# COMPOUND SEMICONDUCTOR

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

30 YEARS ANNIVERSARY

VOLUME 31 ISSUE II 2025

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# 300 mm GaN

## COMPOUND SEMICONDUCTORS ARE GOING LARGE

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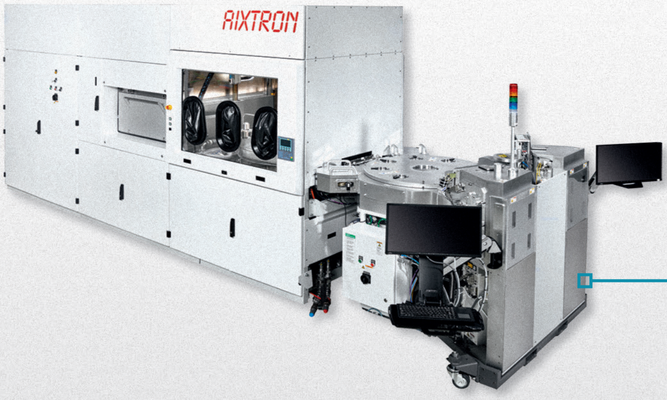
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# VIEWPOINT

BY RICHARD STEVENSON, EDITOR

## Marking another milestone

ARE YOU familiar with the French phrase 'plus ça change, plus c'est la même'? Often translated as 'the more things change, the more they stay the same', these words are apt description of how our industry has aged over the many years of this publication, which is now celebrating its thirtieth anniversary.

In this commemorative edition, as we look back over the last few decades, we can see that little has changed in the fundamentals associated with the production of compound semiconductor devices. Manufacture still involves loading substrates into MBE and MOCVD chambers, depositing a stack of semiconductors, and then processing the resulting epiwafers into devices using the likes of photolithography, etching and metal deposition.

But when we come to the devices themselves, there has been a great deal of change. In some cases, today's performance is vastly superior to that of the mid-1990s, and in other cases there are devices that are now generating billions of dollars that did not exist until well into this millennium. In addition, there are devices that once enjoyed commercial success that are now, from a commercial perspective, extinct.

When it comes to jaw-dropping levels of improvement, it's hard to beat the phenomenal increase in the bang-per-buck of the LED over the last 30 years. In the first edition of *Compound Semiconductor*, coming from a time before the smartphone had yet emerged as the first killer application for this emitter, red LEDs were starting to be deployed in traffic lights, by offering lower running costs. Back then – and now hard to comprehend with the benefit of hindsight – incandescents were tipped to remain as the incumbent source for yellow light, as they are on for less time, so make a smaller contribution to the electricity bill. Now LEDs are everywhere, lighting our homes and offices and backlighting many of our screens, thanks to their peerless efficiency and low cost.

For an obvious example of a device that has emerged from the labs relatively recently to net substantial revenue, I suggest the SiC MOSFET. After a few quite years following its commercial introduction in 2010, it's now one of our industry's biggest sellers, thanks to its deployment in the power train of electric vehicles.

And what about a shining star that has faded into obscurity? Well, for that I put forward the GaAs FET. Back in the twilight years of the twentieth century, GaAs-based digital electronics were playing a leading role in optical network infrastructure, providing key components in laser drivers, transimpedance amplifiers, multiplexers and demultiplexers. But the burst of the 'dot-com' bubble in 2000 thwarted sales, and when the market started to re-emerge, products based on silicon and SiGe took over.

In this issue, you can hear many fascinating stories of the rise, development, success and demise of compound semiconductor devices. Read on and enjoy.

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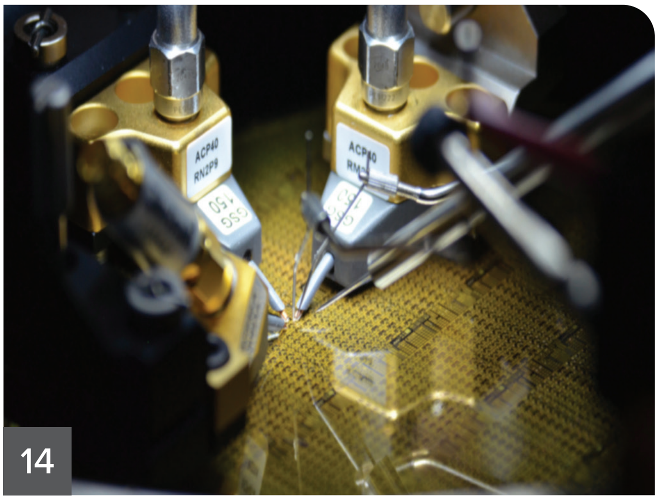

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INDUSTRY NEWS

# $25 billion compound semi market by 2030

**Compound semiconductors are 'enablers' outpacing the broader chip market, says Yole**

THE COMPOUND SEMICONDUCTOR market is set to reach $25 billion by 2030, according to market research firm Yole's latest report, *Status of the Compound Semiconductor Device Industry*.

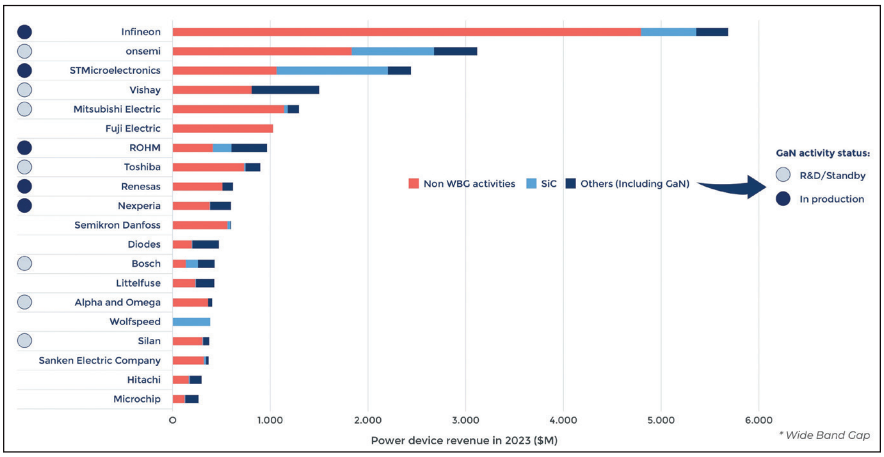
While being only a small part of the $1 trillion semiconductor device market, compound semiconductors are 'enablers', says Yole, driven by rapid growth in automotive, telecom, and mobile sectors.

Ezgi Dogmus, activity manager, compound semiconductors at Yole Group, said: "The compound semiconductor device industry is on a rapid growth trajectory between 2024 and 2030, surging at an impressive CAGR of nearly 13 percent – outpacing the broader semiconductor market. This acceleration is fuelled by the booming automotive and mobility sectors, with strong momentum also coming from telecom, infrastructure, and consumer electronics."

Over the past decade, a rapid push for power SiC adoption saw Wolfspeed divest its RF and LED businesses to concentrate on SiC. In parallel, STMicroelectronics, onsemi, and Infineon Technologies expanded their SiC investments, adopting vertically integrated business models to reduce wafer supply dependencies amid geopolitical tensions.

Following the SiC boom, OEMs are showing stronger interest in GaN for power electronics applications. This interest has led to a change in the landscape. The power GaN market is projected to grow beyond $2 billion by 2029, with a strong 5-year CAGR, according to Yole Group's analysts.

As of 2025, Innoscience, Power Integrations, and Navitas lead the power GaN market. In parallel, semiconductor giants Infineon Technologies and Renesas grew




by acquiring GaN Systems and Transphorm, respectively.

Poshun Chiu, senior technology and market analyst, compound semiconductors, at Yole Group, said: "It has also created synergies with GaN for RF applications. Companies like Infineon Technologies and GlobalFoundries, having invested in power GaN-on-silicon, are exploring synergies to leverage existing equipment, such as epitaxy, for RF production."

RF GaAs was the first compound semiconductor to achieve success in consumer applications, with a well-established ecosystem by 2025. Skyworks leads the market, followed by Qorvo and Murata, securing design wins in consumer end systems. However, geopolitical restrictions are driving Chinese OEMs to develop a local ecosystem.

Aymen Ghorbel, technology and market analyst, compound semiconductors, at Yole Group, said: "RF GaN was initially adopted in defence applications like radar, but over the past decade, it has expanded into telecom infrastructure, meeting 5G base station requirements. Interest in satellite communications and other use cases has also grown."

Semiconductor lasers drive the photonics compound semiconductor industry with an expected $5 billion market by 2029. These technologies are widely used in communication, sensing, and more. With the rise of AI, the datacom sector has experienced significant growth, driving strong demand for silicon photonics.

At Yole Group, analysts have identified a growing number of collaborations between the InP photonics and silicon industries. Major semiconductor giants like TSMC are entering the photonics business. And step by step, more players, such as GlobalFoundries and Samsung, may follow in the future.

The microLED display industry is highly fragmented, with no single entity overseeing manufacturing from start to finish. Unlike traditional vertically integrated display production, microLED manufacturing requires distinct expertise.

Major display makers like BOE and AUO are securing control over LED suppliers, while startups and equipment makers contribute to major technologies. Geographic alliances, particularly in China and Taiwan, are shaping industry dynamics.

Apple's withdrawal has slowed funding, leaving most startups struggling and undermining confidence in microLED's prospects.

# U-M wins up to $7.5 million for heat-tolerant SiC

Open-source effort will build extra-durable SiC chips that can operate at record high temperatures

UNIVERSITY OF MICHIGAN researchers are leading a collaborative effort to bring more heat-resistant sensing and computing chips made of SiC to market for use in advanced aircraft, electric and gas-powered vehicles, renewable energy, defence and space exploration.

Funded by the Silicon Crossroads Microelectronics Commons Hub, the project is launching with $2.4 million in initial funding, and could receive up to $7.5 million over three years.

Engineers at NASA's Glenn Research Center have been researching into the potential of SiC for decades. With an eye toward exploring the surface of Venus, they built a SiC circuit that can withstand 500°C for thousands of hours. NASA Glenn has also shown packaged device operation over a 1,000°C temperature span from -190°C to 812°C with relevance across aerospace.

While SiC is increasingly used in power electronics for EVs, solar and wind energy systems, these applications aren't making the most of its resilience to extreme conditions, say the researchers.

The new project will scale up NASA's technology and manufacturing process to a modern wafer size and make SiC chip design much simpler.

Along with NASA, collaborators include GE Aerospace Research in Niskayuna, New York; Ozark Integrated Circuits, a technology firm in Fayetteville, Arkansas; and Wolfspeed, a North Carolina-based semiconductor manufacturer.

The project will focus on aerospace, including electronics and sensors that make aircraft engines more reliable and help optimise their size, weight and power. A key goal is the demonstration of a packaged actuator for aerospace or engine applications that can convert electrical signals to mechanical motion.

"NASA, GE Aerospace and Ozark IC have done an amazing job of developing this technology, which is very impactful for a variety of applications. This project will provide a critical pathway to advance and commercialise that technology," said principal investigator Becky Peterson, associate professor of electrical and computer engineering and director of the U-M Lurie Nanofabrication Facility.

In the project, NASA Glenn and GE Aerospace will work together to scale a high temperature SiC JFET fabrication process from 100- to 150-mm wafers.

"SiC-based high temperature electronics will be a key enabler for delivering new sensor and actuator functionality that improves the capability of future DoD engine platforms. Beyond jet engines, the ability to handle more extreme temperature capabilities could open exciting new applications in control and sensing for hypersonic applications," said Aaron Knobloch, platform leader, controls and electrical systems at GE Aerospace Research.

This programme builds on Ozark IC's existing Department of Defense work with NASA where DARPA has supported SiC JFET-R technology transition to GE Aerospace's 100 mm facility in New York, and its application to aerospace sensing through the DARPA High Operational Temperature Sensors (HOTS) programme.

SiC specialist Wolfspeed will provide the SiC wafers necessary for these devices, building on its deep expertise and capacity in epitaxy of SiC.

# Partnership aims to secure US gallium supply

Mining company Nimy Resources and supply chain firm M2i Global to collaborate on securing supply of gallium to DoD

NIMY RESOURCES, a mining company, has entered into a collaboration with mineral supply chains firm M2i Global to secure a steady supply of gallium for the US Department of Defense (DoD).

In addition to its role in supply chains, M2i Global has subsidiaries, US Minerals and Metals Corp., involved in engineering, research and services to facilitate access to essential minerals and metals.

Gallium is a critical mineral in compound semiconductors, including GaAs, GaN, and $Ga_2O_3$, used in many defence and security applications, including radar and aerospace technologies.

Nimy Resources chairperson Neil Warburton said: "Nimy's strategy of developing a diversified integrated gallium supply chain continues to gain momentum and the agreement with M2i Global is a continuation of this progress."

M2i president and CEO Major General (Ret) Al Rosendo said: "This agreement with Nimy will assist the work we are doing in support of US National Defense and Economic Security."

M2i will continue its efforts to meet the needs identified by the Manufacturing Capability Expansion and Investment Prioritisation office, which works to assure a reliable, sustainable supply of gallium and other critical materials within the US to be used in the production of semiconductors in the advanced technology sector.

Rosendo added: "DOD wants to build a resilient industrial base to meet current and future national defence requirements."

# CGD secures $32 million in funding

Cambridge University GaN spinout secures Series C funding to expand operations in Cambridge, North America, Taiwan and Europe

CAMBRIDGE GaN Devices (CGD) has closed a $32 million Series C funding round. The investment was led by a strategic investor, with participation from British Patient Capital and supported by existing investors Parkwalk, BGF, Cambridge Innovation Capital (CIC), Foresight Group, and IQ Capital.


The funding will enable the company to expand its operations in Cambridge, North America, Taiwan and Europe, and deliver CGD's unique value proposition to its growing customer base.

CGD's monolithic ICeGaN technology, designed to simplify the implementation of GaN into designs, delivers efficiency levels exceeding 99 percent, enabling energy savings of up to 50 percent in a wide range of high-power applications, including electric vehicles and data centre power supplies.

The global GaN power device market is projected to grow at a remarkable CAGR of 41 percent, reaching $2 billion by 2029. At the same time, ICeGaN is being seen as a viable alternative to existing solutions using SiC, combining high energy-efficiency, miniaturisation, and monolithically integrated smart functionalities.

CGD says this will give it access to a high power market estimated to be in excess of $10 billion by 2029. Giorgia Longobardi, CEO and founder of CGD said: "This funding round marks a pivotal moment for CGD. It validates our technology and vision to revolutionise the power electronics industry with our efficient GaN solutions and make sustainable power electronics possible. We're now poised to accelerate our growth and make a significant impact in reducing energy consumption across multiple sectors. We look forward to collaborating with our strategic investor to penetrate the automotive market."

Henryk Dabrowski, SVP of sales at CGD, said: "This investment will significantly boost our ability to meet the growing demand for our reliable and easy-to-use GaN solutions."

John Pearson, CIO at Parkwalk Advisors, commented: "CGD is at the forefront of technology that can reduce the energy demands of booming industries, like artificial intelligence and electric mobility. It has enormous global potential and widespread applications which will see CGD continue to innovate and grow."

George Mills, director at British Patient Capital, added: "Following years of research, Cambridge GaN Devices have proven the impact of their semiconductor technology. Their GaN devices consume less energy than their silicon-based counterparts, which both reduces costs and has a positive environmental impact."

Mills added: "It's valuable technology that now needs long-term capital to scale."

# Infineon starts 200 mm SiC product-roll out

Chips fabricated in Austria will provide customers state-of-the-art power tech for high-voltage applications

INFINEON TECHNOLOGIES has announced significant progress along its 200 mm SiC roadmap, with customers receiving the first products based on the technology in Q1 2025.

Manufactured in Villach, Austria, these new SiC power devices are targeted for use in renewable energy applications, trains, and electric vehicles.

Additionally, Infineon says the transition of its site in Kulim, Malaysia from 150 mm to 200 mm wafers is on track. The newly built Module 3 is poised to start high-volume production to meet market demand.

Rutger Wijburg, COO of Infineon, said: "By ramping up SiC production in Villach and Kulim in phases, we are improving cost-efficiency and continuing to ensure product quality."

"At the same time, we are making sure our manufacturing capacities can meet the demand for SiC-based power semiconductors."

Infineon's production sites in Villach and Kulim share technologies and processes which allows for fast ramping in both SiC and GaN manufacturing, according to the company.

## Innoscience files lawsuit against Infineon

CHINESE GaN firm Innoscience and its subsidiary Innoscience (Suzhou) Semiconductor have filed a lawsuit against Infineon Technologies (China), its subsidiary Infineon Technologies (Wuxi) and a value-added Chinese distributor called Suzhou Xinwoko Electronic Technology.

The lawsuit concerns patent numbers 202311774650.7 and 202211387983.X (both owned by Inno Suzhou), which respectively involve a GaN power device and its preparation method, and a nitride-based semiconductor device and its manufacturing method.

The complaint is around Infineon's Chinese website, which displays and promotes various GaN semiconductor devices to potential customers in China.

After technical comparisons, Innoscience says amongst the devices are patent- infringing products that are being imported and sold without Innoscience's permission.

Innoscience says this activity constitutes an infringement of the patents involved in the case, and Infineon should stop the infringement and pay compensation.

## Former Wolfspeed CEO joins Power Integrations board

POWER INTEGRATIONS, known for its innovative power technology including PowiGaN, has appointed former Wolfspeed CEO Gregg Lowe to its board of directors.

From 2017 until 2024 Lowe led Wolfspeed's company's transition to a pure-play manufacturer of SiC solutions for high-power applications.

Previously, he was CEO of Freescale Semiconductor from 2012 until its 2015 merger with NXP Semiconductors. Earlier, he had a 27-year career at Texas

Instruments, serving in a succession of leadership roles across field sales, automotive sales, marketing, and integrated circuits.

Lowe currently serves on the boards of Silicon Labs and North Carolina A&T University, and is chairman of the board of the Rock and Roll Hall of Fame Museum.

Balu Balakrishnan, CEO of Power Integrations, said: "We are delighted to welcome Gregg Lowe to our board. Gregg is an ideal fit thanks to his decades of experience in analogue and power semiconductors, particularly his expansive knowledge of the sales and distribution landscape and deep customer relationships in key end markets including automotive and industrial."

# UK SiC fab secures Indian investment

**Clas-SiC to get £12 million investment from Chennai-based Archean Chemical Industries**

Clas-SiC, the UK's only commercial SiC wafer fab, has secured a £12 million investment from Indian chemical firm Archean Chemical Industries, based in Chennai.

In exchange, Archean will gain board representation, with Ranjit Pendurthi appointed as a director.

The Scotland-based company aims to use the funds to advance next-generation semiconductor technology.

Jen Walls, CEO at Clas-SiC, said: "This investment secures next-generation technology development and manufacturing. We already export power semiconductors globally, partnering with customers from North America, Europe and Asia.

"This is an exciting time for us and will further secure our place on the global compound semiconductor market."

UK Science Minister Lord Vallance welcomed the deal, stating: "Attracting investment from around the world is vital in growing the UK's compound semiconductor sector and supporting the work of innovative companies like Clas-SiC."

For Archean Chemical Industries, the investment is seen as a strategic move towards potentially building India's first dedicated SiC power device manufacturing facility in the coming months.

Clas-SiC Wafer Fab is the UK's only commercial SiC-dedicated wafer fabrication facility. It focuses on providing rapid prototyping for early design concepts, reducing time-to-market with short-cycle time and low-rate production in Scotland.

Founded in 2017, Clas-SiC has grown from 24 employees to around 75 through private investment, achieving a 100 percent rise in turnover over the past two years.

# GaN adoption at tipping point, says Infineon

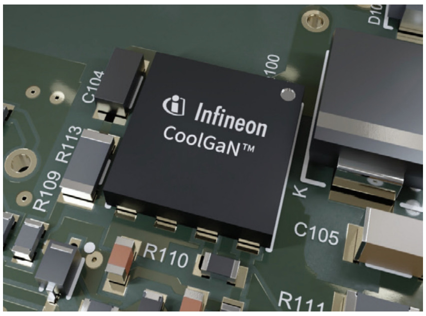
Company's 2025 predictions say GaN is becoming a game-changer across multiple industries

IN ITS 2025 predictions, Infineon says GaN will be a game-changing material across consumer, mobility, residential solar, telecommunication, and AI data centre industries, enabling more-efficient performance, smaller size, lighter weight, and lower overall cost .

While USB-C chargers and adapters have been the forerunners, GaN is now on its way to reaching tipping points in its adoption in further industries, substantially driving the market for GaN-based power semiconductors, according to Infineon.

"Infineon is committed to driving decarbonisation and digitalisation through innovation based on all semiconductor materials silicon, SiC, and GaN," said Johannes Schoiswohl, head of the GaN business line at Infineon. "The relevance of comprehensive power systems will increase with GaN manifesting its role due to its benefits in efficiency, density, and size. Given that cost-parity with silicon is in sight, we will see an increased adoption rate for GaN this year and beyond.

Powering AI will be highly dependant on GaN. The rapid increase of required computing power and energy demand in AI data centres will drive the need for advanced solutions capable of handling the substantial loads associated with




AI servers. Power supplies that once managed 3.3 kW are now evolving towards 5.5 kW, with projections moving towards 12 kW or more per unit.

By using GaN, AI data centres can improve power density, which directly influences the amount of computational power that can be delivered within a given rack space. While GaN presents clear advantages, hybrid approaches combining GaN with silicon and SiC are ideal for meeting the requirements of AI data centres and achieving the best trade-offs between efficiency, power density and system cost.

In the home appliance market, Infineon expects GaN to gain significant traction, driven by the need for higher energy-efficiency ratings in applications like washing machines, dryers, refrigerators and water/heat pumps. In 800 W applications, for example, GaN can enable a two percent efficiency gain, which can help manufacturers achieve the coveted A ratings.

According to Infineon, GaN-based on-board chargers and DC-DC converters in electric vehicles will contribute to a higher charging efficiency, power density, and material sustainability, with a shift towards 20 kW+ systems. Together with high-end SiC solutions, GaN will also enable more efficient traction inverters for both 400 V and 800 V EV systems, contributing to an increased driving range.

In 2025 and beyond, robotics will see widespread adoption of GaN, supported by the material's ability to enhance compactness, driving growth in delivery drones, care robots and humanoid robots. As robotics technology integrates AI advancements like natural language processing and computer vision, GaN will provide the efficiency required for compact, high-performance designs. Integrating inverters within the motor chassis eliminates the inverter heatsink while reducing cabling to each joint/axis and simplifying EMC design.

Infineon says it is further pushing investment in GaN research and development to overcome the challenges of cost and scalability. These include 300 mm GaN wafer manufacturing and bidirectional switch transistors.

# ST, Microoled and Quanta to deliver AR glasses design

Reference design will enable eyewear manufacturers to create diverse models for sports and outdoor applications

Microoled, a Grenoble-based maker of OLED micro-displays and AR smart glasses, the semiconductor company STMicroelectronics, and equipment maker Quanta, will work together develop a reference design for AR smart glasses.

This joint effort focuses on providing a solution for use within sports and other outdoor activities, described as requiring 'mission-critical information in real-time and on-the-move'.

The reference design, engineered and manufactured by Quanta and powered by ST's STM32U5 microcontrollers, will enable smart eyewear manufacturers to rapidly develop and deploy a variety of 'Light AR' glasses models with low power and advanced graphics.

These models can be customised with different optics and display modules to meet specific market needs. Integration with the ActiveLook firmware will provide access to an expanding ecosystem of sports applications and smartwatches compatible with the ActiveLook API, along with a thriving developer community.

"This collaboration represents a significant step forward in making widespread 'Light AR' solutions a reality," said Xavier Bonjour, partnerships and marketing director, Microoled.

"By combining mLED's light AR software platform, Quanta's electronics design and manufacturing expertise, and STM's semiconductor leadership, we are empowering eyewear manufacturers to create innovative smart eyewear that delivers critical information when and where it's needed most: on the move!"

Prototypes of the reference design were exhibited at ShowStoppers, a press event of MWC Barcelona 2025, and were visible at the MWC main show, on the Microoled booth.

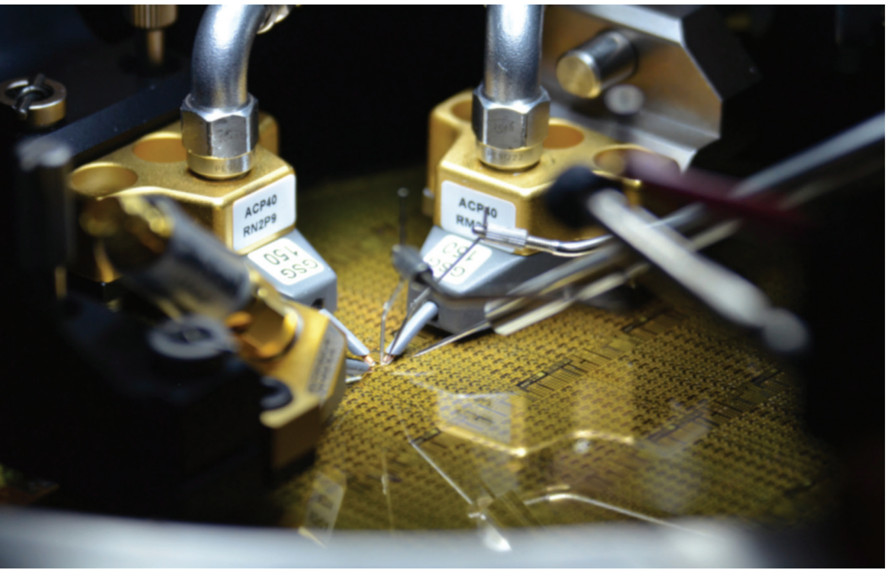
# Displacing GaAs in handsets by 2030

Finwave's roadmap for the commercialisation of its GaN-on-silicon technology begins with switches and amplifiers for infrastructure, will continue with penetration into the handset

**BY RICHARD STEVENSON, EDITOR, CS MAGAZINE**

OVER THE LAST 30 years, opportunities for GaAs microelectronics have narrowed. In the final decade of the twentieth century, digital GaAs served in the infrastructure of optical networks, driving a number of components, including lasers, transimpedance amplifiers and multiplexers. After silicon and SiGe components took over, following the bursting of the dot-com bubble, the RF domain has accounted for all sales of GaAs transistors. While some revenue has come from defence and network infrastructure, the handset is responsible for the lion's share. Initially, GaAs pHEMTs provided the switching function, before they were displaced by silicon-on-insulator technologies, leaving the main role for GaAs as power amplification. But this is now under threat, with US firm Finwave predicting that GaN will be taking on this task in handsets by the end of this decade, while enjoying additional sales from its deployment as a switch and power amplifier in infrastructure and aerospace and defence applications.

According to the CEO of Finwave, Pierre-Yves Lesaicherre, the reason why GaN will trump GaAs in the handset PA is that the incumbent is running out of steam above 6 GHz. "The power efficiency is just too low," claims Lesaicherre, pointing out that Finwave's enhancement-mode MISFET technology, which can run off a 5 volt supply, offers a high power-added efficiency from 6 GHz up to 40 GHz. These strengths, combined with the capability to deliver a high power-density, ensure that the GaN MISFET is a compelling candidate for amplification for WiFi 7, for the FR3 band that's used for 5G communication, and for bands that will be used for 6G communication.




➤ Testing RF devices.

Displacing GaAs PAs is a long-term goal for Finwave, which has made progress on many fronts since Lesaicherre took charge in summer 2023.

A spin-out of MIT, Finwave still has roots in the locality. Roughly half of the 23-strong team are located in Waltham, near Boston, working on processes and device architectures associated with the company's proprietary GaN-on-silicon technology.

The remainder, responsible for product design, product engineering test and quality, and supply chains, are located in San Diego, California. "We have moved to a larger office in the Sorrento Valley next to pSemi and Qualcomm," says Lesaicherre.

Also helping to lay foundations for further success are the hiring of a few additional RF designers, the appointment of a VP of Marketing and a chief financial officer, and the establishing of partners for device production.

"In August '24, we signed a technology licencing and transfer agreement with Global Foundries to transfer our low-voltage E-Mode MISHEMT RF GaN-on-silicon technology for handset applications," says Lesaicherre. "This technology is unique, and it's being transferred to an 8-inch fab in Burlington, Vermont."

The second key partnership that's been cemented in the last few months is with a leading foundry in Taiwan, which has started producing Finwave's RF switches and high-power amplifiers for communication and infrastructure applications.

To produce packaged devices, Finwave has another partner, Unisem, in Malaysia. This provider of back-end services is described by Lesaicherre as a leading test and assembly house for RF semiconductors.

Recently, Finwave's supply chain has been refined through its introduction of a product life management system and a quality management system. And a sales ramp over the coming years will be supported by a distribution agreement with a leading RF distributor, the details of which should emerge in the next few weeks.

## Finwave's product roadmap

Finwave's goals for the first half of this year include process and product qualification of its first RF switches in quarter one, 2025, followed by a ramp in sales of the first three RF switches in the subsequent quarter.

"The products are 10-watt, a 20-watt, and 40-watt RF switches that operate from a few megahertz to 13 gigahertz," reveals Lesaicherre, who argues that these devices offer a unique and compelling combination of assets. They have a capacity to handle high powers and frequencies, and they have very fast switching and settling times –just hundreds of nanoseconds.

Lesaicherre says that one of the one weakness of switches based on silicon-on-insulator (SOI) technology is their limited power handling, as they struggle with signals above 10 watts.

"We see our product more of an extension of the RF SOI switch, rather than a direct competitor," remarks Lesaicherre. "Now, we're competing with GaN-on-silicon carbide switches, but at a much lower production cost, which gives us a major pricing advantage."

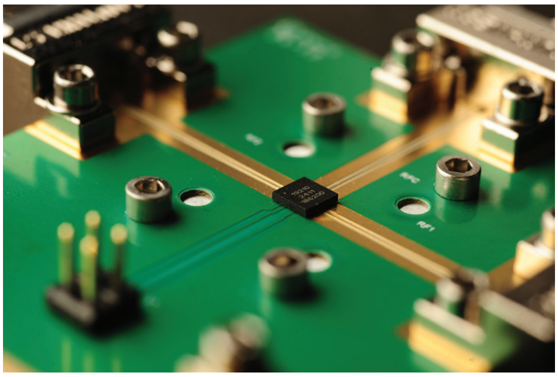
Finwave's switch portfolio will expand this year, due to the introduction of many more products. Improved performance is also in the pipeline, with the company working on second-generation technology.

Switches produced by this fabless firm could serve in a number of applications in both defence and infrastructure sectors. Many opportunities exist, including those in radar, miliary radio systems and base stations.

