited to enter into this new agreement, which will enable II-VI to capitalize on billions of dollars of new market opportunities for power electronics in the automotive, industrial, and other sectors," said Vic Abate, GE's CTO.

"As we work with II-VI to expand its market base, we will also leverage new advancements in silicon carbide power devices and modules to improve GE's position with its silicon carbide products in the aviation market and support other GE products in the energy and health care spaces that will benefit from these more capable power electronics devices."

Bosch steps up SiC chip production

With SiC chips flowing from its Germany fab, Bosch has its sights firmly set on leading the electromobility market, reports **REBECCA POOL**

IN RESPONSE to the ever-buoyant SiC device market, Germany-based Bosch has laid out plans to start volume production of its SiC power semiconductors. As part of its December 2021 announcement, Bosch board member, Harald Kroger stated: "The future for silicon carbide semiconductors is bright. We want to become a global leader in the production of SiC chips for electromobility."

And as Ralf Bornefeld, senior vice president of the engineering and technology heavyweight's Automotive Electronics division tells *Compound Semiconductor*: "It's pretty simple. We've been developing this technology for a long time and are now market-ready – customers trust our automotive history and want to use our chips."

More than a decade ago, Bosch started research on how to fabricate SiC semiconductors, homing in on SiC trench MOSFETs with a vertical architecture following its successes with silicon-based MEMS sensors. Here, a high-aspect ratio plasma etching process, known as the Bosch Process, had been developed to create deep, steep-sided holes and trenches in wafers.

➤ Ralf Bornefeld, Bosch Senior Vice President of Automotive Electronics. [Bosch]

Fast forward to today, and Bosch has applied the technology to SiC, with Bornefeld firmly believing his company's vertical MOSFETs will have the edge on competitor's planar devices. "The trend is to shrink the cell design and save SiC area, and thus cost – so we have used this technology right from the beginning," he says.

Bosch's target market is electric vehicles, with the company intending to fabricate devices for traction inverter, onboard-charging and DC-DC conversion applications. According to Bornefeld, thanks to the high power and high voltage operation, and high semiconductor-count demanded by traction inversion, this application holds huge appeal for SiC semiconductors.

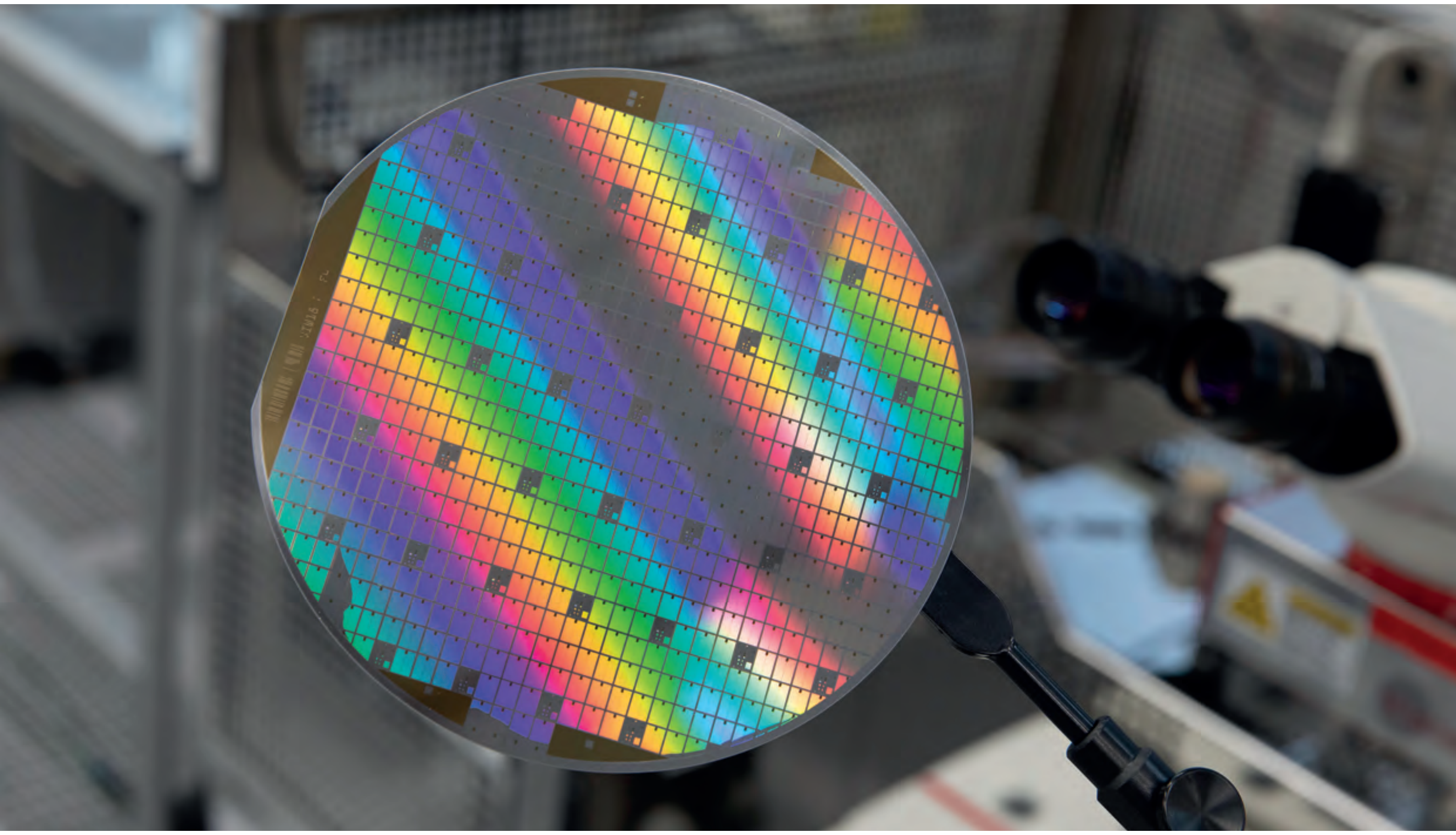
But the Bosch executive is equally confident that the technology will make strong in-roads into onboard charging and DC-DC conversion, despite competition from GaN-based devices. Pointing to onboard charging, he highlights how the market is veering towards fast charging, which could require high voltage battery packs – in the 800 V range – operating alongside 1200 V SiC devices. "If this trend holds, I do not see gallium nitride being a competitive technology here in the foreseeable future," he says.

Still, Bornefeld confirms Bosch is also active in GaN and has some ideas that are in their very early stages. In the meantime, all eyes are on the latest activities at the company's Reutlingen wafer fab, which has been producing SiC chips for customer validation since early 2021 and is now expanding clean room space at the facility.

Alongside expansion, silicon chip production is being shifted from Reutlingen to Bosch's recently opened 300 mm silicon wafer facility in Dresden, which as Bornefeld highlights, frees up space for SiC manufacture and a transition from 150 mm to 200 mm wafers. "We've already started running 200 millimetre silicon carbide wafers on our line," he says. "I cannot say exactly when the wafer transition will happen but it could be somewhere between 2024 and 2026."

So what now for Bosch? The company is currently heading up the €89 million European Union-funded Transform – *Trusted European SiC Value Chain for a greener Economy* – project. The 34 organisations aim to build a competitive European supply chain for SiC-based power electronics devices in myriad applications, including industrial drives, power conversion, renewable energy and, of course, electric mobility.

"Silicon carbide is a core technology that will be seen as important by every region in the world,"



says Bornefeld. “I am a friend of open markets in general… but given the geopolitical tensions we sometimes see, Europe could act as what I would call a ‘neutral zone’.”

“Also, having a complete value chain should make Europe stronger,” he adds.

And of course, manufacture of 750 V and 1200 V SiC MOSFETs continues apace, with the company developing its next generations of SiC chips along the way. Bornefeld confirms future MOSFETs will be based on its tried-and-tested vertical chip architecture, the trench MOSFET, but these smaller devices will be ‘constructed differently’.

“We’re developing the technology for the next generation, and the generation after that,” he says. “We have a lot of ideas on how to make our silicon carbide technology last for a long, successful future.”

➤ Bosch is ramping its SiC production capability [Bosch]

Hexagem: the only way is up

With GaN poised for massive market growth, Sweden start-up Hexagem is set to deliver GaN-on-silicon wafers for vertical devices, with a difference, reports **REBECCA POOL**

AS INDUSTRY PLAYERS far and wide eye GaN devices with increasing excitement, one Sweden-based start-up plans to shake-up the market with its disruptive technology.

Lund University spin-out, Hexagem, is pioneering a vertical nanowire growth process to make GaN-on-silicon semiconductors as efficient as the market's best GaN devices. What's more, the devices are set to contain far fewer defects per square centimetre than today's typical lateral GaN devices, spelling good news for device manufacturers, such as Infineon and ST Microelectronics.

As chief executive, Mikael Björk, says: "At present, [our semiconductors] have 100 million defects per square centimetre. But we believe that we can significantly improve the material quality and soon approach 10 million defects per square centimetre and thus surpass the competition."

➤ Mikael Björk, chief executive at Hexagem. [RISE/David Lagerlöf]

While Hexagem span out from Lund University back in 2015, its big break came in 2019 when it won just over €2 million in European Union funds to coordinate 'eleGaNt'. Here, the project goal was to develop its newly patented method of growing high-quality GaN layers on any substrate.

"The company had been carrying out a lot of university research, but this large EU grant meant we could really expand and hire more people." says Björk." I joined [shortly afterwards], which was basically the beginning of the pandemic, but we've been able to continue work with very few hiccups."

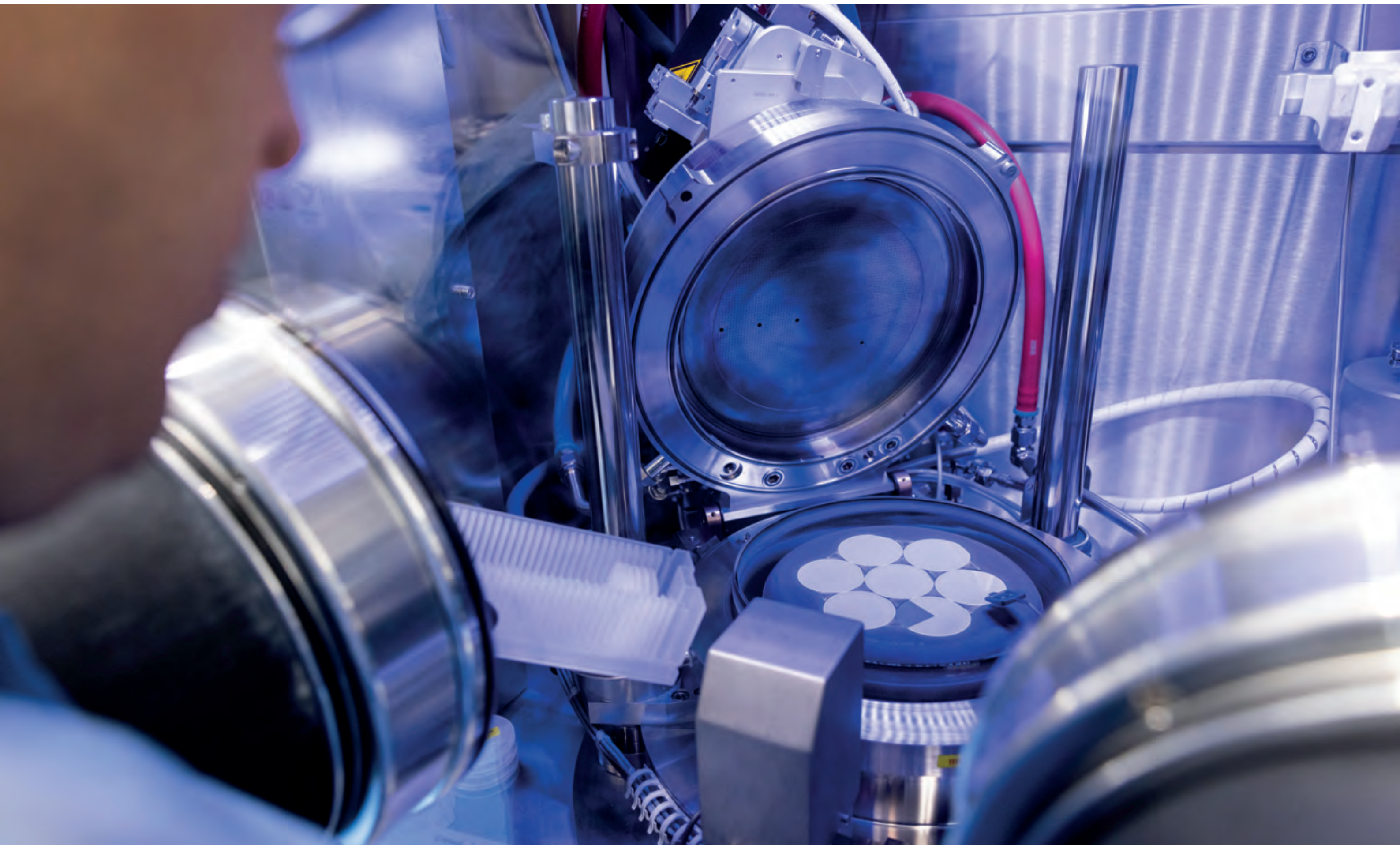
Key to this has been Hexagem's partnership with RISE Research Institutes of Sweden – a hothouse of GaN activity and home to the ProNano testbed for pilot and large-scale GaN device fabrication. Michael Salter is senior project manager at RISE, and as he puts it: "With ProNano we are building a pilot manufacturing infrastructure to support startup companies, like Hexagem, by demonstrating and accelerating their technology to the market."

Key facilities include cleanrooms, an Aixtron MOCVD reactor as well as metrology, including scanning electron microscopy facilities. Critically, Hexagem has been honing its GaN-on-silicon processes here, using MOCVD to create nanowires that eventually form thin layers of GaN on the silicon wafer.

As part of the process, a silicon nitride buffer layer is deposited onto the silicon wafer, which is then patterned with arrays of holes ready for selective epi-growth of the dislocation-free GaN nanowires. Once the nanowires are grown, sidewall epi-growth then takes place to widen the nanowires until these almost impinge on each other, giving a coalesced GaN layer.

"We're 'reshuffling' the material via epitaxial growth to fill the voids and give us this planar film," says Björk. "If you do this properly, you get very few dislocations."

Excitingly, the Hexagem chief executive officer reckons he and colleagues will grow layers as thick as 10 microns on silicon wafers this year, which is sufficient for the fabrication of the high-voltage vertical GaN devices that many in industry have been chasing for some time.



“We also think we’ll be able to use thinner and lower quality buffer layers to grow our wires on top – this will also save costs,” he adds.

GaN with a difference

Vertical GaN devices are not new. Thanks to the promise of extremely efficient devices that can switch at higher frequencies than conventional lateral devices and operate at very high voltages, myriad researchers have been developing vertical GaN semiconductors with a handful of businesses racing to get the technology to market. US-based NexGen Power Systems, for one, is growing low defect-density epi-layers onto bulk GaN substrates.

However, Björk believes that Hexagem’s approach is unique. “We are working with silicon substrates in combination with the unique nanowire coalescence – I doubt anyone else is doing this,” he highlights.

“Of course, we use lithography and patterning that isn’t standard in epitaxy but cost-wise we will compensate by using those less thick buffer layers on the silicon,” he says. “This is not a cost-play game for us – it’s about quality... and once we get to a larger wafer size we could be even cheaper, although this remains to be seen.”

Hexagem has been working with 50 mm wafers, but trials on 150 mm wafers are currently underway.

According to Björk, the company is also in discussions with several ‘big industrial players’ on scaling the technology. Indeed, the company has links with Infineon and Bosch through other EU-funded projects, UltimateGaN and YESvGaN.

“Commercial scale today is 150 millimetre but we also want to go for 200 millimetre wafers,” says Björk. “It’s still a couple of years away but we’re really pushing for the current 150 millimetre demonstration right now... Thanks to our unique strain compensation methods we think we can enable at least 10 micron-thick layers on these larger wafer sizes, and this could take us to 1200 volt vertical devices.”

Looking forward, Björk says Hexagem has no plans to build production facilities, but intends to licence its technology to industry heavyweights. He expects power electronics markets, including electric vehicles, will be the first stop for his GaN-on-silicon wafers, but is also interested in fabricating materials for RF and optoelectronics applications. And ever-thicker layers are also on the horizon.

“We’ll keep on improving quality and enabling thicker layers,” he says. “We can use our technology to also grow on silicon carbide wafers and sapphire wafers but there could be opportunities to transfer layers to, say, a metal contact or other substrates – there are a lot of interesting things to look at.”

➤ MOCVD at ProNano. [RISE/ David Lagerlöf]

Optimising gallium oxide growth

How do you produce great gallium oxide power devices? It's a combination of excellent reactor design, ideal precursors and dopants, a partner material for forming heterostructures, and good dielectrics and contacts.

BY FIKADU ALEMA, AARON FINE AND ANDREI OSINSKY FROM AGNITRON, ARKKA BHATTACHARYYA FROM THE UNIVERSITY OF UTAH AND SRIRAM KRISHNAMOORTHY FROM UCSB

➤ Above Dual module systems, featuring a vacuum transfer, vastly expand the number of material systems that can be grown without breaking vacuum.

THE GLOBAL CONSUMPTION of electricity, the most vital of all our energy sources, is sure to rise over the coming decades. So, in order to save the planet, it is critical to generate more electricity from renewables, and use this precious resource as efficiently as possible.

Efforts are already underway to trim the losses associated with transmitting electricity and its conversion from one form to another, such as from AC to DC. Savings are also coming from the increased adoption of wide bandgap devices, made from SiC and GaN. It's certainly a step in the right direction, but even better results are possible by making power electronic devices out of an even wider bandgap material, β-Ga_2O_3. Compared with that pair of middleweights, it has a higher critical electric field and, at the system level, promises improvements to size, weight and power. What's more, sizeable single crystals can be grown from the melt, enabling manufacture of devices on large native substrates that are cheap to produce – the same can't be said for GaN and SiC.

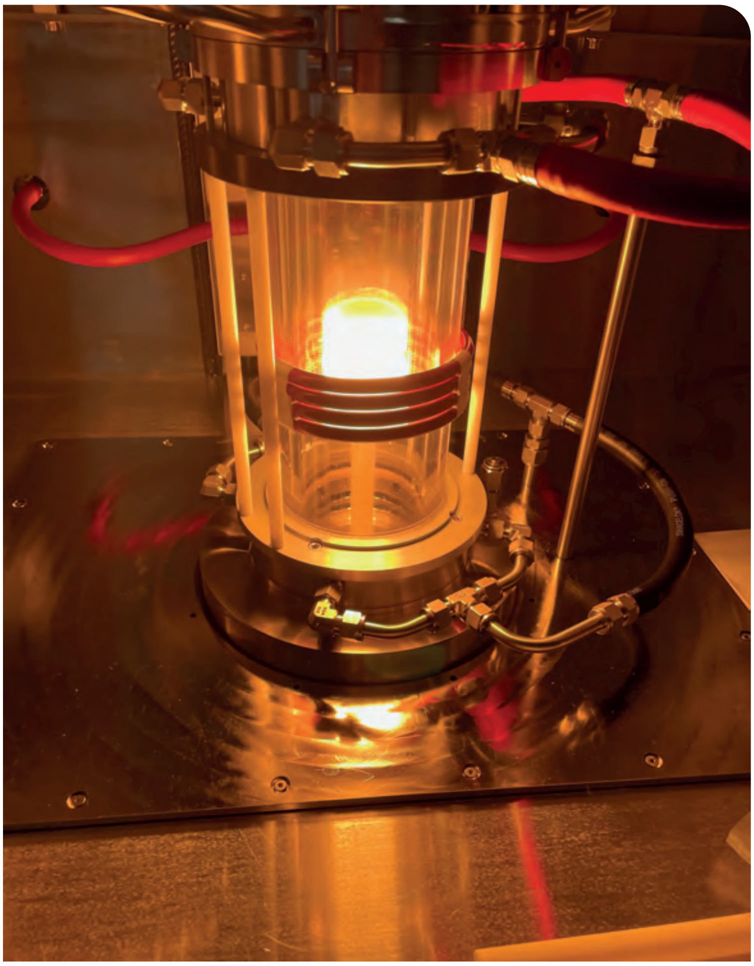
One big decision facing every developer of Ga_2O_3 power devices is which epitaxial process to employ. Films of β-Ga_2O_3 have been produced by MBE, HVPE and MOCVD, but there are strong arguments to suggest that the latter is the best growth technology for this oxide. For example, Ga_2O_3 grown by MOCVD has the highest low-temperature mobility – it is eight times higher than that for samples produced by MBE, and four times that for material made by HVPE (see Figure 1). It is also worth noting that the purity of epitaxial β-Ga_2O_3 films grown by MOCVD is higher than state-of-the-art values for 4H-SiC and GaN materials, which have been studied and refined for decades.

