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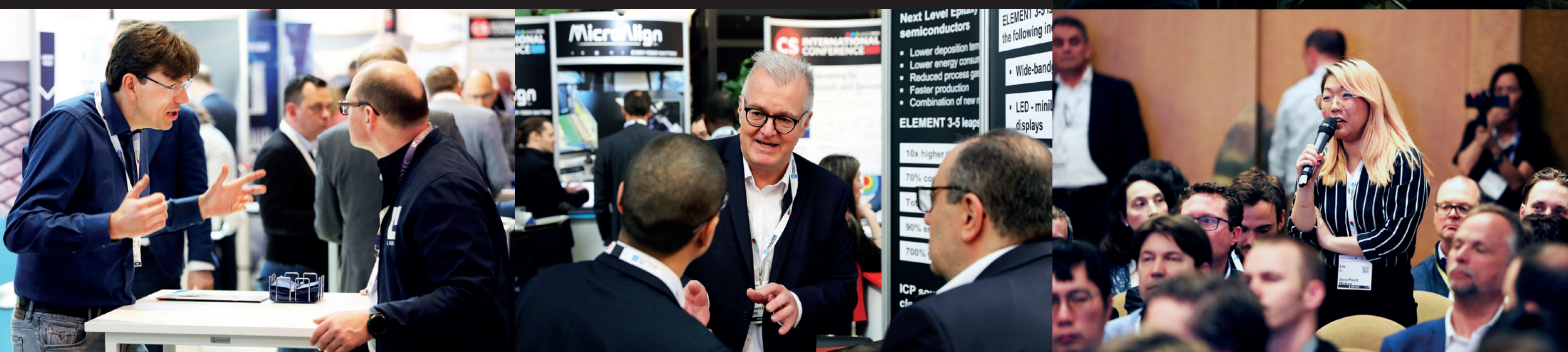

VOLUME 29 ISSUE IV 2023

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INSIDE

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

Moving in the right direction

Hearing the stories of women taking high-profile leadership positions at companies within the CS industry

Taking efficiency towards 50 percent

A record-breaking photovoltaic efficiency comes from bonding a pair of dual-junction cells with different lattice constants

Ferroelectric gate HEMTs

Adding lanthanum doping and a ZnO seed layer trims the leakage current and increases threshold voltage stability

VIEWPOINT

By Richard Stevenson, Editor

A slightly better balance

MY INVOLVEMENT in the compound semiconductor industry dates back more than twenty years. I started in this sector as a process engineer at IQE, Cardiff. While working at that global epifoundry, I got the chance to work alongside several talented female colleagues – but none had a role at the very highest level.

After I made the switch from growing compound semiconductors to writing about them, switching careers in 2004, I saw first-hand that the vast majority of companies within our community were no different from IQE, with men holding all the prominent positions.

In the intervening years progress has been made, although there's still a long, long way to go. Now there are a few women in leadership positions, with great stories to tell on how they have made it there – and in this issue you can read all about their journeys "see p. 24".

What struck me during my interviews with them is the staggeringly varied ways that they have climbed the career ladder. There are so many different paths to the top, certainly more varied than the choice of degree within the physical sciences.

It also struck me that life is full of twists and turns, with many of us ending up in the compound semiconductor industry through events that have disrupted previous plans. For example, the current CEO of Kyma Technologies, Heather Splawn, went off to university to study exercise science, with the intention of being an athletics trainer. However, after being put off by the prospects of having to examine a cadaver, she switched to computer science, went on to develop a sensor during her doctoral studies, and then began to work for a GaN crystal growth company.

However circuitous a route all those that I interviewed have taken, it's abundantly clear they are delighted to work in our industry. And that's hardly a surprise, given what it has to offer: fascinating, fast-paced, evolving technology; plenty of intriguing problems that need to be solved; and the opportunity to have a positive impact on humanity, whether that's through enhancing connectivity, improving consumer electronics or helping tackle climate change.

Reporting on our progress is a joy – and one that I have a woman to thank for. Back in the mid 1990s, Marie Meyer could see that this industry would benefit from another magazine covering breakthroughs in technology, advances in manufacturing and the launch of new products – and so she launched this very publication. Hat's off to her, making an impact at a time when even fewer women were leading the way than they are today.

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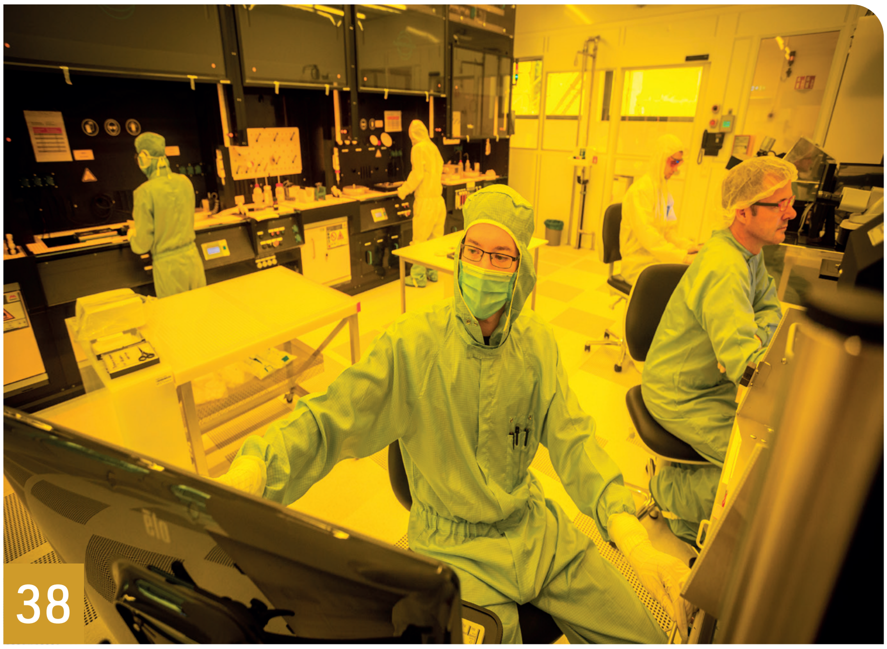

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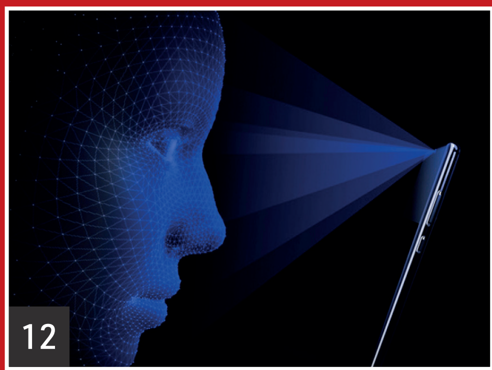

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Infineon and Foxconn to collaborate on SiC for EVs

Companies to leverage respective expertise in EV development

INFINEON and Hon Hai Technology Group (Foxconn), a Taiwanese electronics manufacturing services provider, have agreed to work together on electric vehicles (EVs).

The two companies will collaborate on the implementation of SiC technology in automotive high-power applications like traction inverters, onboard chargers, and DC-DC converters. Both parties intend to jointly develop EV solutions based on Infineon's automotive system understanding, technical support and SiC product offerings, combined with Foxconn's electronics design and manufacturing expertise and the capability of system-level integration.

In addition, the two companies plan to establish a system application centre in Taiwan to further expand the scope of their cooperation.

This centre will focus on optimising vehicle applications, including smart cabin applications, advanced driver assistance systems and autonomous driving applications. It will also address electromobility applications such as battery management systems and traction inverters.

The collaboration covers a wide range of Infineon's automotive products, including sensors, microcontrollers, power semiconductors, high-performance memories for specific applications, human machine interface and security solutions. The system application centre is expected to be established within 2023.

"The automotive industry is evolving. With the rapid growth of the EV market and the associated need for more range and performance, the development of electromobility must continue to advance and innovate," said Peter Schiefer, president of the Infineon Automotive Division. "Infineon's commitment and passion for innovation and zero-defect quality has made us the best partner for our customers. We look forward to writing a new chapter in electromobility together with Foxconn."

"We are pleased to be working with Infineon and are confident that this collaboration will result in optimised architecture, product performance, cost competitiveness and high system integration to provide customers with the most competitive automotive solutions," said Jun Seki, Foxconn's Chief strategy officer for EVs.

US DoD chooses Nuburu for laser contract

COLORADO-BASED blue laser company Nuburu has been selected by the US Department of Defense (DoD) to make prototypes and equipment for solid-state high-energy laser weapon systems.

Nuburu is one of seven companies selected to participate in the $75 million multiple award contract. The other companies include divisions of Rolls-Royce, General Atomics, Dynetics, II-VI, Lockheed Martin, and nLIGHT. Work is expected to be completed by March 2028.

The Naval Surface Warfare Center Dahlgren Division, Dahlgren, Virginia, is the contractor.

"Nuburu has the ability to manufacture laser diode, fibre optic and optical subsystems in the US, making us well positioned to support the DoD with its needs regarding this critical next-generation national security issue," said Mark Zediker, CEO and co-founder of Nuburu. "We are proud to use our automated manufacturing capabilities and a workforce entirely based in the US to provide high-power laser subsystems for our customers."

What hinders UVC LED adoption?

Disinfection and purification systems are moving to UVC LEDs, but performance and cost need optimising, says Piséo

USED for more than 40 years for their germicidal effects, systems based on low-pressure mercury lamps for surface, air, and water disinfection will gradually disappear in favour of UVC LEDs, according to a new report *UVC LED Beyond COVID-19: Performance Analysis and Comparison*, by Piséo, Yole Group's partner.

The adoption of this LED technology is no longer a question of if but when.

As with white-light LEDs, Piséo considers wall-plug efficiency (WPE) as the champion parameter. However, for the time being, most UVC LED WPEs are in the range of 1-4 percent, too low to compete with mercury lamps, which have an efficiency of around 30 percent.

Matthieu Verstraete, senior electronics analyst at Piséo, says: "This creates a cascade effect with, as an end result, a consequence on the cost: the lower the efficiency, the higher the quantity of heat to be dissipated, the more difficult the integration and the higher the cost. Yet, a few companies are beginning to stand out with promising WPEs".

Nichia provides an LED with a WPE of more than 5 percent, although for a 280 nm wavelength, which has a lower germicidal effect. Bolb Inc. and Ams Osram fare well with an efficiency topping 5.5 percent at 265 nm, the optimum wavelength for this application. The interesting fact remains that the global leader in optical solutions introduced its product, which bears an uncanny resemblance to Bolb's design, a few months after acquiring 20 percent of Bolb Inc., leaving no doubt as to the device's origin. Still, with its patented transparent chip UVC LED structure, Bolb Inc., the newcomer, is ahead of the competition with four products featuring between 5.5 and 6.4 percent efficiency.

Cost and lifetimes

Despite a significant decrease between 2016 and 2021 (factor of 200), the cost of UVC LEDs remains high compared with mercury lamps ($0.05/mW versus $0.002/mW). However, it is approaching a sufficiently high level to intensify interest in bringing the product to the market.

Although already superior to mercury lamps (12,000 h against 8,000 h), the lifetime remains a parameter to be improved to offset the purchase cost by a longer operating time and, therefore, a lower maintenance cost. Piséo considers that UVC LEDs could feature a WPE equivalent to that of mercury lamps and a lifetime equal to that of white light LEDs (50,000 h) by 2028.

Joël Thomé, CEO at Piséo, says: "The challenge is in combining all the best parameters – high WPE, low cost, high lifetime, at the optimal wavelength – in one device. With different strategies, the solutions developed by the major players should eventually converge toward the ideal UVC LED."

Many announcements have been made recently. Last month, Bolb boasted a WPE of 8.3 percent on UVC LED prototypes, while Crystal IS claimed a projected L70 lifetime value of over 25,000 hours for its latest product. According to Piséo, more announcements are expected.

CVD Equipment releases SiC PVT system

New system is engineered for growing 150 mm diameter SiC boules/ingots

CVD EQUIPMENT CORPORATION has introduced the PVT150, a physical vapour transport system for SiC crystal boule growth. The PVT150 model is said to be a compact platform design, exclusively engineered for growing 150 mm diameter boules/ingots and is upgradable to 200 mm (PVT200). The company plans to launch its PVT200 in Q3 2023.

The PVT150 /PVT200 are production systems with RF induction heating, process controls that stabilise temperature +/- 0.5 °C at 2500 °C and pressure at +/- 1 percent of set point.

Automatic process chamber load and unload, recipe start, crucible stage rotation and motorised pyrometer alignment by remote-control box for real-time monitoring of the crucible during crystal growth are some of the many system features that drive efficiencies, according to the company. Automated positionable coil with axial vertical travel allows for thermal gradient control to optimise SiC boule growth.

"Our PVT product series provides unmatched precision and reliable control of all process parameters," said Emmanuel Lakios, president and CEO of CVD Equipment Corporation.

He added: "This allows for high yield run to run repeatability as well as system to system matching."
CVD Equipment's product portfolio includes turnkey configured systems as well as customized solutions to fit varying crucible designs.

"Our expanded internal vertical production capacity enables lead times as short as 6 months ARO," remarked Lakios.

The company has recently expanded its US manufacturing facility (135,000 ft²) located in Central Islip, NY, ramping up production capacity for its PVT systems.

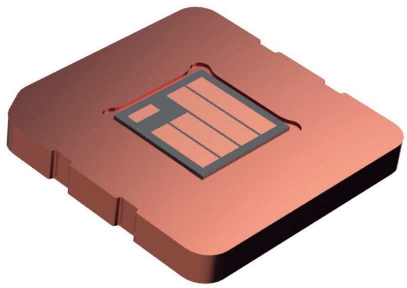
Infineon and Schweizer to embed SiC chips into PCBs

Infineon Technologies and Schweizer Electronic, a PCB company, are developing a solution to embed Infineon's 1200 V CoolSiC chips directly onto printed circuit boards (PCB). They say this will increase the range of electric vehicles and reduce total system costs.

The companies have already demonstrated the potential of this new approach: They were able to embed a 48 V MOSFET in a PCB. This resulted in a 35 percent increase in performance. Schweizer contributes to this success with its p²Pack solution which enables power semiconductors to be embedded in PCBs.

"Our joint goal is to take automotive power electronics to the next level," said Robert Hermann, product line head automotive high-voltage discretes and chips, Infineon. "The low-inductive environment of a PCB allows clean and fast switching. Combined with the leading performance of 1200 V CoolSiC devices, chip embedding enables highly integrated and efficient inverters that reduce overall system costs."

"With Infineon's 100 percent electrically tested standard cells, we can achieve high overall yields in the p² Pack manufacturing process," said Thomas Gottwald, VP technology at Schweizer Electronic AG. "The fast-switching characteristics of the CoolSiC chips are optimally supported by the low-inductance interconnection that can be achieved with the p² Pack. This leads to increased efficiency and improved reliability of power conversion units such as traction inverters, DC-DC converters, or on-board chargers."



Infineon and Schweizer showcased the 1200 V CoolSiC chip embedding technology at PCIM Europe 2023 in Nuremberg, Germany

Bosch to acquire US chipmaker TSI

Company plans to invest $1.5 billion in SiC technology for electromobility

BOSCH is expanding its SiC semiconductor business with plans to acquire assets of the US chipmaker TSI Semiconductors, based in Roseville, California. The aim is to significantly expand its portfolio of SiC devices by the end of 2030 to meet demand from electric cars.

With a workforce of 250, TSI is a foundry for application-specific integrated circuits (ASICs). Currently, it mainly develops and produces large volumes of chips on 200 mm silicon wafers for applications in mobility, telecommunications, energy, and life sciences.

Over the next years, Bosch intends to invest more than $1.5 billion in the Roseville site and convert the TSI Semiconductors manufacturing facilities to state-of-the-art processes. Starting in 2026, the first chips will be produced on 200 mm wafers based on SiC, following a retooling phase. The SiC chips will be produced on 200 mm wafers in a facility offering roughly 10,000 m^2 of clean-room space.

The full scope of the planned investment will be heavily dependent on federal funding opportunities available via the CHIPS and Science Act as well as economic development opportunities within the State of California. Bosch and TSI Semiconductors have reached an agreement to not to disclose any financial details of the transaction, which is subject to regulatory approval.

"With the acquisition of TSI Semiconductors, we are establishing manufacturing capacity for SiC chips in an important sales market while also increasing our semiconductor manufacturing, globally. The existing clean-room facilities and expert personnel in Roseville will allow us to manufacture SiC chips for electromobility on an even larger scale," says Stefan Hartung, chairman of the Bosch board of management.

"The location in Roseville has existed since 1984. Over nearly 40 years, the US company has built up vast expertise in semiconductor production. We will now be integrating this expertise into the Bosch semiconductor manufacturing network," says Markus Heyn, member of the Bosch board of management and chairman of the Mobility Solutions business sector.

"We are pleased to join a globally operating technology company with extensive semiconductor expertise. We are confident that our Roseville location will be a significant addition to Bosch's SiC chipmaking operations," says Oded Tal, CEO at TSI Semiconductors.

By 2025, Bosch expects to have an average of 25 of its chips integrated in every new vehicle. The market for SiC chips is also continuing to grow fast – by 30 percent a year on average. The main drivers of this growth are the global boom and ramp-up of electromobility. In electric vehicles, SiC chips enable greater range and more efficient recharging, as they use up to 50 percent less energy. Installed in these vehicles' power electronics, they ensure that a vehicle can drive a significantly longer distance on one battery charge – on average, 6 percent greater than with silicon-based chips.

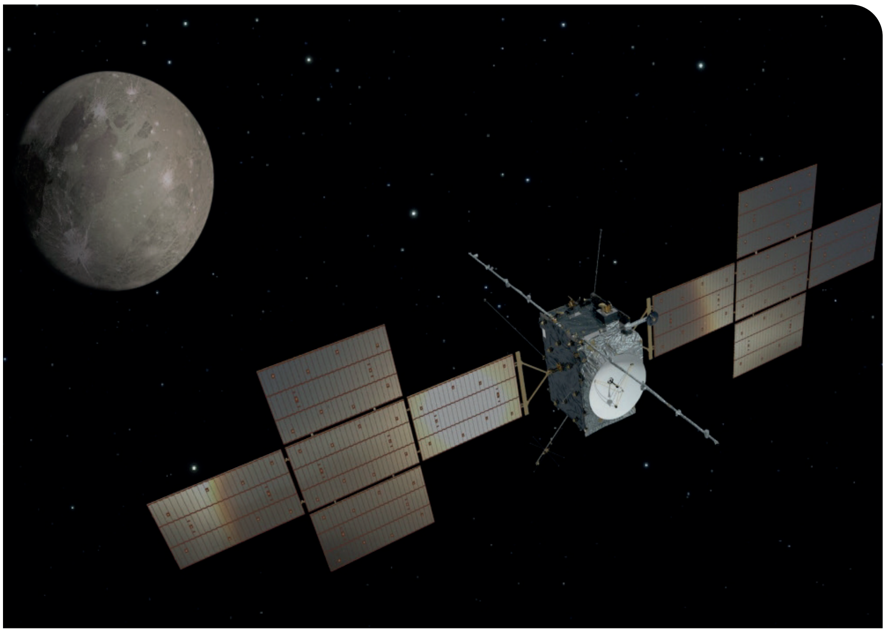
Bosch has been manufacturing semiconductors in Reutlingen, Germany, since 1970. Production at the new Bosch wafer fab in Dresden (300 mm wafers) started in July 2021. At nearly €1 billion, the Dreden wafer fab is the biggest single investment in the company's history.

Bosch invested in the development and production of SiC chips at an early stage. Since 2021, it has been using its own proprietary processes to mass-produce them at Reutlingen. In the future, Reutlingen will also produce them on 200 mm wafers. By the end of 2025, the company says it will have extended its clean-room space in Reutlingen from roughly 35,000 m^2 to more than 44,000 m^2.