As well as growing its switch portfolio, Finwave is focusing on the commercialisation of high-power amplifiers, operating at typically between 15 volts and 28 volts, for communication infrastructure.

"The main competition here is also GaN-on-silicon carbide," claims Lesaicherre. "Again, we have a major cost advantage, and also the ability to scale to eight-inch wafers, and possibly 12-inch wafers in the future."

An additional, exciting opportunity for Finwave is the possibility to integrate the PA,  the low-noise amplifier and the switch on a single GaN-on-silicon chip. According to Lesaicherre, such a technology promises significant cost and integration advantages over today's RF front-ends, which combine multiple chips, manufactured using different material systems. "We think that's a key differentiator for telecom infrastructure."



➤ Finwave's RF Switches mounted on an evaluation board.

For the third opportunity Finwave has identified – displacing the GaAs PA in the handset – the higher performance that GaN-on-silicon provides and the possibility to produce a single chip that incorporates a PA, a low-noise amplifier and a switch could fuel the growth of GaN-on-silicon technology.

## A shift in focus

When Finwave spun-out of the labs at MIT, initially under the moniker Cambridge Electronics, it attracted much attention for its finFET technology. While this is not being used in its emerging switch and power amplifier products, all based on planar architectures, it has not discarded this novel approach to transistor design. "We've also demonstrated that with a 3-D finFET architecture we can improve linearity for D-mode power amplifiers for infrastructure, but we are not yet producing these," reveals Lesaicherre.

Another shift in focus over the last few years has been a move away from pursuing success in the power electronics sector to concentrating on opportunities in the RF domain.

"We had some interesting developments on low-voltage and medium-voltage GaN technology, so we believe our technology is capable of addressing this market, but our current focus is solely on RF applications," insists Lesaicherre. "We've got a lot on our plate with the development of a full range of RF switches and power amplifiers."

Focusing on RF applications, where there are far fewer competitors than there are for GaN power electronics, promises to generate significant sales. According to Lesaicherre, the total addressable market in the 2028 to 2030 timeframe is a few billion dollars per annum for amplifiers in cellular infrastructure, and $4-5 billion for amplifiers in handsets. Given these figures, there's great potential for substantial growth for Finwave throughout this decade and beyond.

# Unleashing the potential of the JFET

The acquisition of Qorvo's SiC JFET portfolio provides onsemi with a great opportunity to accelerate the adoption of this class of transistor in circuit breakers, EV battery-disconnect units and AI infrastructure

**BY RICHARD STEVENSON, EDITOR, CS MAGAZINE**

BACK IN the days of the global credit crunch, many pioneers of SiC transistors were striving to be the first to market with their own particular flavour of this technology.

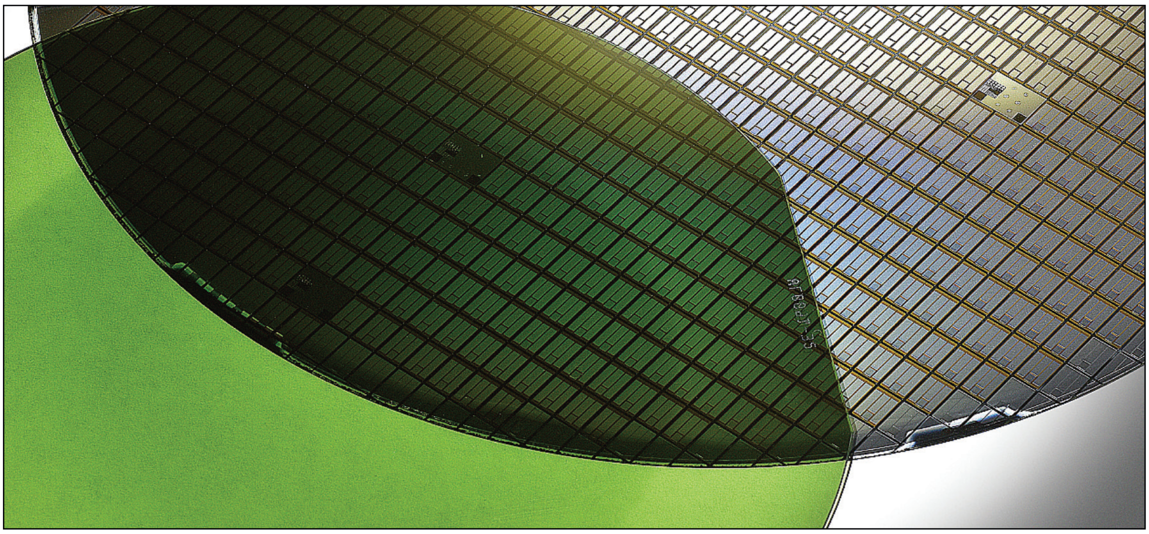
Initially grabbing the headlines were the likes of Semisouth and SiCED, trailblazers of the JFET, and BJT pioneer TranSiC. But their products struggled to make an impression, and when Cree and Rohm introduced the SiC MOSFET, this duo laid the foundations for a market that's now netting over a $1 billion per year and continuing to climb.

Based on this chain of events, it is easy to fall into the trap of concluding that the SiC MOSFET is superior to other forms of SiC transistor, which will never have a role to play. But one can also argue, for good reason, that some of the alternatives were ahead of their time, with circuit designers failing to appreciate their virtues and exploit them.

In a nut shell, that's the view of Sergio Fissore, who holds the position of Vice President and General Manager, Multi-market Power Division, at the electronic components manufacturer onsemi, which has just completed a $115 million acquisition of Qorvo's SiC JFET portfolio. Fissore believes that with this acquisition, onsemi will accelerate deployment of the JFET in EV battery-disconnect units, in AI infrastructure and in industrial solid-state circuit breakers, with total sales from this class of transistor netting several hundred million dollars per annum in the coming years.

Fissore argues that the SiC JFET, a device that's today only available from onsemi, failed to make an impact when initially introduced in the late noughties, due to concerns related to practicality and the long-term reliability of wide bandgap devices. If more designers had taken a closer look at that device back then, they would have been impressed by its performance, as well as that of the BJT, a transistor Fissore worked on during his time at Fairchild. He believes that a reluctance of customers to take a risk with new device technologies impeded sales of the SiC BJT, which were also held back by a lack of expertise in how to drive this device – rather than applying a particular voltage, it's the current that must be considered.

Tesla transformed the *status quo* with the adoption of SiC MOSFETs in its EVs, a move motivated by the opportunity to extend the driving range through an increase in power conversion efficiency, and a willingness to brush off the reliability risks and design complexities and resolve any issues that arose.



➤ An onsemi SiC wafer (left), and a final version (right), created by epitaxial growth, doping, device fabrication and etching.

"Many of our customer realised that if an automotive company takes that risk, those risks were worth taking, given the benefits you get from a wide bandgap," says Fissore.

He believes that today's designers are more adventurous, with a willingness to design gate drives and controllers for many different device requirements. Now, wide bandgap devices are seen as just another type of transistor, and designers are focusing on value, selecting the transistor by considering cost at the system level.

One of the attractions of the JFET is its bang-per-buck. For a given on-resistance, this chip can be smaller than other forms of SiC transistor, and the cost of production is relatively low, with fewer mask layers required for its manufacture compared with that of the SiC MOSFET.

The downside of the JFET is that it's normally-on. So, to provide a normally-off product with good switching and an acceptable level of ringing, the SiC JFET is paired with a low-voltage silicon MOSFET in a cascode configuration.

To optimise this combination, the JFET and the silicon MOSFET must be designed together and matched, a task that plays into the hands of companies such as onsemi, which have expertise in both forms of transistor.

## Market opportunities

onsemi sees a significant opportunity for its SiC JFET in solid-state circuit breakers. This device could replace electromechanical relays, which suffer from arcing that reduces their reliable lifespan when they are switched on and off. As well as an attractive candidate for this application, the SiC JFET could find deployment in EV battery disconnects, thanks to its small size, high reliability and very low on-resistance.

Another opportunity for the JFET is in AI, a technology that has led to a dramatic increase in the power within each rack in the datacentres. The high-voltage AC supply from the mains has to be converted down to a 0.8 volt DC form as efficiently as possible. Inevitable losses occur that lead to heating, with air cooling already replaced by liquid cooling to ensure adequate thermal management. "Our customers are saving twice, by using high-efficiency high-performance transistors. You need cheaper apparatus to cool, and you have less electrical energy wasted in heat, so you reduce the challenge of reliability," enthuses Fissore.

In addition, designs with the SiC JFET can accommodate high frequencies, minimising the size of the inductors. This allows onsemi to compete with companies producing GaN transistors for this application.

## An alternative to the superjunction

onsemi's interest in the JFET started around five years ago, after realising that it would struggle to make an impression in the silicon superjunction market. The company identified the SiC JFET as a promising technology that would complement its SiC MOSFET portfolio, while offering the opportunity to go to higher frequencies.

Initially, onsemi invested internally, before changing direction and deciding to get to market more quickly through an acquisition.

Buying Qorvo's SiC JFET business – which it had acquired in late 2021 through the acquisition of United Silicon Carbide – has given onsemi a broad SiC JFET portfolio, with over 80 products, spanning 650 volts to 1.7 kV. onsemi could have also developed a comparable family of SiC JFETs through internal development, but Fissore estimates that it would have taken three-to-four years to do so.

For $115 million, onsemi has obtained Qorvo's SiC JFET business, its customers, a talented workforce, and IP related to planar and trench forms of this transistor. Little equipment came with the sale, as Qorvo outsourced JFET production, but onsemi is able to continue working with the established foundries and sub-contractors.

Separating Qorvo's JFET business from its other activities has been relatively easy for both sides, as the team working on the JFET were not heavily integrated with other activities. These new staff at onsemi are bringing much valuable experience, and they include those that invented JFET technology and have been working on this class of device for a couple of decades.

Substrate supply is not a concern for onsemi. As well as its own vertically integrated SiC supply chain, the company is able to work with the three suppliers that Qorvo has qualified – and it is looking to add to this list.

Another of onsemi's goals is to refine its JFET portfolio by lowering the on-resistance, measured in milli-ohms, to what is described as "very low single digits".

Efforts will also be directed at improving packaging, and introducing power modules capable of handling thousands of amps.

Given the market opportunities for the JFET, Fissore forecasts that competition will emerge for sales within a few years.

Potential rivals are not a concern, and the focus is on ramping sales of the JFET to generate revenues worth hundreds of millions of dollars.

"I'm sure we'll get there and stay as number-one market share as long as possible, meaning for decades," claims Fissore.

➤ Sergio Fissore holds the position of onsemi Vice President and General Manager, Multi-market Power Division. Fissore has previously worked at Infineon and the Fairchild, acquired by onsemi in 2016.

# AIXTRON looks to 'go large'

Supporting the shift to production with larger wafers is Aixtron, the world's leading manufacturer of MOCVD tools, explains the company's VP technology Jared Holzwarth

**AN INTERVIEW WITH RICHARD STEVENSON, EDITOR, CS MAGAZINE**

**RS:** *Back in 1995, when Compound Semiconductor premiered, Aixtron had already celebrated its tenth anniversary. How does the Aixtron of 1995 compare to how it is today?*

**JH:** Well, I was 17 back in 1995, so I'm not completely sure how it was in '95! But I do know that Aixtron is very much the same in some ways, and in other ways it's a bit different.

What has been the same is the innovative spirit. From its inception, Aixtron's been based on innovation and a desire to challenge the impossible.

Where I think it's changed significantly is how much closer we are to the customer, in terms of process, application, and know how. While we were putting all our focus on delivering performance hardware in the past, today we're looking at turnkey solutions that are closely co-optimised with the customer, to make sure they're successful in all their milestones. I think you can see the results of that with the latest silicon carbide MOSFETs and GaN HEMTs. They really show that new side of Aixtron.

**RS:** *In the late 1990s, the GaAs microelectronics sector dominated high-volume manufacturing within the compound semiconductor industry. Since then, we have seen the growth in sales of GaN LEDs, and more recently wide bandgap power electronics.*

*Aixtron began with MOCVD tools for traditional III-Vs, such as GaAs and InP. How difficult has it been to expand into the nitrides and silicon carbide?*

**JH:** For the nitrides it went in two waves of technology adoption. We developed dedicated solutions for each of those big waves.

For the solid-state lighting push – back at that time, I was actually at a customer of Aixtron, Philips Lumileds – the main focus was associated with the temperature control on each substrate, how that occurred over all the substrates, and how to do that for longer deposition campaigns. We developed a technology with closed-loop temperature control to manage temperatures at the wafer level. With the adoption of 4-inch, at the time of our launch of a G3 platform, higher volume manufacturing started to begin.

The second wave was more focused on GaN-on-silicon structures for power devices. That was more than ten years ago. Here we faced one crucial problem: when we started to grow GaN-on-silicon, it would result in gallium melt-back etching of the silicon substrate, if we didn't have a completely clean reactor. It was a critical point for us, because we were just undertaking development of the very first cassette-to-cassette wafer automation for our MOCVD systems aiming at a full automation for the planetary reactor design. Exchanging any reactor parts between runs, like the covers that protect the reactor walls from getting coated, wouldn't be suitable for volume manufacturing, reliability or cost wise. We took a strategic decision to develop *in-situ* clean technology, which is one of our fundamental technology building blocks since then. It has helped all of our customers master the complex requirements of GaN-on-silicon epitaxy and volume production.

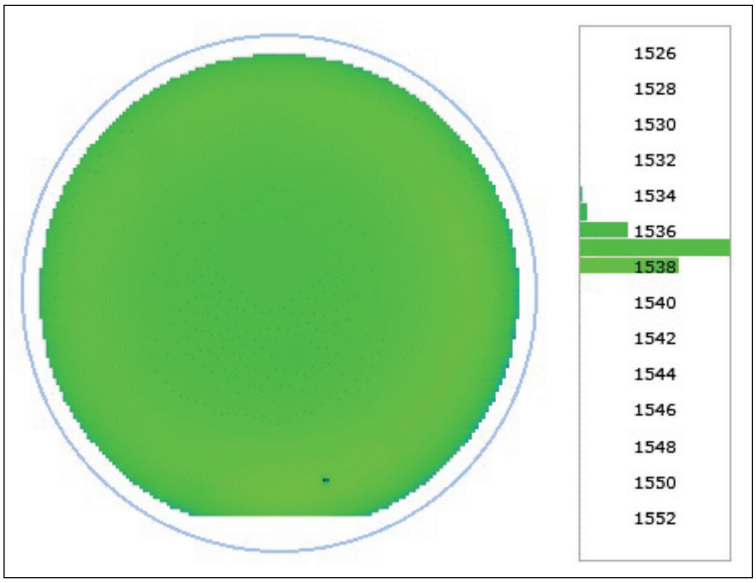
For GaN-on-silicon power devices to succeed, we had to grow highly uniform HEMT structures on silicon substrates, at the time 150 millimetre. It was a big challenge because of lattice mismatch. There was a lot of work that went into managing the strain, to prevent slip lines and edge cracks. At that time, we introduced a curvature sensor to our tools, which really changed the life of process engineers, allowing them to measure and monitor strain build up throughout epitaxy growth in real-time.

For silicon carbide, we've been involved for more than 20 years. We took a big turning point in the last four years, when we really framed a key technology question that plagued us for years. That was: What drives the edge effect or the doping profiles that prevents us from getting even better uniformities?

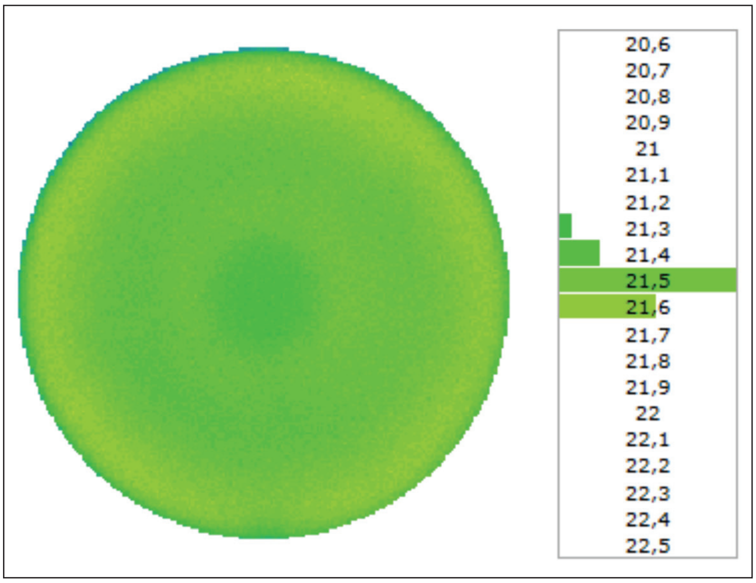
The team I worked with on this was really amazing. Their dedication and efforts to solve this key question, what drives that edge effect, led them to innovate what we call Multi-Ject technology. This solution allowed us to achieve record uniformities on both 150- and 200- millimetre substrates, ahead of what you can get on single wafer tools, and expand rapidly in the silicon carbide market.

**RS:** *In the 1990s you launched your first Planetary reactor. Is this advance, allowing the growth of multiple wafers, arguably the biggest milestone in Aixtron's history?*

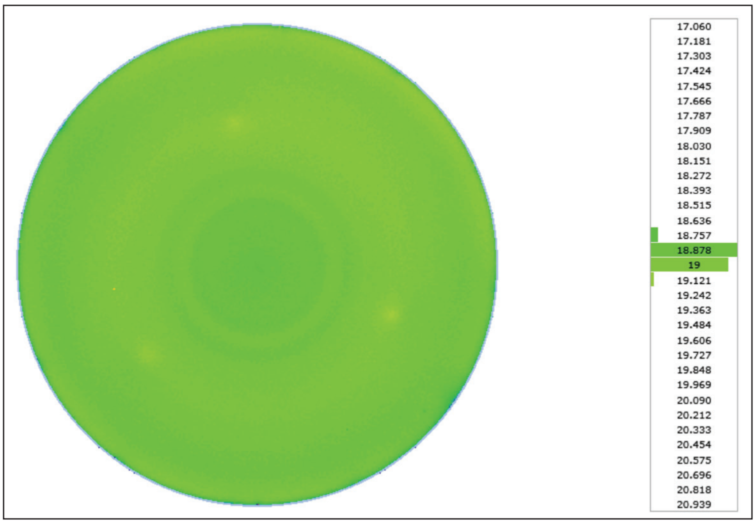
**JH:** It certainly set the direction for Aixtron's development for many years to come. However, I would say the close-coupled shower head, which we brought into our portfolio from the Thomas Swan




➤ Photoluminescence map of a highly strained AlInGaAs multi-quantum-well on a 150 mm InP wafer. The average value is 1536 nm, and the standard deviation, for a 5 mm exclusion zone, is 0.77 nm.




➤ The aluminium composition range of the AlGaN barrier across a 200 mm GaN-on-silicon epiwafer, in absolute terms, is below 0.5 percent.



The aluminium composition range of the AlGaN barrier across a 300 mm GaN-on-silicon epiwafer, in absolute terms, is below 0.4 percent , in line or better than 200 mm performance.

Scientific Equipment Division acquisition – known today as Aixtron Limited – had an equal part to play. Both technologies are fundamental to our success. The Planetary Reactors are our workhorse for 150- and 200-millimetre substrates, allowing the platform to secure the lowest possible cost-per-wafer while achieving single-wafer uniformities. The Showerheads are shining for the larger configurations, in the 300-millimetre product offerings.

**RS:** *Over many decades Aixtron has seen cycles of growth and periods of contraction. Obviously, any manufacturer would prefer steady growth in the market it serves. What strategies have you adopted to support rapid growth, followed by quieter times?*

**JH:** We had to change things after the first LED investment wave. We ended up diversifying our offerings, to decrease our dependency on a single application. At that time, our revenue was mostly driven by sales of equipment to be used for gallium nitride LEDs. Now, because of that diversification, we're serving GaN-on-silicon power markets, silicon carbide power markets, telecom and LEDs. This has resulted in dampening out a lot of ups and downs. The diversification also allows us to keep a more steady demand across different applications, while leveraging synergies between them.

We also work closely with our suppliers and supply chain to ensure we can ramp up on time when our customers want more volume for the next market push.

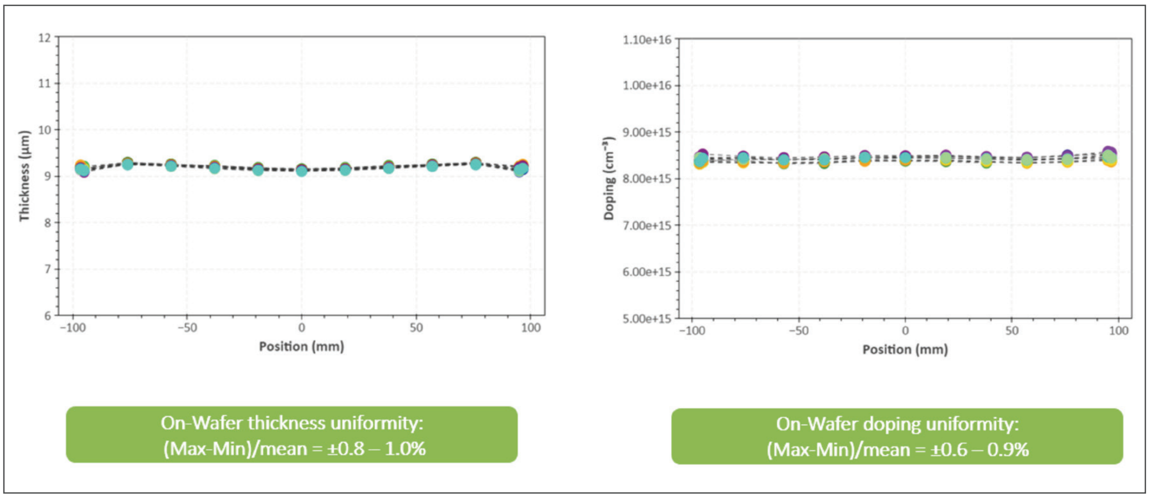
In particular, now with serving the power device end market and inherently the automotive OEM, we were prepared for a potential demand hockey stick and we took great pride in being able to deliver the volumes our customer needed in the last year with the rapid demand growth in GaN and SiC power.

**RS:** *The progress of the compound semiconductor industry can be seen in the increase in substrate size. Your company talks about this, using the phrase 'Going large'. You feel that the first application to really embrace this concept is 200-millimetre GaN power devices. How has Aixtron supported this move?*

**JH:** The shift to larger wafers is typically stirred in one of two ways.

One way is when the volume within one application is large enough that going to the next wafer size can bring a strong advantage – not only in the epitaxy,

➤ The G10-SiC is a batch reactor capable of accommodating 150 mm and 200 mm wafers for high-throughput epitaxy for SiC power electronics.




➤ The Aixtron G10-SiC delivers best-in-class 200 mm epiwafer uniformity. Thickness (left) and (doping) values for six 200 mm wafers.

but back-end cost reduction. Creating a reduction of 30 percent per area is usually the driving factor.

The other driver for large size is technology. Going to a larger wafer allows you to access more refined back-end equipment that has better accuracies or smaller line widths.

Our mission is to just develop the optimum solution whenever the customer needs us to, whether it's 150, 200 millimetre, *et cetera*. We're the first to enable cassette-to-cassette automation for MOCVD, and that includes the *in-situ* clean technology I mentioned earlier. We are still the only one combining this for volume production with large 200-millimetre batch solutions. Furthermore, to support our customer needs, our latest 200-millimetre products all embark on loading wafers through SMIF front-end access, in order to ensure minimum handling and improve particle performance while reducing the cost of the fab. This is an example of how 'Going large' helps you at multiple levels in your production.

**RS:** *Recently, Infineon grabbed the headlines for developing processes to produce GaN power devices on 300-millimetre silicon. We have also seen companies like Aledia touting 300-millimetre GaN plans for microLEDs. In terms of volume production, what do you think will be the next device to 'go large'?*

**JH:** It's a good question. To start, large is a bit relative. For the growing indium phosphide photonics market, for example, 150 millimetres is a really big leap for them, mostly driven by the increase in demand. We are ahead in the solution space for that as well. We have already ported over our learnings from gallium nitride developments, in order to enable full cassette-to-cassette wafer automation with *in-situ* clean technology for our arsenic-phosphide platform, which we call the G10-AsP.

For gallium nitride, we were the first developing production tools for a 300-millimetre ramp up. We believe the lower-breakdown-voltage devices are ideal candidates for this. We see plenty of applications, including powering advanced AI GPUs.

We're working very closely with customers to share the benefits from all process and device know-how we've acquired in the 150- and 200-millimetre evolutions to ensure a smooth transition towards 300-millimetre.

MicroLED is another application that will be a potential candidate for 300-millimetre. That is mostly driven by the need for a very small pixel size – one micron or less. Not every customer will shift to 300-millimetre, though some applications will. We see that as a benefit, based on our introduction into 300-millimetre GaN-on-silicon.

**RS:** *Another exciting piece of news from late 2024 came from SICC, which produced the first 300-millimetre SiC substrate. What is your view on potential 300-millimetre demand for SiC?*

**JH:** Yes, it was exciting to see this first wafer, considering that 200-millimetre substrates are just recently being put into mass production for silicon carbide power devices. We are well aware that it will take quite a few years for the wafer to be cost-

➤ Aixtron's VP of Technology, Jared Holzwarth.


➤ Aixtron's recently opened Innovation Centre.

attractive for our customers, but at the same time, we are making sure the right epi solutions will be there when they are needed.

**RS:** *In general, what are the challenges in developing reactors that can produce 300-millimetre substrates? And when working with this larger size, what are the pros and cons of using single-wafer and multi-wafer tools?*

**JH:** As a matter of fact, we did deliver our first 300-millimetre reactors for compound material in 2006. At the time, indium gallium arsenide was the ideal candidate to replace silicon as a channel material for advanced CMOS. We did engineer the first fully automated 300-millimetre MOCVD tool for compound customers, with systems installed all over the world at leading IDMs or foundries.

Generally, there is no fundamental challenge to developing reactors, in relation to substrate size. We have two core technologies in our portfolio, and depending on specific application requirements, we will shape the ideal product for our customers.

Our GaN power transition from 200- to 300-millimetre has been surprisingly smooth. We were able to show similar performance on 300-millimetre within months of starting up our development programme.

We don't see technology segmented solely on single-wafer versus multi-wafer tools. In particular, we have proven over many years that with our Planetary technology, using a single-wafer approach while being a batch, we have the benefit of both worlds. In the end, we use batch in order to have good cost-effectiveness. We believe that single-wafer 'control' is needed for improved uniformities. In the end, your volume and your individual application requirements will determine whether you select a single-wafer architecture or a batch-wafer reactor.

**RS:** *During the history of Compound Semiconductor, there has been an expansion in the range of materials used to produce devices. Over the last decade, gallium oxide has emerged as the new kid on the block. What's your view on this ultra-wide bandgap semiconductor, and how are you supporting its development?*

**JH:** At Aixtron we're always eager to work on new materials and challenges. We've been involved in gallium oxide since the beginning, having our Close Coupled Showerhead R&D reactor systems placed across leading universities to respond and innovate on these new emerging materials. I think the interest in gallium oxide has been growing for many years, predominantly coinciding with improvements in substrate technology and improvements in epitaxy performance.

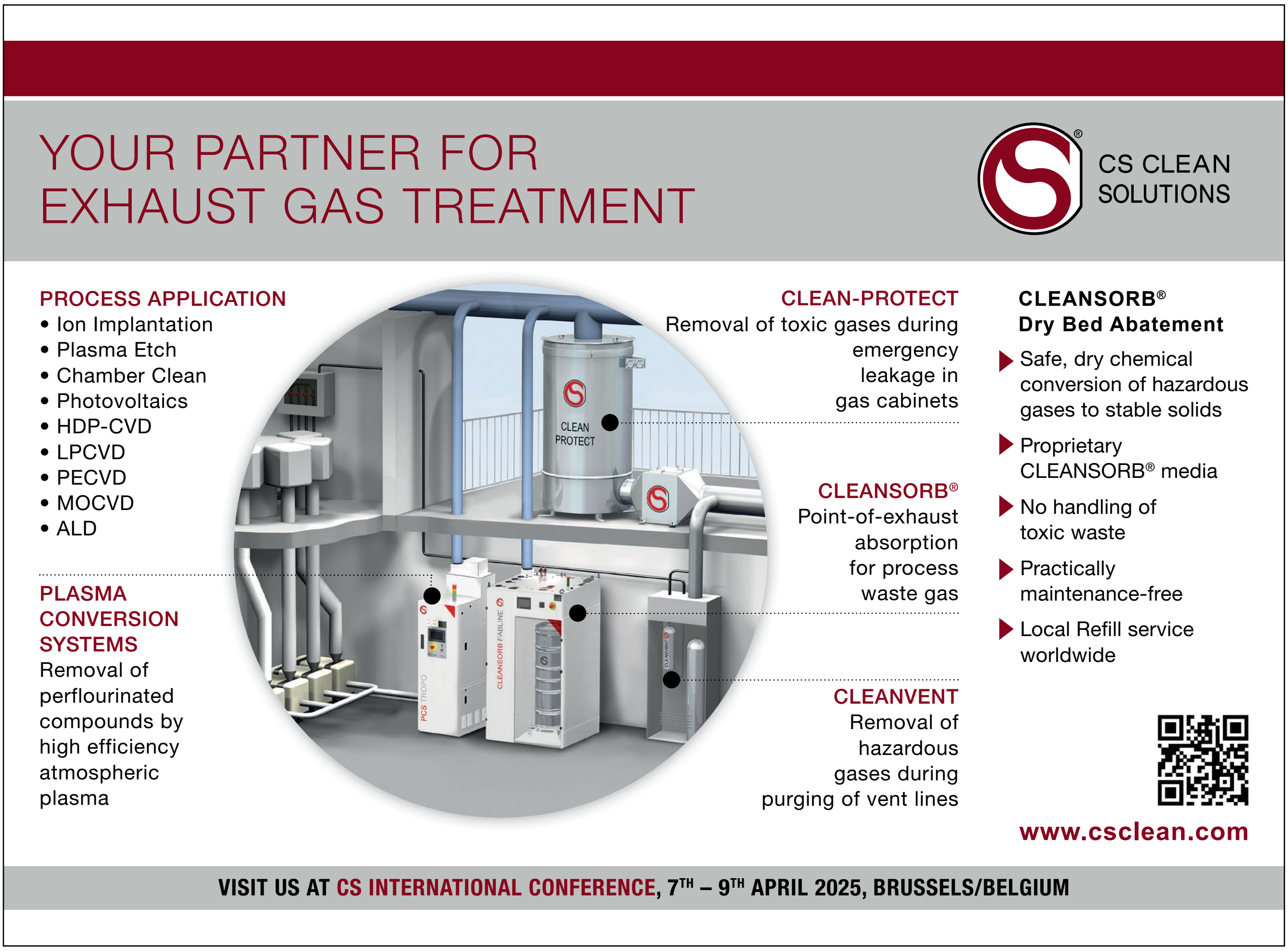
While we see this improving year after year, we anticipate that it will take time to get to volume production. A lesson learned from GaN-on-silicon is that the power market is relatively conservative with new materials. A certain number of players needs to be in place to ensure the full ecosystem is ready to focus and take advantage of the new material. We anticipate the first product for gallium oxide may be launched in a few years, but it is likely that volume production will be more in the next decade.