Additional attributes of MOCVD are that it is capable of producing high-quality, uniform epitaxial films with controllable doping levels at growth rates varying from just 0.1 μm/hr to as much as 10 μm/hr. Controlling the growth rate and the doping level makes MOCVD suitable for producing lateral and vertical devices, both geometries of interest for developers of power devices.

Even though Ga_2O_3 is still in its infancy, there is no need for companies or university groups that are keen to develop and refine Ga_2O_3 power devices to build their own reactors. Commercial tools are available, including those provided by those of us at Agnitron Technology of Chanhassen, MN. Since 2016 we have been actively developing MOCVD reactors to grow high-purity Ga_2O_3 and its related alloys for R&D and commercial applications. Over that time we have built and sold more than ten MOCVD reactors worldwide that are suitable for growing Ga_2O_3.

Our reactors have already produced record-breaking results, as confirmed at our internal R&D laboratory at Agnitron, and also by a number of our customers. Back in 2019, a collaboration between those of us at Agnitron and James Speck's group at the University of California, Santa Barbara (UCSB), unveiled a record-breaking room-temperature electron mobility of 176 $cm^2 V^{-1} s^{-1}$ for unintentionally doped β-Ga_2O_3, grown using our Agilis 100 reactor. Since then, driven by remarkable improvements, both internally and by our customers, even higher mobilities have been reported. They include values for room-temperature electron mobilities from 140 $cm^2 V^{-1} s^{-1}$ to nearly 200 $cm^2 V^{-1} s^{-1}$, the theoretical limit for Ga_2O_3, by Agnitron, Krishnamoorthy's group at the University of Utah (now at UCSB), and Zhao's group at the Ohio State University (OSU) – both are using Agnitron's Agilis 100 reactors (see table 1 for an overview of impressive results for mobility, both at room temperature and cryogenic temperatures).

The close working relationship between our team at Agnitron and a number of world-class researchers has supported the development of our growth reactors and processes. Operating in this manner, we have assembled a great deal of expertise associated with the growth of gallium oxide. We will now share this with you, offering our insights into the choices for the sources of gallium and oxygen, how best to dope this material, how to form a superlattice, and how to add dielectrics and contact materials. After covering all of this, we shall finish by detailing the merits of particular designs with Agnitron's MOCVD portfolio.



➤ The Agnitron Agilis 100 is a single-wafer tool. Using induction heating, wafer carrier temperatures can reach up to 1,700 °C.

Which gallium precursor?

Growers of epitaxial β-Ga_2O_3 films have two forms of gallium precursor to choose between: the more common tri-methyl-gallium (TMGa), and the variant tri-ethyl-gallium (TEGa). Having the upper hand in many regards is TMGa. This precursor has greater availability, thanks to its widespread use for growing various GaN-based and GaAs-based commercial devices; it is relatively low in cost; and it enables fast growth rates.

Using a close-injection showerhead reactor, we have realised a growth rate of around 10 µm/hr. Such a high growth rate shortens the time it takes to form epistructures with layers that are tens of microns thick, required to block voltages in excess of 10 kV.

The faster growth rate for TMGa, compared with TEGa, partly comes from a higher vapour pressure that enables the introduction of a higher concentration of gallium into the growth chamber. In addition, TMGa undergoes faster reaction kinetics. During pyrolysis, TMGa decomposes through a two-step mechanism, while for TEGa it is a three-step process. Shortening the reaction pathway allows

#	μ_{RT} (cm^2/Vs)	n_{RT} (cm-3)	μ_{LT} (cm^2/Vs)	N_A (cm^{-3})	MO/O_2 source	MOCVD Systems	Labs/where the work is done
1	~140	$1.5x10^{16}$	23,400 @32K	$2x10^{13}$	TMGa/O_2	Agilis 500/700	Agnitron/AFRL
2	~160	$5.0x10^{15}$	11,704 @46K	$7x10^{14}$	TEGa/O_2	Agilis 100	Agnitron/UCSB
3	~153	$2.4x10^{14}$	550 @100K	--	TEGa/N_2O	Agilis 100	Agnitron/UCSB
4	~194	$8.0x10^{15}$	9500 @45K	$7x10^{14}$	TEGa/O_2	Agilis 100	OSU
5	~176	$7.4x10^{15}$	3500 @54K	$5x10^{15}$	TEGa/O_2	Agilis 100	Agnitron/UCSB
6	~184	$2.5x10^{16}$	4984 @45K	$9x10^{14}$	TEGa/O_2	Agilis 100	OSU
7	~186	$2.0x10^{16}$	--	--	TEGa/O_2	Agilis 100	U of U

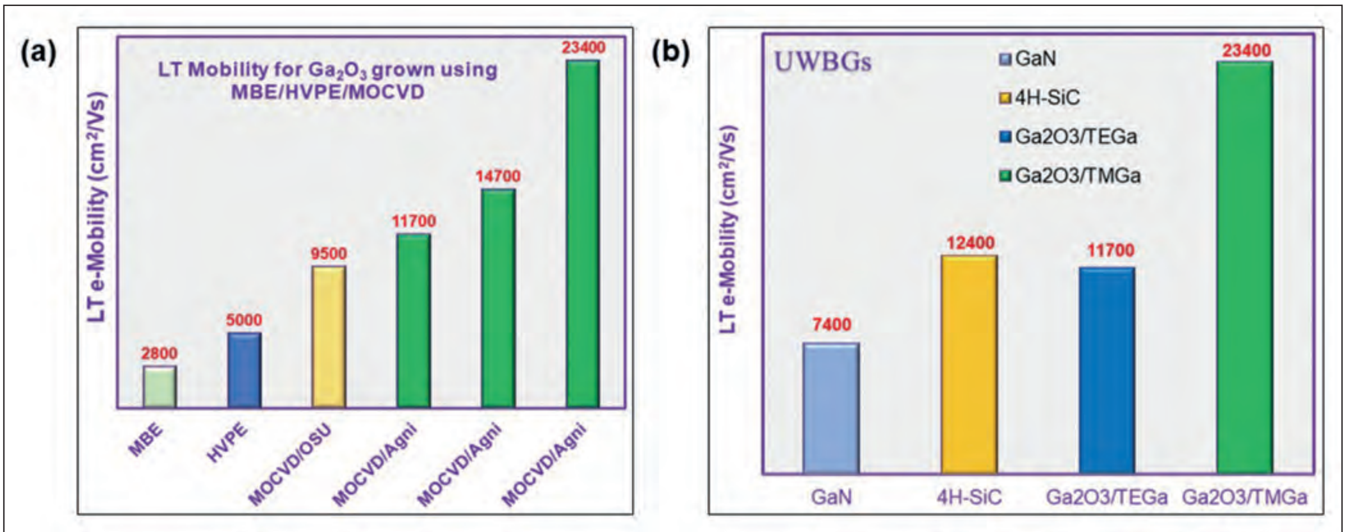
➤ Table I. Room-temperature (RT) and low-temperature (LT) Hall electron mobility data of β-Ga_2O_3 homoepitaxial films grown using various Agnitron MOCVD systems. TEGa/TMGa and pure oxygen/nitrous oxide (N_2O) were used as gallium and oxygen sources, respectively. Also, RT free-carrier concentration(n_{RT}) and accepter concertation (N_A), showing the purity of the material, are presented. The table summarizes data reported both by Agnitron Technology and its customers.

TMGa to react faster with the oxidizing gasses, ensuring a higher growth rate. Mobility is also better with TMGa. According to our in-house study, low-temperature mobility for epitaxial β-Ga_2O_3 grown with the TMGa precursor is around 18,000 $cm^2 V^{-1} s^{-1}$ at 46K, rising to 23,400 $cm^2 V^{-1} s^{-1}$ at 32 K, compared with 11,700 $cm^2 V^{-1} s^{-1}$ at 46K for an epitaxial film grown using TEGa. This has led us to conclude that compared with TEGa, TMGa produces a higher purity film.

There are concerns with TMGa, related to carbon incorporation. How carbon behaves in Ga_2O_3 is debatable, but it is predicted to act as a deep donor state, with some research showing that it takes the form of a positively charged shallow donor. Preventing carbon from incorporating into Ga_2O_3 is not easy, given its presence in precursors. However, for TMGa, carbon incorporation can be enormous, due to the formation of highly reactive methyl radicals during the pyrolysis process. In contrast, decomposition of TEGa produces a stable ethylene group, which exits the reactor, lowering carbon incorporation.
The extent of carbon incorporation into Ga_2O_3 films grown by TMGa depends on the growth conditions. While significant incorporation can occur in an oxygen-deficient environment, optimised conditions are able to mitigate carbon contamination and yield high purity films. And for unintentionally doped Ga_2O_3, silicon impurity concentrations are ten times lower with TMGa than TEGa, explaining why film purity is better with the former precursor.

Nitrous oxide or oxygen?

When growing Ga_2O_3 films, one option for the oxygen source is nitrous oxide (N_2O). This gas can



➤ Figure 1. (a) A comparison of the best low-temperature (LT) mobilities for films grown by MBE, HVPE and MOCVD. The MOCVD films are grown using Agnitron's system at the Ohio State University (MOCVD/OSU), and Agnitron Technology (MOCVD/Agni). MOCVD films were grown using either TEGa or TMGa sources. (b) LT mobilities for TEGa/TMGa grown β-Ga_2O_3 films compared with the state-of-art LT mobilities for 4H-SiC and GaN. It should be noted that the MBE high mobility result was demonstrated in a two-dimensional electron gas (2DEG) β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ heterostructure.

also provide a nitrogen dopant, with variations in substrate temperature enabling nitrogen concentrations ranging from around 2×10^{19} cm^{-3} to a level undetectable by secondary-ion mass spectrometry. When incorporated in Ga_2O_3, nitrogen acts as a deep acceptor, producing semi-insulating material. Compared with films grown with an oxygen source, the free carrier concentration is much lower, an asset for making high-voltage vertical power devices.

If film purity is paramount, it is better to use pure oxygen. Measurements at 100 K show that electron mobility is around six times higher for films grown with a pure oxygen source, rather than N_2O.

Forming heterostructures

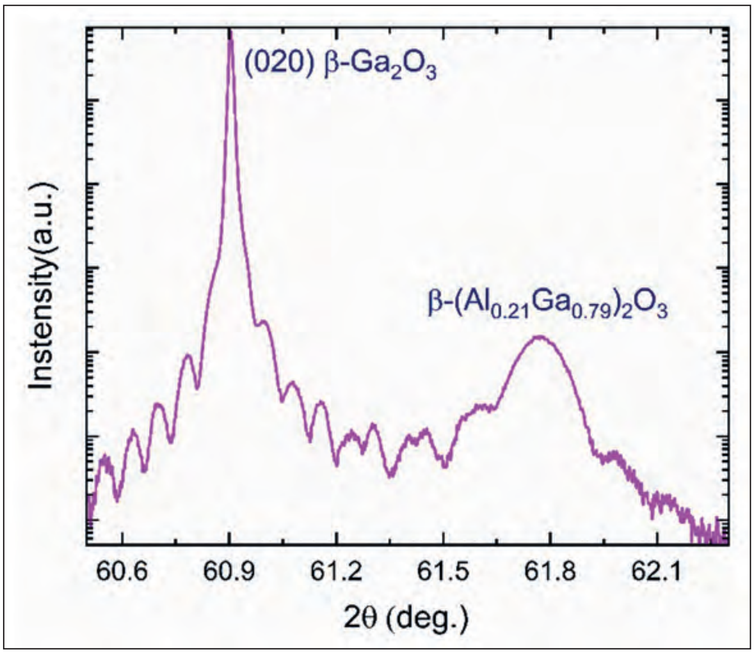
The most obvious partner for Ga_2O_3 for forming a high-quality heterostructure is $(AlGa)_2O_3$. Using single-wafer and multi-wafer MOCVD reactors, we have developed processes for growing high quality $(AlGa)_2O_3$ alloys. We have produced a high-quality, strained single-layer β-$(Al_{0.21}Ga_{0.79})_2O_3$/ Ga_2O_3 heterostructure using our Agilis 700 MOCVD reactor (see Figure 2 for an X-ray diffraction pattern), as well as a superlattice with abrupt interfaces (see Figure 3). These successes are an important milestone, because the $(AlGa)_2O_3/Ga_2O_3$ heterostructure is a critical building block for various device structures, including HEMTs and modulation-doped FETs (MODFETs).

The maximum aluminium content realised in the $(AlGa)_2O_3$ film depends on the orientation of the substrate. It is challenging to realise an aluminium content of more than 25 percent on (010) oriented β-Ga_2O_3, while this is relatively easy to reach without phase segregation with (-201) and (100) orientations. Zhao's group at OSU have reported phase pure β-$(AlGa)_2O_3$ alloys with an aluminium content of up to 52 percent on a (100) β-Ga_2O_3 substrate using one of our reactors, and Krishnamoorthy's group have realized MODFET structures using $(AlGa)_2O_3$ layers. Note that with other phases, such as α-$(AlGa)_2O_3$, phase pure alloys can be grown with aluminium contents from 0 percent to 100 percent.

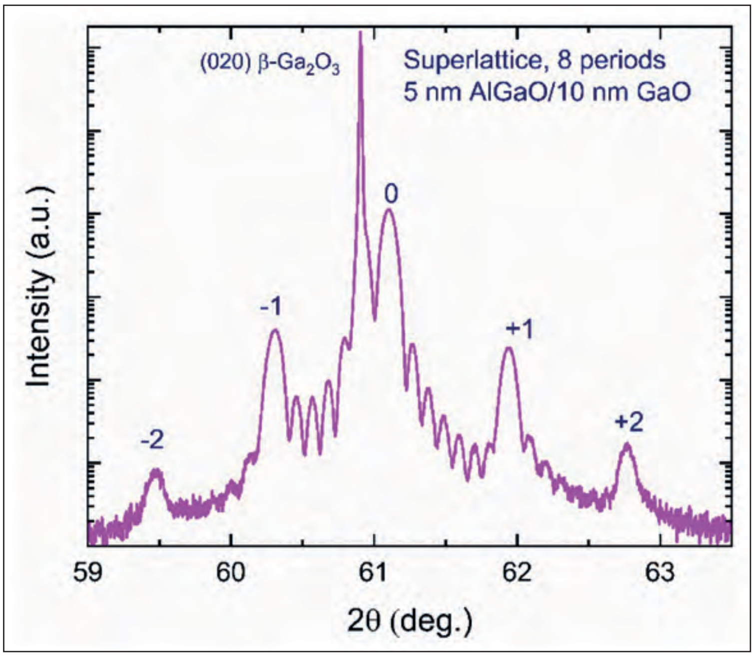
Delivering doping

Thanks to the availability of suitable precursors in either a gas or metalorganic precursor form, silicon, germanium and tin can all be used to dope Ga_2O_3. However, silicon is favoured, due to its efficient incorporation and activation – and unlike germanium and tin, it does not have a memory effect in the reactor.

Using TEGa and TMGa, our studies have shown that with silicon as the dopant *n*-type conductivities can range from 2×10^{14} cm^{-3} to 3.4×10^{20} cm^{-3}, compared with 2×10^{16} cm^{-3} to 2.6×10^{20} cm^{-3} for germanium (see Figure 4). As well as the more limited doping range, germanium is impeded by a strong temperature dependence in stability in the film. When deep acceptor doping is needed, options include magnesium, iron and nitrogen.



➤ Figure 2. X-ray diffraction ω-2θ scan profile for β-$(Al_{0.21}Ga_{0.79})_2O_3$/ Ga_2O_3 grown on a 2 inch (010) β-Ga_2O_3 Synoptics substrate by an Agilis 700 MOCVD reactor. The β-$(Al_{0.21}Ga_{0.79})_2O_3/Ga_2O_3$ layer is 70 nm thick (XRD measurement was done at UCSB by Takeki Itoh from James Speck's group).



➤ Figure 3. X-ray diffraction (XRD) ω-2θ scan profile for aβ-$(Al_{0.21}Ga_{0.79})_2O_3/Ga_2O_3$ superlattice (SL) grown on a 2-inch (010) β-Ga_2O_3 Synoptics substrate using an Agilis 700 MOCVD reactor. The SL has eight periods and the thickness for the β-$(Al_{0.21}Ga_{0.79})_2O_3$ barrier and Ga_2O_3 well are 5 nm and 10 nm, respectively. Observation of Pendellösung fringes in the XRD scan indicates the growth of a coherent and smooth SL using commercial-scale MOCVD reactors (XRD measurement was done at UCSB by Takeki Itoh from James Speck's group).

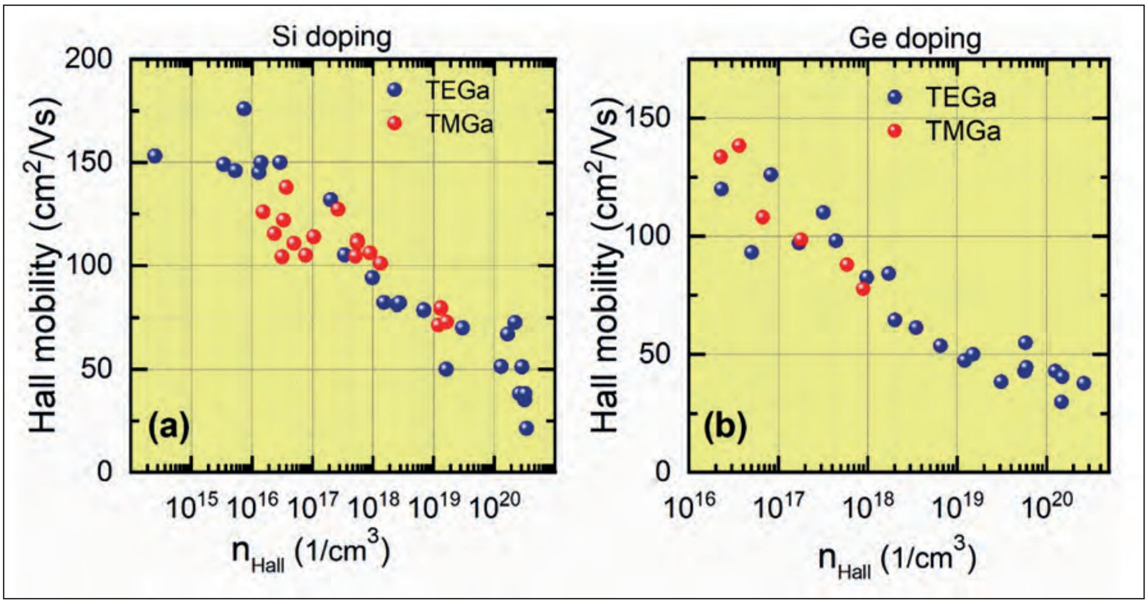


Figure 4. Electron mobility versus free-carrier concentration for silicon (a) or germanium (b) doped β-Ga_2O_3 epitaxial films grown by MOCVD using TEGa and TMGa precursors.