In its wafer fabs in Reutlingen and Dresden, Bosch has invested more than €2.5 billion in total since 200 mm technology was introduced in 2010. On top of this, billions of euros have been invested in developing microelectronics. Independently of the investment now planned in the US, the company announced last summer that it will be investing a further €3 billion in its semiconductor business in Europe, both as part of its investment planning and with the aid of the EU's *Important Project of Common European Interest on Microelectronics and Communication Technologies* program.

Azur's solar cells powering ESA Jupiter mission

Triple-junction cells on a germanium substrate cover Juice's huge solar arrays



5N PLUS INC, a Canada-based maker of specialty semiconductors and materials, has played a key role in the European Space Agency's Jupiter Icy Moons Explorer, Juice, mission. The solar cell technology comes from the company's German subsidiary Azur Space Solar Power GmbH.

The mission to Jupiter presented a unique challenge. The environment around Jupiter is characterised by low sunlight intensity and low ambient temperature conditions as well as harsh particle radiation, which represent demanding operating conditions for solar cells.

After extensive research and testing, Azur's 3G28 solar cell technology was selected by ESA's engineers to cover Juice's 85 m^2 of solar arrays, the largest ever built for an interplanetary spacecraft.

Azur's triple junction 3G28 solar cells, made of GaInP/GaAs/Ge on a germanium substrate, have a beginning-of-life efficiency of around 35 percent. They were laid down by Leonardo in Italy and integrated by Airbus Defence and Space in the Netherlands.

NASA's future Europa Clipper mission to Jupiter moon Europa is also employing Azur's 3G28 solar cells.

"It continues to be a privilege for 5N Plus to work in partnership with the world's leading space agencies, such as ESA and NASA, to help, quite literally, push the boundaries of solar-powered space missions to the benefit of humankind. We are extremely proud of the Azur team for constantly innovating its solar cell technology and working in close partnership with our valued clients to help them achieve mission-critical projects," said Gervais Jacques, president and CEO of 5N Plus.

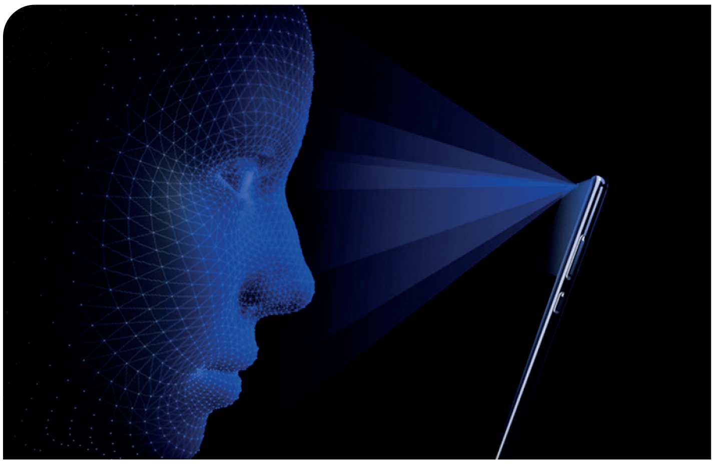
Coherent unveils ultracompact VCSEL architecture

Patented module approach allows dynamic illumination and sensing with backside-emitting VCSEL arrays

Coherent, a US-based optical sensing company, has unveiled a patented module architecture for compact dynamic illumination and sensing with backside-emitting VCSEL arrays.

The rapidly growing number of applications for optical sensing in consumer electronics is driving the demand for optoelectronic sub-assemblies that fit in smaller spaces and achieve higher performance.

Coherent says its patented module technology enables ultra-compact pattern projectors, flood illuminators, and tightly integrated sensing subsystems. The module technology relies on flip-chip assembly of backside-emitting VCSEL arrays on application-specific integrated circuits (ASICs) and supports the integration of photodetector arrays.



"The flip-chip approach eliminates the parasitic inductance from bond wires, improving the depth resolution and accuracy of time-of-flight sensors in consumer electronics," said Julie Sheridan CTO. "Backside illumination optoelectronics enables not only the superior electrical performance of flip-chip assemblies, but also a higher level of optical integration with polarisation-locking and beam-shaping features embedded in the optoelectronic device."

VCSEL arrays from Coherent can be designed to independently address individual or groups of emitters that are steered through diffractive optics, enabling the selective illumination of a region of interest within a dynamic scene.

ZF signs SiC supply agreement with ST

ZF, a company supplying systems for cars, commercial vehicles, and industrial systems, will purchase SiC devices from STMicroelectronics from 2025. Under the terms of the multi-year contract, ST will supply a volume of double-digit millions of SiC devices to be integrated in ZF's new modular inverter architecture going into series production in 2025.

ST will manufacture the SiC chips at its production fabs in Italy and Singapore, with packaging of the chips into STPAK, an ST-developed advanced package, and testing at its back-end facilities in Morocco and China. ST will supply ZF from 2025 with a volume of double-digit millions of third-generation SiC MOSFET devices. ZF says it can connect a number of such devices together to match customers' performance requirements without changing the design of the inverter. Among others, ZF will use the technology in inverters for vehicles of a European car manufacturer whose production start is planned for 2025.

"With this strategically important step, we are strengthening our supply chain to be able to securely supply our customers. Our order book in electromobility until 2030 now amounts to more than thirty billion euros. For this volume, we need several reliable suppliers for SiC devices," says Stephan von Schuckmann, member of the ZF board of management responsible for electromobility as well as materials management.

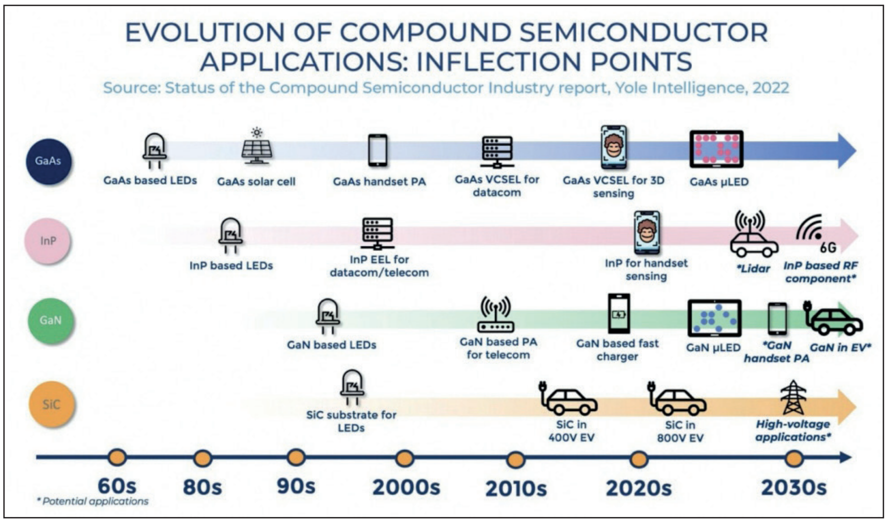
"In STMicroelectronics, we now have a supplier whose experience with complex systems meets our requirements and who, above all, can produce the devices in exceptionally high quality and at the required quantities."

"As a vertically integrated company, we are investing heavily to expand capacity and develop our SiC supply chain to support our global and European customers across automotive and industrial sectors, as they pursue electrification and decarbonisation targets," says Marco Monti, president of ST's automotive and discrete group.

"The key to success in electric vehicle technology is greater scalability and modularity with increased efficiency, peak power, and affordability. Our SiC technologies help deliver these benefits and we are proud to work with ZF, a leading automotive supplier for electrification, to help them differentiate and optimise the performance of their inverters."

CS substrate market to double by 2027

SiC for power applications will represent the largest sector, growing at CAGR of 25 percent, say Yole



As the world demands ever greater power and efficiency, the market for compound semiconductor substrate materials is set to more than double by 2027 – with SiC for power applications expected to significantly increase its market share compared to silicon. All mega trends (electrification, 5G/6G, cloud computing...) have an increased use of compound semiconductor devices in their roadmap.

In its new *Status of Compound Semiconductors 2022* report, Yole Intelligence predicts the CS substrate material market to grow from $945 million in 2021 to $2.3 billion in 2027.

By 2027, SiC for power applications will represent the largest sector, growing at a CAGR 2021-2027 of 25 percent and increasing its market share among compound semiconductor substrates by around 50 percent. The photonics InP market will also increase its share and grow at a 20 percent CAGR. The third major market, RF GaN, which encompasses the substrates silicon and SI SiC, will maintain its market share but continue to grow with other applications at a 11 percent CAGR 2021-2027.

The electrification of vehicles and high-voltage applications are driving demand for SiC materials, and there have been ongoing moves by major players to secure or grow their substrate supply.

The RF GaN market is expected to grow in terms of size but not market share, partly as a result of the impact of the United States sanctions on Huawei in 2019, which impacted the GaN-on-SiC supply chain. In 2023, the market is expected to gain momentum to grow again, thanks to the 5G base station market in various countries, such as India.

In the photonics sector, mergers and acquisitions are helping companies competing in the sensing and telecom/datacom sectors gain more market share and join-up competencies in InP and GaAs. For example, Coherent's acquisition by II-VI saw its competencies in InP and GaAs become more distributed across materials, components and systems.

The acquired competencies will allow the companies to better compete in emerging applications – where 3D sensing in smartphones and lidar, microLEDs, and the transition of 5G to 6G will be important drivers. In particular, the consumer 3D sensing market has witnessed a strategic move by the tech giant Apple. InP-based proximity sensors replaced traditional GaAs VCSELs in 2022 to shrink the notch size in the iPhone 14. This has triggered certain traditional GaAs players to expand their product portfolio to InP.

MicroLEDs, on the other hand, is a serious growth vector for the GaAs photonics market. Ams Osram announced the construction of a €800 milion microLED fab in Malaysia, which will be ready for mass production in 2024, to supply Apple with microLED displays for smartwatches. Several companies have benefited from the move of Apple in the microLEDs business. Aixtron will supply Ams osram with 8-inch MOCVD reactors, while AXT and Freiberger have already demonstrated 8 inch GaAs substrates and are in competition to qualify as a main supplier to Apple.

Wolfspeed's dominance in SiC and also RF GaN substrates means all major device manufacturers have partnered with the company to ensure supply – most recently in December 2022 – and in turn this helps it to secure business at the device level. As of 2023, the only other companies to offer competencies in both power SiC and RF GaN are Coherent and Chinese player SICC.

The growth of the power SiC and photonics markets, and the subsequent need to increase manufacturing capacity, is creating opportunities for silicon fabs. As CS players move from 2, 3, and 4 inches to 6- or 8-inch platforms to scale production, there is a synergy with silicon fabs that have had well-established processes using larger diameter wafers for decades.

In short, the market for CS substrates is growing as the demand for high-power devices drives manufacturing advances and sees CS players moving into different material segments.

CS ANGELTECH INTERNATIONAL CONFERENCE

Empowering CS International to new highs

Insights into the commercial progress of GaN and SiC power devices lay at the very heart of this year's CS International, which attracted record numbers of delegates and exhibitors

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

IT'S OF NO SURPRISE that advances associated with the high-volume manufacture of wide bandgap power devices took centre-stage at CS International 2023. With sluggish handset sales providing a headwind to the GaAs microelectronic market and the production of commercial displays based on microLEDs still to really commence, there is good reason why much of the coverage of this two-day meeting, held at the Sheraton Hotel at Brussels Airport on 18-19 April, centred around ramping and improving the production of GaN and SiC power devices and modules.

Both flavours of wide bandgap power electronics are destined to grow at a phenomenal rate throughout this decade, according to Omdia's Callum Middleton. This market analyst shared a forecast showing that the combined sales of SiC and GaN power devices will climb from below $2 billion this year to eclipse $10 billion in 2018 and exceed $18 billion by the end of this decade.

➤ More than 80 exhibitors had a stand at AngelTech 2023, which incorporated the 13th CS International conference and attracted a record number of delegates.

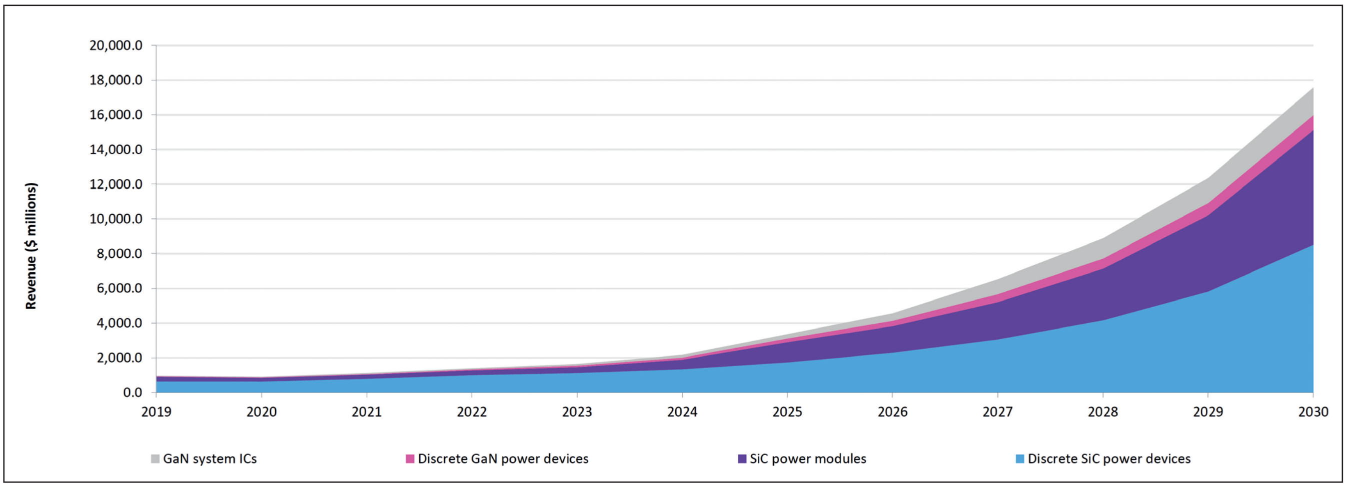
The lion's share of sales will come from SiC, which is expected to net $16 billion by 2030. As is the case today, the SiC MOSFET will account for the most substantial proportion of sales. Shipments of SiC Schottky barrier diodes will only undergo a modest increase over that timeframe, while sales of full SiC modules will soar, making this the second biggest seller by a significant margin.

The driver behind this exceptional growth is the electric and hybrid electric vehicle, which is predicted to account for more than $10 billion of SiC sales by 2030. Additional revenue will come from numerous applications, with this device being deployed in power supplies, PV inverters, hybrid electric vehicle charging infrastructure, and a variety of military, aerospace and industrial applications.

One of the trends that Middleton has observed is the desire for SiC chipmakers to increase their control over the supply chain, due to high demand for SiC substrates. An example of this is onsemi's acquisition of GTAT, a company with expertise in making SiC boules.

"Commoditisation of SiC wafers will happen," remarked Middleton, although this will take time. He added that while there are large capacity expansion plans for SiC wafer production in China, domestic demand will also be high, so initially this additional volume may not support SiC chip production.

For start-ups in the wide bandgap power electronics sector, GaN devices are easier to produce, thanks to the silicon substrate providing the foundation for the epilayers. According to Middleton, compared



➤ Forecasts from Omdia, first given in The SiC & GaN Power Semiconductors Report 2021 (published in early 2022), indicate rapid growth in revenues for SiC and GaN power devices throughout this decade.

to the SiC sector, that for GaN has more specialist companies and is less mature.

A substantial player in SiC is the European powerhouse STMicroelectronics. Speaking on its behalf at CS International, Manuel Gärtner, Marketing and Application Director for Wide Bandgap and Electrification for Europe, the Middle East and Africa, made a strong case for why SiC is superior to the silicon IGBT in electric vehicles.

He explained that this wide bandgap device delivers a gain in efficiency over the IGBT that varies from around 2 percent to 10 percent, depending on load; switching losses plummet by a factor of 7; and switching frequencies can be 5-to-10 times higher. What's more, thanks to the higher operating temperature of SiC – MOSFETs can run at a junction temperature of 200 °C – engineers can downsize the cooling system by around 80 percent.

Gärtner added that the ongoing shift from 400 V to 800 V for the operation of electric vehicles is enhancing the benefit of SiC over silicon. He claimed that this doubling of the voltage results in a reduction in semiconductor area from a factor of 3 to 5, and a boost in efficiency from 3-5 percent to 8-12 percent.

As well as the increase in SiC revenue coming from a hike in electric vehicle sales, this class of power device, along with its rivals, will benefit from a growth in associated infrastructure. According to Gärtner, for every seven electric vehicles there will be one charger; and for every ten chargers one storage station. Note that once the revolution in transportation is well underway, hundreds of thousands of charging stations will have been built.

Providing a GaN perspective, Denis Marcom, General Manager of Innoscience Europe, outlined plans for tremendous growth of this company, as well as making a compelling case for this particular wide bandgap semiconductor.

Marcom pointed out that thanks in part to low values for on-resistance and gate-charge, GaN is able to maintain its efficiency at high frequencies. "Compared with silicon and silicon carbide, the recovery time is zero." This asset enables a shrinking of the size of passive components, and thus a trimming of size, weight and cost at the system level.

According to Marcom, Innoscience boasts the largest GaN capacity worldwide. Last year it could run the equivalent of 10,000 8-inch wafers through its line every month. This capability has enabled the workforce of more than 1500, completely focused on GaN, to have shipped more than 100 million devices – they are a combination of high-voltage products operating at more than 650 V, and variants that are described as medium-voltage (100 V to 150 V) and low-voltage (below 100 V). Shipments are tipped to soar over the coming years as the company undergoes a 7-fold expansion in capacity, realised by 2025.

Many companies offering support to the makers of power devices spoke at the meeting, including those that: provide tools to shape boules prior to processing into substrates; make MOCVD tools, either with single wafer or multi-wafer capacity; offer metrology techniques to scrutinise substrates and epiwafers; and provide software to aid device design through the simulation of performance. Many of these firms also had a stand in the Exhibition Hall, home to over 80 booths, busy with a record number of delegates.

Mirroring the major trend in the wide bandgap industry, CS International – as well as its co-located conferences, PIC International and Power Electronics International – is on an upward curve, with the next event, to be held at the same venue on 16-17 April 2024, promising to surpass its predecessors.

Following the acquisition, Infineon will combine GaN products produced on internal lines with those of fabless GaN Systems.

Image Credit: Infineon Technologies AG

GaN's glorious marriage

Infineon will enhance its prowess in power electronics with the acquisition of GaN Systems

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

ONE OF THE MOST significant milestones for wide bandgap power electronics arrived when silicon powerhouses decided to invest in one flavour of this technology. At that time some went for SiC, while others threw their weight behind GaN; now many of the biggest names have both. In fact, so great is the promise of these successors to silicon that one of the leading players, Infineon, is now planning to strengthen its GaN offering by combining its in-house capabilities with an $830 million acquisition of Canadian fabless firm GaN Systems.

This acquisition - following negotiations that are said to have lasted for months rather than years, and slated to close by the end of 2023 – will equip Infineon with two complementary GaN technologies, according to Adam White, Infineon's Division President, Power and Sensor Systems.

"The device concepts of the technologies are slightly different," argues White, who adds that this difference can help address different application requirements across the application space. For example, soft switching versus hard switching or the level of robustness.

Another appeal behind Infineon's purchase is that it can get its hands on GaN Systems' unique packaging technology, which features chip embedding. "That fits very much along the lines of where we want to go in the roadmap of ultra-low parasitic packaging," says White.

One area where Infineon already excels is in its capability to couple its GaN technology to silicon ICs, such as drivers and controllers. It's a synergistic approach that empowers the company to target customers with products that are designed from a whole system perspective.

Once the acquisition goes through Infineon will instantly double the number of products in its GaN portfolio. In turn, the number of design opportunities will increase by at least this factor. "That would then accelerate our applications understanding," enthuses White, "and from there, of course, ultimately bring value to the customer from a system perspective."