**RS:** *You have just opened the Innovation Center. What is the motivation behind this move, and what do you hope its addition will do for the progress of Aixtron?*

**JH:** We're extremely proud of our new Innovation Center. It opened in December 2024 at the company's headquarters in Herzogenrath, Germany. I can confirm our first tools are rolled in, and we are already processing first wafers.

The motivation for us was really the upcoming move to 300-millimetre, driven by space constraints and by the vision to engage even deeper with our customers in our lab to develop solutions for their need. We're always pushing the application limits, and to do so, we needed the Innovation Center. This new research and development complex with 1,000 square metres of cleanroom space lays the perfect foundation for the transition to 300-millimetre wafer size.

Our executive board decided to invest in the future and really did a great job making that happen quickly. The groundbreaking ceremony and start of construction was in November 2023. One year later we are already celebrated the opening. What it means for us is really setting up ourselves for success in the decade to come. We're excited that compound semiconductors are going mainstream and entering into 300-millimetre fabs around the world, and we are ready to have the infrastructure to make that transition a success for our customers.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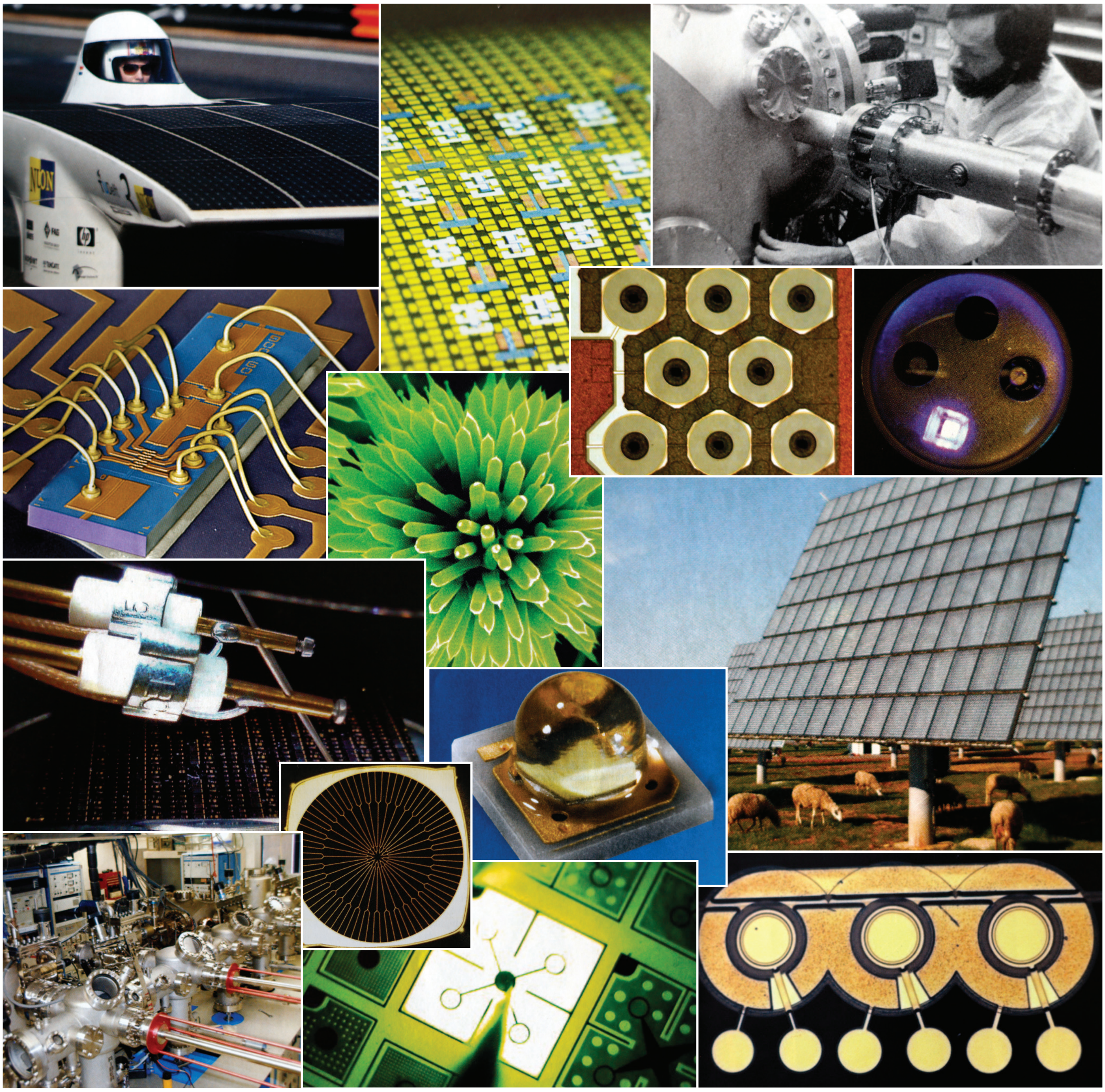


# Marking milestones

As we celebrate the thirtieth anniversary of *Compound Semiconductor* magazine, we take a look back at a pair of commemorate issues, released to mark ten and twenty years of this publication

**BY RICHARD STEVENSON, EDITOR, CS MAGAZINE**

HOW SHOULD an editor cover a milestone in the history of their publication? While there are many paths that one can take, an anniversary edition undoubtedly provides a great opportunity to look back at what has been accomplished over many years, possibly alongside glance into the future. For once, the 'here and now' can take a back seat – although it still would be remiss to fail to cover of the biggest breaking stories.

*Compound Semiconductor* published its tenth anniversary edition a little over a year after I left IQE and started working as Features Editor. A decade on, promoted to Editor under a new publisher, I had to decide what approach to take, and determine the content for that edition. And yet again, as Editor for the thirtieth anniversary edition – I must be in for the long haul – I have had the privilege of devising what to include and what to leave out.

## The tenth anniversary

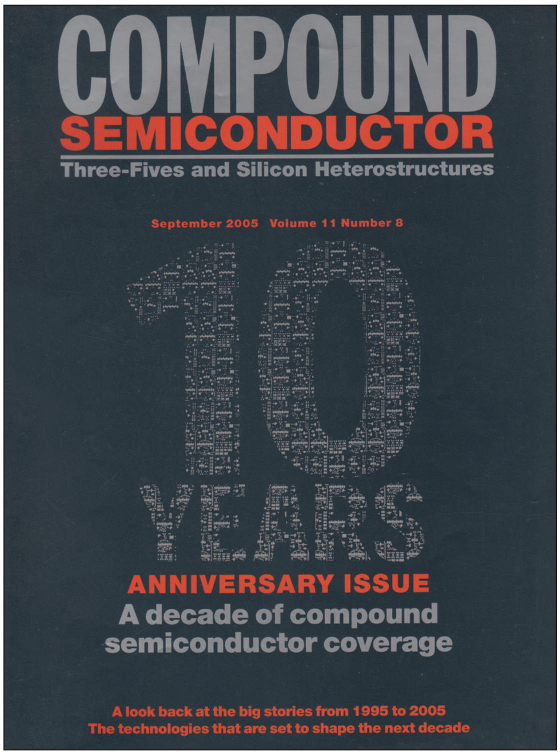
One of the big differences between the current publisher, Angel Business Communications, and the previous owner, the Institute of Physics Publishing, is their view on page count. According to the latter, the number of pages in an edition should reflect the space allocated to adverts, using a rule-of-thumb of a one-to-one ratio. This decree restricted the page count of the tenth anniversary to no more than 40 pages, limiting the ambitions of the editor.

Working within these somewhat cumbersome restrictions, the previous editor, Micheal Hatcher, reviewed the first decade of *Compound Semiconductor* in a handful of spreads that picked out the biggest stories for every issue. Sitting alongside these details are a number of interesting asides: highlights of epitaxy, overviews of the growth of the GaAs microelectronics and high-brightness LED markets, and a short piece discussing the potential for the co-existence of GaAs and CMOS in future front-ends for handsets.

For the highlights on epitaxy, *Compound Semiconductor* drew on the expertise of Gerald Stringfellow from the University of Utah. Stringfellow picked out the three best research papers between 1995 and 2005, selecting those on the lateral epitaxy of low-defect-density GaN layers, key to making GaN lasers; the growth of dilute nitrides; and the growth of nano-trees. Twenty years on, these choices stand the test of time, highlighting important developments that matter to this today.

During the first decade of this publication, the GaAs microelectronics and high-brightness LED markets enjoyed phenomenal growth. Between 1995 and 2000, global GaAs revenue shot up from $500 million to $3.2 billion, fuelled by surging sales of handsets, as well as growth in fibre-optic communication that relied up digital GaAs components in laser drivers, transimpedance amplifiers, multiplexers and demultiplexers. But the market for digital GaAs did not endure – the bursting of the 'dot-com' boom, occurring at the beginning of the new millennium, thwarted sales of components for optical infrastructure, and when commercial opportunties returned, products based on silicon and SiGe took over. Since then, handsets have accounted for the lion's share of GaAs microelectronics sales. This market benefitted from the increasing uptake of mobile phones in the early 2000s, but suffered from a fall in the average selling price of GaAs devices. These two opposing trends led to modest growth in global GaAs microelectronic revenue from 2002 to 2005, to hit $2.5 billion by the end of that timeframe.

In contrast to the roller-coaster revenues of the GaAs industry, sales of high-brightness LEDs climbed steadily between 1995 and 2005, aside from a flat period in 2001. At that time camera flash provided the next opportunity for revenue growth. While opportunities in backlighting screens and general illumination had also been identified, significant improvements in performance were required before the LED could start to penetrate these applications.



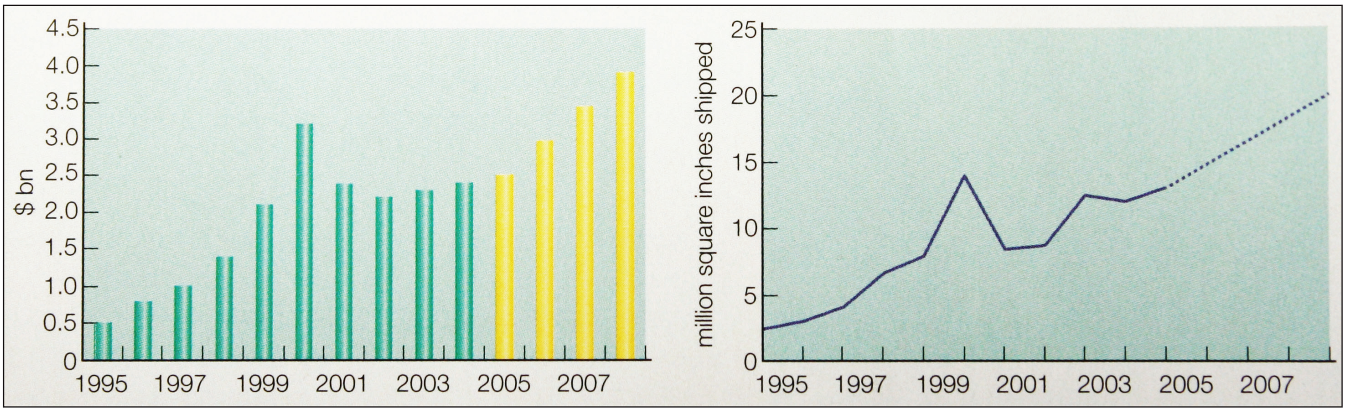

➤ At the heart of the tenth anniversary edition, published by the Institute of Physics Publishing, is an extensive feature listing the biggest stories in every issue to date.

Championing the co-existence of GaAs and CMOS in future handset front-ends in the tenth anniversary issue, Rodd Novak from Peregrine Semiconductor (now known as pSemi), argued for the switching function to be provide UltraCMOS, rather than the GaAs pHEMT. History attests to this vision for the switch, based on silicon-on-insulator technology. For the last decade or more the GaAs HBT, providing amplification, has dominated the revenue of the GaAs microelectronics industry.

## The twentieth anniversary

At twice the size of the tenth anniversary edition, that celebrating the twentieth anniversary devoted more space to the evolution of the GaAs microelectronics and high-brightness LED markets, while also detailing the highlights of the very first edition and looking forward. In addition, this commemorative edition included views of how the world might be deploying compound semiconductor devices in 2035.

An in-depth look at the growth of GaAs microelectronics came from Eric Higham, at the time a director at Strategy Analytics (he is now Technical Editor at *Microwave Journal*). As well as detailing the foundation for the growth of the GaAs industry – a combination of the US MMIC and Microwave Analog Front End Technology programmes – Higham




➤ Reproduced from the commemorative edition from 2005, data from Strategy Analytics revealing the roller-coaster revenues for the GaAs market from 1995 to 2005.

accounted for the hike in sales for 2005 to 2015 coming from mobile networks offering higher data rates. A turning point came in 2005, when operators introduced the first high-speed downlink packet access networks into the GSM community, igniting a data arms race. Ignoring an almost flat year in 2009, when the global economy threatened to implode, GaAs revenue enjoyed an upward trajectory for more than a decade.

Providing great insight into the evolution of the LED industry, Bob Steele, market analyst and founder


➤ The current owners of Compound Semiconductor, Angel Business Communications, published the twentieth anniversary edition. This commemorative issue included detailed reviews of the GaAs microelectronics and high-brightness LED markets by the leading analysts of the day.

of the *Strategies in Light* conference contributed a feature entitled *LEDs: Two decades of glorious growth*. He kicked off this piece by demonstrating the phenomenal strides that this emitter had made in the first 20 years of *Compound Semiconductor*, from deployment in low-brightness indicator lamps and alphanumeric displays to incorporation in white-light sources that, by 2015, had captured one-third of the $80 billion global lighting market.

Like Higham, Steele looked back beyond 2005, reminding readers that the origins of the LED can be traced to 1907, when British radio engineer Henry Joseph Round discovered this device by accident, when investigating the electrical properties of the metal-semiconductor SiC rectifier. Of the many key milestones since them, surely two of the biggest are the invention of the first visible LED by Nick Holonyak and his team at GE Labs in 1962, and the commercial introduction of the GaN-based blue LED in 1993 by Nichia, spearheaded by the pioneering work of Shuji Nakamura.

A key breakthrough that has underpinned the revolution in solid-state lighting came in 1996, when Nichia produced a white emitter by using a blue-emitting chip to pump a yellow-emitting phosphor. Colour-mixing blue and yellow results in white light. Initially, only white LEDs with a high-colour temperature were available. But by 2002, customers could also access a more attractive, warmer form of white light, when Lumileds launched a device featuring both red and yellow phosphors.

During the first decade of this century, the efficiency of the GaN-based LED rocketed, though refinements to device design, such as the introduction of multiple quantum wells, the shaping of chips to increase light extraction, and better packaging to aid thermal management.

Steele also considered the tremendous changes within the LED over the lifetime to date of *Compound Semiconductor.* Between 1995 and 2015 the size of the high-brightness LED market had mushroomed by a factor of 150, input power capability of an LED package had increased by a thousand, and cost-per-lumen had plummeted by a factor of 100.

By 2015, from a market perspective, the golden years were over. Revenue growth had slowed, with the compound annual growth rate declining to around 9 percent. Many more companies were competing for sales, driving down margins.

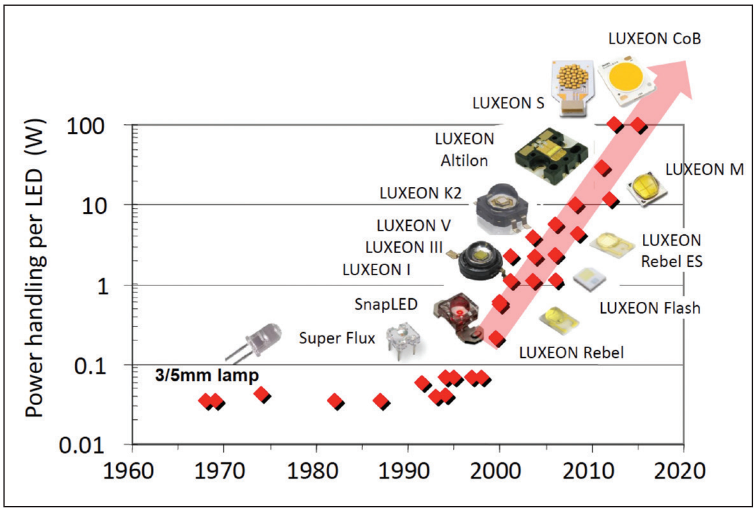
The commemorative edition from 2015 also looked back at the contents of the very first issue of *Compound Semiconductor,* a time when copies were only available in print format. Back then, one piece discussed the merits of using red LEDs in traffic lights. For the red source, it would be possible to use 500-750 devices, with a total cost of $200 and a combined consumption of 20 W. Switching to this from the incumbent, a 150 W source, promised significant energy savings, leading to lower electricity bills. With hindsight, what now appears rather odd is this comment from that time: 'Incandescent lights, however, will likely keep the yellow market – they are on for such short periods of time that the energy savings do not equal the cost of the LED array'. Today, in many parts of the world, it's not easy to find a traffic light that's emission is not based entirely on LEDs.

Thoughts on where our industry may be in 2035 also featured in the twentieth anniversary issue. In that edition, Fred Schubert, an academic at Rensselaer Polytechnic Institute, predicted that the next two decades would witness improvements in the efficiency of green and UV LEDs, progress that has taken place and is expected to continue. In 2015 he argued that general illumination by lighting was unlikely to be overtaken by diode lasers, and he's certainly right so far.

Also sharing views of the future in 2015, Douglas Reep, then Qorvo's Senior Director of Research and now a consultant, predicted that GaAs amplifiers would remain a key component in mobile phones for many years – but there could be possibilities eventually for GaN, which can operate at higher power densities. Reep argued that for GaN to make an impact, it would need to operate in the 3-5 volt range. Today, we might be a little closer to that GaAs-to-GaN transition, which is now being championed by Finwave (see p.14).

The late John Palmour, co-founder of Cree, now Wolfspeed, predicted an increase in sales of SiC power devices, displacing those made from silicon. He expected success in electric vehicles beyond 2020, while that actually came before then.

Palmour also commented on the potential, and drawbacks, of ultra-wide bandgap materials. He pointed out the problems with *p*-doping and thermal management. Progress is being made, and for $Ga_2O_3$ in particular, investment in the development of substrates and devices is rising fast.




➤ In the edition of *Compound Semiconductor* celebrating its twentieth anniversary, the contribution from market analyst Bob Steele included this graph illustrating the evolution of LED package technology. Its source is a presentation from 2015, given by George Craford, Lumileds Solid State Lighting Fellow, at the US Department of Energy Solid-State Lighting Workshop.

## This edition

Compared to these two predecessors, this commemorative edition devotes more space to looking back over developments, while making no projections for the future. Its centrepiece is a year-by-year appraisal of the most significant events in the compound semiconductor industry. In this respect, the passing of time is a benefit, helping to identify advances that really matter – and put to one side those that initially appeared to have a lasting legacy, but only made a short-term impact.

I hope you enjoy reading the coverage of the biggest stories over the last 30 years, as well as taking a look at the views of market analyst Yole on the wide bandgap market, and my picks for the top ten research review stories over the last three decades. Hopefully there's something for you within these pages.

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# The growth of wide bandgap power devices

**Surging sales of SiC and GaN devices, particularly within the automotive industry, are going to create a $10 billion market by the end of this decade**

**BY POSHUN CHIU AND EZGI DOGMUS FROM YOLE GROUP**

SUPPORTED by subsidies and motivated by cutting carbon footprints, more and more drivers are switching to electric vehicles. It's a move that has implications that include helping to drive up revenue for wide bandgap technologies, today the combination of SiC and GaN. Collectively, these devices are expected to double their share of the semiconductor power device market over the next five years, according to our research at Yole Group.

We are now seeing sales of wide bandgap devices climb at great pace, more than 20 years after the first power SiC devices were commercialised. The rapid expansion of this market shows no sign of abating, with GaN technology poised to take off and assist in driving innovation in this segment.

Today, wide bandgap technologies accounts for more than 16 percent of the global power device market, and we forecast that this will jump to more than 32 percent by 2029.

By then, our expectation is that SiC device revenue will represent more than 26 percent of the semiconductor power market, with sales climbing to nearly $10 billion. To get there, revenue will increase with a compound annual growth rate of 24 percent from 2029, from a starting point of $2.7 billion in 2023. Over that timeframe, GaN revenue will grow from $260 million to $2 billion at a compound annual growth rate of 41 percent. Beyond then, we anticipate further growth, spurred by additional high-power and industrial applications.

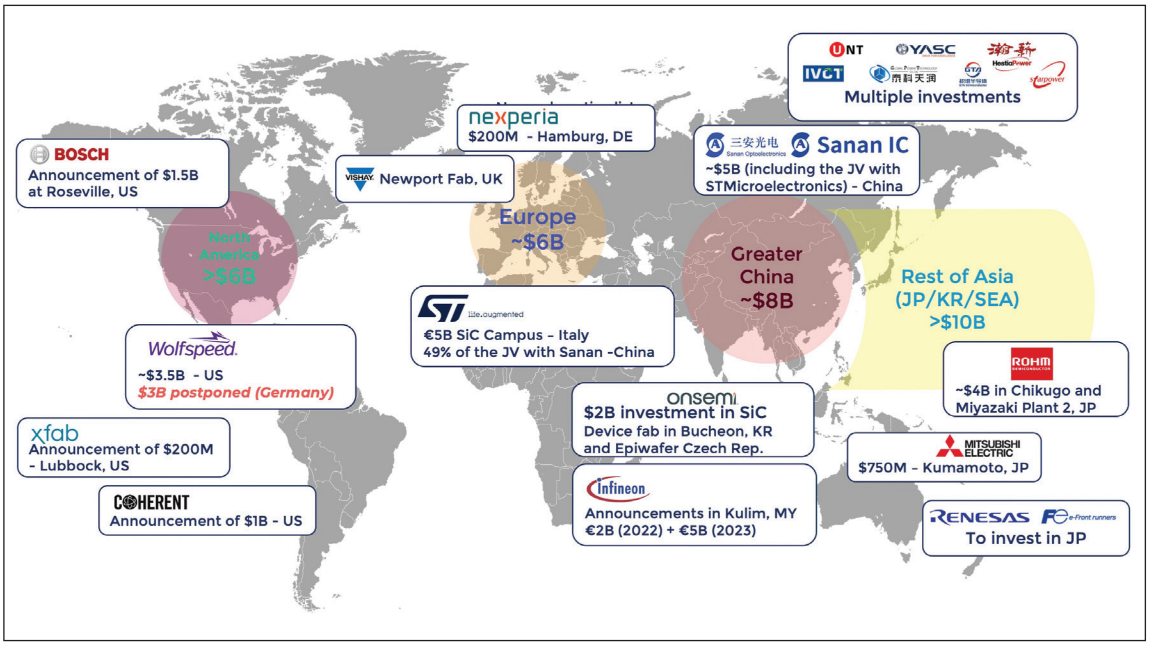
One impact of two decades of development of wide bandgap technology is that it has led to almost every major player in the power semiconductor market having some business in SiC, and preparng for GaN business in the years to come. For the latter, revenue primarily comes from discretes, and system-in-package and system-on-chip products.

Major players in the power electronics market with a sizeable SiC businesses include Infineon, onsemi and ST Microelectronics. Since 2017, the latter has been leading the way in SiC, after it took pole position by entering the supply chain of Tesla – a SiC pioneer in the automotive industry. Other significant manufacturers of SiC devices include Rohm, Bosch, Wolfspeed and Mitsubishi Electric.

## SiC takes hold in automotive

A major milestone in the SiC industry came in 2001, when Infineon launched the first SiC Schottky barrier diode. It is a device that took many years to establish itself, and when emerging on a commercial scale 10 years ago, was a new innovation waiting for a market. These diodes, joined by MOSFETs from 2010 onwards, won deployment in industrial applications, such as power supplies and solar photovoltaic inverters. However, revenues only started to rocket when automotive original equipment manufacturers started adopting SiC power devices for 400 V battery EVs.

We have been tracking the SiC market for several decades, and predicted the rise in its value from



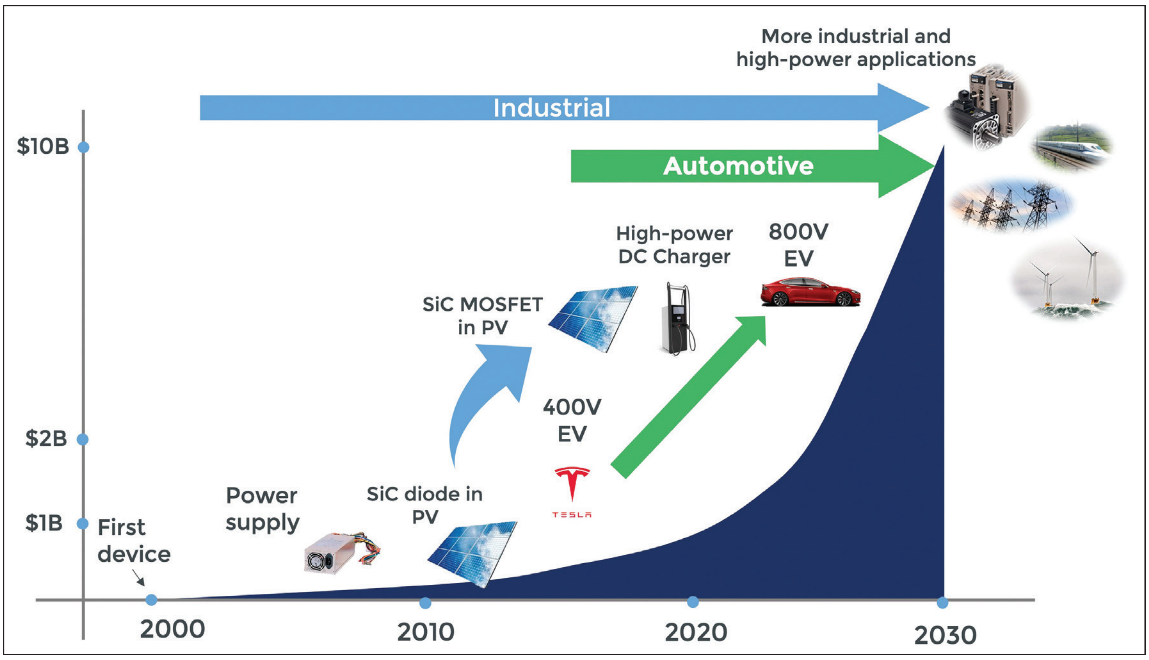

➤ Globally, more than $30 billion of investment has announced for SiC, with the focus on device manufacturing. Source: *Power SiC – Markets and Applications 2024 report*, Yole Intelligence.

around $100 million in 2013 to approaching $800 million in 2020.

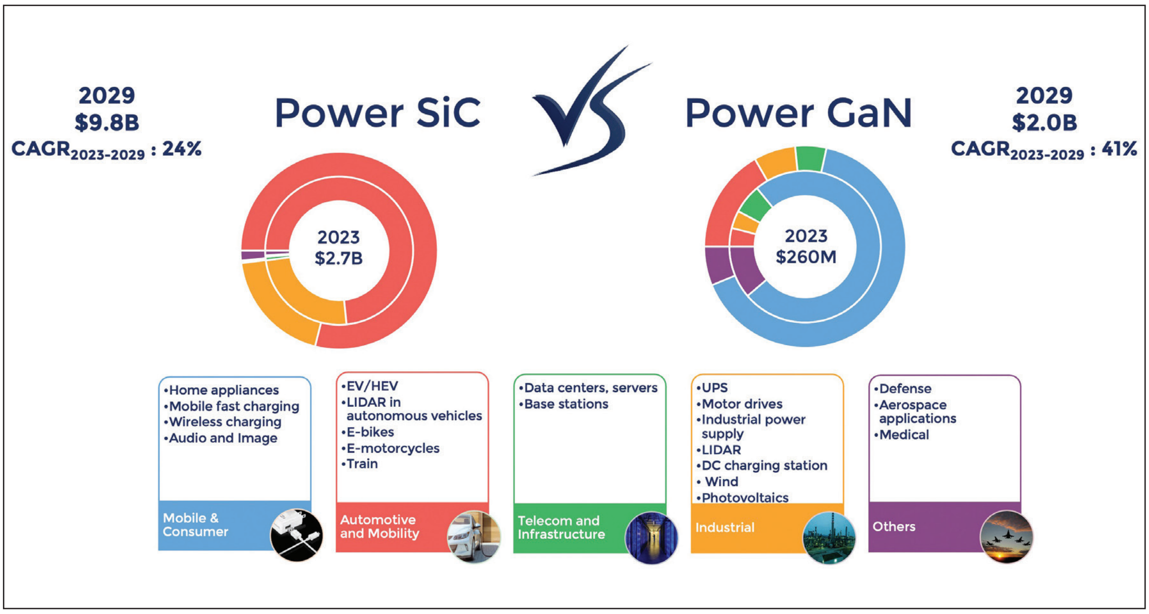
The key partnership between STMicro and Tesla led to SiC first being deployed in the Tesla Model 3, in 2017. The EV maker then adopted SiC in its Model Y, before sales of these electric vehicles took off, and the SiC power device market started to grow rapidly. High volumes of SiC have been shipped to Tesla, but up until now they have only been incorporated in a relatively small number of models.

Where Tesla has led, others have followed, with several other OEMs incorporating SiC in their 400 V battery EV architectures. The next generation of EVs will be based on an 800 V battery system, a migration that will lead to more models featuring SiC technology and increasing its demand. And in parallel, we've seen generations of SiC MOSFETs being launched by different players, in order to provide the advantages of power conversion efficiency or high power-density in various applications.