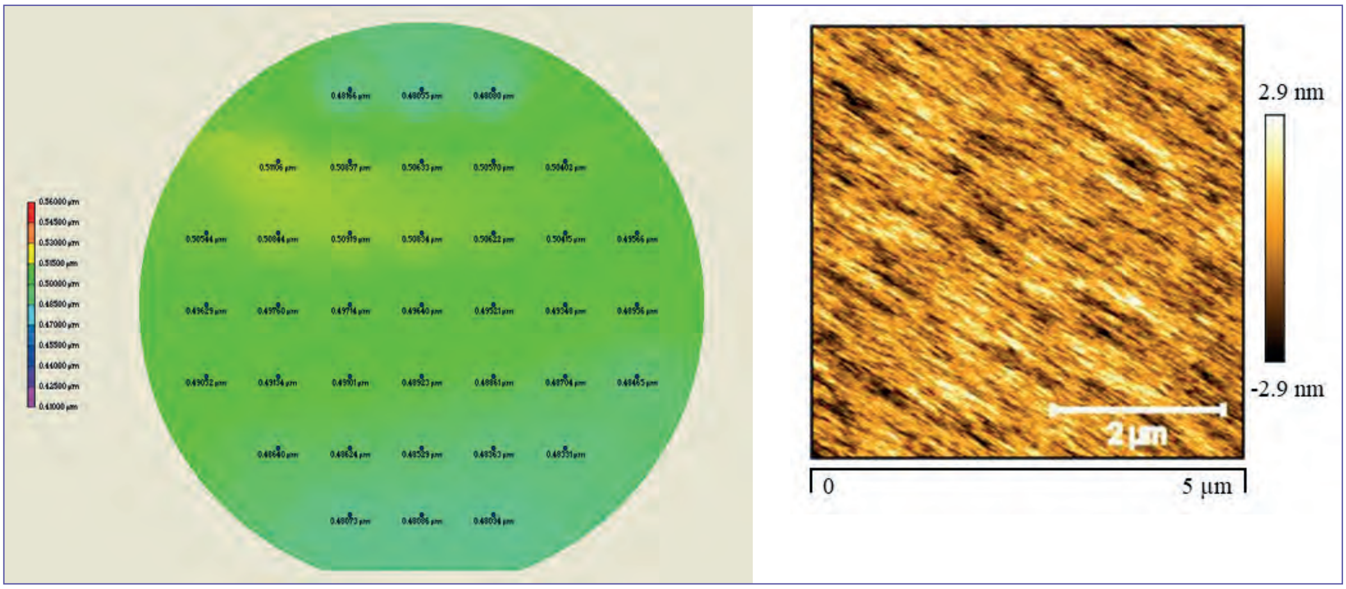
Doping is even possible at low substrate temperatures, such as 600 °C. Work by those of us at Agnitron has demonstrated silicon doping in excess of 3 x 10^{20} cm^{-3}, along with a record conductivity of more than 2500 S/cm. Use of a low temperature ensures a low thermal budget and permits both a masked contact regrowth process and *in-situ* dielectric deposition. Both have been used during device fabrication.

Ohmic contacts and dielectrics

Leveraging low-temperature epitaxy, Krishnamoorthy's group has demonstrated MOCVD-regrown ohmic contacts when fabricating β-Ga_2O_3 MESFETs formed entirely by MOCVD. These transistors offer improved on-state performance, with an on current of 130 mA/mm and an on-off ratio of over 10^{10}. The silicon-doped β-Ga_2O_3 regrown layers deliver exceptional performance, with a record low sheet resistance of 73 Ω/sq, and a record low contact resistance for the metal/β-Ga_2O_3 junction of just 8.3 × 10^{-7} Ω cm^2. When collaborating with those of us at Agnitron, an even lower contact resistance of just 1 x 10^{-7} Ω cm^2 has been realised, very encouraging for high frequency devices, which require low parasitic resistances.

Until recently, one weakness of the Ga_2O_3 device has been its inability to combine a high lateral figure of merit with kilovolt breakdown voltages.

The multi-wafer Agilis GOX300 has a wafer loading capacity of five-4-inch wafers. This tool, designed for high-volume production, delivers repeatable, reproducible growth processes and ensures that epiwafers have excellent deposition uniformity and minimal particle count. Wafer carriers can be loaded into the system at any given time, to enable efficient, steady-state campaign operations involving up to four wafer carriers.



➤ Figure 5. Measurements of the layer thickness and surface roughness highlight the uniformity and smoothness of the Ga_2O_3 epilayers. There is a uniformity of 3 percent (1σ) and RMS roughness of 0.8 nm.

Making devices out of structures grown at Agnitron, Krishnamoorthy's group in collaboration with us at Agnitron, overcame this challenge, reporting record-breaking results for lateral Ga_2O_3 MESFETs featuring a novel field plate design and produced with an improved contact regrowth process, developed at Agnitron. Measurements on a device with a gate-drain spacing of 10 µm revealed a record-high lateral figure of merit of 355 MW cm^{-2}, a breakdown voltage of around 2.5 kV, and an average electric field at breakdown of about 2.5 MV/cm.

More recently, this group has realised new highs, with breakdown voltages in excess of 4 kV, for devices made of Agnitron structures with lateral figures of merit exceeding 100 MW cm^{-2} (results were measured in Uttam Singisetti's group at the State University of New York at Buffalo). Such results showcase the huge potential of these devices for serving in low-to-medium-voltage power systems, which are deployed in power supplies, electric automation and vehicles, power transmissions, and electrical grid integration.

One of the tremendous advantages of an oxide MOCVD system is that, without having to break vacuum, it can be employed after the growth of the channel to deposit dielectrics that provide gate oxides. Krishnamoorthy's group have adopted this approach, carrying out the entire process *in-situ* process – this eliminates the need for surface treatment and minimises the threat of contamination between epitaxial growth and dielectric deposition.

Measurements reveal an interface state density of around just 6.4 × 10^{11} cm^{-2} for the Al_2O_3/ Ga_2O_3 interface produced by *in-situ* growth, and breakdown fields of up to 5.8 MV/cm, a figure comparable to Al_2O_3 dielectrics grown by atomic layer deposition. Such results hold much promise for the future of β-Ga_2O_3-based high-performance MOSFETs.

Agilis MOCVD systems

Thanks to progress of Ga_2O_3 on many fronts – the ability to grow electronic-grade epitaxial films over a wide temperature window, the highly tuneable growth rates and doping levels, and the growth of alloyed single crystals and *in-situ* dielectrics – we can expect an increase in the research, development and prototype production of devices in the coming years. To support such efforts, we are offering four families of MOCVD reactor designed for the growth of β-Ga_2O_3: the Agilis 100, 500 and 700; and the GOX300 series.

Of these, the Agilis 100 is a single-wafer reactor, accommodating one substrate up to 3 inches in diameter; the 500 and 700 house up to five and seven 2-inch wafers, respectively; and the GOX300 can cater for up to five 4-inch diameter wafers. All systems come with our record-setting recipes/ processes and decades of stress-free, low-cost future equipment support and maintenance. Every model can be configured to match individual requirements, budget, and facility constraints.

The Agilis 100, an ideal research tool, has recently been updated to accommodate larger wafers and a faster rotation speed of up to 1,500 rpm. It can be configured with our brand new close-injection showerhead gas distribution system, or it can employ a remote-injection showerhead. Using induction heating, wafer carrier temperatures can reach up to 1,700 °C.

The multi-wafer Agilis 500 and 700, which share the same compact footprint of the 100, are also capable of wafer rotation at up to 1,500 rpm. Both use a close-injection showerhead to minimize the gas phase reaction of precursors. Resistive heating is employed, with the option of selecting multi-zone heaters with active temperature, drawing on measurements from either emissivity compensated pyrometry or thermocouples. Uniformity is excellent (see Figure 5), with epilayer root-mean-square surface roughness between 0.5-0.8 nm, which is within the range needed for lateral channel device structures.

If versatility is paramount, we recommend our dual-module systems, formed by combining two separate Agilis systems via a vacuum transfer mechanism. As well as growing β-Ga_2O_3, these vertical reactor geometry systems can deposit other materials, including III-nitrides, SiC, MgZnO, phosphorene, 2D BN, and the family of transition metal dichalcogenides, such as MoS_2, $MoSe_2$, WS_2 and WSe. Such a wide range of materials is easy to realise, thanks to the opportunity to fit up to 12 metal-organic sources, which can be switched within minutes.

Large-scale production

In response to the growing market demand, those of us at Agnitron have started offering multi-wafer Agilis reactors. The latest addition to this range, the multi-wafer Agilis GOX300 with a wafer loading capacity of five-4-inch wafers, also deliver repeatable, reproducible growth processes and ensures that epiwafers have excellent deposition uniformity and minimal particle count.

With this system, wafer carriers can be loaded into the system at any given time to enable efficient, steady-state campaign operations involving up to four wafer carriers. Transfer is provided with an industry-standard automated robotic arm operating in a high-vacuum transfer chamber. Dwell stations are used for loading and unloading platters of wafers.

The Agilis GOX300 features our proprietary, highly developed rotating disc reactor (RDR) vertical growth chamber. In this chamber, flow dynamics repress recirculation, leaving sensitive areas above and around the wafer carrier clean and free of deposition. The RDR is a proven success, having already been implemented in our A300 series that's designed for growing arsenides and phosphides.

Thanks to the launch of our Agilis GOX300, we have strengthened our suite of tools for the development and production of gallium oxide devices. Supported by our reactors and knowhow, pioneers of this oxide can take power electronics into a new era, building on the benefits wrought by GaN and SiC, and driving down losses on electrical systems to unprecedented levels.

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Enhancing energy storage with thermophotovoltaics

Heating carbon blocks with the grid's spare capacity and recovering this energy with efficient thermophotovoltaics offers a welcome solution to energy storage

BY RICHARD STEVENSON, EDITOR, COMPOUND SEMICONDUCTOR

A LITTLE OVER A DECADE AGO it seemed that III-Vs were destined to play a major role in greening the grid. Systems featuring highly efficient compound semiconductor cells, harvesting concentrated sunlight from dawn to dusk, were promising to trim the cost of solar energy produced in sunny climes, and in turn drive up the deployment of renewable sources. But a double whammy of a global credit crunch and tumbling prices for silicon panels left this nascent industry dead in the water and prevented a really neat solution for energy generation from having the impact it deserved.

But maybe, just maybe, III-V devices that convert radiation into electricity have not been banished to the wilderness for ever and can still make a major contribution to the energy industry. By stretching the absorption sweet spot to longer wavelengths, there is now a renewed hope that III-V cells can help to curb the burning of fossil fuels. How? By helping with the vexing challenge of energy storage. The idea is to build systems that draw on excess electricity within the grid to heat carbon blocks to well over 1000 °C, before III-V thermophotovoltaics convert this thermal energy back into electricity as the thermal store cools. This is the vision of Antora Energy, a west-coast start-up that boasts record-breaking thermophotovoltaic cells and has plans to demonstrate its technology at significant scale later this year.

The origins of Antora can be traced back to 2017 when two of its co-founders, Justin Briggs and Andrew Ponec, started discussing what they would do after they left at Stanford University. Both were driven by a strong desire to tackle climate change, identifying energy storage as the biggest problem that remains.

"We started from a totally technology agnostic standpoint," says Briggs, now COO of Antora. "How do you store cheap solar and wind energy for low cost, so that you can beat fossil fuels on raw economics?"

Seeking an answer, this duo explored many options. While hydro-electric schemes have much to offer, the terrain is unsuitable in many locations. What's needed is a universal approach. In that context, does hydrogen offer the best solution? Or some kind of thermal system? Or maybe a mechanical storage contraption; a kinetic storage system based on the likes of flywheels; or an invention involving compressed air?

As they mulled over all these options, Briggs and Ponec came into contact with their third co-founder, David Bierman, an entrepreneur with a PhD from MIT. At the time all three were participating in the Activate Fellowship for hardtech entrepreneurs.

Briggs, Ponec and Bierman hit it off from the get go. As well as sharing a strong desire to tackle climate change through energy storage, they held very similar views on how a company should go about its business. Their philosophy went further than simply wanting to put together a wonderful, strong team to decarbonise the world with a green energy storage system. They also wanted to create a positive, supportive company culture, where everyone connected through joy and laughter. "We're solving a really tough problem," says Briggs. "Climate change is extremely hard and sad, and when you're working on a big, hard problem, sometimes you need to be uplifted by the people around you."

Another attribute held by these entrepreneurs is an open, humble approach. They know that they don't have all the answers, and accept that it's not always clear what's the best technology and the optimum business model. So they solicit input from experts, collaborators and partners.

A lasting legacy

When this triumvirate were chewing over the options for storing energy, they drew on the knowledge of Ponec, who had previous experience in starting a company. During his degree, Ponec took time out to start a company, Dragonfly Systems, subsequently bought by SunPower. During the acquisition, Ponec got to know SunPower founder Richard Swanson, a trailblazer of thermophotovoltaics. Swanson's legacy includes smashing the record for thermophotovoltaic conversion efficiency – his efforts in the late 1970s and early 1980s propelled efficiency to nearly 30 percent, a record that stood for four decades.

"We thought, if you take all of the advances today that have been made in solar PV, from what it was then to what it is now – decades of research and billions of dollars of development funds – and apply those advances to thermophotovoltaics, what sort of efficiencies could we be hitting?"

Applying this reasoning, the founders decided to switch from silicon, the material used for the thermophotovoltaics pioneered by Swanson, to III-Vs. "Going to those fancier materials, you're paying an upfront cost, but you're reaping the benefits in efficiency and power density," argues Briggs.

At first glance, this line of thinking may raise a few eyebrows, as surely the far, far higher chip costs of the III-Vs overshadow their superior performance. But that neglects that at the temperatures employed for the thermal store, infrared radiation is so intense that it is comparable to solar concentration factors of several hundred. So, like concentrating PV, higher chip costs of the III-Vs are acceptable. What's more, this time they come without additional system costs associated with focusing the radiation and aligning cells to maximise the harvest.

➤ Figure 1: Photograph of one of Antora's prototype thermal storage systems. With a capacity of 500 kWh, this system has been used to demonstrate the core functionality of the technology.

Selecting the best substance for this thermal store has been relatively easy, according to Briggs. He views carbon as a "superhero" material, combining an incredibly high specific heat capacity with a high thermal shock resistance, thermal and mechanical durability and robustness, low cost and a very wide operating range. Note that carbon doesn't melt under ambient temperature, but sublimes above 3000 °C, well beyond what is practical for an efficient thermal stores. For example, while there are many standard insulation materials at 1500 °C, choice is incredibly limited at 3000 °C.

Teaming up with engineers at NREL, primarily Myles Steiner and Dan Friedman, Briggs and his co-workers broke the record for thermophotovoltaics. At the 47th IEEE Photovoltaic Specialists Conference, held in Calgary, Canada, in summer 2020, they announced values of 31 percent and 30 percent for GaAs and InGaAs cells that were harvesting energy from thermal stores at 2330 °C and 1300 °C, respectively. Since then, those at Antora have continued to advance their devices, while moving on to partner with a commercial foundry. The best cells now hit an efficiency of around 45 percent.

While the design of these devices draws heavily on that of III-V solar cells, there are key differences. Aside from the obvious shift in absorption edge, arguably the biggest change is in the back reflector. In a solar cell, photons below the cell's bandgap are not absorbed and this energy is simply lost. But in a high-performance thermophotovoltaic, these photons can be reflected back towards the thermal store, enbaling their energy to be recuperated.

"You're basically eliminating a major loss mechanism," explains Briggs. "You're preventing low-energy radiation from being lost, and instead keeping it in the system." The low energy photons arriving back at the thermal store are converted to phonons, topping up the energy held by the carbon blocks.

Due to the intense radiation produced by the high-temperature thermal store, the thermophotovoltaics have to handle very high current densities. This threatens substantial ohmic losses. To combat this, the team at Antora have worked hard to drive down the series resistance within their cells.

Further gains in performance have come from increasing the crystal quality of the material. This ensures a very long radiative lifetime, and a high external radiative efficiency, leading to a high conversion efficiency for the devices.

Thermodynamic considerations indicate that the cells need to be cooled to maximise efficiency. As these devices are not positioned really close to the heated carbon, essentially nearly all the heat transfer is via radiation; and in that geometry, the intensity of the radiation impinging on the cell does not depending dramatically on the separation distance. To optimise performance at the system level, the cells are cooled to below 100 °C, with the exact temperature balancing the benefit of higher conversion efficiencies against the extent of energy expenditure required for cooling.

Unlike concentrating photovoltaics, efficiency at the system level is very close to that of the cells. Resistive heating of carbon blocks is almost 100 percent efficient, and electrical losses that come from stepping up and down voltages are minimal, along with those associated with ancillary loads. Meanwhile, energy leakage through the thermal insulation is about 1 percent per day. “Of that whole chain of things, thermophotovoltaic efficiency is by far the biggest penalty.”

Tremendous headroom

The good news is that the efficiency of these devices, while impressive, is still far from what is possible. Briggs believes that the team could reach efficiencies of 50 percent or more by: improving the device’s back reflector, driving down series resistance, and increasing crystal quality. While the efficiency for single-junction solar cells, defined by the Shockley-Quessier limit, is just shy of 34 percent, thermodynamic considerations suggest that the upper limit for a thermophotovoltaic is beyond 60 percent. And if a single-junction device is replaced with a multi-junction variant, even higher values are possible.

Although Briggs and colleagues have designed devices that could approach 60 percent efficiency, breaking records and securing well-deserved publicity for these achievements is not high on their agenda. Right now their energy is being directed at demonstrating a pilot system, built with cells that have been produced by a foundry and are sufficiently efficient to commercialise this technology.

To date, the team’s cells have a collective output power of 50 kW, enough for the first power unit of a modular system that will ultimately have an electrical energy storage capacity of 100 MWh, and an electrical power capacity of around 1 MW (see Figure 2 for details of what such a system might look like). Hopefully this customer-sited pilot will enable other potential customers to grasp the capability of Antora’s technology and place orders.

If the company’s technology takes off, and thermophotovoltaics start to be deployed throughout the world to help green grids via energy storage, this would be great news for the entire compound semiconductor industry, swelling volumes for makers of III-V substrates and semiconductor foundries.

“We’re fans of III-V opto-electronics in general,” says Briggs. “We think it’s just a cool technology. If things go well, we hope to be at the point where we’re a driver in that market.”

Let’s hope that happens. If it does, as well as greening the grid and the manufacturing sector, III-V devices will be offering an even better bang-per-buck in many industries, including communication, automotive and healthcare.

➤ Figure 2: Artist’s rendering of Antora’s first product, a thermal storage system with an electrical capacity of 100 MWh / 1 MW. The product stores thermal energy in carbon blocks above 1000°C. The thermal radiation from these blocks can be converted into electricity or industrial process heat. With this product, the Antora team is aiming to decarbonize the manufacturing sector–the largest emitter of greenhouse gases and one of the hardest-to-decarbonize industries on the planet–by providing zero-carbon heat and power on demand. Antora also aims to deploy energy storage products on the grid to enable deeper penetrations of solar and wind resources.

Funding from a variety of organisations has enabled Antora to pursue its vision of using excess energy from the grid to heat a solar store and recapture this energy through efficient thermophotovoltaics, in conjunction with the provision of a thermal discharge that provides heat for an industrial process. Initial investment for Antora’s venture came from the Stanford TomKat Centre for Sustainable Energy and the Activate Fellowship programme. Since then, support has come from a number of federal and state grants, including funding from The National Science Foundation, the California Energy Commission, the Advanced Manufacturing Office, and ARPA-E – as well as private venture investors.


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Audiophile amplification gains from GaN

Exceptional switching characteristics of GaN FETs underpin a new era in high-fidelity amplification

BY LEO AYZENSHTAT FROM ORCHARD AUDIO

FOR MORE THAN half a century lovers of hi-fidelity have argued over the best technology for making audio amplifiers. Sitting on one side of the divide are the valve aficionados, who claim that tubes are the key to providing an engaging, unfatiguing and rewarding listening experience. In the other camp are the fans of the transistor, who view this as by far the better option – one that delivers a realistic, powerful and faithful delivery of the recorded medium.