A key difference between Infineon and GaN Systems is that the former has chip production lines, while the latter is fabless. "That's another benefit of the acquisition upon closing," says White, pointing out that the purchase will lead to more fruitful conversations with foundry partners. "This is definitely a pillar of our growth strategy. We recognise that gallium nitride will need capacity."

On the unveiling of its plan to buy GaN Systems, Infineon's CEO, Jochen Hanebeck, remarked that this move would create an entity with unmatched R&D resources.

Supporting this claim, White says that once GaN Systems is on board, it will give Infineon a 450-strong GaN team. "That doesn't include all the areas of go to market, all the areas of operations. This is just an application knowledge domain, product domain knowledge, and R&D product domain knowledge."

The purchase of GaN Systems is described as a synergistic growth acquisition. No-one within the entity that's due to be acquired should fear for their job, as Infineon's intent is to maintain and motivate these staff, and keep them within the company.

The acquisition will strength Infineon's already formidable patent portfolio. The German chipmaker can already boast of more than 300 patent families, and once GaN Systems is on board, this figure will top 350.

One may wonder what's behind the timing of the acquisition. According to White, one motivation for making the move at this time is that Infineon believes that GaN is now at a "very healthy tipping point", in terms of both the customer's interest in this wide bandgap material and their willingness to pursue sponsored projects.

There's also a level of maturity within the customer base. No longer are the virtues of a GaN device defined in what it can deliver when providing a drop-in replacement for a silicon equivalent. Customers are now thinking about what GaN offers when

> While $830 million may appear a lot to spend on a fabless outfit with a couple of hundred employees, there's definitely the potential for a good return on investment for the German powerhouse

deployed in the right system with the right topology. "You can then unleash the potential of gallium nitride," says White.

He is now starting to see the adoption of GaN in a number of applications. These devices are now being deployed in: charger and adapter markets; server markets for high power; residential solar markets; and the on-board charger, as well as the DC-to-DC converter in cars.

"This is really the reason why now [we've acquired GaN Systems], and hence why we went after this acquisition to complement our approach that we're doing standalone," adds White.

The immediate impact is not the most overriding consideration. What's more important to the German outfit is the mid-term to long-term perspective.

"The addressable market will really justify the value that we are paying for this asset," reasons White, who backs this up by quoting figures from Yole Intelligence. Forecasts from the French analyst include a compound annual growth rate for GaN for power applications of an eye-watering 56 percent from 2022 to 2027, which will propel this market to more than $6 billion by the end of this timeframe.

So, while $830 million may appear a lot to spend on a fabless outfit with a couple of hundred employees, there's definitely the potential for a good return on investment for the German powerhouse.

Championing a true heavyweight: Unleashing the promise of Ga_2O_3

Blessed with an incredibly wide bandgap, shallow donors and the capability of bulk growth from the melt, Ga_2O_3 is making a compelling case as the most promising material ever for power devices

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

Aside from a record number of delegates and a packed exhibition hall, those attending this year's CS International will remember this meeting for the phenomenal level of interest in wide bandgap power electronics. Excitement in this sector is incredibly high, because sales of SiC and GaN devices and modules are set to rocket throughout the remainder of this decade, climbing from an annual revenue that now totals below $2 billion to around $18 billion by 2030. That's great news not only for chipmakers, but also those making related materials, metrology tools and device design software.

A healthy uptake of these two new classes of power electronics with benefit humanity. There will be improvements in the efficiency with which electricity is converted between its AC and DC forms, and is stepped up and down. This leads to a reduction in the carbon footprint of numerous electrical systems. What's more, electric vehicles will travel further on a single charge, helping to sooth concerns related to range anxiety, as well as making a more compelling case for switching away from the combustion engine.

But does the revolution in power electronics end with SiC and GaN? Or is there more to come?

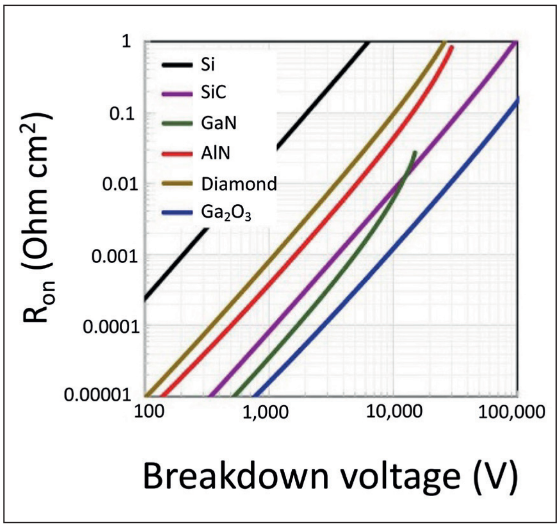
It's the latter, argued three presenters at CS International: Martin Kuball (pictured above), leader of the Centre for Device Thermography and Reliability at Bristol University; Akito Kuramata, CEO of gallium oxide substrate maker Novel Crystal Technology (NCT); and Heather Splawn, CEO of

➤ Martin Kuball, chair of the Royal Academy of Engineering in Emerging Technologies and a physics professor at the University of Bristol, UK, is expanding his research into gallium oxide, thanks to the introduction of an MOCVD growth tool in his labs.

HVPE specialist Kyma Technologies. All made the case that compared with the middleweight duo of SiC and GaN, gallium oxide is a heavyweight with the capability to handle incredibly high voltages and provide switching at even higher efficiencies. These attributes make this oxide a very promising candidate for the ultra-high-voltage market, where it could be deployed for supporting the grid, handling the power produced by wind turbines and finding application in electric trains.

In terms of its physical prowess, Ga_2O_3 is best known for its very wide bandgap of 4.9 eV and a breakdown field that can reach as high as 8 MV cm^{-1}. But how does it perform when benchmarked against the common yardstick for gauging the potential of power devices, Baliga's figure of merit? Well, that depends on what's considered. Initially, while it would appear that oxide is ahead of SiC and GaN by a considerable margin, it lags behind two other heavyweights, diamond and AlN. However, when one considers the depth of the dopants, a crucial factor in determining the capability of power devices, the β form of Ga_2O_3 comes out on top, thanks to relatively shallow dopants (see Figure 1).

Another major asset of Ga_2O_3 is the relative ease of crystal growth. Like silicon, GaAs and InP, it can be grown from the melt, ensuring relatively easy production of substrates with low dislocation densities. That's not the case for SiC, which tends to be produced by vapour phase transport; or GaN, which is yet to have a bulk growth technique suitable for producing native power electronic devices in volume.



➤ Figure 1. Once the level of activity of dopants is considered, Ga_2O_3 emerges as the most promising of the ultra-wide bandgap semiconductors, based on Baliga's figure of merit. This graph is taken from Y. Zhang et al. Semicond. Sci. Technol. **35** 125018 (2020).

Obstacles to overcome

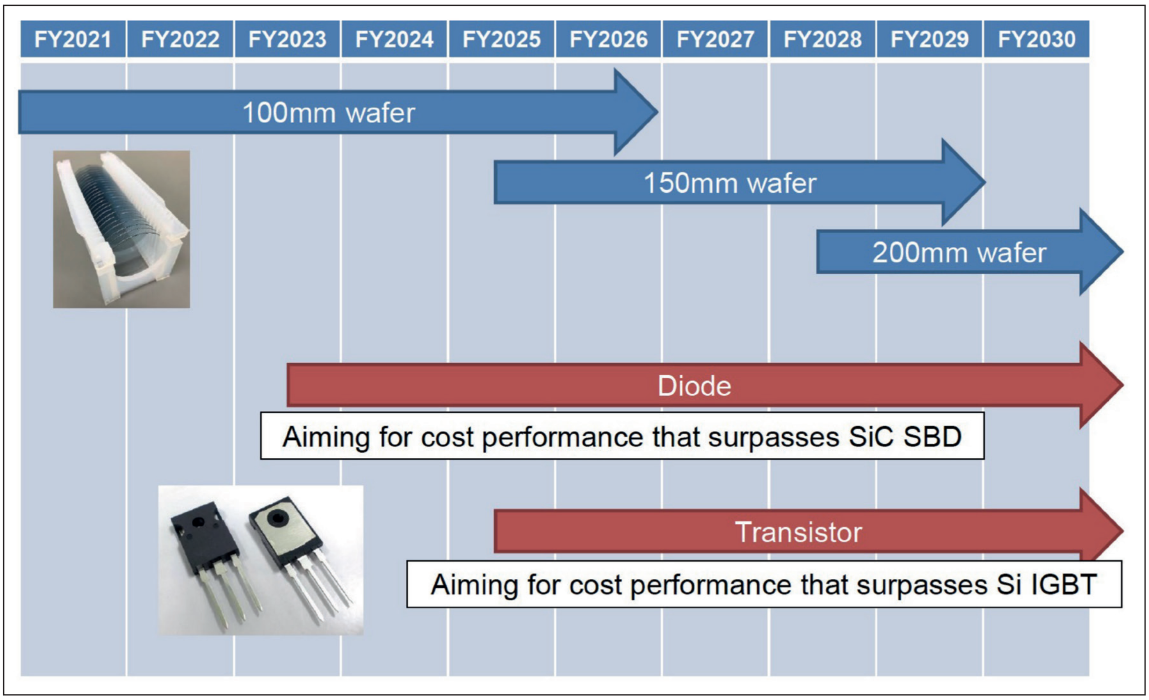
Thanks to all these merits, devices made from Ga_2O_3 are already delivering impressive results. "The performance is already exceeding silicon carbide," remarked Kuball during his presentation to delegates at CS International 2023. However, that does not imply that commercial success is assured, partly due to weaknesses associated with these devices.

➤ Akito Kuramata is CEO of Novel Crystal Technology, a provider of Ga_2O_3 substrates and epiwafers. The company plans to expand into the production of diodes and transistors based on this oxide.

Kuball did not brush aside these concerns, but discussed them head on. One weakness is a high density of defects in the material, with deep-level transient spectroscopy uncovering many different trap states in β-Ga_2O_3. More work is needed, as it is still largely unknown what the killer defects in this oxide might be.

Another concern is the low thermal conductivity of Ga_2O_3, which has led many to claim that this oxide will never be a viable material for power devices, due to overheating of the chip. But this issue can be addressed with engineering, with Kuball suggesting that the introduction of diamond beside the active region could suck heat away. It's an approach his team have already used to improve the thermal management of GaN devices.

The addition of diamond is actually capable of offering much more than simply superior heat extraction. Work by Kuball's team has shown that superjunction Schottky barrier diodes formed by filling trenches in *n*-type Ga_2O_3 with *p*-type diamond enables electrical control of the device. This is encouraging, because the lack of *p*-type doping of

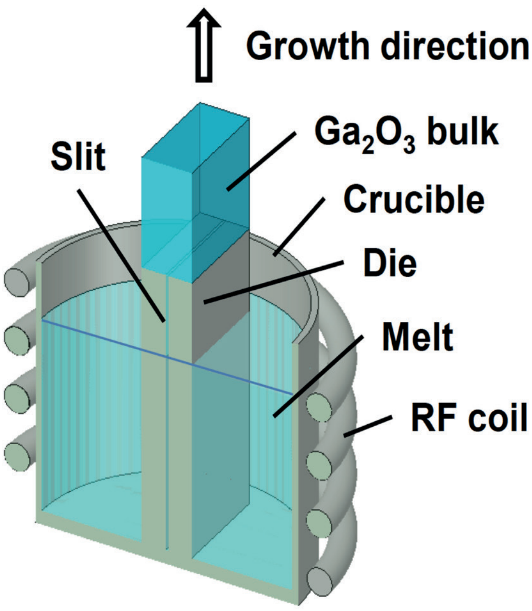


➤ Figure 2. NCT intends to increase the diameter of the substrates it produces, as well as branching out into the production of Ga_2O_3 diodes and transistors. semiconductors, based on Baliga's figure of merit. This graph is taken from Y. Zhang et al. Semicond. Sci. Technol. 35 125018 (2020).

Ga_2O_3 is a major concern – and integrating other *p*-type semiconductors is a promising solution.

When any device is in its infancy, there will always be concerns over its reliability. Kuball and his co-workers have been investigating Ga_2O_3 trench FETs provided by the University of Cornell, with experiments finding failure at the dielectric, Al_2O_3. Efforts will now need to be directed at improving the interface between Ga_2O_3 and Al_2O_3.

Trench Schottky barrier diodes have also been produced by the Bristol team. Benchmarking of these devices, which do not have field plates, indicates a performance comparable to that of the other leading groups in this field.



➤ Figure 3. For high-speed growth of Ga_2O_3 material with a large diameter, edge-defined, film-fed growth delivers unparalleled results.

In May 2022 Kuball's team commissioned the first commercial Ga_2O_3 MOCVD reactor in Europe, an Agnitron Agilis tool. Since then they have been enjoying the opportunity to grow their own material, producing both Ga_2O_3 and $Al_x(Ga_2O_3)_{1-x}$ epilayers for a variety of structures, including vertical devices.

Kuball explained that to improve the thermal performance of devices, they have investigated two-step growth on diamond. Transmission electron microscopy and scanning electron microscopy images of a 245 nm-thick layer of β-Ga_2O_3 have revealed a completely coalesced surface, and different competing crystalline orientations. The physical characteristics of this film are not that different from β-Ga_2O_3 grown on sapphire, leading Kuball to describe results so far as very promising.

Options for boule growth

More insight into the growth of Ga_2O_3 boules came in the presentation from NCT's Kuramata, who discussed both of the growth technologies that his company has employed to produce commercial material: edge-defined, film-fed growth; and vertical Bridgeman growth.

While this Japanese firm, based in Sayama, is better known for its production of substrates and epiwafers, it also has plans to produce chips and packaged devices. Kuramata presented a roadmap for the company, which included the introduction of 150 mm and 200 mm wafers within the next five years, and the launch of diodes and transistors in 2023 and 2025, respectively (see Figure 2 for details). The company's diodes are intended to offer a cost performance exceeding that of the SiC Schottky barrier diode, while judged by the same yardstick, transistors are expected to have the upper hand over the silicon IGBT.

For the production of larger material, edge-defined, film-fed growth leads the way, with NCT already having reported the development of material with dimensions of 6 inches. “It’s the only way to produce large *n*-type substrates at present,” remarked Kuramata.

Another merit of this film-fed growth approach is that it’s the fastest of all the Ga_2O_3 growth technologies – with a growth rate of 15 mm/hour, it’s three times as fast as a float-zone process, and considerable faster than growth by the Czochralski and vertical Bridgeman techniques, which are capable of only 2 mm/hour and 1 mm/hour, respectively.

With edge-defined, film-fed growth, engineers draw molten gallium oxide through a slit by capillary action, leading to growth on seed material (see Figure 3). This yields crystalline material with a plate-like geometry that has a defect density of typically around 10^3 cm^{-2}.

As the Ga_2O_3 industry is still in its infancy, it’s not surprising that today there are no orders for 6-inch material. However, Kuramata is confident that once such orders arrive, NCT will quickly establish production of material of this size.

The Japanese outfit is also developing Ga_2O_3 boules produced by the vertical Bridgeman process, as this yields material with a very high quality. Growth involves a crucible made from a platinum-rhodium alloy and a (010) Ga_2O_3 seed crystal. By carefully controlling the motion of the crucible through the thermal gradient produced in the furnace, molten Ga_2O_3 is cooled to yield a crystalline boule. With this approach, NCT has produced 2-inch (010) substrates – claimed to be the largest size for (010) Ga_2O_3 substrates ever reported.

For the growth of epilayers, NCT employs HVPE, a technology transferred from Tokyo University of Agriculture. Working in partnership with Saga University, NCT has produced Schottky barrier diodes on a 100 mm β-Ga_2O_3 epiwafer, with chip sizes of up to 10 mm by 10 mm. For a 10 μm-thick layer, film thickness uniformity is ± 5 percent; and donors, at a concentration of 1×10^{16} cm^{-3}, have a variation of ± 7 percent.

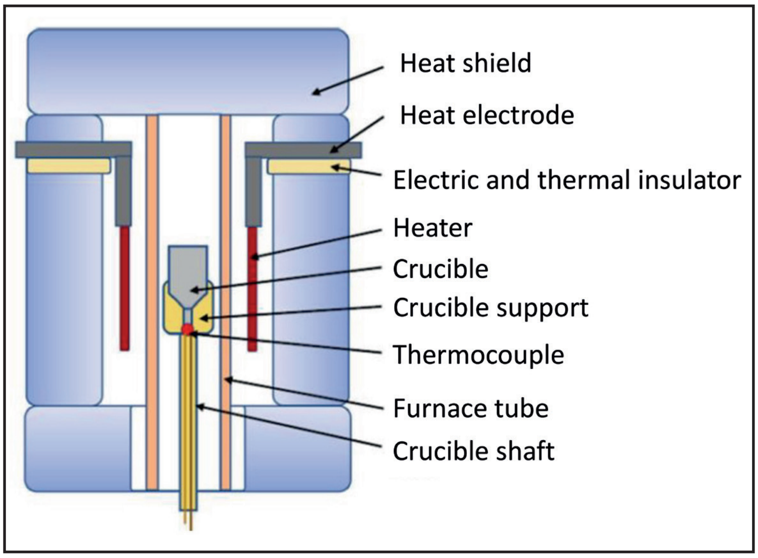
Diodes from this wafer with sides of 10 mm by 10 mm have a yield as high as 51 percent. Based on this figure, the killer defect density for the epiwafers is about 0.7 cm^{-2}.

Championing HVPE

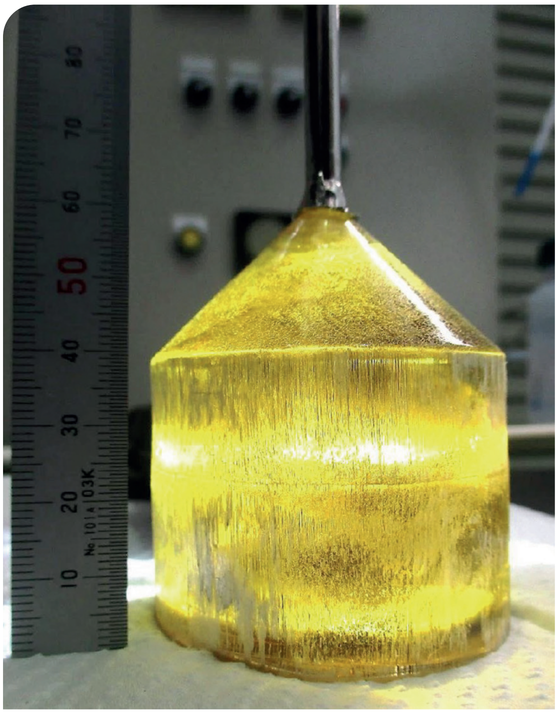
Another advocate of HVPE for gallium oxide high-voltage power electronics is the leader of Kyma Technology, Heather Splawn. She argued at this year’s CS International that this form of epitaxy produces material with a low cost and high performance, using high growth rates that are ideal for device manufacture. Splawn also pointed out that HVPE is inherently cleaner than MOCVD, due to chemically pure precursors and the absence of metal-organics, which contain carbon. Thanks to these assets, HVPE is capable of high-purity growth.

Kyma has launched to market a tool called Katharo, designed for the growth of Ga_2O_3 devices for high-power switching. This reactor is capable of accommodating wafers up to 200 mm in diameter.

While growth on such large diameters is still some way off, the company has realised encouraging results on smaller substrates. In HVPE reactors with 100 mm capability, excellent doping control is realised at epilayer thicknesses that can be more than 20 μm, according to Splawn. Her team has also



➤ Figure 4. NCT uses the vertical Bridgeman process to produce Ga2O3 crystals with a very high quality.