This anticipated trend is contributing to substantial global investment in SiC, totalling more than $30 billion. In North America Bosch is investing $1.5 billion in a facility in Roseville, California, to expand its capacity, Wolfspeed is spending $3.5 billion, Coherent is investing $1 billion, and X-FAB is spending $200 million in Lubbock, Texas. Meanwhile, in Europe, ST Microelectronics is building a new €5 billion facility in Catania, Italy, next to its existing facility, onsemi is investing in epiwafer capacity in the Czech Republic, Nexperia is investing $200 million in Germany, and Vishay has acquired capacity in the UK.




➤ The long-term evolution of SiC is towards electric vehicles with 800 V power trains and a number of industrial applications. Source: *Power SiC – Markets and Applications 2024 report*, Yole Intelligence.



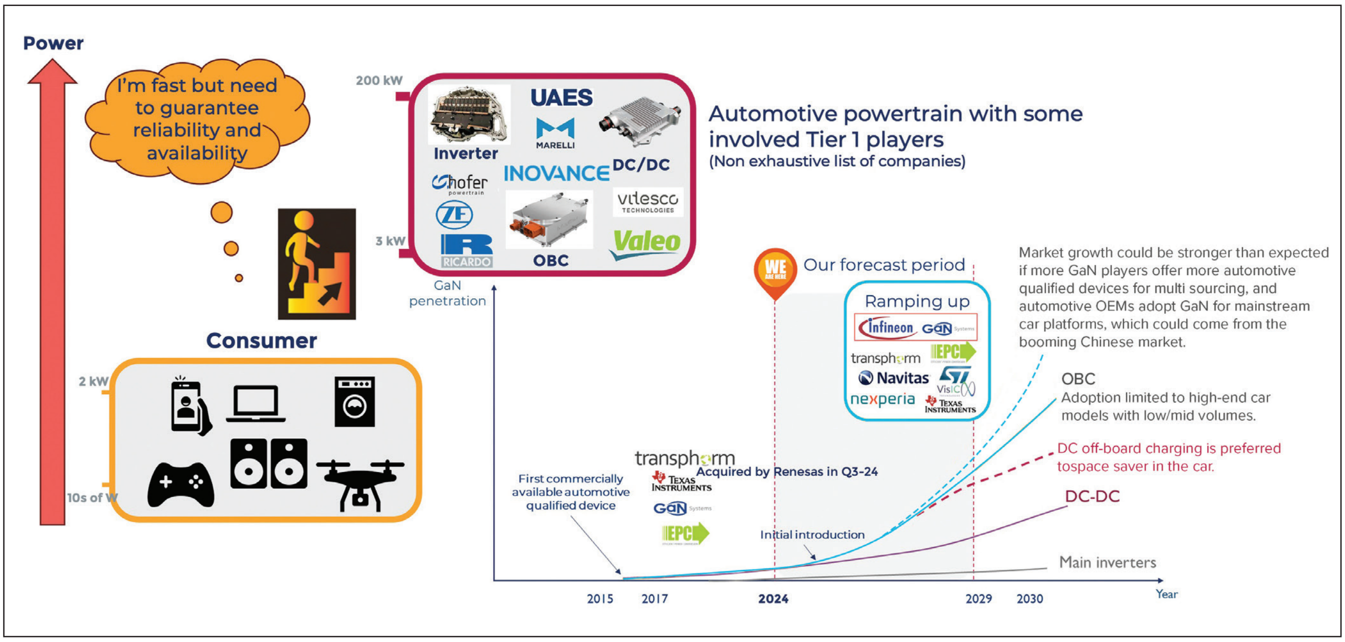

Market forecasts for Power SiC and Power GaN in 2023 and 2029. Sources: *Power SiC – Markets and Applications 2024 report*, *Power GaN 2024 report*, Yole Intelligence.

These investments in North America and Europe, each total around $6 billion. It is a substantial sum, but still overshadowed by investment in Asia. In this region – where manufacturing is shifting to – spending is expected to total $8 billion in China alone, and more than $10 billion across the rest of Asia, including Japan, Korea, and Southeast Asia. Within China, market leaders such as UNT, Sanan IC, YASC and HestiaPower have announced multiple investments.

What does all this investment mean for the market? Our expectation is that while SiC revenue will grow in the next few years, up until 2026 these sales will be smaller than the planned total investment by companies in this technology. Due to this, SiC chipmakers will have to carefully control their injections into CapEx, so that they grow revenues on top of building new facilities. There will be some challenges, such as managing cash flow. One headwind to such activities is the slowdown in the EV market, driving the need for more sustainable investments to continue CapEx injection.

During these years of investment, the SiC industry is transitioning from 6-inch to 8-inch wafers. While chipmakers benefit from this migration, undertaking this upgrade to their infrastructure requires substantial financial resources. If they can weather this period, sunnier times will lie ahead, with declining spending and increasing revenue creating a more sustainable business.

The long-term opportunity for SiC is not limited to an increase in demand that stems from the roll-out of 800 V EVs. The increase in supply of SiC power devices, resulting from new capacity coming to market, will also enable more use of this technology




Considering GaN adoption, with a focus on automotive powertrain applications. Source: *Power GaN 2024 report*, Yole Intelligence.

in other applications, such as: high-power EV chargers; solar PV; and industrial applications, including motor drives, railways and wind turbines. Another consequence of this multi-billion-dollar global investment in SiC is that the shortages in material supply and device capacity that occurred in 2019 to 2022 – when the majority of demand was secured by automotive customers, limiting penetration in industrial applications – will not be repeated in the coming years.

## GaN: A technology for tomorrow

In contrast to SiC, GaN emerged as a technology for consumer devices rather than automotive applications. The first devices were launched in 2010, creating a small market for fast smartphone chargers. Markets for consumer applications started taking off around 2018-2019, climbing to $260 million by 2023.

To ensure that GaN becomes another multi-billion market, suppliers are now looking to enter higher-value markets beyond sub-2kW consumer applications. These new opportunities include high-power automotive and industrial applications.

Manufacturers that are ramping up their GaN development and production include: Infineon, through its acquisition of GaN Systems; Renesas, which acquired Transphorm; Innoscience; STMicro; Texas Instruments; Navitas; and Nexperia.

There are a number of automotive OEMs and Tier 1 manufacturers interested in next-generation GaN technology. They include Hofer ZF and Ricardo, looking at GaN for inverters; UAES, Marelli and Inovance, developers of on-board chargers; and Vitesco and Valeo, considering GaN while pursuing DC-DC converters.

We expect it will take time for the automotive sector to adopt GaN. Used in consumer products today, GaN is generally viewed as a technology for tomorrow in the automotive sector.

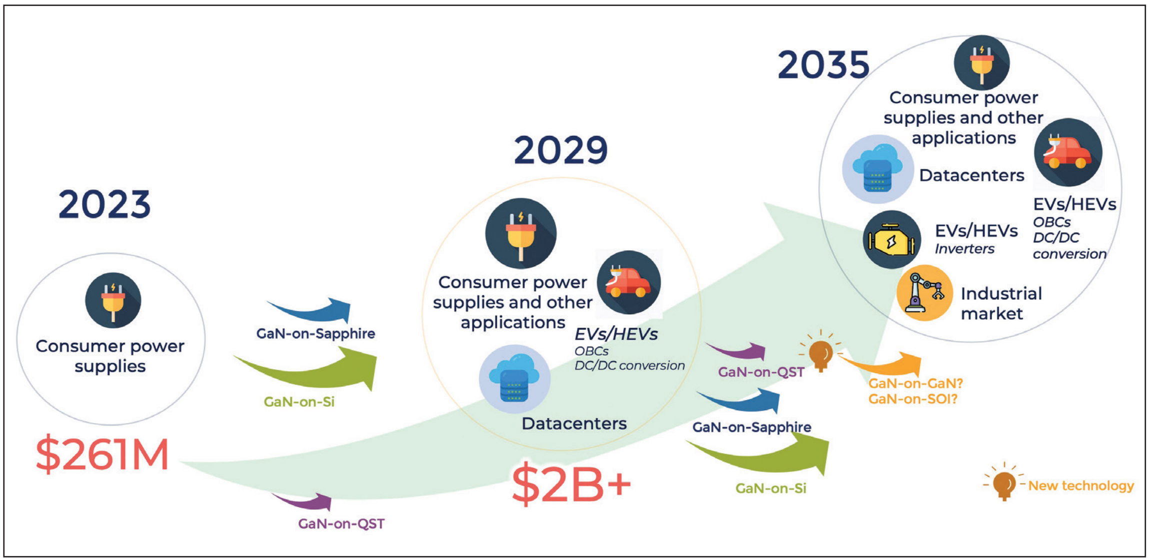
The main GaN application is expected to be on-board chargers for battery EVs and plug-in hybrid vehicles with power levels less than 11 kW. The added value that comes from switching from silicon to GaN DC-DC converters does not justify significant adoption, especially at power levels less than 3 kW.

For main inverters with 400 V systems, GaN will not find it easy to enjoy commercial success. SiC and silicon are already well-established, and GaN power modules allowing operation at power levels above 50 kW are not yet available. For 800 V systems, 1,200 V GaN devices are not yet commercially available, while 650 V GaN has the potential to enter the inverter market with multi-level power topologies. Based on all of this, we are not expecting GaN adoption in main inverters to begin before 2029.

Another reason behind this view is that GaN technology is still relatively young. It takes time to validate reliability and refine the design. Today, major automotive or industrial OEMs are still developing GaN to implement in their vehicles. Motivation for this comes from the unique added value provided by GaN, which includes its higher efficiency than silicon and SiC. At this stage, GaN is tending to win deployment in the lower power range, while adoption in higher-power applications is being developed.

Over the last year or so, the view on what will be the next big application after the consumer market has shifted. Due to the emergence of artificial intelligence (AI) as the 'next big thing', there is much interest in using GaN to increase efficiency in the booming AI data-centre market. Each graphics processing unit consumes 1 kW, matching the power level GaN can provide.

There are different stages in the power supply for servers. There are power supply units (PSUs) in the 400 V AC-DC stages, DC-DC stages, and at the next level, to a lower voltage with a 48 V rating.




➤ Over the coming years, GaN devices will win deployment in an increasing number of applications. Source: *Power GaN 2024 report*, Yole Intelligence.

GaN is a technology suitable for all these requirements. As well as two major voltage ratings, 650 V and 400 V, which can support the PSU, it has a lower 200 V rating, which can match the 48 DC bus requirement that AI data centres demand today.

One of the biggest benefits of GaN is its ability to provide high efficiency, which will increase data-centre profitability by reducing running costs, helping comply with new regulations and trimming the carbon footprint. As the technology is ready, the key question is this: When will some of the big system players decide to take high volumes of GaN?

Device suppliers are striving to convince them that there's cost parity with silicon devices, to be realised while enjoying higher efficiencies that deliver performance benefits.

We forecast that data centres will become one of the most important markets for GaN to enter. Once it's adopted, growth will be strong, spurred by significant demand from AI. This could initially drive the market to nearly $2 billion, our forecast for 2029. Over the longer term, we see potential for GaN to enter industrial applications, as well as the automotive sector. However, consumer applications will still play an important role.

Today's manufacture of GaN devices tends to involve silicon or sapphire substrates. However, alternative foundations are being proposed, and in some cases launched, such as Qromis Substrate Technology – a composite material substrate developed by US-based Qromis. This engineered platform suppresses cracking of the GaN epitaxial layer, enabling large-diameter epitaxial growth. In future, GaN chipmakers may also be able to turn to growth on silicon-on-insulator substrates.

From the technology perspective, we are seeing a lot of options for GaN uptake, as well as a lot of potential for GaN to enter different markets.

## Wide bandgap takes on key role

What's clear is to all is that wide bandgap materials are playing a growing role in the semiconductor power electronics industry. This market is already worth several billion dollars, and has the potential for strong growth throughout the remainder of this decade and beyond.

After 10-to-20 years of development, SiC technology is now on the path to high-volume production and expansion. GaN technology will follow, but is still evolving and discovering different possibilities for future markets.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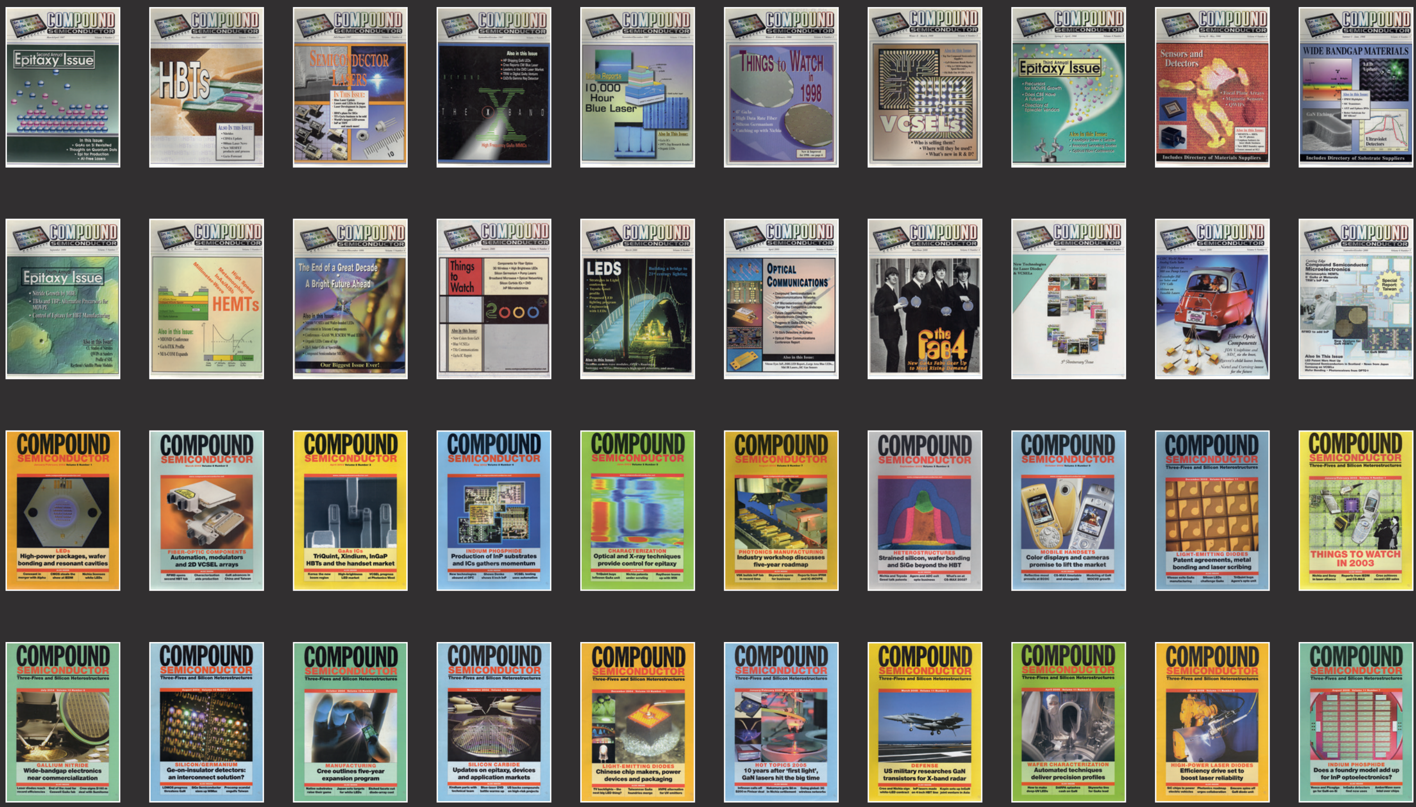
# Retrospective: Lookin
# stories from th

BY RICHARD




g back at the biggest
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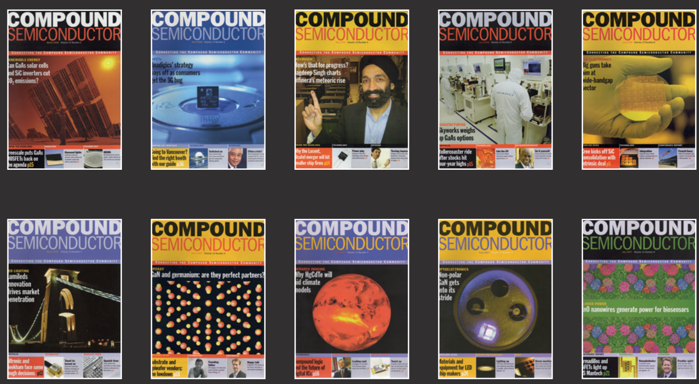
STEVENSON



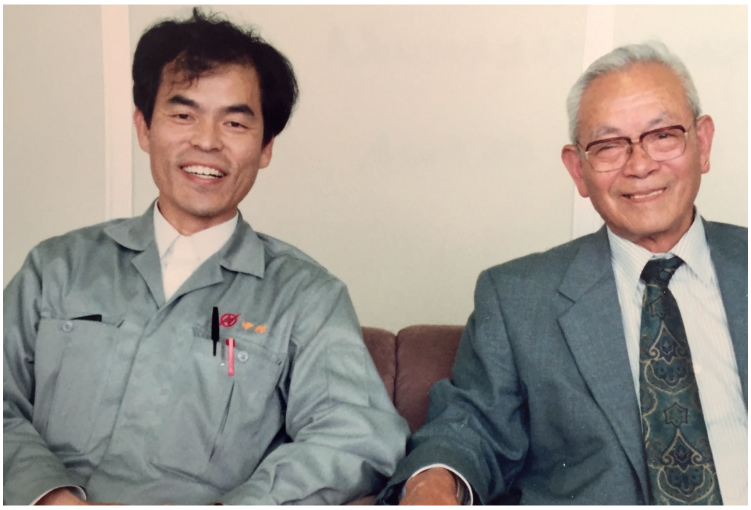

It is staggering how much we have accomplished over the last 30 years. Our inventions include blue and green GaN lasers, variants that emit from the surface of the chip, and a portfolio of gallium oxide power devices. Other triumphs include: refining and improving LEDs, so that they can backlight screens and illuminate homes and offices; increasing the efficiency of electrical circuits, by commercialising SiC and GaN diodes and transistors; and building GaAs fabs that have churned out billions of amplifiers, a key ingredient in mobile phones. Read on to hear about all these successes and many more as we take a look at the biggest story for every year, starting way back in 1995, when this magazine premiered.

# A brilliant laser

**1995** By summer 1995, Shuji Nakamura, trailblazer of efficient blue LEDs, had already become an industry celebrity. After inventing this device in 1993, he remained in the limelight by setting a series of ever higher benchmarks for the performance of this light-emitting chip. These successes enriched his standing within the tech pantheon of all-time greats and brought many accolades, including the biggest of all, a Nobel Prize for Physics, coming in 2014. But he got even greater pleasure from seeing his work laying a foundation for a lighting revolution.

While Nakamura is undoubtedly renowned for contributions to the development of the GaN LED, it is by no means the only ubiquitous device he has invented. He is also the originator of the cousin of the GaN LED, the GaN laser diode. The latter is an astonishing triumph. While many manufacturers are making millions of GaN LEDs every month, 30 years on from its introduction, there are still only two high-volume makers of the GaN laser diode: Nichia, where Nakamura worked throughout the 1990s; and Osram Opto Semiconductors of Regensburg, Germany.

Nakamura's laser breakthrough came in late 1995, with news breaking on 12 December. Nichia's greatest engineer appeared on TV later that month on a national evening news broadcast, demonstrating his wonderful new device.



➤ Shuji Nakamura, inventor of efficient GaN LEDs and GaN lasers, sitting next to Nobuo Ogawa, founder of Nichia. Credit: Bob Johnstone.

By early 1996, details of the laser diode started to appear in the scientific press. A paper in the *Japanese Journal of Applied Physics* described a 30 μm-wide, 1500 μm-long stripe laser grown on a sapphire substrate. Emitting at 417 nm, it had an active region containing 26 quantum wells, each made from a 2.5 nm-thick layer of $In_{0.2}Ga_{0.8}N$. To get this device to lase, the voltage had to be cranked up to 34 V. Driven in pulsed mode at even higher voltages, this chip produced an output of more than 200 mW. Encouragingly, this laser showed no signs of degradation after two hours of operation.

Even before its debut, the entire optoelectronic industry had little doubt regarding the killer application for this short-wavelength laser diode. Back then most music lovers bought CDs, VHS recorders were on the verge of being replaced by DVD players, and even better picture quality was now on the horizon, thanks to a five-fold hike in storage density enabled by blue-violet lasers.

Those keen to splash out on a new generation of disc players that would allow them to watch high-definition movies in their own homes had a really tough time. Early adopters began by getting caught up in a format war between the advocates of HD DVD technology and those giving their backing to Blu-ray. When that had been resolved, allowing customers to pay top whack for one of the first Blu-ray players that hit the shelves in Japan in 2003, further frustration followed – those early adopters had to wait several years for the launch of the first titles.

Fortunately, some good years followed, providing a growing, lucrative market for the blue laser diode. Since then the uptake of streaming services has sent sales of Blu-ray players into terminal decline – but as this door has shut, several others have opened. Blue lasers are now being deployed alongside red and green variants in colour projectors, and used in copper welding systems, where they operate at an absorption sweet spot, enabling excellent welds. There is also the possibility that one day lasers will replace LEDs in general lighting – so maybe, just maybe, there will come a time when society is as thankful to Nakamura for his laser as they are for his LED.

# Photovoltaics fly high

**1996** Back in 1985, very few owned a mobile phone. Those that did included Karen Bertinger, the wife of a Motorola executive, who tried to reach her husband while holidaying in the Caribbean. The call failed to get through, convincing intended recipient Barry Bertinger of the need for a truly global wireless communication network. To build this, Motorola founded and financed Iridium, a spin out that would advance telephony through the launch of 66 satellites, all placed in low-earth orbits.

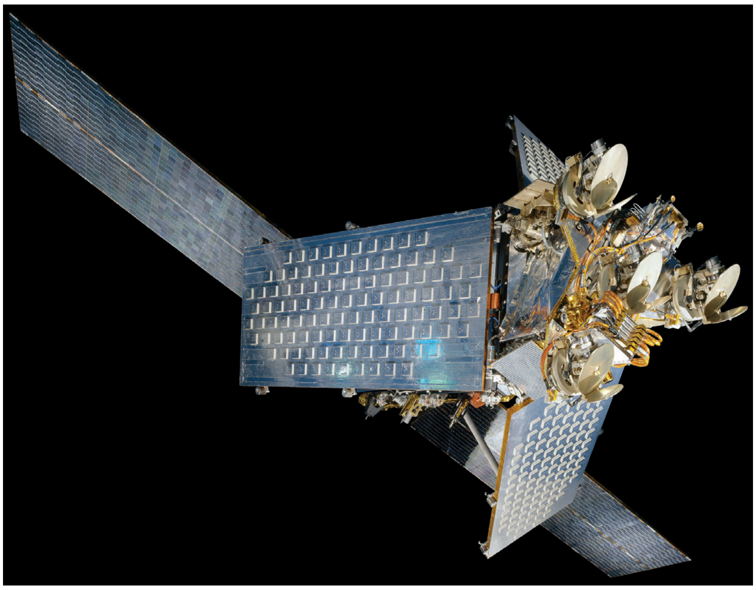
By 1996, makers of III-V photovoltaics were busy producing devices for powering these satellites. Although silicon cells were still winning sales in the space sector, single-junction GaAs devices were in the ascendency. Despite costing five-to-eight times as much as their silicon siblings, they were favoured, due to their higher efficiency. At the start of their life, they had an efficiency 25 percent higher – and crucially, at the end of life, after being battered by radiation, they were 40 percent to 60 percent more efficient. Given that each Iridium satellite required 24 $m^2$ of GaAs cells, using these devices rather than those made from silicon led to a significant reduction in the solar cell footprint.

Helping to fulfil orders for GaAs solar cells were a pair of Californian photovoltaic manufacturers: Spectrolab, at the time a subsidiary of Hughes and now part of Boeing; and Tecstar. For the latter, thanks to involvement in the Iridium project, in 1996 production totalled 200,000 3-inch wafers, equating to 140 kW of power.

Engineers produced these cells on germanium substrates. They were half the price of those made from GaAs, and much stronger. Use of germanium substrates generated much business for the makers of the raw material – the price of high-purity polycrystalline germanium rocketed, climbing by a factor of seven in just 18 months – and ramped sales for two leading substrate makers, US firm Eagle Pitcher and the Belgium outfit Union Minière, now known as Umicore. In 1996 germanium substrate consumption totalled between 300,000 and 500,000, with sizes ranging from 1.5 inch to 4 inch.

On 1 November, 1998, the Iridium network launched to much fanfare, with the first call placed between US Vice President Al Gore and Gilbert Grosvenor, great-grandson of Alexander Graham Bell. However, despite this great publicity, the service never caught on. Potential customers balked at paying $2500 for the handset. Dropping this to $1495 and slashing service costs failed to generate enough business, and even by the end of 1999, Iridium had just 15,000 subscribers, a far cry from an anticipated 500,000. An inevitable filing for bankruptcy followed.

Failure of the venture took its toll on photovoltaic maker Tecstar. In 2001, it tried to branch out into LED epiwafers. Diversification did not go well, and in 2002 Tecstar's management decided to call it a day, selling it solar division to Emcore for $21 million. Today, the technology is in the hands of Rocket Lab. In 2022 Rocket Lab bought SolAero, which formed in late 2014 through the sale of Emcore's solar power business.



➤ With 66 satellites each requiring 24 $m^2$ of GaAs solar cells, the Iridium project, which aimed to provide global cellular coverage, generated much revenue for the III-V photovoltaics industry. Credit: Eric Long, National Air and Space Museum, Smithsonian Institution.

# Growth for gallium arsenide

**1997** Owning a mobile may not have been the norm in the early 1990s, but it became increasingly common towards the turn of the millennium. The uptake of these handsets helped to swell the sales of makers of GaAs microelectronics, and provided the impetus for several of these firms to reach milestones, including three in 1997: the launch of RFMD on the stock market, the shipment of Rockwell's two-millionth HBT, and Anadigics' sale of its millionth GaAs IC.

RFMD, now part of Qorvo, started out as a fabless supplier of GaAs MESFETs, silicon bipolar devices, and HBTs, which provided 85 percent of sales. As demand for the latter ramped, RFMD couldn't keep pace, losing a key contract with Qualcomm.

To prevent this from happening again, RFMD built its 4-inch GaAs fab in Greesnsboro, NC, in the late 1990s. Constructed in two phases, the facility initially produced 10,000 wafers per year, before eventually increasing to 25,000. Funding for this facility came from an IPO, supported by RFMD's source of HBT wafers, TRW. It would become RFMD's biggest shareholder, taking a 31.1 percent stake in the company.

For Rockwell Semiconductor Systems, the latter half of the 1990s will be remembered for an explosive ramp in the production of its HBTs, made in its 4-inch fab. During the 18 months spanning the beginning of 1996 to the middle of 1997, production at this company – which went on to form Skyworks Solutions in 2002 through a merger with Alpha Industries – mushroomed from just 10,000 units per month to 70 times that figure. Buyers of these HBTs included Qualcomm and Samsung. Both valued this class of transistor for its combination of excellent linearity and high efficiency, attributes ideal for making handsets based on CDMA technology that featured long talk times.

Rockwell faced competition for this business from Anadigics, which had shipped more than a million GaAs ICs supporting the CDMA standard by summer 1997. While most of Rockwell's HBTs were being incorporated into phones operating in the 800 MHz to 900 MHz band, parts for Anadigics were providing amplification in transmitters of handsets using spectrum at 1900 MHz.

These higher-frequency products, based on Anadigics core technology, the MESFET, initially positioned the company for future success – but further ahead, contributed to its decline.

By the late 1990s, handset makers had shifted from using 6 V batteries to those providing 4.5 V and then just 3 V. This played into the hands of the increasingly price-competitive HBT. By the early 2000s, Anadigics ceased production of its MESFET, fighting back by developing a new generation of HBT.

Instead of having an AlGaAs emitter, it used InGaP. This refinement increased the HBT's reliability, bolstered its high-temperature operation and improved its linearity. Anadigics' product eventually proved a hit with handset makers, giving the company a healthy share of the 3G market.

# A fabulous fab

1998 When you think of high-volume manufacture of GaAs microelectronic devices, you'll probably think of HBTs for smartphones. But that's not the only market that has existed. In the telecommunications sector, a great deal of GaAs has been produced for laser and modulator drivers, multiplexers, demultiplexers, transimpedance amplifiers, clocks, and data-recovery circuits. In all these components, the higher speeds wrought by GaAs over silicon CMOS yielded higher bit rates.

Back in 1998, when GaAs devices for the telecoms sector were flying off the shelves, Vitesse increased its production capacity by building the world's first 6-inch GaAs fab.

Unlike most construction projects, where deadlines come and go, Vitesse's facility in Colorado Springs, CO, came in more than three months ahead of schedule. The first products, featuring GaAs MESFET technology, came off the line in early 1998, and in the third quarter of the year the company shipped $15 million of chips, based on 16 different products.

Vitesse, which also led the world in the migration from 3-inch to 4-inch GaAs production, built the 6-inch fab to cut the cost per die. Despite incurring a 25 percent hike in substrate-cost-per-unit-area, the switch to larger wafers delivered a 40 percent reduction at the die level.

In the markets that Vitesse served, its technology had to continue to advance so that it could maintain a healthy lead over products based on silicon CMOS.

The bursting of the dot.com bubble dealt a cruel blow, causing sales for Vitesse's 40 Gbit/s devices to collapse and not recover before a 90 nm silicon process had caught up. This ultimately led to the closure of Vitesse's GaAs fab in 2003.

After that, the company shifted focus, concentrating on silicon-based products for the metro, enterprise and storage market; and used its 4-inch InP fab to make high-speed electronic devices. The final chapter in the company's history came in 2015, with its acquisition by Microsemi.

Even today, a 6-inch fab represents the state-of-the art for producing GaAs transistors. This might suggest that in the last two decades progress in chip manufacture has stalled. But consider this: in silicon CMOS fabs, the rapid advances in wafer sizes through the last three decades of the twentieth century have not continued into this millennium, and there may never be a 450 mm silicon fab.

For silicon, the 300 mm fab appears to be the sweet spot for production, with the investment required for any larger size failing to offer a suitable return – and for GaAs, could the same apply to the 6-inch line?

# The perfect marriage

1999 What makes for an ideal merger? In a nutshell, it occurs when the result is greater than the sum of its parts.

That took place when Epitaxial Products International (EPI) joined forces with Quantum Epitaxial Design (QED) in 1999 to create IQE, the world's largest epiwafer supplier. QED of Bethlehem, PA, had built up its business by supplying MBE-grown wafers, used to make electronic devices, to a predominantly domestic market; while UK-based EPI had focused on optoelectronic epiwafers, with two-thirds of its sales coming from Europe and Asia.