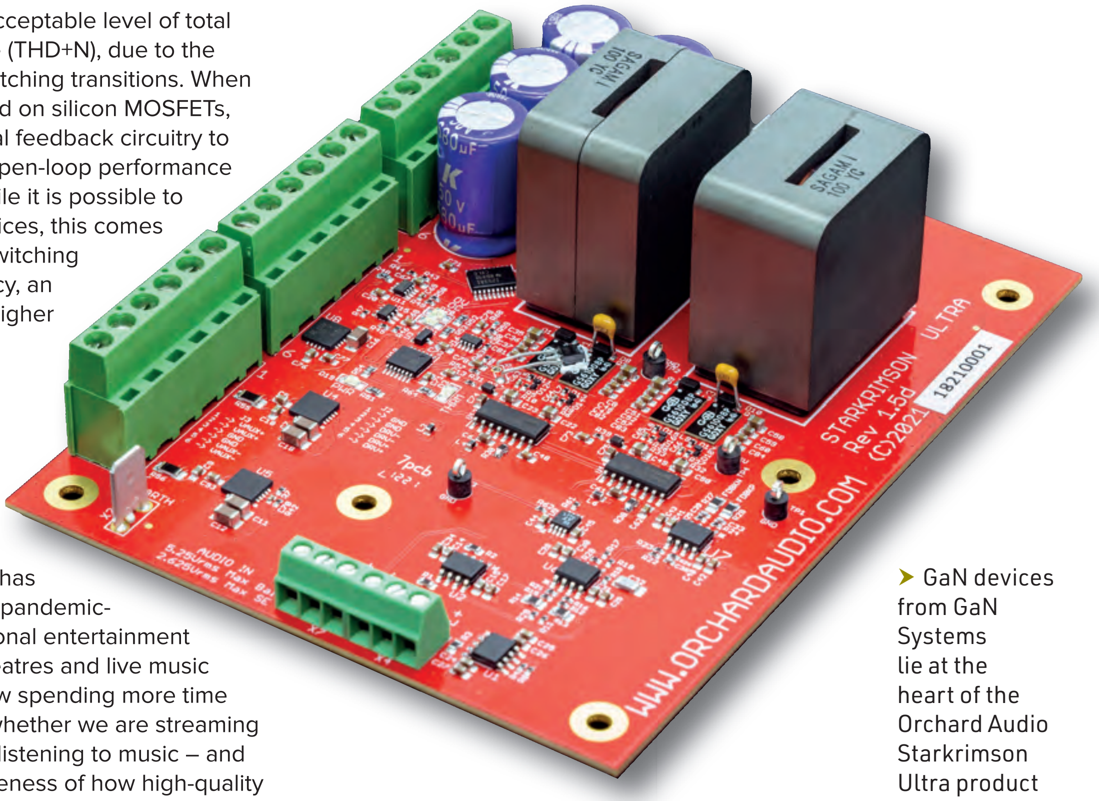
For those that prefer solid-state technology to valves, a decision now awaits. Do they hold on to their cherished amplifier that sports silicon transistors, or do they trade it in for a new breed, built around wide bandgap devices? It is not a difficult decision, because if they do invest in the future, they will reap many rewards.

The benefits are not limited to a better sound for the outlay, but extend to practical gains, such as a far smaller footprint and a higher efficiency that trims household bills.

Over the last decade or so, there has been an increase in sales of all forms of Class-D audio amplifier, which operate at high switching frequencies. With this mode of operation it is challenging to realize an acceptable level of total harmonic distortion + noise (THD+N), due to the need for faster, cleaner switching transitions. When class D amplifiers are based on silicon MOSFETs, they incorporate substantial feedback circuitry to compensate for the poor open-loop performance and subsequent noise. While it is possible to reduce this with larger devices, this comes at the expense of higher switching losses, diminished efficiency, an increase system size and higher material costs.

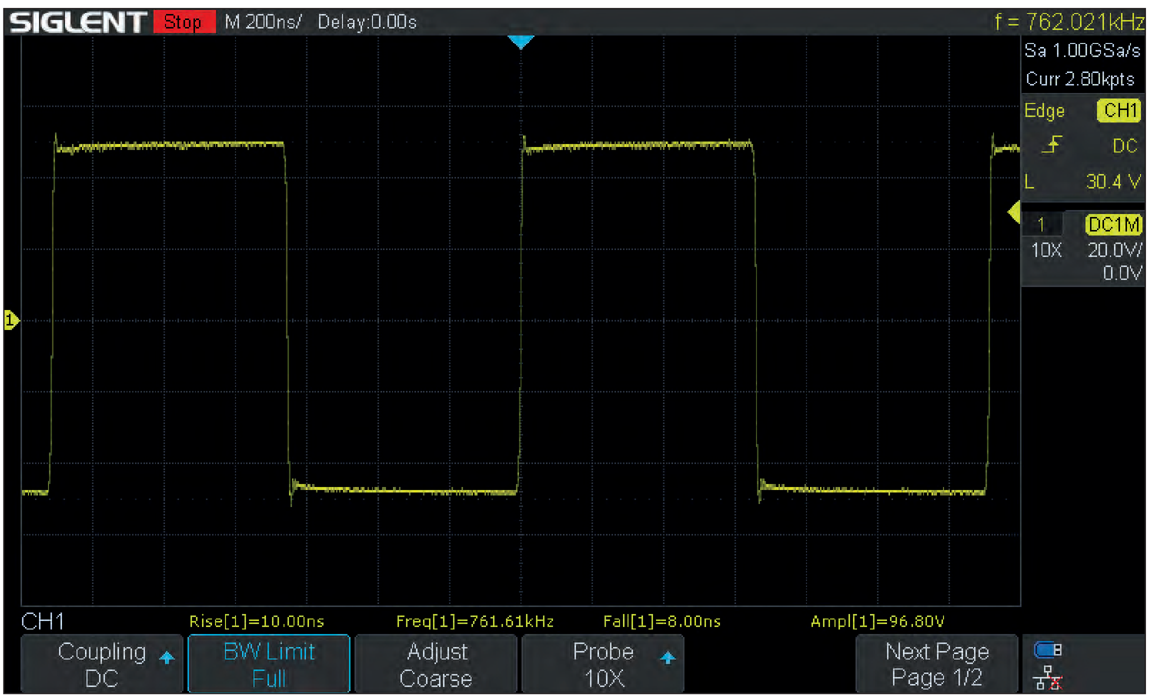
All these issues are not just of concern to high-end audiophiles, who will pay thousands and thousands of dollars for an amplifier. Over the last few years home audio has changed, partly due to the pandemic-driven shut-down of traditional entertainment sources, such as movie theatres and live music venues. Many of us are now spending more time with our audio systems – whether we are streaming movies, playing games, or listening to music – and this has heighten our awareness of how high-quality home audio systems can enhance our listening experience.

Market analysis supports this view. Those in the know are pointing out that demand for high-quality audio is fuelling the growth of the Class-D audio amplifier market, which is tipped to reach $4.92 billion by 2026. This class of amplifier is being deployed in ever more audio applications, including home theatres, high-power smart speakers, pro-touring amplifiers, portable speakers, automotive, marine, and power sports.



➤ GaN devices from GaN Systems lie at the heart of the Orchard Audio Starkrimson Ultra product range.

At Orchard Audio of Succasunna, NJ, we are playing our part in the audio revolution by launching a portfolio of products that feature amplification with GaN transistors. We have adopted these devices because they have exceptional switching speeds. Several benefits result from this attribute: very fast slew rates, which are much valued in a class D amplifier, because this narrows the gap to the ideal square wave (see Figure 1); incredibly precise timing, critical to realizing high-quality audio; and improved efficiency, with amplifier topologies being able to



➤ Figure 1. The Starkrimson Streamer Ultra operates with a very fast slew rate of around 10,000V/µS. This narrows the gap to the ideal square wave.

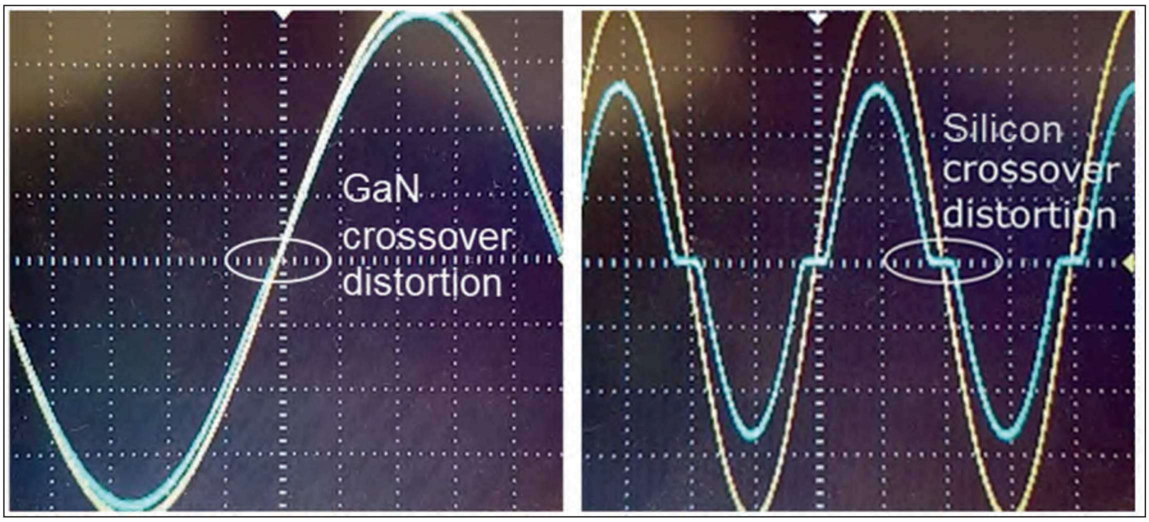


Figure 2. GaN devices result in a far lower crossover distortion than silicon incumbents.

operate with a much shorter dead time, an approach that leads to a much lower cross-over distortion (see Figure 2).

Another benefit of using GaN transistors is that it makes it much easier to design a circuit with no or very limited ringing. Minimising ringing is highly valued, because it eradicates EMI issues and prevents noise. By turning to GaN, our amplifiers combine decreased noise with less distortion, better transient response and a higher bandwidth.

But what does all this mean when it comes to sound quality, the most important metric of all? Well, quite a lot – our amps are renowned for their reduced harshness, cleaner highs, better transparency, and greater audio detail.

Like other electrical units, such as power supplies, using GaN rather than silicon also delivers benefits at the system level. There is a trimming of the cost of other system components, including capacitors, heat sinks, and inductors.

As well as a reduction in the total bill for these components, they are smaller and lighter. Thanks to this, amplifiers built with GaN can be around one-quarter the size of silicon equivalents.

Figure 3. The Starkrimson Streamer Ultra combines a digital-to-analogue converter, an amplifier and a streamer inside an easy-to-use enclosure.

That's a big selling point for potential customers with small homes, and for those that don't want a stack of large audiophile units in their living room.

Why GaN trumps SiC

You may be wondering why we are making our amplifiers with GaN rather than SiC, the other commercialised wide bandgap semiconductor. Well, there are several reasons – some are related to audio, and other due to cost and practicality.

One of the downsides of SiC is that it is not that good at switching at high frequencies. What's more, it's hard to drive this class of device at a high frequency. In comparison, that's not an issue with GaN, thanks to its much simpler, lower-voltage gate drive. Additional attributes of GaN are its low gate charge, zero reverse recovery and flat output capacitance; all of which yield a high-quality switching performance.

Where SiC has enjoyed most of its success is at high voltages, typically 1200 V. Audio amplifiers do not require such high voltages – and for the mid- and low-range voltages where they do operate, GaN has far lower switching losses. For example, at 650 V, switching losses for GaN are at least three times lower than those for SiC.

Even if SiC devices were as good on paper as those made from GaN, there are plenty of reasons to shy away from them. SiC devices are more pricey, and compared with those made from GaN there are limitations associated with both their supply and the supply chain. Amplifiers built with GaN can also enjoy a greater power density than those made from SiC, delivering savings in size and weight.

An expanding portfolio

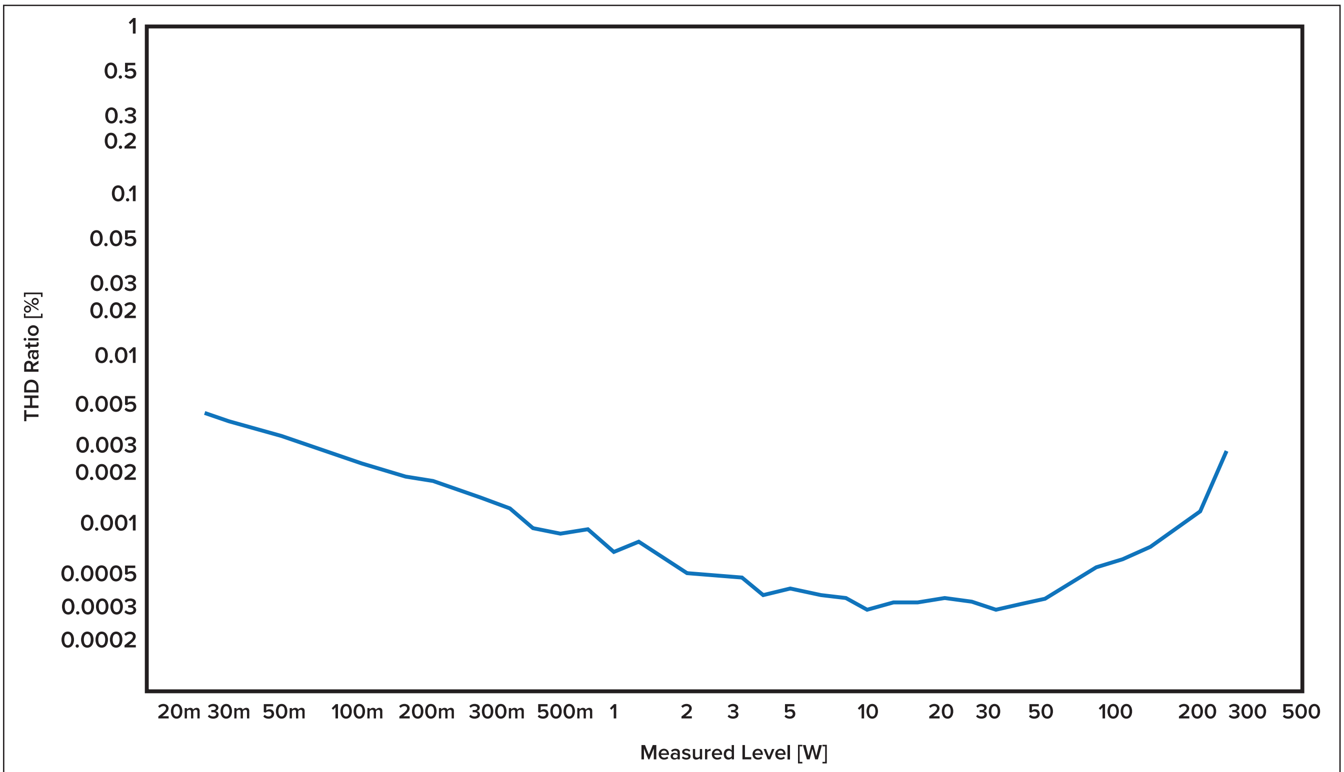
With a goal of delivering the ultimate sonic listening experience, we are continuing to expand our product portfolio. Our range currently includes expertly designed high-performance digital-to-analogue converters (DACs), streamers, and amplifiers. These products are helping consumers to elevate the sound in their home theatres, listening rooms, and recording studios.

Our belief is that every aspect of sound can be measured, a philosophy that underpins our research and development efforts. We are focussed on achieving the best possible objective measurements – and delivering the ultimate, subjective results.

Many of our products incorporate devices made by GaN Systems. This chipmaker produces very fast, true enhancement-mode (E-mode) GaN devices with a simple unipolar gate drive, a feature that makes them close to ideal for audio applications. In comparison, devices made by many other GaN manufacturers require a more complex or slower gate drive, or are cascode, which makes it much more difficult to control the timing of the switching. Further strengths of the products by GaN Systems are a low on-resistance, and a form of packaging that makes it easy to incorporate these devices in circuit boards for audio amplifiers.

One of our most recent products is the Starkrimson Streamer Ultra. It represents a new kind of high-end audio system. Miniaturization enabled by GaN allows a digital-to-analogue converter to be united with amplifiers and a streamer, inside an easy-to-use enclosure (see Figure 3). This level of functionality is typically realised with a rack of components (see Figure 4). A comparable system, including an amplifier, preamplifier, DAC, and a streamer, would typically command a price tag two-to-three times higher than that of the Starkrimson Streamer Ultra. Measurements of our Streamer Ultra confirm the pedigree of this fully balanced unit, which can drive speakers with an impedance as low as 2 Ω. Testing confirms extremely low noise and distortion (Figure 5), ultra-low jitter (Figure 6), and native playback up to 24Bit/192k.

➤ Figure 4. To offer the same level of facilities as the Starkrimson Streamer Ultra requires an amplifier, preamplifier, DAC, and a streamer.



➤ Figure 5. Using a measurement bandwidth of 22 kHz, the total harmonic distortion of the Starkrimson Ultra Amp as a function of power at 1 kHz.

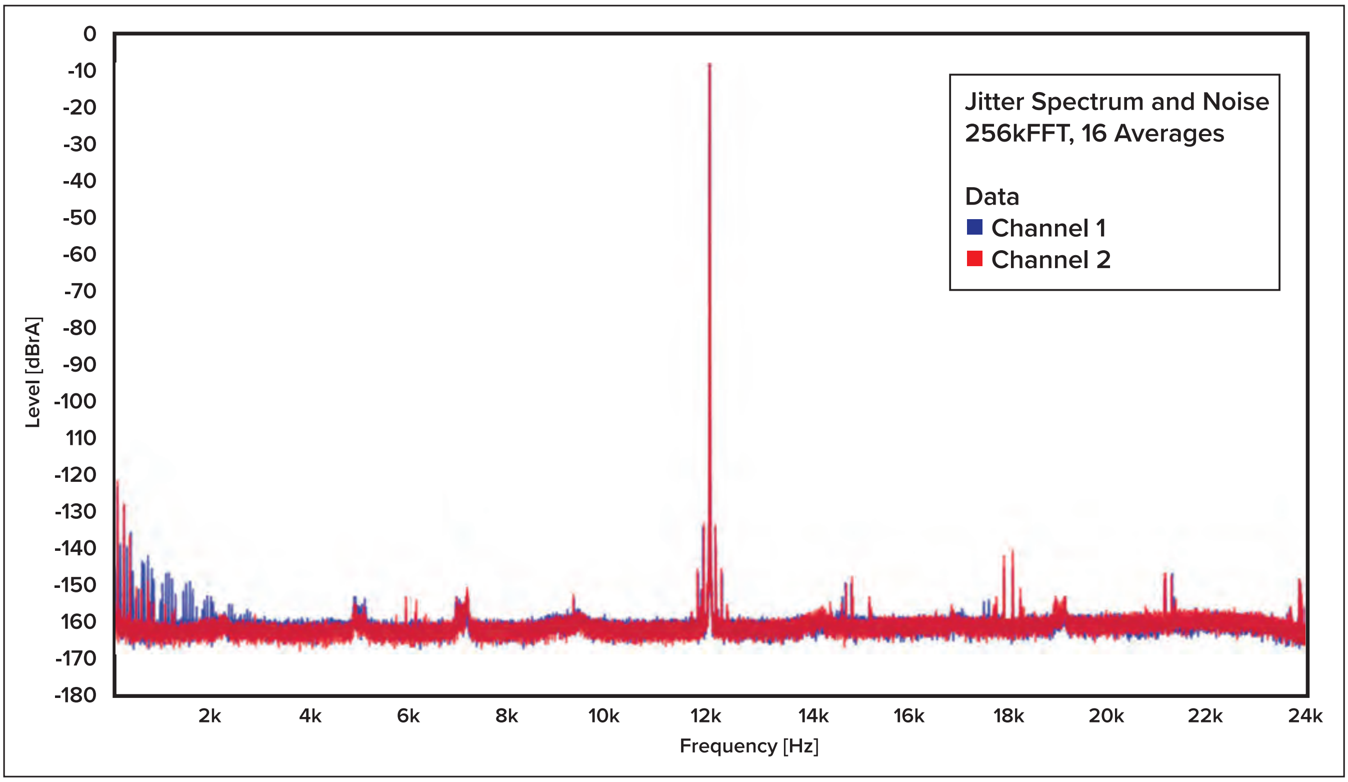


Figure 6: Starkrimson Streamer Ultra Jitter Spectrum and Noise, 256kFFT 16 Averages

Like the Starkrimson Streamer Ultra, its cousin, the Starkrimson Stereo Ultra amplifier, delivers less harshness, cleaner highs, and better overall transparency and detail, alongside vanishingly low noise levels. This amplifier delivers a power of up to 500 W_{RMS} (1,000 W_{PEAK}) and up to 20 A of current, while maintaining extremely low noise and distortion. What's more, this unit has enormous reserves of energy for extended transition. Expanding linearly with load, it is capable of delivering 125 watts into 16 Ω, 250 watts into 8 Ω, and 500 watts into 4 Ω. This culminates in powerful, unrestrained music.