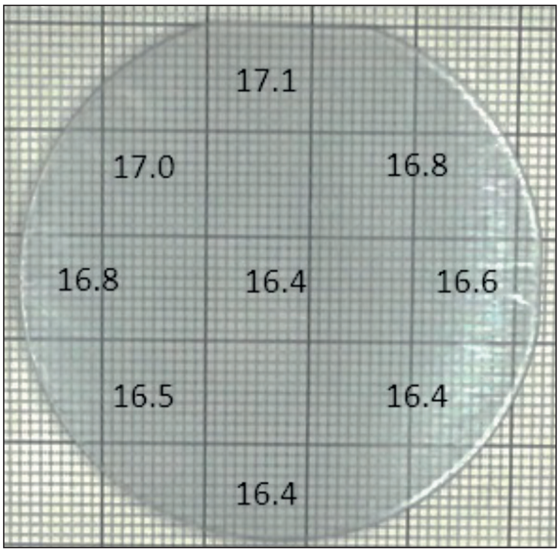
➤ Using the vertical Bridgeman technique, NCT has produced 2-inch (010) substrates.

➤ Kyma's CEO, Heather Splawn, advocates HVPE for HVPE – that's hydride vapour phase epitaxy for high-voltage power electronics

deposited Ga_2O_3 epilayers with uniform doping and thickness on 50 mm wafers, with X-ray diffraction measurements indicating a very high level of crystal quality – linewidths are just 25-30 arcsec.

Material produced by Kyma has been used to produce some very encouraging device results. Breakdown fields in these devices are as high as around 5.5 MV cm^{-1}, and Baliga's figure-of-merit is in excess of 1 GW cm^{-2}, a value very close to the theoretical limit for SiC.

Such results highlight the great promise of Ga_2O_3. With SiC and GaN seemingly assured of a bright future, it will be some time before this oxide makes a really big impact – both at CS International and within the power industry – but there's no doubting that the omens are good.



➤ Using HVPE, Kyma has grown a 16.7 μm-thick layer of Ga_2O_3 on a 2-inch native substrate that has a thickness variation of ± 3 percent. Values for the difference between the concentration of donors and acceptors within this epilayer range from 2.7 x 10^{16} cm^{-3} to 5.8 x 10^{16} cm^{-3}.

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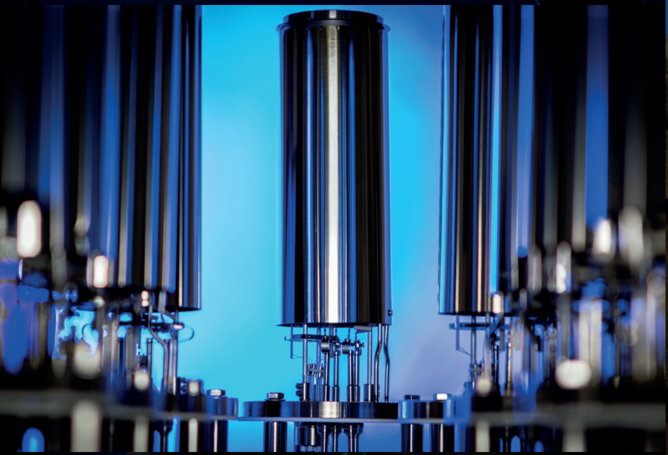

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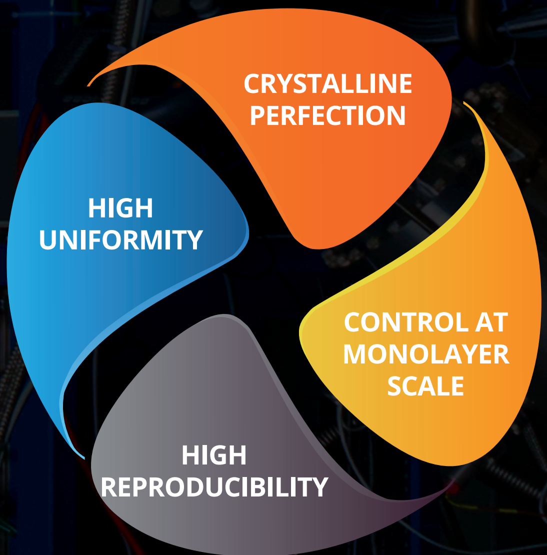

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Moving in the right direction

With a handful of women now in high-profile leadership positions within our industry, the extreme level of male dominance at the very top is starting to fade away

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

One of the weaknesses within the compound semiconductor industry is that it is so male dominated, particularly at the board level. But at least there are signs it is starting to move in the right direction, with more women than ever now holding key leadership positions.

Here we tell the fascinating stories of four of those leaders. With such a small sample size, drawing any significant conclusions is fraught with danger. However, what is clear from all these first-hand accounts is that there's not a single formula behind success. The foundation for rising to the top can be an advanced degree or an apprenticeship; leadership progression can come from working up through an organisation or launching a company; and while some may move continents to further their career, others may never leave the region where they grew up.

Crystal clear objectives

One of the most high-profile women within our industry, Wolfspeed's CTO Elif Balkas, has always had a strong interest in crystalline materials, the foundation for the production of all our devices. She grew up surrounded by them – not that surprising, given that her father is a geologist – and after gaining undergraduate and masters degrees in materials science and engineering in Turkey, she headed overseas, enrolling in a PhD programme at NC State University.

"My project was on gallium nitride bulk crystal growth," says Balkas. However, during her doctoral studies, she also devoted a lot of effort to studying the material at the heart of Wolfspeed, SiC, in the hope that previous breakthroughs in its development could be applied to GaN.

Like the key conclusions from many PhDs, while Balkas' findings were important, they were not revolutionary. "Our conclusion was that the PVT method is not the most suitable for gallium nitride." Colleagues working in the lab that also pursued GaN crystal growth enjoyed more success with high-temperature chemical transport methods and approaches that combine high pressures with high temperatures. However, even those superior alternatives suffered from really slow growth rates that plague the formation of bulk GaN.

Undeterred by the tremendous challenges associated wide bandgap crystal growth, Balkas looked for opportunities to continue to work in this branch of materials science after her PhD. She loved this topic in its own right, and she also valued the now-fulfilled promise that it had a role to play in trimming energy consumption and aiding the environment.

Balkas considered whether she should continue to investigate crystal growth in academia. But as she mulled this over, she realised that was not the path for her, because the pace of progress is too slow. While she has tremendous respect for the advances made by academics, her preference is to work in an environment where results are faster, along with their impact on society.

She had no doubts that her move to industry would keep her in the US, arguing: "This is where innovation happens." One option would have been to stay local and work for Wolfspeed, but this did not fit with Balkas' desire to see more of the US. This led her to consider several opportunities on the West Coast. However, in the end she headed in the opposite direction, deciding to go and work for Intrinsic Semiconductor, a small start-up in Washington DC that's best known for its development of SiC substrates. She joined the company at the start of 2005. Part of the attraction of that move was the chance to work with what she describes as a brilliant group of people, who she knew through reading their papers and hearing them speak at conferences.

Balkas loved her time at Intrinsic, revelling in the great pace of advance made by the company. She also appreciated the hands-on nature of her role, common for staff working at fledgling firms.

Initially, Balkas focused on the epitaxy of GaN on SiC, developing HEMT heterostructures for RF devices. However, through interactions with other researchers developing SiC epi-processes for power devices, she also started to make contributions to that endeavour.

Wolfspeed, in its former guise as Cree, admired the success of Intrinsic, and by the summer of 2006 it had negotiated the acquisition of the start-up. This led Balkas to move to North Carolina, initially

➤ Heather Splawn is CEO of the HVPE specialist Kyma Technologies.

working in epitaxy, before moving to crystal growth. Here she played her part in magnifying crystal dimensions, so substrate diameters could increase from 100 mm to 150 mm and then 200 mm.

Over the years, Balkas has sought and received more responsibility. Her interest in management can be traced back to her undergraduate days, where she took courses on this, and continued as she refined her knowledge with technical leadership seminars at Cree.

Balkas has the right mindset to lead a company, because she ponders on the crucial questions that determine its success. She is keen to work out how to turn great ideas and innovation into a technology with impact, and gives much consideration to what's needed to build successful teams and organisations.

During her climb up the career ladder, Balkas briefly moved out of R&D, spending two years within the manufacturing team. "That was actually a very good experience for me, because it gave me the experience to see things from both sides."

Subsequent promotions led Balkas to Director and ultimately VP of Research and Development, Materials, positions that led her to report directly to the late John Palmour, the CTO of the time. Palmour, who Balkas describes as a natural leader, gave her a great deal of freedom, while ensuring that any small mistakes that she might make would never snowball out of control. "The trust and the relationship was wonderful for me."

Balkas really appreciated the chance to draw on Palmour's amazing breath of knowledge. While he came from a materials background, he had device-related experience accumulated over 30 years.

Late last year Palmour passed away, five years after being diagnosed with lymphoma. During the latter stages of his illness he started to slow down and help prepare Balkas to take over. However, his death came far faster than anyone expected, leading to a tricky transition for the new CTO, who started that role in January.

Balkas knows that Palmour's shoes are too big for any individual to fill: "I was upfront that there's no way one person can replace JP. It's just not possible". So rather than trying and failing to do just that, Balkas has turned to teamwork. "Everybody is actually doing a little bit of what he used to do. It's like we diffuse all of his strengths in multiple people."

Growing within Kyma

Another leader with a strong background in crystal growth is Kyma's current CEO, Heather Splawn. When you look back at her formative years you'll find no clue whatsoever that she would go on to play a leading role with our industry. When she started attending the University of South Carolina, she had very, very different plans in mind.

"I went to college for exercise science," says Spawn. "I was going to be an athletic trainer." However, she started considering alternative courses after discovering that she would have to carry out an autopsy of a cadaver to complete the degree. Splawn's switch to computer science made a lot of sense: she had grown up with a computer at home; her father had a job as a programmer, working for a

➤ Elif Balkas, CTO of Wolfspeed, welcoming US President Joe Bidden to the Durham, NC headquarters in late March. Wolfspeed was first stop on an 'Invest in America' tour.

bank; and during high school, she had taken a C++ programming course, as well two years of physics and advanced maths. With this background, she didn't find herself behind her peers after making the transition.

During her time at the University of South Carolina, Splawn found out about fellowships worth $2000, to fund three-month summer placements in research groups. "I can live for three months on $2000," reasoned Splawn, who went to work for Professor Duncan Buell in her long vacations. "Along the way, I switched into computer engineering, because I was a more interested in how the whole system goes together as opposed to just programming languages."

Initially, Splawn's plan had been to enter the world of work after graduation. Buell, however, introduced her to the possibility of enrolling in a PhD programme. That had tremendous appeal, with Splawn moving to Duke University in 2004 on a National Science Foundation scholarship that provided funds to allow her to spend several months weighing up exactly what to pursue, as initially she did not need sponsorship from a professor. After evaluating her options, she joined Professor Martin Brooke's group focusing on mixed-signal circuit design, where she developed a sensor on a CMOS chip for her dissertation.

While some PhD students are so engrossed in their research that they would only ever leave the lab to go to the library, Splawn had a far more balanced outlook, exploring wider opportunities that highlight her capability to multi-task and embark on different challenges. One such endeavour, taken on with friends, involved organising a charity race that they christened *The Doughman*: a relay involving biking, running, swimming, along with plenty of eating to promote local produce. This quadrathlon gained notoriety, even appearing in an episode of the hit TV show *Man v. Food*.

Splawn also grabbed opportunities associated with Duke's Master of Engineering Management programme. "I was not a formal member, but I went to a few of their open lectures and networking events. That's where I met Keith Evans, who was CEO of Kyma."

When she finished her PhD, Splawn knew that now was the time to head out into industry. And after considering opportunities at several companies, she decided to take up the role of Director of Business Development at Kyma Technologies. It's a diverse position that she thrived in, getting to see first-hand how the business operated, and how negotiations would pan out between the company, its customers and its partners.

Working for a smaller company always offers opportunities that don't exist in larger firms, with those that are keen to take on new challenges getting the chance to do so. While trying to secure a government contract, Kyma had issues with its accounting system. Splawn jumped in, driven by a belief that with some support and what she'd picked up in an accounting class taken in school, she could fix this problem.

➤ Ann Hughes is the founder and Managing Director of the metal-organic provider Pegasus.

This highly desirable can-do attitude has served her well during her rise through the ranks at Kyma. When the company needed more day-to-day planning, they created a COO role that she's fulfilled, and in 2019 she succeeded Evans as CEO.

Under Splawn's leadership, Kyma is directing more efforts at thick epitaxy of GaN and Ga_2O_3, which it is growing via HVPE. This growth technology is well suited for realising high crystal quality, low impurities, and for the growth of very thick layers. "We're not the only ones to do this, but we have some advantages that others don't." She believes that Kyma's HVPE technology produces GaN and Ga_2O_3 materials that are among the highest quality in the world.

Switching semiconductors

While Splawn's involvement in the semiconductor industry is hard to foresee from her formative years, the same cannot be said for Rae Hyndman, Managing Director of Clas-SiC Wafer Fab: she has the semiconductor industry in her blood. Hyndman grew up in a part of Scotland known as 'Silicon Glen', which has been home to several influential semiconductor companies. Hyndman's mother loved her job at one of them, Hughes Electronics, and would very occasionally take her daughter with her to the facility when working overtime at the weekend.

This early interaction with the semiconductor industry could well have influenced Hyndman's decision on what to do after leaving school. Good at maths and science, she could have gone off to university. But instead she took an apprenticeship at Hughes Microelectronics Ltd. In the first year of her apprenticeship she attended engineering training school, learning engineering in a male-dominated environment described as both tough and character building. Out of 200 apprentices aged between 17 and 19, just three were women.

Hyndman has no regrets in taking this pathway, and is very grateful to Hughes for the tremendous level of investment it dedicated to its engineers, in both time and money. "It was one of these old-fashioned companies that believed in families and communities."

The Hughes apprenticeship gave Hyndman a very broad background in engineering. As well as studying its cleaner forms, such as electronics, she learnt about mechanical engineering.

After completing her apprenticeship, she first worked in process engineering, helping to churn out chips for the automotive industry. From there she began a steady succession of promotions within the semiconductor industry that's given her increasing levels of responsibility. Yet, despite this success, there's no evidence that she ever had a burning ambition to lead a company or gain elevated status. What's behind her rise is a steady progression, moving from one rung of the ladder to the next, with a belief that if she got the chance to be in her boss' shoes, she might do a better job. There's also another ingredient, that internal battle: just what might I achieve, if I give it my best shot?

During her time at Hughes, Hyndman initially switched from process engineering to management roles within this division, such as operations. From there, she had a brief spell in production management.

"It wasn't a choice," recollects Hyndman. "I had a tough boss who believed I needed some experience in production management." Fortunately, in hindsight, being forced to take this position for a year had a tremendous upside. "Engineers think in a certain way, but once you get a spell in production, you realise the impact engineering can have on production."

Hyndman's breadth of expertise continued to blossom with a two-year programme in six-sigma at Raytheon Systems Ltd, where she gained a qualification equivalent to a black belt. She values this experience, which she sees as valuable for high-level problem solving.

Within everyone's career, some events are beyond their control, having ramifications that will take them down a new path. For Hyndman, a major event, which subsequently led to her switch from the silicon industry to that of SiC, came in 1997, when US defence giant Raytheon bought Hughes. Initially this had minimal impact, and while the semiconductor department may have been out on a limb from much of Raytheon's activity, its tremendous success ensured its continuation. But as time went on, customers started to moved their orders away from this 100 mm fab, switching to partners with 150 mm and 200 mm lines. Survival required a radical move, realised by shifting to work on SiC, initially using 2-inch substrates of dubious quality. "Before many people had heard of silicon carbide, we reckoned it had a bright future," recollects Hyndman.

During her time at Raytheon, Hyndman enhanced her knowledge and continued to grow, supported for some of that time by a female engineer boss. "She really believed in me more than I ever did myself. That's been hugely important and influential for me."

Another key figure in Hyndman's career is Carl Johnson, founder and former CEO of II-VI. When Raytheon decided to ditch its wafer fab in 2017, the decision alarmed and mystified Johnson, whose company drew on the services of this Scottish fab. Johnson had no doubt in the great potential in SiC, and had an emphatic belief that the knowledge and experience of Hyndman and her colleagues had to be put to good use.

To make this happen, the US entrepreneur raced over to the UK to meet key personnel at Raytheon and set out his vision for the development of a new SiC fab. This led him to found Clas-SiC, appointing Hyndman as Director and Operations Manager. Working with a core foundational team from the closed Raytheon Systems Wafer Fab, Hyndman took on the task of building a brand new 150 mm SiC wafer fab, which had to be located within half an hour of the Raytheon site, to enable the hiring of as many former colleagues as possible. The majority of the 24-strong start-up were engineers, but the team also featured those with managerial skills and expertise in running a facility.

As Clas-SiC took off, Hyndman got her first ever experience of building a wafer fab. "It hugely developed me as a person, and made me confident that with the right team around me that I could pretty much tackle anything."

Two years into the build, Hyndman's co-director retired. For many of us, such a loss leaves us feeling exposed. But countering any fears that Hyndman may have had was the tremendous support of Johnson, who has huge faith in her.

Johnson told Hyndman that he wanted her to be the Managing Director of Clas-SiC. She wasn't so sure, having concerns about her lack of experience in running a business. But Johnson insisted, Hyndman relented, and now she's delighted to have taken the role. "It feels like all things have led to where I am today," reasons Hyndman. "Business is booming – it's fantastic."

While the skills needed to run a business differ from those working as an engineer in the semiconductor industry, Hyndman is sure that she benefits from her background. "It's really important that you understand the constraints on the business from the manufacturing side."

In her latest role, she has learnt how to deal with the risks associated with running a company. "You have to be comfortable with not always knowing, and being confident that you can work it out. It's a really undervalued craft."

Pegasus premier

Another woman at the top of a UK company operating within the compound semiconductor industry is Ann Hughes, Managing Director of Pegasus, a supplier of metal-organic materials.

Like Hyndman, Hughes did not begin her career in our industry. Instead, she initially worked for a small speciality gas supplier Electrochem Ltd., first in an internal sales role, before expanding responsibilities to encompass marketing and external sales activities.

Hughes gained a great deal from working for this company, which had a clear vision, good ethics, and an entrepreneurial spirit. "It was an ideal learning platform for business, and understanding problem solving."

Global multinational chemical company Linde snapped up the small speciality gas supplier in the mid 1990s. That led Hughes to work for Linde for a while, managing the supply of electronic gases within the UK, before she sought a new challenge, moving to Epichem, shortly after the turn of the millennium.

In this new role, as well as taking responsibility for the supply of electronic gases within the UK, she started to support the metal-organic side of the business. "That was the first time I was working specifically on metal organic supply into the semiconductor industry."

Again, the company Hughes worked for got bought out by a multi-national, this time Sigma Aldrich. It's a move that aided her career, as she now manged the metal-organics business on a global scale. But she also got to see the downsides of working for a large public company. "There are sometimes significant challenges to working in a corporation where the customers and people are not necessarily the key drivers".

From Hughes' perspective, another downside of the Sigma Aldrich acquisition – in this case having implications for her colleagues – was the plan to streamline global metal-organic production, including the shutting of the UK site.

For those facing such a threat, a common response is to feel downtrodden and unappreciated. After all, how can those making these top-level decisions fail to grasp the exceptional level of expertise of those work at this crucial facility?

➤ Rae Hyndman, Managing Director of Clas-SiC wafer fab, beside the founder of the company Carl Johnson, who co-founded II-VI.

But rather than simply bemoaning this unfortunate state-of-affairs, Hughes decided to act. Driven by optimism and positivity, she decided to launch a new supplier of metal-organics, Pegasus, keeping the local team intact. Buoyed on by the exceptional capability of her co-workers, she reasoned that the new venture had a very good chance of success. "The key is having the right team," says Hughes. "You've got to have all the pieces of the jigsaw together."