The merged entity, offering a dual source of supply for some products, promised to be a resounding global success, drawing on the growing businesses of both companies. Sales at QED were increasing at a compound annual growth rate of 40 percent, while at EPI they were ramping at 30 percent. To cater for greater demand both sites had capacity expansion plans in place. QED had an order in for an MBE reactor capable of producing multiple 6-inch wafers from a single run, and EPI, which had recently increased the size of its facility, had placed orders for multi-wafer MOCVD tools. Helping to fund these expansion plans, IQE raised $70 million in an IPO, launching on the EASDAQ, the European version of NASDAQ, in summer 1999.

Since then, IQE has strengthened its leading position in the epiwafer market. In 2006, it acquired the epi business of Emcore; the following year it bought MBE Technologies of Singapore; and in 2012 it acquired the epi business of RFMD. It has also broadened its portfolio. The purchase Galaxy Semiconductor of Spokane, WA, in 2010, equipped the company with capability in antimony substrates and infrared technology; in 2012, the investment in Solar Junction strengthened expertise in multi-junction solar cells; and in 2018, the acquisition of Translucent's technology brought capability in crystalline rare-earth oxides on board, enabling compound semiconductor films to be grown on silicon wafers.

However, the last few years have been far from stellar for this colossus of epiwafer manufacturing. Sales are well down from their peak of £178 million in 2020 and after decades of leadership from the company's charismatic founder, Drew Nelson, his replacement, Americo Lemos, has been sacked after less than three years in charge. Turning all this around will not be easy, but thanks to operation in diverse markets, a return to better days is far from impossible.


➤ In 1999 the merger of UK-based Epitaxial Products International and US-based Quantum Epitaxial Design spawned IQE, which launched on the European equivalent of the NASDAQ.

In the late 1990s and early 2000s GaAs fabs were transitioning to larger wafers. Injecting some humour into the race to gain bragging rights with ever larger lines, TriQuint provided ‘evidence’ of its 6-foot fab in a series of images, described in chronological order. (top left) TriQuint announced the start-up of the industry’s first 72-inch wafer assembly line by circulating a press release at the GaAs Mantech conference held in 1999. (top middle). TriQuint then revealed that some of its engineers had been working frantically to prevent heavy lifting. “Man these are some big GaAs-wafers,” commented one operator (top centre). In the next picture story (top right), a TriQuint technician remarked: “I don’t know what happened, it just fell off the wand!” TriQuint went on to explain how equipment maintenance can prove to be quite a chore in a 72-inch wafer fab. This equipment engineer is inspecting just one of the many massive vacuum chambers used in the evaporation process. (bottom left) In the final release (bottom right), TriQuint reported how excitement built at the 72-inch wafer plant as the first finished wafers were distributed through the ‘Silicon Forest’.

# Giddy highs

**2000** Internet traffic soared in the run up to the millennium, placing tremendous strain on optical communication infrastructure. Carriers addressed this by beefing up network capacity. This created an optical component sector worth almost $10 billion and tipped to increase at a compound annual growth rate of 40 percent. Makers of III-V optoelectronics were well-positioned to benefit from this ramp, as their devices accounted for up to half that market.

Understandably, frantic carriers did not want to deal with numerous component suppliers. They longed for one-stop shops, ideally offering modules that would drop into their networks.

To cater for this demand, acquisitions ran rife in the components sector. JDS Uniphase (JDSU), formed in June 1999 through the merger of the Canadian outfit JDS Optics and the US firm Uniphase, led this spending spree. In late 1999 JDSU signed a deal worth $400 million for photodetector maker Epitaxx, and in 2000 it made three monumental acquisitions: it snapped up Optical Coating Laboratory for $6.2 billion, E-Tek Dynamics for $15 billion and SDL Lasers for a whopping $41 billion.

Kevin Kalkhoven, former JDSU CEO, co-founded PKV Racing, later known as KV Racing Technology. This team competed in both the Champ Car World Series and the IndyCar series, amassing five wins, including the 2013 Indianapolis 500.

Once the dot.com bubble had started to burst in the first few months of the new millennium, everyone knew the folly of buying a company for a figure that is many times more than its annual revenue. That made the purchase of SDL, for which JDSU had forked out a sum equating to 142 times the annual revenue, an outrageous blunder. Hindsight exposed any notion of a new world order, rampant in the giddy highs, and traditional economics were back with a vengeance.

During 2000, inventory corrections kicked in within the supply chain, driving down margins. On 30 June of that year JDSU had the dubious distinction of reporting the biggest ever annual corporate loss – an eye-watering $ 56.1 billion (taking inflation into account, it's now in third place, behind AOL Time Warner and the American International Group). However, for JDSU this loss was predominantly on paper. The vast majority of the $56.1 billion came from a write down of goodwill associated with various acquisitions, which were primarily all-stock deals.

For investors, the downturn in company fortunes could not be dismissed so easily. In March 2000, spurred on by analyst claims that out-of-the-box visionaries were leading a great company in exactly the right place at the right time, shares in this Wall Street 'darling' peak at $1200. Go forward a few years and they had fallen by more than 99 percent.

The company's leaders sold some of their shares near their peak, leading to accusations of fraud and insider trading. Some joked that JDSU now stood for Just Don't Sue Us – but those representing the state of Connecticut did just that, hoping to recover losses from a pension fund. The case, filed in 2002, came to court five years on, with management cleared of fraud.

By then the company CEO of the glory days, Kevin Kalkhoven, had retired, using part of his wealth for philanthropic ventures. He also funded a car-racing team that notched up five victories, including the Indianapolis 500 in 2013.

As for JDSU, it no longer exists. The prolonged downturn in the optical component business took a heavy toll, with the company shedding 80 percent of its workforce and closing 29 sites. In August 2015 the company split, forming network test and measurement specialist, Viavi Solutions and the laser manufacturer Lumentum.

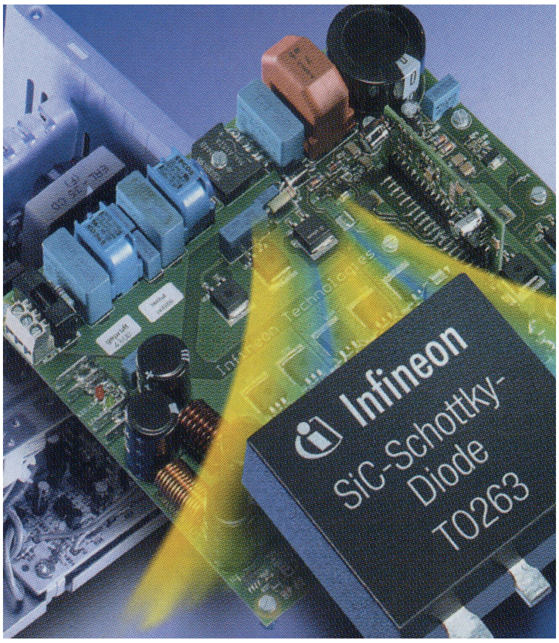
# A powerful start

**2001** What marked the beginning of the wide bandgap power electronic industry? It is surely Infineon's the launch of the SiC Schottky barrier diode, the first wide bandgap power electronic product to hit the market.

When this device made its debut in 2001, it filled a gap. Silicon and GaAs Schottky barrier diodes were limited to blocking below 250 V to avoid very high leakage currents, exacerbated at high temperatures. Infineon's pair of variants could handle 300 V and 600 V while carrying up to 1 A, and were far better at handling heat, giving them an edge for deployment in power supplies.

Infineon, which made these devices from 2-inch SiC wafers at its fab in Villach, Austria, targeted power supplies operating between 200 W and 1000 W. Used in that manner, the company's diodes featured in servers and wireless base stations. The designers that made the switch from silicon diodes to those made from SiC were well rewarded. Their supplies were more reliable and more efficient, and they could be smaller and lighter, as the SiC diodes allowed the operating frequency to increase, opening the door to a reduction in the size and weight of passive components.

Infineon's first generation of SiC diodes sported a simple architecture, selected to try and minimise costs that were dominated by pricey 2-inch SiC substrates. Since then, substrates have increased in size and quality and fallen in price, and diodes have been through several iterations, increasing in complexity. By 2018, Infineon had reached its sixth generation of 650 V SiC Schottky barrier diodes, a family of devices capable of handling currents ranging from 4 A to 20 A. These are still available, alongside fifth-generation variants with blocking voltages of 1.2 kV and 2 kV, and current ratings of up to 80 A and 40 A, respectively.




➤ The birth of the wide bandgap industry came in 2001, with Infineon's launch of the SiC Schottky barrier diode.

# Hooray for handsets

➤ The introduction of colour screens in handsets in the early years of this millennium helped swell sales of LEDs.


**2002** The compound semiconductor industry can never be accused of putting all its eggs in one basket. But at the start of this century, it certainly placed two of its largest in there. Back then, handsets provided the killer applications for the two biggest sellers: LEDs, used to backlight screens, illuminate keypads, and provide camera flash; and GaAs transistors, employed to amplify and switch RF signals.

When the mobile phone industry was in its infancy, the focus would have been on attracting new customers. But it would not have taken long before efforts broadened to include attempts to woo owners to upgrade their devices. In 2002, the cool new features were colour screens, built-in cameras, and picture and photo-messaging services. In Japan, mobile network operator J-phone offered those that purchased a new handset the opportunity to send video clips lasting 5 seconds.

Over the last two decades, the leading brands have changed markedly, shifting the fortunes of the makers of GaAs microelectronics. In early 2002, when phones supporting 2.5G led the way, Nokia dominated the market with a share of more than 35 percent, with its handset production providing the GaAs HBT manufacturer RFMD with about half its shipments. Motorola occupied second spot with 16 percent of the market, followed by Samsung, Siemens, and Sony Ericsson.

Fast forward to 2024 and Apple had moved up to pole position with a 19 percent share, closely followed by Samsung. There has also been a substantial rise annual phones sales.

In 2002, handset sales totalled just over 400 million units, and since 2014 this figure has remained above the billion per annum, peaking in 2018 at just over 1.5 billion.

# Tumultuous times for telecos

2003 After economic shocks, such as those caused by the pandemic or Russia's invasion of Ukraine, financial recovery may take many forms. We will hanker for a "V" – that is, after a sharp decline there will be an equally sharp rise that speeds us to a time of steady, sustained growth. But often the best we can realistically hope for is a "U", with a few tough quarters in store before a return to better days. What we are desperate to avoid is an "L", a decline that leaves a permanent scar on the economy.

Sometimes some sectors will experience an "L", even when the general economy is on the up. That happened to component makers within the telecommunications market in the 'noughties', leading to a flurry of activity in 2003. When the dot.com bubble started to burst, the III-V chipmakers operating in this industry initially put the problem down to inventory corrections.

However, by 2003, with orders still failing to pick up, it became clearer that the real issue was long-term over-capacity. This cannot be fixed when facilities change hands – all that can do is potentially increase production efficiency. The hard reality is that when there are more fabs than needed to supply demand, some have to be closed and workers laid off.

This chain of events can be seen in the activity at Bookham. Shortly after the bubble burst, it picked up Nortel Networks optical components division and Marconi's optical components business. In 2003, to try and streamline operations, it started relocating Nortel's former InP chipmaking facility in Ottawa, Canada, to the ex-Marconi facility in Caswell, UK. In addition, it moved the semi-automated line for laser assembly and test from its site in Zurich, Switzerland, to its facility in Paignton, UK. At that site, used to assemble optical chips into packaged products, headcount had already plummeted from a heyday figure of 7000 to just 800.

When a sector is struggling and showing no signs of recovery, it's a good idea to diversify into new markets. In late 2003 Bookham positioned itself to do just that, purchasing Ignis Optics, a maker of transceivers for datacom networks, and New Focus, a provider of photonics and microwave products for semiconductor, biotech, defence and research industries.

In 2003 another major shift in the optical components landscape came from Avanex's acquisitions of divisions of Alcatel and Corning. The former calved off Alcatel Optronics, while the later parted company with its optical components' plants in Milan, Italy, and its optical amplifier facility in Erwin, NY. Corning's restructuring also involved the closure of its Lasertron pump laser facility, purchased in a $1.8 billion stock deal in November 1999.

Further changes within the components sector in 2003 included: ASIP, a maker of InP optoelectronic components, purchasing struggling rival ThreeFive Photonics; integration of the optical chip processing lines at NTT Electronics and Oki Electric, used for lasers, photodiodes and modulators; Ericsson's exit from the optical component business through its sale of Ericsson Optoelectronics to Swedish start-up Northlight Optronics; and Agere's decision to bid farewell to this sector by selling its West Coast optoelectronics business to Emcore for $25 million in cash.

Following a hive of activity in 2003, restructuring of this sector slowed down, but did not stop. In 2009 Avanex and Bookham merged to form Oclaro, which went on to sell its Zurich GaAs laser diode business in 2013, in a cash deal worth $115 million to II-VI Incorporated, now Coherent. And then, in 2018, Lumentum bought Oclaro, to expand its portfolio of laser products.

While it's easy to view 2003 as just a year of gloom and doom, take a careful look and you can also find a silver lining. Back then, some canny investors were willing to pump cash into this sector, enabling Infinera to raise a whopping $53 million in series D funding in the latter half of the year. This Californian-based outfit has blossomed, netting billions of dollars and making a strong case for the virtues of vertical integration in the telecom sector.

# In search of a new killer app

**2004** The handset provided the first killer application for the GaN LED. Used to illuminate keypads and backlight screens, manufacture of this device exploded as mobiles became a must-have accessory. This led the leading LED makers to face more competition. They knew that their margins in this market would slowly shrink, so they went in search of new, more demanding applications that would allow them to make more money.

The backlighting of far bigger screens offered a very promising opportunity, and in 2004 Nichia, Toyoda Gosei and Osram Opto Semiconductors all promoted LED-backlit screens at various shows. But rival Lumileds drew first blood, winning a supply contract to ship LEDs from its Luxeon range to Sony, for use in two of its flagship TVs for 2004: 40-inch and 46-inch Qualia models, retailing for around $7,500 and $10,000, respectively.

Boasting a far wider colour gamut than screens incorporating cold-cathode fluorescent lamps, these TVs could not fail to impress. And there is no doubt that some early adopters would have been willing to pay a hefty premium to get their hands on this new technology. But the parting of their cash, which helped Sony to claw back some of its investment in R&D, did not lead to tumbling prices over the next few years, alongside a growth in shipments and major market success. Although that has happened for LED-backlit TVs, it has taken a relatively long time. Five years on from Sony's launch, its high-end models were still retailing for thousands of dollars. By then TVs from Samsung, which also introduced LED-backlit TVs in 2004, were on offer for less, but they still had price tags of just under $2000 and $1500 for 46-inch and 40-inch TVs, respectively. It is only in the previous decade that LED-backlighting has become a more affordable, dominant technology.

2004 will also go down in history as the year that China started its quest to take a significant share of the market. The China National Solid-State Lighting Programme kicked off in June of that year, providing a tremendous level of support for home-grown chipmakers. This effort has ultimately been responsible for razor-thin margins in the LED industry, and the commoditisation of this device.


➤ Samsung and Sony pioneered LED-backlit TVs. Launched in 2004 and costing many thousands of dollars, initial sales were sluggish. Thanks to a tremendous reduction in the cost of these screens, they are the incumbent technology today.

# The quest for ultra-efficient lasers

2005 There's an elegance in using a high-power laser to destroy tanks and missiles with a burst of incredibly powerful radiation. But even today, despite research and development into laser-based weapons going back over 60 years, this idea is still a long way from becoming a mainstream military technology. The are various issues, including a phenomenon known as thermal blooming – it is a defocusing of the beam, caused by the creation of a plasma at very high levels of light intensity. Unfortunately, blooming is exacerbated by fog, smoke, dust and rain, none of which are strangers to the battlefield.

Despite all these concerns, in 2003 the US agency DARPA ran a three-year programme called SHEDS – super-high efficiency diode sources – aimed at preparing the way for a laser-based weapon. This effort focused on propelling the wall-plug efficiency of commercial infrared laser bars from well below 50 percent to 80 percent. Hitting this target could lead to a highly-efficient 100 kW laser-based defence weapon, according to the sponsor.

Three US chipmakers took on the laser diode efficiency challenge: Alfalight, nLight and JDSU. All sailed past the 65 percent intermediate goal by refining their devices through initiatives that included the compositional grading of quantum well interfaces, the introduction of materials that enhance optical and electrical confinement, and changes to doping that cut contact resistance. But none could scale the dizzy heights and fulfil the final target, an efficiency of 80 percent.

Despite this failure, the programme left a great legacy. And like many DARPA initiatives, the beneficiaries lie outside the military. Even in 2005, before the programme had finished, gains in laser efficiency were making an impact in industries that use solid-state, diode-pumped lasers for a wide variety of material processing tasks, from shaping medical devices to welding car-body parts. Higher efficiencies were trimming the dollar-per-Watt metric, and in turn reducing expenditure on diodes that could total a third of the system cost. What's more, device reliability improved, because greater efficiency means less heat, and chips running at lower temperatures.

Improvements to the diode's bang-per-buck have also been instrumental in the success of fibre lasers. Offering a simple solution to the tricky problem of how best to focus light on a target, diode-pumped fibre lasers are now widely deployed for cutting, welding, and folding metals and polymers, with sales netting $7.7 billion per year in 2024.

➤ Efforts to turn the vision of laser-based weapons into reality were supported by a DARPA-funded programme aimed at increasing the efficiency of infrared laser diodes from below 50 percent to 80 percent or more.

# Lighting up silicon

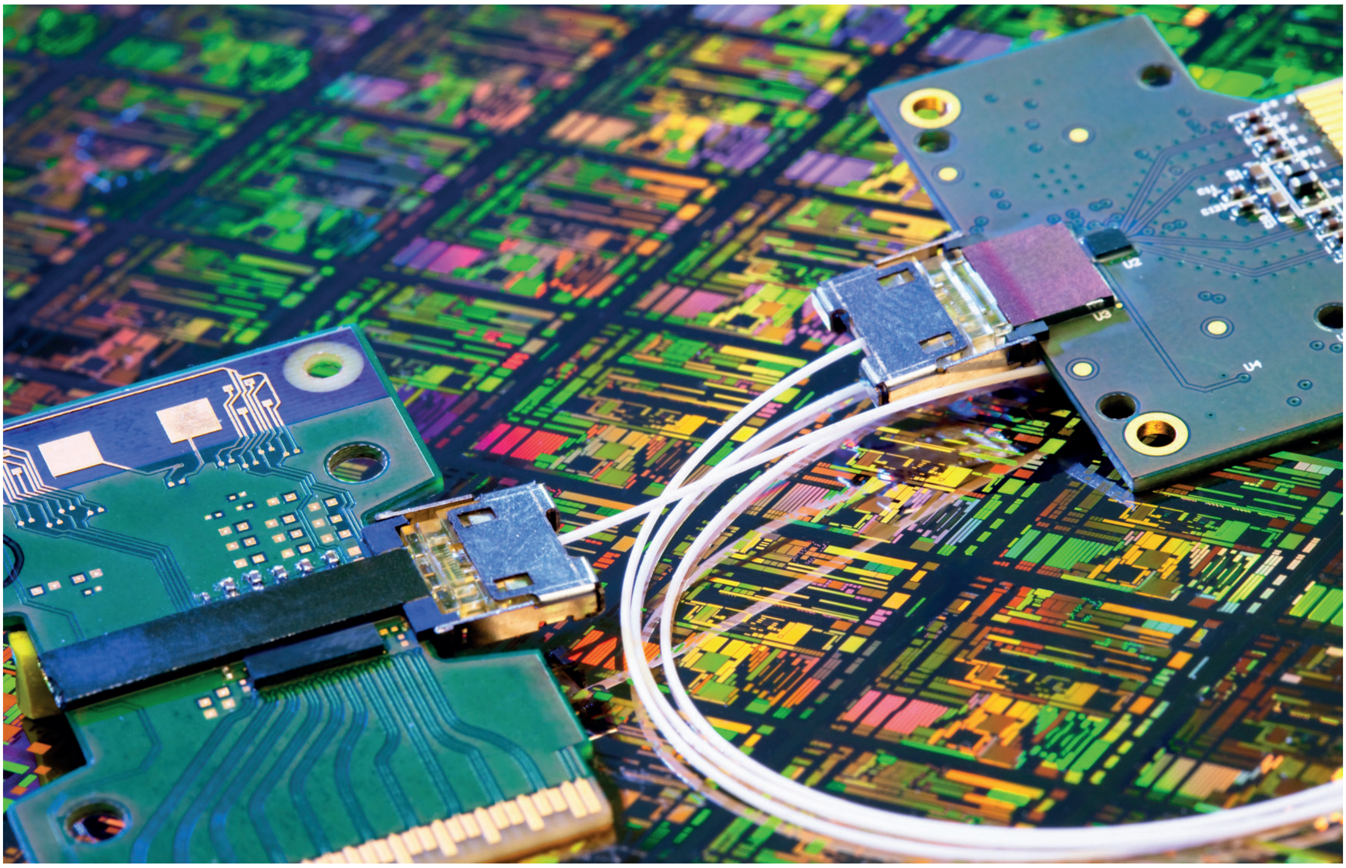
**2006** Silicon photonics sounds great. Whizzing photons around miniature racetracks in silicon chips, churned out in state-of-the-art fabs, promises a future of affordable, breath-taking computational powers and superfast communication.

But I know you'll have concerns, since silicon can't emit light. That makes the manufacture of photonic chips quite a challenge, as if you want your light source on the chip, you'll need to find a way to unite a III-Vs laser with a silicon waveguide while combatting problems arising from the considerable lattice mismatch between these materials.

The first significant success in this endeavour came in 2006, through a partnership between engineers at Intel and John Bower's group at the University of California, Santa Barbara. Using a low-temperature oxygen plasma, these researchers created a thin oxide layer on the surface of both materials. This layer enabled the fusing of an InP-based chip, containing AlGaInAs quantum wells, to a silicon waveguide strip, to create an electrically pumped laser. And due to the excellent coupling between these entities, the silicon waveguide played a fundamental role in the lasing action.

Building on this triumph, Intel developed and commercialised a portfolio of transceiver products. By 2020, the company had shipped more than 3 million 100G pluggable transceivers based on its silicon photonics platform, and demonstrated a four-channel device operating at 400 Gbit/s.

However, in the summer of 2023, as part of cost-cutting measures and efforts to focus on artificial intelligence infrastructure, Intel sold its silicon photonics pluggable transceiver module business to Jabil. It is now offering a portfolio that includes 800 Gbit/s products.



➤ Intel pioneered the integration of InP-lasers and silicon photonics. In this 50 Gbit/s link, the transmit module (left) sends laser light from the silicon chip at the centre of the green board, which travels through optical fibre to the receiver module (right), where a second silicon chip detects the data on the laser and coverts it back into an electrical signal.

# Debating droop

**2007** Some scientific questions pique interest but actually don't matter that much because they are only of academic interest. But in 2007, that was certainly not the case for droop. Back then this mysterious malady pegged back the efficiency of LEDs at the current densities needed to win business in the biggest market of all, general lighting.

At that point in time researchers had ruled out heating as the cause and dismissed indium clustering, attributed as a measurement artefact. The search continued, with much riding on success. Unmasking droop would offer insight into how to build efficient devices that could light our homes and offices.

In February 2007 Philips Lumileds came out with a stunning, bold claim, saying that it had 'fundamentally solved' the problem of droop. According to this Californian chipmaker, LEDs that were free from this malady would follow in a matter of months.

Rather tantalisingly, the company offered no details of the cause of this deficiency. But in September they spilt the beans at the biggest nitride conference of the year. At a buzzing *International Conference on Nitride Semiconductors*, held in the heart of Las Vegas, Mike Krames, at the time the leader of the company's Advanced Laboratories, unveiled Auger-Meitner recombination as the cause.

The claim drew a mixed reception. Partly, it is a cause no-one wanted, because it fails to offer a route to making droop-free devices.

Auger-Meitner recombination is an intrinsic process that depends on the carrier density, and all that can be done to reduce it is a form of social distancing at the atomic scale, such as a widening of the wells. But in practice it's very difficult to produce thick, high-quality quantum wells, due to strain.

What's more, not all researchers agreed with Krames and his co-workers. Some questioned the magnitude of the Auger-Meitner coefficient required for this to be the primary loss mechanism, while others argued that just because it's possible to fit a curve to a graph with a cubed dependence classically associated with Auger-Meitner recombination, that is not proof that Auger-Meitner causes droop.

An alternative theory came from Fred Schubert's group and Rensselaer Polytechnic Institute in Troy, NY, working in partnership with researchers at Samsung and Joachim Piprek, a theorist at the device simulation consultancy NUSOD. This team, which started publishing papers in late 2007, attributed droop to carrier leakage. They went on to build polarisation-matched devices delivering higher efficiencies at higher drive currents.

The debate on the cause of droop raged for many years. In 2013, as we shall soon see, independent work laid claims of a smoking gun, providing definitive proof that Auger-Meitner recombination is the cause of droop. But even that did not convince everyone.

# Sunny times

2008 After many years of waiting, in 2008 the concentrating photovoltaic (CPV) industry looked like it would soon hit the big time. Venture capitalists had tired of investing in the telecommunication market and were starting to put their cash into cleantech, including developers of CPV. This helped a handful of pioneers of CPV systems to win contracts for multi-megawatt deployments, and led two makers of multi-junction cells – Spectrolab and Emcore – to fill up their order books. And as they looked over their shoulders, they saw the likes of Spire Semiconductors, MicroLink and Kopin preparing to launch rival products.

It took a long, long time for the fledgling CPV industry to get this far. The idea of focusing sunlight on highly efficient III-V cells can be traced back as far as the late 1970s. A few years on a prototype had been put together by researchers at the Ioffe Physico-Technial Institute in St. Petersburg, Russia. Their system, reported in 1981 in a paper co-authored by Nobel-prize winning physicist Zhores Alferov, used reflectors as big as bin lids to direct sunlight on 1.7 cm-diameter AlGaAs/GaAs solar cells, butted up against aluminium pipes to prevent overheating. In the decades that followed, more demonstrators were put together and III-V cell efficiencies climbed, culminating in the deployment of a few tens of megawatts in the run up to 2008.

Interest in concentrating photovoltaics reached an all-time high in 2008. A leader in this field, Concentrix, used Fresnel lens to concentrate sunlight by a factor of typically 500 on triple-junction cells. A credit crunch and a dramatic reduction in the price of silicon PV wrought havoc in the fledgling CPV industry. Soitec purchased Concentrix in 2009, and then sold this technology to STACE, Canada, in 2015.

That year, market analyst Lux Research claimed that the long-term signs were great, with expenditure on installations employing III-V solar cells set to total $1.2 billion by 2012. The analyst warned that some CPV start-ups would not survive, because they were failing to tackle important engineering issues surrounding maintenance, cooling and wind resistance. But in an emerging market some firms will always go to the wall.

The unfortunate reality is that come 2012, the CPV industry was in tatters. Many firms had gone bust, while those that were left were on their last legs. The credit crunch, caused by a global economic crisis, starved these pioneers of investment crucial to increasing their size and delivering economies of scale. Another hammer-blow came from falling prices of silicon solar cells at the start of that decade. Despite $500 million of investment, roughly just 100 megawatts of CPV has been deployed, with a lack of business behind the demise of many big names in the sector, including Ammonix, SolFocus, Isofotón, GreenVolts and Semprius.

Today CPV is still down, but not quite out. Late last year CPV expert Frank Dimroth from Fraunhofer ISE told *Compound Semiconductor* that the long-term prospects are positive, due to the need to maximise the energy yield from a given area, and minimise the use of materials. Solar deployments are planned to peak at around 3.4 TW per annum by 3037, and if all that capacity were provided by today's silicon panels, that would consume all the glass currently produced.

Another long-term boost to the prospects of CPV could come from work at the National Renewable Energy Laboratory in Golden, CO, that promises to slash cell costs. Researchers at this facility are developing a dynamic HVPE growth tool that features multiple chambers, each employed to add a single layer at a growth rate of many tens of microns per hour. Some initial results, obtained using HVPE to produce single-junction cells, revealed that this growth technique can deliver photovoltaic efficiencies that are only a couple of percent short of those realised by MOCVD, with some of that superiority coming from optical structures that boost photon recycling. So, there is good reason to believe that a switch to the HVPE growth of III-V solar cells could deliver a hike in throughput, while slashing costs, and ultimately increasing the appeal of this technology that requires far less material than today's incumbent.

# Going green

2009 What do you think is easier – using an efficient blue LED as a starting point to build a laser that emits at roughly the same wavelength; or starting with a laser that emits in the blue-violet, and constructing a variant that emits in the green? I expect your instinct is to start with the latter. After all, to go from an LED to laser, you need to introduce optical confinement, add mirrors, crank up the local carrier concentration and slash the defect density in the active region. In comparison, to turn a blue-violet laser into a green one, all you need to do is add a little more indium to the quantum well.

But if you take a look in the history books, you'll uncover flaws in that line of reasoning. Courtesy of Shuji Nakamura's pioneering work, Nichia reported its first efficient blue LED in 1993, and took just two years to follow it up with a laser. But nearly another 15 years elapsed before our community had made its first green GaN laser.

The first important step towards this source came in 2003, with Nichia's report of a 480 nm laser – still blue, but leaning to the green. Five years on, it had only stretched the wavelength by another 8 nm. Had this device come up against an invisible wall, with blue-green the limit?

Any chances of getting to true green, considered to be 520 nm and beyond, seemed to rely on a radical re-design. Part of the issue facing Nichia's engineers, as well as their rivals, concerned cranking up the indium content to reach longer wavelengths. To increase the indium in the well required a lowering of the growth temperature in the MOCVD chamber. However, this riddled the device with defects, degrading light emission. Compounding the problem, intrinsic electric fields in these heterostructures pull apart electrons and holes in the wells, and as the indium content increases, they get even stronger. While these fields are beneficial on one hand, pushing emission to longer wavelengths, they lead to a build-up of charges at the interfaces within the active region, making it harder to inject carriers into the device. Turning up the voltage forces them through, but negates the benefit of the internal field, so it's goodbye to longer wavelengths.