A significant part of every Class-D amplifiers is its filter. Thanks to the high-speed switching of GaN Systems' transistors – they ensure two-to-three times faster switching than traditional Class D amplifiers using silicon transistors – our design employs a simple LC inductor and capacitor filter. Equipped with these components, our Starkrimson Stereo Ultra amplifier produces practically no phase shift from DC (0 Hz) to 20 kHz.

In our view, high-quality audio is now a 'must-have' across all segments, from pro-audio to home-audio and portable audio. The best approach to this is a Class-D audio systems with GaN devices. Armed with this technology, audio delivers a superior sound quality from smaller, lighter units; and there is no need for active cooling – there can be either no or minimal heart sinking.

How does it sound?

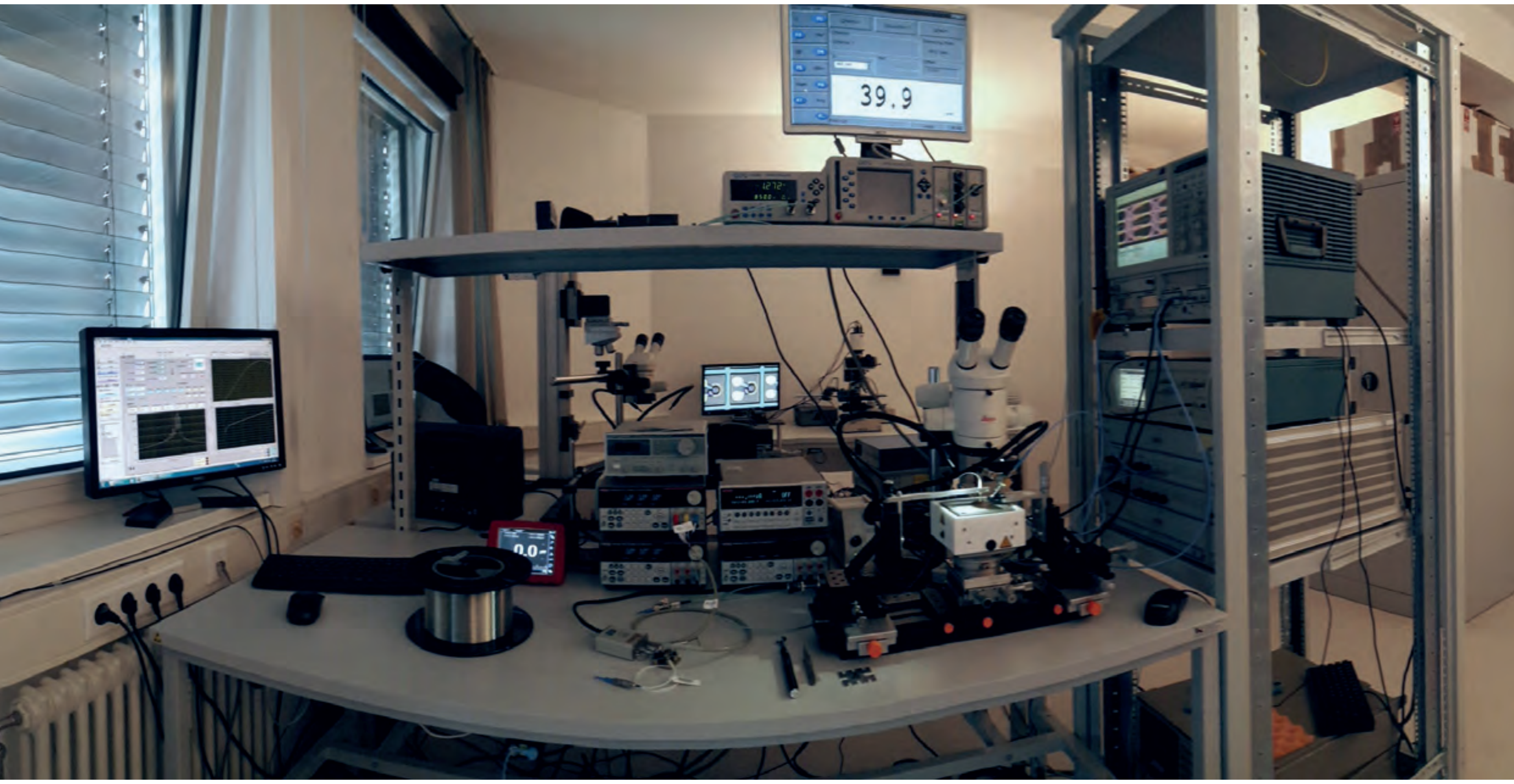
Orchard Audio is winning fans within the audiophile and music lover communities. Those that have heard these audio products are saying:

My speakers are very efficient and tend to make a feature of any noise in the electronics. The Starkrimsons are super-quiet and my music now plays against a silent background. Not only that, but the sound is wonderful. Separation and clarity are improved and the bass is noticeably tighter and more forceful. They are a clear step up from the power amp...

Rich and detailed without being overly analytical, drive and grip, brilliant low end, gorgeous midrange and extra levels of transparency that lift a veil from your music.

His amp is a realization of the benefits of GaN. The Ultra has improved harmonic integrity, dynamics, and resolution over traditional silicon.

With the Starkrimson driving them, the sound became more lively and dynamic but without a trace of harshness. The bass was on a par with the $6k amp, as was the treble smoothness, but the Starkrimson was more open. Playing reference tracks that I've heard dozens of times on the .7s, I was frequently startled — literally — by the realism of instruments and vocals. Micro-detail, textures and subtle dynamics that I hadn't noticed before became clear.



Novel VCSELs speed optical networks

Arrays of VCSELs with oxide-confined apertures could speed data transmission rates to 400 Gbit/s or more, as well as creating single, powerful, coherent sources

BY NIKOLOAY LEDENTSOV FROM VI SYSTEMS

OPPORTUNITIES AND CHALLENGES come from shrinking silicon transistors. On the plus side, the reduced dimensions enable more transistors to be packed into an IC without a hike in cost, leading to an increase in computational power. However, success may hinge on the introduction of a new device architecture that prevents leakage currents from getting out of hand, along with faster electrical interconnects – roughly every two years, there needs to be a doubling of their speed.

Today on-board signalling at 100 Gbit/s is in the final stage of standardization, while the standardization of 200 Gbit/s interfaces has already been started by the IEEE 802.3df 200 Gbit/s, 400 Gbit/s, 800 Gbit/s, and 1.6 Tbit/s Ethernet Task Force. Note that realising any increase in the data transmission rate is not trivial, with ramifications including rises in power dissipation and cross talk for electrical interconnects. To keep these issues at bay, the lengths of copper links have historically shrank by a factor of around four every decade.

An alternative approach to data transfer, which side-steps these issues, is to shift from the electrical domain to the optical domain. Efforts in this regard are already well underway, with optical interconnects playing a continuously increasing role in data communication systems, such as datacentres, enterprise networks and supercomputers. For distances of 100 m or less, the VCSEL is now the preferred optical source, deployed in multi-mode-fibre optical links that minimise cost and energy consumption.

Throughout its history, the normal method of operation for the VCSEL is direct modulation. Driven in this manner, increases in data rate demand an increase in the intrinsic modulation bandwidth, characterized by the resonant oscillation frequency. As the resonant oscillation frequency increases as the square root of the current density, there needs to be a four-fold hike in the current density to double the resonant oscillation frequency, assuming the same VCSEL design and gain medium. However, if such an increase in current density were adopted, that would slash the operational lifetime of the device and introduce thermal roll-over effects. Consequently, starting with the LED, the first source for multi-mode-fibre optical links, each milestone in bandwidth has come from the introduction of a novel design of the light emitter.

Speeding the VCSEL

More than a decade ago, our team members published a patent detailing the use of an anti-waveguiding VCSEL architecture to increase the modulation rate of this form of laser. Thanks to this modification, signalling rates were able to climb from 10 Gbaud, which is 10 Gbits/s in the case of on-off-coding, towards 50 Gbaud, needed for 100 Gbit/s in 4-level pulse-amplitude modulation. Our anti-waveguiding design suppressed light propagation in the lateral direction while enhancing the oscillator strength for the VCSEL transition.

When we introduced this architecture, we could realise a typical bandwidth of 30 GHz at current densities suitable for reliable VCSEL operation. Using this design, we laid the foundation for 100 Gbit/s links, which are now a basis for the upcoming generation of optical interconnects. It has been shown that this VCSEL can even deliver a data transmission rate of 224 Gbit/s per channel, by shifting to a discrete multi-tone modulation format.

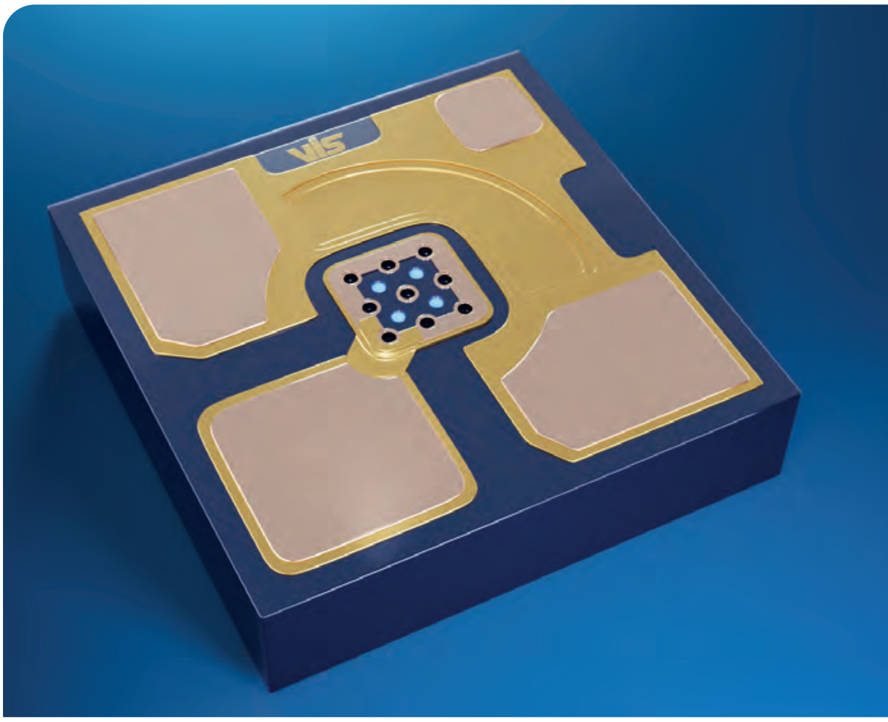
On its own, a tremendous increase in data rate is of limited benefit. To be really useful, it must go hand-in-hand with maintaining the transmission distance over the multi-mode fibre, and increasing the average power of the VCSEL, so that there is no reduction in the power per pulse. By ensuring the latter, the source will match the sensitivity of the bandwidth-scaled receiver circuit.

One of the key characteristics of a standard multi-mode VCSEL is its relatively large spectral width, typically around 0.6 nm. This high value leads to a significant impact of chromatic dispersion in the glass on pulse broadening, restricting the transmission distance over multi-mode fibre. At data rates of 100 Gbit/s, such pulse broadening is particularly an issue, once the fibre link is around 100 m or more. To transmit higher data rates over this distance, or to lengthen these fibre links to a kilometre or more, there needs to be a reduction in the spectral width of the VCSEL to 0.1 nm or less. We have enjoyed some success on this front with multi-mode fibres, using single-mode VCSELs with small oxide-confined apertures. Our triumphs include 100 Gbit/s data transmission over 1 km using the PAM4 modulation format, and 50 Gbit/s non-return-to-zero transmission at distances of up to 2.2 km. However, with small apertures, it is challenging to produce output powers exceeding 2 mW within the required range of operation carrier temperatures, which extend to 85°C at long enough operation lifetimes.

Late last year we revealed that the limitations of modern VCSELs can be overcome by migrating from single sources to compact mini-arrays featuring small oxide-confined current apertures. The merits of such a device include a narrow spectral width, a high output power, low resistance and good reliability (see Figure 1). Armed with these attributes, this source can provide significant bandwidth scaling by applying the coherent interaction of optical modes at small aperture-to-aperture pitch sizes.

It is certainly not a new idea to transmit data down a multi-mode fibre using coherent emission from two-dimensional mini-arrays of apertures. Back in the late 1990s, one of our team members, Jörg-Reinhardt Kropp, filed a patent on this technology during his time at Infineon (US Patent 6785476).

A few years on, thanks to the proliferation of oxide-confined VCSELs, a team from Xerox developed an approach to making mini- and macro-arrays of oxide-confined apertures, realized by selective oxidation of AlAs-rich aperture layers through etched holes in the VCSEL wafer. And applying the same technology, researchers at Palo Alto Research



➤ Figure 1. 3D image of a single-mode VCSEL mini-array with 4 oxide-confined apertures. The lateral chip size is about 200 µm by 200 µm.

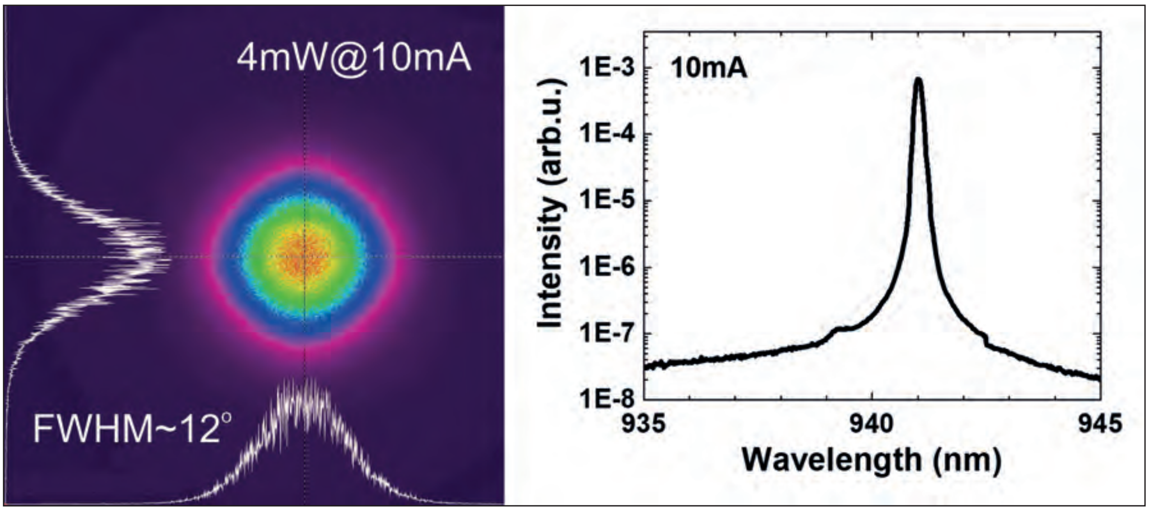


Figure 2. (a) Far-field pattern and (b) optical spectrum of a VCSEL with a 4× aperture mini-array under 10 mA drive current, equating to a current density of 24 kA cm^{-2}.

Centre showed that oxide-confined apertures, coupled through locally non-oxidized regions, can be used to fabricate coherently coupled arrays.

More recently, we have reported another approach to making coherent VCSEL arrays. Our technology involves optical coupling between the neighbouring oxide-confined apertures through in-plane leaky emission, realised by either epitaxial design (US 10,243,330) or through surface-trapped optical modes (US 10,666,017).

Demonstrations of this latest technology included far-field patterns (a) and lasing spectra (b) of a mini-array made up of four single-mode VCSEL apertures. Driven at 10 mA, corresponding to a current density of 24 kA cm^{-2}, the output power is 4 mW. The device produces a narrow far field with a full-width at half-maximum of just 12 °, and an optical spectrum that shows a quasi-single-mode character, with a side-mode suppression ratio of around 20 dB.

We have obtained an 80 percent coupling efficiency into a standard OM3 fibre, due to the high brightness of the array. This efficiency is realised for single-mode-aperture mini-arrays, and for multi-mode-aperture mini arrays with larger apertures. An eye-diagram, using non-return to zero, highlights the high-quality data transmission using our VCSEL mini-array at 50 Gbaud with 3-tap feed-forward equalization (see Figure 3). The intrinsic optical modulation bandwidth of this device is defined as 30 GHz.

Creating coherent sources

When the aperture pitch size is as small as about 12 µm, this leads to a strong optical leakage-induced interaction between the array apertures, and results in coherent lasing of all the apertures. Operation in this manner creates a superstructure, exhibiting characteristics associated with the fundamental mode of a 2D array of coherent emitters (see Figure 4, which shows a far-field image of a mini-array in a single coherent optical state).

By developing coherent arrays of oxide-confined apertures that are free from external resonators and injection locking – and are capable of high-speed data transmission over substantial distances over multi-mode fibre – we have delivered a significant milestone for the VCSEL. Devices with these attributes deliver a strong increase in the brightness

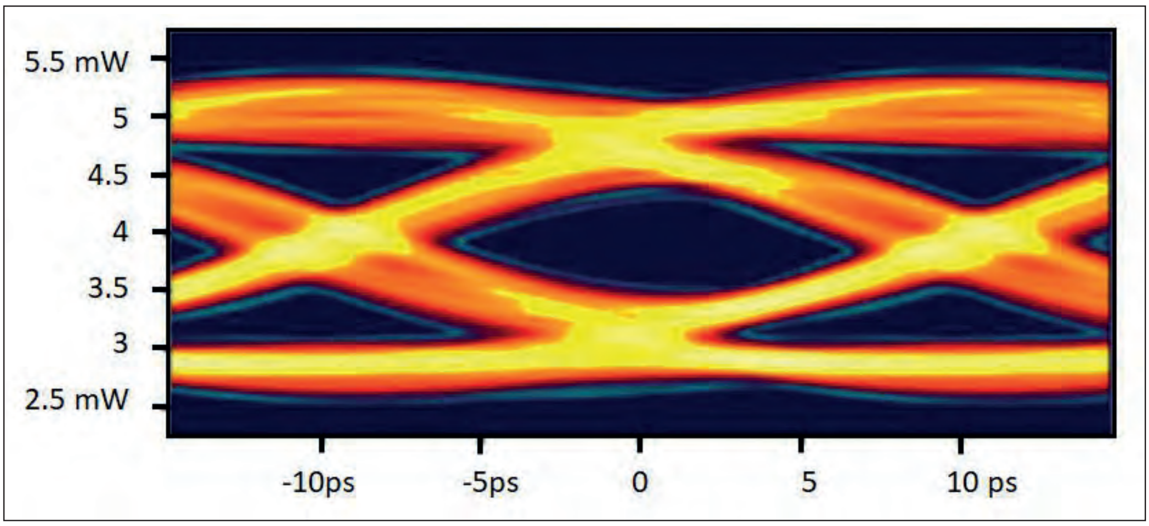


Figure 3. Non-return-to-zero eye-diagram of a ×4 mini-array at 50 Gbit/s. A 3 tap feed-forward equalization is applied.

of the laser beam, accomplished by either applying conventional lenses to form Bessel-like beams, or by allowing arbitrary beam-shaping via diffraction lenses. Where necessary, single-mode fibre coupling can be realised.

It is possible to significantly extend the bandwidth of our source with additional aperture shape engineering and by increasing the interaction between optical modes between the apertures. When the wavelength splitting between the coherent modes of the array and the resulting photon-photon resonances reaches about 0.1 nm, the enhanced modulation bandwidth approaches around 70 GHz. We need to guide effort in this direction to realise this goal in a predictable, well-controlled manner.