Getting any new company off the ground is never a cake walk, given in particular the need to raise funds – but that's not been one of the biggest challenges that Pegasus has faced since it started trading in 2015. What's been far harder has been overcoming the obstacles caused by Brexit. The UK's decision of leave the EU wrought havoc in the shipping of goods, with hazardous materials, such as metal-organics, facing a particularly high level of disruption.

"We overcame that challenge by creating Pegasus Chemicals Europe," explains Hughes. "We had to create a base within Europe where we have sales and distribution."

Another headwind has come from the war in Ukraine. Key ingredients in metal-organic precursors are rare-earth materials, mined from the ground in large land masses. "One of those large land masses is Russia, resulting in a gap in supply chains, so we are expanding and strengthening our manufacturing platform," says Hughes.

To address this issue, stemming from global geopolitics, Pegasus is devoting a great deal of effort to strengthen supply chains. While there's a focus on the UK in this regard, the compound semiconductor industry at large is also high on the company's list of priorities.

While Hughes will be leading and directing efforts to tackle these challenges, she sees her role as far more than just a problem solver and decision maker. As Managing Director, she's also in a position to ensure that the company rewards its staff for their dedication, installs a good culture and work ethic, and is a fun place to be. "Ensuring a safe, focused and enjoyable place to work is as significant as progressing the continued growth of the business".

Maintaining momentum

All four leaders who have told us their stories are united in believing that our industry is a great place to work, and one where it's important to try and chip away at the under-representation of women. Their efforts in this direction vary, but they are all contributing – they are in leading roles that have a high profile, they are willing to talk to the media, and they are inspiring others to follow in their footsteps.

At Clas-SiC there is circumstantial evidence that having a woman at the helm is making a difference. While there is no gender bias in the selection of employees, of the four modern apprentices at the company, two are female. Efforts that can be directed at recruiting, nurturing and elevating women within any company will depend on its size.

In terms of headcount, Wolfspeed dwarfs Kyma, Clas-SiC and Pegasus, and can adopt a different approach to them.

When Wolfspeed appointed Gregg Lowe as CEO in 2017, once of his first initiatives involved creating a number of employee resource groups, including one for women.

"I jumped on this because it was very exciting to me," remarks Balkas. Working with three colleagues, she founded the Women's Initiative at Wolfspeed. Today it has over 800 members.

One of the objectives for them is to increase the level of diversity, in terms of recruitment, to 50 percent. But as well as recruiting women, steps are taken to retain them.

A tricky time for many women is when they have young children. At a time when many will consider quitting their job, the Women's Initiative offers support, encouraging them to persevere with their career. Often, after a few months, difficulties around that work life balance can be resolved. "Then it's a win win, for both the individuals and more so the company."

Attracting women to our industry, retaining them and helping them to thrive is clearly an important goal for all of us. While the compound semiconductor industry has such a bright future ahead, in order to ensure the greatest success, everyone that's keen, committed and capable will need to be given the chance to play their part to the fullest.

CS stocks reflect a general malaise

Gains in share price have been few and far between over the last 12 months, with the majority of players in the CS industry seeing significant falls in valuation during that timeframe

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

ECONOMIC GLOOM is engulfing us all. After decades of steadily improving prosperity, we are heading in reverse. Due in part to rampant inflation, some of those that are in work are skipping meals because they can't afford to eat. Rocketing energy bills are also having devastating consequences on household budgets, leading some to hardly heat their homes and seek out warm spaces provided by their local communities.

Against this backdrop, which has caused countless consumers to reign in their spending, one would not expect the stock market to have thrived. And it hasn't, with many well-known equity indexes recording losses over this last year.

Struggling more than most are technology stocks, including those in the compound semiconductor industry. Of the fifteen firms listed on our leaderboard, just two – IPG Photonics and Aixtron – have increased in valuation over the last 12 months. Many of the remainder have succumbed to substantial falls, with some big names taking a substantial hit: Qorvo's valuation has fallen by roughly 20 percent, Coherent is down by almost 40 percent, and Wolfspeed has plummeted by more than 45 percent.

The two front-runners, IPG and Aixtron, have very little in common. Fractionally out in front is the former, the vertically integrated manufacturer of fibre lasers that footed last year's leaderboard. With manufacturing facilities in Russia, this provider of powerful light sources has been particular impacted by the war in Ukraine. The conflict has contributed to a valuation that is still less than half of that of two years' ago. However, at least IPG has steadied the ship over the last 12 months.

Just a whisker behind IPG is last year's champion, Aixtron, which is enjoying substantial sales of MOCVD tools, thanks to the growth of GaN and SiC power electronics and rising interest in microLEDs.

Enhanced by e-mobility

For the most recently reported quarter within the 12-month timeframe that's used for our leaderboard, sales at IPG were down 8 percent, coming in at $333.5 million. However, they did exceed guidance by nearly $16 million.

Offering insight into these figures in a fourth fiscal quarter 2022 earnings call on 14 February this year, IPG's Director of Investor Relations, Eugene Fedotoff, attributed the unanticipated revenue to additional sales of fibre lasers in the e-mobility, welding and medical sectors.

Fedotoff added that this success, coming against a backdrop of a challenging operating environment and currency headwinds, is due to global investments in e-mobility and renewable energy.

"Our EV sales contributed close to 20 percent of total revenue in 2022, up from around 10 percent a year earlier. We believe that the battery capacity build-out will accelerate in North America and Europe and will continue to increase in China in the next several years to support growing EV sales."

IPG's Director of Investor Relations also noted that customers have recently shifted investments to the US to take advantage of government incentives. Thanks to this, IPG has seen higher levels of activity.

The company offers a number of different products based on fibre lasers, suitable for the manufacture of various parts associated with EVs.

"We recently introduced high-wall-plug-efficiency laser drying solutions for use in battery foil manufacturing, the largest CO2 producing process step of battery manufacturing," remarked Fedotoff. "The solution replaces less efficient infrared bulbs and environmentally unfriendly gas-fired furnaces."

Another of IPG's products is LightWELD. Launched in September 2021, this portable fibre laser is now increasing in sales, with production at a higher margin. This product, which can also be used by battery manufacturers, is said to offer advantages in its broad range of capabilities, its ease of use, and the speed of welding – this can be four times faster than that of rival approaches.

"Traditional welding is very limited in types of materials it can join and requires highly skilled welders to do the job," remarked Fedotoff. "LightWELD addresses many of these challenges, with an ability to join a broad range of materials, including some hard-to-weld metals, such as aluminium alloys, copper, titanium and thin foils."

Note that welders are in great demand in the US, with a 375,000 deficit, according to the American Welding Society. Fedotoff argued that uptake of LightWELD can help to address this shortage, due to its ease of use and its 'presets' for different materials, enabling faster training for unskilled workers that can plug the employment gap.

While there are rivals to LightWELD, IPG argues that it has a leading-edge product. "If you look online, you'll see there are some handheld welders advertised in China, but they're pretty large devices," commenteed IPG CFO Tim Mammen during the February earnings call. "They've got different cooling requirements. They're not really even equivalent to what we're producing."

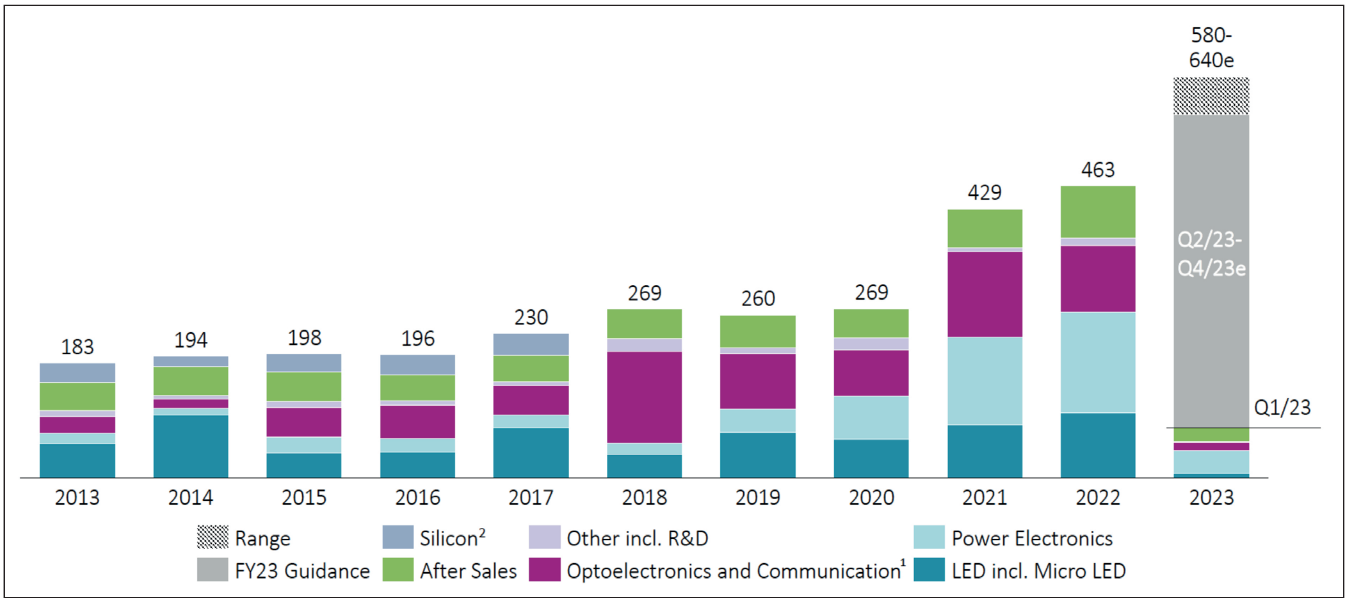
During that call, Fedotoff discussed some of the challenges that IPG has been facing.

***Compound Semiconductor* Shareprice Leaderboard**

Rank	Company	Ticker	Share value, April 27, 2022 ($)	Share value, April 27, 2023 ($)	% appreciation	Change in Rank
1	IPG Photonics	IPGP	95.44	110.98	16.3	15
2	Aixtron (Frankfurt)	AIX	24.87*	28.86*	16.0	+11
3	Riber (Paris)	RIB	1.88*	1.83*	-2.6	0
4	NASDAQ composite	IXIC	12918.00	11913.00	-7.8	0
5	Skyworks	SWKS	116.51	102.18	-12.3	+10
6	IQE (London)	IQE	37.79*	31.94*	-14.9	+9
7	Qorvo	QRVO	112.82	90.34	-19.9	+4
8	Veeco	VECO	23.43	18.55	-20.8	-6
9	WIN Semiconductor (Taipei)	3015.TWO	6.69*	5.20*	-22.3	+3
10	Infinera	INFN	8.01	6.20	-22.6	-1
11	Coherent (II-VI)	IIVI	255.87	155.14	-39.4	-3
12	Lumentum	LITE	85.21	47.56	-44.2	-7
13	Wolfspeed	WOLF	104.20	56.60	-45.7	-7
14	AXT	AXTI	6.04	3.20	-47.0	-1
15	Emcore	EMKR	3.42	1.12	-67.3	-1
16	Rubicon	RBCN	8.97	1.45	-83.8	-9

* Converted to dollars using the exchange rates on 27 April of 1 EURO = 1.1016 USD, 1 GBP = 1.2452 USD and 1 TWD = 0.03250

➤ Over the last 12 months the majority of companies in the compound semiconductor industry have seen a fall in their share price.



➤ Sales of MOCVD tools for the manufacture of power electronics account for an increasing proportion of Aixtron's revenue. Note that: (1) the optoelectronics and communications sector includes applications in consumer optoelectronics, solar and telecom/datacom; and (2), Aixtron sold its silicon ALD/CVD product line in 2017.

"We faced continued soft demand in high power cutting in China, currency headwinds due to a strong US dollar, supply chain disruptions, as well as restrictions on shipments of components from our manufacturing facility in Russia."

To address the difficulties associated with supply chains while improving gross margins, IPG is now investing in locations with lower costs than Germany and the US. Facilities are being built in Poland and Italy, which should help IPG reach its long-term gross margin target of 45-50 percent. For the last fiscal quarter of 2022, IPG reported a gross margin of just 18.2 percent, but this included $74 million of inventory write-downs and other charges related to Russian operations. "Excluding these inventory-related charges, gross margin was approximately 40 percent," remarked Mammen.

For the most recent quarter, reported on 2 May – just outside the timeframe of the leaderboard for this year – IPG announced sales of $347 million. Guidance for the next quarter is $325 million to $355 million.

Aixtron powers ahead

The German epitaxial equipment maker, Aixtron, reported its results for the first fiscal quarter 2023 on 27 April, the closing day for this year's leaderboard. Sales totalled €77 million, realised with a gross margin of 40 percent, enabling a profit of €3.5 million.

However, compared with the equivalent quarter of fiscal 2022, revenue fell by €14 million.

Commenting on this decline during the first fiscal quarter 2023 earnings call, held on the day the results were announced, Aixtron CEO Felix Grawert pointed out that sales had been hampered by delayed export licenses, which had pushed MOCVD shipments into the next quarter.

"We are in close exchange with the authorities," added Grawert, who explained that they have been implementing a request from the government, involving the introduction of an additional layer of protection to ensure that MOCVD tools can only be used for what is described as "targeted end usage". Aixtron has implemented this additional mechanism in the first quarter of this year, and expects to soon receive the outstanding licences; their delay has led to a shift of €70 million of sales from quarter one to quarter two.

While this situation might appear to be new, it's actually not, according to Grawert. He claimed that there have been many such cases in the past: "It is a normal procedure within the proceeding of export licenses."

During the first quarter, tools that will be used to produce power electronic devices accounted for three-quarters of order intake. Historically, there's been a 60:40 split between sales of epitaxial equipment for SiC and GaN growth, but this difference is narrowing.

"The order momentum for GaN epi tools continues to grow," remarked Grawert, adding that this sector accounted for more than one-third of orders in the first fiscal quarter of 2023. "The reason for this is that customers are addressing more and more applications with GaN, most recently with fast-growing volumes in the medium-voltage class and also in photovoltaic applications."

Aixtron continues to bring new tools to market to drive profitability and scale in the manufacture of

GaN power devices. One of its customers is already using a new tool, the G10-GaN, which will be widely launched later this year.

According to Grawert, the SiC business also continues to experience strong growth, driven by an ongoing expansion of electromobility. He explained that several of Aixtron's customers are installing its MOCVD tools in high-volume fabs.

"The new G10-SiC system, which was introduced in Q3 2022, is proving to be very successful," added Grawert. "It is already apparent today that this silicon carbide device manufacturing tool will clearly become the top-selling product in 2023."

Aixtron's tools are also being bought by makers of optoelectronic devices, including lasers used for communication and optical sensing.

On this side of the business, there's also the microLED sector, which Grawert claims to have strong momentum.

"The mass transfer step remains a hurdle," remarked Grawert, who pointed out that while this process can be accomplished from a technical standpoint, it needs to be refined so that it can be undertaken at commercial scale. How long it will take to bridge this gap is hard to say, but success might be possible within the next 18 months, suggested Grawert.

To try and help to fulfil orders as quickly as possible, Aixtron has been increasing its inventory. This climbed in the three months to the end of this March from €224 million to €295 million.

"We are very consciously managing our inventories to enable us to offer acceptable delivery times to our customers," remarked Aixtron CFO Christian Danninger during the recent earnings call. "Our ability to ship is highly appreciated by our customers and has repeatedly enabled us to win against competitors." Today, the lead time for Aixtron's tools is 8-12 months.

Outlook for the German MOCVD maker is very positive. Orders for 2023 are expected to total between €600 million and €680 million, and sales range from €580 million to €640 million. Gross margin is forecast to be around 45 percent, and earnings before interest and taxes to be between 25 percent and 27 percent.

Riber's rising revenue

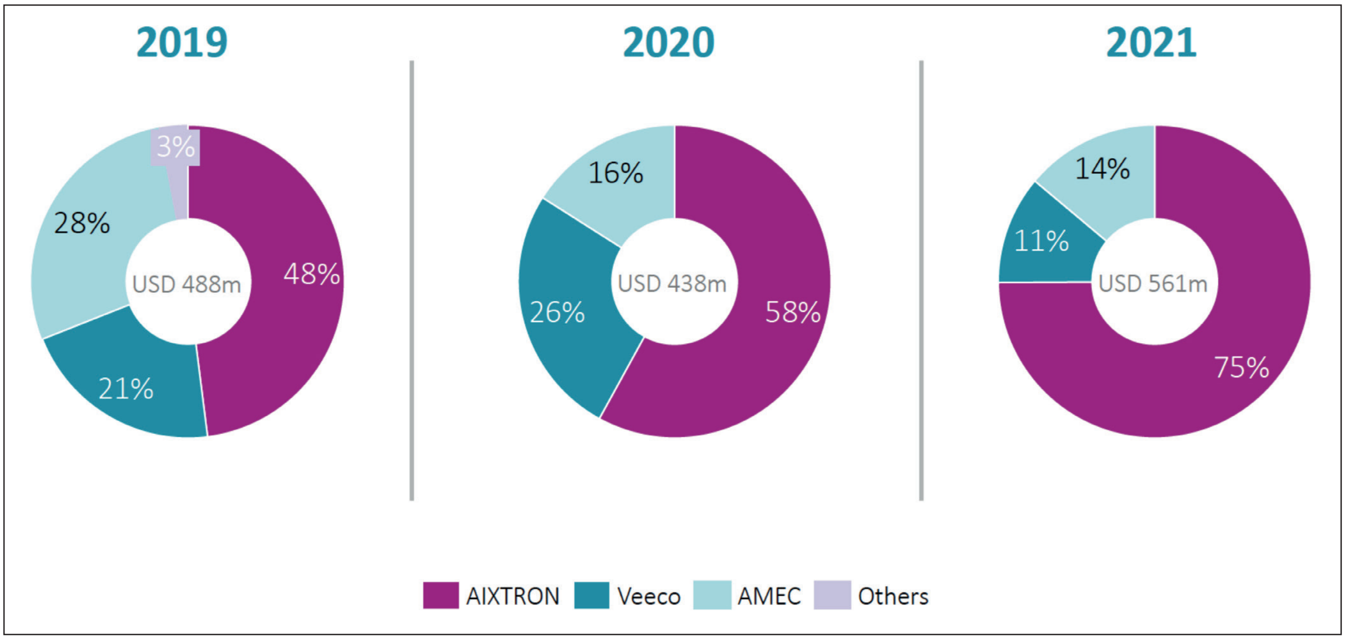
Third on this year's leaderboard is the French maker of MBE tools Riber, which has seen a slight fall in its valuation over the last twelve months.

Results for full year 2022, reported on 14 April, are not that impressive, with revenue of €27.8 million, down from €31.2 million for the previous year. But the outlook is very positive, with sales forecast to hit around €40 million this year.

Sales for 2022 were dented by defered delivery of two research systems, caused by supply chain disruption that impacted electronic components. These systems will be delivered this year.

For the last financial year, Riber reported a gross margin of just over 35 percent, and break-even operating income. A non-current charge of €1.3 million impacted operating income, associated with the discontinuation of the OLED evaporator product line, which led to a depreciation of inventories.

During 2022, Riber's order intake increased significantly, with bookings for 14 systems, plus



➤ According to Gartner, Aixtron's domination of the MOCVD equipment market is increasing.

IPG's LightWELD is enjoying growing sales, spurred by the growth of the manufacture of batteries for electric vehicles.

accessories and services. This will contribute to a 40 percent hike in sales to around €40 million for 2023, expected to be realised alongside a substantial increase in profitability.