A novel way to overcome this issue is to switch growth planes. Growing the device on the non-polar plane eradicates the electric field. In early 2007, a team at the University of California, Santa Barbara, that included Nakamura – he joined this group from Nichia in late 1999 – did just that, and announced the world's first non-polar laser, emitting in pulse mode at 404 nm. Just three days later this device had been trumped by a continuous-wave variant, announced by Rohm. When Rohm announced this milestone, it also set out its true ambition: building a 532 nm laser for colour displays. Before the year was out, it had stretched the emission of its device to 459 nm. Competition came from Sharp, entering the fray in 2008 with a 463 nm non-polar laser. Rohm retaliated with a 481 nm device.

2009 proved a pivotal year. In February 2009, Rohm revealed yet more progress, reaching 499.8 nm, a wavelength eclipsing the best mark for conventional nitride lasers. At that point, a non-polar laser would have been the bookies' favourite in the race for the first GaN green laser. But anyone thinking along these lines got an almighty shock nine days later, when a conventional laser took the lead. This didn't come out of the labs of Nichia, but from a very dark horse – Osram Opto Semiconductors of Regensbuurg, Germany. The German company hit 500 nm by making ground on many fronts. Then, in the spring, Nichia grabbed the record, again with a conventional laser. It first reported success at 510 nm, before revealing it had made a 515 nm laser. How did it do it? It's hard to tell – all the company would say is that it had improved the quality of its active region.

The first true-green laser came in early summer 2009. Snatching the crown came GaN substrate specialist Sumitomo, announcing on 16 July a device emitting at 531 nm. Success came from a halfway house – that is, a semi-polar plane. This orientation quashes internal electric fields while providing a great foundation for growing indium-rich InGaN layers.

Further work has followed on non-polar, semi-polar and conventional planes. In 2019 Sony reported a 525 nm semi-polar laser with a peak wall-plug efficiency of more than 19 percent that is capable of an output of up to 1.75 W. And at *Photonics West* 2020, Nichia revealed that it could do even better, having made a conventional 525 nm laser emitting up to almost 2 W. Since then, there have been no major announcements related to the power and efficiency of green diode lasers, but it's clear that the level of performance is good enough to drive the sales of this class of device in many applications.

# The long-awaited transistor

**2010** Infineon's launch of the world's first SiC Schottky barrier diode in 2001 gave designers of power electronics a far more efficient device for controlling current flow.

However, while this wide bandgap diode helped to trim losses, circuit designers knew that they could do so much better if they could pair these devices with SiC transistors, as that would improve the efficiency for turning currents on and off.

Start-ups and established makers of SiC devices took on this challenge. US outfit SemiSouth got there first, bringing to market a JFET in 2008. And within a few months, an alternative appeared: the BJT, launched by TranSiC, a spin-off of KTH Royal Institute of Technology, Sweden.

But neither of these classes of SiC transistor won favour with designers. Both offered fast switching and a low on-resistance, hallmarks of SiC, but were 'normally-on'. That's a massive concern from a safety perspective. While it is possible to create a normally-off hybrid by pairing this transistor with another device, that's an ugly solution.

Designers craved a more efficient, drop-on replacement for the silicon IGBT.

The SiC MOSFET ticks those boxes, but it is very challenging to produce. One difficulty, taking many years to solve, is how to make a high-quality native oxide, a crucial layer that lies at the heart of the device, sitting between SiC and the metal contact. Engineers had no luck with any of the tricks employed in the silicon industry, so they had to find alternative approaches, such as a thermal growth process. A low channel mobility also applied the brakes to commercialisation, addressed by annealing in nitrogen gas, a step that slashes interface states.

By 2010, two of the biggest hitters in the SiC industry, Cree (now Wolfspeed) and Rohm started to mass produce SiC MOSFETs. Which company won this race is a moot point to this day – both claim victory. The launch did not open the floodgates, with sales held back by high prices.

For example, not long after its launch, Cree's MOSFET, sold through Digikey, retailed for $80 or more.

Since then prices have fallen, while the number of producers has expanded significantly. There is also more choice in blocking voltage and current handling, thanks to expanded portfolios and improved performance. All this activity is swelling sales, with many analysts claiming that global annual revenue for the SiC MOSFETs now exceeds $1 billion, and continues to climb at a very healthy rate.

# A prize-winning bulb

**2011** In the not-too-distant past, many of us would agonise over what to do when our lightbulb failed and we had to replace it. If trimming carbon footprints topped our agenda, we would select a compact fluorescent. But they were never a hit.

After installing one and flicking a switch, this bulb would take a minute or so to reach full brightness, by which time the room had been cast in a rather harsh light. Dimmer switches could not dial back the intensity, and when it came to disposal, care had to be taken with this mercury-ridden source.

If all those compromises were too much for us, we'd buy the well-established filament-based incandescent. It generated far more heat than light, and it didn't last that long – 1,000 hours is typical – but it had many fans, as it instantly bathed the room with a lovely shade of white, and could be dimmed down.

Recognising these concerns and trying to do something about them, the US Department of Energy launched a competition in 2008 called the Bright Tomorrow Lighting Prize, better known as the L-Prize. $10 million were up for grabs, awarded to the first company that produced a bulb that combined the virtues of an incandescent with running costs that bettered a compact fluorescent and an incredibly long lifetime.

In August 2011 Philips claimed victory with a dimmable bulb that drew just 9.7 W while putting out a peak output of 910 lumens – that is 110 lumens more than a typical 60 W incandescent. Philips' bulb underwent a range of tests to evaluate robustness, including being shaken, operated in temperature extremes and high levels of humidity, and driven with an imperfect voltage supply. Passing all evaluations with ease, it offered a lifetime of 25,000 hours, more than double that of a compact fluorescent.

When Philips launched this most impressive of sources it commanded a price so high that it would put off many early adopters. Would anyone really be willing to spend $50 on a single bulb?

Fortunately, prices have plummeted over the last few years. Today, if you shell out $50 on solid-state lighting, you could return from a hardware store with a score of Philips' 60 W-equivalent LED bulbs. Thanks to these competitive prices, many homes are now lit by a collection of light-emitting chips.


The 60 W incandescent bulb has many great attributes: instant on, a nice warm hue, and the opportunity to dim output. The $10 million L-Prize challenged makers of LED bulbs to replicate all these merits, while drawing less than 10 W. Philips Lumileds got their first, before launching their award-winning bulb. One striking feature of this source is the yellow colour of its emitting surface, easily visible when the bulb is not on. The yellow is associated with the remote phosphor, which when pumped with a battalion of 18 LEDs, casts a room in uniform, warm shade of white light.

# Gallium nitride gets its credentials

**2012** Hero results pique interest but don't guarantee sales. Designers want products that combine a great performance with longevity.

Developers at Transphorm understood this completely. They knew that their GaN FETs were attracting much attention, because they were a great product, exceeding the efficiency of silicon and coping far better at elevated temperatures. But to win sales, by assuring potential customers that they should not have any concerns over reliability, they put their 600V FET in for independent device testing. It passed, giving Transphorm, in 2012, the industry's first GaN FET qualified to the JEDEC standard.

Initial products by this West-coast firm were produced on SiC substrates. But production soon switched to silicon. Merits of this move were not limited to a cheaper, larger foundation, but included the opportunity to process devices on mature 200 mm lines, potentially in under-utilised fabs.

More recently, Transphorm qualified its GaN-on-silicon FETs at standard temperatures and 175°C. This helped to drive sales, which surpassed 500,000 in 2019. Fourth-generation products launched in 2020, taking performance of GaN-on-silicon FETs to a new high.


Last January Renesas announced that it would be acquiring Transphorm for $339 million. This deal went through in June, expanding the power portfolio of the Japanese chipmaker beyond silicon and SiC devices.

# Droop's smoking gun?

2013 Would it ever be possible to draw the debate on droop to a close? Given the competing, vigorously defended theories, it would require irrefutable proof. Obtaining this would not be easy, but in Spring 2013 claims of a smoking gun surfaced from a partnership between researchers at the University of California, Santa Barbara (UCSB), and the École Polytechnique in France.

This team's evidence came from an extremely elegant experiment that drew parallels with that made by Robert Millikan at the start of the twentieth century. Millikan studied the photoelectric effect by measuring the kinetic energy of electrons exiting a metal bombarded with beams of photons.

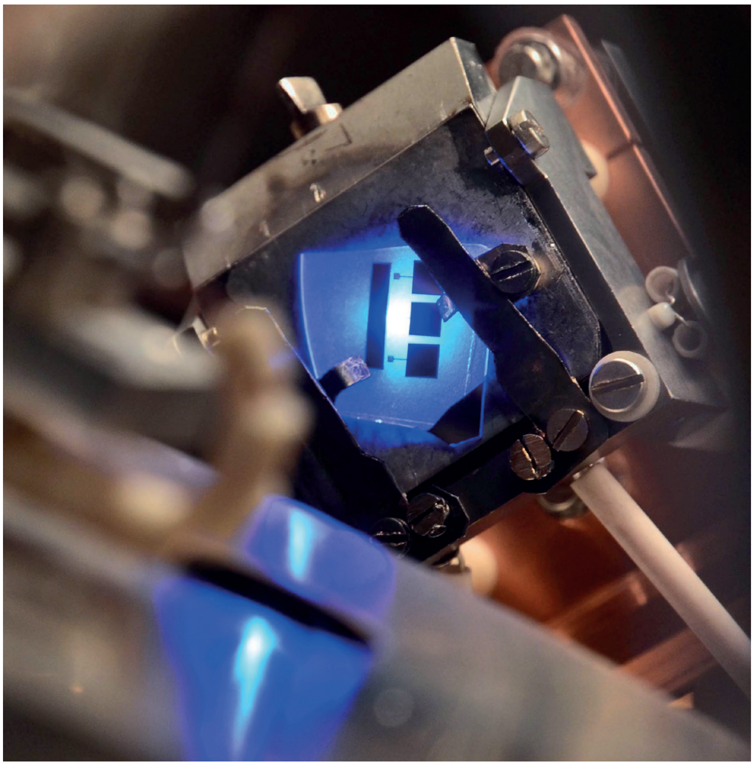
On this more recent occasion researchers injected carriers into the quantum well and recorded two phenomena: the light emitted by the LED, and the energy of electrons exiting through the *p*-side of the device. To ensure all thermalised electrons left the LED, the *p*-side surface had been treated with caesium.

As the scientists from this collaboration cranked up the current through their device, they detected higher energy peaks, associated with the vacuum-emitted electrons. According to them, this observation provided unquestionable proof that Auger-Meitner is the cause of droop. In their view, no other mechanism could be responsible for these 'hot' electron peaks. Strengthening this claim, they found that when droop kicked in, high energy peaks started to emerge.

So, did other researchers working in this field raise a glass, toast this team's success and agree that this work had put the debate on droop to bed? Absolutely not. In general, those that are trying to fathom the cause of droop have entrenched positions and are convinced that after examining all the evidence the theory they postulated is still the most convincing.

Critics argued that the experimental results may have been interpreted incorrectly. Boston University's Enrico Bellotti claimed that the experiment suggests that electron leakage is the cause of droop, with some help from the Auger-Meitner effect.

Fred Schubert from Rensselaer Polytechnic Institute in Troy, NY, tended to agree, suggesting that some electrons detected in the experiment might not be associated with the Auger-Meitner effect at all, having simply leaked out of the LED's quantum well. Another reason why Schubert struggles to view



➤ By tracking the energy of non-radiative electrons that pass through an LED while simultaneously recording the light output of this device, researchers from the University of California, Santa Barbara, and the École Polytechnique, France, claimed they had definitive proof that the Auger-Meitner effect is the cause of droop.

Auger-Meitner recombination as a major contributor to droop is that he considers droop to be stronger at low temperatures, while Auger is weaker.

The team from UCSB and the École Polytechnique addressed their critics in the November & December 2013 edition of *Compound Semiconductor* magazine. In their feature, they argued that in their LEDs, the electric field is not strong enough to cause electron leakage. They also countered claims that it would not be possible to observe Auger-Meitner-generated electrons escaping into vacuum, and expressed concerns related to a claim that free-carrier absorption could be a cause of droop.

Discussing competing theories will have helped to progress efforts to come to a consensus on the cause of droop. But even now, the debate has not completely disappeared.

# A full complement

2014 The prospects of emerging devices can be judged by the actions of the biggest players manufacturing products with the incumbent technology. If alternatives have an outside chance of success, a few leading firms might dabble in them; and if they are certain to play a major role, multi-nationals will invest, either through acquisitions or internal development.

History now attests that the leading producers of power devices have made the right decision to invest heavily in wide bandgap technology. They have all branched out from considering only silicon devices, and made headway with either SiC or GaN, or both alternatives.

A trailblazer in diversification at scale is Infineon. It has not been hedging its bets as to which of these two rivals is going to play a bigger role, but has been pursuing both for more than a decade, viewing GaN as a strong candidate for below 600 V and SiC as the best option for higher voltages. A pioneer of commercialising SiC diodes and MOSFETs, Infineon did not embark on an internal development programme for GaN. Instead, it decided to acquire this technology. In 2014, it agreed to shell out $3 billion in cash for GaN-on-silicon pioneer International Rectifier (IR). Note, however, that as well as gaining IR's GaN-based technology, it also picked up its low-voltage silicon MOSFET family, which accounted for the lion's share of sales. When Infineon took IR into its fold, it viewed GaN-on-silicon as a long-term investment, generating sales at least five years down the line.

In March 2015, Infineon deepened its involvement in GaN, teaming up with Panasonic. This duo signed a deal committing them to jointly develop devices that combined Panasonic's normally-off GaN-on-silicon transistors with Infineon's surface-mounted packages that would house these chips.

More recently, Infineon has broadened its portfolio of CoolGaN products, made using its own devices. So GaN is underway and SiC and silicon are well established, giving this German powerhouse an incredibly broad portfolio.


In 2014, Infineon agreed to purchase International Rectifier for $3 billion. Orchestrators of the deal were Reinhard Ploss (left), CEO of Infineon Technologies, and Oleg Khaykin (right), President and CEO of International Rectifier.

# Two titans unite

2015 During the last 30 years, the two biggest sectors within our industry, LEDs and GaAs microelectronics, have headed in very different directions. In the LED industry five LED chipmakers rose to the fore in the late 1990s – Nichia, Cree, Lumileds, Toyoda Gosei and Osram – and held on to one of these top spots for many years. Now, though, the LED industry is far more fragmented. In stark contrast, the GaAs microelectronics industry has seen a dramatic contraction in the number of competitors, despite a growth in revenue over the last 30 years from below $0.5 billion to more than ten times this figure.

Big players that have left the GaAs industry include Anadigics, snapped up in 2016 by II-VI (now Coherent), which spent several years converting its RF line to the production of VCSELs. Other leading names have merged.

In 2002, Skyworks formed through the marriage of Alpha Industries and Conexant, and more recently Qorvo emerged from the union of two heavyweights, RFMD and TriQuint. The new entity started trading on 1 January, 2015.

That merger had much going for it. Many viewed the two companies as complementary, with RFMD having greater strength in RF technologies for handsets and TriQuint offering a better portfolio of defence products.

Investors clearly approved of the union, with the share prices of both firms enjoying double-digit jumps on disclosure of the plans. The new entity had the potential to initially net an annual revenue of just over $2 billion; and thanks to synergies providing yearly savings of $150 million, gross and operating margins were tipped to be 45 percent and 25 percent, respectively.

Ten years on, has the merger delivered on all those promises? Well, sales for the four most recent fiscal quarters have amassed $3.24 billion, with a gross margin around the targeted value.

However, the company is currently running at a small loss. This appears to be weighing on the share price, which has fallen from a peak of almost $200 in summer 2021 to around $70, the value of this stock on its first day of trading.

# True heavyweight flexes its muscles

**2016** If you are a regular reader of his magazine, then by the middle of the last decade you would have been aware of the tremendous promise of gallium oxide. With a whopping bandgap of around 5 eV – the precise value depends on the particular polytype – it has the potential to deliver a knockout blow to those two much-vaunted middleweights, SiC and GaN. Thanks to gallium oxide's far wider bandgap, it should be able to reign supreme in that most valued of characteristics, the on-resistance as a function of breakdown voltage. But that's not its only alluring attribute: it offers versatility, because thin films of gallium oxide can be deposited by a variety of techniques, including MBE and MOCVD; and there are several options for the substrate. Devices can be grown on sapphire or gallium oxide, which could tumble in price, because boules of this material can be grown by melt-based techniques.

Gallium oxide's great promise has made it easy for researchers and developers to attract interest and initial investment. However, like any material, its future hinged on demonstrations of device capability. For gallium oxide, they came thick and fast in 2016.

During that year, two key breakthroughs emerged from a team at the Air Force Research Labs (ARFL). Using structures made from the $\beta$-polytype and grown on a native substrate, engineers working there grabbed the limelight by producing a MOSFET with a record-breaking critical field strength of 3.8 MV $cm^{-1}$ – that's about four times the critical field strength of GaN. And later that year they realised another breakthrough, reporting the first ever enhancement-mode FET with a high-breakdown voltage in the off-state. This second success demonstrated that a lack of *p*-type carriers in gallium oxide is not a show-stopper to making a normally-off FET. The gallium oxide research programme at ARFL had been inspired by the work at Japan's National Institute of Information and Communications (NICT). Researchers at NICT, working with domestic partners, had driven much early progress in materials and devices, and gone on to produce the world's first MESFETs and MOSFETs in 2012.

Japan also provided another milestone in gallium oxide. In 2016, using a novel growth technique known as mist epitaxy, researchers at Flosfia reported $\beta$-$Ga_2O_3$-on-sapphire Schottky barrier diodes sporting an on-resistance that trumps that of state-of-the-art variants made from SiC. Several years ago, this University of Kyoto spin-off said that it would be commercialising its $\beta$-$Ga_2O_3$ power devices within a matter of months. The company failed to stick to its schedule, with a market launch postponed by reliability issues. However, it appears that Flosfia is now getting back on track, making progress, having recently announced that it has developed a prototype 600 V, 10 A junction barrier diode that will be sampled to customers this year. This device, with a turn-on of 0.9 V, incorporates *p*-type $(IrGa)_2O_3$. As well as this advance, the company has recently demonstrated the operation of a trench-gate MOSFET and scaled its production processes, establishing $\beta$-$Ga_2O_3$ growth technology for 4-inch wafers. With plans to also verify 4-inch wafer manufacturing this year, commercial prospects for $Ga_2O_3$ are on the up.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# Creating the world's first compound semiconductor cluster

**2017** What is the most famous valley in the world? OK, it might not be the first response to trip off your tongue, but a great case can be made for Silicon Valley.

While this region may not have that many fabs today, the engineers that have worked here – many of them, graduates of Stanford University – are to be thanked for not only their advances in technology, but for giving all of us working in the semiconductor industry a higher status in society. Today technology is admired, benefitting many, even if the average man in the street has never heard of holes, bandgaps or lithography.

California is not the only part of the world with a cluster of semiconductor companies. They are also found in Leuven, Belgium; in Dresden, Germany; in Eindhoven, The Netherlands; and in Grenoble, France.

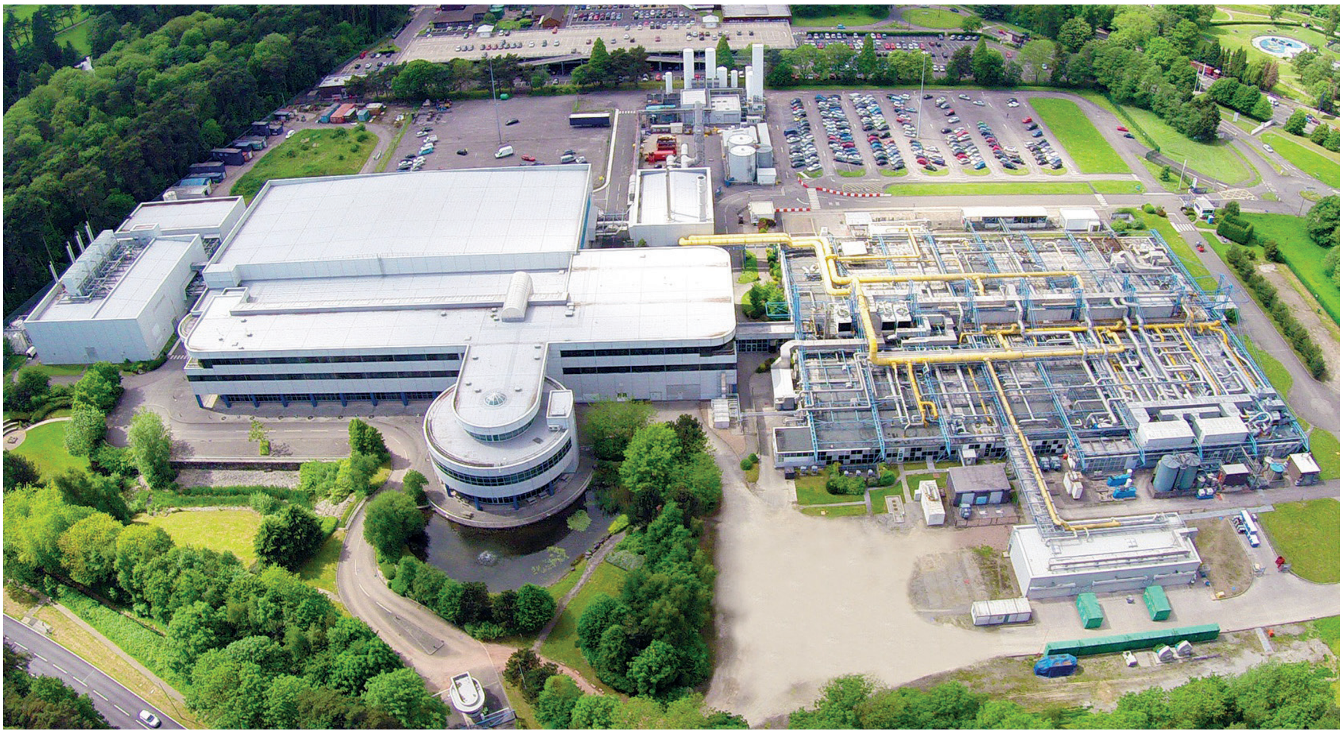
One of the strengths of all these clusters is that by having many companies on each other's doorstep, often operating at different positions within the supply chain, they are able to support one another while attracting more engineering talent to the region. This helps to boost the kudos of the clusters, bringing in yet more business and innovation, while fostering an entrepreneurial outlook that gives local start-ups the best chance of thriving.

Efforts to create the world's first compound semiconductor cluster can be traced back to 2011, when IQE's founder, Drew Nelson, met the economic minister for Wales. Nelson put the case for a far stronger infrastructure within the UK to support the compound semiconductor industry. Back then, IQE had virtually no domestic customers. That's not to say, however, that IQE was the only company in South Wales working in our industry: this part of the UK was and continues to be home to etching and deposition tool maker SPTS, now part of KLA; and a Microsemi facility with packaging expertise, now known as Microchip Technology Caldicot.

Nelson's next steps included working within a group set up by the European Commissioner for Technology for the Digital Economy. Involved in a team considering key enabling technologies, he championed the construction of a sovereign capability for compound semiconductors in South Wales, to rebuild the continent's manufacturing capability for this technology.

Building on these efforts, Nelson lobbied the Welsh Government and Cardiff University to set up an Institute for Compound Semiconductors. He had a vision for a local facility, delivering cutting-edge technology, developed using tools and processes compatible with high-volume manufacturing. In March 2015 the UK Government funded this initiative, and a year on planners gave the go-ahead for the construction of a new building for the Institute for Compound Semiconductors. Forming part of the Innovation Campus, the Institute opened


➤ Not helped by delays due to Covid, the Institute of Compound Semiconductors, part of the Translational Research Hub, opened in May 2023. Nobel Peace Prize winner and climate scientist Donald Wuebbles presided over the opening.



in 2023 after delays partly associated with the pandemic, to play a leading role in the Translational Research Hub.

To help commercialise the technology developed at the Institute for Compound Semiconductors, in 2015 IQE and Cardiff University founded a joint venture: the Compound Semiconductor Centre. Using funding from Cardiff University and some equipment from CSC, it runs collaborative research projects.

In 2016, more links were added to the supply chain. In January, the UK government stumped up £50 million, funding the creation of a Compound Semiconductor Catapult, an open access R&D facility focused on helping UK businesses exploit advances in compound semiconductor technologies. And later that year, the UK's Engineering and Physical Sciences Research Council poured £10 million into a Manufacturing Hub for Compound Semiconductors, targeting the translation of research into high-volume chip manufacturing.

With many pieces of the jigsaw now in place, in summer 2017 the cluster officially opened for business, taking the name CS Connected and holding events with speakers from all key stakeholders. The cluster also took a huge leap forward, grabbing an opportunity to get its hand on a production line. The 200 mm silicon fab in Newport, South Wales, had come into the hands of Infineon through its acquisition of International Rectifier. After the German powerhouse evaluated its global chip manufacturing capabilities, it viewed the Newport Fab as surplus to requirements. This facility was put up for sale, with Nelson leading a private equity buyout. Emerging from this deal, Newport Wafer Fab had guaranteed orders from Infineon for two years. Further ahead, those in the cluster hoped that the lines would also be used to produce compound semiconductor-on-silicon chips, aided by IQE's acquisition of Translucent, a developer of rare earth oxides, which can provide a bridge between a silicon wafer and compound semiconductor epilayers.

Further advances within the cluster included the relocation of the CS Catapult to part of a very large building constructed for LG Semicon, with IQE taking the remainder, using it to create an epifoundry that could house up to 100 MOCVD tools. The cluster has also expanded to include Swansea University, which is constructing a Centre for Integrative Semiconductor Materials.

Threatening to derail some of this progress has been the ownership of the Newport facility, which, in 2021, was bought by Nexperia. As Nexperia is a Chinese-owned company, the take-over drew concern from the UK government, which spent many months deliberating over what to do. In November of 2022, the UK government finally came to a decision, ruling that the fab had to be sold. Twelve months on Vishay bought the facility, and late last year announced that it would be investing $51 million in the fab, which will diversify into the production of SiC power devices, and support the growth of the cluster.

➤ CSconnected, the world's first compound semiconductor cluster, opened for business in 2017. By the end of the year this cluster, based in South Wales, had strengthened its capabilities, thanks to the launch of Newport Wafer fab, a facility Infineon deemed surplus to its requirements.

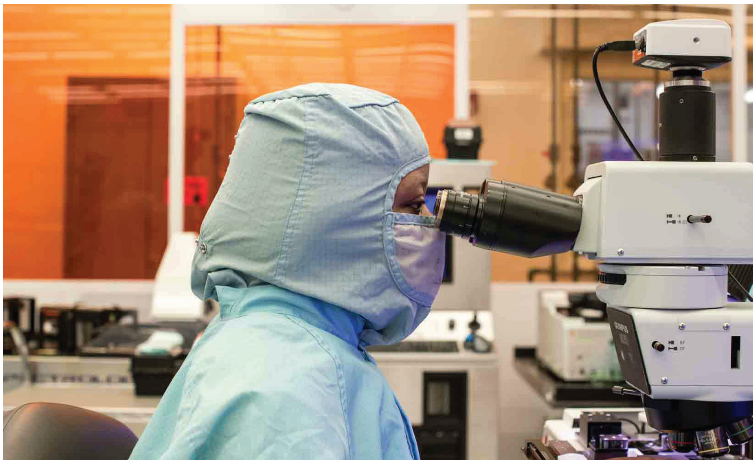
# Getting the blues

**2018** The VCSEL has a wonderful set of attributes. It is efficient, allowing it to run off a battery; it can be turned on and off at very high speeds, making it a great source for transmitting vast amounts of data; by adjusting the size of the aperture, it can produce single-mode emission with a circular profile, simplifying optics; and it is well-suited to high-volume manufacturing, partly because its design allows on-wafer testing.

However, there is room for improvement. Despites decades of development, the VCSEL spans a far narrower range of wavelengths than edge-emitting lasers and LEDs.

Expansion of the spectral domain has been very slow, given the long history of this device. Its roots go back as far as 1965, when Ivars Melngailis, working in the MIT Lincoln Lab, announced a 'longitudinal injection laser' emitting at 5.2 µm, formed from an InSb diode featuring polished top and bottom surfaces to ensure optical feedback. This device, an incredibly impressive feat for its time, is far from practical, with lasing requiring a hefty 20 A drive current and cooling to 10K.

The first real VCSELs came from the labs of Kenicha Iga from Tokyo Institute of Technology. In 1977, Iga proposed a design sharing many of the features of today's VCSEL, and for the next 11 years he almost singlehandedly pioneered this class of device, before other groups noted his breakthrough and redirected their efforts towards this technology. Success followed, with research in the latter part of the twentieth century initially focusing on the near infrared, before attempts were made to widen the spectral range of the VCSEL in both directions.



> To secure a second source for VCSELs, Apple agreed to purchase $390 million of these devices from Finisar.

Initially, breakthroughs with the GaAs-based material system enabled 980 nm and 850 nm VCSELs, before emission stretched to around 650 nm. Wafer-fusion brought yet more success, allowing GaAs-based mirrors to be united with InP-based active regions to realise emission at 1.5 µm.

By the turn of the millennium, researchers started to consider the next goal: expanding emission to the blue and green. Success would open up new markets, allowing devices to be deployed for high-resolution printing, high-density optical data storage, chemical and biological sensing, full-colour displays and lighting.

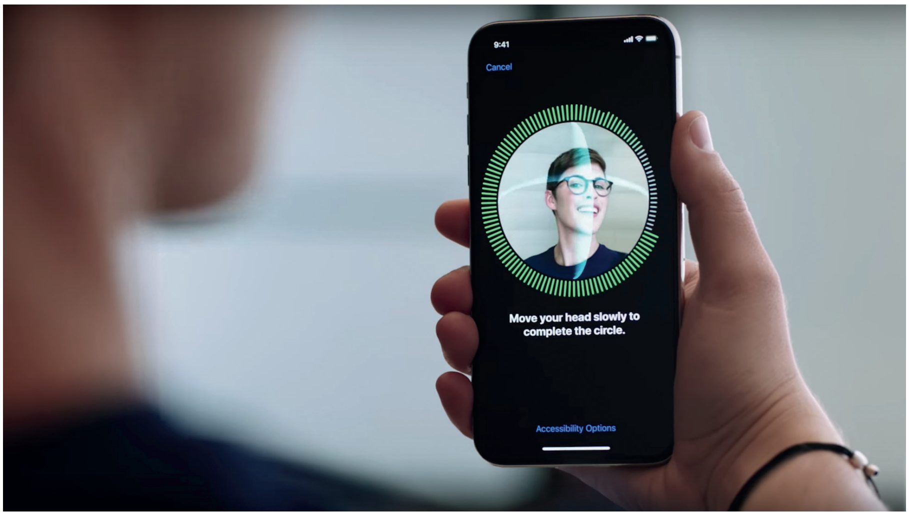
Producing VCSELs operating in this spectral domain is far from easy. To reach these shorter wavelengths, the GaAs-based material system has to be replaced with one based on GaN and its related alloys. This switch may sound a simple, but it's anything but.