Note that at last year's Optical Fibre Conference a team from Japan demonstrated optical modulation bandwidths above 110 GHz and a 256 Gbit/s PAM4 data transmission rate using distributed feedback lasers featuring a distributed Bragg reflector and a membrane structure. This device featured engineered coupled cavity modes and photon-photon resonances. A great merit of drawing on photon-photon resonances is that it enables high modulation bandwidths at low current densities, ensuring a long operational lifetime for the device.

There is no doubt that a VCSEL technology based on compact mini-arrays of oxide-confined apertures has great promising for providing data rates of more than 100 Gbit/s at improved performance, as well as providing the source in the next generations of optical links, operating initially at 200 Gbit/s and then 400 Gbit/s per channel and beyond. Additional opportunities for coherent oxide-confined VCSEL arrays exist in high-brightness lidar and optical wireless, where they combine higher brightness with real beam steering. While one VCSEL can accomplish so much, arrays of them can do far more.

This feature has been co-authored by N. N. Ledentsov, O. Yu. Makarov, N. Ledentsov Jr., M. Bou Sanayeh, L. Chrochos, V.A. Shchukin, V.P. Kalosha, I.E. Titkov, G. Schaefer and J.-R. Kropp (VI-Systems GmbH).

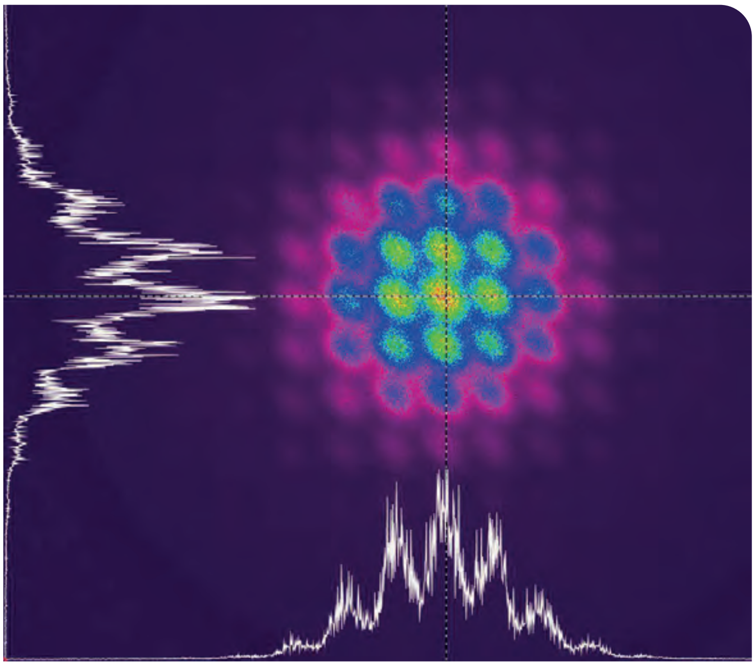


Figure 4. Far-field pattern of a ×4 aperture mini-array at a 12 μm pitch in a coherent single mode lasing state at 10 mA. Peak to peak separation in the superstructure in the far field spectrum is 5°.

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- *N. Ledentsov et al. "Novel multi-aperture VCSELs for optical wireless and multimode fiber communication," 2021 27th International Semiconductor Laser Conference (ISLC), 2021, pp. 1-2, doi: 10.1109/ISLC51662.2021.9615778.*
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Monitoring methane with 3D single-pixel imaging

A novel camera with a single-pixel detector that's operating in photon-counting mode is set to revolutionise detection and tracking of methane, a troublesome greenhouse gas

BY JOLYON DE FREITAS AND NICHOLAS AVLONITIS FROM THE CSA CATAPULT, DOUG MILLINGTON-SMITH AND MURRAY REED FROM QLM AND SIMON DIMLER AND JO-SHIEN NG FROM SHEFFIELD UNIVERSITY

MULTI-PIXEL SENSORS are a great commercial success. Aided by their low-cost and large-scale manufacture they are benefitting from a technological 'lock-in', along with a dependence that is difficult to escape.

Underpinning the meteoric rise of this imaging technology, particularly for digital imaging, is the single-pixel detector. Its origins can be traced back as far as 1965, when the American engineer Frederic Crockett Billingsley used the term 'pixel' for the first time in the context of the picture elements of scanned images. Today, though, this term is used interchangeably – it can mean either the smallest indivisible image element, or the smallest independent sensor element of an array. When a single pixel is used for imaging, it is combined with some form of scanning – this is the approach that has been adopted almost exclusively in low-photon-count situations, both within and outside the visible spectral range.

Several forms of single-pixel optoelectronic device are now available, including photomultiplier tubes and single-element semiconductor devices, such as detectors based on either silicon, germanium or InGaAs. Since the 1970s these detectors have been behind the digital medical imaging revolution in X-ray computed tomography (CT), nuclear medicine, positron emission CT and more recently photon-counting CT. These instruments have transformed healthcare, biology, quality engineering, defence and several manufacturing industry sectors.

Against this backdrop, saying that single-pixel imaging is new might appear to be a contradiction in terms. But that's not the case: single-pixel imaging is not just new, it is radically new. The reality is that, like the radically new approaches of medical imaging in the 1970s, single-pixel photon imaging is on the cusp of a new era. What's more, the similarity in trajectory doesn't end there: single-pixel imaging is now realising a true 3D spatial reconstruction of the object scene thanks to a time-of-flight capability. Normally this is accomplished with light detection and ranging (lidar), a technology that determines the shape of an object.

As well as these new developments, single-pixel imaging is finding niche applications in the short-wave infrared (SWIR), particularly when there is a need for single-photon counting detectors. Such devices are made from either InGaAs/InP, InGaAs/InAlAs or germanium/silicon. These semiconductor detectors can monitor greenhouse gases, support environmental management and help to assess whether regulations are upheld.

For environmental monitoring and gas sensing, compound semiconductor technologies have much appeal. Their merits include enabling the engineering of smaller bandgap energy levels, suitable for the absorption and detection of lower-energy photons. By reaching down to the short-wave and medium-wave infrared, detectors can delve into a spectral domain rich in distinctive vibrational and rotational spectra associated with many greenhouse gases.

The case for methane

Reducing greenhouse gases is key to realising a zero-carbon economy. To get there demands regulation and enforcement, as well as focusing on what matters. While it's easy to get fixated on CO_2, the biggest greenhouse gas, it is folly to neglect other global greenhouse gases. This includes methane, the second biggest greenhouse gas. This hydrocarbon is the main constituent of natural gas, which is seeing increased demand as nations move away from coal and oil. One of the main reasons why methane emissions really matter is that over a 20 year period from their release, they trap 84 times more heat than comparative emission of CO_2. Due to this, it takes just a 3 percent leak rate to make natural gas as bad for climate change as burning coal.

One of the more pleasing outcomes at COP26 has been a commitment signed by more than a hundred nations to reduce their methane emissions. However, you cannot manage what you cannot measure; and that's a big issue, because today there appears to be no proper measurements of methane sources and fluxes.

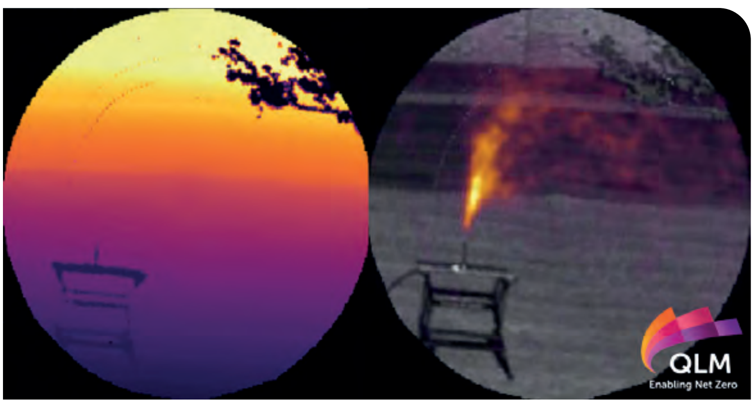
If this is addressed, then as well as tackling the environmental cost associated with methane, financial losses will tumble. According to independent research provider Rhodium Group, leaks of methane are valued at more than $30 billion per year. Due to this, there is a substantial, growing market for natural gas leak detection.

In 2018, the analyst Research and Markets estimated that this market is worth more than $1.5 billion, and increasing at a compound annual growth rate of more than 7 percent, due to a combination of gas becoming the dominant fossil fuel, slowly increasing government regulations, and expanding investor pressure to drive up industry standards.

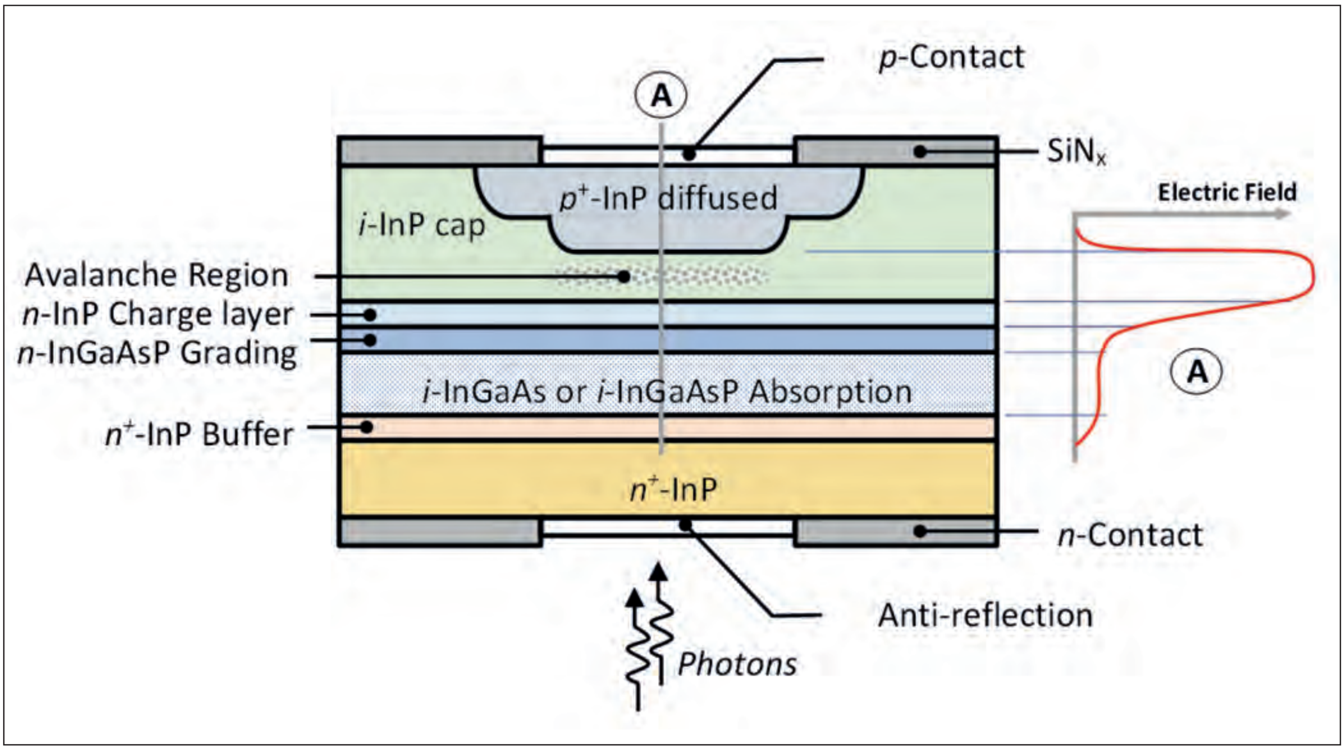
Unfortunately, today's detection technologies are complex, expensive and need trained experts to operate. Consequently, regulations are only enforced after occasional inspections. It's a state of affairs that concerns the gas industry: it wants to find ways to catch these leaks, and ensure that gas suppliers are environmentally responsible and worthy of investment. Success on all these fronts will help to reinstate natural gas as a transition fossil fuel.

For those that are willing to devote time and energy into developing methane monitoring systems, the commercial opportunities do not begin and end with methane production and supply. There is also the petrochemical industry, which consumes natural gas to manufacture a wide range of industrial materials.

The 2,000 chemical plants worldwide have created a gas leak detection market worth $0.5 billion and tipped for substantial growth, due increasing safety regulation, as well as interest from other major industries, such as construction and transport. Additional opportunities exist in environmental monitoring of innovative landfill-gas-to-energy and anaerobic digestion plants – they need improved greenhouse-gas leak detection.



➤ Figure 1. Left: QLM's TDLidar single-pixel 3D gas imaging camera. Right: Multi-dimensional image of methane gas leak detection and distance information. Images conjured up by the TDlidar camera.



➤ Figure 2. Design objectives of a typical InGaAs/InP single-photon avalanche diode (SPAD) design using the SAGCM – Separate absorption, grading, charge and multiplication approach.

A UK solution

Supported by InnovateUK, we are involved in a collaboration that is part of a project entitled SPLICE – an acronym for Single Photon Lidar Imaging of Carbon Emissions – that is targeting the practical detection of methane. Drawing on quantum technology pioneered by the University of Bristol, our team from the Compound Semiconductor Applications Catapult (CSA Catapult), QLM and Sheffield University, is developing disruptive infrared lidar cameras that offer real-time imaging and quantification of greenhouse gases at long range, giving industry what it needs: an accurate, low cost and practical leak detection system that can completely and continuously survey greenhouse-gas emissions. Additional partners in SPLICE include the National Physical Laboratory, and gas industry leaders BP and National Grid Gas.

We are aware that accurately measuring methane emissions is a tricky task. Take a plant, for example, which will have a wide variety of sources of emission: there are vents and exhausts, which are large, localised and planned; there are flares, which are large and localised, but often unplanned and intermittent; and there are fugitive emissions – leaks – that are small, widely distributed, and often unknown until found. Due to this complexity, emissions tend to be estimated rather than measured. This involves the use of simple multipliers and the prediction of emissions based on ideal conditions, a method that can lead to wildly inaccurate results. Another concern is that when leak detection and repair operations take place, they are slow, expensive, labour intensive, and only provide a snapshot in time of the facility. If a component springs a leak the day after the survey, this issue only surfaces during the next survey, months down the line.

The obvious solution is to continuously monitor methane. However, that's not as simple as it sounds. One low-cost option is to install a network of point sensors – but this requires regular calibration and offers little effective localisation or quantification. An alternative, the optical gas imaging camera, addresses the former by visualising emissions with infrared thermal imaging, but it is also weak in terms of quantification. Better in that regard is open path spectroscopy, which uses the atmosphere as the measurement cell, but this trades quantification for localisation. Yet another option is to use imaging from satellites. This approach visualises and quantifies, but monitoring is intermittent, thwarted by clouds, and spatial resolution is limited to no more than a 25 m square.

None of these candidates provides the total package of continuous detection, localisation and quantification that is craved by the gas industry, which faces an immense problem. Consider the following: in North America alone there are 2,000 offshore rigs; worldwide there are nearly 1,000 natural gas storage facilities; and in Britain there are 24 major pipeline compressor stations and hundreds of above-ground installations, all leaking to some degree right now.

Well aware of these issues, oil and gas majors are making various pledges to reduce methane emissions over the coming decades. Among those leading this drive is SPLICE Project Partner BP, which has committed to monitoring methane at all its major sites by 2023. This should enable a 50 percent cut in methane emissions intensity, prior to realising full net zero in 2050.

It is likely that many other gas providers will follow, partly because in recent weeks the US Environmental Protection Agency has proposed changes to monitoring regulations that will lead to more regular reporting. This environmental agency is also making allowances for measurements with new, non-standard technologies. Should this proposal become law, it will grant US-based emitters a range of options for helping to meet more stringent standards.

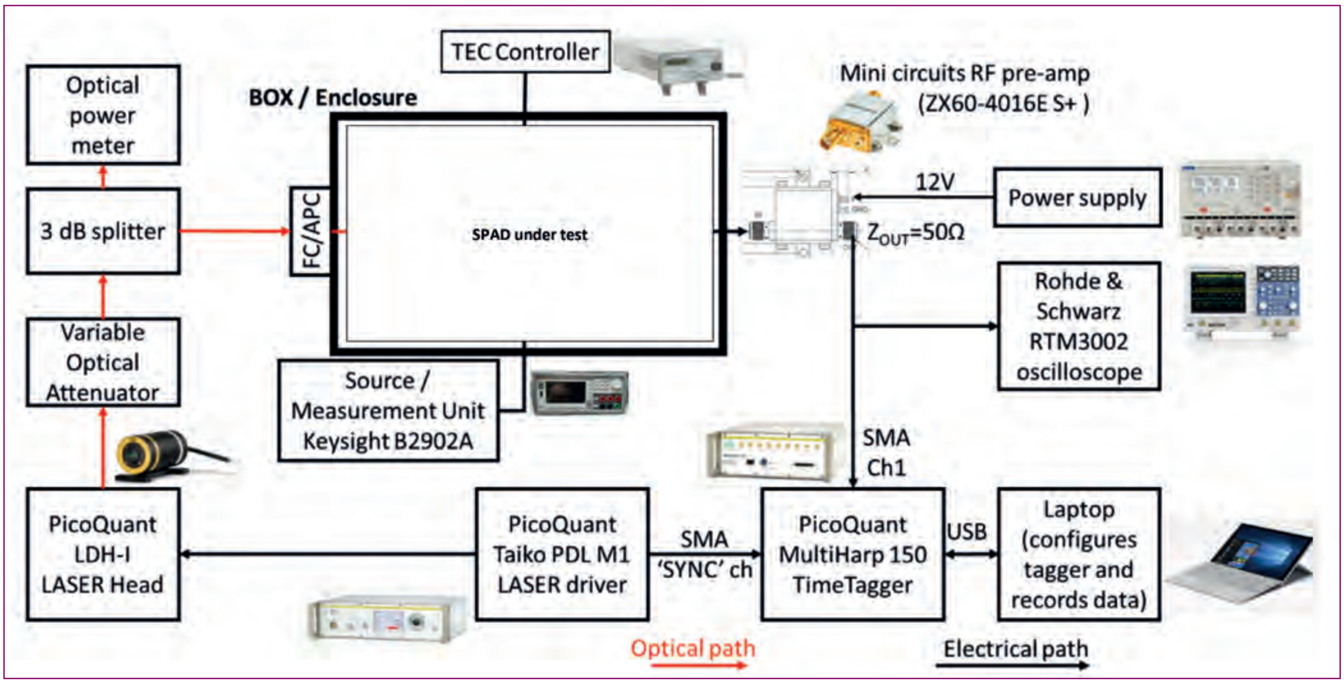
Conjuring images

Within our collaboration, QLM is addressing the needs of the gas industry by using a revolutionary quantum technology to deliver a true measurement of greenhouse gas emissions. This is accomplished with a camera that simultaneously visualises and quantifies plumes in real time. The approach that's taken builds on some of the key advantages of previously described technologies while avoiding their limitations.

Our new sensor employs a technique called tuneable diode lidar (TDlidar). This enables remote spectroscopy and ranging with low-power semiconductor diode lasers, by drawing on aspects of tuneable diode laser absorption spectroscopy, with differential absorption lidar (DIAL) and time-correlated single-photon counting. Initially, our TDlidar methane sensors employed diode lasers with wavelengths around the methane absorption line at 1650.9 nm, and Peltier-cooled single-photon avalanche diode (SPAD) detectors in a random modulation CW lidar system (see Figure 1). With this approach we could realise long-range, accurate imaging of gas uncovered by DIAL, using a much smaller, easily portable form factor.

This prototype has much appeal, promising simple, robust, precise visualisation and quantification of gas emissions on a continuous basis, from a compact, relatively low-cost platform. However, there is a massive difference between demonstrating technology on a laboratory bench and delivering a reliable, environmentally robust, simple-to-operate camera that will add value to real-world operations. Bridging that gap demands improvement to the internal workings of the camera, the mechanical operation and the control and analysis software; and proving that the equipment is at least as good as existing techniques when working in real environments.

On its own, QLM does not have all the skills and experience to tackle this multi-faceted challenge that includes handling multi-dimensional information in images conjured up by the camera. It is a different story, however, once QLM has teamed up with project partners that include CSA Catapult, Bay Photonics, and the Universities of Bristol, Sheffield and Aston. Another partner is STL Technology, which has developed software processing that turns measurements of spectra to representations of methane intensity. Through ergonomic design, our collaboration's camera is evolving towards smaller, lighter, more affordable platforms.