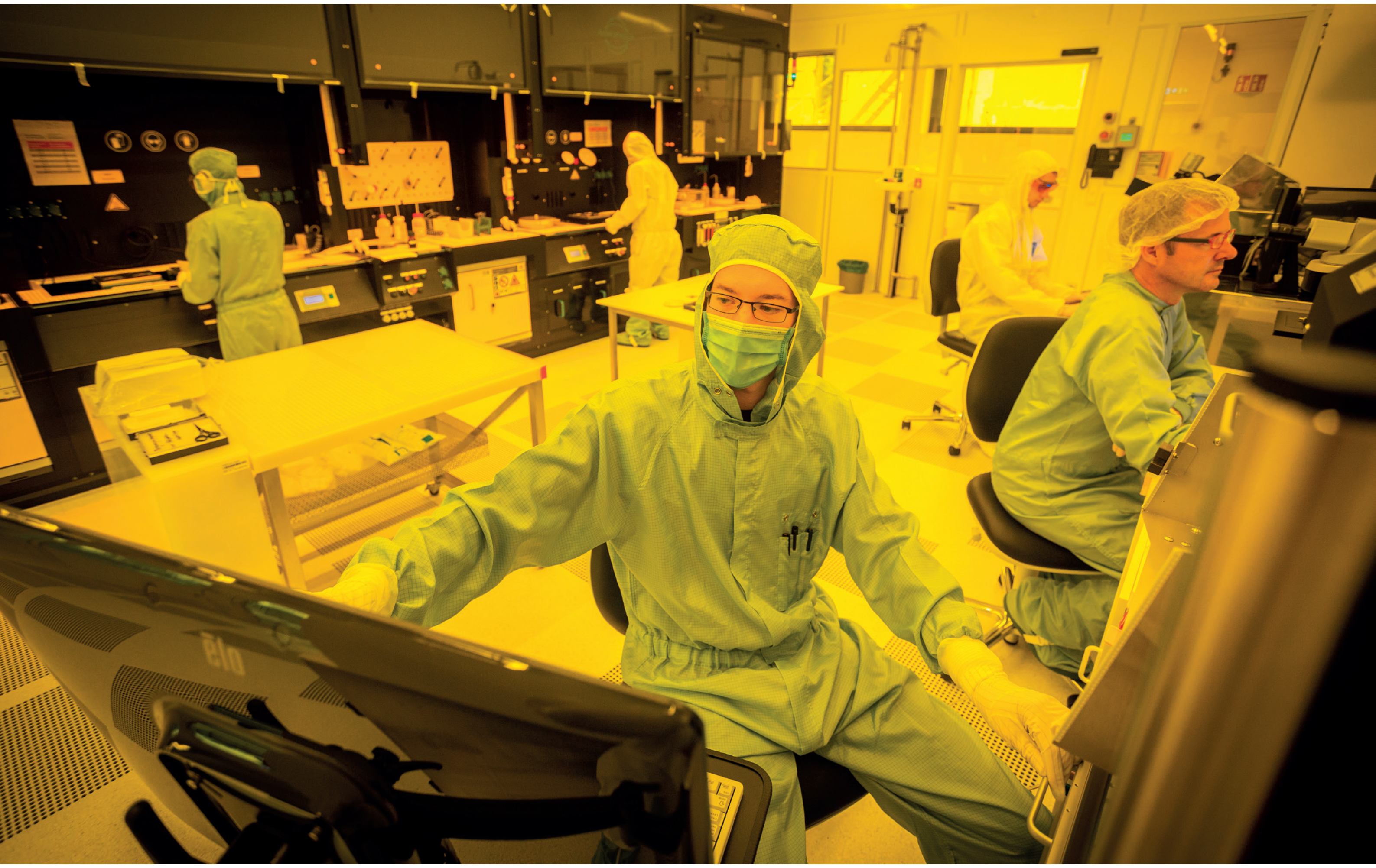
Rubicon in the rubble?

Footing this year's table is the sapphire producer Rubicon. It is no longer providing quarterly earnings figures, and its future is surely in question. Last July the company's share price leapt from $9 to $15, due to a potential acquisition from Janel. According to the class action firm Monterverde and Associates PC, this tender would see shareholders of Rubicon receive $20 in cash per share. In August the company declared a share special dividend of $11 per share. This led to a revised share price of just over $3. Since then this has steadily fallen, to now trade just below $1.50.

In mid-October 2022, NASDAQ informed Rubicon that it no longer complied with a number of independent director requirements, and in December the sapphire maker announced that it would voluntarily de-list from that stock exchange. This year the company has made no public announcements.

While the other companies on the leaderboard are not in the dire straits of Rubicon, the last few years have not been easy for many of them. After getting through difficulties wrought by Covid, many would have hoped for better times ahead. But supply chain constraints, a war in Ukraine and soaring costs have hampered efforts to excel.

Fortunately, there are sign that inflation will fall, while spot prices for gas suggest energy prices should head back towards historical values, helping chipmakers to improve margins and revenue. After two years with falling values dominating the leaderboard, let's hope for some more positive figures in 2024.



Photovoltaics: Towards 50 percent efficiency

A record-breaking photovoltaic efficiency comes from bonding a pair of dual-junction solar cells with different lattice constants

BY OLIVER HÖHN FROM FRAUNHOFER ISE

WHAT'S NEEDED to realise exceptionally high efficiencies with solar cells? A significant degree of concentration is a given, alongside the use of multi-junction solar cells, with history attesting that the best results tend to come when these devices are produced by MOCVD. Allied to these key attributes, the fabrication of best-in-class devices demands great designs, excellent expertise, and thorough process technology.

The success story of multi-junction solar cells begins decades ago, with the deployment of these devices in space. Satellites have been powered by solar cells for many years, and for this application a high efficiency is incredibly valuable. Due to this, III-V multi-junction solar cells have had a stranglehold on this market since the 1990s, when they replaced their silicon siblings. Since then efficiencies have increased, but the standard product for space applications is still the triple-junction solar cell, produced on a germanium substrate that also provides the lowest sub-cell.

To bring this technology from space to earth, it is essential that the expensive III-V solar cell is used far more effectively. This can be accomplished by placing high-efficiency, multi-junction III-V cells in concentrating photovoltaic (CPV) systems. In this case, the expensive large-area semiconductor is replaced by a lens, which focuses sunlight onto a very small solar cell, thereby reducing the size of the III-V material that's required by a factor of 500-1000, depending on the concentration of the lenses.

The benefits of concentration are not limited to slashing the outlay on multi-junction cells. In addition, the increase in concentration enhances the efficiency of the solar cells by a thermodynamic effect. The increase in current density leads to a logarithmic increase in voltage – this is a fundamental consequence of diode characteristics – and as the power that's generated by the solar cell is the product of its voltage and current, there is an increase in efficiency under concentration.

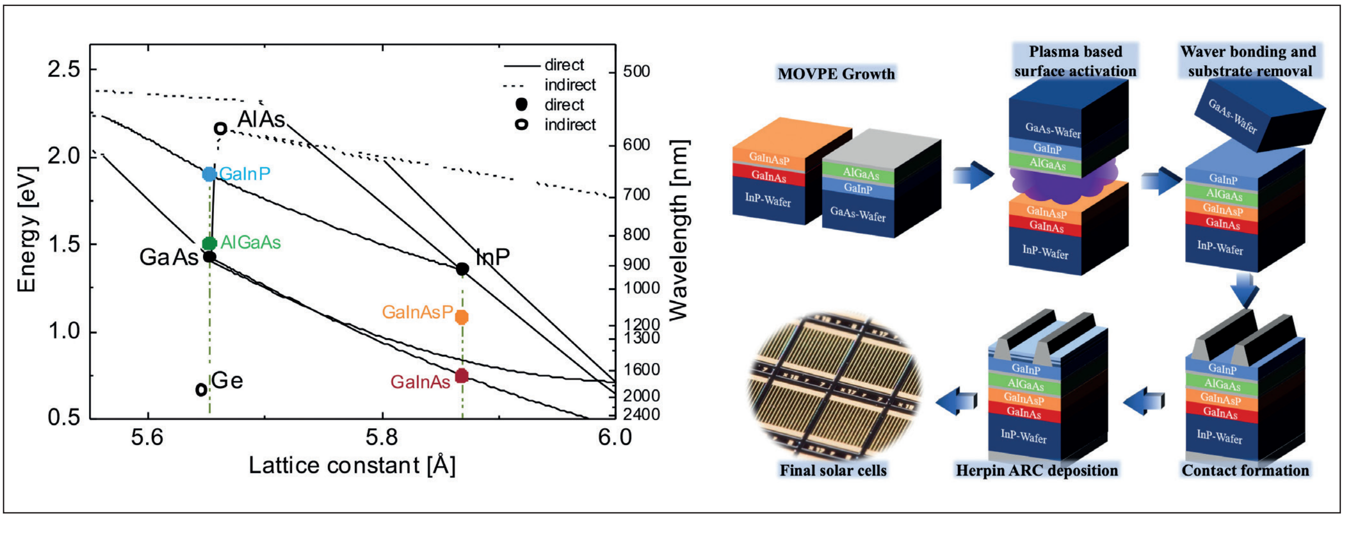
Over the past ten years or so, efforts to increase solar cell efficiency have included the introduction of more junctions, with devices featuring up to six of them. Efforts in this direction highlight the limitations of this approach, with monolithic epitaxial growth requiring lattice-matching of an increasing number of sub-cells, each made from III-Vs differing in content or composition. This requirement restricts the range of band gaps that can be employed within one monolithic device.

In general, two approaches have been pursued to overcome this limitation. One option, arguably the less radical of the two, is to introduce metamorphic buffers that gradually change the lattice constant, thus opening the door to a broader range of band gaps. However, there's a penalty to pay for grading the lattice constant: material quality suffers, dragging down solar cell performance.

At Fraunhofer ISE, our team adopted a different approach. In our case, we grow lattice-matched top junctions with high band gaps on a GaAs substrate; and we use an InP substrate for lattice-matched growth of the bottom junctions, which have lower band gaps (see Figure 1). These two devices, which have totally different lattice constants, are monolithically stacked on one another, using surface-activated direct wafer bonding. By taking this approach, we overcome the limitations in cell performance that stem from a metamorphic buffer.

Over the last few years we have engaged in friendly competition with a team at NREL for the world record in solar cell efficiency. Back in 2015 we gained the lead, in partnership with Soitec and CEA, with a wafer-bonded four-junction solar cell with an efficiency of 46 percent. We held the record until 2019, when NREL reported a metamorphic six-junction device with an efficiency of 47.1 percent. Then last year we announced that we had improved on this value, realising a record for photovoltaic efficiency of 47.6 percent, through a BMWK-funded project entitled '50 Prozent' (03EE1060).

While regaining the record is a triumph in itself, we are particularly pleased that we have accomplished this with a device with just four junctions. We attribute this success to the game-changing direct wafer bond, allied to the excellent design and realisation of a pair of dual-junction lattice-matched ternary and quaternary solar cells on InP and GaAs. We shall soon detail the magic of the wafer bond, but before we get to that, we'll discuss the cell design in more detail.



➤ Figure 1. (Left) The two lattice-matched tandem devices, grown on GaAs and InP, use several different alloys to form the sub-cells. High band gap materials GaInP and AlGaAs are lattice-matched to the GaAs growth substrate, and low band gap sub-cells made from GaInAsP and GaInAs are epitaxially grown on InP. (Right) The process flow for a wafer-bonded four-junction solar cell. After epitaxial growth of two tandem cells on their respective growth substrate, surfaces are cleaned and polished again, activated with an ion beam and then bonded with a direct wafer bonder. Afterwards contacts and an anti-reflection coating are added with microfabrication steps.

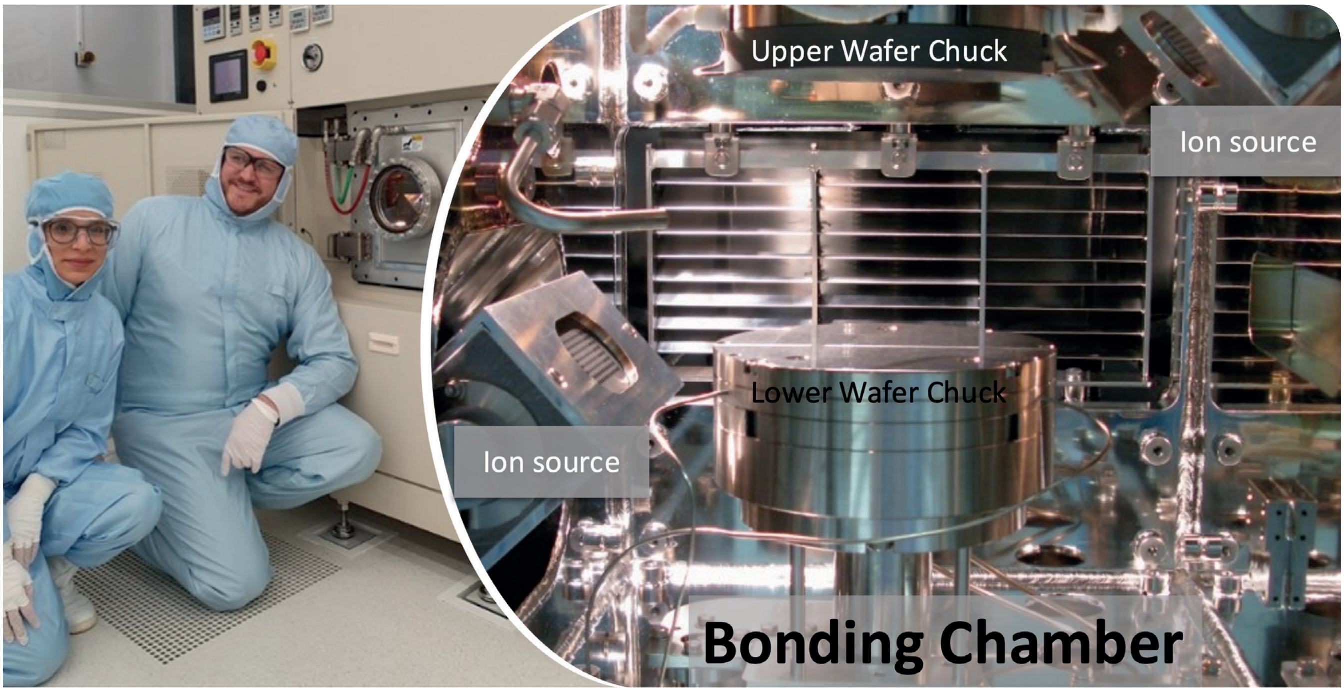


Figure 2. In front of the direct wafer bonder are: technician Rita Freitas, who fabricates wafer-bonded four-junction wafers into solar cells; and Oliver Höhn, head of the group III-V semiconductor technology, and project manager of the BMWK funded project "50Prozent". The bonding chamber includes ion sources for surface activation and chucks for the substrates to be bonded.

Current matching

The starting point for fabricating any highly efficient multi-junction solar cell is an optimised optical and electrical design. In monolithic solar cells, sub-cells are connected in series by so-called tunnel diodes, so it is imperative to carefully match the current generation of these sub-cells, and thus their absorption. While it is possible to optimise the electrical design of each sub-cell independently, carefully selecting values for the likes of the emitter thickness and doping, it is crucial to optimise the optical design for the entire device. Due to this, designers of multi-junction cells tend to use optical modelling tools, such as a transfer matrix algorithm, to determine the exact sub-cell band gaps and thicknesses for the entire device, which will contain tens of layers.

A great design, in itself, is no guarantee of success. What's needed is to transfer this into working devices in a perfect manner. Consequently, the only way to realise solar cells with efficiencies approaching 50 percent is for them to behave exactly as designed.

We have taken major strides in this direction, developing a strategy that links modelling and realisation so accurately that it enables a perfect current match for a four-junction solar cell. Thanks to this advancement, success stems on ensuring a high-quality direct wafer bond between the MOCVD-grown dual-junction bottom cell on InP, and the inverted dual-junction top cell on GaAs, which includes the tunnel diodes and the bonding layers.

Wafer bonding

The idea behind direct wafer bonding is the adhesive-free joining of two flat surfaces, realised by simply bringing them into contact with one another. This should result in one single device with a chemical bond at the interface that is as strong as the bulk materials. With this technique almost any pair of materials can be joined, including crystals with different lattice constants. Consequently, there are many options for direct wafer bonding within the semiconductor industry.

To establish atomically flat surfaces, technicians can turn to chemical-mechanical polishing, which is a combination of mechanical polishing and chemical etching. This is a standard treatment during the fabrication of wafers for the semiconductor industry, because such perfect surfaces are essential for many process steps, including epitaxial growth. If necessary, the surface can be cleaned and polished again before direct wafer bonding, in order to improve bond quality and yield.

In our case, we use direct wafer bonding to join two dual-junction solar cells. Both contain many layers with differing compositions, and are capped with a highly doped bonding layer. We optimise this layer to ensure a good electrical contact of the sub-cells. To that end, we can thin it down with an extremely defined and homogeneous chemical mechanical polish to remove any defects and produce a perfectly smooth surface. We used here the expertise of III-V Reclaim to optimize the processes depending on the compound semiconductor used

and its surface roughness. After this polishing step, we place the wafers inside the bonding chamber (see Figure 2). The surface is then activated by a fast ion beam that removes residuals, such as oxides, from the surface – this is also known as sputter etching. An ultra-high vacuum preserves the dangling bonds of the activated surface atoms. That enables chemical bonding, even at room temperature, when the wafers are pressed together. During this step an amorphous layer forms at the interface – it is optically inactive but electrically conductive, due to a thickness of only a few nanometres. A final annealing step delivers additional improvement to the mechanical strength and the electrical contact. That's all the magic.

Note that while our use of direct wafer bonding for the fabrication of solar cells is novel, the technique itself is tried and tested. It's been known for decades, and has become popular in recent times, where it has found increasing application in the production of micro-electro-mechanical systems and ICs. In some fields, direct wafer bonding has already found its way to high-volume manufacturing. There is a growing interest in this technique, due to its manifold applicabilities, as well as the availability of fully-automated high-throughput tools for production lines.

Precision fabrication

After wafer bonding of the device, we remove the GaAs substrate with a wet-chemical step that creates a monolithic four-junction structure on an InP substrate. We transform this structure into a working solar cell with microfabrication steps that include photolithography, wet-chemical etching, and evaporation.

We take steps to minimise optical losses, which can come from reflection at the front interface and shading losses from fingers. To this end we have developed a specially designed anti-reflective coating that consists of alternating layers of MgF and TiO_2. Applying this coating, which we refer to as four-layer Herpin, ensures the lowest possible reflectance over the broad acceptance range of the solar cell. The fingers that we employ are specially shaped to have a trapezoidal cross section, leading to a significant decrease in shading losses, as light hitting the fingers is partially reflected towards the solar cell, where it contributes to current generation.

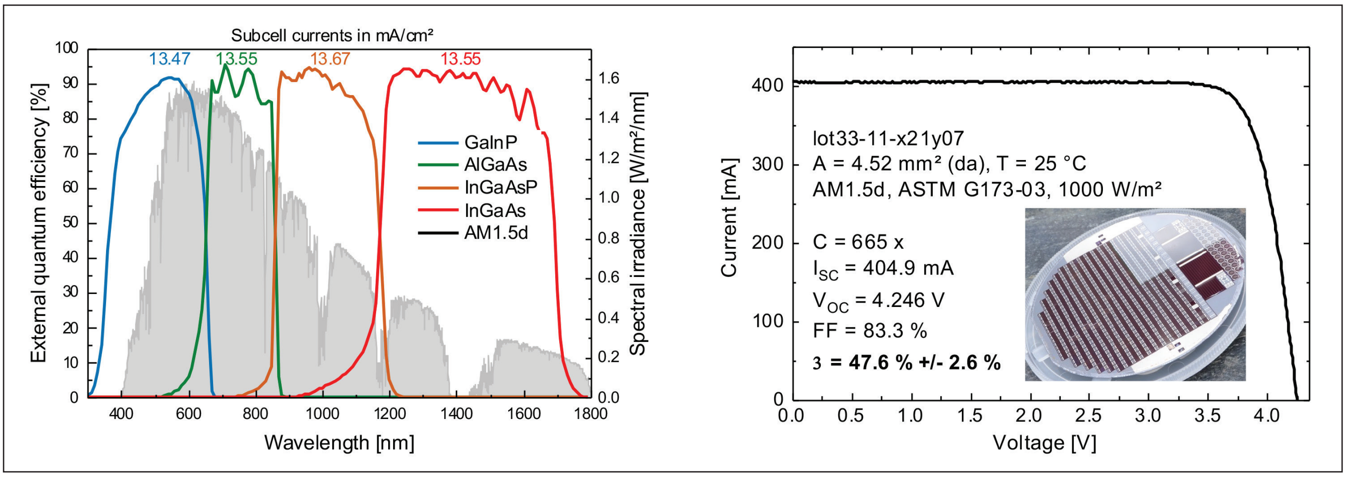
Measurements on this device in our Callab reveal an efficiency of 47.6 percent at a concentration of 665 suns.