The biggest issue is producing the mirrors that sit either side of the active region. This is relatively easy in a GaAs-based VCSEL, because this material system is blessed with the pairing of GaAs and AlGaAs. These III-Vs have very similar lattice constants, so strain is not an issue, and there is a significant difference in their refractive index, aiding reflection. When 20 pairs of alternating layers of GaAs and AlGaAs are used to make a mirror, it has a reflectivity of 99 percent, sufficient to make a high-performance VCSEL.

For blue and green VCSELs, to prevent strain from degrading the mirrors, GaN has to be paired with $Al_{0.83}In_{0.17}N$, a trickier alloy to grow that has a relatively low refractive index contrast. Growing two sets of GaN-based mirrors would take too long, so it is better to combine a nitride-based bottom mirror with a top one based on dielectrics, an approach pioneered by Nicholas Grandjean's team at EPFL. Their high-point came in 2007, when they reported the first optically pumped GaN VCSEL.

Frustratingly, funding dried up for Grandjean, with those holding the purse strings arguing that the first electrical VCSEL would come from Japan. They were more or less right, and now we will never know if Europe could have been the trailblazer of this device.

The first electrically pumped GaN VCSEL actually came from National Chaio Tung University, Taiwan, announced in April 2008. This required cryogenic cooling, a restraint overcome later that year by Nichia, using a pair of dielectric mirrors. Nichia persisted with this design, increasing the output power to 0.62 mW in 2009. Over the next few years it continued to develop this device, but only realised minor additional gains.




Substantial progress came in 2018, when two Japanese companies, working independently, broke the 10 mW barrier – this is roughly the power required for augmented-reality devices, projection systems and displays. Stanley Electric, partnering with Tetsuya Takeuchi and his team from Meijo University, built on the work at EPFL, improving the growth conditions. In the autumn of that year, they reported a blue VCSEL with an output in excess of 15 mW. And in November 2018, Sony unveiled a 12 mW VCSEL with a novel design, featuring a far larger cavity that incorporates a thinned GaN substrate, and a curved mirror grown on the backside of the wafer.

Since then, gains have been modest, with the most powerful GaN VCSELs now emitting just over 20 mW.

Alongside the breakthroughs in blue VCSEL performance, 2018 will be remembered for the market success of infrared cousins. Up until then, datacoms provided by the primary revenue stream for this device. However, in 2018 the market for handsets caught up, thanks to Apple's launch of the iPhone X. This smartphone featured two VCSELs: one for the dot projector, and another for the flood illuminator.

Many rivals in the smartphone sector also launched new models that incorporated VCSELs, used as the light source for time-of-flight technologies to avoid any potential IP issues. These sales have dwindled over the last few years, as makers of Android-based smartphones have tended to ditch the VCSEL in their latest models to free up space for the introduction of components for 5G networks. However, despite this loss of business, VCSEL revenue for the consumer electronic market is still increasing.

When Apple started to deploy VCSELs in its smartphones, Lumentum provided this device. But to reduce supply chain risk by adding a second source, in late 2017 Apple encouraged Finisar to become a VCSEL supplier, promising orders totalling $390 million, with the US manufacturer grabbing this opportunity. Over the intervening years Finisar's VCSEL production business has been acquired by II-VI and subsequently incorporated into Coherent, which now has a significant share of the market.

For the last few years, Coherent and Lumentum have been competing for Apple's business with Trumpf Photonic Components. Recently this chipmaker, which has shipped over 1 billion VCSELs to Apple, has been expandeing its manufacturing facilities for this device at its site in Ulm, Germany, which it bought from Philips Photonics in 2019.

Sales of VCSELs to the datacom market are now outpacing those for consumer electronics. Due to this, in 2022 Yole forecast that the datacom market would be overtaking that for consumer electronics. But more recent trends suggest that consumer electronics will remain the biggest market by far, accounting for $974 million in 2028, compared with $232 million for the telecom and infrastructure sector.

Several years ago, it looked like lidar for autonomous vehicles would be the next killer application for the VCSEL. However, the introduction of self-driving cars has been hampered by safety concerns, and here the VCSEL has come up against strong competition from fibre lasers and edge-emitting lasers, with the latter having the lion's share of this market. This led Yole to predict that by 2028 VCSEL sales to the automotive and mobility market will net just $108 million, a relatively small slice of the $1.4 billion expected that year.

➤ Facial recognition offers a lucrative market for the infrared VCSEL.

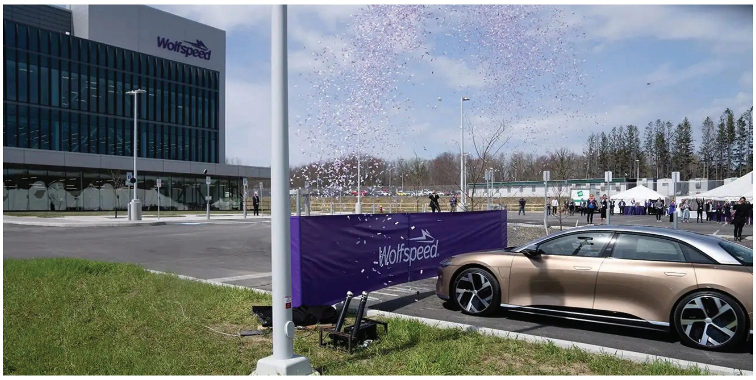
# A phenomenal cash injection for silicon carbide

2019 In spring 2019, Cree, now Wolfspeed, re-aligned its business in emphatic fashion. It's relatively new CEO Greg Lowe had no qualms in carving of the company's Lighting Products division to Ideal Industries; giving the LED business that brought so many years of success a back seat; and focusing on wide bandgap materials, and RF and power devices. Helping to have made this monumental decision would have been a number of lucrative SiC wafer supply deals: contracts with Infineon, ST Microlectronics and other companies totalled $500 million.

By summer 2019 the company's LED business had softened and it had netted the lion's share of its $310 million sale to Ideal. These circumstances would have helped Lowe to move forward with his vision, investing $1 billion in massive expansion of SiC capacity. A state-of-the-art, 200 mm facility would be built by 2024, delivering a 30-fold expansion in capacity compared with the first fiscal quarter 2017.

Later that year the company had an offer it could not turn down – a $500 million grant from the state of New York. Instead of having to spend $450 million retrofitting existing infrastructure at its headquarters in Durham, NC, it could now invest $170 million in building a new, automotive-qualified 200 mm power and RF wafer fabrication plant in Marcy, New York. And instead of ramping up capacity by a factor of 30, it would go up 40 times.

Opened in April 2022 to much fanfare, Wolfspeed described this facility during its christening as 'the first, largest and only 200 mm SiC fab in the world'.




➤ On 25 April, 2022, the day that Wolfspeed opened its 200 mm automotive-qualified SiC fab in Mohawk Valley, Upstate New York, the SiC tech supplier also announced a multi-year agreement with Lucid Motors, to supply SiC power semiconductors. These devices have been deployed in the luxury, all-electric Lucid Air.

Back then, the company rode the crest of a wave, with many bold plans, plenty of backers, and a share price of over $100. But since then, the share price has tumbled, now trading well below $10, as the company has struggled from sluggish growth in the electric vehicle market, while facing increased competition from rival producers of SiC substrates, particularly from China. Last October Wolfspeed shelved plans to build the world's most advanced SiC manufacturing facility in Saarland, Germany, and now it's trimming its workforce by a fifth in a bid to cut costs. Amongst those redundancies is Greg Lowe, axed in November. The company is now seeking a new leader to transform its fortunes.

# Covid's silver lining

2020 Who will forget 2020, a year that will go down in history as one when a pandemic rocked the world, with the rapid spread of Covid-19 having devasting consequences. As well as a high death toll – according the World Health Organisation, fatalities totalled more than 3 million – economies everywhere faced immense strain as the citizens of many nations were forced to isolate, sparking mental health issues with consequences lingering to this day.

While government rulings led many to work from home, those playing a hands-on role in semiconductor industries were seen in a different light. Compound semiconductor facilities continued to churn out chips around the clock, and even benefitted from opportunities associated within this global crisis.

To minimise loss of life, scientists devoted a great deal of effort to the speedy development and roll-out of a vaccine. And in addition to pursuing this game-changer, solutions were sought to kill this virus.

An attractive approach to dis-arming the virus is to subject it to emission from a deep-UV light source. The incumbent option, the mercury lamp, is bulky, fragile, requires a high operating voltage, and is plagued by environmental concerns. One way to address all these weaknesses is to switch to a battalion of deep-UV LEDs. Although they lag the performance of their blue-emitting cousins, they promise to come on in leaps and bounds through greater investment, spurred on by lucrative applications.

During the pandemic, interest in deep-UV LEDs skyrocketed, with firms launching new devices, alongside specialist growth tools and various disinfection systems.

Powerful deep-UV LEDs are far harder to produce than those emitting in the visible, due to a variety of issues, including realising sufficient light extraction and high enough levels of doping. Due to these and other challenges, the established makers of these devices were best-placed to ramp volumes, such as the partnership between Sensor Electronic Technology and Seoul Viosys, a subsidiary of Seoul Semiconductor. During the height of the pandemic, this collaboration started mass-producing UV LED modules that could sterilise 99.9 percent of the coronavirus within 3 seconds. In addition, they began developing a Photon Shower, described as a whole-body sterilisation solution that could sterilise germs on people's clothing in a matter of seconds.


➤ In summer 2020, at the height of the Covid-19 pandemic, Ostaw Digital claimed that it had introduced the world's first disinfection robot using deep-UV LEDs.

To support companies trying to manufacture the deep-UV LED, the Chinese equipment manufacturer AMEC launched a new MOCVD tool, the Prismo HiT3, said to be ideal for producing high-quality layers of AlN, a key material for this short-wavelength source.

During the height of lockdown, new disinfection systems employing deep-UV LEDs were also launched to market. Over the summer of 2020, water-treatment specialist AquiSense launched a surface disinfection system, and Singapore-based robotics manufacturer, Ostaw Digital, unveiled what was claimed to be the world's first disinfection robot using LEDs emitting at appropriate wavelengths. When fully charged, this autonomous robot could be deployed for 5 hours, delivering a disinfection rate of 99.999 percent at a range of 2.5 m.

Sales of deep-UV LEDs emitting at wavelengths suitable for sterilising Covid-19 shot up during 2020, according to market analyst Yole, with revenue almost doubling year-over-year to $308 million. But that's still well short of the value of the visible LED market, and even if the pandemic has provided a catalyst for healthy long-term growth of this source of deep-UV emission, this device is going to be valued more for its importance than its sales.

# Valuing vertical integration

**2021** When do you think our industry began to manufacture devices in high volumes? While it's a question without a definitive answer, a strong case can be made for the late 1990s, a time when fabs started to crank up production of GaAs transistors and GaN LEDs, two key devices for the growing handset market.

To produce LEDs, fabs tended to buy sapphire substrates, carry out epitaxial growth and processing in-house, and send the die to a packaging partner. While with the GaAs HBT, two routes were common, with epitaxial growth either outsourced or undertaken by the chipmaker.

For manufacturers of both LEDs and GaAs HBTs, what was beyond question was the production of the substrate. This task would be undertaken by a company dedicated to growing crystals, slicing them, and polishing the resulting substrates, so that they provided a high-quality foundation for epi-growth.

With SiC, supply chains are far more varied. As SiC cannot be grown from the melt, producing high-quality substrates is far from easy, accounting for the relatively slow progress of devices from the lab to the fab. For chipmakers, getting their hands on a sufficient supply of high-quality substrates has been crucial to making high-performance devices, so when many have wanted to ramp production over the last few years, they have had to negotiate wafer supply agreements.

SiC device pioneer Cree, now Wolfspeed, has met some of this demand. This company has benefitted from using SiC substrates as the foundation for its LED production, a *modus operandi* that has led to a wealth of SiC substrate expertise, derived from producing a product in volume. Higher-quality SiC substrates have resulted, providing a great platform for internal development and commercialisation of SiC power devices.

➤ Sanan IC's manufacturing fab, located at the Changsha high-tech industrial plant, is China's first vertically integrated SiC line.

After looking on in envy at Wolfspeed, many of the other leading makers of SiC diodes and MOSFETs are now bringing matters into their own hands by developing vertically integrated production capabilities that begin with the production of SiC substrates, or even the refining of powders used in their production.

Significant strides in pivoting to extensive vertical integration were taken by many of the big players in SiC power electronics in 2021. They included one of Wolfspeed's long-term rivals, Rohm, which completed its construction of a $190 million SiC wafer and device production plant in Chikugo, Japan, that promised to lead to a five-fold hike in chip production. Prior to this, Rohm acquired the German SiC wafer manufacturer, SiCrystal, in 2019.

Another noteworthy move came from China, with the opening of Sanan IC's manufacturing fab, a $2.3 billion facility that combines crystal growth with the production of power devices and their packaging and testing. Constructed in phases, chip production began with 15,000 6-inch wafers per month, and there are long-term plans to move to 40,000 8-inch wafers.

Onsemi also grabbed the headlines in 2021 with the $415 million acquisition of the US producer of 6-inch and 8-inch SiC material GT Advanced Technologies. Motivations behind this move were to secure and grow Onsemi's supply of SiC, and to meet a growing demand for SiC power electronic devices for electric vehicles and energy infrastructure.

The trend for extensive vertical integration by the biggest players in SiC power devices continues to this day. In late 2022 STMicroelectronics announced that it would be making SiC substrates at its site in Catania, Sicily. The company planned to make a €730 million investment over 5 years, with SiC substrate production expected to begin in 2023. To much fanfare, STMicroelectronics announced further investment of €5 billion in this site last year. In May 2024, supported by €2 billion from the State of Italy in the framework of the EU Chips Act, funding is now enabling the construction of a vertically integrated 200 mm SiC campus, which includes SiC substrate development, epitaxial growth processes, front-end wafer fabrication, module back-end assembly, and a number of R&D initiatives. Production of SiC products at this campus is set to start in 2026, and ramp to full-capacity by 2033, enabling the processing of 15,000 wafers per week.

# Power GaN's inflection point?

2022 For many emerging devices, commercial success is anything but linear. Initial breakthroughs are far from easy, with much effort having to be devoted to convincing potential customers that there is much to gain by adopting a new chip. But if this leads to success, other firms will follow, swelling the sales of this device and demonstrating its prowess. This platform can then provide a foundation for further success, as device deployment branches out into a number of new applications.

For the GaN power device, that inflection point came around 2022, with many of its producers targeting new markets by expanding their portfolio or ramping production. An uptake of GaN HEMTs in mobile chargers, where they enabled far shorter charging times, provided the bedrock for the expansion of this device into new markets. During the summer of 2022, Yole forecast that the consumer power market would expand at a compound annual growth rate of 52 percent between 2021 and 2027 to hit $915 million, and by the end of that timeframe global GaN revenue would total $2 billion. According to the French analyst, power supplies for telecom and datacom would provide substantial, fast-growing sales, with revenue tipped to climb to $620 million by 2027. Helping to secure revenue from this sector were design wins for Transphorm, EPC, Texas Instruments, Infineon and GaN Systems.

By 2022, GaN Systems, now part of Infineon, had also made significant progress in the automotive market, amassing contracts from BMW and Toyota, Canadian GaN powertrain developer FTEX, and EV powertrain system supplier Vitesco Technologies. In addition, GaN Systems had just secured $150 million of investment from BMW i Ventures, Vitesco and other players.

Speaking to *Compound Semiconductor* in early 2022, Jim Witham, then CEO at GaN Systems – and now Senior Vice President at Infineon Technologies – argued that the tremendous high-frequency capabilities of GaN power devices could spur success in on-board chargers and DC-to-DC converters in electric vehicles. He also claimed that GaN could compete with SiC for success in the traction inverter.

➤ Bought from Onsemi, BelGaN had big ambitions for the Oudenaarde fab, planned to be converted to the production of GaN power devices for the automotive industry. But these dreams have not been fulfilled, with BelGaN filing for bankruptcy in July 2024.

The Chinese GaN chipmaker Innoscience also eyed new opportunities in 2022, the year it opened sales offices in the US and Europe and planned to ramp production capacity from its 8-inch fabs in Zhuhai and Suzhou from 10,000 to 14,000 wafers per month. Dominated by sales to makers of fast chargers, this company targeted revenue from DC-to-DC converters in data centres, LED drivers, lidar laser drivers and DC-to-DC conversion in electric vehicles. Looking further ahead, 650 V on-board chargers were viewed as another opportunity.

Other producers of GaN HEMTs pursuing new markets in 2022 included: Rohm, releasing a 150 V HEMT for power supplies in base stations and data centres; EPC, introducing demonstration boards for radiation-hard GaN power devices that could be deployed in space applications; and Navitas, launching GaNSense, a GaN half-bridge power IC. The latter product, claimed to break new ground through the monolithic integration of a gate driver, a power device and sensing and protection functionality, promised to maintain Navitas' position as the leading supplier of GaN power devices. Back then, Navitas' devices were in more than 150 different charging products from different companies, and opportunities had been identified in the solar, data centre and electric vehicle sectors.

2022 also witnessed the start of the transformation of a European silicon fab into one for producing GaN devices. In February of that year, the BelGaN Group bought the fab in Oudenaarde, Belgium, from Onsemi, with the aim of becoming a leading 6-inch and 8-inch GaN automotive foundry in Europe. However, it's not been a story of success for this venture, with BelGaN filing for bankruptcy last summer, putting 440 jobs at risk.

# A new GaN patents war

2023 When it comes to GaN, it seems that the HEMT is following a similar trajectory to that of the LED. In the early days of the high-brightness, GaN-based LED, many companies focused on expanding their portfolio to win lucrative contracts. But once sales had climbed, these chipmakers started to look beyond building better devices, and began waging war with one another, claiming infringement of key patents. Come 2023, history started to repeat itself, triggered by surging sales of GaN power devices.

The first significant shots in the GaN HEMT patent war were fired in May 2023, when the Californian fabless firm EPC issued a press release stating that it had sued Chinese chipmaker Innoscience for infringing four of its US patents. EPC claimed that Innoscience drew on this IP for the production of its 100 V and 650 V products. As well as filing complaints in the federal court and with the US International Trade Commission (ITC), EPC publicly accused Innoscience of poaching two employees that went on to be that chipmaker's CTO and Head of Sales and Marketing – hires said to be behind the launch of very similar products. Innoscience fired back just two days later with a press release claiming innocence, following an internal investigating involving a thorough analysis and finding no infringement.

However, what matters in this war is not the scoring of points in press releases, but producing winning arguments in court, based on the fine print within the patents.

The battle between EPC and Innoscience concerns a particular form of HEMT produced by both parties, a normally off (E-mode) variant featuring a *p*-doped layer of (Al)GaN under the gate of the device.

Initially, EPC's action against Innoscience involved four patents – two from 2013, and another two from 2017. However, EPC dropped the latter two patents in its ITC case.

One of the two contested patents, US 8,350,294, concerns the design and fabrication of a compensated gate MISFET. Here a key issue is whether the phrase 'compensated GaN layer' describes the gate layer in Innoscience's devices, presumably formed by doping GaN with magnesium. Realising effective *p*-type doping is far from trivial, having been a key milestone in the development of the LED.

EPC's other patent taken to court, US 8,404,508, is associated with a self-aligned gate E-mode HEMT. That patent describes a multi-step process involving the use of three different photoresist patterns to produce a self-aligned gate.

Initial rulings in the summer of 2024 by the administrative law judge (ALJ) in the ITC case found that both of EPC's patents are not invalid, and significantly, that the '294 patent is infringed. Another blow to Innoscience came from rulings that counterpart Chinese EPC patents were not invalid.

Last November, the ITC affirmed its initial determination that Innoscience infringed the '294 patent, a decision leading to a ban on Innoscience from importing GaN-related products into the US without a license from EPC. A 60-day Presidential review period followed, completed this January, leading to a final determination by the ITC that Innoscience cannot import and sell its products in the US without a license from EPC.

Additional action against Innoscience has been taken by Infineon, which began by bringing a suit in San Francisco in March 2024 for a patent associated with high-voltage packages featuring so-called 'source sensing'. Innoscience responded by filing a petition in June with the US Patent Office, arguing for invalidation of every single claim. Stepping up its attacks over the summer, Infineon filed several cases in Germany, obtaining a preliminary injunction that prevented a small fraction of Innoscience's high-voltage GaN transistors from being promoted at PCIM. The German powerhouse also added three more patents to the San Francisco case, and filed its own complaint with the ITC.

One of these three additional patents is concerned with the thickness of a titanium nitride capping layer in an electrode stack, and the other two are related to so-called 'merged cascode transistors'.

Patents battles are sure to be in the news this year. This January Innoscience filed a lawsuit against Infineon related to a GaN power device and its manufacturing method, and in the autumn the AJC will make an initial ruling on Infineon's accusations against Infineon. It would be surprising if these actions were to be the last between makers of GaN power devices, given that revenue is rising fast, and more players are entering the field. The history of the LED suggests that the patent war will rage on, and it's hard to foresee a different outcome.

# Catching up with silicon

**2024** Within the semiconductor industry, a well-trodden path to realising economies of scale is to increase the size of the wafers. Silicon has led the way, migrating from 1-inch to 6-inch wafers from the 1960s to the 1990s, shifting to 200 mm by the start of the millennium, and 300 mm becoming increasingly common from the 2010s. But there it has stayed.

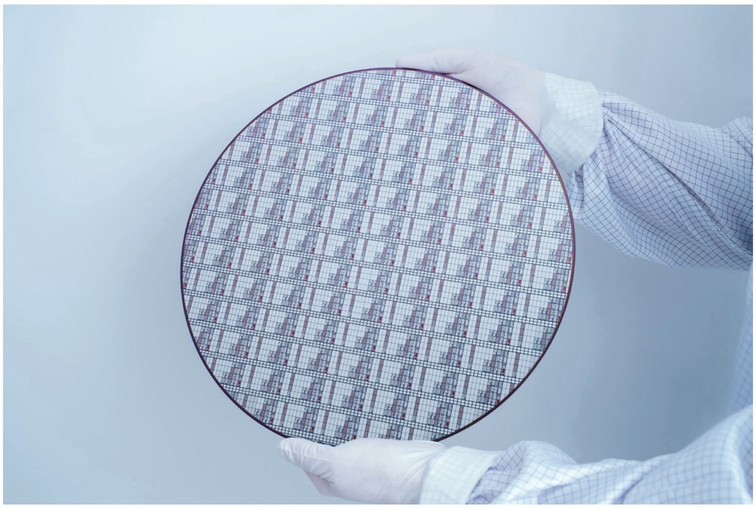
Our industry, often in the shadow of silicon, is now catching up. Leading the way is our power electronics sector, which made great strides in 2024. During the latter part of that year, Infineon claimed development of the first 300 mm power GaN technology, and Chinese provider of SiC substrates, SICC, demonstrated what appeared to be the first 300 mm SiC substrate.

As the production of today's GaN-on-silicon HEMTs uses substrates with a diameter of 200 mm or less, Infineon's breakthrough opens the door to more than doubling the number of devices per wafer. But that's not the only gain that will trim the cost of production, with migration to larger wafers providing improvements to the manufacturing process, such as a higher yield and access to superior metrology. Engineers at Infineon enjoyed these benefits when progressing from 150 mm to 200 mm wafers, and they are seeing them again in the move to the 300 mm platform.

Requiring 18 months of development, Infineon's 300 mm process, built on its 200 mm GaN-on-silicon technology, is claimed to offers the tantalising prospect of reaching cost parity with silicon equivalents. Helping to reach this goal will be: economies-of-scale; improvements in the technology itself, particularly the epitaxial stack; and the lower on-resistance of GaN, enabling smaller die to deliver the same performance as comparable products made from silicon.

The growth of 300 mm epiwafers is challenging, with differences in lattice constant and thermal mismatch threatening to lead to bowing and even cracking. These issues are exacerbated for thicker layers of GaN, required for higher blocking voltages. While a path to progressing from 100 V to 650 V has been identified by Infineon, going beyond that will be more challenging, with a switch to thicker substrates a possible solution.

At the *Electonica* show, held in Munch in mid-November, Infineon released its next-generation G5 HV technology. The German powerhouse is planning to take this process and apply it to 300 mm wafers, with engineering samples reaching customers by the end of this year, and production ramping in 2026.



➤ In the autumn of 2024 Infineon claimed to have developed the first 300 mm power GaN technology, which promises to enable cost-parity with silicon devices.

SICC, the world's second biggest producer of SiC, also selected *Electronica* to showcase its triumph – the world's first 300 mm SiC substrate, cut from a 20 mm-thick boule *n*-type formed using the same axial growth rate employed for manufacturing 200 mm material.

Historically, SiC substrates have been plagued with a variety of imperfections that degrade and even kill devices. However, these issues have now been addressed by many companies, and as the process that SICC employed to fabricate its 300 mm substrate is the same as that used to produce smaller wafers, there is no major barrier to realising state-of-the-art quality with the larger format.

Characterisation of SICC's ground-breaking 300 mm substrate has revealed that micropipes, a critical defect, are not a significant issue, and surface roughness is comparable to that for the company's 200 mm wafers. Of more concern are basal plane dislocations, which need to be reduced.

However, the company is confident it can replicate the density found on its 200 mm *n*-type substrates.

The timing of SICC's commercialisation of its 300 mm *n*-type SiC substrates will be governed by the rate of technical progress of this new format and the level of demand. The expectation is for small production volumes to begin in 2027.

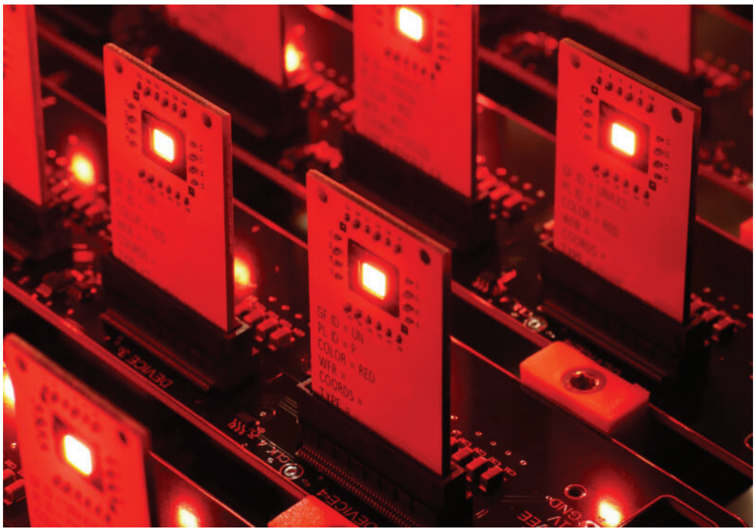
# Is now the moment for the microLED?

2025 In the depths of winter, it's far from easy to determine what will be the most significant milestone for the compound semiconductor industry this year. But based on some of the headlines from the recent *Consumer Electronics Show* (CES), maybe, just maybe, this will year that the microLED starts to fulfil its commercial potential and generate significant sales.

This tiny emitter has certainly had its setbacks over the last few years. As well as falling short of some of the more optimistic forecasts from market analysts, it has faced what might have been a devasting blow last February, when Apple decided to terminate its supply deal with ams Osram.

Apple's move, a decision that drove the European chipmaker to consider selling its second fab in Malaysia, has had widespread implications, because Apple played a major role within this space for many years. Arguably, this tech giant created the microLED industry through the acquisition of start-up Luxvue in 2014. This move provided the catalyst for investing in the technology by dozens of startups, as well as most OEMs and display makers.

Although Apple's decision sent shock waves through the microLED industry, those carefully following developments could have anticipated this outcome. There have been multiple slips in Osram's microLED fab ramp-up timeline, indicating that Apple and its other partners were encountering problems and delays downstream, especially with the mass transfer and assembly of the microLED on the backplane, as well as overall process integration. What's more, yields remained low, hampering efforts to reach cost targets.



➤ This January, UK-based microLED maker Plessey, which is working with meta, claimed to have produced the brightest red microLED display that's suitable for AR glasses.

In the aftermath of Apple's exit from the microLED industry, its epicentre has shifted to Taiwan, which has a strong domestic ecosystem, thanks to AUO and PlayNitride.

Recent highlights for those two companies include AOU's demonstration of a 17.3-inch foldable display last May at *Display Week* 2024, and its construction of a new production line for producing automotive displays, which are expected to launch by 2026 or 2027. PlayNitride's progress is seen in its qualification of a Veeco Lumina MOCVD system for the production of microLEDs, and orders for two of these tools, to be delivered this year.

At CES, attendees were reminded that while Taiwan may be the leader in commercialising microLEDs, it is a global industry. At that show French microLED maker Aledia announced that it has used its nanowire technology to develop a microLED microdisplay with monolithic red, green and blue microLEDs produced on the same substrate that deliver ground-breaking efficiencies. And Canadian firm VueReal used CES to promote its microLED design reference kits, claimed to accelerate the adoption of microLED technology.

Also making headlines this January has been UK-based microLED maker Plessey, which is working with meta. Plessey has just claimed to have produced the brightest red microLED display suitable for AR glasses, a triumph that's claimed to pave the way to the next computing platform.

While all these breakthroughs are encouraging for the future of the microLED, I cannot argue that they will guarantee success. As the incumbent OLED technology is improving all the time, 2025 may well be a year of now or never for the microLED, determining the future for this miniature marvel.