➤ Figure 3. Schematic layout of the CSA Catapult's SPAD testbed. The beam incident on the SPAD active area is adjusted using a beam profiler and a reference detector (Adapted from ETSI GS QKD 011 V1.1.1 (2016-05), GROUP SPECIFICATION: Quantum Key Distribution (QKD); Component characterization: characterizing optical components for QKD systems, May 2016).

Support from the SPLICE programme has helped us evaluate the performance of the camera. Initially, trials took place in controlled release settings, but more recently, as the camera has reached higher levels of readiness, trials have moved on to real-world environments. This has involved using the camera to hunt for leaks that are unknown to the operator, on test beds from both inside and outside the consortium.

Much progress has been made. QLM has already completed trials with SPLICE partner National Grid Gas, and trials are planned with other industrial partners of the project, AMETEK Land and BP.

Playing a very valuable role in supporting this evaluation of the camera has been another SPLICE partner, the National Physical Laboratory. Its scientists are providing test beds for controlled studies and comparative metrology during real-world trials. The insights garnered from this have allowed us to industrially validate the performance of our camera against state-of-the-art survey techniques.

Improving detection

At the heart of our single-pixel camera is a photon-counting detector operating in the SWIR. While SPADs in the visible region have seen significant advances, their cousins operating in the infrared are far less common, and do not always meet the performance requirements of the single-pixel camera. To address that shortcoming, those within our team at Sheffield University are designing and fabricating SWIR SPADs that are targeting higher detection efficiencies and a lower operational noise.

The most common form of SWIR SPAD involves InGaAs and InP. Photons are absorbed in a layer of InGaAs, while InP acts as the avalanche material. However, some research groups switch InP for lattice-matched $In_{0.52}Al_{0.48}As$, as this improves the temperature stability of the detector. An alternative material system for a SWIR SPAD is the combination of a germanium absorber and a silicon avalanche region. However, germanium's indirect bandgap of around 0.8 eV prevents detection beyond about 1.5 µm.

Comparing the numerous SWIR SPADs that have been reported is far from easy, due to variations in the methods of characterisation. This includes differences in quenching methods; and for pulsed operation, variations in pulse duration, the levels of over-bias, and the photon detection efficiency. However, despite these challenges, we have attempted to summarise the typical range of values for some key performance characteristics for SWIR SPADs (see in Table 1).

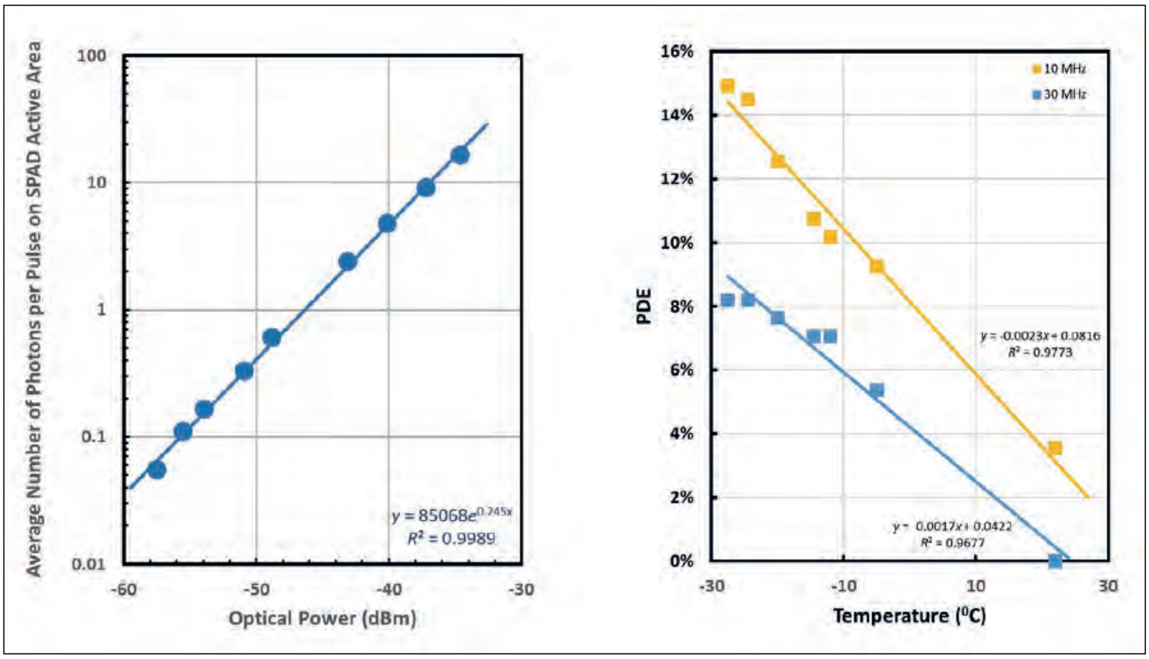
A key figure of merit for the SWIR SPAD is the photon detection efficiency. Specification for this tends to dictates the design of the device's heterostructure. The photon detection efficiency is a product of the SPAD's quantum efficiency and its breakdown probability – both can be increased, independently, by selecting a thicker absorption region and a thicker avalanche region, respectively. However, while this is true in theory, there are practical considerations. For example, thicker avalanche and absorption regions lead to a higher operation voltage, which may be undesirable.

Regardless of the material combination employed for the SWIR SPAD, its design must realise the desired electric field profile. Getting this right ensures that at the device's operating voltage the field in the avalanche region is high enough to realise breakdown, a condition that ensures the detection of a single photon. Another key consideration is maintaining a low electric field in the absorber, which has a lower bandgap than the avalanche material, as this prevents excessive dark currents due to band-to-band tunnelling. To manage the large difference between the electric fields in the avalanche and absorber regions, inserted between them is a charge layer, sometimes referred to as a field-control layer (see Figure 2).

Production of InGaAs/InP SPADs usually involves the growth of the heterostructure by MOCVD, because this approach is already well-established for commercial manufacture of InGaAs/InP APDs originally developed for optical communication. Note that the zinc diffusion technique applied to form *p*-doped InP in those commercial APDs can be applied to InGaAs/InP SPADs.

Device parameter	Unit	Typical range	Notes
Wavelength	nm	1500 - 1650	The majority of results are reported for the telecoms wavelength of 1550 nm
Photon detection efficiency (PDE)		10-60%	20-30% is the most commonly reported range
DCR	cps	< 100 Mcps	Rates as low as a few tens of kilohertz have been reported when the device is operated with a low duty cycle or with very short over-bias pulses.
Device Diameter	µm	20-50 µm	Devices as small as 10 µm and as large as 200 µm have been reported

Table 1: Comparison of typical 1550 nm single-photon avalanche diode (SPAD) specifications.



➤ Figure 4. Left: The average number of photons falling on the single-photon avalanche diode (SPAD) active area can be reduced in a controlled manner to below an average of 0.1 photons per pulse. Right: Photodetection efficiency (PDE) of SWIR SPADs decreases with increasing temperature.

For research projects targeting the mid-technology readiness level, or having a focus on translational research, such as our project that forms part of SPLICE, there are several good reasons why it is best to opt for semiconductor wafer foundries for the wafer source, assuming money is available for this work. During the pandemic, this approach has become even more advantageous, due to the long closures in university research labs in 2020, and the reduced capacity in both that year and 2021. Today, universities are dealing with a significant backlog of multiple experimental projects.

However, turning to a foundry is not always a problem solved. One issue is that they may decline the opportunity, viewing the number of wafers that are ordered as insufficient for the business model. And this may not be resolved by simply approaching other foundries, until one takes the order. Even before the pandemic, very few fabs were offering foundry services, and it is challenging for them to scale up, despite strong demand.

Counting in the fog

It is a tricky business to characterise SWIR SPADs. As the photons are inherently random, there's a need for a statistical approach. Complicating matters, only a few centres are equipped with the instrumentation to carry out these measurements. To help improve this situation, those within our team at the CSA Catapult have developed a SPAD testbed based on the ETSI Group specification QKD 011. This will help companies test different parameters of SPADs – clearing the statistical fog.

This testbed, illustrated in Figure 3, involves a weak laser source. Attenuation ensures that the source provides a 0.1 photons/pulse level on the SPAD's surface. A multi-channel time tagger captures precise timings of arrivals of single photons, allowing the calculation of parameters based on statistics. With this testbed, methods have been developed to measure: the current versus voltage (I-V) characteristic, in order to identify the voltage thresholds; the dark count rate; the photon detection efficiency; and the probability of afterpulsing. Repeating measurements at different temperatures, set by the thermo-electric controller, enables this technique to examine the thermal effects on SPAD structures.

Drawing on the insights provided by the resulting range of measurements, design engineers can select the best components for their applications. In addition, measurements can aid the fine tuning of single-photon (quantum) imagers and sensors.

Turning to a foundry is not always a problem solved. One issue is that they may decline the opportunity, viewing the number of wafers that are ordered as insufficient for the business model. And this may not be resolved by simply approaching other foundries, until one takes the order

Within the SPLICE programme, engineers have derived tremendous benefit from examining the effects of temperature on SPAD structures at different key wavelengths. This has assisted methane and greenhouse gas sensing (see Figure 4).

Multiple milestones

Throughout the project, we have faced many technical and logistic challenges. The pandemic has shut facilities, applied the brakes to global travel, and severely disrupted component supplies and collaborations. Yet despite all these difficulties, we have made strong progress on all our major objectives; and thanks to this progress, we are now fielding high-performing, robust, and user-friendly gas lidar imagers in multiple industrial field trials.

Our quantum systems depend critically on the SPAD detector. We continue to face a major challenge in procuring commercially available SPADs and characterising their performance for gas sensing applications. In it essential to know the area of the SPAD, its dark count rate, photon count probability, operating temperature, and applied voltage.

Championing efforts to understand and prove SPAD gas-imager requirements has been the team at CSA Catapult, which has also set the targets for the design of novel InGaAs-based SPADs by Sheffield University. This has led to the growth of the first SPAD device wafers, with efforts now directed at device fabrication and characterisation, to verify these designs. The best devices emanating from the University of Sheffield will soon be packaged in a form that allows their demonstration in prototype gas imager systems made by partner Bay Photonics.

We have no doubt that the trajectory of development of single-pixel compound semiconductor detector technologies will follow that of medical imaging of five decades ago. This is likely to lead to 4D imaging – that's three spatial dimensions, plus time – along with real-time monitoring of gas plumes, newer ways of image registration and display of multi-dimensional information, and the development of fast, low-noise, multi-pixel photon-counting arrays. We are on the cusp of a revolution.

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Photodetectors
The benefits of adding bismuth

Adding a little bismuth to GaAs drives down the noise of avalanche photodiodes

BY ROBERT RICHARDS FROM THE UNIVERSITY OF SHEFFIELD

THERE'S far more to setting a new low for the noise of a photodetector than winning bragging rights. Success also aids a number of important applications. Take optical networks, which operate in the O and C bands that are centred around 1300 nm and 1550 nm and incorporate intermittent signal boosters. Slashing the noise in the detectors deployed in these networks increases the efficiency of data transfer, either by allowing a reduction in the power of the transmitter or by trimming the number of boosters. Another example is lidar, short for light detection and ranging. It's a technology for serving in autonomous vehicles and geospatial mapping – and for this pair of applications, driving down the noise in the detector enables faster, more accurate measurements.

When there's a need for high speed and high sensitivity, standard photodetectors can fall short. These devices only produce a modest signal from incident light, limiting their signal-to-noise ratio, especially when the measurement time is limited, as is the case with high-speed communications or lidar. While an external amplifier can increase the signal, the noise is also amplified, impairing efforts to improve the signal-to-noise ratio.

A far better option for ensuring both high sensitivity and high speed is the avalanche photodiode. Like a conventional detector, every photon that it absorbs excites an electron to the conduction band, to leave a hole in the valence band – and the internal electric field pulls these carriers in opposite directions. However, in an avalanche photodiode the electric field is far stronger than it is in a standard photodetector, causing the carriers to gain enough energy to excite additional electron-hole pairs, through a process known as impact ionisation. These newly ionised electrons and holes are themselves then accelerated, leading eventually to a large number of electrons and holes contributing to the current, effectively amplifying the original signal.

For most detection below 1000 nm, the incumbent avalanche photodiodes are made from silicon and are well-established commercial products. Silicon is a near-ideal material for making this class of detector because of its technological maturity and because electrons can cause impact ionisation far more readily than holes. This is reflected in the ratio of the electron and hole ionisation coefficients, α and β, which is very large. Thanks to this, the 'excess' noise due to the stochastic nature of the ionisation process is highly reduced.

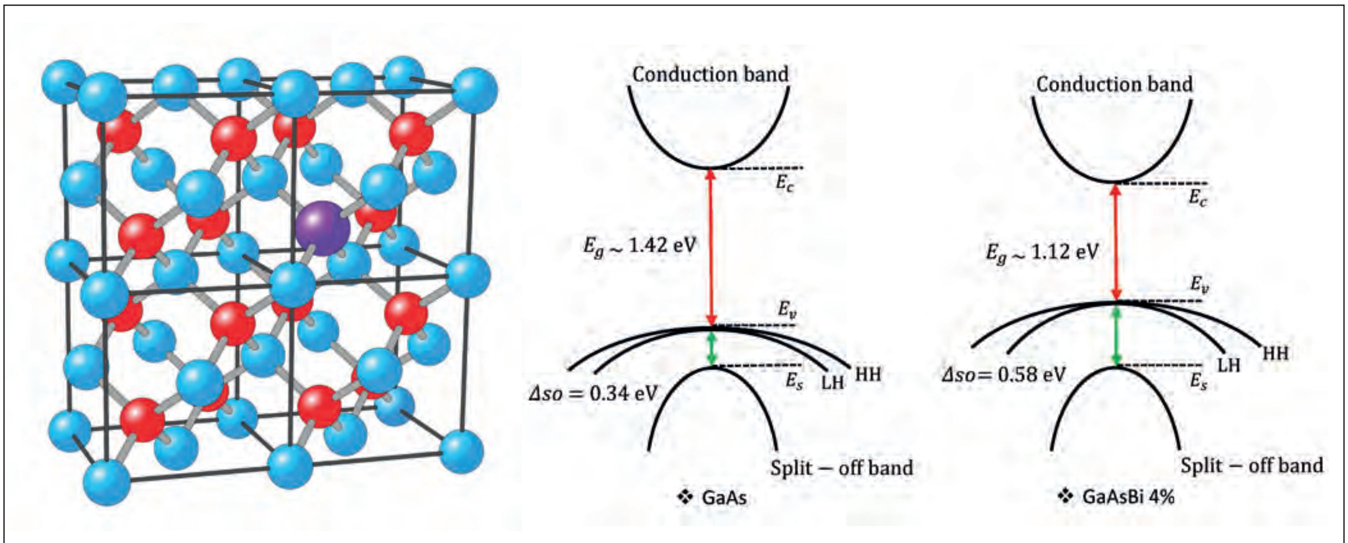
Unfortunately, the detection characteristics for silicon photodiodes are far from ideal. Due to the indirect bandgap of this material, thick layers are needed to ensure sufficient absorption of photons. This is particularly acute for detection at the tail end of silicon absorption, at around 1 μm, where to realise a reasonable quantum efficiency the detector must be very thick – a requirement that prevents high-speed operation. Due to this limitation, silicon avalanche photodiodes are unsuitable for optical communication networks and some lidar systems.

Options for the infrared include HgCdTe and InAs. Both have α/β ratios almost infinitely large, but due to their small bandgap, cooling is needed to reduce dark currents. Another alternative is GaAs, along with its related alloys. Unfortunately, this material system has an α/β ratio near unity, leading to a large excess noise. However, by adding a small amount

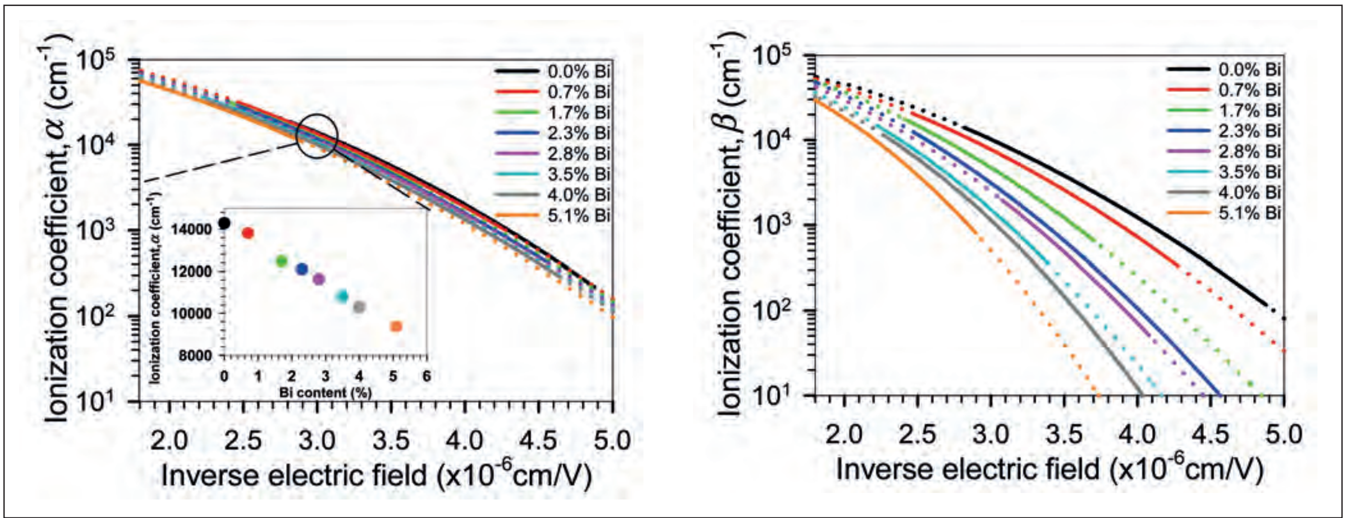
of bismuth to this material system, our team at the University of Sheffield has shown that this difficulty may be overcome, opening the door to a new, highly flexible family of extremely low-noise avalanche photodetectors.

Bismuth benefits

Incorporating bismuth into GaAs has a dramatic effect on the band structure (see Figure 1). When bismuth is added, it takes the place of arsenic and introduces an electronic state that interacts with the valence band edge. This causes the valence band edge to rapidly increase in energy, while the conduction and split-off bands move more slowly. As a result, the band gap reduces by several hundred meV and the spin-orbit splitting (the gap



➤ Figure 1. Left: Bismuth (purple) is a large group V atom that replaces arsenic (red) in the GaAs matrix. Right: The addition of even small amounts of bismuth to GaAs has a profound effect on the material band structure.



➤ Figure 2. Left: The electron ionisation coefficient reduces slowly (linearly) as the bismuth content increases. Right: In contrast, the hole ionisation coefficient reduces rapidly (exponentially) as a function of bismuth content.

between the split-off and valence band edges [Δso]) increases by several hundred meV with the addition of just a few percent bismuth. Δso is a key quantity, because holes in GaAs have to be in the split-off band to acquire enough energy to initiate impact ionisation. Consequently, as Δso increases, it becomes much harder for the holes to reach the split-off band and impact ionise.

The bismuth-induced changes to the bandstructure are helpful for realising low-noise photodetectors with desirable characteristics. The reduction of the bandgap propels the cut-off for detection to 1.1 μm and increases the absorption coefficient; and the increase in Δso reduces β while leaving α largely unchanged, leading to an enhancement in the α/β ratio of a factor between 2 and 100.