Towards 50 percent

Our roadmap to even higher efficiencies includes the introduction of a next-generation design that we are calling the rear hetero-junction solar cell. This device will feature optimised contact fingers that redirect even more light into the solar cell to decrease shading losses. We also plan to increase the number of junctions to six. With all these advances, we anticipate that we will smash the 50 percent barrier.

While this is an important milestone that will highlight the potential of CPV technology, this class of photovoltaic will only be able to compete with silicon PV if there's a fall in costs. Thus, one of our short-term targets is to slash the cost of III-V solar cells. Helping to accomplish this goal is: the implementation of techniques from large-scale silicon technology, such as screen-printed contact fingers; re-use of the substrate; and the introduction of low-cost epitaxy.

Our overarching goal, shared by our industry partners, is to develop a cost-competitive, high efficiency III-V-based solar device that can serve in various earth and space applications, and be integrated into the likes of vehicles and aircraft. The 50 percent cell is an important milestone and a lighthouse. However, it is not yet clear whether commercial success will come from our wafer-bonded cell, or a simpler device based on our findings. Time will tell.



➤ Figure 3. External quantum efficiency (EQE) and current-voltage (I-V) characteristics of the record wafer-bonded four-junction solar cell. The EQE measurement reveals excellent current matching of the four sub-cells.

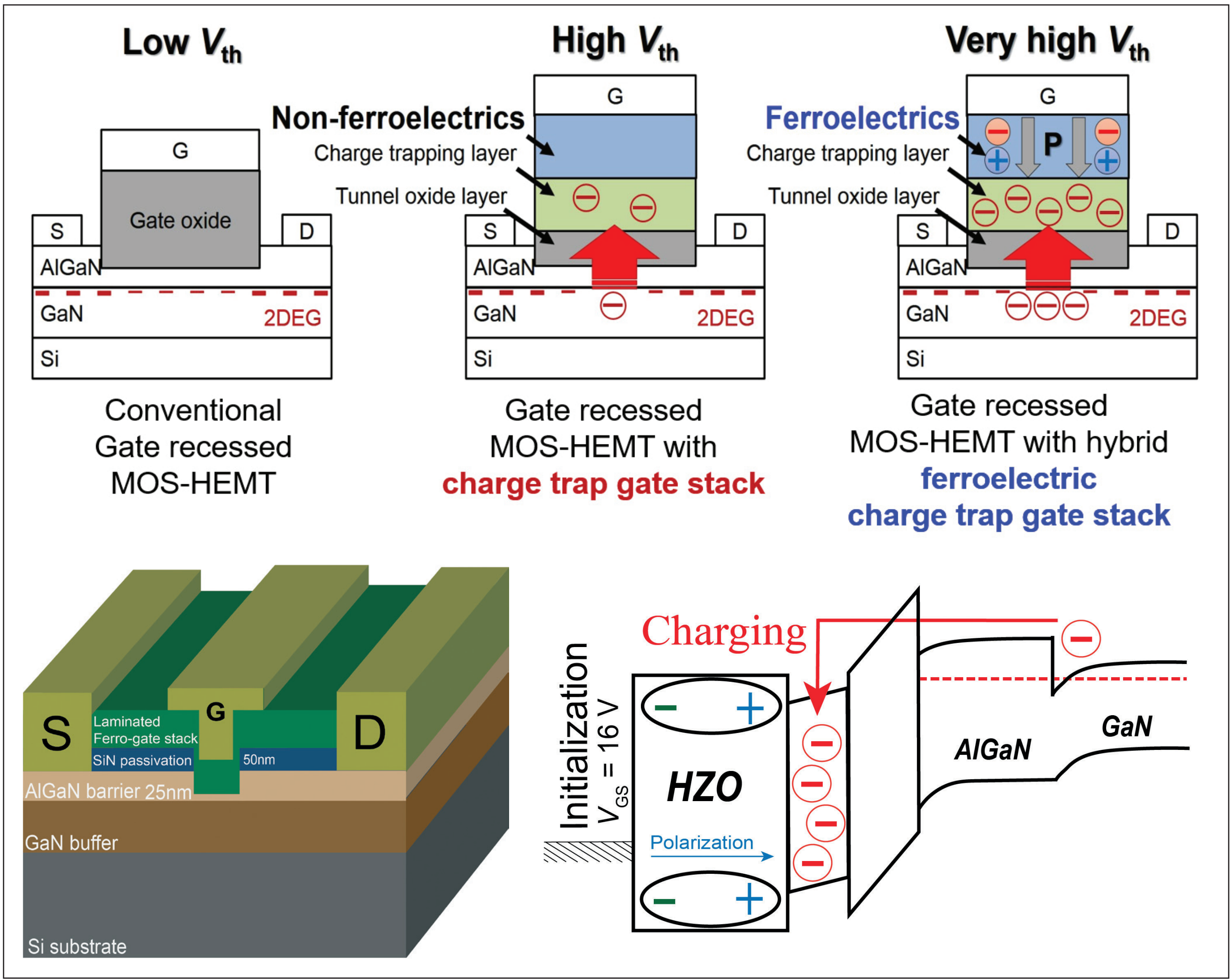
Enhancing the ferroelectric gate HEMT

Adding lanthanum doping and a ZrO_2 seed layer to a normally-off ferroelectric gate HEMT causes leakage currents to fall, threshold voltage stability to increase and lifetime to lengthen

BY EDWARD YI CHANG FROM NATIONAL YANG MING CHIAO TUNG UNIVERSITY

GaN IS AN incredible material for producing high-power and high-frequency electronic devices. In particular, when it is used to make a HEMT, it enables exceptional performance in power switching and radio-frequency applications. Drawing on the unique polarisation-induced electric field, the GaN HEMT combines a very low resistance with a high output power. However, the internal electric field within this device is both a blessing and a curse, as it creates an obstacle to enabling enhancement-mode operation, which is strongly desired for safe operation in power-switching systems.

Given the importance of realising enhancement-mode operation, also known as normally-off, it's not surprising that several technologies have been developed to meet that goal. Those approaches include the introduction of a recessed gate, *p*-GaN gate, fluorine implantation, and oxide charge engineering. For all these designs, to avoid faulty turn-on, the threshold voltage for a power device should be around +3 V. However, meeting this requirement and ensuring normally-off operation has compromised performance, with the approaches just described for realising enhancement mode leading to an inferior current



➤ Figure 1. An enhancement-mode hybrid ferroelectric GaN HEMT with a charge storage gate combines a high threshold voltage with a low on-resistance and a high output current.

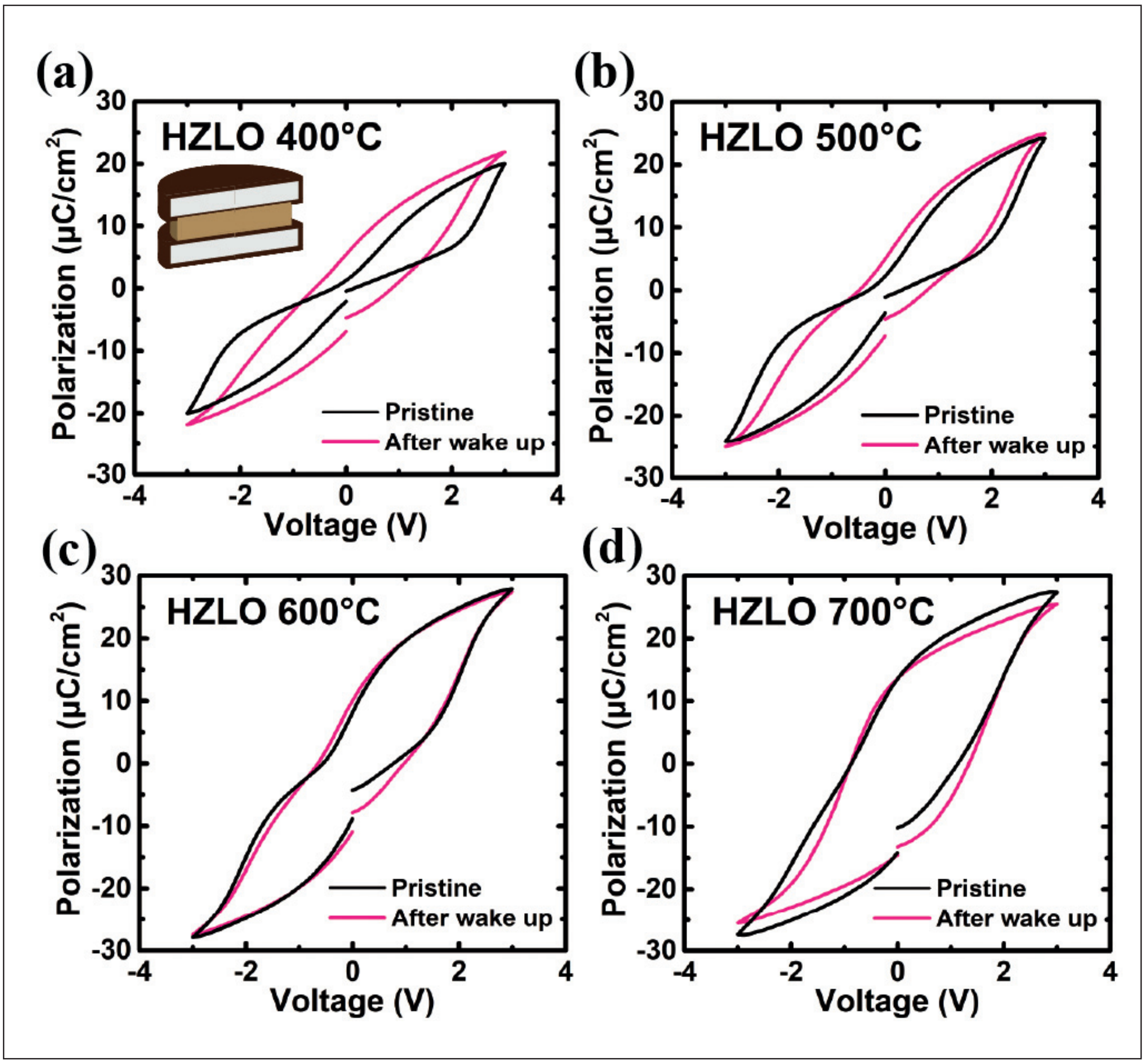
density and on-resistance, compared with state-of-the-art normally-on devices. So the search has continued for a normally-off GaN technology for power devices.

Offering much hope in this regard is the work of our team at the National Yang Ming Chiao Tung University, Taiwan. Recently, we have developed ferroelectric charge trapping gate (FEG) GaN MIS-HEMTs, namely FEG-HEMTs.

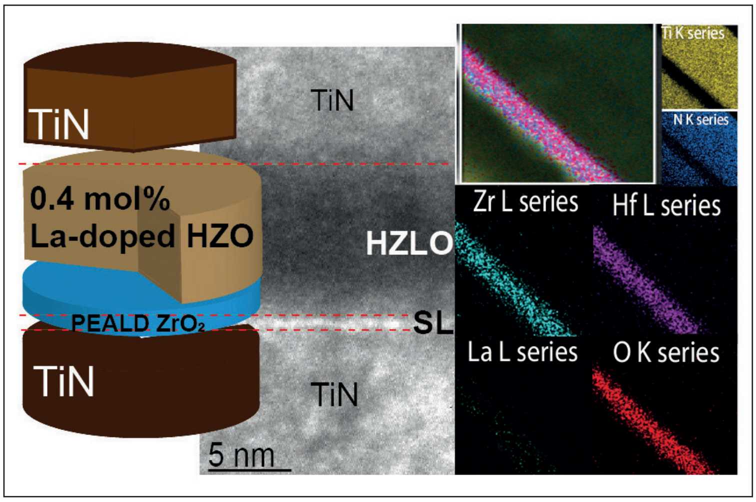
These hybrid, novel, high-performance devices combine good power-electronic characteristics with those associated with flash memory. Drawing on the low crystallisation temperature for solid solutions of $Hf_{0.5}Zr_{0.5}O_2$ and the feasibility of atomic layer deposition, the hybrid ferroelectric charge-trapping gate stack that lies at the heart of our devices has gradually gained a great deal of attention, because it enables a simple way to realise enhancement-mode operation with a threshold voltage of more than 2.5 V. The combination of the charge-trapping layer and the ferroelectric leads to a positive shift in the threshold voltage beyond the safety margin of +2.5 V after a positive gate bias initialisation. This ensures enhancement-mode operation (see Figure 2).

Our FEG-HEMTs deliver extraordinary static and dynamic performance. Their strengths include a high threshold voltage, a high off-state breakdown, and a low dynamic on-resistance. These transistors are particularly attractive for enhancement-mode high-frequency power-switching applications, and especially, their capability to provide a large forward gate voltage swing – this ensures tremendous immunity to large positive-voltage overshoot spikes. However, for the *p*-GaN power transistors, a gate stress of more than 10 V could easily result in gate breakdown.

The ferroelectric charge trap gate is still in its infancy, and more intensive research and development are needed before the commercialisation of this power device. A critical



➤ Figure 2. Polarisation as function of voltage for TiN/ lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$ (HZLO) (10 nm)/ TiN metal-ferroelectric-metal stacks.



➤ Figure 3. Schematic structure, transmission electron microscopy image, and energy-dispersive spectroscopy mapping of the TiN/ lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$/plasma-enhanced ALD ZrO_2 seed layer/ TiN metal-ferroelectric-metal stacks.

issue for every form of enhancement-mode GaN MIS-HEMT is its threshold voltage stability. This is especially important for GaN FEG-HEMTs, due to the charge-trapping nature of the charge-trapping layer, and also the stability of the ferroelectric behaviour – any changes here will have a big impact on threshold voltage behaviour, and can lead to instability in this key characteristic. It's also important to note that the reliability of the FEG-HEMT could be accelerated by electron-impact ionization and the generation of thermal defects.

To further advance our devices, we have introduced lanthanum-doping to our $Hf_{0.5}Zr_{0.5}O_2$, using a seed layer ferroelectric engineering technique. Read on to discover the effect of lanthanum doping on $Hf_{0.5}Zr_{0.5}O_2$ ferroelectric thin films, as well as how a ferroelectric-engineered enhancement-mode FEG-HEMT can increase the charge retention time and the time-dependent dielectric breakdown lifetime for this type of device, as well as improving its gate swing. These advances are helping to bring devices with a ferro-charge-trapping gate stack closer to commercialisation.

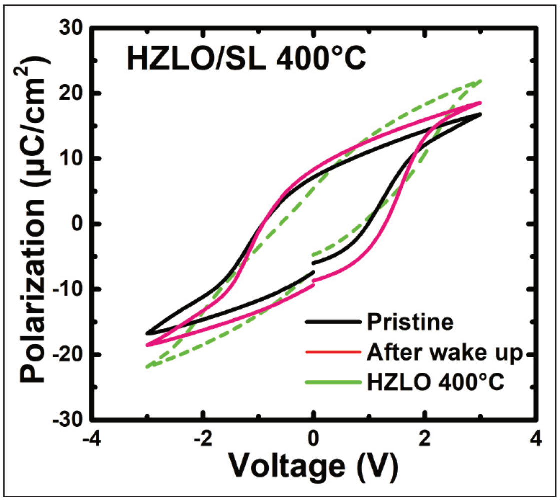
Ferroelectric engineering

The benefit of doping with elements from the lanthanoid series, and large trivalent dopants in general, is that they can increase the ferroelectric phase in HfO_2 films and enhance the stability of the threshold voltage, thanks to a larger remnant polarisation after initialisation. In addition, when lanthanoids are added to $Hf_{0.5}Zr_{0.5}O_2$ films with an acceptor centre, this can shift the Fermi level of the $Hf_{0.5}Zr_{0.5}O_2$ to the mid-gap position, leading to a significant reduction in leakage current. A lower leakage current is advantageous on many fronts, enabling an increase in gate voltage swing, a lengthening of the time-dependent dielectric breakdown, and more complete charging during initialisation.

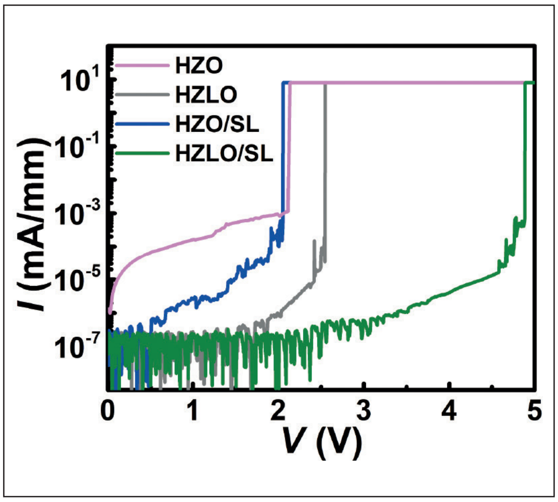
We have plotted polarisation-voltage loops of our lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$ metal-ferroelectric-metal structures for different post-metal annealing temperatures. We found that polarisation increases with annealing temperature, and only the highest annealing temperature, 700 °C, caused the sample to exhibit a wake-up-free behaviour in its pristine state.

Additional measurements showed that lanthanum doping delivers a significant reduction in the leakage current of these structures. Here, lanthanum acts as an amorphiser in hafnium oxide.

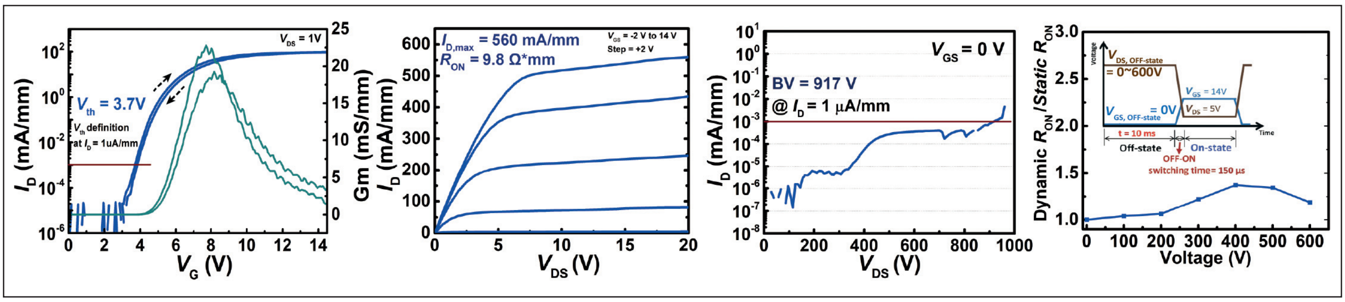
To lower the thermal budget while maintaining the benefits of lanthanum doping – including a high remnant polarisation and a reduced leakage current – we introduced a seeding layer. Inserting a seed layer of ZrO_2, grown by plasma-enhanced atomic layer deposition, beneath the lanthanum-doped



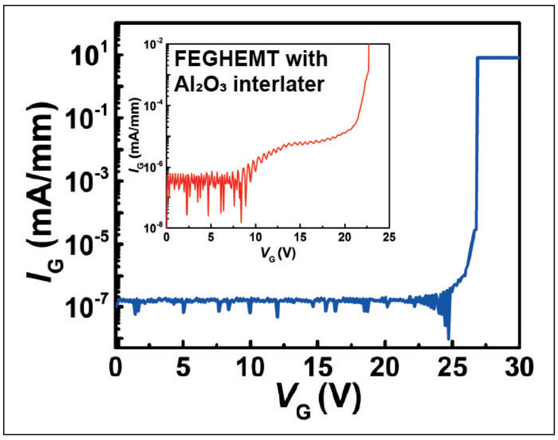
➤ Figure 4. Polarization versus voltage plots of lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$ metal-ferroelectric-metal stacks featuring a ZrO_2 seed layer.