Crystal orientation Metrology
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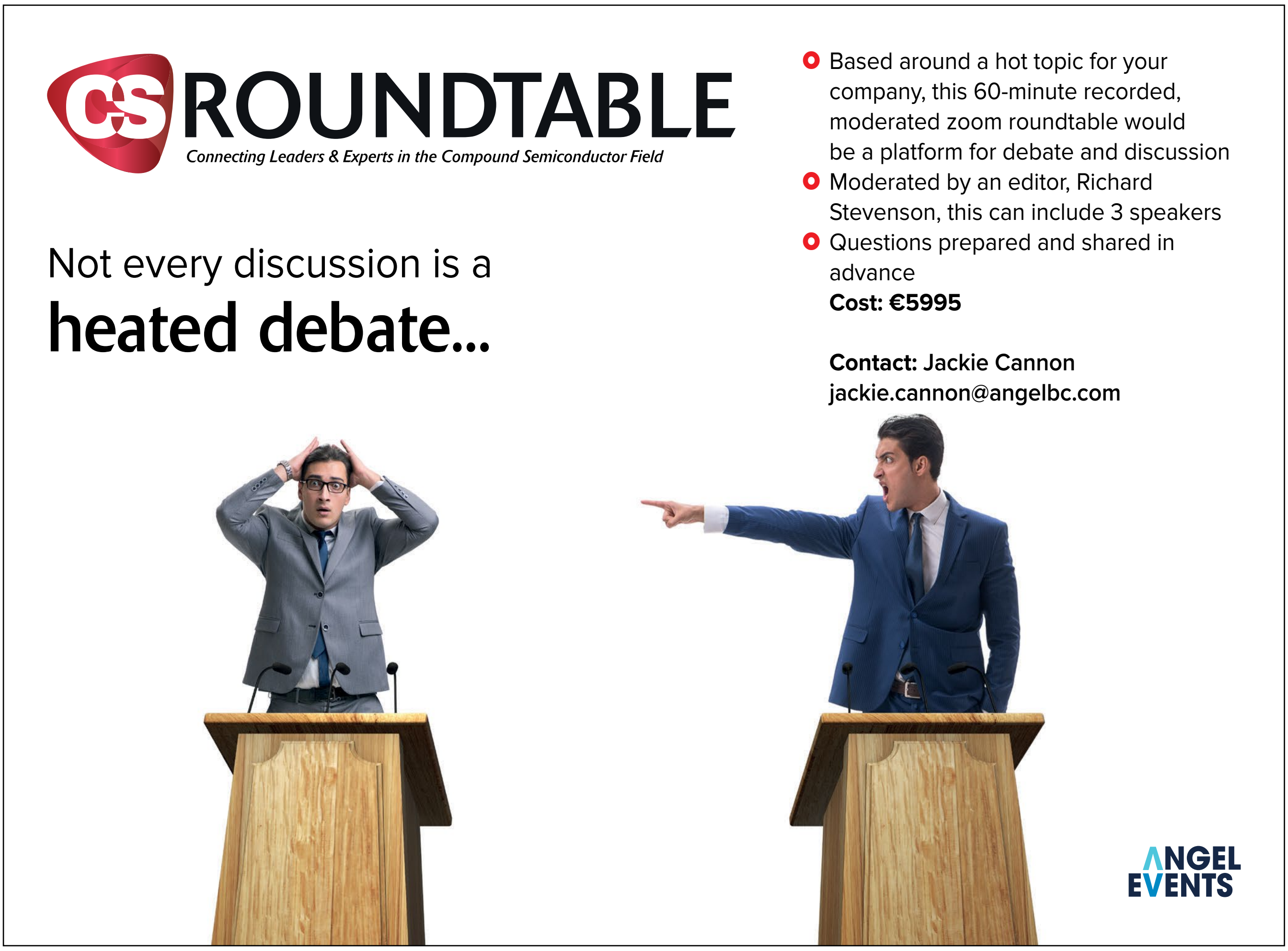
Fully automated vertical three-axis X-ray diffractometerfor ultra-fast crystal orientation
DDCOM
Ultra-fast, bottom surface measuring crystal orientation in a compact package
SDCOM
Ultra-fast, flexible, top surface measuring crystal orientation in a compact package
Wafer XRD 200
Fast, precise and fully equipped solution for wafer orientation and sorting
Malvern Panalytical
a spectris company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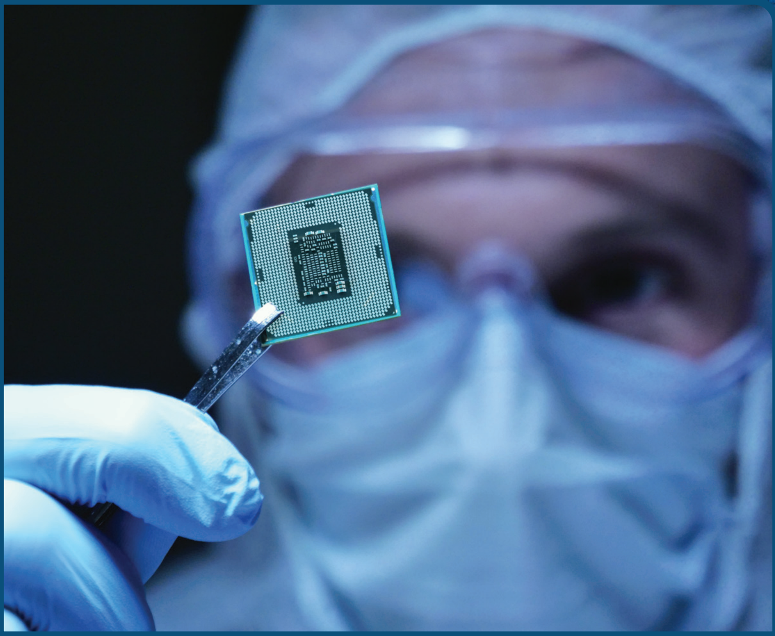
# RESEARCH REVIEW:

## Our ten top stories from the last thirty years



### EXPOSING INDIUM CLUSTERING

HOW can GaN LEDs be so efficient, despite being riddled with defects? One potential answer, attracting much attention in the device's early days, is that defect-free indium clusters in the InGaN quantum wells localise carriers and ensure efficient recombination. But subsequent work by Sir Colin Humphreys' team at the University of Cambridge poured cold water on this idea, indicating that clustering was a measurement artefact, caused by the electron beam. Irrefutable proof followed in 2011, when researchers at Cambridge and Oxford studied two samples with InGaN quantum wells, with one previously irradiated with an electron beam. Using atom probe tomography, this partnership found that the exposed sample had compositional inhomogeneities in its indium content. In comparison, the control sample had a naturally occurring, random distribution of indium atoms.

S. Bennett *et al*. Appl. Phys. Lett **99** 021906 (2011)

### DEBUNKING A DUBIOUS ASSUMPTION

WHEN determining the internal quantum efficiency of a device's active region, researchers tend to assumme that this efficiency will equal 100 percent at very low temperatures. But this approach is flawed, according to investigations by Cam Bayram and co-workers from the University of Illinois at Urbana-Champaign. To obtain accurate values for the internal quantum efficiency of light-emitting structures, they don't advocate any alternations to the starting point, the acquisition of photoluminescence spectra at a wide range of sample temperatures. But they argue that as well as looking at the prominent photoluminescence peak, it's crucial to consider defect luminescence behaviour and thermal quenching. Putting their ideas into practice, this team has obtained values for the internal quantum efficiency of LEDs grown on silicon and sapphire, using modelling and values of photoluminescence intensity from a number of peaks.

Y. Chiu *et al*. Appl. Phys. Lett. 122 091101 (2023)

### PRINTING CHIPLETS

SEVERAL situations require moving thousands of chips from their original wafer to another platform. This often takes place when producing displays from red, green and blue microLEDs, and creating concentrating photovoltaic modules equipped with tiny, multi-junction solar cells. Assisting with this task is the inventor of a powerful technique for massive parallel transfer of various devices, John Rogers from the University of Illinois, Urbana-Champaign. He and his co-workers pioneered using rubber stamps to pick up an array of chiplets and deposit them on another substrate. Their first demonstration began by producing single-wall nanotubes, GaN nanobars and silicon wires on separate substrates. Printing these components on a sheet of polyimide created circuits with a bottom layer of GaN HEMTs, followed by single-wall nanotube thin-film transistors and silicon MOSFETs.

J. Rogers *et al*. Science **314** 1754 (2006)

### GETTING GALLIUM NITRIDE TO THE RED

WHEN LEDs are used to form high-quality white-light sources through colour mixing, or to create the red, green and blue pixels that make up a display, the production process would involves just a single material system. The arsenide family is not an option, because as emission shortens, the bandgap switches from direct to indirect. That makes the only real contender InGaN. While external quantum efficiency in the blue can exceed 80 percent, in the green it is around 50 percent, and for longer wavelengths it is far, far lower. However, there is steady improvement in the orange, yellow and red, with a key milestone reached in 2014, thanks to research at Toshiba. Using an AlGaN interlayer in the active region to reduce the density of energy-sapping defects in the indium-rich quantum wells, this team produced a 629 nm device that broke the 1 mW barrier for a 20 mA drive current.

J-I. Hwang *et al*. Appl. Phys Express **7** 0781003 (2014)

## WINNING THE GREEN RACE

TO participate in the race to make the first green laser, you want access to GaN substrates. That puts those making them at an advantage. Exploiting that to the full came Sumitomo, smashing the record for a long-wavelength nitride laser in the summer of 2009. Until then, teams had built devices on conventional planes or non-polar variants. Sumitomo took a different tack, sporting a semi-polar variant that trims internal electric fields while aiding incorporation of indium in the InGaN quantum wells. First-generation lasers included those producing emission at 531 nm when driven with a 0.5 percent duty cycle. After reporting these results in the August 2009 edition of *Applied Physics Express*, the team switched from a gain-guided to ridge waveguide design, and a month later reported a 520 nm device with a 2.5 mW continuous-mode output in the same journal.

Y. Enya *et al*. Appl. Phys Express **2** 082101 (2009)
Y. Yoshizumi et al. Appl. Phys Express **2** 092101 (2009)

## UVC LASER DELIVERS CW EMISSION

SINCE the fabrication of first GaN laser by Shuji Nakamura in 1995, researchers have devoted much effort to expanding the spectral range of this device. Those striving to reach shorter wavelengths realised a key milestone in 2022, with a team from Asahi Kasei Corporation and Nagoya University producing the first continuous-wave (CW) GaN-based laser emitting in the UVC, which is a spectral range spanning 280 nm to 200 nm. Their 275 nm device, emitting an output power of just over 1 mW, is a promising source for various tasks, including biological and chemical sensing, particle detection, rapid sterilisation, solar-blind communication and materials processing. To produce the first CW UVC laser, the team turned to a novel design that includes polarisation-induced doping, a cladding layer that excels in optical confinement, and a pair of *n*-type electrodes that opened the door to lasing.

S. Kumar *et al*. Appl. Phys. Express **15** 054001 (2022)

## BOOSTING BLOCKING VOLTAGES

WHEN Infineon brought the first SiC Schottky barrier diodes to market in 2001, its pair of offerings could block 300 V and 600 V. The market welcomed these devices, but wanted to see even higher voltages, a feat that could be accomplished given that SiC Schottky barrier diodes had been shown to be capable of blocking 1 kV back in 1994. Those devices, using a palladium metal contact, featured nitrogen-doped, 10 μm-thick layers of 6H-SiC. In the years that followed, 4H-SiC had become available, increasing electron mobility; and researchers had switched to nickel and platinum contacts to realise higher blocking voltages. Drawing on both those advances, in 2003 a partnership between researchers at Rutgers University and United Silicon Carbide broke new ground, fabricating the first SiC junction field-effect transitor that broke the 10 kV barrier. For this class of transitor, their device also broke the record for Baliga's figure of merit.

P. Alexandrov *et al.* IEE Electronics Lett. **39** 1860 (2003)

## ERADICATING ELECTRIC FIELDS

CONVENTIONAL GaN lasers are hampered by the interplay of electrostatic forces and internal stresses that pull electrons in one direction and holes in another, hindering radiative recombination. But this issue can be avoided by turning to new planes for the growth of GaN. Switching to semi-polar planes reduces these fields, and they are eliminated with non-polar planes. Pioneering the later, a team at the University of California, Santa Barbara (USCB), announced the world's first non-polar GaN laser in a press release on 29 January, 2007. Their bragging rights didn't last long. Just three days later Rohm revealed that they too had built a non-polar laser – and one with better performance. While the blue-violet laser from UCSB operated in pulsed mode, that from Rohm could produce a continuous output, with a performance comparable or better than conventional GaN diode lasers.

K. Okamoto *et al*. Jpn. J. Appl. Phys. **46** L187 (2007 )
M. C. Schmidt et al. Jpn. J. Appl. Phys. **46** L190 (2007)

## BLUE LASER BREAKTHROUGH

WAVELENGTH limits data storage capacity. CDs, read by 780 nm lasers, hold just 780 MB, while DVDs, using shorter-wavelength 650 nm lasers, house up to 4.7 GB. Back in the late 1990s when CD players were in their heyday and DVD players were starting to appear on the high street, every maker of consumer electronics and PCs considered the possibilities of an even shorter wavelength laser chip. And it wouldn't be long before they could get their hands on such a device, because by then Shuji Nakamura, Nichia's star, had already laid the groundwork. News of the first GaN laser broke on 12 December, 1995, with details emerging shortly after. Nakamura's laser emitted at 417 nm, not far from the 405 nm used for Blu-Ray players. His device, providing the shortest emission wavelength for laser diodes made from any material system, started to lase at 1.7 A and produced 215 mW of power at a 2.3 A drive current.

S. Nakamura *et al*. Jpn. J. Appl. Phys. **35** L74 (1996)

## AVALANCHE FOR GAN-ON-SILICON

DEVICES that offer avalanche capability have much appeal, with benefits that include the provision of a safety margin at the system level, and by operating safely at close to breakdown, an opportunity to use relatively small devices. For GaN HEMTs, a lateral geometry is unable to provide avalanche characteristics, due to a peak electric field in the gate vicinity. This is not an issue with a vertical architecture, with avalanche behaviour initially realised in devices formed on GaN and sapphire substrates. However, native substrates are expensive, and sapphire suffers from a low thermal conductivity. Overcoming these issues, a team from the University of Lille and Siltronic produced GaN-on-silicon devices with avalanche characteristics. To identify this trait, the team plotted the device's current as a function of reverse bias at different temperatures. These measurements identified the conditions required for impact ionisation, key to avalanche behaviour.

Y. Hamdaoui *et al*. Appl. Phys. Express **17** 016503 (2024)

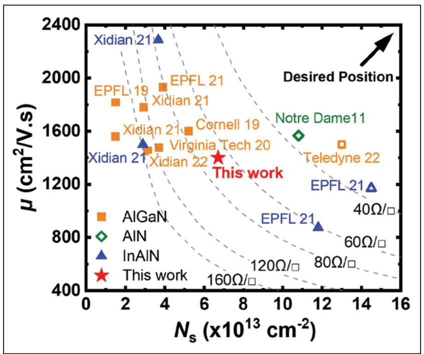
# Building better multi-channel Schottky barrier diodes

## Stable ohmic contacts are enabling multi-channel AlN/GaN Schottky barrier diodes to start fulfilling their potential

RESEARCHERS from Singapore's Nanyang Technological University and its Agency for Science, Technology and Research are claiming to have provided the first successful demonstration of functional devices using multi-channel AlN/GaN heterostructures.

"While other groups have reported impressive results for epiwafers, the critical challenge has been transitioning from material to working devices," explains team spokesman, Hanchao Li, from Nanyang Technological University.

According to Li, a major breakthrough by their team has been the formation of stable ohmic contacts that avoid compromising the channel current in the Schottky barrier diodes. "This achievement is significant because the high aluminium composition and wide bandgap of aluminium nitride make ohmic contact formation particularly challenging in these heterostructures," added Li.




➤ While the team from Singapore has not produced epiwafers with the very best combination of mobility and sheet charge density, they have produced the best device results. Note that the solid symbols are related to reports of fabricated devices on these heterostructures, while hollow symbols indicate otherwise.

Over the last few years, there has been much interest in multi-channel GaN devices. Their appeal is overcoming the limited current conduction of devices with a single channel, and ultimately circumventing the trade-off between sheet charge density and mobility.

A number of research groups have produced multi-channel devices by pairing GaN with either AlGaN or InAlN. However, the team from Singapore prefers the combination of AlN and GaN. This duo provides a higher polarisation-induced charge density, allows for excellent electrostatic control of the channel in the vertical direction when a thin AlN barrier is employed, and enables excellent carrier confinement within the channels.

Fabrication of the team's diodes has involved outsourcing epiwafer growth to a commercial MOCVD facility. The reasoning behind this decision is to ensure stability and reproducibility in epitaxial growth.

"Given that device performance is highly sensitive to material quality, consistent and reliable epitaxial layers are crucial for our device development and optimisation process," argues Li.

Characterisation of the team's epiwafer, featuring five pairs of 4.9 nm-thick AlN barriers and 46.7 nm-thick GaN channels, reveals high-quality material growth. Scanning transmission electron uncovers sharp interfaces between the layers, and reciprocal space mapping produces well-defined, distinct peaks, indicating high-quality crystal growth.

To form diodes, Li and co-workers began by adding a cathode. To form this contact they applied an ohmic recess process, before adding Ti/Al/Ni/Au in this exposed region. The next step involved adding an anode, with this Schottky contact formed by plasma etching that enabled a direct sidewall contact between the two-dimensional electron gas and the anode. Post-anode annealing under nitrogen gas recovered nitrogen vacancies caused by the etching process.

Using the transmission line method, the team determined an optimal ohmic etching depth of 180 nm, corresponding to the mid-point of the fourth channel. Etching deeper, through all five channels, led to an increase in resistance, rising from the optimal value of 0.38 Ω mm to 0.64 Ω mm. The team attributes the higher value to the limited effectiveness of sidewall contacts.

Electrical measurements determined a turn-on voltage of just 0.5 V. For a diode with a lateral anode-to-cathode distance of 3 μm, 1.1 V produces a forward current of 100 mA $mm^{-1}$, and current delivery can be as high as 1050 mA $mm^{-1}$.

Operating under reverse bias, the breakdown voltage – defined as the voltage where the current exceeds a 1 mA $mm^{-1}$ threshold – is 104 V, 268 V and 422 V for anode-to-cathode distances of 3 μm, 5 μm and 20 μm, respectively. These relatively low values are attributed to a combination of: an absence of electric field management structures, such as field plates and guard rinds, leading to a non-uniform electric field distribution and premature breakdown; and multiple cycles of AlN/GaN growth, which may introduce material quality issues that lead to increases in dislocation densities and interface states.

The team are now developing an approach for forming the ohmic contact that is based on the sputtering of GaN, and starting to investigate finFETs that are based on this epitaxial process. "We believe this could lead to enhanced device performance," remarks Li.

**REFERENCE**

➤ H. Li *et al*. Appl. Phys. Express **18** 016502 (2025)

# Optimising green LEDs for near-eye applications

## Eradicating superlattices before the active region boosts the external quantum efficiency to record values

A COMMON approach for producing commercial, high-current LEDs involves the inclusion of pre-well layers – these superlattices, featuring low-indium content layers, are inserted before the active region to aid strain engineering. However, research by a team from China has shown that removing these pre-layers ensures a better performance for green microLEDs for near-eye applications, as their absence trims piezoelectric polarization fields in quantum wells and suppresses Auger-Meitner non-radiative recombination.

According to Junyong Kang from Xiamen University, these benefits that come from removing the pre-well layers stem from a reduction in interfacial defects in quantum wells. Minimising these imperfections leads to a significant enhancement in radiative recombination efficiency at low current densities. "This advancement is critical for near-eye display applications, such as AR/VR/MR," says Kang, who is keen to emphasize that this structure is not suitable for far more powerful LEDs.

The team from Xiamen University and Xiamen Changelight have demonstrated the success that's possible with their approach by producing green microLEDs with either 6 pre-wells, 3 pre-wells, or the absence of pre-wells, and comparing emission characteristics.

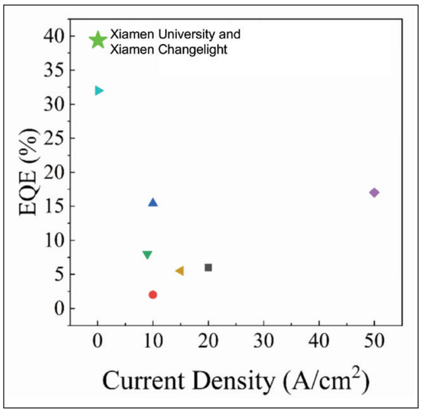
Fabrication of this team's portfolio of green microLEDs began by taking a patterned sapphire substrate and depositing a 45 nm-thick layer of AlON.

"The aluminium oxynitride buffer layer is realised through a combined process of PVD sputtering and MOCVD epitaxy," says Kang, who reveals that depositing this layer is less of a challenge than addressing lattice and thermal mismatches with subsequent, GaN-based epilayers. "During growth, precise control of temperature gradients and V/III ratios is required, coupled with *in-situ* stress monitoring for dynamic compensation."

After loading this AlON-on-sapphire foundation in an MOCVD chamber, the team added a 4 µm-thick layer of undoped GaN, followed by a 2 µm-thick *n*-type layer, an active region with three $In_{0.20}Ga_{0.80}N$ quantum wells, a 20 nm-thick AlGaN blocking layer, and a pair of *p*-doped layers. Variants with pre-wells featured $In_{0.05}Ga_{0.95}N$ superlattices.

Epiwafers were processed into microLEDs with dimensions of 17 µm by 20 µm, using a number of steps that included adding an ITO transparent conductive layer, employing rapid annealing to create an ohmic contact with *p*-type GaN, and applying photolithography and plasma etching to expose areas of *n*-type GaN.

During growth of multiple quantum wells, it is inevitable that defects, which subsequently facilitate the formation of V-pits, are generated at interfaces between quantum wells and adjacent barrier layers. Scanning electron microscopy images of the all three types of epiwafer have confirmed that reducing the number of pre-wells leads to fewer V-pits, thanks to a reduction in the total number of interfaces.




➤ The green microLED produced by Xiamen University and Xiamen Changelight delivers a record-breaking external quantum efficiency of 39 percent at 0.07 A cm$^{-2}$.

Measurements of external quantum efficiency have revealed maximum values of: 31 percent at 0.3 A cm$^{-2}$ for the microLED with six pre-wells, 36 percent at 0.12 A cm$^{-2}$ for the microLED with three pre-wells, and 39 percent at 0.07 A cm$^{-2}$ for the microLED without any pre-wells. According to the team, an external quantum efficiency of 39 percent is the highest value ever reported.

To understand the variation in external quantum efficiency with different designs of microLED, the team applied the well-known ABC model to the data, to determine coefficients for Shockley-Read-Hall recombination, radiative recombination and Auger-Meitner recombination. Compared to the value of Shockley-Read-Hall recombination for the microLED with no pre-wells, variants with three and six pre-wells had values four and six times higher. This finding reveals that decreasing the number of pre-wells increases the quality of the multi-quantum wells, improves uniformity and supresses the non-radiative Shockley-Read-Hall recombination that results from defects.

Kang and co-workers are now planning to build on their expertise in defect engineering, strain compensation and carrier transport optimisation in high-indium-content materials. Future efforts will focus on developing red and yellow LEDs based on InGaN that overcome critical epitaxial growth challenges.

### REFERENCE

➤ A. Wang *et al*. Appl. Phys. Express **18** 011001 (2025)

# Boosting the blocking voltage of birectional HEMTs

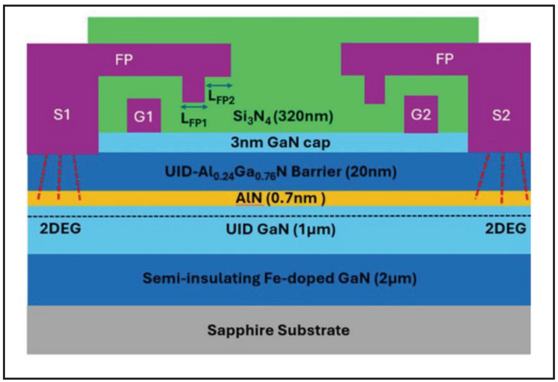
## 3 kV monolithic bidirectional GaN HEMTs are promising candidates for 1200 V class and 1700 V class power converters

ENGINEERS from the University of Wisconsin-Madison are claiming to have raised the bar for the breakdown voltage of monolithic bidirectional GaN HEMTs to 3 kV.

This class of device, providing bidirectional current and bidirectional blocking capability, is a promising candidate for a number of novel power converters – including matrix converters, multi-level T-type inverters, current source inverters and solid-state circuit breakers – that could increase the efficiency of renewable energy infrastructure.

Spokesman for the team from Wisconsin-Madison, Md Tahmidul Alam, told *Compound Semiconductor* that the conventional approach to realising bidirectional functionality involves two transistors and two diodes.

One downside of this approach is a high resistance, caused by contributions to overall resistance from multiple components.




➤ The monolithic bidirectional GaN HEMTs produced by engineers from the University of Wisconsin-Madison is capable of blocking 3 kV.

Additional issues stemming from the high device count include increased complexity and a compromised reliability. "If any of the four components fails, the entire system does not work," says Alam, adding: "Implementing the directional functionality with a single device reduces these complications."

The team from Wisconsin-Madison claims to be the first to break the 2 kV barrier for monolithic bidirectional GaN HEMTs, with 3 kV devices with an on-resistance of around just 20 Ω mm. By breaking through the 2 kV barrier, the team's devices are suitable for the construction of 1200 V class and 1700 V class power converters.

For power converters, normally-off transistors are preferred, as they can withstand accidental damage to the gate driving circuitry. While the team has used normally-on transistors in its latest work, these engineers argue that it is possible to apply similar concepts or designs to normally-off transistors when fabricating high-voltage devices.

Production of monolithic bidirectional GaN HEMTs began by loading a sapphire substrate into an MOCVD reactor and depositing a 2 µm-thick semi-insulating layer of GaN, followed by a 1 µm-thick unintentionally doped layer of GaN, a 0.7 nm-thick layer of AlN, a 20 nm-thick $Al_{0.24}Ga_{0.76}N$ barrier, and a 3 nm-thick GaN cap. The team selected sapphire over silicon for the substrate, so that they could reach blocking voltages beyond 2 kV.

Processing of the epiwafer into devices began by using lithography and metal deposition to form ohmic contacts. The next steps involved: a 750 nm deep mesa etch to isolate the devices; the addition of 200 nm-thick nickel gates; and surface passivation, realised by plasma-enhanced CVD of a 320 nm-thick layer of $Si_3N_4$.

The team produced a range of devices, differing in the lengths of the first and second field plates. The length of both of plates were varied from 1 µm to 3 µm.

Electrical measurements on the monolithic bidirectional HEMTs determined a stable threshold voltage of -3.25 V, a sub-threshold swing of 92 mV $dec^{-1}$, and an on-off ratio of more than $10^5$. According to the team, the stable threshold voltage, low sub-threshold swing and high on-off ratio makes their device suitable for high-frequency operation with low conduction and switching losses.

For most devices with a first field plate length no longer than 2 µm, the team recorded a breakdown voltage of 3 kV, the tool limit. But longer first field plates led to a lower breakdown voltage, possibly resulting from an increase in the electric field strength under the field plates that causes a high impact ionisation rate.

Pulsed current-voltage measurements up to a 40 V off-state switching voltage, using a 100 µs pulse width, have determined that current collapse is less than 10 percent.

One of the next goals is to increase the breakdown voltage and/or decrease on-resistance. Another aim is to measure the switching performance of the transistors at high-voltages, such as 600 V.

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➤ M. T. Alam *et al*. Appl. Phys. Express **18** 016501 (2025)

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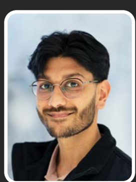

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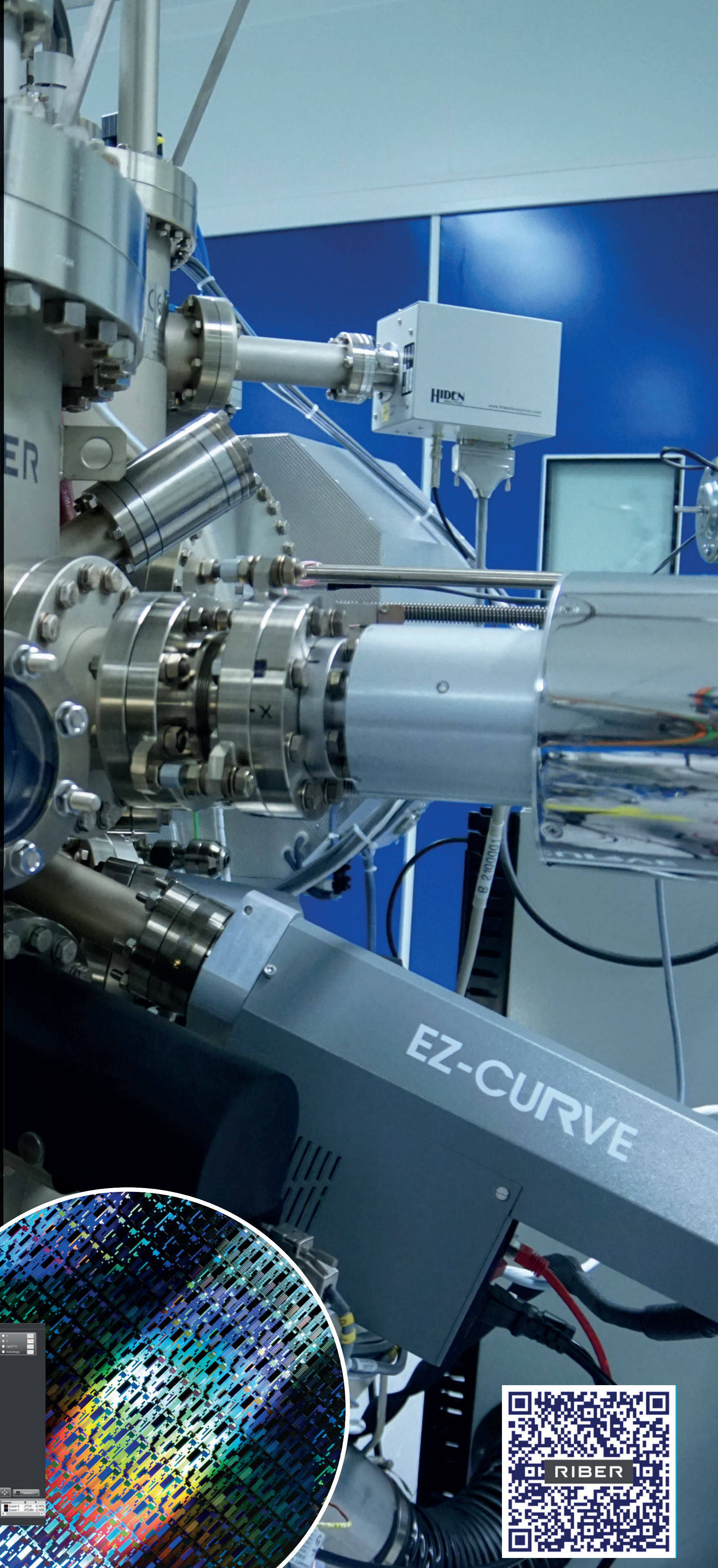


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