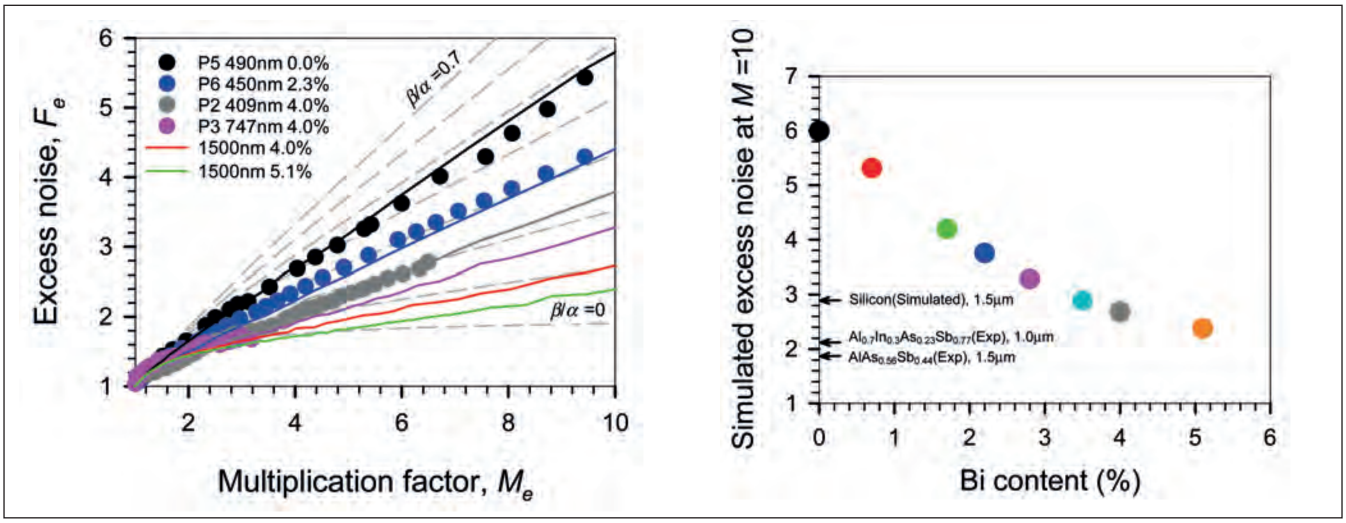
We fabricated a series of GaAsBi photodetectors on GaAs substrates using the MBE technique. On epi-ready (001) substrates we produced epitaxial structures containing an intrinsic layer of GaAsBi with a bismuth content of up to about 5 percent, sandwiched between doped GaAs cladding layers, and capped with a thin, heavily doped layer. Growth rates were in the range 0.3–0.6 μm/hr.

When producing epilayers of GaAsBi, a major consideration is the appropriate growth temperature. We usually operate between 350 °C and 400 °C, because when the temperature exceeds 400 °C bismuth incorporation becomes very small (less than 4 percent). Identifying the ideal growth temperature for GaAsBi is not easy – high growth temperatures impede bismuth incorporation, while low growth temperatures favour the incorporation of antisites, interstitials and vacancies, leading to poor device characteristics.

A key consideration is the abundance of bismuth on the semiconductor surface during growth. Its presence improves material quality by keeping the growing surface smooth, largely counteracting the effects of low growth temperature. However, if there's too much there, bismuth droplets form; as well as disrupting growth, these droplets drain the bismuth surface population and impair incorporation of this element into GaAs.

Another decision facing any grower of GaAsBi epilayers is the appropriate arsenic flux. Set this too high and the excess arsenic will kick bismuth atoms out of the growing lattice, as well as increasing the density of arsenic antisites. To avoid this, it is normal to employ an arsenic-to-gallium atomic flux ratio of between 0.9 and 1.1. There is very much a 'Goldilocks' set of growth conditions for good GaAsBi growth, where the temperature, bismuth flux and arsenic flux are all just right – not too big, not too small.

> For many years, there has been a strong desire to have silicon-like detector properties in devices made from III-Vs. Bismuth-engineering of the bandstructure may bring this closer to reality for the manufacture of low-noise detectors



➤ Figure 3. Left: Reducing the β/α ratio (increasing the disparity between α and β) reduces the noise in an avalanche photodiode. Predictions (solid lines) based on the experimental data (data points) indicate a very low noise for thick, high-bismuth-content layers. Right: For 1,500 nm-thick devices, GaAsBi is expected to out-perform silicon for a bismuth incorporation of 4 percent. Excess noise is predicted to continue to decrease at higher bismuth contents.

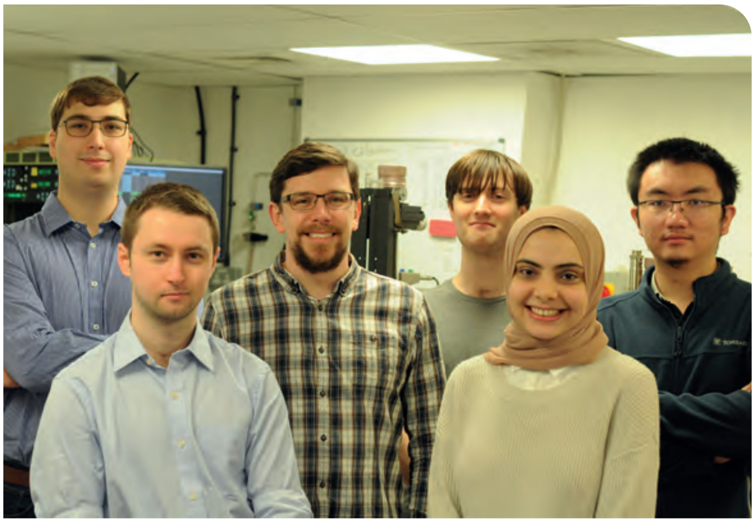
Our range of devices includes a number of *p-i-n* and *n-i-p* structures that have a GaAsBi active region with a thickness varying from 200 nm to 1600 nm and a bismuth content from 0.7 percent to 5 percent. From a combination of X-ray diffraction and photocurrent measurements on these samples, we see that the absorption coefficient at 1064 nm is more than one hundred times that of silicon for bismuth contents over about 3.5 percent – a promising result for photodetectors.

We have also undertaken electrical measurements on our devices. They revealed good forward diode characteristics that scaled with device area, and dark currents of below 10 mA prior to breakdown for devices with diameters of 50 µm. We think that a combination of bulk and surface leakage is behind the reverse-leakage currents in these diodes.

Measurements of electron- and hole-initiated photomultiplication have been used to determine values for α and β. This work revealed that increasing the bismuth content only produced about a 30 percent reduction in α values, while yielding an orders-of-magnitude reduction in β at low electric fields (see Figure 2).

Our calculations suggest that the GaAsBi material system can produce avalanche photodiodes with an excess noise below that achievable even by silicon (see Figure 3). While other III-Vs have reached comparably low noise in the past, this is the first time that this performance has been observed in an avalanche photodiode made with such a dilute (about 5 percent) alloy. Given that this work is in its infancy, even better results are likely to follow.

These results illustrate a mechanism for the production of very-low-noise avalanche photodiodes at wavelengths well beyond 1 µm. For many years, there has been a strong desire to have silicon-like detector properties in devices made from III-Vs. Bismuth-engineering of the bandstructure may bring this closer to reality for the manufacture of low-noise detectors that can serve in telecommunications and lidar.



➤ The Sheffield dilute bismides team in their MBE lab.
From left to right: Matthew Carr (PhD student), Nick Bailey (PhD student), Dr Rob Richards (group lead), Dr Tom Rockett (PDRA), Nada Adham (PhD student) and Shiyuan Gao (PhD student).

FURTHER READING

➤ Y. Liu *et al*. Nat. Commun. **12** 4784 (2021)

Alloyed oxide widens the band gap

Crystals that alloy Ga_2O_3 with Al_2O_3 promise to unlock a new era for ultra-wide bandgap devices

A PROMISING CANDIDATE for producing power devices with incredibly high breakdown voltages, as well as photodetectors that stretch far into the deep UV, is the novel alloy formed by mixing Ga_2O_3 with Al_2O_3.

Efforts at growing this exciting new material, β-$(Al_xGa_{1-x})_2O_3$, are in their infancy, but recent progress has just been reported by a team from St Petersburg, Russia. These researchers at ITMO University just announced that they have used the Czochralski method to produce a range of crystals of bulk β-$(Al_xGa_{1-x})_2O_3$ with aluminium fractions up to 0.23. When cut into substrates, crystals of this form could provide the foundation for ultra-wide-bandgap devices based on heterostructures of β-$(Al_xGa_{1-x})_2O_3$.

➤ A view, from the bottom, of a crystal of $(Al_xGa_{1-x})_2O_3$ produced by the Czochralski method.

This success from St Petersburg surpasses the triumphs of a team from India, which, in 2020, reported the fabrication of β-$(Al_xGa_{1-x})_2O_3$ with an aluminium fraction of up to 0.14 by the floating zone method.

Strengths of the floating zone method include the absence of the crucible and, thanks to melting just a fraction of the material, the opportunity to obtain purer crystals. Due to the latter attribute, this approach is often employed for the purification of material.

"But this technique, in contrast to Czochralski method, cannot be used for substrates production, since it is impossible to obtain crystals of a large diameter," commented spokesman for the Russian team, Dmitri Bauman.

He and his co-workers produced their crystals in a Nika-3 system. Although this growth tool, from the Ezan factory in Chernogolovka, has been designed and manufactured for making bulk sapphire, it is capable of producing a very wide range of crystals from the melt.

"We purchased it just for the gallium oxide project in 2014 and significantly improved it, especially the thermal zone," remarked Bauman.

Using powdered Ga_2O_3 and Al_2O_3 as starting materials, the team produced eight $(Al_xGa_{1-x})_2O_3$ samples with a range of aluminium fractions, starting from 0 and up to 0.23. Samples with a low aluminium content were transparent, but those with higher fractions of this element turned increasing light grey. Deterioration in crystal quality, observed in X-ray diffraction measurements and transmission electron microscopy, accompanied this change in colour. Absorption measurements revealed an increase in bandgap of 0.4 eV between $(Al_{0.23}Ga_{0.77})_2O_3$ and Ga_2O_3.

According to Bauman, once aluminium is added to Ga_2O_3, this prevents the formation of a defect-free crystal – and the more aluminium that's added, the greater the reduction in crystal quality.

"As we see it, crystals of appropriate quality can be grown at an aluminium content of about 5 percent or less," added Bauman, who explained that there are two issues to contend with. Part of the problem is that bond length for aluminium-oxygen is shorter than that for gallium and oxygen; and the other issue is that the oxides of Ga_2O_3 and Al_2O_3 that form a solid solution have different crystal lattices.

The team is now taking its research in three different directions.

"The first and main one is the development of an industrial technology for the manufacture of low-defect bulk gallium oxide crystals and substrates from them," explained Bauman. "This direction has already passed on to the technological stage from the scientific one."

Further efforts by the team are continuing the development of $(Al_xGa_{1-x})_2O_3$. This work will address scientific and technological unknowns, including those related to the thermal properties of this oxide.

"Finally, the last direction of research is related to testing our substrates in the process of epitaxial growth of layers and device structures on them."

REFERENCE

➤ D. Zakgeim *et al.* Appl. Phys. Express **15** 025501 (2022)

Superlattice thwarts degradation in dynamic on-resistance

Superlattices are superior to step-graded buffers at supressing degradation of dynamic on-resistance in GaN-based power devices

A TEAM from China has shown that an AlGaN superlattice is better than a step-graded heterostructure at quashing dynamic on-resistance in GaN-based power devices.

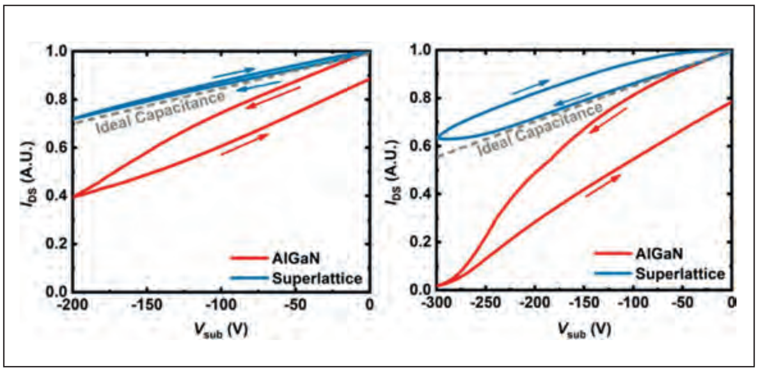
According to the spokesman for the team, Xuelin Yang from Peking University, addressing degradation in dynamic on-resistance is critical because it impairs the performance and the reliability of power devices. "From the viewpoint of application, we need a stable on-resistance."

Efforts by Yang and colleagues from Peking University, working in collaboration with researchers at Beijing University and the Collaborative Innovation Centre of Quantum Matter, have shed new light on a debate concerning the most appropriate architecture for reducing strain and ultimately quashing dynamic on-resistance degradation in GaN-based power devices.

Views expressed within the debate include claims that leakage paths only alleviate the degradation in the dynamic on-resistance, rather than suppress it; that the strain relief layer impacts depletion in the two-dimensional electron gas; and that the strain-relief layer influences the trap density. Other teams, however, see the strain-relief layer as an ideal dielectric, and are more concerned with the role of the carbon-doped buffer that sits on top, employed to boost the breakdown voltage. Extensive experiments by Yang and colleagues are now offering new insight – their investigations show that by providing more-effective blocking of electrons and holes, the superlattice is superior to the step-graded buffer at supressing degradation of the dynamic on-resistance.

The Chinese team came to this conclusion after comparing devices with step-graded and superlattice strain-relief layers. Both types of device had heterostructures grown by MOCVD on *p*-type silicon (111) substrates and featured a back gate on their underside and ohmic source and drain contacts separated by 15 µm. The device with the step-graded layer had a static on-resistance of 8.48 Ω mm, while the superlattice variant measured 9.09 Ω mm.

To uncover the influence of step-graded and superlattice structures on dynamic on-resistance, Yang and co-workers carried out back-gate ramping measurements. This study, revealing the impact of buffer trapping on the density of the two-dimensional electron gas in the channel, involved applying a fixed voltage of 0.5 V to the drain contact and sweeping a voltage applied to the back gate. If the entire epitaxial stack were an ideal dielectric without traps, it would behave as an ideal capacitor; but if there are traps in the buffer, charges would accumulate during this back-gate sweeping process, leading to hysteresis.



➤ Back-gating measurements highlight the superiority of the superlattice.

Experiments revealed that the device with the superlattice behaves far closer to that of an ideal capacitor than the variant with the step-graded structure.

Yang and colleagues have accounted for these findings. According to them, when a negative voltage is applied to a back gate, acceptors start to deplete in the carbon-doped GaN buffer and holes flow to the substrate. When this happens in the team's step-graded structure, the holes face just three energy barriers, compared with 100 barriers for their device with the 100-period superlattice. Consequently, the holes in the step-graded structure can easily leak away, contributing to hysteresis in the measurements; while holes in the superlattice are blocked, confined to this region, and result in an electrically neutral structure that has minimal hysteresis.

It is a similar situation for the electrons in the inversion layer at the interface between AlN and silicon. In the step-graded structure, electrons face just one energy barrier, while in the superlattice they face 100 higher-energy barriers. Due to this, the superlattice structure behaves like a capacitor, while that with a step-graded region acts as a resistor.

Yang and co-workers are now planning to further investigate the role of the superlattice on GaN-based power devices.

REFERENCE

➤ X. He *et al.* Appl. Phys. Express **15** 011001 (2022)

Empowering GaN HEMTs with a *p-n* junction

Adding a *p-n* junction to the GaN HEMT boosts its breakdown voltage

ONE OF the most significant weaknesses of the commercial GaN HEMT is that its gate voltage tends to be limited to no more than about 7 V to ensure safe operation. This restriction reduces the choice of gate drivers and rules out the use of silicon-based designs that have a gate bias of more than 10 V.

To overcome this limitation, a Chinese collaboration between Nanjing University and CorEnergy Semiconductor has developed a novel, reliable, large-area device that offers robust control of the gate. This device combines a HEMT with a *p-n* junction.

According to team spokesman Feng Zhou from Nanjing University, the strengths of their proof-of-concept device, produced with industry standard processes, include a high breakdown voltage of 18.2 V and a capability to operate for a long time under a gate bias of more than 10 V. "This leads us to believe that the *p-n* junction HEMT can be used directly with silicon drivers."

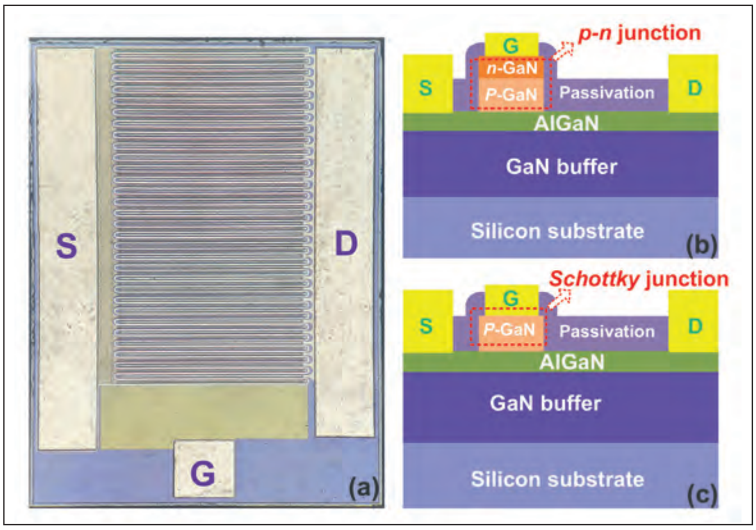
The Chinese partnership has been working on this novel GaN HEMT for several years, filing a patent back in 2019. "To our best knowledge, this is the first patent filed on the concept of the *p-n* junction gate architecture."

Fulfilling this technology's promise has not been easy, with the fabrication of large-area devices more challenging than their smaller counterparts, due to greater susceptibility to process variation.

Recently, the team has overcome this, with recent efforts highlighting the strong performance of devices with an area of 4.9 mm^2. These *p-n* junction HEMTs, along with a control that employs a Schottky junction, have been produced by taking a 150 mm silicon epiwafer, loading this into an MOCVD chamber, and depositing a 4.5 μm-thick buffer, followed by a 300 nm unintentionally doped GaN channel and a 13 nm-thick $Al_{0.2}Ga_{0.8}N$ barrier layer. For the *p-n* junction HEMTs, a 100 nm-thick magnesium-doped *p*-type GaN layer is added, followed by a 40 nm-thick silicon-doped *n*-type layer.

To produce devices from these epiwafers, the engineers etch away the top *p*-type and *n*-type layers from the access region, prior to thermal activation of the remaining *p*-type material, and the addition of ohmic contacts for the source and drain. A 1 μm-thick SiN passivation layer is subsequently added, before removal of a window that allows the addition of the gate contact (see figure for a diagram of this device, and also the control).

The team have deployed their *p-n* junction HEMTs in inductive switching circuits, where, compared with conventional Schottky-junction HEMT, they are said to deliver fast-switching and a strong immunity to dynamic on-resistance, . "What's more, our device shows superior over-voltage reliability, with a record-high dynamic breakdown voltage of 1.62 kilovolts," enthused Zhou.



➤ (a) Optical image and cross-sectional diagrams of the: (b) GaN p-n junction HEMT and (c), the GaN Schottky-junction HEMT.

Measurements of the dynamic blocking voltage have been undertaken with unclamped-inductive-switching experiments. Testing revealed an inferior value for 650 V Schottky-gate HEMTs of 1.45 kV. Having a higher value is very valuable, preventing the failure of power devices and the loss of all channel blocking capability due to gate failure.

An even better set of results could be realised, given that: the epitaxial material and the fabrication process are yet to be optimised, there is a degree of non-uniformity in the gate breakdown voltage, and there is hysteresis in the behaviour associated with the threshold voltage.

When analysing gate characteristics of unoptimized devices, the team found that the *n*-GaN capping layer in the gate stack plays a crucial role in suppressing the gate leakage current and tuning the electric-field distribution within the depletion region. This led them to see the need to improve material characteristics of the *n*-type GaN capping layer, such as its concentration and thickness, as well as its deposition conditions and gate-related fabrication processes.

"Additionally, our team is focused on optimizing device packages for low parasitics," revealed Zhou.

REFERENCE

➤ F. Zhou *et al*. IEEE Trans. Power Electron. **37** 26 (2022)

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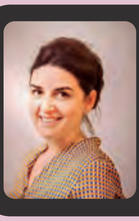

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