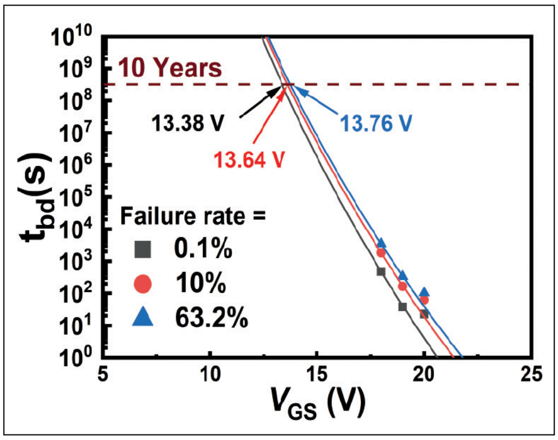
➤ Figure 5. DC leakage current characteristics.



➤ Figure 6. Static and dynamic on-resistance performance of the FEG-HEMT with a laminated ferroelectric gate stack formed with lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$, grown on a ZrO_2 seed layer.



➤ Figure 7. I_G-V_G gate leakage and gate breakdown characteristics. Inset shows data from previous works without the enhanced ferro-charge trapping gate stack.



➤ Figure 8. Lifetime prediction of the FEG-HEMT with lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$, grown on a ZrO_2 seed layer.

$Hf_{0.5}Zr_{0.5}O_2$ enhanced its nucleation and slashed the temperature required for post-deposition annealing (see Figure 3). Our measurements revealed that the addition of the seed layer also increased the strength of the polarisation by 50 percent, and cut the annealing temperature for wake-up-free behaviour from 700 °C to 400 °C (see Figure 4). From this, we have concluded that we have realised a more stable ferroelectric behaviour, which aids the threshold-voltage stability of FEG-HEMTs. The addition of the seed layer, as well as the introduction of lanthanum, benefits electrical characteristics, with the soft breakdown significantly muffled and the hard breakdown further delayed (see Figure 5).

We have found that the addition of our ZrO_2 seed layer promotes the formation of the o-phase, improves crystallinity, and reduces the thermal budget. This led us to investigate whether this seed layer could decrease the annealing temperature required for the FEG-HEMT to exhibit its ideal characteristics.

Initial results are very encouraging. Our enhancement-mode GaN FEG-HEMT exhibits a positive threshold voltage of 3.7 V and threshold voltage hysteresis of just 0.12 V (see Figure 6). The output characteristics are a maximum drain current density of 560 mA/mm and an on-resistance of 9.8 Ω·mm. The off-state breakdown voltage is as high as 917 V at a gate-source voltage of 0 V, while the ratio of dynamic to static on-resistance is low, with a value of just 1.37.

Improving reliability

The combination of the lanthanum-doped $Hf_{0.5}Zr_{0.5}O_2$ and the seed layer leads to promising gate leakage and gate breakdown characteristics for the laminated ferroelectric gate stack (see Figure 7). Thanks to an enhanced nucleation seeding layer and crystallisation of La_2O_3, there is no longer a soft breakdown, and there is a high hard breakdown voltage. Improvements in gate breakdown lead to a larger off-state breakdown voltage, more complete charging of the charge trapping layer, and a higher gate swing.

We have undertaken an electric-field-accelerated time-dependent dielectric breakdown test on our

Our novel hybrid ferroelectric charge trap gate stack scheme has introduced a brand new perspective to realising enhancement-mode operation in GaN MIS-HEMTs, so that they meet system-level requirements found in the likes of the electric vehicle and photovoltaic industries

laminated ferroelectric-gate stacks with lanthanum doping and seed layers (see Figure 8). Using a gate-voltage power-law model to analyse trap generation and gate leakage mechanisms, we determined, using a failure rate of 0.01 percent, that our ferroelectric charge trapping gate stack could withstand a voltage of up to 13.38 V for 10 years.

This is a very encouraging result, given that in the literature, the equivalent figure for *p*-GaN devices with a failure rate of 63.2 percent is below 6.5 V. The high time-dependent dielectric breakdown shows that in addition to exceptional electrical characteristics, our FEG-HEMTs can handle a larger gate voltage swing.

As well as improving gate leakage, our ferroelectric-engineered FEG-HEMTs with a seed layer offer improved threshold voltage stability. These enhancement-mode devices have a threshold voltage of 3.1 V after a 30,000 s threshold-voltage retention test (V_{GS} = 0 V, V_{DS} = 0 V). What's more, the threshold voltage values after 1,000 s shows a stable trend. We estimate a threshold voltage of 2.9 V for a retention time of 10 years.

Our novel hybrid ferroelectric charge trap gate stack scheme has introduced a brand new perspective to realising enhancement-mode operation in GaN MIS-HEMTs, so that they meet system-level requirements found in the likes of the electric vehicle and photovoltaic industries.

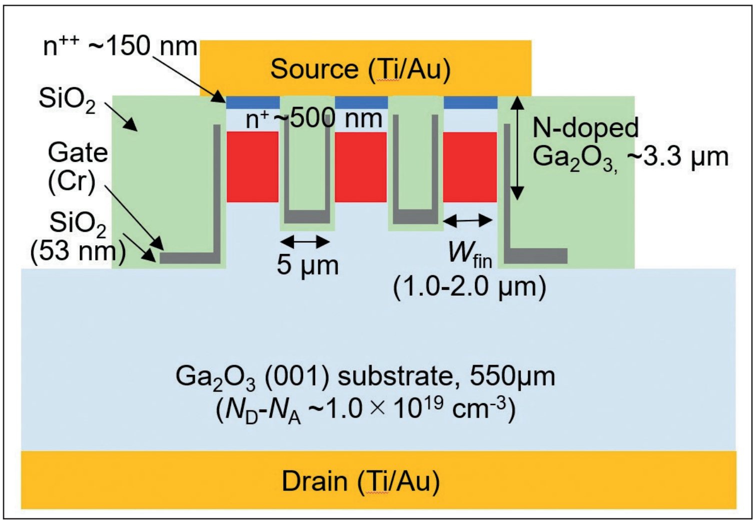
As well as the efforts described here, in recent years investigations have evaluated the possibility of improving FEG-HEMTs via nitrogen incorporation, other forms of ferroelectric engineering, and the addition of a source-connected field plate. With all this progress, there is good reason to believe that enhancement-mode GaN FEG-HEMT technology is destined to play a major role in the future of GaN power electronics.

Making headway with normally-off Ga_2O_3 transistors

Multiple sub-micron fins ensure far greater consistency in threshold voltage

A TEAM from Novel Crystal Technology (NCT), Japan, is claiming to have made significant progress in the design and performance of β-Ga_2O_3 vertical transistors. The team's normally-off devices are said to combine a ground-breaking consistency in threshold voltage with good values for on-resistance, channel mobility and current density.

This success will help to drive the progress of power devices made from β-Ga_2O_3. Drawing on a bandgap of 4.5 eV or more and a theoretical breakdown electric field of 6-8 MV cm^{-1}, devices made from this oxide are promising candidates for power electronics, particularly for deployment in power conditioning, power distribution and switching applications.



➤ Novel Crystal Technology's multi-fin transistors have a relatively small variation in threshold voltage

The Achilles heel for Ga_2O_3 is its lack of *p*-type doping. Due to this, normally-off characteristics have been realised by turning to lateral transistors with a recessed gate and a sub-micron fin-channel. However, with this design the threshold voltage is then governed by the recess depth and the sub-micron fin width.

"Although it is technically possible to fabricate FETs with sub-micron patterns, it requires equipment dedicated to microfabrication, such as an electron-beam exposure machine," argues Daiki Wakimoto from NCT. He explains that 100 mm and 150 mm production lines use i-line stepper exposure tools, which are less accurate and would struggle to offer sufficient control over the dimensions of the sub-micron FETs.

To overcome this issue, some researchers have investigated β-Ga_2O_3 high-resistive *p*-well-like structures, which have a threshold voltage that depends on the dopant concentration of deep acceptors. But these devices are yet to fulfil their promise: in once case, the device only operated in the sub-threshold regime; while another required a positive gate-bias of 25 V.

NCT's devices, which employ several sub-micron fins with a width that has very little impact on the threshold voltage, feature a 3.3 μm-thick nitrogen-doped Ga_2O_3 well layer. This well is grown by HVPE on an n^+ β-Ga_2O_3 substrate that does not have a drift layer.

Fabrication of the transistors began with two silicon-ion implantation steps, employed to connect the MOS channel to the source region, and to enable an ohmic contact to the source. A combination of mask deposition, electron-beam lithography and dry etching defined fin channels with near-vertical sidewalls, before the addition of: a 53 nm-thick SiO_2 gate dielectric by atomic layer deposition; and source, gate and drain contacts by electron-beam evaporation.

The team's portfolio of devices features fins with widths of either 1.0 μm, 1.5 μm or 2.0 μm. Each transistor has 14 fins, but only 10 are covered with the source electrode, because those on the outside often have large errors in dimension, due to what's described as a micro-loading effect.

According to Wakimoto, the etching environment differs between the pattern's outermost periphery and its inside. "We select conditions that stabilise the inner shape, so the error in the outer dimensions becomes larger than the inner dimensions." This problem has been seen in other materials, and resolved by optimising etching conditions. "Therefore, we believe that gallium oxide can be improved in the same way," added Wakimoto

Electrical measurements on the devices revealed: a threshold voltage of around 1.9 V; a current density of 760 A cm^{-2}; an on-resistance of 2.9 mΩ cm^2; and a mobility of around 100 cm^2 V^{-1} s^{-1}, a value that is said to be attractive for making 600 V to 3 kV MOSFETs.

Wakimoto are co-workers are now planning to increase the threshold voltage of their devices, via greater nitrogen doping, to 3 V or more, a pre-requisite for practical power devices.

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➤ D. Wakimoto *et al*. Appl. Phys. Express **16** 036503 (2023)

HEMTs: Optimising the architecture

An AlN back barrier and a thin GaN channel equips the HEMT with better characteristics for wireless communication

A PARTNERSHIP between researchers at Xidian University and Nanjing Electronic Devices Institute is claiming to have broken new ground with the GaN HEMT by combining an ultrathin GaN channel with an AlN buffer layer.

"As a result, the power characteristics, off-state leakage characteristics, voltage endurance characteristic, linearity and high-temperature performance of the device have been greatly improved," enthuses team spokesman Kui Dang from Xidian University.

This team from China is not the first to investigate this particular architecture, which benefits from the switch from a conventionally doped high-resistance GaN buffer to an AlN buffer with a far wider bandgap and the highest thermal conductivity of any common III-N. However, previous HEMTs with this design employed GaN channels more than 200 nm thick, with reports offering little detail into the device's carrier transport properties, high-temperature performance or breakdown characteristics. The HEMT fabricated by Dang and colleagues features a GaN channel just 120 nm-thick, realised by modulating the growth mode.

Growth of this device exploits previous work by the team, which determined that modulation during the MOCVD process alters the film-forming point of a GaN channel grown on an AlN buffer, opening the door to thinner channels. "That is why the results in previous reports all possess a thick GaN channel," explains Dang.

Key to the novel growth is an ammonia partial pressure – this slows deposition and advances the film-forming point of the GaN channel on the AlN buffer.

HEMTs were produced by loading SiC substrates into an MOCVD reactor and depositing: a nucleation layer; an AlN buffer, grown at high temperature; a GaN channel, formed by modulating the growth mode; a 1 nm-thick AlN interlayer; a 20 nm-thick $Al_{0.28}Ga_{0.72}N$ barrier; and a 2 nm-thick GaN cap.

Dang and co-workers have found that the film-forming point for GaN that's grown on AlN varies with the thickness of the AlN layer. Due to this, after deciding the thickness for the GaN channel, it's important to employ the appropriate associated thickness for the AlN buffer. For the 120 nm-thick buffer, a 414 nm-thick back barrier is employed, said to ensure excellent confinement of the two-dimensional electron gas, along with high crystalline quality and excellent transport properties.

The team have compared the performance of a device with this heterostructure with that featuring a more conventional design, including a 200 nm-thick high-resistance iron-doped buffer and a 1 μm-thick channel. HEMTs with a 50 μm gate width, a gate length of 1.5 μm, and a range of gate-to-drain spacings were fabricated from both heterostructures.

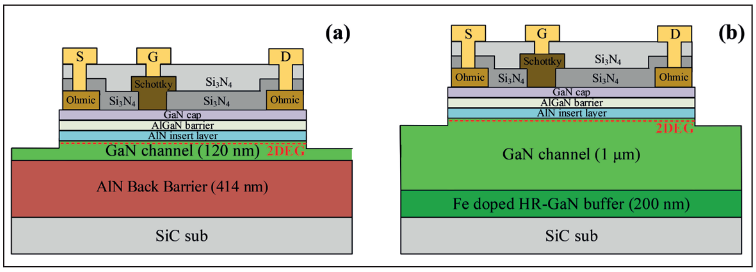
The HEMT with the conventional design had a slightly higher mobility, attributed to less interface scattering, which reduces mobility. However, the sheet density in the novel device is higher, thanks to the back barrier effect of the AlN buffer.

Additional measurements revealed that the HEMT with the AlN back barrier has a maximum drain current density of 1170 mA/mm, realised with a gate-source voltage of 3 V and a drain-source voltage of 8.6 V. This peak current density exceeds that for the conventional device, which topped out at 1047 mA/mm.

Measurements of DC transfer characteristics determined that the device with the AlN back barrier had a transconductance of 185 mS/mm, compared with 175 mS/mm for the reference design. The novel design also provides a greater degree of transconductance flatness, a valuable asset, because it is related to the linearity of microwave power devices. Greater linearity leads to a superior signal quality for communication, and a reduced code error rate.

Further benefits of the AlN back barrier are a quashing of the leakage current, particularly at elevated temperatures, and a hike in breakdown voltage – for devices with a 4.5 μm gate-to-drain spacing, introduction of the AlN barrier increased breakdown from 129 V to 209 V.

One of the team's next goals is to switch to an ultra-wide band gap AlGaN channel, which promises to deliver significant increases in power and efficiency. "The relevant research is under way," says Dong.



➤ Researchers from Xidian University and Nanjing Electronic Devices Institute have demonstrated that HEMTs with an AlN buffer (a) have superior characteristics to those with a GaN buffer (b).

REFERENCE

➤ Y. Zhang *et al.* Appl. Phys. Lett. **122** 142105 (2023)

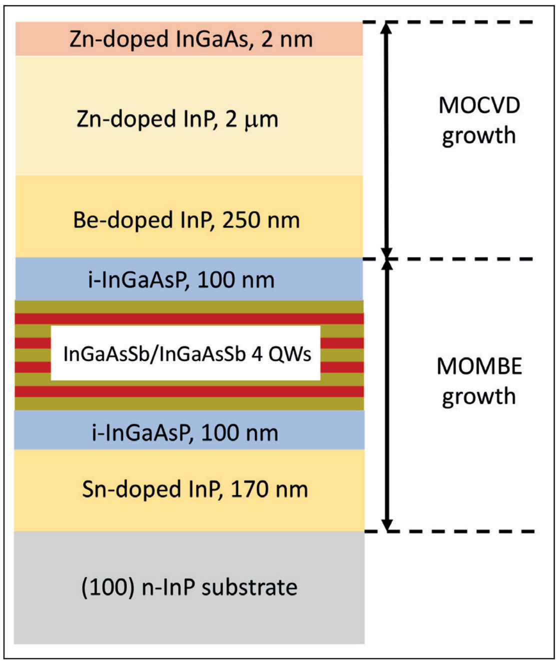
InP-based lasers surpass 2.2 µm

Thanks to the antimonide surfactant effect, strained InP lasers are delivering milliwatt emission at almost 2.3 µm

ENGINEERS from NTT, Japan, are claiming to have enhanced the capability of InP-based lasers by smashing through the 2.2 µm barrier. The team's InP ridge-waveguide lasers, featuring strained InGaAsSb multi-quantum wells, are capable of emitting output powers of several milliwatts at wavelengths up to 2.278 µm.

This breakthrough increases the attractiveness of the InP laser as an alternative to the lattice-matched GaSb-based laser in a number of applications requiring sources in the 2.1 µm to 2.3 µm range. While GaSb-based lasers in this spectral domain can be used for gaseous sensors, biomedical sensors and car exhaust analysers, processing technologies for this material system are not as mature as those for InP, which has been the key material for telecommunications for many decades.

Extending the wavelength of the InP-based laser is far from easy. To reach beyond 2.1 µm with an active region that employs InGaAs quantum wells, strain in this material system must exceed + 1.8 percent. The growth of such structures is challenging, requiring growth temperatures below 500 °C, alongside just a few quantum wells and layers less than 6 nm-thick. Of most concern are defects induced by large strain – they threaten to quash laser emission.



➤ The team from NCT employed a combination of metal-organic MBE and MOCVD for growth of their hetero-structures.

To avoid these issues, the team from NCT has turned to InGaAsSb quantum wells, supressing defect formation with surfactant mediated growth. These engineers are not the first to introduce antimony, which acts as a surfactant during the growth of strained InGaAs wells, but they have stretched the emission further than their peers by cranking up the concentration of this element.

Record-breaking lasers have been realised with a two-step epitaxial process, beginning with the growth of a four-period multi-quantum well active region sandwich by InGaAsP and InP, all grown by metal-organic MBE. After the team studied these structures, they turned to re-growth by MOCVD to add Zn-doped InP and InGaAs layers, prior to the formation of ridge-waveguide lasers. According to team spokesman Manabu Mitsuhara, the strained InGaAsSb lasers produced by NCT, could also be formed by other growth methods, such as MBE and MOCVD, which are capable of growing active regions with sharp interfaces.

Mitsuhara and co-workers studied a pair of samples grown by metal-organic MBE, featuring active regions with different thicknesses. X-ray diffraction determined that both heterostructures have smooth interfaces between the wells and barriers, while simulations of the well-defined satellite peaks suggest that the quantum wells have a strain of +2.3 percent and thicknesses of 6.4 nm in one sample and 8.4 nm in the other. Both samples have 20.6 nm-thick barriers with a strain of -0.23 percent.

Calculations based on the model-solid theory, drawing on photoluminescence measurements and strain value obtained from X-ray diffraction, suggest compositions for the well and barrier of $In_{0.82}Ga_{0.18}As_{0.95}Sb_{0.05}$ and $In_{0.45}Ga_{0.55}As_{0.95}Sb_{0.05}$, respectively.

Using standard processes for making InP telecom lasers, Mitsuhara and co-workers have fabricated ridge-waveguide lasers with a cavity length of 600 µm and a stripe width of 2.5 µm. These lasers, with quantum well thicknesses of 6.4 nm and 8.4 nm, produced several Fabry-Perot modes and had peak wavelengths of 2.190 µm and 2.278 µm, respectively, at 15 °C. Driven at 100 mA, the output power per facet of the longer-wavelength source fell from 5.9 mW to 2.4 mW when its operating temperature increased from 15 °C to 55 °C.

Mitsuhara claims that it should be easy to apply their lasers to absorption spectroscopy, which requires a tunable light source with single-mode operation and an output power of several milliwatts.

REFERENCE

➤ M. Mitsuhara *et al.* App. Phys. Lett **122** 141105 (2023)

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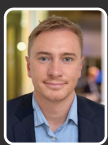

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